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High-energy neutrinos from blazars: flux predictions with LeHa-Paris code and
stacking analysis with KM3NeT/ARCA data

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For all those who have hit the road again

*«Grazie a chi
Mi ha regalato un movimento
Allontanandomi da qualcosa
E avvicinandomi a qualcos'altro»*

Amori con le ali — Niccolò Fabi

ABSTRACT

In the scenario of multi-messenger astronomy, high-energy neutrinos provide a unique probe of hadronic processes occurring in extreme astrophysical environments. These neutrinos are thought to originate from the same sources that accelerate cosmic rays, or from their surroundings, where sufficient matter or radiation fields allow part of the energy to be converted into secondary particles. Because they are neutral and weakly interacting, neutrinos can travel cosmological distances without absorption or deflection, preserving information about their origins. Their detection can therefore play a key role in identifying the sources of cosmic rays, even at the highest energies. For this purpose, large-scale neutrino telescopes are being constructed worldwide. The KM₃NeT Collaboration, building on the experience of the ANTARES telescope, is deploying two Cherenkov neutrino detectors in the deep Mediterranean Sea: KM₃NeT/ARCA and KM₃NeT/ORCA. KM₃NeT/ARCA, primarily dedicated to neutrino astronomy, will instrument a volume of about one cubic kilometer and will be sensitive to neutrinos from 100 GeV up to multi-PeV energies. Thanks to its modular design, it has already been collecting data during construction and is expected to significantly contribute to high-energy neutrino observations.

This thesis focuses on searches for point-like sources of cosmic neutrinos with KM₃NeT/ARCA, targeting blazars as potential extragalactic neutrino factories. Expected neutrino fluxes from high-frequency-peaked BL Lac objects are obtained by modeling the emission of PKS 2155-304 with the LeHa-Paris numerical code, which simulates radiative processes in relativistic jets and photo-meson interactions. This approach is extended to a larger source sample selected from the 3HSP catalogue. The resulting flux predictions are used as templates in stacking analyses based on binned likelihood methods, using data from several KM₃NeT/ARCA configurations. Additionally, the detector performances in identifying point-like neutrino sources are investigated using time-integrated and time-dependent unbinned analysis techniques, laying the basis for more sensitive neutrino point source and flares searches.

CONTENTS

Introduction	1
1 HIGH-ENERGY COSMIC MESSENGERS	5
1.1 Cosmic rays	6
1.1.1 Mass composition	6
1.1.2 Energy spectrum	7
1.1.3 Acceleration mechanism of cosmic rays	10
1.1.4 The puzzle of ultra-high-energy cosmic rays	12
1.1.5 Cosmic particles accelerator candidates	15
1.2 Gamma rays	18
1.2.1 Astrophysical gamma rays: hadronic interactions	20
1.2.2 Astrophysical gamma rays: leptonic interactions	21
1.3 Gravitational waves	23
1.4 Neutrinos	24
1.4.1 Neutrino properties and interactions	24
1.4.2 Neutrino fluxes	26
1.4.3 Atmospheric neutrinos	28
1.4.4 Astrophysical neutrinos	30
1.4.5 The big picture: multi-messenger astronomy	32
2 NEUTRINO ASTRONOMY	35
2.1 Detection principle of high-energy neutrinos	35
2.1.1 Light propagation	36
2.2 Event signatures in neutrino telescopes	38
2.3 Background signatures in deep-sea neutrino telescopes	40
2.3.1 Environmental background	40
2.3.2 Physical background	41
2.4 Neutrino telescopes	42
2.4.1 Under-ice neutrino telescopes	43
2.4.2 Underwater neutrino telescopes	44
2.5 Latest results from high-energy neutrino telescopes	46
2.5.1 Diffuse neutrino signal	47
2.5.2 Diffuse neutrino emission from the Galactic Plane	49
2.5.3 Neutrino point sources	50
3 KM3NET NEUTRINO TELESCOPE	55
3.1 KM3NeT infrastructure	56
3.1.1 Detector sites	56
3.1.2 Photomultiplier tubes	58
3.1.3 Digital Optical Modules and Detection Units	59
3.2 Trigger and data acquisition	61
3.3 Detector calibration	62
3.3.1 Position calibration	62
3.3.2 Charge calibration	63
3.3.3 Time calibration	63

3.4	KM ₃ NeT performances	65
3.4.1	Angular resolution	65
3.4.2	Energy resolution	66
3.4.3	Effective Area	67
3.5	Observation of an ultra-high-energy neutrino with KM ₃ NeT	68
4	EVENT SIMULATION AND RECONSTRUCTION IN KM ₃ NeT	71
4.1	Event generation	71
4.2	Particle propagation and light production	74
4.2.1	Detector Response	74
4.2.2	Run-by-run approach	75
4.3	Event reconstruction	75
4.3.1	Track reconstruction	75
4.3.2	Shower reconstruction	77
5	STATISTICAL METHODS FOR POINT SOURCE SEARCHES	79
5.1	Binned maximum likelihood	80
5.1.1	Background and signal modeling	81
5.1.2	Likelihood formalism	82
5.2	Unbinned maximum likelihood	83
5.2.1	Likelihood PDFs	84
5.3	Pseudo-experiments	87
5.3.1	Binned searches	88
5.3.2	Unbinned searches	88
5.4	Statistical analysis	90
6	MODELING THE EMISSION OF HIGH-ENERGY NEUTRINOS FROM BLAZARS	93
6.1	Blazars	94
6.1.1	Spectral Energy Distribution	95
6.2	LeHa-Paris code	96
6.2.1	Leptonic processes	97
6.2.2	Hadronic processes	99
6.2.3	Physical constraints	101
6.3	The case of PKS 2155–304	102
6.3.1	Model optimization	106
6.3.2	Neutrino flux	109
6.4	Extension to astrophysical catalogues	109
6.4.1	Derivation of neutrino fluxes	112
6.4.2	Model validation	113
7	STACKING SEARCH FOR HIGH-ENERGY NEUTRINOS FROM BLAZARS	117
7.1	Data samples	117
7.1.1	Event selection	118
7.2	Detection prospects with KM ₃ NeT/ARCA6-21	124
7.2.1	Binned analysis	125
7.2.2	Sensitivity and discovery potential	129
7.3	Analysis strategy	130
7.3.1	Flux uncertainty and systematics	131
7.4	Results	133
7.4.1	Upper limits	134

7.4.2	Comparison with IceCube results	135
8	TIME-INTEGRATED AND TIME-DEPENDENT ANALYSES WITH KM3NeT/ ARCA21 USING AN UNBINNED LIKELIHOOD METHOD	137
8.1	Instrument response functions	137
8.1.1	Effective area	138
8.1.2	Point Spread Function	138
8.2	Search methods	140
8.3	Comparison between binned and unbinned approaches	142
8.3.1	Systematics effect	144
8.4	Towards a time-dependent unbinned likelihood framework	144
	Summary and conclusions	149
	Appendix	151
A	STUDY OF THE SYNCHRONIZATION LATENCIES BETWEEN THE BASE MODULES OF KM3NeT/ARCA	153
A.1	White-Rabbit synchronization in KM3NeT	154
A.2	Definitions	155
A.3	Synchronization latencies of KM3NeT/ARCA base modules	156
B	SELECTED BLAZARS FROM THE 3HSP CATALOGUE	159
	Bibliography	179

LIST OF FIGURES

Figure 1	Relative chemical abundances of elements in low energy CRs and in Solar System, normalized to the value 100 of Carbon. Image from [21].	7
Figure 2	The all-particle energy spectrum of CRs. Data are taken from the experiments in the legend. Image from [24].	8
Figure 3	Cosmic-rays energy spectrum and mass composition. This plot reflects a recent attempt for a combined fit of flux and composition measurements by different experiments. The differential energy spectrum has been multiplied by $E^{2.6}$ in order to display the features of the steep spectrum. Features such as the knee, second knee and ankle mark softening or hardening of the spectrum which can be approximated by a power law in between these features. Image from [27].	9
Figure 4	Simulated trajectory of charged particles in the galactic magnetic field. Low-energy charged particles are bent and wound by magnetic fields, but those above 10^{20} eV travel along almost straight trajectories. Image from [28].	9
Figure 5	Picture of Fermi acceleration of I order. Seen in the laboratory frame, the shock is moving towards the left; seen in the shock frame, the upstream fluid is moving towards right. A schematic typical path of a shock-accelerated particle is shown. Image from http://sprg.ssl.berkeley.edu/~pulupa/illustrations/	11
Figure 6	Mass composition of the primary CRs flux performed by PAO, through the study of the maximum development of the associated air shower ($X_{\max}$), expressed in units of g/cm^2 . Image from [35].	13
Figure 7	Comparison between the Pierre Auger UHECR spectrum (in blue dots and referred as <i>this work</i>) and the Telescope Array one (red markers). Spectra are scaled by E^3 to better appreciate its structure. Image from [38].	14
Figure 8	Sky map in equatorial coordinates showing the CR flux above 8 EeV. The Galactic center is marked with an asterisk and the Galactic plane is shown by a dashed line. Image from [39].	14

Figure 9	Hillas plot showing candidate UHECRs sources as colored areas on the $B - R$ plane (magnetic field versus size of the accelerating region multiplied by its Lorentz factor Γ with respect to the observer). Acceleration up to 10^{20} eV is possible only above diagonal lines, that define the minimal value for the BR product needed to satisfy the Hillas condition. The results are shown for protons and iron nuclei, in red and blue respectively, through solid lines for maximum shock velocity ($\beta = 1$) and dashed lines in the case of $\beta = 0.01$. Image from [40].	16
Figure 10	The all-sky Fermi photon count map above 1 GeV. The map is based on Galactic coordinates and is obtained in 12 years of observations. The bright band in the center shows the emissions from our Milky Way. Individual strong sources of extragalactic origin can be also seen as bright spots. (Credits: NASA).	18
Figure 11	Sky map in Galactic coordinates showing the 4FGL sources by their class. All AGN classes are plotted with the same blue symbol for simplicity. Other associations to a well defined class are plotted in red. Un-associated sources and sources associated to counterparts of unknown nature are plotted in black. Image from [48].	19
Figure 12	Significance maps of the region monitored by LHAASO with its two sub-detectors: WCDA and KM2A. Image from [50].	20
Figure 13	SED for photons produced in leptonic and hadronic models. Four different branches for the spectrum are related to different production mechanisms from E^{-2} parent particles and indicated with I, II, III, IV. Image from [28].	22
Figure 14	Top panel: INTEGRAL lightcurve of GRB 170817A with the energy range starting approximately at 100 keV and with a high energy limit of least 80 MeV. Bottom panel: the time-frequency map of GW170817 was obtained by coherently combining LIGO-Hanford and LIGO-Livingston data. Black line is referred to the time of the merger. Image from [55]. . .	23
Figure 15	Neutrino DIS: a neutrino of four-momentum p interacts with a nucleon of mass M , at rest in the laboratory frame, giving in final state a lepton l' , of four-momentum p' , and a hadronic shower of four-momentum P' . Image from [62]. . .	25
Figure 16	Neutrino cross section as a function of the energy. The different curves are for CC (blue) and NC (orange) neutrino-nucleon scattering of neutrinos with energy E . The line with the resonant behavior shows the cross section for Glashow resonance. Image from [64].	26

Figure 17	Natural sources of neutrinos. Neutrino spectra of the cosmic neutrino background (CvB-gray), solar neutrinos (light orange), terrestrial neutrinos (orange), from SN 1987A and the diffuse supernova neutrino background (light red), from atmospheric neutrinos (green), from AGNs and from GRBs (red and cyan, respectively) and GZK neutrinos (violet) are reported. Image from [64].	27
Figure 18	Measurements of the atmospheric neutrinos flux performed by the Fréjus experiment [73], ANTARES [14] and IceCube [5]. The vertical axis is scaled with E^2 for better readability. Image from [64].	29
Figure 19	Photon mean free path as a function of the photon energy. Scattering over different contributions of EBL is reported as follows: infrared (blue), CMBR (red), and radio (green). Image from [44].	32
Figure 20	High-energy fluxes of gamma rays, neutrinos and CRs. Image from [79].	33
Figure 21	Earth map indicating the location of multi-messenger observatories that are either currently operating (circles) or planned (triangles). Satellites are outside to the map. Image from [79].	33
Figure 22	Cherenkov light emission and its wavefront angles. A particle is propagating for a time t with a velocity v in a medium of refractive index n . The wavefronts of light move at velocity c/n after the passage of the charged particle. Image from [64].	36
Figure 23	Absorption and scattering lengths in water as a function of the light wavelength. Image from [86].	37
Figure 24	Topologies for neutrino interactions in the instrumented volume of a neutrino telescope: a) CC interaction of a ν_μ produces a muon and a hadronic shower; b) CC interaction of a ν_τ produces a τ that decays into pions and ν_τ , tracing the double bang signature; c) CC interaction of ν_e produces both an electromagnetic and a hadronic shower; d) a NC interaction produces an undetectable neutrino and a hadronic shower. Image from [82].	38
Figure 25	Left: concentration of luminescent bacteria cultivatable at atmospheric pressure, as a function of depth. The data have been obtained from water samples taken at the Capo Passero site. Right: density of bioluminescent animals at the Capo Passero and Pylos sites, in autumn 2008 and spring 2009. (Dashed lines show 95% C.L.). Image from [88].	40

Figure 26	Flux, as a function of the cosine of the zenith angle θ , for atmospheric muons and atmospheric neutrino induced muons. Blue line refers to a depth of 1680 m in water and green line to a depth of 3880 m. Black line refers to an energy threshold of 100 GeV, while the red line to a 1 TeV threshold. Image from [82].	42
Figure 27	Architecture of the IceCube Observatory. Image from [93]. . .	43
Figure 28	Top view of the IceCube optical detector arrays. Left: the IceCube-Gen2 optical array, in the reference "sunflower" design, instrumenting 7.9 km^3 . Center: the current 1 km^3 IceCube array. Right: the low-energy IceCube Upgrade, focusing on neutrino oscillation properties. Image from [93].	44
Figure 29	General view of the Baikal-GVD detector in season 2025. Yearly progression of detector deployment is shown in the legend. Technological strings carrying lasers are also shown. Image from [96].	45
Figure 30	Schematic representation of the ANTARES detector, featuring 12 detector lines (L1–L12) and an additional line equipped with environmental monitoring instruments (ILO7). Lines L12 and ILO7 include test equipment designed for preliminary investigations into acoustic neutrino detection. On the left, a single storey is shown, comprising three optical modules and a metallic cylinder housing the Local Control Module (LCM). Every fifth storey is equipped with a LED beacon (positioned above the LCM) and a hydrophone (located at the bottom left) to facilitate acoustic triangulation. Image from [97].	46
Figure 31	Energy distribution of the observed cascade events compared to Monte Carlo predictions by the IceCube detector. Image from [102].	48
Figure 32	Overview of astrophysical diffuse flux measurements to date is shown. The green point and contours represent the best-fit and uncertainties from predominantly upgoing tracks in IceCube with 9.5 years of data [106]. These results are overlaid with IceCube data from high-energy starting tracks and cascades (red), predominantly contained cascades (blue), and predominantly starting tracks (orange). ANTARES result (gray) using both cascades and tracks from 9 years of data is also included for comparison. Image from [93].	49

Figure 33	The Galactic Plane in both photons and neutrinos, using Galactic coordinates centered on the Galactic Center. The panels provide various data: (A) optical image partially obscured by gas and dust; (B) integrated gamma-ray flux from Fermi-LAT; (C) expected neutrino flux derived from the π^0 template; (D) adjusted neutrino emission template with detector sensitivity and angular uncertainty; (E) significance of IceCube's neutrino observations. The pre-trial significance of the analysis is shown, with contours indicating regions of predicted diffuse neutrino emission. Image from [89].	50
Figure 34	Sky map of the point source scan in the Northern Hemisphere. The color scale represents the local p-value derived from the maximum likelihood analysis, with the spectral index treated as a free fit parameter, evaluated at each sky location. The map is displayed in Equatorial coordinates using a Hammer-Aitoff projection. Black circles mark the three most significant objects from the source list search, with the circle for NGC 1068 coinciding with the hottest spot in the Northern Sky. Image from [11].	51
Figure 35	Spatial scans of the 2014 neutrino flare candidate near the position of TXS 0506+056 are shown for both the original 2017 data sample (left) and the updated 2022 sample (right). In both panels, the best-fit parameters for the flare's start time, stop time, and spectral index are re-assessed at each location. The position of TXS 0506+056 is indicated by a black cross. Image from [111].	52
Figure 36	Multi-messenger light curves from the direction of the blazar J0242+1101 as a function of time since 2008. The top panel shows the weighted time distribution of ANTARES track-like (within 5°) and shower-like (within 10°) events near the source, with a box profile based on best-fit temporal parameters $\hat{\sigma}_t$ and $\hat{T}_0$. The second panel displays the OVRO radio light curve, highlighting variability over time. The third panel provides the binned gamma-ray light curve derived from Fermi-LAT observations. The bottom panel presents IceCube track-like events near J0242+1101, weighted by event energy, with a color scale indicating the angular distance of events from the source. Image from [117].	54
Figure 37	Cities and sites of KM3NeT. Yellow dots represent the sites where the KM3NeT detectors are being (or might be) instrumented. White dots indicate the cities of Collaboration institutions. Credits: km3net.org	55
Figure 38	Layout of the nominal BB of KM3NeT/ARCA, currently in construction. Detector elements are displayed as indicated in the legend.	57
Figure 39	Layout of the KM3NeT/ORCA BB. Image from [15].	58

Figure 40	<i>Left:</i> QE measurements of the photocathode as a function of wavelength for 56 PMTs. The green lines represent the results for individual PMTs, while the continuous black curve illustrates the mean value, with one standard deviation at each considered wavelength. Image from [123]. <i>Right:</i> the Hamamatsu photomultiplier tube.	58
Figure 41	Measured (effective) attenuation length at different underwater neutrino telescope sites. Image from [125].	59
Figure 42	The KM ₃ NeT digital optical module.	60
Figure 43	A loaded LOM on its anchor-frame ready for deployment. ..	60
Figure 44	a) Tilt amplitude and b) tilt orientation, for KM ₃ NeT/ARCA with 21 DUs. The different lines indicate different DUs. Image from [131].	62
Figure 45	KM ₃ NeT/ARCA angular resolution (left) and energy resolution (right) for ν_μ CC events selected as track and for ν_e CC events selected as shower. It is shown alongside the median angle between the neutrino and the outgoing lepton in CC interactions. Image from [119].	66
Figure 46	<i>Left:</i> the full KM ₃ NeT/ARCA effective area for a flux of $\nu_i + \bar{\nu}_i$ at trigger level for all neutrino flavors and interactions, selected as showers. Solid and dashed lines indicate $\cos(\theta) > 0$ and $\cos(\theta) < 0$ intervals respectively. The Glashow resonance (GLRES) is visible as a read peak in the simulation of $\bar{\nu}_e$ interactions. <i>Right:</i> the effective area for ν_μ CC events selected as tracks for different $\cos(\theta)$ ranges. Image from [119].	68
Figure 47	Normalized distributions of the number of PMTs triggered for simulated muon events with energies of 10, 100 and 1000 PeV. The vertical dashed line indicates the observed value for event KM ₃ -230213A, i.e. 3672. Filled histograms include systematic uncertainties, while dashed lines represent nominal simulations. The apparent truncation at high energies is due to muon tracks crossing the detector peripherally. Image from [12].	69
Figure 48	KM ₃ -230213A is indicated by the red star, with the error regions within R(68%), R(90%) and R(99%) shown as dotted, dashed and solid contours, respectively. The directions of the selected source candidates are shown as coloured markers, whose colours and marker type indicate the criterion according to which the source was selected. The sources are numbered according to their proximity to KM ₃ -230213A. Image from [12].	70
Figure 49	Illustration of the detector can (yellow) relative to the detector lines (blue). Image from [136].	72
Figure 50	Schematic view of the interaction volume for track-like events. Image from [136].	72

Figure 51	Coordinate system used in the muon trajectory fit. Image from [149].	75
Figure 52	The median energy resolution (solid line) of the reconstructed muon energy is shown as a function of the true muon energy, alongside the 68% and 90% quantiles. The standard deviation of the $\log_{10}(E_{\text{reco}}/E_{\mu})$ distribution is less than 0.3. Image from [149].	77
Figure 53	Performance of the shower vertex fit. The dark and light blue bands represent the 68% and 90% containment of the distribution, respectively, while the black line indicates the median. The left plot shows the distance between the reconstructed position and the true neutrino interaction point, projected along the shower axis. The right plot shows the distance between the reconstructed position and the shower axis. No quality cuts are applied. Image from [149].	78
Figure 54	Performance of the direction and energy fits for shower reconstruction. The dark and light blue bands represent the 68% and 90% containment of the corresponding error distributions, respectively, while the black line indicates the median. The left panel shows the median angular resolution as a function of the neutrino energy, whereas the right panel displays the energy resolution. The standard deviation of the error in the energy is approximately 5%. The median angular resolution is about 1.5° . Image from [149].	78
Figure 55	Expected signal (left) and background (right) PDFs at declination $\delta = -85^{\circ}$ for KM ₃ NeT/ARCA21 assuming an E^{-2} spectrum. Signal clusters near the source, while background dominates in bins covering larger solid angles.	81
Figure 56	Fraction of selected track-like events in the KM ₃ NeT/ARCA21 dataset as a function of the declination, for the point source selection described in Chapter 7. Distribution has been fitted using a spline function as functional form.	82
Figure 57	The reconstructed energy distribution of the selected track-like events from the KM ₃ NeT/ARCA21 dataset, corresponding to the point source selection described in Chapter 7, fitted using a sum of three Gaussian functions.	82
Figure 58	Angular resolution distribution, assuming an E^{-2} spectrum, for the tracks sample used in KM ₃ NeT/ARCA21 point source searches.	85
Figure 59	Cumulative angular resolution distribution, assuming an E^{-2} spectrum, for the tracks sample used in KM ₃ NeT/ARCA21 point source searches.	85

Figure 60	Number of selected track-like events in the KM ₃ NeT/ARCA21 dataset as a function of the cosine of their reconstructed zenith, after the point source selection described in Chapter 7. The selection on upgoing and slight horizontal events is visible as a cut at $\cos(\theta) = 0.1$. Distribution has been fitted using a spline function as functional form.	86
Figure 61	Reconstructed energy of KM ₃ NeT/ARCA21, for the selected track-like events from the point source selection, as a function of the true energy, weighted with an E^{-2} spectrum. The median is shown along with the 68% quantiles.	86
Figure 62	Event rate (B_{time}) for data collected by KM ₃ NeT/ARCA21 between September 2022 and September 2023, using a 1-day binning. The events shown are selected including well-reconstructed track-like events from upgoing or horizontal directions. Noise is excluded through cuts on the number of hits used in the reconstruction and on the likelihood fit parameter. Approximately 30,000 events are selected.	87
Figure 63	Normalized distributions of test statistic from the declination $\delta = -85^\circ$ assuming an E^{-2} energy spectrum, for an increasing number of injected signal strengths (colored lines). The null hypothesis (H_0) is indicated as a black line. The conversion between a number of signal events (n_s) and μ_{true} is simply a scaling factor.	88
Figure 64	Normalized distribution showing the angular error, as a function of the reconstructed energy, for simulations of cosmic ν_μ (both charged current and neutral current interactions), obtained at the KM ₃ NeT/ARCA21 point source selection level.	89
Figure 65	Illustration of the areas determining the p-value and the confidence level (C.L.) in two hypothetical H_0 and H_1 Gaussian test statistic distribution functions (λ). Image from [151].	91
Figure 66	KM ₃ NeT/ARCA21 acceptance calculated, at the point source selection level, for different declinations and assuming $\gamma = 2.0$ in Equation 73.	92
Figure 67	Bar chart of the possible contribution of different astrophysical source classes to the astrophysical neutrino flux measured by IceCube based on stacking analyses. The quoted values are 90% C.L. upper limits, except in the case of non-jetted AGN. See [155] for details.	94
Figure 68	The blazar sequence. Black, red, green, light blue and dark blue markers indicate FSRQs, LBLs, IBLs, HBLs and HBLs/TeV blazars respectively. Overlapped curves are analytic approximations. Image from [167].	96
Figure 69	Illustration of the emission region of a blazar traveling at relativistic speed. Distances (not to scale) do not refer to an explicit model, but are given here only for illustration. Image from [169].	97

Figure 70	Multi-wavelength observations of PKS 2155-304 combining data from Swift/UVOT, NuSTAR + XMM-Newton and Fermi/LAT. Data are taken from [176] and correspond to a low-state emission period of the source.	103
Figure 71	SED of PKS 2155-304 for the epoch 0 considered in the study of [178]. Red points are the data already shown in Figure 70, which will be the subject of this work. Black points are radio data, while gray points are the data from the 2008 campaign [179], shown for comparison. The black continuous line is the neutrino spectrum modeled in [178]. Image from [178]. ...	104
Figure 72	$dN/d\gamma$ distributions of the primary populations of electrons (dashed blue) and protons (dashed red), adopting the parameters of [178]. Vertical dashed green line corresponds to γ_{break}	104
Figure 73	Timescales of the processes involving protons and electrons, as a function of $\log(\gamma)$, calculated according to Section 6.2 and adopting parameters from [178].	105
Figure 74	Doppler factor δ as a function of the line-of-sight angle θ , assuming a bulk Lorentz factor $\Gamma = 16.53$ and corresponding to a velocity $\beta = 0.998$	105
Figure 75	Proton luminosity computed with LeHa-Paris as a function of $\log(\gamma_p^{\text{max}})$. Each point corresponds to the model with the lowest reduced χ^2 at that value of γ_p^{max} , and is color-coded by its numerical value.	107
Figure 76	χ^2 minimization grid in the B-R parameter plane. The color map indicates the reduced χ^2 value for each parameter combination, with the minimum (red cross) corresponding to the best-fit region. All parameters other than those shown are fixed at their best-fit values (Table 3).	108
Figure 77	χ^2 minimization grid in the γ_{break} -R parameter plane. The color map indicates the reduced χ^2 value for each parameter combination, with the minimum (red cross) corresponding to the best-fit region. All parameters other than those shown are fixed at their best-fit values (Table 3).	108
Figure 78	SED of PKS 2155-304 for the best-fit model, compared to data from [176]. Associated parameters are reported in Table 3. Radiation components not shown in the plot are subdominant. The blue continuum is the predicted all-flavor neutrino SED.	109
Figure 79	Best-fit single-flavor neutrino flux from PKS 2155-304, derived with the LeHa-Paris code, as a function of the neutrino energy, between 10^2 GeV and 10^8 GeV.	110
Figure 80	Sky map in equatorial coordinates showing the selected HBLs sources from the 3HSP catalogue. A total of 232 sources satisfy the selection criteria. The Galactic Plane is indicated in red.	111

Figure 81	Distribution of the logarithm of $\nu_{\text{peak}}^{\text{syn}}$ [Hz] for the sources selected in this study. 111	111
Figure 82	Distribution of the measured redshift z for the sources selected in this study. 111	111
Figure 83	Logarithm of the synchrotron peak flux as a function of $\log(\nu_{\text{peak}}^{\text{syn}} [\text{Hz}])$ for the selected HBLs (violet dots), in comparison with EHLs (yellow dots). 111	111
Figure 84	Logarithm of the synchrotron peak frequency, $\log(\nu_{\text{peak}}^{\text{syn}} [\text{Hz}])$, as a function of their measured redshift (z) for the HBLs selected in this work. 111	111
Figure 85	Expected neutrino fluxes for the 232 selected HBLs (dashed colored lines) and their stacked flux (solid black line). Both neutrino and antineutrino separation and their oscillated flavor composition at Earth are considered. 113	113
Figure 86	Mrk 421 SED snapshots for the four selected epochs, labeled with different colors. Data are taken from [185]. 114	114
Figure 87	Mrk 421 SED based on parameters in Table 4. The continuous blue line shows the neutrino flux predicted with LeHa-Paris; the continuous red line shows the PKS 2155–304 neutrino template rescaled to Mrk 421. Radiation components not shown in the plot are subdominant. Data are taken from [185]. 114	114
Figure 88	VER J0521+211 experimental SED. Data are taken from Swift-UVOT, Swift-XRT, Fermi-LAT and VERITAS, going from lower to higher energies [186]. 115	115
Figure 89	SED of VER J0521+211 based on the best-fit parameters reported in Table 5. Blue solid line represents the neutrino spectrum of the model, while the solid red line shows the PKS 2155–304 template rescaled to this source. Radiation components not shown in the plot are subdominant. Data taken from [186]. 116	116
Figure 90	<i>Left:</i> ratio between the fluxes of Mrk 421 obtained by rescaling the PKS 2155-304 template (solid red line of Figure 87) and by modeling its SED with LeHa-Paris (solid blue line of Figure 87). <i>Right:</i> ratio between the fluxes of VER J0521+211 obtained by rescaling the PKS 2155-304 template (solid red line of Figure 89) and by modeling its SED with LeHa-Paris (solid blue line of Figure 89). In both panels, the energy range 1–100 PeV is indicated by a gray band. 116	116
Figure 91	Exposure, in Mton-years, as a function of time for the different KM3NeT/ARCA detector configurations. Vertical and horizontal grey dashed lines indicate the dataset which was unblinded in the first iteration of point source and diffuse analyses with KM3NeT/ARCA (e.g., see [134] and [189]). Updated analyses include the full KM3NeT/ARCA21 period (e.g., see [190] and [191]). 118	118

Figure 92	Distribution of the reconstructed energy for KM ₃ NeT/ARCA21 data and MC simulations. KM ₃ -230213A is visible as an outlier of the dataset. The blue line represents the number of atmospheric muons, while the magenta and green lines show the expected numbers of cosmic and atmospheric neutrinos, respectively. The black dots correspond to the observed data, and the MC sum is indicated by the light blue line. Same color codes apply to Figures 93-97.	121
Figure 93	Distribution of the reconstructed track angle (supplementary to the zenith angle) for KM ₃ NeT/ARCA21 data and MC simulations.	121
Figure 94	Distribution of the likelihood-based fit quality variable (lik) for KM ₃ NeT/ARCA21 data and MC simulations.	122
Figure 95	Distribution of the reconstructed track length for KM ₃ NeT/ARCA21 data and MC simulations.	122
Figure 96	Distribution of the number of hits used in the reconstruction ($N_{\text{hits}_{\text{rec}}}$) for KM ₃ NeT/ARCA21 data and MC simulations.	122
Figure 97	Distribution of the uncertainty of the reconstructed track direction (β_0) for KM ₃ NeT/ARCA21 data and MC simulations.	122
Figure 98	Distribution of the reconstructed track energy in the KM ₃ NeT/ARCA6 and KM ₃ NeT/ARCA8 periods. Data are reported as black dots, while MC simulations are color-coded as in the legend. Image from [190].	123
Figure 99	Distribution of the reconstructed track energy in the KM ₃ NeT/ARCA19 and KM ₃ NeT/ARCA21 periods. Data are reported as black dots, while MC simulations are color-coded as in the legend. Image from [190].	123
Figure 100	Median angular resolution of the selected track-like events for different KM ₃ NeT/ARCA configurations, with 68% quantiles shown as colored bands. Image from [190].	124
Figure 101	Effective area of the selected track-like events for different KM ₃ NeT/ARCA configurations, with the ANTARES effective area also shown. Image from [190].	124
Figure 102	Expected signal (left) and background (right) PDFs at $\delta = -85^\circ$ for KM ₃ NeT/ARCA21. Signal PDF is weighted with the PKS 2155-304 flux. Compared to a E^{-2} power-law assumption (Figure 55), the signal PDF exhibits a pronounced shift towards higher reconstructed energies, reaching the PeV scale.	125
Figure 103	Percentage variation of the expected signal event rate from modified MC simulations in KM ₃ NeT/ARCA21, for each parameter modification (as specified in the legend), with respect to the standard MC simulation, shown as a function of reconstructed neutrino energy. Image courtesy of F.Filippini.	126

Figure 104	Fraction of selected track-like events (top panels) and expected signal and background PDFs (bottom panel) for the KM ₃ NeT/ARCA6 first period.	127
Figure 105	Fraction of selected track-like events (top panels) and expected signal and background PDFs (bottom panel) for the KM ₃ NeT/ARCA6 second period.	127
Figure 106	Fraction of selected track-like events (top panels) and expected signal and background PDFs (bottom panel) for the KM ₃ NeT/ARCA8 period.	128
Figure 107	Fraction of selected track-like events (top panels) and expected signal and background PDFs (bottom panel) for the KM ₃ NeT/ARCA19 period.	128
Figure 108	KM ₃ NeT/ARCA6–21 point source sensitivities, expressed as $n_s^{90\% \text{ C.L.}}$, compared between an E^{-2} power-law spectrum (pink dots) and the best-fit neutrino flux of PKS 2155-304 (purple dots). The red dot marks the sensitivity at the true location of PKS 2155-304.	129
Figure 109	KM ₃ NeT/ARCA6–21 point source discovery potential at 3σ ($n_{3\sigma}$) compared between an E^{-2} power-law spectrum (dark green dots) and the best-fit neutrino flux of PKS 2155-304 (yellow dots). The red dot marks the value of $n_{3\sigma}$ at the true location of PKS 2155-304.	129
Figure 110	Top 10 brightest sources, among the selected HBLs of the 3HSP catalogue, ranked by the expected neutrino yield in the KM ₃ NeT/ARCA detector. The expected number of signal events in KM ₃ NeT/ARCA6-21 is shown as a function of the sine of the source declination (δ).	130
Figure 111	Expected single-flavor neutrino fluxes, as derived from the rescaling approach, for the sources shown in Figure 110. The calculation already takes into account neutrino oscillations at Earth and the separation between neutrino and antineutrino.	131
Figure 112	Expected number of signal events in KM ₃ NeT/ARCA6-21, as a function of their energy, derived using the stacked neutrino fluxes of the 100 brightest HBLs in the sample. The energy range where 90% of the signal is expected is indicated as vertical red dashed lines.	132
Figure 113	Neutrino flux predictions for the 100 most luminous HBLs in the sample, obtained by rescaling from PKS 2155-304 (red thin lines). The summed flux levels are shown for their maximum (solid green), central (solid red) and minimum (solid orange) values, assuming an uncertainty factor of 10 determined through the model validation procedure. Theoretical predictions are shown in the energy range where 90% of the signal is expected in KM ₃ NeT/ARCA6-21 for the stacked flux.	132

Figure 114	ϕ_{90}/ϕ_0 at 90% C.L. plotted as a function of the number of stacked sources. Sources are stacked according to their expected neutrino yield in KM ₃ NeT/ARCA6-21 given by the assumed spectral model of LeHa-Paris. 133
Figure 115	Logarithm of the angular separation (α) between all possible pairs among the top 100 brightest sources in the selected sample of HBLs. This value is computed for every unique pair of sources within the top 100 list. 134
Figure 116	Sensitivity at 90% confidence level (solid red line) and discovery flux at 3σ significance (solid green line) for the stacked flux (solid blue), shown in the energy range where 90% of the signal is expected. The shaded light blue region indicates the flux uncertainty. The upper limit on the central flux is indicated as a red dashed line. 134
Figure 117	Sky map in equatorial coordinates of the KM ₃ NeT/ARCA6-21 unblinded dataset. Color code indicates the logarithm of the reconstructed energy for the select track-like events. 135
Figure 118	Comparison of 90% C.L. upper limits (dashed lines) on different neutrino flux models with the astrophysical diffuse flux measured by IceCube (solid green line) [198]. The IceCube upper limits include model-dependent predictions for HSP blazars (purple and black lines) and the 2LAC blazar stacking analysis, in an equal-weighting scheme, with $\Gamma_{\text{SI}} = -2.2$ (dashed green line). Theoretical models and IceCube upper limits are taken from [195]. The HBLs stacked flux calculated in this work is also shown (solid blue line) together with its uncertainty band (light blue shaded region, within its energy range of validity) and the corresponding KM ₃ NeT/ARCA6-21 90% C.L. upper limits (red dashed line). 136
Figure 119	Sky-averaged effective area of KM ₃ NeT/ARCA21, obtained at selection level for all (anti)neutrinos flavors, both in CC and NC interactions. As expected, the A_{eff} of $\bar{\nu}_e$ increases around 6 PeV due to the Glashow resonance (see 1.4.1). 139
Figure 120	KM ₃ NeT/ARCA21 $\frac{dP}{d \log_{10}(\alpha)}$ distribution for all ν_μ CC and NC selected track-like events with an E^{-2} energy spectrum, shown in the indicated energy ranges. 140
Figure 121	KM ₃ NeT/ARCA21 PSF for all ν_μ CC and NC selected track-like events with an E^{-2} energy spectrum. The (not-normalized) distribution is smoothed (red dashed line) in order to have, for very small angles, a constant function. 140
Figure 122	The test statistic as a function of the associated fitted number of signal events, corresponding to the injection of 10 signal events at $\delta = -85^\circ$ 141
Figure 123	Confidence level calculated as a function of the injected number of signal events. Sensitivity is extracted considering the line intersecting the fitted graph at 0.9. 142

Figure 124	P-value calculated as a function of the injected number of signal events. Dots are fitted between the 3σ and 5σ levels (dashed lines), in a one-sided convention. 142
Figure 125	Comparison between binned (solid red) and unbinned (red dashed) KM ₃ NeT/ARCA21 sensitivities to point-like sources, for an E^{-2} neutrino spectrum and considering only track-like events. The unbinned approach yields up to an improvement in sensitivity up to more than 10%. 143
Figure 126	Comparison between point source results in binned (solid lines) and unbinned (dashed lines) analyses. KM ₃ NeT/ARCA21 sensitivities (red), 3σ discovery flux (blue) and 5σ discovery flux (magenta) are compared considering an E^{-2} neutrino energy spectrum. 143
Figure 127	Comparison between binned (blue dots) and unbinned (red squares) KM ₃ NeT/ARCA21 sensitivities to point-like sources, for an E^{-2} neutrino spectrum and considering only the PSF systematic. 144
Figure 128	Comparison between binned (blue dots) and unbinned (red squares) KM ₃ NeT/ARCA21 sensitivities to point-like sources, for an E^{-2} neutrino spectrum, considering systematics on the PSF and on the acceptance. 144
Figure 129	Comparison between binned (blue dots) and unbinned (red squares) KM ₃ NeT/ARCA21 3σ discovery fluxes to point-like sources, for an E^{-2} neutrino spectrum, considering systematics on the PSF and on the acceptance. 145
Figure 130	3σ discovery potential of KM ₃ NeT/ARCA21 as a function of the flare's width σ_t . Results are shown for different declinations (δ) and are compared to the time-integrated discovery potentials (dashed horizontal lines), obtained at the same selection level of the time-dependent ones. 146
Figure 131	3σ discovery potential as a function of flare duration for a flaring source at declination $\delta = -15^\circ$. A uniform temporal distribution (blue dots) and a realistic background (red dots) based on the MJD of KM ₃ NeT/ARCA21's data are assumed. Time-integrated limit is also shown as a purple dashed line. 147
Figure 132	Comparison of the 3σ discovery potential at declination $\delta = -15^\circ$ for different central emission times of the flare: T_0 [MJD] = 59903 (dashed green), T_0 [MJD] = 60023 (dashed blue), and T_0 [MJD] = 60143 (solid red). Time-integrated limit is also shown as a purple dashed line. 148
Figure 133	Layout of KM ₃ NeT/ARCA21 at the time in which data have been collected for this study. Green dots are referred to operating DUs, blue squares to the Cable Termination Frame (CTF), while orange rhombuses indicate the JBs. 153

Figure 134	RTTC variations for DU5 over a 6-month period. Run numbers are reported on the x-axis. A maximum spread of 2.9 ns is observed between the lowest and highest RTTC values.	156
Figure 135	RTTC variations for DU9 over a 6-month period. Run numbers are reported on the x-axis. A jump of 14 ns is observed in correspondence of run 14762, because of the mentioned firmware issues.	157
Figure 136	RTTC variations for DU32 over a 6-month period. Run numbers are reported on the x-axis. A maximum spread of 70 ns is observed in correspondence of run 13842. Despite the presence of jumps, due to firmware issues (see above), the data exhibit periods of good stability, with RTTC variations contained within a few nanoseconds.	157
Figure 137	RTTC variations for DU12 over a 7-month period. Run numbers are reported on the x-axis. A jump of 9 ns is observed in correspondence of run 14762, linked to the known firmware issues.	157
Figure 138	RTTC variations for DU22 over a 7-month period. Run numbers are reported on the x-axis. A jump of 23 ns is observed in correspondence of run 14459, linked to the known firmware issues.	158

LIST OF TABLES

Table 1	Parameters of the lepto-hadronic model for PKS 2155-304, as described in [178], include: electron normalization K_e ; maximum proton Lorentz factor $\gamma_p^{\max}$; proton-to-electron ratio η ; proton spectral index α_p ; electron spectral indices $\alpha_{e,1}$ and $\alpha_{e,2}$; magnetic field B ; emission region size R ; and electron break energy γ_{break}	104
Table 2	Ranges of the proton normalization K_p^* for each value of $\log_{10} \gamma_p^{\max}$	106
Table 3	Parameters of the best-fit model for PKS 2155-304.	107
Table 4	Parameters of the Mrk 421 model using the LeHa-Paris code. Parameters not specified in this table are the same of the best-fit model obtained for PKS 2155-304. Resulting jet luminosity is $3 \cdot 10^{46}$ erg/s.	114
Table 5	Parameters of the VER J0521+211 model using the LeHa-Paris code. Parameters not listed are identical to those of the best-fit model obtained for PKS 2155-304. Resulting jet luminosity is $3 \cdot 10^{48}$ erg/s.	115
Table 6	Summary of event statistics for different KM3NeT/ARCA configurations.	124

INTRODUCTION

Multi-messenger astronomy has emerged over the past decade as a distinct discipline providing unique insights into the properties and processes of the physical Universe. Those insights arise from complementary information carried by cosmic probes as neutrinos, photons, gravitational waves (GWs) and cosmic rays (CRs). Nowadays, multi-messenger astronomy relies on the study of the electromagnetic counterpart in all its energy range (spanning over 20 orders of magnitude, including radio, infrared, optical, ultraviolet, X-rays and gamma-rays frequencies) but also probes the Universe in terms of other astrophysical messengers, combining the new possibilities offered by neutrino telescopes and the latest observatories of GWs, gamma rays and CRs. In such a way, it might be possible to have simultaneous access to the most energetic particles of the Universe, emitted by the same source, even more energetic if compared to the ones achieved by ground-based particle accelerators. At present, the Large Hadron Collider (LHC) at CERN is capable of proton-proton collisions with a center of mass energy of 13.6 TeV. In particular, the study of the flux of CRs showed that the radiation from the outer space not only extends to a wider energy range than previously thought, but is also made by several components. The measurements of the diffuse ultra-high-energy CRs (UHECRs) energy spectrum by the Pierre Auger Observatory [1] started in 2008, put on a firm ground the detection of a spectral cutoff above $10^{19.5}$ eV, possibly compatible with the GZK effect [2]. In addition, the Fermi Gamma-Ray telescope [3] measured a diffuse gamma-rays background extending into the sub-TeV range [4]. Since 2012-2013, IceCube detector at the South Pole [5] discovered, with increasing detail, a diffuse high-energy neutrino background of astrophysical origin at multi-TeV to PeV energies [6], demonstrating the existence of CRs accelerators in the Universe, most likely of extragalactic origin, although not yet associated with any specific source population. Since IceCube's discovery, high-energy neutrino astronomy has entered a new era. Neutrinos are neutral weakly interacting particles and can be generated by a wide range of energetic astrophysical environments. Thanks to their intrinsic properties, they are not diverted or absorbed in their path from their source to the Earth, unlike gamma rays and charged CRs, making them optimal cosmic probes to study the cosmos, since they can trace back to the astrophysical source responsible for their production. Neutrino astronomy has already led to several important milestones, such as the first association between a high-energy neutrino and a single source, i.e. the blazar TXS 0506+056. In September 2017 IceCube observed a neutrino of 290 TeV coming from the region of TXS 0506+056 [7], an Active Galactic Nuclei (AGN), belonging to the class of quasars, previously detected at GeV energies by EGRET [8] and observed in a flaring state by Fermi at the time of the neutrino detection [9]. Subsequently, IceCube archival data revealed that a high-energy neutrino flux from the direction of this source, integrated over the last 10 years, is dominated by a single bright neutrino

flare in 2014, constituted by 13 ± 5 neutrino events pointing to the direction of TXS 0506+056 [10]. More recently, in 2022, after having accumulated a decade of data with improved sensitivity, IceCube reported the evidence of NGC 1068 as a high-energy neutrino source at a significance level of 4.2σ [11], which can be interpreted as a smoking gun signature of hadronic particle acceleration at this source. Nevertheless, the latest milestone came in February 2025, when the KM3NeT Collaboration announced the detection of an UHE neutrino, KM3-230213A, with a reconstructed energy of 220 PeV, the most energetic yet observed [12]. The nature of this observation remains an open question. However, the detection of the KM3NeT event could indicate the existence of a new class of extreme cosmic accelerators, distinct from those responsible for the bulk of the high-energy neutrino flux, or could also represent the first observation of a cosmogenic neutrino, originating from the interaction of UHECRs with the background radiation that permeates the Universe. The hypothesis of a blazar origin is still viable, with several blazar-like catalogued objects reported as potential candidates [13], even if a definitive association remains elusive.

In this scenario, the first promising association between a high-energy neutrino event and TXS 0506+056 motivated successive studies aiming to identify the interconnection of blazars with the origin of astrophysical neutrinos. Their neutrino counterparts have been already studied by ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch), the first undersea neutrino telescope [14] located in the Northern Hemisphere and no longer operative after February 2022, and will be investigated by its successor KM3NeT (Cubic Kilometre Neutrino Telescope) [15], a deep-sea infrastructure housing a network of Cherenkov neutrino telescopes in the Mediterranean Sea. The detector KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss), located near Sicily, is dedicated to high-energy neutrino studies (from sub-TeV up to multi-PeV) and will have a volume of more than one cubic kilometer, reconstructing, with good precision, the neutrino's trajectory and energy. Being located in the Northern Hemisphere, KM3NeT observes most of the Southern Sky, including the Galactic Centre, primarily through track-like upgoing events that provide a clean view with drastically suppressed atmospheric muon contamination, thereby complementing IceCube's field of view. Thanks to its modular design, KM3NeT/ARCA can take data also during construction. Presently, 51 instrumented detector lines have been deployed.

This thesis, developed within the KM3NeT Collaboration, addresses two main objectives. Firstly, it presents a study in which neutrino fluxes from blazars are derived using the LeHa-Paris numerical code and subsequently analyzed through a stacking binned likelihood method with KM3NeT/ARCA. A novel framework is introduced, allowing theoretical predictions of blazar neutrino fluxes to be directly applied to the analysis of KM3NeT/ARCA data, collected during the period in which the detector operated with 6 to 21 detection units (KM3NeT/ARCA6–21). This approach aims to use physically motivated models, improving simultaneously the sensitivity of neutrino searches across different blazar subclasses, with special emphasis on High-frequency-peaked BL Lacs (HBLs), which are candidate accelerators of UHECRs. Secondly, the thesis focuses on the development of an unbinned likelihood approach to study the detection prospects of KM3NeT/ARCA

in its 21-string configuration (KM₃NeT/ARCA21) for the search of point-like neutrino sources. Unbinned analyses, which assess the probability of each event being signal or background, are expected to yield better sensitivity compared to binned approaches. The first time-dependent performances of the KM₃NeT/ARCA detector are also presented, assuming a box-shaped temporal profile for the signal emission. Additionally, a time calibration of the KM₃NeT/ARCA21 detector was performed by studying the synchronization latencies between its base modules (for details, see Appendix A).

The content is organized as follows: Chapters 1–4 review the state of the art in multi-messenger astrophysics and neutrino astronomy, covering the properties of high-energy neutrinos, detection principles and major research infrastructures, such as KM₃NeT. Details on the technical features and expected performances of the KM₃NeT detectors are also provided. Chapters 5–8 present the original work carried out in this thesis. In particular:

- Chapter 1 is dedicated to the various messengers from the high-energy Universe, with a focus on neutrinos, highlighting their properties, fluxes and importance within the multi-messenger astronomy picture;
- Chapter 2 outlines the fundamental detection principles of high-energy neutrinos, presenting major research facilities in the field, addressing the main sources of background and discussing recent results from high-energy neutrino telescopes;
- Chapter 3 describes the KM₃NeT research infrastructure, its trigger and data acquisition system, and the calibration techniques used to ensure precise measurements. It also presents the detector’s performance and highlights the notable observation of the KM₃-230213A event. The KM₃NeT Monte Carlo simulation chain, together with the reconstruction algorithms used to estimate neutrino energy and direction, is discussed in Chapter 4;
- Chapter 5 details the binned and unbinned maximum likelihood methods used in neutrino point source searches with KM₃NeT/ARCA, including the generation of pseudo-experiments and their statistical analysis;
- Chapter 6 introduces the LeHa-Paris code for modeling high-energy neutrino emission from blazars, focusing on the case study of PKS 2155–304, with its model optimization and neutrino flux derivation. The extension of the modeling approach to an astrophysical catalogue of blazars is also discussed;
- Chapter 7 describes a binned likelihood stacking search for high-energy neutrinos from HBLs, combining advanced statistical techniques with theoretical blazar models developed with LeHa-Paris. After describing the detection prospects of KM₃NeT/ARCA6-21 to the estimated PKS 2155-304 neutrino flux, it outlines the stacking analysis strategy and discusses its main results adopting the KM₃NeT/ARCA6-21 dataset;

- Chapter 8 presents additional studies aimed at improving point source sensitivity by means of an unbinned likelihood framework. It compares results from binned and unbinned likelihood methods including systematic effects, and introduces ongoing developments towards a time-dependent unbinned likelihood analysis.

HIGH-ENERGY COSMIC MESSENGERS

Astroparticle physics began with the discovery of cosmic rays (CRs) by the Austrian physicist Victor Hess in 1912 [16]. With a pioneering experiment, he performed ascents in hydrogen balloons in order to measure the atmospheric radiation with a gold-leaf electroscope, discovering that from ground level up to an altitude of 1 km the level of radiation was decreasing, while at 5 kilometers height it was increasing of a factor two if compared to the sea level. This increase could not be attributed to radioactivity from rocks on Earth's surface but was rather linked to the existence of an astrophysical radiation coming from the outer space, that is nowadays known with the name of "cosmic rays". Over the last century, numerous experiments have unveiled the characteristics of CRs flux, showing that their spectrum extends to extremely high energies, with particles reaching values as high as 10^{20} eV [17]. This suggests the existence of cosmic objects capable of accelerating particles or nuclei to such extreme energies. However, the origin of CRs remains one of the most elusive questions in high-energy astrophysics¹. The presence of interstellar and intergalactic magnetic fields bends and distorts the paths of charged CRs, hiding their sources. To trace back the locations of cosmic accelerators, it is essential to rely on neutral messengers. These neutral probes, being unaffected by magnetic fields, can travel in straight lines from their source, providing crucial directional information. According to the Standard Model (SM), two messengers meet these criteria: photons and neutrinos. Gamma rays can be traced back to their source and detected either indirectly, through the electromagnetic showers they induce when interacting with the Earth's atmosphere, or directly by space-based detectors. Despite the detailed sky maps provided by satellites that highlight astrophysical photon sources, the precise astrophysical process that gives origin to gamma rays remains unclear. This uncertainty stems from the fact that gamma rays can result from both leptonic processes, such as synchrotron emission or inverse Compton scattering of relativistic electrons, as well as from hadronic processes, like the decay of neutral pions (π^0) produced in proton-proton collisions. Furthermore, the transparency of the Universe to high-energy photons is not guaranteed at all energy scales. Photons with energies above several TeV may interact with the cosmic microwave background radiation (CMBR) or the infrared background, resulting in the production of electron-positron pairs (e^+e^-), which significantly reduces the flux of gamma rays reaching Earth. This opacity adds complexity to the study of distant sources using only gamma-rays data. Neutrino astronomy, however, provides an alternative and complementary approach

¹ In gamma-ray astronomy, the high-energy and very-high-energy regimes correspond to photon energies of 100 MeV–100 GeV and 100 GeV–100 TeV, respectively. In neutrino astronomy, the "high-energy" label refers to neutrinos in the 1 TeV–100 PeV energy range, and "ultra-high-energy" to those exceeding 100 PeV. In cosmic-ray astronomy, "ultra-high-energy" indicates energies above 1 EeV.

to studying cosmic accelerators. Neutrinos are produced exclusively in hadronic interactions, such as the decay of charged pions ($\pi^\pm$) and kaons ($K^\pm$), which result from proton-proton collisions or photohadronic interactions. Being neutral and weakly interacting particles, neutrinos can traverse dense astrophysical environments without being absorbed or deflected, making them optimal messengers for probing the innermost regions of cosmic sources. For instance, neutrinos with energies around 1 TeV have an incredibly small cross-section, on the order of 10^{-35} cm², allowing them to travel vast distances across the Universe without significant interaction. Detecting neutrinos, however, is a challenging task due to their weak interaction with matter. Large-scale detectors are required to observe a meaningful number of events, typically utilizing arrays of light sensors embedded in transparent media such as water or ice, following Markov’s original idea [18]. Several of these detectors are currently in operation, playing a crucial role in neutrino astronomy, which, together with gamma-ray observations, is essential for identifying the sources of CRs. While high-energy photons help in localizing astrophysical sources, neutrinos provide direct evidence of hadronic acceleration processes, offering a powerful tool for understanding the mechanisms at play in the most energetic environments of the Universe.

In this Chapter, all the messengers from the high-energy Universe are introduced. Cosmic rays, photons and gravitational waves are discussed respectively in Sections 1.1, 1.2, 1.3. Section 1.4 introduces neutrino properties and origin, pointing out their role in the multi-messenger picture.

1.1 COSMIC RAYS

Most of the questions underlying CRs physics are related to their origin and to which kind of physical mechanisms are capable of accelerating particles at such high energies. The answer is not yet fully known. However, it is clear that the greatest part of the flux has a Galactic origin, while highest energy CRs could be of extragalactic nature. Key information about CRs includes: their composition, the energy spectrum and their angular distribution, which at extremely high energies can offer insights into the direction from which they came from.

1.1.1 *Mass composition*

CRs are ordinary atomic nuclei accelerated to very high energies which arrive in the vicinity of the Earth, uniformly and isotropically, impacting the atmosphere and originating the so-called secondary CRs. The energetic particles generated by this process collide with other nuclei, resulting in the production of Extensive Air Showers (EAS). The EAS is generated by a series of interactions of the primary cosmic ray and its progeny with the atmospheric nuclei. These showers can be detected by ground-based experiments, enabling us to deduce the properties of high-energy cosmic rays. Primary Galactic CRs are mainly protons (85%), but also include a fraction (12%) of α particles (He nuclei), 2% of electrons and a remaining 1% of photons, heavy nuclei and neutrinos. These fractions vary highly over their energy range [19]. Figure 1 shows the relative abundance of Galactic CR el-

elements compared to the ones in Solar System. Both distributions show a peak in elements as carbon, oxygen, nitrogen and iron, while there is an excess abundance in CRs for light elements as lithium, beryllium, and boron. Same holds from calcium to manganese. This trend can be well explained by the continuous spallation processes in which oxygen and iron interact with the Interstellar Medium (ISM) producing lighter nuclei [20].

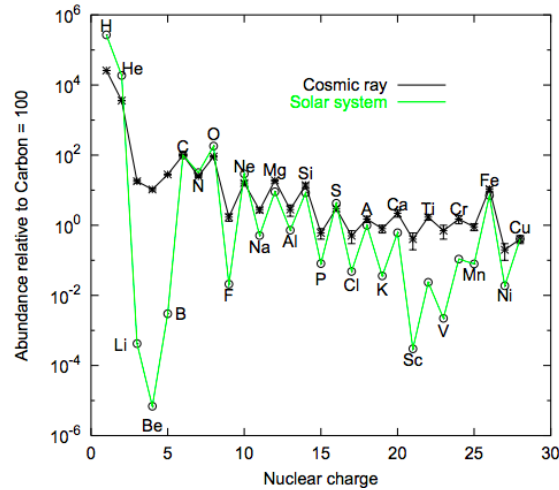


Figure 1: Relative chemical abundances of elements in low energy CRs and in Solar System, normalized to the value 100 of Carbon. Image from [21].

1.1.2 Energy spectrum

The study of CRs actually depends on their differential energy spectrum, which is strongly varying with energy (from ~ 1 GeV and up to ~ 100 EeV) and is effectively described by a power law over a wide range of energies,

$$\frac{dN}{dE} \sim E^{-\gamma} \text{ (GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\text{)}, \quad (1)$$

which is the result of both their acceleration at the source and their propagation in Galactic and/or extragalactic environments. The energy flux, shown in Figure 2, extends over at least 12 decades in energy with a corresponding decline in intensity of more than 10 decades. At the level of $10^{10} - 10^{11}$ eV, the flux is about 1 particle per square metre per second; around the so-called knee (3×10^{15} eV) it becomes 1 particle per square meter per year, while around the ankle (5×10^{18} eV) is at the level of 1 particle per square kilometre per year. Neglecting minor variation of the slope over the energy, we can consider that it is $\gamma \sim 2.7$ below the knee, steepening to $\gamma \sim 3.1$, and then flattening above the ankle, where $\gamma \sim 2.7$. This variation of the flux implies that several detection techniques are needed: for energies below 10^{14} eV direct measurements with balloons or satellites are performed, because it is still possible to detect a significant rate of events with a small sized detector. Beyond the PeV, indirect measurements are necessarily to be performed, exploiting EAS induced in the atmosphere and using ground based Cherenkov and fluorescence detectors [22]. Below 10 GeV the spectrum is modified due to solar modulation effects [23], characterized by recurrence of coronal mass ejections

(CMEs). CMEs are releases of magnetised plasma from the Sun's corona to the heliosphere. They are associated to solar flare episodes and influence the passage of CRs: during periods of solar activity, CME acts like a protective bubble, shifting aside CRs and shielding the Earth and its satellites. While, during periods of low solar activity, the flux reaches its maximum.

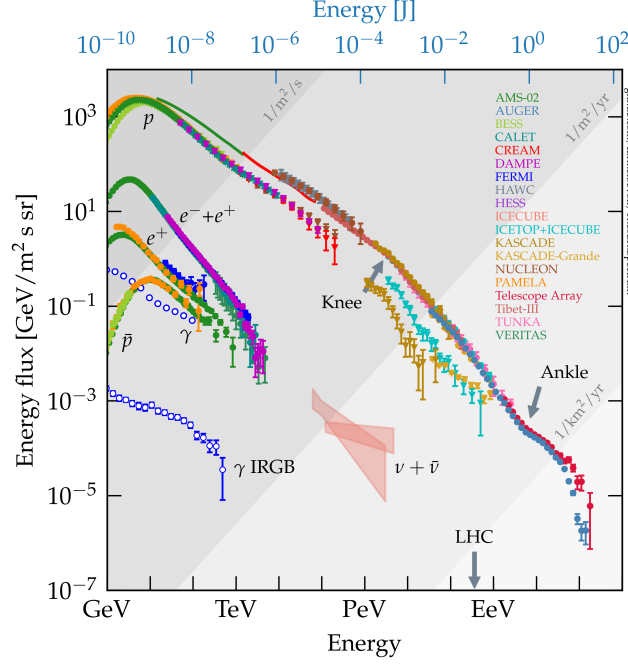


Figure 2: The all-particle energy spectrum of CRs. Data are taken from the experiments in the legend. Image from [24].

The origin of the steepening of the CR spectrum, i.e. the knee, is a long-standing debated point. It has long been suspected to correspond to the energy beyond which Galactic sources of CRs reach their maximum emission efficiency, while the ankle witnesses the onset of an extragalactic component of the particle flux. In fact, in our Galaxy the magnetic field is almost constant, at the level of $3 \mu\text{G}$, and its field lines are parallel to the Galactic Plane, with a small vertical component on the vertical z axis (about $0.2\text{-}0.3 \mu\text{G}$ in the vicinity of the Sun). With such a field, beyond the ankle CRs cannot be confined anymore, as detailed in the following. In this scenario, the knee feature may be interpreted as a steepening of the Galactic light component, assuming a rigidity² dependence of the break for different mass components of the spectrum. So, the spectra of the heavier nuclei of charge Z should steepen at energies ZE_k , where E_k is the knee energy. A second knee would be expected at an energy corresponding to the heaviest CR particle, namely the Fe nucleus, located at $26 \times E_k \simeq 10^{17} \text{ eV}$ [25]. Those features are visible in Figure 3, which shows the CRs energy spectrum together with the information on the mass composition depending on the CRs energy, obtained considering results from different experiments operating in the last decades. In the region of the ankle, CRs

² For a charged particle of charge Ze and momentum p , deflected in a magnetic field, the rigidity is defined as $R = p/Ze$.

have energies so high that, in a magnetic field of $\sim 3\mu\text{G}$, their curvature radius is comparable to the vertical dimension of the Galaxy ($\sim 300\text{ pc}$). The curvature, for a particle of energy E and charge q , immersed in a magnetic field B , is defined as the Larmor radius: $r_L \simeq \frac{E}{qB}$. Therefore, the example suggests that the majority of CRs between the knee and the ankle likely originate from within our Galaxy, while higher energy CRs are not magnetically confined to the Galaxy and are probably of extragalactic origin. This can be seen in Figure 4, where the trajectory of CRs in the Galactic magnetic field have been simulated from 10^{18} eV up to 10^{20} eV , showing that, at ultra-high energies, CRs preserve the original directional information. Also, on the base of the Larmor equation, the escape time decreases with the particle energy. So, taking into account the cross sections of spallation processes with the ISM [26], it is possible to estimate that CRs below the knee have traversed by 1 Mpc of matter before escaping into the intergalactic space, meaning that they are trapped for over 3 million years in our Galaxy. As a consequence, the measured spectrum on Earth is affected by not only the production in extreme astrophysical environments, but also by their diffusion through the ISM, as explained in 1.1.3.

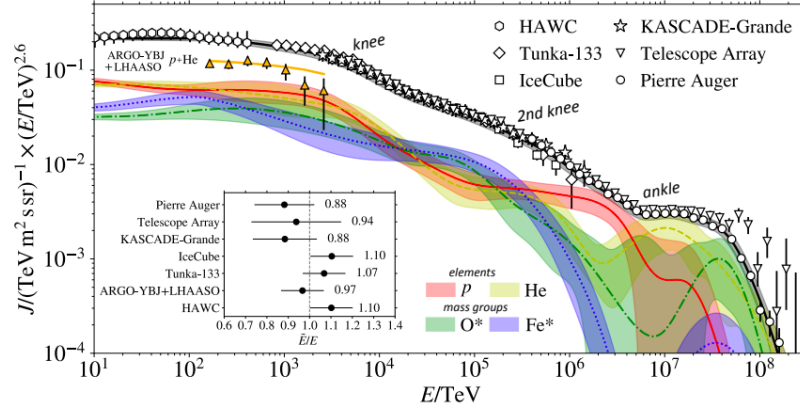


Figure 3: Cosmic-rays energy spectrum and mass composition. This plot reflects a recent attempt for a combined fit of flux and composition measurements by different experiments. The differential energy spectrum has been multiplied by $E^{2.6}$ in order to display the features of the steep spectrum. Features such as the knee, second knee and ankle mark softening or hardening of the spectrum which can be approximated by a power law in between these features. Image from [27].

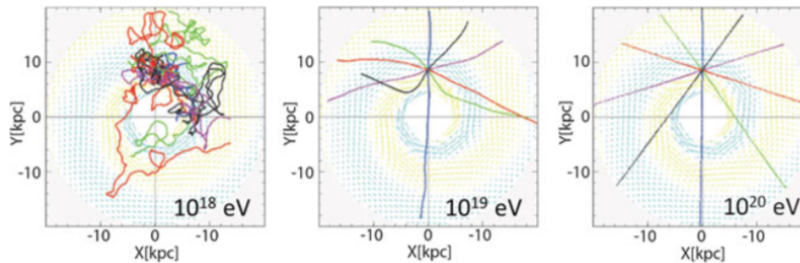


Figure 4: Simulated trajectory of charged particles in the galactic magnetic field. Low-energy charged particles are bent and wound by magnetic fields, but those above 10^{20} eV travel along almost straight trajectories. Image from [28].

1.1.3 Acceleration mechanism of cosmic rays

An intriguing problem in astroparticle physics is the acceleration mechanism up to ultra-relativistic energies. The candidate processes should reproduce the observed spectrum of Equation 1 and also the observed chemical abundances, as well as the spatial distribution of CRs events. In 1949 the Italian physicist Enrico Fermi suggested the so called *Fermi acceleration mechanism of II order*. This model [29] considers a stochastic acceleration of particles in moving random magnetic fields. Particles scatter on magnetized clouds, called magnetic mirrors, which are moving in the ISM isotropically. So, if a particle of energy E and momentum p is injected in a plasma of magnetized clouds moving with velocity β , after one collision the particle is reflected and its momentum changes in the direction of cloud motion. The energy gain after one collision is estimated to be:

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \frac{8\beta^2}{3}. \quad (2)$$

As it is clear from Equation 2, the energy variation is an increase only at second order in the cloud velocity, so it is an inefficient process.

In 1978 Anthony Raymond Bell modified the Fermi acceleration process into what is currently known as *diffusive shock acceleration*. A detailed description can be found in [30]. Bell's process takes place when a shock wave, produced in a very energetic astrophysical event, is propagating in a region of the space where plasma is present. To understand what is a shock, two regions are considered, called *upstream* and *downstream* regions. The former is the region of plasma not yet reached by the shock, described as a fluid with parameters ρ_1 , T_1 and v_1 , indicating its density, temperature and velocity in the shock frame; the latter is the one already reached and overcome by the shock, with parameters ρ_2 , T_2 and v_2 . Exploiting mass, momentum and energy conservation across the shock surface, following the laws of hydrodynamics, it can be shown that the effect of a shock on the surrounding plasma is such that the following equalities hold:

$$\begin{aligned} \rho_2 &= 4\rho_1, \\ T_2 &\gg T_1, \\ v_2 &= \frac{v_1}{4}. \end{aligned} \quad (3)$$

The above Equations indicate that a shock is actually a plasma discontinuity acting as a heater, converting kinetic energy into thermal energy. After the shock passage, plasma is slowed down, heated and compressed. Consider in the same frame a relativistic particle of energy E in the upstream region. After one shock crossing at an angle θ , from upstream to downstream, the particle energy becomes $E_d = \gamma E(1 + \beta\mu)$ with $\mu = \cos(\theta)$, $\beta = v_1 - v_2$ (velocities are normalized to the speed of light in vacuum) and γ the related Lorentz factor. In order to let particle transverse the shock, it should be that $0 \leq \mu \leq 1$. The particle, by scattering on magnetic turbulence, might eventually come back to the upstream, as in Figure 5, so $E_u = \gamma E_d(1 - \beta\mu') = \gamma^2 E(1 + \beta\mu)(1 - \beta\mu') > 0$, where now $-1 \leq \mu' \leq 0$.

Following the classical kinetic theory, the flux of particles going towards upstream

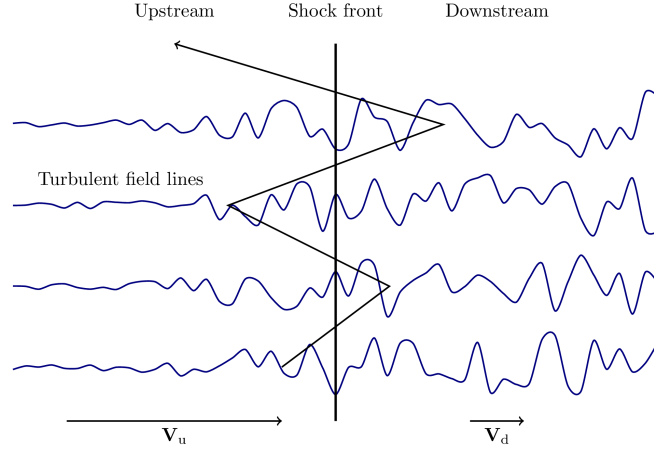


Figure 5: Picture of Fermi acceleration of I order. Seen in the laboratory frame, the shock is moving towards the left; seen in the shock frame, the upstream fluid is moving towards right. A schematic typical path of a shock-accelerated particle is shown. Image from <http://sprg.ssl.berkeley.edu/~pulupa/illustrations/>.

is $Nc/4$, with N the number density of particles accelerated at shock and c the speed of light in vacuum. The probability P to cross the shock at angle between μ and $\mu + d\mu$ is given by:

$$P(\mu)d\mu = \frac{\frac{N}{4\pi}c\mu d\Omega}{\frac{Nc}{4}} = \frac{-\frac{N}{4\pi}c\mu 2\pi d\mu}{\frac{Nc}{4}} = -2\mu d\mu, \quad (4)$$

where $d\Omega$ is the infinitesimal solid angle. Weighting the energy gain with this probability, the following relation is obtained, corresponding to a I order process:

$$\left\langle \frac{E_u - E}{E} \right\rangle = - \int_0^1 d\mu 2\mu \int_{-1}^0 d\mu' 2\mu' [\gamma^2(1 + \beta\mu)(1 - \beta\mu')] = \frac{4\beta}{3}. \quad (5)$$

Interestingly, the energy increase of the particle is found to be linear in the shock speed, after a full cycle across the shock. Starting from this result, it is possible to derive a toy model for particle energy spectrum. Sitting in the downstream reference frame, where the distribution of particles has been isotropized, the probability for a particle to come back to the upstream region after having crossed the shock can be computed as $P_{d \rightarrow u} \sim 1 - 4v_2$, in the limit $v_2 \ll 1$, where velocity is normalized to c . This means that, starting with N_0 relativistic particles injected in the upstream, after 1 cycle, which corresponds to a particle going to downstream and coming back, the number of particles in the upstream that can further go into the acceleration process becomes $N_1 = N_0(1 - 4v_2)$. Instead, after k -cycles the following relations can be obtained:

$$\begin{aligned} E_k &= E_0 \left(1 + \frac{4\beta}{3} \right)^k, \\ N_k &= N_0 (1 - 4v_2)^k, \end{aligned} \quad (6)$$

where k is

$$k = \frac{\ln(\frac{E_k}{E_0})}{\ln(1 + \frac{4\beta}{3})} = \frac{\ln(\frac{N_k}{N_0})}{\ln(1 - 4v_2)}. \quad (7)$$

So it is possible to derive the following relation:

$$\ln \left(\frac{N_k}{N_0} \right) = \frac{\ln(1-4v_2)}{\ln(1+\frac{4\beta}{3})} \ln \left(\frac{E_k}{E_0} \right) \equiv -s \ln \left(\frac{E_k}{E_0} \right), \quad (8)$$

which can be written as:

$$N_k = N_0 \left(\frac{E_k}{E_0} \right)^{-s} \implies \frac{dN}{dE} \sim E^{-\alpha}, \quad (9)$$

where $\alpha = s + 1$. A power law for the differential energy spectrum has been obtained, analogously to Equation 1: an expectation value for the spectral index can be derived.

$$\begin{aligned} \ln(1-4v_2) &\sim -4v_2 \quad (v_2 \ll 1), \\ \ln(1+\frac{4\beta}{3}) &\sim \frac{4\beta}{3} \quad (\beta \ll 1), \\ s &= -\frac{\ln(1-4v_2)}{\ln(1+\frac{4\beta}{3})} \sim \frac{3v_2}{v_1-v_2} \equiv \frac{3}{r-1}, \end{aligned} \quad (10)$$

where r is called compression ratio, defined as $r = \rho_2/\rho_1$. Since non-relativistic shock has been assumed, namely $\beta \ll 1$, the energy gain per cycle is quite contained, because of this low β -value, but at the same time it is highly probable that a particle in the downstream region comes back to the upstream one and continues to be accelerated. For a strong shock³, hydrodynamics sets (Equation 3) $r = 4$ and the spectral index results to be:

$$\alpha = s + 1 = \frac{r+2}{r-1} = 2, \quad (11)$$

thus a power law with spectral index equal to 2 has been obtained. This is not enough to explain the all-particle spectrum, but predicts a power law for primary CRs at sources, whose energy distribution is modified during the travel towards Earth because of their propagation within the ISM. In fact, diffusion process causes the steepening towards $E^{-2.6}$. Taking into account these propagation effects, Bell's model is able to reproduce the measured CRs spectrum with good accuracy.

1.1.4 The puzzle of ultra-high-energy cosmic rays

CRs with energies from 10^{18} eV to beyond 10^{20} eV are called Ultra-High Energy Cosmic Rays (UHECRs). Firstly discovered in 1960s [31], the study of UHECRs has been a tough challenge, because of their low flux intensity (less than 1 particle per km^2 per year), meaning that ground-based detectors covering vast areas are needed to compensate this feature. In particular, a strong flux suppression is observed above 4×10^{19} eV and this may be explained by the Greisen Zatsepin Kuz'min (GZK) effect, a reduction of primary CRs flux due to their interaction with the CMBR [32]. In such a case, protons p interact with photons of CMBR producing a Δ^+ resonance, which decays both into neutral (π^0) and charged ($\pi^\pm$)

³ A shock is defined strong if $M_1 \gg 1$, where M_1 is the Mach number, defined as $M_1 = v_1/c_{s,1}$, with $c_{s,1}$ as the sound speed in the upstream region.

pions. Energy-threshold for proton interaction with CMBR photons is at $\sim 10^{20}$ eV, while a higher threshold should exist for heavier nuclei. The average path length can be evaluated as: $l_{p\gamma} = \langle y \sigma_{p\gamma} n_{\gamma} \rangle^{-1} = 30 \text{ Mpc}$, where y is the Bjorken variable, $\sigma_{p\gamma}$ is the cross section for photohadronic interactions and n_{γ} is the photon target density. Protons coming from distances greater than $\sim 30 \text{ Mpc}$ from Earth should be suppressed because of this effect. The Pierre Auger Observatory [1] (PAO), Agasa Telescope Array [33] and the HI-RES [34] experiments have performed measurements in this energy region in order to study GZK cut-off. Hires and the Pierre Auger Observatory have measured a reduction of the particle flux for energies above the GZK-threshold, while the AGASA experiment observed 11 events above 10^{20} eV. Even if the existence of the GZK cut-off is strongly related to the composition of UHECRs, a clear answer capable of explaining all the observations is still lacking. If UHECRs composition is dominated by protons the likely slope change is explained by GZK cut-off. If composition is heavier at the highest energies, the structure may be due to limits in maximum reachable energy in acceleration processes at sources. The most recent composition measurements, that are performed on a statistical basis, indicate a tendency towards heavier composition above 10^{18} eV, as shown in Figure 6. Nowadays, up-to-date results on UHECRs

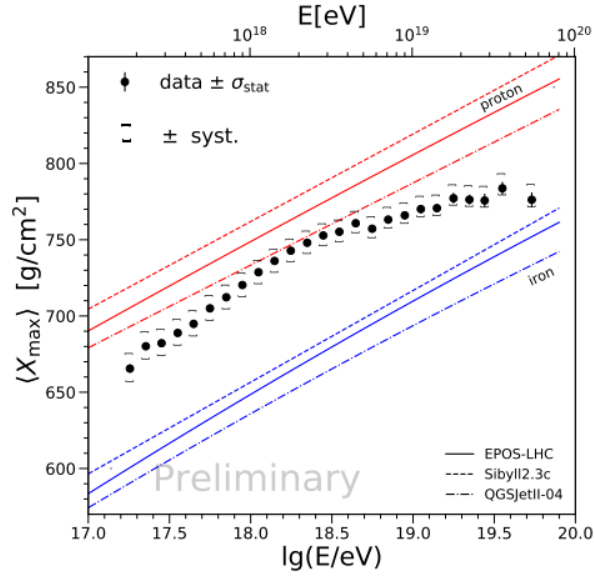


Figure 6: Mass composition of the primary CRs flux performed by PAO, through the study of the maximum development of the associated air shower ($X_{\max}$), expressed in units of g/cm^2 . Image from [35].

above EeV level are provided by PAO and Telescope Array [36] experiments, which allowed to study the features of their energy spectrum with unprecedented precision. The UHECRs spectrum measured by PAO is displayed in Figure 7 and shows new deviations from the power laws features previously described: an additional break around $10^{19.1}$ eV is visible, called *instep*, which could reflect the interplay of light-to-intermediate nuclei. Finally, a suppression of the total flux above $10^{19.7}$ eV may be attributed to energy losses during the propagation of UHECRs, to the limited maximum energy the sources can provide to particle acceleration, or possibly to a combination of both effects [37]. The spectrum measured by Telescope

Array agrees in shape with the one measured by PAO, but highlights a different energy break above $10^{19.5}$ eV, which also persists once systematic effects and uncertainties in the absolute calibration of the fluorescence telescope are taken in to account. A joint effort between the two collaborations is currently underway to better understand the reasons of the observed differences and to study their impact on the spectral features. Anyway, measurements confirm the existence of a flattening of the spectrum around 5×10^{18} eV (the ankle), while a steepening at around $\sim 5 \times 10^{19}$ eV can still be substantiated.

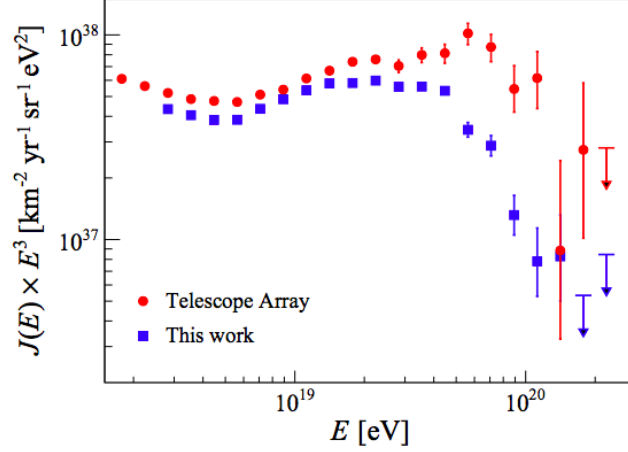


Figure 7: Comparison between the Pierre Auger UHECR spectrum (in blue dots and referred as *this work*) and the Telescope Array one (red markers). Spectra are scaled by E^3 to better appreciate its structure. Image from [38].

Many aspects of UHECRs physics are still unsolved. As previously discussed, the only certainty in the study of UHECRs is their extragalactic origin because at these energies the Galactic magnetic field is not strong enough to confine them. In 2017, PAO reported the observation of thousands of CRs with ultrahigh energies of several EeV (about a Joule per particle), arriving in a slightly dipolar distribution [39], consistent with an anisotropic signal. The distribution of events in equatorial coordinates is shown in Figure 8. The anisotropy can be well repre-

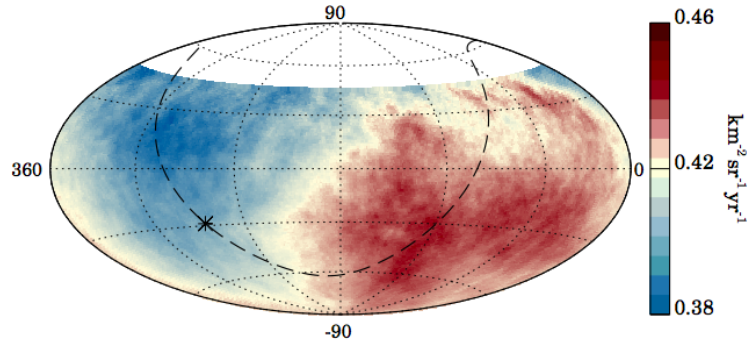


Figure 8: Sky map in equatorial coordinates showing the CR flux above 8 EeV. The Galactic center is marked with an asterisk and the Galactic plane is shown by a dashed line. Image from [39].

sented by a dipole with an amplitude of $6.5_{-0.9}^{+1.3}\%$ in the direction of right ascension $\alpha_d = 100^\circ \pm 10^\circ$ and declination $\delta_d = -24_{-13}^{+12}^\circ$. By comparing results with phenomenological predictions, the magnitude and direction of the anisotropy supports the hypothesis of an extragalactic origin for the highest-energy CRs, rather than sources within the Galaxy. Nevertheless, using the observed anisotropies to deduce the positions and nature of the UHECRs sources appears particularly difficult. To reveal them, complementary information from the neutrinos born in UHECRs interactions may be essential.

1.1.5 Cosmic particles accelerator candidates

The origin of high-energy CRs is still debated. In order to be considered a candidate source for UHECRs, an astrophysical object should satisfy some criteria about geometry and power: the accelerated particle should be kept confined around the shock during the acceleration process and the source should provide the necessary energy gain to accelerate particles. If a particle escapes from the region where it was being accelerated, it will be unable to gain more energy. This situation imposes a limit on the particle maximum energy, expressed as:

$$E_{\max} = \eta^{-1} \beta q B \Gamma R, \quad (12)$$

where q is the electric charge of the accelerated particle, B is the magnetic field, R is the size of the accelerator, η parametrizes the efficiency of the acceleration and β is the velocity of the shock in units of the speed of light, c . Γ accounts for a possible relativistic motion of the acceleration site with respect to the observer. Equation 12 is known as Hillas criterion [40] and is obtained requiring that the Larmor radius of the particles r_L does not exceed the size of the source R . The Hillas plot shown in Figure 9 collects information about typical magnetic fields and sizes of different source classes: lines identify the combination of B and R that guarantee the achievement of a given $E_{\max}$. In other words, only sources located on top of the lines allow particles to get to $E_{\max}$, and are thus possibly responsible for those particle energies. As the energy of the proton increases above 10^{20} eV, the number of candidate sources diminishes drastically. As mentioned, CRs are believed to have a Galactic origin below the knee and an extragalactic component starts to increase right after it. Galactic sources include Supernova Remnants (SNRs) and Pulsar Wind Nebulae (PWNe), while Active Galactic Nuclei (AGN), Gamma-Ray Bursts (GRBs) and Starburst Galaxies (SBGs) are enumerated among the extragalactic sources. In order to reach very high energies, very high magnetic fields and large dimensions of sources are needed. Among candidate sources neutron stars have the highest B field, however the energy loss by charged particles in synchrotron radiation is proportional to B^2 , strongly limiting the achievement of high energies. Neutron stars are therefore excluded from the discussion.

GALACTIC SOURCES

Most of Galactic sources are believed to be associated with SNRs, the remaining of supernovae explosions [41], which mark the end of the life of massive stars (namely stars whose mass M is such that $10M_\odot \leq M \leq 30M_\odot$, with $M_\odot$ the

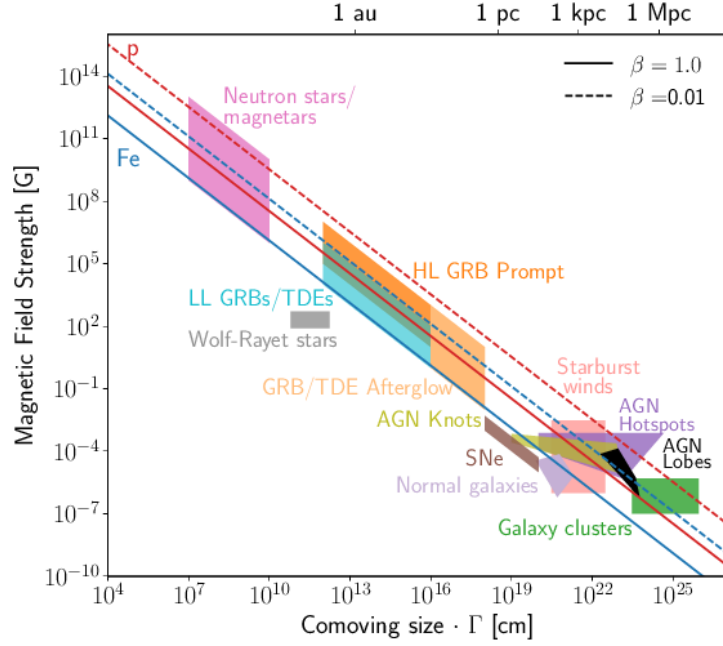


Figure 9: Hillas plot showing candidate UHECRs sources as colored areas on the $B - R$ plane (magnetic field versus size of the accelerating region multiplied by its Lorentz factor Γ with respect to the observer). Acceleration up to 10^{20} eV is possible only above diagonal lines, that define the minimal value for the BR product needed to satisfy the Hillas condition. The results are shown for protons and iron nuclei, in red and blue respectively, through solid lines for maximum shock velocity ($\beta = 1$) and dashed lines in the case of $\beta = 0.01$. Image from [40].

solar mass). Through the stellar evolution, these have developed an iron core surrounded by several onion-like burning shells and an outer envelope of hydrogen and helium. Each shell contains elements that are progressively lighter. The average binding energy per nucleon reaches a maximum at the isotope ^{56}Fe , meaning that no additional burning can generate energy in order to support the core. Stability is reached via degeneracy pressure, a quantum mechanical mechanism in which fermions squeezed in a small volume acquire a given momentum. When the core mass has exceeded the Chandrasekhar limit [42] of $1.4 M_{\odot}$, a rapid collapse starts and the neutronization process becomes energetically favorable during the subsequent compression:



Nearly all protons in the collapsing core are converted into neutrons. Neutrons stop the collapse and a shock wave is formed, ejecting the outer layers of the star and producing a spectacular visible explosion. A neutron star is formed and 99% of the energy is expelled in the form of neutrinos. Additionally during the collapse, in the hot core of the star, all neutrino and antineutrino flavors are produced via the flavor-blind reaction $\gamma\gamma \longrightarrow \nu_{\alpha}\bar{\nu}_{\alpha}$. All the neutrino species are produced with energies $\langle E_{\nu_e} \rangle \sim 11$ MeV, $\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV and $\langle E_{\nu_{\mu,\tau}} \rangle \sim \langle E_{\bar{\nu}_{\mu,\tau}} \rangle \sim 25$ MeV. Those differences are related to neutrino elastic scattering on electrons which are still present in core environment. After the detection of PeVatrons (see Section 1.2),

other potential sources, such as massive stars and superbubbles, have also started to be considered as Galactic accelerators [43].

EXTRAGALACTIC SOURCES

AGN are potential sites for UHECRs acceleration. They are nearly steady sources of electromagnetic emission, although gamma-ray variability is often observed. AGN jets have transverse dimensions of a fraction of a parsec and magnetic fields strong enough (a few Gauss) to produce synchrotron radiation. Using the Hillas criterion, the maximum energy achievable for protons in a region with a magnetic field of $\sim 1 \mu\text{G}$ and a size of $R = 0.1 \text{ pc}$ is estimated to be $\sim 10^{20} \text{ eV}$. Similarly, in the AGN core, where the magnetic field is $B \sim 10^3 \text{ G}$ and the size is $R \sim 10^{-5} \text{ pc}$, the maximum energy is nearly the same. Anyway, under realistic conditions, achieving the quoted maximum energy is unlikely. The realistically attainable maximum energy should decrease due to energy loss mechanisms for charged particles, synchrotron radiation in magnetic fields, and the interaction of high-energy protons with the photon field surrounding the AGN's central engine. This issue is even more severe for nuclei, which will photodisintegrate faster in the radiation fields. This limitation is overcome considering that the final acceleration site is farther from the active core, such as at the terminal shocks of the jets, where the radiation density is lower. A detailed discussion is demanded to Chapter 6.

GRBs represent another population of extragalactic candidates. They are the most energetic events in the Universe and their transient nature might explain the lack of correlation between the arrival directions of the highest-energy CRs and astrophysical objects. In this scenario, sources are not visible because the detected CRs come from various bursts and reach Earth long after the original GRB has occurred. Based on gamma-ray observations, the mechanism producing these bursts likely involves the dissipation of kinetic energy in a relativistic expanding fireball. The magnetic field value at these shocks is estimated to be on the order of $B \sim 10^6 \text{ G}$ at a length of $R \sim 10^{-6} \text{ pc}$ from the center, satisfying the Hillas criterion for an energy of $\sim 10^{20} \text{ eV}$. These parameters may vary at different stages of the GRB explosion. The observed gamma-ray flux from GRBs being comparable to the UHECR flux suggests a strong energetic connection, supporting the hypothesis that GRBs could be one of the sources of UHECRs acceleration [44].

Finally, the class of SBGs may provide in the future important implications for multi-messenger studies. SBGs are a class of galaxies with a high star formation rate, up to $100 M_{\odot}$ per year [45]. The rate of star formation is so large that the galaxy will consume all of its gas reservoir, from which the stars are forming, on a timescale much shorter than the age of the galaxy. The majority of SBGs are in the midst of a merger or close encounter with another galaxy. They have low luminosity, but can be considered sources of high-energy neutrinos, since accelerated CRs can find a high density target gas in the central region, producing neutrinos via hadronic collisions.

As explained, the nature of UHECRs (whether protons or heavier nuclei) is crucial for understanding acceleration mechanisms. If UHECRs are iron nuclei, energies of $\sim 10^{20} \text{ eV}$ can be reached even in shock regions where β is significantly

less than one or in areas with smaller magnetic fields and size scales. If, on the other hand, UHECRs are protons, AGN or GRBs appear to be the most plausible sources given their isotropic distribution in the sky. In addition to that, sources of CRs should also emit high-energy photons up to multi-TeV energies. The mechanism of gamma-ray emission is naturally connected to the acceleration of electrons and/or protons in astrophysical sources and is being discussed in Section 1.2.

1.2 GAMMA RAYS

The presence of magnetic fields in our Universe makes it challenging to localize CRs sources using charged particles. The only way to have information about their acceleration sites is by observing neutral particles, as photons and neutrinos, generated by their interactions during accelerations. In past decades, a new window has been opened by the study of the electromagnetic component of the cosmic radiation up to the highest energies. Gamma rays are photons with energies greater than 100 keV and serve as important probes to test phenomena occurring in high-energy astrophysical environments. Candidate sources are both Galactic and extragalactic objects. The breakthrough in gamma-ray astronomy came with the launch of the Compton Gamma-Ray Observatory (CGRO) [46] in 1991. Today, in the high-energy regime ($100 \text{ MeV} < E < 100 \text{ GeV}$), the field is primarily dominated by the Fermi satellite [3], launched in 2008. The gamma-ray sky is largely shaped by diffuse radiation originating from our Galaxy, caused by the propagation of CRs in the ISM. Extragalactic sources appear as point-like objects and are particularly prominent at high latitudes (see Figure 10). Even if space experiments cover a very broad energy region, above 100 GeV the fluxes of high-energy photons are so small that space-based experiments cannot provide enough statistic. The study of photons up to the highest energies requires ground-based experiments, which exploits the electromagnetic shower induced by a high-energy photon interacting in the upper atmosphere, as explained in 1.4.3. In the next future the leading instrument will be the Cherenkov Telescope Array Observatory (CTAO) [47]. Our knowledge of astrophysical gamma-ray sources is continuously

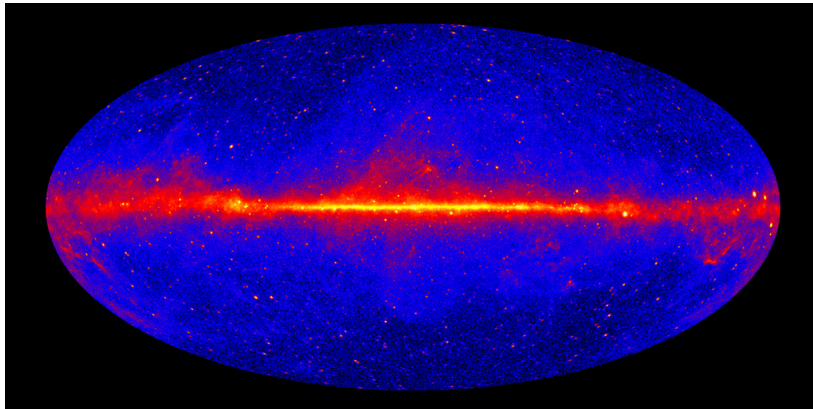


Figure 10: The all-sky Fermi photon count map above 1 GeV. The map is based on Galactic coordinates and is obtained in 12 years of observations. The bright band in the center shows the emissions from our Milky Way. Individual strong sources of extragalactic origin can be also seen as bright spots. (Credits: NASA).

updated by the publication of the Fermi Large Area Telescope (Fermi-LAT) catalogues. Based on 12 years of data in the energy range from 50 MeV to 1 TeV, the latest catalogue (4FGL-DR3) preserves existence and positions of sources in the previous versions [48] and adds new ones, for a total of 6658 accelerator candidates [49]. The identified and associated sources in the 4FGL-DR3 catalogue span various Galactic and extragalactic source classes. The largest Galactic source class remains pulsars, including 135 young pulsars, 120 millisecond gamma-ray pulsars, and 37 associations with non-LAT pulsars. Other Galactic source classes have also expanded: there are now 35 globular clusters (GLCs), 43 SNRs, and 19 PWNe associated with LAT sources. Blazars continue to dominate the extragalactic source class, with 2251 sources identified or associated with BL Lacertae objects (BL Lacs) or flat-spectrum radio quasars (FSRQs) active galaxies, and 1492 with unclassified blazars. A sky map showing 4FGL sources by their class is depicted in Figure 11.

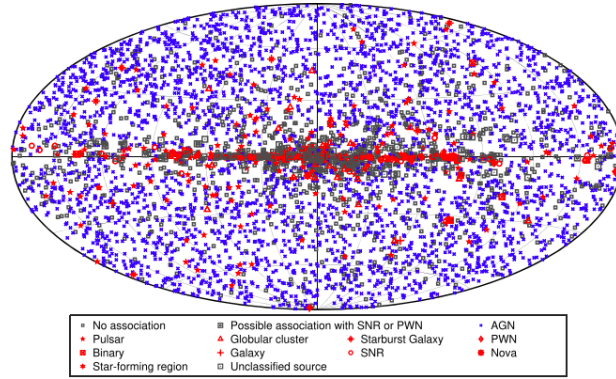


Figure 11: Sky map in Galactic coordinates showing the 4FGL sources by their class. All AGN classes are plotted with the same blue symbol for simplicity. Other associations to a well defined class are plotted in red. Un-associated sources and sources associated to counterparts of unknown nature are plotted in black. Image from [48].

Since Fermi satellite is a space-based mission, it cannot provide a detailed view of the sky beyond hundreds of GeV. In order to get a detailed view of the very-high-energy sky and beyond, ground-based detectors are considered. In particular, one of the groundbreaking discoveries of the field is the publication of a catalogue of very-high energy and ultra-high-energy gamma-ray sources detected by the Large High Altitude Air Shower Observatory (LHAASO) Collaboration [50]. The catalogue was compiled using 508 days of data collected by its sub-detector Water Cherenkov Detector Array (WCDA), from March 2021 to September 2022, and 933 days of data recorded by the Kilometer Squared Array (KM2A) sub-detector, from January 2020 to September 2022. This catalogue presents the main result from the most sensitive large coverage gamma-ray survey of the sky above 1 TeV. Among the 90 sources, 43 sources have been detected with energies greater than 100 TeV, with a significance $> 4\sigma$. Such sources are crucial to explore the origin of PeV CRs within the Galaxy. Figure 12 shows the significance maps obtained in the energy bands $1 \text{ TeV} < E < 25 \text{ TeV}$ and $E > 25 \text{ TeV}$ in Galactic coordinates. The signals are clearly visible. However, most sources in the Galactic plane are nearby and overlapping. Hence, further analysis is needed to derive each source separately. The importance of this discovery lies in the fact that UHE gamma-ray photons

were considered undeniable evidence of Galactic PeV accelerators (PeVatrons). The only plausible mechanism for producing such high-energy photons is thought to be the decay of neutral pions, generated by the interaction of CRs with the source material, as will be explained in 1.2.1.

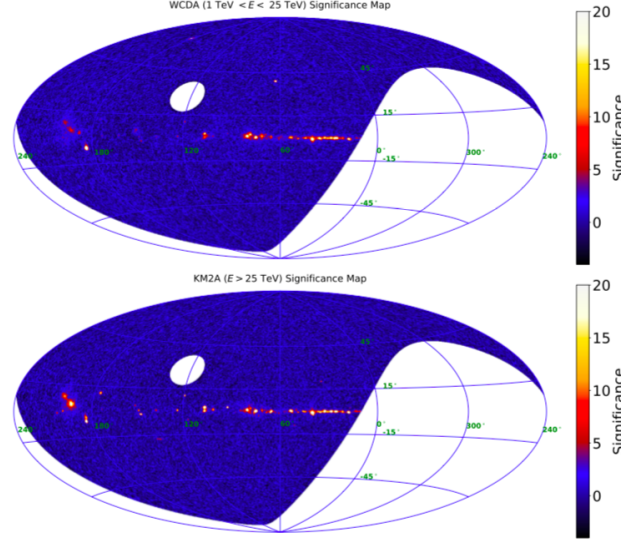


Figure 12: Significance maps of the region monitored by LHAASO with its two sub-detectors: WCDA and KM2A. Image from [50].

1.2.1 Astrophysical gamma rays: hadronic interactions

A signature for the existence of accelerated protons in an astrophysical environment is the simultaneous presence of neutrinos and gamma rays, generated in the decay of charged and neutral pions respectively. A first candidate process is the so-called *astrophysical beam dump* mechanism, in which an accelerated proton collides with a target ambient proton producing mesons and baryons in the final state:

$$p + p \longrightarrow \pi^{\pm} K^{\pm} \pi^0 K^0 p n \dots \quad (14)$$

This interaction is quite similar to a fixed target p - p collision in accelerator experiments, its cross section is about 40 – 50 mb and at high energy is characterized by inelastic channels of collision. A second candidate process is the interaction of high-energy protons with ambient low-energy photons. Those ambient photons are radio, infrared, visible and ultraviolet photons present around astrophysical sources and produced by accelerated electrons in space regions where magnetic fields are present. These processes are called *photoproduction* or *photo-meson* reactions. The principle is similar to what has been discussed for the GZK-effect:

$$\begin{aligned} p + \gamma &\longrightarrow \Delta^+ \longrightarrow \pi^0 p \\ &\longrightarrow \pi^+ n. \end{aligned} \quad (15)$$

The cross section at resonance is 0.250 mb and it is two orders of magnitude lower if compared to the one of p - p collisions. However the probability for this process to happen is related to the environment of the astrophysical source through

the number density of ambient photons, that thus influence the event rate of produced secondary particles, that are mostly protons, neutrons and pions. Secondary protons have a high probability to remain trapped in the environment because of magnetic fields, while the produced free neutrons are unstable and decay via the β -reaction:

$$n \longrightarrow p + e^- + \bar{\nu}_e . \quad (16)$$

At rest, π^0 has a lifetime of 8.5×10^{-17} s and will immediately decay in a couple of photons:

$$\pi^0 \longrightarrow \gamma\gamma. \quad (17)$$

Charged pions will undergo the chain of reactions:

$$\begin{aligned} \pi^+ &\longrightarrow \nu_\mu + \mu^+, \\ \mu^+ &\longrightarrow \bar{\nu}_\mu + \nu_e + e^+ . \end{aligned} \quad (18)$$

Same holds for the charged conjugate reactions. In the standard scenario, neutrinos produced by the decay chain have a flavor ratio of $(\nu_e : \nu_\mu : \nu_\tau) \sim (1 : 2 : 0)$ at the source, which becomes $(1 : 1 : 1)$ due to oscillations over cosmic distances. However, other production mechanisms, such as muon energy losses in dense matter or strong magnetic fields, muon acceleration, and neutron decay, can lead to different flavor compositions at the source [51]. On average, in hadronic processes neutrino energy from pion decay is linked to parent proton energy via $E_\nu \sim 0.05E_p$. In fact, the pion energy in (15) is 0.2 that of the parent proton, while pion decays produce 4 leptons, each with 1/4 the energy of parent pion. For these processes to occur, key features of the source are required: its size should be large enough to let protons interact, but also small enough in order to let pions decay before interacting. Then, since all processes involved in chain (15) are not energy dependent, the spectral index of Fermi accelerated protons will be reproduced by the resulting neutrinos in final state. For this reason, cosmic neutrinos are supposed to follow a E^{-2} differential energy distribution.

1.2.2 Astrophysical gamma rays: leptonic interactions

As an alternative to the hadronic scenario, leptonic models also predict the production of high-energy photons. The presence of magnetic fields B in almost every astrophysical environment makes synchrotron radiation one of the main production mechanisms of photons:

$$e^\pm + B \longrightarrow e^\pm + \gamma_{\text{syn}}. \quad (19)$$

Electrons and positrons moving in magnetic fields generate photons with energy spectrum distributed in the region between infrared and X-rays. In fact, a charged particle moving in a magnetic field is deflected by the Lorentz force that constricts it in a helical path along the magnetic force lines. The particle will radiate following the Larmor formula:

$$P = \frac{2q^2}{3m^2c^3} \gamma^2 \left(\frac{d\vec{p}}{dt} \right)^2, \quad (20)$$

where γ is the particle Lorentz factor, q and m are the charge and the mass of the particle, while $d\vec{p}/dt$ is the temporal variation of the particle's momentum. Photons produced may offer an additional target to the very same electrons and positrons that they originate from. The process in which a low-energy photon gains energy from a high-energy electron is called inverse Compton (IC) scattering:

$$e^{\pm} + \gamma_{\text{soft}} \longrightarrow e^{\pm} + \gamma_{\text{IC}}. \quad (21)$$

This is important since high-energy electrons with a Lorentz factor at the level of 10^9 (ultrarelativistic) exist in astrophysical environments, where also a high density of soft photons is present. The energy distribution of photons resulting from IC starts from X-rays and reaches GeV-TeV level. The resulting Spectral Energy Distribution (SED) across the entire energy range is shown in Figure 13.

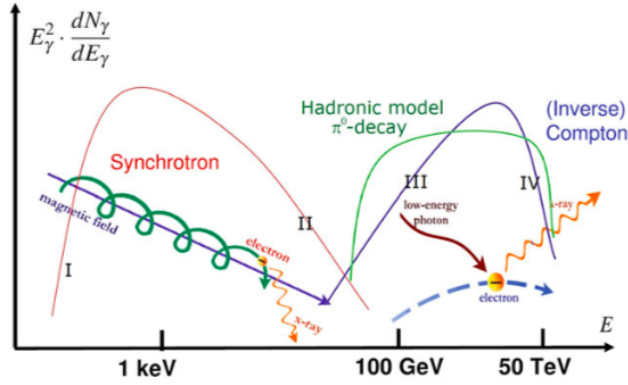


Figure 13: SED for photons produced in leptonic and hadronic models. Four different branches for the spectrum are related to different production mechanisms from E^{-2} parent particles and indicated with I, II, III, IV. Image from [28].

An interesting case is the one in which photons interact with the same relativistic electrons which produced them via synchrotron emission. These electrons increase the energy of the photon field via IC scattering. This is the Synchrotron Self-Compton (SSC) mechanism. Along synchrotron photons and IC mechanism, the SED from π^0 decay is represented in the same Figure. Considering a neutral pion with Lorentz boost factors β and Γ , the energy spectrum of emitted photons in the laboratory frame is obtained via the relation [28]:

$$\frac{dN}{dE_\gamma} = \frac{1}{2} \frac{1}{\beta \Gamma p_\gamma^*}, \quad (22)$$

where p_γ^* is the momentum of photons in center of mass frame. Since all quantities in Equation 22 are constant for given pion energy, spectrum is constant in the range $[E_{\gamma,\text{min}}, E_{\gamma,\text{max}}]$. For a spectrum of accelerated pions, the distribution of photons will be a superposition of uniform distributions, smearing the line and keeping symmetric about $m_{\pi^0}/2 = 67.5$ MeV. Considering Fermi accelerated protons with E^{-2} energy spectrum, the spectrum resulting from π^0 decay in laboratory frame, in $E_\gamma^2 \frac{dN}{dE_\gamma}$ representation, rises below few hundreds of MeV and follows the energy distribution of the parent protons above few GeV (see Figure 13). This feature is

called *pion-decay bump* and identifies the presence of photons originated from the neutral pion decay, being a key feature to discriminate hadronic processes from leptonic ones. In 2013, this feature was for the first time associated with two SNRs detected by Fermi-LAT and AGILE [52], providing crucial evidence in support of the hadronic origin of CRs [53].

1.3 GRAVITATIONAL WAVES

In the panorama of neutral probes, in addition to photons and neutrinos, most violent cosmic events can produce a distinct kind of messenger, called Gravitational Waves (GWs). Massive objects curve space-time, and as they move, they create oscillations in the space-time metrics that propagate at the speed of light. Predicted by Albert Einstein's theory of General Relativity, GWs interact weakly with matter and radiation, allowing them to travel through the Universe with minimal attenuation. GWs were the last messengers to be discovered observationally. In September 2015, the first detection was made by the LIGO detectors in collaboration with the Virgo interferometer in Italy [54]. This event provided the first observational evidence of the inspiral and merger of two stellar-mass black holes (BHs), occurring 1.3 billion light-years away. This marked the beginning of gravitational wave astronomy, offering a new way to explore the Universe and its most energetic phenomena. Among the most remarkable achievements, it is worth to recall the near-simultaneous temporal and spatial observation of GRB 170817A and GW170817 [55]: a binary neutron stars (BNS) merger was detected both as GW by the Advanced LIGO and Virgo detectors and as a short duration GRB, independently, by Fermi/GBM and the Anti-Coincidence Shield for the Spectrometer for the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) [56]. Figure 14 shows the multi-messenger observation of GW170817 and GRB 170817A: the overall duration of GW170817 was about 100 seconds, with GRB 170817A that was detected only 1.7 seconds after the GW signal.

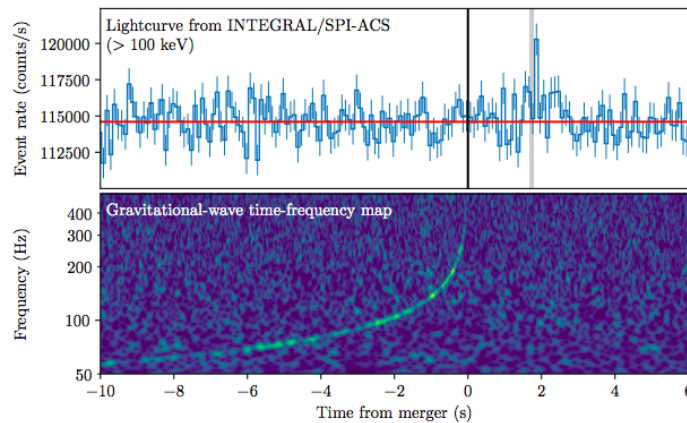


Figure 14: Top panel: INTEGRAL lightcurve of GRB 170817A with the energy range starting approximately at 100 keV and with a high energy limit of at least 80 MeV. Bottom panel: the time-frequency map of GW170817 was obtained by coherently combining LIGO-Hanford and LIGO-Livingston data. Black line is referred to the time of the merger. Image from [55].

This breakthrough of multi-messenger astronomy proves that knowledge gained from GWs can be combined with other cosmic messengers, providing insights into particle acceleration and interactions. Since the physics of compact objects remains poorly understood, coincident neutrino observations could serve as the "smoking gun" for identifying hadronic processes. However, no neutrino-GW detection has occurred up to date and multi-messenger strategies are currently under development to further constrain the observations.

1.4 NEUTRINOS

As discussed earlier, neutrinos play a crucial role in particle astrophysics due to their extremely small interaction cross section, the lowest among elementary particles. This allows them to escape their production sites without interacting, carrying information from the location of the astrophysical objects. Being electrically neutral and weakly interacting, neutrinos can travel cosmological distances to Earth without absorption, unlike gamma rays, and without being deflected, differently from charged CRs. In this sense, neutrinos are considered the ideal cosmic messengers. However, neutrinos are far more difficult to detect than photons since they primarily interact with matter through weak interactions, as discussed in 1.4.1.

1.4.1 *Neutrino properties and interactions*

The existence of a particle called neutrino was postulated by Pauli in 1930, in order to explain the observed β decay spectra [57]. Later on, in 1956, Clyde Cowan and Fred Reines discovered that particle [58], exploiting the fact that during nuclear fission several neutrons are created, which later on decay in a weak β^- process, producing $\bar{\nu}_e$. Hence, with 200 liters of water, mixed with CdCl_2 , they were able to observe the reaction $\bar{\nu}_e + p \rightarrow n + e^+$, occurring with a rate of two events per day, which was far above the expected rate for the background. Only later ν_μ and ν_τ were discovered, completing the panorama of the SM, in which neutrino flavors and three charged leptons are grouped in different generations. Each charged lepton is associated to its neutrino, allowing also the conservation of leptonic number for each family. Neutrinos are neutral, stable and interact mainly through weak interactions. They are spin 1/2 fermions and do not have a mass term in SM. However, the discovery of oscillations of atmospheric neutrinos hints for the presence of physics beyond the SM [59]. Recent results of KATRIN collaboration [60] have put the upper limit of $m_\nu < 0.8 \text{ eV}/c^2$. For this reason, neutrinos are nowadays believed to be the key particle to study physics beyond the Standard Model (bSM): neutrinos may be their own antiparticle, being a Majorana particle. A road-map for the study of this feature is the neutrinoless double beta decay, a weak process of second order in which two nucleons simultaneously decay via β^- . The two neutrinos involved, if Majorana-like, should be emitted and absorbed in the same process, without appearing in final state [61].

Neutrinos interact via gravitational force and weak force. Because of their low mass, only weak interaction will be considered, in the deep-inelastic scattering (DIS) with nucleons. Figure 15 shows the kinematic of the process, in the form of a

Feynman diagram where the nucleon is represented in its quark composition. The following invariant variables are defined: Bjorken variables x and y , and Q^2 . Q^2 is defined as $Q^2 := -q^2 = -(p - p')^2$, where q is the four-momentum transferred in the process; y is the inelasticity, defined as the fraction of the lepton's energy lost in the nucleon rest frame:

$$y := \frac{q \cdot P}{p \cdot P} = \frac{\nu}{E}, \quad (23)$$

with $\nu = E - E'$ being the neutrino's energy loss in the nucleon rest frame. Finally Bjorken variable x is defined as:

$$x := \frac{Q^2}{2M\nu}. \quad (24)$$

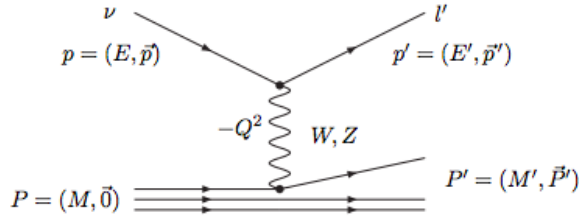


Figure 15: Neutrino DIS: a neutrino of four-momentum p interacts with a nucleon of mass M , at rest in the laboratory frame, giving in final state a lepton l' , of four-momentum p' , and a hadronic shower of four-momentum P' . Image from [62].

DIS neutrino interactions are distinguished in charged current (CC), if mediated by $W^\pm$ bosons, and neutral current (NC) interactions, if Z^0 is the mediator. For CC ones the basic scheme of reaction is:

$$\bar{\nu}_l^{(-)} + N \longrightarrow l^\pm + X, \quad (25)$$

where $\bar{\nu}_l^{(-)}$ is a neutrino of electronic, muonic or tauonic flavor and l the related (flavor conserving) charged lepton. X is a final state hadronic system, which will lead to a particle cascade. For NC interactions the scheme is:

$$\bar{\nu}_l^{(-)} + N \longrightarrow \bar{\nu}_l^{(-)} + X. \quad (26)$$

For both processes, cross section is given by:

$$\sigma(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 dy dx \left(\frac{M^2}{Q^2 + M^2} \right)^2 [f(x, Q^2) + (1-y)^2 \bar{f}(x, Q^2)]. \quad (27)$$

G_F is the Fermi constant, equal to $1.16 \times 10^{-5} \text{GeV}^{-2}$. M_N is the nucleon mass, M is the mass of the mediator, which is $M_W = 80 \text{ GeV}/c^2$ for CC case and $M_Z = 90 \text{ GeV}/c^2$ in NC case. f and $\bar{f}$ are the target parton distribution functions (PDFs), namely the probability to find the interacting quark ($u, d, c, s, t, b, \bar{u}, \dots$) with

a fraction x of the nucleon's momentum, hence depending on x , Q^2 and on the kind of interaction.

An interesting process, which is accessible to $\bar{\nu}_e$ only, is the so-called Glashow resonance, describing the resonant formation of a W^- boson for the interaction of a high-energy $\bar{\nu}_e$ with an electron, peaking at an antineutrino energy of 6 PeV in the rest frame of the electron:

$$\bar{\nu}_e + e^- \longrightarrow W^- \longrightarrow \begin{cases} \bar{\nu}_e + e^- \\ \bar{\nu}_\mu + \mu^- \\ \bar{\nu}_\tau + \tau^- \\ q + \bar{q}. \end{cases} \quad (28)$$

This resonance plays an important role in high-energy neutrino experiments. Events from an astrophysical source of neutrinos should be divided in rates for e , μ and τ like ν interaction. For the electronic flavor, in addition to neutrino–nucleon interactions, is necessary to consider the contribution from Glashow resonance, visible as a peak at $E_\nu = M_W^2/(2m_e) \sim 6 \times 10^6$ GeV (see Figure 16). This kind of process has been object of study in existing neutrino telescopes. In 2021 IceCube Collaboration has observed a cascade of high-energy particles with a measured energy of (6.05 ± 0.72) PeV, consistent with being created at the Glashow resonance [63]. Features of the shower indicated the hadronic decay of a W^- boson, suggesting also the presence of antielectron-neutrinos in astrophysical fluxes. Moreover, this feature for high-energy neutrino interactions provides a way of discriminating neutrinos from their antiparticle.

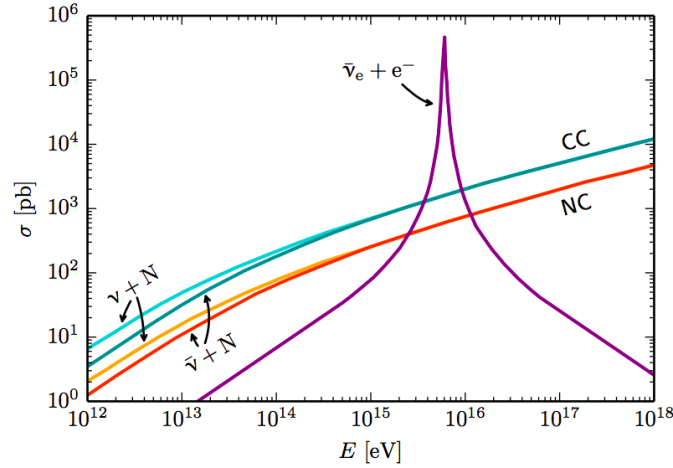


Figure 16: Neutrino cross section as a function of the energy. The different curves are for CC (blue) and NC (orange) neutrino-nucleon scattering of neutrinos with energy E . The line with the resonant behavior shows the cross section for Glashow resonance. Image from [64].

1.4.2 Neutrino fluxes

Fluxes of neutrinos reach Earth across a broad energy range, resulting from different contributions, as shown in Figure 17. Several species of neutrino sources

have been predicted but not yet detected. Some of these species are experimentally firmly established, while others are more speculative. Main contributions to the spectrum can be briefly summarized as follows.

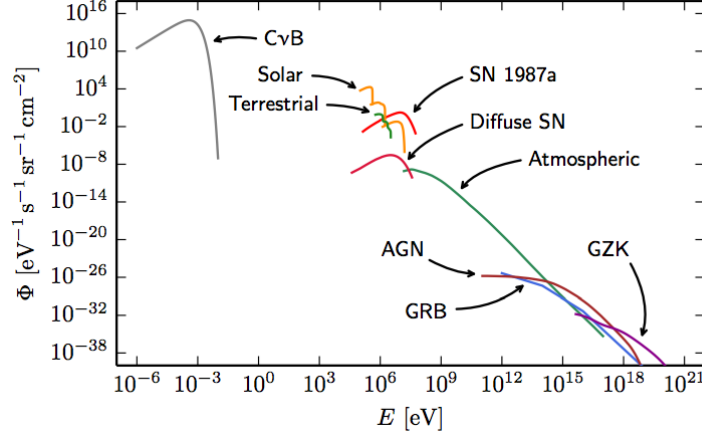


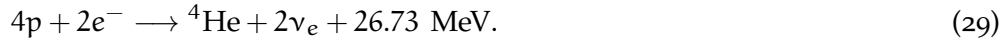
Figure 17: Natural sources of neutrinos. Neutrino spectra of the cosmic neutrino background (CvB-gray), solar neutrinos (light orange), terrestrial neutrinos (orange), from SN 1987A and the diffuse supernova neutrino background (light red), from atmospheric neutrinos (green), from AGNs and from GRBs (red and cyan, respectively) and GZK neutrinos (violet) are reported. Image from [64].

1.4.2.1 The Cosmic Neutrino Background (CvB)

The Universe is expected to be filled with relic neutrinos from the Big Bang, the so-called Cosmic Neutrino Background (CvB) radiation. Those neutrinos have not been measured but their properties are established from cosmological measurements, e.g. from the CMBR [65]. The number density of the CvB is expected to be $\sim 112 \text{ cm}^{-3}$ and the average neutrino momentum is $\sim 5 \times 10^{-4} \text{ eV}$, the lowest energy neutrinos supposed to exist. Several detection methods have been proposed, such as those based on their elastic scattering or capture on radioactive nuclei.

1.4.2.2 Solar Neutrinos

Neutrinos are produced in thermonuclear reactions happening inside stars, and therefore also in our Sun. The basic fusion reactions liberating nuclear binding energy is [66]:



The ν_e flux on Earth is about $6 \times 10^{10} (\text{cm}^2 \text{ s})^{-1}$, the largest part of which is emitted with an energy below 0.4 MeV, though ${}^8\text{B}$ decay extends the spectrum up to 14 MeV. The observation of solar neutrinos was claimed in the 1960s by Ray Davis and collaborators, who established the Homestake experiment to identify the main fusion reactions occurring in the Sun [67]. However, the observed solar neutrino flux was significantly lower than predicted by the standard solar model, a discrepancy known as the “solar neutrino problem.” This puzzle was afterwards resolved by the evidence of neutrino flavor change.

1.4.2.3 Terrestrial Neutrinos

Terrestrial neutrinos are produced by the radioactive decay of isotopes such as uranium, thorium, and potassium in the Earth's interior. These neutrinos provide valuable insights into the heat generation and geochemical composition of the Earth, particularly within the mantle and crust. Unlike solar neutrinos, which come from the Sun, they are a unique tool to study terrestrial processes. In 2005, KamLAND has reported [68] the evidence of a signal originating from terrestrial neutrinos, showing that the technique for their detection is now available.

1.4.2.4 The Diffuse Supernova Neutrino Background

The first (and the only one to date) detection of neutrinos from a supernova occurred in February 1987 with SN 1987A, which had exploded in Large Magellanic Cloud about 160000 years before. A neutrino burst was observed in the Kamiokande II detector [69] during a time interval of 13 seconds. The signal was constituted by eleven events of energy from 7.5 to 36 MeV, of which the first two pointing to the Large Magellanic Cloud. Events were interpreted as positrons detected after the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The resulting fluence and temperature of $\bar{\nu}_e$ was in agreement with phenomenological models of supernova emissions. Supernova explosions of type II in other galaxies are expected produce a cumulative flux of neutrinos that arrive isotropically at Earth, referred to as diffuse supernova neutrino background (DSNB) and not yet conclusively detected. Super-Kamiokande has recently reported a 2.3σ excess consistent with a DSNB signal, suggesting that a first detection of this flux could be imminent [70].

1.4.2.5 Cosmogenic Neutrinos

Usually referred as GZK neutrinos, this component originates from photo-hadronic interactions of cosmic ray protons with the CMBR. As discussed in 1.1.4, the GZK interaction generates a cosmogenic flux of neutrinos, through the decay of secondary charged pions, which subsequently decay into neutrinos. These processes are efficient only in the case of protons, while in the case of heavier nuclei photo-hadronic interactions are significantly suppressed. Therefore the bulk of secondary neutrinos is produced by the lighter components of UHECRs. Their detection is a challenge of the future planned UHECRs and neutrino observatories [71]. Nevertheless, the observation of KM3-230213A [12] has triggered the investigation of its possible origin as a cosmogenic neutrino [72]. Under such hypothesis, only cosmogenic models with strong source evolution and a non-negligible proton fraction at the highest energies can account for the event.

An extensive description of atmospheric and cosmic neutrinos is demanded, respectively, to 1.4.3 and 1.4.4.

1.4.3 Atmospheric neutrinos

The Earth's atmosphere is continuously bombarded by CRs. When a CR collides with an atmospheric atom, it triggers a cascade of secondary particles, known as

an air shower. A complete description of the cascade development, starting from the CR interaction, is done through dedicated Monte Carlo and proper numerical simulations. Among the secondary particles of the shower there are charged pions and kaons, which decay to produce electron and muon neutrinos (atmospheric neutrinos), as well as atmospheric muons, which are the most abundant component at sea level because of their small energy losses. Depending on the nature of the secondary particles produced, there are two kinds of atmospheric neutrinos, which is usually referred as *conventional* and *prompt* neutrinos. Conventional atmospheric neutrinos are created from the decay of charged pions and kaons, while the prompt component results from decay of charmed mesons, as the D-mesons. The spectrum of conventional atmospheric neutrinos behaves as the one of primary CRs at energies up to 100 GeV ($\sim E^{-2.7}$), and then, in the region 100 GeV-100 TeV, becomes steeper as $\sim E^{-3.7}$. In fact, at high-energy, the decay probability of pions and kaons is small, because their decay length becomes much longer with respect to the interaction length. Instead, prompt neutrinos are expected to follow a spectrum that is $\sim E^{-2.7}$: charmed mesons have a characteristic lifetime of 10^{-12} s and immediately decay with a tiny interaction possibility with other nuclei in the atmosphere. This contribution is therefore supposed to exceed the conventional one at the highest energies of the spectrum, but has not been experimentally identified. This is even more difficult to study because the dynamics of charmed particles production in hadronic interactions is still poorly known. Since the spectrum of CRs is well measured, the spectrum of atmospheric neutrinos can be inferred too. However, neutrino oscillations impact the neutrino flavor ratio, though this effect is relatively minor within the energy range spanned by conventional and prompt atmospheric neutrinos. In fact, for energies above ~ 100 GeV, neutrino oscillations can be neglected over terrestrial baselines. Figure 18 displays measurements of the atmospheric neutrino flux performed with the IceCube experiment, the Fréjus experiment and the ANTARES neutrino telescope.

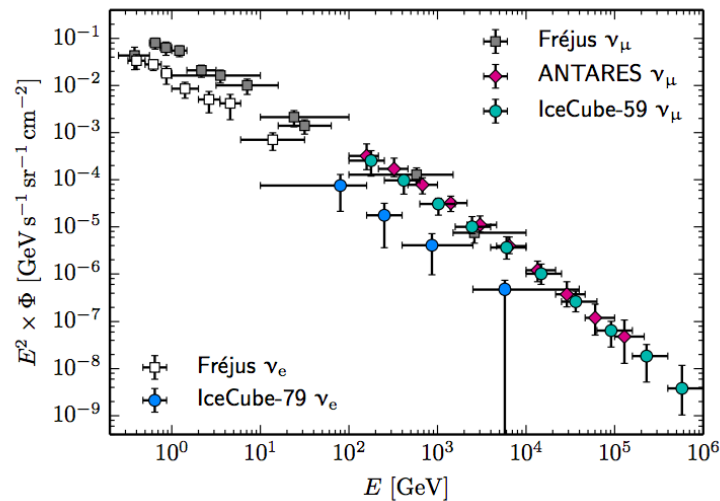


Figure 18: Measurements of the atmospheric neutrinos flux performed by the Fréjus experiment [73], ANTARES [14] and IceCube [5]. The vertical axis is scaled with E^2 for better readability. Image from [64].

Above some TeVs, only neutrino telescopes have the sufficient effective area to detect, with high statistics, the flux of atmospheric neutrinos. As discussed in Chapter 2, atmospheric neutrinos are the major source of background for neutrino telescopes.

1.4.4 Astrophysical neutrinos

It is essentially unavoidable that the sources of UHECRs sources are also sources of neutrinos. In fact, in general a CR accelerator must contain a certain amount of target material, like gas or photons in an environment filled with high densities of radiation. Also, the flux of astrophysical neutrinos has a harder energy spectrum if compared to the flux of atmospheric ones and it should become dominant at energies above 100 TeV. Until few years ago the Sun and supernova SN 1987A were the only known sources of astrophysical neutrinos. Nowadays we know that also AGN are suggested as potential sources [7] [11] and, in addition to that, the discovery by IceCube of an cosmic flux of neutrinos [6] has put the basis for the modern study of neutrino astronomy. Since the observed neutrino flux is isotropic, the majority of neutrino sources is expected to be of extragalactic nature. Though the sources of this flux are still unknown, AGN are considered candidate sources, given the association observed in the multi-messenger analysis. The still limited significance of the coincidence will possibly be increased in future datasets.

1.4.4.1 Production mechanism

High-energy CRs can produce neutrinos when they interact with ambient target particles or radiation. The properties of the produced neutrino flux depend on the primary cosmic-ray flux as well as the properties of the target. There are two classes of mechanisms generally considered: pp and p γ interactions, already introduced in 1.2.1 and 1.2.2. If the acceleration site is surrounded by interstellar gas clouds, the accelerated CRs will collide with gas nuclei, producing neutral and charged pions in inelastic scattering processes. If both interacting nuclei are protons, the production mechanism is the pp scenario, in which charged pions produce neutrinos in their decay, while neutral pions give rise to high-energy gamma rays. This implies a very tight connection between these two messenger particles. The p γ considers that the target for the high-energy CRs are photons from radiation fields that are present at the acceleration sites. The dominating process is the production of the Δ^+ resonance, which decays into pions and produce neutrinos following the same chain of reactions of the pp case. Being a resonant process, the energy of the CRs and of the target photons have to match that in the center-of-mass system. Pions can also be produced during inelastic collisions when the center-of-mass energy surpasses the pion's rest mass, a process known as *multipion production*. Those mechanisms present substantial differences:

- The p γ mechanism has a high threshold for the production of the Δ^+ resonance ($m_{\Delta^+} = 1.232$ GeV). If the photon target is in the UV/X-ray band, as in the case of supermassive black holes, with energies of about 0.1 keV, neutrinos produced will be suppressed below an energy of 100 TeV, while this is not the case for the pp mechanism.

- In the case of $p\gamma$ mechanism, the resulting neutrino and high-energy gamma ray spectra will reflect the shape of the spectrum of the photon target. This is not happening in the pp case, where the secondaries spectra follow the distribution of the primary protons. So, if protons are accelerated according to a power law spectrum, neutrinos will follow the same differential energy distribution.

Each neutrino typically carries about $1/20$ of the original cosmic-ray energy if the CRs are protons and all secondary particles decay without further interactions or energy loss. One way to distinguish between the pp and $p\gamma$ scenarios is by measuring the flux at the Glashow resonance. The interaction cross section for electron antineutrinos ($\bar{\nu}_e$) is significantly enhanced at the resonance around 6.3 PeV. Therefore, if $\bar{\nu}_e$ are present in the cosmic neutrino flux, an increased event rate is expected at this energy. In pp sources, $\bar{\nu}_e$ are directly produced in the decay of π^- . By contrast, $p\gamma$ sources produce fewer $\bar{\nu}_e$. While the neutrino flux reaching Earth from such sources will include $\bar{\nu}_e$ through oscillated $\bar{\nu}_\mu$, their fraction remains smaller compared to the total flux than in pp sources.

1.4.4.2 Connection with gamma-ray astronomy

High-energy neutrinos and photons are produced in cosmic-rays collisions. Studies in gamma-ray astronomy can therefore impose significant constraints on the expected neutrino flux from specific sources. However, it is important to consider the differences between neutrinos and photons. For instance, some emitted photons may arise from leptonic processes that do not generate neutrinos. Additionally, gamma rays can be absorbed in optically thick sources and during propagation via the reaction:

$$\gamma + \gamma_{\text{bkg}} \rightarrow e^+ + e^-, \quad (30)$$

where γ_{bkg} represents the extragalactic background light (EBL). This process attenuates the photon flux for incident photon energies in the hundreds of TeV range, especially when accounting for the infrared background emitted by dust thermal radiation. The mean free path of photons is shown in Figure 19. Efficient neutrino production requires a dense environment, which also renders the source opaque to high-energy gamma rays. Consequently, the energy of photons associated with cosmic neutrinos may fall below the detection thresholds of current, rendering these sources opaque. Absorption poses a challenge for gamma-ray astronomy. However, identifying absorption features in the spectra of GeV–TeV gamma rays can provide valuable insights into the poorly understood EBL. This approach requires precise measurements of the gamma-ray flux from a variety of extragalactic objects across different redshifts z , as well as a good understanding of the intrinsic spectra at the sources. The High Energy Stereoscopic System (H.E.S.S.) Collaboration [74] has established an upper limit on the EBL in the near and mid-infrared wavelengths using gamma-ray measurements from blazars at redshifts of $z \sim 0.1$ – 0.2 . A similar upper limit has been reported by the Fermi-LAT Collaboration for the EBL in optical and UV bands [75]. While these upper limits align with many theoretical predictions regarding the EBL, they are model dependent. Future measurements

are expected from CTAO, which will analyze a larger sample of AGN, and is expected to enhance source statistics.

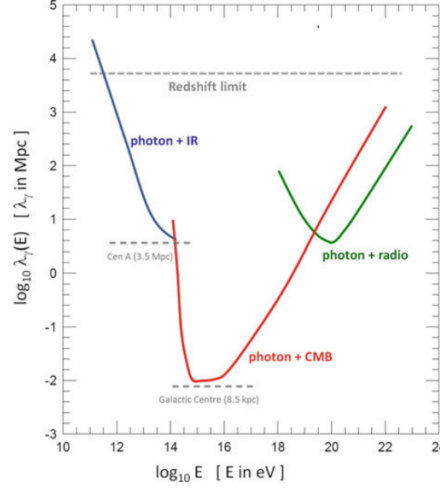


Figure 19: Photon mean free path as a function of the photon energy. Scattering over different contributions of EBL is reported as follows: infrared (blue), CMBR (red), and radio (green). Image from [44].

1.4.5 The big picture: multi-messenger astronomy

In the previous Sections, the properties of all high-energy cosmic messengers have been outlined, as well as the physical processes responsible for their production and their interconnections. The necessity of gathering extensive multi-wavelength and multiprobe data from the Universe has become evident, aiming to study and differentiate the physical processes occurring in astrophysical sources. Combining neutrino data with electromagnetic measurements in a multi-messenger approach will increase our ability to identify the neutrino sources and help to solve long-standing problems in astrophysics such as the origin of UHECRs. In fact, there is so far no confirmation of the sources of either the UHECRs, high-energy neutrino or gamma-ray diffuse backgrounds, but mutual relationships are still expected: high-energy neutrinos are produced when UHECRs collide with low energy target photons and nuclei resulting in charged and neutral pions, which decay in a predictable fraction of high-energy neutrinos and gamma rays. Figure 20 shows that the intensity of gamma rays, neutrinos and UHECRs is comparable, suggesting that they may be powered by the same sources. As blazars are the most abundant extragalactic sources, they are by default the most promising candidates, alongside GRBs and SBGs, which have become increasingly popular in recent years. Finally, by narrowing our search to the Milky Way, one of the questions that will be addressed in the near future through multi-messenger observations is the identification of Galactic cosmic-rays sources and the mechanisms by which these CRs propagate throughout the Galaxy.

Multi-messenger astronomy has already provided important milestones to the scientific community. Excluding the solar neutrino detection, the observation of neutrinos coming from the supernova explosion SN 1987A was the first astronomical

event producing a photon–neutrino coincidence. The identification of the gamma-ray flaring blazar TXS 0506+056 as the first cosmic neutrino source candidate [7] and the detection of GRB 170817A [55], less than two seconds after the event GW170817, marked the beginning of a new era for this kind of searches. Given the numerous experiments currently under construction and in planning, effective communication between collaborations is essential and rapid information exchange is critical. Neutrinos serve as excellent messengers for triggering alerts, as they can escape sources easily. These neutrino alerts provide early warnings to other observatories, enabling prompt follow-up on transient phenomena. Real-time event announcements to the astrophysics community are already facilitated by networks like the Gamma-Ray Coordinates Network (GCN) [76], and platforms such as the Astronomers Telegram (ATEL) [77] provide brief reports on recent observations. Additionally, the Astro-COLIBRI project [78], currently in testing, aims to centralize information from various experiments into an accessible web and smartphone interface. A panorama of all multi-messenger facilities on Earth is shown in Figure 21. The bright future ahead is expected to be revolutionized by the next generation of neutrino telescopes, which will be the subject of Chapter 2.

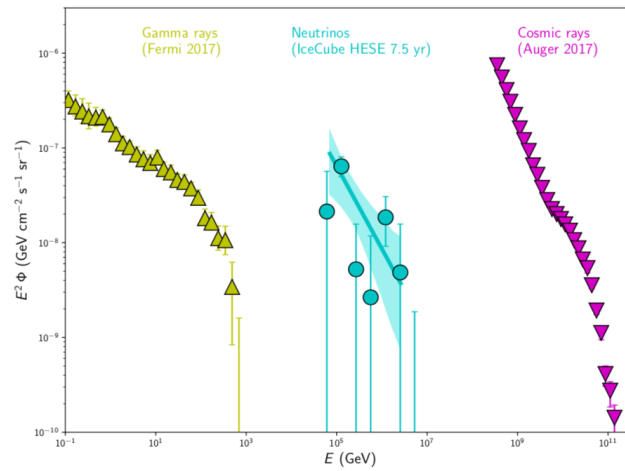


Figure 20: High-energy fluxes of gamma rays, neutrinos and CRs. Image from [79].

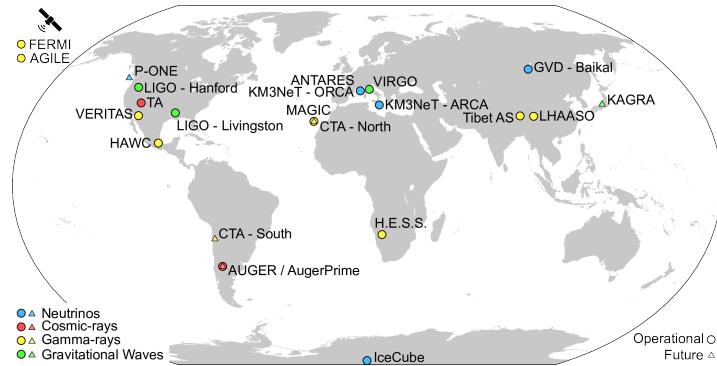


Figure 21: Earth map indicating the location of of multi-messenger observatories that are either currently operating (circles) or planned (triangles). Satellites are outside to the map. Image from [79].

NEUTRINO ASTRONOMY

Astrophysical neutrinos, originating from high-energy hadronic processes in cosmic sources, reach Earth without deflection by magnetic fields and minimal absorption. However, their weak interactions pose a significant challenge for detection, requiring large detector volumes to capture a statistically significant number of neutrino interactions. Following Markov's 1960 proposal [18], major efforts have focused on building detectors in deep water and ice, capable of capturing Cherenkov light from charged particles produced by neutrino interactions with nuclei in the medium surrounding the detector. The phenomenology of their deep-inelastic scattering has been discussed in 1.4.1. Among the experiments that have been or are currently in operation, it is worth to mention the IceCube Neutrino Observatory at the South Pole [5], the Baikal-GVD telescope [80] beneath Lake Baikal, in Russia, and two Mediterranean Sea detectors: ANTARES [14] (dismantled in early 2022) and KM3NeT (under construction) [15]. These observatories aim to capture cosmic neutrino signals, providing insights into high-energy astrophysical phenomena. This Chapter first introduces the basic detection principles of high-energy neutrinos (Section 2.1). The topologies of neutrino interactions are then described in Section 2.2, followed by a discussion of the main sources of background in deep-sea telescopes (Section 2.3) and an overview of the facilities dedicated to high-energy neutrino astronomy (Section 2.4). Finally, Section 2.5 presents the latest results obtained from high-energy neutrino telescopes.

2.1 DETECTION PRINCIPLE OF HIGH-ENERGY NEUTRINOS

A neutrino telescope is made of a matrix of light detectors inside a transparent medium, either ice, like in IceCube, or water, as in the case of ANTARES, KM3NeT and Baikal-GVD. Those media offer a large volume of target nuclei exposed to a neutrino flux, and transmit Cherenkov photons induced by the passage of charged relativistic particles. These particles are produced via charged current (CC) or neutral current (NC) interactions of neutrinos inside or nearby the detector volume. Any charged particle moving at a velocity v higher than the speed of light in the medium induces the emission of Cherenkov radiation. Cherenkov photons are then detected with an array of photomultiplier tubes (PMTs) and from time, position and amplitude of PMTs pulses, it is possible to infer the energy and the direction of the incoming neutrino. Specifically, Cherenkov radiation is emitted as a result of polarization and depolarization effects of molecules in a medium, after the passage of such relativistic particles [81]. Charged particles polarize the molecules along the particle trajectory and an overall dipole moment is created. Once particles have passed, the medium restores the equilibrium, creating an os-

cillating dipole emitting coherent radiation on the surface of a cone (Figure 22), whose characteristic angle with respect to the particle direction (θ_c) is given by:

$$\cos(\theta_c) = \frac{c/n}{v} = \frac{1}{n\beta}, \quad (31)$$

with n being the refractive index of the medium and β the speed of the relativistic particle in units of c . For relativistic particles ($\beta \sim 1$) in the sea, with $n \sim 1.364$, $\theta_c = 43^\circ$, while in ice, for $n \sim 1.3$ and $\theta_c = 41^\circ$. The number of Cherenkov photons induced by a particle of charge e in the unit wavelength interval $d\lambda$ and unit length dx is:

$$\frac{d^2 N_\gamma}{dx d\lambda} = \frac{2\pi}{137\lambda^2} \left(1 - \frac{1}{n^2(\lambda)\beta^2} \right), \quad (32)$$

with λ wavelength of the radiation. Shorter wavelengths contribute more significantly to the Cherenkov radiation. Light absorption by water or ice suppresses some wavelengths and in particular for $\lambda < 300$ nm the signal is strongly attenuated in water. In addition, for particle's velocity at threshold, $\beta = 1/n$, few Cherenkov photons are emitted. However, the PMT quantum efficiency is large in the wavelength range between 300-600 nm, matching very well the region in which ice/water are transparent to light [82]. In that range of λ , the number of Cherenkov photons emitted is about 3×10^4 per meter.

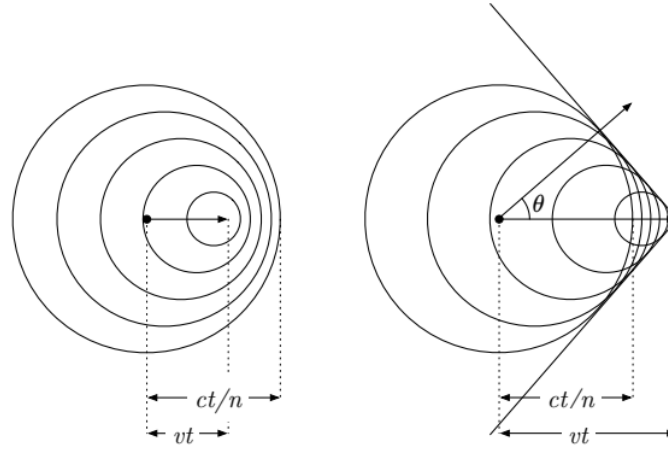


Figure 22: Cherenkov light emission and its wavefront angles. A particle is propagating for a time t with a velocity v in a medium of refractive index n . The wavefronts of light move at velocity c/n after the passage of the charged particle. Image from [64].

2.1.1.1 Light propagation

When Cherenkov photons propagate through seawater, they are affected by absorption and scattering. The *absorption length* l_{abs} is defined as the length after which the number of photons is reduced by a factor $1/e$, where e is the Nepero number. For seawater, this length reaches a maximum of 70 m at a wavelength of 440 nm [83]. Measurements carried out in the deep Mediterranean Sea have shown

that this value is reduced only at the level of 60 m [84]. Instead, at a depth of about 1800 m below the ice surface, $l_{\text{abs}} \sim 80$ m is found at $\lambda = 470$ nm. When trying to identify the best medium for light propagation, the effect of absorption should be considered alongside the light scattering on small grains: the combined contribution is the so-called *attenuation length* l_{att} of the medium. A *scattering length* l_{scatt} of 55 m for $\lambda = 470$ nm has been measured at the ANTARES site and this value is still valid for KM3NeT [85]. Figure 23 shows the scattering and absorption lengths in water as a function of the light wavelength.

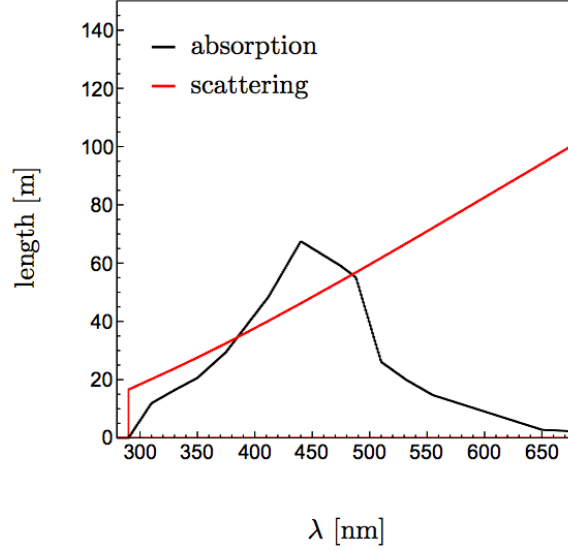


Figure 23: Absorption and scattering lengths in water as a function of the light wavelength. Image from [86].

Finally, laws describing light propagation in water can be written as:

$$I_{\text{abs}}(x, \lambda) = I_0(\lambda) e^{-x/l_{\text{abs}}}, \quad (33)$$

$$I_{\text{scatt}}(x, \lambda) = I_0(\lambda) e^{-x/l_{\text{scatt}}}, \quad (34)$$

$$I_{\text{att}}(x, \lambda) = I_0(\lambda) e^{-x/l_{\text{att}}}, \quad (35)$$

where $I_0(\lambda)$ is the source intensity and x the optical path traversed by the light. In addition, it is customary to define an effective scattering length $l_{\text{scatt}}^{\text{eff}}$, which takes into account that scattering does not depend only on l_{scatt} , but also on the scattering angle θ_s of a single process. This parameter is defined as:

$$l_{\text{scatt}}^{\text{eff}} = \frac{l_{\text{scatt}}}{1 - \langle \cos(\theta_s) \rangle}, \quad (36)$$

where $\langle \cos(\theta_s) \rangle$ is the mean value of diffusion angle in the medium. In water-based neutrino telescopes, for wavelengths at the level of 470 nm, $l_{\text{scatt}}^{\text{eff}}$ has a value of about 270 m, while in ice-based detector, for $\lambda = 400$ nm, $l_{\text{scatt}}^{\text{eff}} \sim 20$ m [87]. Nonetheless, the low absorption cannot be fully exploited because most of the light will be scattered more than twice in one absorption length. Thus, the photon arrival times from the Cherenkov cone are smeared and the uncertainty of the directional information from the muon becomes larger. Compared to ice, the

absorption length of water is less favorable [87], but the scattering properties are much better. A long scattering length allows a high pointing accuracy, such that water-based neutrino telescopes can achieve a better angular resolution. Anyway, it is important to highlight that, while in water the optical properties vary only slightly with depth, in ice the absorption and scattering coefficients change significantly because of stratification of the medium surrounding the detector [64].

2.2 EVENT SIGNATURES IN NEUTRINO TELESCOPES

Products of neutrino interactions induce different light patterns when they cross a transparent dielectric as seawater. Two classes of events can be distinguished in a neutrino telescope: tracks and showers (also called *cascades*). Track-like events are mostly generated by CC interactions of ν_μ where a muon appears in the final state, inducing Cherenkov light and leaving a well-defined track, while shower-like events are characterized by an almost spherically symmetric light emission. Since ν and $\bar{\nu}$ cannot be distinguished by this kind of detectors, no separation between particles and anti-particles can be made case by case. Figure 24 indicates the possible topologies for neutrinos interactions in the instrumented volume of a neutrino telescope. The schematic representation of Figure 24 can be summarized as follows:

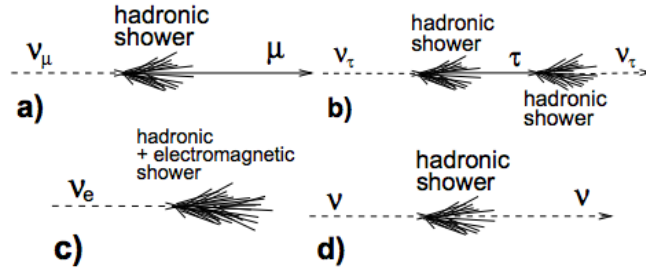


Figure 24: Topologies for neutrino interactions in the instrumented volume of a neutrino telescope: a) CC interaction of a ν_μ produces a muon and a hadronic shower; b) CC interaction of a ν_τ produces a τ that decays into pions and ν_τ , tracing the double bang signature; c) CC interaction of ν_e produces both an electromagnetic and a hadronic shower; d) a NC interaction produces an undetectable neutrino and a hadronic shower. Image from [82].

- Picture **a)** shows the golden channel for neutrino astronomy: CC interaction of a muon neutrino produces a hadronic shower and a muon. However at energies above the TeV level, the length of the muon signature in water is 3 times larger with respect to hadronic shower development. So, only the muon track is clearly seen. In most cases muons are energetic enough to completely traverse the detector, leaving a clear track signature in the instrumented volume. From the kinematics of the interaction above few TeV, the average angle between the incident neutrino and the outgoing muon $\theta_{\nu\mu}$ is [82]:

$$\theta_{\nu\mu} \leq \frac{0.6^\circ}{\sqrt{E_\nu(\text{TeV})}}. \quad (37)$$

Note that such $\theta_{\nu\mu}$ decreases as neutrino energy E_ν increases, so the higher the neutrino energy the better its directional reconstruction. In addition to that, muons suffer energy losses due to ionization, pair production, photonuclear interactions and bremsstrahlung. The energy loss per unit length is parameterized as:

$$\frac{dE_\mu}{dx} = \alpha(E_\mu) + \beta(E_\mu)E_\mu, \quad (38)$$

where $\alpha(E_\mu)$ and $\beta(E_\mu)$ indicate ionisation and radiative losses, respectively. Muons have a long range in water. E.g., a 10 TeV muon can travel 4 km in water. For such reason, high-energy events can be detected even if the neutrino interaction vertex has occurred outside the instrumented detector volume of the telescope. Finally, a muon traveling through ice or water is subject to multiple coulombian scattering, that causes deviations of the muon direction. The deviation of the muon direction due to this process, after traveling a distance x is given by [81]:

$$\theta_{ms} = \frac{13.6 \text{ MeV}}{E_\mu} \sqrt{\frac{x}{X_0}} \left(1 + 0.0038 \ln \left(\frac{x}{X_0} \right) \right), \quad (39)$$

where X_0 is the radiation length of the medium. However, for very high-energy events, the effect of Coulomb scattering can be neglected. Overall, considering both kinematic effects and detector resolution, the muon direction can be measured with a precision less than 1° in ice and 0.2° in water. This difference is due to the smaller scattering length of ice.

- The label **b)** indicates the CC interactions of ν_τ . They produce firstly a hadronic shower and also a τ -lepton that propagates for a given path, depending on its energy, and finally decays, producing a second shower. Below 1 PeV, tauonic tracks cannot be resolved by the instrument, due to the typical spacing of the lines. If the Cherenkov light, induced by the charged particles in the first shower, can be detected and separated from the light induced by the particles produced in the tauonic decay, the signature is referred as *double bang event*. Events in which τ starts or ends outside the instrumented volume are such that a track and a shower can be seen. These are called *lollipop events*.
- Class of events labelled with **c)** indicates CC interaction of ν_e , producing both hadronic and electromagnetic showers. The resulting high-energy electron has a high probability to radiate a photon via bremsstrahlung after few tens of cm of water/ice, then pair production happens and the electromagnetic cascade develops, until particles involved are below the critical energy E_c , whose dependence on the atomic number of the medium Z is expressed as [81]:

$$E_c = \frac{610}{Z + 1.24} \text{ MeV}. \quad (40)$$

The Cherenkov light from electromagnetic showers is emitted isotropically in azimuth with respect to the shower axis. Being its lateral development of

the order of 10 cm, it can be described by its longitudinal development only, which is of the order of a few meters. This makes them appear as point-like sources of Cherenkov photons in the detector. Pointing accuracy for showers is inferior to what can be achieved for the ν_μ channel.

- The label **d)** shows the result of NC scattering of neutrinos that produces a hadronic shower. **c)** and **d)** are not distinguishable in large detectors because of event-by-event fluctuations of hadronic cascades. Shower channel is good for energy reconstruction, since energies loss are fully contained in the detector volume, which behaves as a calorimeter.

2.3 BACKGROUND SIGNATURES IN DEEP-SEA NEUTRINO TELESCOPES

This Section addresses the expected background in deep-sea telescopes, such as KM3NeT, where, as explained in 2.1, optical properties of seawater offer advantages over ice and lake-water detectors. However, disadvantages are constituted by a higher optical background due to the radioactive decay of ^{40}K , and by light emission from living organisms, the so-called bioluminescence. At the same time, atmospheric muons are deeply penetrating particles and represent the bulk of registered events both in deep-sea and under-ice telescopes.

2.3.1 Environmental background

The water in the Mediterranean Sea is abundant with life forms, most of which are light emitters. These organisms contribute to the background in two main ways: a constant component, which exhibits seasonal variability due to bacteria, and short bursts lasting a few seconds, caused by larger organisms. The concentration of these background sources varies depending on the location and depth in the sea. For instance, when considering contributions from ^{40}K and bioluminescence, the background rate per PMT is approximately 7 kHz for KM3NeT/ARCA and 10 kHz for KM3NeT/ORCA [88]. As shown in Figure 25, in 2000, the Istituto Speri-

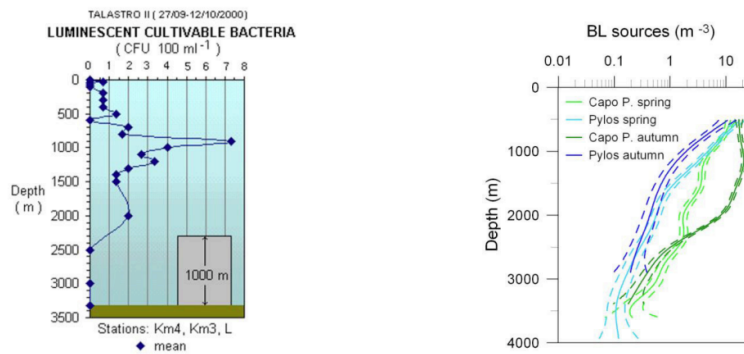
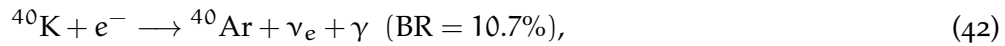
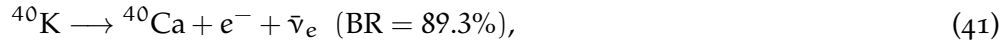


Figure 25: Left: concentration of luminescent bacteria cultivatable at atmospheric pressure, as a function of depth. The data have been obtained from water samples taken at the Capo Passero site. Right: density of bioluminescent animals at the Capo Passero and Pylos sites, in autumn 2008 and spring 2009. (Dashed lines show 95% C.L.). Image from [88].

mentale Talassografico di Messina cultured bacteria from water samples collected near the Capo Passero site and found no cultivable luminescent bacteria at atmospheric pressure from samples taken deeper than 2500 meters. The number of bioluminescent animals per cubic meter of seawater off the coast of Pylos (Figure 25-right) was found to decrease with depth.

Additionally, among salts from seawater, ^{40}K is the most abundant radioactive element. This isotope decays in two dominant modes, both of which usually result in Cherenkov radiation through the following channels:



where BR is the *Branching Ratio*, i.e. the fraction of particles which decay through an individual mode with respect to the total number of particles which decay. Electrons produced via β^- decay (41) have often sufficient energy to induce Cherenkov emission in water. Photons emitted in the process of Equation 42 have 1.46 MeV of energy, that is enough to scatter via Compton effect the electrons of the medium, which as a result acquire energy to induce light emission. Hits produced in the apparatus by these reactions can still mimic signal induced by muon's tracks or by showers. This problem is solved with trigger algorithms which exploit time coincidence of hits and information concerning the PMT angle in order to reduce the amount of background. The concentration of ^{40}K in the Mediterranean Sea is independent of the geographical location. Its contribution is constant and estimated to be at the level of 5 kHz for a 3-inch PMT.

2.3.2 Physical background

Neutrino telescopes continuously suffer from the so-called physical background. Extensive Air Showers (EAS) induced by interactions of cosmic rays with the Earth atmosphere produce atmospheric muons and atmospheric neutrinos. Muons often arrive in bundles almost parallel and with similar energy loss patterns. They can penetrate several kilometers in water/ice, potentially mimicking cosmic neutrino signals in the detector. They can be filtered by selecting upgoing events coming from below the horizon of the telescopes, as the Earth acts as a muon shield (see Figure 26). This selection minimizes the atmospheric muon contamination, leaving only atmospheric neutrinos as the primary background. While telescopes are often placed in deep transparent water/ice, to reduce atmospheric muon flux, residual downgoing muons can still be misreconstructed as upgoing. These events are typically discarded due to bad quality of the track fitting. The effectiveness of further suppressing this source of background mainly depends on the performances of the reconstruction algorithms, which differ from one neutrino telescope to another. At the same time, events induced by atmospheric neutrinos constitute an irreducible background that remains present. However, at energies above the PeV level, the Earth becomes opaque to neutrinos, significantly reducing the flux of upgoing events. Consequently, at such high energies, neutrinos are primarily observed from the upper hemisphere or near the horizon. In fact, in this energy regime, the atmo-

spheric background rate is sufficiently low to allow reliable distinction of signal neutrino events, even when they originate from above the horizon.

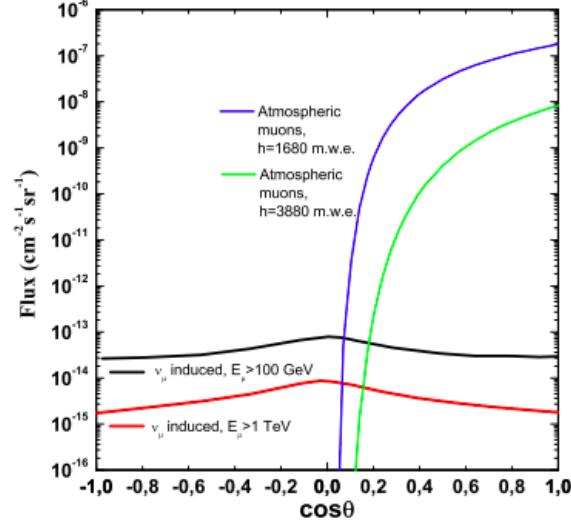


Figure 26: Flux, as a function of the cosine of the zenith angle θ , for atmospheric muons and atmospheric neutrino induced muons. Blue line refers to a depth of 1680 m in water and green line to a depth of 3880 m. Black line refers to an energy threshold of 100 GeV, while the red line to a 1 TeV threshold. Image from [82].

2.4 NEUTRINO TELESCOPES

High-energy neutrino telescopes are a cutting-edge technology designed to probe the most energetic processes of the Universe. These detectors use the weakly interacting nature of neutrinos to observe astrophysical events that are otherwise inaccessible, relying on the detection of Cherenkov light. IceCube [5], the world's largest neutrino telescope, uses an in-ice Cherenkov detection method in Antarctica, instrumenting 1 km^3 of ice with PMTs to detect neutrino interactions. It has provided groundbreaking measurements, among which the discovery of a diffuse astrophysical neutrino flux [6], the observation of a diffuse neutrino emission from the Galactic Plane [89], and hints of phenomena such as the Glashow resonance [63]. Current detectors, such as KM3NeT [15] and Baikal-GVD [80], which are under construction and already taking data, are expected to enhance sensitivity across a wider energy range and Southern Sky coverage. Other initiatives, still in early R&D phases, include P-ONE [90], TRIDENT [91], and the next-generation IceCube-Gen2 [92]. In the coming decades, several innovative experiments aim to explore neutrinos at PeV to EeV energies, utilizing techniques such as radio detection, particle showers, Earth-skimming neutrinos, balloons and satellites. These efforts aim to resolve the spectral properties of astrophysical neutrinos and identify their sources. Additionally, next-generation detectors are targeting EeV and even ZeV neutrinos, predicted to arise from ultra-high-energy cosmic-rays interactions or exotic phenomena. These ambitious projects employ diverse detection methods, from Cherenkov and fluorescence to radio and particle showers.

2.4.1 Under-ice neutrino telescopes

The IceCube Neutrino Observatory, located at the South Pole, is currently the only under-ice telescope and represents the first gigaton-scale neutrino detector ever built. It comprises the in-ice IceCube detector, which is deployed 1450-2450 meters below the Antarctic ice, and the IceTop surface array, used for cosmic-ray studies and as a veto for IceCube. The detector consists of 5160 Digital Optical Modules (DOMs) arranged in 86 strings, with 78 strings forming a hexagonal grid and eight strings configured as a denser infill array to lower the detection threshold to 10 GeV (DeepCore of Figure 27). Each DOM includes a 10-inch PMT, calibration LEDs, and electronics within a pressure-resistant sphere. IceCube measures neutrino fluxes from 100 GeV to several PeV, with sensitivity extending beyond 1 EeV. It also investigates neutrino oscillations, sub-TeV dark matter and core-collapse supernova neutrinos. The observatory achieves precise event reconstructions, such as 0.25° accuracy for muon tracks at 1 PeV and shower events to about 7° at 1 PeV [93]. Since its completion in 2010, IceCube has provided full-sky coverage, with unprecedented sensitivity to TeV neutrinos from the Northern Sky [94]. This capability supports studies of various astrophysical sources, including blazars, diffuse Galactic emissions, Gamma-Ray Bursts and fast radio bursts, as well as broader physics analyses like dark matter searches, neutrino flavor studies and tests of Lorentz invariance [93]. The Southern sky, dominated by atmospheric muons, presents challenges due to background noise, but high-energy tracks and cascades mitigate this limitation. As mentioned, in 2013 IceCube reported the first evidence of an unresolved astrophysical neutrino flux, marking a breakthrough in high-energy astrophysics. Additionally, IceCube has been at the forefront of numerous key observations in neutrino astronomy over the years, most of which will be discussed in Section 2.5.

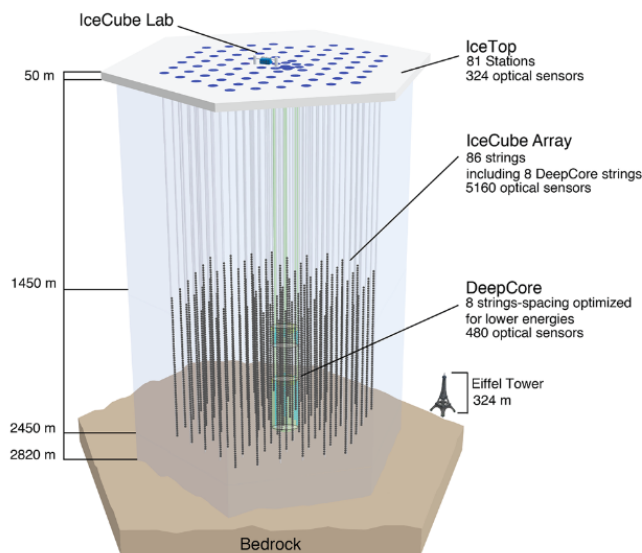


Figure 27: Architecture of the IceCube Observatory. Image from [93].

The IceCube Neutrino Observatory has two major expansions planned. The *IceCube Upgrade* [95] involves the addition of seven new columns of photosensors

near DeepCore, designed to deepen the understanding of the optical properties of glacial ice, allowing to improve the quality of the reconstruction. Its goal is to improve the sensitivity to neutrino oscillations and enable unique measurements of the tau neutrino appearance. The *IceCube-Gen2* expansion [92], displayed in Figure 28, will significantly increase the detector volume and sensitivity. It will consist of an optical array covering 8 km^3 of ice, with improved multi-PMT DOMs that increase photon collection by a factor of 3. The array will be deployed with wider string spacing (240 m) and will offer improved angular resolution and a sensitivity five times greater than the current detector. IceCube-Gen2 will also include a sparse radio array for ultra-high-energy neutrinos detection, extending sensitivity to energies beyond 100 PeV. This array will cover 500 km^2 and enable studies of GZK-neutrino production and high-energy muons.

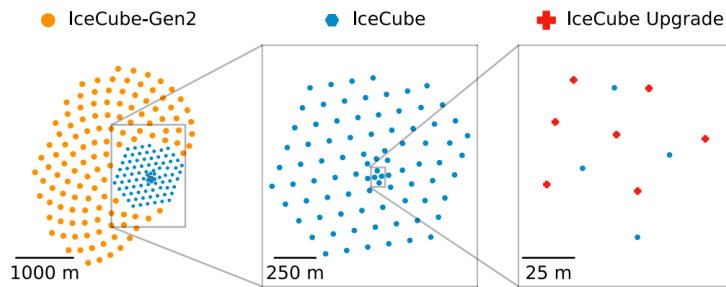


Figure 28: Top view of the IceCube optical detector arrays. Left: the IceCube-Gen2 optical array, in the reference "sunflower" design, instrumenting 7.9 km^3 . Center: the current 1 km^3 IceCube array. Right: the low-energy IceCube Upgrade, focusing on neutrino oscillation properties. Image from [93].

2.4.2 Underwater neutrino telescopes

Placing neutrino detectors underwater offers another way to take advantage of large volumes of transparent natural medium. The primary advantage is the longer scattering length, thus enhancing the angular resolution in reconstructing the particle direction. Compared to ice, underwater setups face challenges such as the detector movement due to sea currents, variability of the environmental background and the corrosive effects of seawater. However, the long experience under the Mediterranean Sea and under lake Baikal has shown that it is possible to deal with all these effects, fully exploiting the numerous advantages of deep water. Several experiments have been or are currently being constructed underwater.

The Baikal-GVD neutrino telescope [80] is located in the Southern part of Lake Baikal, 4 km from shore where the lake depth is nearly constant at 1366-1367 m. The telescope consists of independent structural units, named clusters. As of 2025, the detector includes 117 strings arranged in 14 independent clusters with an effective volume of 0.7 km^3 . A general view is presented in Figure 29. Each cluster of the telescope consists of 8 strings each with 36 optical modules (OMs) and calibration systems. OMs are located at depths ranging from 750 m until 1275 m, with a vertical spacing of 15 m. Cluster radius is 60 m and the horizontal distance be-

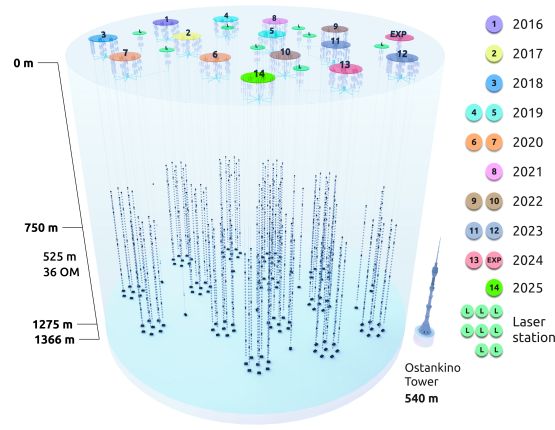


Figure 29: General view of the Baikal-GVD detector in season 2025. Yearly progression of detector deployment is shown in the legend. Technological strings carrying lasers are also shown. Image from [96].

tween central strings of neighboring clusters is $\sim 200 - 300$ m. Baikal-GVD optical module is a glass sphere which hosts PMTs with a 10-inch hemispherical photocathode oriented towards the lake floor. The detector site is characterized by a low concentration of ^{40}K , which is a source of noise in water-based neutrino detectors. This isotope is a β decayer and the resulting electron has an energy of 1 MeV, enough to induce Cherenkov light emission in the detector. Although Baikal-GVD benefits from low optical noise, this advantage is partially offset by the limited light absorption length (about 20 m) and by the fact that Baikal-GVD is located just about one km below the water surface, exposing it to a larger atmospheric flux of muons and neutrinos compared to other telescopes.

The Astronomy Neutrino Telescope and Abyss Environmental RESearch detector (ANTARES) [14] was the first fully operational deep-sea neutrino telescope. Located in the Mediterranean Sea, 40 km off the French coast, at depths of about 2500 m, it began operations in 2007. The detector featured a three-dimensional array of 885 OMs, oriented at a 45° angle downward, and arranged along 12 vertical detection lines. Each OM consisted of a 10-inch PMT housed in a pressure-resistant glass sphere. OMs were grouped in triplets, with 25 triplets per line, spaced 14.5 meters apart vertically. Each detection line extended 450 meters, with line separations ranging from 60 to 75 meters. The lines were connected to a junction box, linked to shore via an electro-optical cable. The main components of ANTARES are shown in Figure 30. Due to the movement of the lines caused by sea currents, acoustic devices were used to determine the position of each OM with a precision of better than 15 cm. The total sky coverage of ANTARES was 3.5π sr, with an overlap of 0.5π sr with IceCube's coverage. The Galactic Center was visible for 67% of the day time through Earth-shielded events. Information about the time, position and pulse width of the signal collected by the OMs was digitized and transmitted to shore via optical fibers. There, events associated with muons were distinguished from the optical background produced by ^{40}K and bioluminescence using trigger algorithms. ANTARES was shut down in February 2022. A summary of the tech-

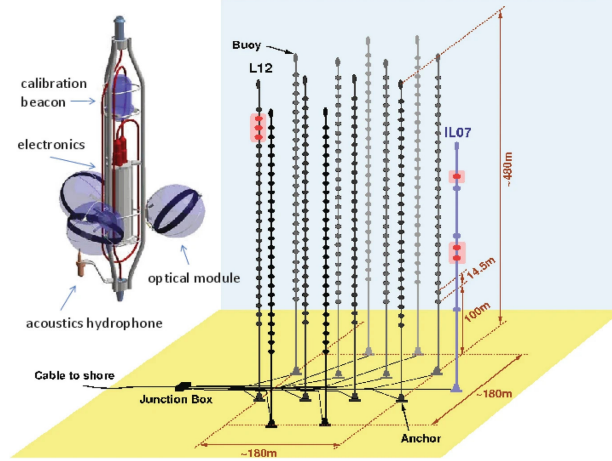


Figure 30: Schematic representation of the ANTARES detector, featuring 12 detector lines (L1–L12) and an additional line equipped with environmental monitoring instruments (ILO7). Lines L12 and ILO7 include test equipment designed for preliminary investigations into acoustic neutrino detection. On the left, a single storey is shown, comprising three optical modules and a metallic cylinder housing the Local Control Module (LCM). Every fifth storey is equipped with a LED beacon (positioned above the LCM) and a hydrophone (located at the bottom left) to facilitate acoustic triangulation. Image from [97].

nological and scientific efforts by the ANTARES Collaboration is reported in [98]. Its successor, KM₃NeT, subject of this work, is a deep-sea research infrastructure hosting two neutrino telescopes: KM₃NeT/ARCA and KM₃NeT/ORCA, currently in construction in the Mediterranean Sea. A detailed description is in Chapter 3.

Planned large-scale neutrino telescopes are the Pacific Ocean Neutrino Experiment (P-ONE) [90] and the TRopical DEep-sea Neutrino Telescope (TRIDENT) [91], still in their R&D phase. P-ONE will be located at a depth of 2660 meters in the Northeast Pacific Ocean, offshore from Vancouver Island, British Columbia, and connected to existing deep-sea infrastructures. Following the successful deployment of two pathfinder missions in 2018 and 2020, which were recovered in 2023 for site assessment, the P-ONE Collaboration is progressing towards the installation of its first detector line, P-ONE₁ [99]. TRIDENT is another next-generation neutrino observatory planned for the South China Sea at a depth of approximately 3500 meters. Situated 180 km from the nearest island, TRIDENT will leverage its equatorial location and utilize advanced hybrid digital optical modules (hDOMs), which combine multiple small PMTs and silicon photomultipliers. The preliminary design consists of 1211 strings, each containing 20 hDOMs spaced 30 meters apart, covering an instrumented volume of around 7.5 km³.

2.5 LATEST RESULTS FROM HIGH-ENERGY NEUTRINO TELESCOPES

In recent years, neutrino astronomy has undergone rapid development, consolidating its practices and analysis methodologies. The IceCube detector, with its 1 km³ of active volume and over 12 years of livetime in its current geometric configu-

ration, remains the leading experiment in the field. However, other neutrino telescopes are either operational or under construction, as discussed in previous Sections. These new instruments will expand and complement IceCube’s field of view, pushing the current limits of detection and fostering new discoveries. Among recent milestones, the KM3NeT Collaboration announced the detection of an extraordinary high-energy neutrino event, named KM3-230213A [12]. This event, observed by the KM3NeT/ARCA neutrino telescope when it comprised 21 detection units, showcased an estimated energy in the range of hundreds PeVs, triggering 3672 PMTs, corresponding to 35% of the total active PMTs in the detector. Given the exceptionally high energy and the reconstruction quality of KM3-230213A, the atmospheric origin of the event, including the prompt atmospheric component, was deemed highly improbable. This detection represents a significant advancement in the field, illustrating the unique capabilities of next-generation neutrino telescopes like KM3NeT. In this section, the current status of neutrino astronomy is briefly reviewed, highlighting its recent achievements and its promising future driven by expanding detector networks. A dedicated Section 3.5 goes into the details of the remarkable KM3-230213A event.

2.5.1 Diffuse neutrino signal

The field of high-energy neutrino astronomy experienced a major breakthrough in 2013 with the IceCube detector’s discovery of a diffuse flux of TeV–PeV neutrinos, detected with a statistical significance well above 5σ [100]. This flux, observed without preferred directions in the sky, implies an extragalactic origin, yet the specific astrophysical sources remain unknown. Since the first discovery, the search for cosmic neutrinos has continued through multiple detection channels. IceCube employs two primary classification strategies: the *High-Energy Starting Events* (HESE) sample, where the neutrino interaction vertex is well contained within the detector’s fiducial volume, and *through-going muon tracks*, where ν_μ -induced tracks are traversing the detector, allowing all-sky observations. IceCube has confirmed the presence of a high-energy, all-sky neutrino flux of astrophysical origin, using HESE with energies above 60 TeV. A recent analysis [101], incorporating 7.5 years of data and improved systematics, reaffirms this discovery and investigates potential sources of astrophysical neutrinos. The observations are consistent with isotropic flux models and a single power-law (SPL) spectrum, that, for each neutrino flavor, reads as [102]:

$$\frac{\Phi_{\nu+\bar{\nu}}^{\text{astro}}(E)}{C_0} = \phi_0 \left(\frac{E}{E_0} \right)^{-\gamma}, \quad (43)$$

where $C_0 = 3 \times 10^{-18} \text{ GeV}^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$ and $E_0 = 100 \text{ TeV}$. A flavor equipartition at Earth, due to vacuum oscillations of neutrinos over cosmic distances, has been assumed. The preferred spectral index for the astrophysical neutrino flux is $\gamma = 2.87^{+0.20}_{-0.19}$, for an all-flavor normalization of $6.37^{+1.46}_{-1.62}$. Another data sample used to study the diffuse astrophysical neutrino flux is the so-called Northern Sky sample [103]. This sample consists of through-going muon tracks from the Northern celestial hemisphere, accumulated over a total livetime of 9.5 years. Assuming a single power-law model, the best-fit parameters yield a per-flavor normalization

of $\phi_0 = 1.44^{+0.25}_{-0.24}$ and a spectral index of $\gamma = 2.28^{+0.08}_{-0.09}$, constrained within the energy range from 15 TeV to 5 PeV. A third sample, collected over a total lifetime of 6 years [102], is based on cascade events. This cascade sample is dominated by electron and tau neutrinos, which contribute approximately 90% in the totality of the sample. The sensitive energy range is from 16 TeV to 2.6 PeV, consistent with a single power-law model. The best-fit parameters are a per-flavor flux normalization of $\phi_0 = 1.66^{+0.25}_{-0.27}$ and a spectral index of $\gamma = 2.53^{+0.07}_{-0.07}$. The energy distribution of the observed cascade events is reported in Figure 31. Finally, an additional study examines astrophysical and atmospheric neutrino interactions at multi-TeV energies using 5 years of IceCube data, with a sample of 2650 tracks and 965 cascades [104]. The energy spectrum of diffuse astrophysical neutrinos is well described by a power law with a best-fit index of $\gamma = 2.62^{+0.07}_{-0.07}$, from 3.5 TeV to 2.6 PeV, and $\phi_0 = 2.04^{+0.23}_{-0.21}$.

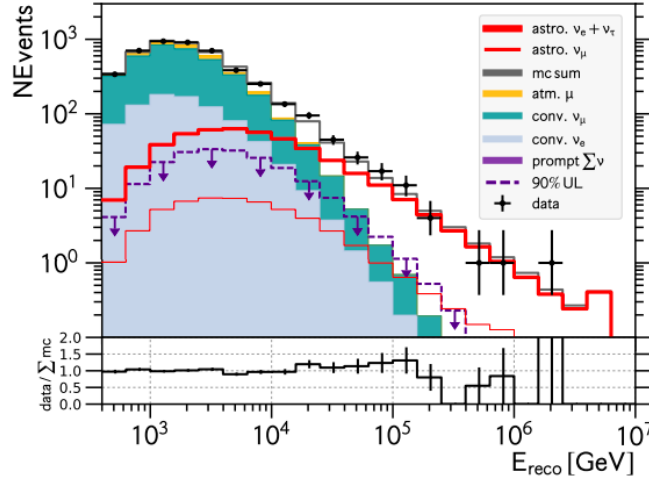


Figure 31: Energy distribution of the observed cascade events compared to Monte Carlo predictions by the IceCube detector. Image from [102].

Figure 32 summarizes these previously described measurements, revealing consistency across energy ranges despite minor tensions in spectral indices. This slight tension between the different measurements could be due to differences in flavor composition, energy range, the accounting of atmospheric backgrounds and the observed portion of the sky. The plot also shows the analysis of the 9-year ANTARES all-flavor data sample, pointing to a mild excess of events above atmospheric background expectations [105]. This excess is consistent with the high-energy diffuse cosmic neutrino signal detected by IceCube, though less significant due to the smaller detector size. The analysis was expanded with ~ 900 additional days of data acquisition, revealing a 1.8σ excess above atmospheric backgrounds, and the null cosmic contribution in the high-energy sample has been excluded at the 90% confidence level. More recently, the Baikal-GVD Collaboration has reported an updated measurement of the diffuse astrophysical neutrino flux using cascade data collected between April 2018 to March 2024 [96]. The diffuse astrophysical neutrino flux is detected with a statistical significance of 5.1σ . Assuming a single power-law model of the astrophysical neutrino flux with flavor equipartition, the best-fit parameters are: $\gamma = 2.64^{+0.09}_{-0.11}$ for the spectral index, and

$\phi_0 = 4.42^{+2.31}_{-1.29} \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ per flavor at 100 TeV. Results for the spectral index are consistent with the measurements reported by IceCube in Figure 32. Combined analyses and next-generation detectors promise to refine these measurements further, especially above 10 PeV, enhancing our understanding of astrophysical neutrino sources and their production mechanisms.

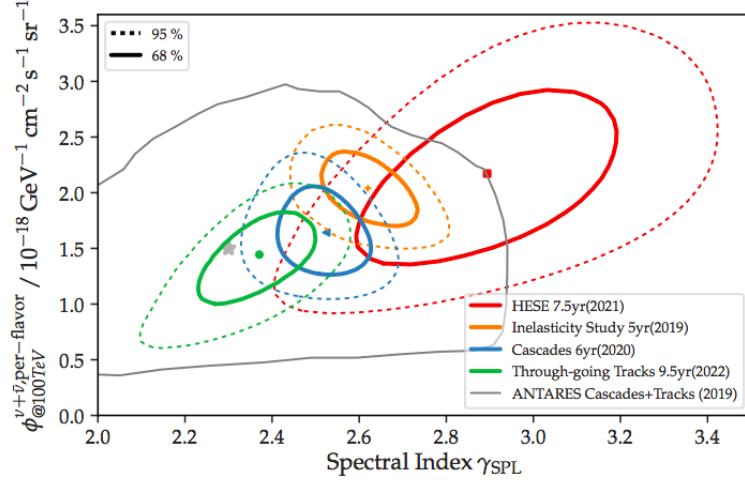


Figure 32: Overview of astrophysical diffuse flux measurements to date is shown. The green point and contours represent the best-fit and uncertainties from predominantly upgoing tracks in IceCube with 9.5 years of data [106]. These results are overlaid with IceCube data from high-energy starting tracks and cascades (red), predominantly contained cascades (blue), and predominantly starting tracks (orange). ANTARES result (gray) using both cascades and tracks from 9 years of data is also included for comparison. Image from [93].

2.5.2 Diffuse neutrino emission from the Galactic Plane

The IceCube Collaboration reported the first observation of neutrino emission from the direction of the Galactic Plane with a significance level of 4.5σ [89]. A significance map of the Galactic Plane, derived from neutrino data, was constructed and compared to model predictions of neutrino distributions, based on gamma-rays observations (Figure 33). Among different emission models, the Fermi- π^0 model was also tested. In such a model, the gamma-ray flux is a mix of leptonic and hadronic contributions, with the π^0 decay contributing around 70% at 10 GeV, decreasing to 45% at 1 PeV. Using the measured gamma-ray flux, the π^0 and neutrino emissions are derived, assuming a power law for the neutrino spectrum. To minimize atmospheric neutrino background, the analysis focused on cascade events, which offer better energy resolution, despite having lower angular resolution. The choice of this topology was necessary because, for IceCube, the Galactic Center is located in the downgoing sky, where the atmospheric muon background is dominant. Deep learning tools, including convolutional neural networks (CNNs), were applied for event selection, improving signal purity and identifying low-energy neutrino events. A hybrid reconstruction method combining deep learning and maximum likelihood estimation refined event properties for

enhanced detection sensitivity, especially for extended sources. This approach improved both the statistics and the angular resolution of IceCube events ($\sim 7^\circ$ at 1 PeV), allowing for a 4.5σ discovery of diffuse neutrino emission from the Galactic Plane. In the Fermi- π^0 scenario, the background-only hypothesis was rejected at 4.71σ , with flux normalization at 100 TeV of $21.8 \times 10^{-12} \text{ TeV cm}^{-2} \text{ s}^{-1}$. Nevertheless, resolving individual sources along the Galactic Plane requires telescopes located in the Northern Hemisphere, which can observe this region using track-like events with superior angular resolution.

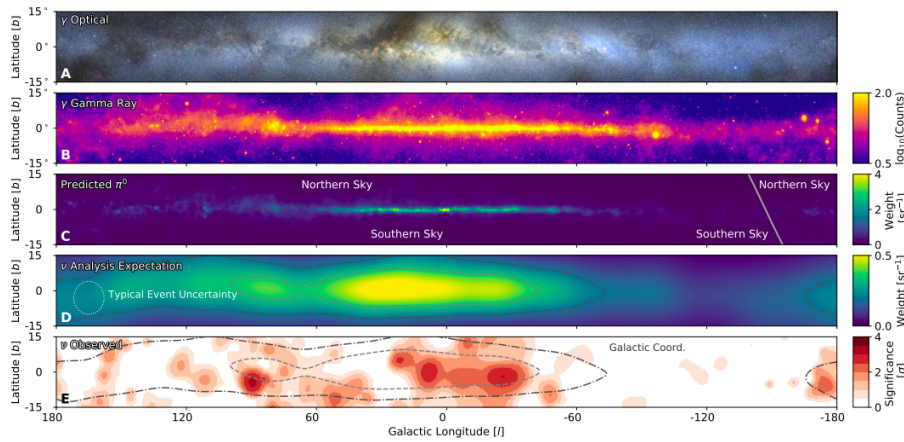


Figure 33: The Galactic Plane in both photons and neutrinos, using Galactic coordinates centered on the Galactic Center. The panels provide various data: (A) optical image partially obscured by gas and dust; (B) integrated gamma-ray flux from Fermi-LAT; (C) expected neutrino flux derived from the π^0 template; (D) adjusted neutrino emission template with detector sensitivity and angular uncertainty; (E) significance of IceCube's neutrino observations. The pre-trial significance of the analysis is shown, with contours indicating regions of predicted diffuse neutrino emission. Image from [89].

2.5.3 Neutrino point sources

The detection of neutrino emission from TXS 0506+056 and NGC 1068 [93] has provided compelling evidence that high-energy neutrinos have an extragalactic origin. This breakthrough discovery also hints at the existence of a rich extragalactic neutrino sky, potentially composed of diverse source populations contributing to the observed cosmic neutrino flux. These populations may include Active Galactic Nuclei (AGN), Starburst Galaxies, Gamma-Ray Bursts, and other energetic phenomena, each with distinct contributions across various energy ranges. Despite significant progress, no resolved Galactic neutrino sources or cosmic-ray accelerators have been confirmed to date. Observatories in the Northern Hemisphere, such as Baikal-GVD and KM3NeT, are expected to offer substantially improved sensitivity to the inner Galactic Plane and center. These regions are associated with intense non-thermal emission and host several candidate cosmic-ray accelerators, including the recently discovered Galactic PeVatrons, discussed in 1.2.

2.5.3.1 NGC 1068

The IceCube Collaboration has recently reported the first evidence of neutrino emission from the nearby active galaxy NGC 1068 [11]. This galaxy is notable as both a type-II Seyfert galaxy, an AGN characterized by radio-quietness and narrow optical emission lines, and a Starburst Galaxy. It has long been considered one of the most promising neutrino sources in the Northern sky. Gamma-ray limits from MAGIC and H.E.S.S. observations indicate that NGC 1068 is a hidden neutrino source, where sub-TeV gamma rays are attenuated or cascaded to lower energies [107]. Data collected by IceCube between May 2011 and May 2020 were analyzed to search for point-like neutrino sources in the Northern sky, where IceCube has optimal sensitivity. The probability sky map of the Northern Hemisphere is shown in Figure 34.

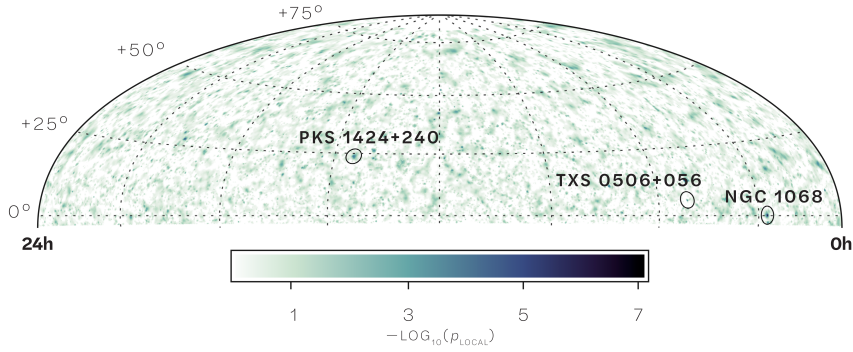


Figure 34: Sky map of the point source scan in the Northern Hemisphere. The color scale represents the local p-value derived from the maximum likelihood analysis, with the spectral index treated as a free fit parameter, evaluated at each sky location. The map is displayed in Equatorial coordinates using a Hammer-Aitoff projection. Black circles mark the three most significant objects from the source list search, with the circle for NGC 1068 coinciding with the hottest spot in the Northern Sky. Image from [11].

The angular resolution of the analysis improves with energy, being 1.2° at 1 TeV, 0.4° at 100 TeV, and 0.3° at 1 PeV. Among the 110 sources tested for neutrino emission based on their γ -ray flux, NGC 1068 was the most significant, with 79 signal events and a post-trial p-value corresponding to a 4.2σ significance. Under a single power-law assumption, the best-fit parameters were a spectral index of 3.2 and a normalization at 1 TeV of $5.0 \cdot 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$. The main neutrino excess originates from energies between 1.5 and 15 TeV. Assuming isotropic emission from a distance of 14.4 Mpc, the inferred neutrino luminosity is $(2.9 \pm 1.1) \cdot 10^{42} \text{ erg s}^{-1}$, an order of magnitude higher than the equivalent gamma-ray luminosity observed in the 100 MeV–100 GeV range. Gamma-ray observations from MAGIC and H.E.S.S., along with theoretical predictions, suggest that high-energy neutrinos from NGC 1068 may originate near its supermassive black hole. Particles may be accelerated in the hot coronae around the accretion disk or by disk-driven winds. Additionally, the AGN corona model suggests that NGC 1068, one of the brightest intrinsic X-ray sources, is among the most promising neutrino sources in the Northern Sky [108]. The IceCube flux could be explained if a fraction

of the accretion power is transferred to protons, and gamma rays are predicted to appear in the MeV range, consistent with current observations by Fermi, H.E.S.S. and MAGIC. Future MeV-scale observations of NGC 1068 would provide crucial insights into its physical processes. Furthermore, next-generation detectors such as KM₃NeT/ARCA are expected to achieve a 5σ discovery of NGC 1068 after three years of operation in its final configuration, assuming a spectral index of 3.2 [109].

2.5.3.2 TXS 0506+056

The blazar TXS 0506+056 is the first astrophysical source linked to high-energy neutrino emission. This association was established following the detection of a high-energy neutrino, IceCube-170922A, on September 22, 2017, with an energy of approximately 290 TeV [7]. The alert triggered multi-wavelength follow-up observations, which identified a spatial and temporal correlation with a flaring state of the blazar TXS 0506+056. In particular, data from Fermi-LAT and MAGIC revealed a significant gamma-ray flare coincident with the neutrino event [110]. This marked the first evidence of a high-energy neutrino source associated with a specific astrophysical object at $>3\sigma$ level. The observed blazar, located at a redshift of $z \sim 0.3365$, is a type of AGN characterized by relativistic jets aligned closely with the line of sight. The subsequent analysis of archival IceCube data revealed an earlier, prolonged neutrino flare from the direction of TXS 0506+056 between 2014 and 2015, with an estimated 13 ± 5 signal events detected over a six-months period. Interestingly, no corresponding gamma-ray flare was observed during this period, and data at lower energies are lacking, making it challenging to fully explain the origin of the neutrino emission. The analysis has been recently updated using the most recent Northern Sky data sample that was used in the analysis of NGC 1068 [111]. The updated sample, which excludes two cascade-like events from the original sample, yields a smaller flux and reduced significance. The cascade events, which were incorrectly classified as track-like in the older data, do not point toward TXS 0506+056 when reconstructed as cascades. The updated results show a shift in the hotspot and a decrease in significance, as depicted in Figure 35.

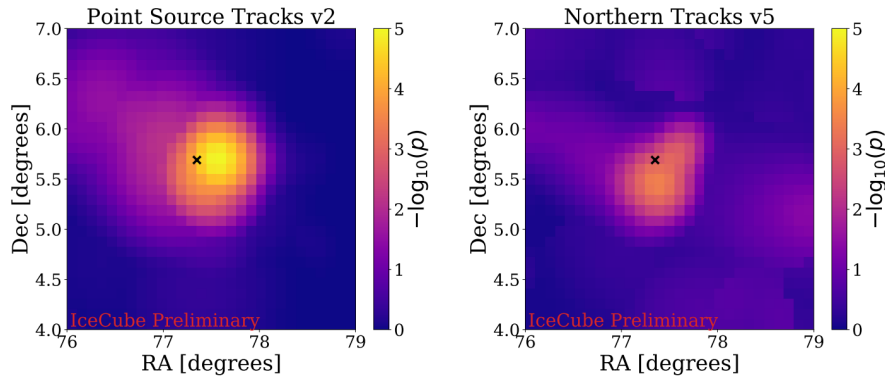


Figure 35: Spatial scans of the 2014 neutrino flare candidate near the position of TXS 0506+056 are shown for both the original 2017 data sample (left) and the updated 2022 sample (right). In both panels, the best-fit parameters for the flare’s start time, stop time, and spectral index are re-assessed at each location. The position of TXS 0506+056 is indicated by a black cross. Image from [111].

2.5.3.3 *Correlation between blazars and neutrino data*

Following the identification of TXS 0506+056 as a candidate neutrino emitter, several studies have reinforced the hypothesis that blazars can act as high-energy neutrino factories. In 2020, a first correlation study [112] has explored whether high-energy neutrinos are produced in radio-bright AGN and, if so, aimed to localize their emission regions. The analysis considered 56 IceCube neutrino events with energies above 200 TeV and directional uncertainties below 10 deg^2 . AGN coincident with these neutrino events exhibit, on average, historically high very-long-baseline interferometry (VLBI) flux densities compared to other AGN within a limited sample of 3388 sources. Simulations indicate that the probability of this correlation arising by chance is only 0.2%. The four brightest AGN dominating this correlation are 3C 279, NRAO 530, PKS 1741–038, and PKS 2145+067. Additionally, periods of enhanced radio emission above 10 GHz were found to correlate with neutrino detections. This correlation persists even when the four brightest AGN are excluded, suggesting that fainter AGN can also produce neutrinos. In particular, PKS 1502+106 exhibits a strong flux enhancement coinciding with a 2019 IceCube event. Results suggest that a significant fraction of $\geq 200 \text{ TeV}$ neutrinos may have originated in the central parsec-scale regions of radio-bright AGN with narrow Doppler-boosted jets directed toward Earth. Protons are supposed to be accelerated near the central black hole, interacting with ambient radiation and producing charged pions that decay into high-energy neutrinos. This evidence was later contradicted by the IceCube Collaboration, who repeated the analysis with a few changes to the method, including more available information, and did not observe the same significance [113].

More recent analyses have instead investigated the possibility of a spatial correlation between blazars listed in the 5th Roma-BZCat (5BZCAT) catalogue [114] and IceCube neutrino detections. As claimed in [115], for neutrinos with energies above 0.1 PeV in the Southern Hemisphere, this correlation reaches a post-trial p-value of 2×10^{-6} , whereas Northern Hemisphere data, sensitive to neutrinos below 0.1 PeV, yielded a post-trial p-value of 6.79×10^{-3} . When combined, these results correspond to a global chance probability of 2.59×10^{-7} , strongly supporting that blazars may contribute to the extragalactic neutrino flux. However, more recent studies [116] have shown that, although the $\sim 4.6\sigma$ correlation can be reproduced using seven years of Southern Sky neutrino data, extending the investigation to the Northern Sky, where IceCube is most sensitive, shows no significant correlation. Similarly, analyses of ten years of IceCube data reveal no significant correlation in either Hemisphere. These findings imply that the strong correlation reported before could be due to a statistical fluctuation and to the non-uniform spatial and flux distribution of blazars in the 5BZCAT catalogue.

The ANTARES Collaboration has also conducted extensive investigations into the relationship between high-energy neutrinos and blazars [117]. The hypothesis of directional correlation yielded a post-trial significance of 2.2σ , while a time-dependent analysis revealed temporal clustering of neutrino candidates in 18 blazars with pretrial significance exceeding 3σ . This analysis suggests a variable neutrino flux originating from these sources. The most remarkable case in-

volved the radio-bright blazar J0242+1101, where neutrino detections coincided temporally with its largest flares observed in radio and gamma-ray wavelengths. Figure 36 presents a multi-messenger timeline for the blazar J0242+1101, illustrating the temporal correlation of neutrino, radio and gamma-ray emissions. The ANTARES panel highlights the best-fit flare period, data produced by the Owens Valley Radio Observatory (OVRO) [118] show a significant radio flare, and the Fermi-LAT panel identifies a coinciding gamma-ray flare. The IceCube panel indicates a 50 TeV neutrino event during the same period, reinforcing the connection between these observations. The a posteriori investigation of this event reported a significance of 2.9σ , strengthening the hypothesis of a shared emission mechanism across neutrino and electromagnetic spectra. This temporal and directional overlap underscores the potential role of flaring blazars as sources of astrophysical neutrinos. Still, an enhanced data integration is needed, as will be provided by the research infrastructure KM3NeT, detailed in Chapter 3.

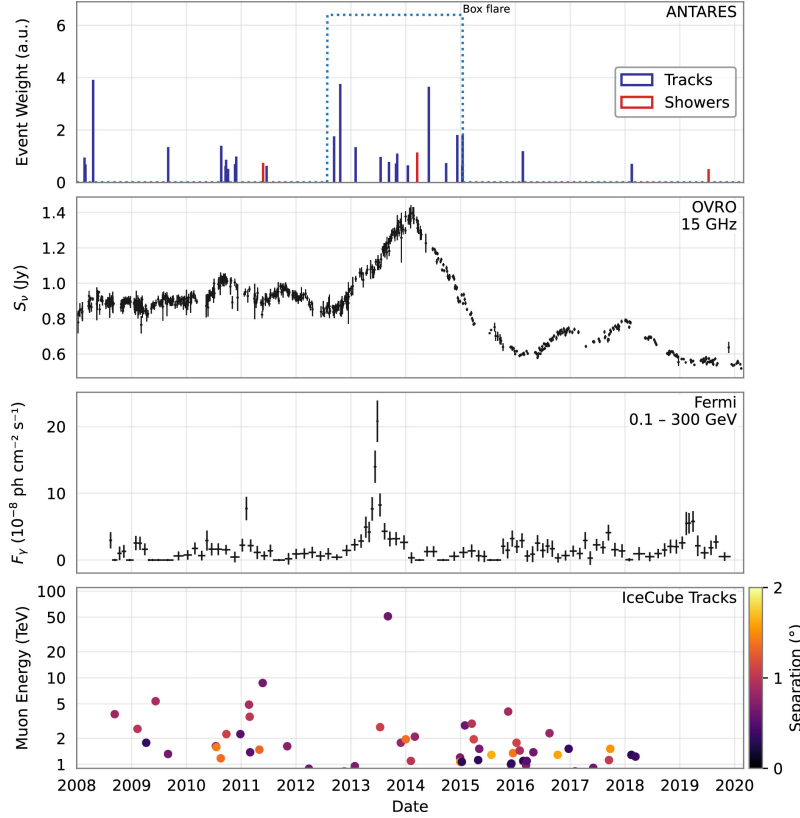


Figure 36: Multi-messenger light curves from the direction of the blazar J0242+1101 as a function of time since 2008. The top panel shows the weighted time distribution of ANTARES track-like (within 5°) and shower-like (within 10°) events near the source, with a box profile based on best-fit temporal parameters $\hat{\delta}_t$ and $\hat{T}_0$. The second panel displays the OVRO radio light curve, highlighting variability over time. The third panel provides the binned gamma-ray light curve derived from Fermi-LAT observations. The bottom panel presents IceCube track-like events near J0242+1101, weighted by event energy, with a color scale indicating the angular distance of events from the source. Image from [117].

KM₃NeT NEUTRINO TELESCOPE

KM₃NeT (Cubic Kilometer Neutrino Telescope) is a research infrastructure housing two neutrino telescopes, currently being constructed at the bottom of the Mediterranean Sea. It aims at performing both physical and astrophysical studies, as the study of neutrino properties and the search for high-energy neutrinos originating from cosmic sources in our Universe. To achieve such different scientific goals, two different detectors are being built with the same innovative technology but optimized to detect neutrinos of different energies. The detector sites are indicated with yellow dots in Figure 37. The KM₃NeT/ORCA (Oscillation Research with Cosmics in the Abyss) detector, designed for low-energy studies (from MeV to sub-TeV), lies off the coast of Toulon (France) at a depth of about 2500 m, and KM₃NeT/ARCA (Astroparticle Research with Cosmics in the Abyss), instead dedicated to high-energy studies (from 100 GeV up to multi-PeV), is located at a depth of about 3500 m close to the Sicilian coast, in Italy. An additional dot is located off the shore of Pylos, in Greece, where a suitable installation site is available to possibly expand the research infrastructure in a future phase. Given

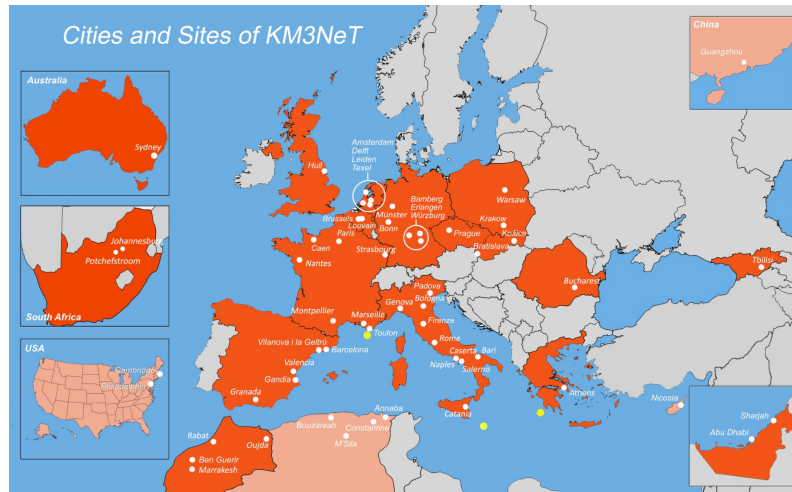


Figure 37: Cities and sites of KM₃NeT. Yellow dots represent the sites where the KM₃NeT detectors are being (or might be) instrumented. White dots indicate the cities of Collaboration institutions. Credits: km3net.org.

its geographical location and better angular resolution, the KM₃NeT/ARCA detector, once completely constructed, is expected to surpass IceCube's sensitivity in the Southern Sky after 7 years of operation, enhancing its astronomy potential to point-like neutrino sources [119]. At the same time, it will be possible to observe most of the Galactic sources within a few years of operation. As an example, KM₃NeT/ARCA can achieve 3σ significance for Vela Jr in ~ 6 years and

RX J1713.7-3946 in ~ 5.5 years [120], assuming their gamma-ray emission is of purely hadronic origin. KM₃NeT/ORCA, instead, aims to determine the neutrino mass ordering by analyzing the flux of atmospheric neutrinos as they propagate through the Earth and studying their oscillation patterns. In its final configuration, it can reach a sensitivity of 4.4σ for normal neutrino mass ordering and 2.3σ for inverted ordering after three years of data collection [121]. Both KM₃NeT detectors consist of vertical strings equipped with multiple photomultiplier tubes (PMTs). As already mentioned, the arrangement of the instrumented lines differs between KM₃NeT/ORCA and KM₃NeT/ARCA, in order to enhance sensitivity to distinct neutrino energy ranges. In KM₃NeT/ORCA the optical modules are arranged in a dense configuration, allowing for the detection of events with energies as low as sub-GeV. The KM₃NeT/ARCA detector array is optimized for the detection of high-energy neutrinos from cosmic sources, so its detection units are sparsely distributed in the volume of seawater. After a detailed overview of the telescope infrastructure in 3.1, Section 3.2 introduces the KM₃NeT's trigger and data acquisition system. In Section 3.3, the methodologies used to calibrate the detectors and attain the needed level of precision are summarized. Finally, KM₃NeT performances in detecting and reconstructing events are presented in Section 3.4, as well as the groundbreaking observation of KM₃-230213A, outlined in 3.5.

3.1 KM₃NeT INFRASTRUCTURE

Even if the KM₃NeT detectors aim at different scientific goals, they are built with the same innovative technology, based on the so-named Digital Optical Modules (DOMs), which are pressure-resistant glass spheres containing 31 PMTs, a number of calibration devices, and the read-out electronics [122]. For the first time in a neutrino telescope, the optical module design was modified from a glass sphere comprising a single large PMT (e.g., the one used by the ANTARES detector) to one with the same diameter housing several PMTs (multi-PMT design), as discussed in the following. The detector consists of a three-dimensional array of detection units (DUs), which are vertical strings with eighteen DOMs each.

3.1.1 *Detector sites*

The KM₃NeT/ARCA site is located at $36^{\circ}16'N, 16^{\circ}06'E$ at a depth of 3500 m, approximately 100 km offshore from Portopalo di Capo Passero, Sicily, Italy. It consists of two KM₃NeT building blocks (BBs). The layout of its nominal BB is depicted in Figure 38. Power and data transmission between the infrastructure and the shore is facilitated through two primary electro-optical cables. While one cable is already operational, an additional cable will be deployed, incorporating 48 optical fibers. Near the underwater installation site, the cable is divided into two branches using a Branching Unit (BU), with each branch terminating at a Cable Termination Frame (CTF). Secondary junction boxes serve as connection points for up to seven KM₃NeT detection strings each. The strings are linked to the junction boxes via interlink cables laid on the seabed. In the KM₃NeT/ARCA configuration, the average horizontal separation between detection strings is approximately

90 m, and 36 m along the vertical axis. The lowest modules lie at about 70 m above the seabed. Onshore, the main electro-optical cables interface with power feeding equipment housed in the shore station at Portopalo di Capo Passero. Additionally, the shore station accommodates data acquisition electronics and a computing cluster for data filtering. After the sea campaign of July 2025, KM₃NeT/ARCA consists of 51 deployed detection lines. The site is shared with the EMSO facility for Earth and Sea science research.

The KM₃NeT/ORCA infrastructure is situated at 42°48'N, 06°02'E, at a depth of 2450 meters, approximately 40 km offshore from Toulon, France. The site is located outside French territorial waters at about 10 km west of the site of the former ANTARES telescope. Figure 39 shows the layout of the complete array, which consists of a single KM₃NeT BB comprising 115 DUs. Power and data are transmitted to and from the infrastructure using two primary electro-optical cables, each containing 36 or 48 optical fibers along with a single power conductor (the return is via the sea). The detection strings are linked to five junction boxes positioned along the perimeter of the array. Each junction box features eight connectors, each capable of powering four detection strings connected in series. Calibration units feature laser beacons and hydrophone acoustic emitters. The strings are connected to the junction boxes through interlink cables that run along the seabed. For the KM₃NeT/ORCA configuration, the average horizontal distance between detection strings is around 20 meters, while the vertical one is about 9 meters. The lowest modules lie at about 30 m above the seabed. The control room onshore is situated at the Ifremer Campus in La Seyne-sur-Mer, where the data acquisition electronics and a facility for data filtering are housed. In December 2014, the first main electro-optic cable was successfully deployed, while the first junction box was connected in 2015. The second node of the submarine infrastructure has been installed in August 2025. After the October 2025 sea campaign, the number of DUs in KM₃NeT/ORCA has been increased to 33.

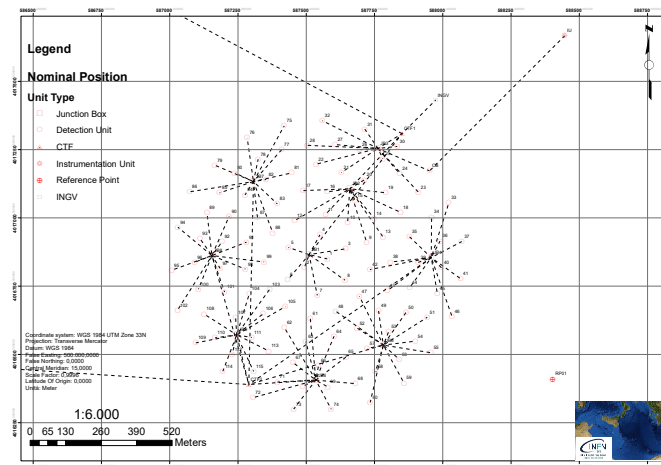


Figure 38: Layout of the nominal BB of KM₃NeT/ARCA, currently in construction. Detector elements are displayed as indicated in the legend.

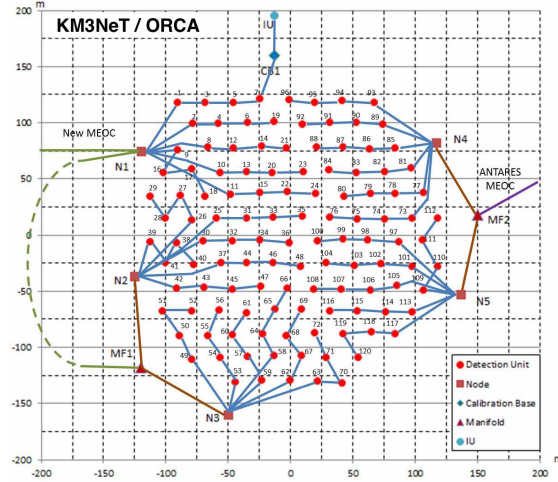


Figure 39: Layout of the KM3NeT/ORCA BB. Image from [15].

3.1.2 Photomultiplier tubes

The characteristics of the PMTs affect the detector event reconstruction accuracy. A Hamamatsu 80-mm diameter hemispherical PMT has been chosen for the KM3NeT detector (see [123] and [124] for details). When a Cherenkov photon hits a PMT, it can be converted into an electronic signal thanks to the photoelectric effect, responsible for the photon-electron conversion. The probability for this process is given by the quantum efficiency (QE), which is wavelength-dependent (Figure 40).

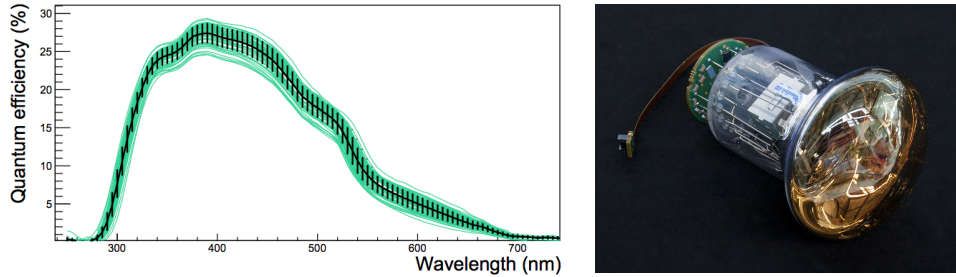


Figure 40: *Left*: QE measurements of the photocathode as a function of wavelength for 56 PMTs. The green lines represent the results for individual PMTs, while the continuous black curve illustrates the mean value, with one standard deviation at each considered wavelength. Image from [123]. *Right*: the Hamamatsu photomultiplier tube.

The produced photoelectron is then accelerated using a focusing electrode towards the electron multiplier. The electron multiplier consists of a series of dynodes with increasing potential. The electrons are multiplied due to secondary emission on the dynodes until they reach the anode. The signal from a photon can then be measured as an electrical pulse. PMTs have their optimal sensitivity between 325 and 480 nm, for which the QE is between 20% and 28%. This wavelength range coincides with the longest effective attenuation length in Mediterranean seawater [125]. In particular, the Mediterranean offers superior optical properties

compared to other deep-sea sites, as shown in Figure 41, where the measured (effective) attenuation length at different neutrino telescope sites are displayed together with the observable Cherenkov spectrum. Additionally, each PMT has a base with a current amplifier and a threshold discriminator. When the signal exceeds a set threshold (0.3 photoelectrons), it is converted to digital signal form and recorded as a hit. Each hit is stored by the central logic board (CLB) of the DOM, which records the time at which it passes the threshold and its duration above it, known as the Time-over-Threshold (ToT). The typical PMT gain, which indicates how many electrons reach the anode per photon, is about 10^6 , but small variations may occur at the same applied voltage. Furthermore, there is also a short delay, called transit time, between a photon striking the photocathode and the detection of the resulting signal. Variability in transit times results from the stochastic nature of electron multiplication and the different paths a photoelectron may take before reaching the first dynode. This spread of about 2 ns [123] limits the timing accuracy. The dark count rate, due to spontaneous emissions that can mimic real photon signals, is measured at 1.3 kHz. Finally, the use of reflector rings around the PMTs increase photon acceptance by 20–40%.

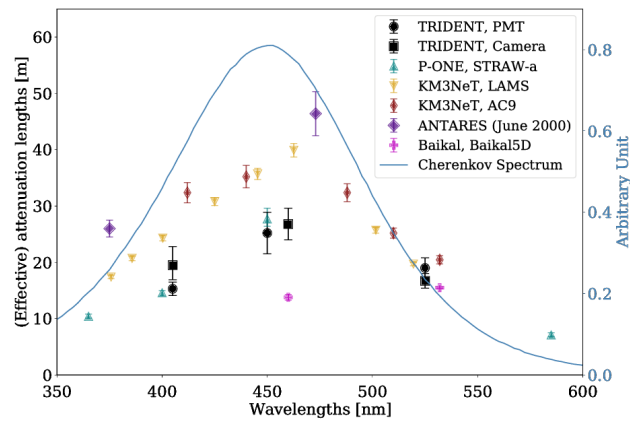


Figure 41: Measured (effective) attenuation length at different underwater neutrino telescope sites. Image from [125].

3.1.3 Digital Optical Modules and Detection Units

The main detector component of the KM3NeT experiment is the DOM [122]. Each DOM (Figure 42) is a 17-inch glass sphere, capable to resist high pressure present at the sea bottom, housing 31 3-inch PMTs, readout electronics and power boards. Power boards are controlled on-shore and provide almost 1000 V per PMT. Of the 31 PMTs, 30 are arranged in five rings at zenith angles of 56° , 72° , 107° , 123° and 148° , while one is at the bottom at zenith 180° . As a result, DOM's lower hemisphere contains 19 PMTs, while the upper one has 12 phototubes. The multi-PMT DOM configuration was first designed by the KM3NeT Collaboration, developed to provide a large photocathode area and enhance its segmentation, thereby improving the ability to distinguish between single-photon and multi-photon hits. The implementation of multiple PMTs within a single DOM not only allows for precise recording of photon arrival times but also provides geometrical informa-

tion about the direction of the detected photons. Compared to a single-PMT implementation, the multi-PMT design specifically enables distinguishing the atmospheric muon signals. Each hemisphere of a DOM is equipped with a signal collection board that channels PMT signals to the CLB. Acting as the core processing unit of the optical module, the CLB manages data acquisition from the PMTs and transmits it to shore. Sub-nanosecond time synchronization is achieved through optical Ethernet communication using the White-Rabbit protocol [126]. In addition to handling data transmission, the CLB operates various monitoring and calibration devices, including an acoustic piezo sensor, a LED beacon, a humidity sensor, multiple temperature sensors, a compass and a tiltmeter.

DUs are vertical structure composed of 18 DOMs. Each string comprises two thin (4 mm diameter) parallel Dyneema ropes to which the DOMs are attached via a titanium collar. Additional spacers are added in between the DOMs to maintain the ropes parallel. Attached to the ropes is the vertical electro-optical cable, a pressure balanced, oil-filled, plastic tube that contains two copper wires for the power transmission and 18 optical fibers for the data transmission. The base of each DU, known as the Base Module, which contains electronic boards to power the DOMs of the string and redirects the optical fibers from the DOMs to the shore station. These cables enter the DOMs through an opening at the top of the spherical structure. The Base Modules are then connected to junction boxes, which allow power distribution and bidirectional data transmission between the deep-sea infrastructure and the shore. Each junction box is linked to multiple DUs.

For both detectors, the same deployment technique is employed using a specialized submarine vehicle called the Launcher of Optical Modules (LOM) [127], illustrated in Figure 43. The LOM carries the rolled-up strings to the seabed, where it anchors the Base Module before gradually unrolling the DU to its full length. Although anchored, DUs are subject to movement due to sea currents. Therefore, each DU is taught by buoyancy at the top to reduce the horizontal displacement of the top relative to the base, in case of large sea currents. At the same time, continuous calibration is required to track DOM positions accurately. The acoustic calibration system is capable of measuring the positions of each DOM in the sea with an accuracy of 10 cm [128].



Figure 42: The KM3NeT digital optical module.

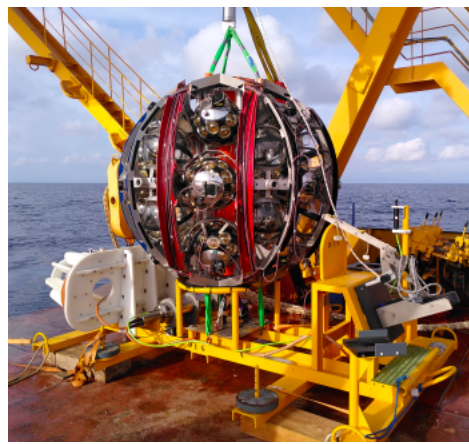


Figure 43: A loaded LOM on its anchor-frame ready for deployment.

3.2 TRIGGER AND DATA ACQUISITION

The KM₃NeT detectors operate under the *all-data-to-shore* principle. If one or multiple photons are detected by a PMT (i.e. the analogue pulse of the PMT rises above 0.3 photoelectrons), a hit is registered by the apparatus. This information is firstly collected and then sent to a server on shore. These hits are called L0 hits and they are grouped together in time windows of 100 ms. The data is sent to shore via an Ethernet network through optical fibers and processed in real time. Each L0 hit corresponds to a hit associated with various PMT characteristics such as timing, gain, efficiency, position and orientation. The precision of these measurements can be significantly improved through accurate calibration of the detector, as will be discussed in 3.3. Additionally, background sources, as ⁴⁰K decay and bioluminescence, generate a considerable number of hits. To distinguish between background hits and hits produced by light from tracks or showers, trigger algorithms are in place. They rely on the time coincidence between hits and on constraints based on the PMT angle, helping to verify whether a set of hits is consistent with a genuine signal. Specifically, when the trigger conditions are met, an event is recorded along with a snapshot of all hits in the detector within a specified time frame surrounding the trigger time. Different trigger criteria can be defined [129]. A Level 1 (L1) condition is met when two L0 hits occur within the same DOM and within a short coincidence time window, such as 20 ns. Similarly, a Level 2 (L2) criterion is achieved when two L1 hits are detected in adjacent DOMs of the detector or when the illuminated PMTs are oriented in similar directions with an opening angle smaller than 90°. For detecting muons and showers, time-position correlations are used to filter out environmental background in real-time, establishing high-level trigger criteria. The estimated L1 rate per optical module is approximately 1000 Hz, with about 600 Hz attributed to coincidences from ⁴⁰K decays. The remaining rate arises from random coincidences, which can be reduced by a factor of two by utilizing the known orientations of the PMTs. Parallel trigger algorithms operate on the telescope data, each optimized for different event topologies. For instance, since the MeV neutrino signal from a supernova (SN) can be identified as a simultaneous increase of the counting rate in the PMTs of the detector, a specific SN trigger is implemented for its detection. It is based on L1 hits with additional constraints on the number of hit PMTs. At the computing farm on shore, the data are collected by a data queue and filtered using trigger algorithms, which select subsets of hits consistent with a relativistic particle crossing the detector. Example of triggers currently in place [130] are:

- **3DShower:** cascade trigger that assumes that all light is emitted isotropically from the neutrino interaction vertex and looks for causally connected L2 hits on DOMs separated by a maximum distance.
- **3DMuon:** the muon trigger algorithm searches for pairs of correlated L2 hits that fulfil the Cherenkov assumption using different muon direction hypotheses. In this case, only PMTs within distances from the track that are smaller than a few times the absorption length of the water are taken into account.

3.3 DETECTOR CALIBRATION

To effectively identify neutrino interaction signatures in underwater Cherenkov detectors and achieve accurate event reconstruction, it is crucial to perform precise calibrations of the detector and assess the environmental factors influencing its operation. This includes calibrating the charge, position, and arrival time of the Cherenkov photons detected by the PMTs. A precise charge calibration is essential for ensuring good energy resolution. Additionally, accurate position and time calibrations are necessary for achieving high angular resolution in the event direction. To obtain the required angular resolution of less than 0.1° for tracks, the positions and orientations of the DOMs must be measured with a precision of 20 cm and 3° , respectively, while the time offsets of the PMTs should be determined with an accuracy of 1 ns.

3.3.1 Position calibration

Due to the influence of sea currents, the DOMs experience tilting, causing both displacement and rotation around their vertical axis, which modifies the orientation of the PMTs. As a result, continuous tracking of the DOM positions and orientations is necessary. The relative positions of the DOMs are calibrated using acoustic signals, which are detected by piezos in each DOM. These acoustic signals, received from various acoustic beacons anchored at the seabed, are used to reconstruct the relative positions of the DOMs. An acoustic fit uses acoustic events as input to adjust and match a model of the detector's geometry to the data. The orientation of the DOMs is determined by compasses. The DU is described by a mechanical model which includes the buoyancy of the modules and contains a tilt angle with respect to a vertical string. The measured tilt angles are used to reconstruct the relative positions of the optical modules. Figure 44 shows the tilt angles as a function of time for 21 DUs of KM₃NeT/ARCA. The maximum tilt angle in the Figure corresponds to a maximum horizontal displacement of several tens of meters at the top of string.

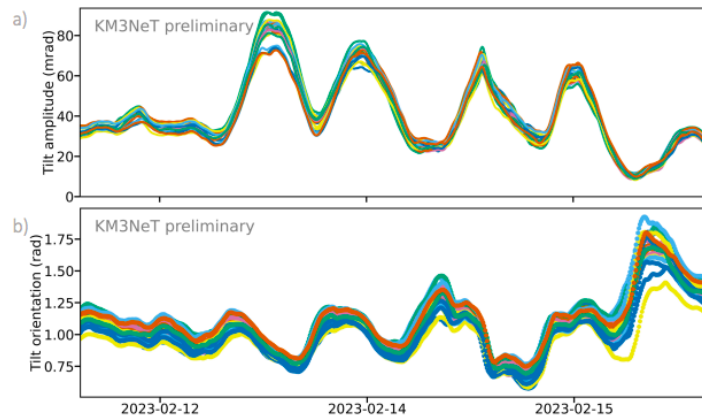


Figure 44: a) Tilt amplitude and b) tilt orientation, for KM₃NeT/ARCA with 21 DUs. The different lines indicate different DUs. Image from [131].

Additionally, the cosmic ray shadow from the Sun and Moon, i.e. a deficit in the number of detected atmospheric muons from their respective positions in the sky, can be used to verify the absolute pointing of the detector, representing the position of the telescope’s mechanical structures, in a geo-referenced coordinate system. This analysis has been performed with data collected by KM₃NeT/ORCA between February 2020 and November 2021, during which the detector operated with 6 DUs. The Moon and Sun shadows were detected at their expected positions with statistical significances of 4.2σ and 6.2σ , respectively, and angular resolutions of $\sigma_{\text{res}} = 0.49^\circ$ and $\sigma_{\text{res}} = 0.66^\circ$, in agreement with the predicted 0.53° from simulations [132]. The relatively modest angular resolution is mainly due to the limited number of DUs available in this detector configuration and to the downgoing nature of the data sample used in the study. A similar analysis is currently being carried out for KM₃NeT/ARCA.

3.3.2 *Charge calibration*

In order to pursue the scientific goals of KM₃NeT, an accurate energy reconstruction is essential. Achieving an optimal energy estimate requires charge calibration. The objective of charge calibration is to establish the relationship between the number of photoelectrons and the measured amplitude of the PMT signal. As said above, when a photon strikes the photocathode at the entrance window of a PMT, it generates electrons, which are then accelerated by a high-voltage field. The resulting signal is converted into a digital value using an Analog-to-Voltage Converter (AVC), providing information about the number of photoelectrons generated in the PMT. PMTs undergo calibration in a dark room before detector deployment, where the single photoelectron signal is measured. Additionally, in-situ calibrations are conducted through dedicated data-taking runs, where ToT distributions are collected at varying high-voltage settings, fitted to extract gain, and then used to determine the optimal operating voltage. Because of the degradation of PMTs performances due to aging, high-voltage adjustments are necessary to maintain the 0.3 photoelectrons threshold level.

3.3.3 *Time calibration*

KM₃NeT events reconstruction relies on measuring the arrival times of Cherenkov photons at the PMTs, requiring an optical modules synchronization within 1 ns to achieve sub-degree angular accuracy. Since the general layout of the KM₃NeT detector can be considered as a large Ethernet network with thousands of nodes, a precise time synchronization of all offshore nodes in the network, including the DOMs and the electronics modules at the base of the DUs, is essential for time calibration. The offshore nodes timestamp signals from the PMTs, with the timestamping performed by the CLB inside each DOM. The KM₃NeT detector employs a fiber-optic broadcast system for clock distribution, utilizing a customized implementation of the White-Rabbit technology [126]. Time synchronization among detector components is continuously monitored in situ by measuring the light propagation time between emitters and PMTs. The PMT time calibration is performed

using multiple methods, including: determining relative time offsets among PMTs within a single DOM (intra-DOM), between different DOMs in a detection unit (inter-DOM), and between different DUs (inter-DU) [133]. An overview of the methods is presented below:

- intra-DOM time offsets depend on PMT transit time and propagation variations across channels. Radioactive potassium decay in seawater, producing up to 150 Cherenkov photons per event, is the primary source of single PMT rates. Decays near a DOM can create signal coincidences between PMTs, enabling time calibration. Time differences between PMT signals are analyzed based on angular separation, with potassium decay serving as a key tool for in-situ calibration and long-term monitoring. Additionally, intra-DOM calibration is performed in a dark-room before deployment using the potassium in the DOM glass;
- inter-DOM time calibration is performed for each DU in a dedicated dark-room before deployment. A blue laser is used to simultaneously illuminate two PMTs per DOM, measuring time delays caused by the sequential arrival of the shore-distributed clock signal. Correction offsets are then applied to align all DOMs within a DU. In-situ verification is performed using two methods: (1) LED beacons, which emit short optical pulses to measure light travel time between adjacent DOMs, and (2) down-going atmospheric muons, which provide a natural, high-rate, reference signal for evaluating relative time offsets;
- inter-DU time calibration is based on precise White-Rabbit measurements of the Round-Trip Time (RTT) of optical signals between the shore-based Master clock and each DU base. In the White Rabbit network, a grandmaster clock distributes both the clock frequency and absolute time across all connected devices. Time synchronization is achieved by aligning each Slave clock's phase and offset with its Master. This alignment relies on measuring four key timestamps: the time the reference signal is sent from the Master (t_1), received by the Slave (t_2), retransmitted by the Slave (t_3), and received back at the Master (t_4). Using these measurements, the total round-trip time (RTT) can be calculated as:

$$\text{RTT} = (t_2 - t_1) + (t_4 - t_3). \quad (44)$$

This RTT measurement is then corrected for relevant latencies and asymmetries, including one-way clock signal propagation delays. Time asymmetries arise from signal path differences in the seabed infrastructure and chromatic dispersion in the electro-optical cable due to different wavelengths used for downlink and uplink signals. The RTT, once corrected for these factors, is referred to as the Round-Trip Time Cable (RTTC). For KM3NeT, the White-Rabbit technology has been modified to support fiber-optic broadcast clock distribution. CLBs located at the base of DUs follow standard WR synchronization, while CLBs in the optical modules synchronize solely to the Master's transmission time, without returning timing signals. This simplification enables the use of commercial Ethernet switches for upstream data handling.

Furthermore, PMT time calibration integrates measurements from the shore station, the seabed infrastructure, and each DU. DU-specific calibrations involve laboratory tests and round-trip cable time measurements, both prior to and after deployment. Appendix A provides a detailed analysis of the time calibration of KM3NeT/ARCA base modules, after the deployment.

3.4 KM3NeT PERFORMANCES

Charged current (CC) interactions of muon neutrinos produce the highest neutrino-induced event rates in neutrino telescopes, primarily due to the long interaction length of muons in matter. High-energy muons can travel several kilometers through water, in contrast to electrons and hadrons of comparable energy, which are typically stopped within a few meters. This characteristic makes muon neutrinos particularly valuable for identifying astrophysical sources, as their resulting muon tracks enable precise directional reconstruction. For the search of point-like neutrino sources, optimal angular and energy resolutions are required, along with high detector efficiency in identifying these muon tracks, commonly quantified by the so-named effective area, defined in 3.4.3. In order to make a decisive contribution to the field of multi-messenger astronomy, Cherenkov neutrino detectors must not only provide high-precision reconstruction of the muon direction, but also have enough instrumented volume to be sensitive to the cosmic neutrino events hidden in the dominant atmospheric background. For the purposes of this thesis, the performances of KM3NeT/ARCA, the detector specifically designed for neutrino astronomy, will be discussed.

3.4.1 Angular resolution

The angular resolution of a neutrino detector characterizes its ability to reconstruct the direction of incoming neutrino events with minimal error, which is crucial for tracing them back to their astrophysical sources. It is defined as the median space angle between the true and the reconstructed neutrino direction and it is obtained from Monte Carlo simulations. This resolution depends on multiple factors: the geometrical layout of the detector, the total photocathode area determined by the number of PMTs, the quality of the reconstruction of the algorithms employed, the optical properties of the seawater and the kinematic angle between the interacting neutrino and the outgoing lepton. Performance improves with detector expansion: in the case of track-like events, with 6 deployed lines of KM3NeT/ARCA the angular resolution reaches approximately 1° at 100 PeV, while in bigger configuration, with 19 or 21 strings, it improves to about 0.2° [134]. For the full KM3NeT/ARCA detector, the angular resolution is expected to reach 0.06° [119] at the same energy. Another contribution to be considered at lower energies (below 1 TeV) is the kinematic angle between the incident neutrino and the resulting lepton, which decreases as energy increases. Conversely, the intrinsic angular resolution becomes the limiting factor at higher energies (above 1 TeV). As shown in Figure 45, the angular resolution for ν_e CC events identified as showers is inherently worse than for tracks, due to their more compact and less directional light patterns. The same

panel also displays the angular resolution for ν_μ CC events reconstructed as tracks, considering two BBs of KM3NeT/ARCA.

3.4.2 Energy resolution

When considering the golden channel for neutrino astronomy, namely track-like events, the energy response of the detector is governed by three main factors: the fraction of energy transferred to the muon during the neutrino interaction, the energy lost by the muon outside the detector volume, and the intrinsic energy resolution of the detector itself. The efficiency in determining the muon energy depends significantly on the energy range considered. Below 100 GeV, muons behave as Minimum Ionizing Particles (MIPs), where the energy loss per unit path length is approximately $dE/dx \sim 2 \text{ MeV/cm}$ [135]. These low-energy events are typically fully contained within the instrumented volume. Above 100 GeV, the full muon range cannot be measured due to the limited detector size. However, the visible track length provides a lower limit on the muon energy, which is useful for the analysis of partially-contained events. For energies exceeding 1 TeV, energy losses are dominated by stochastic processes, making them approximately proportional to the muon's energy. In this regime, radiative processes, such as bremsstrahlung, become dominant, and the muon range increases logarithmically with energy. These additional energy losses improve the detection efficiency at high energies. The expected energy resolution of the full KM3NeT/ARCA detector is shown in the right panel of Figure 45, where E_{visible} is the sum of the energies of the particles that induce Cherenkov light within the region where the detector is sensitive to that light, while the energy resolution is defined as half the difference between the 16th and 84th percentiles of the energy error distributions. Saturation of the PMTs is responsible for the deterioration in the performance of direction and energy reconstruction in the shower reconstruction.

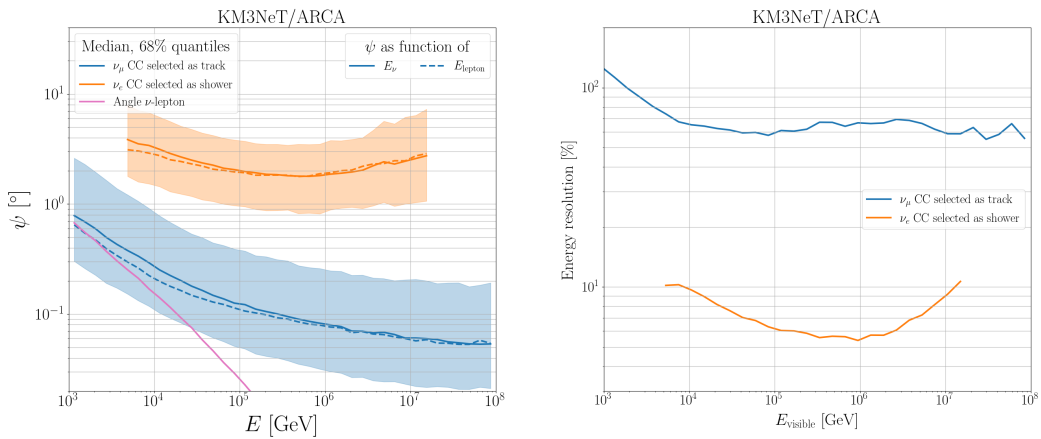


Figure 45: KM3NeT/ARCA angular resolution (left) and energy resolution (right) for ν_μ CC events selected as track and for ν_e CC events selected as shower. It is shown alongside the median angle between the neutrino and the outgoing lepton in CC interactions. Image from [119].

3.4.3 Effective Area

The instrument efficiency with respect to the detection of neutrinos of a given energy and direction can be expressed in terms of the *effective area*, A_{eff} . This quantity is defined as the equivalent area of a detector with 100% detection efficiency, and it can be estimated through Monte Carlo simulations. For track-like events, considering as an example the case of ν_μ , the definition of A_{eff} must consider that the neutrino has to survive Earth absorption and interact sufficiently close to the detector. The resulting muon must reach the instrumented volume and induce enough Cherenkov light to trigger the detector and allow reliable track reconstruction. The effective area can be expressed as [28]:

$$A_{\text{eff}}(E_\nu, \theta) = A \cdot P(E_\nu, E_\mu^{\text{thr}}) \cdot \epsilon \cdot P_{\text{surv}}(E_\nu, \theta), \quad (45)$$

where

- A is the geometrical projected detector surface,
- $P(E_\nu, E_\mu^{\text{thr}})$ is the probability that a neutrino with energy E_ν produces a muon arriving with residual energy above the threshold E_μ^{thr} at the detector,
- ϵ accounts for the trigger efficiency, reconstruction efficiency, and the probability to pass analysis selection cuts,
- $P_{\text{surv}}(E_\nu, \theta)$ is the probability that neutrinos survive their passage through the Earth at zenith angle θ .

The effective area, when convolved with the neutrino flux expected at Earth from a given source and multiplied by the observation time T , directly provides the expected number of detected events:

$$\frac{N_\nu}{T} = \int A_{\text{eff}}(E_\nu, \theta) \cdot \Phi(E_\nu) dE_\nu, \quad (46)$$

where $\Phi(E_\nu) = \frac{dN_\nu}{dE_\nu dS d\tau}$ is the neutrino flux at Earth, expressed as the number of neutrinos per unit energy, surface area and time. Figure 45 shows the effective area for the KM3NeT/ARCA detector in a two BBs configuration. The detector response is assumed uniform in azimuth, but variations with zenith angle and energy are considered. As the zenith angle increases, neutrinos cross larger sections of Earth's interior, leading to higher absorption of very high-energy neutrinos and consequently a drop in the effective area above the PeV scale.

In analogy to the effective area, a neutrino effective volume V_{eff} can be defined: it quantifies the volume in which all neutrinos passing through would be detected with 100% efficiency. This quantity is as well determined via Monte Carlo simulations. Let N_{gen} be the number of neutrino events generated within a simulation volume V_{gen} , which encompasses and exceeds the physical dimensions of the detector, and let N_{det} be the number of events that are detected (i.e., triggered or reconstructed). The detection efficiency for neutrinos of energy E_ν is described by the effective volume:

$$V_{\text{eff}}(E_\nu) = V_{\text{gen}}(E_\nu) \cdot \frac{N_{\text{det}}(E_\nu)}{N_{\text{gen}}(E_\nu)}. \quad (47)$$

Equation 47 is linked to the definition of A_{eff} via the relation:

$$A_{\text{eff}}(E_\nu, \theta) = V_{\text{eff}}(E_\nu, \theta) \cdot \sigma_\nu(E_\nu) \cdot N_A \cdot \rho \cdot P_{\text{surv}}(E_\nu, \theta), \quad (48)$$

where $\sigma_\nu(E_\nu)$ is the neutrino interaction cross-section, N_A is Avogadro's number and ρ is the density of the medium (e.g. seawater).

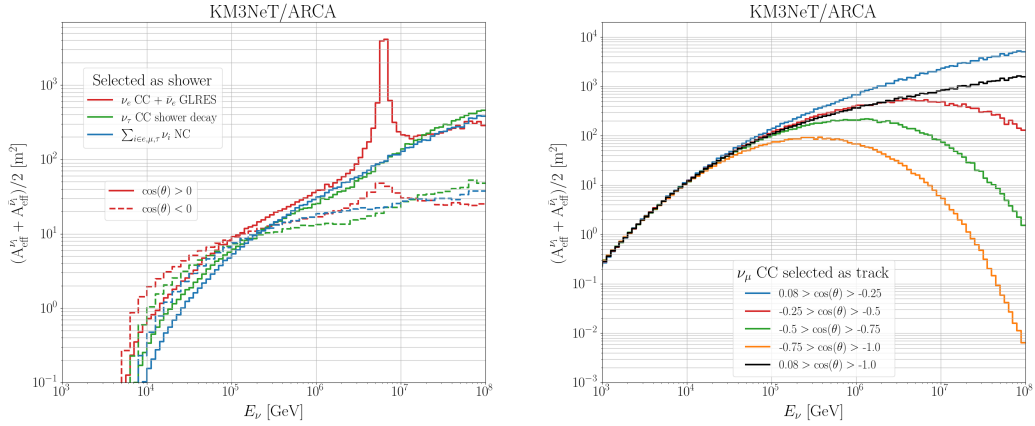


Figure 46: *Left:* the full KM3NeT/ARCA effective area for a flux of $\nu_i + \bar{\nu}_i$ at trigger level for all neutrino flavors and interactions, selected as showers. Solid and dashed lines indicate $\cos(\theta) > 0$ and $\cos(\theta) < 0$ intervals respectively. The Glashow resonance (GLRES) is visible as a read peak in the simulation of $\bar{\nu}_e$ interactions. *Right:* the effective area for ν_μ CC events selected as tracks for different $\cos(\theta)$ ranges. Image from [119].

3.5 OBSERVATION OF AN ULTRA-HIGH-ENERGY NEUTRINO WITH KM3NeT

Thanks to their modular design, KM3NeT detectors can take data even during construction and produce scientific results. Among these, the most significant is undoubtedly the observation of an exceptionally high-energy neutrino event, called KM3-230213A [12], whose detection has been announced in February 2025. The event was observed by KM3NeT/ARCA, which at the time was operating with 21 instrumented DUs. The detected muon was estimated to have an energy of 110 PeV, implying a parent neutrino energy of 220 PeV. This energy estimate is based on the event's brightness, specifically the number of PMTs that recorded Cherenkov light emitted by the muon as it traversed the seawater. For KM3-230213A, a total of 3672 PMTs, approximately 35% of the detector's active PMTs, were triggered. Figure 47 shows the normalized distributions of the number of PMTs triggered in simulated events for muon energies of 10, 100, and 1000 PeV. Uncertainties have been incorporated by weighting the simulations using a normal distribution centered on the nominal value of each nuisance parameter, with an assumed uncertainty of $\pm 10\%$.

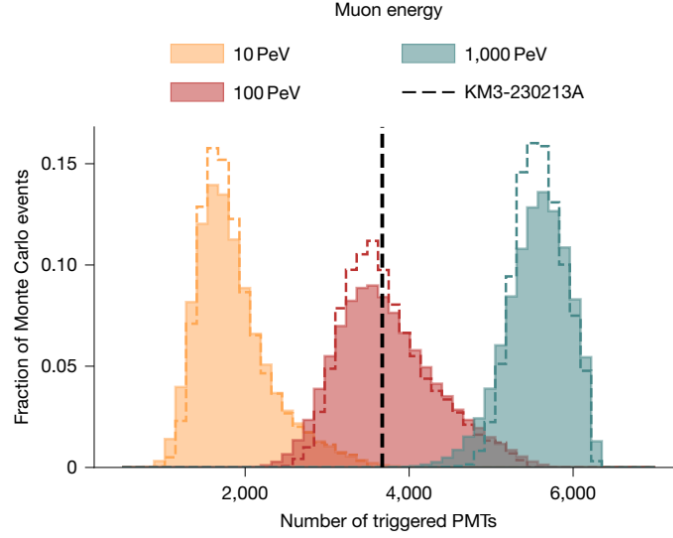


Figure 47: Normalized distributions of the number of PMTs triggered for simulated muon events with energies of 10, 100 and 1000 PeV. The vertical dashed line indicates the observed value for event KM3-230213A, i.e. 3672. Filled histograms include systematic uncertainties, while dashed lines represent nominal simulations. The apparent truncation at high energies is due to muon tracks crossing the detector peripherally. Image from [12].

The muon direction was reconstructed to be horizontal, coming from 1° above the horizon: this is consistent with the fact that Earth is opaque for neutrinos at the PeV scale. Moreover, for neutrinos at these energies, near-horizontal trajectories are the most probable, as downgoing neutrinos mainly traverse the atmosphere, resulting in a significantly smaller interaction probability. In particular, the equatorial coordinates (J2000) and detection time of the KM3-230213A event are: RA = 94.3° , Dec. = -7.8° , and MJD = 59988. The event's directional containment radii, dominated by systematic uncertainties in the absolute orientation of the detector, are: $R(50\%) = 1.2^\circ$, $R(68\%) = 1.5^\circ$, $R(90\%) = 2.2^\circ$, and $R(99\%) = 3.0^\circ$. A recalibration of all data to reduce the uncertainty on the reconstructed muon direction is planned, using information from recently installed acoustic tools. The celestial position of the KM3-230213A event is shown in Figure 48, along with the corresponding error regions. Searches for potential astrophysical counterparts within a 3° radius around the event were performed across multiple wavelengths. Despite the presence of the Orion molecular clouds within the error region, no catalogued galactic source was found in the 99% containment area. No gamma-ray bursts, tidal disruption events, or other transient phenomena in searches for neutrino point sources were identified in GCN notices, the Astronomer's Telegram, or the Transient Name Server. Considering the high energy of the event, a blazar origin was also investigated. A total of 12 blazar candidates were identified by cross-matching multi-wavelength archival data, including gamma-ray, X-ray, optical, and radio observations. In any case, no compelling association could yet be confirmed. Further follow-up observations and analysis are required to constrain the origin of KM3-230213A. A viable alternative hypothesis is the production of cosmogenic neutrinos [72], which are generated when cosmic rays interact with

the extragalactic background light or the cosmic microwave background. Depending on assumptions about the cosmic-ray injection spectrum, mass composition, and the cosmological evolution of sources, the expected number of cosmogenic events in the selected data varies between 1.5×10^{-3} and 0.47 [12]. In the future, KM3NeT sensitivity at the highest energies will enable more precise constraints on the expected cosmogenic fluxes. Nevertheless, the detection of KM3-230213A marks a significant milestone in high-energy neutrino astronomy, offering the first strong evidence that neutrinos of such high energies exist. This event also highlights the capability of the KM3NeT/ARCA detector to identify and reconstruct such rare events, demonstrating its scientific potential to probe the most energetic astrophysical processes in the Universe.

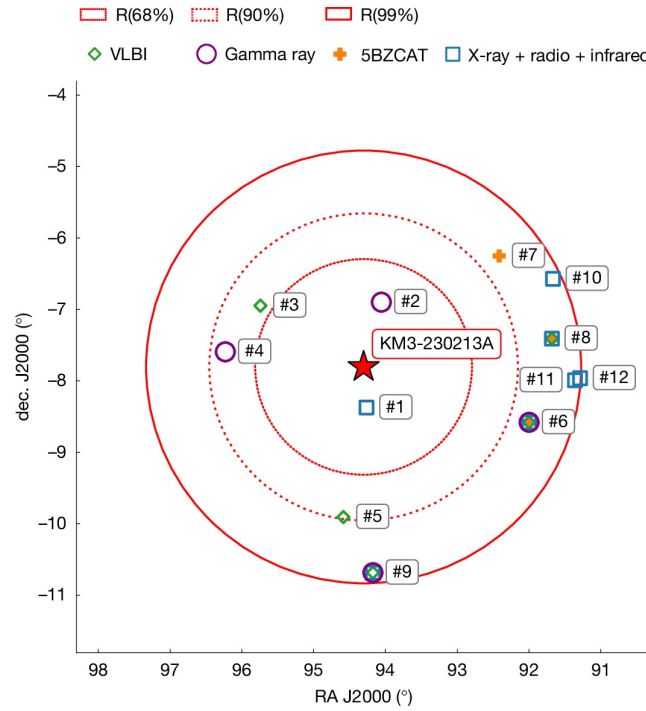


Figure 48: KM3-230213A is indicated by the red star, with the error regions within R(68%), R(90%) and R(99%) shown as dotted, dashed and solid contours, respectively. The directions of the selected source candidates are shown as coloured markers, whose colours and marker type indicate the criterion according to which the source was selected. The sources are numbered according to their proximity to KM3-230213A. Image from [12].

EVENT SIMULATION AND RECONSTRUCTION IN KM₃NeT

Monte Carlo (MC) simulations play a crucial role in studying detector performance, optimizing event selection criteria, and evaluating the detector's sensitivity to a given neutrino flux. The simulation output serves as input to event reconstruction algorithms, which estimate the energy and direction of incoming neutrinos by analyzing the detected light signals across different positions and times within the apparatus. The simulation chain involves several key steps. First, the physical event is generated, focusing on particles that can leave detectable signatures. Next, the interaction of these particles with the surrounding medium is simulated, incorporating both the emission of Cherenkov light and the propagation of particles to the instrumented volume. Finally, the detector's response is modeled. Each stage of this process requires specialized software tools, along with detailed information about the detector configuration, medium properties and data acquisition conditions. In this Chapter, the MC simulation chain (Section 4.1 onward), together with the reconstruction algorithms (4.3), is discussed.

4.1 EVENT GENERATION

Since the complete simulation of neutrino interactions and atmospheric muon bundles can be computationally demanding, events are generated in the proximity of the detector. The instrumented volume can be seen as a cylinder that contains all the optical modules. Surrounding this, there is a larger cylindrical volume known as the *can*, which defines the detector's active volume. Anchored to the seabed, the can encompasses the instrumented volume and is designed to include the majority of Cherenkov light detectable by the experiment. Its radius is typically defined adding a multiple of the light absorption length l_{abs} , commonly set to $3l_{\text{abs}}$, to the instrumented volume. Particle tracking and Cherenkov light emission within the can are simulated across various stages to assess the detector response. A schematic view is provided in Figure 49.

For neutrinos, simulations are performed using the gSeaGen code, as described in [136]. gSeaGen is GENIE based code [137] and represents an updated version of the GENHEN package [138], which was previously employed in the ANTARES experiment. It supports the simulation of all neutrino flavors, accounting for both neutral current (NC) and charged current (CC) interaction channels. Neutrino directions can be generated in two modes: a diffuse mode, which assumes an isotropic distribution of arrival directions, and a point-source mode, in which the source position is fixed in the sky. Simulations can be carried out using either a

local coordinate system (azimuth and zenith) or an equatorial coordinate system (right ascension and declination). A power law E^γ is chosen for the generation spectrum of neutrinos, with γ as input for the simulation.

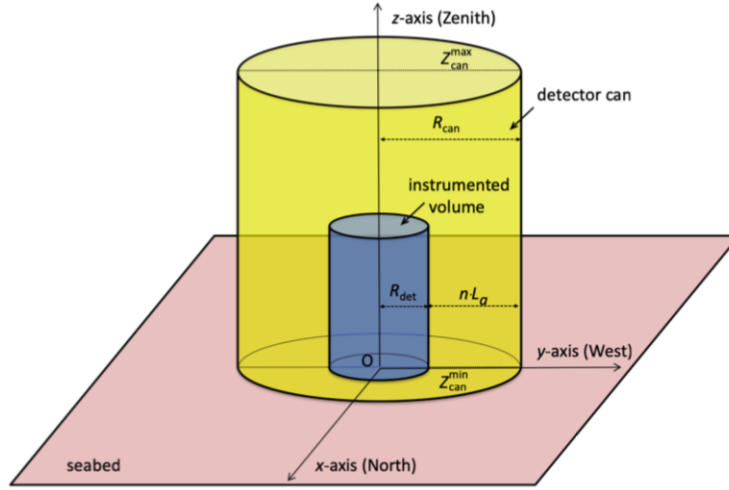


Figure 49: Illustration of the detector can (yellow) relative to the detector lines (blue). Image from [136].

The *neutrino interaction volume* defines the region around the detector in which a neutrino interaction can produce secondary particles that may be detected. It is modeled as a cylindrical volume surrounding the can and consists of both seawater and rock. The size and composition of this volume depend on the event topology. For NC interactions, which typically result in shower-like events, the interaction volume coincides with the can and consists entirely of seawater. In contrast, for CC interactions, especially those involving muons, the resulting track-like events may be detected even if the neutrino interaction occurs outside the can. For such events, the interaction volume is defined as a larger cylinder composed of a seawater layer above a rock layer, with the interface aligned with the seabed (see Figure 50 for a schematic view).

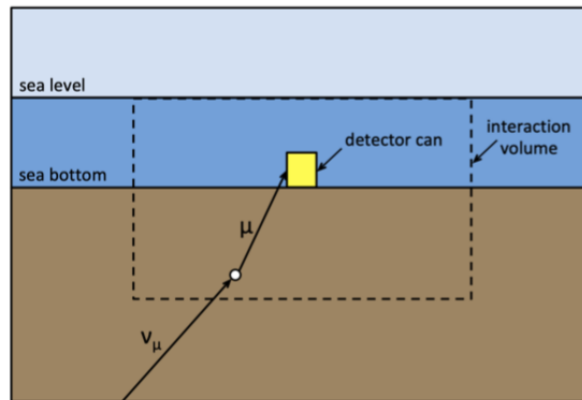


Figure 50: Schematic view of the interaction volume for track-like events. Image from [136].

The radius of this interaction volume equals the can radius plus the maximum range of a muon in water. The depth of the rock layer corresponds to the maximum muon range in rock, while the seawater layer extends from the seabed up to a height equal to the can height plus the maximum muon range in water. If only downgoing events are simulated, the rock layer height is set to zero. The sea layer cannot extend beyond the actual detector site depth. Additionally, gSeaGen has recently introduced the possibility of reading and tracking atmospheric muons, generated with CORSIKA [139], from the sea level to the can [140]. For upgoing neutrinos, absorption within the Earth must be taken into account. Hence, the code provides a proper weight, that can be used to re-weight the generated events according to a specific atmospheric or astrophysical flux, with a specific energy spectrum. A weight can be defined as

$$w_{\text{gen}} = \frac{I_E \cdot I_\theta \cdot T_{\text{gen}} \cdot A_{\text{gen}} \cdot N_\nu \cdot E^\gamma \cdot P_{\text{scale}} \cdot P_{\text{Earth}}(E, \cos \theta)}{N_{\text{tot}}}, \quad (49)$$

where:

- I_E is the energy phase space factor, defined as the integral of the generation spectrum $E^{-\gamma}$ over the simulation energy range;
- I_θ is the angular phase space factor. It is equal to $2\pi(\cos \theta_{\text{max}} - \cos \theta_{\text{min}})$ for diffuse simulations, and 1 for point-source mode. θ_{max} and θ_{min} are the maximum and minimum generated zeniths;
- T_{gen} is the simulated livetime. In point-source mode, it corresponds to the time window during which neutrinos are generated;
- A_{gen} is the neutrino generation area, i.e., the area over which incoming neutrino directions are sampled, expressed in m^2 ;
- N_ν is the number of neutrino types generated;
- E^γ is the inverse of the generation spectrum evaluated at the specific event energy;
- N_{tot} is the total number of simulated neutrino events;
- P_{scale} is the GENIE interaction probability scaling factor [137];
- $P_{\text{Earth}}(E, \cos \theta)$ is the probability that a neutrino of energy E and zenith angle θ reaches the detector without being absorbed by the Earth. It is defined as:

$$P_{\text{Earth}}(E, \cos \theta) = e^{-\sigma(E_\nu) \rho N_A Z(\theta)}, \quad (50)$$

which considers the absorption of neutrinos crossing a path $Z(\theta)$, dependent on the zenith of arrival, but also their total cross section $\sigma(E_\nu)$ and the target nucleon density ρN_A .

To simulate any specific neutrino flux Φ_ν , the event must be weighted by the product $w_{\text{gen}} \cdot \Phi_\nu$. For atmospheric neutrinos, the HONDA flux [141] is typically used, while for cosmic neutrinos, a reference spectrum proportional to E_ν^{-2} is assumed,

as expected from Fermi acceleration mechanisms (see subsection 1.1.3).

Atmospheric muons are simulated using the MUPAGE package [142]. MUPAGE relies on parametric formulas which describe the flux, the angular distribution and the energy spectrum of under-water muon bundles. Simulations are valid for 1.5 and 5 km water equivalent depth and for zenith angles between 0° and 85° . It produces the event kinematics on the surface of a user-defined cylinder, surrounding the virtual detector. The multiplicity of the muons in the bundle, the muon lateral distribution and energy spectrum are simulated according to specific model of primary cosmic-rays flux, whose constraints are derived from underground experiments. In the case of MUPAGE, weights are given by $1/t_{\text{live}}$, where t_{live} is the total simulated lifetime (active data-taking period), analogous to the way experimental data are weighted in data-MC comparisons.

4.2 PARTICLE PROPAGATION AND LIGHT PRODUCTION

Muons produced in neutrino interactions, generated outside the detector can, are propagated using the MUSIC [143] or PROPOSAL [144] codes. Light production and propagation are handled by two packages: KM3SIM [145], particularly suited for simulations at few-GeV energies, relevant in KM3NeT/ORCA, and JSirene, part of the Jpp software framework used in KM3NeT [146] and optimized for higher-energy regimes. KM3SIM propagates all particles individually through GEANT4 [147], providing a detailed modeling of each photon and the corresponding number of photoelectrons recorded by the PMT. This event-by-event tracking enables a direct evaluation of the photoelectron yield without relying on precomputed tables. In contrast, JSirene simulates Cherenkov photon emission along the muon path and uses multidimensional interpolation tables to estimate the detection probability at the DOMs. Since atmospheric muons are generated directly on the can, JSirene also handles their propagation. Both packages account for light absorption and scattering, as well as muon energy losses, multiple scattering, radiative processes and hadronic interactions. Long-lived particles are propagated through the can volume, with water density and composition adjusted for each KM3NeT site. Thanks to the relative homogeneity of seawater, precomputed detection probability tables, parameterized by time, distance, particle energy and photon angle, can be used efficiently and with improved computation time compared to the detailed particle tracking case.

4.2.1 Detector Response

The detector response is simulated using the JTriggerEfficiency package [148], which processes the photons from KM3SIM/JSirene, adds optical background noise, and simulates the readout electronics and trigger algorithms. Background hits are generated with a Poisson distribution based on measured noise rates, accurately replicating data-taking conditions. The electronics response and triggers (as detailed in Section 3.2) are then applied. The output consists of event files that serve as input for the final reconstruction stage of the simulation chain.

4.2.2 Run-by-run approach

MC simulations adopt a run-by-run (RBR) approach to accurately reproduce the detector response under real data-taking conditions. In this mode, each physics run (typically lasting three hours) is associated with a dedicated simulation, using the JTriggerEfficiency package to extract run-specific parameters directly from the data. These parameters include detector status, trigger configuration and optical background rates. Environmental conditions in the deep sea, such as biological activity and seasonal variations, significantly influence the optical background and, consequently, the event detection rate. Since these phenomena are difficult to model analytically, background levels are measured from data and fed into the simulation as inputs for the trigger response. Additionally, temporary or permanent malfunctions of detector components, such as inactive PMTs, are retrieved from a centralized database and incorporated into the simulation chain. This RBR methodology ensures that the variability in detector conditions, including environmental effects and hardware status, is faithfully replicated in the simulated dataset, allowing for a more reliable comparison with real data.

4.3 EVENT RECONSTRUCTION

Reconstruction of triggered events is a critical step in the analysis chain of a neutrino telescope. Different reconstruction algorithms have been developed to handle the different event topologies. Since no particle identification is applied beforehand, each triggered event is processed with all available reconstruction methods.

4.3.1 Track reconstruction

In KM3NeT/ARCA, Jpp applications are used to perform event reconstruction assuming a track topology, determining muon direction and energy after a simulation chain, described in [149]. For the muon trajectory reconstruction, the coordinate system illustrated in Figure 51 is used.

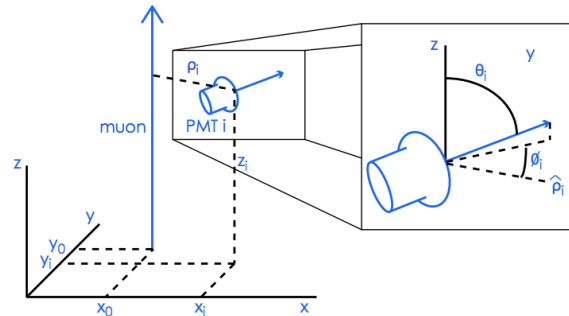


Figure 51: Coordinate system used in the muon trajectory fit. Image from [149].

Assuming a fixed muon direction, the particle is modeled to travel along the z -axis, crossing the plane $z = 0$ at coordinates (x_0, y_0) and time t_0 . Neglecting scattering

and dispersion effects, the expected arrival time t_i of Cherenkov photons on a given PMT i can be expressed as:

$$t_i = t_0 + \frac{z_i}{c} + \frac{\rho_i}{c} \tan(\theta_c), \quad (51)$$

$$\rho_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}, \quad (52)$$

where z_i is the vertical distance from the PMT to the $z = 0$ plane, ρ_i is the perpendicular (transverse) distance from the muon track to PMT i , θ_c is the Cherenkov angle and c is the speed of light.

The details of the reconstruction chain for tracks are summarized as follows:

- **JMuonPrefit** performs an initial fit in the detector, taking N track hypotheses in all directions. By assuming a direction, the remaining parameters to fit are the position of the muon and time at which it crosses a reference plane perpendicular to the muon direction. The parameters describing the muon are obtained by an iterative procedure to minimize the χ^2 , based on the time difference between expected and observed photon arrival time. This approach is repeated for a scan of assumed track directions with a specific grid angle (1° in KM3NeT/ARCA). The N best fitted tracks are used as input to initialize the next steps of the reconstruction chain. The quality of the fit is quantified as

$$Q = \text{DOF} - 0.25 \frac{\chi^2}{\text{DOF}}, \quad (53)$$

where DOF refers to the number of degrees of freedom in the fit.

- **JMuonSimplex** performs an intermediate χ^2 fit of the solutions of JMuonPrefit as starting values, in order to improve the reconstruction accuracy and reduce time residuals.
- **JMuonGandalf** takes the fit results of JMuonSimplex as starting points, performs a scan around the best-fit values and carries out the full final fit. Causally related hits are first selected in order to remove the optical background contribution. Full fit is based on a likelihood scan and makes use of Probability Density Functions (PDFs), which describe the response of the PMTs:

$$\mathcal{L} = \prod_{\text{PMTs hits}} \frac{\partial P}{\partial t}(\rho_i, \theta_i, \phi_i, \Delta t), \quad (54)$$

where ρ_i is the minimum distance of the muon to the PMT, θ_i and ϕ_i are the orientation of the PMT, while Δt is the difference between the expected and measured arrival time of light. JMuonGandalf also has a quality parameter associated with it: $Q = -\chi^2$. Larger values of Q indicate a better quality of the fit.

- **JMuonStart** defines the observed start position of muon trajectory: the first emission point along the track, under the Cherenkov angle, exceeding the random background level, is selected as the start position.

- **JMuonEnergy** determines the muon energy. It is ran after JMuonStart, because knowing the track length is useful for finding the energy. The energy is fitted through the maximization of a likelihood function that considers, as a function of the muon energy, the spatial distribution of hit/no-hit PMTs within a cylindrical volume surrounding the track hypothesis. PMTs within a pre-defined width (typically 200 m in KM3NeT/ARCA) around the muon trajectory are used to compute the hit probability. As an example, in Figure 52 the reconstructed muon energy is compared with the true muon energy, based on simulated events within a single building block of KM3NeT/ARCA. A resolution better than 0.3 in $\log_{10}(E_{\text{reco}}/E_{\mu})$ is achieved roughly between 10 TeV and 10 PeV.

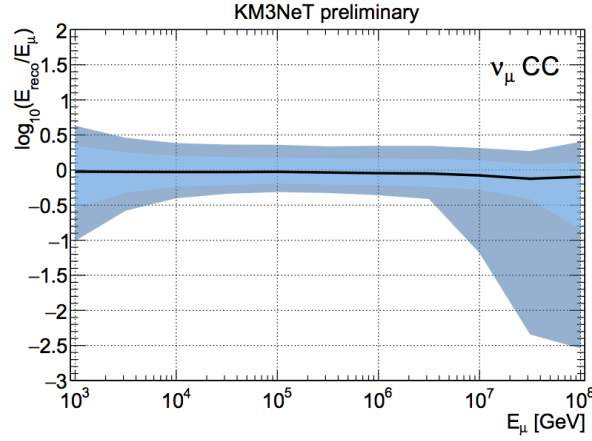


Figure 52: The median energy resolution (solid line) of the reconstructed muon energy is shown as a function of the true muon energy, alongside the 68% and 90% quantiles. The standard deviation of the $\log_{10}(E_{\text{reco}}/E_{\mu})$ distribution is less than 0.3. Image from [149].

4.3.2 Shower reconstruction

The shower reconstruction algorithm, AAshowerfit [149], follows a two-step procedure: the fit of the vertex position, based on hit times, and the estimation of direction and energy, using the spatial information of PMTs being hit or not.

- **Vertex fit:** in the position reconstruction, although showers extend for several meters, they are considered as a point source of light since the majority of the detected signal photons from a shower will be at large distances from it. As a consequence, position and time fitted are not those of the neutrino interaction, but they correspond to a point displaced from it by several meters along the shower axis. This point is located somewhere near the shower-maximum. The fit uses a sample of hits selecting coincidence hits on the same DOM, within a reference time window Δt of 20 ns. Best position and emission time are derived minimizing a M-estimator, which takes into account the expected arrival time of photon hits, propagating on a spherical wavefront, with respect to the measured one. Performances of the vertex fit are shown in Figure 53, for events simulated in one block of KM3NeT/ARCA.

- **Direction and energy fit:** the subsequent production of secondary particles in a shower stops when the energy of each particle is less than a certain threshold. The number of emitted photons will be proportional to the total shower energy. In particular, since charged particles in a shower propagate along shower direction, angular distribution of the emitted photons will be centered at the Cherenkov angle. Also, the distribution of detected photon hits is maximal around the Cherenkov angle, with respect to the shower direction, even if absorption, scattering and electronics effects are not negligible. The maximum of a likelihood function, the hit/non-hit probability of the PMTs, gives the best estimate of the shower direction and energy. Performances of the direction and energy fits can be seen in Figure 54, for events simulated in one block of KM3NeT/ARCA.

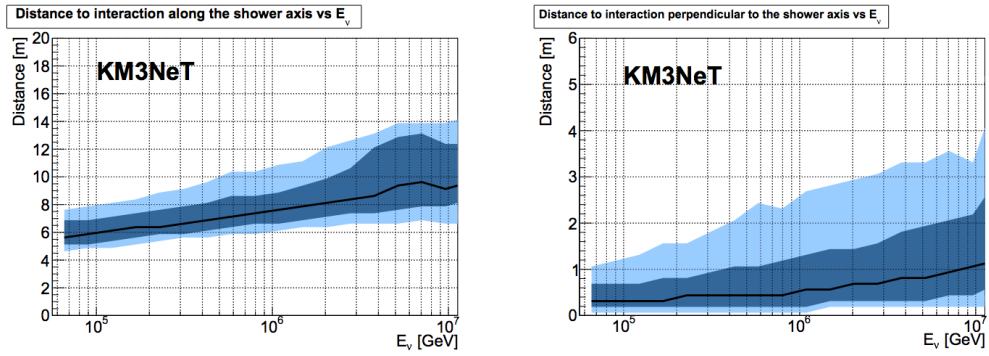


Figure 53: Performance of the shower vertex fit. The dark and light blue bands represent the 68% and 90% containment of the distribution, respectively, while the black line indicates the median. The left plot shows the distance between the reconstructed position and the true neutrino interaction point, projected along the shower axis. The right plot shows the distance between the reconstructed position and the shower axis. No quality cuts are applied. Image from [149].

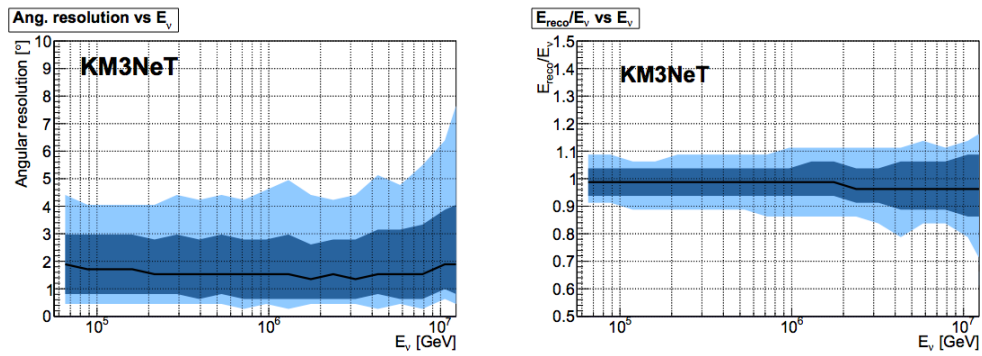


Figure 54: Performance of the direction and energy fits for shower reconstruction. The dark and light blue bands represent the 68% and 90% containment of the corresponding error distributions, respectively, while the black line indicates the median. The left panel shows the median angular resolution as a function of the neutrino energy, whereas the right panel displays the energy resolution. The standard deviation of the error in the energy is approximately 5%. The median angular resolution is about 1.5° . Image from [149].

STATISTICAL METHODS FOR POINT SOURCE SEARCHES

High-energy neutrino astronomy focuses on identifying astrophysical sources that emit neutrinos, looking for excesses of events above the random background fluctuations. These sources may be either steady or transient in nature, point-like in appearance or extended over a region of the sky, and can also contribute to a diffuse flux that spans large angular areas in the sky. To identify such signals, several statistical approaches have been developed. Among these, likelihood-based methods, which generally exploit the reconstructed energy and direction of the events to discriminate signal from background. In fact, reconstructed directions of signal events, originating from astrophysical sources, are expected to cluster around the true source, with a spread defined by the detector's angular resolution, itself constrained by the geometry of the detector, optical module spacing, the scattering and absorption properties of the medium, and the intrinsic neutrino-lepton kinematics. In addition to angular clustering, energy distribution provides a key discriminant. Neutrinos from Fermi accelerated cosmic rays are expected to follow a hard power-law spectrum close to E^{-2} , which is significantly harder than the steeper atmospheric neutrino spectrum of approximately $E^{-3.7}$ above 100 GeV. In the binned maximum likelihood approach, distributions of parameters, such as direction and energy, for which signal and background are expected to follow different behaviors, are used; the number of observed events in each bin is compared to the expected background and potential signal contributions. Although this method is computationally efficient, it can suffer from reduced sensitivity due to binning effects. To overcome these limitations, unbinned maximum likelihood techniques are employed. These methods do not rely on predefined bin sizes; instead, they make use of probability density functions (PDFs) that model the likelihood of each detected event being either signal or a background. The unbinned likelihood approach offers enhanced sensitivity and is preferred in analyses that do not demand immediate processing, although the method becomes increasingly slow as the number of events becomes larger than the number of bins, which is typically the case. It therefore requires more computational resources.

An additional discriminating factor between signal and background is the arrival time of neutrinos, in the case of searches for point-like neutrino sources emitting a non-steady flux. Indeed, in the case of transient emissions, the background from atmospheric neutrinos can be suppressed by restricting the analysis to a narrow time window around the source flare. Time-dependent point source searches may be performed in either triggered or untriggered modes [150]. Triggered searches rely on data from external observatories, which guide the time of the analysis, and look for a neutrino emission in temporal and spatial coincidence with known

electromagnetic events. In contrast, untriggered searches scan the entire time domain without any prior information, relying solely on the neutrino data. Time-integrated and time-dependent studies can be performed either over the entire sky or in the directions of known candidate sources, typically selected based on their multi-wavelength emission or relevance predicted by theoretical models. The former approach offers the advantage of being unbiased with respect to prior electromagnetic observations, despite suffering from a large trial factor due to the vast number of tested positions, the latter reduces the statistical trial factor but may introduce a potential bias, as it assumes a correlation between multi-wavelength observations and neutrino emission, which may not always hold.

Finally, stacking analyses, in both binned and unbinned modes, can be used to enhance sensitivity by searching for the cumulative signal from a class of sources rather than individual objects. All candidates in a predefined catalogue are analyzed together, with a maximum likelihood point source analysis performed for each entry. A global likelihood function is then built, either in a model-independent way, treating all sources equally, or in a model-dependent approach, where weights are assigned according to theoretical predictions of the neutrino flux. Pseudo-experiments (PEs) are used to evaluate the statistical significance and extract limits. This method improves sensitivity to faint populations but may introduce biases related to source selection and flux modeling. A stacking search for high-energy neutrinos from blazars with KM3NeT/ARCA will be addressed in Chapter 7, while a comparison between binned and unbinned likelihood performances, as well as of a time-dependent analysis, will be the subject of Chapter 8.

This Chapter goes into the details of both binned (5.1) and unbinned (5.2) maximum likelihood approaches, focused on those used in searches for neutrino point sources with KM3NeT/ARCA, and describes time-dependent unbinned methods. Afterwards, both the PEs generation (5.3) and their statistical analysis (5.4) are discussed.

5.1 BINNED MAXIMUM LIKELIHOOD

To exploit both angular and energy features, a maximum binned likelihood method can be employed using two-dimensional histograms (PDFs) of the angular separation α and reconstructed energy of the event $\log_{10}(E_{\text{rec}}/\text{GeV})$. Specifically, binned likelihood analyses developed for KM3NeT/ARCA adopt as histogram ranges $\alpha \in [0^\circ, 5^\circ]$ and $\log_{10}(E_{\text{rec}}/\text{GeV}) \in [2, 8]$. As an example, Figure 55 shows the signal and background expectations at declination $\delta = -85^\circ$ for 21 strings of KM3NeT/ARCA (KM3NeT/ARCA21), assuming an E^{-2} spectrum. The signal is concentrated near the source and generally occurs at higher energy. The reason why signal events appear in the leftmost bins is that the bins along the x-axis represent increasing solid angles from left to right. Consequently, the rightmost bin, which covers the largest solid angle, contains the majority of background events. Plots have been produced at the point source selection level for track-like events. The effect of systematics on the PDFs is also considered. Details will be discussed in Chapters 7.

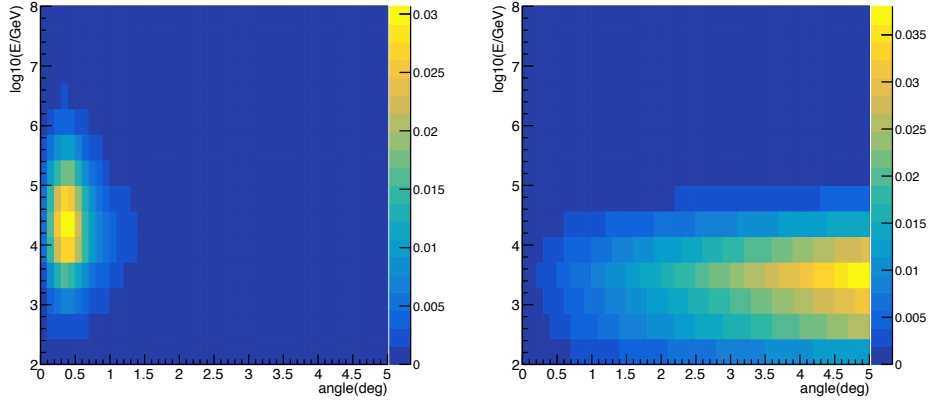


Figure 55: Expected signal (left) and background (right) PDFs at declination $\delta = -85^\circ$ for KM3NeT/ARCA21 assuming an E^{-2} spectrum. Signal clusters near the source, while background dominates in bins covering larger solid angles.

5.1.1 Background and signal modeling

Background and signal modeling for binned point source searches with KM3NeT/ARCA is performed as follows. In each bin i , given the small expected contribution of signal events in the dataset, the expected number of background events B_i is estimated from data using scrambling techniques, i.e. data randomized in right ascension, and calculating the density of background events as a function of the declination δ . Specifically, a factorized model is employed to describe the background dependence on energy and declination. The expected number of background events per unit solid angle and logarithm of the energy is given by:

$$N_{\text{bkg}} = n \cdot F(\delta) \cdot F(\log_{10}(E)) \quad [\text{sr}^{-1} \cdot (\log_{10}(\text{GeV}))^{-1}], \quad (55)$$

where the normalization constant n is chosen such that the integral of N_{bkg} over the full sky and energy range matches the total number of observed events in each dataset. The declination dependence $F(\delta)$ is modeled using a spline fit in $\sin(\delta)$, while the energy dependence $F(\log_{10}(E))$ is parameterized using a sum of Gaussian functions. As an example, Figures 56 and 57 show the distributions of $F(\delta)$ and $F(\log_{10}(E))$, respectively, derived using the track-like event selection optimized for point source searches with KM3NeT/ARCA21, detailed in Chapter 7. Notice that the UHE event KM3-230213A (see 3.5) has been removed from the sample.

The expected number of signal events S_i is derived from detector-specific response functions, including effective area, angular resolution and energy response. In particular, the total expected rate is computed by integrating the product of the flux and effective area over energy, and then applying efficiency factors that account for the fraction of events reconstructed within the specific angular and energy bin. Flux models can be given by as a single energy power law with different spectral indices γ :

$$\phi^{\gamma_r + \gamma_f}(E) = \mu \times \phi_0 \times \left(\frac{E}{\text{GeV}} \right)^{-\gamma}, \quad (56)$$

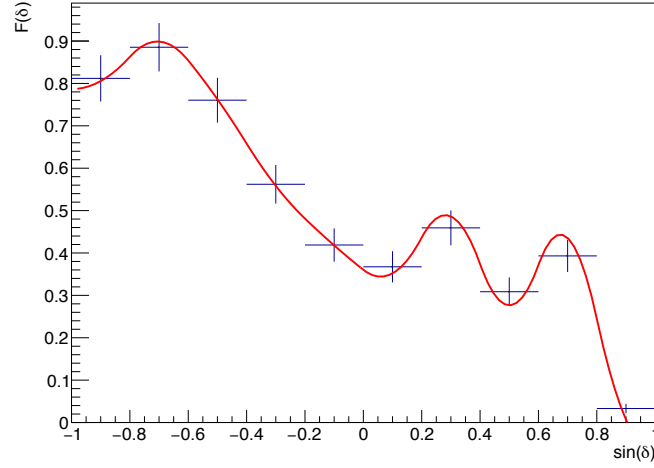


Figure 56: Fraction of selected track-like events in the KM3NeT/ARCA21 dataset as a function of the declination, for the point source selection described in Chapter 7. Distribution has been fitted using a spline function as functional form.

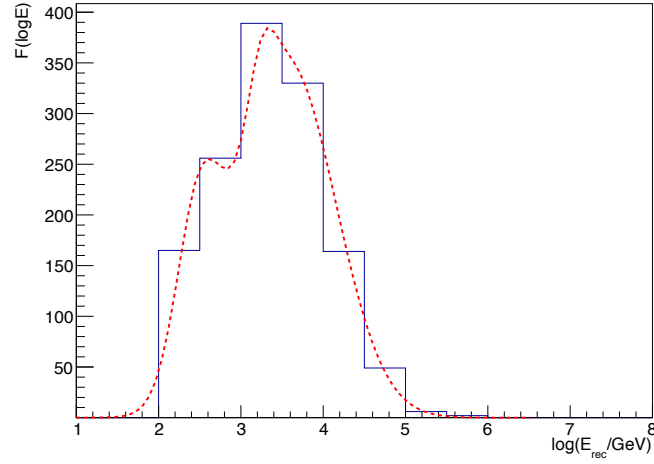


Figure 57: The reconstructed energy distribution of the selected track-like events from the KM3NeT/ARCA21 dataset, corresponding to the point source selection described in Chapter 7, fitted using a sum of three Gaussian functions.

where ϕ_0 is the flux normalization at 1 GeV and μ is the signal strength. In any case, ϕ_0 represents an arbitrary flux normalization, by which μ is scaled; it is μ that is then fitted. Index f labels the neutrino type. Multiple spectral indices can be tested: a canonical E^{-2} spectrum, a softer $E^{-2.5}$ spectrum in line with recent measurements by ANTARES, IceCube, and Baikal (see Chapter 2) and an even softer $E^{-3.2}$ spectrum applied specifically to the NGC 1068 source, as motivated by IceCube observations [11].

5.1.2 Likelihood formalism

To evaluate the compatibility of the data with a signal-plus-background hypothesis (H1) compared to a background-only hypothesis (H0), a likelihood ratio test is used. The test statistic is defined as

$$\lambda = \log \mathcal{L}(\mu = \hat{\mu}) - \log \mathcal{L}(\mu = 0), \quad (57)$$

where μ is the free parameter under optimization and $\hat{\mu}$ is its best-fit value, constrained to $\hat{\mu} > 0.1$ to avoid spurious background-like peaks in the λ distribution. The binned Poisson likelihood is given by:

$$\mathcal{L} = \prod_{i \in \text{bins}} \frac{(\mu S_i + B_i)^{N_i} \exp[-(\mu S_i + B_i)]}{N_i!}, \quad (58)$$

where N_i is the number of observed events in bin i , and $\mu S_i + B_i$ is the expected number of events in that bin. Taking the logarithm and omitting terms independent of μ , the log-likelihood simplifies to:

$$\log \mathcal{L} = \sum_{i \in \text{bins}} [N_i \log(\mu S_i + B_i) - (\mu S_i + B_i)]. \quad (59)$$

Based on the expected signal and background distributions, PEs can be generated, as will be described in Section 5.3. S_i and B_i are differently defined according to the channel (c) under consideration: tracks or showers. Considering both scenarios, the likelihood definition reads as:

$$\log \mathcal{L} = \sum_{c \in \text{channels}} \sum_{i \in \text{bins}} [N_i^c \log(\mu S_i^c + B_i^c) - (\mu S_i^c + B_i^c)]. \quad (60)$$

S_i and B_i distributions for the KM3NeT/ARCA21 track-channel are those already shown in Figure 55.

5.2 UNBINNED MAXIMUM LIKELIHOOD

High-energy neutrino telescopes record astrophysical events as individual detections spread across the sky, each characterized by a reconstructed direction, energy, and time. To evaluate whether a cluster of events originates from an astrophysical source or is merely a statistical fluctuation of the background, unbinned likelihood methods can be used. They rely on the information of each single event, calculating their probability of being either signal or background. For a set of N observed events $\{x_1, x_2, \dots, x_N\}$, the likelihood is a function of the model with parameters θ and is constructed as the product of PDFs associated with each event:

$$\mathcal{L}(\theta) = \prod_{i=1}^N p(x_i; \theta), \quad (61)$$

where $p(x; \theta)$ is the normalized PDF for the event features under the model parameters θ and i runs over all events. As evident from the previous discussion, in both binned and unbinned approaches, $\mathcal{L}(\theta)$ depends on the model parameters, with the difference being whether the product runs over events or bins.

To distinguish between H_0 and H_1 , in analogy to the binned methods, a test statistic is defined based on the ratio of the likelihoods:

$$\lambda = -\log \left(\frac{\mathcal{L}(\text{Data} | H_0)}{\mathcal{L}(\text{Data} | H_1)} \right). \quad (62)$$

In point source searches, the standard likelihood combines contributions from signal and background. Assuming n_s expected signal events (a free parameter) and $n_b = N - n_s$ background events, the total likelihood is:

$$\mathcal{L}_{\text{ML}}(n_s, \theta') = \prod_{i=1}^N (n_s S_i(\theta') + n_b B_i), \quad (63)$$

where S_i and B_i are the signal and background PDFs evaluated for the i -th event, and θ' denotes other model-dependent parameters (e.g., source extension, spectral index, flare duration). The log-likelihood is typically used for numerical stability:

$$\log \mathcal{L}_{\text{ML}}(n_s, \theta') = \sum_{i=1}^N \log (n_s S_i(\theta') + n_b B_i). \quad (64)$$

An alternative formulation is the Extended Maximum Likelihood (EML). The expected number of events N is given by the sum of the signal and background events. As the signal contribution in the data sample is expected to be negligible, the full data sample under study can be treated as background. Therefore, the extended likelihood is defined as

$$\mathcal{L}_{\text{EML}}(n_s, \theta') = \prod_{i=1}^N (n_s S_i(\theta') + N B_i) \cdot e^{-(n_s + N)}, \quad (65)$$

with corresponding log-likelihood:

$$\log \mathcal{L}_{\text{EML}}(n_s, \theta') = \sum_{i=1}^N \log (n_s S_i(\theta') + N B_i) - n_s - N. \quad (66)$$

The likelihood is maximized with respect to the free parameters n_s and θ' , yielding best-fit values $\hat{n}_s$ and $\hat{\theta}'$. The background-only hypothesis corresponds to $n_s = 0$ (H_0).

5.2.1 Likelihood PDFs

The likelihood functions are built from the combination of individual probability densities modeling spatial, energy, and, in case of transient emission, temporal distributions. Different PDFs can be defined whether a steady or transient source is considered:

$$S_{\text{steady}} = S_{\text{space}} \cdot S_{\text{energy}}, \quad B_{\text{steady}} = B_{\text{space}} \cdot B_{\text{energy}}, \quad (67)$$

$$S_{\text{transient}} = S_{\text{space}} \cdot S_{\text{energy}} \cdot S_{\text{time}}, \quad B_{\text{transient}} = B_{\text{space}} \cdot B_{\text{energy}} \cdot B_{\text{time}}. \quad (68)$$

- **Spatial PDFs:** S_{space} is the signal PDF that models the angular distribution of signal events around the source, typically using the detector's Point Spread Function (PSF), i.e. the probability of reconstructing a signal event at a certain angular distance from the direction of the source. The shape of the PSF is determined from Monte Carlo simulations of cosmic neutrinos for the assumed signal energy spectrum. The KM3NeT/ARCA21 distribution of the angular resolution for tracks using the selection optimized for point source searches, as described in Chapter 7, considering an E^{-2} energy spectrum, is shown in Figure 58. The corresponding cumulative distribution is presented in Figure 59.

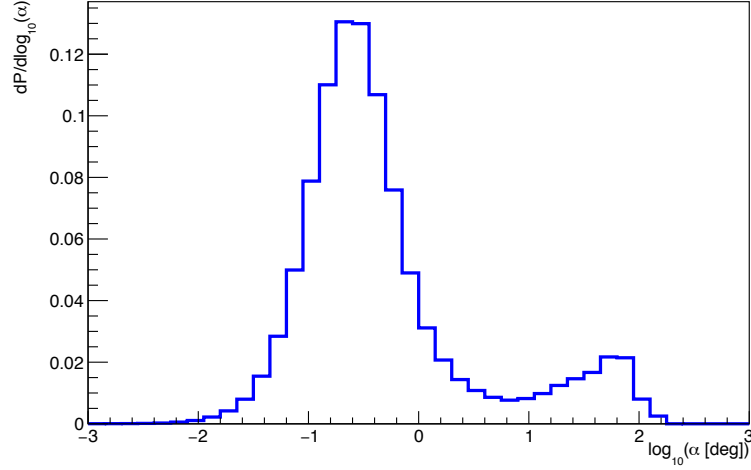


Figure 58: Angular resolution distribution, assuming an E^{-2} spectrum, for the tracks sample used in KM3NeT/ARCA21 point source searches.

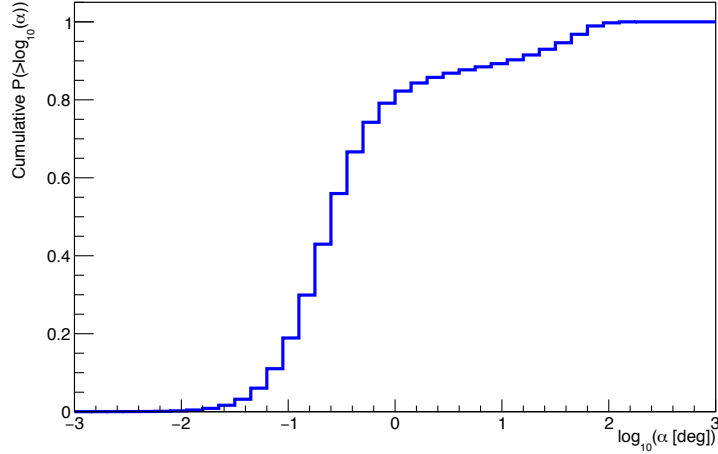


Figure 59: Cumulative angular resolution distribution, assuming an E^{-2} spectrum, for the tracks sample used in KM3NeT/ARCA21 point source searches.

B_{space} reflects the declination distribution of background events and is derived from data due to the low expected signal contamination. Unbinned methods adopted in this work assume as spatial PDF for the background the distribution of the reconstructed zenith of the data. After a spline interpolation of the histogram, the fit is then used as functional form for the proba-

bility spatial distribution (Figure 60). An uniform azimuthal dependence is assumed.

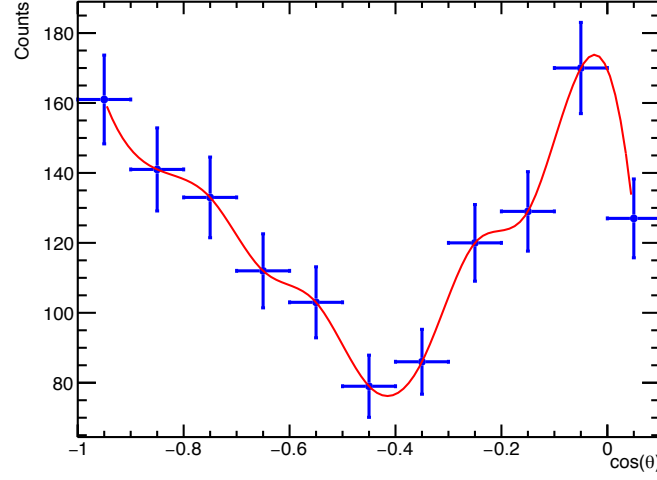


Figure 60: Number of selected track-like events in the KM3NeT/ARCA21 dataset as a function of the cosine of their reconstructed zenith, after the point source selection described in Chapter 7. The selection on upgoing and slight horizontal events is visible as a cut at $\cos(\theta) = 0.1$. Distribution has been fitted using a spline function as functional form.

- **Energy PDFs:** S_{energy} describes the probability of obtaining a signal event with a certain value of reconstructed energy. It is based on simulations of neutrino sources weighted with an assumed spectra (e.g., E^{-2}). Figure 61 displays the reconstructed energy E_{reco} of KM3NeT/ARCA21 for the selected track-like events from the point source selection, plotted as a function of the true energy E_{true} . Median and 68% quantiles are also shown. B_{energy} comes from the data itself. Specifically, the unbinned methods discussed in this work assume as energy PDF for the background PDF the same energy distribution shown in Figure 57, whose fit is then used as functional form for the probability energy distribution.

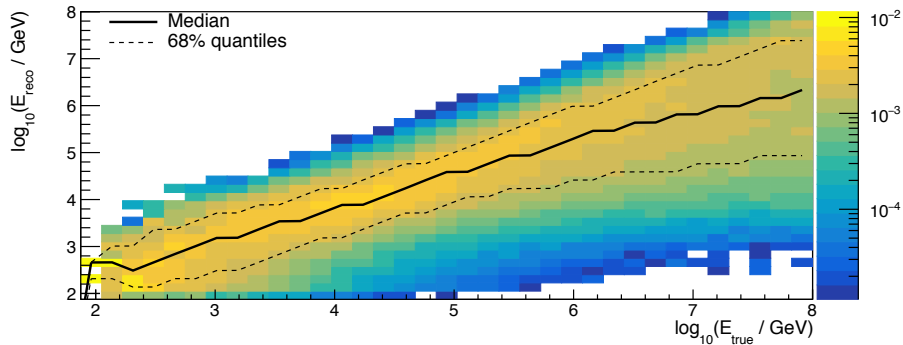


Figure 61: Reconstructed energy of KM3NeT/ARCA21, for the selected track-like events from the point source selection, as a function of the true energy, weighted with an E^{-2} spectrum. The median is shown along with the 68% quantiles.

- **Time PDFs:** in transient searches, S_{time} represents the probability of detecting a signal event at a given time. E.g., in searches for neutrinos from known gamma-ray sources with measured light curves, the emission time distribution derived from photon observations can be used to construct this PDF, assuming that the photon and neutrino emission should happen in coincidence. When the emission time distribution is not known in advance, generic models, such as Gaussian or rectangular-shaped profiles, may be assumed. Instead, B_{time} is derived from the observed time distribution of data events, starting from their Modified Julian Date (MJD). Both the detector livetime and environmental effects are taken into account. To ensure that the time distribution of the data actually reflects the background behavior and avoid statistical fluctuations, this PDF can be produced assuming less stringent cuts. Figure 62 displays the time-dependent event rate, B_{time} , for data collected by KM3NeT/ARCA21 over the period from September 2022 to September 2023, using a 1-day binning for the histogram. The events shown correspond to a less-stringent selection compared to the full point source analysis. Specifically, the selection includes well-reconstructed track-like events originating from upgoing or horizontal directions, while noise events are suppressed through dedicated cuts on the number of hits used in the reconstruction and on the likelihood function defined in Equation 54. After this selection, about 30,000 events are analyzed.

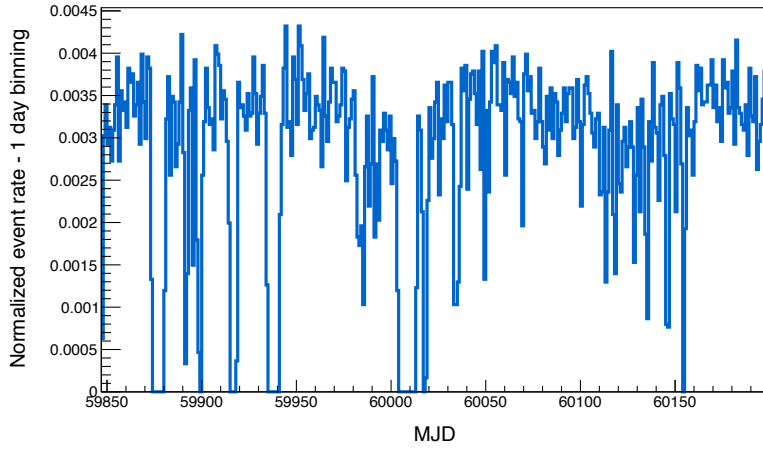


Figure 62: Event rate (B_{time}) for data collected by KM3NeT/ARCA21 between September 2022 and September 2023, using a 1-day binning. The events shown are selected including well-reconstructed track-like events from upgoing or horizontal directions. Noise is excluded through cuts on the number of hits used in the reconstruction and on the likelihood fit parameter. Approximately 30,000 events are selected.

5.3 PSEUDO-EXPERIMENTS

In order to determine the performance of the search strategy and quantify the statistical significance of potential neutrino source detections, PEs are performed. These simulated experiments are used to estimate the distributions of the test

statistic (λ) under various signal hypotheses, enabling the calculation of discovery potential, sensitivity and upper limits. Each PE consists of a pseudo-dataset, constructed to mimic the real observational data while allowing for controlled signal injections. To remove potential clustering in space and time due to real sources in the data, the right ascension of all events is randomized. The number of simulated background events in each PE equals the number of selected events in the real dataset. Each sky map in a PE contains a predefined number of signal events, along with a corresponding number of background events.

5.3.1 Binned searches

In binned searches, for a given value of the signal strength, μ_{true} , PEs are generated by drawing each expected event count N_i from a Poisson distribution with mean $B_i + \mu_{\text{true}}S_i$, where B_i and S_i represent the expected background and signal contributions, respectively (Figure 55). Each PE is then processed using the standard analysis procedure, including a maximum likelihood fit that yields an estimated signal strength $\hat{\mu}$. This value is subsequently used to compute the test statistic λ for that particular PE. Repeating this procedure across many PEs results in a distribution of $\lambda(\mu_{\text{true}})$ values. As an illustrative case, Figure 63 shows such a distribution for declination $\delta = -85^\circ$ assuming an E^{-2} energy spectrum. As the number of assumed signal events increases, the distributions increasingly deviate from the null hypothesis. Typically, a fit to the tail of the H_0 distribution is done in order to assess significance accurately, and not suffer from a lack of statistics.

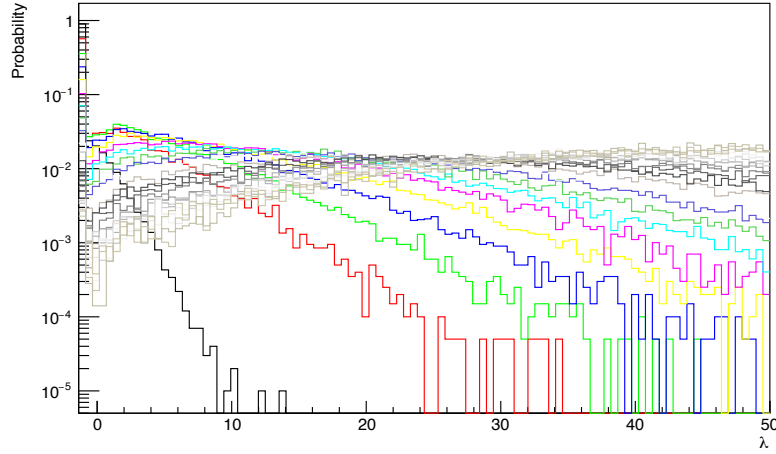


Figure 63: Normalized distributions of test statistic from the declination $\delta = -85^\circ$ assuming an E^{-2} energy spectrum, for an increasing number of injected signal strengths (colored lines). The null hypothesis (H_0) is indicated as a black line. The conversion between a number of signal events (n_s) and μ_{true} is simply a scaling factor.

5.3.2 Unbinned searches

In unbinned searches, signal events are generated based on multi-dimensional histograms derived from Monte Carlo simulations of cosmic neutrinos. Modeling the

detector response to a steady astrophysical point source requires accounting for the apparent motion of the source in the local sky due to Earth's rotation. Although fixed in equatorial coordinates, the source traverses different zenith angles relative to the detector throughout a sidereal day. As a result, the detector's acceptance and angular resolution become functions of time, necessitating a time-resolved description of its response. To incorporate this effect, a three-dimensional histogram is constructed as a function of reconstructed energy (E_{rec}), time of day (expressed as a fractional value over a sidereal day) and angular reconstruction error (α). The construction is based on a precomputed two-dimensional histogram that describes the distribution of reconstructed energy and angular error. An example is shown in Figure 64. The time dependence is introduced by mapping each time-of-day value to the corresponding zenith angle, using the known right ascension and declination of the source, along with the geographic coordinates of the detector. This transformation is achieved through equatorial-to-horizontal coordinate conversion. For each bin in reconstructed energy and time of day, the corresponding true source zenith angle is calculated, and the appropriate detector response is obtained. The probability density is then evaluated as a function of angular error. For each simulated signal event, located at the source coordinates, a triplet of values (angular resolution, energy estimator and time) is randomly sampled from the histogram corresponding to the source's declination. In time-dependent analyses, a time value is also drawn from the assumed temporal emission profile and assigned to each event. In time-integrated searches, time is uniformly extracted within the sidereal day.

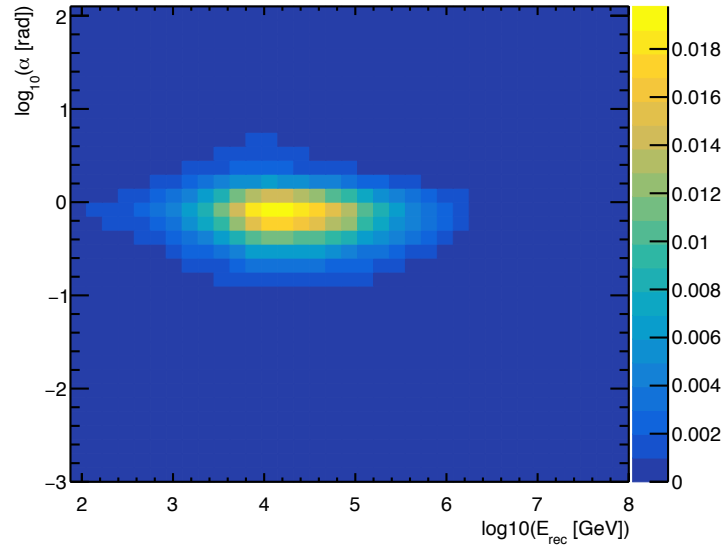


Figure 64: Normalized distribution showing the angular error, as a function of the reconstructed energy, for simulations of cosmic ν_μ (both charged current and neutral current interactions), obtained at the KM3NeT/ARCA21 point source selection level.

For time-integrated searches, background events are distributed uniformly in azimuth and follow the zenith distribution observed in the data. For each simulated background event, a pair of values (reconstructed energy and reconstructed zenith) is extracted from a two-dimensional histogram filled with the reconstructed energy

and reconstructed zenith of the dataset under consideration. In time-dependent analyses, the MJD of each background event is extracted according to B_{time} , shown in Figure 62.

The process of PE generation results in a set of test statistic distributions, each corresponding to a fixed number of simulated detected signal events, similar to those of Figure 63. However, since the number of detected signal events is subject to statistical fluctuations, these fixed-event distributions are replaced by distributions corresponding to a Poisson-distributed mean number of events. To further incorporate systematic uncertainties in the estimation of the signal event count, the test statistic distributions are smeared using a Gaussian uncertainty model. In this work, a 30% systematic uncertainty is adopted for the detector's acceptance, while a 0.5° uncertainty is considered for the PSF, mainly due to the absolute orientation of the detector around the z -axis. Details are given in 7.2. The final distributions, incorporating both statistical fluctuations and systematic uncertainties, are then used for the statistical analysis, as described in the following.

5.4 STATISTICAL ANALYSIS

To derive results, the likelihood ratio is computed by scanning the real data (unblinded, i.e. at their correct coordinates) and computing an observed test statistic, denoted λ_{obs} . The significance of λ_{obs} is assessed by comparing it to the λ distribution from background-only PEs. The probability of observing a value at least as extreme under the null hypothesis (H_0) defines the p-value:

$$\text{p-value} = \int_{\lambda_{\text{obs}}}^{\infty} \left. \frac{dP}{d\lambda} \right|_{H_0} d\lambda, \quad (69)$$

which represents the probability of obtaining λ_{obs} or higher due to background fluctuations alone. To interpret results, p-values are often converted into Gaussian significance levels: 3σ and 5σ correspond to $p \sim 1.3 \cdot 10^{-3}$ and $p \sim 2.9 \cdot 10^{-7}$, respectively (in the one-sided sigma convention). A 5σ significance is the standard threshold for discovery in high-energy physics. If no significant excess is found, an upper limit on the number of signal events is set at 90% confidence level (C.L.), called $n_s^{90\% \text{ C.L.}}$, using the Neyman construction:

$$\int_{\lambda_{\text{obs}}}^{\infty} \left. \frac{dP}{d\lambda} \right|_{H_1(n_s=n_s^{90\% \text{ C.L.}})} d\lambda = 0.90. \quad (70)$$

If λ_{obs} is below the median λ expected from the background-only scenario, the upper limit will match the sensitivity, defined as the median expected upper limit and outlined below. This is a conservative approach to avoid downward fluctuations in the data leading to nonphysical results. A graphical representation of the areas corresponding to the p-value and to the C.L. is shown in Figure 65, where two hypothetical Gaussian test statistic distributions are assumed and probabilities are calculated with respect to the median of the opposite hypothesis. Before deriving upper limits, detector performances can be determined studying the discovery potential (both at 3σ and 5σ) and the sensitivity. The 5σ discovery potential

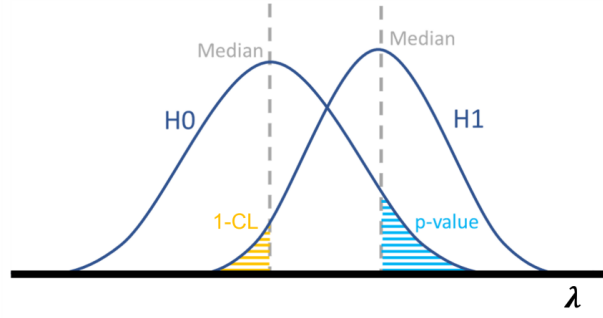


Figure 65: Illustration of the areas determining the p-value and the confidence level (C.L.) in two hypothetical H_0 and H_1 Gaussian test statistic distribution functions (λ). Image from [151].

is defined as the average number of signal events, $n_s^{5\sigma}$, required to yield a 5σ detection in 50% of trials:

$$\int_{\lambda_{5\sigma}}^{\infty} \frac{dP}{d\lambda} \Big|_{H_1(n_s=n_s^{5\sigma})} d\lambda = 0.50, \quad (71)$$

where $\lambda_{5\sigma}$ corresponds to p-value $\sim 2.9 \cdot 10^{-7}$. An analogue definition yields for $n_s^{3\sigma}$:

$$\int_{\lambda_{3\sigma}}^{\infty} \frac{dP}{d\lambda} \Big|_{H_1(n_s=n_s^{3\sigma})} d\lambda = 0.50, \quad (72)$$

where $\lambda_{3\sigma}$ corresponds to p-value $\sim 1.3 \cdot 10^{-3}$. Then, another relevant quantity is the sensitivity, which corresponds to the upper limit that would be obtained if the observed test statistic, λ_{obs} , were equal to the median of the background-only distribution, λ_{med} . Referring to Equation 70, the sensitivity $n_s^{90\% \text{ C.L.}}$ is calculated by replacing λ_{obs} with λ_{med} .

So far, the upper limits, discovery potentials and sensitivity have been expressed as mean number of detected signal events. This quantity can be translated into the source differential astrophysical neutrino flux measured at Earth, using the detector's acceptance. Assuming that the differential neutrino flux in energy is parameterized with an unbroken power-law, the acceptance is defined as:

$$A(\delta, \gamma) = \frac{n_s(\delta, \gamma)}{\phi_0} = \sum_{f,c} \int \left(\frac{E}{E_0 = 1 \text{ GeV}} \right)^{-\gamma} A_{\text{eff}}^{f,c}(\delta, E) dE T, \quad (73)$$

where T is the livetime, γ is the spectral index and δ is the declination under study, while f and c label the flavors and interaction channels, respectively. Therefore, $n_s(\delta, \gamma)$ is converted into a flux normalization, ϕ_0 , via the relation:

$$\phi_0 = \frac{n_s(\delta, \gamma)}{A(\delta, \gamma)}. \quad (74)$$

As an example, Figure 66 shows the acceptance of KM3NeT/ARCA21, calculated at the point source selection cuts, considering an E^{-2} cosmic neutrinos energy spectrum.

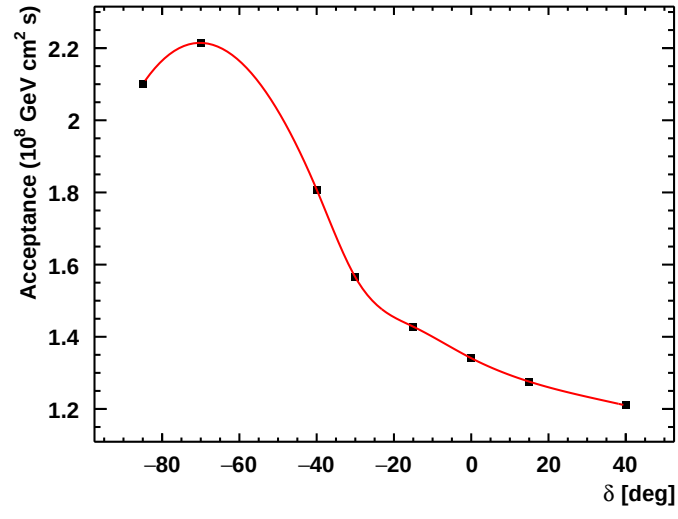


Figure 66: KM₃NeT/ARCA21 acceptance calculated, at the point source selection level, for different declinations and assuming $\gamma = 2.0$ in Equation 73.

MODELING THE EMISSION OF HIGH-ENERGY NEUTRINOS FROM BLAZARS

Active Galactic Nuclei (AGNs) are among the brightest persistent sources of electromagnetic radiation in the Universe. Powered by accretion onto supermassive black holes (SMBHs) with masses up to $10^9 M_{\odot}$, these compact regions at the centers of galaxies can outshine their host galaxies entirely and be detected across cosmological distances, up to redshifts as high as $z = 7.5$ [152]. Within the unified model of AGNs, the observed diversity in the AGN population arises mainly from differences in the inclination of the system with respect to the observer and the presence of structures such as the obscuring dusty torus and emission line regions [153]. A small but significant fraction ($\sim 10\%$) of AGNs are classified as radio-loud, due to their bright and extended radio emission produced by collimated relativistic jets of plasma emerging from the vicinity of the SMBH. These jets, when oriented close to our line of sight, appear exceptionally bright due to relativistic beaming. Such systems are known as blazars and are characterized by strong non-thermal emission across the entire electromagnetic spectrum, rapid variability and high polarization. Despite being a minority population, blazars dominate the extragalactic gamma-ray sky, accounting for approximately 70% of all known sources in that band [48]. Furthermore, this suggests their role as efficient accelerators of particles to energies exceeding 100 TeV. It is plausible that a fraction of these accelerated particles are protons. If these protons interact with ambient matter or photon fields, high-energy neutrinos can be produced via hadronic processes. For this reason, blazars have been proposed since the early 1990s as potential sources of high-energy astrophysical neutrinos (e.g., see [154]). As discussed in Chapter 2, a hint for this connection was provided by the detection of a ~ 290 TeV neutrino by the IceCube Neutrino Observatory, coincident with a flaring state of the blazar TXS 0506+056 [7]. This event marked a milestone in multi-messenger astrophysics and motivated further efforts to identify the dominant classes of neutrino sources. Anyway, as reported in [155], stacking analyses of various astrophysical source populations constrain the contribution of blazars to the diffuse IceCube neutrino flux to below 17%, as shown in Figure 67. Nevertheless, it remains plausible that at least a fraction of IceCube neutrinos originates from these sources.

To model and interpret multi-messenger signals from blazars, advanced numerical tools are required to simulate the interplay of leptonic and hadronic processes in SMBHs jets. The LeHa-Paris code [156] is one such tool, capable of reproducing the Spectral Energy Distribution (SED) of blazars, including both the electromagnetic signal and the expected neutrino production. Initially applied to the case of TXS 0506+056 [157], this code provides a framework for exploring a wide parameter space and optimizing neutrino flux predictions over multi-wavelength data. In this context, one of the goals of this thesis has been to derive the expected neutrino flux from the well-studied high-frequency-peaked BL Lac object PKS 2155–304 us-

ing the LeHa-Paris numerical code, and to derive a set of model predictions that can serve as templates for estimating neutrino emission from other similar sources. This Chapter begins by reviewing the key properties of blazars and the characteristic features of their SEDs (Section 6.1). It then describes the implementation of leptonic and hadronic processes in the LeHa-Paris code (Section 6.2). Focusing on PKS 2155–304, the code is employed to optimize its model parameters and to estimate the associated neutrino flux template (Section 6.3). Finally, starting from the case of PKS 2155–304, a methodology has been developed to extend neutrino flux templates, optimized via LeHa-Paris, to a subset of blazars selected from the 3HSP catalogue [158] (Section 6.4).

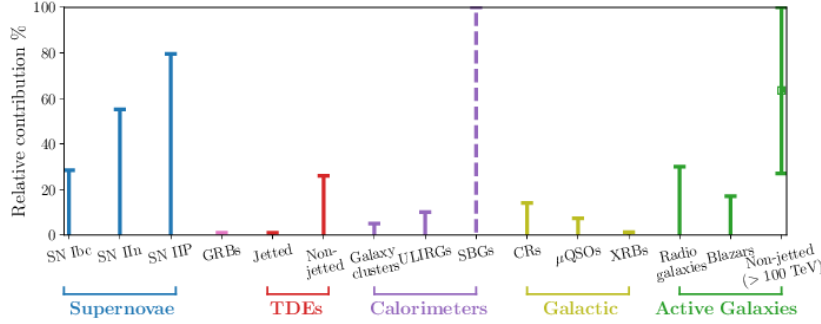


Figure 67: Bar chart of the possible contribution of different astrophysical source classes to the astrophysical neutrino flux measured by IceCube based on stacking analyses. The quoted values are 90% C.L. upper limits, except in the case of non-jetted AGN. See [155] for details.

6.1 BLAZARS

Blazars are generally divided into two main types: BL Lacertae objects (BL Lacs), which are characterized by a featureless non-thermal continuum in the optical/UV spectrum, and Flat-Spectrum Radio Quasars (FSRQs), which instead exhibit broad emission lines from the broad-line region (BLR), as typically seen in quasars. This classification parallels that of their parent population of radio galaxies, which are split into Fanaroff–Riley type I (FR I) radio galaxies, featuring strong core emission and relatively weak jets, and Fanaroff–Riley type II (FR II) radio galaxies, which display powerful jets terminating in shocks with the intergalactic medium [159]. The relativistic jet in a blazar moves with speed $v = \beta c$, corresponding to a Lorentz factor $\Gamma = (1 - \beta^2)^{-0.5}$, and is viewed at a small angle θ . This setup leads to three significant relativistic effects. First, due to projection effects, the apparent motion of plasma in the jet may appear superluminal in the observer’s frame, with a projected velocity which can exceed c . Second, the emission from the jet is Doppler boosted in the direction of motion, with the observed flux density scaling as $F_{\nu}^{\text{obs}} = \delta^3 F_{\nu}$, where δ indicates the Doppler factor, defined as:

$$\delta = \frac{1}{\Gamma(1 - \beta \cos \theta)}. \quad (75)$$

For blazars, typically $\delta \sim 10$ [159], implying that the observed flux can be up to 1000 times greater than in the jet’s rest frame, making blazars appear much

brighter than radio galaxies at the same redshift. Finally, the effect of time-compression translates into a flux variability in the observer's frame much faster than the one in the jet's frame. The observed variability timescale ($\tau_{\text{var}}^{\text{obs}}$), conventionally defined as the flux-doubling timescale, is given by the relation $\tau_{\text{var}}^{\text{obs}} = (1+z) \tau_{\text{var}}/\delta$. For example, a flare lasting one hour in the jet's frame could appear as only a few minutes in the observer's frame.

6.1.1 Spectral Energy Distribution

Blazars usually exhibit a SED¹ with two broad components: a low-energy peak attributed to synchrotron radiation from relativistic electrons and positrons in the jet, and a high-energy peak, whose origin is under debate. In leptonic models, this high-energy emission is attributed to inverse Compton scattering by the same electron/positron population responsible for the synchrotron emission. This scattering may occur on synchrotron photons themselves, known as the synchrotron self-Compton process, detailed in the following, or on external photon fields near the black hole. While hadrons (protons and nuclei) may be present in the jet, they do not significantly contribute to the emission in leptonic scenarios. Hadronic models, by contrast, explain the high-energy component via processes involving relativistic protons, either through direct synchrotron emission or through interactions with photons that produce secondary leptons. While both leptonic and hadronic models often yield similar photon spectra, a key distinction lies in neutrino production: leptonic models do not predict neutrinos, whereas hadronic interactions do.

Observationally, gamma-ray telescopes have revealed that in FSRQs, the majority of the emitted energy lies in the gamma-ray band [160], while in BL Lacs the gamma-ray emission is comparable in power to the radio-to-X-ray synchrotron emission [161]. The peak frequencies of both SED components are highly variable across the blazar population and even within individual sources over time. FSRQs typically show their synchrotron peak in the infrared and their high-energy peak in the MeV range. BL Lacs, instead, span a broader range, with synchrotron peaks occurring anywhere from the infrared to X-rays, and corresponding high-energy peaks ranging from MeV up to TeV energies. Based on the synchrotron peak frequency $\nu_{\text{peak}}^{\text{syn}}$, BL Lacs are further classified into low-frequency-peaked BL Lacs (LBLs, $\nu_{\text{peak}}^{\text{syn}} < 10^{14}$ Hz), intermediate-frequency-peaked BL Lacs (IBLs, 10^{14} Hz $< \nu_{\text{peak}}^{\text{syn}} < 10^{15}$ Hz), and high-frequency-peaked BL Lacs (HBLs, $\nu_{\text{peak}}^{\text{syn}} > 10^{15}$ Hz). Observations from gamma-ray Cherenkov telescopes have also revealed a population of extremely high-frequency-peaked BL Lacs (EHBLs), with synchrotron peaks above 10^{18} Hz [162, 163], extending into the hard X-ray and TeV gamma-ray bands. These EHBLs appear to form a heterogeneous group, displaying all combinations of soft/hard X-ray and soft/hard TeV spectra. A notable trend observed in blazars is an anti-correlation between the SED peak frequency and the source luminosity: the brightest blazars tend to have lower $\nu_{\text{peak}}^{\text{syn}}$, while the faintest sources have the highest peak frequencies [164]. This trend defines the so-called blazar sequence, which, if confirmed as a physical relation, could provide crucial

¹ In the following, the SED is defined in the energy density representation νF_{ν} , where F_{ν} is the flux density and its units are $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$.

insights into the mechanisms shaping blazar emission. Figure 68 shows the blazar sequence as proposed by Fossati et al. ([165], hereafter F98), based on 126 blazars from one X-ray-selected and two radio-selected complete, flux-limited, samples. Only 33 were detected in the gamma-ray band by EGRET aboard the Compton Gamma Ray Observatory, representing the brightest gamma-ray blazars at the time. F98 grouped the sources, on the basis of their 5 GHz radio luminosity, into five bins and averaged their flux at selected frequencies, to construct their average SEDs. This classification was later improved by incorporating average X-ray spectral slopes, yielding a more accurate description of the high-energy component. A refined overview can be found in [166].

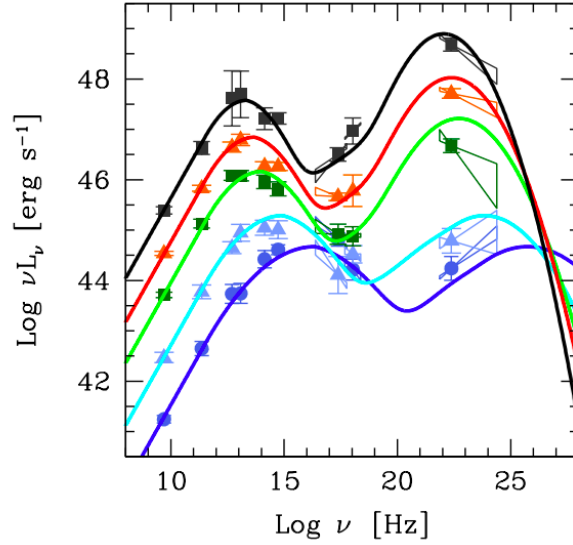


Figure 68: The blazar sequence. Black, red, green, light blue and dark blue markers indicate FSRQs, LBLs, IBLs, HBLs and HBLs/TeV blazars respectively. Overlapped curves are analytic approximations. Image from [167].

6.2 LEHA-PARIS CODE

LeHa-Paris [156] is a steady-state numerical code designed to calculate photon and neutrino emission from populations of relativistic electrons and protons in equilibrium within a spherical region, embedded in a relativistic jet. In order to study the SED of HBLs, a one-zone emission model has been adopted, assuming a spherical emitting region characterized by a radius R , a homogeneous and tangled magnetic field B , and Doppler factor δ . This region is considered solely responsible for the observed emission. An illustration of the structure of a blazar and the location of the emission region is presented in Figure 69. It is crucial to emphasize that the one-zone approach does not imply the existence of a single, fixed, radiating region within the jet. Instead, it reflects the idea that, at any given time, the blazar's emission is dominated by a single zone. Despite their simplicity, such models have proven remarkably effective in interpreting blazar emission, successfully accounting for broad-band SEDs, temporal variability and multi-wavelength correlations [168]. Alternative modeling approaches have also

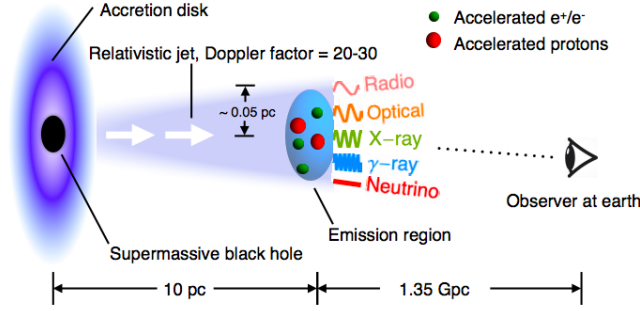


Figure 69: Illustration of the emission region of a blazar traveling at relativistic speed. Distances (not to scale) do not refer to an explicit model, but are given here only for illustration. Image from [169].

been proposed to explain hard very-high-energy (VHE) spectra, particularly those requiring high minimum electron energies. One such possibility involves external Compton (EC) models, in which relativistic electrons upscatter ambient photon fields such as those from the accretion disk, BLR or dusty torus. These EC models are generally considered applicable to FSRQs and LBLs, where external photon fields are prominent [170]. However, their relevance to HBLs, subject of this Chapter, is limited, given the lack of detectable emission from the accretion disk or BLR in these sources. Leptonic and hadronic radiative processes, simulated within the LeHa-Paris code, can be summarized as follows.

6.2.1 Leptonic processes

The leptonic component contains a stationary population of primary electrons² (or more generally, leptons), characterized by a distribution $N_e(\gamma_e)$, where $\gamma_e = E_e/(m_e c^2)$ is the electron Lorentz factor. The quantity $N_e(\gamma_e) d\gamma_e$ gives the number of electrons per unit volume within the Lorentz factor range $[\gamma_e, \gamma_e + d\gamma_e]$. Due to radiative cooling through synchrotron and inverse Compton processes, the electron energy distribution typically follows a broken power law, defined by two spectral indices, $\alpha_{e,1}$ and $\alpha_{e,2}$, three characteristic Lorentz factors $\gamma_{e,\min}$, γ_{break} , and $\gamma_{e,\max}$, and a normalization constant K_e calculated at $\gamma_e = 1$. The high-energy cutoff of the electron spectrum is modeled using an exponential suppression rather than a sharp cutoff, leading to a more realistic behavior.

Synchrotron emission, already introduced in 1.2, is computed using the full relativistic formalism, including precise integration over the pitch angle (ϕ) between the particles momentum and the magnetic field lines. The synchrotron emissivity $j(\nu)$ (defined as the energy density per unit time, volume, frequency and solid angle) is calculated as:

$$j(\nu) = \frac{1}{8\pi} \int_0^\pi d\phi \sin \phi \int_{\gamma_{e,\min}}^{\gamma_{e,\max}} d\gamma_e N_e(\gamma_e) P(\nu, \gamma_e, \phi), \quad (76)$$

² This population can also be interpreted as consisting of electrons and positrons.

where $P(\nu, \gamma_e, \varphi)$ is the single-electron power spectrum, defined as:

$$P(\nu, \gamma_e, \varphi) = \frac{\sqrt{3}e^3 B \sin \varphi}{m_e c^2} \left(\frac{\nu}{\nu_c} \right) \int_{\nu/\nu_c}^{\infty} dx K_{5/3}(x), \quad (77)$$

with $\nu_c = \frac{3eB}{4\pi m_e c} \gamma_e^2 \sin \varphi$, and $K_{5/3}(x)$ the modified Bessel function of the second kind. For computational efficiency, the integral has been pre-tabulated and interpolated. The sign of the charge does not matter: the synchrotron emission from electrons and positrons is not distinguishable since the magnetic field is tangled. Given the synchrotron emissivity, the observed νF_ν flux (in units of $\text{erg cm}^{-2} \text{s}^{-1}$) in the observer's frame is calculated as:

$$\nu F_\nu(\nu) \Big|_{\text{obs}} = \frac{\delta^4}{d_L^2} \left(\frac{4\pi R^3}{3} \right) \nu j_{\text{syn}, \nu}(\nu), \quad (78)$$

where d_L is the luminosity distance of the source.

At low frequencies, synchrotron self-absorption becomes significant: electrons can reabsorb the same photons they emit. This process is characterized by a self-absorption coefficient $\mu_{\text{syn}}(\nu)$ (in cm^{-1}), which is calculated via integration over the electron distribution and the emitted synchrotron power. This absorption alters the synchrotron spectrum at low frequencies. Below the self-absorption frequency $\nu_{\text{self-abs}}$, the source becomes optically thick, and the flux density scales as $\nu^{5/2}$ instead of following the intrinsic electron distribution. As a result, a single emitting region cannot reproduce the radio part of blazar SEDs, which requires optically thin emission, and one-zone models typically treat the radio flux as an upper limit during SED fitting. The radio flux must therefore originate from other, spatially distinct regions in the jet that are transparent to synchrotron radiation.

As mentioned in Chapter 1, the inverse-Compton (IC) scattering considers a high-energy electron that interacts with a low-energy photon, and transfers part of its energy to it. The IC scattering is a very efficient process to produce X-ray and gamma-ray photons in astrophysical sources starting from low-energy photon fields. Its expression accurately takes into account both the Thomson and Klein-Nishina regimes [171]. For isotropic distributions of both electrons ($N_e(\gamma_e)$) and photons (n_{ph}), the inverse Compton emissivity can be written as:

$$j_{\text{IC}}(\nu) = \frac{h^2 \nu}{4\pi m_e c^2} \int d\epsilon n_{\text{ph}}(\epsilon) \int d\gamma_e N_e(\gamma_e) C(\epsilon, \gamma_e, \nu), \quad (79)$$

where $C(\epsilon, \gamma_e, \nu)$ is the Compton kernel that describes the probability of scattering a photon of energy ϵ by an electron of energy γ_e into a photon of frequency ν . Going back to the spheroidal plasmoid, it is natural that the synchrotron photons will suffer IC scattering over the same electrons population that produced them, leading to a synchrotron-self-Compton (SSC) component.

Internal $\gamma\gamma$ absorption ($\gamma\gamma \rightarrow e^+e^-$), due to interactions between high-energy photons and the internal synchrotron photon field, is also included. The code also accounts for the secondary leptons produced via internal $\gamma\gamma$ pair production.

Their injection rate $Q_e(\gamma_e)$, describing the number of pairs injected per unit time and volume, is calculated and used as a source term in the continuity equation:

$$\frac{\partial N_e(\gamma_e, t)}{\partial t} = \frac{\partial}{\partial \gamma_e} \left[\frac{\gamma_e N_e(\gamma_e, t)}{\tau_c(\gamma_e)} \right] + Q_e(\gamma_e) - \frac{N_e(\gamma_e, t)}{\tau_{\text{ad}}}, \quad (80)$$

where $\tau_{\text{ad}} = R/c$ is the adiabatic timescale, and $\tau_c(\gamma_e)$ is the radiative cooling timescale, which includes both synchrotron and inverse Compton losses:

$$\tau_c(\gamma_e) = \frac{3m_e c}{4\sigma_T \gamma_e (u_B + u_{\text{soft}})}, \quad (81)$$

with u_B and u_{soft} being the energy densities of the magnetic field and soft (synchrotron) photons, respectively and σ_T the Thomson cross-section. The steady-state distribution $N_e(\gamma_e)$ is obtained analytically:

$$N_e(\gamma_e) = \frac{e^{-\gamma^*/\gamma_e} \gamma^* \tau_{\text{ad}}}{\gamma_e^2} \int_{\gamma_e}^{\infty} d\zeta Q_e(\zeta) e^{\gamma^*/\zeta}, \quad (82)$$

where the critical Lorentz factor γ^* satisfies $\tau_c(\gamma^*) = \tau_{\text{ad}}$ and is given by:

$$\gamma^* = \frac{3m_e c^2}{8\sigma_T R (u_B + u_{\text{soft}})}. \quad (83)$$

Finally, absorption of high-energy photons due to the extragalactic background light (EBL) is included using a model consistent with current VHE observations (see 1.4.4). This attenuation is applied to the emitted spectra to simulate the effects of photon propagation through intergalactic space.

6.2.2 Hadronic processes

In the framework of hadronic models, relativistic protons are assumed to be co-accelerated with electrons in the emitting region of the jet. In analogy with the electron population, the proton distribution $N_p(\gamma_p = E_p/m_p c^2)$ is described by a power law function, with indexes $\alpha_{p,1}$ and $\alpha_{p,2}$, if broken. The normalization of the proton spectrum is $K_p = \eta K_e$, where the η factor represents the ratio between the number density of protons and electrons at $\gamma_p = \gamma_e = 1$.

Relativistic protons in strong magnetic fields can emit synchrotron radiation, although due to their much larger mass compared to electrons, this emission requires either extremely high Lorentz factors or intense magnetic fields to be efficient. The synchrotron power emitted by each proton is computed with the same formalism used for electrons, replacing the relevant physical constants. Because of the slower synchrotron cooling time for protons, the maximum energy that they can reach is typically limited by the adiabatic escape time of the region rather than by radiative losses. Proton synchrotron emission often contributes to the high-energy component of the SED, and in some extreme cases may explain the entire gamma-ray output of the source [159].

Beyond synchrotron emission, high-energy protons may interact with internal synchrotron photons via photo-meson production (see 1.2.1):

$$p + \gamma \rightarrow \pi^0 + p', \quad p + \gamma \rightarrow \pi^+ + \pi^- + p', \quad p + \gamma \rightarrow \pi^+ + n. \quad (84)$$

The photo-meson cross-section is dominated by resonances, direct pion production and multiple pion production [172]. Primarily, π^0 decays into gamma-rays and $\pi^\pm$ decay into muons and neutrinos. $\mu^\pm$ further decay into electrons/positrons and neutrinos. These secondary electrons and positrons, along with the gamma-rays from π^0 decay, initiate electromagnetic cascades in the emitting region, contributing significantly to the radiative output across a broad energy range. Their energy losses due to synchrotron radiation and IC scattering are treated by solving the relevant transport equations. Specifically, the stationary state of the electromagnetic cascade is evaluated iteratively. The first generation of electron-positron pairs injected into the emitting region is treated analogously to the primary leptonic component: compute their injection rate, determine their stationary energy distribution and evaluate their synchrotron emission. However, in this case, the synchrotron photons produced by these secondary pairs are still energetic enough to interact with the ambient photon field and produce a second generation of pairs. This process can repeat multiple times, with each generation potentially initiating the next. The iteration continues until the contribution of the i -th generation becomes negligible compared to the sum of the previous ones. Computationally, the energy distributions of secondary particles injected via photo-meson interactions are derived by running the Monte Carlo (MC) code SOPHIA [173], which has been modified to accept arbitrary target photon fields, extract muon spectra, and include synchrotron cooling of kaons, pions and muons. These outputs serve as injection terms to compute the steady-state distributions of secondary particles. Photon and neutrino spectra are obtained by multiplying their injection rates by their respective escape timescales.

Another significant radiative process from $p\gamma$ interactions is the synchrotron emission by muons ($\mu^\pm$). Although unstable, muons can survive long enough in the jet environment to radiate appreciable synchrotron emission before decaying into electrons and positrons. This radiation emerges as an additional high-energy component, often peaking in the TeV range, and in some parts of the parameter space, it may dominate the emission in this band. To properly account for this contribution, the equilibrium energy distribution of muons must be computed by modifying the standard transport equation to include the decay term. Specifically, the muon continuity equation includes an additional decay timescale $\tau_{\text{dec}} \approx 2.2 \times 10^{-6}$ s, yielding:

$$\frac{\partial}{\partial t} N_\mu(\gamma_\mu, t) = \frac{\partial}{\partial \gamma_\mu} \left[\gamma_\mu \frac{N_\mu(\gamma_\mu, t)}{\tau_{\text{syn}}(\gamma_\mu)} \right] - \frac{N_\mu(\gamma_\mu, t)}{\tau_{\text{ad}}} - \frac{N_\mu(\gamma_\mu, t)}{\gamma_\mu \tau_{\text{dec}}} + Q_\mu(\gamma_\mu, t), \quad (85)$$

where $Q_\mu(\gamma_\mu, t)$ is the muon injection term, typically obtained from SOPHIA.

The ultimate key process is the Bethe-Heitler (BH) pair production:

$$p + \gamma \rightarrow p' + e^+ + e^-, \quad (86)$$

which competes with photo-meson production at lower proton energies. The threshold energy for BH production is lower than photo-meson by a factor $\sim m_e/m_\pi \approx 0.004$, meaning it can occur for protons with Lorentz factors $\gamma_p > 10^5$ scattering off UV photons (~ 10 eV). Although less efficient in terms of energy transfer per interaction, BH pair production can dominate the energy losses for lower-energy protons and produce a population of secondary $e^\pm$ with lower energies compared to those from photo-meson decays. These pairs then contribute to the total synchrotron and IC emission and may also initiate electromagnetic cascades if the photon field is dense enough. The BH pair injection spectrum can be calculated analytically or via MC methods. Regardless of their origin, all leptonic secondaries in the emitting region are subsequently evolved under the same framework as primary electrons.

6.2.3 Physical constraints

Hadronic models, while energetically more demanding, offer natural explanations for VHE spectral components and the potential production of high-energy neutrinos, thus linking blazar observations with neutrino astronomy. Nevertheless, some physical constraints need to be taken into account:

- proton-proton interactions, where, as with the photo-meson production, a highly relativistic proton interacts with a target low-energy proton, are usually a subdominant contribution in SMBHs jets because of the expected low proton densities;
- the minimum proton Lorentz factor, fixed at $\gamma_{p,\min} = 1$, does not influence the modeling results as long as it remains sufficiently low, but it does impact the total energy density in the emitting region, especially for proton spectral slopes softer than 2. Conversely, the maximum Lorentz factor $\gamma_{p,\max}$ is constrained by the competition between the acceleration and cooling timescales. Assuming diffusive shock acceleration, the acceleration timescale is given, in Gauss units, by:

$$\tau_{\text{acc}} = \frac{1}{\psi} \frac{m_p c}{eB} \gamma_p, \quad (87)$$

where ψ is the acceleration efficiency (typically fixed at 10). The maximum energy is set by equating $\tau_{\text{acc}}(\gamma_{p,\max})$ with the shortest among the cooling timescales: adiabatic losses ($\tau_{\text{ad}} = R/c$), synchrotron losses (τ_{syn}), and photo-meson losses (τ_{pm}), so that: $\tau_{\text{acc}}(\gamma_{p,\max}) = \min [\tau_{\text{ad}}, \tau_{\text{syn}}(\gamma_{p,\max}), \tau_{\text{pm}}(\gamma_{p,\max})]$;

- an additional physical constraint on the maximum proton energy might seem to come from the requirement that the proton gyroradius remains smaller than the size of the emitting region. If a proton's gyroradius exceeds the blob radius R , the particle would escape the region, rendering a stationary emission model inapplicable. The gyroradius of a relativistic charged particle is expressed, in Gauss units, by:

$$R_{\text{gyro}} = \frac{m_p c^2}{eB} \gamma_p. \quad (88)$$

If $\gamma_{p,\max}$ is set by equating acceleration and cooling timescales, as discussed above, R_{gyro} is typically smaller than R , i.e. even the most energetic protons are confined in the blob;

- an essential aspect of any radiative model is its energy budget. The total jet power, expressed in erg s^{-1} , can be written as a function of the energy densities as:

$$L_{\text{jet}} = 2\pi R^2 c \Gamma^2 (u_B + u_e + u_p + u_{\text{ph}}), \quad (89)$$

where u_B , u_e , u_p and u_{ph} are the magnetic, electron, proton and photon energy densities, respectively, in the comoving frame. The factor of 2 accounts for the presence of two jets. Although pure hadronic (i.e., proton-synchrotron) models can successfully reproduce the SEDs of blazars [159], they may require extremely high proton densities. As a result, the inferred luminosity often approaches or even exceeds the Eddington luminosity (L_{Edd})³ of the black hole, challenging the physical plausibility of such models. Lepto-hadronic solutions also face energetic issues: the required jet power can quickly become very high. A possible way-out is to use as target photon field not the electron synchrotron radiation, but external photons.

It is finally worth to mention that, in recent efforts [174], the LeHa-Paris code was compared against multiple independent hadronic blazar codes, including AM³, B13, ATHEvA and LeHaMoC. These comparisons demonstrated close agreement in the shapes of photon and neutrino spectra, proving that the results are independent from the specific radiative code used in the simulation. Absolute flux normalizations differed by up to $\sim 40\%$, consistent with implementation-dependent variations in interaction cross sections and particle tracking schemes.

6.3 THE CASE OF PKS 2155–304

The first step of this work consisted in optimizing the parameters of the LeHa-Paris code for a source selected as representative of a subclass of blazars. Specifically, the source PKS 2155–304 was chosen as a candidate representative of the HBL subclass, as it is the most luminous HBL of the Southern Sky observed in gamma rays, also exhibiting a remarkable TeV emission in 2006, as reported by H.E.S.S. [175]. In addition, joint NuSTAR and XMM-Newton observations have revealed the presence of a hard X-ray tail (Figure 70) that cannot be readily explained within pure leptonic emission scenarios, thereby increasing the interest in its lepto-hadronic modeling. The approach outlined allows the derivation of a neutrino template which, once extended to the entire subset of HBLs, enables a stacking analysis to be performed using KM3NeT/ARCA data, following the methodology that will be outlined in Chapter 7.

PKS 2155–304, located at redshift $z = 0.117$, at right ascension $21^{\text{h}}58^{\text{m}}52.0^{\text{s}}$ and declination $-30^{\circ}13'32''$, is a well-known object, classified as an HBL, located in

³ The Eddington luminosity is defined as $L_{\text{Edd}} = \frac{4\pi G M c}{\kappa}$, with G the gravitational constant, M the black-hole mass, and κ the opacity. For a SMBH of mass $M_{\text{BH}} = 10^9 M_{\odot}$, $L_{\text{Edd}} \simeq 10^{47} \text{ erg s}^{-1}$.

the Southern Sky. PKS 2155-304 has been the focus of extensive studies, with several authors noting potential contamination of the hard X-ray spectra by a high-energy component, referred to as the hard tail [176]. However, the absence of VHE data during these studies limited constraints on the VHE gamma-ray flux. A previous multi-wavelength campaign [177], using X-ray instruments, Fermi-LAT and H.E.S.S., successfully modeled data in both leptonic and lepto-hadronic scenarios. Then, a more comprehensive campaign was conducted from June to October 2013, involving NuSTAR, XMM-Newton, H.E.S.S., the Swift Observatory and Fermi-LAT [178]. For the first time, contemporaneous observations across a broad energy spectrum, from ultraviolet to TeV photons, provided improved X-ray and gamma-rays coverage compared to previous campaigns. Multi-wavelength data from the 2013 campaign have been used to study source variability and X-ray spectra, exploring lepto-hadronic modeling scenarios for the neutrino emission and investigating the low-state emission period of the source. Figure 70 shows the multi-wavelength observation of PKS 2155-304 including contemporaneous data from Fermi-LAT, obtained over 10 days centered on the NuSTAR observation. Swift/UVOT fluxes are also reported. At first glance, the first peak of the SED is visible and the NuSTAR data appear to belong to its descent, while Fermi/LAT data are expected to belong to the second peak of the SED.

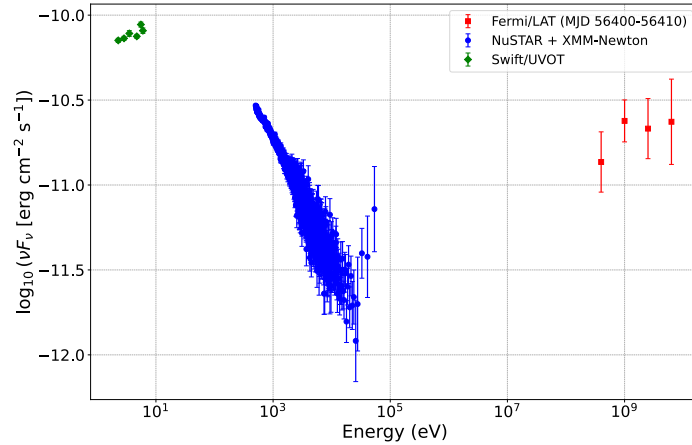


Figure 70: Multi-wavelength observations of PKS 2155-304 combining data from Swift/UVOT, NuSTAR + XMM-Newton and Fermi/LAT. Data are taken from [176] and correspond to a low-state emission period of the source.

To initiate the parameter-space exploration, the SED of PKS 2155-304 has been modeled using the parameter values reported in [178]. That work investigated whether the multi-wavelength data, spanning UV to TeV energies in different epochs, collected by several instruments, could be explained by the presence of a sub-dominant hadronic component in the blazar SED. The main parameters adopted in this preliminary modeling, for the so-called epoch 0, are listed in Table 1. The corresponding SED is shown in Figure 71, where the hadronic emission is dominated in the X-ray band as emission from BH pairs and the $\text{p}\gamma$ cascade emerges at VHE. On the basis of such parameters, Figure 72 shows the $\text{dN}/\text{d}\gamma$ distributions for primary electrons and protons. Minimum and maximum Lorentz factors of the primary electrons energy distribution correspond to $\gamma_{e,\text{min}} = 2 \cdot 10^3$

$K_e [\text{cm}^{-3}]$	$\log_{10}(\gamma_p^{\text{max}})$	η	α_p	$\alpha_{e,1}$	$\alpha_{e,2}$	$B [\text{G}]$	$R [\text{cm}]$	γ_{break}
$2.1 \cdot 10^4$	8.0	0.01	2.0	2.5	4.6	0.042	$5.9 \cdot 10^{16}$	$5.5 \cdot 10^4$

Table 1: Parameters of the lepto-hadronic model for PKS 2155-304, as described in [178], include: electron normalization K_e ; maximum proton Lorentz factor γ_p^{max} ; proton-to-electron ratio η ; proton spectral index α_p ; electron spectral indices $\alpha_{e,1}$ and $\alpha_{e,2}$; magnetic field B ; emission region size R ; and electron break energy γ_{break} .

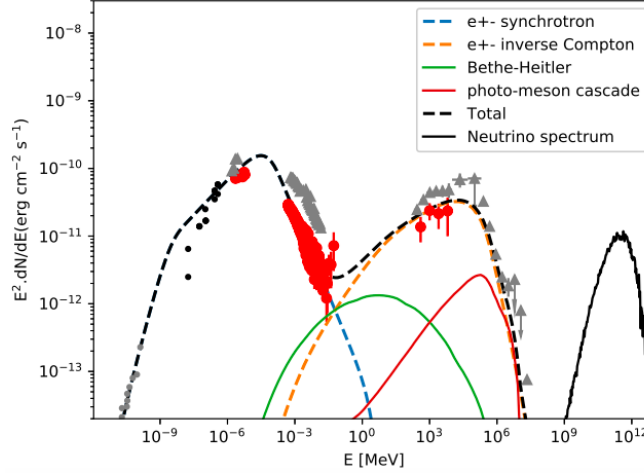


Figure 71: SED of PKS 2155-304 for the epoch 0 considered in the study of [178]. Red points are the data already shown in Figure 70, which will be the subject of this work. Black points are radio data, while gray points are the data from the 2008 campaign [179], shown for comparison. The black continuous line is the neutrino spectrum modeled in [178]. Image from [178].

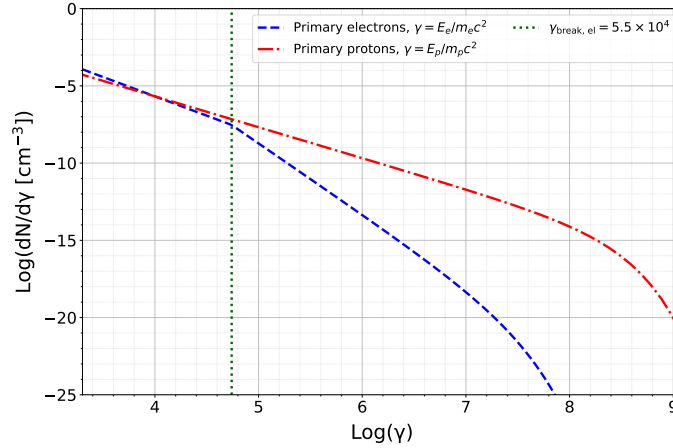


Figure 72: $dN/d\gamma$ distributions of the primary populations of electrons (dashed blue) and protons (dashed red), adopting the parameters of [178]. Vertical dashed green line corresponds to γ_{break} .

and $\gamma_{e,\text{max}} = 10^7$, while their break happens at $\gamma_{\text{break}} = 5.5 \times 10^4$. In contrast, the proton distribution exhibits no such break, as their synchrotron cooling time, scaling with the particle's mass, is significantly longer, pushing the expected break

to much higher energies than those explored in this model, which extends up to $\gamma_p = 10^8$. Then, protons follow a standard E^{-2} power-law distribution, consistent with Fermi acceleration mechanisms. Additional physical constraints are illustrated in Figure 73, which presents the relevant timescales of the processes under consideration, as a function of $\log(\gamma)$. Photo-meson and BH interaction timescales are also reported. The maximum allowed proton Lorentz factor γ_p , defined by the condition $R_{\text{gyro}} \equiv R$, is also shown, while a scaling factor $\psi = 10$ is adopted in Equation 87.

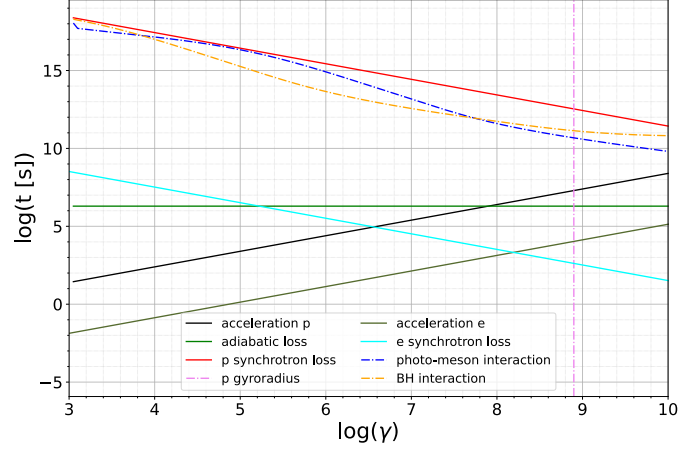


Figure 73: Timescales of the processes involving protons and electrons, as a function of $\log(\gamma)$, calculated according to Section 6.2 and adopting parameters from [178].

Furthermore, through the model optimization procedure, a Doppler factor $\delta = 33$ [178] and a line-of-sight angle 0.1° are assumed⁴, implying a bulk Lorentz factor $\Gamma \sim 16$ for the emitting region. Figure 74 shows the Doppler factor as a function of the line-of-sight angle θ , assuming $\Gamma = 16$ and a factor β of 0.998. Lastly, the electron parameters $\alpha_{e,1}$, $\alpha_{e,2}$, $\gamma_{e,\min}$ and $\gamma_{e,\max}$ are not subject to optimization and are fixed to the values used to produce the distributions of Figure 72.

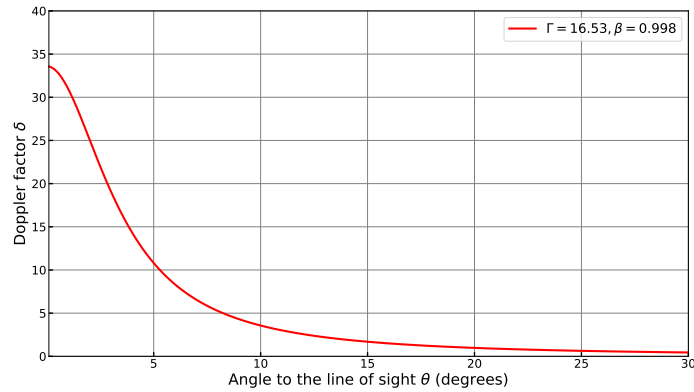


Figure 74: Doppler factor δ as a function of the line-of-sight angle θ , assuming a bulk Lorentz factor $\Gamma = 16.53$ and corresponding to a velocity $\beta = 0.998$.

⁴ Blazars with small jet viewing angles may resolve the longstanding discrepancy between Doppler factors inferred from VLBI and VHE observations, as reported in [180]. Nevertheless, the viewing angle is not a free parameter in the model.

6.3.1 Model optimization

To determine the best-fit LeHa-Paris parameters reproducing the low-state observations, a χ^2 optimization was performed, exploring the parameter space of the electron normalization K_e at $\gamma_e = 1$, the proton-to-electron ratio at Lorentz factor $\gamma_p = \gamma_e = \gamma = 1$ (η), the proton spectral index α_p of the unbroken proton energy distribution, the proton normalization at $\gamma_p^* = 10^4$ (K_p^*), the emission region size R , the magnetic field B , the electron energy break γ_{break} and the maximum proton energy, expressed via γ_p^{max} . Parameters of Table 1 are used as starting points in the optimization procedure. Optimizing over K_p^* rather than the proton normalization at $\gamma_p = 1$ enables effective exploration of different α_p , since low-energy protons minimally affect BH or photo-meson processes. K_p^* at $\gamma_p^* = 10^4$ better constrains the high-energy proton distribution, with the relation:

$$K_p(\gamma_p^*) = \eta(\gamma = 1) K_e(\gamma_e = 1) (\gamma_p^*)^{-\alpha_p}, \quad (90)$$

allowing retrieval of $\eta(\gamma = 1)$ from K_p^* . The normalization K_p^* increases for lower values of γ_p^{max} , as a less extended proton energy distribution requires a higher normalization to satisfy observational constraints. To avoid exploring vast parameter spaces repeatedly, specific ranges for K_p^* have been defined depending on the γ_p^{max} under study, as detailed in Table 2. α_p values have been explored dis-

$\log_{10} \gamma_p^{\text{max}}$	Range of K_p^*
5.0	$[K_p^* \times 10^{3.2}, K_p^* \times 10^{3.6}]$
5.6	$[K_p^* \times 10^{1.8}, K_p^* \times 10^{2.2}]$
6.2	$[K_p^* \times 10^{1.0}, K_p^* \times 10^{1.4}]$
6.8	$[K_p^* \times 10^{0.2}, K_p^* \times 10^{0.6}]$
7.4	$[K_p^* \times 10^{-0.2}, K_p^* \times 10^{0.2}]$
8.0	$[K_p^* \times 10^{-0.6}, K_p^* \times 10^{-0.2}]$

Table 2: Ranges of the proton normalization K_p^* for each value of $\log_{10} \gamma_p^{\text{max}}$.

cretely as $\{1.8, 2.0, 2.2\}$, while the other parameters are sampled on a grid of 6 equally spaced points within the following ranges: $\log_{10} \gamma_p^{\text{max}} \in [5, 8]$, $K_e(\gamma_e = 1) \in [10^{3.7}, 10^{4.7}] \text{ cm}^{-3}$, $B \in [9 \times 10^{-3}, 5 \times 10^{-2}] \text{ G}$, $R \in [10^{16.5}, 10^{17}] \text{ cm}$, and $\gamma_{\text{break}} \in [10^{4.6}, 10^{5.1}]$. Such choice of tested values results in 139968 scenarios, all of which have been explored. Their models have been compared to the observed electromagnetic SED through a χ^2 statistic, calculated as:

$$\chi^2 = \sum_{i=1}^N \frac{(y_i - f(x_i, \theta))^2}{\sigma_i^2}, \quad (91)$$

where N is the number of data points with coordinates (x_i, y_i) and variance σ_i^2 ; f is the model under study. A reduced χ^2 has then been calculated as $\chi^2/(N - 1)$. The best-fit solutions minimize the reduced χ^2 while also satisfying additional physical constraints. In particular, as said before, the radio data serve as a strong

upper limit, and any models that exceed this constraint are discarded. Furthermore, among the acceptable solutions, preference is given to those that minimize the total jet luminosity, mostly driven by the luminosity in protons (Equation 89). After computing the χ^2 grid for all parameters combinations, for each fixed $\gamma_p^{\max}$, the solution with the lowest reduced χ^2 was selected. Figure 75 shows the proton luminosity (L_p) as a function of $\log(\gamma_p^{\max})$, computed by LeHa-Paris for the models corresponding, at such fixed value of $\gamma_p^{\max}$, to the lowest reduced χ^2 . Solutions at

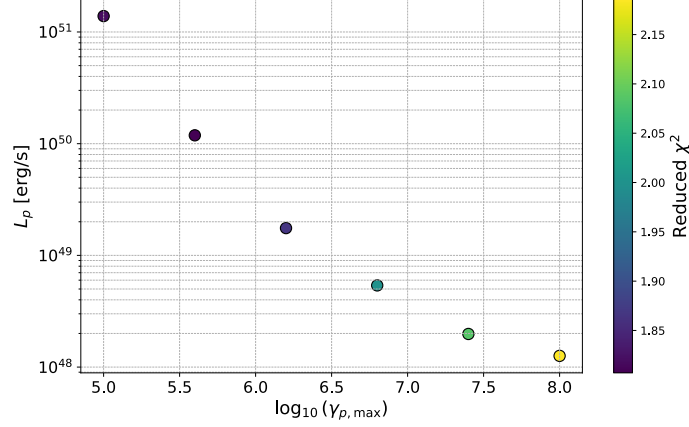


Figure 75: Proton luminosity computed with LeHa-Paris as a function of $\log(\gamma_p^{\max})$. Each point corresponds to the model with the lowest reduced χ^2 at that value of $\gamma_p^{\max}$, and is color-coded by its numerical value.

the lowest values of $\gamma_p^{\max}$, despite being better in terms of χ^2 , violate the radio upper limit. The solutions corresponding to the two highest values of $\gamma_p^{\max}$, instead, have similar energy budgets ($1.9 \cdot 10^{48}$ erg/s and $1.3 \cdot 10^{48}$ erg/s respectively), and the lowest jet power in the sample. As introduced in 6.2 and well known in blazar hadronic modeling, the total power required to produce the observed emission is a critical parameter, as it can easily exceed the Eddington luminosity of the black hole by orders of magnitude. In this case, the solutions with the lowest proton power are still super-Eddington, but remain within a factor of around 10. Among these two solutions, the one at the lowest reduced χ^2 has been selected as optimal solution. The best-fit parameters are reported in Table 3, corresponding to a reduced χ^2 of about 2.1, an improvement over the initial value of 4.1 obtained with the parameters of Table 1. As an example, Figures 76 and 77 display the χ^2 minimization grids for two pairs of parameters: B–R and R– γ_{break} . These grids illustrate how the reduced χ^2 value varies across different regions of the probed parameter space, with the minimum clearly identifiable. All parameters other than those shown are fixed at their best-fit values (see Table 3).

$K_e [\text{cm}^{-3}]$	$\log_{10}(\gamma_p^{\max})$	η	α_p	$K_p^* [\text{cm}^{-3}]$	B [G]	R [cm]	γ_{break}
$1.3 \cdot 10^4$	7.4	0.003	1.8	$2.3 \cdot 10^{-6}$	0.036	$7.9 \cdot 10^{16}$	$6.3 \cdot 10^4$

Table 3: Parameters of the best-fit model for PKS 2155-304.

Figure 78 reports the SED modeled with the best-fit parameters. The optimal solution requires an acceleration mechanism for the protons with an $E^{-1.8}$ spectrum,

while the resulting size of the emitting region is larger with respect to what was claimed in [178], with a less intense magnetic field. The γ_{break} value reflects the position of the first bump of the SED, which is once again well explained by synchrotron emission from the primary electrons population. As found in previous studies [181], the best-fit scenario is a lepto-hadronic scenario where the BH pair production processes are responsible for the transition between the two bumps of the SED. The hadronic contribution emerges also as the synchrotron radiation from the primary protons and from the cascades initiated by $\pi^\pm$ and π^0 decays. All the other radiation components are subdominant. The SED of the expected all-flavor neutrino flux exhibits a peak at the level of 100 PeV.

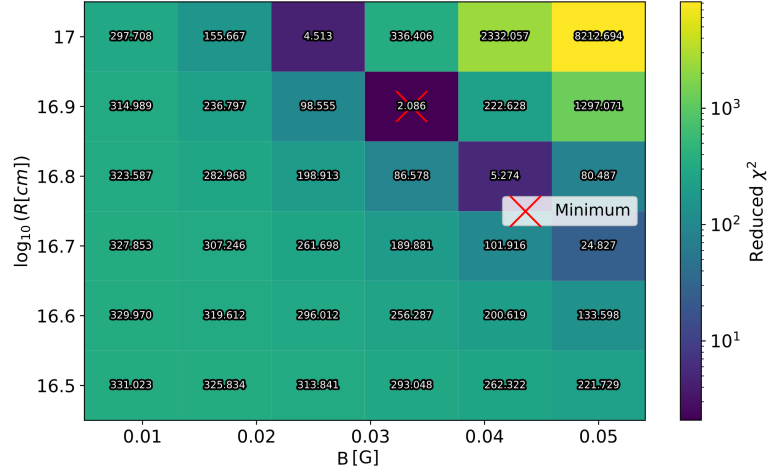


Figure 76: χ^2 minimization grid in the B-R parameter plane. The color map indicates the reduced χ^2 value for each parameter combination, with the minimum (red cross) corresponding to the best-fit region. All parameters other than those shown are fixed at their best-fit values (Table 3).

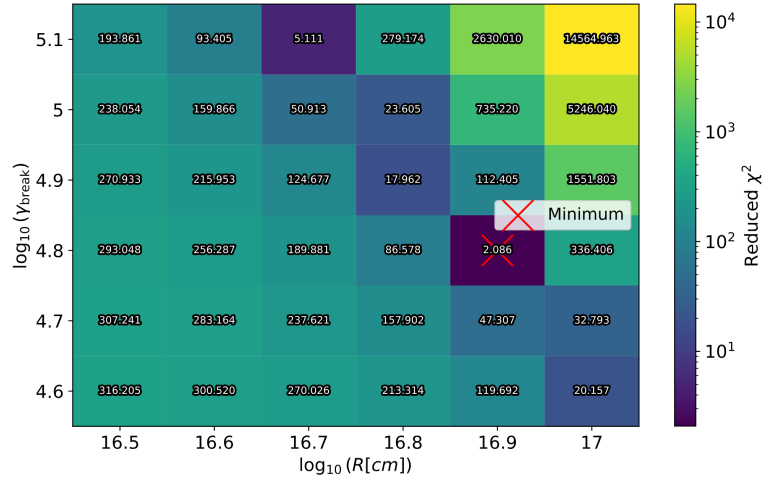


Figure 77: χ^2 minimization grid in the γ_{break} -R parameter plane. The color map indicates the reduced χ^2 value for each parameter combination, with the minimum (red cross) corresponding to the best-fit region. All parameters other than those shown are fixed at their best-fit values (Table 3).

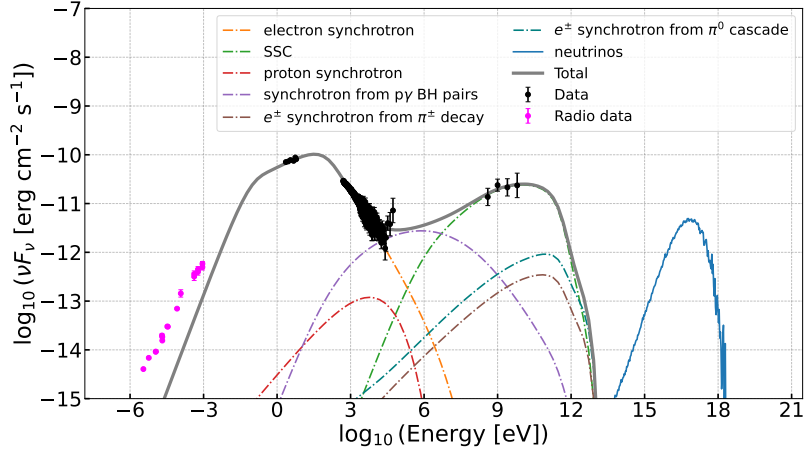


Figure 78: SED of PKS 2155-304 for the best-fit model, compared to data from [176]. Associated parameters are reported in Table 3. Radiation components not shown in the plot are subdominant. The blue continuum is the predicted all-flavor neutrino SED.

6.3.2 Neutrino flux

Inside the 68% C.L. intervals from the χ^2 best-fit solution, there is only one extra solution which shares the same parameters of the previous one, except in the value of the normalization of K_p^* , corresponding to $1.9 \cdot 10^{-6} \text{ cm}^{-3}$. The ratio of their respective all-flavors neutrino templates is compatible with 1 and solutions can be considered equivalent. The one corresponding to the solid blue line of Figure 78 has been chosen as best-fit neutrino template after the PKS 2155-304 optimization procedure. To make such flux suitable for the astronomy studies with KM3NeT/ARCA's data, it has been rescaled accounting for neutrinos and antineutrinos separation, as well as their mixed flavor composition at Earth, due to neutrino oscillations over cosmic distances ($\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$). The single-flavor differential neutrino flux from PKS 2155-304, in units of $\text{GeV}^{-1} \text{m}^{-2} \text{s}^{-1}$, as a function of the neutrino energy, is reported in Figure 79. The considered energy range on the x-axis goes from 10^2 GeV to 10^8 GeV , which is the one for which the design of KM3NeT/ARCA has been optimized.

6.4 EXTENSION TO ASTROPHYSICAL CATALOGUES

After optimizing the LeHa-Paris parameters, the best-fit flux derived for PKS 2155-304 has been extended to an astrophysical catalogue of blazars. In particular, this work focuses on the 3HSP catalogue, which represents the largest sample of High Synchrotron Peaked (HSP) blazars ($\nu_{\text{peak}}^{\text{syn}} > 10^{15} \text{ Hz}$) and Extreme blazars as of today. It includes 2013 sources, surpassing previous compilations such as the 2WHSP sample [182], which contained 1691 sources. Approximately 88% of the sources have redshift estimates, a significantly higher fraction than in earlier catalogues. The 3HSP catalogue incorporates new gamma-ray detections from the First and Second Brazil ICRANet Gamma-ray Blazar catalogues (1BIGB [183] & 2BIGB [184]), considers associations with the Fermi-LAT 4FGL catalogue [48] and

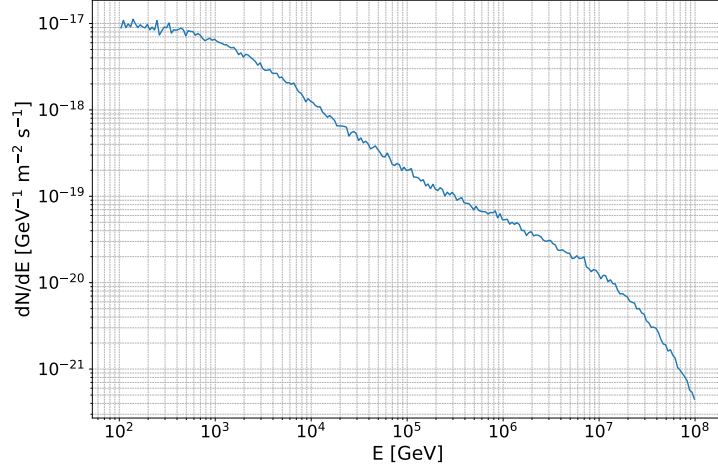


Figure 79: Best-fit single-flavor neutrino flux from PKS 2155–304, derived with the LeHa-Paris code, as a function of the neutrino energy, between 10^2 GeV and 10^8 GeV.

cross-matches with IceCube neutrino detections. Each source in the catalogue is identified by a unique designation in the format 3HSPJHHMMSS.s+DDMMSS. Celestial coordinates are provided as right ascension and declination in the J2000 reference frame and expressed in decimal degrees. A source classification flag indicates the nature or reliability of the identification, and, when available, the corresponding counterpart in the BZCat blazar catalogue [114] is listed for cross-referencing. Key synchrotron peak parameters are provided: the logarithm of the peak frequency (in Hz) and the logarithm of the corresponding synchrotron peak flux ($vF_{\gamma, \text{peak}}$, in $\text{erg cm}^{-2} \text{s}^{-1}$). Another flag denotes the quality of the synchrotron peak estimate. The information of the measured redshift (z), crucial for this work, is included when known, along with a flag (f_z) indicating the origin or reliability of the measurement. Gamma-ray counterparts from Fermi observations are also listed and a Figure of Merit (FOM)⁵ is assigned to each source. Additionally, when applicable, the previous 2WHSP counterpart is reported.

In view of a prospective stacking analysis, sources were selected according to the following criteria: requiring a secure source identification; a firm redshift measurement; a declination less than 40 degrees, to account for KM₃NeT/ARCA’s visibility; and a synchrotron peak frequency in the range $15.0 < \log(v_{\text{peak}}^{\text{syn}}/\text{Hz}) < 16.8$. This frequency range was adopted in line with the standard definition of HBLs. These selection criteria resulted in 232 selected HBLs, whose distribution in the sky is shown in Figure 80. Figures 81 and 82, instead, show the distribution of $\log(v_{\text{peak}}^{\text{syn}}/\text{Hz})$ and measured z for the HBLs sources under consideration. The only source at redshift $z > 1$ is 3HSPJ025038.0+171208, with $z = 1.1$. To better assess any potential dependence of the synchrotron peak parameters on the catalogue variables, Figure 83 displays the measured synchrotron peak flux as a function of the respective peak frequency for each source. The class of Extreme HBLs (EHBLs) is also shown for comparison. Furthermore, Figure 84 presents the synchrotron peak frequency as a function of the measured redshift, considering only the HBLs

⁵ The FOM is a dimensionless parameter that quantifies the detectability of HSP blazars in the TeV gamma-ray band. It is defined as the ratio of the flux at the synchrotron peak of a given source to the peak flux of the faintest blazar detected in the TeV band, based on earlier catalogues.

selected in this work. No evident correlation can be observed in both plots. A list detailing the properties of the studied sources is provided in Appendix B.

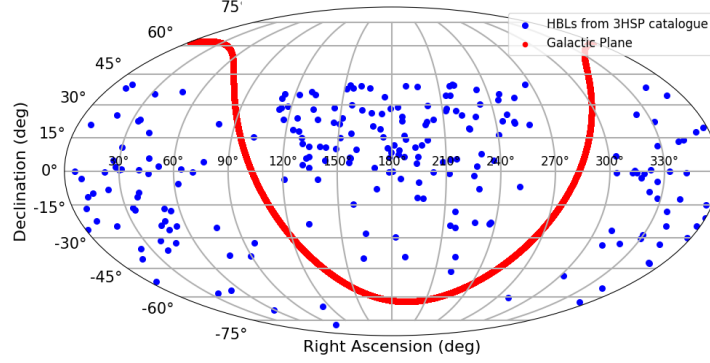


Figure 80: Sky map in equatorial coordinates showing the selected HBLs sources from the 3HSP catalogue. A total of 232 sources satisfy the selection criteria. The Galactic Plane is indicated in red.

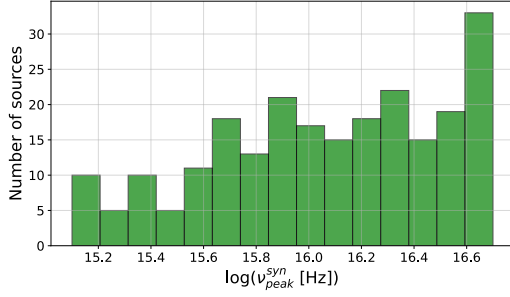


Figure 81: Distribution of the logarithm of $\nu_{\text{peak}}^{\text{syn}}$ [Hz] for the sources selected in this study.

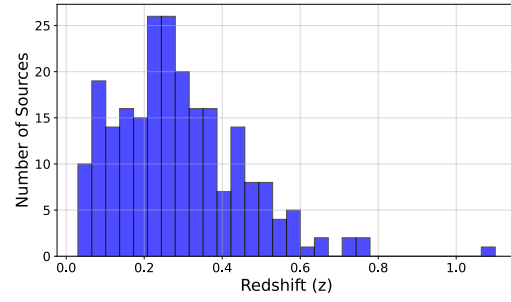


Figure 82: Distribution of the measured redshift z for the sources selected in this study.

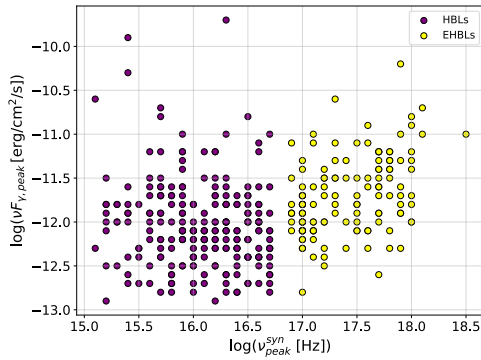


Figure 83: Logarithm of the synchrotron peak flux as a function of $\log(\nu_{\text{peak}}^{\text{syn}} [\text{Hz}])$ for the selected HBLs (violet dots), in comparison with EHBs (yellow dots).

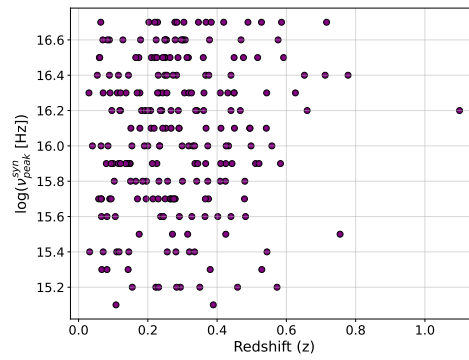


Figure 84: Logarithm of the synchrotron peak frequency, $\log(\nu_{\text{peak}}^{\text{syn}} [\text{Hz}])$, as a function of their measured redshift (z) for the HBLs selected in this work.

6.4.1 Derivation of neutrino fluxes

As explained before, the aim of this study is to adopt, for each source in the selected sample, a physically motivated neutrino template, by extending the neutrino flux optimization done on PKS 2155-304. These fluxes will be used in the stacking analysis presented in Chapter 7. Rather than re-optimizing the model parameters for each individual selected HBL from the 3HSP catalogue, the expected neutrino flux is obtained by rescaling the neutrino best-fit flux of PKS 2155-304 according to source-specific observables reported in the catalogue itself, thereby making the model predictive for a larger population. In particular, to rescale the neutrino flux from a reference blazar at redshift z and synchrotron peak flux $F_{\gamma,\text{peak}}$ to a target source with redshift z' and flux $F'_{\gamma,\text{peak}}$, the following relations are used:

- **energy scaling:** due to the cosmological expansion of the Universe, the observed frequency is related to the emitted frequency through the redshift:

$$\nu_{\text{obs}} = \frac{\nu_{\text{em}}}{1+z}. \quad (92)$$

For a second blazar at redshift z' , the observed frequency is:

$$\nu'_{\text{obs}} = \frac{\nu_{\text{em}}}{1+z'}. \quad (93)$$

Matching the intrinsic emitted frequencies, $\nu_{\text{em}} = \nu_{\text{obs}}(1+z)$, the observed frequency (ν'_{obs}) transforms as:

$$\nu'_{\text{obs}} = \nu_{\text{obs}} \frac{1+z}{1+z'}, \quad (94)$$

which is then translated into an energy via the Planck constant ($E = h\nu$);

- **flux scaling:** working under the assumption that all sources are intrinsically similar in terms of their physical conditions, namely that particle acceleration and radiation mechanisms are comparable across the population, and that external photon fields do not contribute to neutrino production, it is reasonable to adopt the synchrotron peak flux $F_{\gamma,\text{peak}}$ as a proxy for the neutrino flux (F_{ν}), which transforms to F'_{ν} according to:

$$F'_{\nu} = F_{\nu} \cdot \frac{F'_{\gamma,\text{peak}}}{F_{\gamma,\text{peak}}}. \quad (95)$$

Another argument supporting this scaling is the assumption that all sources share the same Doppler factor. While this is clearly a simplification, it enables a consistent comparison across the sample. Because both photon and neutrino luminosities scale identically with this parameter (Equation 78), the ratio of neutrino luminosities between sources can be reasonably approximated by the ratio of their synchrotron peak fluxes.

This method preserves the spectral shape of neutrino templates while adjusting their normalization based on synchrotron flux. Neutrino fluxes for the 232

selected HBLs have been derived: their stacked (summed) contribution is depicted in Figure 85, along with the predicted fluxes of individual blazars. The fluxes are displayed in the energy range from 100 GeV to 100 PeV, relevant for high-energy neutrino studies with KM3NeT/ARCA. The calculation accounts for neutrinos and antineutrinos separation, as well as their mixed flavor composition at Earth due to neutrino oscillations over cosmic distances. Because of the adopted rescaling procedure, all the templates share a common spectral shape, featuring a peak at about 10^{17} eV. This spectral shape is then shifted in energies due to the redshift, but given that the range in redshifts is rather small, with a peak at $z \sim 0.25$ (Figure 82), this energy translation is rather minor and not visible in Figure 85.

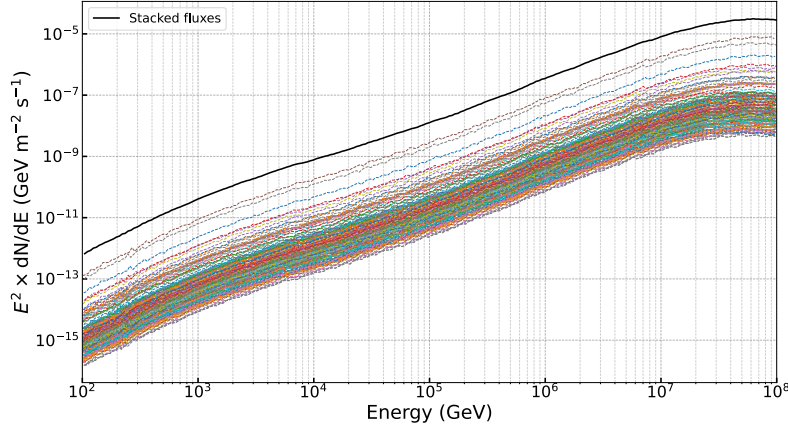


Figure 85: Expected neutrino fluxes for the 232 selected HBLs (dashed colored lines) and their stacked flux (solid black line). Both neutrino and antineutrino separation and their oscillated flavor composition at Earth are considered.

6.4.2 Model validation

The phenomenological approach has been validated considering as target sources the HBLs Mrk 421 [185] and VER J0521+211 [186], well-studied in multi-wavelength observational campaigns and exhibiting high synchrotron peak fluxes. The same proton content as PKS 2155–304 was assumed for both sources, while allowing the parameters of the electron population and source properties (magnetic field B and emission region size R) to vary in the one-zone LeHa-Paris modeling.

Mrk 421 is a nearby HBL located at $z = 0.03$, known for strong variability across the electromagnetic spectrum. Its SED typically shows a synchrotron peak in the X-ray band, shifting toward higher energies during flaring states. The source is often used as a benchmark for emission model testing due to its brightness ($\log_{10}(\nu F_{\gamma, \text{peak}} [\text{erg cm}^{-2} \text{s}^{-1}]) = -9.7$). As reported in [185], four observational epochs of SED snapshots were assembled using simultaneous multi-wavelength data from Swift-UVOT, Swift-XRT, NuSTAR, Fermi-LAT, MAGIC and VERITAS, with most data collected within 12 hours, except for Fermi-LAT and radio data, which were accumulated over about a week. Data from this broadband SED (Figure 86) have been used as a reference for developing a lepto-hadronic model of Mrk 421, utilizing LeHa-Paris. Table 4 reports the set of parameters that has been found to reproduce the lower state emission of Mrk 421 in a lepto-hadronic sce-

nario, assuming the same proton content of PKS 2155-304. The choice to fit the low-state, among the available datasets, represents the most conservative approach, as it prevents the model from overshooting the data and ensures a better reproduction of the hard X-ray component of the SED. The neutrino emission derived from the model is presented together with the PKS 2155-304 neutrino template rescaled to Mrk 421, according to the previously described methods.

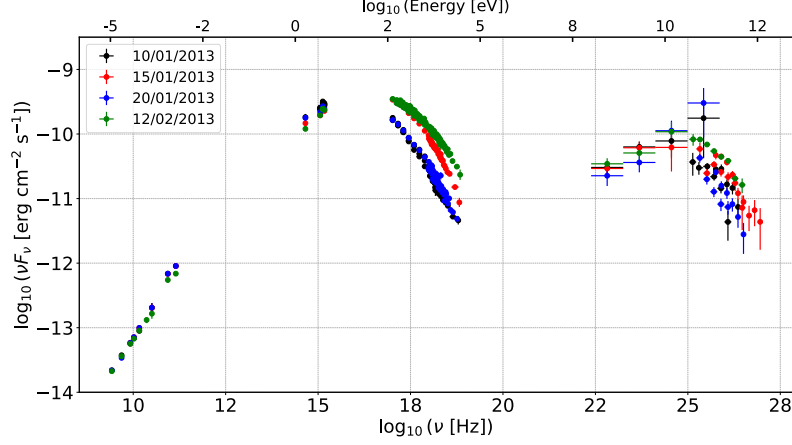


Figure 86: Mrk 421 SED snapshots for the four selected epochs, labeled with different colors. Data are taken from [185].

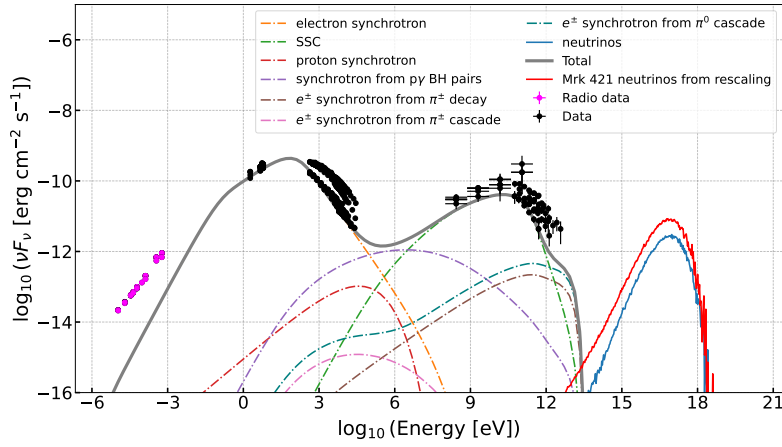


Figure 87: Mrk 421 SED based on parameters in Table 4. The continuous blue line shows the neutrino flux predicted with LeHa-Paris; the continuous red line shows the PKS 2155-304 neutrino template rescaled to Mrk 421. Radiation components not shown in the plot are subdominant. Data are taken from [185].

B [G]	R [cm]	η	$K_e [\text{cm}^{-3}]$	$\alpha_{e,1}$	$\alpha_{e,2}$	γ_{break}
0.2	$0.9 \cdot 10^{16}$	0.06	600	2.0	5.0	$3 \cdot 10^4$

Table 4: Parameters of the Mrk 421 model using the LeHa-Paris code. Parameters not specified in this table are the same of the best-fit model obtained for PKS 2155-304. Resulting jet luminosity is $3 \cdot 10^{46}$ erg/s.

Secondly, VER J0521+211, a HBL object located at redshift $z = 0.108$, has been studied. The value of its measured redshift has been reported by Shaw et al. (2013), based on weak [N II] emission lines [187]. This detection has not been confirmed by further studies, which reported a featureless optical spectrum and placed a lower limit of $z > 0.18$ based on Ca II absorption from the host galaxy [188]. The estimation of VER J0521+211 redshift is still controversial and, for the sake of this analysis, the information reported in the 3HSP catalogue has been used for consistency. The source is also among the brightest in the sample in terms of synchrotron peak flux, corresponding to $\log_{10}(\nu F_{\gamma, \text{peak}} [\text{erg cm}^{-2} \text{s}^{-1}]) = -10.6$, and has been subject of extensive multi-wavelength campaigns involving the Fermi Gamma-ray Space Telescope, the Swift Observatory and ground-based Cherenkov telescopes, such as VERITAS. This source was monitored over a 48-days period between October and December 2013, during which it exhibited an elevated TeV gamma-ray state. Data, shown in Figure 88, are able to well characterize the second bump of its SED, also in its descendant part. A lepto-hadronic model was therefore developed for this source using LeHa-Paris, under the same assumptions as for source Mrk 421. The best-fit parameters are summarized in Table 5, implying a resulting jet luminosity is $3 \cdot 10^{48}$ erg/s, which remains within roughly an order of magnitude of the Eddington limit for a SMBH of mass $M_{\text{BH}} = 10^9 M_{\odot}$. The resulting SED is shown in Figure 89, where the modeled neutrino flux is presented along with the PKS 2155–304 neutrino template rescaled to match VER J0521+211.

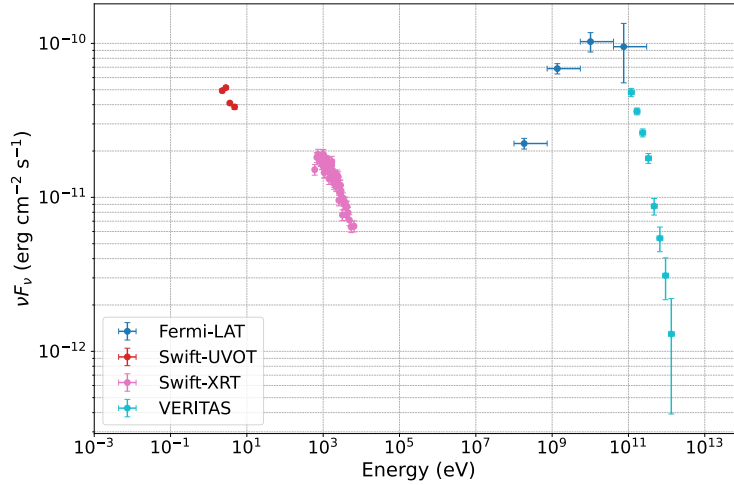


Figure 88: VER J0521+211 experimental SED. Data are taken from Swift-UVOT, Swift-XRT, Fermi-LAT and VERITAS, going from lower to higher energies [186].

B [G]	R [cm]	η	$K_e [\text{cm}^{-3}]$	$\alpha_{e,1}$	$\alpha_{e,2}$	γ_{break}
0.01	$1.3 \cdot 10^{17}$	$3 \cdot 10^{-6}$	10^7	3.0	3.6	10^5

Table 5: Parameters of the VER J0521+211 model using the LeHa-Paris code. Parameters not listed are identical to those of the best-fit model obtained for PKS 2155–304. Resulting jet luminosity is $3 \cdot 10^{48}$ erg/s.

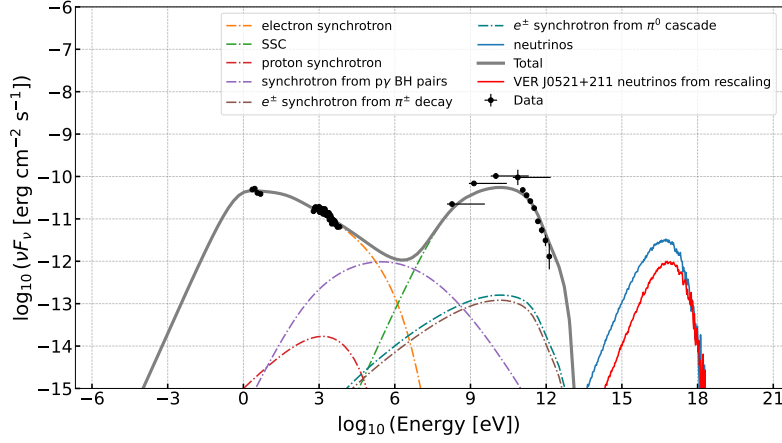


Figure 89: SED of VER J0521+211 based on the best-fit parameters reported in Table 5. Blue solid line represents the neutrino spectrum of the model, while the solid red line shows the PKS 2155–304 template rescaled to this source. Radiation components not shown in the plot are subdominant. Data taken from [186].

The ratio between the modeled neutrino fluxes and the rescaled PKS 2155-304 flux shows that, in the neutrino energy range $1 \text{ PeV} \leq E_\nu \leq 100 \text{ PeV}$, the Mrk 421 model agrees with the rescaling within a factor of 5, while the VER J0521+211 model agrees within a factor of 10 (Figure 90). The obtained results indicate that the spectral shape of the modeled fluxes closely follows that of the rescaling approach, in the considered energy range. The main difference lies primarily in the normalization, which reflects the uncertainty introduced by the rescaling procedure. This uncertainty will be explicitly accounted for in the stacking analysis presented in the following. This demonstrates that, by employing the LeHa-Paris code, it is possible to generate expected neutrino spectra for a specific subclass of blazars. The good agreement between the modeled fluxes and the rescaled template, especially in the PeV energy range and beyond, makes these studies particularly relevant for high-energy neutrino telescopes like KM3NeT/ARCA, as discussed in Chapter 7.

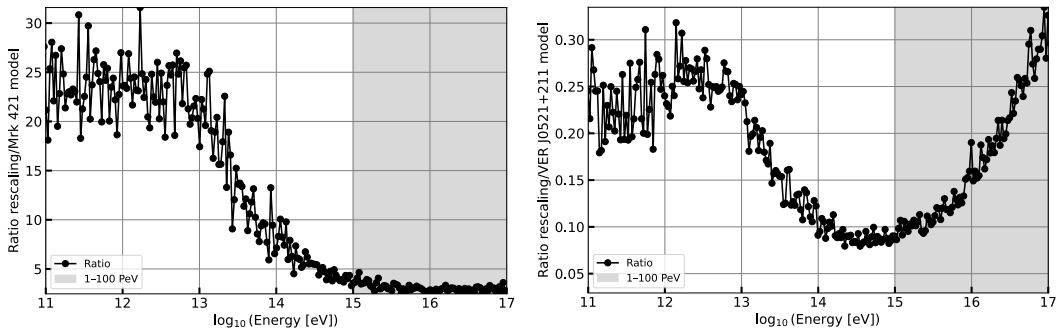


Figure 90: *Left*: ratio between the fluxes of Mrk 421 obtained by rescaling the PKS 2155-304 template (solid red line of Figure 87) and by modeling its SED with LeHa-Paris (solid blue line of Figure 87). *Right*: ratio between the fluxes of VER J0521+211 obtained by rescaling the PKS 2155-304 template (solid red line of Figure 89) and by modeling its SED with LeHa-Paris (solid blue line of Figure 89). In both panels, the energy range 1–100 PeV is indicated by a gray band.

STACKING SEARCH FOR HIGH-ENERGY NEUTRINOS FROM BLAZARS

The previous Chapter discussed the importance of accurate numerical multi-messenger modeling codes for predicting high-energy neutrino fluxes from blazars, which are candidate extragalactic hadronic factories. Establishing a neutrino–blazar connection would allow to estimate their potential contribution to the acceleration of cosmic rays up to the highest energies. Furthermore, it would offer valuable insights into the physical conditions within their relativistic jets, offering a way to test whether leptonic or lepto-hadronic processes dominate their high-energy emission. In this context, the study of the HBL blazar PKS 2155-304, conducted with the LeHa-Paris code in a one-zone lepto-hadronic scenario, revealed an expected neutrino flux whose SED peaks around 100 PeV. Afterwards, a total of 232 sources were selected from the 3HSP catalogue (6.4). For each of these sources, a neutrino flux template was derived by rescaling the best-fit neutrino flux of PKS 2155-304 according to observables reported in the catalogue, enabling predictions for a larger sample. The validation of the approach showed a promising agreement in the neutrino energy range $1 \text{ PeV} \leq E_\nu \leq 100 \text{ PeV}$, motivating the investigation of such neutrino fluxes using data collected by KM3NeT/ARCA in configurations with 6 to 21 deployed strings (KM3NeT/ARCA6–21). Building on this, a further aim of this thesis has been to develop a binned likelihood stacking analysis to search for a cumulative high-energy neutrino emission from this subset of 232 HBLs, assuming the spectral shape derived using the LeHa-Paris code. The KM3NeT/ARCA6–21 dataset adopted in the analysis and its event selection are described in Section 7.1. Then, the detection prospects of KM3NeT/ARCA6–21 for the PKS 2155-304 neutrino flux are presented in Section 7.2, where its sensitivities and discovery potentials are compared to those obtained for a conventional E^{-2} power-law scenario. Finally, the stacking analysis is presented in Section 7.3, while its main results, based on KM3NeT/ARCA6–21 data, are discussed in Section 7.4.

7.1 DATA SAMPLES

As outlined in Chapter 3, thanks to their modular design, KM3NeT detectors are capable of acquiring data even during the construction phase and with a partial array of detection units (DUs). The data included in the analyses reported in this Chapter were collected by the KM3NeT Collaboration from May 2021 to the end of 2023. The datasets corresponding to the four detector configurations active during this period were analyzed, for a total livetime of about 640 days:

- **KM3NeT/ARCA6:** KM3NeT/ARCA was in operation from May 2021 to September 2021 with 6 DUs, for a total livetime of 92 days. Within this period, the dataset is split into two sub-periods:

1. From the start of data-taking up to 22 July 2021, accounting for 60.2 days of livetime (*first period*).
 2. From 22 July to 10 September 2021, during which erroneous time calibrations were applied at the trigger level. This resulted in an estimated 32% loss in the number of signal events, after preliminary cuts (*second period*). A dedicated MC treatment allowed good agreement with data and full exploitation of this second dataset.
- **KM₃NeT/ARCA8:** the detector was operational from the end of September 2021 to the end of May 2022 with 8 DUs, with a total livetime of 212.3 days.
 - **KM₃NeT/ARCA19:** KM₃NeT/ARCA collected data from June 2022 to September 2022 with 19 deployed DUs, for a livetime of 48.4 days.
 - **KM₃NeT/ARCA21:** KM₃NeT/ARCA was operating with 21 detector strings from September 2022 to September 2023, collecting a livetime of 287.40 days. This configuration will be also examined in Chapter 8.

Figure 91 shows the exposure, expressed in Mton-years (effective volume times running time), for the configurations under study as a function of time.

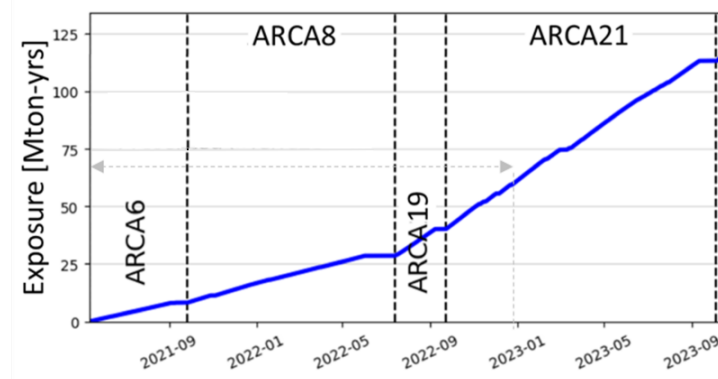


Figure 91: Exposure, in Mton-years, as a function of time for the different KM₃NeT/ARCA detector configurations. Vertical and horizontal grey dashed lines indicate the dataset which was unblinded in the first iteration of point source and diffuse analyses with KM₃NeT/ARCA (e.g., see [134] and [189]). Updated analyses include the full KM₃NeT/ARCA21 period (e.g., see [190] and [191]).

7.1.1 Event selection

The event selection used in this work follows the procedure defined in previous point source searches [134, 151, 190, 192], where track-like events were considered and an E^{-2} spectrum was taken into account for the cosmic neutrino flux. Such selection aims to retain astrophysical neutrino-induced track-like events while effectively suppressing the dominant backgrounds, namely atmospheric muons, neutrinos and environmental noise. Environmental background is primarily reduced at the trigger level by requiring causally connected clusters of photon hits across different DOMs. Events that survive this initial filter are further cleaned using fixed

cuts on reconstruction variables such as the likelihood and number of hits used in the reconstruction. Atmospheric muons, which are predominantly downward-going, are more challenging to reject. A cut on the reconstructed zenith angle is applied to exploit the Earth as a natural shield, minimizing the contamination from downward-going particles misreconstructed as upward-going. The residual background is further reduced using Boosted Decision Trees (BDTs), which classify and reject surviving atmospheric muons based on a multivariate approach. This two-step selection (initial fixed cuts followed by a BDT classification) has been optimized for these datasets, balancing signal efficiency and background suppression in the search for neutrino point sources. Specifically, the optimization aimed to simultaneously minimize the atmospheric muon contamination and enhance the discovery potential for point-like astrophysical neutrino sources. The series of selection cuts can be summarized as follows:

- **Preliminary selection (precuts):** events are required to be successfully reconstructed as tracks and to have passed at least five reconstruction stages (see 4.3). Additionally, the likelihood of the reconstruction must be positive ($\text{lik} > 0$), the reconstructed track length must be greater than zero, the angular error estimate β_0 must be positive, and the reconstructed track energy must exceed 100 GeV. These criteria ensure that only physically meaningful and well-reconstructed events are considered in the analysis.
- **Horizontal & upgoing selection:** to reduce the overwhelming background of atmospheric muons, a directional cut is applied on the reconstructed zenith angle. Events are retained only if $\cos(\theta_{\text{tr, rec}}) > -0.1$, which corresponds to reconstructed zenith angles greater than about 85° , selecting horizontal or upgoing tracks.
- **Anti-noise selection:** environmental background events, such as random coincidences from ^{40}K decay and bioluminescence, often mimic track-like events with poor reconstruction quality (e.g., low likelihood, low number of hits). These noise events are not modeled in Monte Carlo (MC) simulations and need to be removed. A likelihood threshold of $\text{lik} > 50$ and a minimum of 20 hits ($N_{\text{hits}_{\text{rec}}} > 20$) are imposed to reject such events. This selection efficiently removes most of the noise without significantly affecting the signal.
- **Final fixed cut selection:** three additional cuts are applied to suppress atmospheric muons that survive the previous selections, especially at the highest energies. First, a cut on the angular error estimator β_0 is applied, requiring $\log_{10}(\beta_0[\text{rad}]) < -2.25$, which preferentially removes misreconstructed atmospheric muons with large directional uncertainty. Secondly, a cut is applied on the reconstructed length of the muon track, requiring a track length > 100 m, based on the observation that atmospheric muons typically produce shorter tracks compared to muons induced by high-energy neutrino interactions. Finally, a more stringent cut on the likelihood parameter of the reconstructed track fit is applied, requiring $\text{lik} > 10^{1.8}$. The combination of these cuts has been demonstrated to be highly effective in rejecting residual atmospheric muon background.

- **BDT classification:** the final step involves applying a BDT classifier trained to distinguish between signal and background events. The classification is performed using the ROOT::TMVA software package [193], which is widely adopted for multivariate analyses in high-energy physics. The event sample is split into two subsets: one for training and one for evaluation, in order to validate the model performance and mitigate over-training effects. The BDT provides a continuous score, referred to as the *track score*, where higher values indicate a higher probability that the event is of astrophysical neutrino origin. The model is trained using a set of variables that effectively discriminate signal from background. These variables include topological, reconstruction quality and Cherenkov-hit-based quantities. The five most relevant contributors are:
 - the number of photo-electrons along the reconstructed track;
 - the estimated angular uncertainty of the reconstructed track direction (β_0);
 - the distance between the closest and furthest Cherenkov hits in the μ -track hypothesis;
 - the reconstructed track length;
 - the maximum difference between reconstructed zenith angles of the prefits (see 4.3 of Chapter 4).

The remaining observables, such as the number of prefits, the reconstructed track energy and the fraction of Cherenkov hits near the vertex, are listed in full in [192]. A BDT score cut at 0.9996 is chosen as optimal one in order to reduce the muon contamination at the level of 16% and also minimize the neutrino flux needed for a 5σ discovery of a point-like source emitting with an E^{-2} spectrum.

As an example, Figures 92–97 show the distributions of several reconstructed variables in KM3NeT/ARCA21 data and MC simulations, where all the previously mentioned cuts have been applied in consecutive order. The contributions from atmospheric muons, atmospheric neutrinos and cosmic neutrinos are included, along with their MC sum. The lower panel of each plot shows the Data/MC ratio, on average at the level of 1.5. A total of 1362 data events survive the cuts, with ~ 11 expected to be cosmic neutrinos for an E^{-2} spectrum. Then, the following quantities are determined:

- **Neutrino purity** = $\frac{\text{Number of atmospheric and astrophysical neutrinos}}{\text{the sum of all MC terms}} = 84\%$.
- **Signal efficiency** = $\frac{\text{Number of astrophysical neutrinos}}{\text{the sum of all MC terms}} = 1\%$.
- **Muon contamination** = $\frac{\text{Number of atmospheric muons}}{\text{the sum of all MC terms}} = 16\%$.

After selection, the daily event rates expected in the KM3NeT/ARCA21 detector are dominated by atmospheric neutrinos, with approximately 2.6 events per day. Contributions from cosmic neutrinos following an E^{-2} spectrum and atmospheric muons are significantly lower, at about 0.04 and 0.5 events per day, respectively. This indicates that atmospheric neutrinos are the primary source of background

events, while atmospheric muons contribute only marginally. For the sake of this study, the UHE event KM3-230213A (see 3.5) has been excluded from the sample, as its inclusion would inevitably produce a significant excess from its direction. After this removal, 1361 events are left in the data sample of KM3NeT/ARCA21.

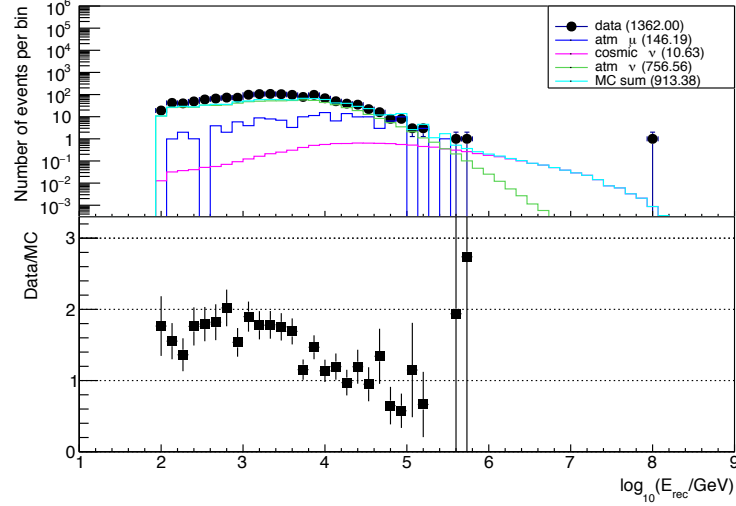


Figure 92: Distribution of the reconstructed energy for KM3NeT/ARCA21 data and MC simulations. KM3-230213A is visible as an outlier of the dataset. The blue line represents the number of atmospheric muons, while the magenta and green lines show the expected numbers of cosmic and atmospheric neutrinos, respectively. The black dots correspond to the observed data, and the MC sum is indicated by the light blue line. Same color codes apply to Figures 93-97.

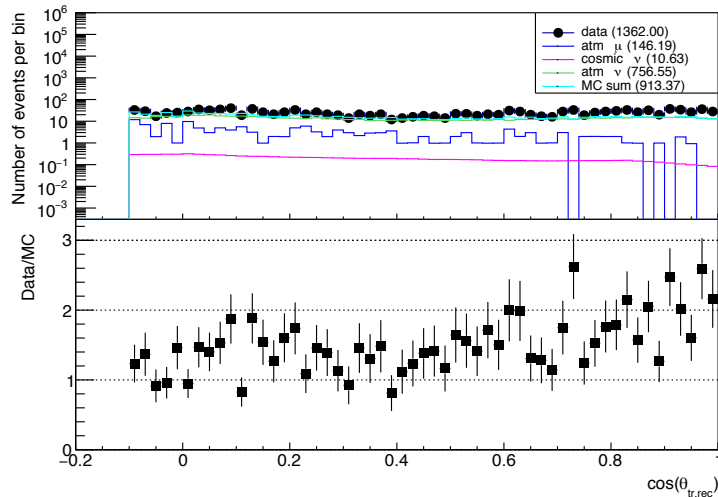


Figure 93: Distribution of the reconstructed track angle (supplementary to the zenith angle) for KM3NeT/ARCA21 data and MC simulations.

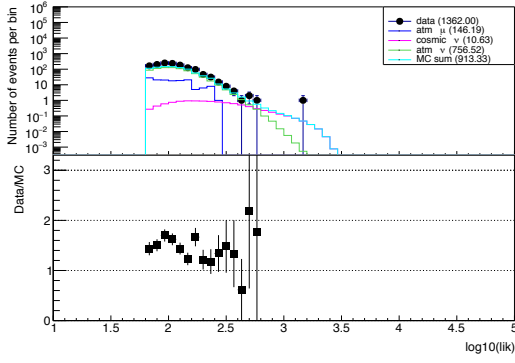


Figure 94: Distribution of the likelihood-based fit quality variable (lik) for KM3NeT/ARCA21 data and MC simulations.

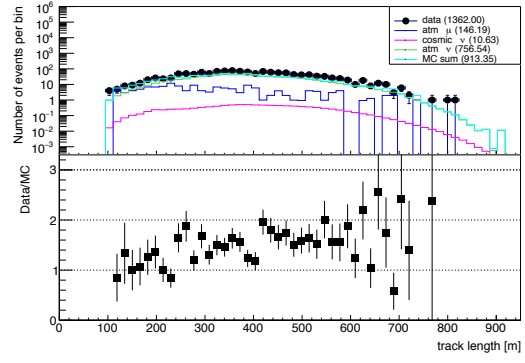


Figure 95: Distribution of the reconstructed track length for KM3NeT/ARCA21 data and MC simulations.

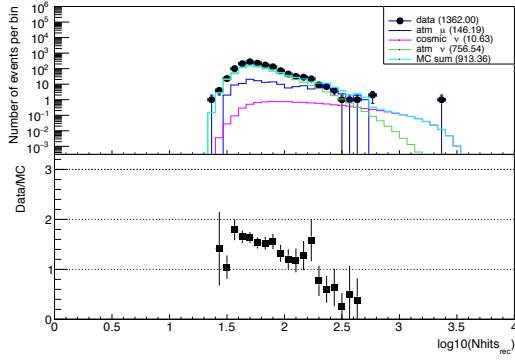


Figure 96: Distribution of the number of hits used in the reconstruction ($N_{\text{hits}_{\text{rec}}}$) for KM3NeT/ARCA21 data and MC simulations.

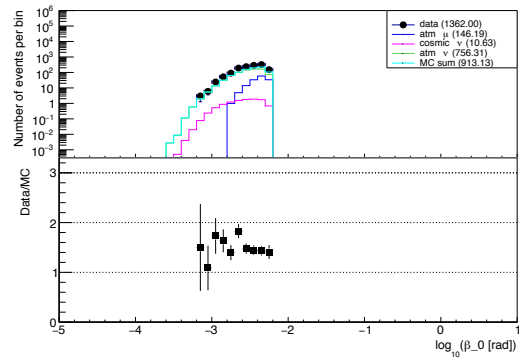


Figure 97: Distribution of the uncertainty of the reconstructed track direction (β_0) for KM3NeT/ARCA21 data and MC simulations.

Regarding the selection for the rest of the configurations, only one of the periods under study uses the same selection chain as KM3NeT/ARCA21, while the others apply a partial selection with an additional cut:

- KM3NeT/ARCA6-8 data are selected on the basis of the precuts, directional cuts and anti-noise cuts specified above (omitting the cut at 100 GeV on E_{rec}). Additionally, a further powerful parameter for signal-background discrimination is the reconstructed zenith angle obtained from the shower reconstruction algorithm (θ_{shw}). Atmospheric muons passing the upgoing track selection often produce electromagnetic showers along their path due to energy losses via bremsstrahlung. It has been observed that the shower reconstruction algorithm can correctly identify these muons, because the resulting electromagnetic cascades are highly collinear with the parent muon due to Lorentz boosting. Therefore, when both the track and the shower reconstruction agree in classifying a track as upgoing, the event can be considered more reliably upgoing. For consistency with the track zenith cut, the same threshold is applied, retaining events with $\cos(\theta_{\text{shw}}) > -0.1$. Figure 98 shows the distribution of the reconstructed track energy variable, in

both KM3NeT/ARCA6 and KM3NeT/ARCA8 periods. A total of 15742 data events are selected and the bin-averaged Data/MC ratio is about 1.1. The muon contamination of this sample is quite high (95%). As in Figure 99, the label *signal* refers to events with an outgoing muon reconstructed better than 1° , which is upward-going.

- KM3NeT/ARCA19 follows the same event selection of KM3NeT/ARCA21. Together, both periods constitute the dominant sample of the point source analysis. Figure 99 shows the distribution of the reconstructed track energy variable in both KM3NeT/ARCA19 and KM3NeT/ARCA21 periods. In total, 1544 data events are selected and the bin-averaged Data/MC is at the level of 1.5. The muon contamination is at approximately 16%.

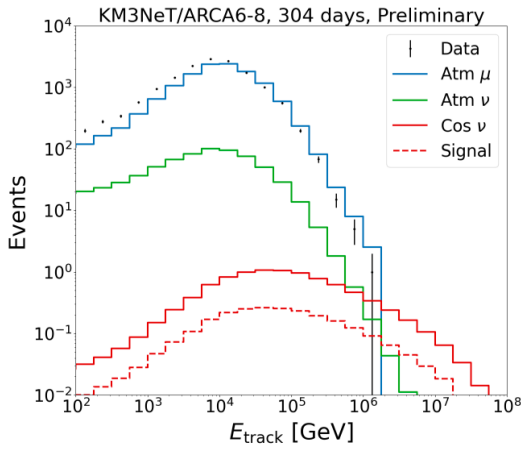


Figure 98: Distribution of the reconstructed track energy in the KM3NeT/ARCA6 and KM3NeT/ARCA8 periods. Data are reported as black dots, while MC simulations are color-coded as in the legend. Image from [190].

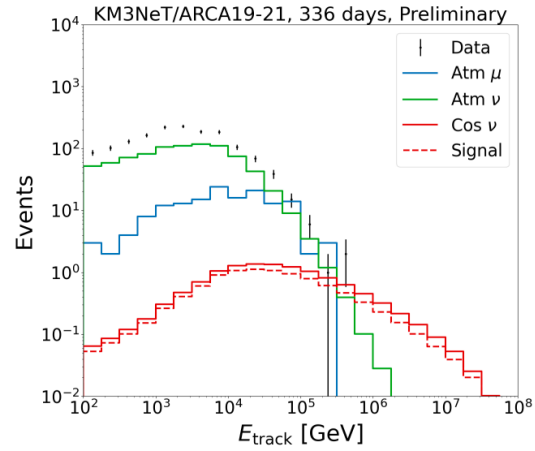


Figure 99: Distribution of the reconstructed track energy in the KM3NeT/ARCA19 and KM3NeT/ARCA21 periods. Data are reported as black dots, while MC simulations are color-coded as in the legend. Image from [190].

Table 6 shows the detailed number of data and MC events for the periods under consideration. A total of 17286 events are considered, which changes to 17285 events after excluding KM3-230213A. A cosmic neutrino flux of $\phi_{\nu+\bar{\nu}} = 1.2 \times 10^{-4} \left(\frac{E_\nu}{\text{GeV}}\right)^{-2} \text{ GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ per flavor yields a total of 21.4 cosmic neutrino events in the full KM3NeT/ARCA6-21 sample, of which 12.1 contain an upward-going muon reconstructed with an angular resolution better than 1° . Figure 100 shows, at selection level, the angular resolution (ψ) as a function of the simulated true neutrino energy, plotted together with the 68% quantiles. The angular resolution is below 2° , above 100 TeV, for KM3NeT/ARCA6-8, while this improves significantly to less than 0.3° in KM3NeT/ARCA19-21. In addition, Figure 101 reports the effective area for upgoing track-like events, specifically evaluated for each detector geometry at the same analysis selection level. The effective area of ANTARES is also reported [194], although it should be noted that the respective data samples have different muon contamination levels (14% for the ANTARES track-like event selection).

	ARCA6-8	ARCA19-21	ARCA6-21
Data	15 742	1 544	17 286
MC total	14 037.86	1 025.16	15 063.02
Muons	13 278.50	150.00	13 428.50
Atmospheric ν	749.94	863.17	1 613.11
Cosmic ν	9.42	11.99	21.42
Signal (cosmic ν with μ at $< 1^\circ$)	2.45	9.60	12.05
Data/MC	1.12	1.51	1.15
Muon contamination	95%	16%	89%

Table 6: Summary of event statistics for different KM3NeT/ARCA configurations.

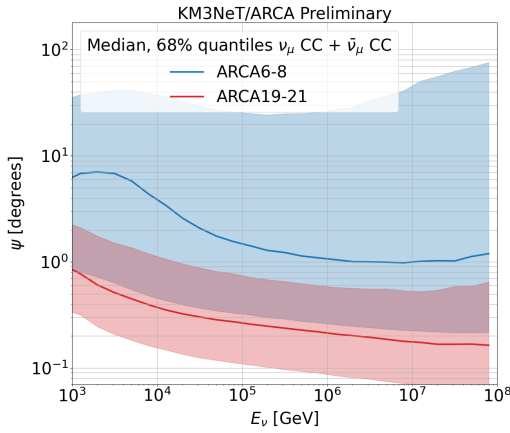


Figure 100: Median angular resolution of the selected track-like events for different KM3NeT/ARCA configurations, with 68% quantiles shown as colored bands. Image from [190].

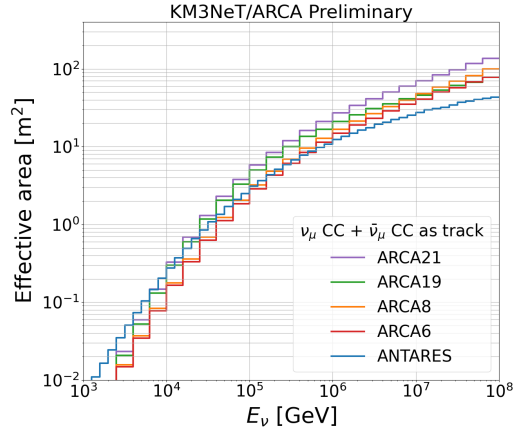


Figure 101: Effective area of the selected track-like events for different KM3NeT/ARCA configurations, with the ANTARES effective area also shown. Image from [190].

7.2 DETECTION PROSPECTS WITH KM3NeT/ARCA6-21

As a preliminary study, a point source analysis has been carried out to investigate the detection prospects of KM3NeT/ARCA for a neutrino emission as the one derived for PKS 2155–304. The declinations studied are:

$$\delta \in \{-85^\circ, -70^\circ, -40^\circ, -30.22^\circ, -15^\circ, 0^\circ, 15^\circ, 40^\circ\},$$

where the value -30.22° corresponds to the true declination of PKS 2155–304 and 40° denotes the visibility limit of KM3NeT/ARCA, when using only upgoing events. At each declination, the best-fit model shown in Figure 79 is assumed as cosmic neutrino point source flux, rather than a typical power-law spectrum. A binned likelihood-based test is performed according to the methods described in Chapter 5 and further detailed in Chapter 8: signal and background MC pseudo-datasets are generated for the set of specified declinations in order to characterize

the detector response; test statistic distributions are produced and are then used to determine the point source sensitivities and discovery potentials.

7.2.1 Binned analysis

The binned point source analysis follows the same strategy introduced in Chapter 5 and described in detail in Chapter 8. Pseudo-datasets are simulated for various values of the true signal strength (μ_{true}), considering only the track channel but including contributions from all neutrino flavors. For the null hypothesis H0 ($\mu_{\text{true}} = 0$), 10^5 pseudo-experiments (PEs) are generated, while $2 \cdot 10^4$ are produced for the alternative hypothesis H1. This procedure is repeated for each declination and, following the method outlined in Section 5.4, is used to derive the corresponding sensitivities, discovery potentials, and statistical limits from the test statistic distributions. The novelty of the approach relies on the usage of a more physically motivated neutrino flux as input to the framework. In particular, the signal binned PDF, as detailed in 5.1, is now weighted for the flux reported in Figure 79. Figure 102 shows the signal and background probability density functions (PDFs) at declination $\delta = -85^\circ$ for KM₃NeT/ARCA21, assuming the PKS 2155-304 single-flavor neutrino flux. Compared to Figure 55, the signal PDF exhibits a clear shift towards higher reconstructed energies, reaching the PeV scale. This feature arises from the different energy spectrum of the expected neutrino flux and enhances the separation between the signal and background expectations.

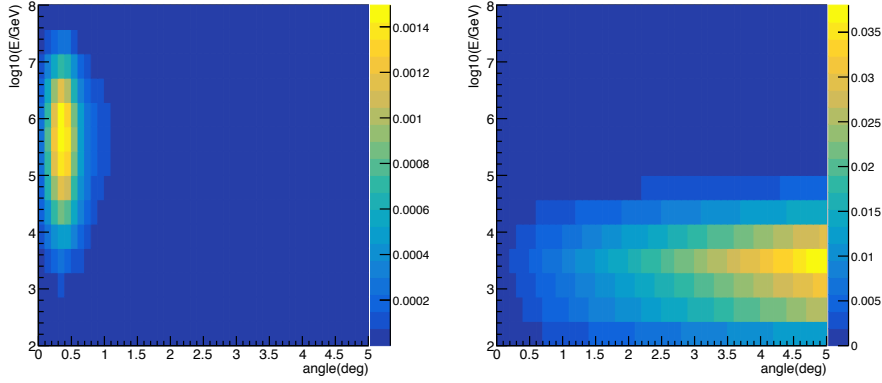


Figure 102: Expected signal (left) and background (right) PDFs at $\delta = -85^\circ$ for KM₃NeT/ARCA21. Signal PDF is weighted with the PKS 2155-304 flux. Compared to a E^{-2} power-law assumption (Figure 55), the signal PDF exhibits a pronounced shift towards higher reconstructed energies, reaching the PeV scale.

The plots are produced at the point source selection level, including the effects of systematic uncertainties. In the case of KM₃NeT/ARCA, the dominant contribution to the angular uncertainty arises from a potential misalignment in the detector's absolute orientation around its vertical axis. This misalignment can cause a deviation between the true and reconstructed directions of neutrino events, particularly affecting the azimuthal angle. The resulting uncertainty is estimated to be 0.4° , based on comparisons between beacon positions measured during de-

ployment and calibration. Uncertainty in the zenith direction is not yet fully characterized, due to the lack of direct measurements of seabed flatness. However, dynamic calibrations suggest a potential tilt-induced miscalibration, estimated at 0.3° , assuming that strings average out to straight lines over long or quiet periods. Combining both effects, a symmetric Gaussian angular uncertainty of 0.5° is applied uniformly to all candidate source directions by convolving it with the Point Spread Function (PSF). Another systematic uncertainty is the one on the acceptance (or effective area) of the detector. This is estimated from dedicated MC simulations, considering as main contributors to the systematic the PMTs quantum efficiency and the water properties, i.e. the light absorption length. In order to disentangle the different contributions to the overall uncertainty, only one parameter was varied at a time during simulations. Figure 103 shows the relative event rate difference between modified and standard MC productions, computed in bins of reconstructed neutrino energy. These preliminary studies result in a conservative estimate at the level of 30% when effects are summed [151, 189, 192]. When producing PEs for a specific signal strength (or number of signal events), the signal strength (or n_s) is subjected to Gaussian smearing to account for this effect. Further dedicated studies are required to better quantify this uncertainty.

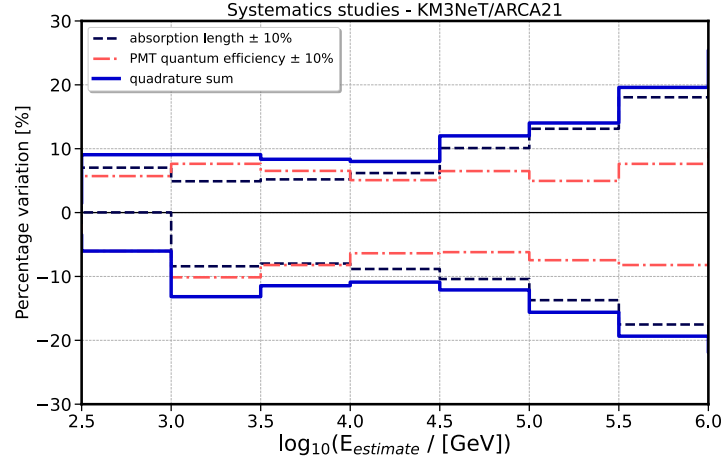


Figure 103: Percentage variation of the expected signal event rate from modified MC simulations in KM₃NeT/ARCA21, for each parameter modification (as specified in the legend), with respect to the standard MC simulation, shown as a function of reconstructed neutrino energy. Image courtesy of F.Filippini.

Since the analysis considers different detector geometries, the definition of the binned likelihood function (Equation 59) implicitly includes a sum over the various data-taking periods of KM₃NeT/ARCA. For each period, a specific set of signal and background PDFs is defined at a given declination. In addition, $F(\delta)$ and $F(\log_{10} E)$ functions, are introduced for each geometry, to properly describe the background dependence on declination and reconstructed energy, as in Equation 55. The PDFs used in this analysis are shown in Figures 104–107, corresponding respectively to KM₃NeT/ARCA6 first and second periods, KM₃NeT/ARCA8 and KM₃NeT/ARCA19 data-taking periods. KM₃NeT/ARCA21 PDFs have already been detailed in Chapter 5.

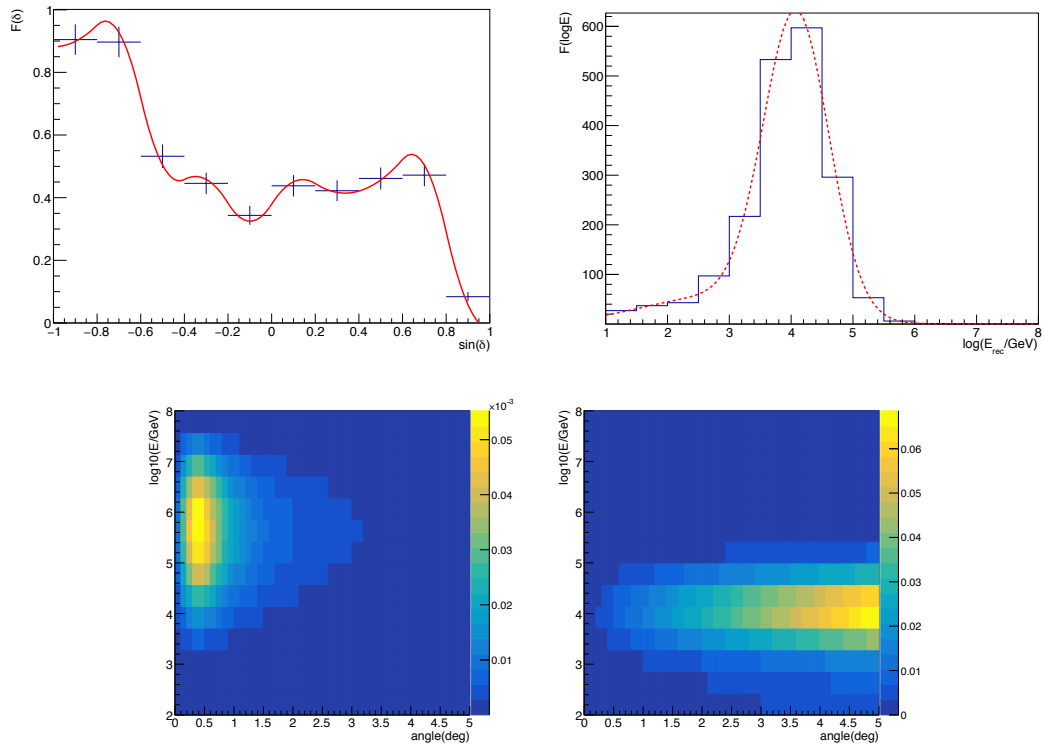


Figure 104: Fraction of selected track-like events (top panels) and expected signal and background PDFs (bottom panel) for the KM3NeT/ARCA6 first period.

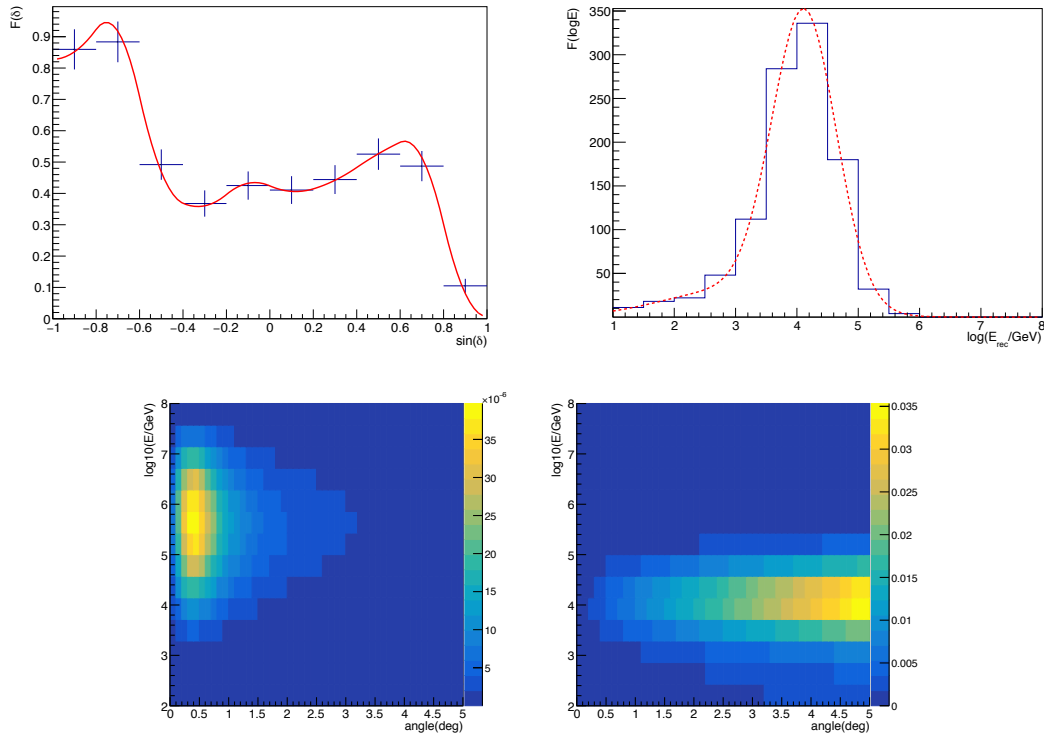


Figure 105: Fraction of selected track-like events (top panels) and expected signal and background PDFs (bottom panel) for the KM3NeT/ARCA6 second period.

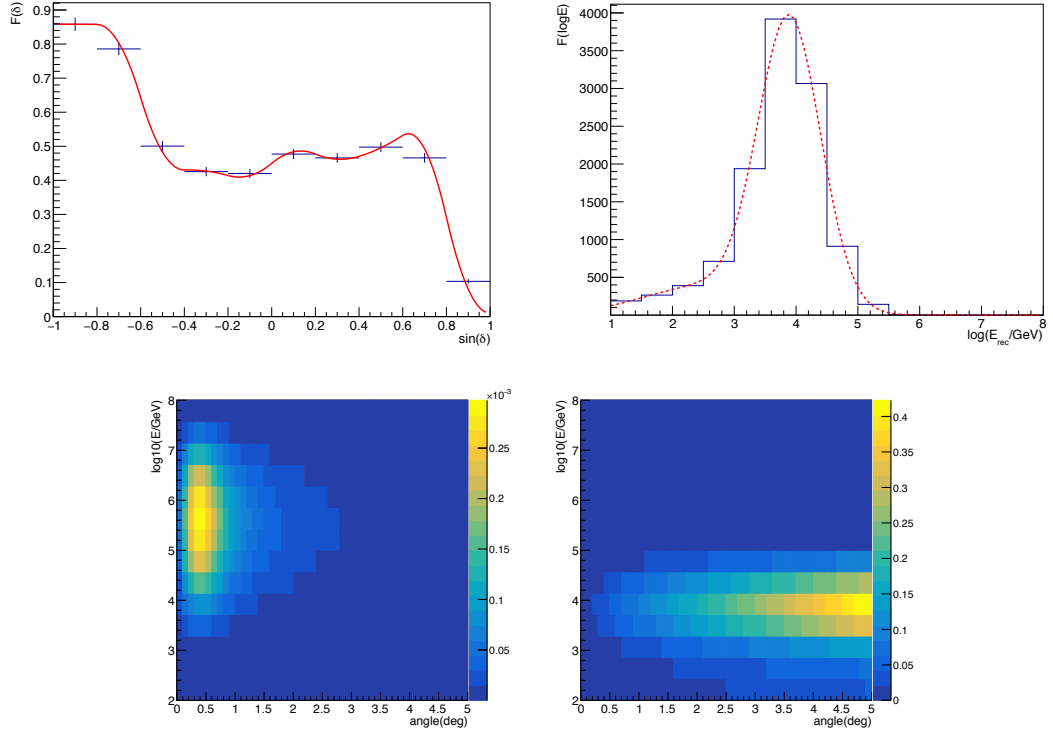


Figure 106: Fraction of selected track-like events (top panels) and expected signal and background PDFs (bottom panel) for the KM3NeT/ARCA8 period.

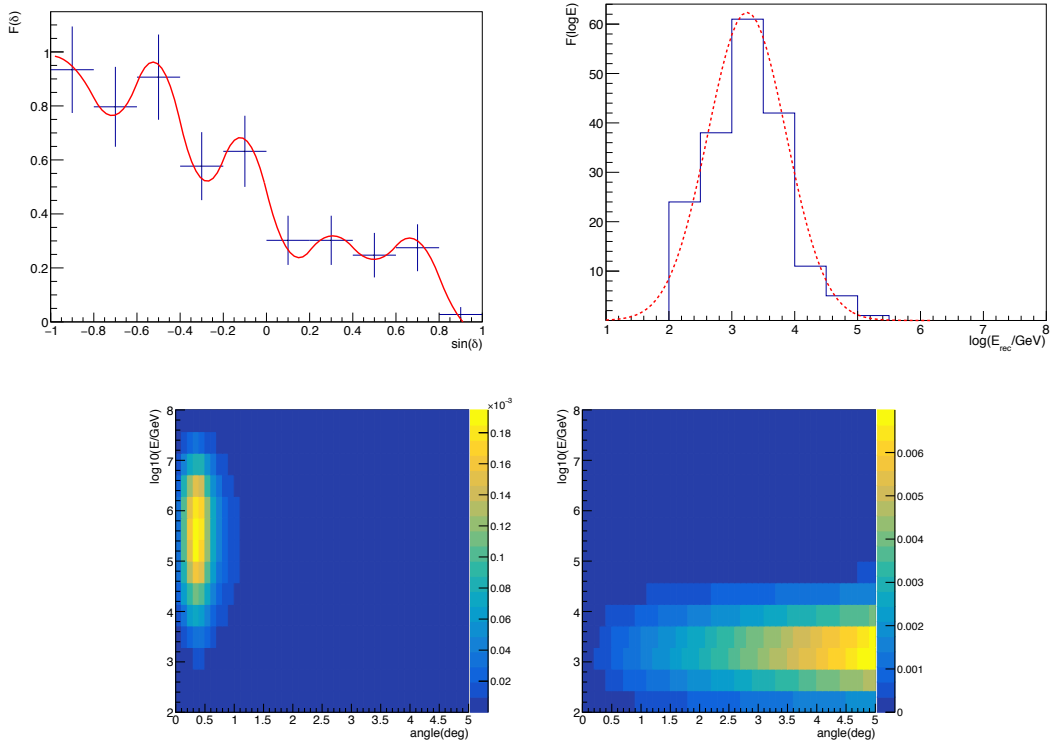


Figure 107: Fraction of selected track-like events (top panels) and expected signal and background PDFs (bottom panel) for the KM3NeT/ARCA19 period.

7.2.2 Sensitivity and discovery potential

Expectations from the binned analysis have been derived and are shown in Figures 108 and 109, in terms of sensitivity ($n_s^{90\% \text{C.L.}}$) and 3σ discovery potential ($n_{3\sigma}$) respectively. These have been compared with results obtained assuming an E^{-2} power-law spectrum at the same declinations. As evident from both Figures, the harder neutrino spectrum resulting from simulation is more easily distinguishable from the background with respect to an E^{-2} power-law assumption, leading to improved performances. Particularly, it can be observed that $n_{3\sigma}$ improves almost by a factor 2 for negative declinations, with this improvement becoming less pronounced at higher declinations. Building on the extension of the PKS 2155-304 flux to a subset of HBL sources, described in Chapter 6, a binned likelihood stacking analysis can therefore be performed to search for a cumulative emission of astrophysical neutrinos from blazars in the KM3NeT/ARCA6-21 dataset.

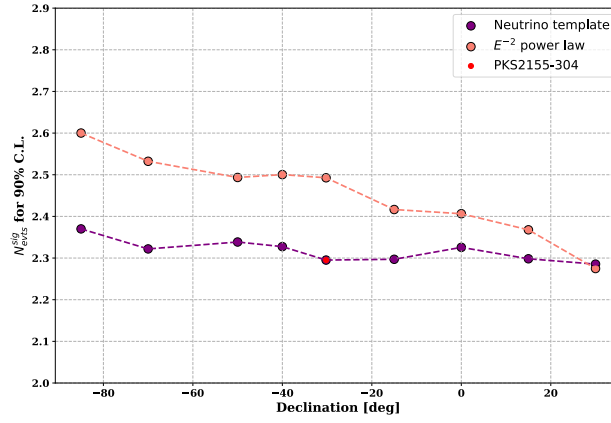


Figure 108: KM3NeT/ARCA6-21 point source sensitivities, expressed as $n_s^{90\% \text{C.L.}}$, compared between an E^{-2} power-law spectrum (pink dots) and the best-fit neutrino flux of PKS 2155-304 (purple dots). The red dot marks the sensitivity at the true location of PKS 2155-304.

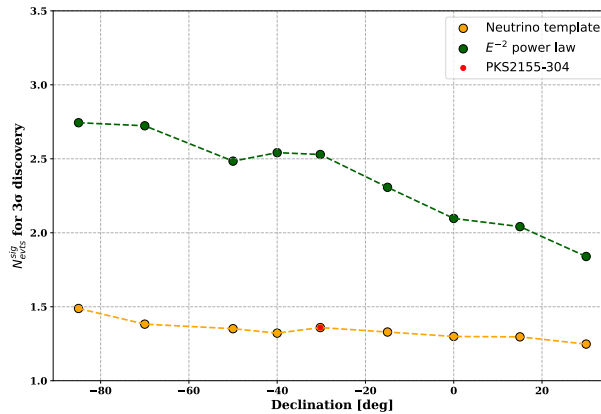


Figure 109: KM3NeT/ARCA6-21 point source discovery potential at 3σ ($n_{3\sigma}$) compared between an E^{-2} power-law spectrum (dark green dots) and the best-fit neutrino flux of PKS 2155-304 (yellow dots). The red dot marks the value of $n_{3\sigma}$ at the true location of PKS 2155-304.

7.3 ANALYSIS STRATEGY

Using the KM₃NeT/ARCA6-21 dataset described in 7.1, a binned likelihood stacking analysis is implemented to target the sample of 232 HBLs, selected according to the methods described in Section 6.4. The sources are ranked by their respectively expected neutrino yield in KM₃NeT/ARCA6-21 given by the assumed spectral models (see Figure 85). Figure 110 shows the 10 sources that contribute the most to the expected signal, because of their high synchrotron peak fluxes, among which the earlier mentioned Mrk 421, which is an outlier of this population, PKS 2155-304 and VER J0521+211. Their predicted neutrino fluxes are shown in Figure 111. Following this ordering, a binned likelihood point source analysis is carried out individually for each candidate source, according to methods of Chapter 5, to obtain their respective likelihood profiles. These profiles are subsequently combined to perform a joint fit. This is achieved summing the individual likelihoods across the catalogue to construct a global likelihood function:

$$\log \mathcal{L}_{\text{combined}}(\mu) = \sum_i \log \mathcal{L}_i(\mu), \quad (96)$$

where i indexes the sources. This approach preserves the relative contribution of each source and allows for a single signal strength parameter μ to be fitted globally. PEs are carried out separately for the H0 and H1 hypothesis. Specifically, 10^5 PEs were generated for H0, while $2 \cdot 10^4$ PEs were simulated for each H1 scenario. From the resulting distribution of test statistic values, discovery potentials and sensitivities are then computed using the same technique as implemented in KM₃NeT/ARCA's binned point source analysis [190].

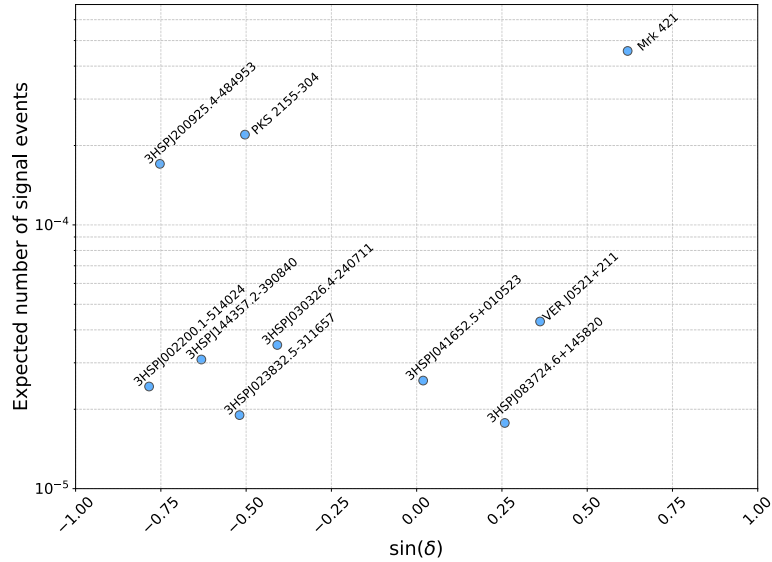


Figure 110: Top 10 brightest sources, among the selected HBLs of the 3HSP catalogue, ranked by the expected neutrino yield in the KM₃NeT/ARCA detector. The expected number of signal events in KM₃NeT/ARCA6-21 is shown as a function of the sine of the source declination (δ).

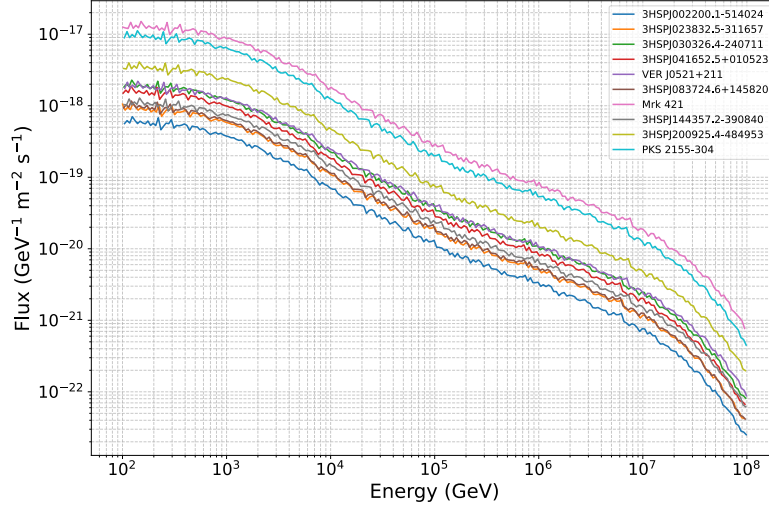


Figure 111: Expected single-flavor neutrino fluxes, as derived from the rescaling approach, for the sources shown in Figure 110. The calculation already takes into account neutrino oscillations at Earth and the separation between neutrino and antineutrino.

To obtain a reliable estimate of discovery potentials, the tail of the test statistic distribution under the H_0 hypothesis is fitted with an exponential function. This approach enables an accurate evaluation without the need for a large statistics of PEs.

7.3.1 Flux uncertainty and systematics

The model validation performed with Mrk 421 and VER J0521+211 (see 6.4) indicated an agreement within factors of 5 and 10, respectively, in the energy range [1 PeV, 100 PeV]. These factors account for the intrinsic limitations of the rescaling method, which assumes identical proton content and similar physical conditions across all sources in the catalogue. A band spanning one order of magnitude around the flux based on the PKS 2155-304 rescaling is therefore adopted for each source. The range [1 PeV, 100 PeV] also encompasses the energies where 90% of the signal is expected in KM₃NeT/ARCA6-21 for the stacked flux of the 100 brightest sources analyzed, corresponding to approximately [6.1, 7.8] in $\log_{10}(\text{Energy/GeV})$, as shown in Figure 112. The reason for restricting the analysis to the 100 most luminous sources is discussed in Section 7.4. The factor-10 band is a safe estimate that also encompasses other catalogued sources. In fact, after the group of the four brightest sources, the one ranking fifth in terms of flux, 3HSPJ030326.4-240711 (see Figure 85), is approximately a factor of 10 fainter than Mrk 421, in the aforementioned energy range. Hence, even if flux was misestimated by about a factor of 10, it would still lie within the adopted uncertainty band and therefore remain subdominant in the overall stacked signal. Figure 113 shows the individual neutrino fluxes for the 100 most luminous HBL sources in the sample, obtained by rescaling the best-fit neutrino flux of PKS 2155-304. For each source, additional flux levels, corresponding to a factor of 10 lower and higher than the rescaled flux, are included. In the same plot, the summed fluxes, displaying their minimum, cen-

tral and maximum values, are also reported. The central flux corresponds to the stacked flux shown in Figure 116, while the minimum and maximum fluxes define its associated uncertainty region. In the following, limits are computed using the central flux in the likelihood, while the uncertainty band illustrates the range of possible stacked flux values.

Regarding systematic uncertainties on detector performance, a 0.5° Gaussian smearing to the PSF and a 30% Gaussian spread to the acceptance are considered, as detailed before

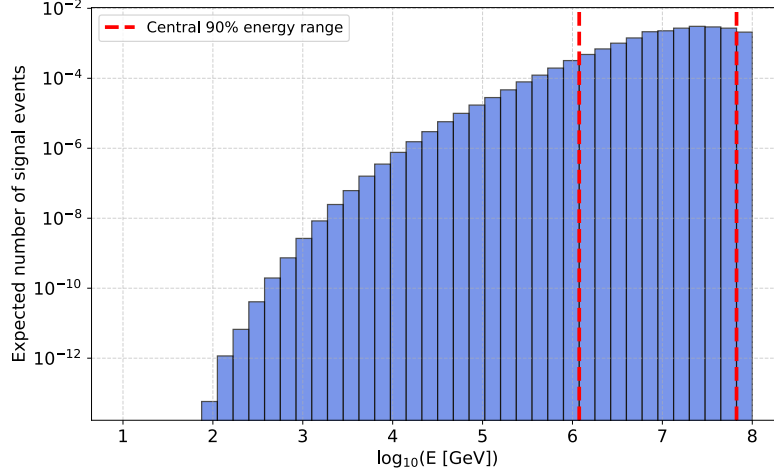


Figure 112: Expected number of signal events in KM3NeT/ARCA6-21, as a function of their energy, derived using the stacked neutrino fluxes of the 100 brightest HBLs in the sample. The energy range where 90% of the signal is expected is indicated as vertical red dashed lines.

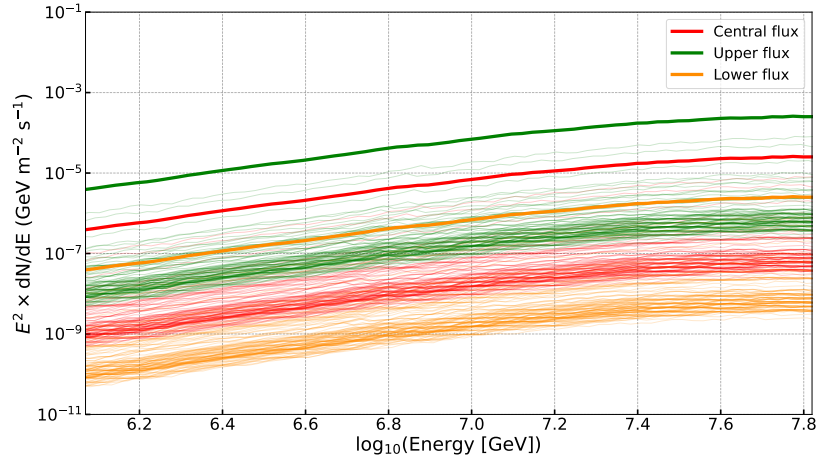


Figure 113: Neutrino flux predictions for the 100 most luminous HBLs in the sample, obtained by rescaling from PKS 2155-304 (red thin lines). The summed flux levels are shown for their maximum (solid green), central (solid red) and minimum (solid orange) values, assuming an uncertainty factor of 10 determined through the model validation procedure. Theoretical predictions are shown in the energy range where 90% of the signal is expected in KM3NeT/ARCA6-21 for the stacked flux.

7.4 RESULTS

The analysis was extended by progressively adding sources from the catalogue, to investigate the improvement in sensitivity (ϕ_{90}) with an increasing number of stacked sources. The following number of stacked situations are considered: 1, 2, 3, 5, 10, 30, 50, 70, 80, 90, 100, 110 and 120 sources. After the inclusion of the first 10 sources, the incremental improvement from adding new sources became less significant, reaching a plateau at approximately 100 sources, beyond which further additions yielded negligible gains. This trend is illustrated in Figure 114, which shows ϕ_{90}/ϕ_0 at 90% C.L. as a function of the number of stacked sources, where ϕ_0 denotes the normalization of the expected stacked flux. Those 100 sources have been unblinded. The sensitivity and discovery potential derived from the KM3NeT/ARCA6-21 full dataset are computed for the 100 brightest sources of the sample. Results are shown in Figure 116. Both the 90% confidence level sensitivity and the 3σ discovery flux lie approximately two orders of magnitude above the stacked central flux. The associated flux uncertainty described before is also shown. Before unblinding the data, the potential impact of source overlap on stacking analyses was evaluated by assessing the angular separation among the 100 most luminous sources in the catalogue. The objective was to identify pairs with separations below the angular resolution of KM3NeT/ARCA. Figure 115 shows the logarithm of the angular separation for all possible pairs among the top 100 brightest sources in the selected HBLs sample. Among these sources, only two pairs exhibit separations smaller than 1° : 3HSPJ021252.1+224452 and 3HSPJ021632.1+231450 are separated by 0.97° , while 3HSPJ231905.1-420648 and 3HSPJ232240.4-422042 are separated by 0.7° (see Appendix B for their exact coordinates). In the latter case, the separation is comparable to the detector resolution. As both sources are relatively faint (53rd and 55th in luminosity) and sensitivity saturation is already reached at this stage, their exclusion does not affect the results, as verified by repeating the analysis without them, which yielded consistent performances.

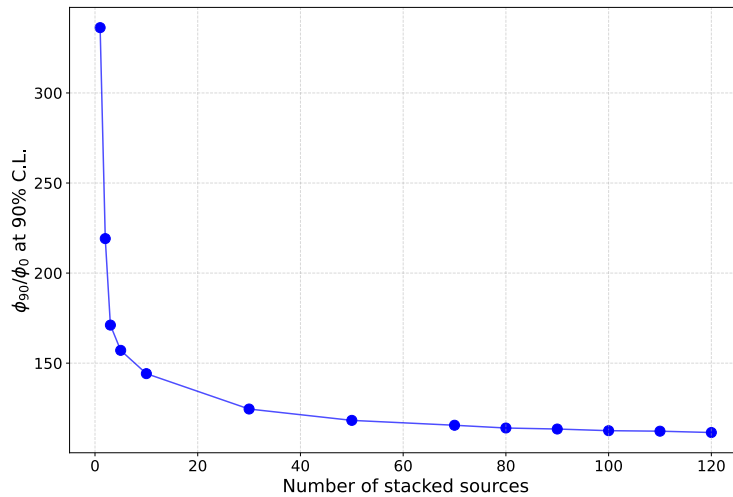


Figure 114: ϕ_{90}/ϕ_0 at 90% C.L. plotted as a function of the number of stacked sources. Sources are stacked according to their expected neutrino yield in KM3NeT/ARCA6-21 given by the assumed spectral model of LeHa-Paris.

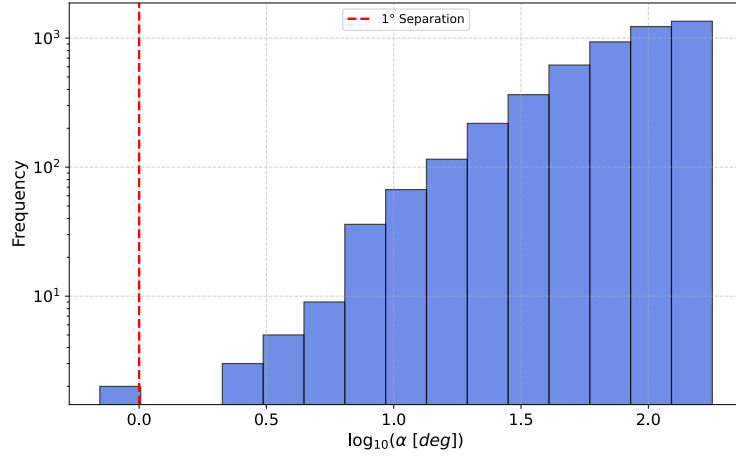


Figure 115: Logarithm of the angular separation (α) between all possible pairs among the top 100 brightest sources in the selected sample of HBLs. This value is computed for every unique pair of sources within the top 100 list.

7.4.1 Upper limits

Subsequently, data have been unblinded: the analysis was repeated using a realization of the dataset in which the true locations of the selected events, expressed in equatorial coordinates, were considered. The sky map of unblinded data is shown in Figure 117. No significant excess of events was observed over the background expectation. The calculated p-value is 0.07, corresponding to a statistical significance of 1.4σ , in a one-sided convention. Then, 90% confidence level upper limits on the stacked flux have been derived and are shown in Figure 116, lying approximately a factor 40% above the sensitivity and a factor ~ 150 above the central expected flux.

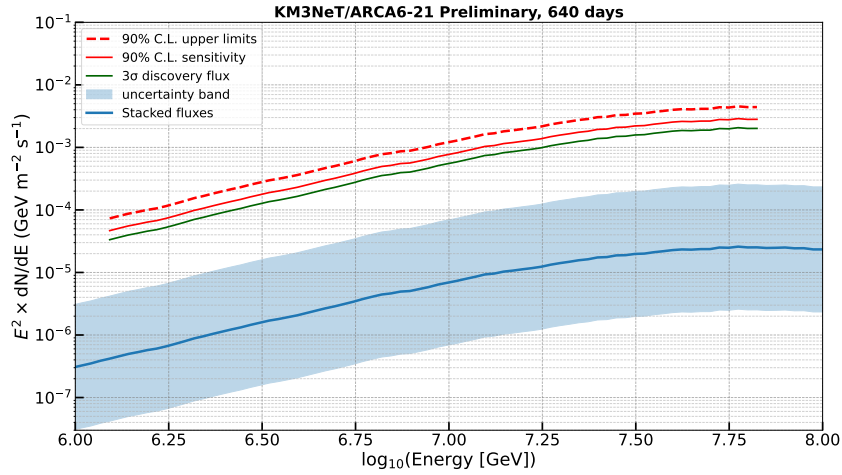


Figure 116: Sensitivity at 90% confidence level (solid red line) and discovery flux at 3σ significance (solid green line) for the stacked flux (solid blue), shown in the energy range where 90% of the signal is expected. The shaded light blue region indicates the flux uncertainty. The upper limit on the central flux is indicated as a red dashed line.

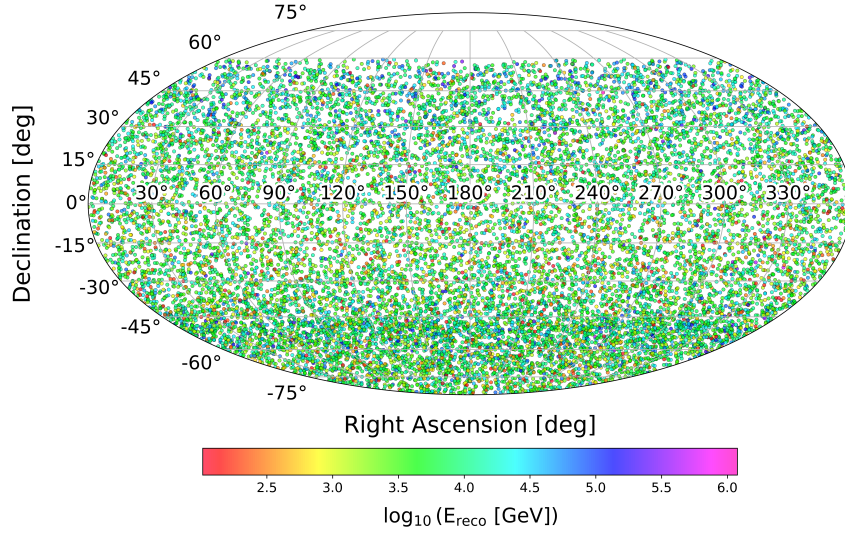


Figure 117: Sky map in equatorial coordinates of the KM3NeT/ARCA6-21 unblinded dataset. Color code indicates the logarithm of the reconstructed energy for the select track-like events.

7.4.2 Comparison with IceCube results

The upper limits derived in this work can be placed in the broader context of previous IceCube searches for neutrino emission from blazars. To enable such a comparison, the stacked single-flavor neutrino flux from HBLs was extrapolated to a quasi-diffuse level by dividing it by the relevant solid angle. The solid angle corresponding to the adopted declination cut at 40° (see Section 6.4) was used, calculated as $\Delta\Omega = 2\pi[\sin(40^\circ) - \sin(-90^\circ)] \approx 3.3\pi$. This choice is justified because the estimated flux is valid only within this portion of the sky and within the considered redshift range. Assuming an isotropic distribution and that all sources behave similarly, the flux per unit solid angle should be representative of other sky regions. Figure 118 compares the results of this analysis with constraints obtained by IceCube using a stacking analysis of blazars from the 2nd Fermi-LAT AGN (2LAC) catalogue [195]. In that study, IceCube performed a stacking likelihood analysis searching for cumulative neutrino emission from blazars with a dataset collected between 2009 and 2012, utilizing its 59-string (IC-59), 79-string (IC-79), and 86-string (IC-86) configurations, optimized for the detection of track-like events. No statistically significant excess was observed, and the resulting limits were interpreted as constraints on the maximal contribution of blazars to the diffuse TeV–PeV neutrino flux. The analysis also provides constraints on several theoretical models for neutrino production in blazars.

As evident from Figure 118, results obtained by IceCube, assuming a single power-law spectral index (Γ_{SL}) of -2.2 for the flux of all 2LAC blazars (equal-weighting scheme), are higher than those derived in this work. This difference is expected, as the spectral assumption in this analysis differs significantly from the power-law hypothesis used by IceCube. In particular, in the energy range between 1 and 3 PeV, the upper limits for HBLs improve upon those from IceCube, indicating a stronger constraint on the contribution of those sources to the diffuse astrophys-

ical neutrino flux. An important remark is that this analysis focuses solely on HBLs, while the IceCube study considered the whole 2LAC blazar population, which is dominated by FSRQs. Also shown in Figure 118 are IceCube upper limits on specific theoretical predictions for the diffuse ($\nu_\mu + \bar{\nu}_\mu$) emission from HSP blazars. These limits are obtained using the same IceCube dataset but test model-dependent expectations. These models do not use the same source catalogue as in this work, and both provide predictions for the diffuse flux. Therefore, the approach is different: rather than starting from individual sources and extrapolating to the quasi-diffuse flux, these studies directly estimate the diffuse emission. The models themselves also differ in their assumptions and methodologies. In particular, Padovani et al. [196] assume a correlation between neutrino and gamma-ray emission above 10 GeV, while Mücke et al. [197] model neutrino production within the Proton Synchrotron Blazar scenario, where the high-energy peak of the SED arises from proton synchrotron radiation and electromagnetic cascades initiated by $p\gamma$ interaction. Neutrinos are generated via photo-meson production with the synchrotron peak photon field. It is anyway worth noting that the theoretical ($\nu_\mu + \bar{\nu}_\mu$) flux predicted in [197] falls within the uncertainty band of the quasi-diffuse single-flavor neutrino flux from HBLs, modeled using LeHa-Paris. Finally, a comparison with the IceCube diffuse astrophysical neutrino flux allows to place a constraint on the maximal contribution of HBLs to the observed diffuse emission. Although IceCube measurements do not extend beyond the PeV scale, the limits derived in this work imply that, at energies of the order of 1 PeV, HBLs can contribute no more than roughly 25% to the observed diffuse neutrino flux.

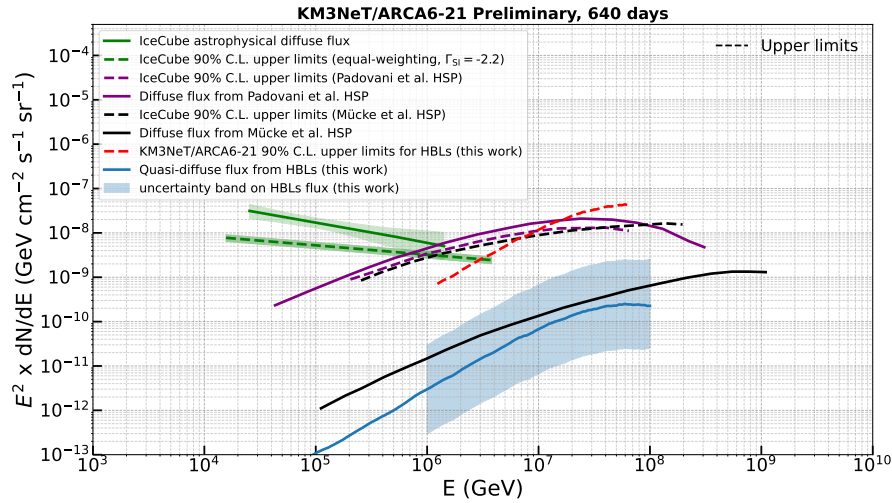


Figure 118: Comparison of 90% C.L. upper limits (dashed lines) on different neutrino flux models with the astrophysical diffuse flux measured by IceCube (solid green line) [198]. The IceCube upper limits include model-dependent predictions for HSP blazars (purple and black lines) and the 2LAC blazar stacking analysis, in an equal-weighting scheme, with $\Gamma_{SI} = -2.2$ (dashed green line). Theoretical models and IceCube upper limits are taken from [195]. The HBLs stacked flux calculated in this work is also shown (solid blue line) together with its uncertainty band (light blue shaded region, within its energy range of validity) and the corresponding KM3NeT/ARCA6-21 90% C.L. upper limits (red dashed line).

TIME-INTEGRATED AND TIME-DEPENDENT ANALYSES WITH KM₃NeT/ARCA₂₁ USING AN UNBINNED LIKELIHOOD METHOD

As shown in Chapter 7, the expected neutrino fluxes from HBL blazars are about two orders of magnitude below the current sensitivity of KM₃NeT/ARCA6-21. Although the sensitivity is expected to improve rapidly with larger detector configurations, it remains important to develop methods that enhance the performances with the present array. Two methods can be exploited: replacing the binned likelihood with an unbinned likelihood approach, since unbinned methods are expected to provide better sensitivities, and incorporating the event time information into the likelihood. Indeed, because blazars are highly variable sources, exploiting neutrino arrival times can improve signal-background separation. In this context, this Chapter presents the development of an unbinned likelihood framework for time-integrated point source searches, adapting existing unbinned analysis codes, originally developed for the full KM₃NeT/ARCA configuration (230 strings), to the detector in its 21-string configuration (KM₃NeT/ARCA₂₁). The method is based on an extended unbinned likelihood-ratio approach, introduced in Chapter 5, which compares a signal-plus-background hypothesis to a background-only scenario by evaluating, for each event, the probability of being either signal or background. The performances of KM₃NeT/ARCA₂₁ in the search for neutrino point sources are compared with those of a binned likelihood approach, in order to study relative performance between different statistical frameworks. Both methods rely on accurate detector modeling through its Instrument Response Functions (IRFs), which include effective area, Point Spread Function (PSF) and energy resolution. Then, a time-dependent component was also added into the unbinned framework by assuming a rectangular-shaped profile for the signal time emission, leading to the first time-dependent performances of KM₃NeT/ARCA.

Considering the KM₃NeT/ARCA₂₁ data sample and event selection outlined in 7.1, the Chapter firstly presents the construction and usage of the detector IRFs (8.1), alongside the statistical frameworks employed (8.2); after the statistical analysis, the performances of binned and unbinned extended likelihood methods are compared in 8.3, including a discussion about the application of systematic effects. Finally, ongoing developments towards a time-dependent unbinned likelihood framework are introduced in 8.4. The detection prospects here presented are preliminary and represent the initial steps toward a full implementation of unbinned likelihood methods for astronomy point source studies.

8.1 INSTRUMENT RESPONSE FUNCTIONS

The signal expectation is derived from Monte Carlo (MC) simulations, using the IRFs. These functions, such as effective area and PSF, characterize the performance

of the detector and the reconstruction software, and they enable a fast estimation of event rates for a given neutrino flux. Most of them have already been introduced in Chapters 3, describing the performances of KM3NeT/ARCA, and 5, while describing the ingredients of binned and unbinned maximum likelihood analyses.

8.1.1 Effective area

The effective area, already defined in 3.4.3, can be obtained directly from the MC simulation, using the generation weights described in Chapter 4. The (average) effective area in a bin of energy E and solid angle Ω , for any flux, can be computed through the relation:

$$A_{\text{eff}} = \frac{N_{\text{det}}}{\iint \Phi \, dE \, d\Omega \, T}, \quad (97)$$

where N_{det} is the expected number of detected events, Φ is the assumed flux and T is the livetime. Because the effective area is independent of the flux, it is convenient to calculate it using a non-physical isotropic flux equals to $\Phi = E^{-1} [\text{GeV}^{-1} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}]$. In such a case, it can be written as:

$$A_{\text{eff}} = \frac{N_{\text{det}}}{\int_E \int_{\Omega} E^{-1} \, dE \, d\Omega \, T} = \frac{N_{\text{det}}}{\Delta\Omega \times T \times \int_{E_{\text{min}}}^{E_{\text{max}}} \frac{1}{E} \, dE} \quad (98)$$

$$= \frac{N_{\text{det}}}{\Delta\Omega \times T \times [\ln(E_{\text{max}}) - \ln(E_{\text{min}})]} = \frac{N_{\text{det}}}{\Delta\Omega \times T \times \ln(10) \times W}, \quad (99)$$

where $W = [\log_{10}(E_{\text{max}}) - \log_{10}(E_{\text{min}})]$ and represents the width of the logarithmic energy bin. For every bin, $\Delta\Omega = 4\pi/N_{\text{bins}}$ sr, where N_{bins} is the number of bins used in solid angle. For the KM3NeT MC simulations, the number of expected neutrino events can be related to the generation weight w_{gen} with the relation $N_{\text{det}} = \sum_{i \in \text{bin}} w_{\text{gen},i} E_i^{-1}$. Thus, the effective area reads as:

$$A_{\text{eff}} = \frac{1}{\Delta\Omega \ln(10) W T} \sum_{i \in \text{bin}} w_{\text{gen},i} E_i^{-1}. \quad (100)$$

Figure 119 shows the sky-averaged effective area (A_{eff}) of KM3NeT/ARCA21, as obtained from MC simulations of cosmic neutrinos. All (anti)neutrino flavors were simulated, including both charged current (CC) and neutral current (NC) interactions. The track-like event selection described earlier has been applied.

8.1.2 Point Spread Function

As explained in Chapter 5, in the case of tracks, the PSF describes the probability of reconstructing a signal at a given angular distance from the true source direction. Physically, this angle arises from the kinematic angle between the parent neutrino and the produced lepton, but, more importantly, it is affected by the reconstruction process. In simulations, to get the PSF, the angle between the generated muon direction and the reconstructed track direction is convolved with the angle between

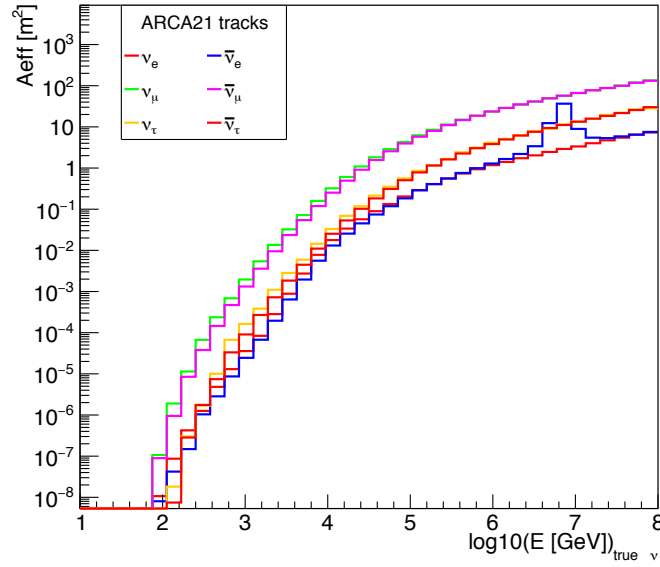


Figure 119: Sky-averaged effective area of KM3NeT/ARCA21, obtained at selection level for all (anti)neutrinos flavors, both in CC and NC interactions. As expected, the A_{eff} of $\bar{\nu}_e$ increases around 6 PeV due to the Glashow resonance (see 1.4.1).

the interacting neutrino and the generated muon. From the angular error distribution, it is possible to derive the probability distribution that describes how signal events are expected to spatially distribute around a candidate point source. This distribution can be defined as the probability density of the angular separation α per unit solid angle Ω . By definition, the PSF satisfies the relation:

$$\int \frac{dP(\alpha)}{d\Omega} d\Omega = 1. \quad (101)$$

It can be visualized in various ways. In particular, the PSF in terms of solid angle is related to the angular separation via the Jacobian transformation:

$$\frac{dP}{d\Omega} = \frac{d\alpha}{d\Omega} \cdot \frac{dP}{d\alpha} = \frac{1}{2\pi \sin(\alpha)} \cdot \frac{dP}{d\alpha} = \frac{1}{2\pi \alpha \ln(10) \sin(\alpha)} \cdot \frac{dP}{d \log_{10}(\alpha)}. \quad (102)$$

Figure 120 illustrates the PSF for all ν_μ CC and NC events with an E^{-2} energy spectrum, expected to be detected during the KM3NeT/ARCA21 data-taking period. The distributions are averaged over the full zenith range and shown for several energy intervals. The quantity $\frac{dP}{d \log_{10}(\alpha)}$ is plotted as a function of α , which is the angle between the true and reconstructed tracks. For flavor ν_μ , the median angular errors of the distributions are 0.27° for $\log_{10}(E/\text{GeV}) \in [4,6]$, 0.20° for $\log_{10}(E/\text{GeV}) \in [6,8]$, and 0.46° for $\log_{10}(E/\text{GeV}) \in [2,4]$. The all-energy all-flavors $\frac{dP}{d \log_{10}(\alpha)}$ distribution of KM3NeT/ARCA21 exhibits a median angular error at the level of 0.3° (Figure 58). Figure 121, instead, displays the function $\frac{dP}{d\Omega}$, not-normalized, for the energy range $\log_{10}(E [\text{GeV}]) \in [4,6]$, which contains the bulk of the expected events for the power law under study in this Chapter. The distribution has also been smoothed and constrained to a constant value at very small angles. This reflects the expectation that all directions close to the source should be nearly equally probable.

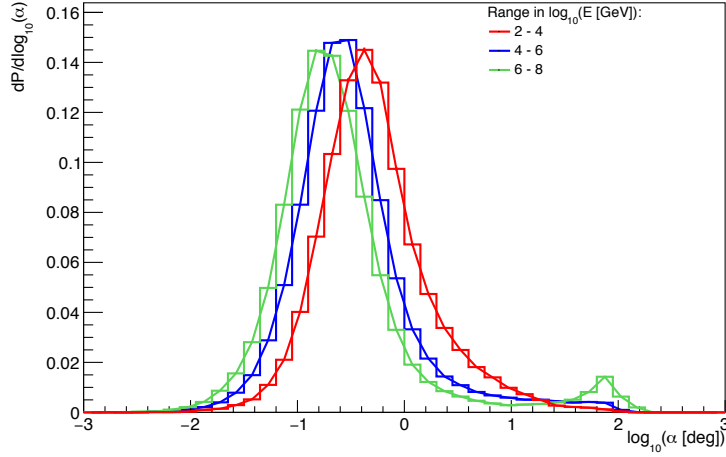


Figure 120: KM3NeT/ARCA21 $\frac{dP}{d\log_{10}(\alpha)}$ distribution for all ν_μ CC and NC selected track-like events with an E^{-2} energy spectrum, shown in the indicated energy ranges.

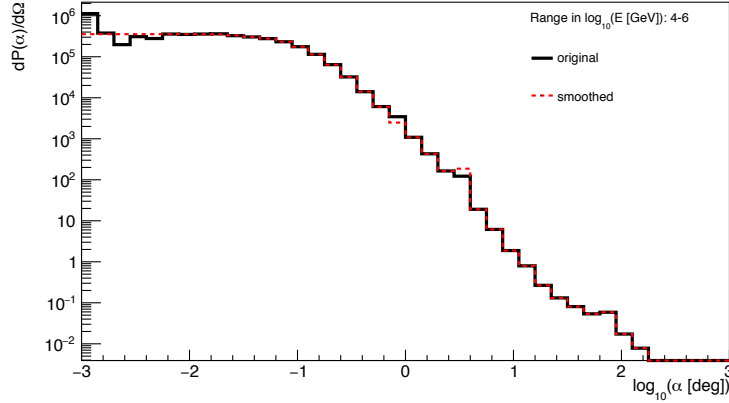


Figure 121: KM3NeT/ARCA21 PSF for all ν_μ CC and NC selected track-like events with an E^{-2} energy spectrum. The (not-normalized) distribution is smoothed (red dashed line) in order to have, for very small angles, a constant function.

8.2 SEARCH METHODS

The goal of this study is to compare the binned and unbinned extended maximum likelihood frameworks introduced in Chapter 5. In particular, the binned likelihood, defined in Equation 59, represents the reference method already in use in the Collaboration, while the unbinned likelihood, defined in Equation 65, has been adapted from the full detector implementation to the partial KM3NeT/ARCA21 configuration. Being a steady point source analysis, the unbinned likelihood has been built considering only the energy and the direction in the definition of the PDFs. The study has been performed over a representative range of declinations, spanning from the Southern to the Northern celestial Hemisphere. Specifically, the following set of declination values has been considered:

$$\delta \in \{-85^\circ, -70^\circ, -40^\circ, -30^\circ, -15^\circ, 0^\circ, 15^\circ, 40^\circ\},$$

analogue to the declination grid adopted in Section 7.2. Signal strengths (or number of signal events) are varied systematically across both frameworks. Inside the unbinned codes, the number of simulated signal events (n_s) is varied from 0 to 11 at a step of 0.5, while in the binned case, the simulated signal strength (μ_{true}) is varied between 0 and 6 at a step of 0.1. Ranges differ because of the flux normalization adopted in the two approaches, while the step sizes are chosen as a compromise between results accuracy and computational time. It was verified that the specific choice of these parameters does not affect the final results. Only the track channel is considered, including contributions from all neutrino flavors, as detailed above. The simulation involves a large number of pseudo-experiments (PEs), with higher statistics allocated to the unbinned framework, in order to better populate the tail of the H_0 distribution: specifically 6 millions of PEs have been simulated for the H_0 hypothesis of the unbinned case, while $5 \cdot 10^4$ have been considered in the H_1 case. Binned results, instead, have been obtained simulating $2 \cdot 10^5$ PEs for H_0 and $5 \cdot 10^4$ for H_1 . These numbers of PEs are sufficient to obtain stable and reliable results, and increasing them further would not affect the stability of the estimates. Figure 122 displays the test statistic (λ) as a function of the number of fitted signal events ($\hat{n}_s$), based on 50,000 simulations of a dataset containing 10 injected signal events, using the unbinned likelihood framework. As expected, a linear correlation between the two quantities is observed.

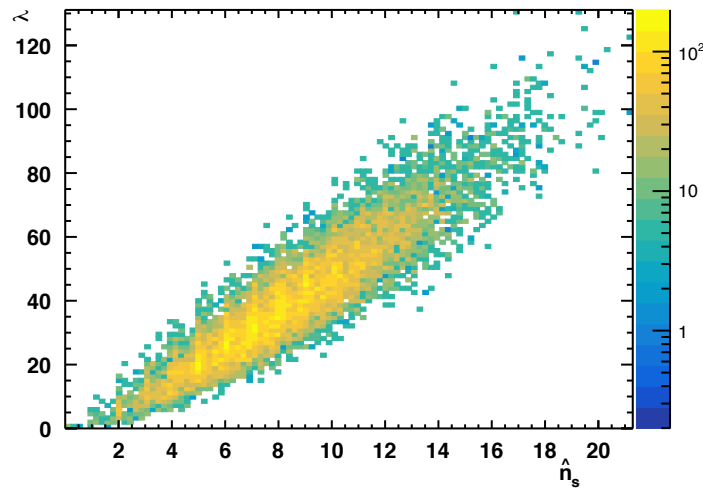


Figure 122: The test statistic as a function of the associated fitted number of signal events, corresponding to the injection of 10 signal events at $\delta = -85^\circ$.

After that test statistic distributions have been produced, analyses performances in terms of sensitivity and discovery potential are derived as outlined in 5.4, employing a one-sided convention method for evaluating the discovery potentials. To do so, confidence level (C.L.) and p-values have been computed for each simulated scenario, corresponding to a given number of n_s , according to methods of 5.4. Figures 123 and 124 show the C.L. and p-value as a function of the simulated number of signal events in the unbinned codes, obtained at declination $\delta = -85^\circ$ as an example. The sensitivity is determined by identifying the point where the fitted curve intersects the horizontal line at 0.9. The 3σ and 5σ discovery thresholds (one-sided convention) are shown in Figure 124, from which the corresponding

discovery potentials are derived and then converted into discovery fluxes. A similar approach is adopted in the binned case. The statistical analysis is repeated for each declination and performances between the two likelihood methods are compared, as reported in the following.

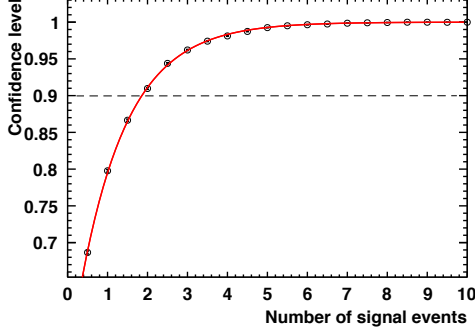


Figure 123: Confidence level calculated as a function of the injected number of signal events. Sensitivity is extracted considering the line intersecting the fitted graph at 0.9.

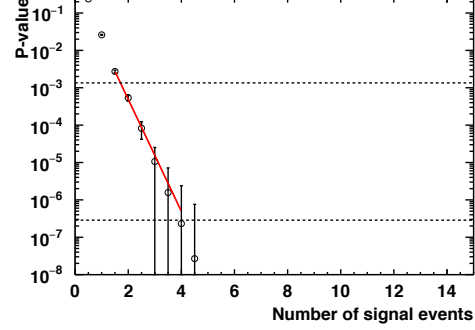


Figure 124: P-value calculated as a function of the injected number of signal events. Dots are fitted between the 3σ and 5σ levels (dashed lines), in a one-sided convention.

8.3 COMPARISON BETWEEN BINNED AND UNBINNED APPROACHES

In order to test the performances of KM₃NeT/ARCA21 to detect a neutrino point source, it's sensitivity to point-like sources is compared, across different declinations, considering both a binned and unbinned likelihood frameworks, and without considering, for the moment, any systematic uncertainty. After that $n_s^{90\% \text{ C.L.}}$ is derived as in Figure 123, it is converted into a single-flavor flux, using the acceptance definition of Equation 73. Figure 125 shows the comparison between the binned and unbinned KM₃NeT/ARCA21 sensitivities to point-like sources, assuming an E^{-2} cosmic neutrino spectrum and considering only track-like events. The unbinned sensitivity curve lies approximately 10% below the binned one in both the Southern and Northern Sky.

The comparison is extended to include the 3σ and 5σ discovery fluxes. Figure 126 presents the discovery fluxes for the binned and unbinned cases alongside the corresponding sensitivities. In the unbinned case, the 3σ discovery flux shows an improvement of approximately 5% compared to the binned result in the Southern Sky. However, the unbinned performance degrades as the analysis approaches the visibility limit of KM₃NeT/ARCA, lying above the binned line. The ratio between binned and unbinned 5σ limits is consistent with a factor 1 in the Southern Sky, while in the Northern Sky it remains unclear which method performs better, as the trend appears to be dependent of declination. The origin of this behavior is still under investigation. It is evident that the 3σ and 5σ single-flavor discovery fluxes in the unbinned framework tend to flatten in the Northern Sky. This may be attributed to inaccuracies in the background modeling, particularly because the

current description of the data's background distribution (Figure 57) is declination-independent. An updated framework, introducing energy PDFs defined per declination band, is currently under development to address this possible limitation.

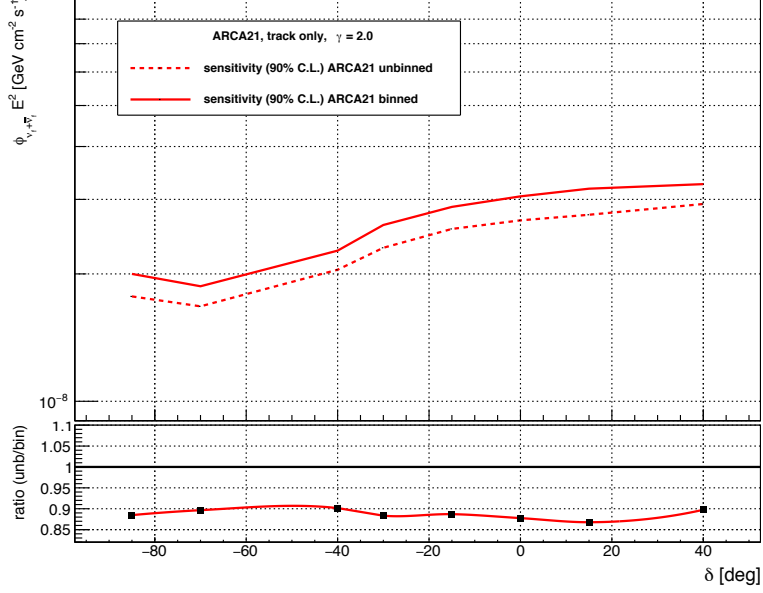


Figure 125: Comparison between binned (solid red) and unbinned (red dashed) KM3NeT/ARCA21 sensitivities to point-like sources, for an E^{-2} neutrino spectrum and considering only track-like events. The unbinned approach yields up to an improvement in sensitivity up to more than 10%.

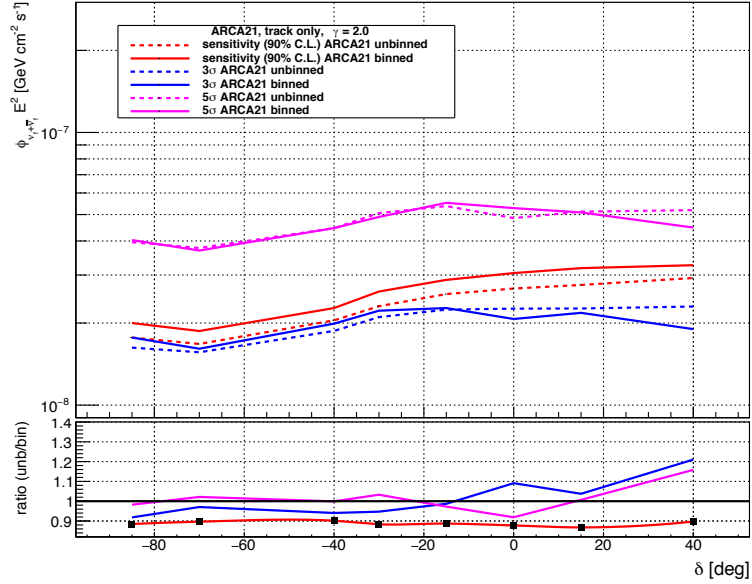


Figure 126: Comparison between point source results in binned (solid lines) and unbinned (dashed lines) analyses. KM3NeT/ARCA21 sensitivities (red), 3 σ discovery flux (blue) and 5 σ discovery flux (magenta) are compared considering an E^{-2} neutrino energy spectrum.

8.3.1 Systematics effect

The same systematic uncertainties as those used in the point source analysis presented in Section 7.2 are considered. They mainly affect two key detector performance parameters: the angular resolution (0.5° uncertainty) and the acceptance (30% spread). These uncertainties have been included in both the binned and unbinned analyses, and their impact has been evaluated by introducing each of them individually. Figure 127 shows the comparison between KM3NeT/ARCA21 sensitivities for an E^{-2} spectrum, analogously to Figure 125, adding also the effect of the systematic on the PSF: still a 10% improvement is seen in the unbinned case. Adding also the systematic on the acceptance, at most a 5% improvement is observed with unbinned methods (Figure 128).

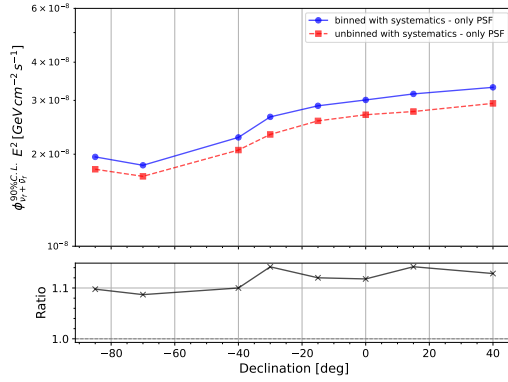


Figure 127: Comparison between binned (blue dots) and unbinned (red squares) KM3NeT/ARCA21 sensitivities to point-like sources, for an E^{-2} neutrino spectrum and considering only the PSF systematic.

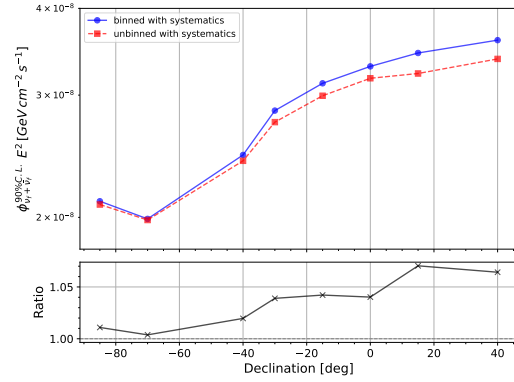


Figure 128: Comparison between binned (blue dots) and unbinned (red squares) KM3NeT/ARCA21 sensitivities to point-like sources, for an E^{-2} neutrino spectrum, considering systematics on the PSF and on the acceptance.

Figure 129 presents the comparison between the binned and unbinned frameworks for the 3σ single-flavor discovery flux, taking into account the impact of both systematic uncertainties. In this case, the trend reverses: the binned analysis outperforms the unbinned one, achieving an improvement of up to 20%. These results indicate that systematic uncertainties have a stronger impact on unbinned methods, likely because they evaluate each event individually. In contrast, the binned approach, which relies on two-dimensional histograms, may partially mitigate these effects through statistical averaging. A similar trend is also found in the case of the 5σ discovery flux. Further investigations are undergoing to understand this result.

8.4 TOWARDS A TIME-DEPENDENT UNBINNED LIKELIHOOD FRAMEWORK

Figure 125 demonstrated the potential of unbinned methods to enhance sensitivity in the search for point-like neutrino sources. Beyond this, unbinned techniques are

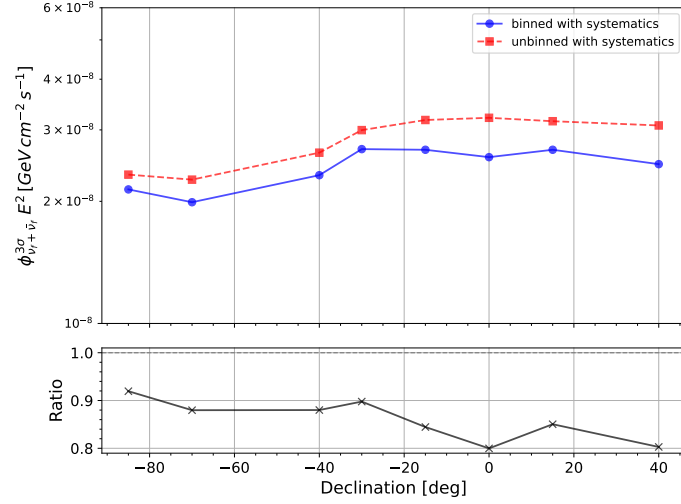


Figure 129: Comparison between binned (blue dots) and unbinned (red squares) KM3NeT/ARCA21 3σ discovery fluxes to point-like sources, for an E^{-2} neutrino spectrum, considering systematics on the PSF and on the acceptance.

particularly well-suited for time-dependent analyses, where a temporal PDF with two additional parameters (flare center and duration) is included in the likelihood maximization. This section presents initial developments toward a time-dependent unbinned likelihood framework. In this setup, the signal temporal PDF assumes a rectangular-shaped (or box-shaped) profile (see Section 5.2), while the background temporal PDF can be either assumed to be a uniform distribution inside the data-taking period of KM3NeT/ARCA21 or can be derived directly from the Modified Julian Date (MJD) distribution of its data, shown in Figure 62. Such data have been analyzed according to the methods of Section 8.2, with less stringent selection criteria compared to those described in Section 7.1. Specifically, the background temporal modeling was performed using events that passed the precuts, directional cuts and anti-noise selection, already introduced in 7.1. This provides a time distribution shape that adequately reflects the expected background behavior while remaining conservative in terms of event selection, given that the goal is limited to framework testing, and ensuring sufficient statistics for the construction of B_{time} . For the signal PDFs, an additional BDT cut at 0.95 was applied, following the selection optimized by the Collaboration in previous point source analyses, as described in [134] and [192]. The same selection is also applied to the non-temporal background PDFs, namely B_{space} and B_{energy} .

As an initial test, the point-source search is performed for three representative declinations: -15° , 0° , and 15° . In each case, a box-shaped neutrino flare is assumed, characterized by its central emission time T_0 and temporal width σ_t , yielding a total flare duration of $2\sigma_t$. Its PDF can be defined as:

$$S_{\text{time}}(\text{MJD}) = \begin{cases} \frac{1}{2\sigma_t}, & \text{if } \text{MJD} \in [T_0 - \sigma_t, T_0 + \sigma_t], \\ 0, & \text{otherwise.} \end{cases} \quad (103)$$

The central time T_0 is fixed at the midpoint of the data-taking period, corresponding to T_0 [MJD] = 60023, while the following values of σ_t have been tested: {2, 5, 10, 30, 50, 170}, expressed as number of days. B_{time} is assumed to be a uniform distribution between the first and last day of data-taking (1-day binning), meaning that each day is associated to the same background probability. As in Section 8.3, the number of signal events remains the only free parameter in the analysis, and the energy and spatial PDFs are combined with the corresponding temporal PDF in the likelihood definition. After that the PEs generation has been performed, the statistical analysis allows to derive the discovery potentials from test statistic distributions. These values are inferred for each specific case of flare duration ($2\sigma_t$). Figure 130 shows the 3σ discovery potential, obtained for an E^{-2} flaring neutrino source, with a box-shaped profile of width σ_t . Results are shown for all

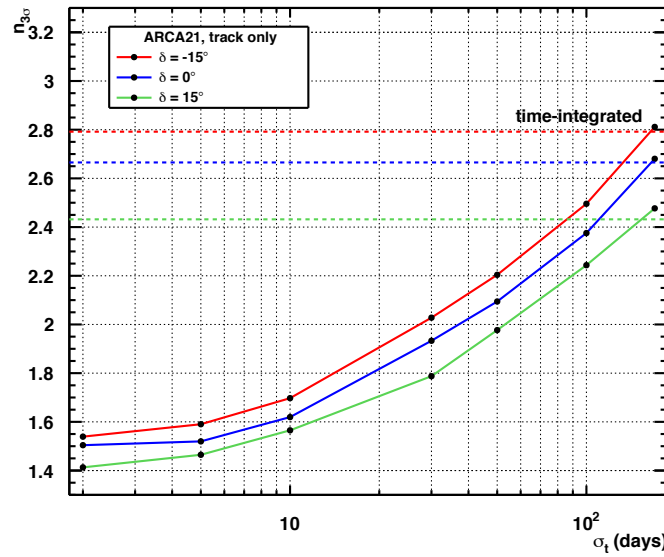


Figure 130: 3σ discovery potential of KM₃NeT/ARCA21 as a function of the flare's width σ_t . Results are shown for different declinations (δ) and are compared to the time-integrated discovery potentials (dashed horizontal lines), obtained at the same selection level of the time-dependent ones.

the declinations under consideration and are compared to the time-integrated limits obtained for the same selection level. It can be observed that, for shorter flares, $n_{3\sigma}$ improves significantly compared to the time-integrated analysis, due to the additional information provided by the temporal component. As the flare duration increases and approaches the length of the KM₃NeT/ARCA21 data-taking period, the signal becomes less distinguishable from the background, since its time profile increasingly resembles that of the uniform background distribution. Additionally, as expected, the discovery potential improves with decreasing declination, from positive to negative, similarly to the time-integrated cases.

Since previous results rely on the assumption of a uniform background temporal PDF, the model has been further tested using the actual time profile of the data, as shown in Figure 62. In this scenario, the analysis becomes sensitive to variations in the background rate across different days of data-taking. Using the same central emission time, corresponding to the midpoint of the KM₃NeT/ARCA21

data-taking period, Figure 131 shows the 3σ discovery potential as a function of the flare duration, for a source at declination $\delta = -15^\circ$ and assuming an E^{-2} neutrino spectrum. Results are shown for both a flat background hypothesis and a realistic background model based on the observed MJD of data. The realistic background model yields an improved discovery potential, showing that a flat temporal PDF overestimates the background within the considered time window, as the true background rate at that time is lower than the lifetime average.

Finally, the impact of varying the central emission time of the flare has been investigated, still assuming a realistic background based on the MJD of the data. Additional central emission times considered are the beginning (T_0 [MJD] = 59903) and toward the end (T_0 [MJD] = 60143) of the data-taking period. The unbinned time-dependent likelihood analysis was repeated for these cases and compared to the results obtained using the midpoint as T_0 . The outcomes at $\delta = -15^\circ$ are presented in Figure 132. The shape of the discovery potential curve highlights that, for short flares, results are compatible across different T_0 , despite being slightly influenced by the features of the background temporal PDFs around that specific central emission day. As σ_t increases, results referred to T_0 [MJD] = 59903 and T_0 [MJD] = 60143 converge, remaining below the values of $n_{3\sigma}$ for T_0 [MJD] = 60023. This is due to the fact that, when placing the central emission time at the border of the period, part of the flare lies outside the data-taking interval. Since signal events are generated only within this window, the injection is confined to a shorter time span, which results in having signal events more temporally concentrated, and therefore enhancing the discovery potential. Conversely, when T_0 is set at the center of the data-taking period, the box-shaped flare is fully contained and events are instead spread over the whole time interval.

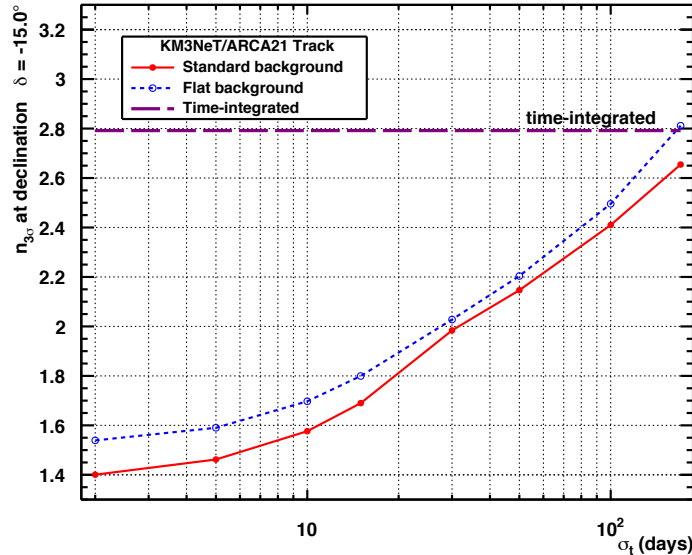


Figure 131: 3σ discovery potential as a function of flare duration for a flaring source at declination $\delta = -15^\circ$. A uniform temporal distribution (blue dots) and a realistic background (red dots) based on the MJD of KM3NeT/ARCA21's data are assumed. Time-integrated limit is also shown as a purple dashed line.

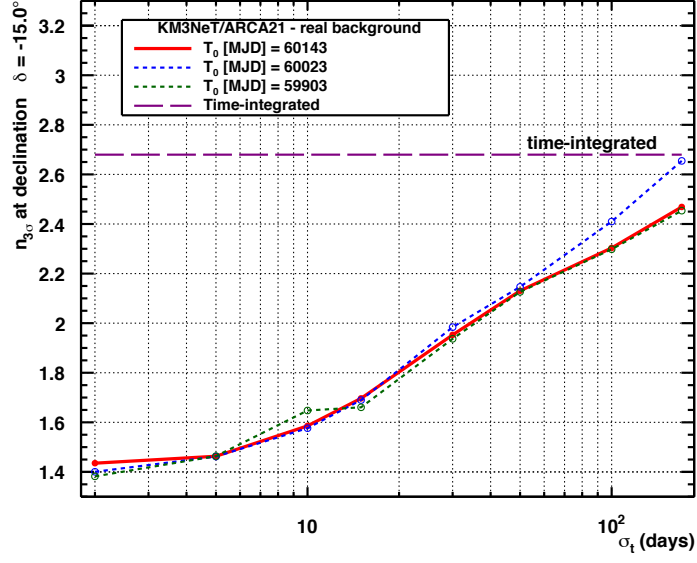


Figure 132: Comparison of the 3σ discovery potential at declination $\delta = -15^\circ$ for different central emission times of the flare: T_0 [MJD] = 59903 (dashed green), T_0 [MJD] = 60023 (dashed blue), and T_0 [MJD] = 60143 (solid red). Time-integrated limit is also shown as a purple dashed line.

This section has highlighted the potential of time-dependent unbinned methods over time-independent approaches in the search for transient and variable neutrino point sources. Moreover, it presents the first time-dependent performance of the KM₃NeT/ARCA detector and provides the foundation for future neutrino flares searches with KM₃NeT/ARCA data.

SUMMARY AND CONCLUSIONS

This thesis, developed in the context of the KM₃NeT Collaboration, investigated the role of blazars as potential sources of high-energy neutrinos. It firstly discussed the modeling of their radiation processes in a one-zone lepto-hadronic scenario using the LeHa-Paris code, from which the corresponding expected neutrino fluxes were derived. Afterwards, a stacking binned likelihood method is applied to KM₃NeT/ARCA data, considering configurations with 6, 8, 19, and 21 instrumented detection units (KM₃NeT/ARCA6–21) and based on flux predictions from LeHa-Paris. Finally, it studied the performances of the KM₃NeT/ARCA neutrino telescope in detecting point-like neutrino sources adopting different statistical techniques, proving that KM₃NeT/ARCA21 sensitivity can be enhanced with an unbinned likelihood approach. Moreover, a time-dependent term was incorporated into the analysis framework by assuming a box-shaped emission time profile for the signal component, allowing a comparison between the time-dependent and time-integrated analysis performances.

In the first part of the thesis, a general overview of multi-messenger astronomy was presented, emphasizing the complementarity of cosmic rays, gamma rays, neutrinos, and gravitational waves in unveiling the most energetic phenomena in the Universe. Special attention was given to the principles of neutrino detection, including light propagation in the medium and characteristic event signatures in neutrino telescopes. A comparative overview of neutrino telescopes was provided, distinguishing under-ice and underwater detectors, preceded by a discussion on the main background sources in deep-sea experiments. The design of the KM₃NeT telescope was then examined in detail, along with an overview of the detection of the ultra-high-energy (UHE) neutrino event KM₃-230213A, which marked a significant milestone for the astroparticle physics community.

As main topic, this thesis addressed high-energy neutrino production in blazars. Using the LeHa-Paris steady-state numerical code, the Spectral Energy Distribution (SED) of the high-frequency-peaked BL Lac (HBL) object PKS 2155-304 was modeled, enabling the derivation of its associated neutrino flux under lepto-hadronic scenarios, in which both relativistic protons and electrons are accelerated in the jets of the source. Its predicted neutrino SED peaks at around 100 PeV and exhibits a harder spectrum compared to a commonly assumed E^{-2} power-law scenario. Then, a methodology was developed to extend the neutrino model of PKS 2155-304 to the class of selected HBLs. This phenomenological approach assumed the synchrotron peak flux of each source as a proxy for its expected neutrino flux, while the respective neutrino energy was transformed according to the source redshift. Cross-validation with the HBLs Mrk 421 and VER J0521+211 showed that, in the neutrino energy range $1 \text{ PeV} \leq E_\nu \leq 100 \text{ PeV}$, the Mrk 421 model agrees with the rescaling within a factor of 5, while the VER J0521+211 model agrees within a factor of 10. This factor of 10 is considered as the uncertainty inherent to the phenomenological method. As an initial evaluation, a point source binned likelihood analysis was subsequently performed with KM₃NeT/ARCA6–

21, whose selection has been optimized for neutrino point source searches, leading to a total of 17285 candidate track-like events over a livetime of 640 days. Adopting the simulated PKS 2155-304 neutrino flux, the detection prospects of KM₃NeT/ARCA6-21 indicate improved sensitivities and discovery potentials compared to a conventional E^{-2} point source search. Building on this, a binned stacking analysis on a sample of HBL blazars was performed, motivated by the expectation that the collective contribution of many individually faint sources could yield a detectable neutrino signal. A total of 232 sources were selected from the 3HSP catalogue. The stacking search using KM₃NeT/ARCA6-21 data revealed no significant neutrino excess after unblinding, and upper limits were set, lying approximately 40% above the KM₃NeT/ARCA6-21 sensitivity to the stacked flux. When compared with the IceCube diffuse astrophysical neutrino flux, these results indicate that HBLs can account for at most $\sim 25\%$ of the observed diffuse neutrino emission at PeV energies. With the ongoing expansion of KM₃NeT/ARCA's deep-sea infrastructure, future analyses with increased exposure and refined reconstruction capabilities are expected to improve these results.

Since the expected neutrino fluxes from HBL blazars are about two orders of magnitude below the current sensitivity of KM₃NeT/ARCA6-21, it remains crucial to develop methods that optimize the telescope's performance with the existing configurations. Because of that, the third part of the thesis focused on the development of unbinned likelihood methods to improve KM₃NeT/ARCA sensitivity to point-like neutrino sources. Two different statistical approaches to point source searches were compared, highlighting their relative advantages. In particular, an extended unbinned maximum likelihood framework was shown to achieve better sensitivities for point source analyses under an E^{-2} power-law assumption, yielding, in the absence of systematic uncertainties, a more than 10% enhancement compared to binned approaches. The gain is less pronounced when considering 3σ and 5σ discovery fluxes, where a more accurate declination-dependent background description may still be required. The comparison between binned and unbinned methods was further extended by incorporating systematic uncertainties. Under these conditions, the unbinned technique still provided a sensitivity improvement of about 5% for point source searches, while the binned method outperformed the unbinned one in terms of 3σ discovery flux, achieving an improvement of up to 20%. Results are preliminary and further checks are ongoing. Finally, the extension of the unbinned framework to time-dependent searches, assuming a rectangular-shaped temporal profile for the signal component, was outlined as a promising direction for prospective neutrino flare searches with KM₃NeT/ARCA data. In the future, unbinned likelihood stacking analyses, based on physically motivated neutrino fluxes, with the possibility of accounting also for the source time variability, may become an essential tool to deepen our understanding of the mechanisms powering cosmic accelerators.

Appendix

STUDY OF THE SYNCHRONIZATION LATENCIES BETWEEN THE BASE MODULES OF KM₃NeT / ARCA

This Appendix presents an analysis of the synchronization latencies within the KM₃NeT / ARCA detector base modules, specifically focusing on KM₃NeT / ARCA operating with 21 instrumented detection units (DUs). The study covers the period from 22 September 2022 to 20 March 2023, corresponding to data runs whose number ranges from 13288 to 15121. The analysis targets three DUs: DU₅, DU₉, and DU₃₂, each connected to a distinct junction box (JB), allowing for a representative assessment across different sub-sea connection devices. Figure 133 shows the detector configuration at the time of this study, when 21 strings were taking data. The estimation of the Round-Trip Time (RTT) relies on the WR_MU parameter stored in the KM₃NeT database, and repeatedly measured during each run. The Round-Trip Time Cable (RTTC) is then calculated by adjusting the measured RTT to account for all relevant transmission and reception latencies at both the Slave and Master ends, as outlined in the RTT relation in Section 3.3, and correcting for the associated delays. Its stability in time has been subsequently analyzed.

After a general overview of the White Rabbit system in KM₃NeT (A.1) and the introduction of some initial definitions (A.2), the results of the time calibration procedure are presented and discussed in Section A.3.

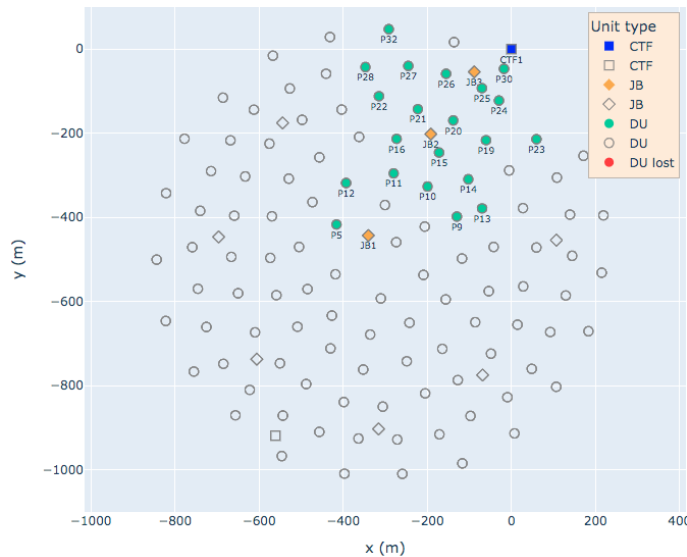


Figure 133: Layout of KM₃NeT/ARCA21 at the time in which data have been collected for this study. Green dots are referred to operating DUs, blue squares to the Cable Termination Frame (CTF), while orange rhombuses indicate the JB.

White-Rabbit (WR) is a technology that allows for precise synchronization of clocks across separate devices in an Ethernet network, such as Ethernet switches, Central Logic Boards (CLBs), or any device with the WR protocol installed [126]. WR enables point-to-point communication over bidirectional optical fibers, designed to reduce time signal degradation that typically occurs with long cables, and obviated also with the usage of powerful lasers (e.g. with output power between 4 dBm and 10 dBm). Upon startup, Ethernet devices initialize asynchronously, so internal clocks may initially differ. Clock frequencies are first phase-locked to ensure that one second measured on any device is equal in duration to that on another. Absolute time synchronization requires the Master to send its timestamp to the Slave. Specifically, the Master sends a message at time t_1 (Master clock) to the Slave, which receives it at t_2 (Slave clock). The Slave then sends a return message at t_3 (Slave clock), received by the Master at t_4 (Master clock). Because the wavelengths used for downlink (Master to Slave) and uplink (Slave to Master) differ, the propagation delays Δt and $\Delta t'$ are also different due to chromatic dispersion. From this, WR derives both the round-trip delay and the clock offset: $t_2 = t_1 + \Delta t + t_{\text{offset}}$ and $t_4 = t_3 + \Delta t' + t'_{\text{offset}}$. Assuming $t_{\text{offset}} = t'_{\text{offset}}$, and following Equation 44, the offset can be written as:

$$t_{\text{offset}} = \frac{(t_2 - t_1) + (t_4 - t_3) - \Delta t - \Delta t'}{2} = \frac{1}{2}[\text{RTT} - (\Delta t + \Delta t')], \quad (104)$$

If we define $\Delta t' = \alpha \Delta t$ (with α representing asymmetry), it becomes:

$$t_{\text{offset}} = \frac{1}{2}[\text{RTT} - \Delta t(1 + \alpha)]. \quad (105)$$

Synchronization thus requires an accurate determination of this asymmetry, which depends on wavelength dispersion. Fiber dispersion is described empirically as:

$$t = A(1 + B \cdot 10^{-8}((\lambda - \lambda_0)^2 + C(\lambda - \lambda_0))), \quad (106)$$

where A is the delay at zero-dispersion wavelength λ_0 , and B and C are fiber-specific constants. This leads to asymmetry α between two wavelengths λ_1 and λ_2 :

$$\alpha = \frac{1 + B \cdot 10^{-8}((\lambda_1 - \lambda_0)^2 + C(\lambda_1 - \lambda_0))}{1 + B \cdot 10^{-8}((\lambda_2 - \lambda_0)^2 + C(\lambda_2 - \lambda_0))}. \quad (107)$$

Measurements in Capo Passero and Toulon showed small but non-negligible asymmetries, e.g., $\alpha \approx 0.999995$ resulting in time delays of a few nanoseconds over long fiber lengths (e.g., 100–200 km) [199]. These values were obtained using WR round-trip measurements with ~ 100 ps precision. In WR Slave devices, three key parameters are stored: the total fixed delay from Master to Slave, from Slave to Master, and the measured asymmetry. It is assumed that the round-trip-time is a (slowly) varying parameter of the system, but the asymmetry is a constant. This means that any temperature variations, modifying the length of the cable, for instance enter as the same factor in the Master to Slave path as in the Slave to Master

path. Typically the time difference is due to chromatic dispersion due to the different wavelength for the path from Master to Slave and viceversa.

KM3NeT modifies standard WR in two key ways: (1) a single shore-based broadcast channel distributes t_1 from the Master to all slaves, and pseudo-masters (Level 1 of WR switches) record t_4 values for each Slave, which are communicated via Ethernet; (2) base modules use standard bidirectional WR links, while digital optical modules have a unidirectional WR downlink and return data via separate fibers, thus requiring additional handling. These adaptations complicate the synchronization scheme but allow the use of commercial Ethernet switches for data routing and help scale the system while maintaining accurate synchronization.

A.2 DEFINITIONS

Before describing the RTTC calibration procedure, some initial definitions have to be clarified:

- **WR device and calibrator:** any device that supports the WR protocol for the time synchronization over an optical link. Its calibrator is any device that is used as reference to calibrate all the other devices in a synchronization system.
- **WR device TX latency:** is the delay from the moment it is timestamped in the transmission circuit inside the FPGA (WR Endpoint module) to the moment when the transmitted packet reaches a fiber link. It is the sum of transmission delay inside the FPGA chip, the propagation delay of electronic components and SFP¹ transmitter delay.
- **WR device RX latency:** the delay from the moment the signal reaches the receiving SFP module to the moment it is timestamped in the reception circuit inside the FPGA. It is the sum of: SFP receiver delay, propagation delay of electronic components and reception delay inside the FPGA circuit.
- **WR device asymmetry:** is the difference between the TX and RX latency (also called 2β).
- **Fiber round trip latency (δ):** is the total round-trip delay over a fiber link, without considering the TX/RX latencies. It is the sum of the one-way propagation delays: Master to Slave (δ_{MS}) and Slave to Master (δ_{SM}).
- **Relative delay coefficient:** it is the relative difference between Master-to-Slave and Slave-to-Master propagation delays, namely $(\delta_{MS} - \delta_{SM})/\delta_{SM}$.
- **Round trip delay:** it is the total packet of delays on a WR link. It considers the sum of communicating parties (Master and Slave) fixed latencies (RX and

¹ The Small Form Factor Pluggable (SFP) transceiver is a compact, hot-swappable optical module used to connect network devices to fiber-optic or copper cabling. In the context of KM3NeT, it's used to enable high-speed, long-distance communication between the onshore and offshore electronics through optical fibers [200].

TX latencies in the Slave and Master endpoints are referred to as TXS, RXS, TXM and RXM) and fiber round-trip latency (δ).

Considering the previous definitions, the RTTC, subject of this study, can be defined as:

$$\text{RTTC} = \text{RTT} - (\text{TXS} + \text{RXS} + \text{TXM} + \text{RXM}) \equiv \delta_{MS} + \delta_{SM}, \quad (108)$$

and thus coincides with the fiber round trip latency. All the parameters involved in its definition are measured and stored in the KM3NeT database, possibly multiple times for the same run. In such cases, an average value is used.

A.3 SYNCHRONIZATION LATENCIES OF KM3NeT/ARCA BASE MODULES

The analysis has been conducted on three different DUs, connected to three different JBs, namely DU5, DU9 and DU32. Results show that DU5 over the 6-month period has a maximal RTTC spread at the level of 2.9 ns, indicating a good stability over time. DU32 and DU9 reach bigger spread, at the level of 70 ns and 14 ns respectively, but a cross-check with other DUs, linked to the same JBs, has brought to the conclusion that those events can be related to expected firmware issues occurring on CLB reboot, and currently under investigation. Beyond those events, periods contained between consecutive RTTC jumps still have a good stability, since their spread is contained between few ns. Results are summarized in Figures 134, 136, and 135. For DU5, the highest percentage difference of RTTC, computed between consecutive entries in the time series, occurs at run 14961 and corresponds to a factor $3.0 \cdot 10^{-4}\%$. In the case of DU32, a significantly larger RTTC spread was recorded, reaching up to 70 ns, with the maximum percentage variation detected at $7.0 \cdot 10^{-3}\%$ in run 13842. DU9 showed intermediate behavior, exhibiting the largest percentage difference in run 14762 at $1.5 \cdot 10^{-3}\%$ level. These large variability events have been investigated and traced back to specific issues or maintenance activities: the jump observed in run 14961 corresponds to the day the JB2 switch was replaced and thus data-taking was stopped; during run 13842, a power outage occurred at the KM3NeT/ARCA shore station; and in run 14762, a reboot of JB2 took place.

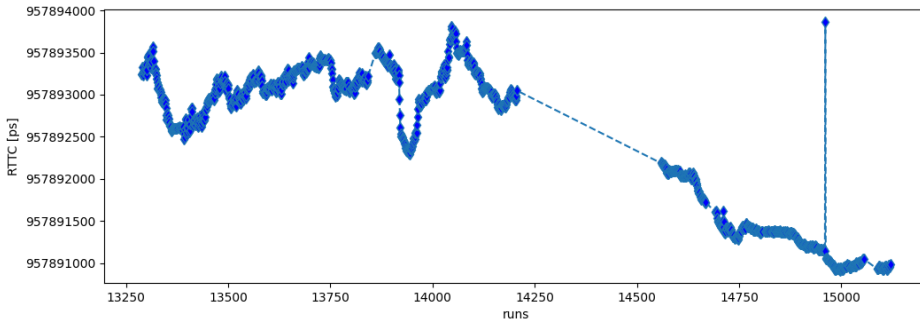


Figure 134: RTTC variations for DU5 over a 6-month period. Run numbers are reported on the x-axis. A maximum spread of 2.9 ns is observed between the lowest and highest RTTC values.

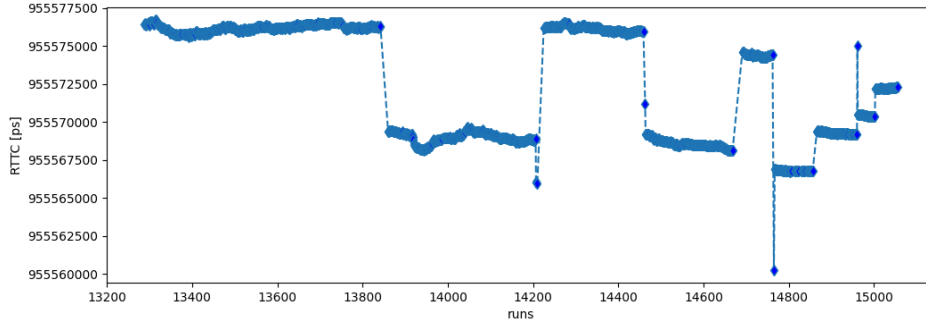


Figure 135: RTTC variations for DU9 over a 6-month period. Run numbers are reported on the x-axis. A jump of 14 ns is observed in correspondence of run 14762, because of the mentioned firmware issues.

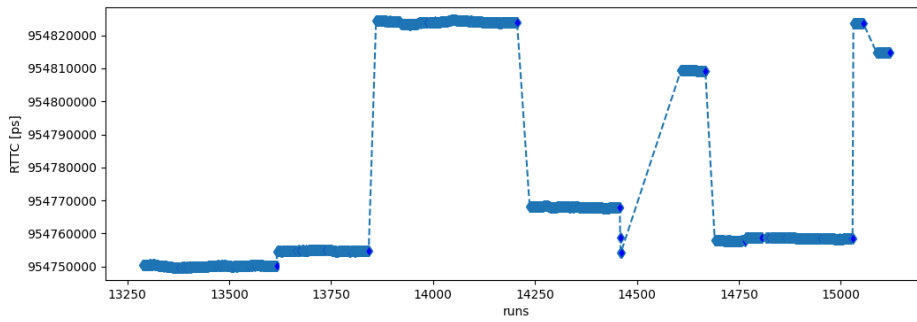


Figure 136: RTTC variations for DU32 over a 6-month period. Run numbers are reported on the x-axis. A maximum spread of 70 ns is observed in correspondence of run 13842. Despite the presence of jumps, due to firmware issues (see above), the data exhibit periods of good stability, with RTTC variations contained within a few nanoseconds.

To further validate the observed behavior, two additional DUs were analyzed over a 7-month period: DU12 and DU22. DU5 was the only one connected to JB1, therefore this validation was not possible for that specific JB. For DU12, the second-highest RTTC spread was approximately 9 ns, occurring at run 14762, the same run in which the maximum spread was observed for DU9 (Figure 137). Notably, both DUs are connected to the same JB, suggesting a common cause. The maximum relative percentage difference for DU12 was recorded to be $10^{-3}\%$. In

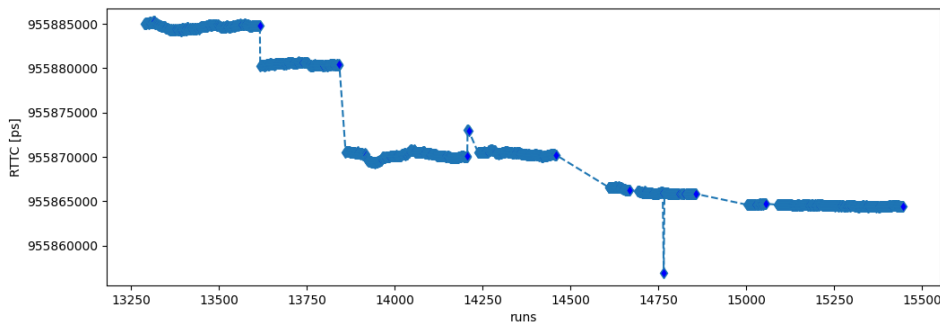


Figure 137: RTTC variations for DU12 over a 7-month period. Run numbers are reported on the x-axis. A jump of 9 ns is observed in correspondence of run 14762, linked to the known firmware issues.

the case of DU22, the RTTC spread reached up to 23 ns, observed at run 14459 (Figure 138). Interestingly, DU32, also connected to the same JB as DU22, had a jump of 9 ns happening at the same run, pointing to a possible recurring issue. The maximum percentage difference for DU22 was identified at $2.4 \cdot 10^{-3}\%$ level. No significant issues were identified on the day run 14459 was ongoing, apart from the replacement of the functioning GPS receiver with a new one. Anyway, these findings reinforce the correlation between RTTC jumps and specific hardware events or conditions linked to known but still unfixed firmware issues, while also highlighting the existence of stable periods with low variability across multiple DUs.

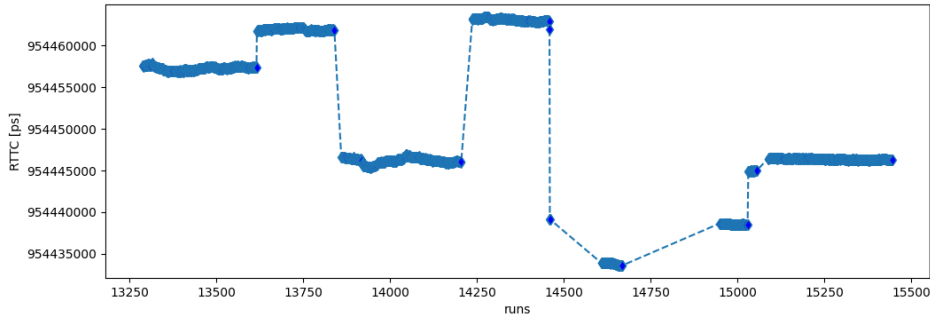


Figure 138: RTTC variations for DU22 over a 7-month period. Run numbers are reported on the x-axis. A jump of 23 ns is observed in correspondence of run 14459, linked to the known firmware issues.

SELECTED BLAZARS FROM THE $_3$ HSP CATALOGUE

Source	RA [deg]	Dec [deg]	Redshift	$\log_{10}(\nu_{\text{peak}}^{\text{syn}} [\text{Hz}])$
3HSPJ000513.7-261438	1.30717	-26.24394	0.32	15.4
3HSPJ002200.1-514024	5.50033	-51.67339	0.25	15.7
3HSPJ002201.0+000658	5.50396	0.11611	0.306	16.3
3HSPJ002928.1+205333	7.36917	20.89269	0.367	16.4
3HSPJ003020.4-164713	7.58508	-16.78694	0.237	15.6
3HSPJ003631.7-031326	9.13204	-3.22414	0.317	16.5
3HSPJ003908.2-222001	9.78421	-22.33372	0.064	16.7
3HSPJ004123.0+375855	10.34596	37.98214	0.38	15.3
3HSPJ004348.7-111607	10.95271	-11.26861	0.264	15.7
3HSPJ004755.2+394857	11.98008	39.816	0.252	16.1
3HSPJ005620.1-093630	14.08358	-9.6085	0.1	15.9
3HSPJ010956.6-402050	17.48571	-40.34747	0.313	16.5
3HSPJ011546.1+251953	18.94225	25.33153	0.375	15.7
3HSPJ011747.0-244333	19.44583	-24.72603	0.279	16.6
3HSPJ012750.8-001346	21.96175	-0.2295	0.44	15.6
3HSPJ013241.1-080404	23.17138	-8.06803	0.149	15.9
3HSPJ013312.1-351916	23.30054	-35.32128	0.174	16.5
3HSPJ014522.9+045129	26.34537	4.85814	0.35	15.2
3HSPJ015239.6+014717	28.165	1.78817	0.08	15.9
3HSPJ015934.4+104705	29.89325	10.78494	0.195	15.7
3HSPJ015953.6+004815	29.97329	0.80419	0.652	16.4
3HSPJ020441.7+004957	31.17358	0.83269	0.626	16.3
3HSPJ020838.2+352312	32.159	35.38692	0.318	16.3
3HSPJ021252.1+224452	33.22004	22.74783	0.459	15.2
3HSPJ021515.2-161738	33.8135	-16.29394	0.283	16.4
3HSPJ021632.1+231450	34.13367	23.24728	0.288	16.2
3HSPJ021905.5-172512	34.77287	-17.42025	0.128	16.6
3HSPJ023109.3-575506	37.78863	-57.91833	0.032	15.4
3HSPJ023241.1-112020	38.17462	-11.33894	0.209	16.1
3HSPJ023734.0-360328	39.39183	-36.05789	0.411	16.1
3HSPJ023813.7-092431	39.55692	-9.40872	0.419	16.7

Source	RA [deg]	Dec [deg]	Redshift	$\log_{10}(v_{\text{peak}}^{\text{syn}} [\text{Hz}])$
3HSPJ023832.5-311657	39.63529	-31.28275	0.2329	16.3
3HSPJ024302.9+004627	40.76217	0.77422	0.409	16.3
3HSPJ025038.0+171208	42.65813	17.20247	1.1	16.2
3HSPJ030326.4-240711	45.86	-24.11978	0.266	15.7
3HSPJ030330.2+055430	45.87575	5.90842	0.196	15.8
3HSPJ030433.9-005404	46.14142	-0.90119	0.511	15.9
3HSPJ031234.1-322317	48.14229	-32.38806	0.067	15.3
3HSPJ031250.3+361519	48.20954	36.25544	0.071	16.3
3HSPJ031614.9-260757	49.06221	-26.13256	0.443	15.9
3HSPJ031633.7-221612	49.14062	-22.27022	0.228	16.7
3HSPJ032523.5-563544	51.34804	-56.59572	0.06	16.5
3HSPJ032541.1-164616	51.42121	-16.77133	0.291	15.6
3HSPJ032613.9+022514	51.55808	2.42075	0.147	15.9
3HSPJ033812.5-244350	54.55221	-24.73056	0.251	16.5
3HSPJ033913.7-173600	54.80708	-17.60022	0.066	15.6
3HSPJ035733.0-680932	59.38733	-68.15911	0.089	16.6
3HSPJ040905.0-053235	62.27092	-5.54322	0.346	16.7
3HSPJ041652.5+010523	64.21867	1.08997	0.287	16.5
3HSPJ044230.2-001829	70.62596	-0.30831	0.449	16.3
3HSPJ050534.8+041554	76.39483	4.26514	0.424	15.8
3HSPJ050601.7-382055	76.50696	-38.34875	0.182	16.2
3HSPJ050939.9-251403	77.41612	-25.23417	0.264	16.5
3HSPJ052146.0+211251	80.4415	21.21428	0.108	15.1
3HSPJ055806.4-383831	89.52675	-38.64211	0.302	16.6
3HSPJ061518.3-782830	93.82621	-78.475	0.112	16.3
3HSPJ062445.1-323055	96.18771	-32.51542	0.252	16.6
3HSPJ064847.6+151624	102.19854	15.27356	0.179	16.6
3HSPJ073026.1+330722	112.60858	33.12303	0.11	15.4
3HSPJ073049.5-660218	112.70633	-66.03858	0.106	15.6
3HSPJ073152.7+280433	112.96967	28.07586	0.248	16.5
3HSPJ073329.6+351542	113.37321	35.26189	0.177	16.3
3HSPJ073701.9+284646	114.25775	28.77947	0.272	15.7
3HSPJ074914.0+231316	117.30838	23.22131	0.175	15.5
3HSPJ075109.6+291335	117.78992	29.22661	0.185	15.8
3HSPJ080312.0-033600	120.80042	-3.60022	0.365	15.6
3HSPJ080938.1+345537	122.41212	34.92703	0.083	16.6
3HSPJ081435.4+183028	123.64733	18.50783	0.342	16.2
3HSPJ082051.2+235345	125.21329	23.89589	0.402	15.6

Source	RA [deg]	Dec [deg]	Redshift	$\log_{10}(v_{\text{peak}}^{\text{syn}} [\text{Hz}])$
3HSPJ082904.8+175415	127.27012	17.90442	0.089	16.4
3HSPJ083724.6+145820	129.35262	14.97239	0.278	16.7
3HSPJ083918.7+361855	129.82812	36.31547	0.335	15.4
3HSPJ083955.1+121702	129.97963	12.28414	0.336	15.9
3HSPJ084225.1+025252	130.60629	2.88131	0.425	15.5
3HSPJ084701.6-233701	131.75654	-23.61714	0.061	16.5
3HSPJ085036.2+345522	132.65079	34.92297	0.145	15.4
3HSPJ085103.0+054906	132.76238	5.81833	0.48	15.8
3HSPJ085410.2+275421	133.54233	27.90597	0.494	16.1
3HSPJ085542.8+110315	133.92853	11.05407	0.3	15.8
3HSPJ085730.1+062727	134.37546	6.45767	0.338	16.2
3HSPJ085749.1+013530	134.45754	1.59172	0.281	15.4
3HSPJ090900.6+231112	137.25262	23.18692	0.223	15.2
3HSPJ091714.1-034314	139.31087	-3.72061	0.308	16.6
3HSPJ091925.6+110659	139.85687	11.11653	0.425	15.9
3HSPJ093239.4+104235	143.16404	10.70981	0.361	16.2
3HSPJ093303.0+045235	143.26417	4.87658	0.378	16.6
3HSPJ094223.3+284414	145.59704	28.73731	0.366	15.7
3HSPJ094606.1+215138	146.52554	21.86067	0.489	16.7
3HSPJ095549.7+101429	148.95692	10.24153	0.373	15.8
3HSPJ095929.9+212321	149.87454	21.38917	0.36	16.5
3HSPJ100408.2+144909	151.03404	14.81936	0.712	16.4
3HSPJ100444.8+375212	151.18654	37.87	0.44	16.4
3HSPJ100520.5+240504	151.33529	24.08469	0.476	16.5
3HSPJ101258.3+393238	153.24308	39.54414	0.17	15.7
3HSPJ102128.9+380645	155.3705	38.1125	0.467	16.2
3HSPJ102339.8+300057	155.91567	30.01608	0.433	16.0
3HSPJ102523.0+040229	156.34596	4.0415	0.208	16.2
3HSPJ102703.0+060933	156.76417	6.15942	0.449	16.5
3HSPJ102827.1+055515	157.11504	5.92086	0.234	16.0
3HSPJ102839.3+170210	157.16383	17.03633	0.169	16.3
3HSPJ103335.8-143627	158.39937	-14.60761	0.367	15.9
3HSPJ104029.0+094753	160.12075	9.79831	0.304	16.7
3HSPJ104149.2+390119	160.45483	39.02211	0.21	16.5
3HSPJ104551.2-400041	161.46313	-40.01139	0.243	16.3
3HSPJ104938.8+274213	162.41163	27.70361	0.144	16.4
3HSPJ105750.8-275410	164.4615	-27.90303	0.091	16.3
3HSPJ110427.3+381231	166.11383	38.20886	0.03	16.3

Source	RA [deg]	Dec [deg]	Redshift	$\log_{10}(v_{\text{peak}}^{\text{syn}} [\text{Hz}])$
3HSPJ111207.9+260803	168.03308	26.13439	0.45	16.1
3HSPJ111706.3+201407	169.27608	20.23542	0.138	15.9
3HSPJ112059.1+014456	170.24879	1.74911	0.368	16.1
3HSPJ112552.0-074220	171.46658	-7.70581	0.279	15.7
3HSPJ113302.9+184704	173.26229	18.78469	0.716	16.7
3HSPJ113650.0+255052	174.20879	25.84786	0.155	15.2
3HSPJ114023.5+152809	175.09783	15.46942	0.24	16.2
3HSPJ114221.8+334201	175.59071	33.70053	0.409	15.8
3HSPJ115017.0+101652	177.57088	10.28136	0.284	16.7
3HSPJ115404.6-001009	178.519	-0.16933	0.254	16.6
3HSPJ115531.3+060855	178.88046	6.14881	0.368	16.7
3HSPJ115709.5+282200	179.28971	28.36686	0.3	16.6
3HSPJ115853.0+081943	179.72167	8.32869	0.29	16.1
3HSPJ120106.2-000701	180.27579	-0.11706	0.165	16.5
3HSPJ120412.1+114555	181.0505	11.76539	0.296	16.6
3HSPJ120818.0-293759	182.07508	-29.63325	0.249	16.4
3HSPJ121407.5+290328	183.53133	29.05803	0.469	16.6
3HSPJ121511.0+073204	183.79575	7.53464	0.137	16.3
3HSPJ121606.2+092909	184.02588	9.486	0.094	15.9
3HSPJ121945.7-031423	184.94046	-3.23994	0.299	16.0
3HSPJ122401.0+223939	186.00421	22.66092	0.482	15.6
3HSPJ122424.2+243623	186.10083	24.60656	0.218	16.1
3HSPJ122644.2+063853	186.68425	6.64808	0.583	15.9
3HSPJ122820.5+155655	187.08554	15.94864	0.232	15.8
3HSPJ123123.1+142124	187.84962	14.35678	0.256	15.4
3HSPJ123417.2-385635	188.57146	-38.94306	0.236	16.2
3HSPJ123623.0+390000	189.09588	39.00025	0.389	15.1
3HSPJ125117.9+103907	192.8245	10.65197	0.245	15.6
3HSPJ125347.0+032630	193.44583	3.44178	0.066	15.7
3HSPJ125616.0-114637	194.06646	-11.77703	0.058	15.7
3HSPJ125822.1+062827	194.59504	6.47422	0.542	16.1
3HSPJ125848.0-044745	194.70017	-4.79583	0.586	16.7
3HSPJ130531.3+385522	196.38029	38.92281	0.376	16.4
3HSPJ130711.9+115316	196.79975	11.88794	0.085	16.0
3HSPJ131012.2-115749	197.55075	-11.96372	0.14	15.9
3HSPJ131639.8+205514	199.16604	20.92081	0.255	16.3
3HSPJ131931.7+140533	199.88225	14.09256	0.573	15.2
3HSPJ132057.0+222516	200.23917	22.42133	0.234	16.0

Source	RA [deg]	Dec [deg]	Redshift	$\log_{10}(v_{\text{peak}}^{\text{syn}} [\text{Hz}])$
3HSPJ132615.0+293330	201.56242	29.55856	0.431	16.3
3HSPJ133105.1-002221	202.77375	-0.37256	0.243	16.1
3HSPJ133612.1+231958	204.0505	23.33303	0.267	16.1
3HSPJ135159.7+041212	207.99867	4.20344	0.257	15.8
3HSPJ140635.8-005548	211.64933	-0.93022	0.255	16.4
3HSPJ140653.5+272606	211.72312	27.43511	0.203	16.7
3HSPJ141003.9+051557	212.51633	5.26606	0.544	15.4
3HSPJ141029.6+282055	212.62317	28.34881	0.521	15.9
3HSPJ141409.3+343058	213.53863	34.51614	0.275	15.7
3HSPJ141612.2-241813	214.05071	-24.30372	0.136	15.9
3HSPJ142320.6+053000	215.836	5.5	0.543	16.3
3HSPJ142412.4-175008	216.05146	-17.83569	0.082	15.6
3HSPJ142422.9+343356	216.09546	34.56575	0.576	16.6
3HSPJ142739.6-252103	216.91496	-25.35083	0.318	16.0
3HSPJ142745.9+390832	216.94125	39.14225	0.165	15.8
3HSPJ143109.6+271020	217.79	27.17231	0.2	16.0
3HSPJ143555.0+395729	218.97908	39.95831	0.755	15.5
3HSPJ143917.5+393242	219.82283	39.54522	0.344	15.9
3HSPJ144236.0-462301	220.65167	-46.38383	0.103	15.8
3HSPJ144334.0+251558	220.89337	25.26614	0.529	15.3
3HSPJ144357.2-390840	220.98833	-39.14444	0.065	15.7
3HSPJ145508.2+192015	223.78425	19.33761	0.115	15.9
3HSPJ145707.0+185438	224.28087	18.91081	0.373	16.0
3HSPJ150020.2-020122	225.08425	-2.02303	0.273	16.4
3HSPJ150653.1+021904	226.72417	2.31789	0.22	16.5
3HSPJ151212.7-225508	228.05312	-22.919	0.315	15.5
3HSPJ151324.2-075451	228.35075	-7.91431	0.04	16.0
3HSPJ151556.2+242620	228.98404	24.43892	0.228	16.3
3HSPJ151826.7+075222	229.61113	7.87292	0.41	15.9
3HSPJ153202.2+301628	233.00929	30.27469	0.065	16.0
3HSPJ153447.0+371554	233.69667	37.26519	0.143	15.3
3HSPJ154418.7+045821	236.07796	4.97272	0.326	16.3
3HSPJ154546.6-233928	236.44408	-23.65789	0.121	16.2
3HSPJ154849.8-225102	237.20733	-22.85069	0.192	16.2
3HSPJ160135.5+161239	240.39783	16.21106	0.528	16.7
3HSPJ161608.4+224107	244.03517	22.68528	0.33	16.0
3HSPJ162007.8+323027	245.03267	32.50775	0.778	16.4
3HSPJ162625.9+351341	246.60775	35.22819	0.498	16.0

Source	RA [deg]	Dec [deg]	Redshift	$\log_{10}(v_{\text{peak}}^{\text{syn}} [\text{Hz}])$
3HSPJ162839.0+252756	247.16262	25.46558	0.22	16.7
3HSPJ164220.3+221143	250.58467	22.1955	0.592	16.5
3HSPJ164319.3+213107	250.83029	21.51869	0.154	16.0
3HSPJ164328.9-064619	250.8705	-6.77208	0.082	15.3
3HSPJ170052.7+332431	255.21942	33.40864	0.383	16.7
3HSPJ171531.5+205935	258.88121	20.99317	0.177	16.1
3HSPJ174537.8+395130	266.40733	39.85853	0.267	16.2
3HSPJ183820.6-602522	279.586	-60.42289	0.121	15.9
3HSPJ200925.4-484953	302.35579	-48.83153	0.071	15.4
3HSPJ201428.6-004722	303.61933	-0.78967	0.231	15.2
3HSPJ201431.1+064852	303.6295	6.81458	0.341	15.8
3HSPJ203649.5-332830	309.20621	-33.47514	0.23	16.4
3HSPJ203844.1-263632	309.68712	-26.60897	0.44	16.2
3HSPJ204921.7-003926	312.34058	-0.65733	0.25	16.6
3HSPJ205456.8+001537	313.73687	0.26053	0.151	16.1
3HSPJ205938.6-003755	314.91067	-0.63219	0.335	16.0
3HSPJ210844.7-025034	317.18637	-2.84278	0.15	15.8
3HSPJ211501.0-005641	318.75587	-0.94489	0.226	15.9
3HSPJ211754.1-324328	319.47879	-32.7245	0.215	15.7
3HSPJ212940.7+003527	322.41942	0.591	0.426	16.0
3HSPJ213135.0-091523	322.89754	-9.25653	0.449	16.3
3HSPJ213314.4+252859	323.30983	25.48306	0.294	15.2
3HSPJ214533.4-043439	326.38908	-4.57753	0.07	16.6
3HSPJ215051.7+111916	327.71546	11.32131	0.495	16.1
3HSPJ215214.0-120541	328.05879	-12.09478	0.121	16.3
3HSPJ215852.0-301332	329.71687	-30.22556	0.117	15.4
3HSPJ215910.9-284116	329.7955	-28.68789	0.271	15.5
3HSPJ220704.1+222231	331.76713	22.37542	0.558	16.0
3HSPJ221108.3-000302	332.78471	-0.05064	0.362	16.3
3HSPJ222253.9-175321	335.72446	-17.88917	0.29	16.1
3HSPJ223928.8-243944	339.87008	-24.66228	0.115	16.4
3HSPJ224046.9+132602	340.19537	13.43411	0.66	16.2
3HSPJ224340.0-123059	340.91792	-12.51647	0.226	16.5
3HSPJ224820.8-003221	342.0865	-0.53931	0.249	16.6
3HSPJ225005.7+382437	342.52392	38.41033	0.119	16.2
3HSPJ225354.2+140436	343.476	14.07692	0.327	15.6
3HSPJ225613.3-330338	344.05546	-33.06064	0.243	16.5
3HSPJ225819.0-552537	344.579	-55.42703	0.479	15.7

Source	RA [deg]	Dec [deg]	Redshift	$\log_{10}(v_{\text{peak}}^{\text{syn}} \text{ [Hz]})$
3HSPJ231905.1-420648	349.77462	-42.11344	0.054	16.4
3HSPJ232039.8-630918	350.16604	-63.15503	0.2	16.2
3HSPJ232240.4-422042	350.66833	-42.34517	0.09	15.7
3HSPJ232244.0+343613	350.68342	34.60383	0.094	15.7
3HSPJ232903.0+174330	352.26379	17.72511	0.213	15.9
3HSPJ234538.0-144928	356.41004	-14.82461	0.224	16.6
3HSPJ235001.7+194151	357.50729	19.6975	0.517	16.5
3HSPJ235023.3-243602	357.59721	-24.60081	0.19	16.0
3HSPJ235034.0-300604	357.64292	-30.10119	0.23	15.7
3HSPJ235604.0-002353	359.01671	-0.39825	0.283	15.2
3HSPJ235919.5-204756	359.83138	-20.79892	0.096	16.2

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