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**Search for Slow Charged Long-Lived Particles
with the ATLAS Detector at the LHC.**

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Abstract

This thesis presents a search for beyond the Standard Model slow, charged long-lived particles produced in proton–proton collisions at the Large Hadron Collider with the ATLAS detector. The search uses Run 2 (2015–2018) and Run 3 (2022–2024) data, corresponding to integrated luminosities of 140 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ and 169 fb^{-1} at $\sqrt{s} = 13.6 \text{ TeV}$. The analysis relies on independent measurements of the particle mass from the ionisation in the Inner Detector and the Muon Spectrometer and the time-of-flight in the Muon Spectrometer and the Hadronic Calorimeter.

This work focuses on the combination of the ionisation information from the Inner Detector and the time-of-flight from the Muon Spectrometer. The time-of-flight measurement requires a dedicated reconstruction chain, provided by the “Slow Muon” algorithm. The performance of the algorithm and the developments implemented in recent software releases are discussed. A framework for tube-level calibration of the Muon Spectrometer barrel was developed, and the corresponding corrections are discussed.

A new analysis channel was introduced to extend the sensitivity of the search using the full analysis statistics. The background estimation is performed using the data-driven method.

The studies documented in this work demonstrate that particle travelling with the speed significantly smaller than the speed of light can be measured with high efficiency. The developed Muon Spectrometer time-of-flight calibration method allows to use the obtained particle speed measurement with a precision of 4%. The estimated sensitivity indicates that the search is expected to exclude the pair-produced detector-stable stau with masses up to 700 GeV.

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List of Acronyms

2HDM	Two-Higgs-Doublet Model
ADC	Analogue-to-Digital Converter
AFP	ATLAS Forward Proton
ALFA	Absolute Luminosity for ATLAS
ALICE	A Large Ion Collider Experiment
ALP	Axion-like Particle
AMSB	Anomaly-mediated Supersymmetry Breaking
ASIC	Application-Specific Integrated Circuit
ATLAS	A Toroidal LHC ApparatuS
AOD	Analysis Object Data
BC	Bunch Crossing
BI	Barrel Inner (RPC layer)
BSM	Beyond the Standard Model
BT	Barrel Toroid
CB	Combined muon
CC	Charged Current
CC	Climate Chamber
CDM	Cold Dark Matter
CKM	Cabibbo–Kobayashi–Maskawa Matrix
CMB	Cosmic Microwave Background
CMOS	Complementary Metal–Oxide–Semiconductor
CMS	Compact Muon Solenoid
CP	Charge–Parity
CR	Control Region
CSC	Cathode Strip Chamber
CT	Calorimeter-Tagged muon
CTP	Central Trigger Processor
CU	Cooling Unit
DAOD	Derived Analysis Object Data
DAQ	Data Acquisition
DCS	Detector Control System

Acronyms

DQ	Data Quality
DUT	Device Under Test
ECT	End-cap Toroid
EM	Electromagnetic
EMCal	Electromagnetic Calorimeter
EMFlow	EM-scale particle-flow
EW	Electroweak
FCal	Forward Calorimeter
FE	Front-End
FPGA	Field-Programmable Gate Array
GMSB	Gauge-mediated Supersymmetry Breaking
GRL	Good Runs List
GSF	Gaussian-Sum Filter
GSW	Glashow-Weinberg-Salam Model
HGTD	High Granularity Timing Detector
HL-LHC	High-Luminosity Large Hadron Collider
HLT	High-Level Trigger
HPK	Hamamatsu Photonics K.K.
HV	High Voltage
IBL	Insertable B-Layer
ID	Inner Detector
INFN	Istituto Nazionale di Fisica Nucleare
IO	Inside-Out (reconstruction chain)
IP	Interaction Point
ITk	Inner Tracker
JER	Jet Energy Resolution
JES	Jet Energy Scale
JVT	Jet Vertex Tagger
KIT	Karlsruhe Institute of Technology
ΛCDM	Lambda-Cold Dark Matter Model
LAr	Liquid Argon
LB	Luminosity Block
LEP	Large Electron-Positron Collider
LH	Left-handed
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty
LINAC	Linear Accelerator
LLP	Long-lived Particle
LGAD	Low-Gain Avalanche Diode
LO	Leading Order
LRT	Large-Radius Tracking

LSP	Lightest Supersymmetric Particle
LV	Low Voltage
MC	Monte Carlo (simulation)
ME	Matrix Element
MDT	Monitored Drift Tube
ME	MS-extrapolated muon
MET	Missing Transverse Energy
MS	Muon Spectrometer
MSSM	Minimal Supersymmetric Standard Model
NLO	Next-to-Leading Order
NNLO	Next-to-Next-to-Leading Order
MuCTPI	Muon–Central Trigger Processor Interface
NC	Neutral Current
NLSP	Next-to-Lightest Supersymmetric Particle
NN	Neutral Naturalness
NSW	New Small Wheel
OPC	Open Platform Communications
PanDA	Production and Distributed Analysis
PDb	Production Database
PDF	Parton Distribution Function
PFlow	Particle Flow
PMNS	Pontecorvo–Maki–Nakagawa–Sakata Matrix
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
QC	Quality Control
QCD	Quantum Chromodynamics
QFT	Quantum Field Theory
RDO	Raw Data Object
RH	Right-handed
RMS	Root Mean Square
RNN	Recurrent Neural Network
RO	Readout
RoI	Region of Interest
RPC	R-parity Conserving (supersymmetry)
RPC	Resistive Plate Chamber
RPV	R-parity Violating (supersymmetry)
sMDT	Small-diameter Monitored Drift Tube
sTGC	Small-strip Thin Gap Chamber
SCT	Semiconductor Tracker
SiF	Silicon-associated forward muon
SM	Standard Model

Acronyms

SPS	Super Proton Synchrotron
SR	Signal Region
SSR	Solid-State Relay
SSB	Spontaneous Symmetry Breaking
ST	Segment-Tagged muon
SW	Software
SUSY	Supersymmetry
TDAQ	Trigger and Data Acquisition
TC	Thermal Cycles
TGC	Thin Gap Chamber
TileCal	ATLAS Tile Calorimeter
ToF	Time of Flight
TRT	Transition Radiation Tracker
TST	Track-based Soft MET Term
TTC	Trigger, Timing and Control
UV	Ultraviolet
vev	Vacuum Expectation Value
VR	Validation Region
WP	Working Point
ZDC	Zero Degree Calorimeter

Introduction

The Standard Model (SM) of particle physics provides a precise description of the fundamental particles and their interactions and has been extensively validated by experimental results. The lifetimes of the Standard Model particles cover a very broad range, from 10^{-25} s for the Z boson to infinity for the electron. Long particle lifetimes can result from small coupling constants, limited phase space, or scale suppression in the decay processes. Beyond the Standard Model (BSM) theories, such as supersymmetry, predict new heavy charged particles that can acquire long lifetimes through these mechanisms and travel the distances measurable at the detector.

Although the Large Hadron Collider (LHC) detectors, such as ATLAS, are primarily designed to reconstruct promptly decaying particles, long-lived particles (LLPs) can still be detected through unconventional signatures. Heavy charged LLPs are characterised by anomalously high ionisation energy loss and delayed timing signals compared with Standard Model particles. The ionisation energy loss can be measured in the Pixel detector and the Muon Drift Tubes (MDTs), while the time-of-flight (ToF) information can be obtained from the Tile Calorimeter and several parts of the Muon Spectrometer, including the MDT system.

This analysis extends previous Run 2 searches for highly ionising LLPs using anomalous ionisation in the ATLAS Pixel detector only and anomalous ionisation in the ATLAS Pixel detector together with large time of flight to the ATLAS Tile Calorimeter. The present work further exploits time-of-flight information from the Muon Drift Tubes, providing additional sensitivity to particles that reach the Muon Spectrometer.

This thesis presents a search for BSM slow, charged long-lived particles produced in pp collisions at centre-of-mass energies of 13 and 13.6 TeV using ATLAS Run 2 (2015–2018) and Run 3 (2022–2024) data, corresponding to integrated luminosities of 140 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ and 169 fb^{-1} at $\sqrt{s} = 13.6 \text{ TeV}$, respectively. Particular emphasis is placed on the combination of the Pixel dE/dx and MDT time-of-flight measurements, which provide complementary sensitivity to slow particles traversing the Muon Spectrometer.

The analysis combines Pixel dE/dx and Muon Drift Tube time-of-flight mea-

Introduction

surements, supported by dedicated calibration and reconstruction developments. The work includes the tube-level calibration of the MDT barrel, performance studies of the Slow Muon reconstruction algorithm, and the development of a new analysis channel together with dedicated selections. A sensitivity study for the benchmark model of the GMSB pair-produced detector-stable stau was performed. The analysis employs a background estimation strategy based on a fully data-driven method intended to derive both the background yield and its distribution.

The thesis is organised as follows.

Chapter 1 provides the necessary theoretical context for particle searches at the LHC. The Standard Model framework and several BSM models predicting LLPs are presented. The mechanisms allowing particles to have long lifetimes are discussed.

Chapter 2 presents an experimental overview of long-lived particle searches using multipurpose detectors such as ATLAS and CMS, with a focus on charged LLPs that can be directly detected. The limits on models predicting charged LLPs are reviewed.

Chapter 3 gives an overview of the main systems of the ATLAS experiment at the LHC.

Chapter 4 describes the standard objects used in ATLAS physics studies, and their reconstruction and identification.

Chapter 5 describes the standard ATLAS data-processing chain and a modified data flow used in the search for LLPs presented in this work. The modified data flow is based on selective reprocessing using the Event Picking Service. The data and Monte Carlo samples used in the search are presented in this chapter.

Chapter 6 is devoted to the Slow Muon reconstruction algorithm, its performance, and the issues that arose during the preparation phase of the analysis. The Slow Muon reconstruction algorithm provides a key measurement for the search — the MDT timing information at the hit level. Due to its design, the algorithm is sensitive to slow particles.

Chapter 7 describes the Pixel dE/dx and MDT time-of-flight calibrations. The search for slow, charged LLPs is based on Pixel dE/dx and MDT ToF measurements, which makes the calibration one of the essential components of the study. The MDT ToF calibration aspects and procedure are presented in detail.

Chapter 8 is devoted to the search for charged long-lived particles, characterised by anomalous ionisation in the Pixel detector and delayed time-of-flight to the Muon Spectrometer. The analysis strategy and design are described in this chapter.

Appendix A presents the ATLAS Inner Tracker (ITk) project, which will replace the current Inner Detector of ATLAS during the Phase-II upgrade. The main focus of the chapter is on the ITk pixel module quality control (QC) procedures

and the ITk test beam results.

Appendix [B](#) contains the additional plots presenting the extended details of the MDT ToF calibration.

A summary of the author's **original contributions** is presented below:

- The study of the Slow Muon reconstruction efficiency and an active contribution to the recovery of its performance within the group, as detailed in Chapter [6](#).
- Development of the framework and strategy for the MDT time-of-flight (ToF) calibration (Chapter [7](#)).
- Development of the analysis strategy incorporating the MDT ToF measurement, including the design of a new analysis channel and the corresponding event selections. The author performed a sensitivity study for stable stau signal models in the designed analysis channels. The background estimation strategy for the search, combining Pixel dE/dx measurements with the MDT ToF measurement, was proposed by the author. The corresponding studies are described in Chapter [8](#).
- As part of the ATLAS Authorship Qualification (November 2022 – November 2023), the author contributed to the pixel module quality control for the ITk project. Subsequently, the author participated in the ITk pixel module test beam at the SPS at CERN. The related activities and results of the test beam are presented in Appendix [A](#).

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Chapter 1

Theoretical Fundamentals

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The mechanisms which allow a particle to have a long lifetime and the examples of the Standard Model long-lived particles (LLPs) are given in Section 1.2. Section 1.3 gives an overview of the Beyond Standard Model (BSM) theories which predict LLPs.

In this chapter, natural units are employed, with $\hbar = c = 1$. Whenever required, the conversion to conventional units is made using $\hbar c = 197.3 \text{ MeV} \times \text{fm}$.

1.1 The Standard Model of Particle Physics

The Standard Model (SM) of particle physics describes the electromagnetic, weak, and strong interactions of the fundamental particles within the framework of quantum field theory (QFT) [1, 2]. Gravity, however, is not included in the SM.

The dynamics of such systems in QFTs (and in the SM in particular) can be formulated in terms of the Lagrangian formalism using the action $\mathcal{S}$:

$$\mathcal{S} = \int d^4x \mathcal{L}, \quad (1.1)$$

where $\mathcal{L}$ is the Lagrangian density of the system. The Lagrangian density $\mathcal{L}(\phi, \partial\phi)$ is a function of the fields and their derivatives. The equations of motion can be derived, following the principle of least action, by requiring that the variation of the action equals zero: $\delta\mathcal{S} = 0$.

The Lagrangian of the system can be split into two parts:

$$\mathcal{L} = \mathcal{L}_{free} + \mathcal{L}_{int}, \quad (1.2)$$

where $\mathcal{L}_{free}$ corresponds to the free fields and $\mathcal{L}_{int}$ describes their interactions.

The SM is defined by a local gauge symmetry of the Lie group:

$$SU(3)_c \times SU(2)_L \times U(1)_Y. \quad (1.3)$$

The strong interaction corresponds to the group $SU(3)_c$ and is described in terms of Quantum Chromodynamics (QCD) through the exchange in colour c . The electroweak interaction, described by the Glashow–Weinberg–Salam (GSW) model [3, 4], is based on the symmetry group $SU(2)_L \times U(1)_Y$. The group $SU(2)_L$ is associated with the weak isospin T , and the group $U(1)_Y$ is associated with the weak hypercharge Y . The electric charge Q is then given by the Gell-Mann–Nishijima formula [5, 6]:

$$Q = T_3 + \frac{Y}{2}, \quad (1.4)$$

where T_3 is the third component of the isospin vector.

Matter is described as Dirac fields ψ in the form of spin-1/2 particles, which follow Fermi-Dirac statistics and the Pauli exclusion principle (fermions). Fermions ψ can be represented in terms of the left-handed (LH) or right-handed (RH) chiral projections:

$$\begin{aligned} \psi &= \psi_L + \psi_R, \\ \psi_L &= \frac{1}{2}(1 - \gamma^5)\psi, \\ \psi_R &= \frac{1}{2}(1 + \gamma^5)\psi, \end{aligned} \quad (1.5)$$

where $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$ and $\gamma^0, \gamma^1, \gamma^2, \gamma^3$ are gamma matrices or Dirac matrices [1, 2]. Left-handed fermions are grouped into doublets of weak isospin T in $SU(2)_L$, and right-handed fermions are singlets with hypercharge Y in $U(1)_Y$.

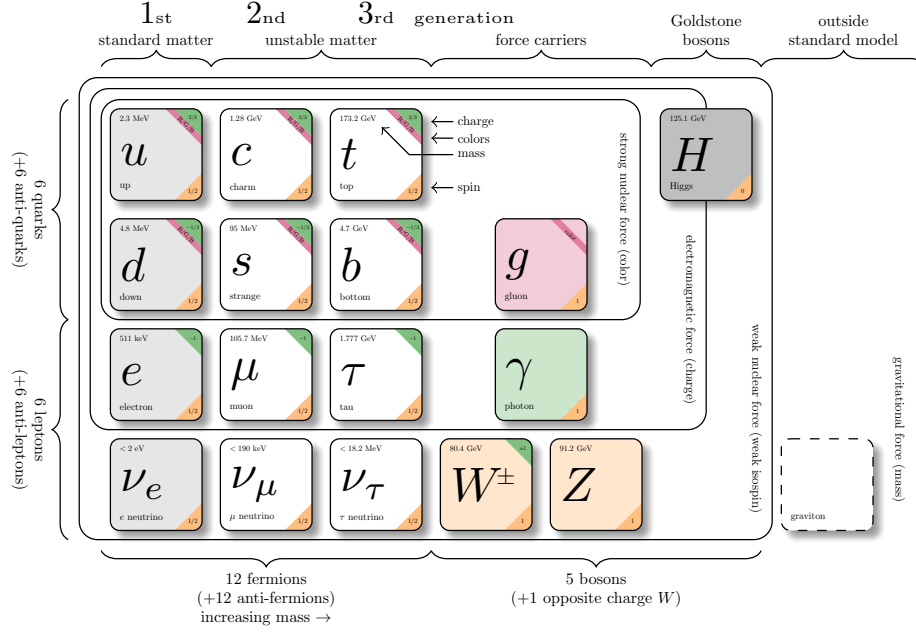


Figure 1.1: Scheme of the SM of particles. Fermions are shown on the left. Gauge bosons and the Higgs boson are shown on the right. Taken from Ref. [7].

Fermions are interacting particles, described by quantum numbers, and are categorised as leptons and quarks. Antifermions exist for all fermions. Figure 1.1 gives a summary of the Standard Model particles.

The left-handed leptons are arranged into three families corresponding to the electron e , the muon μ , and the tau τ flavours. Each family ordered by increasing mass, contains a charged lepton and a neutral partner, the neutrino (ν_e , ν_μ , ν_τ). The right-handed component does not include neutrinos. Together LH and RH leptons can be summarised as it follows:

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L, \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L, e_R, \mu_R, \tau_R.$$

Charged leptons participate in both electromagnetic and weak interactions, while neutrinos couple exclusively through the weak force. Neutrinos exhibit flavour oscillations, arising from the misalignment between flavour and mass eigenstates.

Quarks are classified into three families, each consisting of one up-type ($Q = \frac{2}{3}e$) and one down-type ($Q = -\frac{1}{3}e$) state. The six flavours are up u , down d , strange s , charm c , bottom b , and top t . Left-handed doublet and right-handed

singlet components for the quarks can be written as it follows:

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L, u_R, d_R, c_R, s_R, t_R, b_R.$$

Quarks carry colour charge c and interact via the strong force. In nature, quarks are confined within colour-neutral bound states, realised as mesons (quark-antiquark pairs) or baryons (three-quark states), tetraquarks (four-quark states), and pentaquarks (five-quark states).

Interactions in the SM are mediated by vector (spin-1) fields, corresponding to the vector bosons, which follow Bose–Einstein statistics. Each of the Lie Algebra groups $SU(n)$ in the symmetry (Eq. (1.3)) is defined by the $n^2 - 1$ group generators:

- $SU(3)$: 8 generators, corresponding to the gluons;
- $SU(2)$: 3 generators, corresponding to gauge fields, $W_\mu^a(x)$, with $a = 1, 2, 3$;
- $U(1)$: 1 generator, corresponding to gauge field, $B_\mu(x)$.

Gluons are massless, electrically neutral carriers of the strong force, with eight states associated with the generators of the $SU(3)_c$ gauge group.

Four gauge fields W_i and B , after electroweak symmetry breaking, as described below, are associated with four gauge bosons ($W^\pm, Z^0, \gamma$).

The electroweak interaction is mediated by the $W^\pm$ and Z bosons. The $W^\pm$ couple only to left-handed fermions and right-handed antifermions, while the Z couples to both fermions and antifermions.

Local gauge invariance means that the transformations of the Lagrangian depend on locally defined parameters which vary from point to point. To achieve this, the covariant derivative for the electroweak interaction is introduced as [1, 2]:

$$\mathcal{D}_\mu = \partial_\mu + ig \frac{\sigma_a}{2} W_\mu^a + ig' \frac{Y}{2} B_\mu, \quad (1.6)$$

with the σ_a Pauli matrices generating $SU(2)$, and the coupling constants for $SU(2)_L$ and $U(1)_Y$, g and g' , respectively.

Then it is possible to introduce the field strength tensors:

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g\epsilon^{abc} W_\mu^b W_\nu^c \quad (1.7)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu. \quad (1.8)$$

The EW Lagrangian can be derived as:

$$\begin{aligned}
\mathcal{L}_{EW} &= \sum_{j=1}^3 i\bar{\psi}_j(x)\gamma^\mu\mathcal{D}_\mu\psi_j(x) \rightarrow \text{Lepton propagation and interaction} \\
&\quad - \frac{1}{4}W_{\mu\nu}^a W_a^{\mu\nu} \rightarrow SU(2)_L \text{ fields free propagation} \\
&\quad - \frac{1}{4}B_{\mu\nu} B^{\mu\nu} \rightarrow U(1)_Y \text{ field free propagation}
\end{aligned} \tag{1.9}$$

The symmetry $SU(2)_L \times U(1)_Y$ undergoes the Spontaneous Symmetry Breaking (SSB) [8–10]. After SSB, the corresponding gauge bosons of the broken group ($W^\pm$ and Z^0) receive mass, while the photon γ remains massless corresponding to the unbroken $U(1)_{em}$ (with EM standing for electromagnetic).

The interaction happening through a neutral boson can be described as a neutral current (NC), and through a charged boson as a charged current (CC). Charged currents arise from the linear combination:

$$W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}} \tag{1.10}$$

Neutral currents arise from the mixing of $SU(2)_L \times U(1)_Y$:

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}, \tag{1.11}$$

where θ_W is the Weinberg angle that relates the neutral and charged currents. θ_W is related to the gauge coupling constants of $SU(2)_L$ and $U(1)_Y$, denoted by g and g' , respectively:

$$\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}. \tag{1.12}$$

$W_\mu^\pm$ describe the interaction through $W^\pm$ bosons; Z_μ and A_μ correspond to interaction through the Z^0 boson and the photon γ , respectively.

Electroweak symmetry breaking is realised through the introduction of a $SU(2)$ isospin doublet complex scalar Higgs field:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \tag{1.13}$$

The corresponding Higgs Lagrangian $\mathcal{L}_{Higgs}$ is introduced in the SM in the form of:

$$\mathcal{L}_{Higgs} = (\mathcal{D}_\mu\phi)^\dagger (\mathcal{D}^\mu\phi) - V(\phi), \tag{1.14}$$

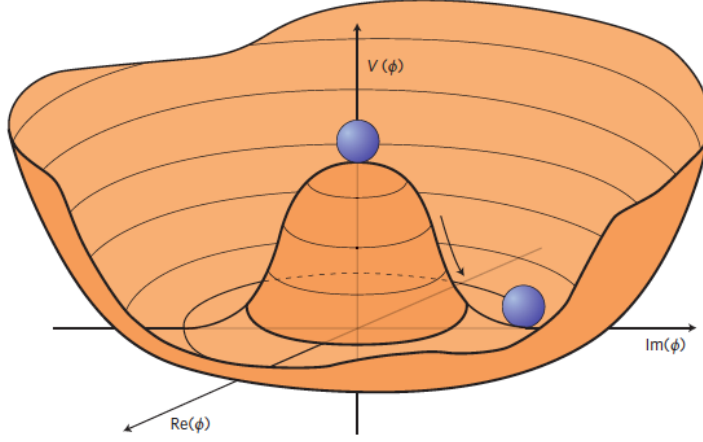


Figure 1.2: The illustration of the Higgs potential $V(\phi)$ for $\mu^2 < 0$ with a local minimum at $\phi = 0$ and non-zero vev $v = \sqrt{-\mu^2/\lambda}$ [11].

where the first term is related to the kinetic part, $\mathcal{D}_\mu$ is the covariant derivative in Eq. (1.6) and the second part of the Lagrangian is the Higgs potential, $V(\phi)$:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2. \quad (1.15)$$

The vacuum expectation value (vev) is the minimum value of the potential obtained for the values $\mu^2 < 0$ and $\lambda > 0$:

$$|\phi^\dagger \phi| = -\frac{1}{2} \frac{\mu^2}{\lambda} \equiv \frac{1}{2} v^2. \quad (1.16)$$

The schematic view of the Higgs potential $V(\phi)$ with $\mu^2 < 0$ is shown in Figure 1.2. The minimum of this potential is defined by requiring $\phi_1 = \phi_2 = \phi_4 = 0$ and $\phi_3^2 = -\mu^2/\lambda \equiv v^2$, thereby spontaneously breaking the symmetry of the weak interaction. The field can be rewritten as follows:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \quad (1.17)$$

where $h(x)$ is the small excitation above the minimum, representing the physical Higgs boson. The SSB results in the following mass terms for the gauge bosons and the Higgs boson:

$$m_{W^\pm} = \frac{1}{2} v g \quad (1.18)$$

$$m_{Z^0} = \frac{v g}{2 \cos \theta_W} = \frac{m_{W^\pm}}{\cos \theta_W} \quad (1.19)$$

$$m_H = \sqrt{2\lambda} v. \quad (1.20)$$

The Higgs Lagrangian described in Eq. (1.14) generates the gauge boson masses, leaving SM fermions massless, while experimentally fermions have a non-zero mass. Fermion masses can be added to the Lagrangian, through the introduction of Yukawa interactions coupling to the Higgs boson, preserving the local gauge invariance. The Yukawa Lagrangian for leptons can be written as:

$$\mathcal{L}_{Yukawa}^{Leptons} = -G \left[(\bar{\nu}_\ell, \bar{\ell})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \ell_R + \bar{\ell}_R (\phi^-, \bar{\phi}^0) \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L \right]. \quad (1.21)$$

With the effect of spontaneous symmetry breaking, lepton masses are obtained:

$$\mathcal{L}_{Yukawa}^{Leptons} = -\frac{G}{\sqrt{2}} \left[v (\bar{\ell}_L \ell_R + \bar{\ell}_R \ell_L) - (\bar{\ell}_L \ell_R + \bar{\ell}_R \ell_L) h \right], \quad (1.22)$$

with a value of $m_\ell = Gv/\sqrt{2}$. RH (ℓ_R) and LH (ℓ_L) leptons are written as singlet and doublet terms, respectively. While neutrinos, which do not have RH states, remain massless. Similarly, the Higgs interaction with quarks leads to the following Lagrangian:

$$\mathcal{L}_{Yukawa}^{Quarks} = -m_d^i \bar{d}_i d_i \left(1 + \frac{h}{v} \right) - m_u^i \bar{u}_i u_i \left(1 + \frac{h}{v} \right), \quad (1.23)$$

where i represents the number of quark doublets. Fermion masses derived in Eq. (1.22) and (1.23) are free parameters of the theory.

The $SU(3)$ Lagrangian can also be derived as follows:

$$\mathcal{L} = \bar{\psi}^\alpha \left(iD^{\alpha\beta} - m\delta^{\alpha\beta} \right) \psi^\beta. \quad (1.24)$$

Similarly to the covariant derivative in Eq. (1.6), an additional derivative can be introduced to guarantee the local gauge invariance of the $SU(3)$ Lagrangian:

$$D_\mu^{\alpha\beta} = \delta^{\alpha\beta} \partial_\mu + ig_s A_{\mu a} (T^a)^{\alpha\beta}, \quad (1.25)$$

where $\delta^{\alpha\beta}$ is the Kronecker delta, g_s is the QCD coupling constant, T^a are the group generators, and $A_{\mu a}$ is the gluon propagator. The gluon field is then represented by a tensor field:

$$F_{\mu\nu}^a = \partial_\nu A_\mu^a - \partial_\mu A_\nu^a + g_s f_{abc} A_\mu^b A_\nu^c, \quad (1.26)$$

where f_{abc} are the fine structure constants of the group. The indices a, b, c indicate a sum on the eight colour degrees of freedom of the gluon field. The last term of the field structure arises from the noncommutative nature of the QCD generators, implying gluon self-interactions. Finally, the QCD Lagrangian can be written:

$$\mathcal{L}_{QCD} = -\frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu} - \sum_{flavour} \bar{\psi}_f (\gamma^\mu D_\mu - m_f) \psi_f. \quad (1.27)$$

The Cabibbo–Kobayashi–Maskawa (CKM) matrix [12, 13] describes the mixing between the different quark flavours. The magnitudes of the elements of the CKM matrix V_{ij} correspond to the probabilities of charged-current transitions from a quark i to a quark j :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (1.28)$$

V_{CKM} can be parametrised as follows:

$$\begin{aligned} V_{CKM} &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \end{aligned} \quad (1.29)$$

where $s_{ij} = \sin \theta_{ij}$, $c_{ij} = \cos \theta_{ij}$, δ is the phase responsible for CP-violating phenomena in flavour-changing processes in the SM. Angles θ_{ij} can be chosen to lie in the first quadrant, $s_{ij}c_{ij} \geq 0$. The values V_{ij} are measured experimentally [14].

The CP transformation combines charge conjugation C with parity P . Under C , particles and antiparticles are interchanged, conjugating all internal quantum numbers, e.g., $Q \rightarrow -Q$, for electromagnetic charge. Under P , the handedness of space is reversed, $\vec{x} \rightarrow -\vec{x}$. Thus, for example, a left-handed electron e_L^- is transformed under CP into a right-handed positron, e_R^+ .

It was observed experimentally that neutrino has non-zero mass, and can oscillate [15]. As an extension of the Standard Model, an unitary matrix, similar to the CKM matrix, was introduced. The matrix is called the PMNS (for Pontecorvo–Maki–Nakagawa–Sakata) [16–18] and relates the mass eigenstates described by the fields ν_1 , ν_2 and ν_3 to the weak eigenstates described by the fields ν_e , ν_μ , ν_τ .

1.1.1 Standard Model Limitations

The Standard Model suffers from several theoretical and cosmological shortcomings (see Ref. [19, 20] for a comprehensive discussion). Two illustrative examples are outlined in more detail below.

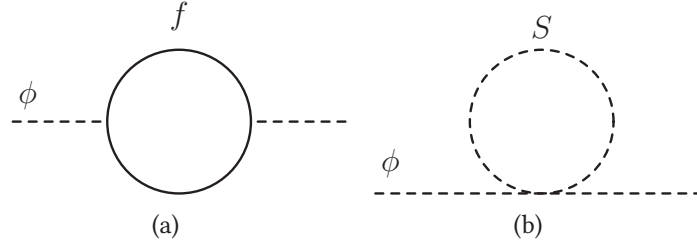


Figure 1.3: One-loop quantum corrections to the Higgs squared mass parameter m_H^2 , due to (a) a Dirac fermion f , and (b) a scalar S . ϕ represents the Higgs field.

The Gauge Hierarchy Problem. In the SM each interaction is characterised by a typical energy scale. For QCD this scale is $\mathcal{O}(200)$ MeV, while for the electroweak (EW) interaction it is set by the Higgs vacuum expectation value (vev), $v = 246$ GeV. Quantum-gravitational effects are expected to become relevant only at the Planck scale, $M_{\text{Planck}} \sim \mathcal{O}(10^{19})$ GeV [21].

The Higgs boson mass can be written in the form:

$$m_H^2 = m_{H_0}^2 + \delta m_H^2, \quad (1.30)$$

where m_{H_0} is the bare mass of the Higgs boson, which is obtained from the Higgs Lagrangian (Eq. 1.14), and δm_H^2 is the radiative correction.

It is known experimentally [22] that $\langle \phi \rangle = \sqrt{-m_{H_0}^2/2\lambda}$ is approximately 174 GeV from measurements of the properties of the weak interactions. At the same time, the measured mass m_H of the Higgs boson is 125 GeV [23, 24]. This results in $\lambda = 0.126$, $m_{H_0}^2 = -(92.9 \text{ GeV})^2$.

Figure 1.3a represents a Feynman diagram of a loop correction from a Dirac fermion. Then the Higgs field couples to f with a term in the Lagrangian $-\lambda_f \phi \bar{f} f$, resulting in the correction:

$$\delta m_H^2 = \frac{|\lambda_f|^2}{8\pi} \Lambda_{UV}^2 + \dots \quad (1.31)$$

Here λ_f^2 is the fermion f coupling to the Higgs boson, and Λ_{UV} is an ultraviolet momentum cut-off used to regulate the loop integral, which should be interpreted as at least the energy scale at which new physics enters to alter the high-energy behaviour of the theory. Above the EW scale, defined by the Higgs vev, the SM does not assume the presence of new interactions until gravity appears at M_{Planck} .

In such a scenario, radiative corrections to the Higgs mass evaluated at the Planck scale exceed the bare mass by about 30 orders of magnitude. The

observed Higgs mass can be reproduced either by imposing an extreme fine-tuning on each divergent contribution or by introducing new states or interactions at scales below M_{Planck} that cancel the quadratic divergences.

A fine-tuning of $\mathcal{O}(10^{30})$ is in sharp conflict with the naturalness criterion [22]. The more consistent resolution is the presence of new physics that stabilises the Higgs sector. Additional particles beyond the SM could couple to the Higgs in loop corrections, leading to cancellations of divergent terms and leaving the bare mass at a value consistent with the measured one.

For example, the corrections may come from hypothetical scalar particle S which couples with the Higgs field with a term in the Lagrangian $-\lambda_S |\phi|^2 |S|^2$. The Feynman diagram of a loop correction from a scalar particle is shown in Figure 1.3b. This results in the correction:

$$\delta m_H^2 = \frac{\lambda_S}{16\pi^2} \left[\Lambda_{UV}^2 - 2m_S^2 \ln(\Lambda_{UV}/m_S) + \dots \right]. \quad (1.32)$$

Dark matter. The standard framework for cosmology is the Λ CDM model, which provides a consistent description of structure formation and the large-scale distribution of matter in the Universe. In this model the total energy density is dominated by a cosmological constant Λ (dark energy, $\sim 68.5\%$) and cold dark matter (CDM, $\sim 26.5\%$), with only a subdominant contribution from ordinary baryonic matter ($\sim 4.9\%$) [14]. These fractions are usually denoted as Ω_λ , the density parameter, where λ is a symbol corresponding to the type of energy or matter contributing into the total density: $\sum_\lambda \Omega_\lambda = \Omega_{tot} \approx 1$ [14]. The value of the dark energy density parameter Ω_Λ , has been determined from several independent probes. Type Ia supernovae give $\Omega_\Lambda = 0.669 \pm 0.038$ [25], while the Planck satellite measurements of the CMB provide $\Omega_\Lambda = 0.6848 \pm 0.0073$ [26, 27]. These results are mutually consistent and establish Λ as the dominant component driving the present accelerated expansion.

Within Λ CDM, baryonic matter is described by the Standard Model (SM), while the CDM component requires new physics beyond the SM. No viable SM candidate exists, and the identification of the dark matter particle remains one of the central open problems.

Thus Λ CDM, while phenomenologically successful, is regarded as an effective description. The microscopic origin of dark energy and the particle nature of dark matter remain unresolved.

1.2 Particle Lifetimes

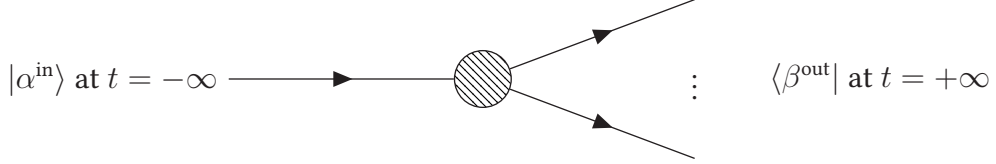


Figure 1.4: A cartoon representation of a decay process [28].

The proper lifetime τ of the particle is connected with the full decay width Γ_{tot} by:

$$\tau = 1/\Gamma_{tot}, \quad (1.33)$$

where the full decay width is the sum of the partial decay widths corresponding to all possible decay modes. The decay width for a mode $\Gamma(\alpha^{in} \rightarrow \beta^{out})$ is an integral over the phase-space volume: $\Gamma = \int_{\Omega} d\Gamma$.

The decay width per unit of phase-space volume of the final states can be explicitly computed:

$$d\Gamma = \frac{d\Pi_f}{2E_{\alpha}} |\mathcal{M}_{\beta\alpha}|^2, \quad (1.34)$$

where $d\Pi_{\beta}$ is a Lorenz-invariant phase-space volume:

$$d\Pi_f \equiv (2\pi)^4 \delta^4(p_{\alpha}^{\mu} - \sum p_{\beta}), \quad (1.35)$$

and $\mathcal{M}_{\beta\alpha}$ is a matrix element of the decay process (Figure 1.4), computed by integrating and summing over all the final momentum and spin states. $\mathcal{M}_{\beta\alpha}$ can be extracted from the second term of the S -matrix:

$$S_{\beta\alpha} = \langle \beta^{out} | \alpha^{in} \rangle = \delta_{\beta\alpha} + (2\pi)^4 \delta(p_{\beta} - p_{\alpha}) \mathcal{M}_{\beta\alpha}. \quad (1.36)$$

1.2.1 Long-Lived Particles in the Standard Model

Particles in the Standard Model (SM) have lifetimes spanning an enormous range of magnitudes, from the Z boson ($\tau \sim 2 \times 10^{-25}$ s) to the proton ($\tau > 10^{34}$ years) and electron (stable). Figure 1.5 gives an overview of the lifetimes of the Standard Model particles.

From the point of view of high energy particle experiments, such as the ATLAS experiment [30], the particle becomes a “long-lived” when its decay length becomes visible at the detector level. A detector-significant value of decay length corresponds to $c\tau \gtrsim 10 \mu\text{m}$, or τ is of $\mathcal{O}(10^{-14})$ s and higher.

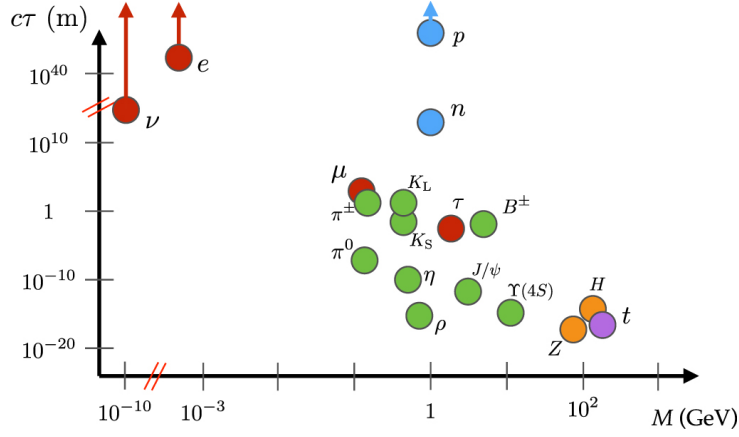


Figure 1.5: Particle lifetime $c\tau$, expressed in meters, as a function of particle mass, expressed in GeV, for a variety of particles in the Standard Model [29].

According to expression (1.34), the proper lifetime τ of a particle depends on two properties: the decay phase space and the matrix element $|\mathcal{M}_{\beta\alpha}|^2$ of the decay process. Longer lifetimes are achieved when one or both values are reduced. The most common mechanisms of decay suppression are:

- decays mediated by a heavy particle;
- small mass differences (splittings) between the particles and their decay products, which lead to the limited decay phase space;
- small couplings (small matrix element).

A few examples of the longevity mechanisms in the SM are given below.

Decays via a heavy particle (off-shell decays). Muon is one of the examples of the SM long-lived particles. The muon lifetime is $\tau_\mu = 2.197 \times 10^{-6} \text{ s}$ [14]. The only allowed decay channel for the muon is mediated by the W -boson:

$$\mu^- \longrightarrow \nu_\mu \bar{\nu}_e e^- \quad (1.37)$$

The muon lifetime can be written in the form, showing the clear dependence on the decay mediator mass [31]:

$$\tau_\mu = \left(\frac{m_W}{m_\mu g_W} \right)^4 \frac{12(8\pi)^3}{m_\mu}, \quad (1.38)$$

where m_W is the mass of the W -boson, and g_w is an electroweak coupling (Eq. 1.6).

Limited phase space (small mass splittings). Another example of the long-lived Standard Model particles is the neutron. The neutron lifetime ($\tau_n \approx 880$ s) [14] originates from the limited phase-space scenario. A free neutron decays through the β -decay:

$$n \longrightarrow p^+ e^- \bar{\nu}_e. \quad (1.39)$$

The mass difference between the neutron and the proton is small: $m_n - m_p \approx 1.293$ MeV, leading to a significant suppression of the decay phase space.

Another example of the SM LLP motivated by the same scenario is the neutral kaon K_L^0 , which decays to pions:

$$K_L^0 \longrightarrow \pi^+ \pi^- \pi^0 \quad (1.40)$$

The resulting phase space is severely limited, with only $\Delta m \approx 80$ MeV available for the three-body system. This suppression reduces the decay width by almost three orders of magnitude, yielding $\tau_{K_L^0} \approx 5 \times 10^{-8}$ s.

Small couplings. In bottom hadrons, the relevant flavour-changing transitions are the charged-current processes $b \rightarrow c$ and $b \rightarrow u$. The decay amplitudes are proportional to the CKM elements $|V_{cb}|$ and $|V_{ub}|$, respectively:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.225 & \mathbf{0.003} \\ 0.225 & 0.973 & \mathbf{0.041} \\ 0.009 & 0.040 & 0.999 \end{pmatrix} \quad (1.41)$$

As a result, the lifetimes of the $B_{u,d,s}$ hadrons are of the order 1.5 ps.

1.3 BSM Scenarios Predicting LLPs

The existence of long-lived particles within the Standard Model demonstrates that extended lifetimes may result from suppressed couplings, small mass splittings, or decays mediated by heavy states. Many theories beyond the Standard Model predict additional particles whose longevity arises from the same mechanisms. This section summarises representative examples, including Supersymmetry, Neutral Naturalness, and Portal theories, which constitute theoretical frameworks predicting LLPs.

1.3.1 Supersymmetry

Supersymmetry (SUSY) is a generalisation of the space–time symmetries of quantum field theory, which transforms fermions into bosons and vice versa [14]. A symmetry operator Q creates such a transformation:

$$Q |fermion\rangle = |boson\rangle; \quad Q |boson\rangle = |fermion\rangle. \quad (1.42)$$

The generators Q and $Q^\dagger$ must satisfy an algebra of anticommutation and commutation relations in schematic form [22]:

$$\{Q, Q^\dagger\} = P^\mu, \quad (1.43)$$

$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0, \quad (1.44)$$

$$[P^\mu, Q] = [P^\mu, Q^\dagger] = 0. \quad (1.45)$$

Here, P^μ is the four-momentum generator of space-time translations.

The Minimal Supersymmetric Standard Model (MSSM) is a supersymmetric extension of the SM. The gauge symmetry group corresponding to the MSSM is the same as for the SM, $SU(3)_C \times SU(2)_L \times U(1)_Y$.

The particles described by the SM and their supersymmetric partners are arranged into supermultiplets, each of which contains two bosonic and two fermionic degrees of freedom. Fermions appear in two polarisations and have the form of Weyl spinors [32]. One bosonic state is associated with each fermion polarisation. Depending on the spin of the particles, it is possible to divide supermultiplets into chiral, gauge, and gravitational supermultiplets.

The superpartner of the particle X is normally denoted as $\tilde{X}$. Chiral supermultiplets contain the spin-1/2 SM fermions (both RH and LH) and their spin-0 superpartners from the SM extension (‘sfermions’ with ‘s’ for ‘scalar’). Gauge supermultiplets contain the massless spin-1 SM gauge vector bosons fields, together with their two spin-1/2 Weyl superpartners labelled as gauginos. Gravitational supermultiplets contain the spin-2 graviton G and its spin-3/2 supersymmetric partner, the gravitino $\tilde{G}$.

The Higgs sector of the SM can be extended only after considering the existence of two Higgs doublets. Thus, the SM is first extended to the two-Higgs-doublet model (2HDM). In such a model, two Higgs doublets, ϕ_1 with hypercharge $Y = -1$ and ϕ_2 with hypercharge $Y = 1$, are required to generate mass for the down-type quarks and charged leptons via the ϕ_1 doublet, and up-type quarks via the ϕ_2 doublet [33]. Two scalar fields correspond to eight degrees of freedom; after the SSB, the masses of the $W^\pm$ and Z^0 are generated by three of them. The remaining five degrees of freedom correspond to the Higgs bosons in the MSSM. Altogether,

there are two CP-even neutral bosons h (the SM Higgs boson with mass 125 GeV) and H , one CP-odd neutral pseudoscalar A , and one charged pair $H^\pm$.

The particle content of the chiral and gauge supermultiplets is shown in Tables 1.1 and 1.2, respectively.

Table 1.1: Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks ($\times 3$ families)	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	$(3, 2, \frac{1}{6})$
	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(3, 1, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(3, 1, \frac{1}{3})$
sleptons, leptons ($\times 3$ families)	L	$(\tilde{\nu}, \tilde{e}_L)$	(ν, e_L)	$(1, 2, -\frac{1}{2})$
	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(1, 1, 1)$
Higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(1, 2, \frac{1}{2})$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	$(1, 2, -\frac{1}{2})$

Table 1.2: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$(\tilde{W}^\pm, \tilde{W}^0)$	$(W^\pm, W^0)$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

It is possible to define a discrete R symmetry:

$$R \equiv (-1)^{3(B-L)+2S}, \quad (1.46)$$

where B , L , and S are the baryon number, lepton number, and spin, respectively. $R = +1$ for all SM particles, and $R = -1$ for their supersymmetric partners.

In scenarios with conserved R -parity (RPC theories), SUSY particles cannot decay into SM-only final states. In RPC scenarios, the lightest supersymmetric particle (LSP) remains stable, so it is considered a long-lived particle. If the LSP is neutral, it can be a cold dark matter candidate.

R-parity violation (RPV)

Explicit R -parity violation can be included by adding the following terms to the Lagrangian [34]:

$$W_{\text{RPV}} = \mu_i L_i H_u + \frac{1}{2} \lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \frac{1}{2} \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k, \quad (1.47)$$

where L , Q , e , u , d are matter multiplets, H_u is the up-type Higgs field, and $(\lambda, \lambda', \lambda'')$ are the RPV couplings. Non-zero values for both λ' and λ'' lead to proton decay.

RPV operators are highly constrained by flavour measurements and the non-observation of proton decay [35], which leads to small values of RPV coefficients, naturally imposing LLPs as part of the RPV models. Long lifetimes in this case are motivated by small couplings.

Gauge-mediated symmetry breaking (GMSB)

The simplest SUSY model that gives rise to LLP signatures is Gauge-Mediated SUSY Breaking (GMSB) [34, 36]. In GMSB, SUSY is broken via the gauge interactions of the chiral messenger superfields, Φ , which interact with the goldstino superfield X through the superpotential:

$$W = \lambda_{ij} \bar{\Phi}_i X \Phi_j. \quad (1.48)$$

SUSY is broken when X acquires a vacuum expectation value (vev) along the scalar and auxiliary components,

$$\langle X \rangle = M + \theta^2 F, \quad (1.49)$$

where M is the messenger mass scale and $\sqrt{F}$ is proportional to the mass splitting inside the supermultiplet. One feature of GMSB is that the gravitino, $\tilde{G}$, is typically the LSP, and the attributes that give rise to LLP signatures depend only on F . In particular, the next-to-lightest superpartner (NLSP) decays to the gravitino and an SM particle via higher-dimensional operators that are suppressed by $1/F$.

Perhaps the best-motivated examples arise from theories of GMSB, which frequently predict spectra where the right-handed stau is the NLSP. The lifetime of a slepton NLSP decaying via $\tilde{l} \rightarrow l \tilde{G}$ can be expressed [37] as:

$$c\tau \approx 100 \mu m \left(\frac{100 \text{ GeV}}{m_{\tilde{l}}} \right)^5 \left(\frac{\sqrt{F}}{100 \text{ TeV}} \right)^4, \quad (1.50)$$

Even for a relatively low SUSY-breaking scale $\sqrt{F} \sim 100 \text{ TeV}$, the decay lengths of such sleptons become measurable with multipurpose detectors like ATLAS. A detailed discussion of such measurements is provided in Chapter 2.

Anomaly-Mediated SUSY Breaking (AMSB)

Another SUSY-breaking scenario [38, 39] is introduced through a combination of anomaly and gravity effects. This is known as anomaly-mediated SUSY breaking

(AMSB) and gives rise to a different pattern of masses and signatures from those of GMSB.

$$\tau \sim \Gamma^{-1}(\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^0 + X^{\pm}) \sim \left(\frac{800 \text{ MeV}}{m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}^0}} \right)^3 \times 10^{-3} \text{ ns}, \quad (1.51)$$

where $X^{\pm}$ is an SM particle. In the case of the AMSB chargino, the lifetime is defined by the mass splitting $m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}^0}$ [39]. When the splitting is small, the phase space is reduced, and the chargino becomes long-lived.

Split-SUSY

In split-SUSY models [40, 41], SUSY breaking occurs at the squark mass scale, $m_S \gg 1000 \text{ TeV}$, and all the scalars are ultra-heavy except for one, which serves as the Higgs boson. At the same time, the predicted fermions due to chiral symmetries can have weak-scale masses.

Models of split-SUSY predict gluinos with long lifetimes. Such lifetimes are motivated by decays mediated by squarks, which are ultra-heavy by the model design.

The effective operators that give rise to gluino decay are higher-dimensional and suppressed by the squark mass scale:

$$\mathcal{O}^{(6)} \sim \frac{g_s^2}{m_S^2} \bar{q} \tilde{g} \tilde{\chi} q, \quad \mathcal{O}^{(5)} \sim \frac{g_s^2}{16\pi^2 m_S} \tilde{g} \sigma_{\mu\nu} \tilde{\chi} G^{\mu\nu}, \quad (1.52)$$

where g_s is the strong-coupling constant.

The gluino decays $\tilde{g} \rightarrow \chi^0 g$, $\tilde{g} \rightarrow \chi^0 q \bar{q}$ and $\tilde{g} \rightarrow \chi^{\pm} q \bar{q}'$ can be described with these operators. The decay width for gluino can be estimated as it follows [34]:

$$\Gamma^{-1} \sim \frac{4}{N} \left(\frac{m_S}{1000 \text{ TeV}} \right)^4 \left(\frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^5 \times 10^{-4} \text{ ns}. \quad (1.53)$$

1.3.2 Neutral Naturalness

Neutral naturalness models attempt to solve the SM electroweak hierarchy problem by introducing light states, which are not coloured or even fully neutral with respect to the Standard Model. The electroweak hierarchy is achieved through discrete symmetries, which naturally lead to hidden valleys [42–44] without SM quantum numbers.

In these scenarios, the hidden sector appears neutral to the SM but can interact with the SM via ‘portal’ mediators described in Section 1.3.3.

Examples of long-lived particles in neutral naturalness can be found in the Twin Higgs [45, 46], Folded SUSY [47], and Quirky Little Higgs [48] models.

In these models, long lifetimes are achieved either through small couplings or reduced decay phase space.

1.3.3 Portal Theories

A class of BSM theories known as ‘portal’ theories introduces an interaction between the SM and the dark sector through a mediating field. The interaction Lagrangian for a portal theory can generally be written as follows [34]:

$$\mathcal{L}_{tot} = \mathcal{L}_{SM} + \mathcal{L}_{HS} + \mathcal{L}_{portal}, \quad \mathcal{L}_{portal} = \sum O(SM) \times O(DS). \quad (1.54)$$

In Eq. (1.54), $\mathcal{L}_{DS}$ is the Lagrangian of the Dark Sector, which remains unknown, and $\mathcal{L}_{portal}$ is the Lagrangian of the portal field. Examples of the corresponding couplings for different types of portal theories are given in Table 1.3. There are three kinds of renormalisable portal theories depending on the type of mediator: a scalar, which can be mediated through a dark Higgs boson S [49, 50]; a vector, which can be mediated through a dark photon A' [50–52]; and a fermionic portal, mediated through a heavy neutral lepton N [53–59]. In addition to renormalisable fields, the portal can also be a pseudoscalar field [60, 61], where higher-dimensional operators appear in the interaction of SM fields and the mediator. Axion-like particles (ALPs) [62–66] are generic pseudo-Nambu–Goldstone bosons associated with the breaking of global symmetries.

ALPs have derivative couplings to fermions, and therefore their masses are protected from radiative corrections through a shift symmetry. As a result, one can have naturally light ALPs.

Table 1.3: Dominant interaction terms that give rise to the portals of the different types [34].

Portal type	$\mathcal{L}_{portal}$ couplings
Vector: dark photon (A')	$-\frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} F^{\mu\nu}$
Scalar: dark Higgs (S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Fermion: heavy neutral lepton (N)	$y_N L H N$
Pseudoscalar: ALPs (a)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad \frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}, \quad \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$

1.3.4 LLP Model Summary

The theoretical frameworks discussed above, including Supersymmetry (SUSY), Neutral Naturalness, and Portal models, predict long-lived particles whose extended lifetimes originate from the same mechanisms as those observed in the

Standard Model. In these theories, longevity typically arises from suppressed couplings, limited decay phase space, or scale suppression associated with heavy mediators or high energy scales. The dominant features responsible for long lifetimes in each model are summarised in Table 1.4.

Table 1.4: Dominant features that give rise to long-lived particles in the theoretical models and mechanisms discussed in the text, adopted from [34].

	Model	Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

The properties and interactions of LLPs determine how they can be experimentally probed. Theoretical models giving rise to LLPs can be classified by LLP properties and interactions with the Standard Model. Supersymmetric frameworks such as Gauge-Mediated SUSY Breaking (GMSB), Anomaly-Mediated SUSY Breaking (AMSB), Split-SUSY, RPV SUSY predict electrically and colour charged LLPs. Electrically charged states, such as sleptons and charginos, interact electromagnetically. Coloured states, including gluinos and squarks, hadronise into R -hadrons that interact hadronically and, if charged, also electromagnetically. Hidden-sector models, including Neutral Naturalness frameworks and Portal theories, predict neutral LLPs that are uncoloured and do not interact directly with the Standard Model. Their decays produce Standard Model particles, leading to photon, lepton, or hadron final states. Models with conserved symmetries, such as RPC SUSY and some realisations of Neutral Naturalness, predict stable or effectively invisible LLPs, appearing as missing transverse momentum in the event.

Chapter Summary

The Standard Model of elementary particles, which describes the known particles and their interactions, was reviewed in this chapter. The lifetime is one of the key properties of a particle. The Standard Model describes particles with lifetimes

ranging from $\mathcal{O}(10^{-25})$ s to stable ones. When the lifetime of a particle reaches the values of $\mathcal{O}(10^{-14})$ s, the particle is classified as a long-lived particle (LLP). There are three mechanisms by which the lifetime of a particle can result in the relatively large values: its decay may be mediated by a heavy particle, the available phase space may be limited, or the matrix element of the decay process may be small. LLPs are predicted by several BSM theories. A description of such models, with a focus on SUSY theories, was given in this chapter. Particles produced in these models can be classified according to the types of interactions they can have with SM particles. The type of interaction of an LLP or its decay products, or the absence thereof, defines the strategy for the BSM search for such a particle. Various possible strategies are discussed in the next chapter.

Chapter 2

LLP Searches at the LHC

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2.2	Direct Searches for Charged LLPs	28
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ATLAS [30] and CMS [67] experiments at the LHC [68] were designed with a main focus on prompt physics processes. Details of the reconstruction of standard objects in ATLAS are given in Chapter 4. Some detector features allow searches for particles with significant lifetimes (so-called long-lived particles, or LLPs) using unconventional signatures described in Section 2.1. This chapter provides an overview of existing long-lived particle searches, focusing on the main LLP signatures at ATLAS or CMS. A detailed description of the search techniques used for the direct detection of charged LLPs is the subject of Section 2.2. The experimental limits for the selected models describing charged LLPs are given in Section 2.3.

2.1 LLP Signatures

Depending on the signature, long-lived particles can be detected at general-purpose detectors such as ATLAS or CMS. A schematic overview of the experimental signatures of LLPs is shown in Figure 2.1. Generally, LLP searches at the LHC can be divided into two categories: searches for the products of LLP decays and direct searches for the LLPs themselves. When a hypothetical LLP has the ability to interact with the detector subsystems (electromagnetically or

hadronically), it can be detected directly. In the case of non-interacting LLPs, the search using the decay products remains the only choice.

Depending on the type and the lifetime of a hypothetical LLP, its decay may occur in the inner detector (ID), the electromagnetic (EM) or hadronic calorimeters, the muon spectrometer, or outside the detector. Figure 2.1 shows the time needed for a particle with speed $\beta = 1$ to reach each of these systems. This time can be used as a relative scale to estimate the lifetime ranges of sensitivity of different LLP signatures.

Direct searches require the particle lifetime to be long enough to reach the corresponding system and interact with it. This sets only a lower boundary for the lifetime sensitivity range. In the general case, this means that this class of measurements can be used even for stable-particle searches. The situation with the searches reconstructing LLPs is the opposite: they imply that the LLP decayed before reaching the relevant subsystem, setting upper limits on the lifetime sensitivity ranges.

In order to perform a direct search for an LLP, the particle must interact electromagnetically with the detector (leave ionisation) or hadronically (interact

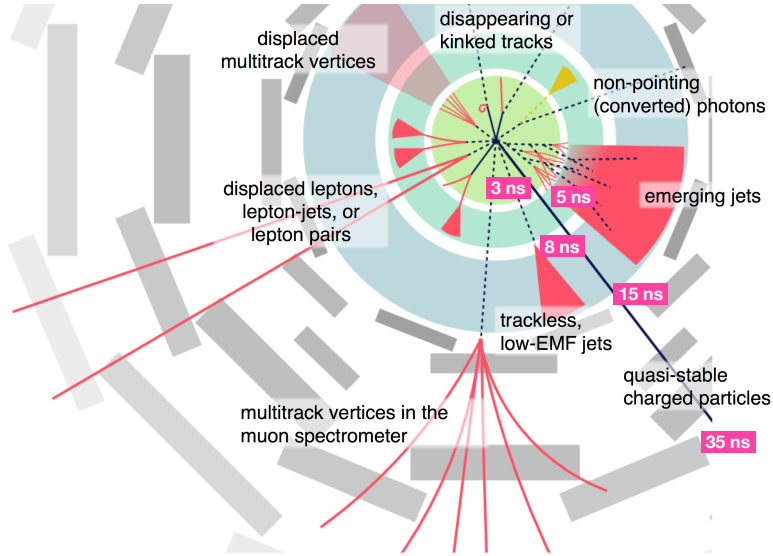


Figure 2.1: Adopted from Ref. [69]. Schematic illustration of possible experimental signatures arising from BSM long-lived particles (LLPs) in LHC detectors. The figure shows a cross-section in the azimuthal angle, ϕ , of a general-purpose detector such as ATLAS or CMS. From the innermost to outermost subsystem: the inner detector (light green), the electromagnetic calorimeter (pale green), the hadronic calorimeter (pale cyan), and the muon system (grey). The times, in nanoseconds, indicate the minimum time required for a particle travelling at $\beta = 1$ to reach each subsystem.

with the hadronic calorimeter), and have a lifetime long enough to reach a system where this interaction can be detected. Searches involving *disappearing tracks* (*tracklets*) [70, 71] and *(quasi-)stable charged particles* [72–76] can be performed directly. A tracklet is a short charged track which has several measurements in the vertex detector, such as the ATLAS Pixel detector, but then disappears and does not have hits in the outer layers of the ID (SCT and TRT, in the case of ATLAS). Tracklet searches require the absence of ID hits at radii larger than the apparent point of disappearance (~ 122 mm, which corresponds to $\tau \lesssim 1$ ns) and large missing momentum in the event. In addition, a tracklet (a direct LLP) may be combined with a *kink*, a short-radius charged track originating at the secondary vertex.

Two signatures are typical for heavy charged LLPs leaving tracks: large specific ionisation in the ID or muon spectrometer, and a delayed timing signal in the calorimeters or muon spectrometer. Section 2.2 provides a detailed description of direct searches for LLPs.

The description of the searches using the decay products of the LLPs is provided below. *Displaced leptons* [77–79], *lepton-jets* [80] or *lepton pairs* [81–84], and *displaced multitrack vertices* [85] are examples of unconventional signatures that are not typical for SM particles produced at the LHC, while being consistent with the hypothesis of the decay of a neutral LLP produced promptly.

Non-pointing (converted) photons [86–88] (photons which cannot be traced back to the primary vertex), reconstructed in the EM calorimeter, can also be considered as products of an LLP decay inside the ID. Such signatures arise in models that allow a neutral LLP to decay into a photon and a particle invisible to the detector.

Interactions of hypothetical LLP products with the hadronic calorimeter, with non-typical signatures, allow tests of Dark QCD models. In such models, hypothetical dark quarks form bound states of dark mesons. Depending on the lifetime of such mesons, different signatures are exploited for the search. If a dark meson decays promptly, a dark-jet signature characterised by an anomalous substructure can be used. A ‘*semi-visible*’ jet [89, 90], a jet with missing momentum aligned with it, can be used in searches for dark mesons with lifetimes that allow a small displacement at decay. In searches for metastable dark mesons, the ‘*emerging jet*’ [91–95] signature can be used. An emerging jet contains very few prompt tracks near the interaction point and many displaced tracks from several small vertices along its axis. As these decays occur at increasing radii, the visible energy and track density rise outward, giving the jet a gradually emerging profile. Most dark mesons decay within the tracker, so the missing transverse energy is small.

Multitrack vertices [96] (including a signature with a *muon pair* [81, 97]) in the muon spectrometer that cannot be connected to a charged track also contribute

to the set of neutral LLP signatures described above.

2.2 Direct Searches for Charged LLPs

A LLP that is much heavier than Standard Model particles is expected to have a smaller speed β . In case of the charged LLP β can be measured. This property can be used to distinguish it from the Standard Model background in searches. Both delayed timing and anomalous ionisation LLP signatures exploit this feature. The construction of a strategy for an analysis using these observables will be the subject of Chapter 8.

Searches for charged LLPs are often optimised for SUSY models, with sleptons, R-hadrons, or charginos as LLPs. The models and mechanisms granting the large lifetimes for these particles are described in more detail in Chapter 1.

A heavy detector-stable slepton would appear muon-like at high momentum: it would leave a track in the ID, traverse the calorimeter, and continue into the muon spectrometer. Unlike a high- p_T muon, such a charged LLP would propagate slowly and exhibit enhanced ionisation. Among long-lived sleptons, staus have the highest predicted production cross-section while having the same signature.

An R-hadron instead undergoes hadronic interactions while traversing the detector at low velocity. The heavy constituent parton typically remains a spectator, acting as a reservoir of kinetic energy, while the light quarks and gluons undergo low-energy scattering with detector nuclei.

The resulting calorimeter signature is not that of a conventional hadronic shower, but instead corresponds to a penetrating particle with reduced energy loss compared to an SM hadron [72]. Hadronic scattering can also alter the light-quark content, leading to charge exchange and allowing the electric charge of the R-hadron to vary along its trajectory. When charged, the R-hadron further loses energy through ionisation.

To detect these LLPs, the measurement of the specific ionisation loss is a key ingredient. The mean rate of energy loss by a charged particle in a speed region $0.1 \lesssim \beta\gamma \lesssim 1000$ can be obtained using the Bethe–Bloch formula [14]:

$$\left\langle -\frac{dE}{dx} \right\rangle = KQ^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right], \quad (2.1)$$

where W_{max} , Z , A , and I are parameters of the material in which the ionisation occurs, $K = 4\pi N_A r_e^2 m_e c^2$, and Q is the charge of the particle.

The track ionisation is normally measured in the pixel part of the ID in experiments like ATLAS (or CMS). Pixel dE/dx searches are sensitive to the LLPs with lifetimes longer than $\mathcal{O}(1)$ ns due to the requirement to have a high-quality dE/dx measurement in the Pixel detector. The requirement to have a track with

high quality increases the lower edge of the lifetime sensitivity to $\mathcal{O}(3)$ ns, since the measurement by the full ID is needed.

The effort in ATLAS started in Run 1 [98, 99], and then continued with a partial Run 2 [100, 101] search and the full Run 2 search [72]. ATLAS searches for LLPs with anomalous ionisation [72, 73] use a truncated mean $\langle dE/dx \rangle_{\text{trunc}}$. After a set of corrections (described in more detail in Chapter 7) this information can be used to determine the $\beta\gamma$ of the charged track. Since the momentum p of the charged particle is measured by the ID, it is possible to compute the mass $m = p/(\beta\gamma)$ of the charged LLP candidate.

CMS searches [74, 75] exploiting the same principle use squared-harmonic-mean dE/dx estimators, which are used to compute the mass of the particle using the momentum measurement, bypassing the direct evaluation of $\beta\gamma$.

Some searches do not extract $\beta\gamma$ or mass from the specific track ionisation losses, but instead use a significance variable built from dE/dx and its resolution [102].

The search for LLPs with large ionisation energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment and the full Run 2 dataset has observed a 3.3 (3.6) global (local) Z -significance excess at 1.4 TeV using only the Pixel dE/dx , in 140 fb^{-1} of Run 2 collisions [72].

The ‘di-track’ channel of the analysis [73], optimised for a signature of pair-produced sleptons, used a combination of the mass measurements from two tracks coming from the same primary vertex. Both mass measurements were obtained from the ionisation only. The di-track channel was sensitive to the signal with a mass range lower than 1.4 TeV, and did not observe any excess.

If the charged particle lives long enough to reach the calorimeter or muon spectrometer, it is also possible to perform the search using time-of-flight measurements that allow measurement of its speed β_{ToF} .

In the case of the ATLAS hadronic calorimeter (TileCal) ToF, the timing information was extracted [73] from the cells with sufficient (≥ 500 MeV) energy deposits associated with an ID track with high energy deposition. The requirement to reach and interact with the calorimeter shifts the lifetime sensitivity range to $\mathcal{O}(8)$ ns and longer.

The most recent ATLAS search for charged LLPs with Pixel dE/dx and TileCal ToF in 140 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV [73] did not confirm the excess observed by the dE/dx -only search [72]. The seven events in the 3.3 Z -significance excess observed in the signal region defined by the dE/dx -only search are excluded by the β_{ToF} selection. The check has shown that the particles in the excess had a value of speed β compatible with 1. This indicates that the observed excess was not due to the slow particles.

ToF measurements in the muon spectrometer in both ATLAS [76] and CMS [74] searches required a potential signal track to be reconstructed with one

of the muon reconstruction algorithms, which give access to ToF information. The detailed description of such an algorithm, used in the ATLAS searches, is given in Chapter 6. In order to obtain a high-quality measurement, the particle must interact with a sufficient volume of the MS. Using the same estimates, the lifetime sensitivity range is $\mathcal{O}(30)$ ns and higher.

The search for LLPs performed in ATLAS with 36.1 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$ [76] used an observable built from the ionisation energy loss in the Pixel detector and the time-of-flight to the TileCal and the muon spectrometer (MDT and RPC).

After β_{ToF} is known, the mass of the particle can be computed in the same way as for the anomalous ionisation signature. Moreover, small values of β_{ToF} imply large ionisation losses in the ID, according to equation 2.1.

A significant advantage of such a combination is that dE/dx and ToF are provided by different sub-detectors, and thus are not correlated. The combination of compatible mass measurements obtained independently from low β_{ToF} and high dE/dx provides a powerful tool for background rejection.

Backgrounds for direct searches of charged LLPs with anomalous ionisation in the Pixel detector, as well as in combination with a long time-of-flight to the TileCal, arise from instrumental effects and tails in the measurements of SM processes, leading to unavoidable Landau tails of the deposited ionisation energy in the case of dE/dx . To take into account all such effects, fully data-driven background-estimation methods are used to predict the mass distribution of the tracks from background processes in the signal regions (SRs).

2.3 Summary of the Limits on Charged LLPs

The recent limits obtained by ATLAS and CMS in the searches for charged long-lived particles are summarised in this section. Figure 2.2 gives a summary of the mass reach for a selected set of the SUSY models obtained in the ATLAS searches. Exclusion limits at 95% CL obtained by the searches with charged LLP predicted by the SUSY models are shown. Figure 2.3 gives a summary of the exclusion limits at 95% CL obtained in LLP searches by the CMS Collaboration. The lifetime ranges in which the models describing the LLPs were excluded are given. The selected set of the models includes non-SUSY models describing neutral LLPs.

The 95% CL exclusion limits for long-lived charged particles in the mass–lifetime planes for the chargino, the gluino in the form of R-hadrons, and for the GMSB stau, set by the ATLAS Collaboration, are provided in Figures 2.4 and 2.5, 2.6, respectively. The obtained limits are compatible to those of CMS to the same set of models and shown in Figure 2.3.

For the very short lifetimes (less than 0.01 ns), the searches exploiting standard

Summary of the Limits on Charged LLPs

LLP Searches at the LHC

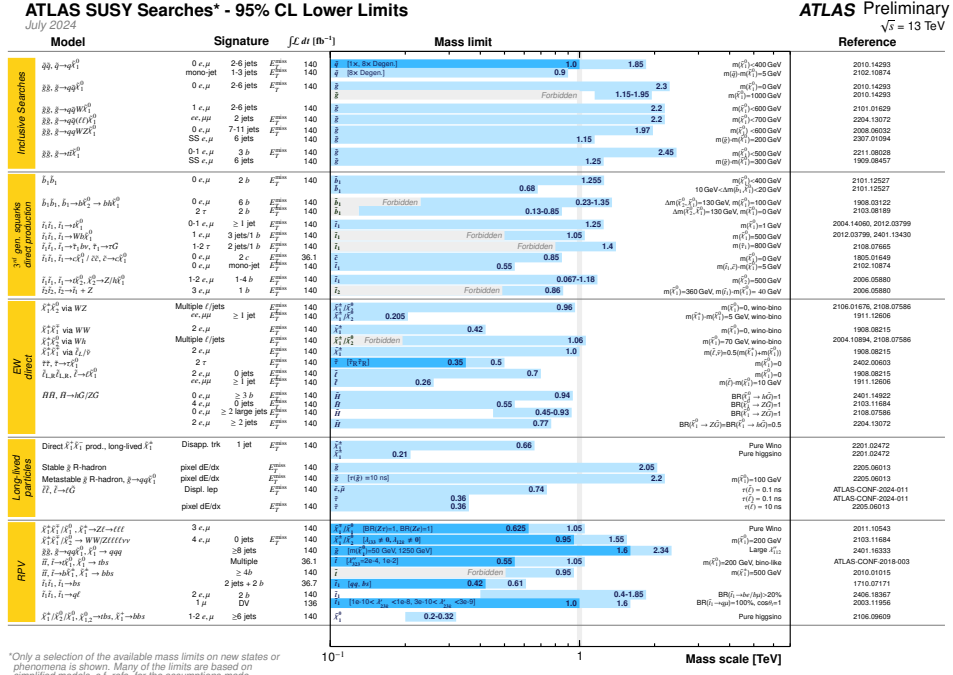


Figure 2.2: Mass reach of the selected ATLAS searches for Supersymmetry [103]. A representative selection of the available search results is shown. Results are quoted for the nominal cross section in both a region of near-maximal mass reach and a demonstrative alternative scenario, in order to display the range of search sensitivity.

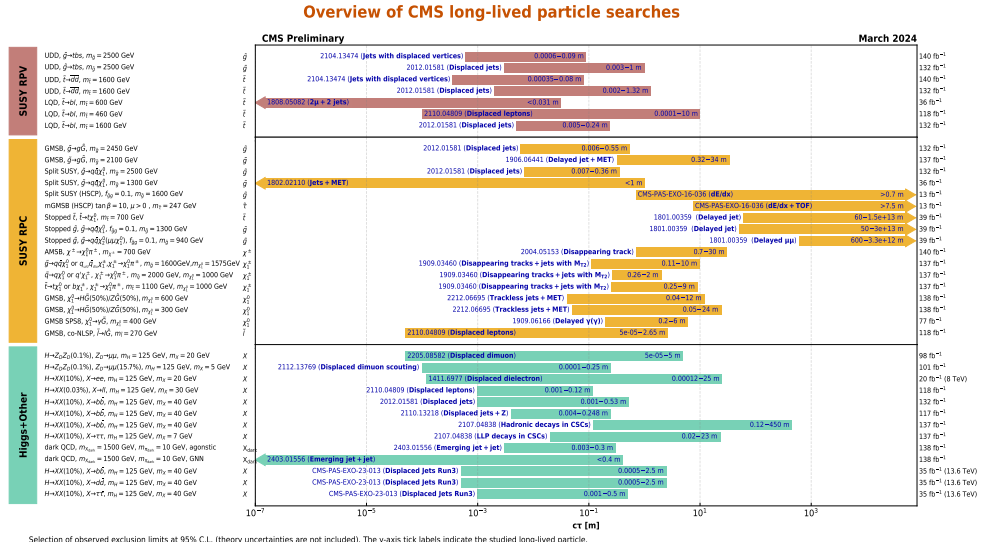


Figure 2.3: Excluded regions, at 95% CL, in the lifetimes of long-lived particles in several models, as obtained by CMS [104].

techniques not including LLP signatures remain the most sensitive. For lifetimes between 0.01 ns and 3 ns (where decays inside the ID are most probable), searches using the disappearing track [70] or displaced vertex [105] signatures are the most sensitive. Above 3 ns the limits are set by the analysis using a single Pixel dE/dx measurement. The limits were updated by the search using a combination of the Pixel dE/dx and TileCal ToF [73] in the lifetime range 10 ns and higher.

Limits for the GMSB stau have been updated by the recent ATLAS search for pair-produced charged LLPs with high anomalous dE/dx [73] and are shown in Figure 2.7.

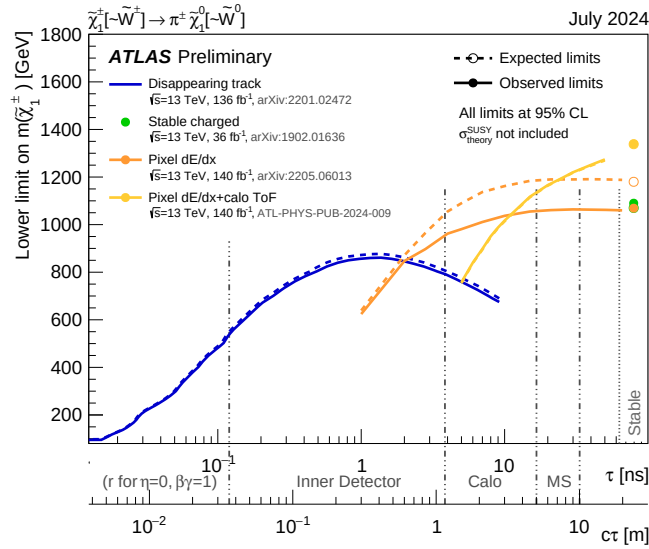


Figure 2.4: Limits at 95% CL on the chargino mass in a model where the wino-like chargino is almost degenerate with the LSP, as a function of chargino lifetime, as obtained by ATLAS [103]. The solid lines indicate the observed limits, while the dashed lines indicate the expected limits. The regions below the curves are excluded.

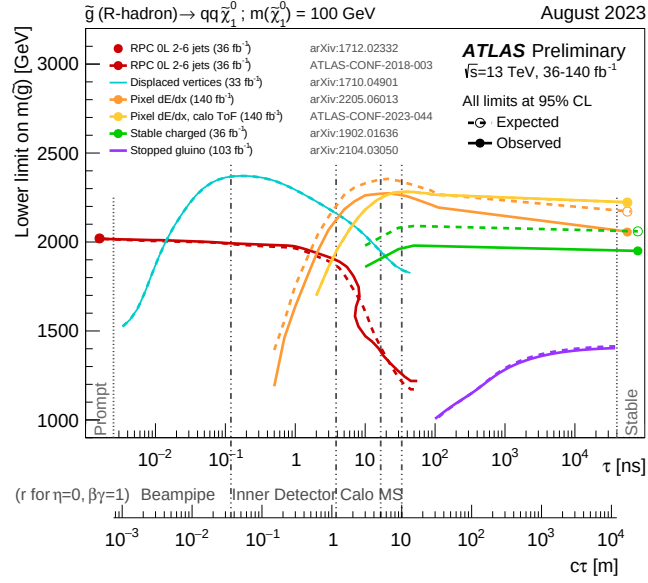


Figure 2.5: Limits at 95% CL on the gluino mass in R-hadron models, as a function of gluino lifetime, as obtained by ATLAS [103]. The solid lines indicate the observed limits, while the dashed lines indicate the expected limits. The regions below the curves are excluded.

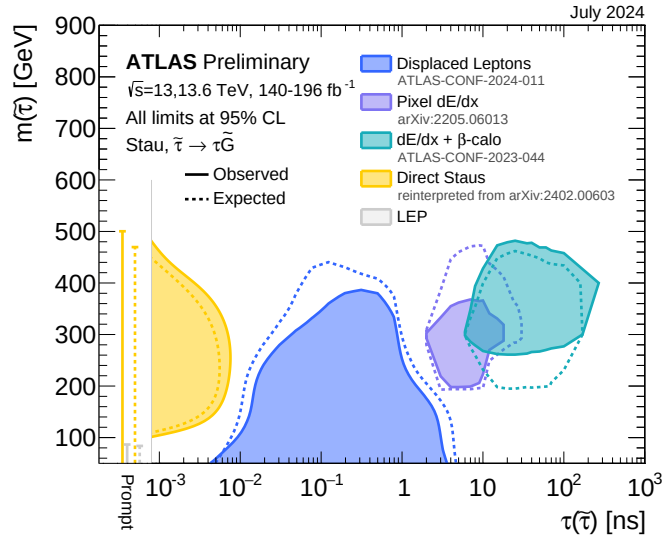


Figure 2.6: Summary of 95% CL exclusion limits based on 13 and 13.6 TeV data in the (mass, lifetime) plane for different analyses probing stau pair production, with decays into τ plus gravitino, in the GMSB scenario. Staus, $\tilde{\tau}_{1,2}$, are the mixed states of the superpartners of the left- and right-handed τ -leptons [103].

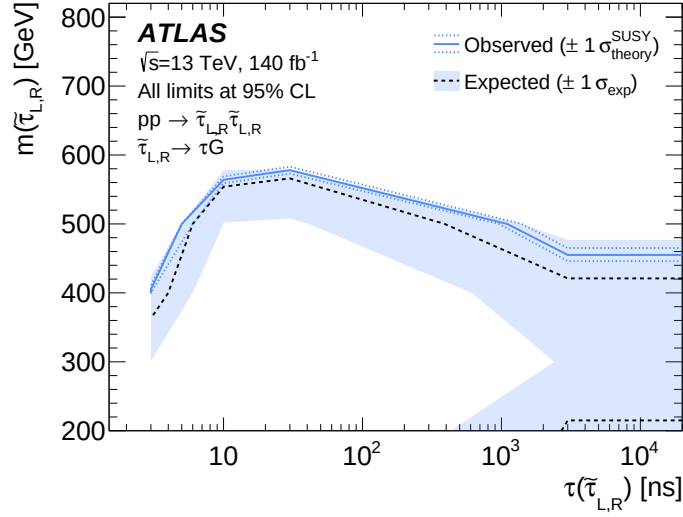


Figure 2.7: The contour for the excluded mass–lifetime region for stau pair production 95% CL exclusion for stau pair production obtained with the ‘di-track’ channel of the search [73].

Chapter Summary

Although certain optimisations of charged LLP searches are performed for specific benchmark models, it is important to underline that the signatures for the direct detection of charged LLPs remain highly model independent.

This chapter has provided an overview of the most common signatures for LLP searches at collider experiments such as ATLAS and CMS, with the main focus on the detection of charged LLPs.

The main techniques for LLP searches with high anomalous ionisation and delayed timing signals were discussed. An overview of the mass–lifetime limits for the signal models representing charged LLPs was given.

Chapter 3

The LHC and the ATLAS experiment

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This thesis is devoted to a Beyond Standard Model search using the proton-proton collision data collected by the ATLAS experiment at the Large Hadron Collider [68] (LHC). In this chapter, the LHC and the ATLAS experiment are described in detail.

3.1 The Large Hadron Collider

The LHC is a two-ring superconducting hadron collider. It is hosted at the CERN (Conseil Européen pour la Recherche Nucléaire) facility and located underground on the territory of France and Switzerland near Geneva. The machine is installed in a 26.7 km long tunnel, which previously hosted LEP [106] collider. The tunnel has eight straight sections and eight arcs and lies between 45 m and 170 m below the surface.

3.1.1 Acceleration Chain

The accelerator complex at CERN is a series of machines that accelerate particles to increasingly high energies. Each machine boosts the energy of a beam of particles before injecting it into the next machine in the sequence. In the Large Hadron Collider (LHC) — the last element in this chain — particle beams are accelerated up to the record energy of 6.8 TeV per beam.

The schematic view of the current configuration of the CERN accelerator complex is shown in Figure 3.1.

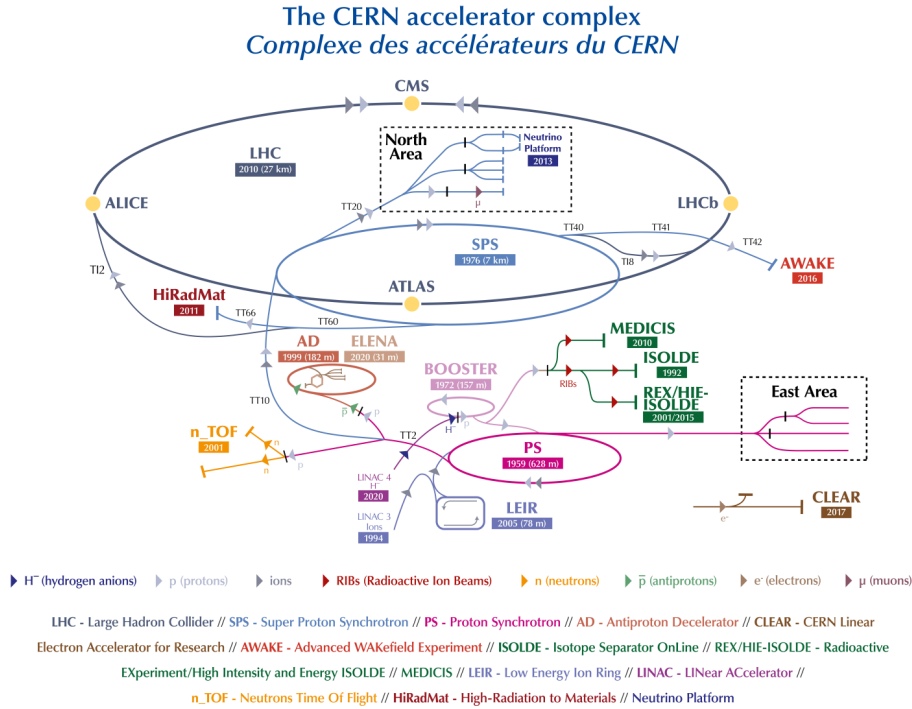


Figure 3.1: Scheme of the CERN accelerator complex [107].

The key machines of the CERN acceleration chain from Linac 4 (source of proton beams) to the LHC are described below.

Linac 4 is a linear accelerator [108] which accelerates negative hydrogen ions (H^-) to 160 MeV and transfers them to the Proton Synchrotron Booster (PSB). Negative hydrogen ions are pulsed through the accelerator for 400 microseconds at a time.

PSB (marked as “BOOSTER” in Figure 3.1) converts the H^- beam to the (p^+) beam and accelerates it to 2 GeV. PSB consists of 4 superimposed synchrotron rings. Each PSB ring has a set of 4 pulsed dipole magnets (BSW) creating the required injection bump and a stripping foil allowing the negative hydrogen ion beam to be converted to the proton beam. Protons accelerated up to 2 GeV are then injected into the Proton Synchrotron (PS).

PS is a key component in the CERN accelerator complex, where it usually accelerates either protons delivered by the Proton Synchrotron Booster or heavy ions from the Low Energy Ion Ring (LEIR). PS was the first synchrotron at CERN, it started operating in 1959 and has circumference of 628 metres. PS bends the beams around the circular trajectory and produces a proton bunch every 25 ns with energies up to 26 GeV. The beam is then sent to the Super Proton Synchrotron (SPS).

SPS is the second largest machine in the CERN accelerator complex. It is a circular accelerator measuring 7 km in circumference. SPS operates up to 450 GeV using 1317 electromagnets and 744 dipoles, keeping the beams on a circular trajectory. Its role is to take particles from the PS and accelerate them to provide beams for the LHC.

In addition to that, the SPS serves an important community of multiple fixed-target experiments, including test beams.

LHC is the final stage of the accelerator chain. The beams are transferred from the SPS into two beam pipes at the LHC, one beam circulating clockwise and the other counter-clockwise.

In 20 minutes, each beam reaches its final energy of 6.8 TeV and collisions start.

The beams circulate for several hours inside the LHC beam pipes under normal operating conditions.

The two beams are brought into collision inside four detectors — ALICE, ATLAS, CMS, and LHCb — where the total centre-of-mass energy at the collision point is equal to 13.6 TeV:

ATLAS (A Toroidal LHC ApparatuS) is a multi-purpose detector designed to work at high luminosity ($\mathcal{L} = 10^{34} \text{cm}^{-2} \text{s}^{-1}$) searching signatures of new physics and to perform precise Standard Model measurements;

CMS (Compact Muon Solenoid) is a multi-purpose experiment which works at high luminosity. CMS is situated at the point of the LHC ring opposite to the ATLAS experiment and pursues the same physics goals as ATLAS but using different detector technologies.

LHCb (The Large Hadron Collider beauty) performs precise flavour physics measurements. LHCb works at lower values of luminosity ($\mathcal{L} = 10^{32} \text{cm}^{-2} \text{s}^{-1}$), using an asymmetric design covering the forward direction along the beam pipe;

ALICE (A Large Ion Collider Experiment) is designed to study the quark-gluon plasma state produced in heavy ion collisions (mainly ions). Using nucleus-nucleus collisions, it can work with a luminosity of $\mathcal{L} = 10^{27} \text{cm}^{-2} \text{s}^{-1}$.

3.1.2 Beam Performance

The instantaneous luminosity $\mathcal{L}$ of the LHC as a pp collider can be expressed as [109]:

$$\mathcal{L} = \frac{R_{inel}}{\sigma_{inel}}, \quad (3.1)$$

where R_{inel} is the rate of inelastic collisions and σ_{inel} is the pp inelastic cross-section.

Then the luminosity of a single pair of colliding proton bunches is given by [110]:

$$\mathcal{L}_b = \frac{\mu f_r}{\sigma_{inel}}, \quad (3.2)$$

where μ is a pile-up parameter, i.e. the number of inelastic interactions in the current pp bunch-crossing, and f_r is the LHC bunch revolution frequency (11246 Hz for protons [111]).

The expression 3.1 can be rewritten as:

$$\mathcal{L} = \sum_{n_b} \mathcal{L}_b = n_b \langle \mathcal{L}_b \rangle = \frac{n_b f_r}{\sigma_{inel}} \langle \mu \rangle, \quad (3.3)$$

where n_b is the number of proton bunch pairs colliding at the interaction point (IP) and $\langle \mu \rangle$ is the pile-up parameter averaged over all colliding bunch pairs.

The instantaneous luminosity can be measured by monitoring μ_{vis} , the visible inelastic interaction rate per bunch-crossing for a particular luminosity algorithm, based on a chosen luminosity-sensitive detector [111]:

$$\mathcal{L}_b = \frac{\mu_{vis} f_r}{\sigma_{vis}}. \quad (3.4)$$

Once σ_{vis} is known, the pile-up parameter μ can be determined from $\mu = \mu_{vis} \sigma_{inel} / \sigma_{vis}$.

In ATLAS, a measurement of μ_{vis} is done over the time interval – a luminosity block (LB). The requirement for collisions to belong to the same LB is the stability of data-taking conditions (including the instantaneous luminosity).

Circulating along the LHC ring, mainly due to bunch collisions, beams lose intensity according to the relation:

$$\mathcal{L} = \mathcal{L}_0 \cdot e^{-\frac{t}{\tau}}, \quad (3.5)$$

where $\tau \sim 15$ h and is a time constant for the LHC and $\mathcal{L}_0$ is the LHC peak luminosity.

The integrated luminosity for a certain time period T is a result of the integration of the instantaneous luminosity over time:

$$\mathcal{L}_{int} = \int_0^T \mathcal{L} dt. \quad (3.6)$$

3.1.3 Operation Periods of the LHC and the ATLAS Detector

The ATLAS detector has been in operation since autumn 2009. During this period, the LHC and ATLAS have alternated between distinct running periods (Runs) and Long Shutdown (LS) periods:

Run 1, 2009–2013: ATLAS recorded 5 fb^{-1} of pp collision data at $\sqrt{s} = 7 \text{ TeV}$ and 21 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$; $167 \mu\text{b}^{-1}$ of Pb+Pb collisions were recorded in 2010 and 2011; 29.8 nb^{-1} of p +Pb collisions were recorded in 2013.

Long Shutdown 1 (LS1), 2013–2015: This shutdown was used to consolidate the LHC machine elements (repairing the magnet splices and upgrading the collimation scheme) to increase the centre-of-mass energy and reach the design luminosity.

Run 2, 2015–2018: ATLAS recorded 147 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$; 179.8 nb^{-1} of p +Pb collisions were recorded in 2016 and 1.76 nb^{-1} of Pb+Pb collisions were recorded in 2018. The LHC reached a peak instantaneous luminosity of $\mathcal{L} = 2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and, on average, delivered $\langle \mu \rangle = 33.7$ interactions per bunch crossing.

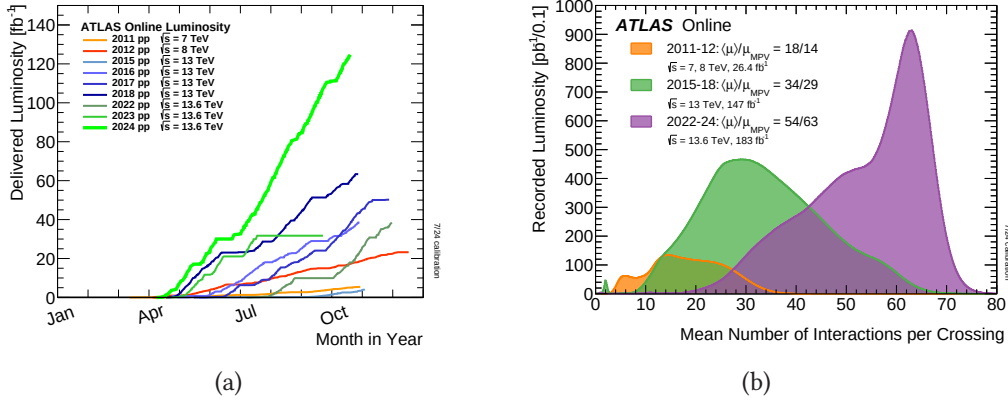


Figure 3.2: (a) Cumulative luminosity versus day delivered to ATLAS during stable beams for Runs 1 – 3 high energy pp collisions. (b) Integrated luminosity as a function of the mean number of interactions per crossing, $\langle\mu\rangle$, for the 2011–2024 pp collision data.

Long Shutdown 2 (LS2), 2019–2022: During this shutdown, a new linear accelerator (LINAC-4) was connected into the injector complex [108], and the injection beam energy of the PS Booster was upgraded in order to reduce the beam emittance. New cryogenics plants were installed to separate the cooling circuits of the superconducting RF cavities from those of the superconducting magnets. The ATLAS Phase-I Upgrade was installed and commissioned during LS2.

Run 3, 2022–2026: The LHC is expected to deliver a peak instantaneous luminosity of approximately $\mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and an integrated luminosity of 250 fb^{-1} of proton-proton collision data at a centre-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$.

Figure 3.2 gives a summary of the luminosity delivered to ATLAS and pile-up over all the period of data-taking at the ATLAS experiment up to the end of 2024.

Long Shutdown 3 (LS3), 2026–2030: The LHC will undergo a major upgrade of its components. The ATLAS Phase-II Upgrade will be installed and commissioned. Phase-II ATLAS Upgrade and HL-LHC era are described in detail in Section 3.3

High Luminosity Large Hadron Collider (HL-LHC), 2030 and beyond:

The LHC complex is expected to deliver a levelled peak instantaneous luminosity of $\mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and an annual integrated luminosity of approximately 250 fb^{-1} to reach a total dataset of 3000 fb^{-1} .

3.2 The ATLAS Detector

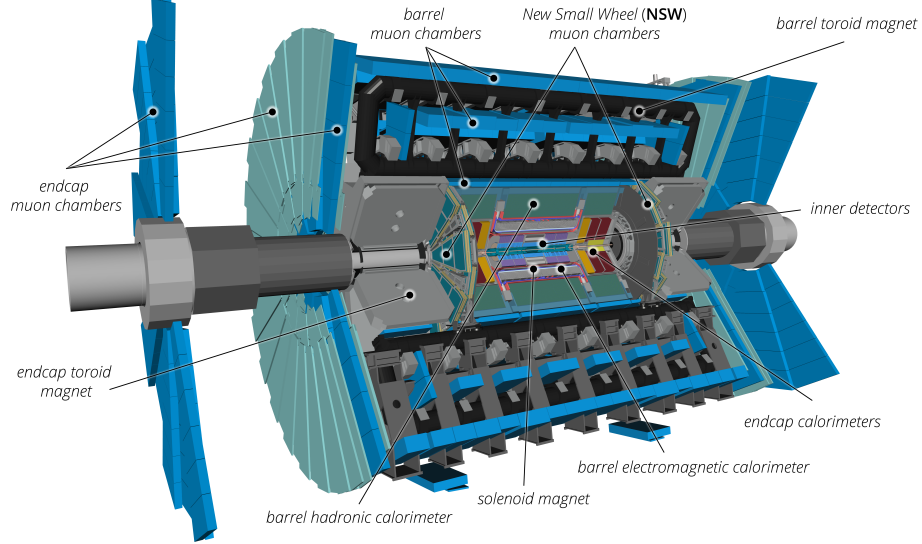


Figure 3.3: Cut-away view of the Run 3 configuration of the ATLAS detector indicating the locations of the larger detector sub-systems [112].

The ATLAS detector [30] (Figure 3.3) is a multi-purpose particle detector installed in its experimental cavern at Point 1 of the Large Hadron Collider (LHC) at CERN. It was originally designed for proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 14$ TeV with an instantaneous luminosity of $\mathcal{L} = 10^{34} \text{cm}^{-2}\text{s}^{-1}$, and heavy ion collisions at $\sqrt{s} = 5.5$ TeV per nucleon pair and $\mathcal{L} = 10^{27} \text{cm}^{-2}\text{s}^{-1}$.

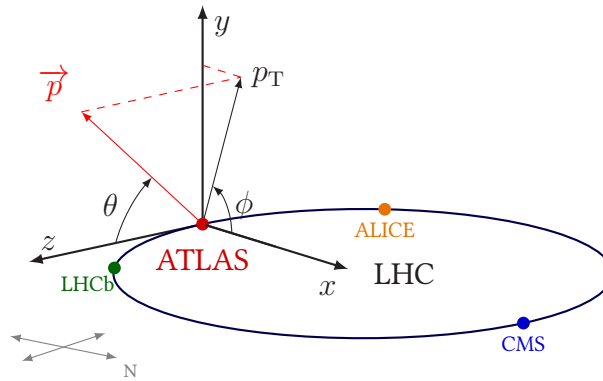


Figure 3.4: ATLAS coordinate system. Modified from Ref. [113].

To define the position of objects inside the ATLAS detector, a cylindrical coordinate system is used. The nominal interaction point is defined as the origin

of the coordinate system, while the beam direction defines the z -axis and the x - y plane is transverse to the beam direction. The illustration of the ATLAS coordinate system is shown in Figure 3.4.

The positive x -axis is defined as pointing from the interaction point to the centre of the LHC ring, and the positive y -axis is defined as pointing upwards. The side-A of the detector is defined as that with positive z and side-C is that with negative z . The azimuthal angle ϕ is measured as usual around the beam axis, and the polar angle θ is the angle from the beam axis. The transverse momentum p_T , the transverse energy E_T and the missing transverse energy E_T^{miss} are defined in the x - y plane. Assuming that colliding bunches have the same momentum in the absolute value, the transverse component of the system momentum is 0.

In the case of massive objects as jets, the Lorentz invariant rapidity y is used:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (3.7)$$

In the ultra-relativistic case ($\gamma \gg 1$) the rapidity of the particle is equal to the pseudorapidity which is defined using only polar angle θ :

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right]. \quad (3.8)$$

The ATLAS detector is designed to reconstruct the products of the pp collisions and is composed of several sub-detectors arranged coaxially around a beam pipe in the following order (Figure 3.3): inner detector, electromagnetic and hadronic calorimeters, and muon spectrometer.

The Inner Detector (ID) performs the tracking of the charged particles and determines the position of the pp collisions (interaction vertex). The electromagnetic calorimeter is designed to absorb and measure energy from photons and electrons. In addition to that, it measures a significant fraction of energy left by hadron jets. The hadronic calorimeters, in their turn, absorb and record the rest of the energy from hadron jets. The muon spectrometer is used for the tracking of muons.

The magnet system allows to measure the momentum of charged particles based on the curvature ρ of the particle trajectory:

$$\rho = \frac{|\vec{p}|}{q |\vec{B}|}. \quad (3.9)$$

Neutrinos are invisible to the detector; however, it is possible to compute the missing transverse energy E_T^{miss} , since $\Sigma \vec{p}_T = 0$.

Figure 3.5 summarises the main features of object identification in the ATLAS detector, and Chapter 4 gives a detailed overview. Table 3.1 provides a summary of the resolution and pseudorapidity coverage of different ATLAS systems.

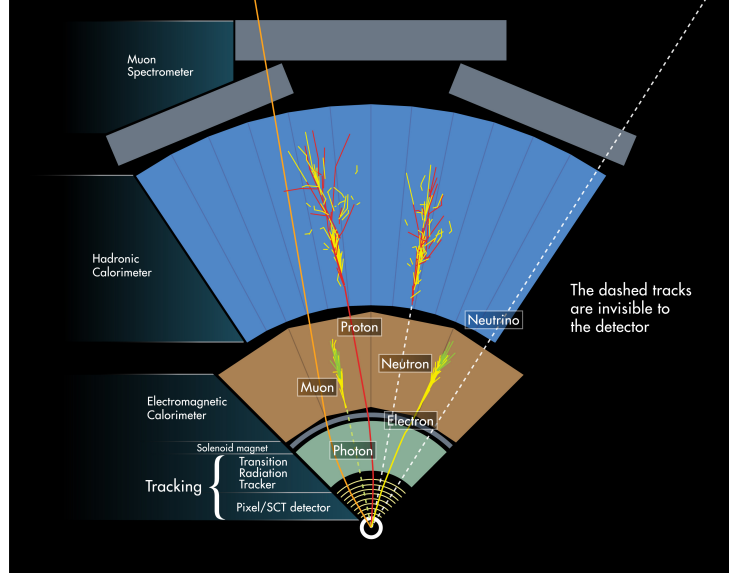


Figure 3.5: Diagram of particle paths in the ATLAS detector

Table 3.1: General performance goals [30] and achieved resolutions in 2015 [114] for the ATLAS detector. Unless otherwise indicated, the units for E and p_T are in GeV.

Detector component	Required resolution	Achieved resolution (2015)	η coverage	
			Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$	$\sigma_{p_T}/p_T = 0.038\% p_T \oplus 1.5\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.2\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)				
Barrel (Tile) and end-caps (LAr)	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
Forward (LAr)	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	–	$3.1 < \eta < 4.9$	$3.1 < \eta < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV	$\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV	± 2.7	± 2.4
Combined with tracker	–	$\sigma_{p_T}/p_T = 7\%$ at $p_T = 1$ TeV	± 2.7	± 2.4

3.2.1 Inner Detector

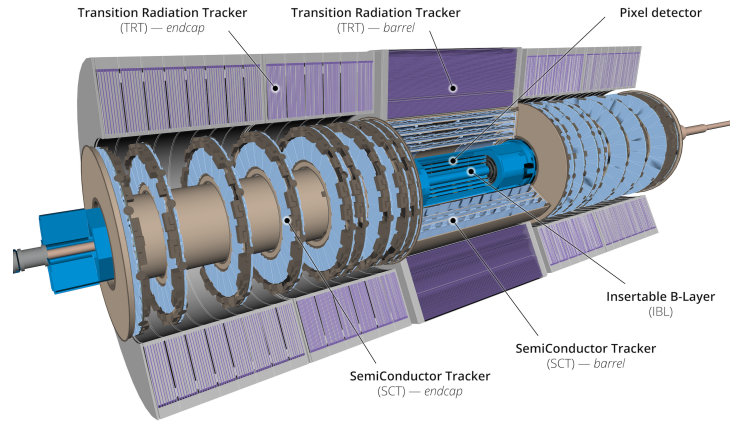


Figure 3.6: Transverse view of the ATLAS ID, including the IBL detector [112].

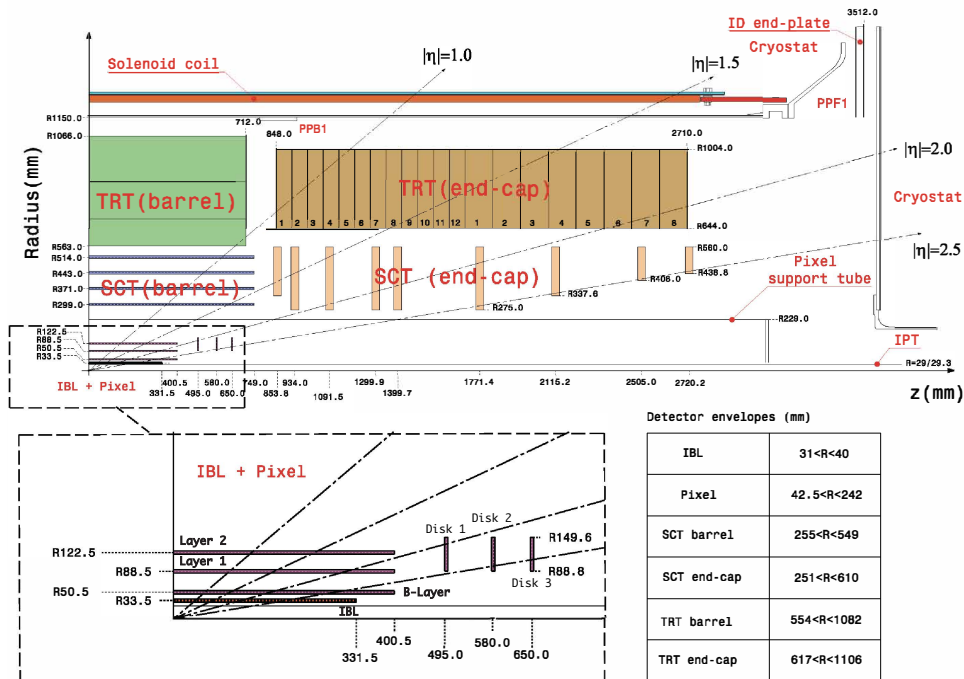


Figure 3.7: The layout of the ATLAS ID including the IBL detector [112].

The Inner Detector (ID) [115] is the closest part of the ATLAS detectors to the beam pipe (and to the collision point). The layout of the ID is shown in Figure 3.6.

The ID is the primary tracking device for measuring the paths of all charged particles in ATLAS. It has been designed to provide hermetic and robust pattern recognition, excellent momentum resolution, and both primary and secondary vertex measurements for charged-particle tracks. It is contained in a cylindrical envelope 7024 mm long and 1150 mm in radius, immersed in the 2 T field of a solenoidal magnet. The detector consists of three complementary sub-detectors: a high-resolution silicon Pixel detector [116], the Semiconductor Tracker (SCT) [117] and the Transition Radiation Tracker (TRT [118]). The sub-detectors are positioned coaxially and cover the pseudorapidity range $|\eta| < 2.5$.

The Pixel Detector

The ATLAS Pixel detector consists of two main parts: The Insertable B-Layer (IBL) and the original part of the Pixel detector. The IBL was mounted inside the Pixel detector during the LS1 and started its operation at the beginning of Run 2.

The original part of the barrel of the Pixel detector [119] is composed of three layers: Layer-0 (so-called B-layer), Layer-1 and Layer-2, placed at 50.5, 88.5 and 122.5 mm accordingly from the detector centre. In addition to that, there are two identical end-cap regions of the Pixel detector, each with three disk layers.

The basic unit of the Pixel detector is a module composed of silicon sensors, front-end electronics, and flex-hybrids with control circuits.

Sensors are the sensitive part of the Pixel detector used for charged particle detection and function as a solid-state ionisation chamber.

The main parameters of the original Pixel detector and the IBL are provided in Table 3.2. All pixel sensors in the original part are identical and are $50 \mu\text{m} \times 400 \mu\text{m}$ ($\phi \times z$) in size and are made with n-in-n planar technology [119]. The IBL is constructed by utilising two types of modules: planar and based on 3D technology [120].

The total area covered by the Pixel system is about 1.7 m^2 . Due to the effect of the Lorentz deviation [119], in the barrel region, the pixel modules are tilted to 20° with respect to the cylinder's tangent.

Typically, the track of the charged particle has 4 hits in the Pixel detector.

The Pixel Detector plays a key role in the analysis described in Chapter 8: All four Pixel layers have the ability to provide a measurement of the specific ionisation loss of the charged particle, by measuring the signal amplitude through a time-over-threshold (ToT) measurement. The specific ionisation loss dE/dx will be one of the variables that will be used to discriminate the signal from long-lived, charged heavy particles from the background. The definition and calibration of the dE/dx estimator is described in Chapter 7.

Table 3.2: Comparison of the main characteristics of the IBL pixels with those of the original Pixel detector layers.

Technical characteristic	Original Pixel	IBL
Active surface (m^2)	1.73	0.15
Number of channels ($\times 10^6$)	80.26	12.04
Pixel size (μm^2) – nominal/long	$50 \times 400/600$	$50 \times 250/500$
Pixel array (columns $\times$ rows)	160×18	336×80
Front-end chip size (mm^2)	7.6×10.8	20.2×19.2
Sensor type	Planar	Planar/3D
Sensor thickness (μm)	250	200/230

The Semiconductor Tracker

The middle system of the ATLAS ID is the Semiconductor Tracker (SCT) [121]. The SCT consists of 4088 modules of silicon-strip detectors arranged in four concentric barrels (2112 modules) and two end-caps of nine disks each (988 modules per end-cap).

All sensors are $285 \mu\text{m}$ thick and are constructed of high-resistivity n-type bulk silicon with p-type implants.

The barrel modules follow a uniform design, with strips approximately parallel to the magnetic field and beam axis. Each module consists of four rectangular silicon-strip sensors with strips with a constant pitch of $80 \mu\text{m}$; two sensors on each side are daisy-chained together to give 768 strips of approximately 12 cm in length.

Each end-cap disk consists of up to three rings of modules with trapezoidal sensors. The strips are arranged radially with a constant azimuthal alignment. The modules in the outer and middle rings consist of two daisy-chained sensors on each side, whereas those in the inner rings contain a single sensor per side.

The SCT typically provides 8 strip measurements (corresponding to four space-points) for the track of the charged particle.

The Transition Radiation Tracker

The Transition Radiation Tracker (TRT) [118] is the outermost of the three ID tracking subsystems and comprises several layers of drift straw tubes interleaved with transition radiation material (radiators). Apart from tracking, TRT performs electron identification. Straw tubes are cylindrical thin-walled proportional gas detectors. The diameter of the straw tube is 4 mm, the straw walls are $35 \mu\text{m}$ thick and are made on the base of the polyimide film. The length of the tubes is 144 cm for the barrel and 37 cm for the end-caps. TRT uses two types of straw

gas mixture: Xenon-based (70% Xe, 27% CO₂, 3% O₂) and Argon-based (70% Ar and 30% CO₂) with 5–10 mbar overpressure. The achieved gas gain is 2.5×10^4 .

TR radiators consist of a number of foil layers interleaved with gas gaps. TR photons are emitted at each media transition with a certain probability when fast charged particle crosses them.

Straw tubes register the ionisation from the charged particle tracks and absorb X-Ray Transition Radiation (TR) photons emitted by Radiators. The probability of emitted TR is proportional to the Lorentz factor γ of the charged particle. This principle allows electron identification to be performed thanks to the significant difference between the electron γ factor and the γ factor of the other light charged particles. Thus, mainly, TRT performs $e^\pm/\pi^\mp$ separation.

3.2.2 Calorimeter System

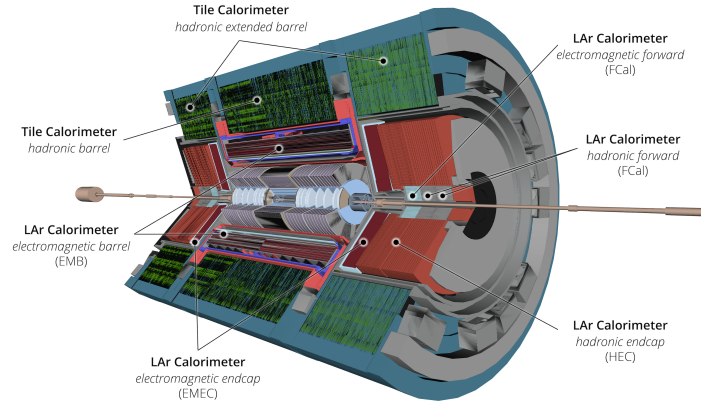


Figure 3.8: Cut-away view of the ATLAS calorimeter system [112].

ATLAS calorimeter system consists of a number of sampling detectors with full ϕ -symmetry and coverage around the beam axis: the electromagnetic (EM) LAr calorimeter and hadronic calorimeters, the Tile Calorimeter (TileCal), the LAr Hadronic End-cap Calorimeter (HEC), and the Forward Calorimeter (FCal). A view of the sampling calorimeters is presented in Figure 3.8 and the description is given below.

These calorimeters cover the range $|\eta| < 4.9$, using different techniques suited to the widely varying requirements of the physics processes of interest and of the radiation environment over this large η -range. In the η region that is matched to the inner detector, the fine granularity of the EM calorimeter is ideally suited for precision measurements of electrons and photons. The coarser granularity of

the rest of the calorimeter is sufficient to satisfy the physics requirements for jet reconstruction and E_T^{miss} measurements.

Calorimeters must provide good containment for electromagnetic and hadronic showers and must also limit punch-through into the muon system. Hence, the depth of the calorimeter is an important design consideration. The total thickness of the EM calorimeter is approximately 22 radiation lengths (X_0) in the barrel and approximately 24 X_0 in the end-caps.

The resolution of hadronic calorimeters is less precise, both in energy magnitude and in localisation, than the EM. The main reason for this decrease is that a significant fraction of the initial energy diverted to low energy nuclear processes is not reconstructed. Additionally, hadronic showers also have electromagnetic components which interact differently with the HCAL than hadronic parts.

LAr Electromagnetic Calorimeter

The EM calorimeter is divided into a barrel part $|\eta| < 1.475$ and two end-cap components ($1.375 < |\eta| < 3.2$), each housed in their own cryostat. Liquid argon (LAr) is used as the active medium. It is kept around 88 K and filled in gaps of 4.5 mm between the absorber layers made of lead. The ECAL has an accordion geometry which makes it possible to cover the full ϕ range without an instrumentation gap and also allows a fast and azimuthally uniform response.

Hadronic Calorimeters

Tile Calorimeter (TileCal). The Tile Calorimeter is placed directly outside the EM calorimeter envelope. The TileCal [122] is a sampling calorimeter using steel as absorber and scintillator as active medium. The scintillating tiles are placed in the plane perpendicular to the beam axis and are radially staggered in depth.

The ATLAS TileCal covers the region $|\eta| < 1.7$ using pseudo-projective calorimeter towers composed of scintillating tiles in a steel matrix, read out by wavelength-shifting fibres. The TileCal comprises a cylindrical barrel section that surrounds the LAr EMB cryostat and two Extended Barrels that surround the LAr end-cap cryostats. The cryostat scintillation counters sit between the central and end-cap cryostats. They are mounted to the TileCal Extended Barrel and are read out through the TileCal electronic system. They are used for luminosity monitoring and to correct for energy losses in the outer wall of the barrel cryostat and ID services in this region where there is a large amount of passive material. The counters present in Runs 1 and 2 covered the region $1.2 < |\eta| < 1.6$, while for Run 3 this coverage has been extended to $1.2 < |\eta| < 1.72$.

The Minimum Bias Trigger Scintillators (MBTS) cover $2.0 < |\eta| < 4.0$ and are used to trigger and monitor luminosity. As they are read out through the TileCal electronic system, they have historically been considered as part of the Tile.

TileCal cells are one of the detection elements exploited by current analysis (Chapter 8), and were used in the preceding search the slow charged long-lived particles [73]. Each cell can provide timing information and can be used to measure time-of-flight of the charged particles from the interaction point.

LAr Hadronic End-cap Calorimeter. The Hadronic End-cap Calorimeter (HEC) consists of two independent wheels per end-cap, located directly behind the end-cap electromagnetic calorimeter and sharing the same LAr cryostats and covers a pseudorapidity range of $1.5 < |\eta| < 3.2$. The HEC also uses LAr as the active material for energy measurement. However, its absorber material is made of copper instead of lead.

LAr forward calorimeter. The Forward Calorimeter (FCal) is integrated into the end-cap cryostats, as this provides clear benefits in terms of uniformity of the calorimetric coverage and reduced radiation background levels in the muon spectrometer. The FCAL covers a pseudorapidity range of $3.1 < |\eta| < 4.9$, where the particle flux is extremely high.

The FCAL is segmented into three layers and all of them use LAr as the active material. The first layer uses copper as the absorber material to measure electromagnetic showers, while the other two layers deploy tungsten absorbers, targeting a reconstruction of hadronic showers.

3.2.3 Muon system

The Muon Spectrometer (MS) [123] is the outermost subsystem in the ATLAS experiment and detects charged particles exiting the barrel and end-cap calorimeters, measuring their momentum in the pseudorapidity range $|\eta| < 2.7$; the layout of the muon spectrometer is shown in Figure 3.9. The muon system is based on the magnetic deflection of muon tracks in the large superconducting air-core toroid magnets, instrumented with separate trigger and high-precision tracking chambers. In the range $|\eta| < 1.4$, magnetic bending is provided by the large barrel toroid. For $1.6 < |\eta| < 2.7$, muon tracks are bent by two smaller end-cap toroid magnets inserted into both ends of the barrel toroid. In between these two regions, $1.4 < |\eta| < 1.6$, magnetic deflection is provided by a combination of barrel and end-cap fields. This magnet configuration provides a field that is mostly orthogonal to the muon trajectories, while minimising the degradation

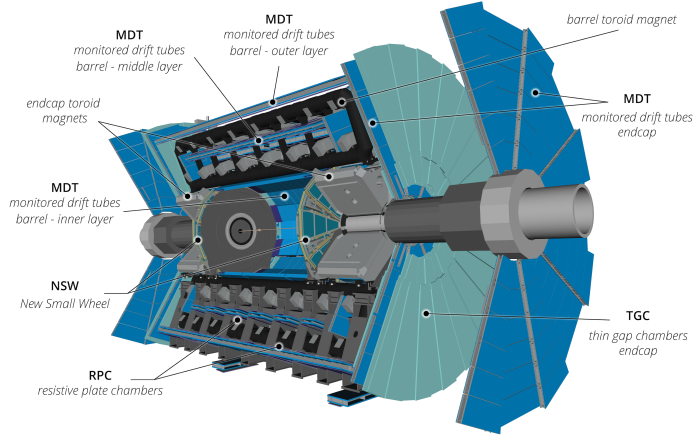


Figure 3.9: Cut-away view of the ATLAS muon system [112].

of resolution due to multiple scattering. The muon detector is included in the trigger system in the region $|\eta| < 2.4$.

Monitored Drift Tubes (MDTs)

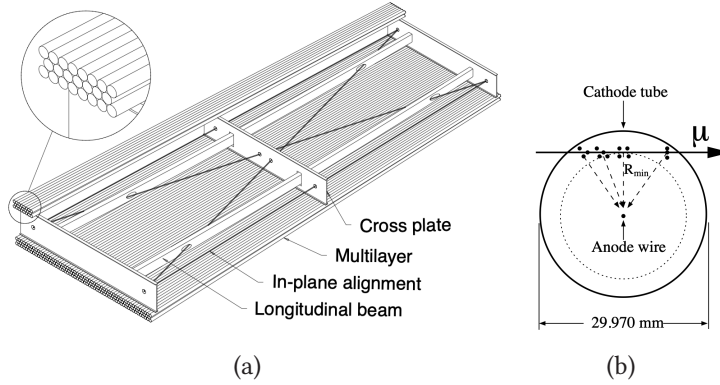


Figure 3.10: (a) Schematic drawing of a rectangular MDT chamber constructed from multilayers of three monolayers each, for installation in the barrel spectrometer. The chambers for the end-cap are of trapezoidal shape, but are of similar design otherwise [123]. (b) MDT tube cross-section with ionisation clusters distributed along a track [124].

The basic element of the monitored drift tube chambers (Figure 3.10b) is a pressurised drift tube with a diameter of 29.970 mm, operating with Ar/CO₂ gas (93/7) at 3 bar.

The MDT detector is formed by two multi-layer (3 or 4 layers) drift tubes,

covering the pseudorapidity region $|\eta| < 2.7$, except for the innermost end-cap layer which covers $|\eta| < 2.0$.

The operating gas was selected because of its good ageing properties. A disadvantage of this gas mixture is the non-linear space-drift time relation and the drift time of about 700 ns.

The chambers are rectangular in the barrel and trapezoidal in the end-cap. Their shapes and dimensions were chosen to optimise solid angle coverage, while respecting the envelopes of the magnet coils, support structures, and access ducts. The direction of the tubes in the barrel and end-caps is along ϕ , i.e. the centre points of the tubes are tangential to circles around the beam axis. Although all tubes in a barrel chamber are identical in length (with the exception of some chambers with cutouts), the tube lengths in the end-cap chambers vary along R in steps of 24 tubes.

All regular MDT chambers consist of two groups of tube layers, called multilayers, separated by a mechanical spacer. In the innermost layer of the muon detector, each multilayer consists of four tube layers to enhance the pattern recognition performance; in the middle and outer layer of the muon detector, each multi-layer consists of three tube layers only. A schematic drawing of a MDT chamber and a MDT tube cross section are shown in Figure 3.10.

The MDT chambers, as well as the Pixel detector, play a key role in the search for the long-lived particles described in Chapter 8. MDT tubes provide muon time-of-flight measurements to the detector element.

Resistive Plate Chambers (RPCs)

In the barrel, the trigger system consists of the RPCs, made by three concentric cylindrical layers around the beam-axis covering the region $|\eta| < 1.05$. The low- p_T (below 10 GeV) trigger requires a coincidence in the middle RPC layers while the high- p_T (above 10 GeV) trigger requires a further coincidence of hits in the outer RPC layer,

Cathode Strip Chambers (CSCs)

The CSCs are multiwire proportional chambers with the wires oriented in the radial direction with respect to the beam-axis to provide muon momentum in the region $2 < |\eta| < 2.7$. Cathode planes are segmented both perpendicular and parallel to the wires to allow measurements in the longitudinal and transverse coordinate, respectively. The track position is obtained by the interpolation of the charges induced on neighbouring cathode strips. The CSC wire signals are not read out. Considering a readout pitch of 5.31 mm and 5.56 mm for the large and small chambers in the bending direction respectively, the CSC reaches a

resolution of $60\ \mu\text{m}$ per CSC plane in the ϕ direction and of the order of one cm in η . The time resolution is about 7 ns.

The CSCs are segmented into large and small chambers in ϕ with two disks with eight chambers each. Each chamber contains four CSC planes to provide four independent measurements in η and ϕ along the track.

In the first layer of the end-cap for $\eta > 2$, the MDTs are replaced by CSCs, which combine high spatial, time, and double track resolution with high-rate capability and low neutron sensitivity.

Thin Gap Chambers (TGCs)

TGCs are multiwire proportional chambers segmented radially into one end-cap and forward region. The peculiarity of these chambers is that the wire-to-cathode distance of 1.4 mm is smaller than the wire-to-wire distance of 1.8 mm, allowing for very short drift time, less than 20 ns. The TGCs are filled with a highly quenching gas mixture of CO_2 and $\text{n-C}_5\text{H}_{12}$ (n-pentane), to allow for operation in a quasi-saturated mode. The highly quenching gas prevents streamers from occurring under all operating conditions.

The TGCs provide azimuthal coordinate measurements complementing the one given by the MDTs in the bending (radial) direction. The TGCs need good time resolution to tag the beam-crossing with high efficiency ($\geq 99\%$) and fine granularity to provide a sufficiently sharp cut-off in the momentum of the triggering muon. To satisfy all physics requirements for momentum resolution, the size of the wire groups varies from 6 to 31 mm as a function of η , corresponding to a variation in width from 10.8 to 55.8 mm. The spatial resolution of the TGCs is 4 mm in the radial direction and 5 mm in the coordinate ϕ .

New Small Wheels (NSW)

During LS2 as a part of Phase I Upgrade of the ATLAS detector, the Small Wheels (EI) were replaced by the New Small Wheels (NSW) to provide very fast and precise track segment matching, while maintaining the offline tracking performance of the SW from Runs 1 and 2. The NSW uses two chamber technologies: small-strip TGC (sTGC) detectors, and micro-mesh gaseous structure (Micromegas) detectors. Both can be used for triggering: the single BC identification capability. (more than 95 % of the signals are collected within one BC) of the sTGC makes them particularly suitable for the primary triggering role, and the small drift gap in the Micromegas chambers means that they are also very fast, with very little dead time. Both technologies have precision tracking capabilities, with ultimate resolutions in the bending direction on the order of $100\ \mu\text{m}$. In the Micromegas detectors the resolution is due in part to their very fine strip pitch (less than 0.5 mm), while

the sTGC (with a strip pitch of 3.2 mm) rely more heavily on charge sharing. Such precision is crucial to maintain the current muon momentum resolution in the high background environment of the upgraded LHC when the full track reconstruction is run.

Second-coordinate resolution (in the azimuthal direction) is improved with respect to the original EI wheels. Trigger-level second-coordinate information is provided by the sTGC pads and the Micromegas stereo roads, while the sTGC wire groups and the full Micromegas stereo strips contribute to the resolution in the final offline reconstruction. The combination of sTGC and Micromegas chambers provides redundancy in tracking at both the trigger and offline reconstruction stages, and is designed to satisfy the performance requirements of Run 3 and the HL-LHC.

3.2.4 Forward Detectors

The ATLAS Forward detectors are a set of four detectors installed along the LHC beam pipe at different distances from the IP. These four detectors are used for different purposes, all of them using the information carried by particles whose detection is missed by the rapidity coverage of the ATLAS central detector. The layout of the forward detectors is shown in Figure 3.11:

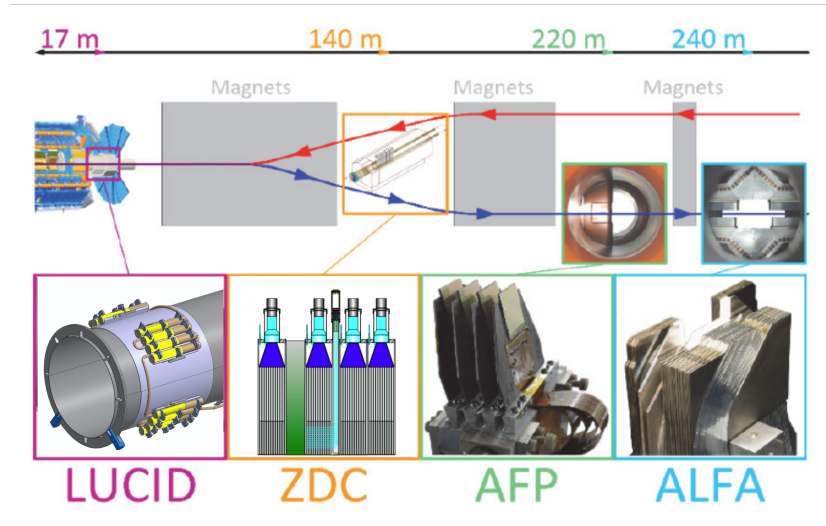


Figure 3.11: Layout of the ATLAS forward detectors [112].

LUCID (LUMinosity Cherenkov Integrating Detector) [125] inside the main ATLAS volume provides a high-precision luminosity measurement;

ZDC (Zero Degree Calorimeters) located just beyond the point where the two beams diverge, measure the energy of “spectator” neutrons in heavy-ion collisions;

AFP (ATLAS Forward Proton) [126] detectors measure time-of-flight and can trigger on bunch crossings producing forward protons in special low-pileup runs;

ALFA (Absolute Luminosity for ATLAS) Roman Pot detectors determine the total proton-proton cross-section by measuring elastic proton scattering at very small angles.

3.2.5 Magnet System and Magnetic Field

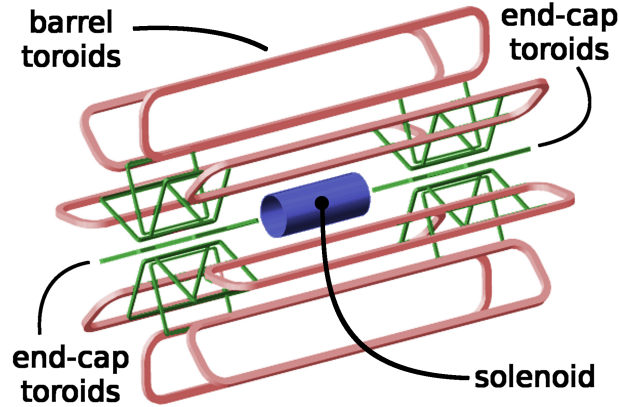


Figure 3.12: A scheme of the spatial arrangement of the ATLAS Magnet System with the central solenoid and the three toroids.

The magnetic system of the ATLAS detector [30] consists of two systems of superconducting magnets (Figure 3.12):

- a Central Solenoid (CS),
- Toroids: Barrel Toroid (BT) and End-Cap Toroids (ECTs).

CS is placed between the ID and ATLAS calorimeter system. The solenoid is aligned on the beam axis and provides a 2 T axial magnetic field for the inner detector, while minimising the radiative thickness in front of the barrel electromagnetic calorimeter.

BT and ECTs toroidal magnetic fields of approximately 4 T for the muon detectors in the central and end-cap regions, respectively.

The toroidal field is perpendicular to the solenoidal field, and the solenoid is magnetically decoupled from the toroids.

3.2.6 Trigger, Readout, Data Acquisition and Control Systems

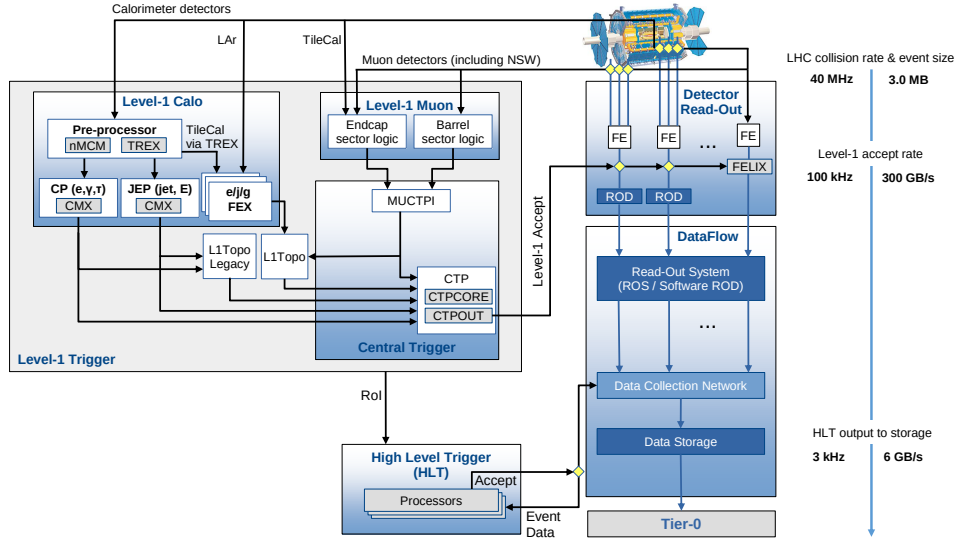


Figure 3.13: Schematic overview of the Trigger and DAQ system at the beginning of Run 3 [112].

As described in Section 3.1.1, proton-proton collisions take place in ATLAS with a frequency of 40 MHz. At the same time, the frequency of event data recording is limited to about 1 kHz, based on technology and resource limitations. Trigger and Data Acquisition (TDAQ) System (the scheme is given in Figure 3.13) is based on a two-level trigger (event selection) system served by the Data Acquisition (DAQ) System that transports the triggered data from custom subdetector electronics to offline processing.

Level-1 Trigger System

The L1 trigger system, shown in Figure 3.13, uses reduced granularity information from the calorimeters and muon system to search for signatures of high- p_T muons, electrons, photons, jets and τ -leptons that decay into hadrons, as well as events with large missing transverse energy or large total transverse energy. It consists of the Level-1 Calorimeter Trigger (L1Calo) and Level-1 Muon Trigger (L1Muon)

trigger systems, the Muon-CTPInterface (MuCTPI), the Level 1 Topological Processor (L1Topo) and the Central Trigger Processor (CTP). The L1Calo trigger system identifies high- E_T objects such as electrons, photons, jets, and τ -leptons. Isolation requirements may also be applied to these objects. It also selects events with large E_T^{miss} or large total transverse energy. The L1Muon trigger system selects events containing high- p_T muons, based on input from the RPC in the barrel region and from the TGC and NSW in the endcaps, and then transmits data to the CTP via the MuCTPI. The L1Topo trigger system takes input TriggerObject (TOB) containing kinematic information (e.g. E_T and $\eta - \phi$ coordinates) from the L1Calo and L1Muon systems and applies topological selections. As shown in Figure 3.13, both the legacy L1Topo and the upgraded L1Topo systems are in use during the commissioning phase.

The final decision on the L1 trigger is made by the CTP. The CTP receives hit multiplicities from the L1Calo, L1Muon, and L1Topo systems and accepts events that satisfy requirements based on the type of object and the threshold multiplicity. Up to 512 different L1 trigger items can be configured in the CTP. The L1 trigger decision, as well as the 40.08 MHz LHC bunch-crossing clock, is distributed to the detector front-end and readout systems via the Trigger, Timing, and Control system (TTC system) [127].

The maximum Level-1 Trigger Accept (L1A) rate supported by the detector readout systems is 100 kHz, so the trigger selection menu is tuned to allocate a share of the rate budget to each underlying physics object according to the ATLAS analysis goals.

High-Level Triggers (HLT)

If accepted by the L1 trigger, events are then sent to the HLT. At this level, software processes reconstruct the event at higher levels of detail than L1, seeded by RoI, which are regions of the detector in which possible trigger objects have been identified by the L1 trigger.

HLT algorithms use full-granularity information from the calorimeters and the muon and tracking systems to provide better energy and momentum resolution for threshold selections, as well as precision tracking for particle identification. The overall selection criteria for the HLT are once again provided by the trigger menu, tuned so as to maximise the data available for key analyses for the given resources.

The Detector Control System

The Detector Control System (DCS) permits the coherent and safe operation of the ATLAS detector hardware and serves as a homogeneous interface to all

subdetectors and to the technical infrastructure of the experiment. It controls, continuously monitoring and archiving the operational parameters, signals indicating any abnormal behaviour to the operator, and allows automatic or manual corrective actions to be taken. The DCS also enables bi-directional communication with the data acquisition system in order to synchronise the state of the detector with data-taking. It also handles the communication between the sub-detectors and other systems which are controlled independently, such as the LHC accelerator, the CERN technical services, the ATLAS magnets, and the detector safety system.

3.3 High Luminosity LHC

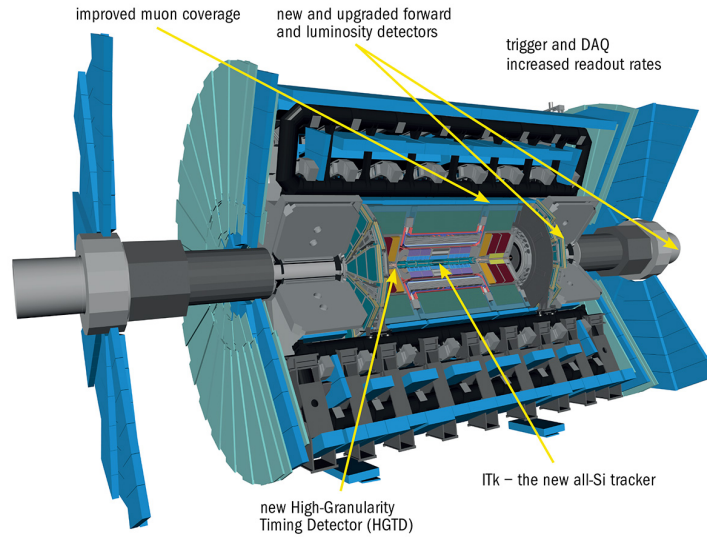


Figure 3.14: A cut-away view of ATLAS for the high-luminosity era [128].

According to the current ATLAS and the LHC project planning, after Run 3 and LS3, the LHC will function in the high luminosity mode (with instantaneous luminosity $\mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) starting the high luminosity phase (HL-LHC). This value corresponds to a 5-fold increase with respect to current values.

According to the current plan, the data taking has to continue for 10 years in such conditions and the aim for the ATLAS experiment is to collect up to 3000 – 4000 fb^{-1} of proton-proton collision data at centre-of-mass energy $\sqrt{s} = 14 \text{ TeV}$.

In order to reach the tracking performance required by the ATLAS physics programme for HL-LHC, the ATLAS detector will undergo the following changes (Figure 3.14):

ATLAS Inner Tracker (ITk) [129, 130] will replace the current ATLAS ID, which will be fully removed. The ITk will consist of all-silicon pixel and strip parts and cover a pseudorapidity range $|\eta| < 4$. A more detailed description of the ITk is given in the Appendix A.

High Granularity Timing Detector (HGTD) [131] based on a novel silicon technology, Low Gain Avalanche Detectors (LGADs), will be installed in the end-cap region in the gap between the barrel and end-cap calorimeters. It will cover a pseudorapidity range $2.4 < |\eta| < 4$ and has to achieve a time resolution of 30-50 ps. In this way the HGTD will allow to improve the rejection of pileup jets with $30 < p_T < 50$ GeV in the forward region by up to 40%, and reduce the inefficiencies of forward lepton isolated tracks by a factor two.

Additional muon chambers sMDT, TGC, and RPC will be installed in the ATLAS muon system [132]. The existing Monitored Drift Tubes (MDT) chambers will be replaced with new inner barrel small-sector sMDT chambers. In the barrel-endcap transition region, new Thin Gap Chambers (TGC) triplets replace the current TGC doublet.

New RPCs with an increase in the rate capability in the inner barrel layer (BI) have to improve the acceptance and robustness of the trigger selection.

Chapter Summary

In this chapter, an overview of the LHC and the ATLAS detector is given. The evolution of the detector during its operation and the main subsystems and their components are described. Measurements from some of the ATLAS subsystems are specifically important for the BSM analysis described in this thesis. ATLAS Pixel detector (part of the ATLAS Inner System) is used for ionising energy loss measurements, TileCal provides information about charged particles time-of-flight and the MDT allows to measure both timing information and ionising energy loss for tracks of long-lived charged particles.

Chapter 4

Object Reconstruction

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ATLAS physics analyses, including the one discussed in this thesis, operate with reconstructed objects originating from detector-acquired data and Monte Carlo (MC) simulations. The reconstruction algorithms are applied uniformly, independent of the data provenance. This chapter outlines main types of reconstructed objects and algorithms performing such reconstruction.

The fully reconstructed final state of the proton–proton collisions in ATLAS includes identified individual particles including electrons, photons, muons, τ -leptons, and such objects as jets and quantities like missing transverse momentum E_T^{miss} .

To be used further in analysis, a reconstructed object is selected by a set of requirements based on the quality and compatibility of the measurements in involved detector systems, quality of reconstruction fits, and other variables. The process of selection is also known as object identification, and the set of requirements is referred to as a selection working point (WP).

The main focus in this chapter is made on tracks and muons, since those objects are used in this analysis the most.

4.1 Object Isolation

In object reconstruction and identification at dense conditions at the LHC it is important to evaluate how much the object of interest is spatially separated from the surrounding objects. Object isolation variables are constructed in a way which allows one to quantify the amount of activity in the vicinity of the candidate object with respect to the neighbouring objects.

Usually, isolation variables are built on the basis of the transverse energies of the clusters in the calorimeter or the transverse momenta and the dimensions $(\Delta\eta, \Delta\phi)$ of the isolation cone $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the direction of the object candidate, excluding the candidate itself.

Several components enter into building such isolation variables: identifying the candidate object itself, its direction, and its contribution to the activity within the cone, and summing, in a pile-up and underlying event robust way, the other activity found within the cone.

For example, the track isolation variable denoted as $p_T^{\text{cone}XX}$ is built from the scalar sum of the transverse momentum of all tracks found inside the isolation cone of size XX that fulfil:

- $p_T > 1 \text{ GeV}$
- $|z_0 \sin \theta| < 3 \text{ mm}$.

This is the simplest definition from which the rest of the track isolation variables inherit.

The more complex track isolation variable $p_{T, \text{var}}^{\text{isol}}$ has identical track selections but the radius of the isolation cone shrinks with increasing p_T as follows [133]:

$$\Delta R = \min \left(\frac{k_T}{p_T}, R_{\text{max}} \right), \quad (4.1)$$

where $k_T = 10$ GeV (fixed constant), p_T is the transverse momentum of the particle (electron/photon/muon) and $R_{\max}$ is the maximum cone size.

4.2 Tracks and Vertices

4.2.1 Tracks

The reconstruction of charged-particle trajectories in the inner detector is based on fitting a trajectory model to a set of measurements. The reconstructed charged-particle trajectories are hereafter referred to as tracks.

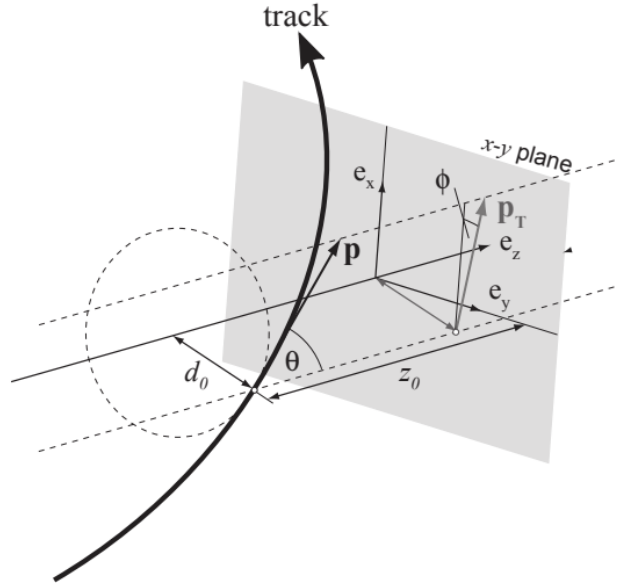


Figure 4.1: Global track parameters in ATLAS [134].

The tracks are described by five parameters $(d_0, z_0, \phi, \theta, \frac{q}{p})$, defined with respect to a reference axis, where d_0 and z_0 are the transverse and longitudinal impact parameters, ϕ and θ are azimuthal and polar angles, and $\frac{q}{p}$ the charge divided by the momentum. The illustration is given in Figure 4.1.

The primary reconstruction of the ATLAS ID track is by exploiting the “inside-out” algorithm that propagates the candidate track from the innermost layers of the ATLAS ID to the outermost (Figure 4.2). ID tracks are reconstructed for $p_T > 500$ MeV and $|\eta| < 2.5$, where the minimum momentum is driven by the track curvature in the magnetic field and the pseudorapidity interval by the instrumented detector geometry.

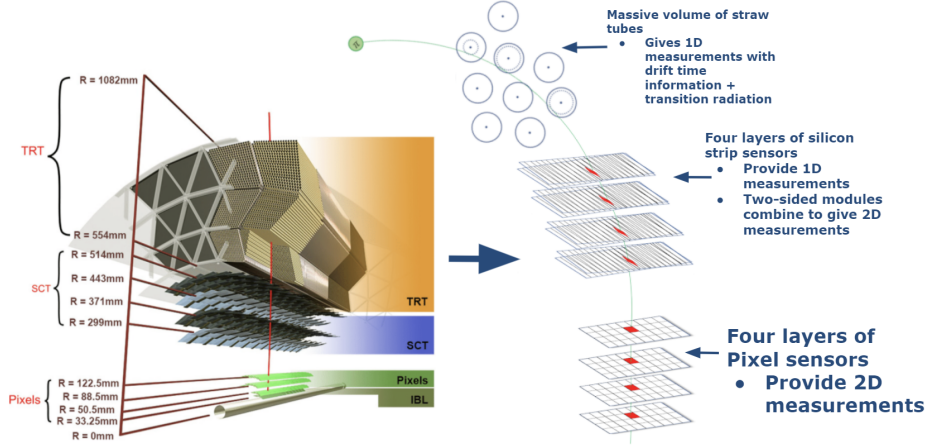


Figure 4.2: An illustration of the track reconstruction in the ATLAS ID [134].

The reconstruction starts from the formation of clusters from the Pixel and SCT hits, in which the deposited energy yields a charge above the threshold, with a common edge or corner in the clusters [135].

Clusters can be:

- *single-particle*, if they are created by charge deposits from one particle,
- *merged*, if they are created by charge deposits from multiple particles,
- *shared*, in case are used in multiple reconstructed tracks but are not sufficiently compatible with the properties of a merged cluster to be identified as merged by the reconstruction,
- *multiply used* clusters — clusters used by multiple tracks — are either identified as *merged* or *shared* but never both.

Pairs of one-dimensional SCT clusters on either side of a sensor module or individual pixel clusters are then converted into 3-dimensional space-points, with position uncertainties determined by the detector geometry and sensor pitch.

The next step in the reconstruction of primary ATLAS ID track is the formation of the so-called “track seeds”. Each seed consists of three measurements at compatible space-points in different layers of the Pixel detector and SCT that could conceivably originate from a single charged particle track produced near the pp IP. This approach maximises the possible number of combinations and already allows one to make a first estimate of track momentum.

After the seeds are constructed, search roads in 3D space are built through the remaining detector based on the estimated seed trajectory. Each search road

consists of sets of detector modules expected to contain clusters compatible with the seed.

The tracks are extended out towards the TRT along the search road from the seed using a combinatorial Kalman filter [136]. The next step in track reconstruction is ambiguity solving. To do that, each track candidate is assigned the track score, which places the track in an order that scores the candidates most likely to correctly represent the trajectory of a charged primary particle [135].

Track candidates are rejected by the ambiguity solver if they fail to meet any of the following basic quality criteria:

- $p_T > 400$ MeV,
- $|\eta| < 2.5$,
- Minimum of 7 pixel and SCT clusters (12 are expected),
- Maximum of either one shared pixel cluster or two shared SCT clusters on the same layer,
- Not more than two holes in the combined Pixel and SCT detectors,
- Not more than one hole in the Pixel detector,
- $|d_0^{\text{BL}}| < 2.0$ mm,
- $|z_0^{\text{BL}} \sin \theta| < 3.0$ mm,

where d_0^{BL} is the transverse impact parameter calculated with respect to the measured beam-line position, z_0^{BL} is the longitudinal difference along the beam line between the point where d_0^{BL} is measured and the primary vertex (Section 4.2.2). A “hole” is a place in a fitted trajectory, where it passes through a layer without hits, while one is expected.

For track candidates fulfilling the requirements, a high-resolution fit is performed using all available information. Fitted tracks which pass through the ambiguity solver without modification are added to the final track collection.

The remaining unused silicon hits can be taken by the “outside-in” algorithm that can fit TRT segments and then extend them back into the silicon detector [137]. The general scheme of “inside-out” and “outside-in” track reconstruction algorithms is given in Figure 4.3.

In addition to the described algorithms, a neural network based clustering algorithm [138] is used to assist in the ambiguity solving in cases where a cluster is shared by multiple track candidates.

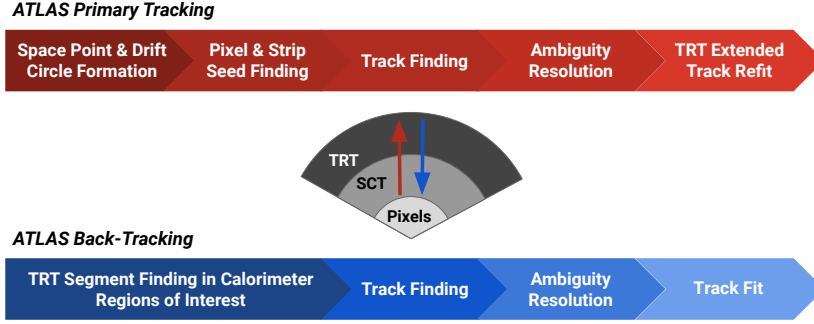


Figure 4.3: Summary of track reconstruction in the ATLAS ID [137].

4.2.2 Primary Vertex

After the track candidate search is finalised, the locations of the underlying pp interactions (vertices) are identified by a dedicated vertex reconstruction procedure [139] which uses a collection of reconstructed tracks as an input. Primary vertex reconstruction is divided into two stages: vertex finding and vertex fitting. During vertex finding reconstructed tracks are associated to vertex candidates. The vertex fitting stage deals with reconstruction of the actual vertex position and its covariance matrix.

Each primary vertex is required to contain at least two tracks. The vertex with the highest sum of squares of transverse momenta of the tracks (Σp_T^2) is defined as primary vertex, other vertices are assumed to belong to the pile-up.

4.3 Muons

Muon reconstruction [140] in the MS starts with a search for hit patterns inside each muon chamber to form segments. In each MDT chamber and nearby trigger chamber, a Hough transform [141] is used to search for hits aligned on a trajectory in the bending plane of the detector. The MDT segments are reconstructed by performing a straight-line fit to the hits found in each layer. The RPC or TGC hits measure the coordinate orthogonal to the bending plane. The segments in the CSC detectors are built using a separate combinatorial search in the η and ϕ detector planes. The search algorithm includes a loose requirement on the compatibility of the track with the luminous region.

Combined (CB) Muons. CB muon track reconstruction is performed independently in the ID and MS, and a combined track is formed with a global refit that uses the hits from both the ID and MS sub-detectors. During the global fit procedure, MS hits may be added to or removed from the track to

improve fit quality. Most muons are reconstructed following an outside-in pattern recognition, in which the muons are first reconstructed in the MS and then extrapolated inward and matched to an ID track.

An inside-out combined reconstruction, in which ID tracks are extrapolated outward and matched to MS tracks, is used as a complementary approach.

Segment-Tagged (ST) Muons. A track in the ID is classified as a ST muon if, once extrapolated to the MS, it is associated with at least one local track segment in the MDT or CSC chambers. ST muons are used when muons cross only one layer of MS chambers due to either low p_T or because they fall in regions with reduced MS acceptance.

Calorimeter-Tagged (CT) muons. To be reconstructed as CT muon, the ID track has to be matched to an energy deposit in the calorimeter compatible with a minimum-ionising particle. CT has the lowest purity of all the muon types, but it allows to recover acceptance in the region where the ATLAS muon spectrometer is only partially instrumented to allow for cabling and services to the calorimeters and inner detector. The identification criteria for CT muons are optimised for that pseudorapidity $|\eta| < 0.1$ and momentum range $15 < p_T < 100$ GeV.

Extrapolated (ME) Muons. In ME algorithm a trajectory of a muon object is reconstructed based only on the MS track and a loose requirement on compatibility with originating from the IP. The parameters of the muon track are defined at the interaction point, taking into account the estimated energy loss of the muon in the calorimeters.

ME muons are mainly used to extend the acceptance for muon reconstruction into the barrel region $2.5 < |\eta| < 2.7$, which is not covered by the ID.

Silicon-associated forward (SiF) muons. For $|\eta| > 2.5$, MS tracks may be combined with short track segments reconstructed from hits in the Pixel and SCT detectors, leading to a subset of CB muons referred to as silicon-associated forward (SiF) muons.

The inside-out (IO) combined reconstruction chain allows [137] to recover combined muons with low transverse momenta that are not found in the outside-in reconstruction. It starts from ID track candidates. Inside-out and outside-in muon reconstruction chain are schematically summarised in Figure 4.4. The predicted muon chamber crossing locations and directions of their trajectories, as evaluated in the pre-processing phase, are used to build search roads in the MS. Using these roads, a dedicated muon segment-finding pass is performed.

The direction and momentum information from the ID-based search roads is used to calibrate the MDT measurements for this phase, allowing to account for the predicted location of the charge deposit along the wire direction when interpreting the drift time measurement. The found segments are collected and added to the track. Using the ID track and the segments recovered in this way, a global re-fit is performed in the same way as for the outside-in chain, to obtain combined muon candidates.

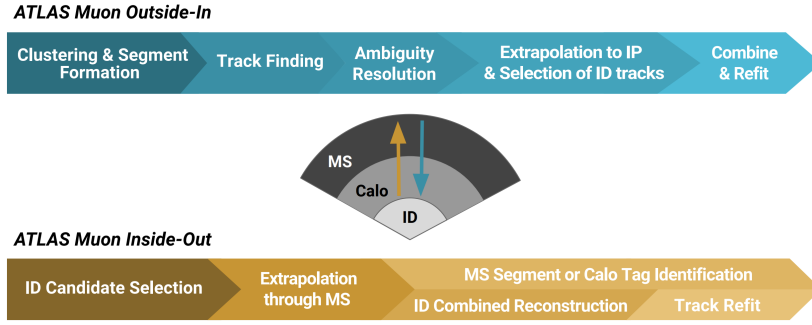


Figure 4.4: Summary of muon combined reconstruction in ATLAS: outside-in and inside-out [137].

In all muon reconstruction algorithms described in this chapter, reconstructed objects are assumed to be ultra-relativistic, so that their speed β is equal to 1. As a result, such an assumption leads to misreconstruction in the cases of slower objects.

To achieve a precise reconstruction of tracks in the muon spectrometer the inside-out algorithm keeping β as a free parameter in a fit can be used. The detailed description is given in Chapter 6.

4.3.1 Muon Identification

For CB muons (both outside-in and inside-out) it is possible to define quality criteria based on the compatibility of q/p and p_T measurements in MS and ID:

$$(q/p) \text{ compatibility} = \frac{|(q/p)_{ID} - (q/p)_{MS}|}{\sqrt{\sigma^2((q/p)_{ID}) + \sigma^2((q/p)_{MS})}} \quad (4.2)$$

$$\rho' = \frac{|p_{T,ID} - p_{T,MS}|}{p_{T,CB}} \quad (4.3)$$

The working points are inclusive: objects can belong to multiple WPs if they pass selection criteria [142].

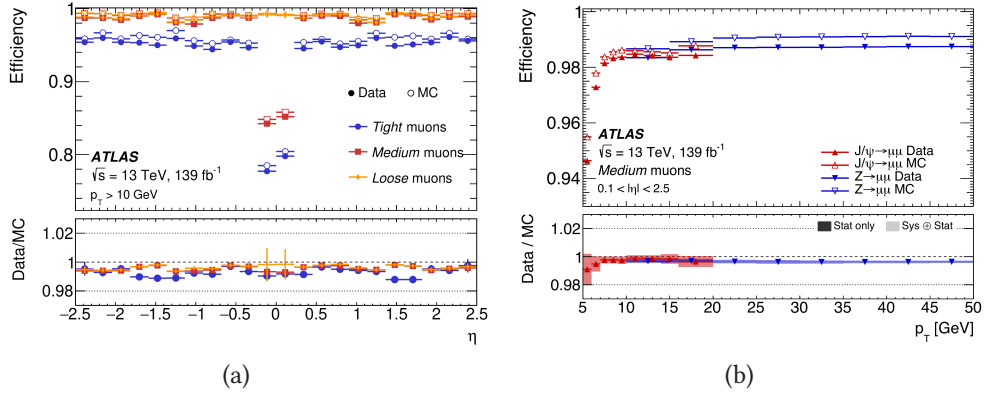


Figure 4.5: Muon reconstruction and identification efficiencies: (a) for the *Loose*, *Medium*, and *Tight* WPs measured in $Z \rightarrow \mu\mu$ events as a function of η , for muons with $p_T > 10 \text{ GeV}$ and (b) for the *Medium* WP measured in $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ events as a function of p_T for muons with $0.1 < |\eta| < 2.5$ [142].

Medium WP. In the ID acceptance region $|\eta| < 2.5$, the *Medium* WP accepts only CB and IO muons. Each muon track has to have at least two precision stations (MDT or CST), except in the region $|\eta| < 0.1$, where muons with only one precision station are also included, provided they have at most one precision hole station. The q/p compatibility is required to be less than 7 to ensure a loose agreement between the ID and MS measurements.

Outside of the ID coverage Medium WP accepts ME and SiF muons, required to have at least three precision stations, in the range $2.5 < |\eta| < 2.7$.

Loose WP. The *Loose* selection WP accepts all the muons passing the *Medium* WP. In addition, it includes CT and ST muons in the range $|\eta| < 0.1$, where the gap in the MS coverage leads to a loss of efficiency for CB muon reconstruction. To increase the efficiency of the Loose criteria for low- p_T muons, IO muons with p_T below 7 GeV and only one precision station are accepted in the range $|\eta| < 1.3$, provided they are independently reconstructed also as ST muons. Requiring that IO muons are independently confirmed by the ST reconstruction strategy significantly increases their purity.

Tight WP. To pass *Tight* muon selection, a muon has to be reconstructed as CB or IO, pass the *Medium* selection WP and has to have hits in at least two precision stations. The normalised χ^2 of the combined muon track fit is required to be less than 8.

Figure 4.5 shows the muon reconstruction and identification efficiencies for different WPs. The plot in Figure 4.5a demonstrates efficiencies for Tight, Medium and Loose working points as a function of object η . The plot in Figure 4.5b shows the dependence of the reconstruction efficiency on the momentum for the Medium muons.

Exploiting similar principles it is also possible to define *High- p_T* and *Low- p_T* WPs optimised for the muons with $p_T > 100$ GeV and $p_T < 18$ GeV, respectively [142].

4.4 Electrons and Photons

Electrons and photons are reconstructed from energy deposits in the calorimeter cells using a dynamic, variable cluster-size algorithm to form superclusters [143, 144], which enables the recovery of energy from bremsstrahlung photons or from electrons originating from photon conversions. A supercluster is a variable-size electromagnetic cluster formed by combining a seed EM topo-cluster with nearby clusters associated with bremsstrahlung or photon conversions, in order to recover the full electromagnetic shower. This approach improves the containment and energy resolution of reconstructed electrons and photons.

A converted photon is defined as a cluster matched to one or more conversion vertices, while an unconverted photon is a cluster matched to neither an electron track nor a conversion vertex.

The reconstruction of superclusters begins from topological clusters (topo-clusters) in the electromagnetic (EM) calorimeter.

4.4.1 Topo-Clusters

The topo-clusters are formed from calorimeter cells in both the EM and hadronic calorimeters, using noise-suppression algorithms that incorporate information about the local energy significance of each cell. The cell significance is expressed as

$$\zeta_{cell}^{EM} = \frac{|E_{cell}^{EM}|}{\sigma_{noise, cell}^{EM}} \quad (4.4)$$

where the noise term includes contributions from electronic noise and the average pile-up conditions during data taking.

EM topo-clusters are defined as those for which the fraction of the cluster energy deposited in the EM calorimeter is larger than 0.5 [143]. These EM topo-clusters serve as the seeds used in constructing the superclusters employed in electron and photon reconstruction.

4.4.2 Electrons

An electron is defined as an object consisting of a cluster built from energy deposits in the calorimeter (supercluster) and a matched track (or tracks).

Initial electron candidates are reconstructed from the EM topo-clusters that are matched to at least one ID track. If standard pattern recognition fails [133, 143] for a silicon track seed, track candidates are then fitted with the global χ^2 fitter, allowing for additional energy loss when the standard track fit fails. Additionally, tracks with silicon hits loosely matched to fixed-size clusters are re-fitted using a Gaussian sum filter (GSF) algorithm [145] for improved track parameter estimation.

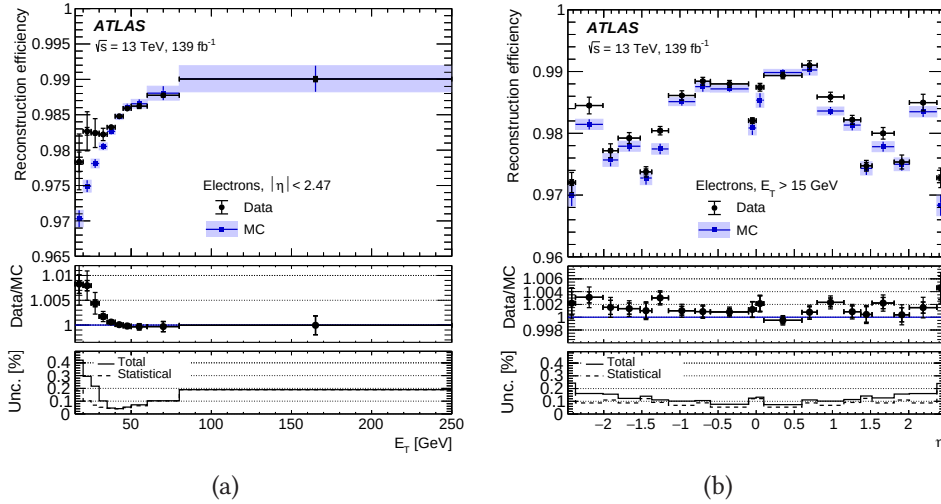


Figure 4.6: Reconstruction efficiencies of electrons from $Z \rightarrow e^+e^-$ decays as a function of the electron E_T (a) and (b) η respectively [146].

The electron primary track is chosen using a metric that depends on the extrapolation of the track from the perigee to the second layer of the EM calorimeter. The algorithm uses either measured momentum of the track or magnitude of the momentum rescaled to match the cluster energy.

The electron reconstruction efficiency as a function of the electron E_T and η measured with the $Z \rightarrow e^+e^-$ process is shown in Figure 4.6. Uncertainties of the electron identification efficiency as a function of the electron E_T are demonstrated in Figure 4.7 for the main pp data-taking periods at the LHC. The identification efficiency was measured for the electron Medium WP [146].

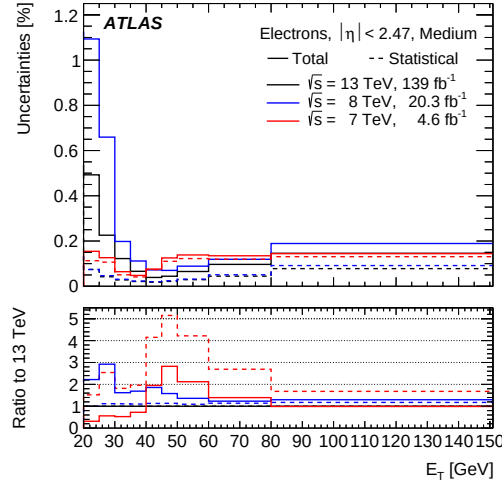


Figure 4.7: Uncertainties of the electron identification efficiencies shown for the underlying kinematics of $Z \rightarrow e^+e^-$ events at 13 TeV, as a function of the electron transverse energy. The Medium identification working point is shown and compared for the main pp data-taking periods at the LHC [146].

4.4.3 Photons

Initial photon candidates can be either reconstructed as converted or unconverted photon candidates. A converted photon object is based on an EM topo-cluster matched to one or several conversion vertices, where the photon has undergone conversion into an electron-positron pair [143, 147, 148]. General reconstruction flow of the photon objects is relatively similar to the electrons. Photons are not used in this search, and thus described in less detail.

4.5 Jets

The starting point of jet reconstruction is the formation of particle-flow objects [149], which are reconstructed from tracks and topo-clusters. The signals from both the tracker and the calorimeter are combined to represent individual particles. The idea behind particle-flow reconstruction comes from the fact that low- p_T charged particles are better measured by the tracker than the calorimeter. P-flow is an attempt to identify the calorimeter energy deposit associated with each track. Once the association is completed, the energy deposited in the calorimeter by all charged particles is removed.

Jet reconstruction is then performed using the anti- k_t algorithm [150] on an ensemble of particle flow (PFlow) objects.

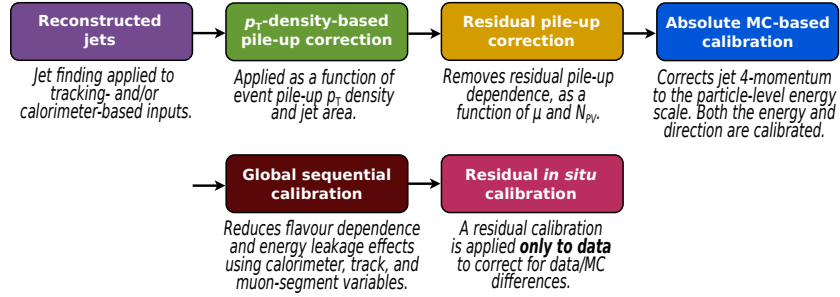


Figure 4.8: Stages of jet energy scale calibrations. Each one is applied to the four-momentum of the jet [151].

4.5.1 Jet Energy Scale and Resolution

Jets built from topo-clusters are initially reconstructed at the electromagnetic (EM) scale, where the calorimeter response to electromagnetic showers is well understood. Applying the jet energy scale (JES) correction to these EM-scale jets yields the EM+JES calibration scheme. Alternatively, PFlow jets combine tracking and calorimeter information to improve the energy and angular resolution, particularly at low transverse momentum; applying the JES correction to these particle-flow jets results in the EMPFlow+JES calibration scheme.

To account for the non-linear response of the calorimeter, energy deposited outside the detector acceptance, and energy losses due to both jet misreconstruction and inactive regions of the detector, the JES correction is applied in the jet energy calibration stage (Figure 4.8).

Precise knowledge of the jet energy resolution (JER), which quantifies the spread of the reconstructed jet energy around its true value, is important for measurements of SM jet production and for studies of the properties of SM particles that decay to jets, as well as searches for BSM physics involving hadronic final states. The JER also affects the calculation of the missing transverse momentum, which is crucial for many searches for new physics.

The relative JER can be parametrised in terms of contributions expected from the calorimeter-based response:

$$\frac{\sigma(p_T)}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C, \quad (4.5)$$

where N , S , and C correspond to the noise, stochastic, and constant terms, respectively.

Comparisons of the JER for EMPFlow+JES and EM+JES jets as functions of p_T^{jet} and η^{jet} are shown in Figure 4.9. The fitted resolution as a function of p_T^{jet}

demonstrates an improvement for EMPFlow+JES jets relative to EM+JES jets at low p_T^{jet} . The jet energy scale uncertainty as a function of p_T^{jet} is shown in Figure 4.10.

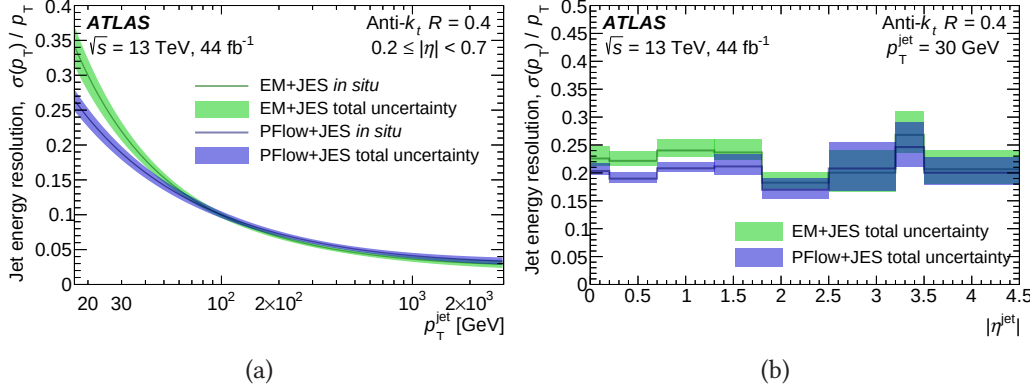


Figure 4.9: The relative jet energy resolution for fully calibrated EMPFlow+JES jets (blue curve) and EM+JES jets (green curve) (a) as a function of p_T^{jet} and (b) as a function of η^{jet} . The fit to the resolution as a function of p_T^{jet} for the EMPFlow+JES jets shows an improvement in resolution over EM+JES jets at low- p_T [151].

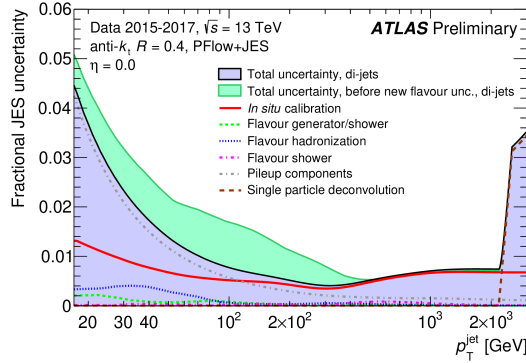


Figure 4.10: Jet energy scale uncertainty [151].

4.5.2 Flavour Tagging

The topology of the jet depends on its origin. Light jets originate from u , d , c quarks or gluons, b -jets and s -jets originate from b and s quarks, respectively.

B -hadrons have a long lifetime (~ 1.5 ps) due to the CKM matrix mechanism (described in Chapter 2), therefore they can travel up to a few cm inside the detector before decay, creating a secondary vertex in the event.

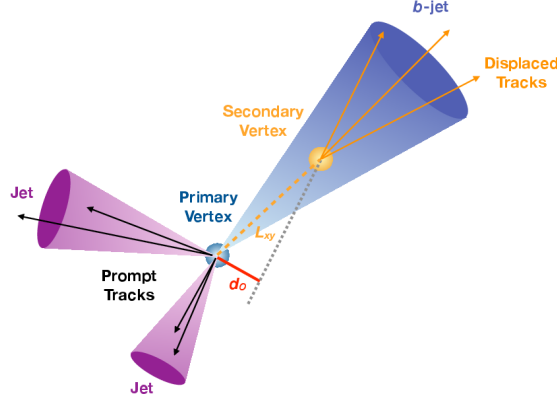


Figure 4.11: A schematic diagram of an interaction producing two light-flavour jets and one b -jet, shown in the transverse plane. L_{xy} corresponds to a transverse decay length (typically a few mm), produces displaced tracks originating from a secondary vertex at the transverse impact parameter, d_0 (typically large for tracks originating from the decay of b -hadrons) [152].

Low-level b -tagging algorithms exploit this specific topology (Figure 4.11) to look for secondary vertices and displaced tracks.

Reconstruction of b -jets is performed in a few steps. Firstly, low-level algorithms reconstruct the characteristic features of the b -jets via two complementary approaches: one that uses the individual properties of charged-particle tracks, later referred to as tracks, associated with a hadronic jet, and a second which combines the tracks to explicitly reconstruct displaced vertices [153, 154]. After that, in order to maximise the b -tagging performance, the results of the low-level b -tagging algorithms are combined in high-level algorithms consisting of multivariate classifiers.

For Run 3, a transformer-based tagger GN2 [155] was introduced. GN2 learns the displaced-vertex structure directly from track information, assisted by auxiliary training tasks that guide the network to recognise decay origins. GN2 has been validated on collision data and is recommended for Run 3 physics analyses, offering improved rejection of charm- and light-flavour jets at a given b -tagging efficiency compared with earlier taggers.

4.6 Tau Leptons

The τ lepton has a mass of 1.777 GeV and decays either leptonically ($\tau \rightarrow \nu_\tau \nu_l l$, $l = e, \mu$ or hadronically ($\tau \rightarrow \nu_\tau + \text{hadrons}$) with fractions 35% and 65%, respectively. Proper decay length of a τ lepton is 87 μm [156], what corresponds to the decay in the innermost layer of the ATLAS Pixel detector, thus τ leptons are reconstructed through their decay products.

The tau candidates are seeded by calo-only jets, with no track information used [144]. Identification of hadronically decayed τ -leptons is currently performed with RNN classifier [157, 158].

4.7 Missing Transverse Energy

Missing transverse momentum p_T^{miss} also referred to as E_T^{miss} (or MET) is a crucial observable for the ATLAS experiment [159]. MET is an experimental proxy for the transverse momentum carried by undetected particles produced in pp collisions recorded by the ATLAS detector.

The missing transverse momentum reconstruction consists of two main components: p_T^{hard} and p_T^{soft} . The term p_T^{hard} comprises hard-event signals in the form of reconstructed and calibrated “hard objects”: electrons, photons, τ -leptons, muons and jets. The p_T^{soft} component comes from soft-event signals, and currently consists of reconstructed charged-particle tracks that are associated with the hard-scatter vertex but not associated with a hard object.

Altogether, the missing transverse momentum vector can be computed as:

$$p_T^{\text{miss}} = - \left(\underbrace{\sum_{\text{selected electrons}} p_T^e + \sum_{\text{accepted photons}} p_T^\gamma + \sum_{\text{accepted } \tau\text{-leptons}} p_T^\tau + \sum_{\text{selected } \mu} p_T^\mu + \sum_{\text{accepted jets}} p_T^{\text{jet}}}_{\text{hard term}} + \underbrace{\sum_{\text{unused tracks}} p_T^{\text{track}}}_{\text{soft term}} \right) \quad (4.6)$$

The missing transverse energy is defined as an absolute value of the vector of missing transverse momentum given by the expression 4.6 above: $E_T^{\text{miss}} = |p_T^{\text{miss}}|$. In addition to that, it is possible to extract an angle $\phi^{\text{miss}} = \tan^{-1}(p_y^{\text{miss}}/p_x^{\text{miss}})$ which gives a direction of the MET in the transverse plane.

By definition, E_T^{miss} is very sensitive to double-counting of objects and its reconstruction performance is fully dependent on the reconstruction performances of each object in event.

Figure 4.12 shows distributions of p_T^{miss} and the $p_T^{\text{miss, soft}}$ in data and MC simulation for events satisfying a jet inclusive $Z \rightarrow \mu\mu$ selection [159]. As demonstrated in Figure 4.12b, events with high values of $p_T^{\text{miss, soft}}$ are often mismodelled. Such

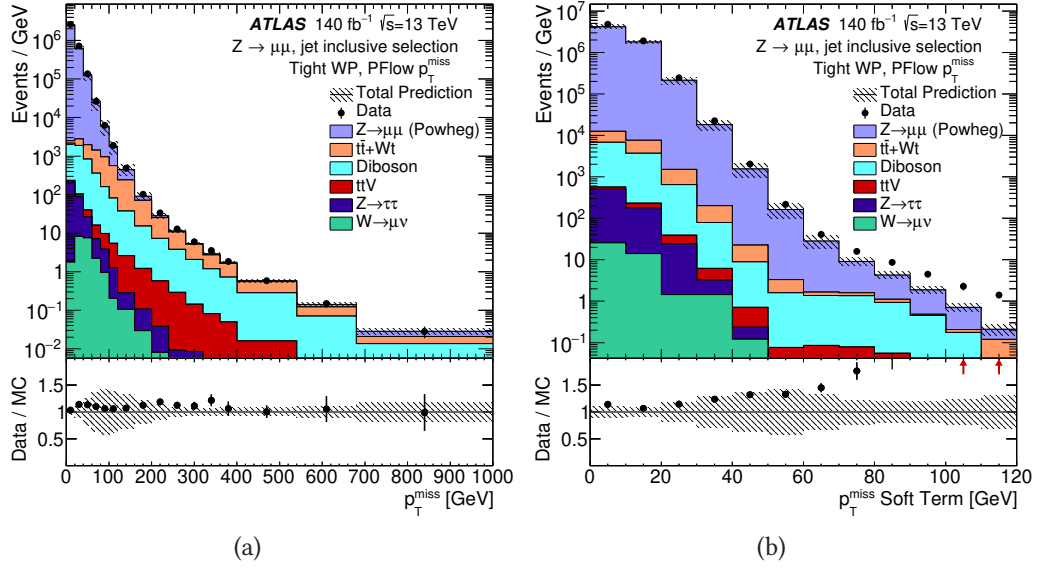


Figure 4.12: Distributions of p_T^{miss} (a) and the p_T^{misssoft} (b) in data and MC simulation using the Powheg + Pythia $Z \rightarrow \mu\mu$ generator. Events satisfy a jet inclusive $Z \rightarrow \mu\mu$ selection [159].

mismodelling originates in a definition of the soft term as tracks unassociated with any particular object (unidentified).

Chapter Summary

In this chapter an overview of the reconstruction of the main physics objects used in ATLAS analysis was given. Among all objects discussed in this chapter, the main contribution in this work is given by tracks, muons and missing transverse momentum objects.

Chapter 5

Data Preparation

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This chapter gives an overview of the standard data preparation chain driven by the Athena software framework [160].

Section 5.5 gives a description of the data and Monte Carlo samples used in the search for the heavy charged long-lived particles presented in this thesis. The specific software needs and a modified data processing workflow containing the event-picking stage are discussed as well.

5.1 Data Preparation chain

ATLAS physics analyses rely on collision data recorded by the detector and on events generated through Monte Carlo simulation. Both data and MC are processed within a common software workflow managed by the Athena framework [161], which applies consistent reconstruction and derivation procedures

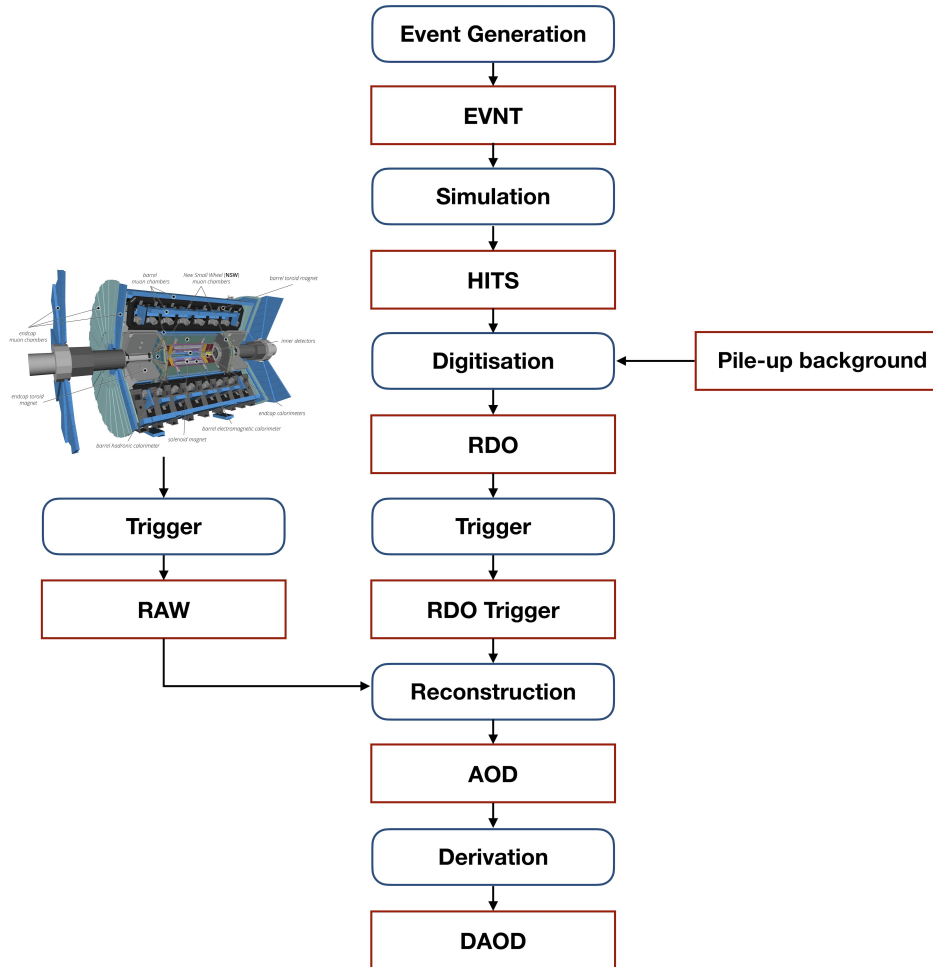


Figure 5.1: Adapted from Ref. [161]. The standard software workflow of the ATLAS experiment. Processing steps are represented by blue ovals; output formats are represented as red boxes. The steps and data formats are described in the text.

to ensure uniform treatment of the two. Figure 5.1 shows the standard software workflow of the ATLAS experiment. The steps in the standard data-processing workflow for the simulated and recorded datasets are described below.

Event generation. The first step in MC-simulation production is event generation. A schematic view of an event simulation is shown in Figure 5.2. Event generation means the modelling of the pp collision for the required process. The simulation of pp collisions in ATLAS begins with the calculation of the matrix element (ME), which provides the perturbative description of the hard-scattering process. The ME can be evaluated at different orders in perturbation theory: Leading Order (LO), Next-to-Leading Order (NLO), or Next-to-Next-to-Leading Order (NNLO). Higher-order corrections, such as those at NLO and NNLO, reduce renormalisation-scheme ambiguities in QCD by including virtual loop contributions from quarks and gluons. Matrix-element calculations are typically performed using generators such as MADGRAPH5_aMC@NLO [162] (MADGRAPH), POWHEG [163], or SHERPA [164].

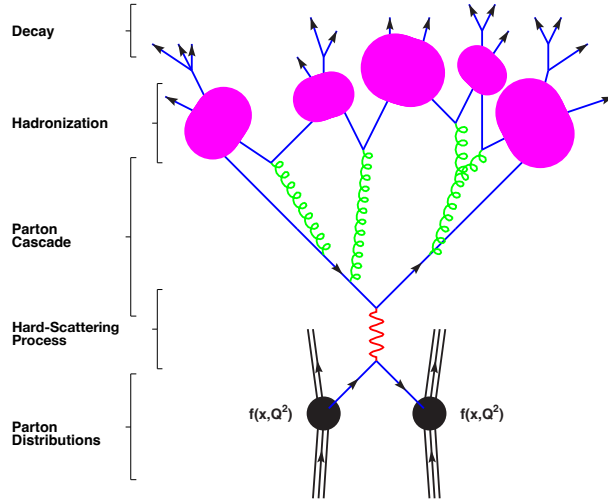


Figure 5.2: A sketch of a MC event generation. Each stage corresponds to a different simulation step. Adapted from Ref. [165].

The resulting calculation defines the kinematics and production rates of a small number of outgoing partons, referred to as hard-scatter or matrix-element final states. These parton-level events form the input to the parton-shower simulation, which models the successive emission of quarks and gluons through soft and collinear QCD radiation, thereby approximating higher-order effects and producing a more complete description of the event.

A proton–proton collision can be viewed as the interaction between several partons (quarks and gluons), with the probabilities of finding partons carrying a given momentum fraction described by parton distribution functions (PDFs). The parton-shower evolution is typically performed using programs such as PYTHIA [166] or HERWIG [167], which simulate the perturbative QCD cascade that develops between the hard-scatter scale and the onset of hadronisation.

The subsequent stage is hadronisation, a non-perturbative process implemented in PYTHIA and HERWIG, in which coloured partons combine to form colour-neutral hadrons. It is followed by the decays of unstable hadrons into stable particles.

For some processes (for example, W -boson production), it is possible to use a single generator like SHERPA, PYTHIA, or HERWIG to produce complete events, parton showering, hadronisation, and particle decays.

In some processes, afterburners such as EVTGEN [168] and TAUOLA++ [169] are used to refine specific aspects of the event generation. EVTGEN improves the modelling of heavy-flavour hadron decays, particularly for B -physics and flavour-tagging studies, while TAUOLA++ provides a precise description of τ -lepton decays.

EVNT format. An event generator configuration produces HepMC output [170]. After that, events are written in the **EVNT** format. The EVNT file contains the particles output from the event generator and metadata about the generator job configuration.

Simulation. ATLAS employs two simulation frameworks to model particle interactions with the detector material: a full simulation and a fast simulation. The full simulation uses the GEANT4 toolkit [171], providing a detailed and precise Monte Carlo modelling of particle transport and interactions in the detector.

The fast simulation, implemented with ATLFAST3 [172], employs parameterised and machine-learning-based techniques to reproduce the detector response. The framework achieves an order-of-magnitude improvement in performance relative to the full simulation, with good agreement for most physics observables. The full simulation is used when maximum precision is required, whereas the fast simulation is preferred for high-statistics studies and large-scale Monte Carlo production.

HITS format. The outcome of the simulation step is written in the **HITS** format. The HITS file contains records of the energy deposits and timing information produced by each particle, in every sub-system, together with truth

information appended to the generator record and metadata describing the simulation configuration. Information about the particles created or destroyed during the simulation is included.

Digitisation. The digitisation step emulates the response of the detector electronics to the simulated energy deposits, producing a realistic detector output.

During this stage, pile-up is modelled through the addition of background interactions, using one of several approaches: the overlay of multiple simulated events, the use of a pre-digitised collection of simulated interactions, or the inclusion of specially recorded data events.

RDO format. The digitisation output is stored in **RDO** (Raw Data Object) format, which is conceptually similar to the raw data collected from the detector. The RDO files also propagate the truth records from the simulation and include additional information linking true particles to the corresponding detector signals, together with further metadata.

Trigger. During the trigger simulation stage, a trigger menu specific to the MC simulation is emulated. Trigger decisions and the corresponding trigger object collections are added to the output. Both the hardware and high-level triggers are reproduced.

RDO Trigger format. The output of the trigger simulation step is written to an **RDO Trigger file**. By its structure, this file is an RDO with trigger information and metadata added to it.

RAW format. The data coming from the detector are written in a custom bytestream format, called **RAW**. The RAW files can be filtered to create DRAW (derived RAW) datasets. DRAW datasets collect the events with specific signatures. For example, they can collect events typical for the $Z \rightarrow \mu\mu$ or $Z \rightarrow e\gamma$ decays (DRAW_ZMUMU and DRAW_EGZ, respectively), or typical for τ decay (DRAW_TAUH). Due to the smaller size compared with the RAW datasets, and the applied event pre-selection, such datasets can be processed with special settings (i.e. a specific reconstruction version, additional variables, or lower momentum thresholds).

The RAW and RDO Trigger files are then treated in the same way, and from this stage onwards the MC and data-processing workflows are identical.

Reconstruction. Reconstruction is performed in the same way for MC-simulated events and for the events recorded at the ATLAS experiment

during the actual data taking. The detailed description of the object reconstruction in ATLAS is given in Chapter 4.

AOD format. The output of the data reconstruction is written to an **AOD** (Analysis Object Data) format.

Derivation. The next stage after the main reconstruction is the derivation production. It serves primarily as a data-reduction step but also reconstructs secondary physics objects whose inputs are available in the AOD. For example, jets are built from particle-flow objects, and heavy-flavour tagging is performed using these jets and associated tracks. Further data reduction is achieved through variables that summarise multiple inputs.

ATLAS defines four standard operations for building derived data files:

- Skimming — the removal of entire events based on criteria related to their properties or reconstructed features;
- Thinning — the removal of individual objects within an event, according to criteria related to the properties of those objects;
- Slimming — the removal of variables within a given object type, applied uniformly across all objects of that type and all events. Unlike the other operations, slimming does not depend on any event- or object-level property, as the same variables are removed for every event and object;
- Augmentation — the addition of new information in the form of extra variables (decorations) or derived objects that summarise aspects of the reconstructed data, allowing much larger data volumes to be discarded.

DAOD format. Several derivations are produced in a common **DAOD** (derived AOD) format, differing in event selection and in the level of detail retained for each physics object.

5.2 Data Quality

Once data taking is completed and the RAW data are recorded, a two-stage offline data-quality (DQ) assessment [174] is performed. The first stage takes place during the calibration loop, and the second uses the results from the prompt bulk reconstruction, which includes all promptly processed data streams.

Time-dependent information, such as detector and trigger status or run configuration, is stored in the ATLAS Conditions Database [175]. Data-quality issues

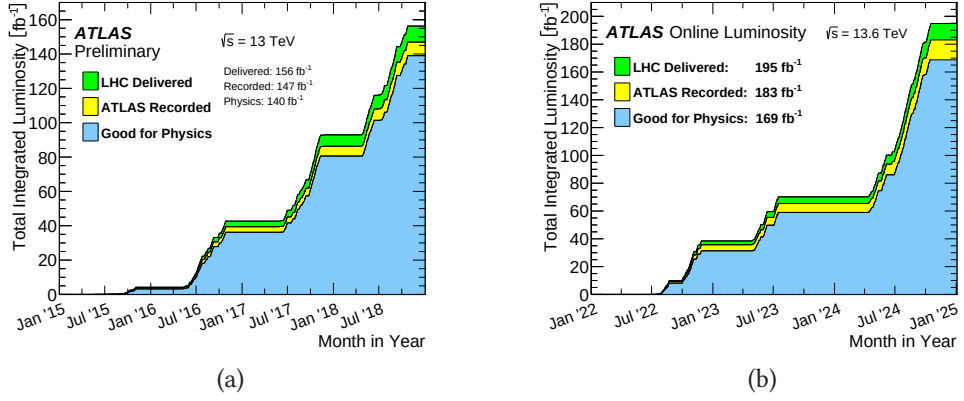


Figure 5.3: Cumulative luminosity versus time delivered to (green), recorded by ATLAS (yellow), and classified as good for physics (blue) during stable beams for: (a) pp collisions at $\sqrt{s} = 13$ TeV in LHC Run 2 (2015–2018), (b) pp collisions at $\sqrt{s} = 13.6$ TeV in the part of Run 3 (2022–2024) [173].

are tracked in the Defect Database, a subcomponent of the Conditions Database, where defects are set for each run according to the outcome of the DQ assessment. If a defect affecting a given luminosity block is severe enough to preclude its use in physics analyses, that block is excluded from the resulting Good Runs List (GRL).

The GRL lists the runs and luminosity blocks certified for use in physics analyses. It is used to exclude data affected by anomalous conditions and is fully integrated into ATLAS analysis tools. The integrated luminosity corresponding to the luminosity blocks included in the GRL is referred to as the “Good for Physics” luminosity, representing the total recorded luminosity that passes all data-quality requirements and is certified for physics analyses. The “Good for Physics” luminosity constitutes the vast majority of the data recorded by ATLAS, corresponding to about 94% of the total recorded luminosity in Run 2 and 92% in Run 3 [173]. The evolution of delivered, recorded, and good-for-physics luminosity during these data-taking periods is illustrated in Figure 5.3.

5.3 Athena Software Framework

The ATLAS software framework, Athena, uses Python as an object-oriented scripting and interpreter language to configure and load C++ algorithms and objects. All stages of the ATLAS data-processing workflow [161] are integrated and controlled within the Athena framework, which provides a unified environment for configuration, execution, and data management. Athena ensures the

consistent operation of external software packages, such as the event generators described in Section 5.1 and the GEANT4 simulation toolkit, by managing their configuration and integrating their outputs into the standard ATLAS data model. Digitisation, reconstruction, and derivation are performed within Athena using configurable Algorithms, Tools, and Services managed by the framework. Event and conditions data are centrally managed within Athena, ensuring consistent access for all processing components. Athena also manages input and output operations, metadata recording, and the creation of ROOT-based [176] datasets.

To meet the higher event rates, detector complexity, and computational demands expected for Run 3 data taking, the ATLAS offline software framework was redesigned [161] to use the available resources more efficiently. During Run 2, ATLAS employed a process-based parallelism model, where independent processes handled individual events. For Run 3, the framework was redesigned to support multithreaded event processing within a single process, allowing concurrent execution of multiple events and meeting the requirements of Run 3 data taking.

The changes in the ATLAS software are controlled by physics validation [161] to ensure consistency with previous releases. However, rarely used algorithms and objects appear not to be covered by the validation. During the early stages of the analysis design of the search described in this work, it was observed that the Slow Muon reconstruction algorithm, which provides access to hit-level information in the MDT, drastically suffered from the software transition. A more detailed description of this problem and the recovery of the algorithm in the latest Athena releases are given in Chapter 6.

5.4 Event Picking Service

The standard ATLAS data-processing workflow covers the needs of a major part of the physics analyses. However, certain specialised studies require refined access to detector-level information or additional variables that are not retained in the standard data formats. To enable such selective reprocessing, ATLAS developed the Event Picking Service, a tool that extracts individual events from the distributed data-management system using the EventIndex catalogue for reprocessing with the desired software release or calibration.

The EventIndex is the global catalogue of ATLAS events, providing event-level metadata for all recorded and simulated samples. Each event is assigned a unique EventID, composed of the run and event numbers together with auxiliary information. These identifiers link to the datasets and files where each event is stored, together with the associated trigger stream, processing history, and provenance information.

The Event Picking Service enables the targeted retrieval of selected events from the ATLAS distributed data-management system without accessing complete datasets. Users provide lists of Run Number and Event Number pairs, accompanied by the trigger stream, data-taking year, and the format to be extracted: typically RAW or AOD. The Event Picking Service queries the EventIndex to determine the datasets and file locations of the requested events and resolves their unique file identifiers. After that, it submits extraction jobs through the PanDA workflow system [177] to the Worldwide LHC Computing Grid [178]. Depending on where the input data reside, files may first be staged from tape to disk before extraction. The selected events are copied directly from the original files, without any modification or transformation, and stored in the EOS disk space [179] at CERN in their original format, ready for subsequent processing. The service is intended for selective event retrieval and is typically used for samples of up to $\mathcal{O}(10^5)$ – $\mathcal{O}(10^6)$ events [180]. Requests of larger size are considered bulk reprocessing, which must be treated differently.

5.5 Data and Simulation Samples in the Analysis

The search for slow, anomalously ionising, charged long-lived particles presented in this thesis uses ionisation (dE/dx) measurements from the Pixel detector and time-of-flight (ToF) information from the MDT as observables. The use of these variables lies outside the standard ATLAS analysis framework, and their calibrations and corrections are not included in the default data-processing workflow.

Due to radiation damage, the dE/dx information requires a dedicated correction, described in detail in Chapter 7. The dE/dx corrections in Run 2 [72, 73] were applied per data-taking period. The strategy for the dE/dx correction for the combined Run 2 and Run 3 search contains per-module corrections, which require access to the cluster-level information about the dE/dx . Such information is not a part of the standard ATLAS datasets. A dedicated option in Athena reconstruction that saves pixel-cluster information for the selected tracks was developed by the analysis team.

Information about ToF for the MDT is provided at the tube level by the Slow Muon reconstruction algorithm. The benchmark performance of the algorithm was achieved in Release 21 of the Athena software, used in most analyses based on Run 2 data. Following the software transition between Run 2 and Run 3, this performance was lost. The official ATLAS Run 3 datasets were processed with a non-functional version of the reconstruction algorithm.

The performance of the Slow Muon reconstruction algorithm was recovered by part of the analysis team, including the author. A more detailed description

of the algorithm, its performance, and the related developments are provided in Chapter 6. The tube-level calibration of the ToF measurement is described in Chapter 7.

The events over the full Run 2 (2015–2018) and partial Run 3 (2022–2024) periods of data taking and the corresponding MC samples must be processed with the same software version to avoid release-dependent differences. This version must contain the following non-standard options:

- pixel-cluster information is saved and forwarded to the AOD level;
- Slow Muon reconstruction algorithm at the validated high level of performance.

These requirements were first met in Athena Release 24.0.88. This release, or any later validated version, can be used for processing the data and MC samples required for the analysis.

5.5.1 Data Samples

The full dataset used by the search consists of the full Run 2 pp collisions data at $\sqrt{s} = 13$ TeV (140 fb^{-1}) and the partial Run 3 pp collisions data at $\sqrt{s} = 13.6$ TeV (169 fb^{-1}).

Reprocessing of the whole dataset with the listed software requirements is very intensive in terms of both computing resources and storage, which is not feasible for the collaboration in cases of very limited usage. Using the standard ATLAS datasets and standard variables, the full dataset was filtered to keep all the events used in the analysis regions, while lowering the event rate to be affordable for the Event Picking Service. The exact selections for the signal regions (SRs), control regions (CRs), and validation regions (VRs) used in the search are given in Chapter 8.

The selected events in RAW format were extracted using the Event Picking Service and collected into datasets for further dedicated processing. Table 5.1 gives the data rates before the event-picking selections and the number of picked events for the data-taking periods used in the analysis. The total number of picked events is 2.67×10^6 , which corresponds to 0.026% of the whole statistics.

During the design phase of the analysis described in Chapter 8, the dataset corresponding to the 2018 data-taking and consisting of 60 fb^{-1} pp collisions at $\sqrt{s} = 13$ TeV was used. The dataset was processed in Athena Release 21, standard for Run 2. As mentioned above, and as discussed in Chapter 6, this software version corresponds to the benchmark efficiency of the Slow Muon reconstruction algorithm.

Table 5.1: Data samples corresponding to the event-picking campaign for the search for heavy charged LLPs with anomalous ionisation and large ToF. Picked events include SRs/CRs/VRs used in two analysis channels. Integrated luminosity $\mathcal{L}$ corresponds to “good for physics”.

data-taking period	$\mathcal{L}, \text{fb}^{-1}$	total N events	N events picked	fraction picked
Run 2 (2015–2018)	140	5.9×10^9	1.54×10^6	0.026%
Run 3 (2022–2024)	169	5.7×10^9	1.43×10^6	0.025%

5.5.2 Data Samples for Calibration

MDT timing calibration, described in Chapter 7, is performed using the $Z \rightarrow \mu\mu$ dataset processed with the Athena release containing the Slow Muon and pixel-cluster software requirements.

DRAW_ZMUMU [181] datasets contain events from the $Z \rightarrow \mu\mu$ decay in the RAW format. To enter these datasets, events are selected according to the following criteria:

- Event selection:
 - muon trigger selection;
 - event contains at least one muon with $p_T > 20 \text{ GeV}$;
 - event contains at least one $\mu^+\mu^-$ pair with $70 < m_{\mu\mu} < 110 \text{ GeV}$.
- Muon selection:
 - CB muon with the *Medium* identification WP within $|\eta| < 3.0$;
 - leading muon $p_T > 25 \text{ GeV}$;
 - subleading muon $p_T > 20 \text{ GeV}$;
 - isolation: $p_T^{\text{cone40}}/p_T < 0.3$.

For calibration purposes, the DRAW_ZMUMU datasets corresponding to 2015–2018 (Run 2) and 2022–2024 (Run 3) were processed with Athena Release 24.0.89, with all required information at the pixel-cluster level. The whole dataset contains $\mathcal{O}(10^8)$ events Table 5.2 gives a more detailed overview of the dataset for the different data-taking periods used in the calibration. The table provides number of events before and after the Z tag-and-probe selection used for the calibration (details of the selection are described in Chapter 7).

Table 5.2: $Z \rightarrow \mu\mu$ data samples used for the MDT ToF calibration.

data-taking period	total N events	N events passed selections
2015	3×10^6	2×10^6
2016	29×10^6	20×10^6
2017	42×10^6	26×10^6
2018	51×10^6	33×10^6
Run 2 (2015–2018)	1.25×10^8	0.80×10^8
2022	22×10^6	13×10^6
2023	26×10^6	15×10^6
2024	103×10^6	57×10^6
Run 3 (2022–2024)	1.51×10^8	0.85×10^8
total	2.76×10^8	1.65×10^8

5.5.3 Simulated Signal Samples

Monte Carlo samples of long-lived pair-produced staus in a gauge-mediated supersymmetry scenario (GMSB) were used as signal MC samples during the design phase of the analysis. The stau mass hypothesis in the range from 200 to 700 GeV, with a step of 100 GeV, was considered. The stau lifetime was set to 3000 ns, corresponding to the effectively stable case. This ensures that the detector response does not include contributions from decays inside the ATLAS detector, as would occur for shorter lifetimes.

The samples were simulated as a part of the standard Run 2 MC sample production within the standard MC processing workflow described in Section 5.1 and reconstructed with Athena Release 21. The HITS files for the MC were processed using the following settings listed in Table 5.3.

Table 5.3: Settings for the MC simulation samples used in the analysis.

	$\tilde{\tau} \tilde{\tau}$	$Z \rightarrow \mu\mu$
Matrix Element	MADGRAPH5_AMC@NLO (v2.6.1)	POWHEG(v1_r2856)
Parton showering and hadronisation	PYTHIA8 (8.230)	PYTHIA8 (v8.186)
Afterburner	EVTGEN	PHOTOS
PDF + generator tune	A14_NNPDF23LO	AZNLO CTEQ6L1
Detector simulation	GEANT4	

In addition, the long-lived stau and $Z \rightarrow \mu\mu$ HITS files were used in the performance studies needed to recover the efficiency of the Slow Muon reconstruction algorithm, as described in Chapter 6. $Z \rightarrow \mu\mu$ MC was produced as a

part of the Run 2 MC sample production with the settings given in Table 5.3.

Chapter Summary

This chapter provides an overview of the standard processing chains for ATLAS recorded data and Monte Carlo simulations, together with the software infrastructure supporting these workflows. The Event Picking Service, a non-standard tool used for selective event reprocessing of a limited number of events, is described. The search for heavy charged long-lived particles requires specific software versions, available only in the most recent releases, to process the combined Run 2 and partial Run 3 pp dataset. The events from the signal, control, and validation regions were selected using the standard ATLAS datasets and subsequently collected for reprocessing with the Event Picking Service. The description of these procedures and of the MC and data samples used in the search is provided.

Chapter 6

Slow Muon Performance

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6.1 Introduction

This chapter provides the first description of the implementation of the MUGIRLOWBETA algorithm (also referred to as the “Slow Muon reconstruction algorithm” in this thesis) in the software releases relevant to Run 3. The personal contribution of the author of this thesis was the study of the reconstruction efficiency as a function of particle speed in different software releases. These studies played a crucial role in recovering the algorithm performance in Run 3.

6.2 MUGIRLOWBETA Reconstruction Algorithm

The main difference between the signatures of heavy charged LLPs and muons relevant for reconstruction is the speed with which a particle reaches the MS; for prompt muons, it is close to the speed of light ($\beta \approx 1$), whereas for hypothetical

Slow Muon Performance MuGIRLLOWBETA Reconstruction Algorithm

heavy charged LLPs, it is lower due to the large mass. All main muon reconstruction algorithms described in Chapter 4 assume a fixed value $\beta = 1$, making them well suited for relativistic muon reconstruction. However, this assumption makes the reconstruction of slower objects inefficient.

MuGIRLLOWBETA (formerly named MuGIRLSTAU) [182–184] exploits the similarity of the muon signature and charged BSM LLPs and allows the reconstruction of muon-like objects over a wide range of particle speeds ($0.2 < \beta < 1$). The output of this algorithm is a muon-like object referred to as a ‘Slow Muon’.

The MuGIRLLOWBETA reconstruction algorithm is described below:

1. The MuGIRLLOWBETA algorithm exploits inside-out matching of the inner tracks to the MS segments.
2. To build the segments, MuGIRLLOWBETA uses the hits that have already been found by the Standard Combined (CB) muon reconstruction algorithm (inside-in and outside-out parts) described in Chapter 4. In the barrel part of the ATLAS MS, covering the pseudorapidity range $|\eta| < 1.05$, the algorithms use hit information from RPC strips and MDT precision chambers.

Previously (in Release 21 of the Athena [185] software) MuGIRLLOWBETA also performed the search for the MS hits. This method was very CPU-intensive and, for performance reasons, is no longer used.

3. A segment fit is performed, keeping the β of the particle as a free parameter. First, the particle speed estimate β is obtained by fitting the RPC hit time. Then the fit of the MDT hits is performed.

For MDT tubes, the position of the hit is obtained using the known relation between the drift distance and the drift time $R = R(t_{drift})$. For a standalone tube, the result would be a ring with radius R about a wire. However, since hits from tubes along the particle trajectory are treated together, the hit positions are chosen to lie on a common trajectory while being at a distance R from the wire. The drift time t_{drift} is calculated as the difference between the signal arrival time and the particle time-of-flight (ToF):

$$t_{drift} = t_{signal} - \text{ToF}, \quad (6.1)$$

where, in the general case, the ToF can be computed by knowing the distance L from the primary vertex to the detecting element and the particle speed β :

$$\text{ToF} = L/(\beta c). \quad (6.2)$$

In equation 6.1, only the signal arrival time t_{signal} is known. On the other hand, depending on the particle speed, the estimates of ToF can be very different;

therefore, an assumption of $\beta = 1$ results in an underestimated ToF value and a longer drift time t_{drift} , giving an overestimated value of R . Altogether, it may lead to the situation illustrated in Figure 6.1. The trajectory of a slow particle (red line) is reconstructed under the assumption $\beta = 1$ (blue line).

Although some of the MDT tubes associated with the reconstructed particle trajectory belong to the original trajectory, the reconstructed path appears different from the original. As can also be seen, with an incorrect estimation of the drift radii, the new trajectory has fewer MDT hits associated with it. Such tracks are considered to have low reconstruction quality and are rejected. As a result, the reconstruction becomes inefficient and biased.

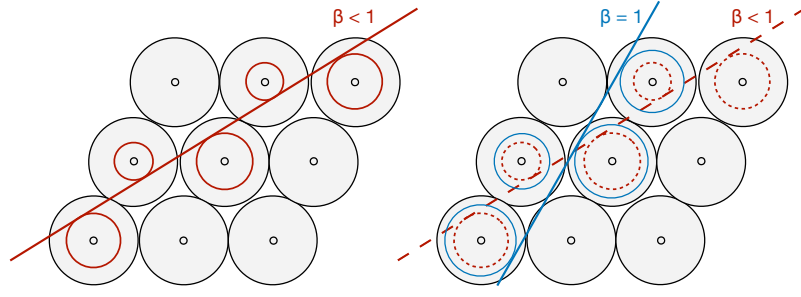


Figure 6.1: Adapted from Ref. [182]. A correct (right, in red) and incorrect (left, in blue) segment reconstruction in an MDT chamber. The wrong reconstruction is due to a longer time-of-flight, which results in the overestimation of the drift distance.

To summarise, leaving β as a free parameter in the MUGIRLLowBETA fit has a set of advantages:

- The particle speed β measurement, as well as the particle ToF, are the outputs of the fit. Other muon reconstruction algorithms fit the trajectory with a fixed value $\beta = 1$. In these cases, all information about the particle ToF is lost, which makes such algorithms inappropriate for ToF measurements used in the search described in this thesis.
- Hit positions are obtained with higher precision for particles with $\beta < 1$, as described above.
- For slow particles with $\beta < 1$, an overall increase in reconstruction efficiency is achieved, since the tracks are not discarded due to the misreconstruction of the track coordinates.

Slow Muon Performance MU GIRLLOWBETA Reconstruction Algorithm

As an output, the MU GIRLLOWBETA algorithm returns:

- object-level information: (η, ϕ, p_T) coordinates, β as the output of the fit, etc.;
- hit-level information: (x, y, z) hit positions, hit ToF, information about the type of detecting element (i.e. MDT, RPC η strip, RPC ϕ strip, etc.), and information on the fit quality at the hit level. The hit maps for the MDT and the RPC, obtained using the hit positions of the Slow Muon objects, are shown in Figure 6.2.

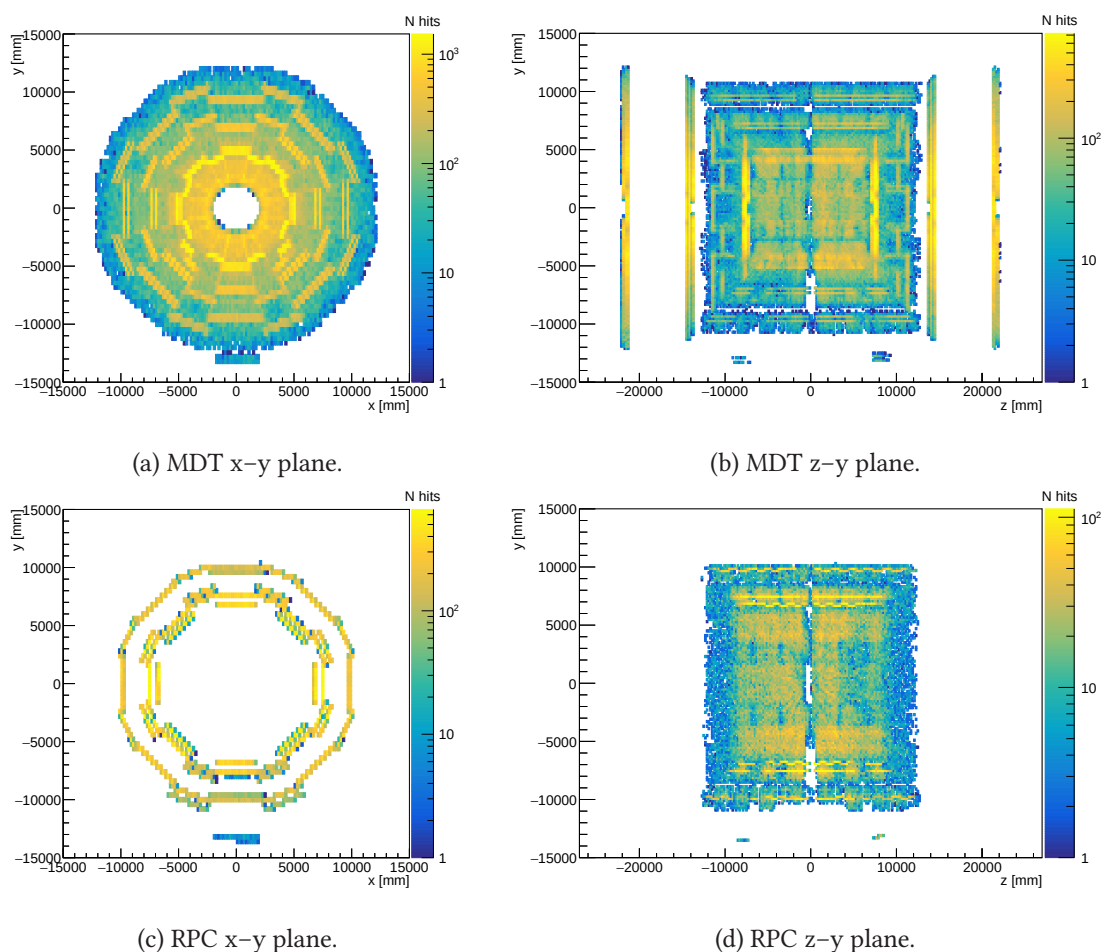


Figure 6.2: Hit maps of Slow Muon objects reconstructed in the ATLAS Muon Spectrometer. Panels (a) and (b) show the MDT hit distributions in the x-y and z-y planes, respectively, while panels (c) and (d) show the corresponding RPC hit distributions.

6.3 Reconstruction Efficiency

For the MC, here and throughout, the reconstruction efficiency is defined as the fraction of reconstructed objects geometrically matched to the corresponding truth object within $\Delta R < 0.05$, defined by (η, ϕ) coordinates of reconstructed and truth objects:

$$\Delta R = \sqrt{(\eta_{truth} - \eta_{reco})^2 + (\phi_{truth} - \phi_{reco})^2}. \quad (6.3)$$

The concept of the truth object is discussed in Chapter 5 of this thesis.

In addition, both truth and reconstructed objects have to pass the same set of kinematic selections.

This chapter focuses on the reconstruction efficiency of Slow Muon objects as a function of pseudorapidity η and particle speed β . As benchmarks for the efficiency studies, a 700 GeV, 3000 ns $\tilde{\tau}$ MC sample (as an example of a long-lived slow BSM particle) and a $Z \rightarrow \mu\mu$ MC sample (as an example of an SM sample) were chosen. These samples are discussed in detail in Section 5.5.3.

6.3.1 Reconstruction Efficiency of the Slow Particles

In Ref. [184], it was shown that MUGIRLOWBETA shows the best reconstruction performance among ATLAS muon reconstruction algorithms in the range $0.2 < \beta < 0.9$ for hypothetical slow heavy long-lived particles. Figure 6.3 shows the comparison of the reconstruction efficiencies from this study for all muon reconstruction algorithms used in Run 2 data and MC reconstruction in Release 21 of the Athena software.

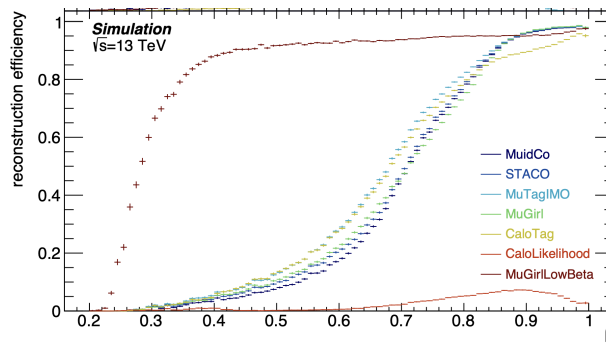


Figure 6.3: Reconstruction efficiency for signal particles as a function of β for different ATLAS muon reconstruction algorithms. Particles have to fulfil the selection criteria $p_T > 35$ GeV and $|\eta| < 2.5$ and are matched to truth. They count as reconstructed by an algorithm if the algorithm is one of their authors. Reconstruction algorithms without significant contribution have been omitted [184].

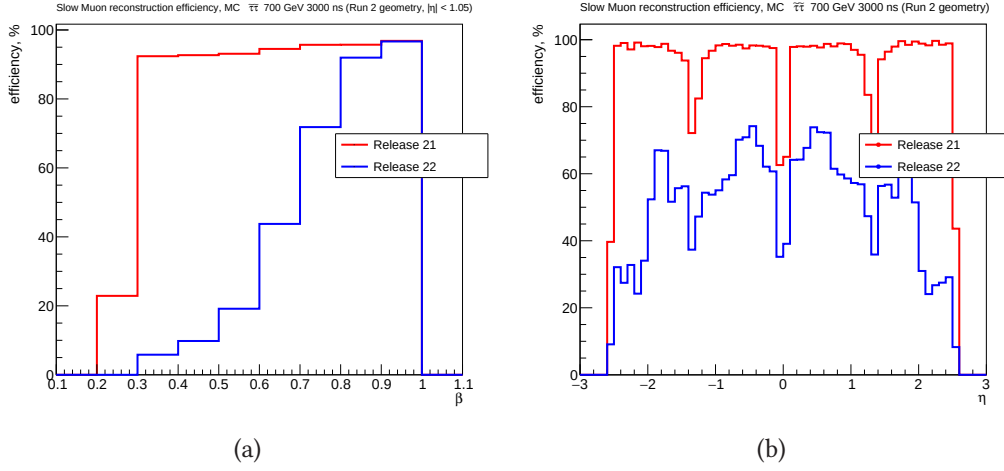


Figure 6.4: Slow Muon reconstruction efficiency in Releases 21 (red) and 22 (blue) of the Athena software as a function of (a) particle speed β in the MS barrel region and (b) pseudorapidity η for a $\sqrt{s} = 700$ GeV MC sample. All Slow Muon objects have to fulfil the selection criteria $p_T > 35$ GeV and are matched to truth.

Release 21 was used for a long time as the main software for processing, most of the published Run 2-only ATLAS searches were using the data processed with this release. Currently Release 22 is the recommended version of the software for Run 2-only analyses in ATLAS. Despite the fact that its performance for standard objects is better than that of Release 21, the situation for unconventional object reconstruction, such as Slow Muons, is different. The transition between Releases 21 and 22 resulted in a drop in MUonRECON reconstruction efficiency. The corresponding efficiency comparison as functions of η and β in the MS barrel ($|\eta| < 1.05$) is shown in Figure 6.4. The next software transition was made to allow all ATLAS systems to process data efficiently in Run 3 and beyond. Unfortunately, this transition was especially harmful for MUonRECON and resulted in an almost complete degradation of its reconstruction performance in early Release 24/25 (Figure 6.5). This made the MUonRECON algorithm completely unusable in Run 3 ToF studies. The problem was first discovered during the design phase of the MDT time-of-flight part of this analysis.

The recovery of the algorithm performance in the barrel part of the ATLAS MS was carried out in two steps:

1. The efficiency was restored to the level of Release 22 by resolving a logic error that occurred during the transition to Releases 24/25. This step is illustrated in Figure 6.6. The efficiency at the beginning of the Run 3 studies corresponds to Release 25.0.5; the version with the implemented correction

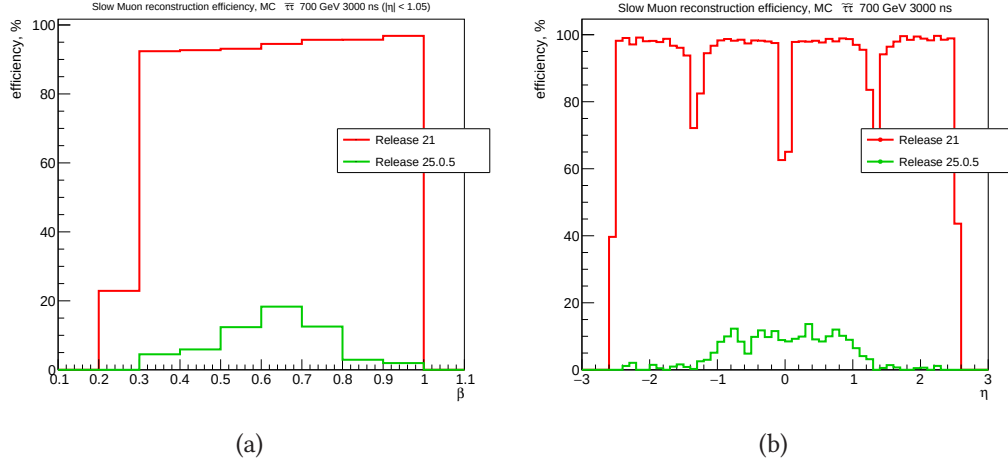


Figure 6.5: Slow Muon reconstruction efficiency in Releases 21 (red) and 25.0.5 (green) of the Athena software as a function of (a) particle speed β in the MS barrel region and (b) pseudorapidity η for a $\sqrt{s} = 700$ GeV MC sample. All Slow Muon objects have to fulfil the selection criteria $p_T > 35$ GeV and are matched to truth.

is Release 25.0.24. *This fix was implemented by colleagues from the Harvard University (A. Mulski).*

2. The efficiency was restored to the level of Release 21 (the benchmark efficiency for this algorithm) after ensuring that β , as an intermediate fit output, is passed through all the steps of the algorithm. The final version of the algorithm corresponds to release numbers 24.0.86 and higher, and 25.0.30 and higher. *This fix was introduced by colleagues at the University of Bologna with the active personal contribution of the author.*

The performance work was focused on the reconstruction in the MS barrel, which configuration remains almost unchanged between Run 2 and Run 3. The achieved efficiency of the algorithm in Run 3 conditions (Figures 6.7 and 6.8) allows the use of Slow Muon objects for a combined Run 2 + Run 3 analysis in the MS barrel region.

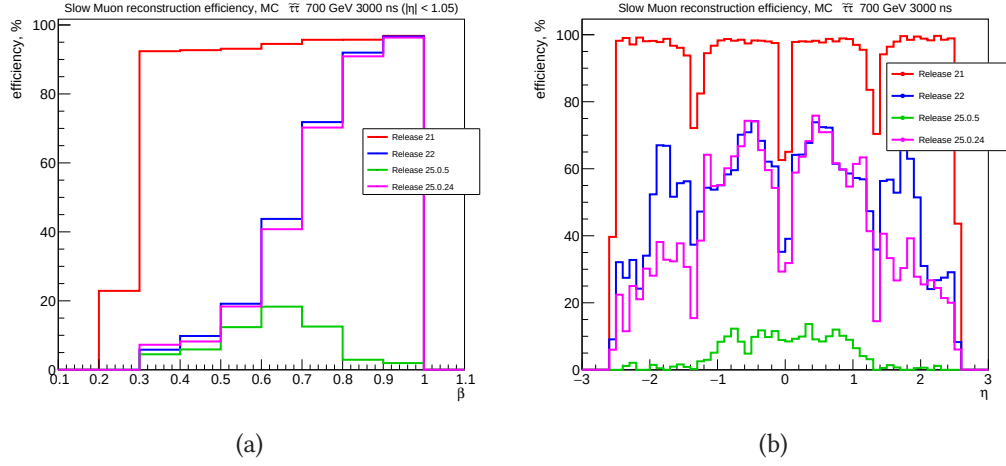


Figure 6.6: Slow Muon reconstruction efficiency in Releases 21 (red), 22 (blue), 25.0.5 (green), and 25.0.24 (magenta) of the Athena software as a function of (a) particle speed β in the MS barrel region and (b) pseudorapidity η for a $\sqrt{s} = 700$ GeV MC sample. All Slow Muon objects have to fulfil the selection criteria $p_T > 35$ GeV and are matched to truth.

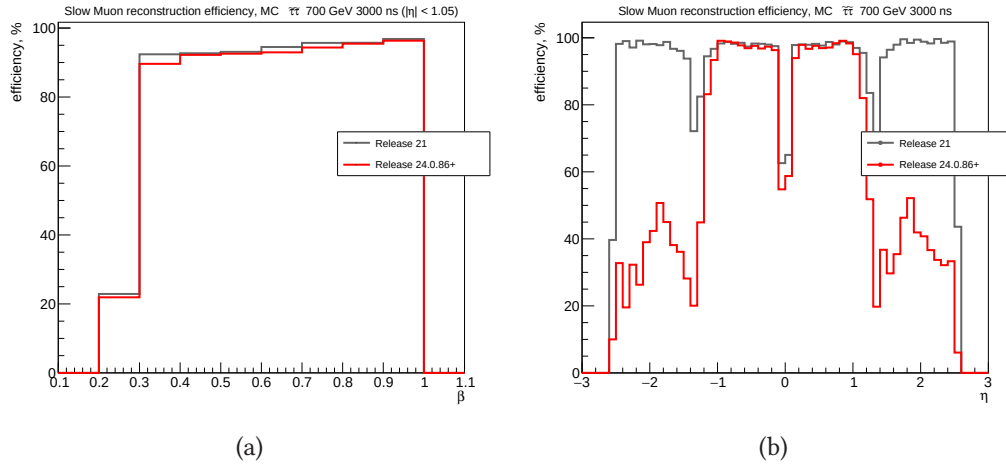


Figure 6.7: Slow Muon reconstruction efficiency in Releases 24.0.86 (red) and 21 (grey) of the Athena software as a function of (a) particle speed β in the MS barrel region and (b) pseudorapidity η for a $\sqrt{s} = 700$ GeV MC sample. All Slow Muon objects have to fulfil the selection criteria $p_T > 35$ GeV and are matched to truth.

6.3.2 Reconstruction Efficiency of the Fast Muons

The high reconstruction efficiency of the algorithm for SM muons from Z -boson decays (demonstrated in Figure 6.8) allows the ToF calibration of the MS and the recomputation of a refined value of β_{ToF} . This process is described in detail in Chapter 7.

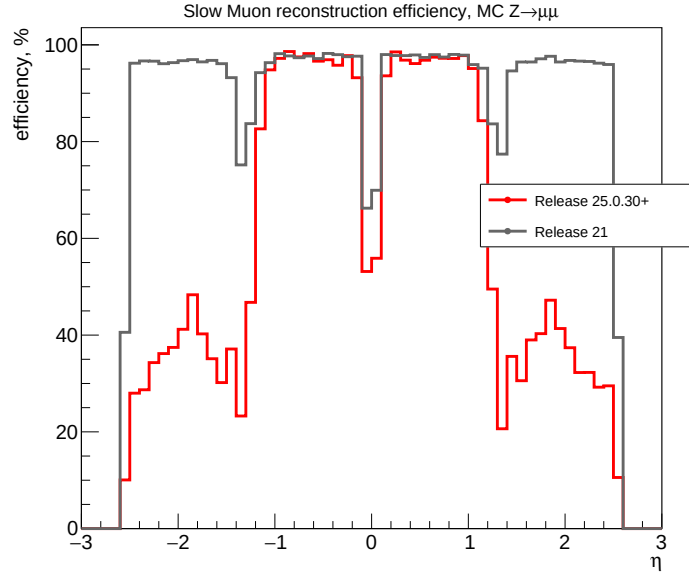


Figure 6.8: Slow Muon reconstruction efficiency in Releases 25.0.30 (red) and 21 (grey) of the Athena software as a function of pseudorapidity η for a $Z \rightarrow \mu\mu$ MC sample. All Slow Muon objects have to fulfil the selection criteria $p_T > 35$ GeV and are matched to truth.

Using a fraction of the $Z \rightarrow \mu\mu$ dataset described in Section 5.5.2, Slow Muon reconstruction performance in data has been studied. The efficiency, corresponding to the fraction of CB muons in the $Z \rightarrow \mu\mu$ selection that are matched to the Slow Muon object, has been measured for the Run 2 and Run 3 samples. The reconstruction efficiency, defined in this way, has been studied as a function of the pseudorapidity η . A Run 2 versus Run 3 comparison of the efficiencies is shown in Figure 6.9. Reconstruction efficiencies for the muons in the Run 2 and Run 3 data coincide in the barrel region of the Muon Spectrometer. Differences in the end-cap regions may be explained by detector geometry changes between Run 2 and Run 3.

The comparison between the Slow Muon reconstruction efficiency for the $Z \rightarrow \mu\mu$ MC and the $Z \rightarrow \mu\mu$ data is shown in Figure 6.10. Since the efficiencies for the MC and data are defined differently in this study, one can

treat the data reconstruction efficiency as a product of the Slow Muon and CB muon reconstruction efficiencies (see Chapter 4 and Figure 4.5). The CB muon efficiency is close to 1 in the barrel region ($0.1 < |\eta| < 1.05$), and demonstrates a reduction in the central region ($|\eta| < 0.1$) of the MS. The efficiencies for data and MC shown in Figure 6.10 match each other in the barrel region of the MS, where CB muons are reconstructed with an efficiency close to 1. Differences in the end-cap regions of the MS can be explained as a result of a lower efficiency of the CB muon reconstruction. This study illustrates agreement between Slow Muon reconstruction performance for muons in the MC and the data and confirms high reconstruction efficiency (96 – 99%) in the MS barrel region ($0.1 < |\eta| < 1.05$).

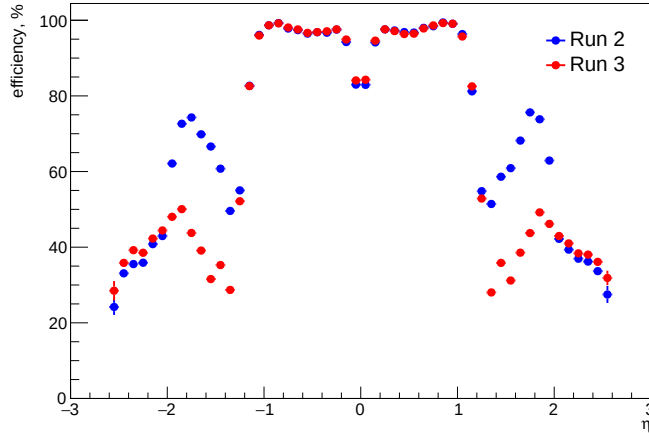


Figure 6.9: Slow Muon reconstruction efficiency for muons from data reconstructed using Release 24.0.89 of the Athena software for Run 2 (blue) and Run 3 (red) as a function of pseudorapidity η . Muon objects are required to pass the $Z \rightarrow \mu\mu$ selection. Efficiency is measured as a fraction of CB muons with the associated Slow Muon object.

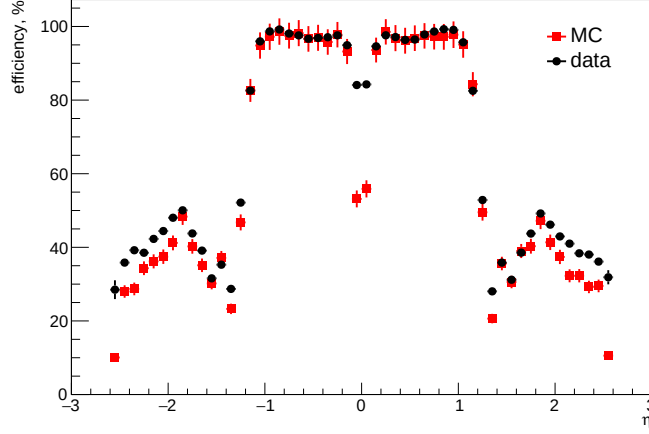


Figure 6.10: Slow Muon reconstruction efficiency for muons for the $Z \rightarrow \mu\mu$ MC (red) and $Z \rightarrow \mu\mu$ Run 3 data (black) as a function of pseudorapidity η . MC and data are reconstructed with the recent Athena software release. For the MC, the efficiency is defined as a Slow Muon truth matching efficiency. For the data, the efficiency is measured as a fraction of CB muons, passing $Z \rightarrow \mu\mu$ selection, associated with the Slow Muon object.

Chapter Summary

The MUGIRLOWBETA reconstruction algorithm demonstrates high efficiency in reconstructing particles over a wide speed range ($0.2 < \beta < 1$), while providing hit-level information on the particle ToF. These features make it suitable for searching for hypothetical slow-moving LLPs using ToF in the ATLAS MS. Initially, during Run 3, the algorithm performance was not optimal, preventing its use in a combined search. However, after improvements that included contributions from the author of this thesis, the algorithm reconstruction efficiency was returned to high levels in the barrel region of the ATLAS MS. Consequently, it is now possible to perform a combined Run 2 and Run 3 search for LLPs using Slow Muon objects.

Slow Muon reconstruction efficiency has been studied for slow objects as a function of particle speed β and pseudorapidity η , and for fast objects ($\beta = 1$) as a function of η . The reconstruction efficiency in recent software releases is high (96 – 99%) for objects reconstructed in the barrel region of the ATLAS MS ($0.1 < |\eta| < 1.05$).

Chapter 7

Calibration

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The search for heavy, charged, long-lived particles relies on several measurements of the charged-particle track to determine its mass, given by $m = p/(\beta\gamma)$. One $\beta\gamma$ measurement is derived from the Pixel ionisation (dE/dx) measurements, while another, β_{ToF} , is obtained from the MDT time-of-flight (ToF) information using the Slow Muon reconstruction algorithm described in Chapter 6.

To obtain unbiased values of the observables, dedicated corrections and calibrations of the measurements are required. This chapter provides an overview of the Pixel dE/dx corrections and the MDT ToF corrections and calibration. Section 7.1 describes the principles and procedures of the Pixel dE/dx corrections. Section 7.2 outlines the MDT timing measurements, and Section 7.3 details the MDT time-of-flight calibration.

The MDT ToF calibration is the original contribution in this work. The calibration is based on the Z -boson tag-and-probe method with muons reconstructed using the Slow Muon algorithm. It is performed for the MDT barrel region ($|\eta| < 1.05$) at the level of individual MDT tubes. A set of additional corrections

for the MDT time is introduced, and a method for computing the corrected β_{ToF} obtained from the MDT ToF measurement is proposed.

7.1 Pixel dE/dx Corrections

A track ionisation dE/dx (measured in $\text{MeV g}^{-1}\text{cm}^2$, also known as ‘mass stopping power’ [14]), used in this analysis, is obtained from ATLAS Pixel detector. As described in Chapter 3, the Pixel detector is the closest subdetector to the collision and consists of four layers of pixel modules.

The measurement of the dE/dx is done at the cluster [135] level. The charge of the cluster Q is measured by digitising the time interval with the signal above a preset threshold (time-over-threshold or ToT), which is approximately proportional to the ionisation charge [186]. Then the charge is translated to the ionisation loss dE/dx :

$$dE/dx = \frac{QW}{\rho x e}, \quad (7.1)$$

where W is the average energy required to ionise an electron–hole pair, e is the elementary charge, ρ is the density of silicon, and x is the particle path length through silicon [187].

The probability density function of the dE/dx can be described with a Landau distribution [188, 189], the main features of which are a narrow peak and a long tail.

Cluster measurements are then combined using the truncated-mean algorithm to obtain a dE/dx measurement for the track. The truncated-mean estimator, $\langle dE/dx \rangle_{\text{trunc}}$, is computed by rejecting the largest cluster-level contributions and averaging the remaining cluster dE/dx values.

In the absence of an IBL [190] overflow measurement ($\text{IBL}_{\text{OF}} = 0$), the truncation depends on the number of associated clusters: for tracks with up to four clusters, the single highest cluster dE/dx value is rejected; in rare cases with more than four clusters (possible due to module overlaps), the two highest cluster dE/dx values are rejected.

If an IBL overflow measurement is present ($\text{IBL}_{\text{OF}} = 1$), the corresponding overflow cluster is always rejected. A further cluster is rejected only if at least one of the remaining clusters has dE/dx larger than the dE/dx of the rejected overflow cluster; in that case, the highest dE/dx among the remaining clusters is removed. The absence and the presence of the IBL_{OF} are denoted as OF0 and OF1, respectively.

The resulting $\langle dE/dx \rangle_{\text{trunc}}$ provides an estimate close to the most probable value of the track dE/dx , reducing the impact of the long Landau tail in the dE/dx distribution.

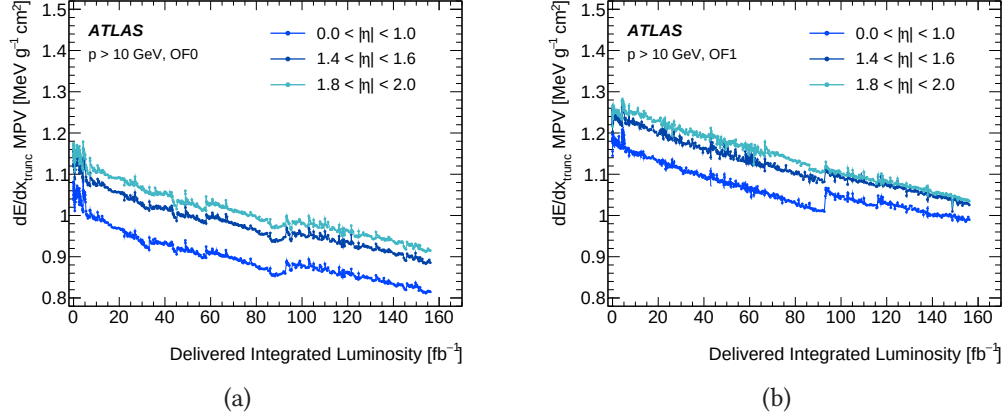


Figure 7.1: Taken from Ref. [72]. The drift of MIP-MPV $\langle dE/dx \rangle_{\text{trunc}}$ as a function of the delivered integrated luminosity in Run 2, divided into different pseudorapidity ranges, for MIP tracks of $p > 10$ GeV (a) without an IBL overflow (OF0) or (b) with an IBL overflow (OF1). The lower $\langle dE/dx \rangle_{\text{trunc}}$ in (a) is due to the contribution of the IBL clusters which are restricted by the overflow to be under ≈ 2 MIPs.

As observed in Ref. [72], the MPV of the track $\langle dE/dx \rangle_{\text{trunc}}$ decreases with integrated luminosity as a result of radiation damage (Figure 7.1). It was also observed that the effect of the radiation damage depends on $|\eta|$ of the module. In the previous approach, the value of $\langle dE/dx \rangle_{\text{trunc}}$ for each track was corrected as a function of the run number and $|\eta|$.

During Run 3 studies, it was observed that the difference between the radiation damage of the innermost and other pixel layers had become more significant, which may bias the $\langle dE/dx \rangle_{\text{trunc}}$ measurement by removing the measurement from the outer layers. Under the new strategy, the corrections are applied at the cluster level first, and $\langle dE/dx \rangle_{\text{trunc}}$ is computed afterwards.

In order to derive the $\beta\gamma$ from the Pixel dE/dx , the low-momentum SM particles are used. Pion, kaon, proton and deuteron tracks with momenta in range from 100 MeV to a few GeV are used. The $\beta\gamma$ - dE/dx dependence is derived from the data using the Beta-Bloch parametrisation with the assumption $\beta\gamma < 1$. The mapping of $(\beta\gamma, \text{MPV}_{dE/dx})$ is obtained for the different identified SM particle tracks. Using such technique, the $\beta\gamma$ range from 0.35 to 3 can be covered.

An example of mapping used in Run 2 dE/dx calibration is shown in Figure 7.2. The calibrated Run 2 dE/dx measurements were used in the development phase of the analysis described in Chapter 8. A detailed description of the Run 2 strategy for the Pixel dE/dx calibration is provided in Ref. [72].

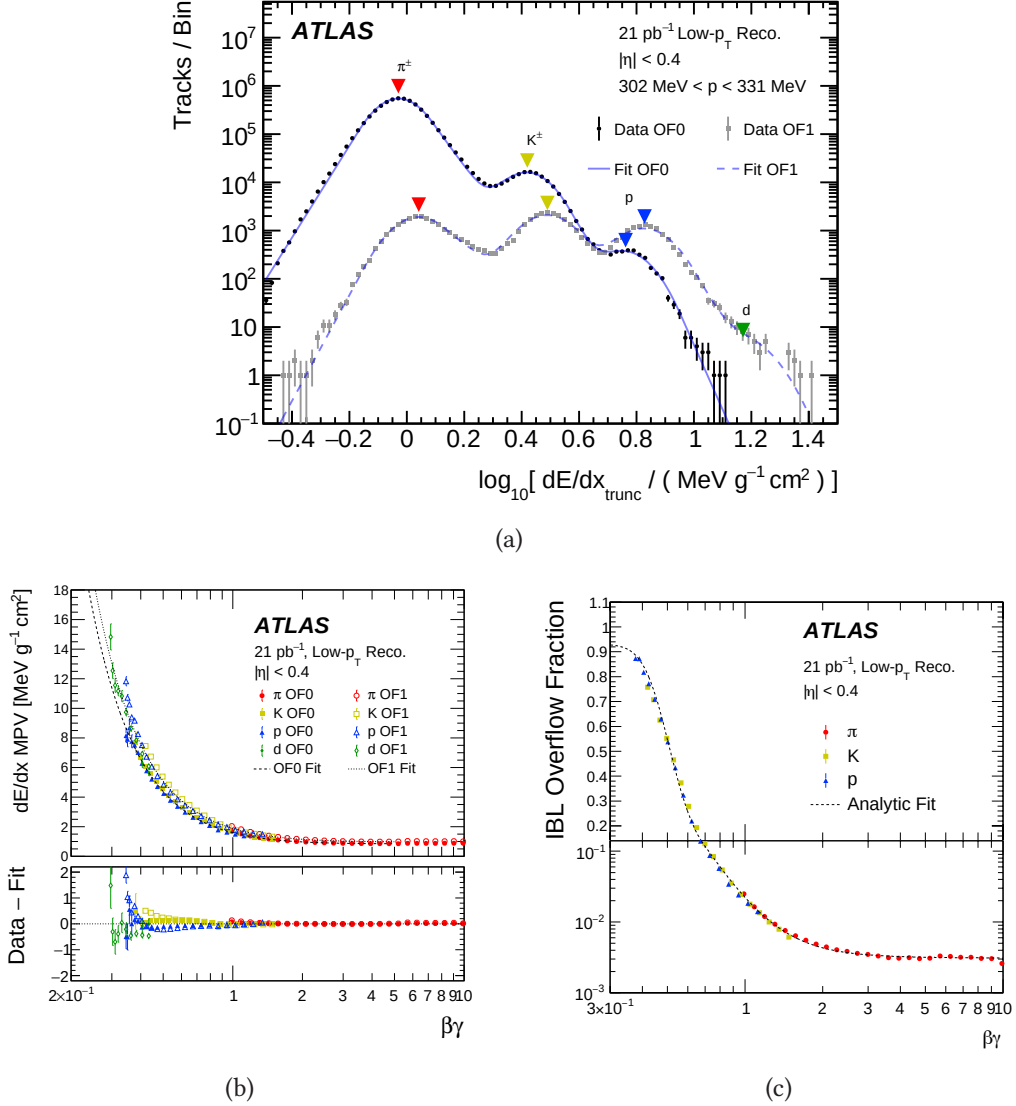


Figure 7.2: Taken from Ref. [72]. (a) An example of a $\langle dE/dx \rangle_{\text{trunc}}$ distribution of low- $\langle \mu \rangle$ minimum-bias charged-particle tracks in a momentum slice of 302 MeV < p < 331 MeV in the pseudorapidity range $|\eta| < 0.4$. Tracks are classified by IBL overflow. Triangle markers indicate identified MPVs corresponding to pions (red), kaons (yellow), protons (blue) and deuterons (green). The result of fitting a superposition of the $\langle dE/dx \rangle_{\text{trunc}}$ distributions of identified particles is also overlaid for each data series. (b) MPV values of $\langle dE/dx \rangle_{\text{trunc}}$ as a function of particle $\beta\gamma$ in $|\eta| < 0.4$, classified by IBL_{OF}. The data values are fitted by a function respecting the Bethe–Bloch formula. (c) The fraction of IBL_{OF} = 1 tracks as a function of particle $\beta\gamma$ in $|\eta| < 0.4$.

7.2 Timing Measurement in the MDT

The key elements of the MDT detector are described in Chapter 3.

The MDT drift tube signal, or hit, provides the pulse arrival time, and a quantity reconstructed as the collected electric charge of the signal pulse. The hit time data are recorded in $1.2 \mu\text{s}$ windows initiated by a first-level trigger signal with a 0.78125 ns minimum digitisation time [191]. The charge contained in the leading edge of the signal is stored as voltage on a capacitor and read out as a run-down time using the Wilkinson technique [124].

The signal arrival time is measured with respect to the bunch crossing corresponding to a pp collision, defined in 25 ns intervals synchronised with the LHC global 40 MHz clock (the BC clock). The raw pulse arrival time is obtained in the read-out electronics by subtracting the bunch-crossing time.

The pulse arrival time t_{pulse} can be represented as a sum of the drift time t_{drift} and the time offset T_0 :

$$t_{\text{pulse}} = T_0 + t_{\text{drift}}. \quad (7.2)$$

Time offset T_0 consists of the time-of-flight of a muon ToF_μ produced in pp collisions from the interaction point (coinciding with the nominal ATLAS centre of coordinates) to the tube, propagation time along the tube wire Δt_{prop} , and various fixed electronics and cable latencies $\Delta t_{\text{fix.el.}}$:

$$T_0 = \text{ToF}_\mu + \Delta t_{\text{prop}} + \Delta t_{\text{fix.el.}}. \quad (7.3)$$

The drift time is the transit time of electrons generated by the primary ionisation and subsequent avalanche multiplication to arrive at the anode wire. Using the drift time to drift distance transfer relation $R(t_{\text{drift}})$, it is possible to extract the drift radius. An example of such a relation is shown in Figure 7.3.

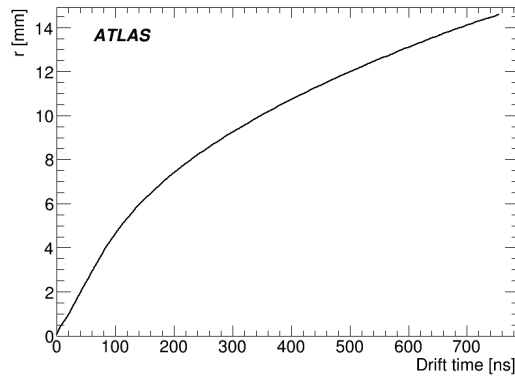


Figure 7.3: MDT gas-monitor chamber $R(t_{\text{drift}})$ function for standard conditions, obtained via auto-calibration [191].

The offset T_0 can be interpreted as a drift time produced by a particle created in a collision exactly in synchronisation with the BC clock in the nominal centre of ATLAS and crossing the MDT tube at the wire (which corresponds to the drift radius R equal to 0). This value is assigned for each tube individually. For each tube, the drift time is then computed as the difference between the raw hit time and the offset T_0 . The T_0 offset is a property of a single MDT tube, while an $R(t_{\text{drift}})$ function is associated with a single MDT chamber.

7.3 MDT ToF Calibration

This section presents the strategy and framework for the MDT barrel calibration. The calibration is performed using a sample containing $\mathcal{O}(10^8)$ events, preselected with the DRAW_ZMUMU selection, from the full Run 2 (2015–2018) and part of Run 3 (2022–2024) pp collision data, and reconstructed with a recent Athena release containing all fixes to the Slow Muon reconstruction algorithm described in Chapter 6. A detailed description of the sample is provided in Chapter 5.

The outcome of the calibration is an updated value of the particle speed β . The speed measurement is obtained from the individual time-of-flight values to the MDT tubes. These MDT ToF measurements are performed using the hit-level information provided by the Slow Muon reconstruction algorithm. In total, the calibration is required for $\mathcal{O}(2 \times 10^5)$ individual tubes located in the barrel region of the MDT [123]. The calibration constants are derived for each data-taking year independently.

The time-of-flight calibration is performed using a Z tag-and-probe method. A pair of muons from the same event is selected from data to originate from the $Z \rightarrow \mu\mu$ decay, with the following set of requirements:

- the invariant mass of the muons has to fall into the range $70 < m_{\mu\mu} < 110$ GeV;
- the ‘tag’ muon must have $p_T > 35$ GeV and satisfy the ‘Medium’ WP selections;
- the ‘probe’ muon must be reconstructed with the Slow Muon reconstruction algorithm, have $p_T > 25$ GeV, and satisfy the ‘Medium’ WP selections.

Since the calibration is performed only for the barrel region of the MDT, only ‘probe’ muons with $|\eta| < 1.05$ are selected.

A set of quality selections has been applied to the probe muon candidates to ensure the quality of the calibration.

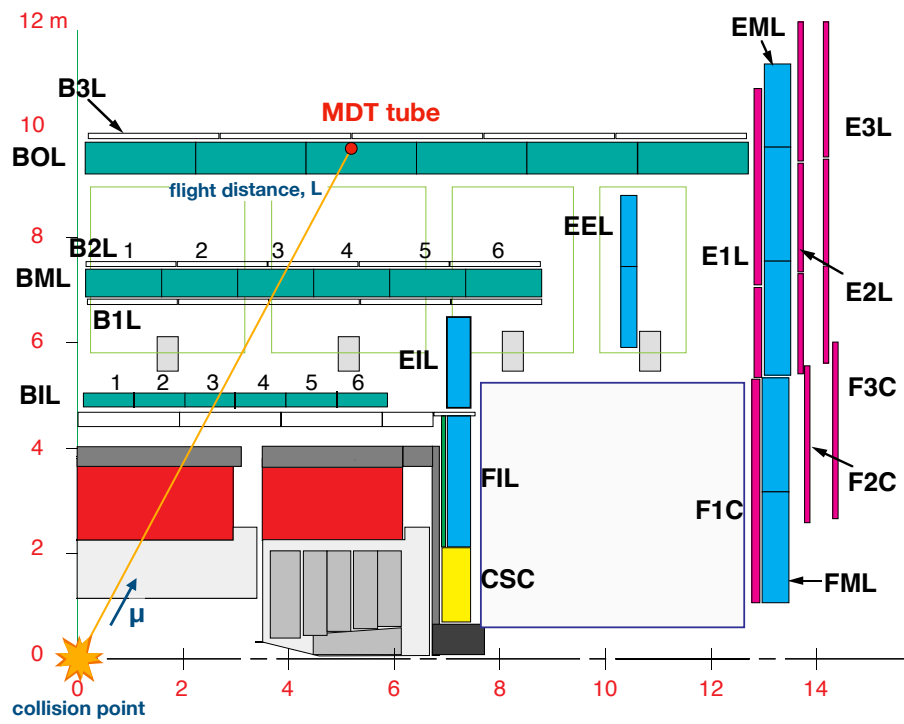
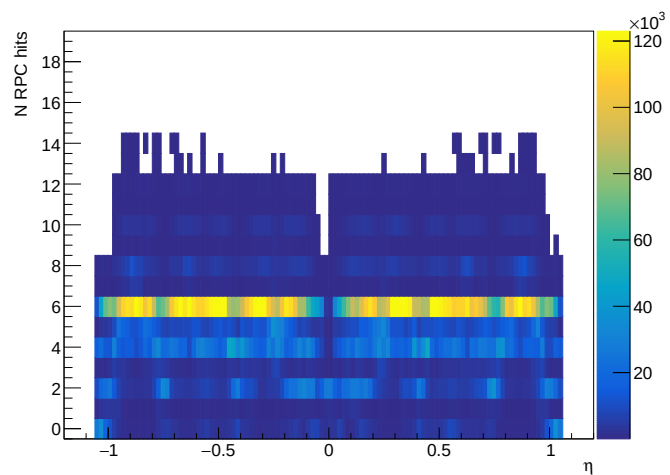
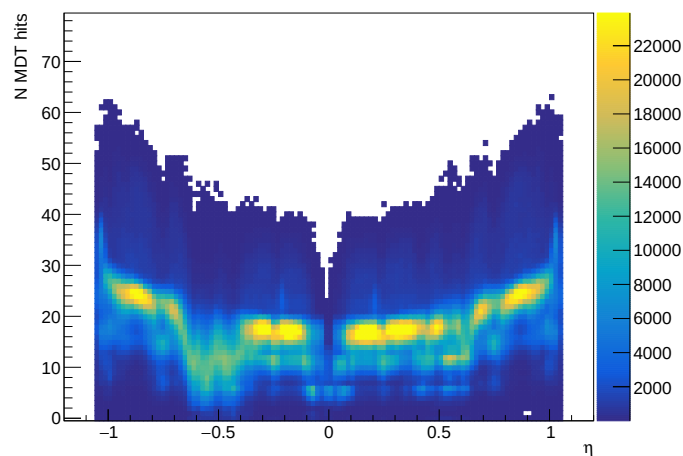


Figure 7.4: A schematic view of the MDT barrel calibration. The probe muon is used to calibrate the MDT tube (in red) located at the distance L from the PV.



(a)



(b)

Figure 7.5: Two-dimensional distributions of the number of hits associated with a Slow Muon track versus pseudorapidity η : (a) number of RPC hits vs η ; (b) number of MDT hits vs η . The Slow Muon object is required to be matched to the muon passing the Z tag-and-probe selections. Only objects in the barrel region ($|\eta| < 1.05$) are considered.

It is required that each probe muon, reconstructed as a Slow Muon object, passes the hit requirements (number of RPC hits, N_{RPC} , and number of MDT hits, N_{MDT}) based on the track pseudorapidity η :

- $|\eta| < 0.1$: $N_{\text{RPC}} \geq 0$, $N_{\text{MDT}} \geq 10$;
- $-0.6 < \eta < -0.4$: $N_{\text{RPC}} \geq 4$, $N_{\text{MDT}} \geq 5$;
- all other tracks with $|\eta| < 1.05$: $N_{\text{RPC}} \geq 4$, $N_{\text{MDT}} \geq 10$.

Such a selection has been chosen due to the clear η -dependence of the numbers of MDT and RPC hits on the Slow Muon object track. Distributions of the numbers of MDT and RPC hits as a function of pseudorapidity, before the hit-based selections, are shown in Figure 7.5. The drop in the number of hits in the central ($|\eta| < 0.1$) region is explained by the absence of detecting elements. At the same time, the distribution of MDT hits in the region $-0.6 < \eta < -0.4$ suffers from reconstruction issues that are not yet explained, which, however, do not affect the reconstruction efficiency, as demonstrated earlier in Chapter 6.

Muons coming from the decay of the Z boson are relativistic, what allows the assumption that they are moving with $\beta = 1$. Such an assumption allows the timing of the MDT tubes in which the ‘probe’ muon left hits to be corrected.

The timing is accessible for all the MDT and RPC hits on the Slow Muon object track, which allows the per-tube calibration of the MDT detector. Schematically the calibration is illustrated in Figure 7.4.

With reference to Eq. (7.2) and (7.3), for a real muon, the ToF measurement can be biased by:

- Incorrect estimations of Δt_{prop} and $\Delta t_{\text{fix.el.}}$;
- Differences in time between the actual pp collision time and the BC clock. These can be induced by:
 - A global shift between the BC clock and the LHC bunch delivery;
 - Event-by-event time and location fluctuations of the pp collision within the BC.

For each MDT hit it is possible to compute the following value:

$$t_0 = \text{ToF} - \frac{L}{c}, \quad (7.4)$$

where ToF is the particle time-of-flight, L is the distance from the primary vertex to the MDT tube (rather than the ATLAS nominal centre), and c is the speed of light. ToF and the hit coordinates are the properties of the Slow Muon object

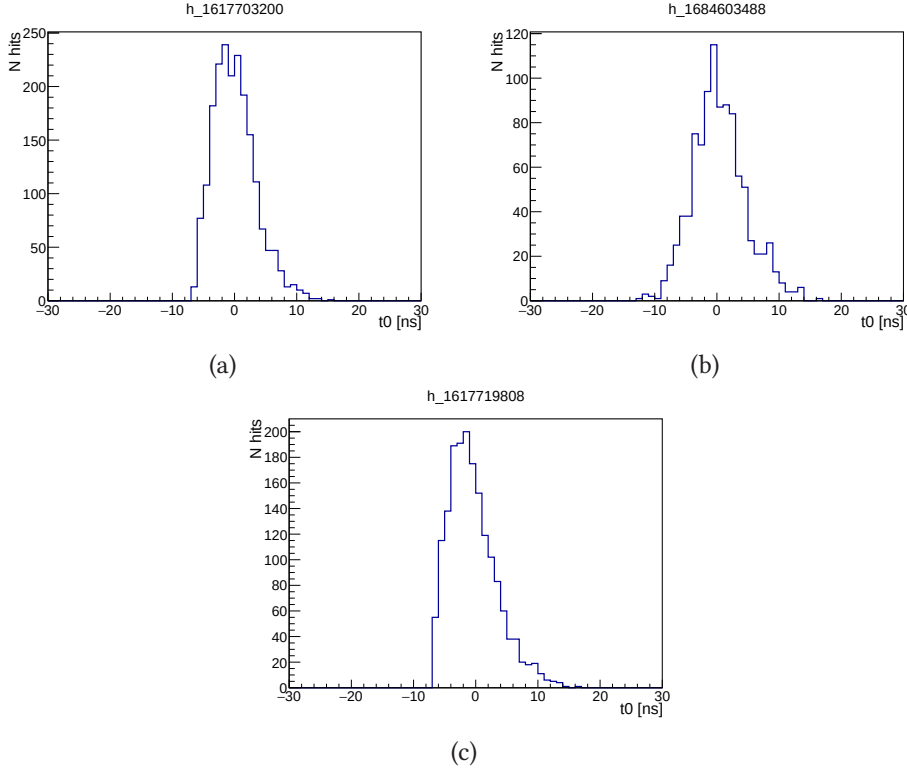


Figure 7.6: Examples of t_0 distributions for different MDT tubes in the barrel region.

associated to this muon. For the ‘probe’ muon, t_0 has to be equal to 0, since the muon is assumed to move with a speed close to the speed of light.

The distribution of the t_0 values can be obtained for all the MDT tubes in the detector. Figure 7.6 shows t_0 distributions for three different MDT tubes inside the detector. The raw distributions are not centred at 0 and are not symmetric, thus calibration is required.

Only the ‘probe’ muons with $t_0 \leq 25$ ns were taken into account for the timing calibration purposes in order to reject muons coming from neighbouring bunch crossings.

The number of probe muon t_0 measurements per MDT tube in the MS barrel, obtained from the $Z \rightarrow \mu\mu$ 2018 dataset, is shown in Figure 7.7.

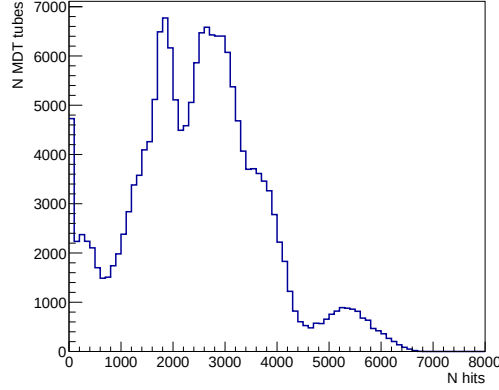


Figure 7.7: MDT tube population in the data 2018 calibration sample.

7.3.1 Timing Corrections

A set of possibilities to correct the timing as a part of the timing calibration were studied.

PV Corrections

It was observed that a precise determination of the distance L in the t_0 measurement is crucial. The computation of L takes into account the z position of the primary vertex. For this study, t_0 values were averaged over the MDT stations (Inner, Middle and Outer), and four η slices: $[-1; -0.5]$, $[-0.5; 0]$, $[0; 0.5]$, and $[0.5; 1]$. An example of such distributions for the Inner station of the MDT and $-1 < \eta < -0.5$ is shown in Figure 7.8. It was observed that $\langle t_0 \rangle$ has a clear dependence on the position of the PV. The PV-position-aware computation of the time is required:

$$t_0 = \text{ToF} - L/c; \quad L = \sqrt{(x_{\text{abs}}^{\text{hit}} - x_{\text{PV}})^2 + (y_{\text{abs}}^{\text{hit}} - y_{\text{PV}})^2 + (z_{\text{abs}}^{\text{hit}} - z_{\text{PV}})^2}, \quad (7.5)$$

where $(x_{\text{abs}}^{\text{hit}}, y_{\text{abs}}^{\text{hit}}, z_{\text{abs}}^{\text{hit}})$ and $(x_{\text{PV}}, y_{\text{PV}}, z_{\text{PV}})$ are the hit coordinates and the PV coordinates respectively in the absolute ATLAS coordinate system.

Time Stability of the MDT ToF

The next study was performed to check the effect of the LHC clock shift on the MDT timing, observed in previous studies [183, 184]. For this purpose, t_0 values corrected for the PV position were averaged over each station (Inner, Middle and Outer) and over all the MDT barrel region for each run of the data-taking.

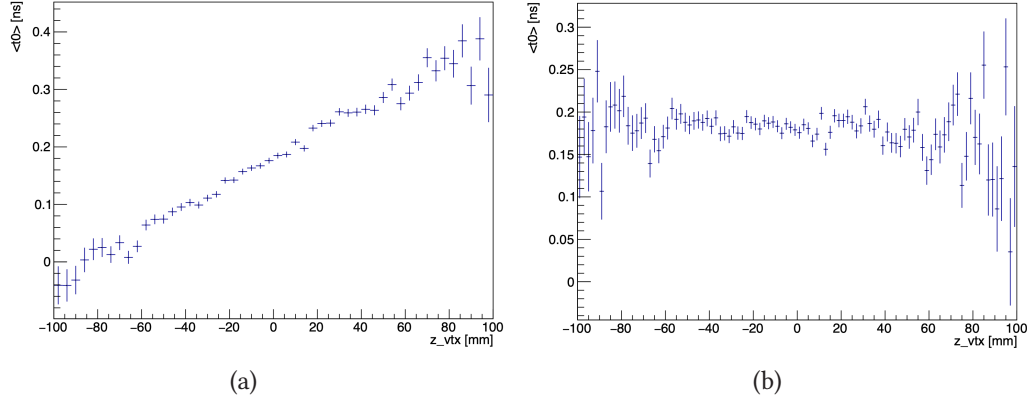


Figure 7.8: A distribution of the mean t_0 value versus the z position of the PV for t_0 computation: (a) regardless of the z position of the PV and (b) z -position aware. The average is performed for the Inner station and in the pseudorapidity range $-1 < \eta < -0.5$.

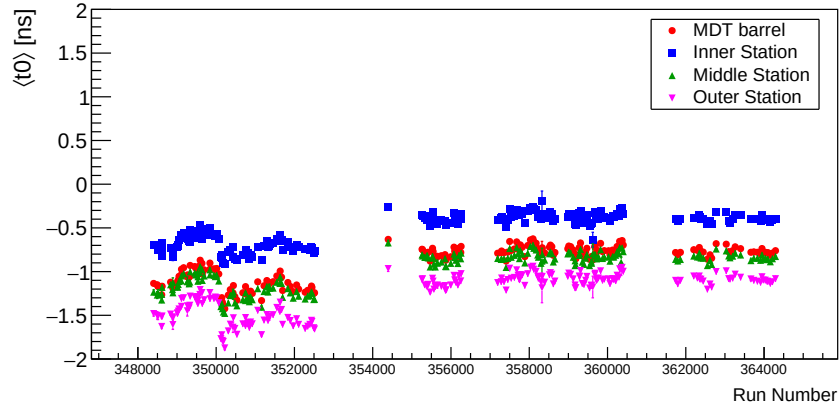
Figure 7.9a shows the mean values of t_0 , $\langle t_0 \rangle$, for the Inner, Middle and Outer stations, and for the whole barrel as a function of the run number for each run in the calibration dataset corresponding to 2018 year of data-taking. The times $\langle t_0 \rangle$ experience a per-run shift, which is independent of the MDT station. The corresponding time variation is of order $\mathcal{O}(1)$ ns. After applying the station-independent per-run correction, the distribution becomes more uniform, as shown in Figure 7.9b; the corresponding timing variation is reduced to $\mathcal{O}(0.1)$ ns. Such behaviour confirms the presence of the Run-dependent timing fluctuations in the MDT barrel, as a whole system. The distributions for the other years of in the calibration dataset are provided in Appendix B.

7.3.2 Calibration Procedure

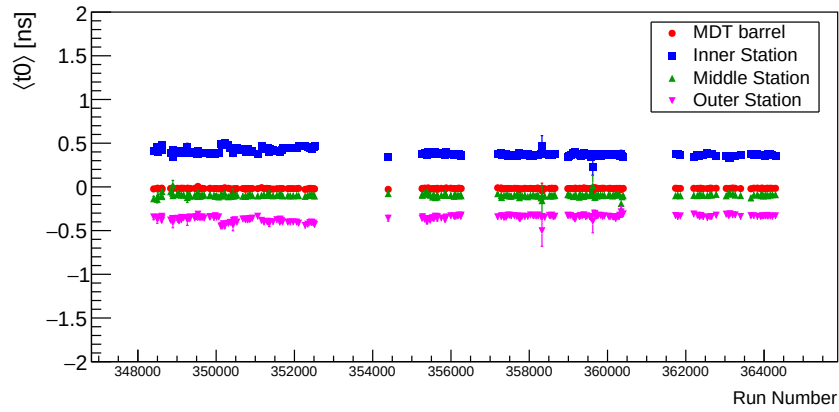
The MDT time-of-flight calibration procedure is performed for each year of the data-taking individually and consists of several steps, described below.

1. Raw t_0 values are computed for each MDT tube the L calculated with respect to the PV, as in Eq. (7.5).
2. After that, per-run correction factors $t_{0\text{Run}}^{\text{corr}} \equiv \langle t_0 \rangle_{\text{Run}}$ are derived for each run.
3. The t_0 values, corrected with run-dependent shifts, are written as histograms for each MDT tube:

$$t_0 = t'_0 - t_{0\text{Run}}^{\text{corr}}, \quad (7.6)$$

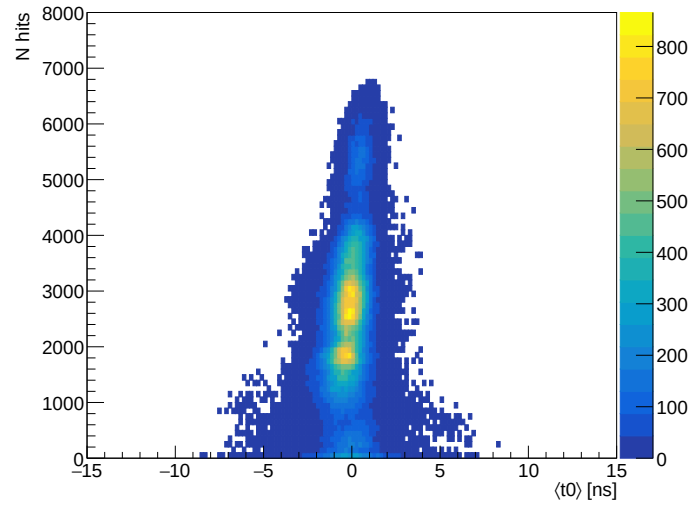


(a)

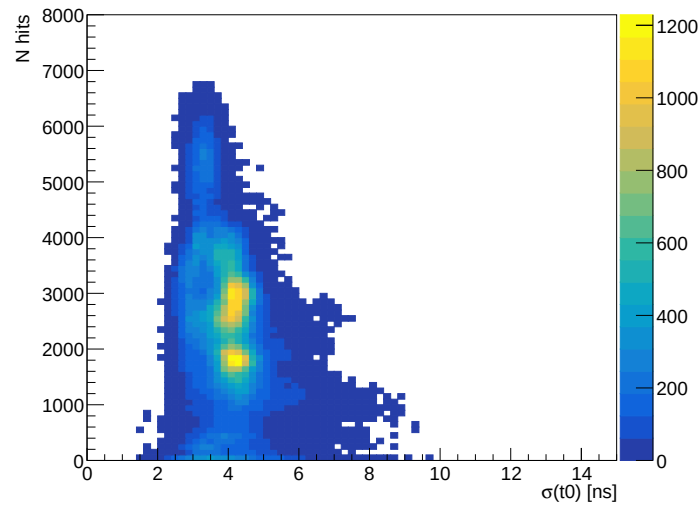


(b)

Figure 7.9: The average values t_0 per run for 2018 data: (a) before and (b) after the per-run timing correction. The values are averaged for the MDT tubes located in: the whole MDT barrel (in red), Inner Station of the MDT barrel (in blue), Middle Station of the MDT barrel (in green), and the Outer Station of the MDT barrel (in magenta).



(a)



(b)

Figure 7.10: Number of hits per MDT tube versus (a) $\langle t_0 \rangle$ and (b) RMS, $\sigma(t_0)$ of the t_0 distribution.

where t'_0 is a value before per-Run correction.

4. The tube-level correction factor $t_{0\text{ tube}}^{\text{corr}}$ and the error on it, $\sigma_{\text{tube}}^{\text{corr}}$ derived as the mean and the RMS of the t_0 distribution of the corresponding MDT tube, respectively.

Such approach showed itself as more stable comparing to a Gaussian fit for a large fraction of the tubes, due to the observed asymmetric behaviour of t_0 distributions (as demonstrated in Figure 7.6).

5. After all correction factors are derived, the corrected value of the $t_{0,\text{corrected}}$ and its error $\sigma(t_{0,\text{corrected}})$ can be obtained as it follows

$$t_{0,\text{corrected}} = t_{0,\text{raw}} - t_{0\text{Run}}^{\text{corr}} - t_{0\text{tube}}^{\text{corr}}; \quad \sigma(t_{0,\text{corrected}}) = \sigma_{\text{tube}}^{\text{corr}}, \quad (7.7)$$

where $t_{0,\text{raw}}$ is a raw value of t_0 , obtained using Eq. (7.5). The final value $t_{0,\text{corrected}}$ is then used to recompute the corrected particle speed β .

7.3.3 Particle Speed Computation

After the MDT tubes have been assigned the calibration constants, it is possible to compute the corrected value of the speed β for each Slow Muon object.

β can be computed as a weighted average of the β_i values associated with each hit in the MDT tube i :

$$\beta^{-1} = \frac{\sum_i^N \frac{\beta_i^{-1}}{\sigma^2(\beta_i^{-1})}}{\sum_i \frac{1}{\sigma^2(\beta_i^{-1})}}. \quad (7.8)$$

β_i and its uncertainty can be computed as follows:

$$\beta_i = \frac{1}{1 + \frac{ct_{0,i}}{L_i}}; \quad \sigma(\beta_i^{-1}) = cL_i^{-1}\sigma(t_{0,i}), \quad (7.9)$$

where L_i is the distance from the PV to the MDT tube, and $t_{0,i}$ is the corresponding t_0 value associated with this tube, corrected according to the procedure described above.

Using the values of the errors for the individual tubes from Eq. (7.9), it is possible to estimate the error on the β of the track obtained in Eq. (7.8):

$$\sigma(\beta^{-1}) = \left(\sum_i \frac{1}{\sigma_i^2(\beta_i^{-1})} \right)^{-1/2}, \quad (7.10)$$

$$\sigma(\beta) = \beta^2 \sigma(\beta^{-1}). \quad (7.11)$$

The χ^2 corresponding to such a method of β^{-1} evaluation can be computed as follows:

$$\chi^2 = \sum_i^N \frac{(\beta^{-1} - \beta_i^{-1})^2}{\sigma^2(\beta_i^{-1})}, \quad \nu = N - 1, \quad (7.12)$$

where N is the number of MDT tubes used in the computation, and ν is the corresponding number of degrees of freedom. Examples of the distributions of $\sigma(\beta)$ and χ^2/ν for the probe muons from the data 2018 sample are shown in Figure 7.11. The distributions of β for the muons selected to be from the $Z \rightarrow \mu\mu$

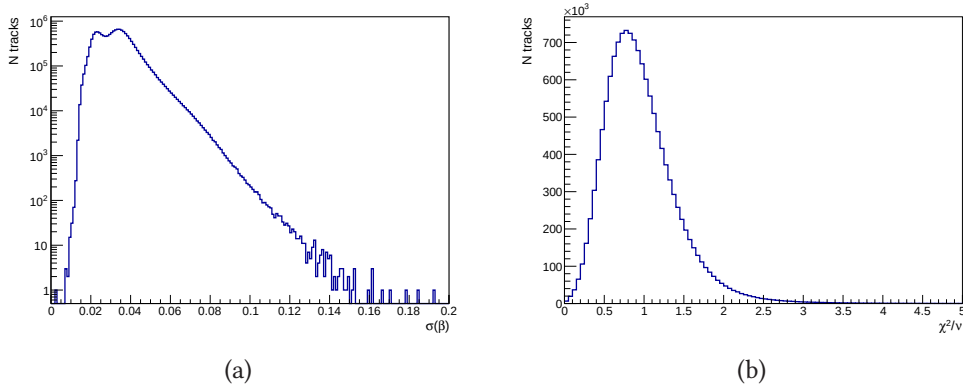


Figure 7.11: Parameters characterising the quality of the calibrated β measurement for a Slow Muon object: (a) error $\sigma(\beta)$ of the β measurement; (b) χ^2/ν of the β^{-1} computation. Slow Muon object is required to be matched to the muon passing Z tag-and-probe selections. Plots correspond to the data 2018 calibration sample.

decay, before and after calibration for data 2018, are shown in Figure 7.12. The muon tracks for which β is computed fall within the barrel region of the MDT. The distributions for the other years in the calibration dataset are provided in Appendix B.

The uncalibrated β distribution (in blue) is shifted from 1. The effect of the calibration (in red) is the centring of the β distribution at 1 and the reduction of its width (improving the resolution). The β resolution after calibration corresponds to 4.4%.

The parameters $\sigma(\beta)$ and χ^2/ν , obtained during the computation of the calibrated value of β using Eq. (7.11) and Eq. (7.12), respectively, can be used to reject β measurements with poor quality that populate the tails of the β distribution. As an example, the following selection was applied:

- $\sigma(\beta)/\beta < 0.5$;
- $\chi^2/\nu < 2$.

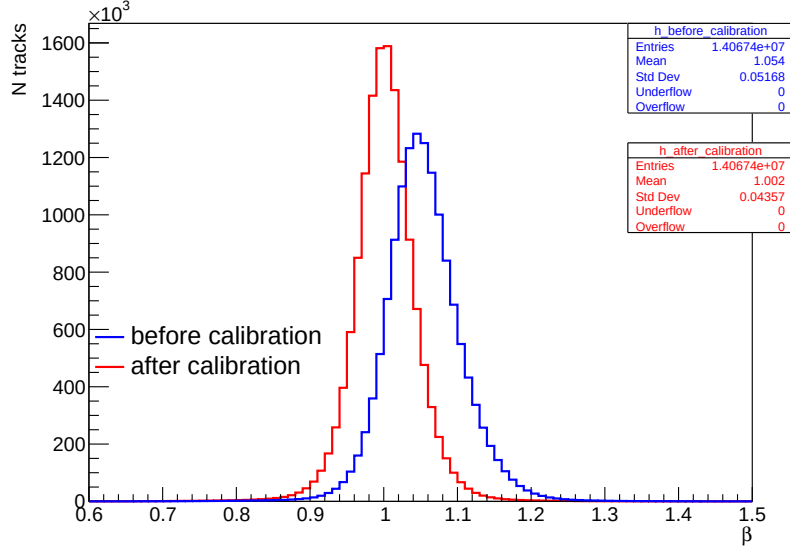


Figure 7.12: β distribution before (in blue) and after MDT ToF calibration (in red) for muons passing Z tag-and-probe selection, data 2018.

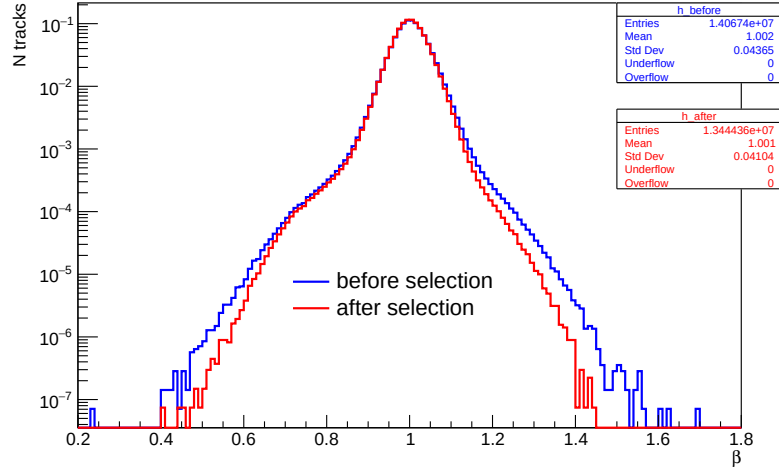
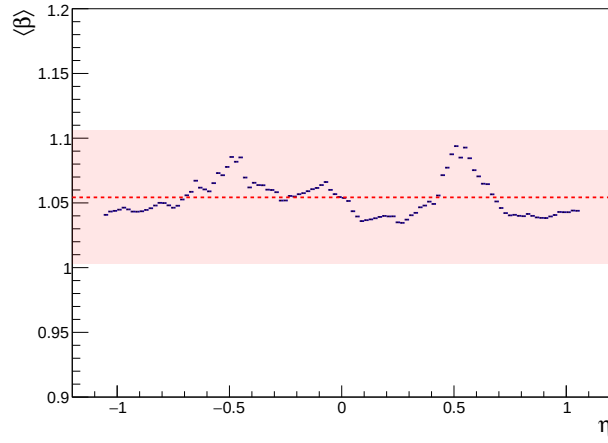
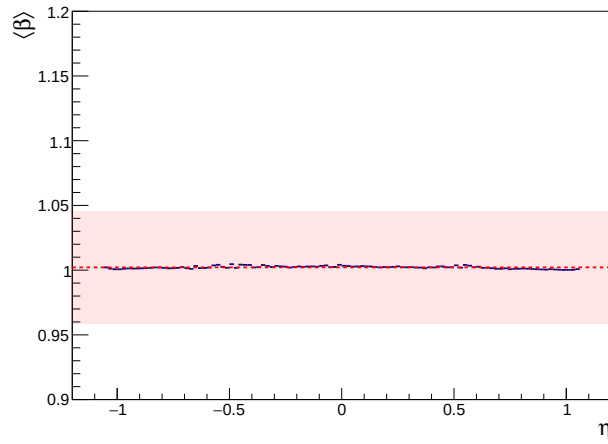


Figure 7.13: Calibrated β distributions for muons passing Z tag-and-probe selection before (in blue) and after (in red) the β quality selection, data 2018.

The normalised probe muon β distributions before and after the selection are shown in Figure 7.13. Per-tube MDT ToF calibration reduces the correlation between β and η of the track. The effect is shown in Figure 7.14, showing distributions of $\langle\beta\rangle$ versus η before (Figure 7.14a) and after (Figure 7.14b) calibration.



(a)



(b)

Figure 7.14: Distributions of $\langle\beta\rangle$ versus η : (a) before and (b) after MDT ToF calibration. The red dashed line corresponds to the mean of the distribution from Figure 7.12, and the red band corresponds to the width of that distribution. The β is averaged over all the tracks falling in the corresponding η bin.

Chapter Summary

This chapter has described the calibration procedures relevant to the observables used in the search for heavy, charged long-lived particles. The discussion of the Pixel dE/dx corrections and the principles of the MDT time-of-flight (ToF) measurement provides the necessary experimental context for the calibration work performed in this analysis.

The main part of the chapter presented the calibration of the MDT ToF measurement, which constitutes an original contribution of this work. The procedure is based on a $Z \rightarrow \mu\mu$ tag-and-probe technique with muons reconstructed by the Slow Muon algorithm. A set of quality selections for the probe muons was defined to ensure reliable hit timing in both MDT and RPC detectors.

Several corrections were developed to improve the timing precision, including a PV-position-aware computation of the distance to the MDT tube and a per-run correction to account for LHC clock shift. A per-tube calibration method was then established to determine the individual t_0 offsets and associated uncertainties for all MDT tubes. The calibrated constants were used to recompute the particle speed β for Slow Muon tracks.

The results of the calibration are presented in this chapter and in Appendix B. The calibration leads to a significant improvement in the timing performance: the β distribution for muons from $Z \rightarrow \mu\mu$ events is centred at 1 with a resolution of about $4.3 - 4.7\%$ over the different years of the data-taking before β -quality selections; the residual correlation between β and η is removed. These developments comprise the calibration framework design, the tag-and-probe method, the quality selections, the PV and per-run timing corrections, and the per-tube calibration procedure. They represent the main original contributions of this work and provide the basis for the use of MDT ToF information in the combined LLP analysis.

Chapter 8

Search for Slow Charged LLPs

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Several BSM models predict heavy charged particles with lifetimes long enough to be considered detector-stable. These models are described in detail in Chapter 1.

This chapter describes the analysis strategy for the search for heavy charged LLPs with anomalously high ionisation in the Pixel detector and time-of-flight (ToF) to the Muon Spectrometer at the ATLAS experiment.

The analysis aims to combine track mass measurements provided by the Pixel detector, TileCal, and the MDT. The analysis strategy is described in Section 8.1. This analysis extends previous Run 2 searches for highly ionising LLPs using anomalous ionisation in the ATLAS Pixel detector only [72] and anomalous ionisation in the ATLAS Pixel detector and large time-of-flight to the ATLAS Tile calorimeter [73]. An overview of the LLP searches, including the discussion of these analyses, is given in Chapter 2.

The full analysis dataset consists of the full Run 2 and partial Run 3 pp collision data, resulting in a total of 309 fb^{-1} (140 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ and 169 fb^{-1} at $\sqrt{s} = 13.6 \text{ TeV}$). The design of the analysis channels and the sensitivity estimates were carried out using a partial Run 2 dataset corresponding to the 2018 data-taking period, resulting in 60 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$.

The main contributions of the author are: the development of the analysis strategy for the MDT ToF combinations in the combined analysis using Run 2 and partial Run 3 data, the design of the muon trigger channel and the corresponding selections, signal sensitivity studies using the 2018 dataset, and the proposal of the background estimation strategy for the muon trigger channel and combinations with MDT ToF.

8.1 Analysis Strategy

The search targets potential BSM slow heavy charged detector-stable particles produced in pp collisions at the LHC.

A hypothetical heavy, charged, long-lived particle (LLP) would interact with the detector and travel significantly slower than the speed of light. A large energy deposition in the Pixel detector and a delayed signal in the outer layers of the ATLAS detector providing timing information (such as the TileCal or the Muon Spectrometer) are expected. The search aims to exploit these features by combining independent measurements from different ATLAS sub-detectors. The particle mass $m = p/(\beta\gamma)$ can be computed independently for the Pixel, TileCal, and Muon Spectrometer, providing β (or $\beta\gamma$) measurements for the same track and combined afterwards. The momentum p measurement is provided by the ATLAS Inner Detector. The number of possible mass measurement combinations for the same track can vary depending on the lifetime of the hypothetical LLP. For example, for a particle moving with $\beta = 0.8$, the ToF to the MS is of the order of $\gtrsim 20 \text{ ns}$. Thus, it sets a scale on the lifetime required for the MS ToF combination with the Pixel measurements. When a charged particle has a lifetime

long enough to reach the barrel of the ATLAS Muon Spectrometer, it can be reconstructed with very high efficiency by the Slow Muon algorithm, as demonstrated in Chapter 6. In general, the search is model-agnostic and depends only on the kinematic properties of the signal particle. However, a set of benchmark models was considered for the analysis optimisation: stau (sleptons predicted by the simplified GMSB model), charginos (produced under predictions of the AMSB model), and hadronised gluinos in the form of R-hadrons (split-SUSY model). Representative production diagrams are shown in Figure 8.1. Particles with masses above 200 GeV and lifetimes down to 10 ns are considered in the full analysis. The maximum lifetime considered for the stau is 3000 ns. Later in this chapter, such signals are referred to as ‘stable’, since particles with these lifetimes decay almost entirely outside the ATLAS detector, making them effectively indistinguishable from particles with infinite lifetimes.

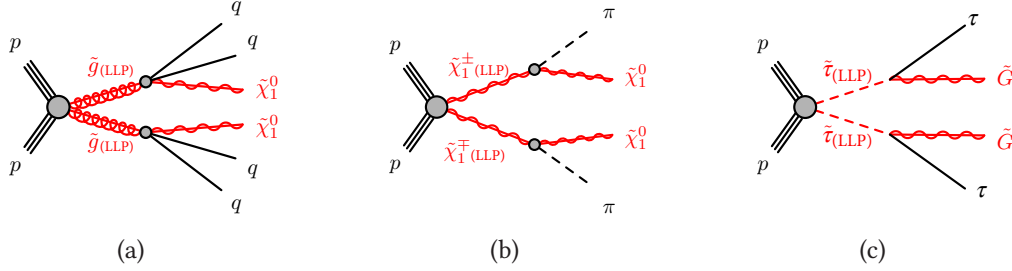


Figure 8.1: Representative production diagrams for (a) pair-produced gluinos which form R-hadrons decaying into neutralinos, (b) pair-produced charginos decaying into neutralinos, and (c) pair-produced staus decaying into gravitinos.

The following track measurements are considered in the full analysis:

- Ionisation losses (dE/dx) in the Pixel detector. The $\beta\gamma$ value is derived from the $\langle dE/dx \rangle_{\text{trunc}}$ on track (Section 7.1).
- Timing information from the TileCal calorimeter. The β_{ToF} corresponding to this measurement is computed as a weighted average from the timing measurements on track, as described in Ref. [73].
- Timing information from the MDT. The MDT ToF calibration and the following β_{ToF} computation are described in Chapter 7.
- Ionisation losses (dE/dx) in the MDT. The corresponding $\beta\gamma$ value has to be extracted using the MDT dE/dx estimator. The previous version of such an estimator was used in the ATLAS search for multi-charged particles [192].

In the previous study [73], the MDT measurements were not present.

To develop the selections, optimise the analysis channels, and study the signal sensitivity for the combination including MDT ToF information, a dedicated study was performed. This study considers only the track ionisation losses (dE/dx) in the Pixel detector and the track speed reconstructed as Slow Muon β_{ToF} as observables. This is done to avoid interference with effects related to the TileCal ToF and MDT dE/dx measurements and to focus on the MDT ToF combination with the Pixel measurement. This study is referred to further as the ‘analysis design’. The full analysis will combine measurements from the full Run 2 pp collisions at $\sqrt{s} = 13$ TeV dataset and partial (2022–2024 years of data-taking) Run 3 pp collision data at $\sqrt{s} = 13.6$ TeV dataset. To be able to use the Pixel cluster-level and the MDT tube-level information, dedicated reconstruction and access to specific variables are required. Due to software limitations, as the existing ATLAS datasets do not contain events with Pixel cluster-level information and the software version providing the full performance of the Slow Muon reconstruction, data reprocessing is required.

The analysis design was carried out using the partial Run 2 dataset corresponding to the 2018 data-taking period, resulting in 60 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV. Within the scope of the analysis design, no data reprocessing was required. The calibration of the dE/dx measurement was performed as a part of the previous study [73]. The performance of the Slow Muon reconstruction in this dataset represents the optimal benchmark level.

To reduce the background level and enhance the signal sensitivity, a set of selections was applied to the datasets. The selections include event- and track-level data-quality requirements, together with criteria targeting signature-based background rejection. Explicitly, the requirements are described in Section 8.3. Two mutually exclusive analysis channels are considered in the search with the MDT ToF track measurement. The channels represent two different event signatures possible in the events with charged LLPs reaching the Muon Spectrometer.

The first signature has been considered in the previous full Run 2 searches [72, 73] and is characterised by a large value of the transverse missing momentum in the event. The events in this channel are required to pass the $E_{\text{T}}^{\text{miss}}$ trigger [193] selection. The $E_{\text{T}}^{\text{miss}}$ trigger selects the events based on energy deposited throughout the calorimeter and does not take into account soft tracks not reaching the calorimeter and muons (or muon-like objects) escaping from the calorimeter to the MS. The events where one of two produced charged LLPs is reconstructed or decays early with detector-invisible products belong to this channel, which is referred to as the ‘MET trigger channel’. Events with mismeasured track momenta contribute to this channel as well.

The second channel was introduced in the analysis design phase. It exploits the fact that the track reaches the MS and is reconstructed as a Slow Muon. Thus,

it has a muon-like signature and, as a result, may fire the muon trigger [194]. Only the events that do not pass the E_T^{miss} trigger selection are accepted in this channel, referred to as the ‘muon trigger channel’.

The design of the data selections allows the use of standard ATLAS datasets and variables to select the events relevant for the search. Using the Event picking method (Chapter 5), the events in the RAW format over all required years of data-taking can be selected into a relatively small dataset and then reprocessed with a required software version, including fixed Slow Muon reconstruction (Chapter 6), which allows the precise tracking of slow muon-like particles in the MS and gives access to the hit-level information in the MS. In addition to that, reprocessed data contain track information at the level of pixel clusters, which allows precise calibration and correction of the track ionisation losses in the Pixel detector (Section 7.1).

In this analysis, the background is dominated by fluctuations arising from detector effects and imperfections in the reconstruction algorithms. This type of background is treated using fully data-driven techniques. The full analysis background estimation strategy is based on the method of kinematic templates. The probability of obtaining an accidentally large dE/dx or an accidentally low β_{ToF} is estimated using control samples, while the kinematic properties of the background events after signal selection (i.e. the distribution of tracks in (p_T, η) space) and the dE/dx or β_{ToF} probabilities are orthogonalised. The technique is described with a higher level of detail in Section 8.7. The background number of events used in the sensitivity study (Section 8.5) was estimated with more simplified data-driven methods.

8.2 Signal Characterisation

In order to define the strategy for the analysis, including the set of selections, the main features of the BSM signal representing a charged heavy long-lived particle have been studied. This section presents the comparison of the MC for the signal and the data for the background taken before any selections described in Section 8.3.

MC samples are shown for the model of pair-produced staus with lifetime $\tau = 3000$ ns and masses 200, 400, and 700 GeV. The background is represented by the partial Run 2 dataset corresponding to the 2018 data-taking period, resulting in 60 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV.

Figure 8.2 demonstrates the comparison of the signal and the background for the main observables used in the search: β (Figure 8.2a) and dE/dx (Figure 8.2b). The value of β is taken before calibration, while the dE/dx is calibrated. The figure confirms that the search can use the signature of a slow, highly ionising

particle: the signal tends to populate low values of β and higher values of dE/dx . With the increase of the signal mass, the measured value of β becomes lower. The signal populates the β range $0.4 < \beta < 1.05$, while the background distribution is mostly located within $0.85 < \beta < 1.2$. A significant difference in the ionisation of the signal and the background appears at $dE/dx > 1.5 \text{ MeV g}^{-1}\text{cm}^2$.

Figure 8.3 shows a selected set of the kinematic distributions: the distribution of missing transverse energy in the event E_T^{miss} , the leading track transverse momentum p_T distribution, the pseudorapidity distribution, and the relative track isolation distribution. The track distributions are shown only for the objects with Slow Muon information associated with them. The kinematic distributions demonstrate that the signal has the signature of a high- p_T isolated track (Figures 8.3b and 8.3d). In a significant fraction of the signal events, the value of E_T^{miss} is high (Figure 8.3a). The value of the E_T^{miss} in the event becomes more probable with the increase of the signal mass. For the 200 GeV stau, the E_T^{miss} distribution behaves similarly to the background one. The pseudorapidity distribution (Figure 8.3c) demonstrates that a large fraction of the reconstructed signal is reconstructed in the barrel region of the ATLAS MS ($|\eta| < 1.05$).

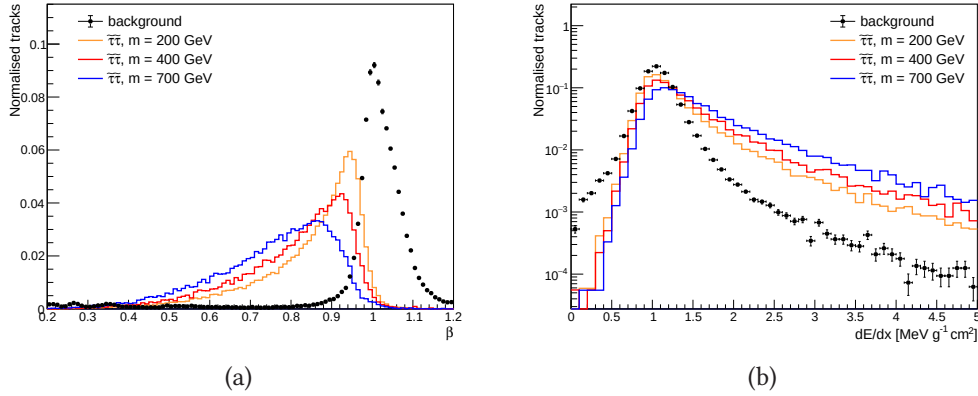


Figure 8.2: Distributions of the main observables: (a) particle speed β (uncalibrated); (b) track ionisation dE/dx (calibrated). Signal is represented by stable stau with mass $m = 200 \text{ GeV}$ (in orange), $m = 400 \text{ GeV}$ (in red), $m = 700 \text{ GeV}$ (in blue). Background is shown in black. The distributions are shown normalised.

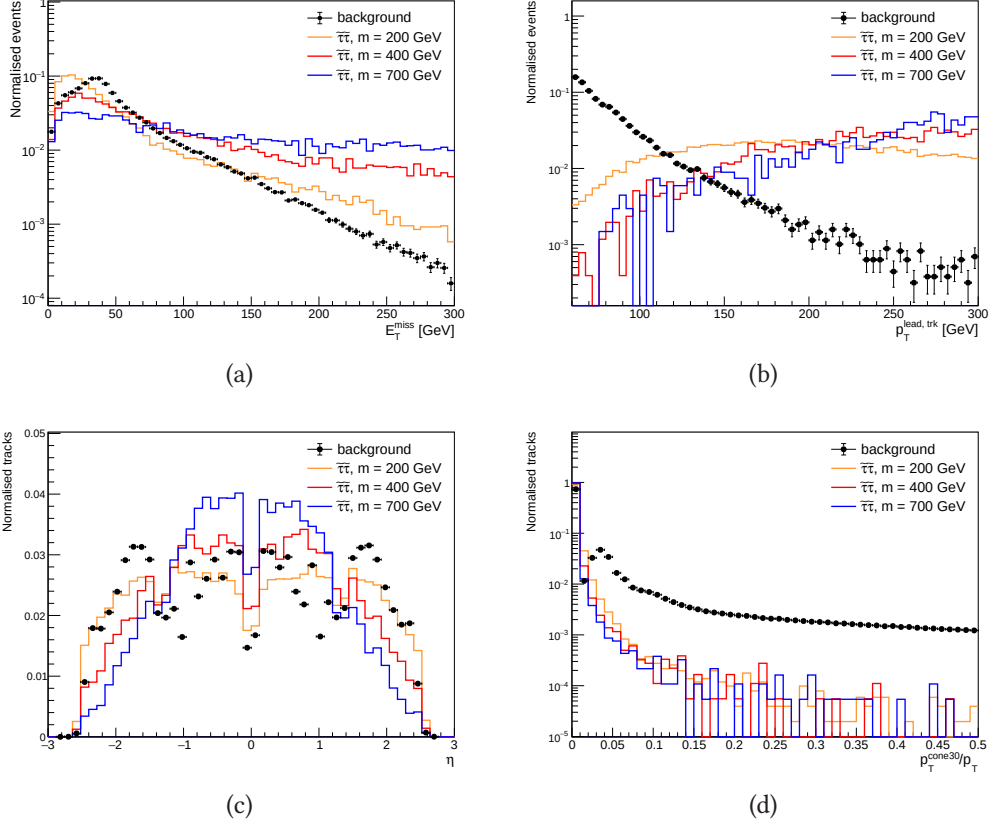


Figure 8.3: Distributions of kinematic properties for the signal and background: (a) transverse missing energy E_T^{miss} in the event; (b) transverse momentum p_T of the leading track associated with Slow Muon object; (c) pseudorapidity η distribution for the tracks associated with Slow Muon object; (d) relative track isolation p_T^{cone30}/p_T . Signal is represented by stable stau with mass $m = 200$ GeV (in orange), $m = 400$ GeV (in red), $m = 700$ GeV (in blue). Background is shown in black. The distributions are shown normalised.

8.3 Selections

A set of requirements to extract the signal from the Standard Model background has been identified by comparing signal events (stau $\tilde{\tau}$ pair production, $m_{\tilde{\tau}} = 400$ GeV, $\tau_{\tilde{\tau}} = 3000$ ns) to a small fraction of Run 2 data (60 fb^{-1} from the 2018 data-taking). The signal is characterised by charged pair-produced staus $\tilde{\tau}^{\pm}$, which decay into a tau lepton $\tau^{\pm}$ and a nearly massless neutral gravitino $\tilde{G}$.

Selections are implemented as a series of consecutive requirements, defined first at the event level and then at the track level.

After event-level selections are applied, events are filtered further using track-level selections. To pass the selection, an event must contain at least one track that satisfies the full list of conditions.

To obtain the datasets with the required dedicated reconstruction version, the selective event reprocessing is needed. Using event picking procedure, described in Chapter 5, the events in RAW format are collected in the datasets for the reprocessing. The number of the picked events must not exceed a few million events. At the same time, the final list of events must contain all the events needed to construct the analysis regions for both analysis channels. In order to provide the list of events for the event picking, the set of selections based on the standard ATLAS variables has been developed. The detailed description of these selections is given below.

8.3.1 Data Quality Selections

Data quality selections for the event picking are fully inherited from the previous stage of this analysis [73].

GRL. During GRL selection only events belonging to runs and lumi-blocks listed in GRL (a more detailed description of GRL is given in Section 5.2) are chosen to ensure that only high-quality data are used in analyses.

Event cleaning. All events are required to pass standard event cleaning requirements, which prevent detector issues from contaminating physics measurements. Only the events without an error state flag in the subdetectors are chosen. In addition to that, potentially incomplete events are filtered out at this stage.

Jet cleaning. The aim of the “jet cleaning” selection is to remove non-collision background events and events with spurious calorimeter signals which would affect the calculation of E_T^{miss} [73].

8.3.2 Trigger Requirements

Events of interest can be classified at the event level based on their signature into two orthogonal analysis channels: the MET trigger channel and the muon trigger channel. If the MET trigger is fired, the event belongs to the MET trigger channel. In case the MET trigger is not fired, but the muon trigger is passed, the event is sorted into the muon trigger channel.

The MET trigger is designed such that it does not include muon momentum in the E_T^{miss} calculation. Thus, it is agnostic to the fact that a particle decayed into other particles (including semi-invisible components) in the MS or not. However, as the particle lifetime decreases, a larger fraction of particles decay before reaching the MS, firing the MET trigger in the case of invisible decay components.

For pair-produced LLPs, such as the stau, the trigger signature depends on their lifetime.

MET Trigger Channel

Table 8.1: MET HLT trigger list

data period	trigger
Run 2	HLT_noalg_L1J400
	HLT_xe70
	HLT_xe70_mht
	HLT_xe90_mht_L1XE50
	HLT_xe110_mht_L1XE50
	HLT_xe90_pufit_L1XE50
	HLT_xe110_pufit_L1XE55
	HLT_xe110_pufit_L1XE50
	HLT_xe100_pufit_L1XE50
	HLT_xe100_pufit_L1XE55
	HLT_xe110_pufit_xe70_L1XE50
	HLT_xe120_pufit_L1XE50
	HLT_xe110_pufit_xe65_L1XE50
	HLT_xe55_cell_xe70_tcpufit_xe90_psum_vssk_L1XE50
Run 3	HLT_xe55_cell_xe70_tcpufit_xe95_psum_cssk_L1XE50
	HLT_xe60_cell_xe95_psum_cssk_L1XE50
	HLT_xe65_cell_xe100_mhtpufit_pf_L1XE50
	HLT_xe65_cell_xe105_mhtpufit_em_L1XE50
	HLT_xe65_cell_xe95_psum_vssk_L1XE50
	HLT_xe75_cell_xe65_tcpufit_xe90_trkmht_L1XE50
	HLT_xe55_cell_xe70_tcpufit_L1XE50
	HLT_xe65_cell_xe90_pfopufit_L1XE50
	HLT_xe80_cell_xe115_tcpufit_L1XE50
	HLT_xe65_cell_xe105_nn_L1XE50
	HLT_xe65_cell_xe105_nn_L1jXE100
	HLT_xe65_cell_xe90_pfopufit_L1jXE100
	HLT_xe80_cell_xe115_tcpufit_L1jXE100

MET Trigger. In order to be selected to the MET trigger channel, the event has to pass one of the unrescaled lowest MET HLT triggers from Table 8.1.

Muon Trigger Channel

Muon trigger. In order to be selected to the muon trigger channel, the event firstly has to pass one of the muon HLT triggers listed in Table 8.2. In addition to that, the event is not allowed to fire any of the lowest-unprescaled MET triggers from Table 8.1.

Low $E_T^{\text{miss, calo}}$ requirement. Only the events with a low value of the calorimeter MET term ($E_T^{\text{miss, calo}} < 100$ GeV) are selected. A detailed discussion of the selection is provided in Section 8.5.1.

Table 8.2: Muon HLT trigger list

data period	trigger
Run 2	HLT_mu40
	HLT_mu50
Run 3	HLT_mu60_L1MU14FCH
	HLT_mu60_L1MU14FCH

8.3.3 Common Track-level Selections

Association to primary vertex. The candidate tracks are required to be associated with the primary vertex.

ID track quality requirements. The ID track must satisfy a set of requirements that ensure its reconstruction quality:

1. dE/dx Used Hits: the candidate track needs to have at least 2 pixel clusters, after discarding the cluster with the highest ionisation, to perform dE/dx calculation.
2. IBL/B-Layer Hits: the candidate track needs to have a cluster in the IBL (if this is expected), or a cluster in the next-to-innermost pixel layer (if this is expected while a cluster is not expected in the IBL).
3. Shared/Split Hits: the track cannot have any shared pixel hits or split pixel hits.
4. SCT Hits: the number of hits in the SCT has to be more than 5.
5. Track momentum uncertainty requirement: the relative uncertainty of the inverse of the charge-signed track momentum, $\sigma_p \equiv |\delta(p^{-1})/(p^{-1})|$, needs to satisfy the following requirement:

$$\sigma_p < \max \left(10\%, \left(-1\% + 90\% \times \frac{|p|}{\text{TeV}} \right) \right) \text{ and } \sigma_p < 200\%. \quad (8.1)$$

Track isolation. The track has to satisfy an isolation criterion: $\sum p_T^{trk} < 5 \text{ GeV}$ inside cone $\Delta R < 0.3$, excluding the track itself.

Track vetoes. Tracks associated with electrons and SM hadrons are removed using the electron and hadron vetoes, respectively, as in Ref [72].

Track momentum magnitude. Only high-momentum tracks are accepted. For both the muon and MET trigger channels, tracks with $p_T > 120 \text{ GeV}$ are selected.

Track pseudorapidity range. For further analysis using MS information, only the tracks with $|\eta| < 1.05$ (MS barrel acceptance region) are selected. However, at the event picking stage, the track pseudorapidity selection for the MET trigger channel is wider ($|\eta| < 1.6$) due to the needs of other analysis streams beyond the scope covered by this thesis. For this channel, the $|\eta| < 1.05$ selection is applied after event picking and data reprocessing.

m_T requirement (MET trigger channel specific). Tracks are required to satisfy a condition on their transverse mass $m_T(\vec{p}_{trk}, \vec{p}_T^{\text{miss}}) > 130 \text{ GeV}$, where m_T is defined as:

$$m_T(\vec{p}_{trk}, \vec{p}_T^{\text{miss}}) \equiv \sqrt{2p_T^{trk} E_T^{\text{miss}} (1 - \cos \Delta\phi(\vec{p}_T, \vec{p}_{trk}))} \quad (8.2)$$

This selection is designed to reject tracks from $W^\pm \rightarrow l^\pm \nu$ events in the region where the MET trigger is fired.

8.3.4 Event Picking Selections Summary

Tables 8.3 and 8.4 give the summary of the requirements applied consecutively and the number of events left after each cut. Signal yields for stable stau with masses 200, 400 and 700 GeV for Run 2 selections for the analysis channels are presented in Table 8.5.

Table 8.3: Muon trigger channel selections: Run 2 (a) and partial Run 3 (b).

(a) Run 2 (140 fb ⁻¹)			(b) Partial Run 3 (166.9 fb ⁻¹)		
Cut	N(Events)	Eff.	Cut	N(Events)	Eff.
Total	5.90053e+09	1	Total	5.67118e+09	1
GRL	5.63085e+09	0.9543	GRL	5.2426e+09	0.92443
Event Cleaning	5.62653e+09	0.95356	Event Cleaning	5.2368e+09	0.92341
Jet Cleaning	5.57855e+09	0.94543	Jet Cleaning	5.00131e+09	0.88188
Trigger	3.59496e+08	0.06093	Trigger	1.98242e+08	0.03496
$E_T^{\text{miss, calo}} < 100$ GeV	3.31769e+08	0.05623	$E_T^{\text{miss, calo}} < 100$ GeV	1.76595e+08	0.03114
Track in PV	3.31667e+08	0.05621	Track in PV	1.76579e+08	0.03114
$p_T > 50$ GeV	1.93631e+08	0.03282	$p_T > 50$ GeV	1.40752e+08	0.02482
dE/dx Used Hits	1.79436e+08	0.03041	dE/dx Used Hits	1.29436e+08	0.02282
IBL/B-Layer Hits	1.77061e+08	0.03001	IBL/B-Layer Hits	1.27229e+08	0.02243
Shared/Split Hits	1.68395e+08	0.02854	Shared/Split Hits	1.20126e+08	0.02118
SCT Hits	1.65172e+08	0.02799	SCT Hits	1.17659e+08	0.02075
Track Isolation	1.01688e+08	0.01723	Track Isolation	7.39011e+07	0.01303
$p_T > 120$ GeV	1.035e+06	0.00018	$p_T > 120$ GeV	543661	0.0001
Track p uncertainty	957241	0.00016	Track p uncertainty	536229	9e-05
Central track	673873	0.00011	Central track	387353	7e-05
Electron veto	670397	0.00011	Electron veto	386358	7e-05
Hadron veto	657865	0.00011	Hadron veto	382820	7e-05
$ \eta < 1.05$	309411	5e-05	$ \eta < 1.05$	205248	4e-05

Table 8.4: MET trigger channel selections: Run 2 (a) and partial Run 3 (b).

(a) Run 2 (140 fb ⁻¹)			(b) Partial Run 3 (166.9 fb ⁻¹)		
Cut	N(Events)	Eff.	Cut	N(Events)	Eff.
Total	5.90053e+09	1	Total	5.67118e+09	1
GRL	5.63085e+09	0.9543	GRL	5.2426e+09	0.92443
Trigger	5.93886e+08	0.10065	Trigger	3.1563e+08	0.05566
Track in PV	5.92258e+08	0.10037	Track in PV	3.15411e+08	0.05562
$p_T > 50$ GeV	1.0931e+08	0.01853	$p_T > 50$ GeV	9.27748e+07	0.01636
Loose track Isolation	4.10144e+07	0.00695	Loose track Isolation	3.47824e+07	0.00613
Event Cleaning	4.09535e+07	0.00694	Event Cleaning	3.47165e+07	0.00612
Jet Cleaning	4.05119e+07	0.00687	Jet Cleaning	3.31105e+07	0.00584
dE/dx Used Hits	3.36317e+07	0.0057	dE/dx Used Hits	2.67459e+07	0.00472
IBL/B-Layer Hits	3.30129e+07	0.00559	IBL/B-Layer Hits	2.61257e+07	0.00461
Shared/Split Hits	3.10705e+07	0.00527	Shared/Split Hits	2.43143e+07	0.00429
SCT Hits	2.98489e+07	0.00506	SCT Hits	2.32638e+07	0.0041
Track Isolation	1.69835e+07	0.00288	Track Isolation	1.44459e+07	0.00255
$p_T > 120$ GeV	5.00071e+06	0.00085	$p_T > 120$ GeV	4.4357e+06	0.00078
Track p uncertainty	4.96932e+06	0.00084	Track p uncertainty	4.38416e+06	0.00077
Central track	3.61966e+06	0.00061	Central track	3.20635e+06	0.00057
$m_T > 130$ GeV	707899	0.00012	$m_T > 130$ GeV	642904	0.00011
Electron veto	586708	0.0001	Electron veto	520682	9e-05
Hadron veto	534836	9e-05	Hadron veto	497544	9e-05

Table 8.5: Signal yield estimates after selections for: (a) MET trigger channel and (b) muon trigger channel. Signal is represented by the pair produced stable stau. Luminosity used in corresponds to full Run 2 (140 fb^{-1}). The signal cross-section used in the reweighting corresponds to $\sqrt{s} = 13 \text{ TeV}$.

(a) MET trigger channel

Cut	Stau 200 GeV		Stau 400 GeV		Stau 700 GeV	
	N(Events)	Eff.	N(Events)	Eff.	N(Events)	Eff.
Total	4243.4	1.000	260.3	1.000	17.3	1.000
GRL	4243.4	1.000	260.3	1.000	17.3	1.000
Event Cleaning	4243.4	1.000	260.3	1.000	17.3	1.000
Jet Cleaning	4197.7	0.989	257.7	0.990	17.1	0.989
MET Trigger	538.3	0.127	38.1	0.146	3.3	0.193
Vertex nTrack	538.3	0.127	38.1	0.146	3.3	0.193
Track in PV	536.6	0.126	38.0	0.146	3.3	0.193
$p_T > 50 \text{ GeV}$	527.9	0.124	37.9	0.146	3.3	0.193
dE/dx Used Hits	521.8	0.123	37.6	0.145	3.3	0.192
IBL/B-Layer Hits	521.1	0.123	37.6	0.144	3.3	0.192
Shared/Split Hits	520.2	0.123	37.5	0.144	3.3	0.191
SCT Hits	518.1	0.122	37.5	0.144	3.3	0.191
Track Isolation	513.3	0.121	37.3	0.143	3.3	0.189
$p_T > 120 \text{ GeV}$	492.0	0.116	37.0	0.142	3.3	0.188
Track p uncertainty	491.5	0.116	36.9	0.142	3.2	0.188
Central track	431.1	0.102	34.6	0.133	3.1	0.180
$m_T > 130 \text{ GeV}$	266.8	0.063	27.1	0.104	2.6	0.151
Electron veto	266.8	0.063	27.1	0.104	2.6	0.151
Hadron veto	266.8	0.063	27.1	0.104	2.6	0.151
$ \eta < 1.05$	167.0	0.039	17.5	0.067	1.8	0.105

(b) Muon trigger channel

Cut	Stau 200 GeV		Stau 400 GeV		Stau 700 GeV	
	N(Events)	Eff.	N(Events)	Eff.	N(Events)	Eff.
Total	1818.6	1.000	111.5	1.000	7.4	1.000
GRL	1818.6	1.000	111.5	1.000	7.4	1.000
Event Cleaning	1818.6	1.000	111.5	1.000	7.4	1.000
Jet Cleaning	1799.0	0.989	110.4	0.990	7.3	0.989
Trigger	1309.8	0.720	77.0	0.690	4.3	0.583
$E_T^{\text{miss, calo}} < 100 \text{ GeV}$	1099.2	0.604	61.4	0.550	3.2	0.430
Track in PV	1094.9	0.602	61.2	0.549	3.2	0.430
$p_T > 50 \text{ GeV}$	1094.5	0.602	61.2	0.549	3.2	0.430
dE/dx Used Hits	1085.2	0.597	60.7	0.544	3.2	0.427
IBL/B-Layer Hits	1084.9	0.597	60.7	0.544	3.2	0.426
Shared/Split Hits	1082.2	0.595	60.6	0.543	3.2	0.426
SCT Hits	1079.3	0.594	60.5	0.542	3.1	0.425
Track Isolation	1076.0	0.592	60.3	0.541	3.1	0.423
$p_T > 120 \text{ GeV}$	995.7	0.548	60.1	0.539	3.1	0.423
Track p uncertainty	995.3	0.547	60.1	0.538	3.1	0.421
Central track	830.3	0.457	52.6	0.472	2.9	0.392
Electron veto	830.3	0.457	52.6	0.472	2.9	0.392
Hadron veto	830.3	0.457	52.6	0.472	2.9	0.392
$ \eta < 1.05$	502.7	0.276	34.3	0.308	2.1	0.278

8.4 Post-Processing selections

After the event picking, selected events in a RAW format are then reprocessed with the relevant release as described in Chapter 5. When data are re-reconstructed, the event-picking selections are re-applied to ensure that events after reprocessing retain their properties and remain suitable for use in the analysis. One of the outcomes of the reprocessing is a recovered high reconstruction efficiency of Slow Muon objects in the barrel region of the ATLAS muon spectrometer. Slow Muon track measurements in this analysis are performed with the barrel part of the MS. The barrel region geometrical acceptance limits track pseudorapidity ($|\eta| < 1.05$) for both MET and muon trigger channels.

Since the analysis operates with the track objects, associating the information (p_T , dE/dx , etc.) to it, the similar association with the Slow Muon information is needed. Reprocessed ID tracks satisfying ID track selection requirements can be associated with Slow Muon objects. Such association is performed within $\Delta R(ID\ track, Slow\ Muon) < 0.03$.

8.4.1 Slow Muon Track Quality Selections

To ensure the high reconstruction quality of the Slow Muon object, requirements are imposed on the number of MDT and RPC hits per track. Each Slow Muon track has to have at least 2 RPC hits and at least 5 MDT hits, allowing a high-quality β_{ToF} measurement to be achieved.

The Slow Muon track quality selections were developed during signal sensitivity studies using the 2018 Run 2 dataset, as described in Section 8.5.

8.5 MDT ToF Analysis Optimisation

To design the analysis, define the set of selections for the analysis channels, and perform initial signal sensitivity studies, the full 2018 Run 2 dataset, corresponding to 60 fb^{-1} , was used. Events were processed with Release 21 of the Athena software [160, 185], which was known to achieve good, validated performance of the Slow Muon reconstruction algorithm (Chapter 6).

The data were used unblinded, as they had already been employed in several previous searches that did not result in any discovery [73]. The full dataset used in the analysis itself is processed with a different software version and includes 4 years of Run 2 data-taking and 3 years of Run 3 data-taking, resulting in 309 fb^{-1} (140 fb^{-1} at $\sqrt{s} = 13\text{ TeV}$ and 169 fb^{-1} at $\sqrt{s} = 13.6\text{ TeV}$) pp collision data, which is significantly larger than the statistics used for the analysis design. In the following, the 2018 data are treated as “background”.

The main observables used in this study are:

- β_{ToF} , associated with a track of a Slow Muon object. β_{ToF} here is an output of the Slow Muon fit, using the hits from the ATLAS MS (as described in Chapter 6). No additional calibration has been applied.
- dE/dx in the Pixel. The variable is associated with the same track. dE/dx was calibrated as a part of the search [73].

The search is based on the main features of the hypothetical charged LLP: the high ionisation (dE/dx) in the Pixel and the low speed β_{ToF} . The SM background, by its origin, is not expected to demonstrate any dE/dx (β_{ToF}) correlation.

8.5.1 MET Selection for the Muon Trigger Region

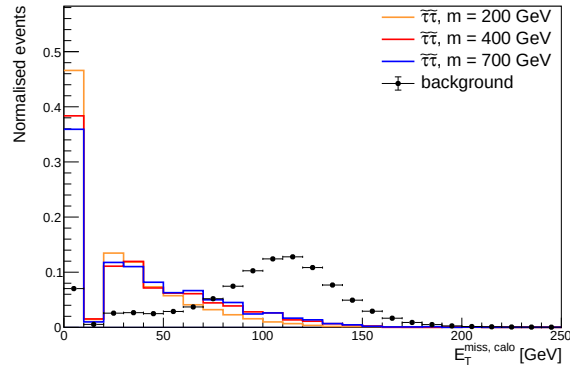


Figure 8.4: The normalised distribution of the $E_T^{\text{miss, calo}}$ variable for the background (in black) and for the stable stau signal sample with masses 200, 400 and 700 GeV (in yellow, red and blue, respectively) for the muon trigger channel.

As it is described in Section 8.3, two types of events are considered depending on the E_T^{miss} signature of the process. Only the events which do not fire the E_T^{miss} trigger, but fire the muon trigger, are selected in the muon trigger channel. The E_T^{miss} trigger accepts events based solely on the transverse momentum imbalance within the calorimeter only; this implies that the value of the calorimeter component of the missing transverse momentum $E_T^{\text{miss, calo}}$ is significant [193]. If an event is not selected by the E_T^{miss} trigger, in most cases this means that the $E_T^{\text{miss, calo}}$ value in the event lies below a certain threshold. Muons are approximately invisible in the calorimeter, and, as a result, the value of the offline missing transverse E_T^{miss} , the computation of which is described in Chapter 4, does not always coincide with the value of $E_T^{\text{miss, calo}}$.

The design of the non-trigger part of the selection for the MET channel has remained almost unchanged compared with the previous analysis [73]. However, the same set of selections is not suitable for events in the muon trigger channel. According to Equation (8.2), the value of m_T becomes high also in the case of a large $\vec{p}_{trk}$ and a mild value of the E_T^{miss} , which is the main scenario in this channel. As a result, the requirement $m_T > 130$ GeV becomes inefficient and negatively affects the signal yield, reducing the number of events with tracks with high transverse momentum.

To keep the background yield under control, an alternative requirement was implemented. Figure 8.4 shows the normalised distribution of the calorimeter MET term, $E_T^{\text{miss, calo}}$, for the background and for the stable stau signal in the mass range from 200 to 700 GeV. The full list of selections excluding MET-dependent selections from Section 8.3 was applied. The plot represents the muon trigger region. The signal distributions tend to have low values of $E_T^{\text{miss, calo}}$, while the background events are shifted to higher values. This behaviour allows the background-rejecting selection to be defined as a threshold on $E_T^{\text{miss, calo}}$. In order to keep the signal yield high, the value of the threshold was set to 100 GeV.

8.5.2 Slow Muon Specific Track Quality Selections

Figure 8.5 shows β_{ToF} as a function of dE/dx for tracks passing all selection criteria in Section 8.3, for both the background and signal (Figures 8.5a and 8.5b, respectively). The background does not display any significant correlation between the two variables, while the signal shows the expected anti-correlation. This observation forms the basis of the background estimation strategy. Two event populations are observed: one with $\beta_{\text{ToF}} \sim 1$ corresponding to the bulk of the events, and one populating tails at low values of dE/dx . In order to understand the origin of the low β_{ToF} tail, three different samples were considered:

Sample A: Data 2018 sample, $dE/dx < 1.2 \text{ MeV g}^{-1}\text{cm}^2$, $\beta_{\text{ToF}} < 0.6$ (red zone in Figure 8.5a).

The range of dE/dx ensures the sample is populated with background. This area of phase space has an enhanced contribution of pathological Slow Muons. The selection by design must remove these events.

Sample B: Data 2018 sample, $dE/dx < 1.2 \text{ MeV g}^{-1}\text{cm}^2$, $0.9 < \beta_{\text{ToF}} < 1.2$ (green zone in Figure 8.5a).

Such a signature is common for MIP SM muons. The Slow Muon reconstruction algorithm is also very efficient for the reconstruction of fast muons ($0.9 < \beta_{\text{ToF}} < 1.2$). These events are used as an example of how a healthy background track looks.

Sample C: MC sample, stau with mass 400 GeV and lifetime 3000 ns (full phase space in Figure 8.5b).

These events show how a good signal track looks.

A set of selections applied to the Slow Muons is designed to reduce background fakes without decreasing the signal yield.

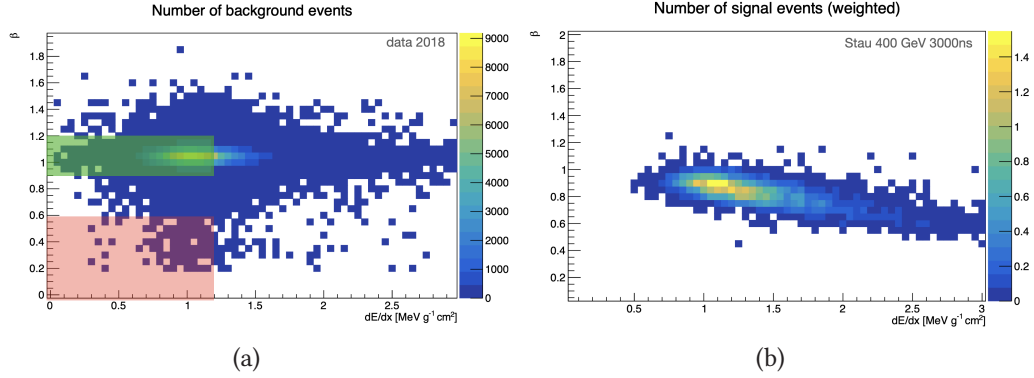


Figure 8.5: The dE/dx versus β_{ToF} distribution of (a) the background events (data 2018) and (b) the signal events (MC stau 400 GeV 3000 ns) before Slow Muon track quality selections.

The main properties of the Slow Muon tracks affecting the β_{ToF} fit quality are the numbers of hits in the timing technologies — MDT and RPC. Distributions of the number of hits in the detecting elements of the corresponding technology (RPC and MDT) per Slow Muon track for the described samples have been plotted (Figure 8.6). It is noticeable that for the Sample A, the number of hits of both technologies is lower in comparison with the Samples B and C. It is important to highlight that the actual Slow Muons in the signal (Sample C) and good muons in the background data share the similar features in Figure 8.6.

As a starting point, the set of cuts based on the number of hits in the MS has been chosen as a Slow Muon quality selection for a design phase of the analysis:

- $N(\text{RPC hits}) \geq 2$,
- $N(\text{MDT hits}) \geq 5$.

After the Slow Muon track quality selections are defined and applied to the data, the number of events falling into regions with β_{ToF} far from 1.0 decreases. This effect is also seen in the potential signal region (low β_{ToF} and high dE/dx). Two-dimensional distributions of events surviving all sets of selections before and after Slow Muon track quality selection are shown in Figures 8.7a and 8.7b,

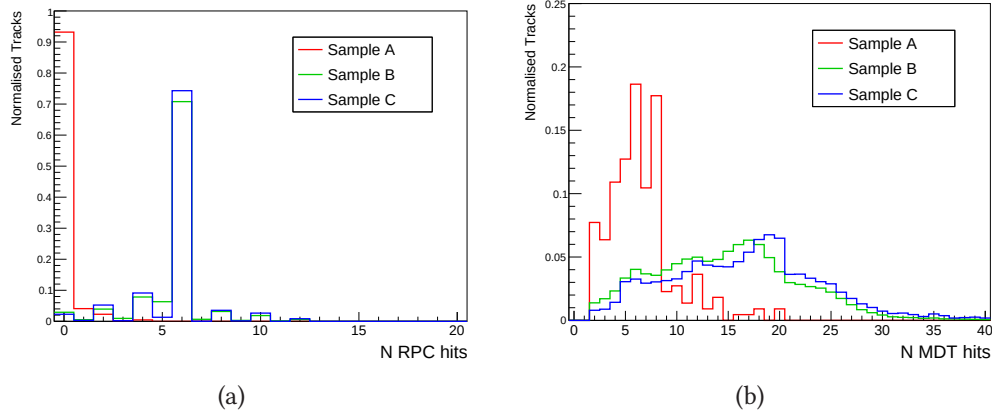


Figure 8.6: Distribution of the number of (a) RPC hits and (b) MDT hits per Slow Muon track for Sample A in red, Sample B in green, and Sample C in blue.

correspondingly. It is important to note that the two-dimensional distribution of track β_{ToF} versus dE/dx does not acquire any correlation after this selection is applied.

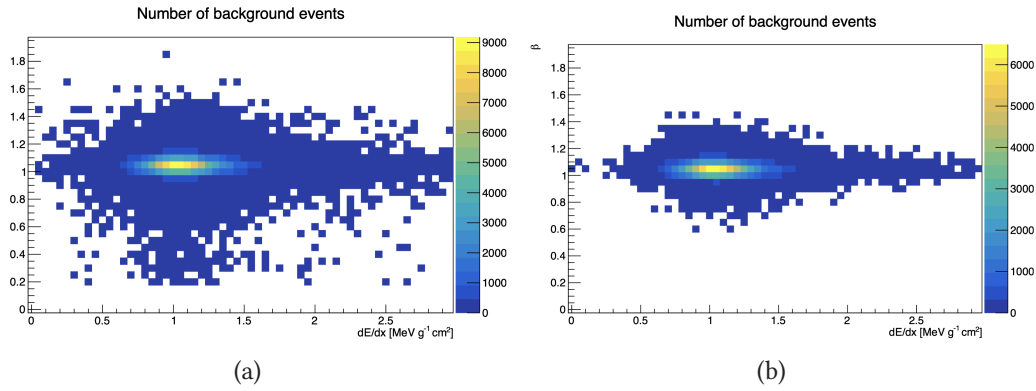


Figure 8.7: The dE/dx versus β_{ToF} distribution of the background events (a) before and (b) after applying Slow Muon track quality selections.

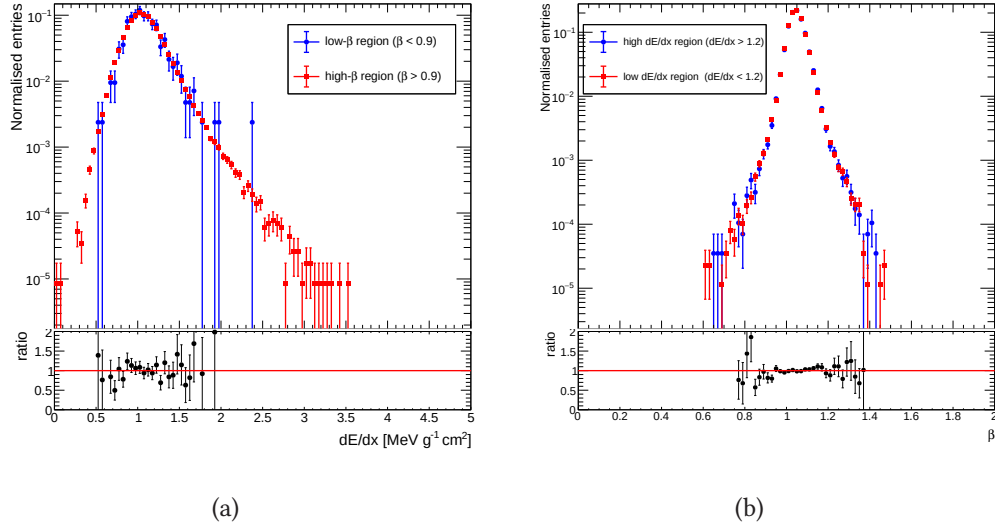


Figure 8.8: Normalised distributions for background: (a) dE/dx distributions in the Pixel detector in low (blue) and high (red) β_{ToF} regions and (b) β_{ToF} distributions in low (red) and high (blue) dE/dx regions in logarithmic scale. The lower part of the plots shows the ratio of distributions in different regions.

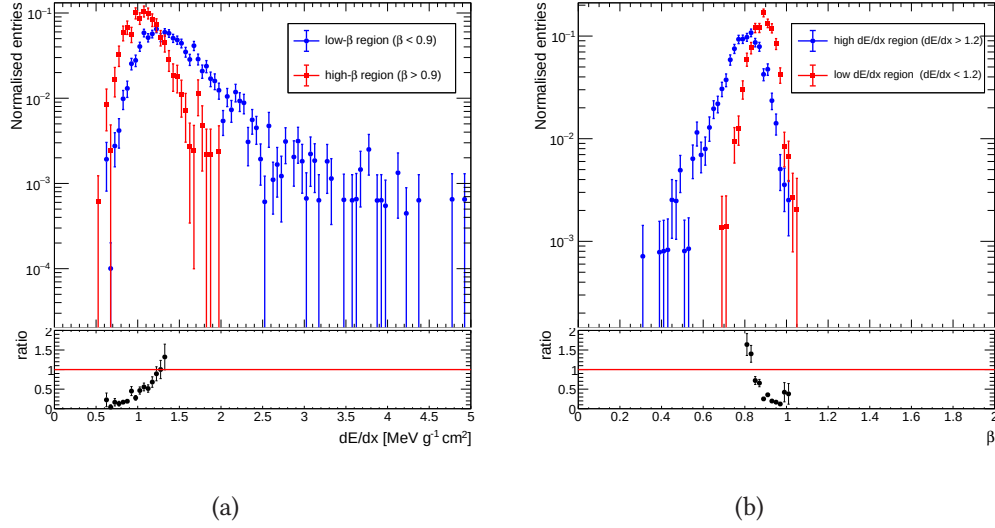


Figure 8.9: Normalised distributions for signal: (a) dE/dx distributions in the Pixel detector in low (blue) and high (red) β_{ToF} regions and (b) β_{ToF} distributions in low (red) and high (blue) dE/dx regions for the signal events in logarithmic scale. The long-lived stau sample ($m_{\tilde{\tau}} = 400$ GeV, $\tau = 3000$ ns) was chosen as a benchmark for signal. The lower part of the plots shows the ratio of distributions in different regions.

8.6 Signal Sensitivity Estimates

After the full set of selections from Section 8.3 are applied, the one-dimensional distributions of the main observables are used to check the possible correlation between them. To do that, the dE/dx distributions were obtained for the ‘low- β ’ region (β_{ToF} less than 0.9) and the ‘high- β ’ region (β_{ToF} greater than 0.9). For the β_{ToF} distributions, the ‘low- dE/dx ’ (dE/dx less than $1.2 \text{ MeV g}^{-1}\text{cm}^2$) and ‘high- dE/dx ’ (dE/dx greater than $1.2 \text{ MeV g}^{-1}\text{cm}^2$) regions were formed. For the same observable, the ratio plots of the normalised distributions were obtained. Figure 8.8 represents the background distributions of the track dE/dx and β_{ToF} , and Figure 8.9 represents the signal (stable stau, $m = 400 \text{ GeV}$).

Figures 8.8a and 8.8b show the dE/dx and β_{ToF} distributions for the background, respectively. Within the regions with high statistics, the ratio of the normalised histograms fluctuates around 1, indicating the absence of correlation between the distributions in these regions of parameter space. This proves that the dE/dx and β_{ToF} distributions are uncorrelated to a large extent. Such behaviour allows the use of data-driven techniques for the estimation of the background contribution in the different parameter-space areas.

Figures 8.9a and 8.9b for dE/dx and β_{ToF} for the signal (dE/dx and β_{ToF} distributions respectively) show clear anti-correlation of dE/dx and β_{ToF} . The signal tracks tend to have lower β_{ToF} values and high dE/dx values simultaneously. This behaviour confirms that slow, highly ionising tracks survive the selection.

The next step of the analysis design aims to study the sensitivity to the stable stau signal and to define the preliminary “signal region” (SR), which has to have an enhanced sensitivity to heavy, charged, and slow LLPs. A two-dimensional scan over possible β_{ToF} and dE/dx thresholds defining the “signal region” (SR) was performed. In order to estimate sensitivity to signal in various regions of the dE/dx – β_{ToF} plane, for each pair of (dE/dx_{cut} ; β_{cut}), the number of events in the area ($dE/dx > dE/dx_{\text{cut}}$; $\beta_{\text{ToF}} < \beta_{\text{cut}}$) was counted. This procedure was performed for both the background (illustrated in Figure 8.10a) and the signal (Figure 8.10b shows an example for the stable stau signal with a mass of 400 GeV). For the signal MC, the number of generated events was reweighted to correspond to 2018 pile-up conditions and a luminosity of 60 fb^{-1} (assuming the cross-section of the process at $\sqrt{s} = 13 \text{ TeV}$). The red area in the plots represents the SR. Using the number of background and signal events inside the SR and assuming the systematic error to be at the level of 30%, the statistical significance values were computed using the BinomialExpZ function in ROOT [176]. The 2D scan of the statistical significance for different cuts for the stable stau ($m = 400 \text{ GeV}$) for the muon trigger channel is shown in Figure 8.11. The scan is performed among values of dE/dx_{cut} and β_{cut} . Each point in the 2D plot is associated with a value

of significance in a corresponding SR defined by the values of the cut.

The same procedure was repeated for both the muon and MET trigger channels for stable staus with masses in the range from 200 to 700 GeV. The maximum sensitivity for all mass points is observed at $dE/dx > 1.5 \text{ MeV g}^{-1}\text{cm}^2$ and $\beta_{\text{ToF}} < 0.75$. These thresholds correspond to a single background event in the SR.

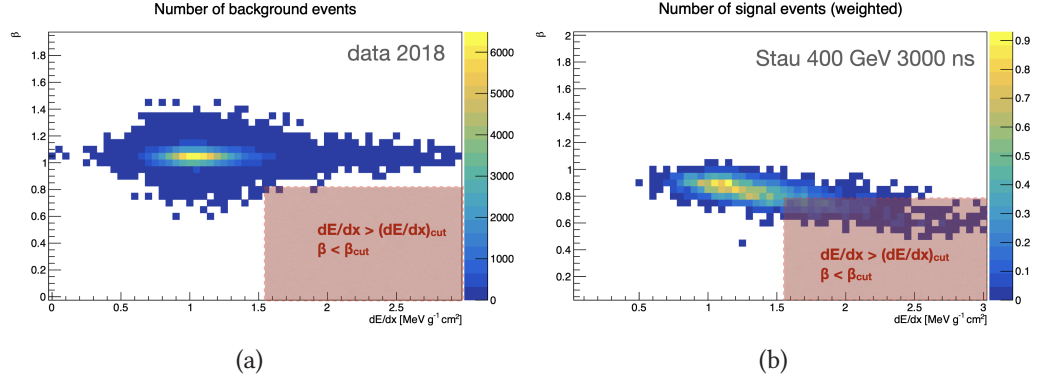


Figure 8.10: The dE/dx versus β_{ToF} distribution of (a) the background events (data 2018) and (b) the signal events (400 GeV 3000 ns stau MC) after Slow Muon track cleaning.

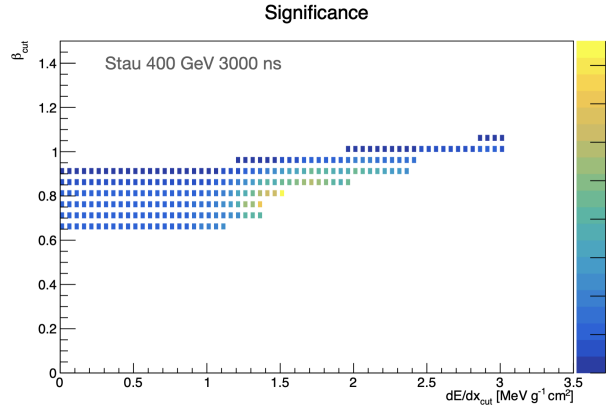


Figure 8.11: The significance 2D scan plot for the 400 GeV 3000 ns stau signal model.

After the statistical significance was estimated for an integrated luminosity of 60 fb^{-1} using the 2018 data results, significance estimates for higher statistics can be obtained by linearly rescaling the luminosity, the number of signal events, and the number of background events. The result of such rescaling is shown in Figure 8.12 for (a) the MET trigger channel and (b) the muon trigger channel. The estimates were made for a stable stau signal for the mass range from 200 GeV to 700 GeV. The number of signal events was not additionally reweighted to

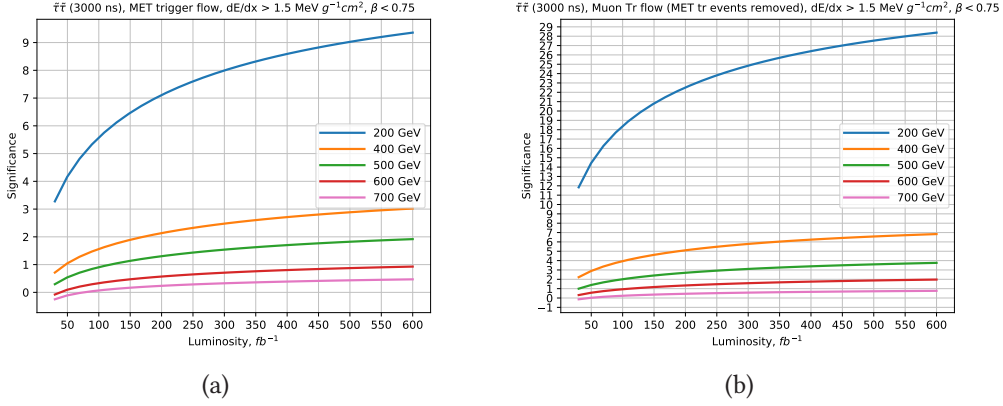


Figure 8.12: Values of the significance extrapolated for different luminosity values with stable stau as a signal in the mass range from 200 GeV to 700 GeV: (a) MET trigger channel; (b) muon trigger channel. Rescaling was performed for the signal production cross-section corresponding to $\sqrt{s} = 13 \text{ TeV}$.

correspond to the production cross-section at $\sqrt{s} = 13.6 \text{ TeV}$ (as it is during Run 3) or to a pile-up profile different from the 2018 year. Systematic uncertainty is assumed to be 30% as well.

According to these estimates, at the integrated luminosity of 300 fb^{-1} , the MET trigger channel allows the exclusion of stable staus with masses less than 400 GeV. The muon trigger channel is more sensitive for the stau particles within the studied mass range and already excludes the 500 GeV mass point.

Due to the fact that the MET and muon trigger channels are mutually exclusive, the final result can be achieved as their statistical combination.

The described method allows the estimation of lower limits of sensitivity to the signal and is far from the final results. The main disadvantage of such a method is the absence of background estimation, due to which the limits defining the SR have become too loose. The SR is chosen in a way that it has a minimum of 1 background event in data 2018; otherwise, the computation of the statistical significance is not possible with this technique. Another simplification which lowers the sensitivity estimate is the fact that the β_{ToF} value is used uncalibrated and with a quite loose Slow Muon track selection.

8.6.1 Simplified Background Estimation

In addition to the ‘event count’ study performed for both analysis channels, another study was performed with the events passing the selection of the muon trigger channel. The study was performed by a bachelor student [195] under the

supervision of the author. This study aims to gain more precision in the sensitivity estimates for this channel using a simplified background estimation method. The technique exploits the lack of correlation between the main observables, demonstrated in Figure 8.8. During this study, the shapes of the distributions of the main observables, dE/dx and β_{ToF} , were derived within the regions of high β_{ToF} ($\beta_{\text{ToF}} > 1.05$) and low dE/dx ($dE/dx < 1.2 \text{ MeV g}^{-1}\text{cm}^2$), respectively. For each distribution, a one-dimensional fit function has been obtained. The fit predictions were validated using the background events in different parameter-space regions: fit predictions of dE/dx were validated inside the region ($0.9 < \beta_{\text{ToF}} < 1.05$), and β_{ToF} predictions were validated within the region ($dE/dx > 1.2 \text{ MeV g}^{-1}\text{cm}^2$).

Figure 8.13 shows the distributions of dE/dx and β_{ToF} for the background events in the regions of the parameter space used to obtain the shape of the fit functions (in grey), and to validate the fit predictions (shown as black dots). The fit functions are shown as red lines. The accuracy of the fit is evaluated using the residuals, computed as follows:

$$\text{Residual}(x) = \frac{N_{\text{events},bkd}(x) - \text{Fit}_{1D}(x)}{\sqrt{N_{\text{events},bkd}(x)}}, \quad (8.3)$$

where x is a value of the observable (dE/dx or β_{ToF}) at the point where the residual is computed; $N_{\text{events},bkd}$ is the number of the background events from the validation region, and $\text{Fit}_{1D}(x)$ is the fit prediction at the same point.

The one-dimensional fit predictions show good accuracy within the ranges $dE/dx \leq \text{MeV g}^{-1}\text{cm}^2$ and $\beta_{\text{ToF}} \geq 0.65$.

The two-dimensional function describing the distribution of dE/dx versus β_{ToF} can be obtained as a product of the one-dimensional functions corresponding to each distribution with a certain normalising coefficient. The two-dimensional fit function is normalised in order to return the number of events within a parameter-space area after the integration.

Using this function, the number of the background events in the area ($dE/dx > dE/dx_{\text{cut}}; \beta_{\text{ToF}} < \beta_{\text{cut}}$) was evaluated for the background. The number of the signal events in the same area was estimated in the same way as in the ‘event count’ study. The maximum of the 2D significance among the ($dE/dx_{\text{cut}}; \beta_{\text{cut}}$) values was obtained for the stable stau signal in the mass range from 400 to 700 GeV. The obtained significance was extrapolated for the integrated luminosity values up to 600 fb^{-1} using the same technique as in the ‘event count’ study. Figure 8.14 shows the signal significance extrapolation performed by the simplified background estimation and the event count. The simplified background estimation method shows more optimistic signal sensitivity predictions.

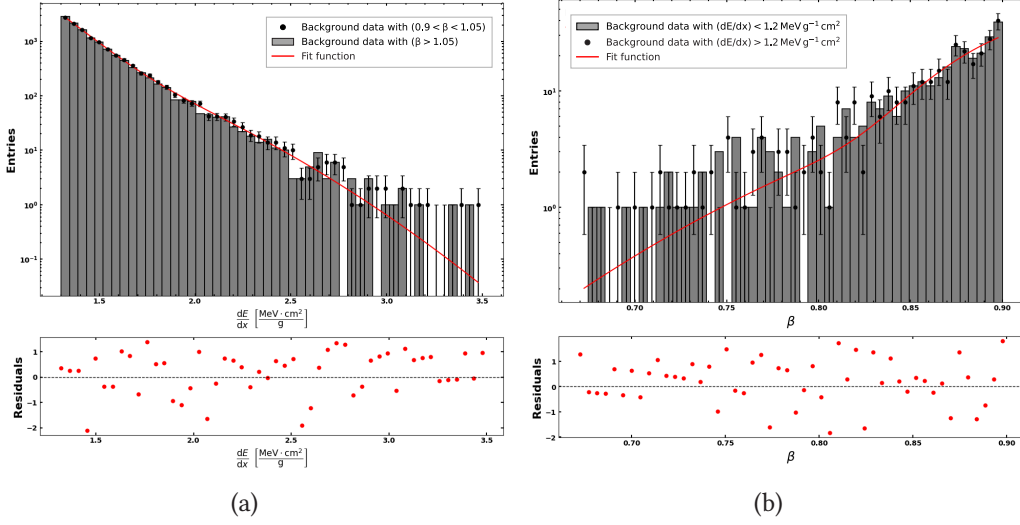


Figure 8.13: The distributions of the background events in the different regions of parameter space for the main observables: (a) the dE/dx variable and (b) the β_{ToF} variable. The regions of parameter space shown in grey were used to obtain a fit approximation (red line). The black dots correspond to the regions used to validate the fit accuracy. The bottom part of the plot shows the residual of the fit, representing the fit accuracy [195].

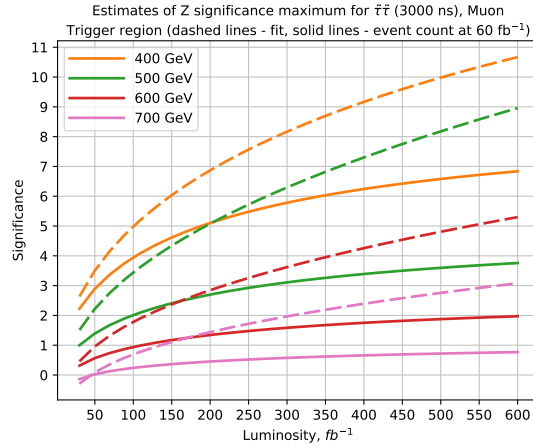


Figure 8.14: Values of the significance extrapolated for different luminosity values with a stable stau as a signal in the mass range from 400 GeV to 700 GeV for the muon trigger channel. Rescaling was performed for the signal production cross-section corresponding to $\sqrt{s} = 13$ TeV. The solid lines represent the ‘event count’ technique of the background contribution in the SR; the dashed lines represent the simplified background estimation method [195].

8.7 Background Estimation Strategy

In the full analysis using Run 2 and partial Run 3 data, the SR is used blinded in order not to bias the results. In order to predict the number of background events in the SRs, a background estimation technique is used.

Using the 2018 data sample, the absence of correlation between dE/dx and β_{ToF} was checked. Comparisons of the dE/dx distributions in the regions of low and high β_{ToF} and β_{ToF} distributions in the regions of low and high dE/dx were performed (Figures 8.8a and 8.8b, respectively).

Correlation between dE/dx and β_{ToF} is not observed, thus the $(dE/dx, \beta_{\text{ToF}})$ plane can be used to form control regions (CRs), validation regions (VRs), and signal regions in a fully data-driven background estimation method for the full analysis. The method is similar to the one used in the search [73] preceding the current one. During background estimation, the templates of p_T , dE/dx , and β_{ToF} are derived from the control regions. To generate a ‘pseudo-data’ background track, a pair of p_T and $|\eta|$ values is sampled from the kinematic CR template. A dE/dx (or a β_{ToF}) value is sampled from the corresponding $|\eta|$ bin of the dE/dx (or β_{ToF}) template. Afterwards, $m_{dE/dx}$ or m_{ToF} is computed using these values for each track.

Validation regions are used to check the predictions made based on the distributions in the CRs. The VRs are designed to be mutually exclusive, and also exclusive with respect to the SR.

Definitions of kinematic CRs are different for MET and muon analysis channels; they are given in Table 8.6 and in Table 8.7, respectively.

Table 8.6: MET trigger channel CR/VR definitions

search region	E_T^{miss} [GeV]	dE/dx [MeV g ⁻¹ cm ²]	β_{ToF}
SR	$> E_T^{\text{miss}}_{\text{cut,high}}$	$> dE/dx_{\text{high}}$	$< \beta_{\text{cut}}$
kin-CR	$> E_T^{\text{miss}}_{\text{cut,high}}$	$< dE/dx_{\text{low}}$	< 1.0
$\beta\gamma$ -CR	$< E_T^{\text{miss}}_{\text{cut,low}}$	–	< 1.0
High- β_{ToF} -VR	$> E_T^{\text{miss}}_{\text{cut,high}}$	$> dE/dx_{\text{high}}$	$[\beta_{\text{cut}}, 1.0]$
High- β_{ToF} -VR kin-CR	$> E_T^{\text{miss}}_{\text{cut,high}}$	$< dE/dx_{\text{low}}$	$[\beta_{\text{cut}}, 1.0]$
High- β_{ToF} -VR $\beta\gamma$ -CR	$< E_T^{\text{miss}}_{\text{cut,low}}$	–	$[\beta_{\text{cut}}, 1.0]$
Low- dE/dx -VR	$> E_T^{\text{miss}}_{\text{cut,high}}$	$[1.05, dE/dx_{\text{low}}]$	$< \beta_{\text{cut}}$
Low- dE/dx -VR kin-CR	$> E_T^{\text{miss}}_{\text{cut,high}}$	< 1.05	< 1.0
Low- dE/dx -VR $\beta\gamma$ -CR	$< E_T^{\text{miss}}_{\text{cut,low}}$	$< dE/dx_{\text{low}}$	< 1.0

SR. The signal region where the final signal selection is applied. The events with high dE/dx (corresponding to the value $dE/dx > dE/dx_{\text{high}}$ in the table) and low β_{ToF} ($\beta_{\text{ToF}} < \beta_{\text{cut}}$). The values of dE/dx_{high} and β_{cut} for the final SRs in the muon and the MET trigger channels are not required to coincide and will be defined at the final stages of the analysis. In addition

Table 8.7: Muon trigger channel CR/VR definitions

search region	p_T [GeV]	dE/dx [MeV g ⁻¹ cm ²]	β_{ToF}
SR	> 120	$> dE/dx_{\text{high}}$	$< \beta_{\text{cut}}$
kin-CR	> 120	$< dE/dx_{\text{low}}$	< 1.0
$\beta\gamma$ -CR	[100, 110]	–	< 1.0
High- β_{ToF} -VR	> 120	$> dE/dx_{\text{high}}$	$[\beta_{\text{cut}}, 1.0]$
High- β_{ToF} -VR kin-CR	> 120	$< dE/dx_{\text{low}}$	$[\beta_{\text{cut}}, 1.0]$
High- β_{ToF} -VR $\beta\gamma$ -CR	[100, 110]	–	$[\beta_{\text{cut}}, 1.0]$
Low- dE/dx -VR	> 120	[1.05, dE/dx_{low}]	$< \beta_{\text{cut}}$
Low- dE/dx -VR kin-CR	> 120	< 1.05	< 1.0
Low- dE/dx -VR $\beta\gamma$ -CR	[100, 110]	$< dE/dx_{\text{low}}$	< 1.0

to that, the SR in the MET trigger channel is also subject to the condition $E_T^{\text{miss}} > E_{T, \text{cut, high}}^{\text{miss}}$.

In the previous search [73], the $E_{T, \text{cut, high}}^{\text{miss}}$ was equal to 170 GeV, the dE/dx_{high} was set to 1.8 MeV g⁻¹cm², and $\beta_{\text{cut}} = 1 - 2\sigma_{\beta_{\text{ToF}}}$.

kin-CR. The kinematic template control region used to provide the p_T and $|\eta|$ spectra of background tracks. It is defined by inverting the dE/dx requirement and relaxing the β_{ToF} cut. The dE/dx is required to be lower than dE/dx_{low} . In the previous study, dE/dx_{low} was set to 1.4 MeV g⁻¹cm². This region also contains the sub-region used for normalisation ($\beta_{\text{ToF}} > \beta_{\text{cut}}$ and $m_{dE/dx}, m_{\text{ToF}} < 160$ GeV), which is employed to fix the overall background yield.

$\beta\gamma$ -CR. The template control region for the dE/dx and β_{ToF} distributions. It is constructed by relaxing both the dE/dx and β_{ToF} cuts and by inverting a kinematic condition. For the MET trigger channel, the E_T^{miss} selection ($E_T^{\text{miss}} < E_{T, \text{cut, low}}^{\text{miss}}$) is inverted; for the muon trigger channel, the track p_T is required to belong to a lower p_T range ($100 \text{ GeV} < p_T < 110 \text{ GeV}$). The dE/dx and β_{ToF} distributions extracted from this region are used to predict $m_{dE/dx}$ and m_{ToF} in the signal region. Only tracks with $\beta_{\text{ToF}} < 1$ are considered when constructing the templates.

High- β_{ToF} -VR. This validation region is designed to contain tracks that fail the β_{ToF} requirement used in the signal selection but extend to high dE/dx values. It is defined by the same selections on E_T^{miss} (for the MET trigger channel) or p_T (for the muon trigger channel). The dE/dx requirement matches that of the SR, β_{ToF} is set within the range of high values (greater than β_{cut}), but below 1.

This region is used to validate the background prediction at high ionisation and for high β_{ToF} values. The corresponding control regions used for the background estimation are defined analogously to those of the signal region:

- **High- β_{ToF} -VR kin-CR.** This region is used to derive the p_T template. Apart from the β_{ToF} cut, all the selections coincide with those from the kin-CR. The β_{ToF} requirement is the same as for the High- β_{ToF} -VR.
- **High- β_{ToF} -VR $\beta\gamma$ -CR.** Apart from the β_{ToF} cut, all the selections coincide with those from the $\beta\gamma$ -CR. The β_{ToF} requirement is the same as for the High- β_{ToF} -VR. This region is used to derive the dE/dx and β_{ToF} templates.

Low- dE/dx -VR. The validation region which is designed to contain tracks that fail the dE/dx requirement used for the signal selection (ionisation in the range of $[1.05, dE/dx_{\text{high}}]$ MeV g⁻¹cm²) but that satisfy low β_{ToF} values. The Low- dE/dx -VR therefore targets events that do not satisfy the signal ionisation criterion but that remain within the low- β_{ToF} regime used for the signal selection. Apart from the dE/dx requirement, the rest of the selections are identical to those of the SR.

This region is used to validate the background prediction in the low-ionisation regime. The corresponding control regions used for its background estimation are:

- **Low- dE/dx -VR kin-CR.** The region is used to derive the p_T and $|\eta|$ templates. The ionisation requirement for this region is $dE/dx < 1.05$ MeV g⁻¹cm²; the kinematic and the β_{ToF} cuts coincide with those of the kin-CR.
- **Low- dE/dx -VR $\beta\gamma$ -CR.** dE/dx and β_{ToF} distributions are derived from this region similarly to those in the $\beta\gamma$ -CR. The ionisation cut for this region is $dE/dx < dE/dx_{\text{low}}$ MeV g⁻¹cm². The rest of the requirements are identical to the $\beta\gamma$ -CR.

The described technique is general and describes one dE/dx and one β_{ToF} measurement. In the case of a combination of more than two measurements, the strategy for the SR definition has to enforce the consistency of these measurements. The CR definition may remain as described above and either ask for the consistency of the corresponding dE/dx and β_{ToF} measurements when needed, or an additional CR may be formed in case of incompatible measurements or $\beta_{\text{ToF}} > 1$ measurements. For example, the full dE/dx can be derived from the region with the same kinematics as the SR, but with $\beta_{\text{ToF}} > 1$, as was done in the simplified background estimation study in Section 8.6.1.

Chapter Summary

This chapter has presented the analysis framework for the search for heavy, charged long-lived particles (LLPs) predicted in several BSM scenarios. The search targets charged particles travelling significantly slower than the speed of light, producing anomalously high ionisation in the Pixel detector and delayed time-of-flight signatures in the ATLAS Muon Spectrometer, extending the previous study [73]. The focus of the study analysis was on the combination of the Pixel dE/dx measurement with the MDT ToF information, using tracks reconstructed with the dedicated Slow Muon algorithm.

Two complementary analysis channels were defined: one employing the MET trigger, and another, introduced and developed as part of this work, based on the muon trigger. Both channels rely on the Slow Muon reconstruction to identify slow-moving tracks in the Muon Spectrometer. The muon-trigger channel was optimised for pair-produced staus, improving the efficiency for LLPs that reach the Muon Spectrometer and extending the search coverage beyond that of previous analyses. Within this framework, dedicated Slow Muon quality selections were defined to ensure robust reconstruction and accurate timing performance.

The analysis uses the full Run 2 pp collision dataset at $\sqrt{s} = 13$ TeV (140 fb^{-1}) and the available Run 3 data at $\sqrt{s} = 13.6$ TeV (169 fb^{-1}), with optimisation and sensitivity studies performed on the 2018 dataset (60 fb^{-1}). A fully data-driven background-estimation strategy was proposed for the analysis including MDT ToF information, with the strategy for the muon-trigger channel representing an original contribution of this work.

The inclusion of MDT ToF measurements significantly improves the sensitivity to long-lived and detector-stable charged particles, with the analysis being most sensitive to particles whose lifetimes are sufficient for them to traverse the full detector, while still maintaining acceptance for lifetimes down to around 10 ns. Sensitivity studies for stable staus were carried out in both analysis channels, with the muon-trigger channel achieving sensitivity to stau masses of approximately 700 GeV. The developments presented here, in particular the design and optimisation of the muon-trigger channel, the definition of Slow Muon quality selections, the integration of MDT ToF information, the proposal of a new data-driven background-estimation strategy for the MDT-based analysis, and the sensitivity study for stable staus in both channels, constitute the main original contributions of this work.

Conclusions

This thesis has presented the search for BSM slow charged long-lived particles produced at the LHC using ATLAS pp collision data collected during Run 2 (2015–2018) and Run 3 (2022–2024), corresponding to integrated luminosities of 140 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ and 169 fb^{-1} at $\sqrt{s} = 13.6 \text{ TeV}$, respectively. The search was based on several independent and compatible measurements of the LLP mass for a single anomalously ionising and slow-moving particle. The LLP masses were computed using β (or $\beta\gamma$) measurements obtained from the Pixel ionisation (dE/dx) information, the TileCal time-of-flight (ToF), and the MDT ToF and dE/dx . A single particle track could therefore have up to four compatible measurements.

This thesis has focused on the aspects of the search that use the combination of the Pixel dE/dx and MDT ToF measurements.

The MDT time-of-flight information was obtained using the Slow Muon reconstruction algorithm. After a set of developments to which the author has contributed, the algorithm achieved high reconstruction efficiency for slow particles ($0.2 < \beta < 1$) within the barrel region of the ATLAS Muon Spectrometer ($|\eta| < 1.05$) in the latest versions of the ATLAS reconstruction software.

The measurements used in this search required a set of dedicated calibrations and corrections. The framework and strategy for the MDT ToF calibration were developed by the author. The calibration was based on hit-level Slow Muon measurements obtained in the MDT and on the Z tag-and-probe method to derive corrections for $\mathcal{O}(1.9 \times 10^5)$ individual MDT tubes located in the barrel of the MS. The calibration included run-wise corrections and tube-wise corrections. The correction factors were applied to obtain an unbiased and more precise estimate of the particle speed β . Current studies indicate that a corrected MDT β achieves a precision of about 4%. To obtain the full set of run-wise corrections and ensure sufficient population of individual tubes, the complete calibration was performed using $\mathcal{O}(10^8)$ $Z \rightarrow \mu\mu$ events from the full Run 2 and partial Run 3 data.

Due to the specific software requirements for the data processing for the search, including the pixel cluster-level information and the latest version of the Slow Muon reconstruction algorithm, the full Run 2 and partial Run 3 data

Conclusions

reprocessing was required. A modified data flow for the data processing was chosen. The events for the two analysis channels in the regions of interest, resulting in $\mathcal{O}(2 \times 10^6)$ events, were selected using the standard ATLAS analysis datasets and then collected for the dedicated reprocessing using the Event Picking Service.

The analysis strategy for the search combining the Pixel dE/dx and MDT ToF measurements was developed by the author using a partial Run 2 sample consisting of 60 fb^{-1} of pp collision data. Pair-produced staus decaying to a tau lepton and a gravitino were chosen as the target benchmark signal model for the development of the analysis strategy. A new analysis channel, the muon trigger channel, and the corresponding event selections were proposed by the author. These selections were used in event picking for the data reprocessing. The estimated sensitivity of the newly introduced muon trigger channel alone, in the search using the full Run 2 and partial Run 3 data sets, is expected to allow the exclusion of detector-stable staus with masses up to 700 GeV. After combination with the MET channel, which is mutually exclusive with the muon trigger channel, this limit can be further improved. The background estimation strategy for the search is based on a data-driven method. The strategy for estimating the number of background events in the search with MDT ToF information, including that for the muon trigger channel, was suggested by the author.

Altogether, the results presented in this work can be summarised as it follows:

- After a set of developments and fixes the Slow Muon reconstruction algorithm has a high reconstruction efficiency for the slow ($0.2 < \beta < 1$) muon-like objects in the barrel region of the ATLAS Muon Spectrometer. This measurement is available in the latest versions of the ATLAS reconstruction software and can be used for the ATLAS Run 2 and Run 3 data processing.
- An MDT time-of-flight calibration framework has been developed. Estimated precision of the calibrated value of the particle speed β is 4%.
- The search for heavy charged long-lived particles using full Run 2 and partial Run 3 datasets can be performed, using the combination of the Pixel dE/dx and the MDT ToF measurements. The estimated mass reach for the analysis extends the reach of the previous LLP searches. The estimated mass reach is above 700 GeV for the detector-stable pair-produced GMSB stau.

Appendix A

The ATLAS Inner Tracker

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Introduction

The upgrade of the ATLAS Inner Detector for operation at the High-Luminosity LHC (HL-LHC) involves the construction of a new all-silicon tracking system,

the Inner Tracker (ITk). The higher collision rates and radiation levels expected during HL-LHC operation require detector modules with excellent reliability and a well-defined quality-control (QC) framework to ensure stable performance over time.

This chapter provides an overview of the ITk project, focusing on the Pixel Detector and the procedures used to verify the quality and functionality of its modules. It outlines the design of the pixel modules, the production and testing workflow within the Italian cluster, and the electrical and thermal qualification steps.

As part of the ATLAS authorship qualification project, the author contributed to the development of the QC infrastructure. The contributions include software integration, standardisation of testing procedures, and documentation work. A detailed description is provided in Section [A.4](#).

In addition, the author participated in the ITk pixel test-beam campaign in 2024. The corresponding description and results are given in Section [A.5](#).

A.1 The ITk Project

The luminosity of the Large Hadron Collider (LHC) during the High-Luminosity phase (HL-LHC) is expected to reach $\mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, corresponding to a fivefold increase relative to current values. According to the present schedule, data taking is planned to continue for approximately ten years under these conditions. The ATLAS experiment aims to collect more than 3000 fb^{-1} of pp collision data at a centre-of-mass energy $\sqrt{s} = 14 \text{ TeV}$.

To achieve the tracking performance required by the ATLAS physics programme for the HL-LHC, the ATLAS Inner Detector (ID) [\[30\]](#), which currently consists of silicon pixel and silicon strip detectors together with a Transition Radiation Tracker (TRT), will be completely replaced by a new detector, the Inner Tracker (ITk). The ITk will be an all-silicon tracking detector comprising two subsystems: a Pixel Detector [\[129\]](#), surrounded by a Strip Detector [\[130\]](#). The layout of the detector is provided in Figure [A.1](#).

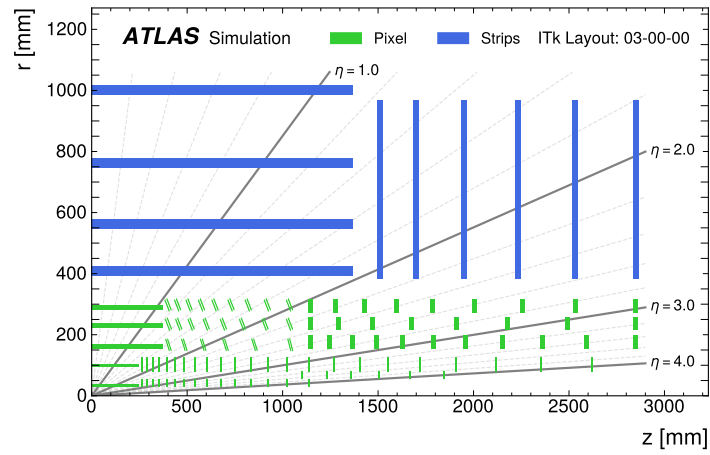
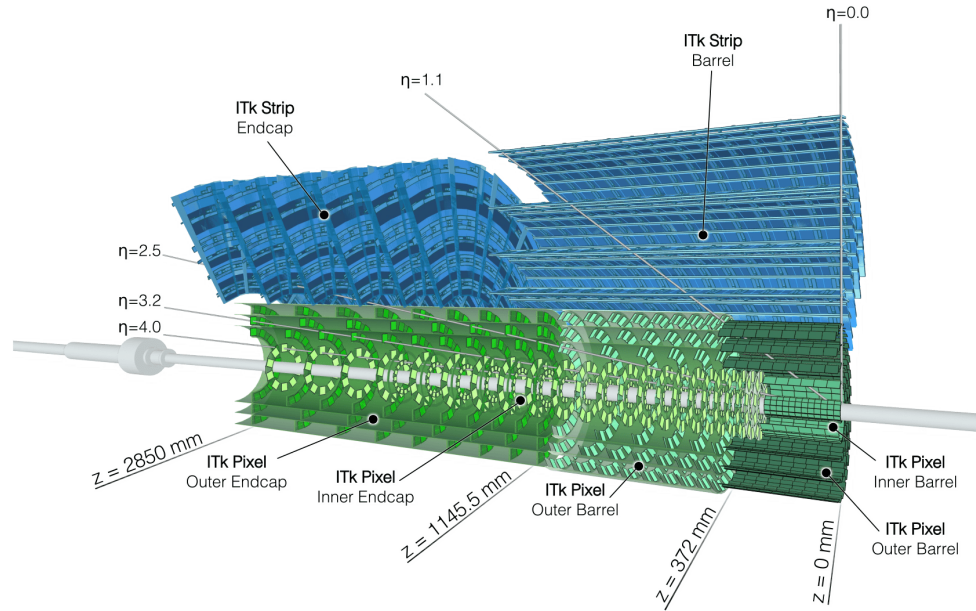


Figure A.1: Longitudinal view of the Inner Tracker layout (top); layout of one detector quadrant showing the active elements of the Strip (blue) and Pixel (green) subsystems (bottom) [196].

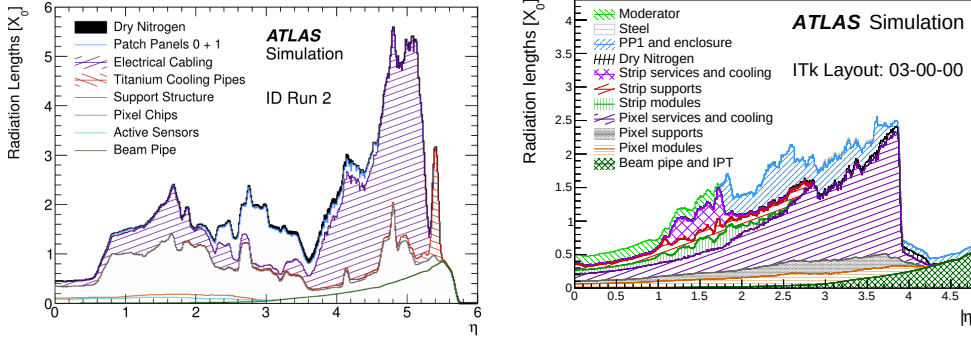


Figure A.2: Radiation length X_0 versus pseudorapidity $|\eta|$: ATLAS ID during LHC Run 2 (left) [129] and ATLAS ITk (right) [196].

The increase in luminosity inherently leads to a higher pile-up, $\langle\mu\rangle$, which is expected to rise from 60 (ATLAS Run 3) to 200. Under these conditions, minimising multiple scattering in the detector material becomes one of the principal objectives of the project. For the ITk, this will be achieved by reducing the material budget of the detector. Figure A.2 illustrates the changes in material budget between the Run 2 configuration of the ATLAS Inner Detector (ID) and the ITk, which will replace it. The material budget is expressed in units of radiation length for both the current ATLAS ID and the future Inner Detector, the ITk.

A.2 ITk Pixel Detector

The ITk Pixel Detector will comprise five barrel layers and a set of end-cap rings, resulting in approximately 13 m² of instrumented area. The design of the new detector allows coverage of the pseudorapidity range up to $|\eta| = 4$.

A.2.1 ITk Pixel Modules

The principal detecting element of the ITk Pixel Detector is the pixel module. These modules are produced using a hybrid technology. The outcome of the module hybridisation process is referred to as a “bare” module. Hybridisation is the procedure during which silicon sensors are bump-bonded to the front-end (FE) read-out chips. Solder bumps connect each pixel of the sensor to the corresponding pixel of the FE chip. Each sensor consists of 400×384 pixels. The read-out chip is based on the 65 nm CMOS technology developed by the RD53 collaboration [198, 199]. Following hybridisation, the module assembly takes place: bare modules and flexible printed circuit boards (flexes) are glued together and subsequently wire-bonded. During wire-bonding, about 170 wires

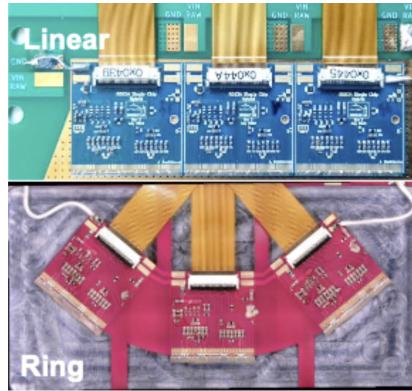


Figure A.3: Linear triplet (top) and ring triplet (bottom) modules.

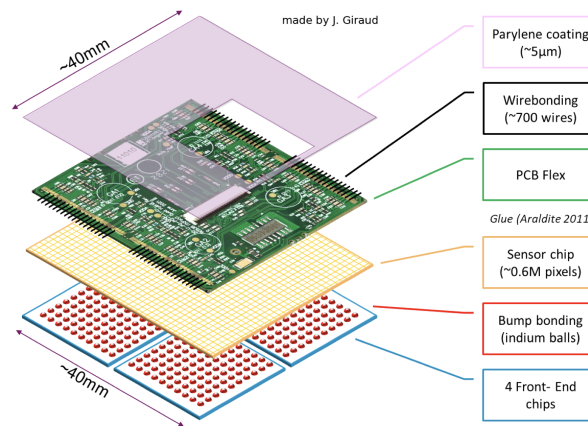


Figure A.4: A schematic view of the various sub-components comprising a pixel quad module [197].

are used to establish the electrical connections between the module flex and each FE chip. Three types of modules will be employed in the ITk Pixel Detector: quad modules, linear triplet modules, and ring triplet modules (Figure A.3). A quad module consists of a single $4 \times 4 \text{ cm}^2$ planar sensor bump-bonded to four read-out chips [129]. A schematic representation of a quad pixel module is shown in Figure A.4. A triplet module comprises three single chips, each one bonded to a $2 \times 2 \text{ cm}^2$ 3D sensor [120]. Triplets will be used in the innermost layer, which will experience the highest radiation fluence due to its proximity to the collision point. Consequently, this layer of the detector is designed to be replaced once during the high luminosity run. The use of 3D sensor technology is motivated by the superior radiation hardness [120] of such sensors compared with those based on planar technology [129]. The parameters of the ITk pixel modules and their placement within the detector layers (from the innermost L0 to the outermost L4) are listed in Table A.1. L0 linear triplets will be installed in the barrel region of the ITk, while L0 ring triplets will be placed in the end-cap region. The outer layers (L1 – L4) of the barrel and end-caps will be composed of the same type of planar quad modules.

Table A.1: Layers and properties of the modules in the ITk Pixel detector.

Layer	Module type	Sensor type	Sensor thickness (μm)	Pixel size (μm^2)
L0 (linear)	Linear triplet	3D	270	25×100
L0 (ring)	Ring triplet		250	50×50
L1 – L4	Quad	Planar	150	50×50

A.2.2 Italian Cluster for ITk Pixel. Production Chain

The Italian cluster of the ITk Collaboration is responsible for the construction of one of the two outer end-caps of the ITk Pixel Detector. The full production chain of the end-cap will be carried out by several institutions, including INFN Bologna. The production chain consists of the following steps:

Module assembly. During this step, the bare modules and module flex are mechanically connected (glued) and electrically connected (wire-bonded). The bump-bonding (hybridisation step) is the final fabrication stage and is performed by industry before the bare modules are sent to the assembly sites. After assembly and wire-bonding, the quad modules are coated with parylene, which acts as an electrical insulator, allowing the modules to operate at high voltage after irradiation.

Module assembly is carried out in Milan and Genoa.

Module testing. Module testing includes visual inspection, chip functionality tests, sensor tests, connectivity checks, and thermal cycles (TC). All the previously listed tests are performed before and after TC. This stage is crucial to ensure the quality of the modules that will be installed in the future detector and will operate reliably throughout more than 10 years of HL-LHC data-taking. Modules that pass the tests proceed to the next stages, while those that fail may either be returned to the assembly sites for repair or discarded.

The sites responsible for module testing within the cluster are Bologna and Udine. INFN Bologna is the only site in the cluster capable of performing TC; all modules assembled by the Italian cluster will undergo TC in Bologna.

Module loading. Modules, electronics, and cooling pipes are loaded onto the half-ring carbon-fibre local supports.

The Genoa and Lecce sites are responsible for module loading.

End-cap integration. During this stage, all half-rings are integrated into the end-cap, tested, and then transported to CERN and subsequently installed in the ATLAS experiment cavern during the long shutdown.

The half-rings will be integrated in Frascati laboratory.

A.3 ITk Pixel Module Testing

The final set of the testing procedures will be defined only after the pre-production stage; however, the principal procedures necessary to ensure the quality of the module can already be described.

A.3.1 Visual Inspection

Visual inspection is usually performed before shipping the module and after its reception. It is performed first without any instruments and then using a microscope. This test is used as an initial check of the module condition after it has been shipped from one site to another. This test allows the identification of mechanical damage and visible problems in the electrical connections.

A.3.2 Electrical Tests

To perform a more detailed assessment of module quality, a series of electrical tests are carried out. These can be grouped into three main categories: connectivity checks, chip functionality tests, and sensor tests. Connectivity checks verify the electrical paths and the integrity of the digital communication between

components. Chip functionality tests are performed to verify and calibrate the performance of the FE chip. Sensor tests assess the properties of the silicon sensor and its connection to the chip through the following measurements.

All electrical tests are performed using the YARR (Yet Another Rapid Read-out) [200] data acquisition (DAQ) system. YARR is a modular framework developed for the characterisation and testing of ITk pixel modules. It provides an interface between the front-end readout chips and the host system, enabling full control of configuration, calibration, and data readout. YARR integrates high-level C++ software with firmware implemented on Field-Programmable Gate Arrays (FPGAs), allowing communication with the pixel readout ASICs. It supports automated test procedures, known as YARR scans, used to evaluate both the analogue and digital parts of the module.

To assess the functionality and integrity of the modules, several dedicated tests are performed. A summary of these tests is provided below.

Digital YARR scan. The Digital YARR scan is a connectivity test that checks the digital part of the front-end (FE) chip and ensures that all electrical connections between the chip and the module are functioning correctly.

ADC calibration. During this test, the chip internal ADC is calibrated, and the quality of the calibration is verified. When calibration is successful, the ADC can be used to measure internal chip voltages and currents.

Analogue YARR scan. This type of scan tests the analogue part of the chip using charge injection. YARR injects a signal N times (typically $N = 100$) into each pixel. If the number of detected signals does not deviate significantly from N , the pixel is classified as “good”; otherwise, it is excluded from further measurements, i.e. it is “masked”. If the number of masked pixels is not excessive, the module can still be used in the construction of the ITk detector.

Threshold YARR scan. The Threshold YARR scan determines the threshold of each pixel. The threshold represents the minimum amount of charge (in units of the elementary charge e) that is counted as a hit. A charge smaller than a threshold cannot be registered by the pixel.

Threshold tuning. This procedure allows the adjustment (“tuning”) of pixel thresholds to achieve a uniform response across all pixels within the module.

IV measurement. During this test, different values of high-voltage bias are applied to the sensor. By studying the dependence of the leakage current I on the bias voltage V , it is possible to determine the operational and

breakdown voltages and to compare IV characteristics at different stages to identify any damage or variation in response.

Source/X-ray scan. This scan is performed using either a radioactive source or an X-ray gun. The test verifies the ability of the module to perform data taking. During this scan, both the sensor and its connections to the chip are tested, allowing the identification of areas with disconnected or defective bumps. Disconnected or dead pixels are identified.

All electrical tests are conducted under two temperature regimes: at room temperature and under “cold” conditions (-15°C for quad modules and -25°C for triplet modules). The cold conditions reproduce the operational environment expected during LHC data taking.

A.3.3 Thermal Cycles

According to the estimations [129], the ITk pixel detector elements are expected to experience approximately 100 thermal cycles during operation, with temperatures reaching as low as -45°C . It is also possible that the temperature may reach -55°C once during the entire detector lifetime.

Such extreme conditions may occur due to the large thermal inertia of the cooling system in the event of a power outage. In addition, during transportation, integration, or storage, parts of the detector may undergo heating up to $+55^{\circ}\text{C}$, for example in the case of a failure in the shipping or storage conditions.

To ensure that the modules can withstand such extreme variations in environmental conditions and remain operational throughout the lifetime of the ATLAS ITk detector, TC are performed as part of both the production and pre-production module qualification procedures.

The TC operation during the module pre-production phase consisted of one cycle between -55°C and $+60^{\circ}\text{C}$, followed by ten cycles between -45°C and $+40^{\circ}\text{C}$. For the module production, only 1 cycle between -45°C and $+40^{\circ}\text{C}$ is performed as QC.

Testing sites perform TC either in a custom cooling unit or in a climate chamber. At the INFN Bologna testing site, an industrial climate chamber is used for module testing.

A.4 Contributions to Module QC Infrastructure

During the ATLAS authorship qualification task, the author worked as part of the module QC team at the home institute, ATLAS Bologna. This work included the customisation of the common QC tools for the electrical tests, development

and optimisation of the module quality-control infrastructure and the related documentation.

A.4.1 Customisation of Common Electrical QC Tools

During the ATLAS authorship qualification task, the author worked as part of the module quality control (QC) team at the home institute, ATLAS Bologna. To perform the electrical QC tests described in Section [A.3.2](#), the testing sites use a common Python-based QC tools framework developed by the ITk Pixel community. One of the author's responsibilities during the qualification task was to integrate this QC tools framework with the Detector Control System (DCS) infrastructure used in Bologna.

The DCS at Bologna consists of two main software layers: WinCC, which provides the graphical interface and scripting capabilities, and an OPC server, which interfaces directly with the hardware devices employed during testing, such as low-voltage (LV) and high-voltage (HV) power supply channels and the chiller. Python-based QC tools interact directly with the OPC server, bypassing the WinCC user interface, and can therefore issue control and monitoring commands without requiring WinCC itself to mediate them. In this setup, the OPC server handles the communication with the hardware devices and schedules the execution of commands, while WinCC is primarily used for monitoring and supervisory control and for displaying the status of the hardware interlock system. The hardware and software interlocks are functionally independent: the hardware interlock operates autonomously, and the software interlock can run without the hardware interlock being active, and vice versa.

Environmental monitoring is achieved using devices based on the ESP32 microcontroller that transmit data to the DCS. The DCS displays the environmental parameters in real time and records them in the database. It also issues alerts whenever the environmental conditions fall outside the defined operational range.

In the case of a custom DCS implementation, the interaction between the QC tools and the test instruments is established via a set of Python scripts. These scripts communicate directly with the OPC server, which interfaces with the hardware devices such as the LV and HV power supplies and multimeters. In this setup, the OPC server is the software layer responsible for issuing and scheduling the commands sent to the instruments, while WinCC is used primarily for monitoring and supervisory logic.

The common QC tools framework interfaces with the instruments, YARR, the module, and the database, automating the sequence of electrical tests. Each test comprises the measurement itself and an evaluation phase. Once a measurement is completed, the QC tools perform consistency checks on the relevant quantities. If the results lie within the predefined reference intervals, the module is considered

to have passed QC, confirming that it meets the requirements to be integrated into the ITk Pixel detector.

A.4.2 Thermal Cycle Qualification Document

The author was one of the three editors of the thermal cycle (TC) pixel module site qualification document. This document defines the requirements for the setups used to perform TC tests, which are designed to identify modules capable of withstanding repeated thermal stress. During such tests, the modules are not powered, and a vacuum system is employed to ensure module flatness, thereby reproducing the mechanical conditions expected during operation.

The thermal cycle test serves as a qualification procedure to verify that a module can survive significant temperature variations. Passing this test demonstrates that the module can operate reliably within the ITk Pixel detector, which may be exposed to extreme heating or cooling events during its lifetime [129]. To guarantee consistency across testing sites, the procedure was standardised so that all laboratories conduct the TC test in the same way, allowing a uniform assessment of module performance and ensuring that environmental factors, such as humidity, remain under control.

The document specifies that thermal cycling can be performed either using a dedicated Cooling Unit (CU) or an industrial Climate Chamber (CC). Both devices must be capable of operating within a temperature range from -55°C to $+60^{\circ}\text{C}$. Throughout the test, a set of environmental and operational parameters is monitored continuously and recorded in the local database at defined time intervals. The update frequencies for monitoring and data storage are explicitly prescribed to ensure reproducibility of the results.

To maintain module safety throughout the procedure, the document also outlines a number of safety conditions. These include maintaining a constant dry air flux inside the testing chamber and ensuring that the ambient dew point remains sufficiently below the module temperature to prevent condensation. Furthermore, the test sequence itself is defined: it consists of one thermal cycle between -55°C and $+60^{\circ}\text{C}$, followed by ten cycles between -45°C and $+40^{\circ}\text{C}$. Interlock conditions are also defined, specifying the circumstances under which the test must be aborted to avoid damage to the modules.

Overall, the thermal cycle qualification document ensures that all testing sites perform this essential stress test under equivalent and safe conditions, providing a consistent basis for assessing the robustness of ITk Pixel modules prior to integration.

A.4.3 ITk Pixel Module Testing Twiki Pages

During the ATLAS authorship qualification, the author served as the editor of two ITk Pixel Module Testing Twiki pages. These pages [201, 202] were created to centralise all information required for a testing site to qualify for performing pixel module quality control (QC) tests at that time. During the qualification period, the author revised both pages to ensure that they contained accurate, up-to-date, and relevant content. The author also added detailed guidance for navigating the Production Database Web Application (PDB WebApp) [203]. Module tracking from assembly through to installation is handled by the Production Data Base (PDB). The PDB WebApp functioned as an interface to the PDB and was used in particular to upload measurements not included in the automated electrical QC tests (e.g. visual inspection and metrology) and to request site qualification.

The first Twiki page provided a complete set of instructions for testing sites seeking qualification in the following infrastructure areas: cold testing setup, thermal cycling, hardware interlock, Detector Control System (DCS) and software (SW) interlock, testing parallelisation setups, stability testing, source or X-ray test setup, and room-temperature test setup. These sections collectively defined the infrastructure and procedural requirements that a site had to fulfil at that time in order to be approved for module testing.

The second Twiki page [202] is dedicated to the documentation associated with the qualification of the testing sites required to perform the tests mentioned above. It compiles all relevant testing site qualification documents and templates, and provides a detailed step-by-step description of the review procedure by which members of one testing site can evaluate the qualification slides of other institutions. The instructions for this review process were written entirely by the author.

A.4.4 Hardware Interlock System

To satisfy the ITk safety requirements for the hardware (HW) low-voltage (LV) interlock system used during module QC tests, INFN Bologna designed and produced a custom LV_breaker board – a low-voltage distribution and relay board.

The HW interlock system consists of several components that work together to ensure the safe operation of modules during testing. These include:

- Microcontrollers (MCUs) that receive temperature and relative humidity (%) data from two test stations, as well as reset signals from manual buttons, and generate power enable signals;

- HW devices that receive enable signals for the LV power supplied to each module readout (RO) chip and the corresponding Peltier element;
- Push-buttons used to reset and initialise the interlock logic;
- A Keithley 2410 SourceMeter with an embedded interlock;
- A dedicated Python script to record interlock events independently of the Detector Control System (DCS).

The LV interlock uses relays to disconnect the module RO chip and the Peltier element from their power sources when necessary. For each module under test, two relays are employed: a standard electromechanical relay for the Peltier and a solid-state relay (SSR) for the module itself. Tests confirmed that the use of SSRs mitigates switching spikes, although they present a slightly higher resistance compared with standard relays.

Custom LV_breaker boards (Figure A.5) were designed and produced in Bologna to implement the requirements defined by the ITk collaboration. The boards satisfy the following operational conditions:

1. To enable output voltage, both the GLOBAL and CHANNEL enable signals must be high for at least 2.5 s;
2. The input voltage must remain below 80 mV for activation;
3. A reset signal is required to reinitialise the circuitry following an interlock.

Each board has four channels and can control up to two modules (two SSRs and two standard relays). Consequently, three interlock signals are required: one common signal and two individual interlock lines (INTERLOCK_1 and INTERLOCK_2) for the connected modules. In addition, two reset signals are needed to initialise the logic. Figure A.6 illustrates the control-signal sequence necessary to enable the relay on the LV_breaker board.

Further documentation and technical drawings are available in Ref. [204].

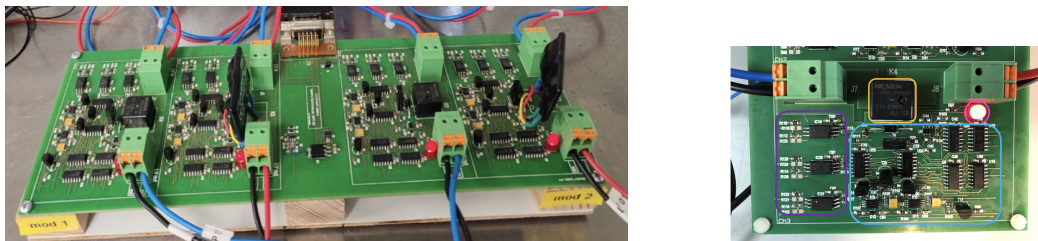


Figure A.5: The LV_breaker board (left) and a detailed view of one of its sections (right).

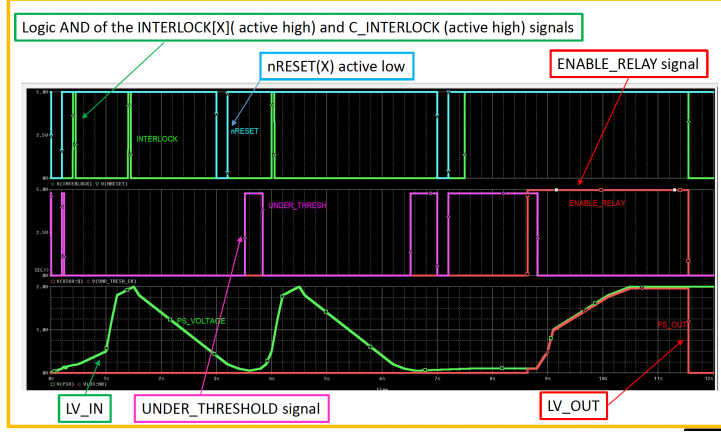


Figure A.6: Example of the control-signal sequence required to enable the relay.

A.5 Test Beam Studies

In the HL-LHC era, the innermost parts of the detectors surrounding the interaction points are expected to reach unprecedented levels of radiation, with non-ionising fluences up to $1 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ and ionising doses of 5 MGy.

To probe the radiation hardness of the ITk Pixel modules under production, their efficiency after irradiation needs to be measured at the SPS facility at CERN. The 2024 test-beam campaign took place at the CERN SPS H6 [205] beam line with a 120 GeV pion beam. During the campaign, both 3D and planar pixel sensor modules were tested. 3D sensor modules were tested as single-chip cards (SCCs), whereas the 3D modules to be installed in the ITk use a triplet configuration. Table A.2 gives a summary of the tested irradiated and unirradiated modules.

Table A.2: Summary of the modules tested at the test beam. The fluence values for the irradiated modules exceed expected total lifetime doses for the corresponding modules [129].

Technology	Vendor	Fluence, $\text{n}_{\text{eq}}/\text{cm}^2$	Modules
3D	SINTEF	1.7×10^{16}	2 (SCC 0099S, SCC 4S)
Planar	Advafab	unirradiated	1 (QV2)
	HPK	unirradiated	2 (QV2, KEKQ9)
	Micron	unirradiated	2 (Q18, Q19)
	HPK	4.31×10^{15}	1 (KEKQ16)
	Micron	2×10^{15}	2 (PPPQ8, PPPQ12)

The testing setup (Figure A.7) used a beam telescope [206] with six Mimosas26 tracking planes and an FBK FE-I4 timing plane. The devices under test (DUTs) were

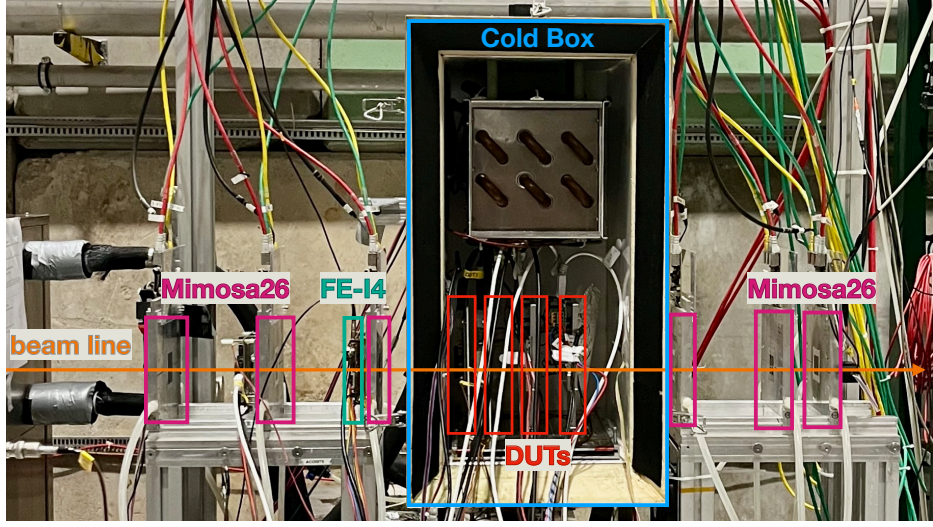


Figure A.7: The setup used during the 2024 ITk Pixel test-beam campaign.

kept in a cooled box with controlled conditions. Separate data-acquisition systems for the telescope and the DUTs were run with EUDAQ v2 [207]. The telescope provided the trigger and track reconstruction for the sensor studies. Tracks were reconstructed with the Corryvreckan framework [208] and extrapolated to the DUTs, where hits were checked at the intersection point. Tracks passing through disabled or masked DUT pixels, or through adjacent pixels, were left out of the efficiency calculation. During beam tests, the threshold was tuned to $1000\ e^-$ and the sensors were operated at temperatures around -35°C over bias ranges appropriate for each sensor type, with the beam incident perpendicularly to the sensor surface.

The 3D sensors were fabricated by SINTEF using deep reactive ion etching (DRIE) to form p^+ and n^+ columns in $150\ \mu\text{m}$ -thick silicon. The new sensor version incorporated a Si_3N_4 passivation layer deposited by plasma-enhanced chemical vapour deposition (PECVD), which improved mechanical stability and reduced curvature compared to earlier prototypes that exhibited wafer bowing and mechanical distortions [210]. Each sensor was bump-bonded to an RD53B [211] ASIC with a $50 \times 50\ \mu\text{m}$ pixel pitch and a matrix of 384×400 pixels. The 3D sensors were irradiated with 25 MeV protons at the Karlsruhe Institute of Technology (KIT) to a fluence of $1.7 \times 10^{16}\ \text{n}_{\text{eq}}/\text{cm}^2$, corresponding to a dose exceeding the expected lifetime in the ITk L0 region.

The planar sensors were tested in a quad-chip configuration comprising four RD53B readout ASICs bump-bonded to a single sensor. These quad modules feature an inter-chip region with specially shaped pixels designed to bridge the gap between adjacent chips. Unirradiated planar modules were supplied by

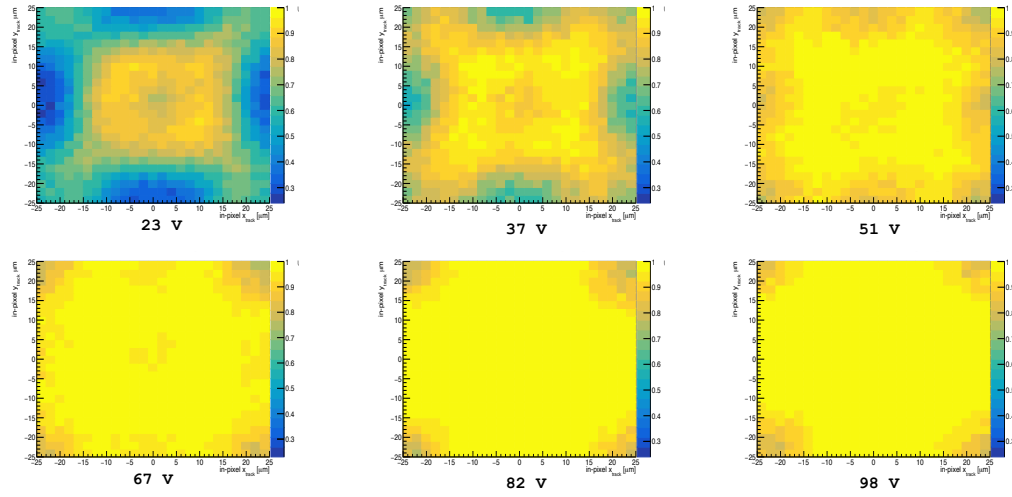


Figure A.8: In-pixel efficiency maps for 3D sensors at different bias voltages [209].

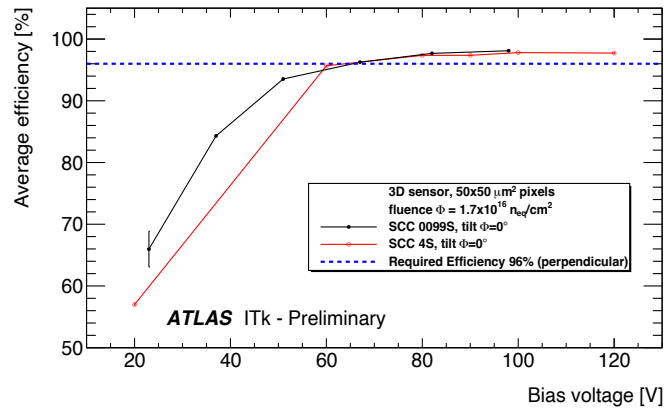


Figure A.9: Hit efficiency of 3D sensors as a function of bias voltage [209]. Red and black lines represent the average efficiency achieved by the tested 3D sensors.

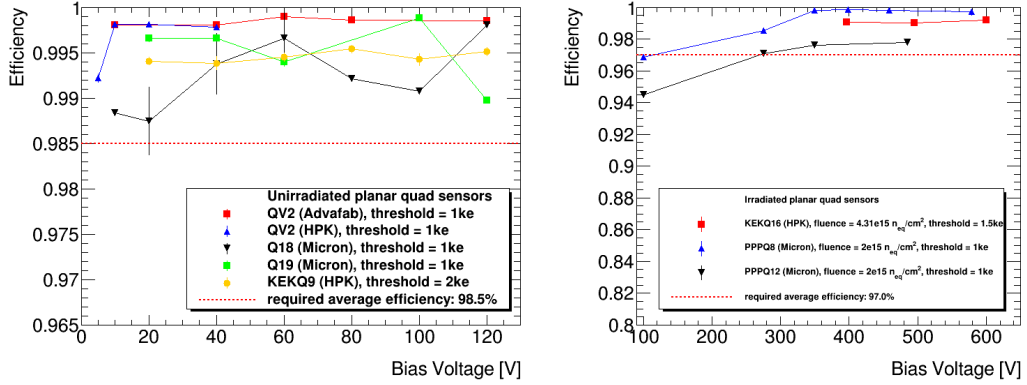


Figure A.10: Hit efficiency of planar sensors as a function of bias voltage [209].

Advafab (QV2), HPK (QV2, KEKQ9), and Micron (Q18, Q19), while irradiated modules included HPK (KEKQ16) at a fluence of $4.31 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and Micron (PPPQ8, PPPQ12) at $2 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.

The hit detection efficiency was evaluated as a function of bias voltage for both sensor types. The in-pixel efficiency is defined as the ratio of particle tracks whose associated hits are detected within a given pixel, to the total number of tracks predicted to traverse that pixel [209]. The prediction is provided by the reference telescope.

Figure A.8 shows in-pixel efficiency maps for the 3D sensors at different bias voltages. The efficiency increases with voltage, and at 51 V, inefficiencies in the central pixel region are no longer observed, while those near the corners persist, corresponding to the p^+ etched columns. Such effects are consistent with the expected behaviour of 3D sensors under perpendicular incidence and are expected to be reduced for track angles of about 15° , as expected in the ITk.

The overall hit efficiency for 3D sensors as a function of bias voltage is presented in Figure A.9. The ITk requirement of at least 96 % efficiency for irradiated 3D sensors under perpendicular incidence was achieved at 67 V, with a maximum measured efficiency of 98.2 %. The modified passivation design performed comparably to the previous version, achieving similar efficiency at higher voltages and showing potentially improved behaviour at lower voltages, while maintaining radiation hardness.

The efficiency of planar sensors as a function of bias voltage is shown in Figure A.10. According to ITk requirements, unirradiated planar sensors must achieve an efficiency above 98.5 %, while irradiated ones must exceed 97 %. These criteria were met during beam tests at bias voltages of 20 V for non-irradiated and 250 V for irradiated sensors. However, stable and simultaneous operation of all four chips on irradiated modules proved challenging, possibly due to limited

operational experience with irradiated assemblies, inhomogeneous irradiation, or issues in the data acquisition (DAQ) system.

Appendix Summary

This chapter presented an overview of the ATLAS Inner Tracker (ITk) and the quality-control procedures established to ensure the reliability of the ITk pixel modules. Within this framework, the author contributed to the development and optimisation of the module quality-control infrastructure. The work involved integrating the common Python-based QC tools with the WinCC-OA Detector Control System, standardising the thermal-cycle qualification procedure, updating and extending the ITk Pixel module-testing Twiki documentation, and contributing to the design of the hardware low-voltage interlock system used to ensure safe module operation during electrical tests.

The author also participated in a test-beam campaign as a member of the ITk Pixel testing team, gaining direct experience with detector operation under beam conditions.

These activities improved the quality-control framework of the ITk Pixel project, ensuring consistent testing procedures and reliable module performance in the upgraded ATLAS Inner Tracker.

Appendix B

Additional Plots

B.1	MDT ToF Calibration. Run-wise Corrections.	171
B.2	MDT ToF Calibration. Particle Speed Recomputation	174

B.1 MDT ToF Calibration. Run-wise Corrections.

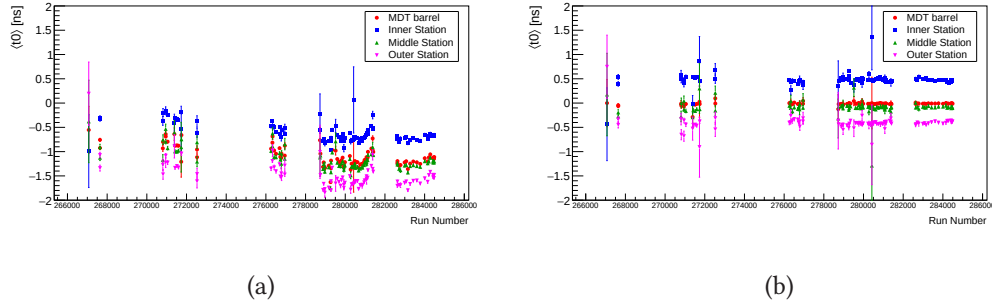
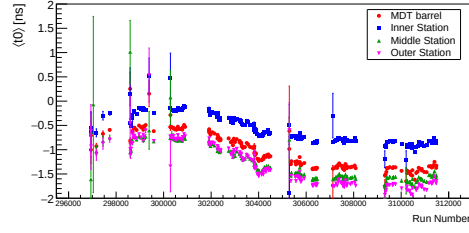
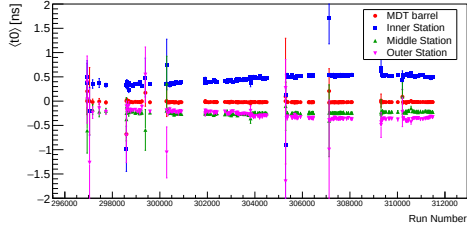


Figure B.1: The average values t_0 per run for 2015 data: (a) before and (b) after the per-run timing correction. The values are averaged for the MDT tubes located in: the whole MDT barrel (in red), Inner Station of the MDT barrel (in blue), Middle Station of the MDT barrel (in green), and the Outer Station of the MDT barrel (in magenta).

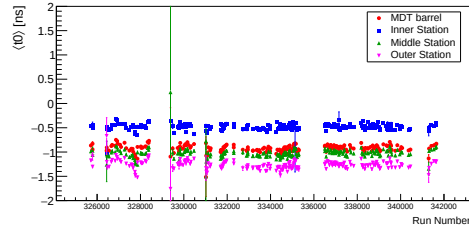


(a)

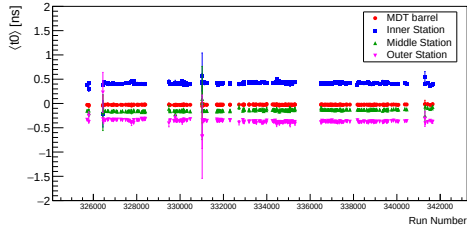


(b)

Figure B.2: The average values t_0 per run for 2016 data: (a) before and (b) after the per-run timing correction. The values are averaged for the MDT tubes located in: the whole MDT barrel (in red), Inner Station of the MDT barrel (in blue), Middle Station of the MDT barrel (in green), and the Outer Station of the MDT barrel (in magenta).

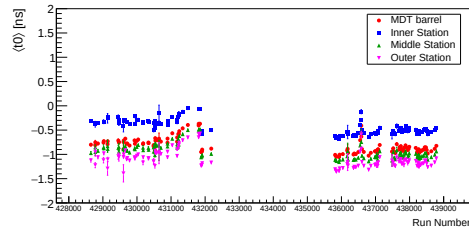


(a)

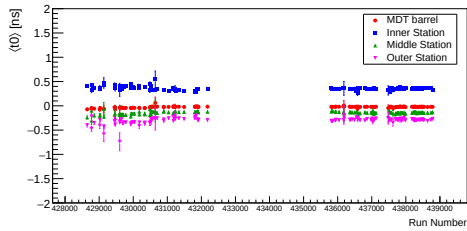


(b)

Figure B.3: The average values t_0 per run for 2017 data: (a) before and (b) after the per-run timing correction. The values are averaged for the MDT tubes located in: the whole MDT barrel (in red), Inner Station of the MDT barrel (in blue), Middle Station of the MDT barrel (in green), and the Outer Station of the MDT barrel (in magenta).

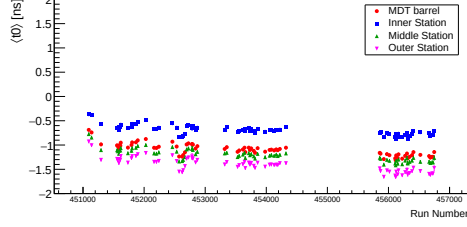


(a)

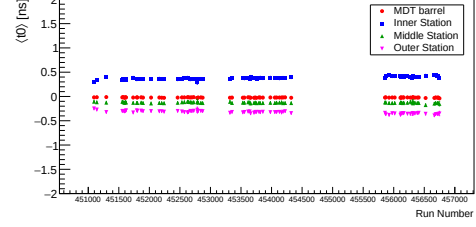


(b)

Figure B.4: The average values t_0 per run for 2022 data: (a) before and (b) after the per-run timing correction. The values are averaged for the MDT tubes located in: the whole MDT barrel (in red), Inner Station of the MDT barrel (in blue), Middle Station of the MDT barrel (in green), and the Outer Station of the MDT barrel (in magenta).

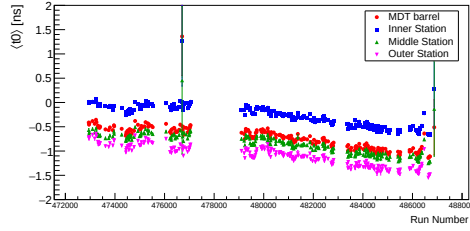


(a)

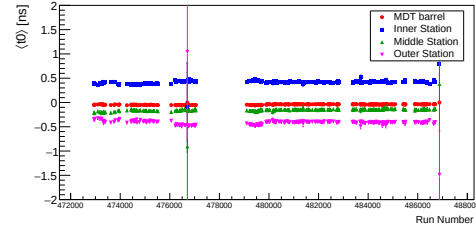


(b)

Figure B.5: The average values t_0 per run for 2023 data: (a) before and (b) after the per-run timing correction. The values are averaged for the MDT tubes located in: the whole MDT barrel (in red), Inner Station of the MDT barrel (in blue), Middle Station of the MDT barrel (in green), and the Outer Station of the MDT barrel (in magenta).



(a)



(b)

Figure B.6: The average values t_0 per run for 2024 data: (a) before and (b) after the per-run timing correction. The values are averaged for the MDT tubes located in: the whole MDT barrel (in red), Inner Station of the MDT barrel (in blue), Middle Station of the MDT barrel (in green), and the Outer Station of the MDT barrel (in magenta).

B.2 MDT ToF Calibration. Particle Speed Recomputation

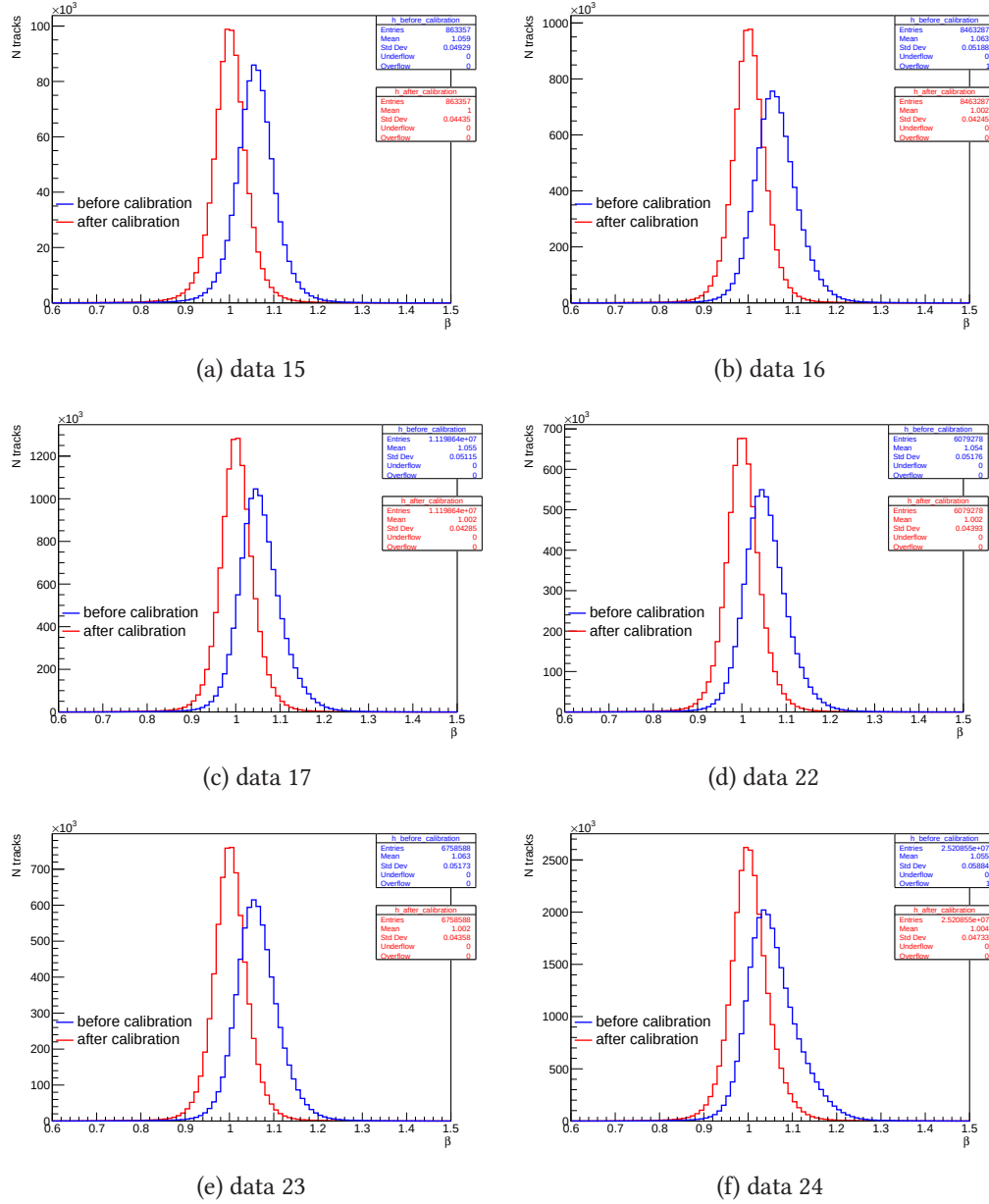


Figure B.7: Particle speed β distribution before (in blue) and after MDT ToF calibration (in red) for muons passing Z tag-and-probe selection.

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