

Searching for heavy, charged, long-lived
particles via ionization energy loss and
time-of-flight in the ATLAS detector using
 140 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton-proton
collision data

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ABSTRACT

Many extensions to the Standard Model predict the existence of new, massive, long-lived particles. Such heavy particles produced in proton-proton collisions at center-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ are expected to move significantly slower than the speed of light as they traverse a detector. As a charged particle passes through a material, the amount of energy it loses via ionization is related to its speed. This property can be used to identify slow-moving particles. A heavy, charged, long-lived particle should be identifiable in a detector as a trajectory with high momentum and anomalously large ionization energy loss. The first search for heavy, charged particles using ionization energy loss in the full ATLAS Run 2 dataset observed an excess with a global significance of 3.3σ at high mass. We discuss these results and present a followup search for slow-moving particles in 140 fb^{-1} of ATLAS Run 2 data. This new search expands the analysis strategy by incorporating a second measure of particle speed, time-of-flight measurements, to significantly reduce background and improve sensitivity to heavy, charged, long-lived particles. Results are interpreted in terms of supersymmetric models that predict long-lived gluinos, charginos, and sleptons.

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1

Introduction

The Standard Model of particle physics leaves many questions unaddressed, motivating a wide array of Standard Model extensions that offer solutions to these problems and predict new particles as a result. Many of these models predict the existence of charged particles that have macroscopic lifetimes and are heavy relative to existing Standard Model long-lived particles. Since such particles would traverse some or all of a typical detector before decaying, their properties can be directly mea-

sured as they interact with detector materials. These properties, such as momentum and speed, can be used to reconstruct a mass for the particle, allowing us to search for high-mass long-lived particles in collider experiments.

This thesis presents a search for heavy, charged, long-lived particles in 140 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton-proton collision data collected by the ATLAS experiment in Run 2 of the Large Hadron Collider. Chapter 2 describes the Standard Model and motivates searches for new massive, charged, long-lived particles. Chapter 3 describes the Large Hadron Collider and the ATLAS experiment, which are used to collect the dataset that is studied in this search. Triggering and object reconstruction in the ATLAS experiment are discussed in Chapter 4.

New heavy long-lived particles are expected to be slow-moving relative to light Standard Model particles at high momenta. This search uses two methods of determining particle speed to identify slow-moving, and thus heavy, long-lived particles. Measurements of ionization energy loss in silicon pixel tracker and time-of-flight in the hadronic calorimeter are used to determine particle speed. Chapter 5 details the measurements of ionization energy loss and time-of-flight that are used in this search.

The two independent measurements of particle speed, in combination with a momentum measurement, are used to reconstruct two masses for each particle. Chapter 6 describes the set of requirements placed on the ATLAS Run 2 dataset that are designed to select high-momentum, slow-moving particles. The use of the two reconstructed masses to extract the highest possible sensitivity to new massive particles is also discussed.

As measurements of ionization energy loss and time-of-flight are sensitive to detector conditions

and not well-modeled by simulation, the predicted background mass distribution is constructed using a data-driven method. The background estimation procedure is discussed in Chapter 7. The systematic uncertainties on the background prediction are detailed in Chapter 8.

Finally, the data selected through the criteria described in Chapter 6 is compared to the background prediction. The results are described in Chapter 9. Chapter 10 concludes the search and describes future work.

Many plots and tables shown in this thesis are adapted from documentation that is internal to the ATLAS Collaboration, ANA-SUSY-2022-12-INT1 [1]. Figures that are adapted from this internal note are marked with a dagger (†) in the caption. The public ATLAS Note ATLAS-CONF-2023-044 ([2]) summarizes the work presented in this thesis.

2

Motivation

The Standard Model of particle physics is a theory that describes the particle content and interactions in our universe. Since its development in the 1970s, the Standard Model has proven robust against tests carried out by experimental physicists for decades.

However, the Standard Model is incomplete- it leaves several fundamental questions unanswered. A wide range of proposed Standard Model extensions offers solutions to these questions. Many of

these Standard Model extensions would require new physics lurking at higher energy scales and new high-mass particles awaiting discovery.

Section 2.1 qualitatively introduces the Standard Model. Section 2.2 describes several open questions that remain unanswered by the Standard Model. Section 2.3 discusses some extensions to the Standard Model that address these questions and propose the existence of new high-mass particles as a result. Section 2.4 describes the current experimental status of searches that probe the models explored in this thesis, including the predecessors that directly motivate the search detailed in this thesis.

2.1 THE STANDARD MODEL

The Standard Model describes the particle content of the universe as well as the interactions that can take place between them. The particles of the Standard Model are shown in Figure 2.1.

Ordinary matter is made up of fermions, or particles with spin $1/2$. The Standard Model contains two types of fermions: leptons and quarks.

The Standard Model contains six leptons organized in three generations as well as their corresponding antiparticles. The three charged leptons are the electron (e), the muon (μ) and the tau (τ), each with electric charge -1 . The positron, antimuon, and antitau have electric charge $+1$. While the electron is a stable constituent of atoms and has a mass of 0.511 MeV, muons have a finite lifetime of $2.2\mu\text{s}$ and a mass ~ 200 times heavier than the electron. Taus have a mass nearly 3500 times the mass of the electron and a lifetime of 2.9×10^{-13} s [3].

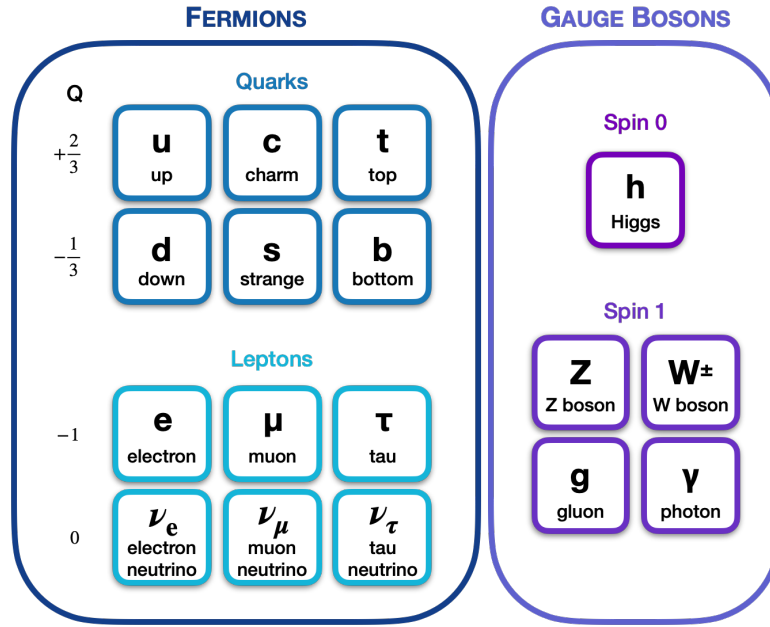


Figure 2.1: The particles of the Standard Model.

Each charged lepton has a corresponding neutrino, which are leptons that do not have electric charge. The Standard Model treats neutrinos as massless. However, results from experiments studying solar and atmospheric neutrinos [4, 5] have indicated that neutrinos have non-zero masses [6], although the mass values have not yet been determined.

There are six quarks in the Standard Model, as well as their six anti-quarks. Quarks, like leptons, are organized into three generations, with each generation more massive than the last. Up-type quarks, or the up, charm, and top quarks, carry electric charge $+2/3$. Down-type quarks (down, strange, and bottom quarks) carry electric charge $-1/3$. Quarks also carry color charge, which allows them to interact via the strong force. Quarks come in three colors (red, green, blue) while anti-quarks carry the corresponding anti-colors (anti-red, anti-green, anti-blue). A bare quark cannot be

observed on its own, and instead must form color-neutral bound states. A bound state of a quark and an antiquark is called a meson, and a colorless bound state of three quarks and antiquarks is called a baryon.

Particle interactions are mediated by bosons with spin 1. Two charged W bosons ($W^\pm$) and one neutral Z boson are the carriers of the weak force. The W and Z bosons are massive, with masses measured at 80.4 GeV and 91.2 GeV, respectively [3]. The photon (γ) is the carrier of the electromagnetic force and is massless. The gluon (g) is the carrier of the strong force, and is also massless. The gluon also carries color charge.

Particles that carry electric charge can interact via the electromagnetic force. This includes all quarks and the charged leptons. Particles that carry color charge, quarks and gluons, can interact via the strong force. The neutrinos, which do not carry electric charge or color charge, can only interact with other particles through the weak force. All fermions can interact via the weak force.

The Higgs boson, discovered in 2012 by the ATLAS and CMS Collaborations at the Large Hadron Collider (LHC), is the most recently discovered Standard Model particle. It is also the only fundamental particle with spin 0. The Higgs boson is responsible for giving mass to other particles. The W and Z bosons acquire mass through the Higgs mechanism as a result of electroweak symmetry breaking. Quarks and charged leptons acquire mass through Yukawa couplings to the Higgs field [7].

The dynamics of the Standard Model can be described by a Lagrangian with 19 parameters. These parameters include the masses of the Higgs boson, the 3 charged leptons, and the 6 quarks. The other parameters are 3 quark mixing angles, the coupling constants of the electromagnetic,

weak, and strong forces, a CP-violating phase, the Quantum Chromodynamics (QCD) Θ_{QCD} term, and the vacuum expectation value of the Higgs field [7–9].

2.1.1 NOTE ON PARTICLE LIFETIMES

Figure 2.2 shows the masses and proper lifetimes of selected Standard Model particles. Standard Model particles span a wide range of lifetimes, from the W and Z bosons with a proper lifetime on the order of 10^{-25} seconds to electrons, which are stable.

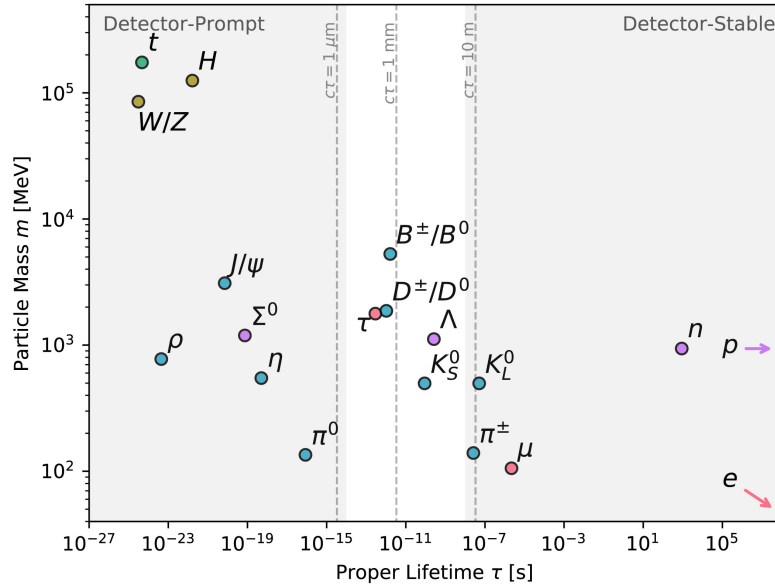


Figure 2.2: Standard Model particles as a function of mass and proper lifetime. The shaded regions represent the length scales of a typical detector [10].

The shaded regions represent the length scale of a typical detector, and demonstrate the typical distance that a particle would travel before decaying, in the absence of interactions with material. *Detector-prompt* particles decay so quickly after they are produced that a typical detector would be

unable to resolve their flight distance from the point of production. A *metastable* particle survives long enough that its flight distance can be resolved from the point where it was produced, or long enough that it decays within the detector volume. A *detector-stable* particle survives the length scale of a typical detector without decaying. The terminology *long-lived* describes particles that have a lifetime such that they travel macroscopic distances before decaying.

A particle is stable if its decay into lighter particles would violate the conservation of some conserved quantity. For example, the electron is stable because there is no lighter Standard Model particle available that is electrically charged, and the decay of an electron would violate the conservation of electromagnetic charge. Without a symmetry or conservation law preventing a decay, a particle will decay into lighter particles. The time scale of this decay is determined by the proper lifetime of the particle, which is driven by many factors. The lifetime τ of a particle is the inverse of its decay width Γ , defined as:

$$\tau^{-1} = \Gamma = \frac{1}{2m} \int d\Pi_f |\mathcal{M}(m \rightarrow \{p_f\})|^2 \quad (2.1)$$

where m is the mass of the particle, $\mathcal{M}$ is the matrix element for the decay to decay products with momentum p_f , and $d\Pi_f$ is the Lorentz-invariant phase space for the particle's decay [10].

A variety of mechanisms can lead to long-livedness. From Equation 2.1, we can see that a long lifetime can be produced by a small matrix element $\mathcal{M}$ or a small Lorentz-invariant phase space $d\Pi_f$ for the available decays.

A small Lorentz-invariant phase space could occur if the particle and the next-lightest particle it

could decay to are nearly mass-degenerate. Such small mass splittings between particles can occur when the particles are related by an approximate symmetry. If there is no other lighter particle to decay to without violating conservation laws, a small mass splitting with respect to the next available lighter particle will lead to a long particle lifetime.

A small matrix element can be the result of a small coupling constant. A small matrix element could also arise from a decay via a mediator that is much more massive than the particles involved. The intermediate particle would be highly virtual, suppressing the matrix element. If the only decay modes available are through a highly virtual intermediate state, the particle will have a long lifetime. This is the cause of the long lifetime ($2.2\mu\text{s}$) of the muon, which has a mass of 106 MeV decays via the W boson, which is ~ 800 times heavier.

2.2 BEYOND THE STANDARD MODEL

Although the predictions of the Standard Model have withstood decades of tests, the Standard Model still leaves many questions unaddressed. Experiments have also observed phenomena for which the Standard Model offers no explanation.

For example, numerous cosmological observations have indicated the presence of dark matter in the universe. Starting in the 1930s, early calculations of the masses of galaxies and galaxy clusters via Doppler shift measurements of their components did not align with the amount of luminous mass observed [11]. These results were confirmed in the 1980s by Vera Rubin, who found that the rotation curves of 60 galaxies could not be explained by the amount of visible matter, indicating the

existence of invisible mass, or dark matter [12]. This conclusion has been corroborated by observations of gravitational lensing. Other cosmological evidence for dark matter can be found in [11].

A fundamental particle that is colorless, electrically neutral, weakly-interacting, and stable could fill the role of dark matter. The Standard Model offers no such candidate.

The Standard Model also presents a puzzle of scales, offering no explanation of why the gravitational Planck scale (described by a mass on the order of $\sim 10^{19}$ GeV) is so much larger than the next-lowest physical scale, the electroweak scale ($\sim 10^2$ GeV). Related to this question is the *hierarchy problem*, or the question of why the mass of the Higgs boson has been measured at $m_H = 125$ GeV, a mass far below the Planck mass.

The Higgs mass suffers large quadratic corrections (Δm_H^2) due to virtual quantum contributions from the interactions of massive particles with the Higgs field. As the top quark is the heaviest fundamental Standard Model particle, it couples the most strongly to the Higgs field and contributes the largest correction. This correction is proportional to the square of the high-energy cutoff scale of the theory, beyond which the theory may not be valid and a new physics takes over. For lack of a more reachable scale provided by the Standard Model, this cutoff scale is presumably the Planck scale. Through these quantum corrections, the Higgs mass is sensitive to physics at much higher scales [9, 13].

In order to measure such a small Higgs mass, the enormous quantum corrections must be cancelled. This could occur through *fine-tuning*, the very coincidental cancellation of the huge quadratic terms with the bare Higgs mass to result in the Higgs mass that we measure. Or, these contributions could be cancelled or reduced through the contributions of new particles appearing at the $\sim \text{TeV}$

scale. This observation motivates the search for new massive particles at the TeV scale, reachable by the Large Hadron Collider [13].

Since the final piece of the Standard Model was put in place with the discovery of the Higgs boson in 2012, no clear signals of Beyond Standard Model physics at high energy scales have made themselves known. Yet, the Standard Model gives only an incomplete description of the phenomena we observe in our universe, and the open questions surrounding the Standard Model suggest the appearance of new particles at higher masses, perhaps not far above the weak scale.

If such new particles exist, there are several reasons why they may not yet have been detected in the decade of searching at the Large Hadron Collider. They could have very high masses that, unfortunately, lie beyond the reach of current collider energies. It is also possible that they could be produced at such low rates in collision events that we have not yet collected enough collision data to spot them. Or, they could leave signatures in detectors that are difficult to target with current search methods.

One example of this final case is the possibility that the new particles are long-lived. Since Standard Model lifetimes span many orders of magnitude due to a variety of mechanisms, it is reasonable to expect that Beyond Standard Model particles would obey similar mechanisms and span a wide range of lifetimes as well. However, long-lived particles may have escaped detection through search methods that assume the prompt decay of any new massive particles.

In a growing effort in the Large Hadron Collider community to cover this under-explored possibility, new searches are being designed to specifically target long-lived particles. As these searches target particles that may travel through or decay within the detector volume, they often require new

data-taking triggers, custom vertex-finding and track reconstruction algorithms, and a detailed understanding of detector-related effects that may not be well-modeled in simulation.

Searches for long-lived particles with masses on the order of the TeV scale are well-motivated by a variety of models. This thesis focuses on supersymmetric models. Several key supersymmetric scenarios that predict long-lived particles serve as a common basis in which to interpret the results of long-lived particle searches.

2.3 SUPERSYMMETRY

Supersymmetry (SUSY) is a symmetry that relates fermions and bosons. Models with supersymmetry predict the existence of fermionic *superpartners* for Standard Model bosons, and bosonic superpartners for Standard Model fermions.

Such models provide a convenient solution to the hierarchy problem. Fermions and bosons contribute terms with opposite sign to the enormous quantum corrections to the Higgs mass. Introducing bosonic superpartners for Standard Model fermions and vice versa serves to cancel out these problematic corrections and solves the hierarchy problem [13].

In addition, supersymmetric models can provide a candidate for dark matter. In the most general renormalizable and gauge-invariant form, the Lagrangian for a supersymmetric model predicts terms that would lead to the decay of protons to lighter Standard Model particles via a supersymmetric particle [13]. However, proton decay has not been observed experimentally, and constraints on the lifetime of the proton have been set to $>10^{29}$ years [3].

Imposing the conservation of a quantity known as R -parity can resolve this inconsistency. Standard Model particles are assigned even R -parity and their superpartners are assigned odd R -parity. R -parity conservation prevents the decay of protons through superpartners by prohibiting the decay of a superpartner, which has odd R -parity, into only Standard Model particles, which have even R -parity [13].

Another consequence of R -parity conservation is that the decay of the lightest superpartner to Standard Model particles is prohibited. With no lighter superpartners available to decay to, the lightest supersymmetric particle (known as the LSP) is stable. SUSY models that conserve R -parity therefore can provide a ready candidate for dark matter.

The Minimal Supersymmetric Standard Model (MSSM) is the the simplest supersymmetric extension to the Standard Model, adding the only the new particle states and interactions that are necessary for self-consistency. The MSSM incorporates superpartners into the theory by forming a *supermultiplet* of a Standard Model particle and its superpartner [13].

Each quark and lepton has a corresponding superpartner of spin 0. These scalar superpartners are named by prepending an s that stands for *scalar*. The superpartners of leptons are referred to as sleptons, and the superpartners of quarks are referred to as squarks. The fermionic superpartners of the Standard Model bosons are named by adding the suffix *-ino*. For example, the superpartner of the gluon is the spin-1/2 gluino. Supersymmetric particles are denoted with a tilde ($\sim$) over their symbol. For example, the stau or *scalar tau* is denoted by $\tilde{\tau}$.

In the MSSM, the Higgs sector must be expanded to contain two Standard Model Higgs doublets in order to avoid gauge anomalies, and to give mass through Yukawa couplings to up-type

quarks, down-type quarks, and charged leptons. Therefore two Higgs supermultiplets are necessary in the MSSM, where the superpartners of the Higgs bosons are known as higgsinos [13].

Prior to electroweak symmetry breaking, the Standard Model spin-1 gauge bosons are the $W^\pm$, W^0 , and B^0 . After electroweak symmetry breaking, the W^0 and B^0 states mix to form the Z boson and the photon. Similarly, the superpartner gauginos before electroweak symmetry breaking are the $\tilde{W}^\pm$, $\tilde{W}^0$, and $\tilde{B}^0$ states, known as the *winos* and the *bino*. After electroweak symmetry breaking, the wino, bino, and higgsino states mix to form mass eigenstates. The two resulting eigenstates that are electrically charged are known as *charginos*, and are denoted by $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$, where the sparticles are ordered by increasing mass. The other four eigenstates, denoted by $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$, are electrically neutral and are known as *neutralinos* [13, 14].

The particle content of the MSSM is summarized in Figure 2.3.

2.3.1 SUPERSYMMETRY-BREAKING MECHANISMS

If it exists, supersymmetry cannot be an exact symmetry. An exact symmetry would require that (apart from spin) the superpartner particles should have identical properties to their Standard Model counterparts, including mass. In effect, the selectron would have a mass identical to the mass of the electron at 0.511 MeV. However, no such scalar electron of that mass, or any superpartners of the same mass as Standard Model particles, have been discovered.

Therefore, supersymmetry must be a broken symmetry. To account for this, a SUSY-breaking term $\mathcal{L}_{\text{soft}}$ is added to the MSSM Lagrangian:

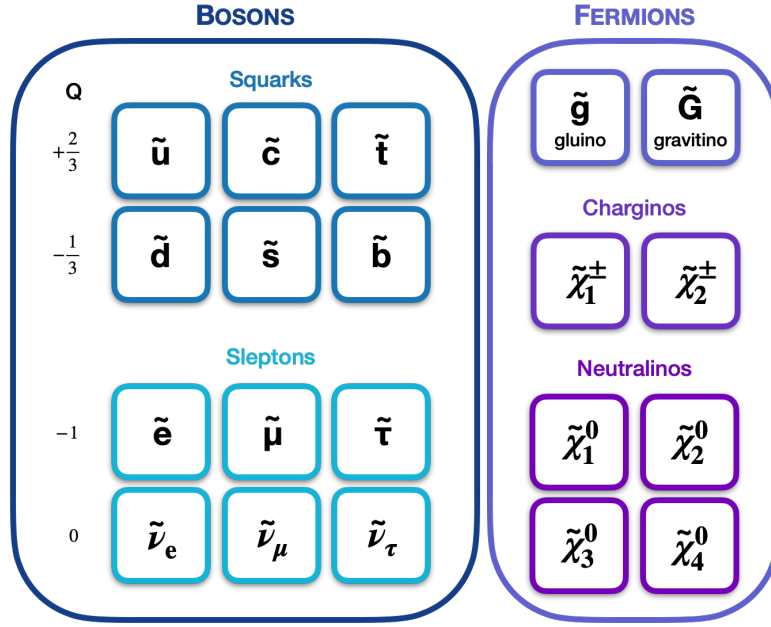


Figure 2.3: The supersymmetric particles of the Minimal Supersymmetric Standard Model. Each Standard Model fermion has a corresponding spin-0 superpartner. There are spin-1/2 partners for Standard Model bosons.

$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}} \quad (2.2)$$

As $\mathcal{L}_{\text{soft}}$ is responsible for supersymmetry breaking, $\mathcal{L}_{\text{soft}}$ governs the extent of the mass splittings between the Standard Model particles and their superpartners. However, SUSY provides a solution to the hierarchy problem only to the extent that the mass-dependent corrections of the superpartners to the Higgs mass cancel the contributions from the Standard Model particles. In order to maintain supersymmetry as a useful solution to the hierarchy problem, the mass splittings between the particles and their superpartners is required to be small. Sufficiently small mass splittings would predict the lightest sparticle masses around the TeV scale [13].

Although a general $\mathcal{L}_{\text{soft}}$ term can be added to the MSSM Lagrangian, the MSSM does not provide an explanation for its origin. Many models have been proposed to extend the MSSM through various spontaneous SUSY-breaking mechanisms. This thesis explores three particular examples of SUSY-breaking scenarios that naturally result in long-lived sparticles that could be detectable at the LHC: Gauge-Mediated Supersymmetry Breaking (GMSB), Anomaly-Mediated Supersymmetry Breaking (AMSB), and Split-Supersymmetry (Split-SUSY).

GAUGE-MEDIATED SUPERSYMMETRY BREAKING

In Gauge-Mediated Supersymmetry Breaking (GMSB), supersymmetry-breaking occurs in a sector that is only linked to the MSSM through messenger fields. These messenger fields communicate SUSY-breaking to the MSSM through gauge boson and gaugino interactions, and the $\mathcal{L}_{\text{soft}}$ term in the MSSM Lagrangian arises due to the loop diagrams of the messenger particles [13, 15].

If the characteristic mass scale of the messenger particles is small compared to the Planck scale, the gravitino becomes very light [13]. Since the gravitino is the Lightest Supersymmetric Particle (LSP), the gravitino is stable if R -parity is conserved. In addition, supersymmetric particles will eventually decay to final states that include the gravitino. The decay rate of a particular supersymmetric particle $\tilde{X}$ into its Standard Model partner X and a gravitino $\tilde{G}$ is given by:

$$\Gamma(\tilde{X} \rightarrow X\tilde{G}) = \frac{m_{\tilde{X}}^5}{48\pi M_P^2 m_{3/2}^2} \left(1 - \frac{m_X^2}{m_{\tilde{X}}^2}\right)^4 \quad (2.3)$$

where $m_{3/2}$ is the mass of the gravitino and M_P is the Planck mass [13]. For the Next-Lightest

Supersymmetric Particle (NLSP), Equation 2.3 constitutes the only possible contribution to the decay width (and therefore to the lifetime) of the NLSP. In GMSB models, the NLSP could easily be a long-lived stau or a long-lived neutralino [14]. If the NLSP is a long-lived stau, it could be observed as a track in a particle detector before it decays to a tau and a gravitino. More details about GMSB can be found in Reference [15].

ANOMALY-MEDIATED SUPERSYMMETRY BREAKING

In the Anomaly-Mediated Supersymmetry Breaking (AMSB) scenario, supersymmetry-breaking is mediated to the Standard Model through a superconformal anomaly [16, 17]. This form of supersymmetry-breaking results in different phenomenological characteristics than GMSB. The lightest superpartners are predicted to be the MSSM gauginos. The gaugino masses can be parameterized as:

$$\begin{aligned} M_1 &= \frac{11\alpha}{4\pi \cos^2(\theta_W)} m_{3/2} \\ M_2 &= \frac{\alpha}{4\pi \sin^2(\theta_W)} m_{3/2} \\ M_3 &= -\frac{3\alpha_s}{4\pi} m_{3/2} \end{aligned} \tag{2.4}$$

where θ_W is the weak mixing angle, $m_{3/2}$ is the mass of the gravitino, α is the electromagnetic coupling constant, and α_s is the strong coupling constant [17]. The gauginos are expected to follow a mass hierarchy such that $|M_2| < |M_1| < |M_3|$ [13].

In AMSB scenarios, the LSP is expected to be a neutralino that is mostly wino in content. The NLSP is predicted to be the lightest chargino. An interesting feature of AMSB scenarios is that the

mass splitting between the NLSP and the LSP is predicted to be small, around 200 MeV [13]. Due to the small phase space available for the chargino decay, the chargino can have a long lifetime. A long-lived chargino can leave a track in a particle detector, forming a signature that can be searched for at LHC experiments. More details about AMSB can be found in Reference [16].

SPLIT SUPERSYMMETRY

In Split-SUSY models, the idea that supersymmetry-breaking must be small is discarded. Supersymmetry-breaking occurs at a scale many orders of magnitude above the TeV scale, and the masses of the squarks and sleptons are placed similarly far above the TeV scale. The resulting mass splittings between the Standard Model fermions and their scalar superpartners are too large for Split-SUSY models to conveniently solve the hierarchy problem. However, these models address other open questions. For example, Split-SUSY models supply a dark matter candidate in the form of a neutralino LSP, and provide a solution to achieve gauge coupling unification [18].

Although Split-SUSY models predict very heavy scalar superpartners, the fermionic superpartners can be protected through chiral symmetries to have masses at the TeV scale [18]. A feature of Split-SUSY models is that the gluino is expected to have a long lifetime. The only decay mode available to the gluino is via an ultra-heavy squark. Such a highly virtual intermediate state suppresses the decay rate of the gluino. The lifetime of the gluino can be estimated as:

$$\tau = 3 \times 10^{-2} \text{sec} \left(\frac{m_S}{10^9 \text{GeV}} \right)^4 \left(\frac{1 \text{TeV}}{m_{\tilde{g}}} \right)^5 \quad (2.5)$$

where m_S and $m_{\tilde{g}}$ are the masses of the squark and the gluino, respectively [19].

A long-lived gluino carries color charge and forms color-neutral bound states with Standard Model partons (quarks or gluons) called R-hadrons. Depending on the composition of the R-hadron, the R-hadron can be electrically charged or neutral, and the exchange of partons as an R-hadron passes through material can produce a change in its electric charge [20]. A long-lived gluino in the form of a charged R-hadron could be visible as a track in a detector at an LHC experiment. More information about Split-SUSY can be found in References [18, 19].

2.4 EXPERIMENTAL STATUS

Many searches for supersymmetric particles have been conducted by collaborations at the Large Hadron Collider (LHC) in Geneva, Switzerland. The current exclusion limits on various supersymmetric particles placed by searches in the ATLAS Collaboration are summarized in Figure 2.4.

These searches are interpreted in terms of simplified models. A simplified model is constructed considering only a subset of particle interactions within a particular supersymmetric model [22]. In Figure 2.4, the “Model” column describes the process within the simplified model considered in each search. The “Signature” column describes the detector signature used as a handle to search for the target process. The blue horizontal bar chart shows the range of masses that have been excluded for the supersymmetric particles considered in each search.

This thesis searches for long-lived particles. The “Long-lived particles” row in Figure 2.4 highlights the long-lived particle searches conducted using the ATLAS experiment. These results are

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2023

ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$

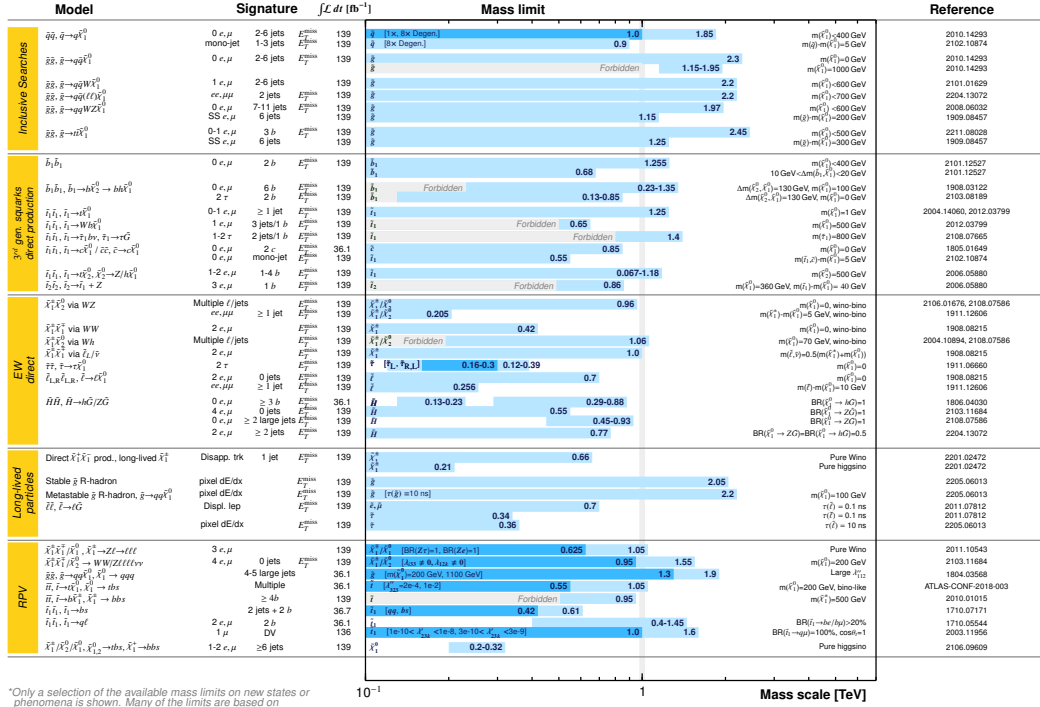


Figure 2.4: The status of ATLAS searches for supersymmetry interpreted in simplified models, as of April 14, 2023. The left column describes the simplified model or process targeted by the search. The signature column describes the signatures that were targeted. The integrated luminosity used in each search is listed. The blue bars in the mass limit plot show the range of targeted particle masses excluded by the search [21].

interpreted in simplified models predicting long-lived charginos, gluinos, and staus. Although the strategies used in some searches may have sensitivity to more generic long-lived particles, these models serve as a common framework for comparing the results of various searches.

A growing long-lived particle search effort seeks to explore a wide range of masses and lifetimes using experiments at the Large Hadron Collider. A detailed review of searches for long-lived particles at colliders can be found in [10]. In addition to ongoing searches at the ATLAS and CMS experiments, complementary experiments dedicated to the detection of long-lived particles have been

proposed at the LHC.

For example, the MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles (MATHUSLA) experiment is a proposed detector that would be placed ~ 60 meters above the LHC collision point where the CMS detector is located. MATHUSLA would be sensitive to the decays of very-long-lived neutral particles, which may escape detection at existing LHC experiments [23]. AN Underground Belayed In-Shaft search experiment (ANUBIS) is another proposed experiment dedicated to detecting long-lived particles. ANUBIS would be situated inside the installation shaft of the ATLAS experiment and would improve LHC sensitivity to neutral particles with decay lengths longer than the typical scale of LHC detectors (~ 10 m) [24].

Searches using the ATLAS detector can be designed to target a variety of long-lived particle signatures. This thesis focuses on searching for charged particles that are either stable or have lifetimes long enough that the particles pass through at least part of the detector before decaying. These long-lived charged particles would be directly detectable through their interactions with detector materials.

Such signatures can be interpreted in terms of gluinos, charginos, and staus. Figure 2.5 shows the current limits set by the ATLAS experiment for gluinos as a function of lifetime and mass, where gluino masses below the curves have been excluded. The simplified model considered assumes that the gluinos are pair-produced and decay to two Standard Model quarks and a neutralino of mass 100 GeV.

In the lifetime range from $\sim 2 \times 10^{-2}$ ns to ~ 4 ns, the strongest limits are set by a search for displaced vertices that would indicate the decays of long-lived particles [25]. The strongest lim-

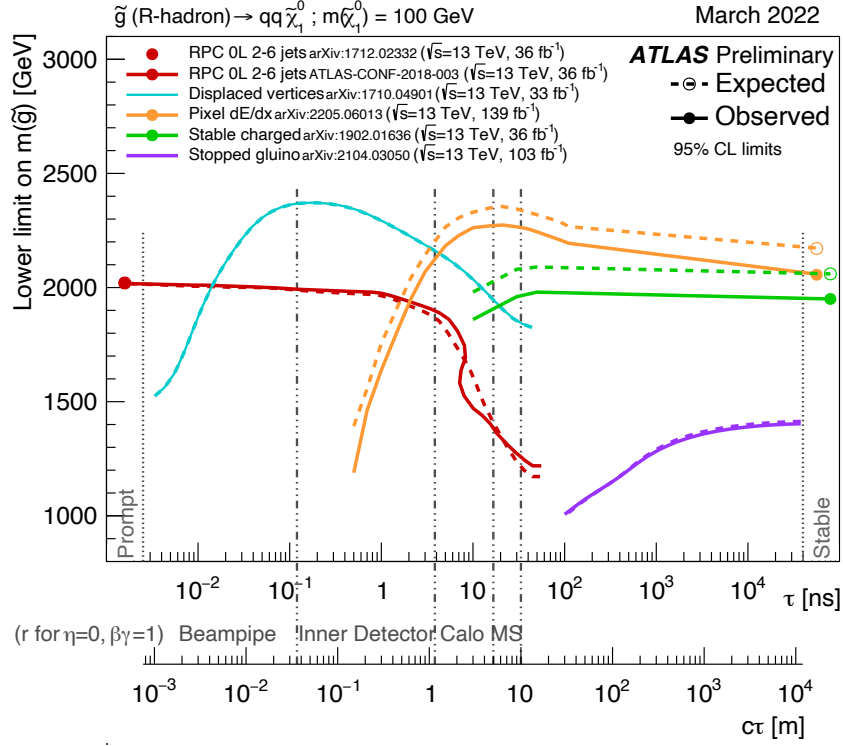


Figure 2.5: The limits placed on long-lived gluinos as a function of mass and lifetime by ATLAS Run 2 searches [21].

its on gluino masses for a lifetime range greater than 4 ns are currently set by a search for highly-ionizing particles in the silicon pixel tracker in 140 fb $^{-1}$ of $\sqrt{s} = 13$ TeV proton-proton collision data [26]. This search is the predecessor to the search described in this thesis, and is referred to as “pixel dE/dx” in Figures 2.4-2.6.

Figure 2.6 shows the current ATLAS limits for charginos in a simplified model that assumes that the chargino decays into a neutralino and a charged pion. For lifetimes below ~ 2 ns, the strongest limit is given by a search for short charged particle trajectories that indicate the decay of a charged particle within the tracking volume [27]. For lifetimes above 2 ns, the strongest limit is set by the

Run 2 pixel dE/dx search.

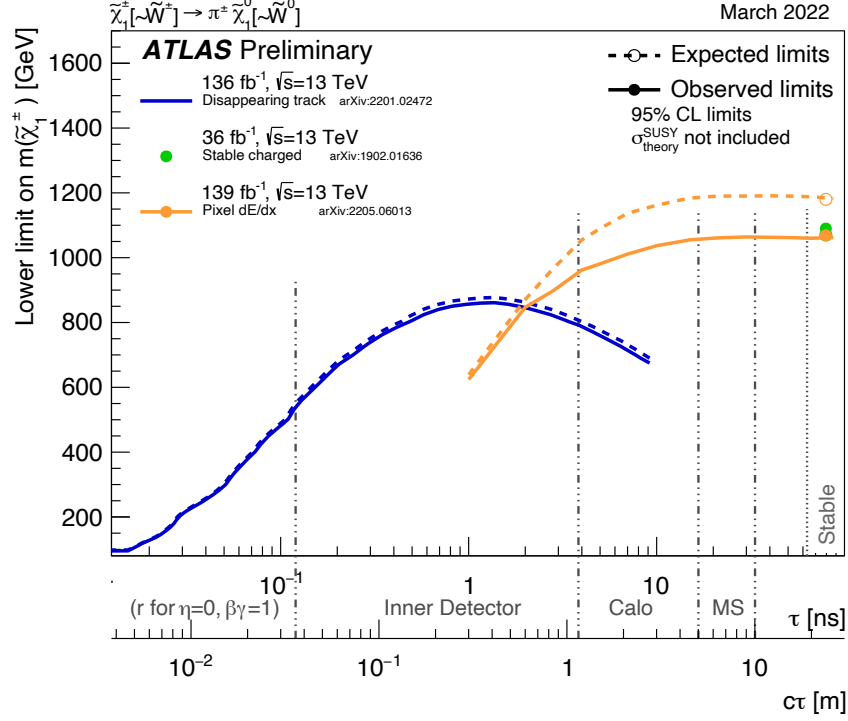


Figure 2.6: The limits placed on long-lived charginos as a function of mass and lifetime by ATLAS Run 2 searches [21].

The current ATLAS limits on staus are shown in Figure 2.4 for a simplified model in which a stau decays to a tau and a gravitino. Staus with a lifetime of 0.1 ns and mass less than 340 GeV have been excluded by a search for the displaced leptons that would result from the decay of a long-lived slepton [28]. Longer-lived staus of lifetime 10 ns with masses up to 360 GeV have been excluded by the pixel dE/dx search.

The search described in this thesis follows up and expands upon the Run 2 pixel dE/dx search described in [26]. The pixel dE/dx search targeted heavy, charged, long-lived particles using ion-

ization energy loss in the ATLAS silicon pixel tracker. As a charged particle passes through material, the amount of energy lost to ionization is related to the speed of the particle, where a large amount of ionization energy loss (referred to as dE/dx) indicates a slower speed. As heavier particles ($\gtrsim \mathcal{O}(100 \text{ GeV})$) are expected to move more slowly than Standard Model particles at high momenta, anomalously high dE/dx can be used as a signature for heavy, charged, long-lived particles.

Using dE/dx as a proxy to particle speed and using momentum reconstructed from the trajectory of a charged particle, a mass can be reconstructed and assigned to each charged particle detected in the search. In this way, the pixel dE/dx search was able to observe the reconstructed mass distributions directly for any hint of new massive particles.

Figure 2.7 shows the pixel dE/dx search result. The mass distribution of data (black points) is compared with the predicted mass distribution of the background (blue histogram). In the mass range $[1100, 2800] \text{ GeV}$, 7 events are observed in data, while only 0.7 ± 0.4 events are expected from background processes. This constitutes an excess of events with a local significance of 3.6σ , and a global significance of 3.3σ [26].

The premise of the pixel dE/dx search was that anomalously high ionization energy loss indicates a high-mass particle moving significantly slower than the speed of light in the high momentum range considered. However, the speed of the particles in the 7 excess events was cross-checked using time-of-flight measurements in the ATLAS calorimeter and muon systems, and was found to be consistent with the speed of light. If the excess is caused by a real new particle, that particle must lose an anomalously high amount of energy via ionization while moving at speeds close to the speed of light. A multiply-charged heavy particle that is boosted could produce this signature [29].

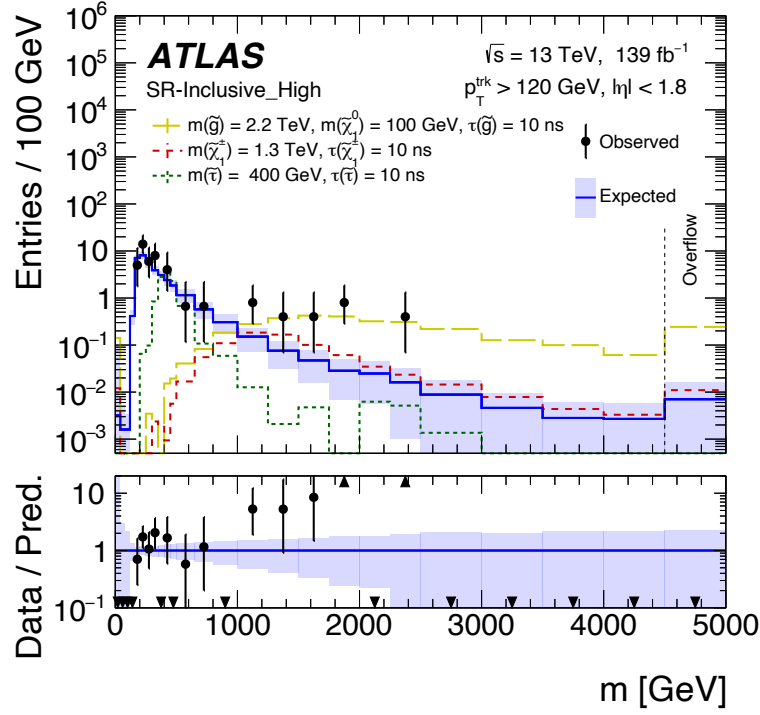


Figure 2.7: The results of the ATLAS Run 2 search for heavy, highly-ionizing particles. The reconstructed mass distribution of the data (black points) is compared to the predicted mass distribution of the background (blue histogram). The simulated expected mass distributions of a 2.2 TeV gluino, a 1.3 TeV chargino, and a 400 GeV stau of lifetime 10ns are shown for comparison [26].

However, the excess could be caused by a statistical fluctuation. Very high dE/dx values are needed to reconstruct the very high masses in the excess range. The high extremum of the dE/dx variable is sparsely populated and could be subject to statistical fluctuations that could significantly affect the result. Another possibility is that the background prediction procedure did not fully capture a physical effect present in the data, and was not able to accurately model the background distribution at high masses.

This thesis presents a search in 140 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ ATLAS Run 2 data for heavy, charged,

long-lived particles using two measures of particle speed: ionization energy loss measured in the silicon pixel tracker, and time-of-flight measured in the hadronic calorimeter. Requiring that a particle has anomalously high dE/dx in conjunction with a low speed measured through time-of-flight makes the search more robust by protecting against statistical fluctuations in either measurement of particle speed. In addition, we incorporate the time-of-flight information into the background estimation procedure to strengthen the background modelling. Finally, the use of a second measure of particle speed significantly reduces the amount of background in the search, allowing greater sensitivity to signals that may have been obscured by background in the pixel dE/dx analysis. We expect to improve sensitivity to sleptons, gluinos, and charginos with lifetimes >10 ns.

3

The LHC and the ATLAS Experiment

The Large Hadron Collider is a circular accelerator with a circumference of 27 kilometers located at CERN, on the border of France and Switzerland. Powerful superconducting magnets bend two circulating beams of protons in opposite directions and bring them into collision at four interaction points around the LHC. The ATLAS, or A Toroidal LHC Apparatus, detector sits at one of the interaction points and records the outcome of the collisions. The ATLAS detector comprises a variety

of subsystems that allow the detection and study of Standard Model particles, as well as searches for physics beyond the Standard Model. This chapter provides an overview of the LHC and the ATLAS detector.

3.1 THE LHC

The Large Hadron Collider is the final ring in a multistep system of accelerators at CERN, shown in Figure 3.1. Protons obtained by stripping hydrogen atoms are accelerated to an energy of 50 MeV in the linear accelerator Linac2. Then, these protons are injected into the Proton Synchrotron (PS) Booster, where they are accelerated to an energy of 1.4 GeV before being sent to the PS, where the beam is accelerated to an energy of 25 GeV. The proton beam is then fed into the Super Proton Synchrotron (SPS), where it is accelerated to an energy of 450 GeV [30].

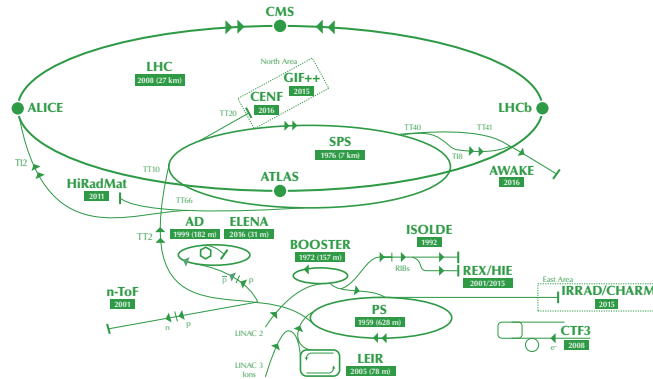


Figure 3.1: A diagram of the CERN accelerator complex [30].

Finally, the protons are delivered to the LHC in two counter-rotating beams, where they are accel-

erated to an energy of 6.5 TeV in 8 radiofrequency cavities, or RF cavities [30]. RF cavities accelerate the protons via oscillating electromagnetic fields while keeping protons organized in bunches. Each bunch contains $\sim 10^{11}$ protons, and the bunches are spaced 25 nanoseconds apart, or about 7.5 meters. A detailed explanation of the RF cavities and the design of the LHC can be found in [31].

The proton bunches are kept in a circular orbit in the LHC ring using 1232 8-T superconducting dipole magnets supercooled to 1.9 K with superfluid helium. 392 quadropole magnets serve to focus the beams.

Instantaneous luminosity is a measure of collision density at a collider. Instantaneous luminosity is dependent on beam parameters through Equation 3.1:

$$L = f \frac{N_1 N_2}{4\pi\sigma_x\sigma_y} \quad (3.1)$$

where N_1 and N_2 are the number of proton in each colliding bunch, f is the bunch crossing frequency, and σ_x and σ_y describe the gaussian width of the bunch in the direction transverse to beam travel. A more tightly focused beam, an increased number of protons in each bunch, or increased frequency of bunch crossings will lead to increased instantaneous luminosity.

At the interaction point, a single proton bunch has a 3-dimensional gaussian profile with $\sigma_x \approx \sigma_y \approx 20 \mu\text{m}$, with a length σ_z of approximately 7.5 cm [31]. The design instantaneous luminosity of the LHC is $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [30].

A single crossing of two proton bunches is referred to as an *event*. For each bunch crossing, many simultaneous collisions occur. Collisions other than the most energetic inelastic collision in the

event are referred to as *pileup*.

During Run 2 of the LHC, which took place in the years 2015-2018, proton bunches collided with a center-of-mass energy of 13 TeV and a bunch spacing of 25 ns. Over the course of Run 2, the ATLAS detector recorded a total integrated luminosity of $140.1 \pm 1.2 \text{ fb}^{-1}$ that is usable as physics data. This thesis uses this Run 2 dataset collected by the ATLAS detector.

3.2 ATLAS

The ATLAS detector is a large cylindrical multipurpose particle detector measuring 44 meters in length and 25 meters in diameter. A diagram of the ATLAS detector is shown in Figure 3.2.

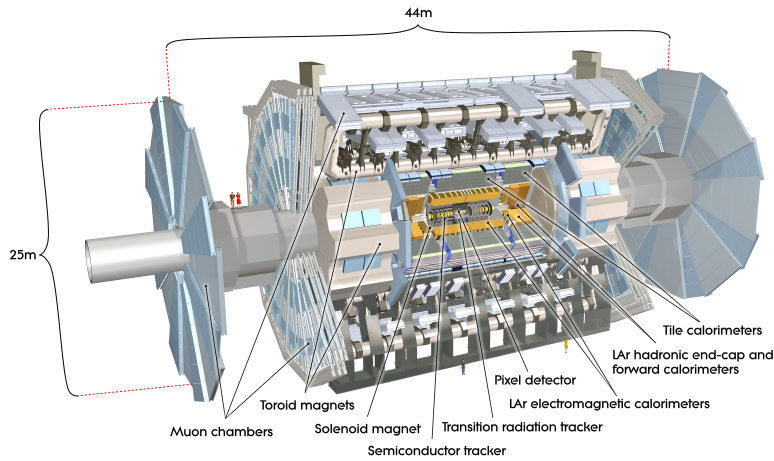


Figure 3.2: A diagram of the ATLAS detector [32].

The ATLAS detector is composed of layers of detector technologies designed to identify particles emerging from proton-proton collisions and measure their momentum and energy. The Inner Detector tracking system is located closest to the beam line, where the collisions occur. The Inner De-

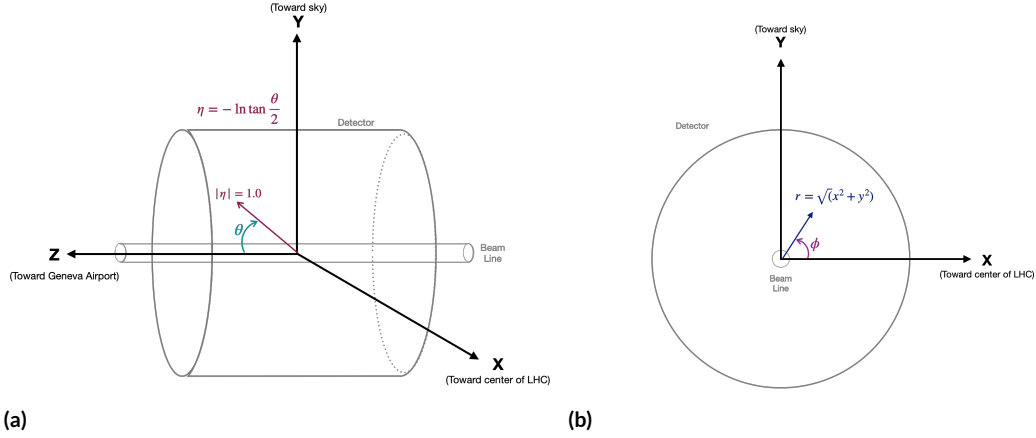


Figure 3.3: Diagrams showing the coordinate system of the ATLAS detector. a) shows the definition of x , y , z , θ , and η . b) shows the definition of r and ϕ .

ector is immersed in a 2T magnetic field from a superconducting solenoid to bend the trajectories of charged particles within the tracker. Outside of the solenoid, the electromagnetic and hadronic calorimeters measure the energy of particles that shower electromagnetically or hadronically. Finally, the outermost detector layers form the muon system, which provides tracking information for any charged particles surviving the calorimeters. A 4T air-core toroidal magnet system provides a magnetic field to the muon system, bending the trajectories of charged particles to aid momentum reconstruction.

The coordinate system of the ATLAS detector is depicted in Figure 3.3.

The detector uses a right-handed cartesian coordinate system stemming from the interaction point at the center of the detector, where the x axis points to the center of the LHC, the y axis points upward, and the z axis points in the direction of the beam line toward the airport in Geneva, Switzerland. As the ATLAS detector is roughly cylindrical in shape, the detector lends itself well to

polar coordinates. These coordinates are r , θ , and ϕ , where $r = \sqrt{x^2 + y^2}$ represents the transverse distance from the beam line, ϕ is the angle from the x-axis in the plane transverse to the beam axis, and θ is the polar angle measured from the z axis.

The plane transverse to the beam axis (x-y or r - ϕ plane) is particularly useful for defining physics quantities. Due to momentum conservation, the total momentum before the collision between the partons, or components of the protons, will equal the total momentum of the collision products. However, as we do not know what fraction of the proton momentum is carried by each parton involved in the collision, the final momentum along the beam axis is unknown. In contrast, the partons have negligible momentum in the transverse plane, and therefore the sum of momenta of the collision products in the transverse plane will be zero. It is therefore useful to examine the projections of variables in the transverse plane. One commonly used quantity is $p_T = p \sin \theta$, or the component of momentum transverse to the beam line.

The quantity *pseudorapidity*, denoted by η , is used to describe angles relative to the z axis of the detector. Pseudorapidity is related to the polar angle θ through the relation:

$$\eta = -\ln \tan \frac{\theta}{2} \quad (3.2)$$

A polar angle of 90 degrees corresponds to $\eta = 0$, and a polar angle of 0 degrees corresponds to $\eta = \infty$.

The “pseudo” prefix refers to another quantity used in particle physics: rapidity, given by $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$, where E is the energy of the particle and p_z is its momentum along the beam line. Ra-

rapidity is a useful quantity because changes in y are Lorentz-invariant to boosts along the z axis.

Rapidity reduces to pseudorapidity in the case where the particle is massless. As pseudorapidity depends only on θ , any location in the detector can be fully described by r , η , and ϕ .

Because of the cylindrical shape of ATLAS, one refers to the *barrel* and *endcap* components of detector systems. The barrel region is the central cylindrical portion, roughly covering the region $|\eta| < 1.0$ depending on the subsystem, and the components referred to as endcap detectors provide coverage for the region approximately $1.0 < |\eta| < 3.0$.

The following sections describe the various subsystems in the ATLAS detector. As the Tile Calorimeter and the Pixel detector provide measurements that are of particular importance to this thesis, these detector systems will be emphasized in detail.

3.3 INNER DETECTOR

The Inner Detector (ID) is the tracking system closest to the beam pipe, which is located at a radius of 24.3mm [33]. The ID is situated in the range $3\text{cm} < r < 1\text{m}$ and provides tracking coverage for $|\eta| < 2.5$. The purpose of the ID is to detect the passage of charged particles with spatial precision to aid in track, vertex, and momentum reconstruction. Moving outward from the beam line, the ID is composed of silicon pixels, followed by the Semiconductor Tracker, and finally the Transition Radiation Tracker. A diagram showing the radial placement of these subsystems of the ID is shown in Figure 3.4.

The primary vertexing resolution of the ID can be used as a benchmark of its tracking perfor-

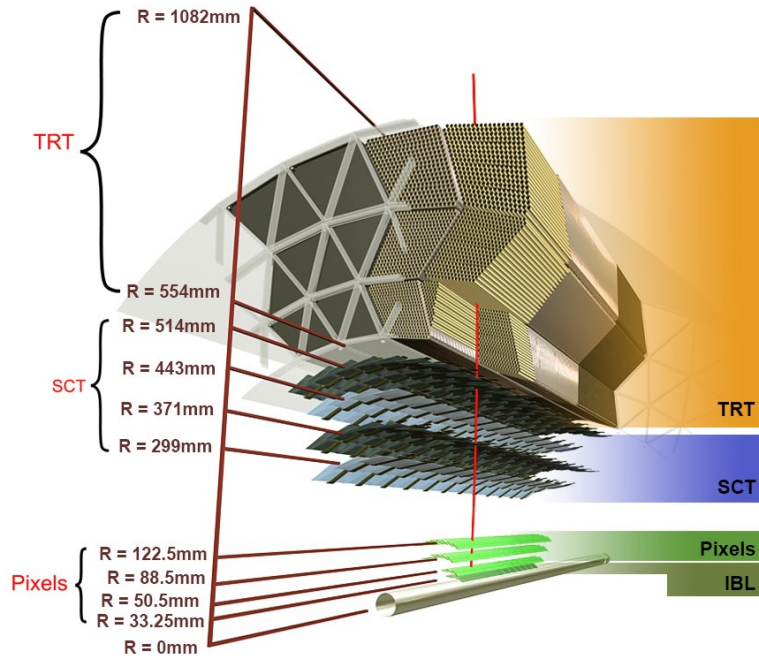


Figure 3.4: A diagram of the subsystems of the ATLAS Inner Detector in the barrel region [34].

mance. Tracks in the ID are associated to primary vertices to pinpoint the position of a proton-proton interaction. In Run 2, the ID allowed the identification of primary vertices with a resolution of ~ 0.07 mm in the x and y directions, and ~ 0.15 mm in the z direction, for vertices associated to between 5 and 10 tracks [35].

This section describes the Pixel detector, the Semiconductor Tracker, and the Transition Radiation Tracker.

3.3.1 PIXELS

In the Pixel tracker, small silicon sensors record information about the trajectory of charged particles. As a charged particle passes through a silicon sensor, it ionizes atoms, creating electron-hole pairs. These electrons and holes travel through the sensor due to an electric field and induce a signal. For example, a muon with a momentum of 300 MeV creates approximately 20,000 electron-hole pairs in 250 μm of silicon [36]. Front-end electronics process the resulting signal. If the signal exceeds a programmable threshold, the passage of the charged particle constitutes a *hit*.

The Pixel subsystem of the ID is composed of four barrel layers of silicon pixels and three pixel layers in each endcap. During Run 1, the pixel detector contained only three barrel layers, and was designed to withstand particle rates at the LHC design instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The B-Layer, Layer-1, and Layer-2 were placed at radii of 5, 8.9, and 12.2 cm, respectively.

However, as the LHC instantaneous luminosity was expected to double in Run 2, a fourth pixel layer was inserted at a radius of 3.3 cm from the beam line to cope with the increased particle rate. Because it was developed and added separately, this additional layer, known as the Insertable B Layer or the IBL, has different pixel properties and readout compared to the other three barrel pixel layers. The layout of the pixel detector is shown in Figure 3.5.

The original pixel layers contain 1744 modules mounted on 160 carbon-fiber support structures called staves. Each module contains 46,080 n^+n^- silicon pixel cells [37], resulting in a total of approximately 67 million silicon pixels in the barrel and 13 million pixels in the endcaps. The sensors in the endcap disks and original 3 barrel layers form a total active surface area of 1.73 m^2 , providing

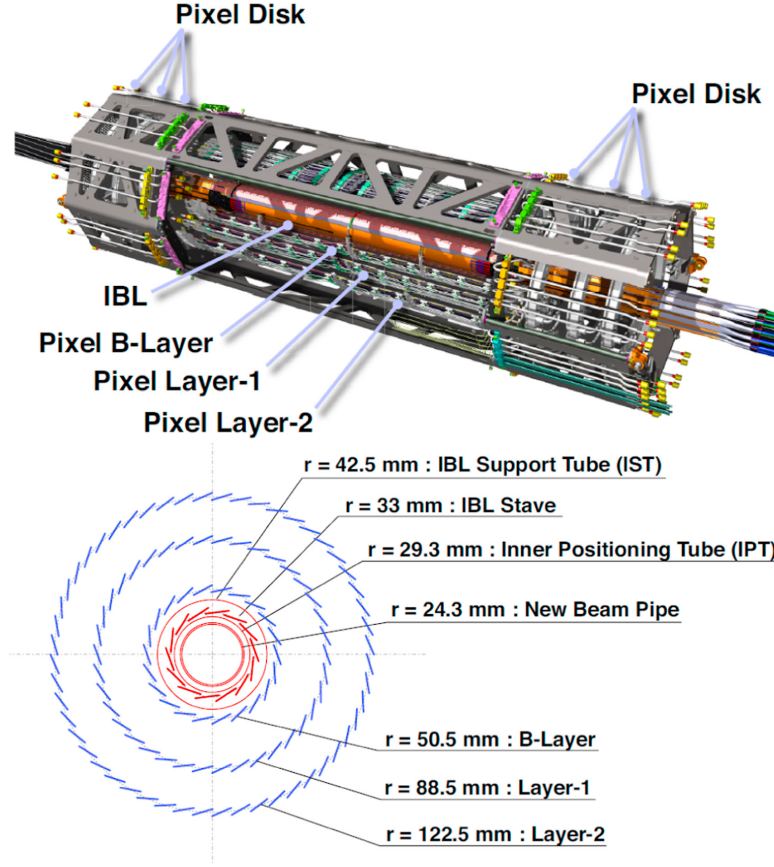


Figure 3.5: A diagram of the pixel detector and the radii of the barrel pixel layers, including the IBL [33].

coverage in the region $|\eta| < 2.5$. Each pixel measures $400 \mu\text{m}$ in the z direction (for the barrel sensors) or r direction (for the endcap disks) and $50 \mu\text{m}$ in the ϕ direction, each with a thickness of $250 \mu\text{m}$ [38]. The pixel tracker achieves a spatial resolution of $8 \mu\text{m}$ in the r - ϕ direction and $75 \mu\text{m}$ in the z direction [39].

The IBL is composed of 14 carbon-fiber staves with 20 modules mounted on each stave. 12 of these modules contain planar silicon sensors, similar to the original pixel layers. The other 8 modules, located on the ends of each stave, contain 3D silicon sensors. The 3D sensors were developed

to withstand high radiation environments and offer the advantage of a shorter drift time due to columnar electrodes embedded in the sensor perpendicular to the sensor surface [40]. The layout of the planar and 3D modules on each stave as well as the layering of the staves around the Inner Support Tube are shown in Figure 3.6.

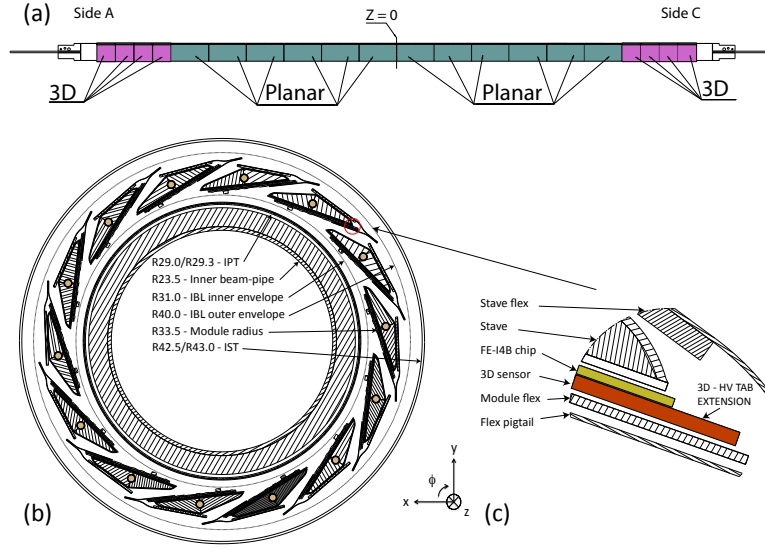


Figure 3.6: The structure of the IBL. a) The placement of planar and 3D modules along a stave, which extends a total of 330 mm longitudinally. b) An r - ϕ view of the orientation of staves between the Inner Positioning Tube (IPT) and the Inner Support Tube (IST). c) The placement of a 3D sensor and front-end chip FE-14B on a stave [40].

The IBL contains a total of approximately 12 million pixels and provides coverage in the region $|\eta| < 3.0$. The total active surface area of the IBL sensors is 0.15 m^2 . To reduce occupancy and provide a more powerful vertexing resolution in a high particle rate environment, these pixel cells are smaller than those of the original pixel layers. The IBL pixels measure $50 \text{ }\mu\text{m}$ in the ϕ direction and $250 \text{ }\mu\text{m}$ in the z direction. The planar sensors measure $200 \text{ }\mu\text{m}$ in thickness, while the 3D sensors have a thickness of $230 \text{ }\mu\text{m}$ [40].

A charged particle traversing the pixel sensor induces a signal current that is shaped and amplified in the front-end electronics. Relative to a 40 MHz LHC clock, the time that this signal exceeds a threshold is called Time over Threshold (ToT), and is related to the amount of charge collected [38].

In the original pixel layers, the sensors in each module are read out through 16 FE-13 front-end chips [38]. A typical hit threshold during Run 2 for the original pixel layers corresponds to approximately 3500 electrons [39]. 8 readout bits are devoted to ToT information, which means that the dynamic range covers up to approximately 200,000 electrons [26]. If the collected charge exceeds the dynamic range of the ToT readout, the hit is lost and not recorded [38].

The sensors in each stave of the IBL are read out through 32 FE-14B front-end chips, which are designed to be radiation-hard [40]. The hit threshold during Run 2 corresponds to approximately 2500 electrons. In the IBL, only 4 readout bits are devoted to ToT information, which corresponds to an upper limit of the dynamic range at approximately 30,000 electrons [26]. However, if the deposited charge exceeds the ToT dynamic range, an overflow bit is set. Although the precise amount of charge is unknown, the hit is still recorded [40].

The differing readout electronics of the original pixel layers and IBL will affect the interpretation of the ToT information in this thesis, and special consideration is taken to ensure proper handling of the IBL overflow bit.

3.3.2 SEMICONDUCTOR TRACKER

The Semiconductor Tracker, or SCT, is a silicon strip tracker designed to obtain precision measurements of particle trajectories in the r - ϕ coordinate. The working principle of a silicon strip detector

is similar to that of a silicon pixel detector, in which a charged particle traversing the silicon sensor creates electron-hole pairs. The electrons and holes drift through the sensor due to an applied electric field, and induce a signal that can be recorded as a hit in that sensor.

The SCT is composed of 4 cylindrical barrel layers as well as 9 disk layers in each endcap. The barrel layers surround the pixel detector and sit at radii of 299 mm, 371 mm, 443 mm, and 514 mm. The barrel layers provide tracking coverage for the region $|\eta| < 1.4$, and the endcap disks cover the region $1.4 < |\eta| < 2.5$ [41].

The module is the building block of the SCT detector. Each module is composed of 4 silicon sensors that measure $285 \mu\text{m}$ in thickness. Each sensor contains 770 strips of pitch $80 \mu\text{m}$ and length of 6 cm. The 4 sensors on each module are arranged as shown in Figure 3.7. A pair of silicon sensors is attached via wirebonding such that their strips of length 6 cm form readout strips of length 12 cm. A second pair of wirebonded silicon sensors is glued on the other side of a thermal plate, at an angle of 40 mrad to the first pair of sensors. The angled placement of the second pair of sensors relative to the first pair allows the determination of the position of a hit in the direction of the length of the strips. ABCD readout chips are situated on a hybrid and readout the channels on each pair of sensors [42].

The barrel layers contain a total of 2112 modules. The modules are arranged such that the length of the strips is oriented along the z coordinate. There are 988 modules per endcap, where the modules are shaped trapezoidally and form three rings at increasing radii on each disk [42].

The silicon sensors of the SCT amount to an active area of 61 m^2 and 6.2 million readout channels, with 3 million strips in the endcaps and 3.2 million strips in the barrel [41]. The SCT achieves

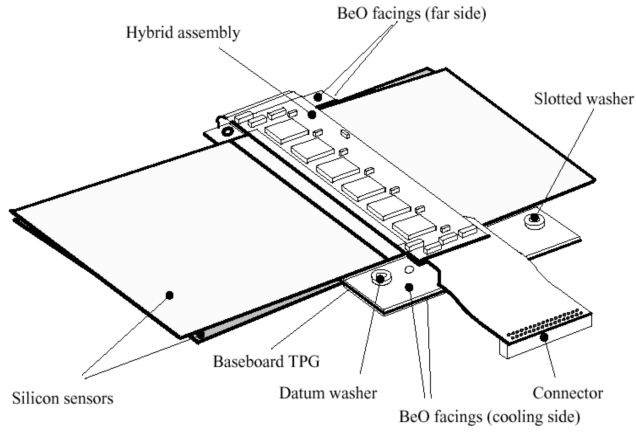


Figure 3.7: The layout of the SCT barrel modules. A pair of silicon sensors is attached lengthwise via wirebonding such that their strips of length 6 cm form readout strips of length 12 cm. A second pair of wirebonded silicon sensors is glued on the other side of a thermal plate, at an angle of 40 mrad to the first pair of sensors. Readout chips are hosted on a hybrid. [43]

a spatial resolution of $20\ \mu\text{m}$ in the r - ϕ direction and $580\ \mu\text{m}$ in the z direction [42]. This spatial precision allows tracks $\sim 200\ \mu\text{m}$ apart to be distinguished [41].

3.3.3 TRANSITION RADIATION TRACKER

The Transition Radiation Tracker, or TRT, is composed of drift tubes that provide tracking information. The TRT also uses transition radiation to identify electrons.

A charged particle passing through a drift tube ionizes gas molecules. The freed electrons drift toward an anode wire suspended in the center of the tube due to a voltage applied to the anode wire. Close to the wire, where the electric field is strongest, the drifting electrons ionize other gas molecules, forming an avalanche of electrons. The avalanche of electrons traveling toward the wire and the positively charged gas ions drifting away from the wire induce a signal current on the anode

wire, allowing the detection of a charged particle passing through the drift tube.

Transition radiation is emitted when a highly relativistic particle traverses a boundary between materials with different dielectric constants. The probability to emit transition radiation is proportional to the Lorentz factor $\gamma = E/m$. As the electron mass is two orders of magnitude smaller than the muon mass, the next lightest Standard Model particle, electrons have a much higher Lorentz factor than other particles of the same energy. Transition radiation from other particles is therefore suppressed by at least two orders of magnitude compared to electrons. This allows the identification of electrons by emission of transition radiation.

The TRT contains 298304 carbon-fiber-reinforced kapton straws that each measure 4 mm in diameter. The straw tube wall is 70 μm thick and is kept at a potential of -1530 V relative to the gold-plated tungsten anode wire measuring 31 μm in diameter. The gas mixture used in most tubes is 70% Xe, 27% CO_2 , and 3% O_2 . In Run 2, the Xenon gas mixture in sections of tubes with gas leaks was replaced with a mixture of 70% Ar, 27% CO_2 , and 3% O_2 [44].

The TRT is divided into barrel and endcap regions. The barrel section covers the radial region $560\text{mm} < r < 1080\text{mm}$ and extends longitudinally over the region $|z| < 712\text{mm}$. The TRT barrel contains 52,544 straws aligned with the z axis and arranged in 73 radial layers. The straws are embedded in polypropylene and polyethylene fibers to produce transition radiation in the form of X-rays. The distance between straws in r and ϕ is approximately 6.8 mm. Each straw has a length of 142.4 cm, but the anode wire is electrically divided such that the halves at positive and negative z are read out separately [44].

The endcap region of the TRT is composed of 122,880 straws oriented to point radially from

the z axis. Each endcap contains two wheels and extends over the region $827 \text{ mm} < |z| < 2744 \text{ mm}$. The endcap straw tubes are 36 cm long and are embedded in polypropylene foil that acts as the transition radiator material [44].

The signal induced on the anode wire by cascading electrons is compared to two thresholds. A low level (LL) threshold is set at $\sim 300 \text{ eV}$ and indicates the passage of a charged particle for tracking purposes. The high level (HL) threshold is typically set at $\sim 6\text{-}7 \text{ keV}$ and indicates high ionization produced by transition radiation, aiding in electron identification. The Time over Threshold (ToT), or the time that the signal spends above a particular threshold, is digitized and read out [44].

The straws in the 9 innermost layers of the barrel region are electrically split into three regions, with only 34 cm on either side read out. Nevertheless, occupancy was a challenge for the TRT in Run 2. Depending on pileup conditions, the TRT straws had an occupancy of up to 90%. Although the TRT readout provides a measure of high ionization, it is not used to identify highly ionizing particles in this search due to gas leak problems and high occupancy in Run 2 that limit the ability of the TRT to flag highly ionizing particles.

Despite the high occupancy, the TRT provides an average of ~ 30 hits per track in the region $|\eta| < 2.0$ with a spatial resolution of $\sim 130 \mu\text{m}$ to aid in tracking and momentum reconstruction [46].

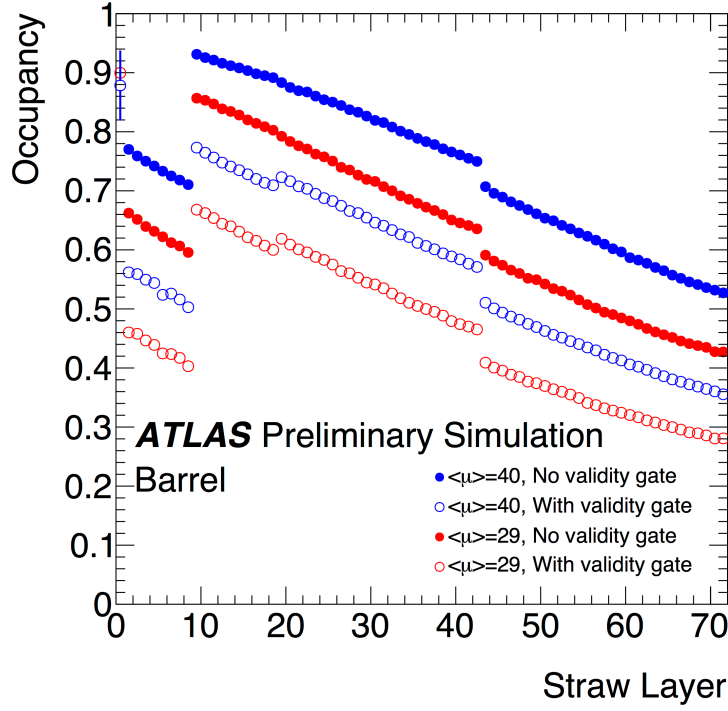


Figure 3.8: The occupancy of the TRT as a function of barrel straw layer for two different pileup conditions: average interactions per bunch crossing $\langle \mu \rangle = 29$ and $\langle \mu \rangle = 40$. The validity gate selects a subset of the 75ns readout window that is used to reconstruct hit information. In 2015 and 2016, a validity gate of 28.125ns was used. The 9 innermost straw layers are divided into three regions, with only 34 cm read out on either side to reduce occupancy [45].

3.4 SOLENOID MAGNET

The ability of the Inner Detector to reconstruct momentum relies on the bending of charged particles in the r - ϕ plane via a 2T axial magnetic field provided by a superconducting solenoid. The solenoid is situated between radii of 1.23 m and 1.28 m with a length of 5.8 m in the z direction. The solenoid material budget was optimized to be as low as possible to avoid interfering with the calorimetry measurements of the Electromagnetic and Hadronic Calorimeters, located outside the

solenoid. The solenoid materials amount to ~ 0.66 radiation lengths. The flux return is provided by the steel of the Tile Calorimeter and its support structures [47].

The radial and z-components of the magnetic field of the solenoid within the Inner Detector at varying radii are shown in Figure 3.9. The 2T magnetic field in the ID is designed to meet a transverse momentum resolution requirement of $\sigma_{p_T}/p_T = 0.05\%p_T \oplus 1\%$ [47].

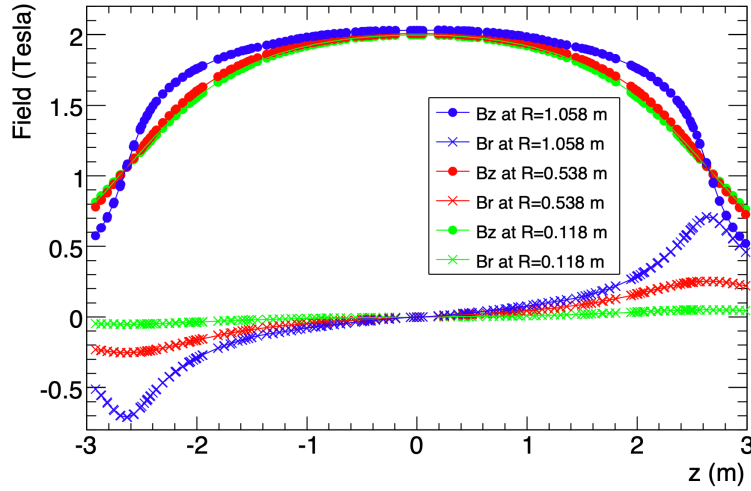


Figure 3.9: The radial and z components of the solenoid magnetic field in the Inner Detector. The axial components of the magnetic field at varying radii converge to 2 T at $z=0$ [47].

3.5 CALORIMETERS

The calorimeter system is designed to contain electromagnetic and hadronic showers and measure their energy. The electromagnetic (EM) calorimeter is composed of lead-liquid argon (LAr) sampling calorimeters in the barrel and endcap regions. The hadronic calorimeter is composed of steel-scintillator barrel and extended-barrel sampling calorimeters as well as LAr calorimeters in the end-

caps and in the forward ($3.1 < |\eta| < 4.9$) region.

A diagram of the calorimeter system in ATLAS is shown in Figure 3.10. The Tile barrel and Tile extended barrel sections of the hadronic calorimeter are collectively referred to as the Tile Calorimeter, and are of particular importance to this thesis.

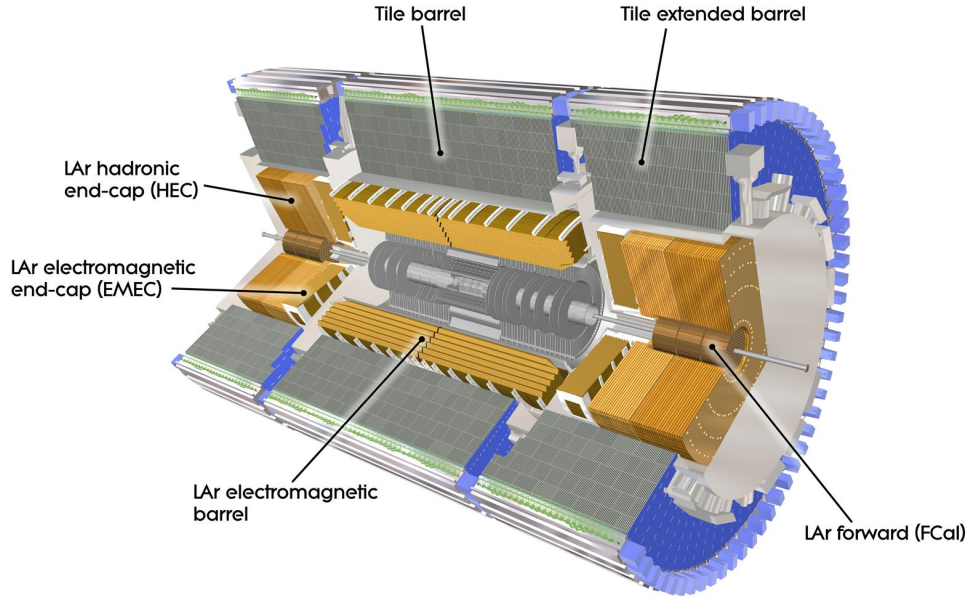


Figure 3.10: The ATLAS calorimeter system [48].

3.5.1 ELECTROMAGNETIC CALORIMETER

The goal of the electromagnetic calorimeter is to contain electromagnetic showers produced by electrons and photons. The electromagnetic (EM) calorimeter is a sampling calorimeter with lead as the absorber material and liquid Argon (LAr) as the active material. The lead absorber plates are

arranged in an accordion shape and provide full azimuthal (ϕ) coverage [47].

The barrel EM calorimeter covers the range $|\eta| < 1.475$. Each endcap EM calorimeter is divided into two wheels which together cover up to $|\eta| < 3.2$. In the region $|\eta| < 2.5$, the EM calorimeter is segmented in three layers. A presampler with $|\eta| < 1.8$ coverage is composed of one active LAr layer 1.1 cm thick in the barrel and 0.5 cm in the endcap [47].

An example barrel EM calorimeter module and the granularities in η and ϕ of the various layers is shown in Figure 3.11.

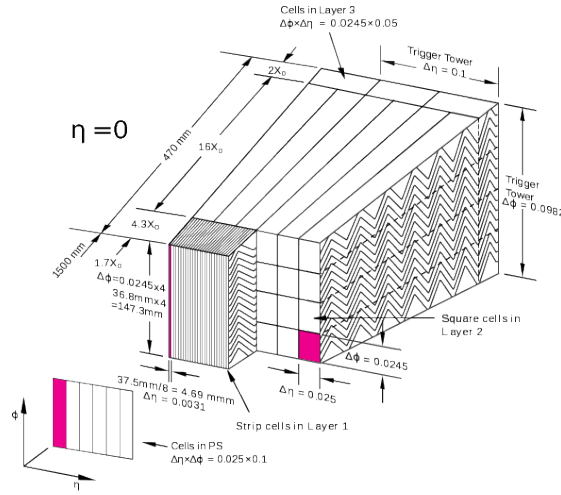


Figure 3.11: A barrel module of the electromagnetic calorimeter. Cells in the presampler (PS), as well as the accordion calorimeter layers are shown [49].

3.5.2 HADRONIC CALORIMETER

The hadronic calorimeter contains two endcap LAr-based sampling calorimeters, a LAr-based forward calorimeter, and the barrel and extended barrel Tile calorimeters. The LAr hadronic endcap

detector (HEC) consists of two wheels per endcap with copper acting as the absorber material. The HEC provides coverage over $1.5 < |\eta| < 3.2$ [47].

The LAr forward calorimeter is located at a range of $3.1 < |\eta| < 4.9$. There are three forward modules in each endcap. The innermost module uses copper as an absorber to measure electromagnetic components of the shower, while the other two use tungsten to measure hadronic interactions [47].

The Tile calorimeter is a hadronic sampling calorimeter composed of alternating layers of steel absorber and active scintillating plates read out by wavelength-shifting fibers. The Tile calorimeter spans the radius $2280 \text{ mm} < r < 4230 \text{ mm}$. The barrel component is 5640 mm long in the z direction and covers a range of $|\eta| < 1.0$. The two extended barrel components each have a length of 2910 mm in the z direction and cover a range of $0.8 < |\eta| < 1.7$. The Tile calorimeter is shown in gray in Figure 3.10. The barrel and extended barrel sections of the Tile calorimeter are separated by a gap of 600 mm, which is necessary to place readout and service cables for the Inner Detector and the LAr EM calorimeter [50].

The basic unit of the Tile calorimeter is the wedge. The steel absorbers in a wedge connect to a steel support structure called a girder, which also houses readout electronics. 64 wedges form a full cylinder in ϕ . A schematic of a wedge is shown in Figure 3.12.

The scintillating tiles are oriented in the r - ϕ plane. Wavelength-shifting readout fibers connect neighboring scintillating tiles to photomultiplier tubes to form a readout *cell*. In the barrel, each wedge contains 46 readout cells. As the cells are read out on each open side of the wedge, this amounts to 96 total readout channels per barrel wedge. The Tile calorimeter contains a total of

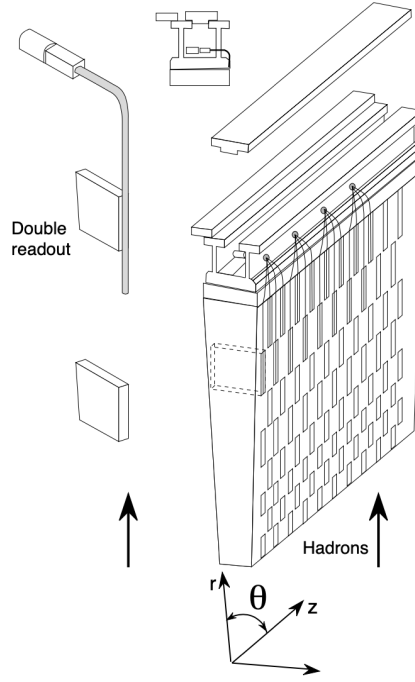


Figure 3.12: A wedge of the Tile Calorimeter. Scintillating tiles oriented in the r - ϕ plane are grouped together with radial wavelength-shifting fibers to form readout cells. The readout is connected on both sides of the tiles [50].

5980 readout channels in the barrel and 3640 readout channels in the extended barrel [50].

The granularity of the Tile calorimeter is 0.1×0.1 in $\Delta\eta \times \Delta\phi$, and the Tile calorimeter is segmented radially in three layers. At $\eta = 0$, the three layers are 1.4, 3.9, and 1.8 nuclear interaction lengths thick, respectively. This granularity achieves an energy resolution of $\Delta E/E = 50\%/\sqrt{E} \oplus 3\%$ for $|\eta| < 3$ [50].

To improve the hermeticity of the Tile calorimeter, an Intermediate Tile Calorimeter (ITC) is inserted in the gap region next to the extended barrel sections. The ITC is composed of a calorimeter plug in the region $0.8 < |\eta| < 1.0$, with active scintillator tiles placed in the region $1.0 < |\eta| < 1.6$ to

maximize active material [50].

An estimated 9 interaction lengths of material are sufficient to contain hadronic showers and limit punchthrough to the muon spectrometer. The amount of material in the Tile Calorimeter in interaction lengths as a function of rapidity is shown in Figure 3.13.

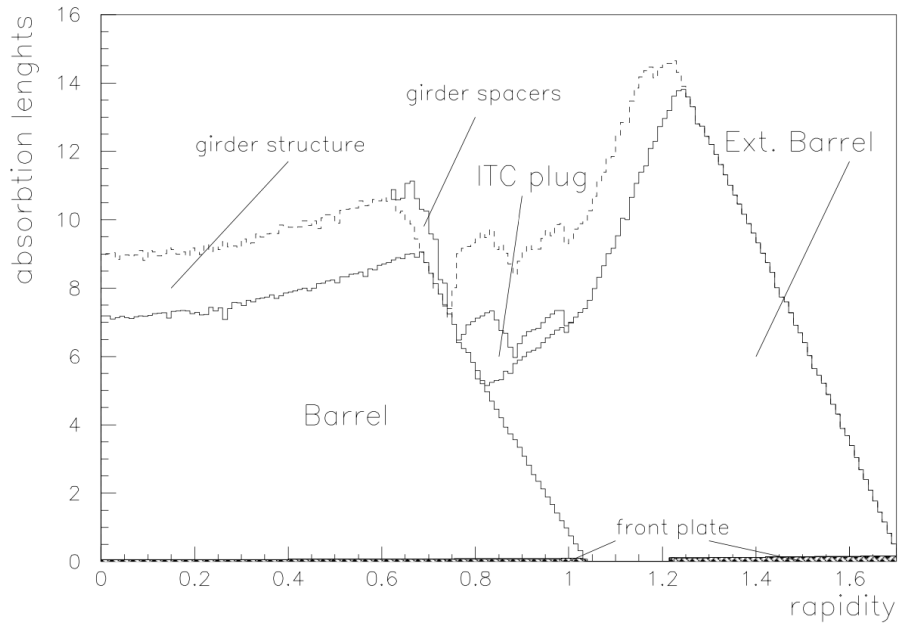


Figure 3.13: The material of the Tile calorimeter as a function of rapidity, as measured in interaction lengths [50].

3.6 MUON SPECTROMETER

The muon spectrometer is designed to identify the trajectories and measure the momenta of muons. As high-momentum final state muons can be indicative of interactions involving massive particles and possibly new physics at the interaction point, the muon spectrometer is equipped with detector

systems with triggering capabilities in addition to detector systems responsible for precision tracking. The muon triggering system is composed of Resistive Plate Chambers (RPCs) in the barrel region and Thin Gap Chambers (TGCs) in the endcaps, covering a region of $|\eta| < 2.4$. Monitored Drift Tubes (MDTs) provide precision tracking in the η direction, which is the direction of bending of charged particles due to the toroidal magnetic field. Close to the beam line, at high η , Cathode Strip Chambers are equipped with higher granularity to obtain precision tracking measurements at high particle rate.

In the barrel region, chambers are arranged in three layers known as *stations*. In each endcap region, three stations are arranged in the plane transverse to the beam line [47]. The layout of the muon spectrometer is shown in Figure 3.14.

The Monitored Drift Tubes (MDT) provide precision tracking in the z direction in the barrel and radially in the endcaps. The drift tubes are made of aluminum with walls $400\ \mu\text{m}$ thick and diameter of 30 mm. The anode wire has a diameter of $50\ \mu\text{m}$. A charged particle passing through the gas mixture, ArCH_4N_2 , ionizes atoms. The resulting electrons drift toward the anode wire held at a potential of 3270 V. Close to the wire, where the electric field is strongest, the electrons cascade and cause a signal pulse on the wire. The maximum drift time of the MDTs is 480 ns. The single-wire spatial resolution of the MDTs is $80\ \mu\text{m}$ [52].

The MDTs are arranged in three barrel layers and three endcap layers. The first layer covers a range of $|\eta| < 2.0$ while the outer layers cover a range of $|\eta| < 2.7$. In total, there are 354,000 MDT readout channels [51].

In the range $2.0 < |\eta| < 2.7$ and close to the beam line, a higher granularity detector is required

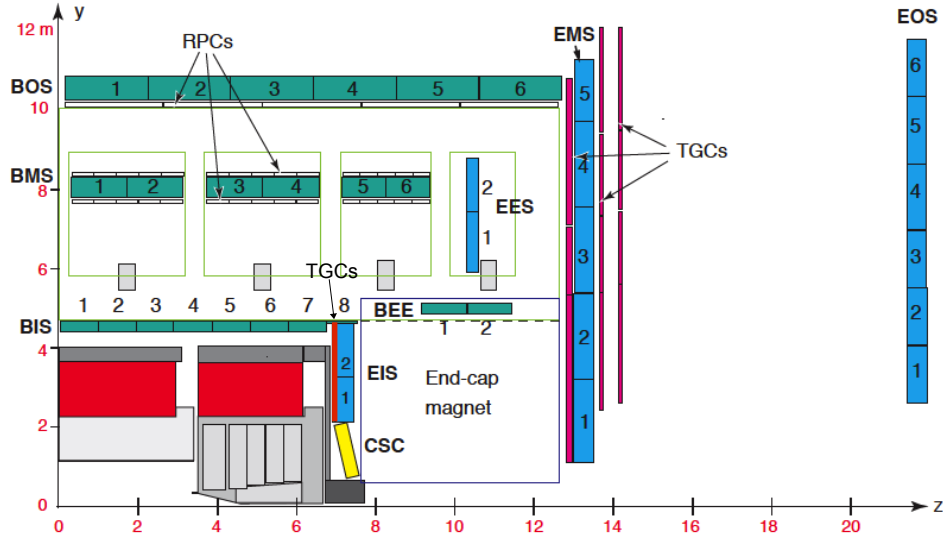


Figure 3.14: The layout of the muon spectrometer in one quadrant of the r-z plane of the ATLAS detector. The barrel MDTs are shown in green, while the endcap MDTs are shown in blue. The TGCs are pointed out in red and pink. The RPCs are pointed out in white. The CSC is shown in yellow [51].

to provide precision tracking while coping with higher particle rates. The Cathode Strip Chambers (CSCs) are placed close to the beamline for this purpose. The CSCs are multiwire proportional chambers. The operating principle of a multiwire proportional chamber is similar to a drift tube, except there are many anode wires placed between two parallel cathode planes. The cathode planes are segmented in the direction perpendicular to the anode wires [52].

The CSCs have an anode wire separation of 2.54 mm and a strip pitch of 5.08 mm. The drift time is approximately 30 ns and the CSC chambers achieve an overall timing resolution of 7 ns with

a spatial resolution of $60\text{ }\mu\text{m}$ [52].

The trigger system requires timing resolution on the order of 1 ns. Resistive Plate Chambers (RPCs) covering a range of $|\eta| < 1.05$ and Thin Gap Chambers covering a range of $1.05 < |\eta| < 2.7$ provide timing information and position information in the ϕ coordinate, which is perpendicular to the precision coordinate obtained by the Monitored Drift Tubes and Cathode Strip Chambers.

The RPCs are gaseous parallel plate detectors with a gas gap of 2.0 mm bounded by parallel resistive bakelite plates. A charged particle passing through the gas gap ionizes atoms. The resulting electrons avalanche in an electric field and induce a signal pulse on metal strips of 30 mm pitch used for readout. The RPCs are arranged in three barrel layers and offer a total of 373, 000 readout channels [51, 52].

The TGCs are multiwire proportional chambers with anode wire separation of 1.8 mm and a gas gap of 2.8 mm. The cathode planes are segmented into readout strips of pitch 14.6-49.1 mm in the ϕ coordinate direction. The TGCs have a total of 318, 000 readout channels [51, 52].

The r - ϕ cross-sectional diagram in Figure 3.15 shows the arrangement of RPCs and MDTs in the barrel region of the muon spectrometer. The chambers are interleaved in 16 sections to reflect the symmetry of the 8 barrel toroid coils described in the following section.

3.7 TOROID MAGNET SYSTEM

The toroid system bends charged particles passing through the muon system in the η direction for the purpose of reconstructing momentum. The toroid system is composed of one air-core toroid

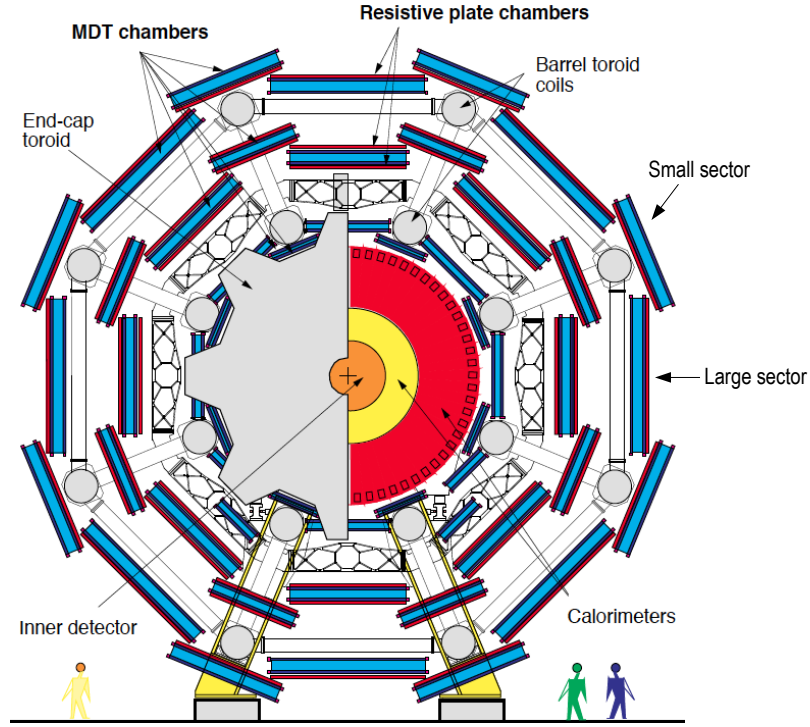


Figure 3.15: A cross-sectional diagram of the ATLAS detector in the r - ϕ plane showing the placement of RPC and MDT chambers in the barrel [51].

with 8 coils in the barrel region and two air-core toroids each with 8 coils in the endcap regions. The layout of the toroid coils is shown in Figure 3.16.

The barrel toroid has an inner diameter of 9.4 m and outer diameter of 20.1 m, with a length of 25.3 m. The endcap toroids each have an inner diameter of 1.65 m, an outer diameter of 10.7 m, and extend 5.0 m in the z direction. The orientation of the endcap toroids is rotated by 22.5 degrees to interleave the endcap toroid coils between the barrel coils [47].

The magnetic field provided by the toroid system is nonuniform in r and ϕ . The magnetic field is monitored by ~ 1800 Hall sensors in the muon spectrometer. In the barrel region, spanning $|\eta| <$

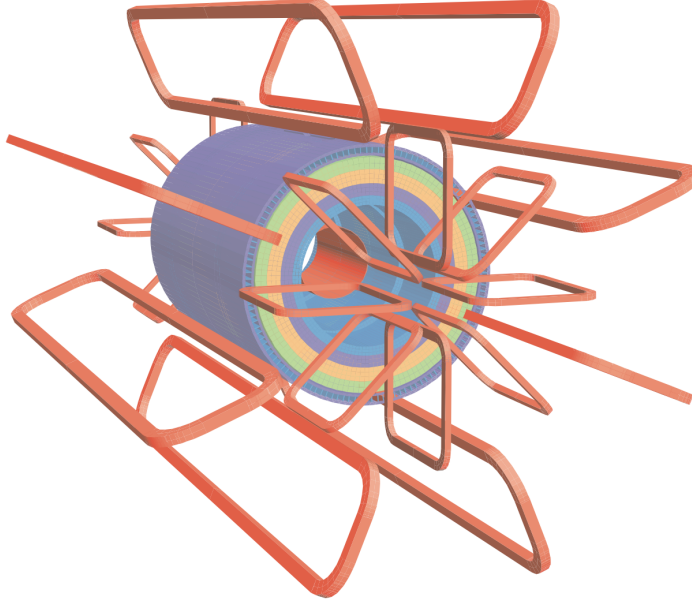


Figure 3.16: The layout of the barrel and endcap toroid coils is shown in red, encircling the steel Tile Calorimeter and solenoid structure [47].

1.4, the magnetic field ranges from 0.15 to 2.5T with an average value of 0.5T. The magnetic field in the endcaps, covering $1.6 < |\eta| < 2.7$, varies from 0.2 to 3.5T [47].

The quantity relevant for momentum reconstruction and resolution is bending power, $\int Bdl$, where B is the component of the magnetic field perpendicular to the charged particle's direction of travel. The bending power in the barrel toroid ranges from 1.5-5.5 Tm. In the endcap, the bending power ranges from 1.0-7.5 Tm. The bending power calculated from the innermost to the outermost layer of the MDTs is shown in Figure 3.17. The bending power is reduced in the transition region between the barrel and endcaps, $1.4 < |\eta| < 1.6$, due to the overlapping magnetic fields acting to cancel one another [47].

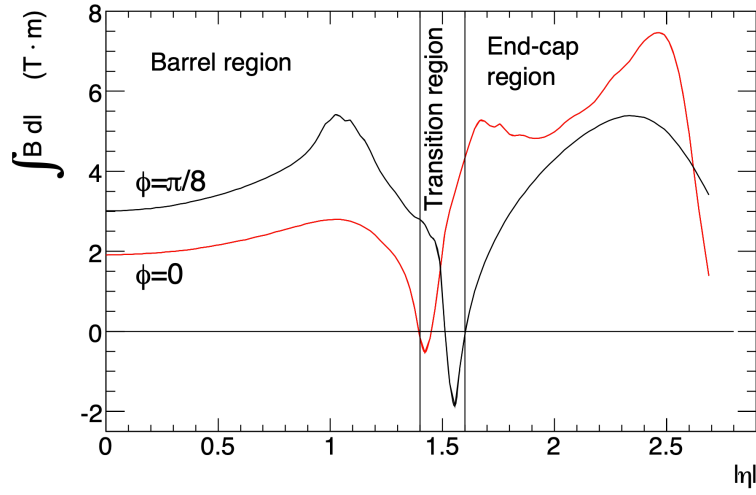


Figure 3.17: The bending power as a function of $|\eta|$, calculated from the innermost to the outermost layer of the MDTs, assuming muons of infinite momentum. The bending power for azimuthal angles of $\phi = 0$ and $\phi = \pi/8$ are shown in red and black [47].

The toroid system was designed to provide magnetic fields that would allow transverse momentum reconstruction with a resolution of $\sigma_{p_T}/p_T = 10\%$ for a muon of $p_T = 1$ TeV [47].

4

Collecting Data & Reconstructing Objects

The rate of proton-proton collisions in ATLAS is ~ 40 MHz. ATLAS employs a triggering system to identify and save potentially interesting events to disk. The average rate of events recorded to disk is ~ 1 kHz.

From these recorded events, detector signals from particles interacting with various subsystems are *reconstructed* into physics objects such as tracks, muons, or jets. This chapter describes the AT-

LAS trigger system, the particular set of triggers that is used to collect the data presented in this thesis, and the definitions of the physics objects relevant to this thesis.

4.1 ATLAS TRIGGER SYSTEM

The ATLAS detector operates with a two-level trigger system. Starting from the 40MHz collision rate, the trigger system is designed to reduce the recorded event rate down to 1 kHz.

The first level of the trigger is the Level-1 (L1) trigger. The L1 trigger is a hardware-based system that makes decisions based on low-granularity information received from the calorimeters and muon detectors. The L1 trigger acceptance rate is ~ 100 kHz. The L1 trigger latency, or the amount of time in which the trigger decision must be made, is $2.5 \mu\text{s}$ [53].

For each event that is accepted by the L1 trigger, all data corresponding to the event is read out from the front-end electronics of all of the detectors. This data waits in Read Out Drivers for the acceptance of the second level of the trigger system, the High-Level Trigger (HLT). The HLT is a software-based trigger system that makes decisions based on data from the full event within 500 ms [54]. Events passing the criteria of an HLT trigger are recorded to disk. The average acceptance rate of the HLT trigger in Run 2 was 1.2 kHz, corresponding to a data storage rate of 1.2 GB/s [53].

To study or search for a particular physics process, an analysis team will use data collected with triggers that select events similar to the target process. Approximately 1500 different triggers were defined in the Run 2 trigger menu [53].

4.2 E_T^{miss} TRIGGER

The search presented in this thesis uses Run 2 data collected with a trigger based on missing transverse momentum, which has a magnitude denoted as E_T^{miss} .

The transverse plane (x-y plane) relative to the beam axis is useful for defining physics quantities. Due to momentum conservation, the total momentum of the colliding partons should be equal to the total momentum of the collision products. The total initial momentum in the direction of the beam line is unknown because we do not know what fraction of the proton momentum is carried by the parton. However, the initial total momentum in the plane transverse to the beam line should be negligible. Therefore, since we know the total momentum in the transverse plane should be zero, it is useful to consider transverse projections of physics quantities.

E_T^{miss} is one such transverse quantity. E_T^{miss} is the negative vector sum of momentum in the transverse plane. This sum should be zero if all momentum in the event is accounted for by the detector. Significant E_T^{miss} reveals a momentum imbalance present in the event, which could indicate that a high-momentum particle has escaped from the detector. A trigger based on E_T^{miss} is therefore useful for many searches for new particles that do not interact with detector material, or particles whose decay products are invisible to the detector.

However, computing the sum of transverse momentum in an event is a computationally-intensive task that requires track reconstruction, taking on the order of seconds to complete [54]. For compatibility with the latency of the L1 and HLT triggers, only information from the calorimeters is used for the E_T^{miss} trigger. Contributions to transverse momentum from other objects, such as muons or

Inner Detector tracks, are added later, *offline*. The reconstruction of offline E_T^{miss} is discussed at the end of this chapter, after the relevant objects have been defined.

For the purpose of the trigger, *online* E_T^{miss} is calculated from the sum of energy deposits in the calorimeters. E_T^{miss} is the magnitude of a two-vector with components E_x^{miss} and E_y^{miss} given by:

$$\begin{aligned} E_x^{\text{miss}} &= \sum_i E_i \sin \theta_i \cos \phi_i \\ E_y^{\text{miss}} &= \sum_i E_i \sin \theta_i \sin \phi_i \end{aligned} \tag{4.1}$$

The sum occurs over objects constructed from energy deposits. The definitions of the objects in the sum depend upon the particular HLT algorithm used. E_i is the energy in each object, with directionality given by the ϕ and θ (related to η) values associated with the energy deposits. The magnitude E_T^{miss} is given by [54]:

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \tag{4.2}$$

The L1 E_T^{miss} trigger receives sums of energy deposits within groups of calorimeter cells that form trigger towers with granularity $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$. Of these sums, only those that pass an η -dependent energy threshold are used to form sums in coarser-granularity towers that span $\Delta\eta \times \Delta\phi$ 0.2×0.2 . E_T^{miss} at L1 is computed using Equation 4.1 using the energy deposit sums in the coarse-granularity towers. If the E_T^{miss} passes the predefined L1 threshold, the event is accepted by the L1

E_T^{miss} trigger, and the event is passed to the HLT, which will recalculate E_T^{miss} with more refined object definitions. The E_T^{miss} trigger contributes an average of 5-10 kHz to the total L1 acceptance rate of 100 kHz [54].

E_T^{miss} triggering at the HLT employs several algorithms that apply different object definitions and calibrations to the energy deposits summed over in Equation 4.1. Three of these algorithms are relevant for Run 2, and are known as the `cell`, `mht`, and `pufit` algorithms.

The `cell` algorithm performs a sum over all 188,000 calorimeter cells. The cells included in this sum pass an energy cut such that $|E_i| > 2\sigma_i$ to reduce noise and pileup, where σ_i is a measure of the expected noise in the cell. Cells with large negative energy deposits, $|E_i| > -5\sigma_i$, are also removed from the sum [54].

The `mht` algorithm sums over energy deposits that are first reconstructed into HLT jets. HLT jet objects are reconstructed from topological clusters, which are formed similarly to the procedure described in Section 4.6. The advantage of using jet objects is that energy calibrations can be applied. In addition, reconstructed jets can be corrected for pileup effects. Jets with a pre-calibration energy greater than 7 GeV are used in the E_T^{miss} sum [54].

During Run 2, pileup increased by a factor of 4. This posed a challenge to the E_T^{miss} trigger and necessitated the creation of an HLT algorithm to more effectively deal with pileup. The `pufit` algorithm assumes that energy deposits with lower scalar energy sums are caused by pileup, whereas larger energy deposits result from the main inelastic collision in the event. The `pufit` algorithm performs a fit over the lower-energy deposits and subtracts the result from the higher-energy deposits in the event. The remaining energy deposits are summed over in Equation 4.1 [54].

The E_T^{miss} triggers, HLT algorithms, and L1 and HLT thresholds used in Run 2 are shown in Table 4.1. HLT performance was found to improve by requiring combinations of HLT algorithms to pass the HLT threshold. As a result, the pufit and cell algorithms are used together in the years 2017 and 2018 [54].

Year	Trigger name	HLT algorithm [GeV]	L1 threshold [GeV]	HLT threshold [GeV]	$\int \mathcal{L} dt$ [fb ⁻¹]
2015	HLT_xe70_mht_L1XE50	mht	50	70	3.5
2016	HLT_xe90_mht_L1XE50	mht	50	90	12.7
2016	HLT_xe110_mht_L1XE50	mht	50	110	30.0
2017	HLT_xe90_pufit_L1XE50	pufit, cell	50	90, 50	21.8
2017	HLT_xe100_pufit_L1XE50	pufit, cell	50	100, 50	33.0
2017	HLT_xe110_pufit_L1XE50(55)	pufit, cell	50 (55)	110, 50	47.7
2018	HLT_xe110_pufit_xe65_L1XE50	pufit, cell	50	110, 65	57.0
2018	HLT_xe110_pufit_xe70_L1XE50	pufit, cell	50	110, 70	62.6

Figure 4.1: The E_T^{miss} trigger thresholds and algorithms used during Run 2. The L1 and HLT thresholds are shown, as well as the integrated luminosity collected. As the data-taking periods of these various algorithms overlapped, the luminosity cannot be summed to find the total luminosity over Run 2 [54].

One metric of performance of the E_T^{miss} trigger is its efficiency, which can be measured using $pp \rightarrow Z + X$ events collected with a dimuon trigger. Since muons do not shower in the calorimeters, they do not leave large energy deposits that are accounted for in the online E_T^{miss} calculation. However, the other particles produced in the event (perhaps a jet) may be accounted for in the E_T^{miss} calculation, resulting in significant E_T^{miss} . The sum of transverse momenta of the two muons, $p_T(\mu\mu)$, which is equivalent to the p_T of the Z , can be used as a proxy to E_T^{miss} . The fraction of $pp \rightarrow Z + X$ events with $p_T(\mu\mu)$ passing the E_T^{miss} trigger gives the efficiency of the E_T^{miss} trigger at that expected missing transverse momentum value [54].

The efficiency of the E_T^{miss} trigger over Run 2 with the thresholds given in Table 4.1 is shown in

Figure 4.2. The efficiency of the E_T^{miss} triggers is approximately 90% for an expected missing p_T of 170 GeV.

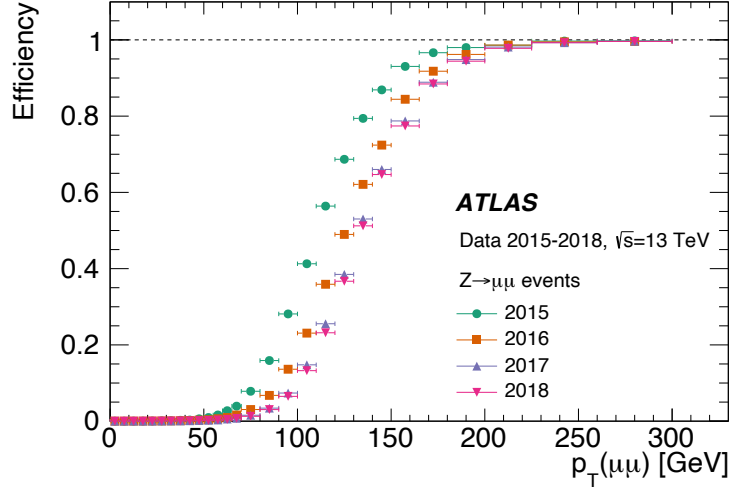


Figure 4.2: The efficiency of the E_T^{miss} trigger as a function of the sum of transverse momentum of the muon pair in events from a $pp \rightarrow Z + X$ data sample. The efficiency of the E_T^{miss} triggers in 2018 was $\sim 90\%$ for an expected missing p_T of 170 GeV [54].

4.3 INNER DETECTOR TRACK RECONSTRUCTION

Inner Detector (ID) tracks play an important role in this thesis. A search for charged long-lived particles using ionization energy loss relies on tracking in the Inner Detector to identify the trajectories of high-momentum charged long-lived particles and to identify pixel sensor hits with high energy deposition associated with the track.

Track reconstruction begins in the pixel tracker and the SCT. Individual hits in pixel and SCT layers are grouped into clusters. An iterative track finding procedure uses the cluster locations to

form track candidates. The candidates are passed through an ambiguity solver that applies quality requirements and resolves cases where more clusters are assigned to more than one track. Tracks output from the ambiguity solver are extended to the TRT according to details found in Reference [55].

4.3.1 CLUSTERING

As a charged particle passes through a silicon sensor, it ionizes atoms, forming electron-hole pairs. These charges may be collected by multiple neighboring pixels in pixel layers, or multiple neighboring strips in an SCT layer. Neighboring pixels or strips in which the collected charge exceeds a threshold are formed into a cluster via a Connected Component Analysis (CCA) described in [56].

The point in space where the incident particle crossed the silicon sensor can be determined from the characteristics of the cluster. This 3D (r, ϕ, z) measurement is known as a *space point*. Each pixel cluster allows the construction of one space point. In the SCT, clusters on both layers of the double-sided modules are needed to obtain an estimate of the third coordinate for the space point [57].

In the high-particle-rate environment in Run 2, particles passed through the silicon layers with high occupancy. The spatial separation between tracks traversing a silicon sensor could be just a few pixels. In this case, the CCA algorithm may group deposits from multiple particles into one cluster. Clusters containing energy deposits from multiple particles are referred to as *merged clusters*. An artificial neural network is used to identify clusters as merged, and is further discussed in Section 4.3.4 [57].

Several other definitions are useful in discussing clusters. A cluster formed from the energy de-

posit of a single charged particle traversing a sensor is known as a *single-particle cluster*. A *shared cluster* is associated to several track candidates, but has not been identified as merged [57].

4.3.2 TRACK FINDING

An iterative combinatorial track finding algorithm groups space points into track seeds. A seed is composed of three space points. A rough estimate of track momentum is obtained from the three space points, and rough estimates of the track's impact parameters are determined under the assumption that the particle follows a helical trajectory [57].

Track seeds are considered in an order that maximizes *purity*, or the probability that the seed will yield a good-quality track. Purity tends to be highest in track seeds composed of space points from the SCT. After SCT-only seeds, seeds with pixel-only space points are considered, followed by seeds formed from a mix of SCT and pixel space points. To further increase purity, the track seeds are required to pass selection criteria based on momentum and impact parameters that depend on the seed's detector-type, and an extra space point must be located that is consistent with the trajectory of the track seed [57].

Track candidates are built from the seeds using a combinatorial Kalman filter [58]. The Kalman filter constructs all combinations of space points that are consistent with the seed's trajectory [57]. As a result, many track candidates overlap or share clusters. An ambiguity-solving procedure is applied to remove track candidates where clusters are shared or misassigned [57].

4.3.3 AMBIGUITY SOLVING

The ambiguity solving stage of track reconstruction begins by rating tracks by a *track score* based on several metrics of track quality. Track candidates are ordered by track score, and the track candidates with the highest scores are processed first [57].

The track score is affected by the number of clusters observed in the track candidate relative to the number of clusters expected in detector layers. The track score is negatively affected by holes, which are defined as the lack of a cluster in a sensitive detector element lying along the track trajectory. The score is also affected by the χ^2 of the track fit, as well as the logarithm of the momentum of the track, as tracks constructed with misassigned clusters tend to have lower momentum [57].

An important job of the ambiguity solver is to limit the number of shared clusters. Multiple track candidates may be assigned the same cluster. This could be a valid assignment if the cluster is identified as merged by the artificial neural network. However, if the cluster is not identified as merged, this could indicate that the cluster has been incorrectly assigned to one of the track candidates [57].

The ambiguity solver processes candidates in order of descending track score. A cluster can be shared by a maximum of two track candidates, and track candidates are allowed a maximum of two shared clusters. If a track candidate shares a cluster with two tracks that have already been accepted by the ambiguity solver, the cluster is removed from the candidate track and the track is rescored and reprocessed [57].

In addition, the candidates must pass quality criteria concerning their impact parameters, number of holes, number of clusters, and number of shared clusters. Most notably, a candidate must

have $p_T > 400$ MeV, at least 7 clusters, a maximum of two holes in the silicon detectors, and a maximum of one hole in the pixel layers. Candidates that do not pass these criteria are rejected [57].

4.3.4 IDENTIFYING MERGED CLUSTERS

The robust identification of merged clusters is doubly important for this thesis. Merged cluster identification is necessary for efficient track reconstruction, and is critical for the strategy of this thesis, which searches for new charged particles based on anomalously high energy deposition in the pixel sensors.

Multiple charged particles passing through neighboring pixels can result in high energy deposition associated with a single cluster. If that cluster is not correctly identified as merged, it could be misinterpreted as an anomalously high energy deposition from a single particle. Quality requirements described in Section 4.3 are placed on the clusters and tracks used in this search to mitigate this source of background.

An artificial neural network that is trained to identify merged clusters is called by the ambiguity solver when a cluster is found to be assigned to multiple tracks. The inputs to the neural network (NN) are cluster properties such as the charge collected and the positions of the pixels within the cluster, as well as the angle of incidence through the sensor, derived from the track trajectory [57].

The NN identifies whether a cluster is merged and predicts whether the merged cluster originates from two particles, or from three or more particles. The NN correctly identifies merged clusters created by two particles at a rate of $\sim 90\%$. The neural network correctly identifies merged clusters originating from three particles with an efficiency of $\sim 85\%$ [57].

The NN misidentifies single-particle clusters as merged two-particle clusters at a rate of a few percent, and misidentifies single-particle clusters as 3-particle merged clusters at a negligible rate [57].

Other than the NN identification, a cluster can be identified as merged in one other way. Collimated particles tend to separate spatially in ϕ as they travel outward through the detector. Therefore, if a cluster in an outer layer has been identified as merged through the neural network, a cluster associated to the same tracks on an inner layer are also likely to be merged. In this circumstance, the inner layer cluster is identified as merged regardless of the NN determination [57].

4.3.5 PERFORMANCE

The track reconstruction requirements succeed in reconstructing particle tracks with very high efficiency while suppressing background due to random combinations of hits, allowing a muon reconstruction efficiency of $>99\%$ [59]. The transverse (d_0) and longitudinal (z_0) impact parameter resolutions of Inner Detector tracks as a function of η in Run 2 are shown in Figure 4.3.

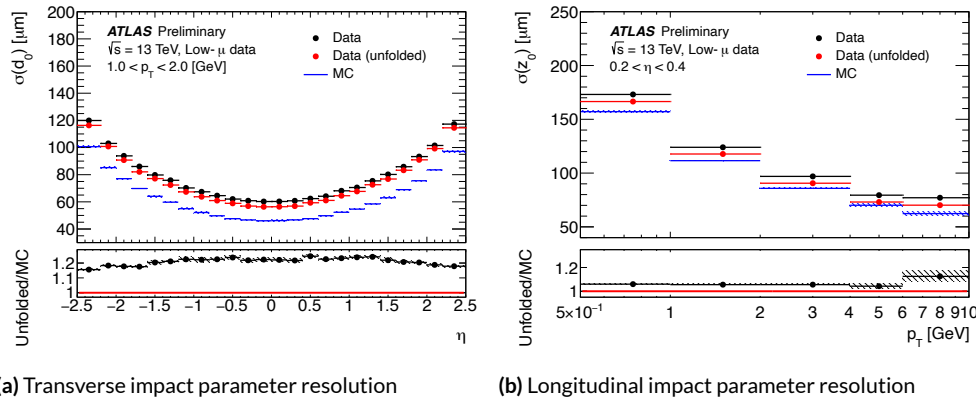


Figure 4.3: a) Transverse and b) longitudinal impact parameter resolutions for ID tracks with $1.0 < p_T < 2.0$ GeV. Data was taken during a low-pileup run in 2015. Data (black points) is compared to simulation (blue lines). Data unfolded to remove dependence upon the resolution of the primary vertex is shown in red [34].

4.4 PRIMARY VERTEX RECONSTRUCTION

The interaction region, or *beam spot*, has a Gaussian shape with σ_x and $\sigma_y \approx 8 \mu\text{m}$ and $\sigma_z \sim 35\text{mm}$ in Run 2 [60]. The precise size and location of the beam spot varies over the course of a run. Vertex finding and fitting algorithms are used to associate tracks stemming from a particular point of origin and determine the location of the hard-scatter event in the beam spot [61].

The vertex finding algorithm selects ID tracks according to requirements found in [61]. The vertex finding algorithm determines the location of a vertex seed from the z-coordinate distribution of the selected tracks close to the center of the beam spot. An adaptive vertex fitting algorithm, described in [62], iteratively fits the position of the vertex using the vertex seed and the set of associated tracks. Tracks that are deemed inconsistent with the vertex (fit $\chi^2 > 49$) are used to seed new vertices [61].

The primary vertex of the event is identified as the reconstructed vertex with the highest $\sum_i p_{T,i}$, where i is the set of tracks associated to the vertex and $p_{T,i}$ is the transverse momentum of the i th track. Further details about primary vertex reconstruction in Run 2 can be found in Reference [61].

4.5 MUON RECONSTRUCTION

Reconstructed muons are used as inputs to offline E_T^{miss} reconstruction. Muon reconstruction begins by collecting hits from MS layers into short track segments. Track segments in different MS regions are associated through an estimation of the muon trajectory in the magnetic field. 3-dimensional track candidates are constructed using the precision coordinate in the $|\eta|$ direction

from the precision tracking chambers and the second coordinate in the azimuthal direction from the triggering chambers. A global χ^2 fit is performed on the track candidates to obtain the trajectory of the muon candidate [63].

Muon track candidates are extended to the rest of the ATLAS detector by incorporating information from the Inner Detector and the calorimeters. There exist several strategies for reconstructing muons globally in ATLAS.

For example, combined (CB) muons are formed by matching the MS track candidates to ID tracks and refitting the muon trajectory, accounting for energy lost in the calorimeters. Inside-out combined (IO) muons are formed by extrapolating ID tracks to the MS to locate MS hits along the track trajectory. Outside of the ID acceptance but within the MS coverage, $2.5 < |\eta| < 2.7$, a muon-spectrometer extrapolated (ME) muon can be formed by extrapolating the MS track to the interaction point, or a silicon-associated forward (SiF) muon can be formed by associating the MS track to short track segments in the pixel and SCT detectors [63].

To identify a muon candidate as a muon, a set of criteria must be fulfilled. Tighter selection criteria leads to higher background rejection and thus a higher purity of identified muons, but lowers the muon identification efficiency. As different physics analyses and searches have different purity and efficiency needs, several sets of muon identification criteria, or “working points” have been defined.

The offline E_T^{miss} reconstruction uses muons identified with the “medium” working point. In the region $|\eta| < 2.5$, CB and IO muons must have a minimum of three hits in each of ≥ 2 MDT stations. In the region $|\eta| < 0.1$, where a gap exists in MS detector coverage, this requirement is reduced to accept muon tracks with at least 3 hits in at least one MDT station, with up to one station

allowed where three hits are expected but missing. In addition, the q/p significance must be less than 7, where q/p significance is a metric of compatibility between the p_{ID} and p_{MS} measurements [63]:

$$q/p \text{ significance} = \frac{|q/p_{ID} - q/p_{MS}|}{\sqrt{\sigma(q/p_{ID})^2 + \sigma(q/p_{MS})^2}} \quad (4.3)$$

In the region $2.5 < |\eta| < 2.7$, ME and SiF muons satisfy the medium working point if they contain a minimum of three hits in each of ≥ 3 MDT stations [63].

The reconstruction efficiencies of medium muons as a function of η and as a function of p_T are shown in Figure 4.4. The reconstruction efficiency of medium muons is around 99%, except for the region $|\eta| < 0.1$, where there is a gap in the coverage of the muon spectrometer [64]. Muon reconstruction efficiency is $\gtrsim 98\%$ for muons of $p_T > 10$ GeV [63].

4.6 JET RECONSTRUCTION

Reconstructed jets are used as inputs to the offline E_T^{miss} reconstruction. In addition, jets present in events selected in this thesis must satisfy a set of requirements to suppress background originating from electrons and τ leptons. Details of these requirements can be found in Chapter 6.

The jet objects used in this thesis are reconstructed from clusters of energy deposits in calorimeter cells, called *topo-clusters*. The clustering algorithm aims to extract cell signals from jets originating from the primary hard-scatter event, against a background of cell noise and pileup contributions, which typically deposit less energy in calorimeter cells. To aid in background suppression, the cluster

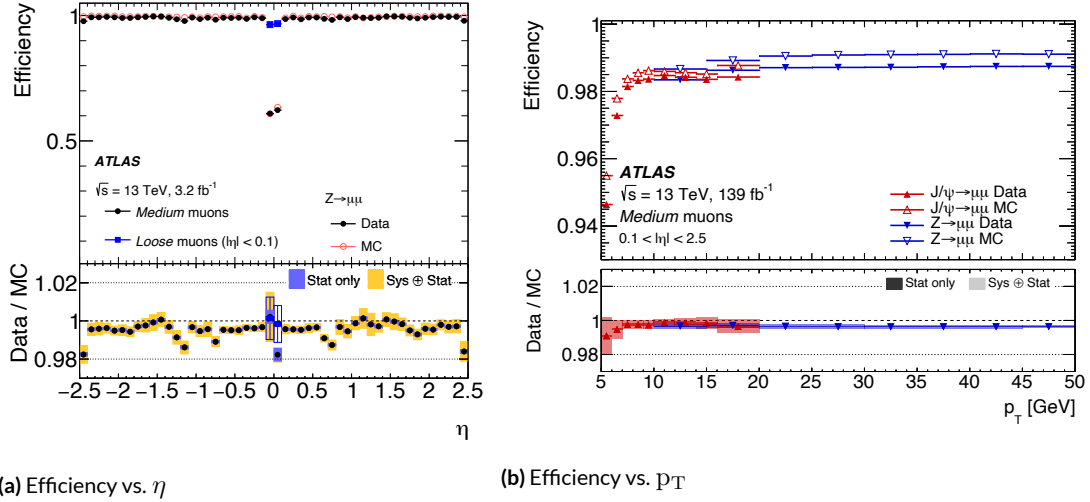


Figure 4.4: The efficiency of reconstructing muons that satisfy the medium working point. (a) shows the efficiency of medium muons (black) identified in a $Z \rightarrow \mu\mu$ sample in early Run 2 data. The efficiency is $\sim 99\%$ except for $|\eta| < 0.1$, where there is a gap in MS coverage [64]. (b) shows the efficiency as a function of p_T for reconstructed medium muons in a $Z \rightarrow \mu\mu$ data sample in the full Run 2 dataset. Efficiency plateaus at $> 98\%$ for $p_T > 10$ GeV [63].

formation is guided by a signal-to-noise ratio defined as the ratio of the cell energy to the average noise in the cell [65].

In each event, calorimeter cells with a signal-to-noise ratio > 4 serve as cluster seeds. Cells adjacent to a seed cell are added to the cluster. If an adjacent cell has a signal-to-noise ratio exceeding 2, its neighboring cells are also added to the cluster. This process continues iteratively, and cluster formation is complete when no more added neighboring cells exceed the signal-to-noise ratio of 2 [65].

Topo-clusters are used as inputs to jet object reconstruction defined using the anti- k_t algorithm [66] with a radius parameter $\Delta R = 0.4$ [67]. Figure 4.5 shows the jet energy resolution for jets reconstructed from topo-clusters after calibrations and corrections have been applied, using dijet events in 2017 data. For jets with a transverse momentum of 100 GeV, the jet energy resolution is

~ 0.1 . Jet energy resolution improves with increasing jet p_T [68].

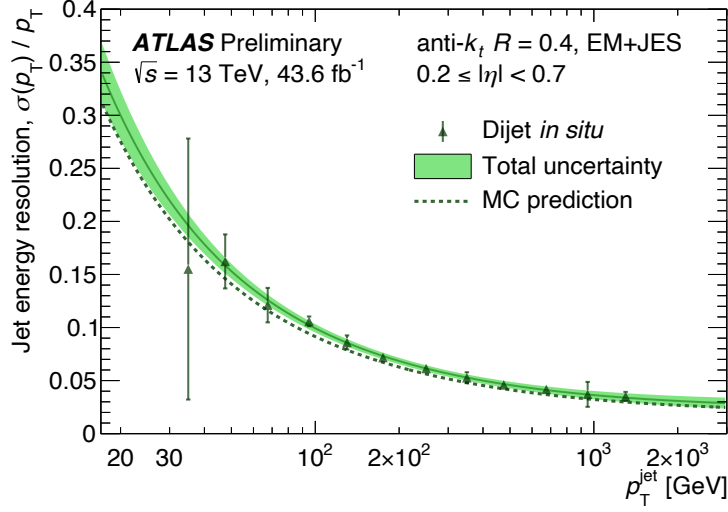


Figure 4.5: The jet energy resolution as a function of p_T for topo-cluster jets after calibrations, for dijet events in 2017 data. The jet energy is calibrated with an in situ technique described in [67]. Monte Carlo prediction is shown as a dashed line. Data is shown in triangles surrounded by an uncertainty band that represents the uncertainty from the in situ calibration methods [68].

A discriminant called the *jet-vertex-tagger* (JVT) can be computed to determine the likelihood that the jet originated from the hard-scatter of the event rather than from pileup. This discriminant includes as inputs the p_T of the calibrated jet, the sum of p_T of tracks associated with both the jet and the primary vertex, the sum of p_T of tracks associated with the jet that originate from pileup vertices, and the total number of pileup tracks in the event [69]. The JVT discriminant ranges from 0 to 1, with a higher number indicating a higher probability that the jet originated from the hard-scatter vertex. Details of the JVT determination can be found in Reference [69]. A JVT requirement is imposed on jets entering the offline E_T^{miss} calculation to reduce contributions from pileup [70].

4.7 OTHER OBJECTS

Electrons are used in the calculation of reconstructed offline E_T^{miss} . The electron reconstruction procedure consists of matching Inner Detector tracks to clusters of energy deposits in the electromagnetic calorimeters. More details on electron reconstruction can be found in Reference [71].

ATLAS also employs dedicated reconstruction algorithms to reconstruct τ lepton objects and photon objects. These objects are not included in the offline E_T^{miss} calculation used in this search and are not otherwise used in this thesis. More information about the reconstruction of τ leptons and photons can be found in Reference [72] and Reference [73], respectively.

4.8 OFFLINE E_T^{miss} RECONSTRUCTION

After the full reconstruction and calibration of objects in the event takes place, the offline missing transverse momentum E_T^{miss} can be calculated from the transverse momenta of the reconstructed objects. E_T^{miss} refers to the magnitude of the vector $\mathbf{E}_T^{\text{miss}}$, which is determined from the negative vector sum of the transverse momenta of each collection of reconstructed objects:

$$\mathbf{E}_T^{\text{miss}} = - \sum \mathbf{p}_T^e - \sum \mathbf{p}_T^\mu - \sum \mathbf{p}_T^{\text{jet}} - \sum \mathbf{p}_T^{\text{tracks in PV}} \quad (4.4)$$

The first term accounts for the transverse momenta of electrons that are consistent with the LooseAndBLayer set of requirements defined in Reference [71]. In addition, electrons must satisfy a minimum p_T of 10 GeV and $|\eta| < 2.47$ to be included in this term.

The second term accounts for the transverse momenta of muons that satisfy the Medium selection defined in Section 4.5. The muons must have $|\eta| < 2.7$ and $p_T > 10$ GeV to be included in the p_T^μ term.

The p_T^{jet} term includes jets that satisfy requirements of $p_T > 20$ GeV and $|\eta| < 2.8$. A minimum jet-vertex-tagging requirement of 0.59 is imposed for jets with $20 \text{ GeV} < p_T < 60 \text{ GeV}$ to reduce jets originating from pileup [70].

The final term includes Inner Detector tracks that are associated with the primary vertex (PV) of the event, but are not associated to any other objects in the event that are considered in the E_T^{miss} calculation. These tracks must pass the quality requirements for Inner Detector tracks described in Section 4.3 [70].

The determination of E_T^{miss} includes a procedure to remove overlap between the different terms. This prevents detector signals from being double-counted in the E_T^{miss} calculation [70].

The performance of the E_T^{miss} reconstruction algorithm can be characterized by the resolution of the E_x^{miss} and E_y^{miss} components of the $\vec{E}_T^{\text{miss}}$ vector. Figure 4.6 shows the resolution of these components for a E_T^{miss} definition given in [70] which includes terms dedicated to reconstructed photon and τ lepton objects. The RMS of E_x^{miss} and E_y^{miss} is shown in 2015 data as a function of the total transverse energy in the event, defined as the scalar sum of the transverse momentum of objects used to calculate E_T^{miss} [70]. For a total transverse energy of 500 GeV, the RMS of the E_T^{miss} components is ~ 25 GeV [70].

More details on offline E_T^{miss} reconstruction can be found in Reference [70].

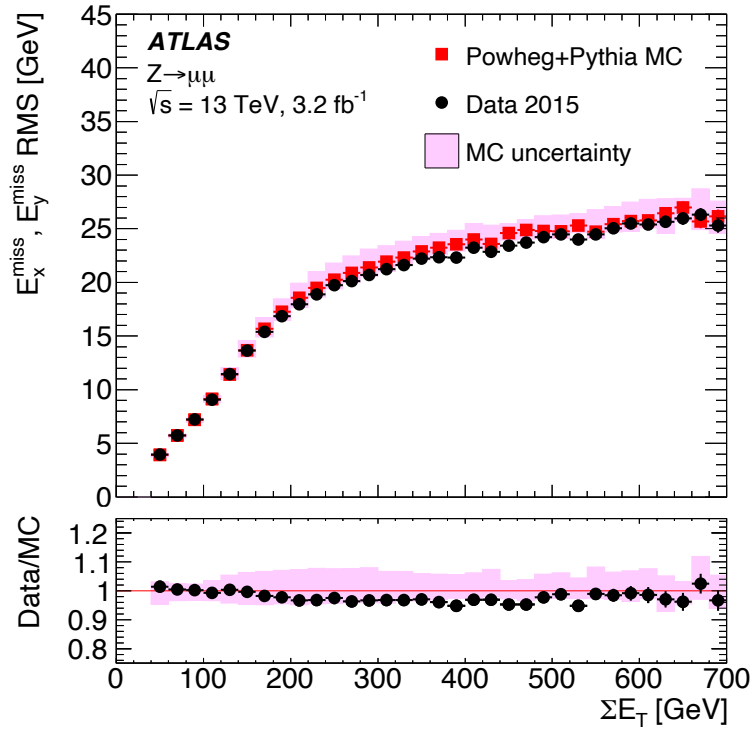


Figure 4.6: The RMS of the E_x^{miss} and E_y^{miss} components of the E_T^{miss} as a function of total transverse energy in the event in a 2015 $pp \rightarrow Z + X$ data sample. Data (black points) is compared to MC simulation prediction (red points). Total transverse energy ΣE_T is the scalar sum of the p_T of all objects included in the E_T^{miss} calculation [70].

5

Measuring Speed

If a particle is charged and long-lived enough to pass through part of the ATLAS detector before decaying, it is possible to directly detect its interactions with the detector material. In particular, a particle's interactions with the detector can allow us to deduce its mass through Equation 5.1:

$$m = \frac{p}{\beta\gamma} \tag{5.1}$$

where m is the mass of the particle, p is its momentum, β is the ratio of the particle's speed to the speed of light, and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ is the Lorentz factor, and is a function of β . As the speed of light $c = 1$ in natural units, the quantity β will be referred to as the particle's speed.

To find a particle's mass using Equation 5.1, its momentum and its speed must be determined. Momentum p is measured in the ATLAS detector using the curvature of the trajectory of the charged particle in the magnetic field. In order to reconstruct the particle's mass, all that remains to determine is the particle's speed β .

A measurement of β can be found in multiple ways in the ATLAS detector. This thesis uses two independent methods of determining β : ionization energy loss in the pixel tracker, and time-of-flight measured in the Tile Calorimeter.

5.1 IONIZATION ENERGY LOSS

A charged particle passing through material ionizes atoms. The amount of energy that the passing particle loses to these ionization interactions is known as ionization energy loss. The shorthand dE/dx describes the ionization energy loss per unit length, divided by the density of the material. The quantity dE/dx is related to the speed β of the incident particle.

This section describes the Bethe-Bloch equation, which relates dE/dx to $\beta\gamma$. The measurement of dE/dx in the ATLAS pixel tracker is described, as well as detector-related corrections. Finally, the calibration of measured dE/dx to $\beta\gamma$ is discussed, so that dE/dx as measured by the ATLAS detector can be used as a window to particle speed, and ultimately particle mass.

5.1.1 THE BETHE-BLOCH EQUATION

Mean energy loss due to ionization $\langle dE/dx \rangle$ is related to particle speed β through the Bethe-Bloch equation [3]:

$$\left\langle -\frac{dE}{dx} \right\rangle = 4\pi N_A r_e^2 m_e c^2 \frac{q^2 Z}{\beta^2 A} \left[\frac{1}{2} \ln \frac{2m_e c^2 (\beta\gamma)^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (5.2)$$

N_A is Avogadro's number, $r_e = e^2/4\pi\epsilon_0\hbar c$ is the classical electron radius, m_e is the mass of the electron. Z and A are the atomic number and atomic mass of the material, I is the mean excitation energy of the material, and W_{max} is the maximum possible energy transfer to an electron in the material. q is the charge of the incident particle [3].

The units of $\langle -\frac{dE}{dx} \rangle$ in this equation are MeV g⁻¹cm², or energy per unit length divided by density of the material.

The behavior of ionization energy loss as a function of $\beta\gamma$ in silicon is shown in Figure 5.1.

For slow particles ($\beta\gamma < 1$), dE/dx falls steeply as a function of $\beta\gamma$ due to the $\frac{1}{\beta^2}$ coefficient of the Bethe-Bloch equation. This behavior can be understood by considering that a slower incident particle spends more time in the material. The electromagnetic field of the material acts upon the particle for a longer period of time, and more energy is lost to ionization.

At higher particle speed ($\beta\gamma > 3$), the logarithmic term in the Bethe-Bloch equation becomes significant. This logarithmic term is a function of $(\beta\gamma)^2$ and causes the “relativistic rise” seen in the Bethe-Bloch curve for highly relativistic particles. The electric field of a relativistic charged particle

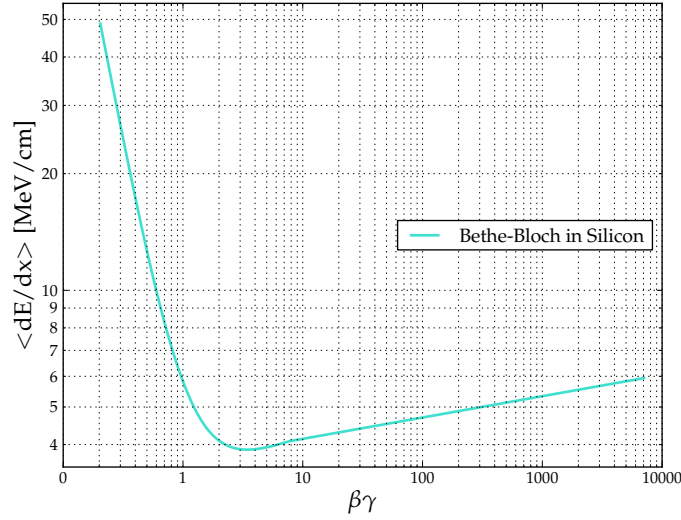


Figure 5.1: The Bethe-Bloch curve of a charged particle traversing silicon.

becomes elongated in the transverse direction. This increases the reach of the electric field in the material, ionizing more atoms and increasing the energy lost due to ionization.

The turnover between the classical $\frac{1}{\beta^2}$ behavior and the relativistic rise occurs at $\beta\gamma \sim 3$, creating a minimum in the Bethe-Bloch curve. Particles with speed such that $\beta\gamma$ lies near the minimum of the Bethe-Bloch curve are known as minimally ionizing particles, or MIPs. For example, a muon with momentum 300 MeV would sit at the minimum of the Bethe-Bloch curve.

The β^2 term of the Bethe-Bloch equation results from a derivation accounting for quantum effects. The $\delta(\beta\gamma)$ term arises from the polarization of the material against the incident particle's electric field, limiting its reach in the material. This polarization term tends to lessen the relativistic rise [3].

A derivation of the Bethe-Bloch equation can be found in Reference [74].

5.1.2 MEASURING dE/dx

To be sensitive to long-lived particles of lifetimes down to a few nanoseconds, we want to measure particle speed as close to the interaction point as possible. The pixel tracker, discussed in Section 3.3.1, is capable of measuring ionization energy loss of particles passing through the 4 silicon pixel layers.

Each pixel reads out Time over Threshold (ToT), which is calibrated to the amount of charge collected in the pixel, or the number of electrons from atoms ionized by the passing charged particle. The particle may ionize atoms in more than one pixel as it passes through the layer. Sets of neighboring hit pixels are formed into clusters according to the procedure defined in Section 4.3.1. After charge calibration, the charge collected in each pixel of the cluster is summed to form the total charge Q , which can be related to ionization energy loss dE/dx [36].

The total cluster charge may be mismeasured if the cluster is located at the edge of a module or in a region where pixel sensors are connected to the same electronics channel. Clusters belonging to these regions are removed. For the remaining fiducial clusters, the total charge Q collected in the cluster can be converted to energy loss due to ionization dE/dx through the relation:

$$\frac{dE}{dx} = \frac{QW}{e\rho l} \quad (5.3)$$

Q divided by the electron charge e gives the total number of electrons. W is the work function of

silicon, or the energy needed to create an electron-hole pair, and is 3.68 ± 0.02 eV. The path length l of the charged particle through the silicon sensor is determined using the track's trajectory to find the angle of passage. The density of silicon, $\rho = 2.33$ g/cm³, is placed in the denominator to give dE/dx in units of MeV g⁻¹cm² [36].

The innermost pixel layer, called the IBL, has different readout electronics from the other three pixel layers. The IBL has 4 bits allocated to ToT readout relative to 8 bits in the other pixel layers. This results in a lower dynamic range for charge and therefore a lower dynamic range for dE/dx . However, the IBL readout electronics compensate for this by including an overflow bit that is set when the ToT exceeds its dynamic range, corresponding to approximately 30,000 electrons [26]. IBL clusters containing this overflow bit are labeled as overflow clusters.

Typically, a track passing through the barrel of the pixel detector has 4 clusters associated to it. However, it is possible to have more than 4 clusters due to azimuthal overlapping of modules. Each cluster has a cluster dE/dx value calculated using Equation 5.3.

The dE/dx values of the clusters must be combined to find one dE/dx value that is representative of the track, such that the speed of the charged particle can be deduced. The probability density function of dE/dx is described by a Landau distribution [75], depicted in Figure 5.2.

Each cluster measurement of dE/dx represents one sampled value of the dE/dx Landau distribution. To characterize this distribution in one dE/dx value, ideally we would average all of the cluster dE/dx values to obtain the mean ionization energy loss. However, due to the long upper tail, the Landau distribution does not have a well-defined mean. Instead, the goal is to approximate the Most Probable Value (MPV) of the Landau distribution, which is the dE/dx value correspond-

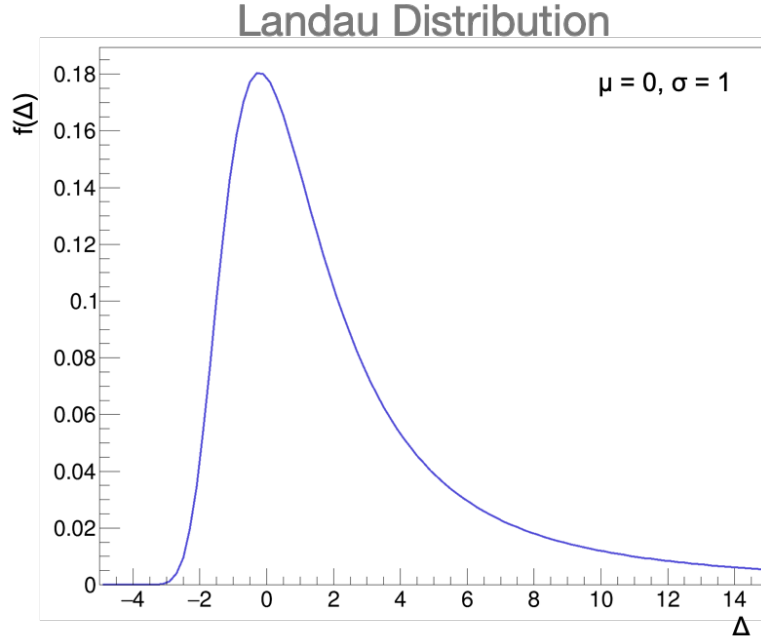


Figure 5.2: A Landau distribution with parameters $\mu=0$ and $\sigma=1$. The probability density function of dE/dx is a Landau distribution.

ing to the peak of the probability distribution.

Due to the long upper tail, an average of the cluster dE/dx values would result in an approximation of the MPV that is skewed high. To account for this, a truncated mean procedure is used. The basic idea of the truncated mean algorithm is that the clusters with the highest dE/dx values are discarded before averaging the rest of the cluster dE/dx values. More details about the truncated mean procedure can be found in Reference [74].

The truncated mean procedure converts the individual cluster dE/dx values for a track to a single dE/dx value that can be used to describe the track. From this point forward, the track dE/dx variable refers to the truncated mean of the track's cluster dE/dx values.

5.1.3 dE/dx CORRECTIONS

The dE/dx variable is highly sensitive to pixel detector conditions. As a result, several corrections to track dE/dx must be applied to ensure that a particular dE/dx value has the same meaning over years of detector operations and in different regions of the detector.

A plot of the truncated mean dE/dx as a function of delivered integrated luminosity over Run 2 is shown in Figure 5.3. In each run, events and Inner Detector tracks are selected according to the criteria outlined in Section 6.2. The truncated mean dE/dx distribution of tracks with $p_T > 10$ GeV is fit to a Crystal Ball function. Each point in Figure 5.3 represents the MPV of the dE/dx distribution as extracted from the fit.

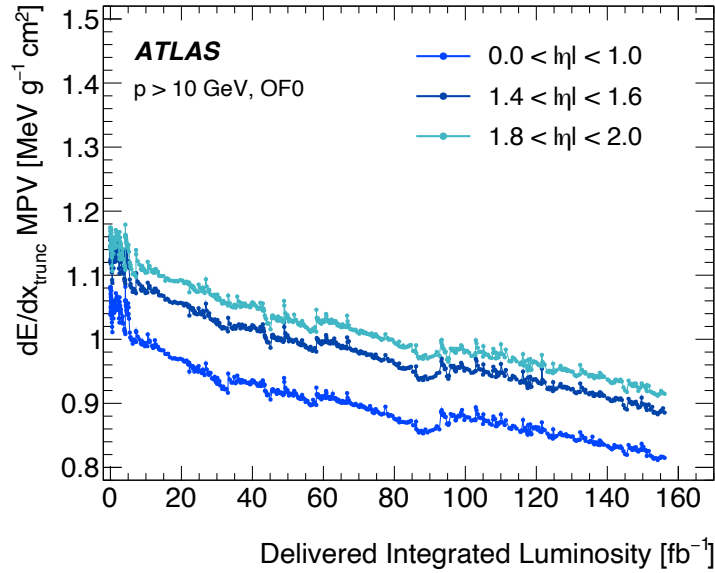


Figure 5.3: The truncated mean dE/dx MPV as a function of delivered integrated luminosity over Run 2 for ID tracks with $p_T > 10$ GeV and no overflow bit set in an IBL cluster (OF0). The truncated mean dE/dx displays a downward trend over time. Differences in dE/dx for three different ranges of $|\eta|$ are also shown. Higher $|\eta|$ regions tend to have higher truncated mean dE/dx due to the larger path length traversed through the pixel sensor [76].

Over the course of Run 2, an overall downward trend in dE/dx is observed. This is due to radiation damage in the pixel sensors. Radiation damage can displace silicon atoms from the semiconductor lattice, disrupting the energy bandgap structure, or cause defects that trap ionized charges, limiting charge collection efficiency [77]. The accumulation of these effects over time reduces the ability of a pixel sensor to collect charge, which results in lower measured dE/dx values. Smaller variations in the downward trend result from changes in detector settings, such as the voltage applied on the silicon sensor.

To equalize the dE/dx MPV values across the whole of Run 2, a reference run is selected and the dE/dx MPV values of other runs are scaled to match the reference run. As higher $|\eta|$ regions receive more radiation damage than regions at lower $|\eta|$, the dataset is divided into bins of $|\eta|$ before applying a scale factor to equalize the dE/dx MPV to the reference run. Tracks with and without IBL overflow clusters are also treated separately.

Higher truncated mean dE/dx values are observed in Figure 5.3 in regions at higher $|\eta|$. For thin silicon sensors, dE/dx has a dependence on the path length traversed through the sensor. The dominant $|\eta|$ -dependent effect on measured dE/dx is the different path length traversed by a particle passing through the pixel sensors at different angles. The pixel modules are aligned parallel to the beamline. Particles originating from the interaction point will thus traverse a greater length of silicon in each sensor at higher $|\eta|$ regions than at lower $|\eta|$ regions. This results in a higher measured dE/dx MPV at higher $|\eta|$.

To equalize the dE/dx MPV values across all $|\eta|$ regions of the detector, a reference $|\eta|$ bin is chosen, and the dE/dx MPV values of the other $|\eta|$ bins are scaled to match the reference $|\eta|$ bin.

This correction is applied after the run-dependent correction. The chosen reference bin is $2.4 < |\eta| <$

2.5.

In addition to the upward shift in MPV as a function of $|\eta|$, the shape of the dE/dx distributions also varies as $|\eta|$ increases. The shape of the dE/dx distribution becomes more Gaussian at higher $|\eta|$ due to the increased number of interactions along the path length, and the resolution tends to improve. The $|\eta|$ correction does not equalize these shape differences. As a result, the dE/dx variable will be considered separately for different regions of $|\eta|$ in this thesis.

5.1.4 dE/dx CALIBRATION

In order to use the corrected truncated mean dE/dx values to find particle speed and calculate mass, the dE/dx variable must be calibrated to $\beta\gamma$. This calibration consists of using particles of known mass in data to derive a Bethe-Bloch-like function that relates corrected truncated mean dE/dx to $\beta\gamma$.

The long-lived charged particles of known mass at our disposal are Standard Model particles such as the pion, kaon, and proton. At the usual high momenta of reconstructed Inner Detector tracks, for example $p_T > 10$ GeV, these particles are highly relativistic. To calibrate the behavior of dE/dx at low $\beta\gamma$ ($\beta\gamma < 3$), where the Bethe-Bloch steep decline as $\frac{1}{\beta^2}$ becomes visible, we must reconstruct tracks at low momenta.

Figure 5.4 shows dE/dx as a function of charge times momentum (qp) in a 2010 ATLAS data sample in which tracks with $p_T > 100$ MeV were reconstructed. Since momentum $p = \beta\gamma m$, plotting dE/dx vs momentum p reveals the Bethe-Bloch curve as a function of $\beta\gamma$ scaled by mass

m for each particle. dE/dx bands for the pion, kaon, proton, and deuteron are visible.

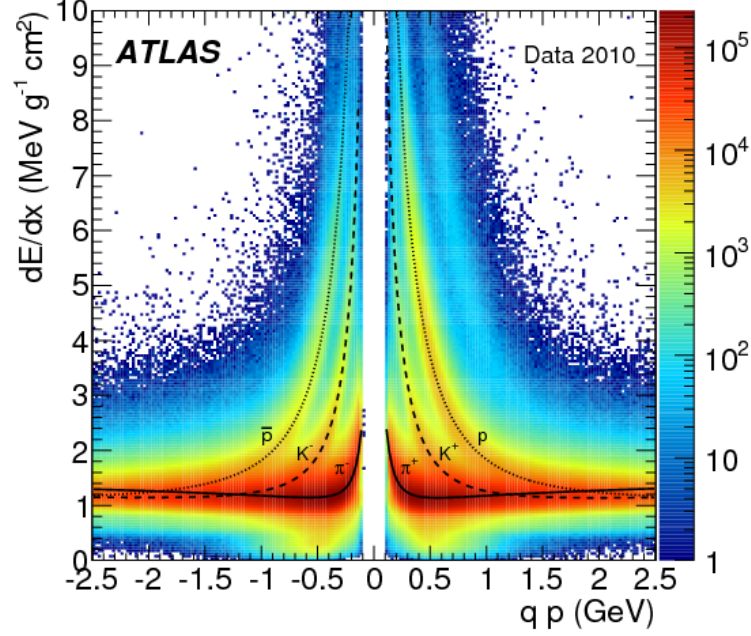


Figure 5.4: dE/dx as a function of charge times momentum (qp) in a 2010 data sample with low- p_T track reconstruction down to 100 MeV. The Bethe-Bloch curves for the pion, kaon, proton, and deuteron appear [78].

Track reconstruction becomes computationally intensive at low momenta due to the amount of low-energy particles originating from pileup interactions. A low-pileup minimum-bias data sample taken in 2017 with low- p_T track reconstruction down to 100 MeV is used for this calibration. A minimum-bias data sample is triggered using dedicated scintillators in order to provide the least model-dependent and unbiased data sample possible [79].

This data is divided into narrow ranges of momentum. Within each momentum slice, dE/dx of Inner Detector tracks is plotted in bins of $|\eta|$. Tracks with and without overflow clusters (OF1 and OF0) are considered separately. An example dE/dx plot in a momentum slice of 302-331 MeV and

$|\eta| < 0.4$ is shown in Figure 5.5.

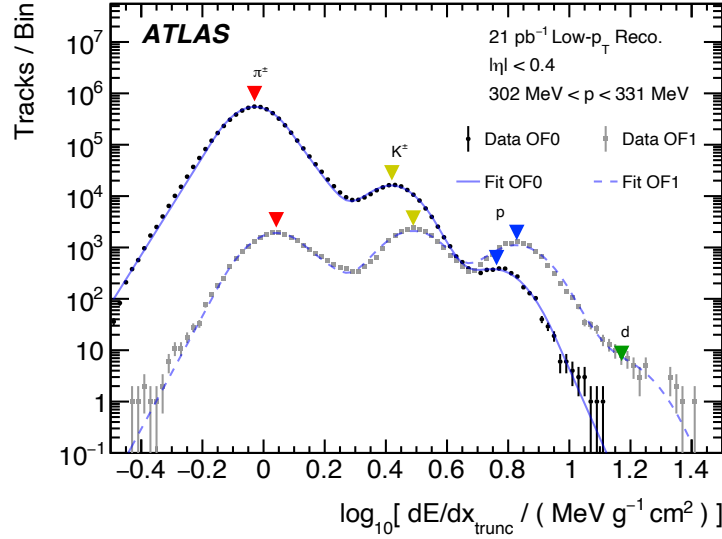


Figure 5.5: dE/dx of tracks in a low pileup, minimum bias run with low- p_T track reconstruction down to 100 MeV. Tracks with momentum in the range 302-331 MeV and $|\eta| < 0.4$ are shown. Tracks with overflow clusters (OF1) and without overflow clusters (OF0) are considered separately. Peaks in the dE/dx distribution corresponding to the pion, kaon, proton, and deuteron are visible. The triangles mark the fitted peak dE/dx value for each particle. The location of these peaks relates the measured dE/dx values at known momenta to known particle masses, and thus to known $\beta\gamma$ values through $\beta\gamma = p/m$ [76].

Plotting dE/dx in a narrow momentum slice is analogous to extracting a narrow vertical slice of Figure 5.4, where dE/dx bands corresponding to the Bethe-Bloch curve for each particle are visible. Peaks appear in the dE/dx distributions in Figure 5.5 that correspond to the pion, kaon, proton, and deuteron. These peaks are fit to extract the location of the dE/dx MPV for each particle. The location of the MPVs relates the measured dE/dx values to particles of known masses at fixed momenta. Since $\beta\gamma = p/m$, the known momenta and known particle masses relate measured dE/dx values to $\beta\gamma$ values.

Repeating this process for different slices of momenta relates measured dE/dx to $\beta\gamma$ over a wide range of $\beta\gamma$. The resulting dE/dx - $\beta\gamma$ curve for $|\eta| < 0.4$ is shown in Figure 5.6. Further details about the calibration procedure can be found in Reference [74].

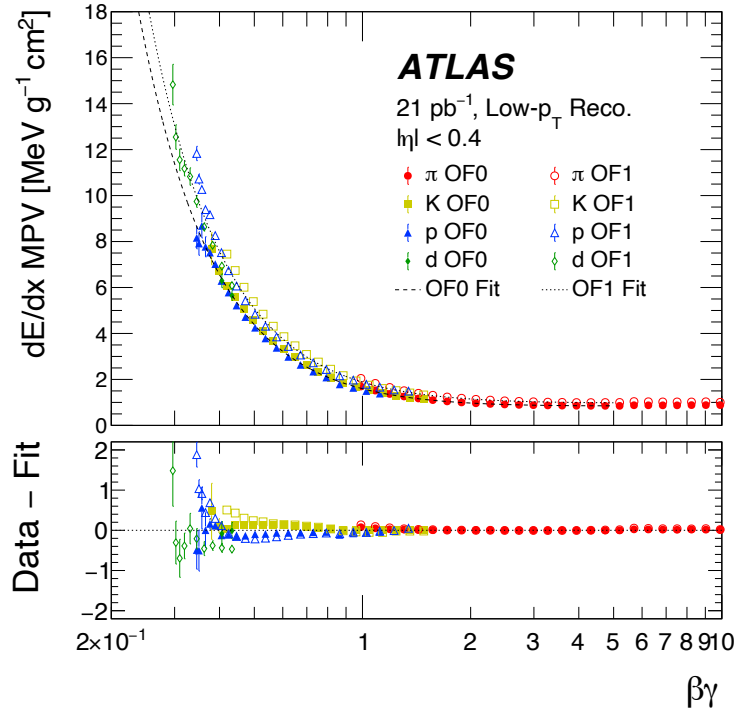


Figure 5.6: A data-driven Bethe-Bloch-like calibration between measured dE/dx and $\beta\gamma$ for $|\eta| < 0.4$. The points represent the dE/dx MPVs for the pion, kaon, proton, and deuteron extracted from dE/dx distributions at fixed momenta. Tracks with and without overflow clusters (OF1, OF0) are considered separately. The curves are fit with a Bethe-Bloch-like function that is used to map dE/dx to $\beta\gamma$. The fits are shown in dashed lines [76].

As the most massive and thus slowest particles considered for a fixed momentum, the proton and deuteron MPV peaks in varying momentum ranges relate dE/dx down to the lowest $\beta\gamma$ values, ~ 0.35 . The kaon peaks relate dE/dx to $\beta\gamma$ for $0.4 < \beta\gamma < 1.5$. The pion peaks relate dE/dx to $\beta\gamma$ for $\beta\gamma > 1$ and cover the minimally ionizing region near $\beta\gamma \sim 3$.

The curves in Figure 5.6 are fit with a Bethe-Bloch-like function of the form:

$$\text{MPV}_{dE/dx}(\beta\gamma) = \frac{1 + (\beta\gamma)^2}{(\beta\gamma)^2} (c_0 + c_1 \log_{10}(\beta\gamma) + c_2 [\log_{10}(\beta\gamma)]^2) \quad (5.4)$$

where c_0 , c_1 and c_2 are constants extracted from the fit in each $|\eta|$ bin. Inverting Equation 5.4 allows the conversion of a particular measured dE/dx value to a $\beta\gamma$ value for the track.

With this calibration, it is possible to reconstruct a mass for a track given its ionization energy loss measured in the pixels and momentum measured in the Inner Detector via $m = p/\beta\gamma$.

In this thesis, we are searching for new charged long-lived particles that are more massive than existing Standard Model particles. At high momenta, it is expected that such massive particles will travel more slowly than Standard Model particles. For example, a new particle of mass 600 GeV and momentum 300 GeV would result in a $\beta\gamma$ value of 0.5, or $\beta \approx 0.45$. At the same momentum, a proton would have $\beta\gamma \approx 300$ and $\beta \approx 0.99999$. Thus, particle speed at high momenta allows us to discriminate between existing long-lived Standard Model particles, which are highly relativistic, and possible heavier new particles.

Note that slow particles ($\beta\gamma \lesssim 1$) lose more energy to ionization losses than faster-moving particles. Therefore, dE/dx can be used to discriminate heavy, slow-moving particles from light, fast-moving Standard Model particles, given high particle momentum. Anomalously high dE/dx , coupled with high momentum, forms a signature for heavy, slow-moving particles. This observation is key to the search strategy used in this thesis, detailed further in Chapter 6.

Owing to detector effects such as the thinness of the pixel sensors as well as the truncated mean

procedure which eliminates high- dE/dx clusters, the “relativistic rise” at high $\beta\gamma$ is not observed in Figure 5.6. Instead, dE/dx and $\beta\gamma$ appear uncorrelated for $\beta\gamma \gtrsim 2$. This lack of correlation between dE/dx and momentum for highly relativistic particles forms the cornerstone of the background estimation strategy, which is described fully in Chapter 7.

5.2 TIME-OF-FLIGHT

Particle speed can also be determined using a time-of-flight measurement in a subsystem of the ATLAS detector. Since the location of the detector subsystem is known, the distance to the interaction point at the origin of the ATLAS detector is also known. Using a time-of-flight measurement and this known distance, the particle’s speed can be deduced.

In this search, the Tile calorimeter is used to measure time-of-flight (ToF). In Run 2, the Tile calorimeter had a timing resolution of down to 0.4 ns with high cell energy deposits (~ 1 TeV) [80]. The liquid argon barrel electromagnetic calorimeter also has a precise timing resolution, measured at 0.25-0.3 ns at similar cell energies in Run 2 [81].

However, the resolution of β depends not only on the timing resolution available, but also on the distance to the interaction point. A longer flight distance from the interaction point corresponds to a better β resolution. The Tile calorimeter is situated at a radius 2.28-3.87 m from the interaction point, whereas the LAr system covers only $1.4 \text{ m} < r < 2 \text{ m}$. The Tile calorimeter has a longer flight distance available for the determination of particle speed [47].

Despite the advantageous β resolution in the Tile calorimeter due to the longer flight distance,

the use of the barrel LAr calorimeter was also investigated to add additional timing measurements. However, it was found that particles losing energy primarily through ionization rather than showering deposit too little energy in the LAr calorimeter to extract a timing measurement.

The time-of-flight measurement is interpreted assuming that the particle originated from the interaction point, at the detector origin, synchronously with the LHC 40 MHz bunch crossing clock. However, the *beam spot* or the volume in which collisions occur, had a Gaussian profile with σ_x and $\sigma_y \approx 8 \mu\text{m}$ in Run 2, and σ_z extending to $\sim 35 \text{ mm}$ [60]. This spread in distance, along with any associated difference in time, is not accounted for in the determination of β and contributes to the overall timing resolution. However, the size of the beam spot is dwarfed by the size and resolution of the Tile calorimeter cells. The LHC clock jitter is on the order of picoseconds and is negligible [82].

Figure 5.7 shows a diagram of the Tile calorimeter. The three layers of readout cells are shown in blue, green, and yellow. η is marked by dashed red lines. The Tile calorimeter coverage ends at $|\eta| \approx 1.7$.

This section describes the measurement of ToF in the Tile calorimeter, as well as the ToF calibration procedure developed for the search presented in this thesis.

5.2.1 TILE CALORIMETER TIMING

As a charged particle travels through the Tile calorimeter, it loses energy via ionization, as well as by showering if it is relativistic enough to radiate photons or undergoes hadronic interactions with detector material. Most of the energy loss occurs within the steel absorber layers of the Tile Calorime-

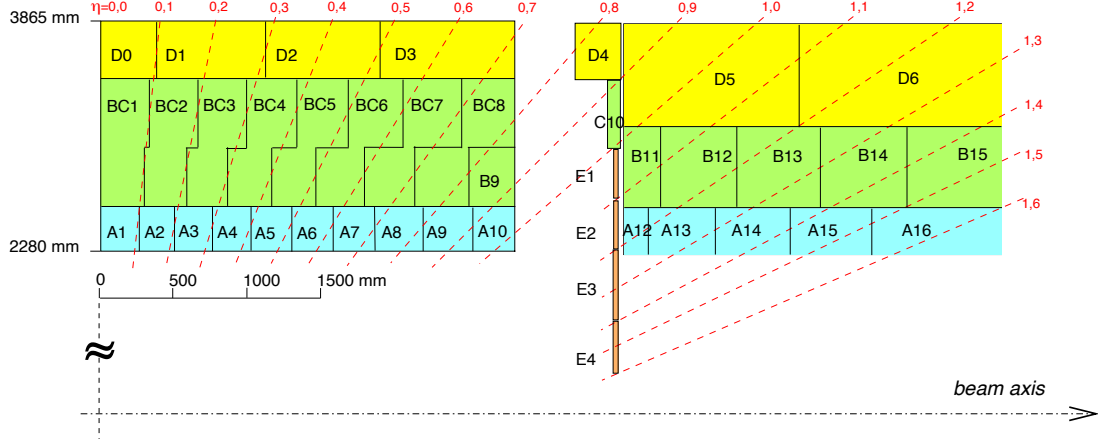


Figure 5.7: One quadrant of the r - z plane cross-section of the Tile calorimeter readout cells in Run 2. The three layers of readout cells are shown in blue, green, and yellow. η is marked by dashed red lines. The Long Barrel (LB) and Extended Barrel (EB) are shown. Cells A1-A10, BC1-BC8, B9, and D0-D3 are located in the Long Barrel. Cells A12-A16, B11-B15, and D5-D6 are located in the Extended Barrel. Cells D4, C10, and E1-E4 make up the Intermediate Tile Calorimeter (ITC) discussed in Section 3.5.2. [83].

ter, while the energy loss is sampled and measured in the active scintillator layers. Scintillation photons travel through wavelength-shifting fibers to a photomultiplier tube, which produces an electronic signal. The amplitude of this signal corresponds to the energy deposited in the cell [84].

The signal is digitized and read out to a Read Out Driver, where the signal is reconstructed with an Optimal Filtering algorithm to extract energy and timing information. More information about the Optimal Filtering algorithm used for the Tile calorimeter can be found in Reference [84].

Cells are associated to an Inner Detector track by extrapolating the track through the Tile calorimeter. To reduce the impact of detector noise, a minimum energy threshold of 500 MeV in each cell is imposed before associating the cell to a track.

The timing quantity that is relevant for the calculation of β in each cell is referred to as *cell time* t_0 . Cell time is the difference between the measured ToF and the ToF that would be measured in the

cell for a particle traveling at the speed of light originating from the interaction point:

$$t_0 = \text{ToF}_{\text{measured}} - \text{ToF}_{v=c} = \text{ToF}_{\text{measured}} - \frac{d}{c} \quad (5.5)$$

where d is the distance from the interaction point to the center of the cell.

Then, β can be calculated in each cell using the cell time measurement:

$$\beta = \frac{d}{c \text{ToF}_{\text{measured}}} = \frac{d}{c(t_0 + \frac{d}{c})} = \frac{1}{1 + \frac{ct_0}{d}} \quad (5.6)$$

Finally, the β values from all cells associated to the track are combined to obtain a single β value to describe the particle's speed. This is done using a weighted average, where the cell β values are weighted by the β resolution in each cell. Track β_{ToF} is found using the equation:

$$\frac{1}{\beta_{\text{ToF}}} = \frac{\sum_i \frac{1/\beta_i}{\sigma^2(1/\beta_i)}}{\sum_i \frac{1}{\sigma^2(1/\beta_i)}} = \frac{\sum_i \frac{d_i(d_i + ct_i)}{\sigma^2(t_i)}}{\sum_i \frac{d_i^2}{\sigma^2(t_i)}} \quad (5.7)$$

where the sum is over all cells associated to the track, β_i is the β determined in each cell, d_i is the distance from the interaction point to each cell, t_i is the cell time measured in each cell, and $\sigma(t_i)$ is the cell time resolution in each cell.

The β_{ToF} measurement can be improved by implementing a series of corrections to the cell time, collectively referred to as the cell time calibration procedure.

5.2.2 CELL TIME CALIBRATION

The heavy long-lived particles searched for in this thesis are expected to lose energy primarily via ionization rather than showering in the calorimeter. This behavior is similar to muons passing through the Tile calorimeter. Therefore, a data sample of muons from $Z \rightarrow \mu\mu$ decays is used to derive the cell time calibration.

As the muons are highly relativistic, it is expected that the mean cell time $\langle t_0 \rangle = 0$ in each cell. The goal of the calibration procedure is to derive corrections such that $\langle t_0 \rangle = 0$ for the $Z \rightarrow \mu\mu$ data sample in each cell. These corrections can then be applied to any measured t_i in the cell to get a calibrated cell time for entry in Equation 5.7.

The first correction applied is a cell-by-cell correction. Tile calorimeter cells may become desynchronized over the course of a data-taking year. The cell time distribution in each cell is examined for $Z \rightarrow \mu\mu$ data samples taken in 2015, 2016, 2017, and 2018. The cell time distributions are fit to a Gaussian in the $\pm 2\sigma$ region, and the mean $\langle t_0 \rangle$ is extracted.

Example cell time distributions for 2018 $Z \rightarrow \mu\mu$ data are shown in Figure 5.8.

For the two cells pictured, it can be observed that $\langle t_0 \rangle$ is not 0, as would be expected for relativistic muons. To correct this, the quantity $0 - \langle t_0 \rangle$ must be added to all measured cell time values in the distribution, which shifts the distribution such that $\langle t_0 \rangle = 0$.

The second correction applied is dependent upon the geometry of the cells. In the definition of cell time t_0 in Equation 5.5, the reference ToF for a particle traveling at the speed of light is determined using the distance d , which is assumed to be the distance from the interaction point to

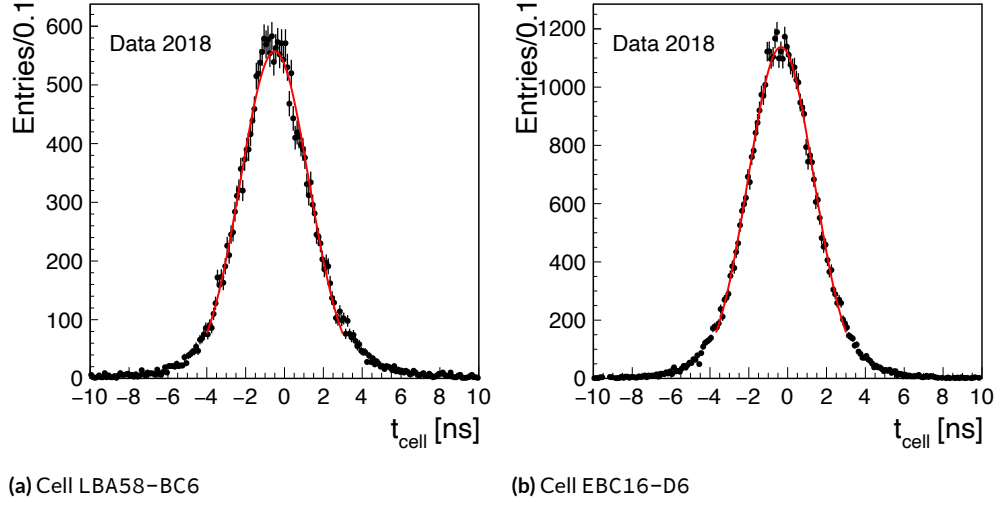


Figure 5.8: Cell time distributions in two Tile calorimeter cells using 2018 $Z \rightarrow \mu\mu$ data. The distributions are fit with a Gaussian in the $\pm 2\sigma$ region, shown in red. The mean of the fit is used to derive the cell-by-cell correction. a) shows the cell time distribution in a cell in the Long Barrel (LB) section of the Tile calorimeter. b) shows the cell time distribution in a cell in the Extended Barrel (EB) section of the Tile calorimeter.[†]

the center of the cell. However, the particle may not pass directly through the center of the cell, as shown in Figure 5.9. This difference in flight distance will result in a skewed cell time measurement. As Tile calorimeter cells can be up to a meter in width, the effect on cell time can be significant.

In each cell, the average cell time is examined as a function of $\Delta\eta = \eta_{track} - \eta_{cell}$. Average cell time plotted as a function of $\Delta\eta$ is shown in Figure 5.10 for one of the largest Tile calorimeter cells. At $\Delta\eta = 0$, or when the track passes through the center of the cell, it can be seen that average cell time is 0, as expected. As $\Delta\eta$ increases, the average cell time becomes skewed away from 0.

The mean cell time as a function of $\Delta\eta$ is fit with a line. For a given track η , the value of the fit at the corresponding $\Delta\eta$ indicates the factor that needs to be subtracted from a measured cell time to correct it to 0.

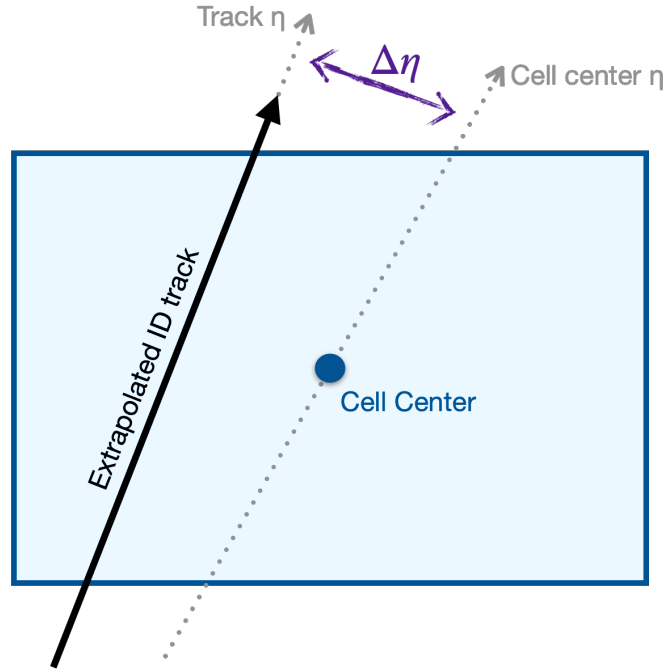


Figure 5.9: The extrapolated Inner Detector track of a particle passing through a Tile calorimeter cell. The track passes through the cell with a different η direction than the center of the cell. Because the track does not pass through the cell center, the measured cell time will be skewed. A correction is implemented to account for the difference $\Delta\eta$ between the track and the center of the cell.

The resolution of cell time depends on cell energy: if more energy is deposited in a cell, the electronic signal will have a higher amplitude, and a better timing measurement can be extracted. It is possible that the mean cell time would also depend on the energy deposited in the cell. An energy-dependent cell time correction was investigated, but found that the mean cell time displays negligible dependence on cell energy.

The calibration procedures described above determine the calibrated t_i that enters Equation 5.7. In summary, a measured cell time is calibrated by applying the cell-dependent factor derived from the cell-by-cell calibration, followed by applying the track- η -and-cell-dependent factor derived in the

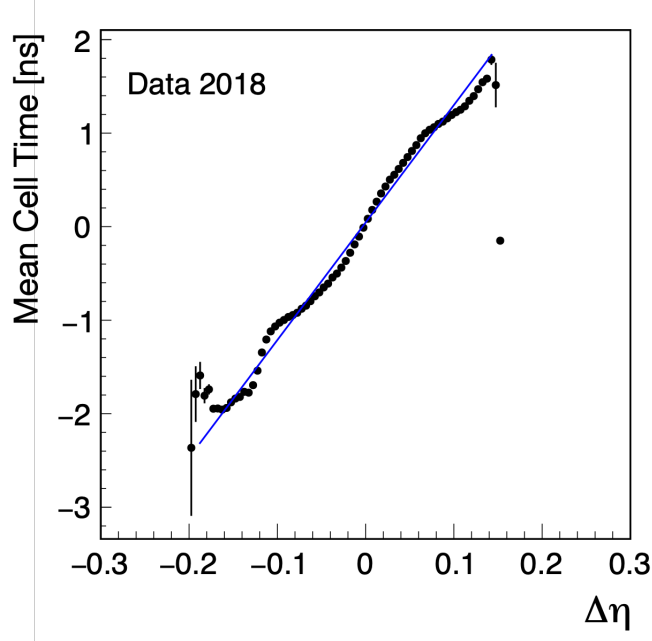


Figure 5.10: The mean cell time in bins of $\Delta\eta = \eta_{track} - \eta_{cell}$ for high p_T muons in 2018 $Z \rightarrow \mu\mu$ data. The cell studied here is in the final layer of the extended barrel, and is one of the largest Tile calorimeter cells. At larger $|\Delta\eta|$, or larger difference between track η and cell center η , the measured mean cell time is skewed from 0. The data is fit with a line (blue) which is used to derive a correction to the measured cell time.[†]

geometric calibration.

To calculate a calibrated β_{ToF} , it remains to determine a calibrated $\sigma(t_i)$ for each cell. The cell time resolution is expected to depend on the amount of energy deposited in the cell.

Calibrated cell times from muons in $Z \rightarrow \mu\mu$ data samples are divided into bins by cell energy. For each cell energy slice, the calibrated cell time is fit to a Gaussian and the standard deviation is taken to be the cell time resolution in that energy bin.

Cells of the same radial layer are grouped together such that the cell time resolution is determined separately for each radial layer of the Long Barrel and Extended Barrel Tile calorimeter sections.

The energy dependence of cell time resolution for two example Tile calorimeter layers is shown in

Figure 5.11.

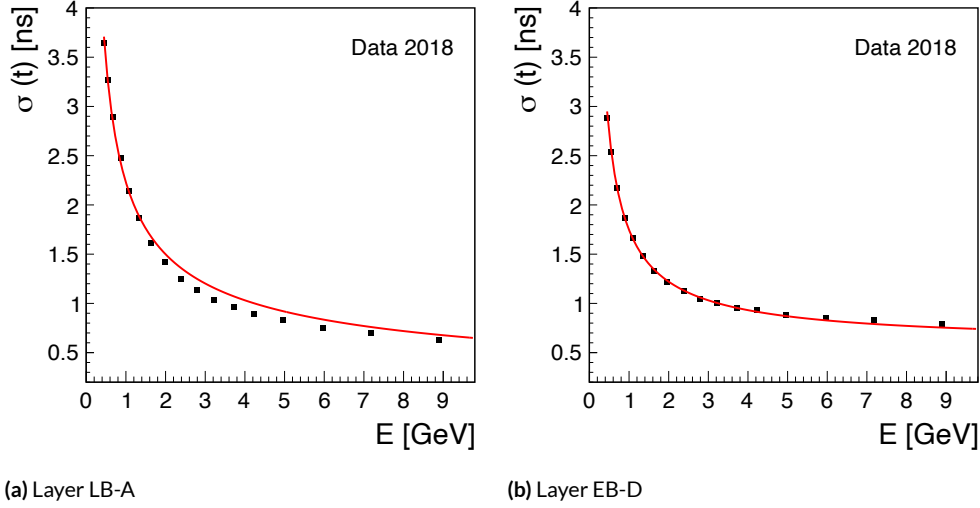


Figure 5.11: Cell time resolution per energy slice as a function of cell energy for (a) the first layer of the Long Barrel (LB) and (b) the last layer of the Extended Barrel (EB). The cell time resolution is extracted from a Gaussian fit in the $\pm 2\sigma$ region to the calibrated cell time distribution for 2018 $Z \rightarrow \mu\mu$ data. The cell energies are fit with the function described in Equation 5.8 to provide a continuous relationship between cell energy and cell time resolution.[†]

The cell time resolution as a function of energy is fit to the function:

$$\sigma(t) = \sqrt{p_0^2 + \frac{p_1^2}{E} + \left(\frac{p_2}{E}\right)^2} \quad (5.8)$$

where E is the cell energy, and p_0 , p_1 , and p_2 are parameters of the fit. This fitted function provides a continuous relation between measured cell energy E and calibrated cell time resolution $\sigma(t)$.

Now, with calibrated cell time t_i and $\sigma(t_i)$ available for use, a β_{ToF} value for the track can be determined with Equation 5.7. A β_{ToF} value determined with calibrated cell time and cell time resolution is considered a *calibrated* β_{ToF} value.

A comparison between uncalibrated and calibrated β_{ToF} in 2018 $Z \rightarrow \mu\mu$ data is shown in Figure 5.12.

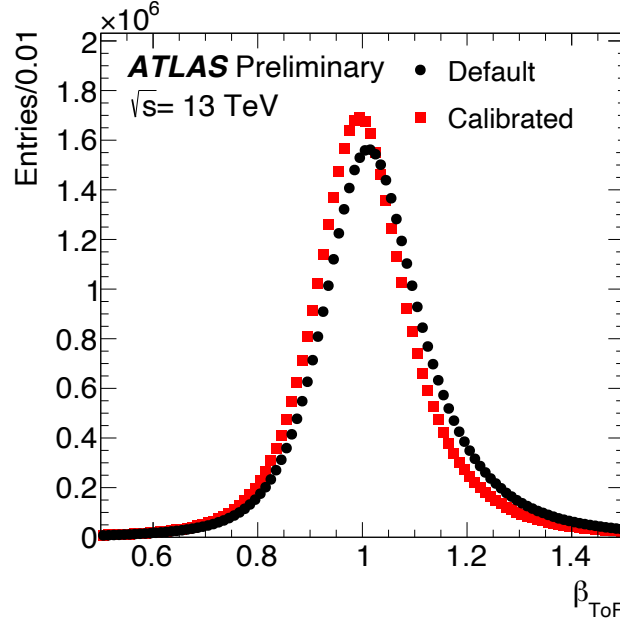


Figure 5.12: Uncalibrated β_{ToF} (black points) compared with calibrated β_{ToF} (red points) in 2018 $Z \rightarrow \mu\mu$ data [2].

Overall calibrated β_{ToF} and $\sigma(\beta_{\text{ToF}})$ values are shown in Table 5.1. The resolution is determined by fitting the β_{ToF} distribution with a Gaussian in the $\pm 2\sigma$ region. As β_{ToF} is not well-described by a single Gaussian in the tails, the RMS values are shown as well.

The β_{ToF} resolution as a function of $|\eta|$ is shown in Figure 5.13. The β_{ToF} resolution varies as a function of $|\eta|$ due to the varying structure of the Tile calorimeter in $|\eta|$, which can be seen from Figure 5.7. The resolution roughly depends on the number of cells included in the β_{ToF} calculation. The peak in resolution in the region $0.8 < |\eta| < 1.0$ corresponds to the transition region between the Long Barrel and the Extended Barrel Tile calorimeter sections. The increased resolution at $|\eta| >$

Calibration	Mean β_{ToF}	$\sigma(\beta_{\text{ToF}})$	RMS
Uncalibrated	1.020	0.100	0.131
+ cell calib.	0.995	0.095	0.126
+ η corr.	0.998	0.093	0.125

Table 5.1: The mean β_{ToF} , $\sigma(\beta_{\text{ToF}})$, and RMS of the β_{ToF} distribution for 2018 data. The first line of values is found with no calibrations on cell time. The second line shows the effect with the cell-by-cell calibration only. The third line shows the final calibrated performance with both the cell-by-cell and η -dependent calibrations implemented. The resolution $\sigma(\beta_{\text{ToF}})$ is determined by fitting the β_{ToF} distribution with a Gaussian in the $\pm 2\sigma$ region. As β_{ToF} is not well-described by a single Gaussian in the tails, the RMS values are shown as well.[†]

1.5 corresponds to the region where only two cells, or even only one cell, are available for a timing measurement as the Tile calorimeter $|\eta|$ coverage ends.

Due to the dependence of $\sigma(\beta_{\text{ToF}})$ on $|\eta|$, the variable β_{ToF} must be considered separately in different $|\eta|$ regions in this analysis.

With a calibrated β_{ToF} value, we can reconstruct mass of a charged particle passing through the Tile calorimeter using $m = p/\beta\gamma_{\text{ToF}}$, where $\beta\gamma_{\text{ToF}} = \beta_{\text{ToF}}/\sqrt{1 - \beta_{\text{ToF}}^2}$.

This thesis searches for new charged long-lived particles that are heavier than existing Standard Model particles. For example, a heavy long-lived charged particle of mass 400 GeV and momentum 300 GeV would give $\beta\gamma = p/m = 0.75$, or $\beta = 0.6$. By contrast, a Standard Model muon of the same momentum would travel with $\beta \approx 0.9999999$. With β resolution $\sigma(\beta_{\text{ToF}}) \sim 0.1$, these two β values can be distinguished. In this way, β_{ToF} can be used to distinguish between heavy, slow-moving new particles and highly relativistic Standard Model particles, which constitute background in this search.

However, it is not possible to distinguish between a muon of momentum 300 GeV ($\beta \approx 0.9999999$) and a muon with momentum 120 GeV ($\beta \approx 0.9999997$), or even a muon with momentum as low

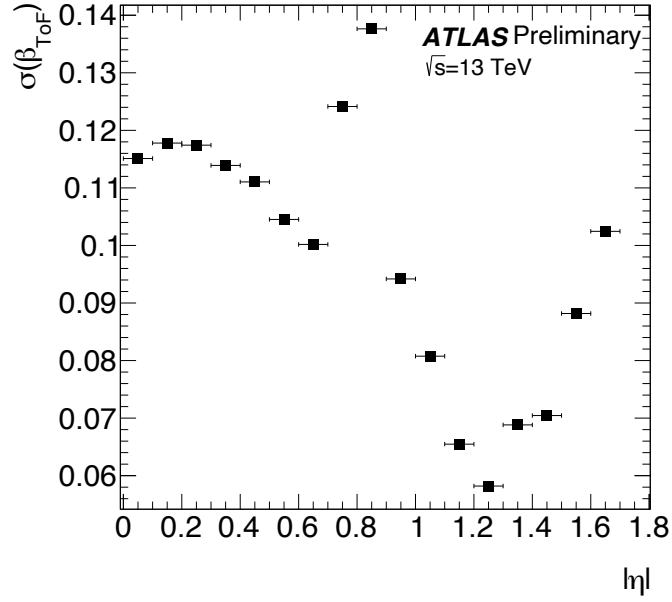


Figure 5.13: The resolution of calibrated β_{ToF} in different $|\eta|$ regions. The worsened resolution at $0.8 < |\eta| < 1.0$ corresponds to the transition region in the Tile calorimeter between the Long Barrel and the Extended Barrel sections. The worsening resolution at $|\eta| > 1.5$ is due to fewer cells available for timing measurements as Tile calorimeter coverage ends [2].

as 10 GeV ($\beta \approx 0.99995$) or 1 GeV ($\beta \approx 0.995$). This means that for Standard Model particles moving with high momenta, momentum and Tile calorimeter β_{ToF} are practically uncorrelated variables. This observation, that p and β_{ToF} are uncorrelated for background particles, is a key idea in the background estimation strategy, which is described fully in Chapter 7.

6

Analysis Strategy

This thesis presents a search for heavy, charged, long-lived particles. Heavy long-lived particles (mass $\mathcal{O}(100\text{GeV})$ and above) are expected to traverse the ATLAS detector with slower speed than Standard Model particles. Thus, measurements of particle speed can be used to discriminate a heavy long-lived particle from light long-lived Standard Model particles.

This thesis makes use of two methods of measuring particle speed: ionization energy loss (dE/dx)

measured in the pixel tracker, and Time of Flight (ToF) measured in the hadronic Tile calorimeter. These choices of measurements affect the sensitivity of the search. Both methods of measuring speed require that the particle interacts electromagnetically with the detector material in the form of ionization energy losses. This restricts the search sensitivity to only particles that are electrically charged. Additionally, requiring a measurement of calorimeter ToF requires that the particle survives long enough to traverse the Tile calorimeter before decaying. This restricts the lifetime sensitivity of this search to $> \mathcal{O}(10\text{ns})$.

This search method has sensitivity to particles that are charged, long-lived enough to pass through the Tile calorimeter, and massive enough that their speed is low enough to be discriminated from Standard Model particles. Such particles could appear in many theoretical models, including those discussed in Chapter 2, or could be particles that have not yet been hypothesized. In effect, this search method offers a degree of model-independence, allowing sensitivity to generic heavy, charged, long-lived particles irrespective of the details of how they are produced. The results of a *model-independent* search can be interpreted in terms of many models. This is in contrast to a *model-dependent* search, in which the analysis design is tailored to the details of a particular model, such as a specific final state or kinematic characteristics.

Simulation of heavy, charged, long-lived particles from signal models is necessary to help make design choices in this analysis, as well as to optimize sensitivity and interpret the results of the search. The models chosen for this purpose are referred to as *benchmark* models. This analysis chooses to benchmark on a variety of Supersymmetric (SUSY) models. The broad range of well-motivated models available allows us to design the analysis to probe a range of mechanisms that lead to long-

livedness over a wide kinematic phase space. Section 6.1 describes the benchmark signal models chosen for this search.

From Run 2 ATLAS data, we aim to select tracks that are most likely to result from heavy long-lived particles while rejecting Standard Model background. The selection requirements placed on events and on the tracks within the events define a region-of-interest called the Signal Region (SR). Section 6.2 details the selection requirements placed on the events and tracks considered in this search.

The use of two independent measures of particle speed provides a powerful opportunity to reject background, which increases the sensitivity to signal particles. The two measures of particle speed allow the reconstruction of two masses for each track through the equation $m = p/\beta\gamma$. For a new particle, these two reconstructed masses should be consistent within the mass resolution. Within the Signal Region, imposing consistency between the two reconstructed masses further optimizes the sensitivity of this analysis. Section 6.3 describes the reconstruction of mass and the method of imposing consistency between the two masses through the application of mass windows.

6.1 SIMULATION STRATEGY

Heavy, charged, long-lived particles can result from a variety of Supersymmetric (SUSY) models. We choose to benchmark the search results on simulation from signal models that predict long-lived sleptons, charginos, and gluinos. Our choice of signal models allows the search to probe a variety of SUSY-breaking mechanisms and reasons for particle long-livedness over a wide kinematic phase

space. This section discusses the signal models probed in this analysis.

In each case, Monte Carlo (MC) simulation is generated using MADGRAPH5_aMC@NLO [85], PYTHIA8 [86] with the A14 set of tune parameters [87], and EVTGEN [88]. Interactions of the generated particles with the ATLAS detector are simulated using GEANT4 [89, 90].

A production cross-section for each signal model is assumed in order to determine the number of simulated events that are expected to fulfill the analysis selection. The sensitivity of the analysis is therefore interpreted in terms of the cross-section assumed for the benchmark signal models. The production cross-sections used for the slepton, chargino, and gluino models are shown in Figure 6.1.

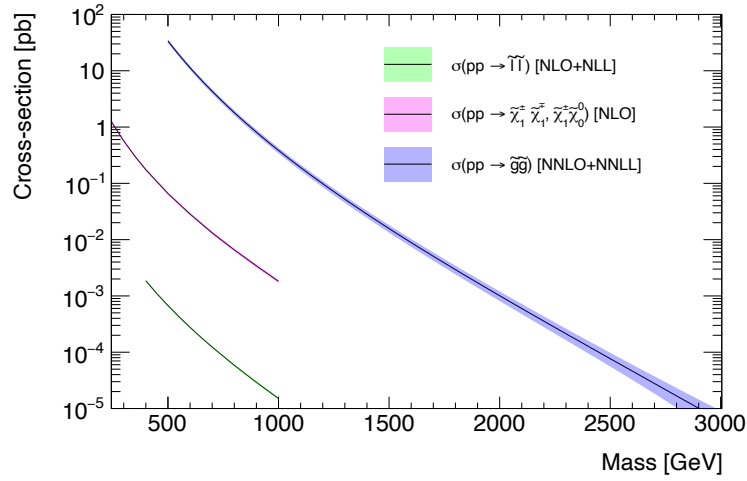


Figure 6.1: The production cross-sections as a function of particle mass for the slepton, gluino, and charginos used as benchmark signals.[†]

6.1.1 SLEPTONS

As discussed in Chapter 2, Gauge-Mediated Supersymmetry Breaking (GMSB) models can give rise to long-lived sleptons. Figure 6.2 shows the Feynman diagram for sleptons pair-produced in proton-proton collisions. In GMSB models, the charged long-lived particle that this search could detect is the slepton. The slepton would decay to a Standard Model lepton and a gravitino.

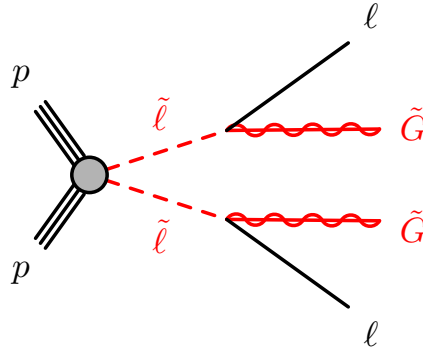


Figure 6.2: A Feynman diagram for pair-produced GMSB sleptons from proton-proton collisions. Each slepton decays to a Standard Model lepton and a gravitino [91].

This search uses simulation of pair-produced GMSB staus that decay to a tau and a gravitino. The gravitino is assumed to be massless. The signal samples are generated with stau lifetimes of 3 ns, 10 ns, 30 ns, and 3000 ns. For each lifetime point, signal samples are generated at stau mass points in the range 100 GeV–1 TeV.

Compared to the previous iteration of this analysis that used dE/dx as the sole window to particle speed, the background reduction provided by the use of time-of-flight from the calorimeter should improve sensitivity to low-mass sleptons in the mass range 100GeV–500GeV. To take advan-

tage of this improved expected sensitivity, signal mass points have been generated with a granularity of 50 GeV in this mass range.

6.1.2 GLUINOS

Split-SUSY models can result in long-lived gluinos. Figure 6.3 shows the Feynman diagram for pair-produced gluinos. If the gluinos are not stable, they each decay into two Standard Model quarks and a neutralino.

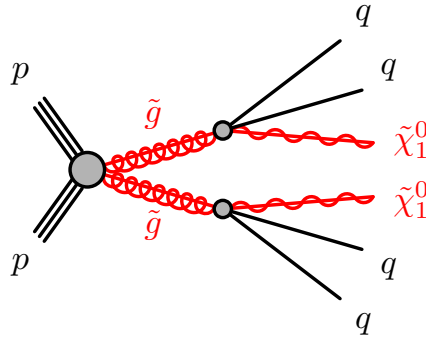


Figure 6.3: A Feynman diagram for pair-produced gluinos. The gluinos hadronize into bound states of gluinos and partons called R-hadrons. Each gluino decays to two Standard Model quarks and a neutralino [91].

The gluinos themselves are neutral. However, they carry color charge and therefore hadronize into colorless bound states with Standard Model partons. These bound states are called R-hadrons, and may be electrically charged. The R-hadron serves as the heavy, charged, long-lived particle detectable by this search.

The composition of an R-hadron may change as it moves through the detector due to interactions with material. The composition of R-hadrons as a function of r in the ATLAS detector

is shown in Figure 6.4 for a gluino of mass 1.4 TeV, simulated using Pythia8. An R-meson is a bound state of a gluino and a meson, an R-baryon is a bound state of a gluino and a baryon, and a gluinoball is a bound state of a gluino and a gluon. After passage through the Tile calorimeter, more than 98% of the simulated R-hadrons have converted into R-baryons [20].

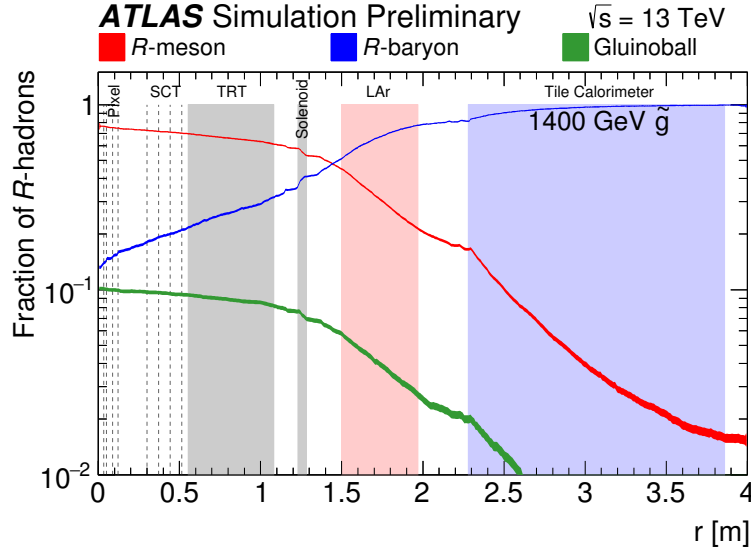


Figure 6.4: The fraction of R-hadrons in the form of R-mesons, R-baryons, and gluinoballs for a gluino of mass 1.4 TeV as a function of r in the ATLAS detector in simulation using Pythia8 and GEANT4. R-hadrons may change composition as they traverse the detector via the exchange of partons with the material [20].

Details about simulation of R-hadrons in ATLAS can be found in Reference [20].

This search uses simulation of gluinos with lifetimes of 3 ns, 10 ns, and 30 ns, as well as stable gluinos. For each lifetime point, signal samples are produced at mass points in the range 1.4 TeV–2.6 TeV. This search considers two possible scenarios for the mass splitting between the gluino and the neutralino. In one scenario, the neutralino is considered to be massless. In the other scenario, the gluino and the neutralino are assumed to have a fixed mass splitting, where the mass of the

neutralino is set to be 30 GeV less than the mass of the gluino. Samples are produced for both cases and allow us to explore decays with different kinematic phase space.

6.1.3 CHARGINOS

Anomaly-Mediated Supersymmetry Breaking (AMSB) models can result in charginos that are long-lived due to a small mass splitting between the chargino and the neutralino. Figure 6.5 shows a Feynman diagram for pair-produced charginos in proton-proton interactions. The chargino is assumed to decay to a soft pion and a neutralino.

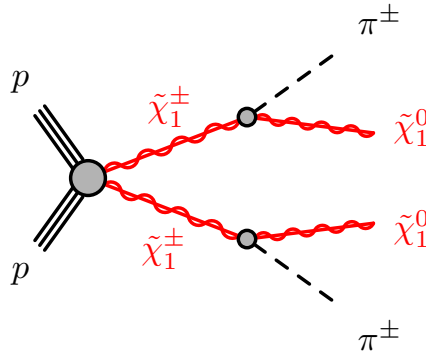


Figure 6.5: A Feynman diagram for pair-produced AMSB charginos. Each chargino decays to a pion and a neutralino [91].

This search uses simulation of chargino-chargino ($\tilde{\chi}_1^+ \tilde{\chi}_1^-$) and chargino-neutralino ($\tilde{\chi}_1^\pm \tilde{\chi}_1^0$) events that are produced separately and then combined for each lifetime and mass point. The mass splitting between the chargino and the neutralino is fixed to be approximately 170 MeV. Chargino samples are generated at lifetime points of 4 ns, 10 ns, 30 ns, and stable. The chargino signal samples are generated at mass points in the range 700 GeV–1.4 TeV.

This search is designed to primarily target sleptons of masses less than 1 TeV. Additionally, R-hadron samples are generated at higher masses to probe a mass range of R-hadrons that has not yet been excluded. Chargino samples are used to cover the intermediate mass range between the slepton and the R-hadron samples and quantify our sensitivity to potential signals in this mass range.

6.1.4 dE/dx AND TIME OF FLIGHT IN SIMULATION

As discussed in Chapter 5, the dE/dx and time-of-flight (ToF) measurements are sensitive to detector conditions. The simulation of dE/dx and ToF in the generated signal samples does not capture all relevant detector effects. To correct for this, a data-driven procedure replaces the simulated dE/dx and ToF values in the signal samples with values derived from data. This procedure allows us to directly compare signal simulation with data.

DATA-DRIVEN dE/dx REPLACEMENT

The dE/dx observable is not described well by simulation due to its sensitivity to detector effects, such as radiation damage. Figure 6.6 shows a comparison between the truncated mean dE/dx in data and simulation after the corrections discussed in Section 5.1.3. The simulated dE/dx distributions are narrower than the dE/dx distributions in data because the simulation does not account for all detector effects. The simulated dE/dx values do not describe the data, motivating the replacement of simulated dE/dx values by data-driven values.

The replacement dE/dx values are sampled from a dE/dx template that is constructed in bins of $|\eta|$ and $\beta\gamma$. The template is filled using the same low-pileup minimum-bias data sample from

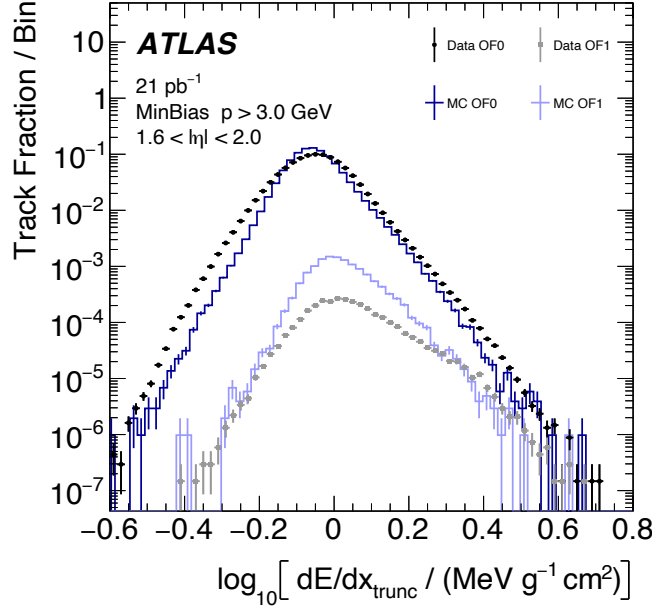


Figure 6.6: A comparison of truncated mean dE/dx after corrections have been applied in simulation (histograms) and in data (points). The distributions are plotted separately according to whether the track contains an IBL overflow cluster (OF1) or does not contain an overflow cluster (OF0). The dataset shown is the same minimum-bias dataset used for the dE/dx calibration. The simulated dE/dx distributions do not agree with the data, motivating the replacement of simulated dE/dx values with data-driven values [76].

2017 with low- p_T track reconstruction that is used for the dE/dx - $\beta\gamma$ calibration described in Section 5.1.4. The calibration extracts the dE/dx - $\beta\gamma$ mapping from the proton, pion, and kaon peaks in dE/dx distributions in $|\eta|$ and momentum slices, separated by IBL overflow status (OF0, OF1). The various particle contributions to these dE/dx distributions are used to fill the template. Overlapping dE/dx contributions from different particles in the same $\beta\gamma$ slice are averaged.

The resulting templates for the bin $|\eta| < 0.4$ are shown in Figure 6.7. Figure 6.7a shows the dE/dx template for tracks without an IBL overflow cluster (OF0). Figure 6.7b shows the dE/dx template for tracks that include an IBL overflow cluster (OF1). Tracks in the OF1 template are con-

centrated at lower $\beta\gamma$ because an overflow cluster in the IBL indicates high ionization energy loss, corresponding to low $\beta\gamma$. Tracks without an IBL overflow cluster are more likely to be concentrated at higher $\beta\gamma$, as seen in the OF0 template.

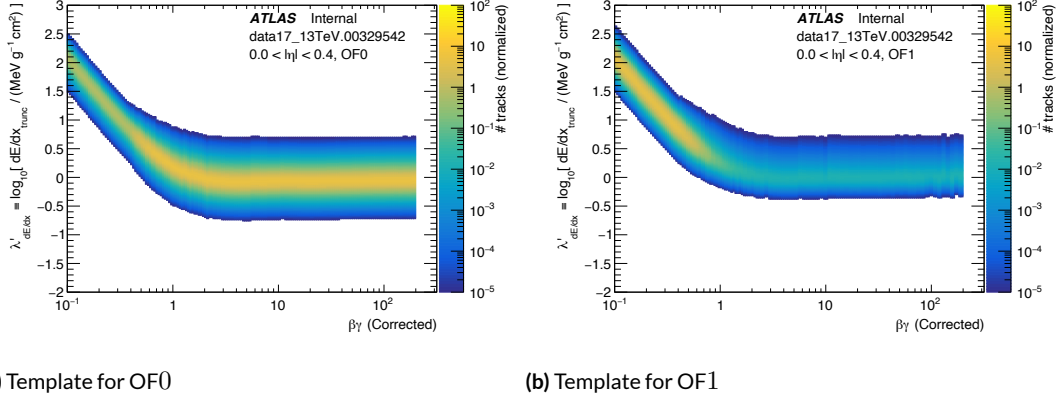


Figure 6.7: dE/dx templates in bins of $\beta\gamma$ for $|\eta| < 0.4$. The templates are constructed separately for tracks that do not contain an IBL overflow cluster (OF0), shown in (a), and tracks that do contain an IBL overflow cluster (OF1), shown in (b). The templates are used to replace simulated dE/dx values in the signal simulation samples.[†]

The simulated dE/dx values are replaced by dE/dx values drawn from the templates according to the η and $\beta\gamma$ that the simulated particle was generated with. First, the simulated particle is assigned an IBL overflow value of 0 or 1. This is done using an η -dependent probability distribution that describes the proportion of tracks of that particular $\beta\gamma$ containing an IBL overflow cluster in that particular $|\eta|$ slice, as derived in data.

The IBL overflow assignment and the η of the simulated particle determine which dE/dx template will be used. A random dE/dx value is drawn from the corresponding $\beta\gamma$ bin and is used in place of the simulated dE/dx value for the simulated particle. Finally, the $|\eta|$ -dependent correction described in Section 5.1.3 is applied.

A comparison of the data-driven replacement dE/dx distribution in chargino samples to the dE/dx distribution in data is shown in Figure 6.8 for the IBL overflow OF0 and OF1 cases. The data-driven replacement dE/dx distribution (black histogram) shows improved agreement with the data distribution (unfilled squares) compared to the original simulated dE/dx distribution (red histogram).

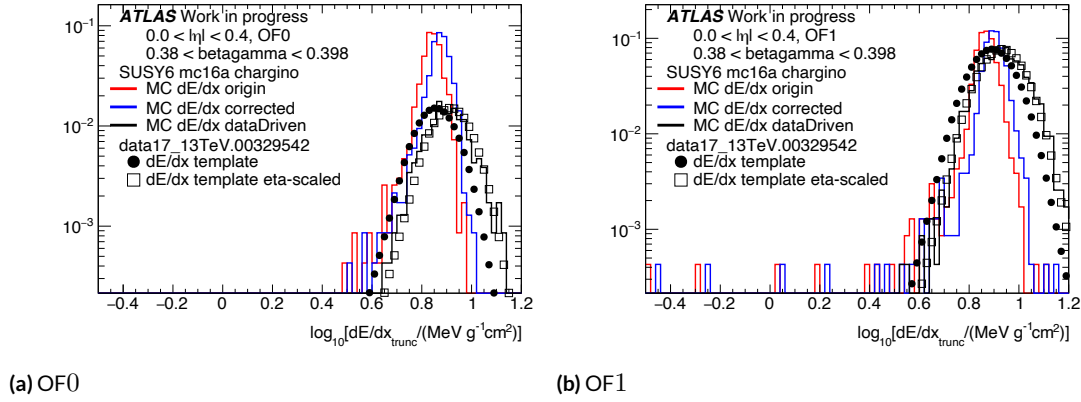


Figure 6.8: dE/dx distributions in a bin $0.38 < \beta\gamma < 0.398$ and $|\eta| < 0.4$, for IBL overflow status (a) OF0 and (b) OF1. The original dE/dx distribution in chargino Monte Carlo simulation is shown in the red histogram. The blue histogram shows the simulated dE/dx distribution with a rudimentary scaling correction applied that is insufficient to describe the dE/dx distribution in data, shown in the unfilled squares. The data prior to the $|\eta|$ -dependent correction described in Section 5.1.3 is shown in black dots. The data-driven dE/dx distribution is shown in the black histogram. The data-driven dE/dx distribution shows agreement with the $|\eta|$ -corrected data (unfilled squares).[†]

DATA-DRIVEN TOF REPLACEMENT

Tile calorimeter cell time is not well-modeled by simulation. Figure 6.9 shows the cell time distribution in 2018 $Z \rightarrow \mu\mu$ data compared to the cell time distribution in $Z \rightarrow \mu\mu$ simulation. The cell time resolution in simulation is narrower than in data.

In order to reliably compare signal simulation to data, a procedure has been developed to replace

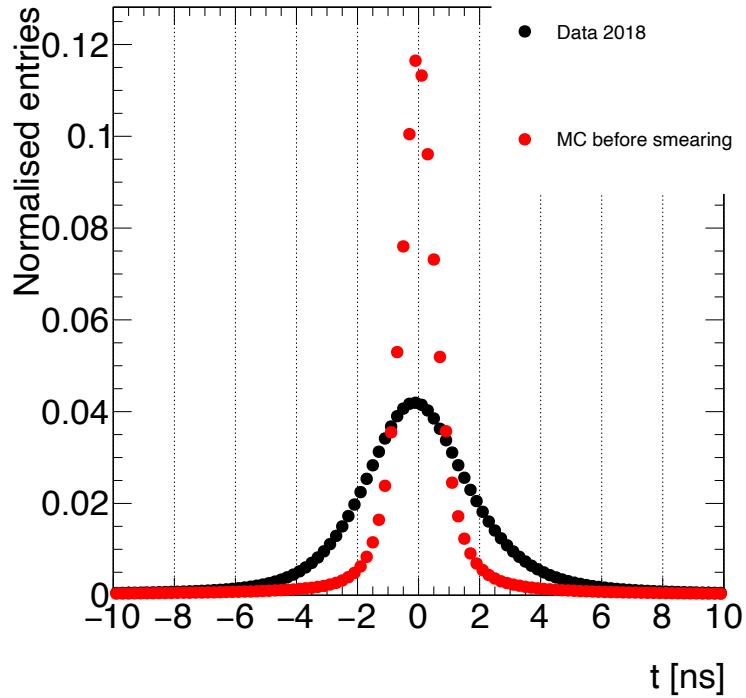


Figure 6.9: The cell time distribution in 2018 $Z \rightarrow \mu\mu$ data (black points) compared to the cell time distribution in $Z \rightarrow \mu\mu$ simulation (red points). The cell time distribution is wider in data than in simulation because the simulation does not model all relevant detector conditions and effects.[†]

the simulated cell time with values derived from data such that the cell time resolution in simulation will match the resolution in data. This *smearing* procedure is performed separately for each cell. As cell time resolution depends upon the cell energy, the smearing is also performed separately in bins of cell energy.

The smearing of simulated cell time is determined through a probability function that relates the cell time value in simulation to a cell time value in data. This function compares the normalized cumulative distribution function of cell time in simulation to the normalized cumulative distribu-

tion function of cell time in data. The probability function relates a simulated cell time value to a data cell time value such that the fraction of the simulated cell time distribution lying below the simulated value is equal to the fraction of the data cell time distribution lying below the chosen data value. In this way, the resolution of simulated cell time is smeared to match that of data by construction.

The β_{ToF} value calculated with smeared cell time is referred to as a smeared β_{ToF} value. For particles with low speed ($\beta \lesssim 0.8$), a residual dependence of smeared β_{ToF} was found on the β value that the particle was generated with, or the *truth* β . Ideally, the smeared β_{ToF} value would match the truth β value for the particle. Figure 6.10 shows that the smeared β_{ToF} values do not necessarily match the truth β values, and that the deviation between smeared β_{ToF} and truth β depends on truth β . A quadratic fit is performed, shown as the red curve in Figure 6.10, and a correction is added to the smeared β_{ToF} to account for this effect.

The corrected smeared β_{ToF} distribution in $Z \rightarrow \mu\mu$ simulation compared to the β_{ToF} distribution in 2018 $Z \rightarrow \mu\mu$ data is shown in Figure 6.11. There are some residual fluctuations in the simulation relative to the data. However, the ratio between simulation and data is stable in the low- β ($\beta_{\text{ToF}} \lesssim 0.9$) region-of-interest in this search. The deviation of the simulation-to-data ratio from unity is covered by a systematic uncertainty of 3% on the smearing factors.

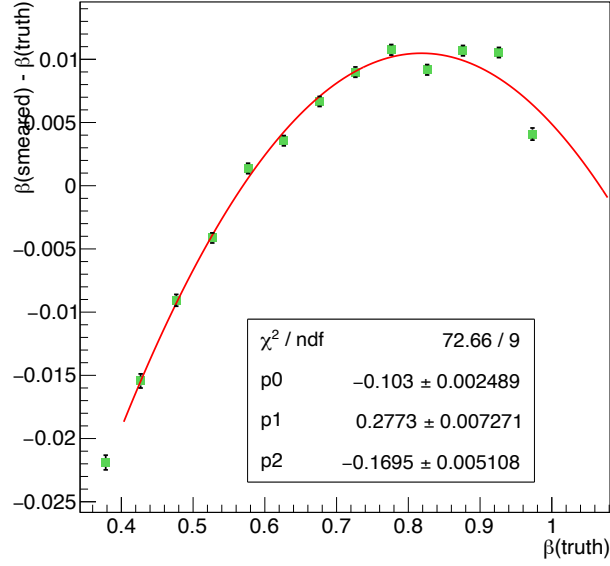


Figure 6.10: The difference between β_{ToF} calculated after smearing and the β the particle was generated with (truth β), as a function of truth β . Below truth β 0.8, there is a dependence of the smeared β_{ToF} on truth β . A quadratic fit is performed and used to derive a correction to the smeared β_{ToF} .[†]

6.2 SELECTION

This thesis uses $140.1 \pm 1.2 \text{ fb}^{-1}$ of Run 2 data. To search for heavy, charged, long-lived particles, we place requirements on this data to define a region of variable space that we expect to be enriched with signal relative to the amount of background. This region-of-interest is called the Signal Region. We place requirements on events in the Run 2 dataset as well as on the tracks within those events to select tracks that have properties we would expect from our target signal particles, while rejecting tracks that likely come from background processes. Tracks that satisfy all of these requirements are located in the Signal Region.

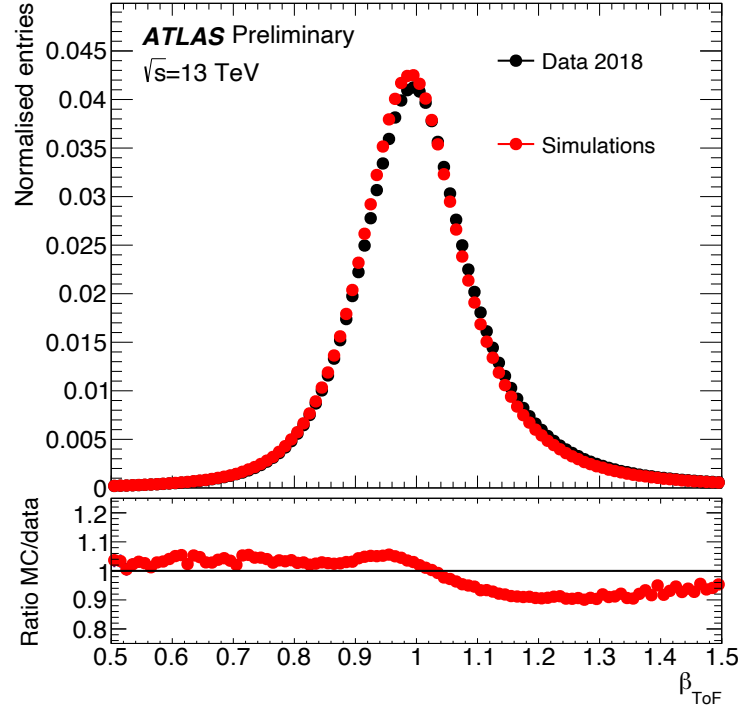


Figure 6.11: The corrected smeared β_{ToF} (red points) compared to 2018 $Z \rightarrow \mu\mu$ data (black points). While residual fluctuations remain after the smearing procedure, the ratio of smeared simulation to data is stable in the region $\beta_{\text{ToF}} \lesssim 0.9$, which includes the region of interest in this search [2].

A summary of the Signal Region selection is shown in Figure 6.12. This section discusses the purpose and the impact of the selection requirements.

6.2.1 EVENT SELECTION

EVENT QUALITY REQUIREMENTS

Events must come from datasets listed on the Good Run List (GRL), which is a set of data-taking runs that satisfy ATLAS data quality requirements. In addition, events must pass event cleaning

SIGNAL REGION SELECTION

EVENT-LEVEL

- GRL, Event cleaning, Jet cleaning
- Event passes E_T^{miss} trigger
- Offline $E_T^{\text{miss}} > 170$ GeV
- PV associated to ≥ 2 tracks

TRACK-LEVEL

TRACK QUALITY

- Require hit in IBL/B-Layer
- No split or shared hits
- ≥ 6 hits in SCT
- Pass p-dependent σ_p cut

TRACK KINEMATICS

- $p_T > 120$ GeV
- $|\eta| < 1.6$

ISOLATION/VETOES

- Σp_T in cone of $\Delta R=0.3 < 5$ GeV
- $EM_{\text{frac}} < 0.95$
- $E_{\text{jet}} / p_{\text{track}} < 1$
- $m_T(\text{track}, E_T^{\text{miss}}) > 130$ GeV

MEASUREMENTS OF SPEED

- $dE/dx > 1.8 \text{ MeVg}^{-1}\text{cm}^2$
- $\beta_{\text{ToF}} < \eta\text{-dependent } \beta_{\text{cut}}$

Figure 6.12: A summary of the selection requirements that form the Signal Region. The Signal Region is composed of the highest- p_T track that fulfills the track selection contained within events that fulfill the event selection.

requirements, which remove events in which error flags are raised due to detector system issues that could corrupt the data in the event. To remove spurious calorimeter signals that may affect the E_T^{miss} calculation, a custom jet cleaning procedure removes events containing jets that do not fulfill a set of quality criteria.

TRIGGER

This search looks for heavy, charged, long-lived particles that would leave high-momentum tracks in the Inner Detector (ID) of ATLAS. To collect collision data relevant to the search, ideally we would choose to use a trigger that saves events containing high- p_T ID tracks. However, as tracking is computationally intensive, such a trigger was unavailable during Run 2. For lack of a track-based trigger, we must choose another trigger that selects events with features common to a variety of models producing heavy, charged, long-lived particles.

This search uses data collected with the E_T^{miss} trigger discussed in Section 4.2. The online E_T^{miss} trigger makes decisions based only on energy deposition information from the calorimeters. Events with a large imbalance in calorimeter deposits in the transverse plane, regardless of signals in other detector systems, will have high E_T^{miss} . Over the course of Run 2, the lowest online E_T^{miss} trigger threshold varied from 70 GeV to 110 GeV. Events passing the E_T^{miss} trigger are selected for use in this analysis.

The heavy long-lived particles targeted in this search are not expected to leave large energy deposits in the calorimeters. Therefore, we rely on the presence of objects in the event that leave large calorimeter deposits (such as jets or taus) in order to pass the online E_T^{miss} trigger.

Figure 6.13 sketches out how online E_T^{miss} can arise in events containing long-lived particles. An event containing particles that are stable on the scale of the detector can result in significant E_T^{miss} if the stable particles are offset in the transverse plane by a jet resulting from QCD initial-state radiation. An event containing metastable particles (particles that decay within the detector volume) can

result in high E_T^{miss} if the decay products are Standard Model quarks that give rise to jets and a high-momentum particle that escapes the detector without interacting significantly with the material.

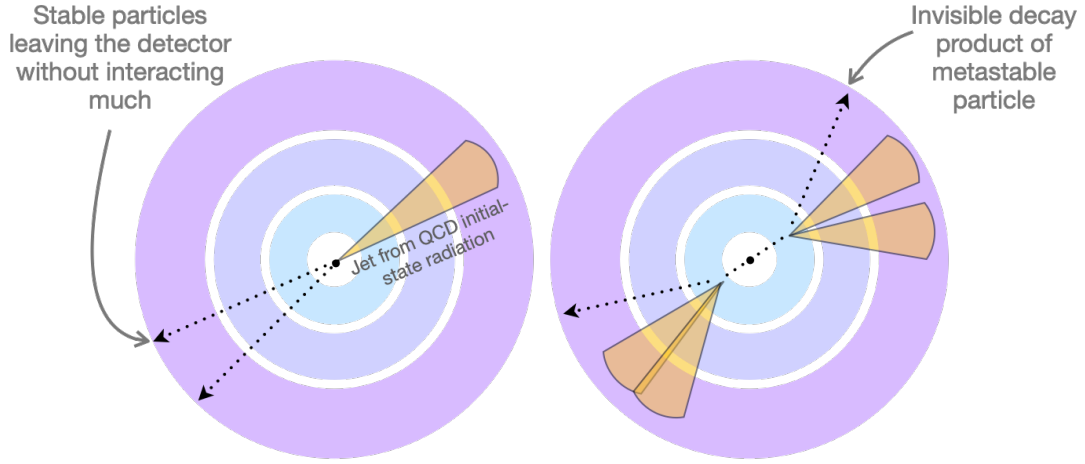


Figure 6.13: A sketch of how online E_T^{miss} (a large imbalance in calorimeter deposits), can appear in events containing long-lived particles. An event with pair-produced stable particles can result in significant E_T^{miss} if the particles are offset in the transverse plane by a jet from QCD initial-state radiation. The heavy stable particles are not expected to interact significantly with the calorimeter, resulting in an overall imbalance in calorimeter deposits and therefore E_T^{miss} . Metastable particles, or long-lived particles decaying within the detector volume, can result in E_T^{miss} if they decay into a Standard Model quark that produces a jet and a high-momentum particle that escapes the detector without interacting significantly with the material.

As different models predict event topologies that result in different amounts of E_T^{miss} , the choice to use the E_T^{miss} trigger impacts the degree of model-independence accessed by this search. The efficiency with which the E_T^{miss} trigger selects events is impacted by the mass, lifetime, and kinematics assumed in the signal models. Efficiency is defined as:

$$\text{efficiency} = \frac{\text{number of events passing cuts}}{\text{total number of events}} \quad (6.1)$$

Figure 6.14 shows the efficiency of simulated slepton, R-hadron, and chargino events, where the

relevant cuts in the numerator of Equation 6.1 are the event cleaning requirements and the E_T^{miss} trigger requirements.

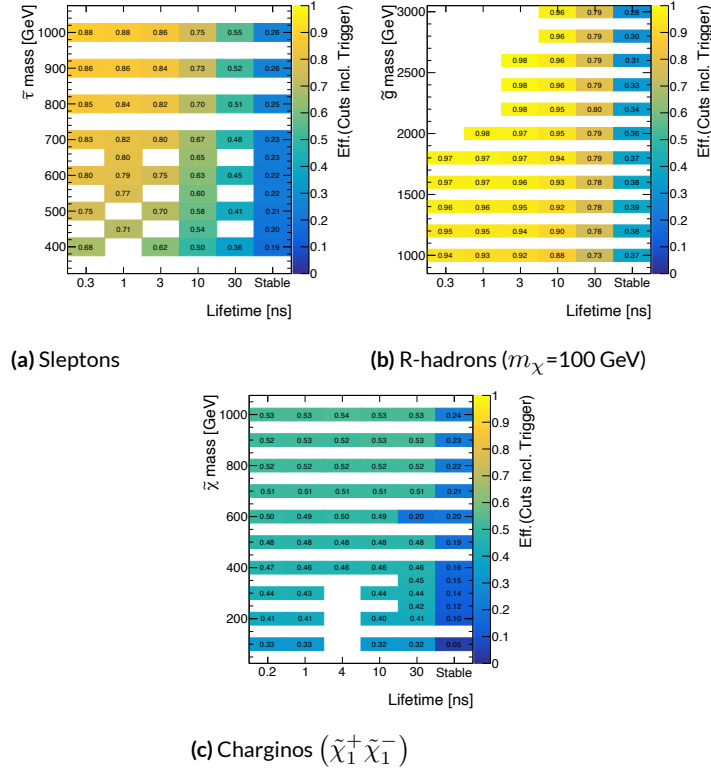


Figure 6.14: The efficiency of (a) slepton events, (b) R-hadron events where $m_\chi = 100$ GeV, and (c) chargino-chargino ($\tilde{\chi}_1^+ \tilde{\chi}_1^-$) events passing the event quality requirements and the E_T^{miss} trigger requirements as a function of mass and lifetime.[†]

The efficiency of the simulated events to pass the E_T^{miss} trigger varies as a function of mass and lifetime. As seen in Figure 6.14, the trigger efficiencies are highest for short lifetimes and high masses. The more massive the particle is, the more momentum it imparts to its decay products. An undetected decay product therefore results in a higher energy imbalance in the event and higher E_T^{miss} , resulting in a higher probability to pass the E_T^{miss} trigger. A particle with a short lifetime has a greater

probability to decay before reaching the calorimeter. Its visible decay products deposit energy in the calorimeter and the invisible neutral decay products leave the detector, resulting in E_T^{miss} . For particles that are stable on the scale of the detector, the presence of E_T^{miss} relies upon a jet originating from QCD initial-state radiation to create the energy imbalance in the event. Therefore, the E_T^{miss} trigger efficiency is lower for stable particles.

Event kinematics also play a role in trigger efficiency. In the signal models considered, the metastable sleptons and charginos each decay to a neutral and thus invisible decay product (a gravitino for the slepton case and a neutralino for the chargino case) as well as Standard Model particles that would result in large energy deposits in the calorimeter (see Figures 6.2 and 6.5). However, for a given mass and lifetime point, the efficiency of the chargino events passing the E_T^{miss} trigger is less than the trigger efficiency for the slepton events. The mass splitting between the chargino and the neutralino is assumed to be ~ 170 MeV, so there is much less phase space available for the decay products than in the case of the slepton, which is assumed to decay to a massless gravitino. Therefore the decay products of the chargino will be less energetic and result in less E_T^{miss} .

OFFLINE E_T^{miss}

Each event is required to have offline $E_T^{\text{miss}} > 170$ GeV. Offline E_T^{miss} , discussed in Section 4.8, is reconstructed using information from all detector systems and includes contributions from reconstructed muons, Inner Detector tracks, jets, and electrons.

Sources of offline E_T^{miss} vary according to the event topology considered. For metastable particles that decay to neutral particles, the momentum carried away by the neutral decay product will be

a source of offline E_T^{miss} . However, the topology of stable pair-produced charged particles does not offer a ready source of offline E_T^{miss} , as the tracks in the ID and the muon system should be reconstructed and included in the E_T^{miss} calculation (see Figure 6.13). Nevertheless, these events may still contain significant offline E_T^{miss} if the momentum of either particle is mismeasured or the event contains objects that do not meet the requirements to be accounted for in the offline E_T^{miss} calculation.

Figure 6.15 shows the offline E_T^{miss} distribution for simulated events containing sleptons, R-hadrons, and charginos of several masses and lifetimes. Stable events tend to have lower E_T^{miss} . Metastable events containing neutral decay products have larger E_T^{miss} . The chargino-neutralino events tend to contain more E_T^{miss} than the chargino-chargino events due to the neutral neutralino carrying away energy in the event, resulting in E_T^{miss} .

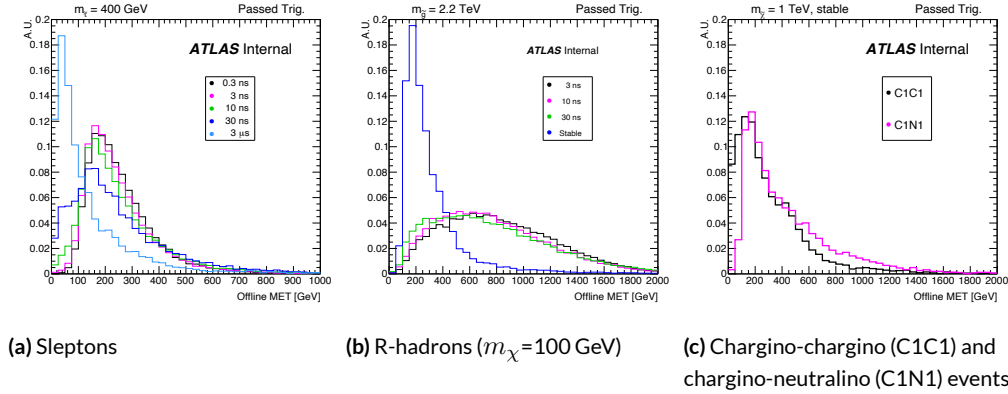


Figure 6.15: The offline E_T^{miss} distributions of events containing (a) sleptons of mass 400 GeV and varying lifetimes, (b) R-hadrons ($m_\chi = 100$ GeV) of mass 2.2 TeV at varying lifetimes, and (c) stable charginos of 1 mass TeV, where chargino-chargino (here referred to as C1C1) and chargino-neutralino (C1N1) events are considered. The events have passed the event quality requirements and the online E_T^{miss} trigger requirements.[†]

PRIMARY VERTEX

Each event is required to contain a primary vertex with at least 2 associated tracks. The primary vertex of the event is identified as the reconstructed vertex where the assigned tracks have the highest sum of p_T .

6.2.2 TRACK SELECTION

TRACK QUALITY

Candidate tracks must be associated to the primary vertex. The track must contain at least 6 hits in the SCT.

A photon converting to a small-angle electron-positron pair can lead to a single reconstructed track measured with anomalously high dE/dx . Tracks resulting from photon conversions often lack a hit in the first layer of the pixel tracker. To reject this source of background, the candidate track is required to have a hit in either the IBL or the B-Layer depending on the coverage of the IBL and B Layers in that region.

A momentum uncertainty requirement is applied to the candidate tracks to ensure the quality of the momentum measurement. As momentum resolution is linearly dependent on momentum, the cut placed on the momentum uncertainty is also momentum-dependent. The momentum uncertainty $\sigma_p \equiv \delta(q/p)/(q/p)$ must satisfy the following requirement:

$$\sigma_p = \min(f(p), 200\%) \tag{6.2}$$

where the function $f(p)$ is given by:

$$f(p) = \max \left(-1\% + 90\% \frac{|p|}{\text{TeV}}, 10\% \right) \quad (6.3)$$

To ensure the quality of the dE/dx measurement, at least 2 pixel hits from different layers are required to enter into the calculation of dE/dx . In addition, the track cannot contain any shared or split pixel hits. Shared pixel hits are hits that are used in the reconstruction of multiple tracks but are not identified as merged by the neural network described in Section 4.3.4. Split hits are pixel hits that are identified as likely to originate from multiple tracks by the neural network, but are ultimately assigned to only one track. Tracks containing split or shared hits are rejected to ensure that the track dE/dx measurement is not affected by hits that could have originated from overlapping tracks.

TRACK KINEMATICS

Candidate tracks are required to have $p_T > 120$ GeV. Signal tracks are expected to have high momentum, while the p_T spectrum of background tracks is expected to fall, as shown in Figure 6.16a. Additionally, requiring high p_T ensures that Standard Model particles will travel with a particle speed β close to 1, so that measures of particle speed through dE/dx and time-of-flight can be used to discriminate between signal and background.

Tracks are required to lie in the region $|\eta| < 1.6$. Although the Inner Detector extends up to $|\eta| \approx 1.8$ in the barrel region and up to 2.5 in the endcaps, the Tile calorimeter coverage ends near

$|\eta| = 1.7$. The track is required to be located within the range $|\eta| < 1.6$ to ensure that it has passed through multiple Tile calorimeter cells. Heavy signal particles are expected to have an η distribution that is central compared to background, as seen in Figure 6.16b. The η requirement therefore also serves to reject background while retaining most of the signal tracks.

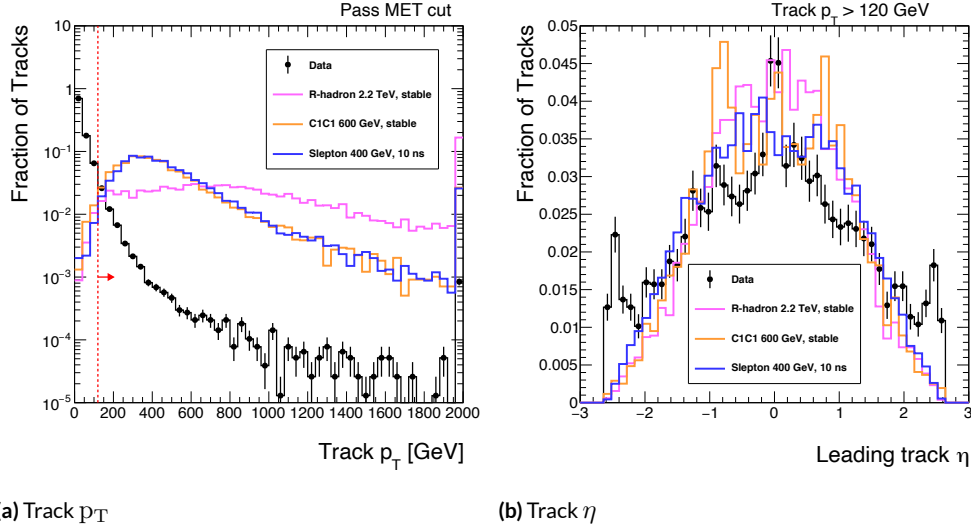


Figure 6.16: Kinematic distributions of signal tracks compared to data. (a) shows the p_T distribution of tracks passing the offline E_T^{miss} cut. The p_T cut is shown in the red dotted line. Tracks with $p_T > 120$ GeV are selected. (b) shows the η distribution of tracks passing the p_T requirement. Tracks falling within $|\eta| < 1.6$ are selected.[†]

TRACK ISOLATION AND VETOES

Heavy, charged, long-lived particles are expected to produce highly ionizing tracks in the Inner Detector. The presence of other tracks near the candidate track may indicate that hits forming the track could have originated from multiple particles depositing energy in the same pixels, which would produce an anomalously high dE/dx value assigned to the track. We apply an isolation cut requiring that within a cone of $\Delta R = 0.3$ around the candidate track, the sum of p_T of other tracks must be

less than 5 GeV.

An electron veto is applied to reject tracks produced by electrons. Calorimeter deposits originating from electrons characteristically have a significant fraction of energy in the electromagnetic calorimeter. To reject electrons, the candidate track is associated to the nearest jet with $p_T > 20$ GeV within a cone of radius $\Delta R = 0.4$. If the fraction of the total jet energy deposited in the electromagnetic calorimeter (EM_{frac}) exceeds 95%, the track is rejected.

Hadronic background can be similarly rejected by associating the track to the nearest jet with $p_T > 20$ GeV within a cone of radius $\Delta R = 0.4$. As the signal tracks are not expected to leave large energy deposits in the calorimeters, the track is rejected if the energy of the associated jet is greater than the momentum of the candidate track.

Background from W boson decays is suppressed through a requirement that the transverse mass of the track and the E_T^{miss} is greater than 130 GeV. Transverse mass m_T is defined as:

$$m_T = \sqrt{2p_T^{\text{track}}E_T^{\text{miss}}(1 - \cos \Delta\phi)} \quad (6.4)$$

where E_T^{miss} is the offline E_T^{miss} in the event, p_T^{track} is the p_T of the candidate track, and $\Delta\phi$ is the difference in azimuthal angle between the candidate track and the offline E_T^{miss} in the event.

IONIZATION REQUIREMENT

As discussed in Section 5.1, heavy, high-momentum, long-lived particles are expected to travel more slowly than high-momentum Standard Model particles, and slow-moving particles ($\beta\gamma \lesssim 1$) lose

more energy to ionization losses while traversing material. Thus, anomalously high ionization energy loss can be used to discriminate slow-moving, heavy new particles from Standard Model background.

Tracks are required to have $dE/dx > 1.8 \text{ MeV g}^{-1}\text{cm}^2$. The dE/dx distribution for tracks in signal simulation and in data is shown in Figure 6.17.

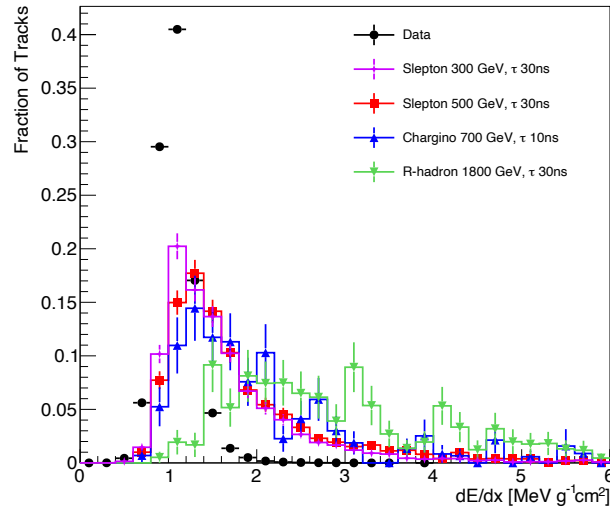


Figure 6.17: The dE/dx distribution for several signal points compared to background-dominated data. Data satisfies Signal Region selection except $E_T^{\text{miss}} < 150 \text{ GeV}$, no dE/dx requirement is placed, and $\beta_{\text{ToF}} < 1$.

TIME-OF-FLIGHT REQUIREMENT

Similarly, as discussed in Section 5.2, time-of-flight (ToF) as measured in the hadronic Tile calorimeter can be used to distinguish heavy long-lived particles from light, fast ($\beta \approx 1$) particles. A cut on β_{ToF} is applied to select slow-moving particles.

Due to the structure of the Tile calorimeter, the resolution of β_{ToF} depends on $|\eta|$, as discussed in Section 5.2.2 and shown in Figure 6.18a. For this reason, the β_{cut} requirement to the candidate track is different in different regions of $|\eta|$. The β_{cut} requirement is defined in bins of 0.1 width in $|\eta|$.

Tracks are required to have $\beta_{\text{ToF}} < \beta_{\text{cut}}$, where β_{cut} is given by:

$$\beta_{\text{cut}} = 1 - 2\sigma_{\beta} \quad (6.5)$$

and σ_{β} is the resolution of β_{ToF} in the $|\eta|$ bin corresponding to the η of the candidate track.

Figure 6.18b shows the distribution of β_{ToF} expected for signal and for background tracks in a particular bin of $|\eta|$.

The cut in Equation 6.5 is defined such that the β requirement imposed by the β_{ToF} cut approximately matches the β requirement imposed by the dE/dx cut. The β_{cut} values lie around $\beta_{\text{ToF}} = 0.8$, which roughly corresponds to the β requirement imposed by the ionization cut $dE/dx > 1.8 \text{ MeV g}^{-1}\text{cm}^2$.

6.2.3 THE SIGNAL REGION

Events must pass all of the described event selection and contain at least one track that passes all of the described track selection. The highest- p_T track in the event that meets all of the track criteria is added to the Signal Region.

The basic format of ATLAS data is the Analysis Object Data (AOD) format, described in [92].

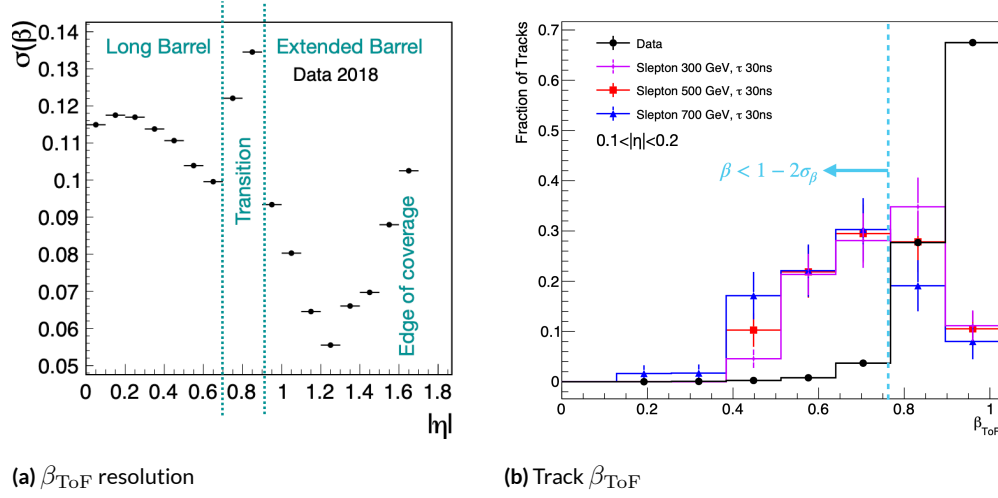


Figure 6.18: (a) shows the dependence of the β_{ToF} resolution σ_β on $|\eta|$ due to the structure of the Tile calorimeter in 2018 $Z \rightarrow \mu\mu$ data.[†] (b) shows the β_{ToF} distributions of selected signal samples compared to Run 2 data. The data is background-dominated and satisfies Signal Region selection except $E_T^{\text{miss}} < 150$ GeV, no dE/dx requirement is placed, and $\beta_{\text{ToF}} < 1$. Tracks falling below the β_{cut} value for the given $|\eta|$ slice would be selected for the Signal Region in data that satisfies all Signal Region requirements. For $0.1 < |\eta| < 0.2$, the β_{cut} selects tracks falling below $\beta_{\text{ToF}} = 0.76$.

Selection	N(Events)	Eff.
SUSY6	4497855936	1
GRL	4371758464	0.972
Trigger	800674320	0.178
Track in PV	560531996	0.125
$p_T > 50$ GeV	144883491	0.032
Loose track isolation	50310121	0.011

Table 6.1: The cutflow for the preselection requirements on the events and tracks for data events skimmed from the DAOD to the mini-xAOD data format.[†]

A derivation framework reduces the size of AODs to produce derived AOD data samples, or DAODs.

This search uses a DAOD called the SUSY6 DAOD, which contains useful observables for analyses

searching for long-lived particles. This data is skimmed to produce a data file smaller in size, called

a mini-AOD. This skimming procedure applies several event-level and track-level pre-selection cuts

shown in Table 6.1.

The mini-AOD data format is processed into ntuples that contain event and track information

and have the selection requirements discussed in this chapter applied. The cutflow, or the efficiency of each selection requirement, of the Run 2 dataset is summarized in Table 6.2.

The cutflow for several signal samples is shown in Tables 6.3- 6.5. Table 6.3 shows the cutflow for a slepton sample of mass 400 GeV and lifetime 10 ns. Table 6.4 shows the cutflow for charginos of mass 800 GeV and lifetime 10 ns. Table 6.5 shows the cutflow for stable R-hadrons ($m_\chi=100$ GeV) of mass 2.2 TeV.

Cut	N(Events)	Eff.	Rel. Eff.
mini-xAOD	50310121	1.000	1.000
GRL	50310121	1.000	1.000
Event Cleaning	50265190	0.999	0.999
Jet Cleaning	49666647	0.987	0.988
Trigger	49666647	0.987	1.000
Primary Vertex	49666647	0.987	1.000
Offline E_T^{miss}	2696480	0.054	0.054
Track in PV	2696480	0.054	1.000
$p_T > 50$ GeV	2696480	0.054	1.000
dE/dx Used Hits	2451467	0.049	0.909
IBL/B-Layer Hits	2411925	0.048	0.984
Shared/Split Hits	2291630	0.046	0.950
SCT Hits	2187593	0.043	0.955
Track Isolation	1560198	0.031	0.713
$p_T > 120$ GeV	390642	0.008	0.250
Track p uncertainty	385291	0.008	0.986
Central track	339695	0.007	0.882
$m_T > 130$ GeV	86794	0.002	0.256
Electron veto	36462	0.001	0.420
Hadron veto	25440	0.001	0.698
Signal Region	N(Events)	Fraction	
	-	-	

Table 6.2: The cutflow for the full Run 2 dataset. The resulting number of data events in the Signal Region after the application of the particle speed (dE/dx and β_{ToF}) requirements can be found in Chapter 9.[†]

Cut	N(Events)	Eff.	Rel. Eff.
Total	258.364	1.000	1.000
GRL	258.364	1.000	1.000
Event Cleaning	258.364	1.000	1.000
Jet Cleaning	255.914	0.991	0.991
Trigger	128.823	0.499	0.503
Primary Vertex	128.823	0.499	1.000
Offline E_T^{miss}	87.042	0.337	0.676
Track in PV	84.859	0.328	0.975
$p_T > 50$ GeV	83.710	0.324	0.986
dE/dx Used Hits	82.237	0.318	0.982
IBL/B-Layer Hits	82.193	0.318	0.999
Shared/Split Hits	81.784	0.317	0.995
SCT Hits	80.351	0.311	0.982
Track Isolation	79.401	0.307	0.988
$p_T > 120$ GeV	78.927	0.305	0.994
Track p uncertainty	78.314	0.303	0.992
Central track	73.317	0.284	0.936
$m_T > 130$ GeV	60.581	0.234	0.826
Electron veto	60.022	0.232	0.991
Hadron veto	58.820	0.228	0.980
$dE/dx > 1.8 \text{ MeVg}^{-1} \text{cm}^2$	12.977	0.050	0.221
Signal Region	N(Events)	Fraction	
$\beta_{\text{ToF}} < \beta_{\text{cut}}$	5.089	0.020	

Table 6.3: Cutflow for sleptons with mass 400 GeV and lifetime 10 ns. The mass windows discussed in Section 6.3 have not been applied.[†]

Cut	N(Events)	Eff.	Rel. Eff.
Total	91.455	1.000	1.000
GRL	91.455	1.000	1.000
Event Cleaning	91.455	1.000	1.000
Jet Cleaning	90.973	0.995	0.995
Trigger	19.102	0.209	0.210
Primary Vertex	19.102	0.209	1.000
Offline E_T^{miss}	13.376	0.146	0.699
Track in PV	13.305	0.145	0.995
$p_T > 50$ GeV	12.590	0.138	0.946
dE/dx Used Hits	12.100	0.132	0.961
IBL/B-Layer Hits	12.086	0.132	0.999
Shared/Split Hits	11.900	0.130	0.985
SCT Hits	11.479	0.126	0.965
Track Isolation	10.840	0.119	0.944
$p_T > 120$ GeV	10.785	0.118	0.995
Track p uncertainty	10.637	0.116	0.986
Central track	9.664	0.106	0.907
$m_T > 130$ GeV	7.868	0.086	0.816
Electron veto	7.862	0.086	0.999
Hadron veto	7.862	0.086	1.000
$dE/dx > 1.8 \text{ MeVg}^{-1} \text{cm}^2$	2.866	0.031	0.365
Signal Region	N(Events)	Fraction	
$\beta_{\text{ToF}} < \beta_{\text{cut}}$	1.133	0.012	

Table 6.4: Cutflow for charginos with mass 800 GeV and lifetime 10ns. The mass windows discussed in Section 6.3 have not been applied.[†]

Cut	N(Events)	Eff.	Rel. Eff.
Total	49.472	1.000	1.000
GRL	49.472	1.000	1.000
Event Cleaning	49.472	1.000	1.000
Jet Cleaning	49.170	0.994	0.994
Trigger	16.997	0.344	0.346
Primary Vertex	16.997	0.344	1.000
Offline E_T^{miss}	12.672	0.256	0.746
Track in PV	12.592	0.255	0.994
$p_T > 50$ GeV	10.330	0.209	0.820
dE/dx Used Hits	9.469	0.191	0.917
IBL/B-Layer Hits	9.418	0.190	0.995
Shared/Split Hits	8.886	0.180	0.944
SCT Hits	8.753	0.177	0.985
Track Isolation	7.125	0.144	0.814
$p_T > 120$ GeV	7.068	0.143	0.992
Track p uncertainty	6.703	0.135	0.948
Central track	6.225	0.126	0.929
$m_T > 130$ GeV	5.516	0.111	0.886
Electron veto	5.516	0.111	1.000
Hadron veto	5.516	0.111	1.000
$dE/dx > 1.8 \text{ MeVg}^{-1}\text{cm}^2$	5.036	0.102	0.913
Signal Region	N(Events)	Fraction	
$\beta_{\text{ToF}} < \beta_{\text{cut}}$	3.727	0.075	

Table 6.5: Cutflow for stable R-hadrons with mass 2.2 TeV. The mass windows discussed in Section 6.3 have not been applied.[†]

6.3 MASS RECONSTRUCTION AND MASS WINDOW OPTIMIZATION

We are searching for charged long-lived particles that are heavy compared to Standard Model particles. Because a particle that is charged and long-lived would interact with the detector material, we are able to measure its speed β . Mass is related to particle speed β and momentum p through the equation:

$$m = \frac{p}{\beta\gamma} \quad (6.6)$$

Momentum is measured from the trajectory of the track in the Inner Detector. Therefore we can reconstruct mass for each track in the Signal Region.

6.3.1 MASS RECONSTRUCTION

We measure particle speed in two independent ways: ionization energy loss dE/dx measured in the pixel tracker and time-of-flight (ToF) measured in the hadronic calorimeter. This allows us to reconstruct two masses for each track, $m_{dE/dx}$ and m_{ToF} :

$$m_{dE/dx} = \frac{p}{\beta\gamma_{dE/dx}} \quad (6.7)$$

$$m_{ToF} = \frac{p}{\beta\gamma_{ToF}} \quad (6.8)$$

where p is the momentum measured for the Inner Detector track, $\beta\gamma_{dE/dx}$ is the $\beta\gamma$ value ob-

tained from the track dE/dx through the dE/dx - $\beta\gamma$ calibration discussed in Section 5.1.4, and

$\beta\gamma_{ToF}$ is calculated from the β_{ToF} value:

$$\beta\gamma_{ToF} = \frac{\beta_{ToF}}{\sqrt{1 - \beta_{ToF}^2}} \quad (6.9)$$

Figure 6.19a shows the mass distribution calculated from dE/dx , $m_{dE/dx}$, for several signal samples. Figure 6.19b shows the mass distribution calculated from β_{ToF} , m_{ToF} , for several signal samples.

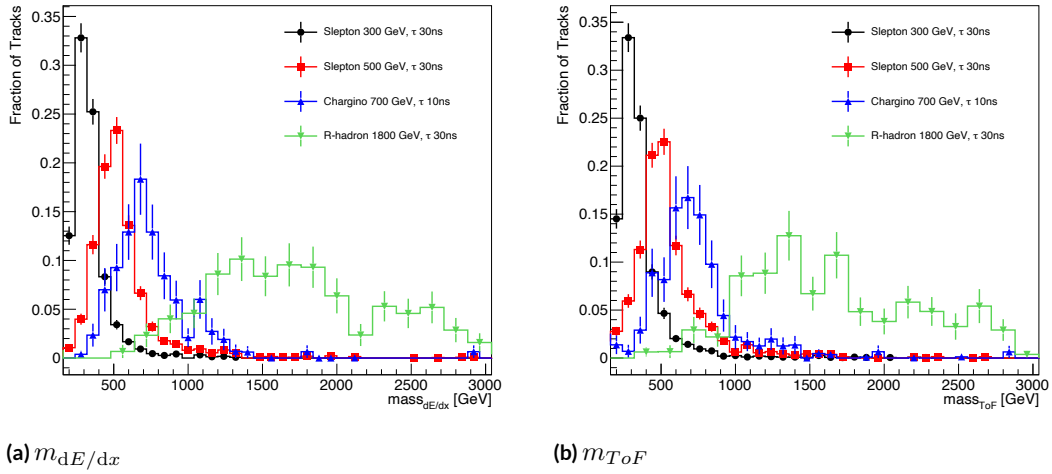


Figure 6.19: Mass distributions for mass reconstructed from (a) dE/dx and (b) ToF for several signal samples. These tracks satisfy Signal Region requirements except $E_T^{\text{miss}} < 150$ GeV, no dE/dx requirement is placed, and $\beta_{ToF} < 1$.[†]

The mass resolution is dominated by the momentum resolution, which degrades at high momentum. To illustrate the degradation of the momentum resolution, consider the momentum uncertainty requirement described in Section 6.2.2. This requirement places a cut on the uncertainty of the reconstructed momentum of the track. The cut loosens at higher momenta to reflect the worsen-

ing momentum resolution at high momenta. For a given momentum of 500 GeV, this requirement accepts tracks with momentum uncertainty up to $\sim 44\%$. For a much higher momentum of 2.4 TeV, tracks with momentum uncertainty up to 200% are accepted. By contrast, the $\beta\gamma$ resolution as measured via dE/dx and β_{ToF} is expected to be on the order of 10–20%. As higher mass tracks are reconstructed using higher momentum values, the spread in the mass distributions shown in Figure 6.19 is wider for samples of higher mass, mainly driven by the momentum resolution.

Figure 6.20a shows the 2-dimensional $(m_{dE/dx}, m_{\text{ToF}})$ plane for Signal Region tracks in an example slepton sample of mass 400 GeV and lifetime 30 ns. Figure 6.20b shows the $(m_{dE/dx}, m_{\text{ToF}})$ plane for Signal Region tracks for a sample of stable R-hadrons of mass 2.2 TeV.

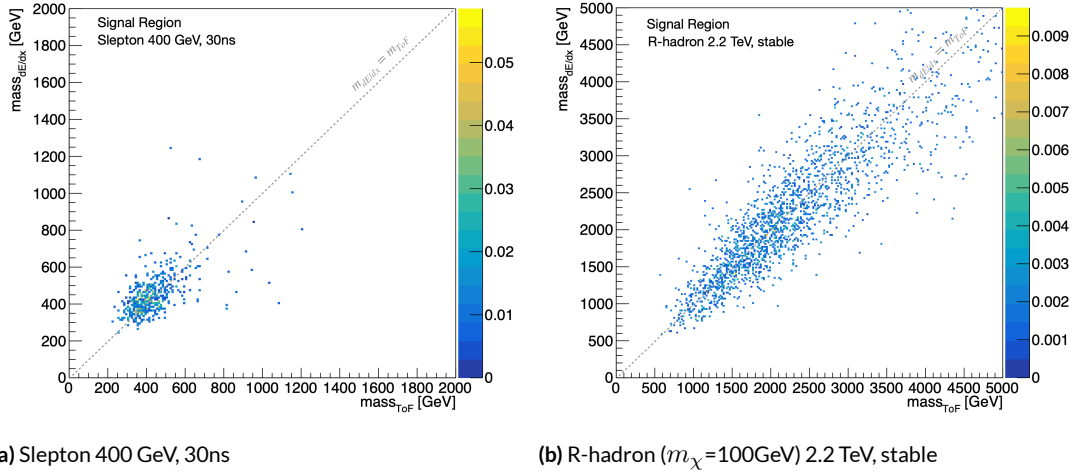


Figure 6.20: Distributions in the 2D $(m_{dE/dx}, m_{\text{ToF}})$ plane for a (a) slepton sample with mass 400 GeV and lifetime 30ns, and a (b) stable R-hadron sample with mass 2.2 TeV. The line $m_{dE/dx} = m_{\text{ToF}}$ is shown in a gray dashed line. These tracks satisfy all Signal Region requirements.[†]

The spread of these mass distributions in the 2D mass plane can be understood through the behavior of the mass resolution. The uncertainty σ_m on the reconstructed mass (either $m_{dE/dx}$ or

m_{ToF}) of a track is related to the resolution of the momentum measurement σ_p and the resolution of the $\beta\gamma$ measurement $\sigma_{\beta\gamma}$:

$$\begin{aligned}
\sigma_m &= \sqrt{\left(\frac{p}{(\beta\gamma)^2}\right)^2 \sigma_{\beta\gamma}^2 + \left(\frac{1}{\beta\gamma}\right)^2 \sigma_p^2} \\
&= \sqrt{\left(\frac{m}{\beta\gamma}\right)^2 \sigma_{\beta\gamma}^2 + \left(\frac{m}{p}\right)^2 \sigma_p^2} \\
&= m \sqrt{\left(\frac{\sigma_{\beta\gamma}}{\beta\gamma}\right)^2 + \left(\frac{\sigma_p}{p}\right)^2} \tag{6.10}
\end{aligned}$$

Consider the limit in which the momentum resolution is perfect and the resolution of both $\beta\gamma$ measurements is perfect ($\sigma_p = \sigma_{\beta\gamma} = 0$), implying perfect ToF and dE/dx resolution. Assuming the particle has a decay width of zero, the reconstructed $m_{dE/dx}$ and m_{ToF} would both be equal to the mass of the particle in question. As seen in Figure 6.20, this limit is clearly not the case, as the reconstructed masses exhibit a spread around the nominal mass point, which is (400 GeV, 400 GeV) for the slepton sample and (2.2 TeV, 2.2 TeV) for the R-hadron sample.

Consider the limit that the momentum resolution is nonzero, but the $\beta\gamma$ resolution is perfect ($\sigma_{\beta\gamma} = 0$). This implies perfect dE/dx and ToF resolution. Since $m_{dE/dx}$ and m_{ToF} are calculated with the same momentum, reconstructed $m_{dE/dx} = m_{ToF}$ for each track. However, due to the uncertainty in the momentum measurement, this reconstructed mass value is not necessarily equal to the nominal mass of the sample. Thus the reconstructed 2D mass points would lie along the diagonal line $m_{dE/dx} = m_{ToF}$, denoted in Figure 6.20 by a gray dashed line. The spread of the

points along this line is driven by the momentum resolution.

Therefore we see that the spread in the 2D mass distribution along the line $m_{dE/dx} = m_{ToF}$ is driven by the momentum resolution, while the spread in the distribution in the orthogonal direction is driven by the resolution in the $\beta\gamma$ measurements. The distributions are roughly symmetric about the line $m_{dE/dx} = m_{ToF}$ because the resolutions of $\beta\gamma_{dE/dx}$ and $\beta\gamma_{ToF}$ are comparable.

It is also important to note that the uncertainty in the reconstructed mass is linearly related to the reconstructed mass (see Equation 6.10). Within each sample depicted in Figure 6.20, the width of the distribution orthogonal to the line $m_{dE/dx} = m_{ToF}$ scales with reconstructed mass, such that the mass distribution becomes wider at higher reconstructed masses. The length of the 2D mass distributions along the line $m_{dE/dx} = m_{ToF}$ also scales with reconstructed mass such that the R-hadron sample of mass 2.2 TeV has a greater spread along this line than the slepton sample of mass 400 GeV. This reflects the degrading momentum resolution at higher momenta.

In summary, if signal tracks were to appear in the Signal Region, we would expect them to be clustered around a particular mass point in the 2D mass plane, within some spread driven by the resolution at that mass point.

In contrast, we expect the reconstructed $m_{dE/dx}$ and m_{ToF} values of background tracks to be less correlated. Background tracks are produced by particles that are not traveling slowly, but are accepted by the Signal Region requirements. This could occur due to statistical fluctuations in the high tail of the dE/dx distribution or the low tail of the β_{ToF} distribution, or due to a mismeasurement of momentum. The sources of background are further discussed in Chapter 7.

Figure 6.21 shows the 2D mass distribution of the expected background, as predicted through

the procedure described in Chapter 7. Note that the background mass distribution is concentrated at low reconstructed masses and falls steeply with increasing mass. In addition, the distribution exhibits a wide spread orthogonal to the line $m_{dE/dx} = m_{ToF}$, reflecting the lack of correlation between $\beta\gamma_{dE/dx}$ and $\beta\gamma_{ToF}$ in background tracks.

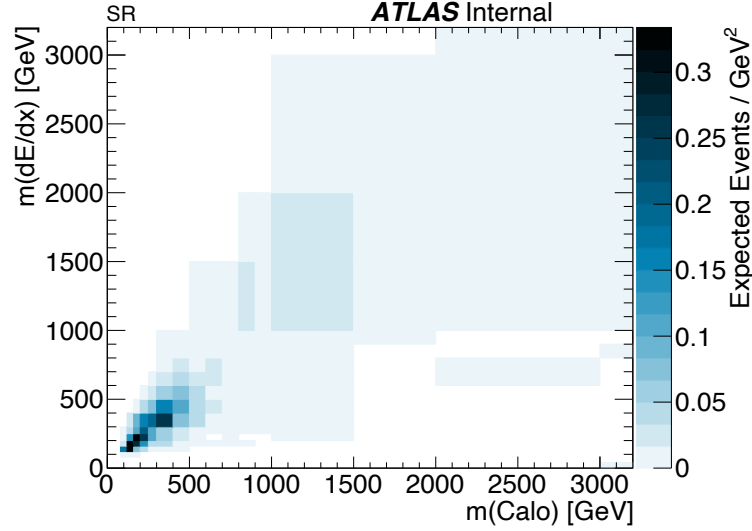


Figure 6.21: The predicted background distribution in the $(m_{dE/dx}, m_{ToF})$ plane. The background prediction is obtained through the procedure described in Chapter 7.[†]

6.3.2 MASS WINDOWING

We can exploit the differing topology in the 2D mass plane of the simulated signal distributions relative to the predicted background distribution to further increase the sensitivity of the Signal Region. For each signal mass point, we define a subregion of the 2D mass plane that contains as many of the signal tracks and as few of the background tracks as possible. The final sensitivity of the

Signal Region to a signal of that particular mass is evaluated within that subregion, or *mass window*.

This results in a set of overlapping mass windows where each window is tailored to maximize the sensitivity to a particular signal mass point.

The mass windows should be defined to contain as little background as possible. The background distribution extends much farther orthogonally from the line $m_{dE/dx} = m_{ToF}$ than the signal distributions due to the lack of correlation between $\beta\gamma_{dE/dx}$ and $\beta\gamma_{ToF}$ for background tracks. For signal tracks, $\beta\gamma_{dE/dx}$ and $\beta\gamma_{ToF}$ should be correlated within their resolutions. As discussed above, the extent of the spread orthogonal to the line $m_{dE/dx} = m_{ToF}$ is driven by the $\beta\gamma$ resolution and scales linearly with mass (see Equation 6.10).

To reflect this linear scaling, we impose two linear boundaries in the 2D mass plane, stemming from the origin and symmetric about the line $m_{dE/dx} = m_{ToF}$. The slopes of these lines are defined such that the spread in the signal tracks due to the $\beta\gamma$ resolution is contained within the two lines. These lines are depicted imposed on the background prediction in Figure 6.22.

These linear boundaries are collectively referred to as “the cone.” The mass windows for all signal mass points are defined within the boundaries of the cone, removing background tracks with highly uncorrelated $m_{dE/dx}$ and m_{ToF} from consideration. As the $\beta\gamma$ resolution and the linear scaling of the resulting component of the mass resolution are common to all signal samples, the same cone is used to define the mass windows for all mass points.

A cone with an opening angle of 22° removes 24% of the background tracks in the Signal Region, while retaining $>90\%$ of signal tracks for most samples. For example, 95% of the tracks in the Signal Region in a slepton sample of mass 400 GeV and lifetime 30 ns fall within the cone. For a stable

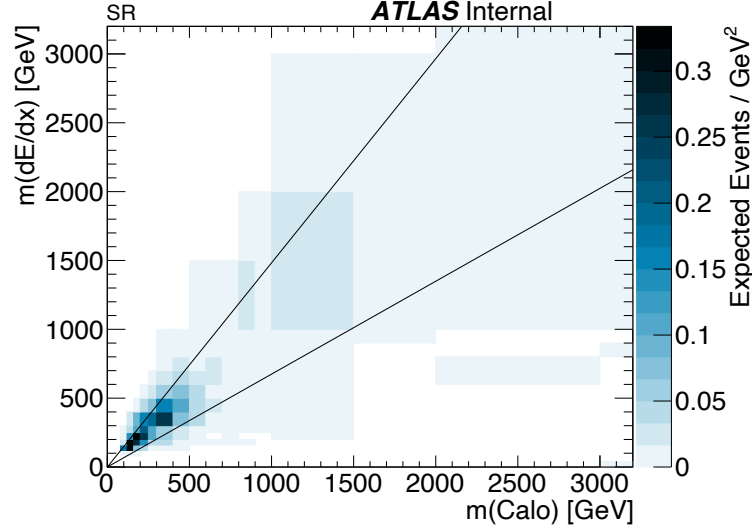


Figure 6.22: Two linear boundaries, referred to as a “cone”, are imposed on the predicted background distribution in the $(m_{dE/dx}, m_{ToF})$ plane. The background prediction is obtained through the procedure described in Chapter 7. The cone has an opening angle of 22° that is determined through an optimization procedure. The mass windows are defined within the cone.[†]

R-hadron of mass 2.2 TeV, the cone contains 97% of the signal tracks in the Signal Region.

Within the cone, the mass window for each signal point is formed by imposing an upper and lower boundary orthogonal to the line $m_{dE/dx} = m_{ToF}$ to form a trapezoid, as depicted in Figure 6.23. The placement of the upper and lower edges is determined through an optimization procedure.

First, a lower boundary is placed in the cone, intersecting the line $m_{dE/dx} = m_{ToF}$ at a mass much lower than the nominal mass of the signal sample. The lower boundary is then moved up along the line $m_{dE/dx} = m_{ToF}$. The location of the lower boundary is optimized to maximize the sensitivity metric [93]:

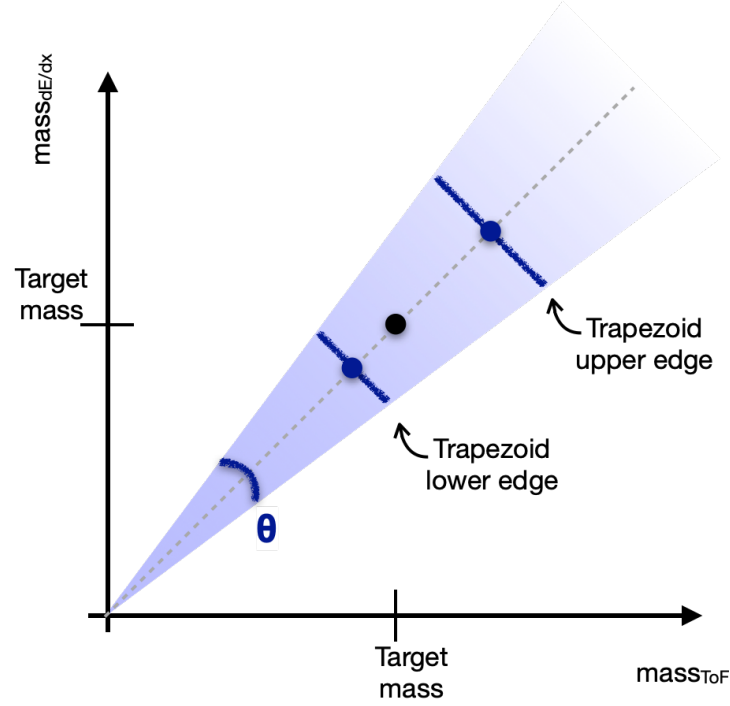


Figure 6.23: A sketch of how trapezoidal mass windows are constructed within the cone in the 2D $(m_{dE/dx}, m_{ToF})$ plane. The shaded region represents the cone with opening angle θ . Upper and lower edges of the trapezoid are imposed within the cone around the target mass point, which is highlighted with a black dot. The placement of the upper and lower trapezoid edges is determined through an optimization procedure. The trapezoid is parameterized by the cone angle θ and by the mass values at the center of the upper and lower edges where the edges intersect the line $m_{dE/dx} = m_{ToF}$, shown in a dashed gray line [2].

$$Z = \sqrt{2 \left((s + b) \ln \left(1 + \frac{s}{b} \right) - s \right)} \quad (6.11)$$

where s and b are the number of signal and background tracks within the cone and above the lower boundary. Since most of the background distribution is concentrated at low mass, the optimization of this lower boundary is important to remove as much background as possible from the mass window while retaining signal tracks.

Then, an upper boundary is set such that its center is located at the highest mass point possible, (7000 GeV, 7000 GeV), which is located beyond the mass reach of this Signal Region and is effectively at infinity. The upper boundary is moved downward along the line $m_{dE/dx} = m_{ToF}$ until the sensitivity metric Z is maximized or until the fraction of Signal Region signal tracks located within the trapezoid falls below 70%, whichever comes first. For signal samples with mass $\gtrsim 1$ TeV, the likelihood to find a signal track at very high masses is much greater than for background tracks, and imposing any upper boundary is not advantageous for maximizing the sensitivity. For these mass points, the upper boundary is fixed at (7000 GeV, 7000 GeV), or effectively at infinity.

One mass window is defined per signal mass. To define the optimized trapezoidal mass window, signal samples of the same mass are combined before applying the optimization procedure described above. For example, to create the boundaries of a trapezoid designed for the mass 700 GeV, 700 GeV slepton samples of all available lifetime points and 700 GeV chargino samples of all available lifetime points are combined into one 2D mass histogram. The cone angle is optimized by scanning over many possible angles and choosing the angle that results in trapezoids with the highest sensitivity for the majority of signal models.

The trapezoidal mass windows are parameterized by the opening angle of the cone, the mass value at the center of the lower trapezoid boundary, and the mass value at the center of the upper boundary. The trapezoidal mass window parameters are shown in Table 6.6.

The windows tend to be asymmetric about the target mass point, with the lower edge of the trapezoid located closer to the target mass than the upper edge. This results from the optimization of the lower bound to remove low-mass background. It is advantageous for the mass window to be

Target mass [GeV]	Trapezoid Parameters, Cone angle 22°	
	Lower edge mass [GeV]	Upper edge mass [GeV]
150	120	210
200	160	290
250	210	380
300	250	490
350	270	640
400	320	680
450	370	700
500	400	810
550	470	930
600	480	1360
650	530	1360
700	530	1360
800	580	1760
900	710	2610
1000	820	2380
1400	860	7000
1600	950	7000
1800	950	7000
2000	1100	7000
2200	1200	7000
2400	1200	7000
2600	1660	7000

Table 6.6: The 2D mass window parameters derived using the trapezoidal method, given a cone opening angle of 22° . The lower edge mass identifies the mass point $(m_{TOF}, m_{dE/dx})$ at the center of the trapezoidal lower edge. The upper edge mass locates the center at the point $(m_{TOF}, m_{dE/dx})$ of the trapezoid upper edge in the 2D mass plane. The definitions of mass windows in the range 800 GeV to 1.3 TeV will be finalized using chargino simulation that is still in production at the writing of this thesis. The 800 GeV, 900 GeV, and 1000 GeV mass windows were determined using existing chargino samples with lifetimes 4 ns and 10 ns.[†]

located at higher masses (while retaining signal tracks) in order to avoid including the background distribution, which falls steeply with increasing mass. The windows increase in size with increasing mass, reflecting the worsening mass resolution at high masses due to the degradation of the momentum resolution at high momenta.

The trapezoidal mass windows are used as mini Signal Regions tailored to optimize sensitivity to each signal mass point. The evaluation of systematic uncertainties as well as the statistical interpretation of the results of the search occur within the mass windows.

Table 6.7 shows the number of signal and background tracks within the trapezoid, the fraction

of signal tracks in the Signal Region falling within the mass window, and the expected sensitivity for several signal samples.

Signal	Mass [GeV]	Lifetime [ns]	Signal Tracks	Background Tracks	Signal Efficiency	Sensitivity
Slepton	200	10	3.7	1.4	0.82	2.38
Slepton	400	30	4.3	0.9	0.88	3.13
Chargino	700	10	1.8	0.3	0.85	2.15
R-hadron	2200	stable	3.2	0.1	0.89	4.36

Table 6.7: The results of the application of the trapezoidal mass window for a few signal samples. The mass of the signal sample determines the parameters of the trapezoid that is applied. The number of signal tracks in the trapezoid, the number of predicted background tracks in the trapezoid, the signal efficiency of the trapezoid relative to the Signal Region, and the sensitivity determined with the metric $\mathcal{Z}$ (Equation 6.11) [93] are shown.

7

Background Estimate

The Signal Region is composed of tracks that have high p_T , high dE/dx , and low β_{ToF} . Although these requirements are optimized to search for potential high mass signals, some Standard Model tracks will also contribute to the data in the Signal Region. Since the processes that lead to this contribution are difficult to model, this analysis uses a technique to extract the expected background distribution from data. This chapter details the possible sources of background, a procedure for esti-

inating the background in the Signal Region using data in adjacent regions, and a strategy to test the effectiveness of this background estimation procedure.

7.1 SOURCES OF BACKGROUND

The background in the Signal Region is composed of Standard Model tracks with a high reconstructed mass. A high reconstructed mass can come from an anomalously low $\beta\gamma$ measurement, or a high measurement of momentum. An underestimate of $\beta\gamma$ through β_{ToF} is possible due to the timing resolution of the calorimeter cells. An underestimate of $\beta\gamma$ through dE/dx is possible due to the probabilistic nature of the dE/dx measurement.

As described in Section 5.1.2, the probability density function of a single dE/dx measurement is described by a Landau function, which has a long upper tail. A truncated mean procedure is used to combine the individual pixel dE/dx measurements into one dE/dx value that estimates the Most Probable Value (MPV) of the Landau distribution. With only a limited number of pixel dE/dx measurements available, the long tail of the Landau distribution can skew the truncated mean dE/dx value high and overestimate the dE/dx MPV.

These statistical and detector-dependent properties are difficult to simulate. Therefore, this analysis uses a data-driven approach to background estimation, in which data in signal-depleted regions is used to model the background in the Signal Region.

7.2 ESTIMATION PROCEDURE

The predicted m_{ToF} and $m_{dE/dx}$ background distributions in the Signal Region are constructed by generating “toy” tracks that are expected to have similar kinematic and dE/dx properties as background tracks in the Signal Region. This is done by randomly sampling kinematic and dE/dx variables from histograms in background-dominated regions, and using those values to reconstruct a mass using $m = p/\beta\gamma$.

7.2.1 CONTROL REGIONS

The background-dominated regions used to construct the background mass distributions are referred to as Control Regions (CRs). Two CRs are needed to generate mass via $m = p/\beta\gamma$: a kinematic CR from which to determine momentum, and a $\beta\gamma$ CR from which to determine $\beta\gamma$, either through dE/dx or β_{ToF} . Events in the CRs fulfill identical selection criteria as the Signal Region apart from E_T^{miss} , dE/dx , and β_{ToF} requirements.

For background tracks, which have $\beta \approx 1$ at the high momenta considered, the variables p_T , dE/dx , and β_{ToF} should all be uncorrelated within a narrow slice of $|\eta|$. dE/dx and momentum are assumed to be uncorrelated for fast background particles because at high $\beta\gamma$ values, the data-driven dE/dx - $\beta\gamma$ curve plateaus. Similarly, at high momentum, small differences in β due to small differences in momentum of very light particles would not be resolvable with the available β_{ToF} resolution. Therefore at high momenta, where light particles are traveling close to the speed of light, dE/dx and β_{ToF} should be effectively uncorrelated from momentum. More detail on this point

can be found in Sections 5.1.4 and 5.2.2.

Due to this lack of correlation, the p_T distribution of background tracks in the Signal Region will be similar to the p_T distribution of background tracks at a lower dE/dx range, within a particular $|\eta|$ slice. This motivates the placement of the kinematic CR at $dE/dx < 1.6$.

The dE/dx properties of background tracks as measured in the silicon pixels should be independent of E_T^{miss} calculated in the event. Similarly, measured β_{ToF} values and E_T^{miss} are expected to be uncorrelated. It follows that $\beta\gamma$ found through β_{ToF} or dE/dx sampled from a different E_T^{miss} range than the Signal Region ($E_T^{\text{miss}} > 170$ GeV) can be used to model $\beta\gamma$ in the Signal Region. For this reason, the $\beta\gamma$ CR can be defined at a lower E_T^{miss} range ($E_T^{\text{miss}} < 150$ GeV) than the Signal Region.

Although the purpose of the CRs is to predict the behavior of the background in a region where $dE/dx > 1.8$, the $\beta\gamma$ CR extends over all dE/dx values. This choice provides generated toy tracks that will serve to scale the generated background estimate to data in a background-dominated region at low dE/dx .

Although the CRs are meant to predict background in a range where $\beta_{\text{ToF}} < \beta_{\text{cut}}$, both CRs cover the range $\beta_{\text{ToF}} < 1.0$. This enriches the CRs with statistics, and does not affect the shape of the background estimate due to the mutual lack of correlation between p_T , dE/dx , and β_{ToF} in a given $|\eta|$ slice. Tracks with $\beta_{\text{ToF}} \geq 1$ are not considered in the Control Regions because γ is undefined for these values, and a valid γ value is necessary for the reconstruction of mass.

A map summarizing the placement of the Control Regions relative to the Signal Region is shown in Figure 7.1.

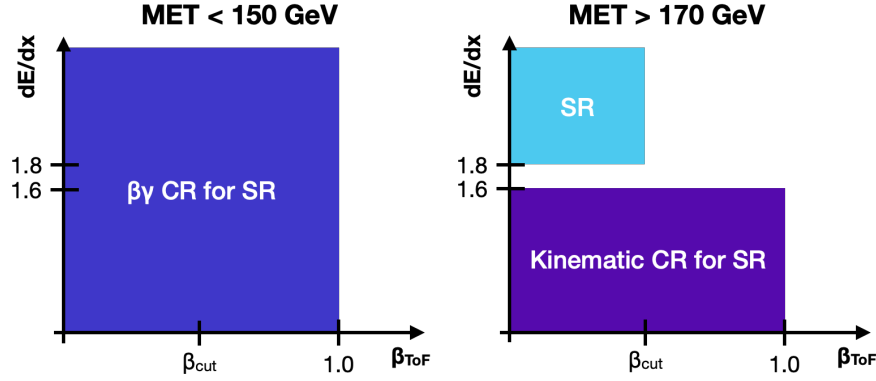


Figure 7.1: Schematic diagram of the Signal region and its Control Regions. MET refers to E_T^{miss} .

7.2.2 GENERATING BACKGROUND TRACKS

This section describes the procedure used to generate a toy track. First, in the kinematic CR, a 2D histogram of $|\eta|$ vs $1/p_T$ is randomly sampled to obtain a set of values $(|\eta|, 1/p_T)$. This histogram, referred to as the kinematic template, is shown in Figure 7.2. These values are used to calculate a momentum value for the track via the relation $p = p_T \cosh(\eta)$.

Next, a dE/dx histogram is sampled in the $\beta\gamma$ CR to get a dE/dx value for the track. Due to the correlations between dE/dx and $|\eta|$ discussed in Section 5.1.3, a separate dE/dx histogram is created for each 0.2-wide $|\eta|$ slice in the $\beta\gamma$ CR. The appropriate dE/dx histogram is selected according to the $|\eta|$ value sampled from the kinematic CR in the previous step. These $|\eta|$ -binned dE/dx histograms that are sampled to construct toy tracks are collectively referred to as the dE/dx templates. An example dE/dx template is shown in Figure 7.3.

Then, a β_{ToF} histogram is sampled in the $\beta\gamma$ CR to obtain a β_{ToF} value for the toy track. The β_{ToF} histograms are binned in 0.1-wide slices of $|\eta|$ due to the $|\eta|$ -dependence of β_{ToF} discussed

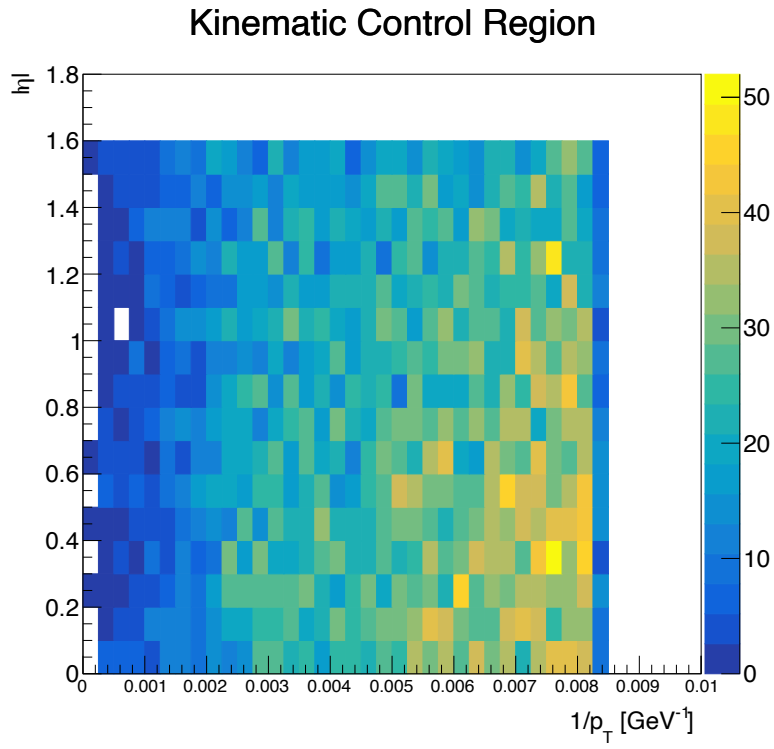


Figure 7.2: The template in the kinematic CR from which $(|\eta|, 1/p_T)$ values are sampled and used to construct momentum for toy tracks.

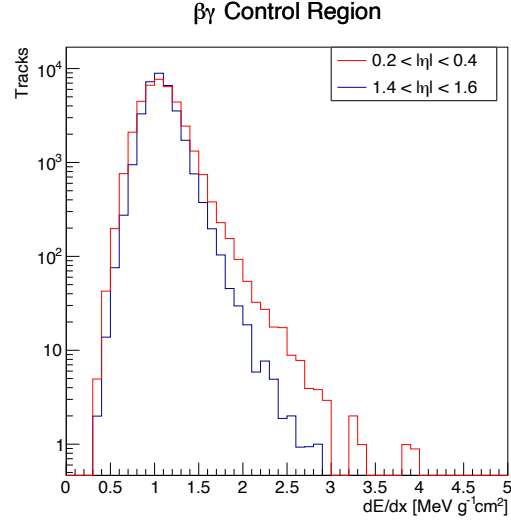


Figure 7.3: Example dE/dx histograms in the $\beta\gamma$ CR from which dE/dx values are sampled for toy tracks.

in Section 5.2.2. As in the dE/dx case, the sampled β_{ToF} histogram is indexed according to the $|\eta|$ value sampled from the kinematic CR. An example β_{ToF} histogram is shown in Figure 7.4.

Finally, a $m_{dE/dx}$ value and a m_{ToF} value are reconstructed for the toy track. The $(|\eta|, p_T, dE/dx)$ values of the track are used as inputs to the dE/dx - $\beta\gamma$ calibration discussed in Section 5.1.4 to obtain a $m_{dE/dx}$ value. The (p, β_{ToF}) values are used to calculate m_{ToF} via $m = p/\beta\gamma$.

This procedure is repeated 10 million times, creating 10 million toy tracks, to generate the shapes of the predicted background $m_{dE/dx}$ and m_{ToF} distributions in the Signal Region.

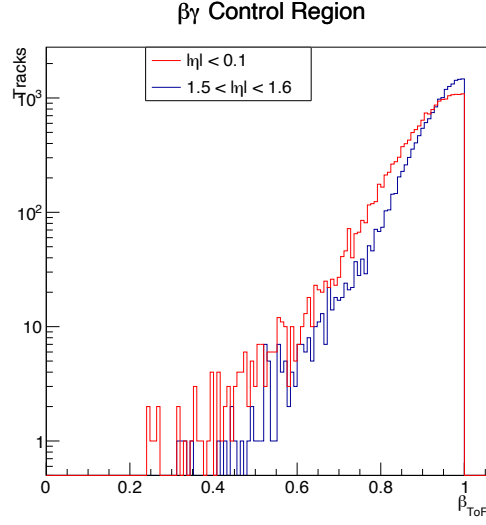


Figure 7.4: Example β_{ToF} histograms in the $\beta\gamma$ CR from which β_{ToF} values are sampled for toy tracks.

7.2.3 NORMALIZATION

The integrals of these distributions must be scaled to data in order to effectively predict the number of background tracks in the Signal Region. A normalization procedure relates the number of generated toy tracks to the number of data tracks in a background-dominated region. The normalization factor, or scale factor, will scale the number of generated toys passing the Signal Region dE/dx and β_{ToF} requirements to predict the number of background tracks in the Signal Region.

This scaling procedure is done by calculating the ratio of generated tracks whose dE/dx values fall below 1.6 and whose β_{ToF} values fall between β_{cut} and 1, to the set of tracks in data with identical requirements. The data tracks correspond to tracks in the kinematic CR with the added requirement of $\beta_{\text{cut}} < \beta_{\text{ToF}} < 1$. To reduce possible signal contamination from signal particles with high mass, the ratio is calculated only in a mass range such that $m_{dE/dx}$ and m_{ToF} are both less than 160

GeV. This ratio, or scale factor, is then applied to scale the number of generated toys with $dE/dx > 1.8$ and $\beta_{\text{ToF}} < \beta_{\text{cut}}$ to predict the number of background tracks in the Signal Region.

The predicted $m_{dE/dx}$ and m_{ToF} distributions in the Signal Region are shown in Figure 7.5 and Figure 7.6. The predicted background distribution in the 2D mass plane in the Signal Region is shown in Figure 7.7 in the blue histogram. Several example signal samples are shown for comparison in the red, green, and yellow histograms.

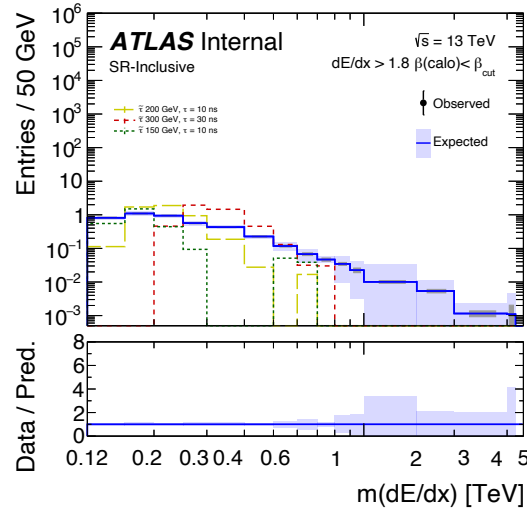


Figure 7.5: The predicted $m_{dE/dx}$ background (blue histogram) in the Signal Region. The blue band represents the total systematic uncertainty on the background estimate. Several example signal samples are shown for comparison in the red, green, and yellow histograms.[†]

7.3 VALIDATION OF BACKGROUND ESTIMATE

The background estimation procedure is tested in background-dominated regions called Validation Regions (VRs). Two VRs are defined in this analysis with the same selection as the Signal Region

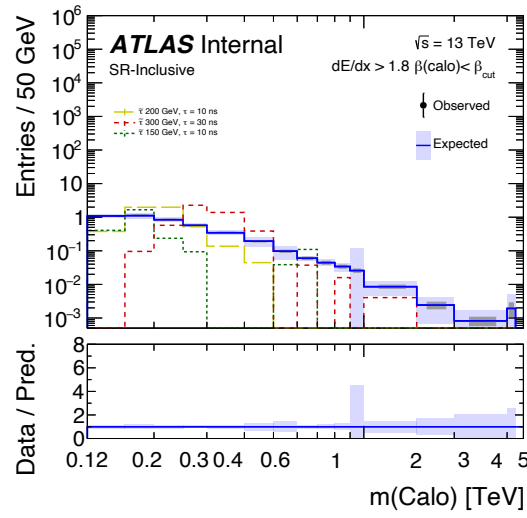


Figure 7.6: The predicted $m_{T_{oF}}$ background (blue histogram) in the Signal Region. The blue band represents the total systematic uncertainty on the background estimate. The spike in the uncertainty band at 1 TeV is caused by low statistics in the systematic uncertainty calculation at high mass. This spike does not reflect a physical effect and is removed using a smoothing procedure before the application of mass windows. Several example signal samples are shown for comparison in the red, green, and yellow histograms.[†]

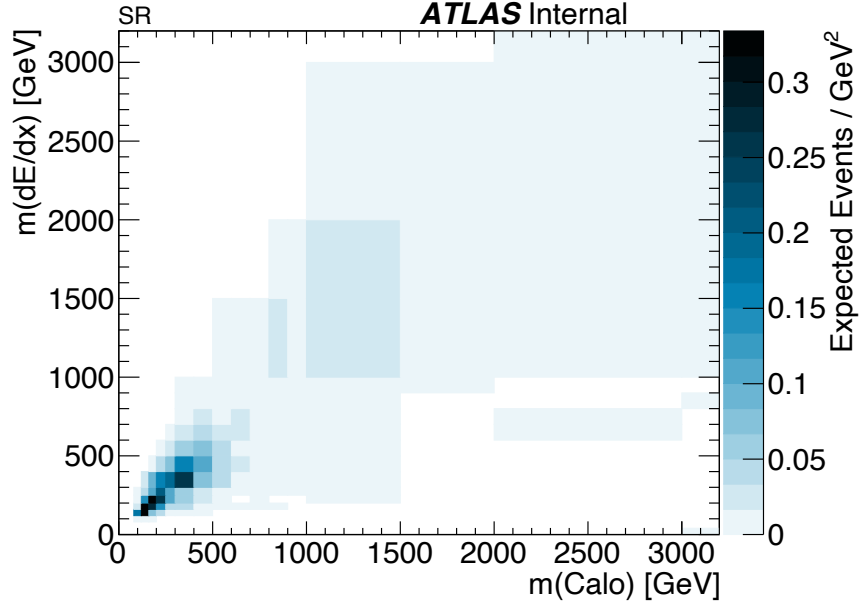


Figure 7.7: The predicted background (blue histogram) in the $m_{dE/dx}$ vs m_{ToF} plane in the Signal Region.[†]

except for changes in the dE/dx and β_{ToF} requirements. The Low dE/dx VR is composed of tracks with identical selection to the Signal Region except for a requirement that $1.05 < dE/dx < 1.6$. Similarly, the High β_{ToF} VR is composed of tracks with identical selection to the Signal Region except that β_{ToF} ranges from β_{cut} to 1.0. A schematic of the VRs relative to the SR is shown in Figure 7.8.

Since Standard Model background tracks have $\beta \approx 1$, the majority of them should be measured as having low dE/dx and high β_{ToF} relative to the Signal Region. Any background tracks that fall into either the SR or the VRs result from either an anomalously high dE/dx measurement (High β_{ToF} VR), an anomalously low β_{ToF} measurement (Low dE/dx VR), or both (SR). For fast background tracks, these anomalous measurements should be uncorrelated. In effect, an anomalously

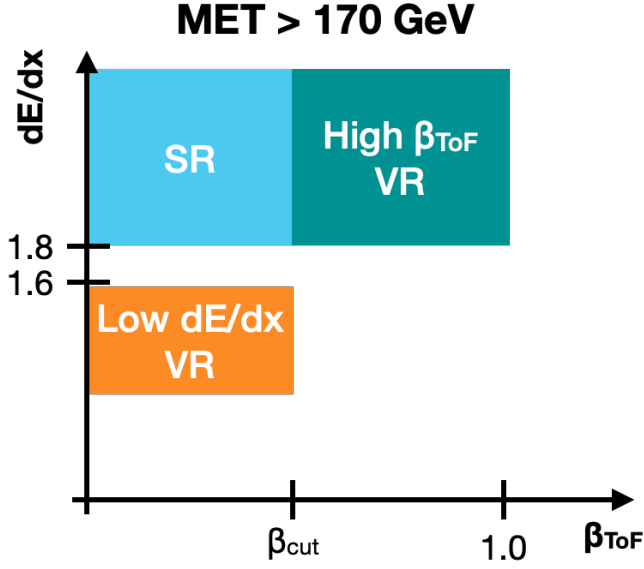


Figure 7.8: Schematic diagram of the Signal region, Low dE/dx VR, and High β_{ToF} VR. MET refers to $E_{\text{T}}^{\text{miss}}$.

high pixel dE/dx measurement of a fast background particle should give no information about the time-of-flight that is measured in the calorimeter. By choosing adjacent regions to the Signal Region in the $dE/dx - \beta_{\text{ToF}}$ plane to act as Validation Regions, the background estimate is separately tested in regions where dE/dx is measured anomalously high and where β_{ToF} is measured anomalously low. The closure of the background prediction with data in both VRs will validate the background estimate procedure.

Associated $\beta\gamma$ and kinematic CRs are defined for each Validation Region, where events in these Control Regions pass all Signal Region selection except for the dE/dx , β_{ToF} , and $E_{\text{T}}^{\text{miss}}$ cuts. The layout of the Low dE/dx VR and its Control Regions is shown in Figure 7.9. The kinematic CR requires $dE/dx < 1.05$, $\beta_{\text{ToF}} < 1.0$, and $E_{\text{T}}^{\text{miss}} > 170$ GeV. The $\beta\gamma$ CR is defined by $dE/dx < 1.6$,

$\beta_{\text{ToF}} < 1.0$, and $E_{\text{T}}^{\text{miss}} < 150$ GeV.

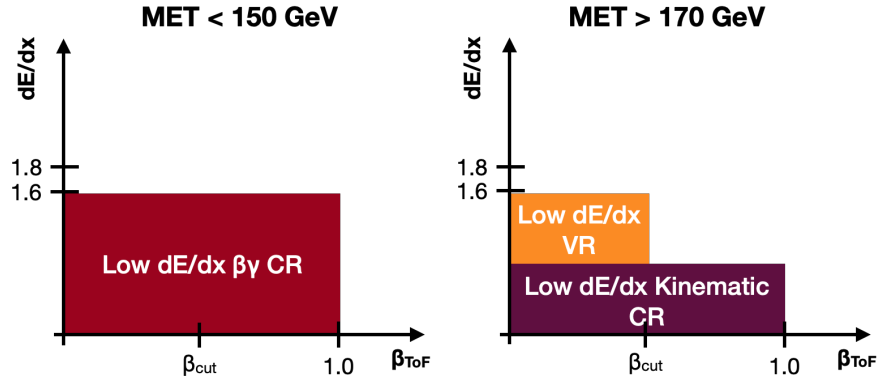


Figure 7.9: Schematic diagram of the Low dE/dx Validation Region and the corresponding Control Regions. MET refers to $E_{\text{T}}^{\text{miss}}$.

The layout of the High β_{ToF} VR and its Control Regions is shown in Figure 7.10. The kinematic CR is defined by $\beta_{\text{cut}} < \beta_{\text{ToF}} < 1$, $dE/dx < 1.6$, and $E_{\text{T}}^{\text{miss}} > 170$ GeV. The $\beta\gamma$ CR is located in the region where $\beta_{\text{cut}} < \beta_{\text{ToF}} < 1$ and $E_{\text{T}}^{\text{miss}} < 150$ GeV.

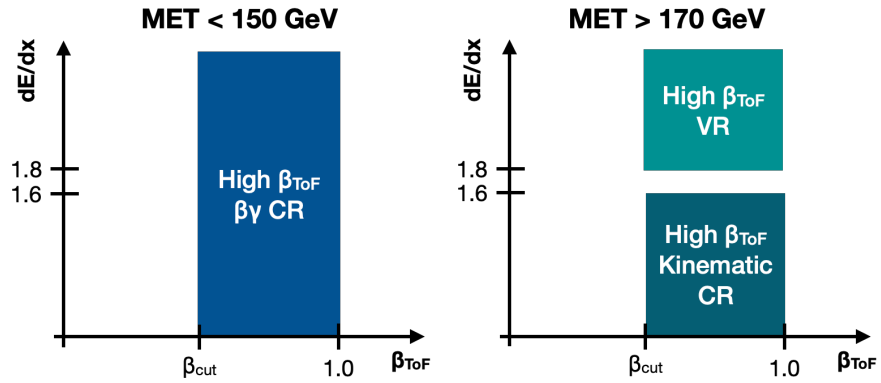


Figure 7.10: Schematic diagram of the High β_{ToF} Validation Region and the corresponding Control Regions. MET refers to $E_{\text{T}}^{\text{miss}}$.

Signal, Validation, and Control Region definitions are summarized in Table 7.1.

Table 7.1: Definitions of the Signal, Control and Validation regions. All events and tracks satisfy the Signal Region selection apart from E_T^{miss} , dE/dx , and β_{ToF} requirements.[†]

Region	E_T^{miss} [GeV]	dE/dx [MeV g ⁻¹ cm ²]	β_{ToF}
SR	> 170	> 1.8	$[0. - \beta_{\text{cut}}]$
CR-kin	> 170	< 1.6	$[0. - 1.0]$
CR- $\beta\gamma$	< 150	> 0	$[0. - 1.0]$
VR-Low dE/dx	> 170	$[1.05 - 1.6]$	$[0. - \beta_{\text{cut}}]$
CR-Low dE/dx -kin	> 170	< 1.05	$[0. - 1.0]$
CR-Low dE/dx - $\beta\gamma$	< 150	< 1.6	$[0. - 1.0]$
VR-High β_{ToF}	> 170	> 1.8	$[\beta_{\text{cut}} - 1.0]$
CR-High β_{ToF} -kin	> 170	< 1.6	$[\beta_{\text{cut}} - 1.0]$
CR-High β_{ToF} - $\beta\gamma$	< 150	> 0	$[\beta_{\text{cut}} - 1.0]$

In each Validation Region, the background m_{ToF} and $m_{dE/dx}$ distributions are calculated from the Control Regions and compared to data.

The predicted m_{ToF} background compared to the m_{ToF} distribution of the data in the Low dE/dx VR is shown in Figure 7.11. The predicted $m_{dE/dx}$ background compared to the $m_{dE/dx}$ distribution of the data in the Low dE/dx VR is shown in Figure 7.12. In both cases, the background prediction and data agree in shape and normalization.

The predicted m_{ToF} background compared to the m_{ToF} distribution of the data in the High β_{ToF} VR is shown in Figure 7.13. The predicted $m_{dE/dx}$ background compared to the $m_{dE/dx}$ distribution of the data in the High β_{ToF} VR is shown in Figure 7.14. In both cases, the background prediction and data agree in shape and normalization.

The 2D $m_{dE/dx}$ vs m_{ToF} histograms for the Validation Regions are shown in Figures 7.15- 7.16. The blue histograms represent the predicted background and the data is shown as red points.

The predicted and observed yields in the Validation Regions, as well as the expected yield in the

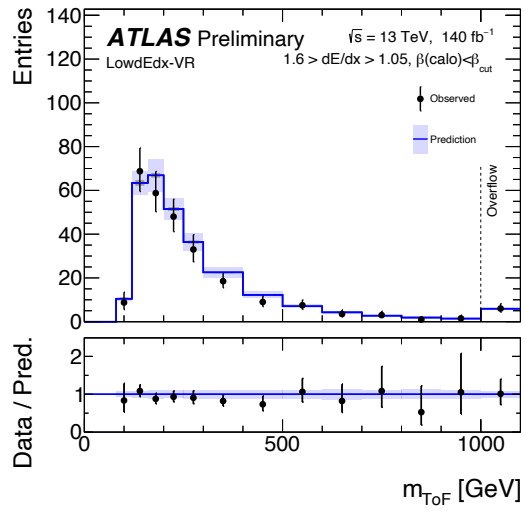


Figure 7.11: Comparison of predicted m_{ToF} background (blue histogram) to data (black points) in the Low dE/dx Validation Region. The blue band represents the total systematic uncertainty on the background estimate [2].

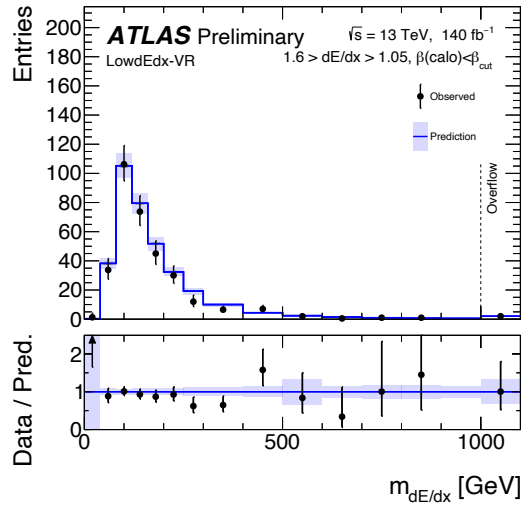


Figure 7.12: Comparison of predicted $m_{dE/dx}$ background (blue histogram) to data (black points) in the Low dE/dx Validation Region. The blue band represents the total systematic uncertainty on the background estimate [2].

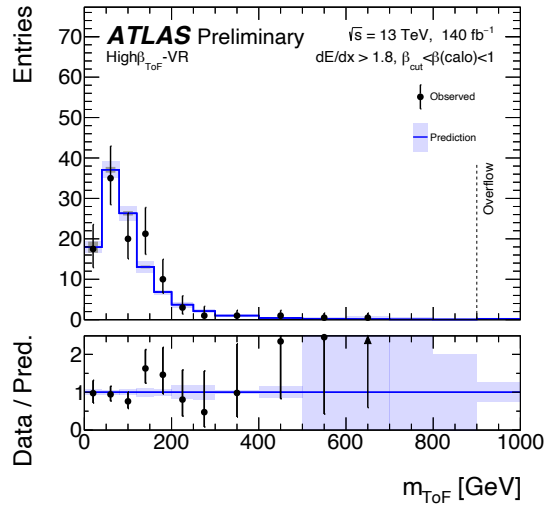


Figure 7.13: Comparison of predicted m_{ToF} background to data in the High β_{ToF} Validation Region. The blue band represents the total systematic uncertainty on the background estimate [2].

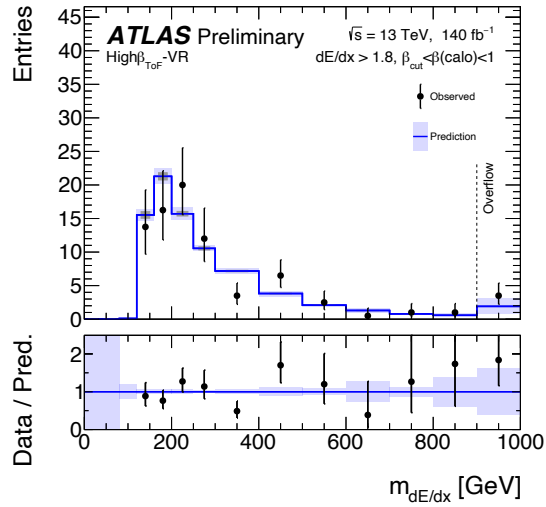


Figure 7.14: Comparison of predicted $m_{dE/dx}$ background to data in the High β_{ToF} Validation Region. The blue band represents the total systematic uncertainty on the background estimate [2].

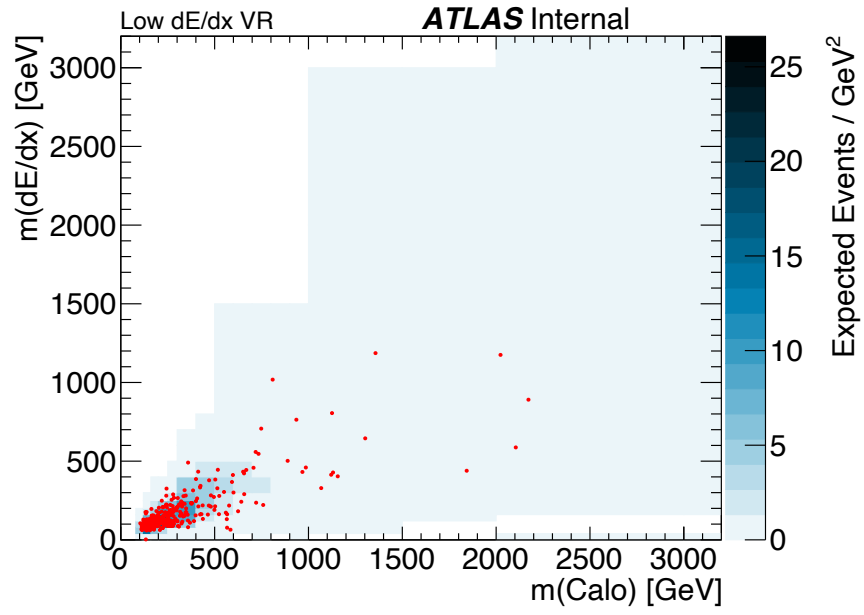


Figure 7.15: The predicted background (blue histogram) compared to data (red points) in the $m_{dE/dx}$ vs m_{ToF} plane in the Low dE/dx Validation Region.[†]

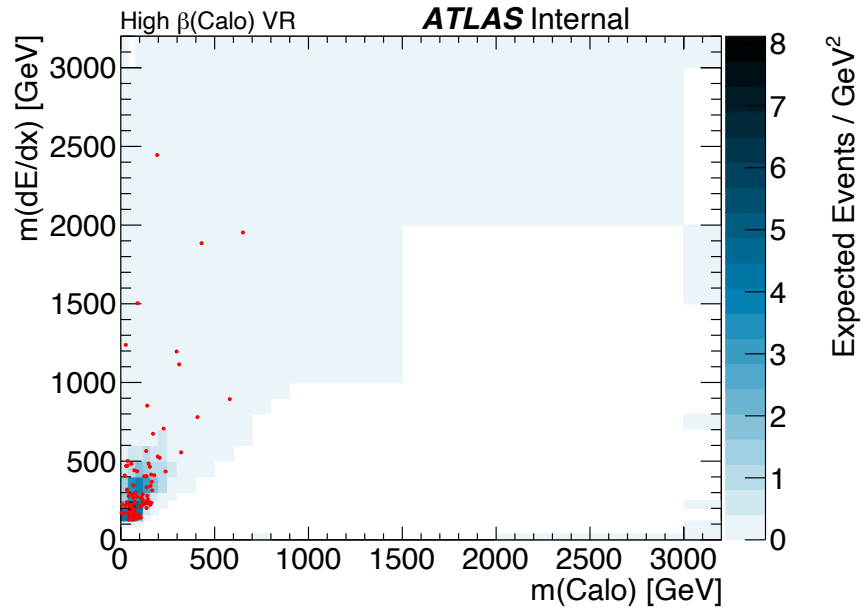


Figure 7.16: The predicted background (blue histogram) compared to data (red points) in the $m_{dE/dx}$ vs m_{ToF} plane in the High β_{ToF} Validation Region.[†]

Region	Predicted Yield	Observed Yield
VR-Low dE/dx	316 ± 27	290
VR-High β_{ToF}	91 ± 6	93
SR	5.1 ± 0.5	–

Table 7.2: The expected and observed number of tracks in the Low dE/dx Validation Region and High β_{ToF} Validation Region, and the expected number of tracks in the Signal Region. The uncertainties shown are the total systematic uncertainties on the background prediction in the Signal Region, as detailed in Chapter 8. See Chapter 9 for the number of events in the Signal Region observed in data.[†]

Signal Region, are summarized in Table 7.2. In each Validation Region, the predicted number of background tracks agrees with the observed number of tracks.

The Validation Regions are able to validate different ranges of $m_{dE/dx}$ and m_{ToF} depending on the differences in β acceptance imposed by the dE/dx and β_{ToF} requirements in each region. In the High β_{ToF} VR, higher $m_{dE/dx}$ values can be reconstructed than m_{ToF} values because the High β_{ToF} VR is defined at $\beta_{\text{cut}} < \beta_{\text{ToF}} < 1.0$ and $dE/dx > 1.8$. The higher dE/dx values correspond to lower $\beta\gamma_{dE/dx}$ values and allow the reconstruction of higher $m_{dE/dx}$ values. The higher β_{ToF} values allow a more limited $\beta\gamma_{\text{ToF}}$ and m_{ToF} range.

However, due to the identical dE/dx requirement as the Signal Region, the High β_{ToF} VR is able to validate the modeling of the $m_{dE/dx}$ distribution in the same mass range as the Signal Region. Similarly, the Low dE/dx VR is able to validate the background modeling of the m_{ToF} distribution over the same mass range as the Signal Region.



Systematic Uncertainties

Many assumptions and choices made in designing the track selection and the background estimate procedure can affect the shapes and integrals of the predicted background distributions. It is important to understand the extent of the effects that these choices have on the background estimate. This chapter discusses the various sources of uncertainty and evaluates their effect on the background prediction in the Signal Region.

8.1 TEMPLATE CORRELATION UNCERTAINTY

In the background estimation procedure, it is assumed that independently sampling dE/dx , β_{ToF} , and kinematic variables to form a toy track results in valid physical distributions that can be compared to data. This is equivalent to the assumption that dE/dx , β_{ToF} , and momentum are all mutually uncorrelated for background tracks.

This assumption is made because at high momentum, light background particles should be traveling close to the speed of light. At high $\beta\gamma$ values, the data-driven dE/dx - $\beta\gamma$ curve plateaus. Similarly, at high momentum, small differences in β due to small differences in momentum of very light particles would not be resolvable with the available β_{ToF} resolution. Therefore at high momenta, where light particles are traveling close to the speed of light, dE/dx and β_{ToF} should be effectively uncorrelated from momentum. These points are also discussed in Sections 5.1.4 and 5.2.2.

Since dE/dx and momentum are assumed to be uncorrelated, we can sample dE/dx from the full dE/dx distribution in the appropriate $|\eta|$ -binned template, regardless of the sampled p_T of the toy track. Similarly, we can sample β_{ToF} from the β_{ToF} distribution in the appropriate $|\eta|$ -binned template, regardless of the sampled p_T of the toy track.

We also expect the dE/dx and β_{ToF} variables to be uncorrelated for background tracks. At high momentum, we expect light background particles to have a speed $\beta \approx 1$, and therefore low dE/dx values and high β_{ToF} values compared to slower, heavier particles. Anomalously high dE/dx values or low β_{ToF} values for background tracks are assumed to originate from fluctuations in each variable. In effect, for a fast background particle, a high dE/dx value should provide no informa-

tion on what β_{ToF} value is expected. This assumption of uncorrelation is built into the background estimation procedure, where toy tracks are formed from separately sampling dE/dx and β_{ToF} .

These assumptions are tested using the $\beta\gamma$ Control Region. Within the $\beta\gamma$ Control Region, a Test Signal Region is defined with loosened dE/dx and β_{ToF} requirements relative to the Signal Region to increase statistics for this test. Figure 8.1 shows the Test Signal Region in the $\beta\gamma$ Control Region placed at $dE/dx > 1.6$ and $\beta_{\text{ToF}} < 1 - 1\sigma_{\beta_{\text{ToF}}}$, where $\sigma_{\beta_{\text{ToF}}}$ is the η -dependent β_{ToF} resolution. A new background prediction is generated in which both the kinematic and the $\beta\gamma$ variables are sampled from templates in the $\beta\gamma$ Control Region. The resulting generated background toys with $dE/dx > 1.6$ and $\beta_{\text{ToF}} < 1 - 1\sigma_{\beta_{\text{ToF}}}$ are compared with the data in the Test Signal Region.

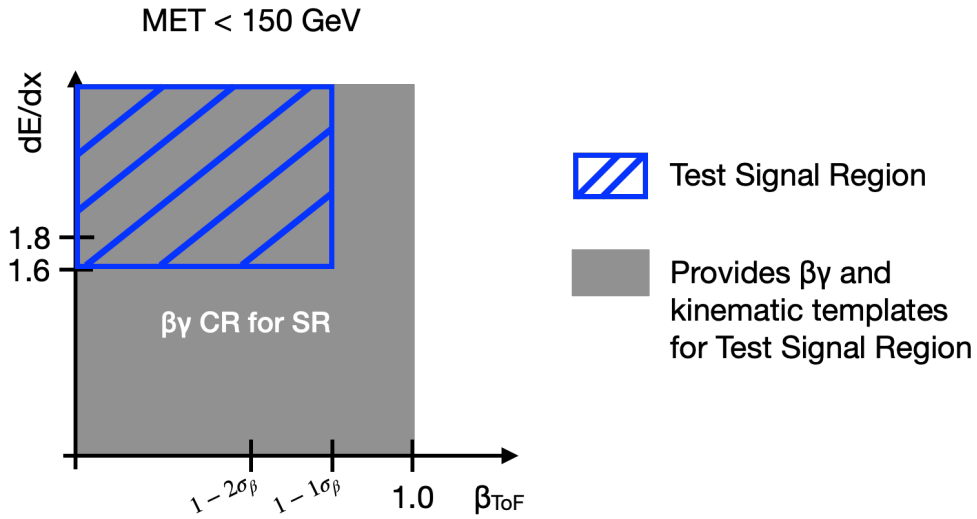


Figure 8.1: A diagram of the regions used to determine the uncertainty on the background estimate due to template correlations. A Test Signal Region is defined within the $\beta\gamma$ Control Region. The $\beta\gamma$ Control Region provides both the $\beta\gamma$ and the kinematic templates to derive a background estimate that is compared to data in the Test Signal Region. MET refers to E_T^{miss} .

We use the same set of tracks to independently sample the kinematic and $\beta\gamma$ variables. If the as-

sumption that momentum, dE/dx , and β_{ToF} are all uncorrelated is valid, we can construct valid toy tracks by sampling each of those variables independently, and background mass distributions generated from the toy tracks will match the data. Any difference between the resulting generated toys and the data in the Test Signal Region reveals correlations between these variables. The difference between the new background prediction and the data in the Test Signal Region is taken to be an uncertainty covering unaccounted-for correlations within the background templates.

The template correlation uncertainty is the dominant uncertainty in this analysis. Figure 8.6 shows the template correlation uncertainty (blue squares) evaluated in each mass window. The template correlation uncertainty increases at high masses mainly due to lack of statistics in the Test Signal Region at high mass.

8.2 dE/dx TEMPLATE BINNING UNCERTAINTY

As described in Section 5.1.3, the shape of the dE/dx distribution varies as a function of $|\eta|$. To account for this, the dE/dx templates used in the background estimation procedure are sliced in $|\eta|$. The choice of $|\eta|$ binning impacts the shape of the dE/dx templates, and can therefore directly impact the generated background distributions.

In the nominal templates, or templates used to generate the background prediction for the Signal Region, the $|\eta|$ bin edges are:

$$[0, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6]$$

We can evaluate the effect of this choice of $|\eta|$ binning by generating a new background predic-

tion with a different choice of $|\eta|$ binning. A different but also reasonable choice of $|\eta|$ binning is:

$$[0, 0.15, 0.25, 0.45, 0.65, 0.85, 1.05, 1.25, 1.45, 1.6]$$

To evaluate the effect of the particular choice of $|\eta|$ binning on the background prediction, a new background prediction is generated with the dE/dx templates binned in this alternative $|\eta|$ binning scheme. The new background estimate is compared to the nominal background estimate. The uncertainty is evaluated in each mass window, where the difference in the number of tracks predicted by each background estimate is taken to be the uncertainty due to the choice of $|\eta|$ binning. Figure 8.6 shows this uncertainty (magenta triangles) evaluated in each mass window.

8.3 dE/dx TAIL UNCERTAINTY

As the Signal Region contains tracks measured with high dE/dx , it is important to correctly model the high tail of the dE/dx distribution in the background estimation procedure. This means that the high dE/dx tails in the dE/dx templates must be well-populated so that the background prediction properly models high dE/dx tracks.

The extent to which fluctuations due to sparse statistics in the high tails of the dE/dx templates affects the background estimate can be evaluated by fitting each template to a continuous function. Crystal Ball functions are typically used to model lossy processes with a long tail and a Gaussian core, and were found to model the high dE/dx tail well in high-statistics samples. The Crystal Ball function used for the fit is defined as:

$$\begin{aligned}
&\text{for } \left(\frac{(m - m_0)}{\sigma} < \alpha \right) : f(m) = \exp \left(-\frac{(m - m_0)^2}{2\sigma^2} \right) \\
&\text{for } \left(\frac{(m - m_0)}{\sigma} > \alpha \right) : f(m) = \left(\frac{n}{|\alpha|} \right)^n \times e^{-\alpha^2/2} \times \left[\frac{(m - m_0)}{\sigma} - \left(|\alpha| - \frac{n}{|\alpha|} \right) \right]^{-n}
\end{aligned}
\tag{8.1}$$

where the m_0 , σ , α , and n variables are free parameters in the fit. An example dE/dx template and its Crystal Ball function fit are shown in Figure 8.2.

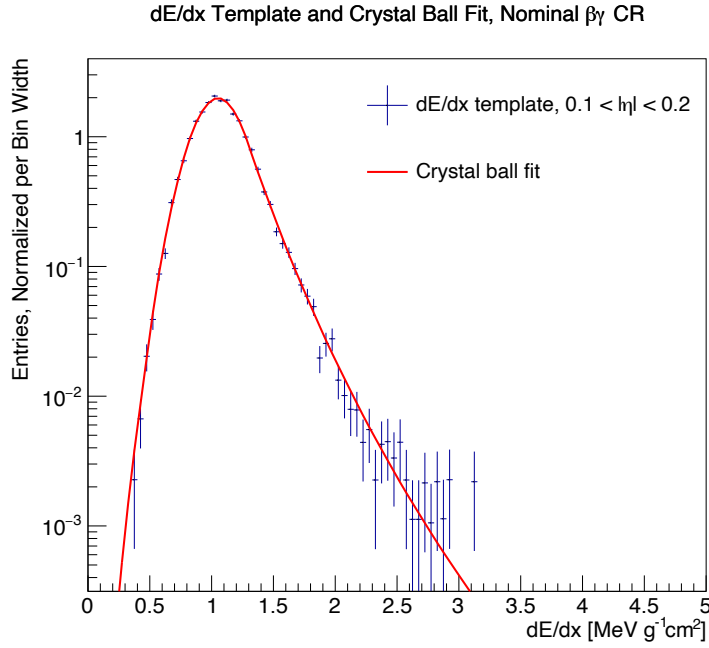


Figure 8.2: The dE/dx template in the bin $0.1 < |\eta| < 0.2$, fit to a Crystal Ball function. The fit and the dE/dx distribution show good agreement at low dE/dx values. To estimate the uncertainty in the background modeling of the high dE/dx tail, dE/dx values sampled from the template in the range $dE/dx > 1.8$ are instead sampled from the Crystal Ball fit, which is smooth and continuous in this region.[†]

A new background prediction is generated in which dE/dx values for $dE/dx > 1.8$ are sampled

from the Crystal Ball fit rather than from the dE/dx template. The difference between this new background prediction and the nominal background prediction is taken to be the uncertainty due to the high dE/dx tail modeling. The effect of this uncertainty evaluated in each mass window is shown in Figure 8.6 (unfilled green triangles).

8.4 E_T^{miss} REWEIGHTING UNCERTAINTY

As mentioned in Section 4.2, the lowest E_T^{miss} trigger threshold changed over the course of Run 2. As a result, events with lower E_T^{miss} that passed one trigger but would not have passed another trigger used at a different point in Run 2 are underrepresented in the dataset compared to events with higher E_T^{miss} . To prevent these trigger differences from impacting the $\beta\gamma$ Control Region where the dE/dx and β_{ToF} templates are sampled, events are reweighted according to their E_T^{miss} trigger.

The potential uncertainty introduced to the background estimate through this reweighting procedure is evaluated by generating a new background prediction where dE/dx and β_{ToF} are sampled from un-reweighted templates. The difference between this new background prediction and the nominal background prediction is taken to be the uncertainty introduced by the E_T^{miss} trigger reweighting. The E_T^{miss} trigger reweighting uncertainty evaluated in each mass window is shown in Figure 8.6 (unfilled magenta triangles).

8.5 β_{ToF} TEMPLATE BINNING UNCERTAINTY

As described in Section 5.2.2, the β_{ToF} resolution is dependent on η . For this reason, the β_{ToF} cut is defined separately in bins of η . The β_{ToF} templates used in the background generation are sliced in the same η binning to reflect the dependence of the β_{ToF} variable on η . The nominal choice of η -binning is:

$$[0, 0.1, 0.2, 0.3, \dots, 1.3, 1.4, 1.5, 1.6]$$

The nominal β_{ToF} cuts are defined using the resolution of the β_{ToF} distributions within those η slices.

However, while the granularity of the η binning is motivated by the structure of cells in the Tile-Cal, the particular choice of η bins is relatively arbitrary. To evaluate the systematic effect of the choice of η binning on the background estimate, a new background estimate is generated using a different choice of η bins and a new set of β_{ToF} cuts defined within those new η bins. The new choice of η -binning is:

$$[0, 0.15, 0.25, 0.35, \dots, 1.35, 1.45, 1.6]$$

The new η -dependent cuts $\beta_{\text{cut,syst}}$ are defined as $1 - 2\sigma_\beta$, where σ_β is the resolution defined in each new η slice. The σ_β values derived for this new set of η bins are shown in Figure 8.3.

These new cuts and η bins are used to generate a new background estimate where β_{ToF} values are drawn from templates sliced in the new η -binning scheme. The drawn β_{ToF} values are compared to the $\beta_{\text{cut,syst}}$ corresponding to the new η bins. The new generated background toys are normalized to data in the kinematic Control Region where $m_{\text{d}E/\text{d}x} < 160 \text{ GeV}$, $m_{\text{ToF}} < 160 \text{ GeV}$, and $\beta_{\text{cut,syst}}$

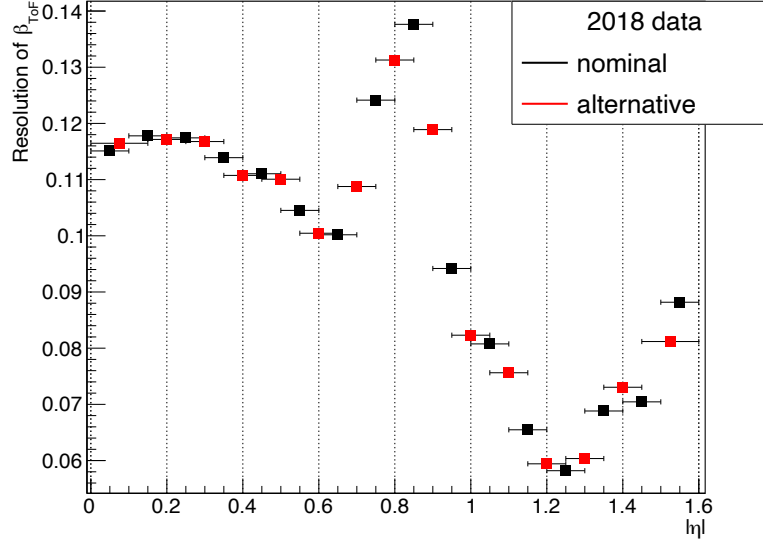


Figure 8.3: The resolution of β_{ToF} in the nominal (black squares) and systematic-shifted (red squares) η -binning schemes.[†]

$< \beta_{\text{ToF}} < 1$. This new normalized background is compared to the nominal background estimate.

The difference between them is taken to be the uncertainty on the background prediction due to the choice of η -binning. The β_{ToF} η -binning uncertainty evaluated in each mass window is shown in Figure 8.6 (unfilled beige squares).

8.6 β_{ToF} TAIL UNCERTAINTY

The β_{ToF} tail modeling uncertainty evaluates how well the background estimate models the low tail of the β_{ToF} distribution. The low tails may not be well-populated in the η -sliced β_{ToF} templates, and so not all η -dependent effects might be captured in the background estimate. To account for

this, a new background estimate is created where β_{ToF} is drawn from a continuous fitted function rather than from the low tails of the β_{ToF} templates. The difference between this new background estimate and the nominal background estimate is taken to be the uncertainty due to the modeling of the β_{ToF} tail.

A function is chosen that describes the low tail of the β_{ToF} distribution in a sample with high statistics. The function $p_0 \exp(p_1 x + p_2 x^2 + p_3 x^3)$ was found to describe the low β_{ToF} tail well, as shown in Figure 8.4 for tracks in the $\beta\gamma$ CR in the β_{ToF} range $[0.2, 0.9]$.

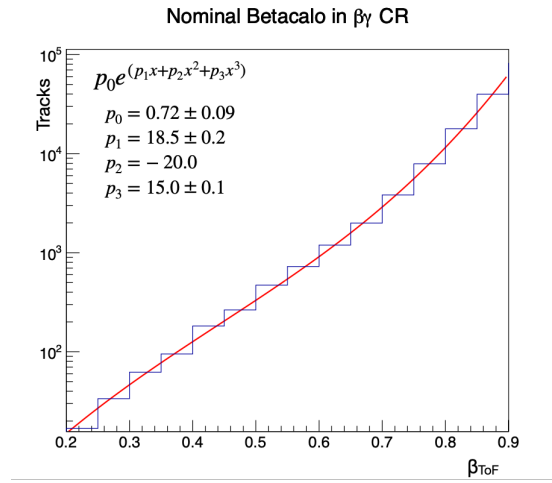


Figure 8.4: The fitted function (red) used to describe the low tail of the β_{ToF} distribution (blue) in the β_{ToF} range $[0.2, 0.9]$ agrees well with data in the $\beta\gamma$ CR.[†]

This function is then fit to each η -binned β_{ToF} template in the $\beta\gamma$ CR. Several η -binned fitted templates are shown in Figure 8.5.

A new background estimate is generated where β_{ToF} is drawn from the templates, and if the drawn β_{ToF} falls within the range of the fitted function at the low tail, the β_{ToF} value is replaced

by a β_{ToF} value drawn from the fit instead. In this way, a new background estimate is constructed where the β_{ToF} low tails are modeled by a continuous fitted function rather than sparsely populated templates. The difference between this new background estimate and the nominal background estimate represents the uncertainty due to the modeling of the β_{ToF} tail. The β_{ToF} tail uncertainty evaluated in each mass window is shown in Figure 8.6 (unfilled gray crosses).

8.7 NORMALIZATION UNCERTAINTY

The normalization uncertainty evaluates the uncertainty on the background estimate due to the scale factor used to normalize the background estimate. The scale factor, as defined in Section 7.2.3, is the ratio of generated background toys to data tracks in the normalization region.

The normalization uncertainty is calculated by propagating the statistical uncertainties on the background toys and data tracks in the normalization region through to the scale factor. As the number of generated background toys can be arbitrarily large, the scale factor uncertainty is dominated by the statistical uncertainty on the number of data tracks.

A new background prediction is generated, where the scale factor used to normalize the background prediction is adjusted to be the scale factor plus the scale factor uncertainty. The difference between the resulting background prediction and the nominal background prediction is taken to be the uncertainty due to the normalization procedure. The normalization uncertainty evaluated in each mass window is shown in Figure 8.6 (orange crosses).

8.8 STATISTICAL UNCERTAINTY

Although the number of generated background toys can be arbitrarily large, the statistics of the templates from which the toys are generated can affect the shape of the resulting predicted background distributions. Therefore, the uncertainty due to the population of the $\beta\gamma$ and kinematic templates must be accounted for.

To evaluate the effect of template statistics on the background estimate, the bin contents of the templates are fluctuated according to a Poisson distribution to represent the effect of statistical fluctuation, and a new background estimate is generated. In total, 30 new background estimates are generated, each using a new set of Poisson-fluctuated templates. The RMS of this collection of background estimates is taken to be the uncertainty due to template statistics. The uncertainty on the background prediction due to template statistics evaluated in each mass window is shown in Figure 8.6 (green triangles).

8.9 SUMMARY

For each source of systematic uncertainty discussed in this chapter, a new background prediction is generated and compared to the nominal background prediction. The number of tracks predicted by the alternative background estimate and the nominal background estimate are compared within the mass windows defined in Section 6.3.2. The difference in the predicted number of tracks is taken to be the uncertainty on the background estimate due to that source of uncertainty.

Figure 8.6 shows the systematic uncertainties calculated in each mass window in the Signal Re-

gion. The leading uncertainty is the template correlation uncertainty. This uncertainty tends to increase as a function of mass due to sparse statistics at high mass.

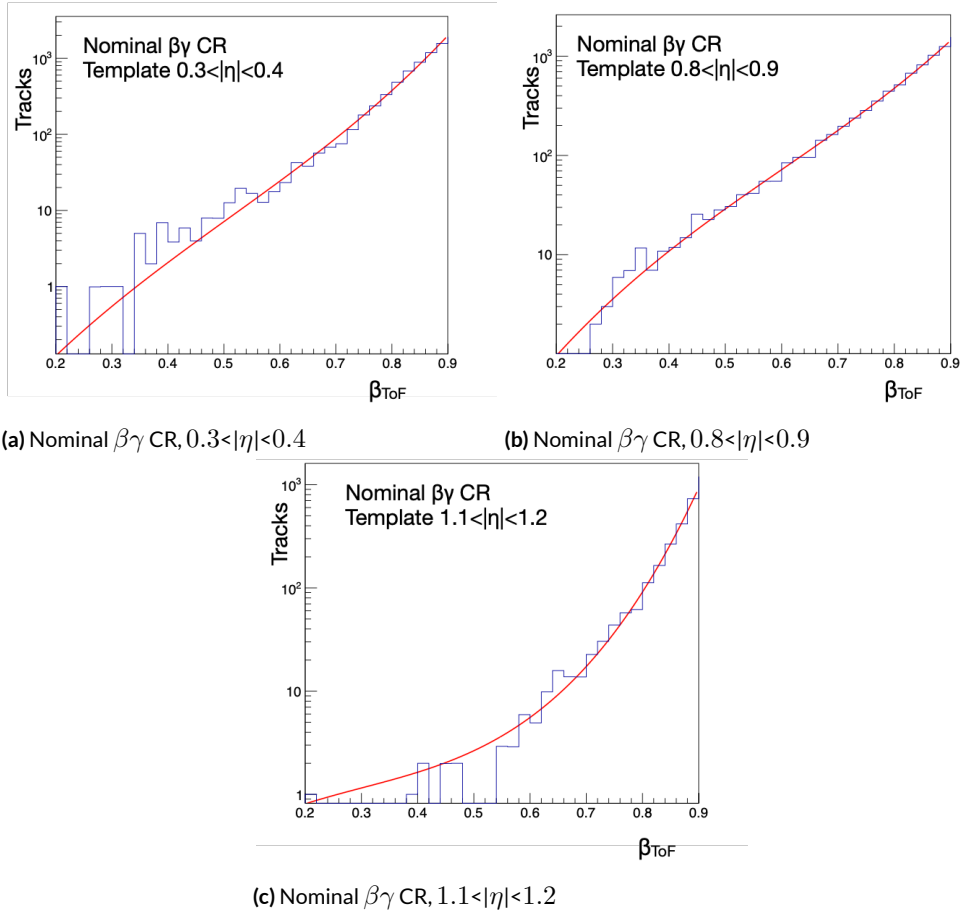
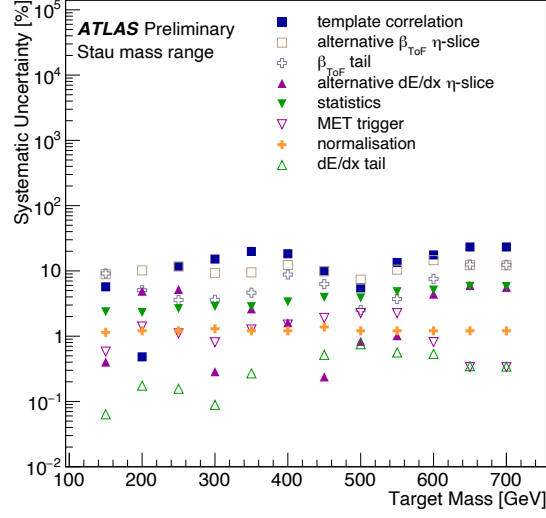
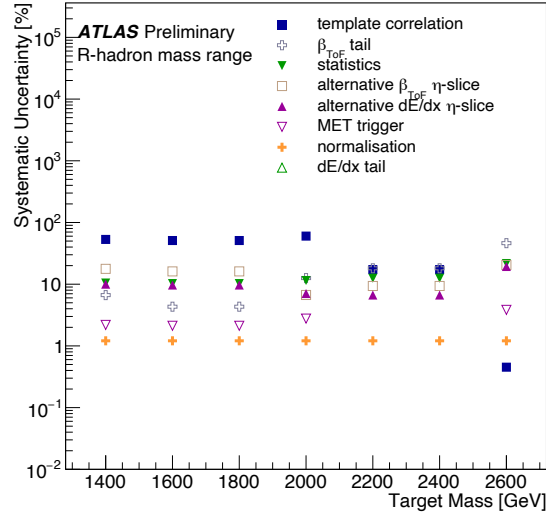


Figure 8.5: Various β_{ToF} templates from different η slices are overlaid with their respective fits. The fit provides a good model for the β_{ToF} distributions.[†]



(a) Mass windows for target masses ≤ 700 GeV



(b) Mass windows for target masses ≥ 1400 GeV

Figure 8.6: A summary of the uncertainties related to the background estimation in the Signal Region. The uncertainty is calculated within each trapezoidal mass window defined in Section 6.3.2 [2].

9

Results

This chapter discusses the results of this search for heavy, charged, long-lived particles. The observed data is compared to the predicted background in the Signal Region. The results are compared with signal simulation to determine upper limits on the production cross sections of heavy, charged, long-lived particles in several signal models. Section 9.1 discusses the data observed in the Signal Region. Section 9.2 describes the interpretation of the results in terms of the signal models considered in this

search.

9.1 RESULTS IN THE SIGNAL REGION

The distribution of data in the 2D $(m_{dE/dx}, m_{ToF})$ plane is shown in Figure 9.1. In the 2D mass plane, 5.1 ± 0.5 tracks are expected from the background prediction, and 9 tracks are observed in data.

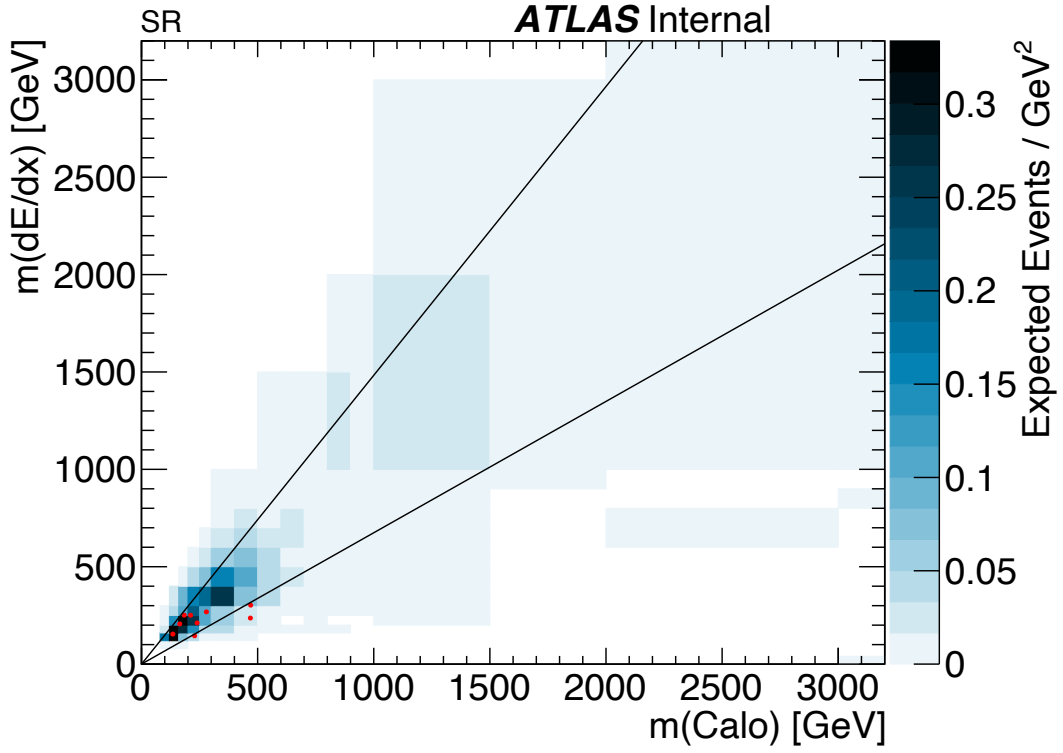


Figure 9.1: The results in the Signal Region in the $(m_{dE/dx}, m_{ToF})$ plane. The background prediction is shown in the blue histogram. The observed data is shown as red dots. The black lines denote the linear boundaries imposed on the Signal Region 2D mass plane discussed in Section 6.3.2.[†]

Various properties of the 9 tracks in the Signal Region are summarized in Table 9.1. No data tracks have reconstructed masses greater than 500 GeV.

Track	$m_{dE/dx}$ [GeV]	m_{ToF} [GeV]	dE/dx [MeV g ⁻¹ cm ²]	β_{ToF}	p_T [GeV]	η
1	218	238	1.97	0.66	165	0.70
2	209	163	2.13	0.75	185	-0.06
3	253	213	1.93	0.75	226	-0.40
4	269	276	1.84	0.69	152	-1.16
5	260	189	2.34	0.74	120	1.15
6	157	139	1.90	0.74	154	0.07
7	149	223	1.80	0.57	142	0.38
8	230	469	1.90	0.43	200	0.50
9	301	466	1.81	0.55	243	-0.73

Table 9.1: Properties of the 9 observed tracks that enter the Signal Region. The tracks are numbered in no particular order. The reconstructed $m_{dE/dx}$ and m_{ToF} values are shown for each track, as well as their dE/dx , β_{ToF} , p_T , and η .

Figure 9.2 shows the $m_{dE/dx}$ and m_{ToF} distributions of the data observed in the Signal Region. The black dots represent the data in the Signal Region, while the blue histogram is the background prediction found in Chapter 7. The $m_{dE/dx}$ and m_{ToF} distributions of several slepton samples of varying masses and lifetimes are shown for comparison.

Figure 9.3 shows the dE/dx , β_{ToF} , p_T , and $|\eta|$ distributions of the data in the Signal Region.

Of the 9 tracks observed in the Signal Region, 6 lie inside the linear boundaries forming the cone discussed in Section 6.3.2. This cone serves to impose consistency between the two reconstructed masses within the mass resolutions. The background prediction within the cone is 3.7 ± 0.4 tracks.

Figure 9.4 zooms in on the distribution of data in the 2D ($m_{dE/dx}$, m_{ToF}) plane in the mass range where the data is observed. The tracks observed inside the cone are highlighted as red dots, whereas the tracks lying outside the cone are marked as green dots. In Table 9.1, the tracks numbered 1-6 lie inside the cone.

Figure 9.5 shows the $m_{dE/dx}$ and m_{ToF} distributions of the 6 data tracks inside the cone, compared to the background distributions and several slepton samples inside the cone. The average of the reconstructed $m_{dE/dx}$ and m_{ToF} values for the tracks found inside the cone is shown in Figure 9.6. The dE/dx , β_{ToF} , p_T , and $|\eta|$ distributions of the 6 tracks inside the cone are shown in Figure 9.7.

The results of the search are evaluated within the trapezoidal mass windows defined in Section 6.3.2. Table 9.2 shows the number of predicted background tracks and the number of observed tracks in each mass window. The largest deviation from the background prediction occurs in the mass window designed to target particles of mass 200 GeV. In the 200 GeV mass window, 1.9 ± 0.2 tracks are expected and 5 tracks are observed. This upward fluctuation near 200 GeV can be observed in the 1D $m_{dE/dx}$ and m_{ToF} distributions in Figures 9.2 and 9.5, as well as in the average mass distribution shown in Figure 9.6.

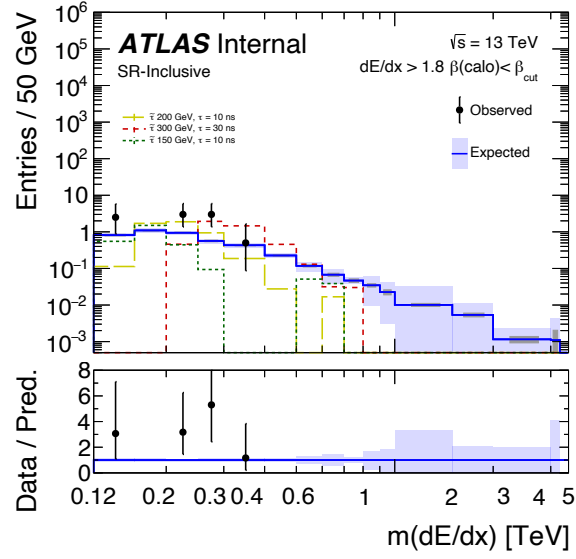
The agreement of the observed data with the background prediction in each window can be quantified using the p_0 value, which is defined in [93]. Qualitatively, the p_0 value gives the probability of observing at least as many tracks as were observed in the data given the background-only hypothesis. In other words, the p_0 value represents the probability of a statistical fluctuation in the background that deviates from the nominal background prediction at least as much as the observed data. A smaller p_0 value corresponds to less agreement between the data and the background expectation.

Figure 9.8 shows the p_0 value calculated for mass windows up to 700 GeV. The lowest p_0 value, 3.26×10^{-2} , is measured in the mass window at 200 GeV. This relatively low p_0 value reflects the

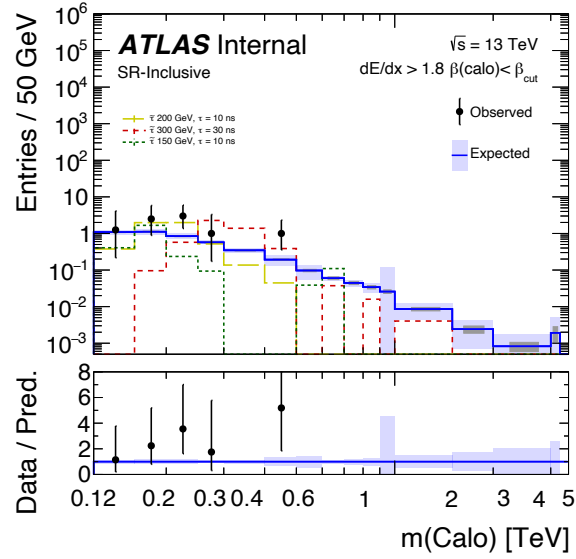
Mass [GeV]	Expected Yield	Observed Yield
150	1.7 ± 0.2	2
200	1.9 ± 0.2	5
250	1.4 ± 0.2	4
300	1.2 ± 0.2	1
350	1.2 ± 0.2	0
400	0.9 ± 0.2	0
450	0.6 ± 0.1	0
500	0.6 ± 0.1	0
550	0.4 ± 0.1	0
600	0.4 ± 0.1	0
650	0.3 ± 0.1	0
700	0.3 ± 0.1	0
1400	0.1 ± 0.1	0
1600	0.1 ± 0.1	0
1800	0.1 ± 0.1	0
2000	0.1 ± 0.1	0
2200	0.07 ± 0.02	0
2400	0.07 ± 0.02	0
2600	0.03 ± 0.03	0

Table 9.2: The number of tracks expected from the background prediction and the number of observed tracks in data in each trapezoidal mass window. The definitions of mass windows in the range 800 GeV to 1.3 TeV will be finalized using chargino simulation that is still in production at the writing of this thesis. The mass windows are defined in Section 6.3.2.[†]

deviation between background expectation and observed data in that window, and corresponds to a significance of less than 2σ .

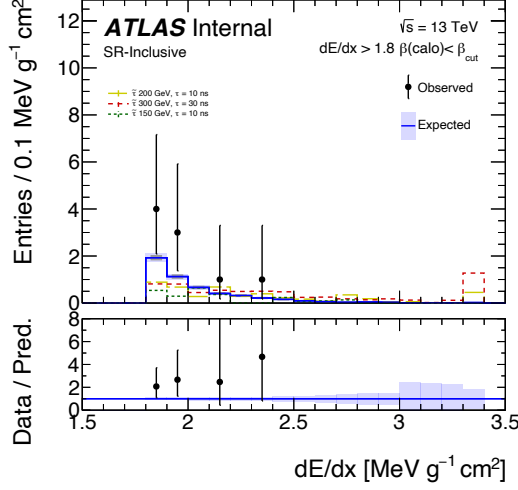


(a) $m_{dE/dx}$

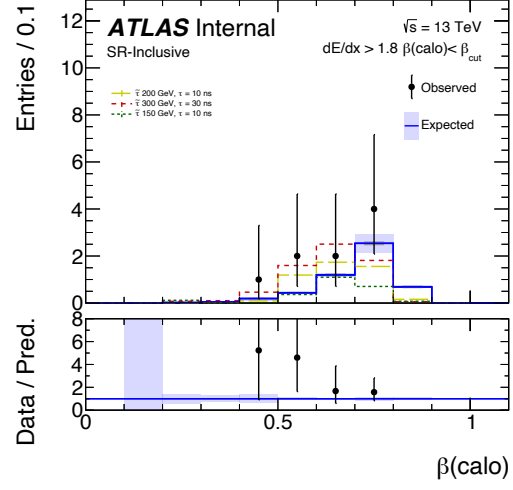


(b) m_{ToF}

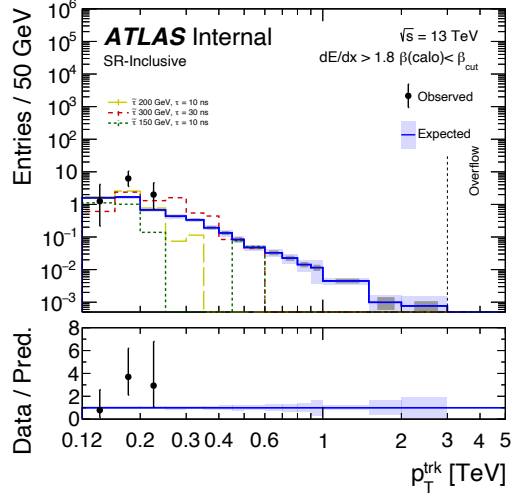
Figure 9.2: The $m_{dE/dx}$ and m_{ToF} distributions in the Signal Region. The background prediction is shown in the blue histogram. The uncertainties on the background estimate are represented by the blue bands. The black dots are the observed data in the Signal Region. Several example signal samples are shown for comparison in the red, green, and yellow histograms.[†]



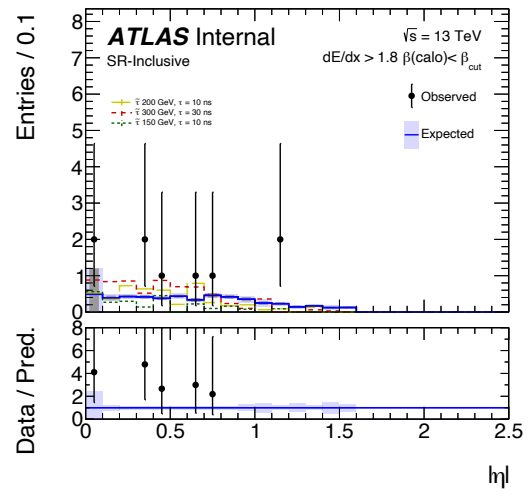
(a) dE/dx



(b) β_{ToF}



(c) p_T



(d) $|\eta|$

Figure 9.3: The dE/dx , β_{ToF} , p_T , and η distributions in the Signal Region. The background prediction is shown in the blue histogram. The uncertainties on the background estimate are represented by the blue bands. The black dots are the observed data in the Signal Region. Several example signal samples are shown for comparison in the red, green, and yellow histograms.[†]

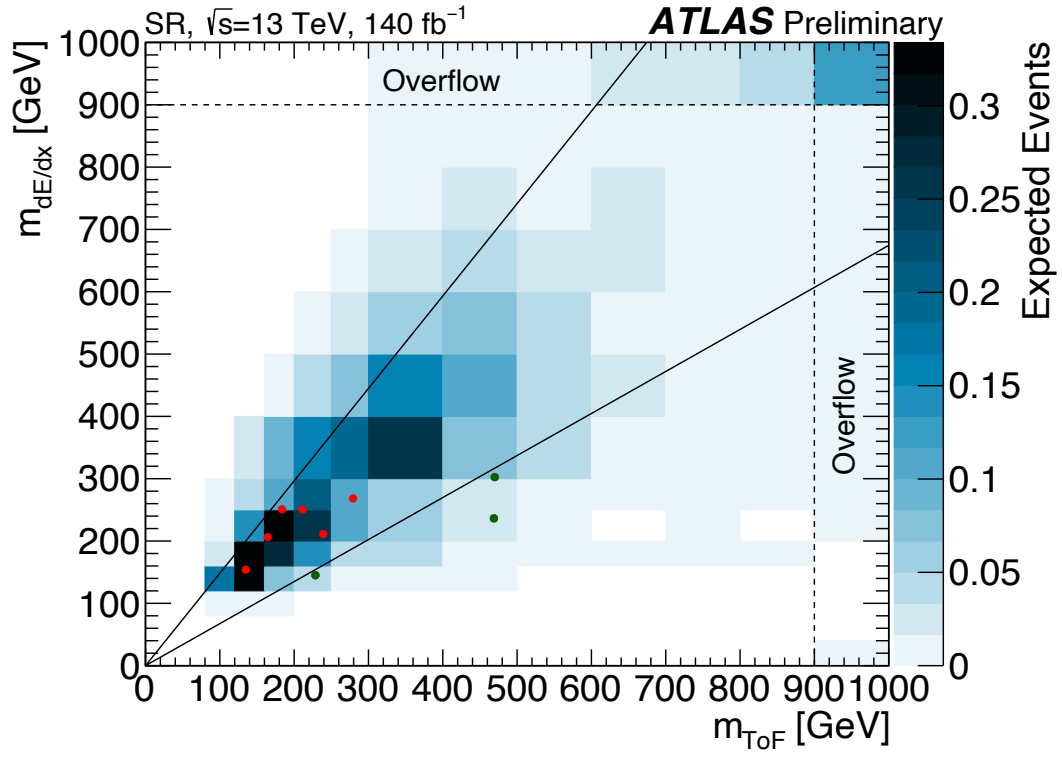
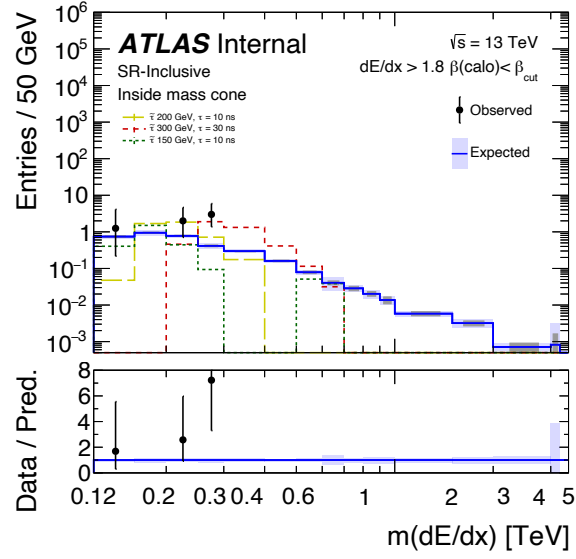
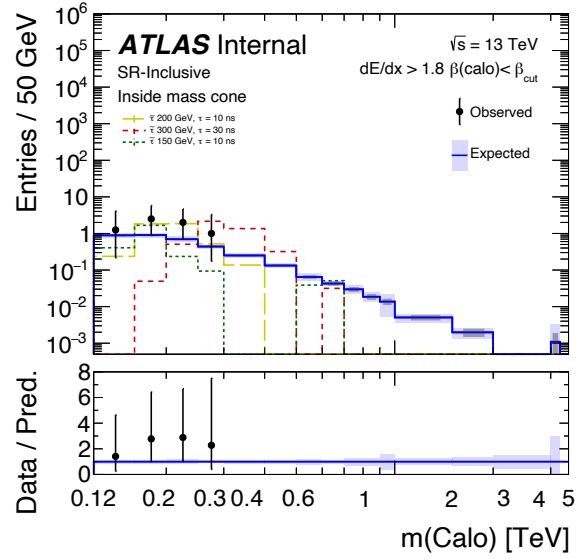


Figure 9.4: The results in the Signal Region in the $(m_{\text{dE/dx}}, m_{\text{ToF}})$ plane, zoomed in to the mass range where the observed tracks lie. The background prediction is shown in the blue histogram. The black lines denote the linear boundaries imposed on the Signal Region 2D mass plane discussed in Section 6.3.2. The observed tracks lying within the cone are shown as red dots. The observed tracks lying outside the cone are shown as green dots [2].



(a) $m_{dE/dx}$ inside cone



(b) m_{ToF} inside cone

Figure 9.5: The $m_{dE/dx}$ and m_{ToF} distributions inside the cone in the Signal Region. The background prediction is shown in the blue histogram. The uncertainties on the background estimate are represented by the blue bands. The black dots are the observed data in the Signal Region. Several example signal samples are shown for comparison in the red, green, and yellow histograms.[†]

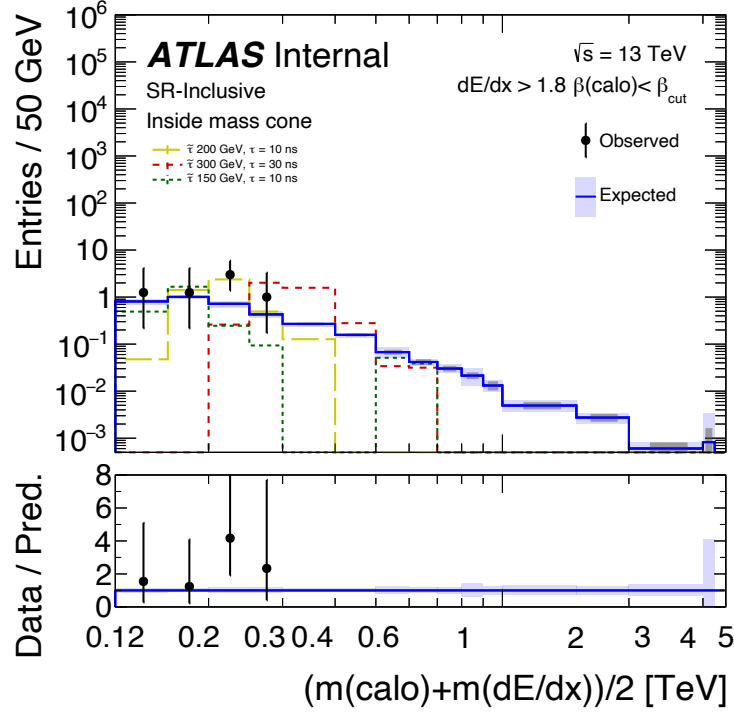
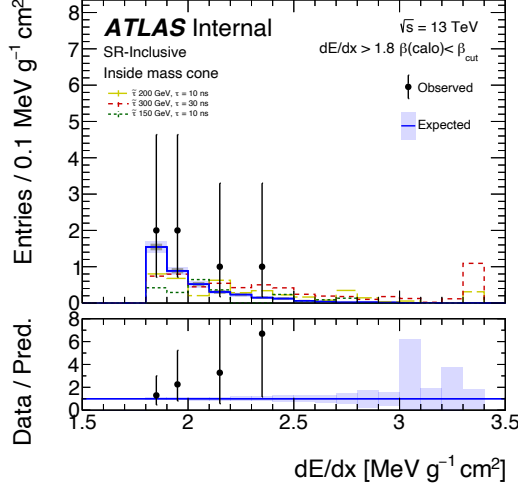
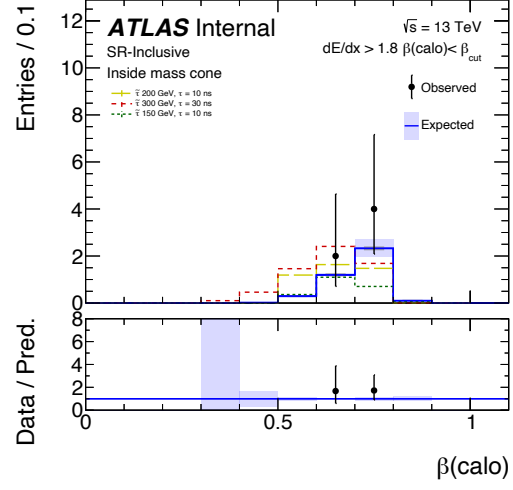


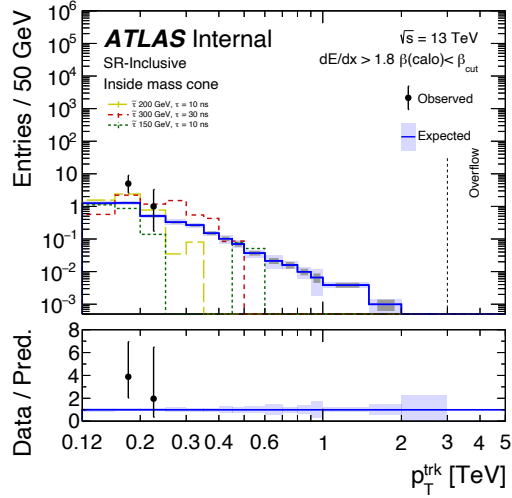
Figure 9.6: The distribution of the average of the $m_{dE/dx}$ and m_{ToF} values for each track inside the cone in the Signal Region. The background prediction is shown in the blue histogram. The uncertainties on the background estimate are represented by the blue bands. The black dots are the observed data in the Signal Region. Several example signal samples are shown for comparison in the red, green, and yellow histograms.[†]



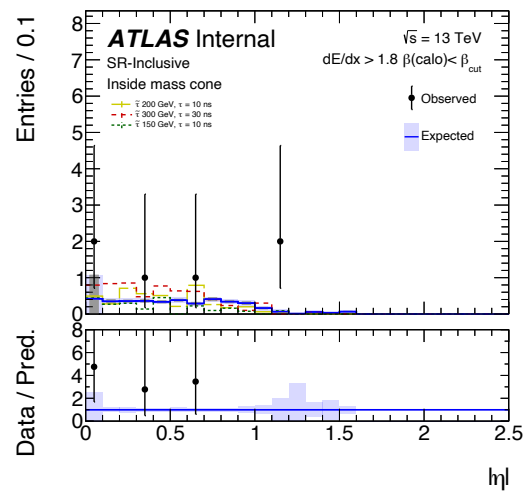
(a) dE/dx inside cone



(b) β_{ToF} inside cone



(c) p_T inside cone



(d) $|\eta|$ inside cone

Figure 9.7: The dE/dx , β_{ToF} , p_T , and η distributions inside the cone in the Signal Region. The background prediction is shown in the blue histogram. The uncertainties on the background estimate are represented by the blue bands. The black dots are the observed data in the Signal Region. Several example signal samples are shown for comparison in the red, green, and yellow histograms.[†]

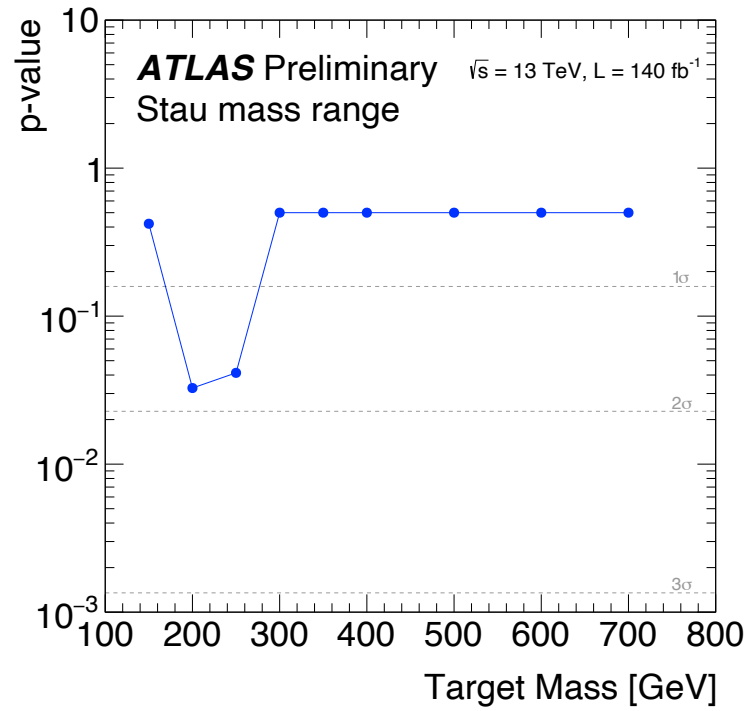


Figure 9.8: The p_0 values calculated in each mass window up to 700 GeV. p_0 values corresponding to significances of 1σ , 2σ , and 3σ are marked with gray dashed lines for reference. The lowest measured p_0 value, indicating the mass window with the largest disagreement, is found in the 200 GeV mass window [2].

9.2 INTERPRETATION IN SIGNAL MODELS

Results are interpreted in each mass window in terms of the signal models considered. The expected background yield and the observed yield in each mass window are used to set upper limits on the cross sections of sleptons and R-hadrons. For each signal mass and lifetime hypothesis, upper limits on the production cross section at the 95% confidence level (CL) are extracted using the CLs prescription [94].

Figures 9.9- 9.10 show the 95% CL upper limits placed on the slepton production cross section for slepton lifetimes of 3, 10, 30, and 3000 ns as a function of mass. The cross section predicted by the simplified model is shown in a gray line. The expected upper cross-section limit in the background-only hypothesis is shown in the dashed line. The limit extracted from the observed data is shown in the solid black line. The teal bands represent the 1 and 2 σ uncertainty ranges on the upper limit. For each mass point considered, cross sections above the solid black line are considered excluded. If the theoretical cross section lies above the observed line at a particular mass, sleptons of that mass produced in this model are excluded by these results.

Through the reduction in background resulting from the inclusion of time-of-flight as a second measure of particle speed, this search targets signals of masses on the order of several hundred GeV. This search places the most stringent limits to date on sleptons with lifetimes on the order of tens of nanoseconds. For sleptons of lifetime 10 ns, we expected to exclude masses 288–414 GeV, and the observed cross section limits exclude masses 295–448 GeV. For sleptons of lifetime 30 ns, we expected to exclude masses 199–449 GeV, and the observed limits exclude masses 294–485 GeV.

The search is not sensitive to sleptons of lower lifetimes (3 ns) due to the requirement that the particle passes through the hadronic calorimeter before decaying. The sensitivity to detector-stable sleptons is restricted by the use of the E_T^{miss} trigger. Sensitivity ends at high masses due to the decreasing production cross section of higher mass sleptons. At lower masses, sensitivity is limited by the high- p_T and low-speed requirements.

The observed limits are weaker than the expected limits near 200 GeV. This is due to the deviation from prediction seen in the 200 GeV mass window, where 1.9 ± 0.2 tracks are expected and 5 tracks are observed.

This deviation in the 200 GeV mass window may be a statistical fluctuation, or may be a hint of a new particle. A similar search is in progress in Run 2 ATLAS data that looks for heavy, charged, long-lived particles via two highly-ionizing tracks in the same event, and does not include time-of-flight information. This new search is expected to have sensitivity to sleptons with masses near the deviation around 200 GeV, and may be able to weigh in on this deviation.

Figure 9.11 shows the limits placed on sleptons in the 2D mass-lifetime plane. The black dashed contour shows the expected limit as a function of mass and lifetime, while the solid teal line shows the observed limit. The teal bands represent the 1σ and 2σ uncertainty ranges. The mass-lifetime area inside the contour has been excluded. As in the 1D limit plots, the observed limit is weaker than the expected limit near 200 GeV due to the deviation in the 200 GeV mass window.

Figure 9.12 compares the limits placed on sleptons as a function of mass and lifetime in this search to limits placed by previous searches. The expected and observed limits placed in this search are shown in teal dashed and solid lines, respectively. The purple contours show the limits placed in the

previous iteration of this search, described in [26], which used ionization energy measured in the ATLAS silicon pixel detector as the sole measure of particle speed. The blue contours represent the limits placed by a search for displaced leptons, described in [28], which targeted sleptons of a lower mass and lifetime range than the search presented here.

Compared to the Pixel dE/dx search, the $dE/dx + \beta_{\text{ToF}}$ search targets sleptons of longer lifetimes and slightly higher masses. This search requires that a particle traverses the tile calorimeter in addition to the Inner Detector to obtain a second measure of particle speed, time-of-flight. Requiring that the particle survives long enough to pass through the tile calorimeter reduces the sensitivity to shorter lifetimes. However, the second measurement of particle speed results in significant background reduction, which allows greater sensitivity to sleptons of longer lifetimes and higher masses in previously unexplored areas of this mass-lifetime plane.

Figures 9.13- 9.14 show the 95% CL upper limits placed on the R-hadron production cross section for varying lifetimes as a function of mass for the case where the mass of the neutralino is fixed to 100 GeV. In this scenario, R-hadrons of lifetime 3 ns are excluded for masses less than 1860 GeV. R-hadrons of lifetimes 10 and 30 ns are excluded up to masses 2180 and 2278 GeV, respectively. Stable R-hadrons are excluded up to masses of 2222 GeV, which is the most stringent limit on stable R-hadrons to date.

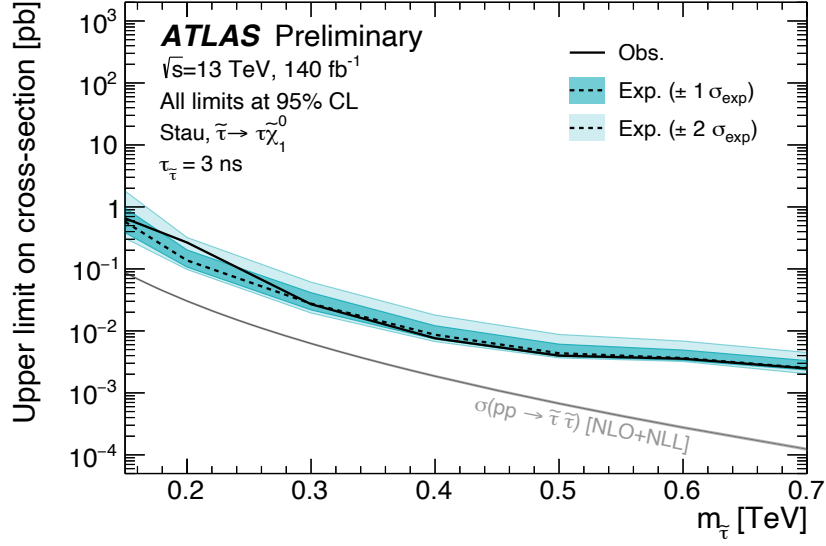
Figures 9.15- 9.16 show the 95% CL upper limits on the R-hadron production cross section for the case where the mass difference between the gluino and the neutralino is fixed to 30 GeV. In this scenario, R-hadrons of lifetimes 3 ns, 10 ns, and 30 ns are excluded up to masses 1557, 1968, and 2130 GeV, respectively.

Figure 9.17 summarizes the limits placed on R-hadrons as a function of mass and lifetime. Figure 9.17a shows the R-hadron limits in the mass-lifetime plane for the case where the neutralino mass is assumed to be fixed at 100 GeV. Figure 9.17b shows the limits placed on R-hadrons in the case that the mass difference between the gluino and the neutralino is fixed to be 30 GeV. For a given lifetime, masses below the limit contour are excluded.

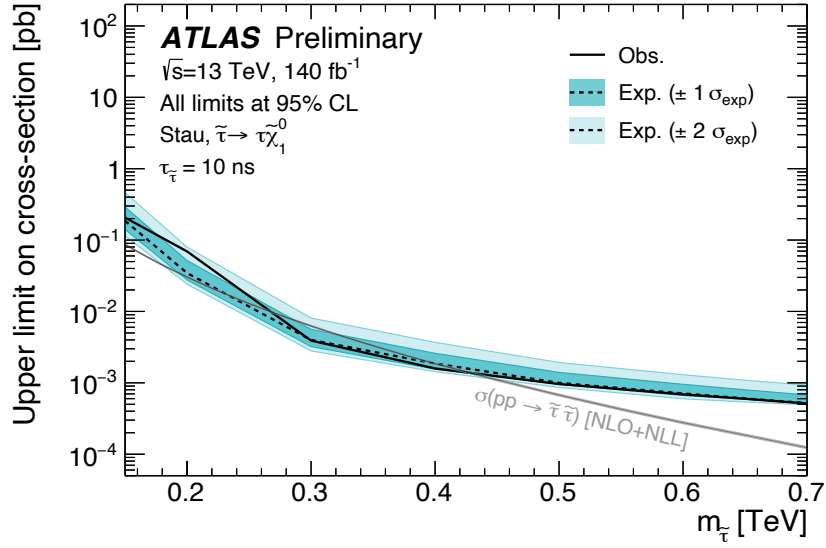
The limits placed on the R-hadrons of lifetime 30 ns in both cases are the most stringent to date. Relative to the previous iteration of this search, which looked for heavy, charged, long-lived particles via highly ionizing tracks [26], this search is able to place slightly stronger limits on R-hadrons in the 30 ns lifetime range. This search places weaker limits on shorter-lived R-hadrons due to the additional requirement that the particle must traverse the hadronic calorimeter before decaying.

However, as this search primarily targets particles of masses on the order of 100s of GeV, the gain in sensitivity at very high masses is slight, and is limited by sparse statistics at high masses. Nonetheless, through the time-of-flight requirement that targets slow-moving particles, this search slightly improves limits on R-hadrons that were weaker than expected in the previous iteration of analysis due to the excess at very high masses discussed in Section 2.4. The tracks in this excess were determined to have a calorimeter time-of-flight measurement consistent with the speed of light, which is not consistent with a heavy (~ 2 TeV) R-hadron.

The results of this search can be re-interpreted in terms of other signal models that predict heavy, charged, long-lived particles. Limits on charginos will be placed pending the production of signal simulation.

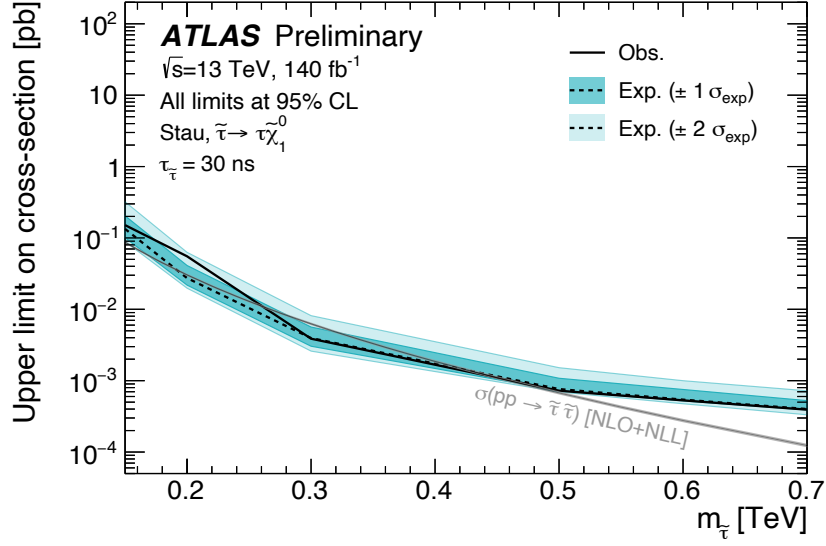


(a) 3ns slepton

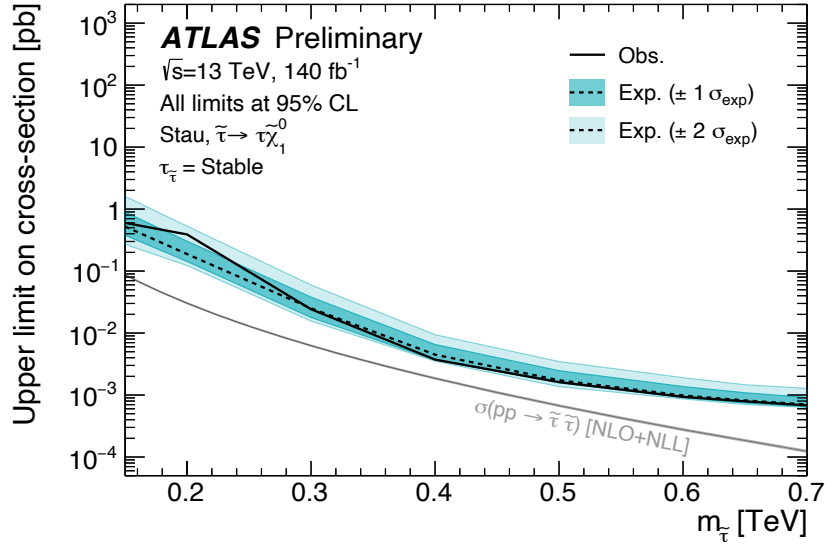


(b) 10ns slepton

Figure 9.9: 95% CL upper limits on the production cross section of sleptons of lifetimes 3 and 10ns as a function of mass. The cross section predicted by the simplified model is shown in a gray line. The expected upper cross-section limit in the background-only hypothesis is shown in the dashed line. The limit extracted from the observed data is shown in the solid black line. The teal bands represent the 1 and 2 σ bounds on the upper limit [2].



(a) 30ns slepton



(b) 3000ns slepton

Figure 9.10: 95% CL upper limits on the production cross section of sleptons of lifetimes 30 and 3000ns as a function of mass. The cross section predicted by the simplified model is shown in a gray line. The expected upper cross-section limit in the background-only hypothesis is shown in the dashed line. The limit extracted from the observed data is shown in the solid black line. The teal bands represent the 1 and 2 σ bounds on the upper limit [2].

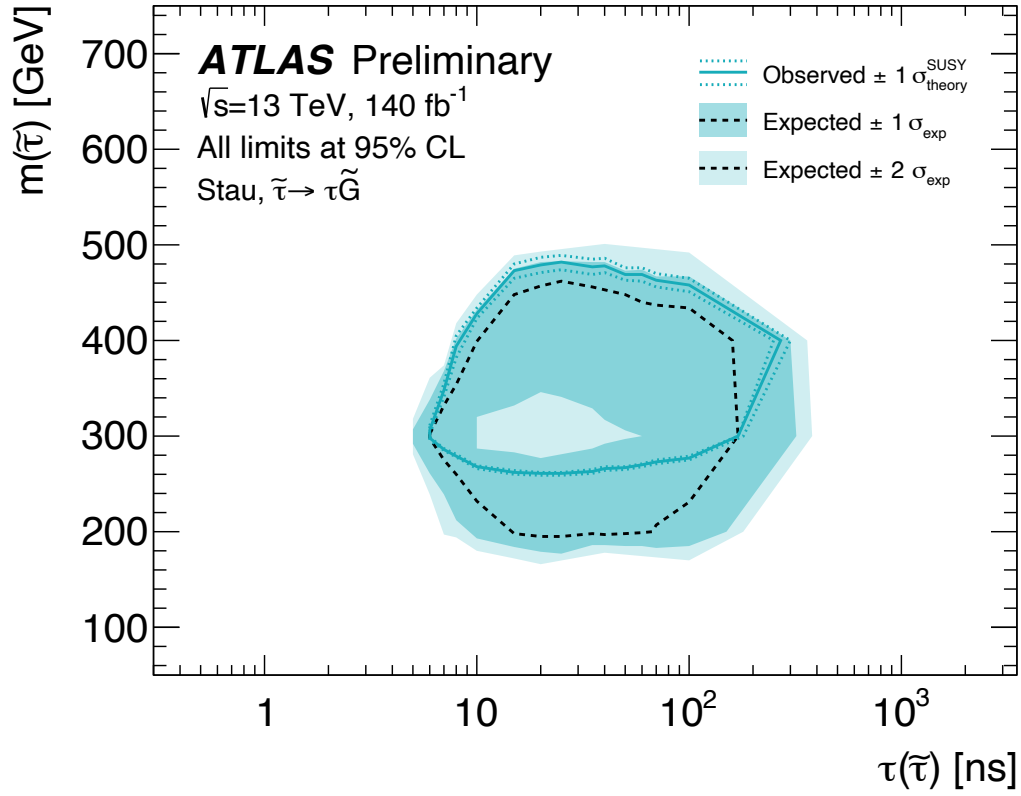


Figure 9.11: Limits placed on sleptons in the mass-lifetime plane. The black dashed contour shows the expected limit, while the solid teal line shows the observed limit in the 2D mass-lifetime plane. The teal bands represent the 1σ and 2σ uncertainty ranges. The mass-lifetime area within the contour has been excluded. The observed limit is weaker than the expected limit around a mass of 200 GeV due to the deviation of observed data from background expectation in the 200 GeV mass window [2].

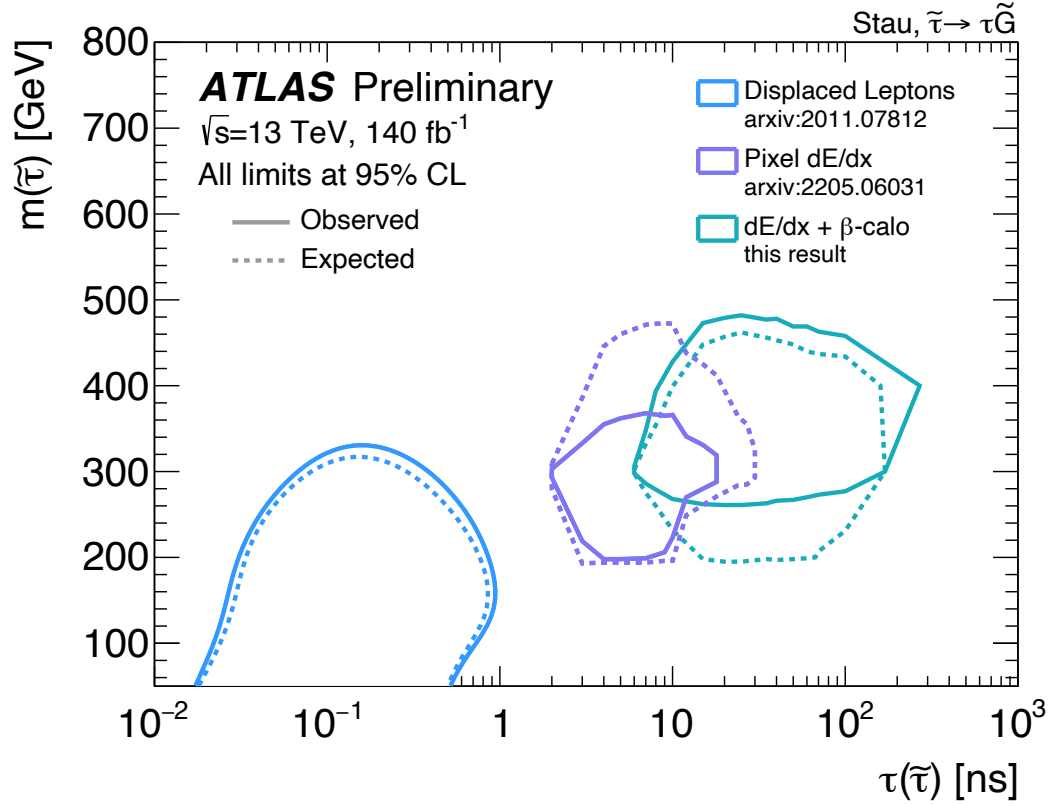
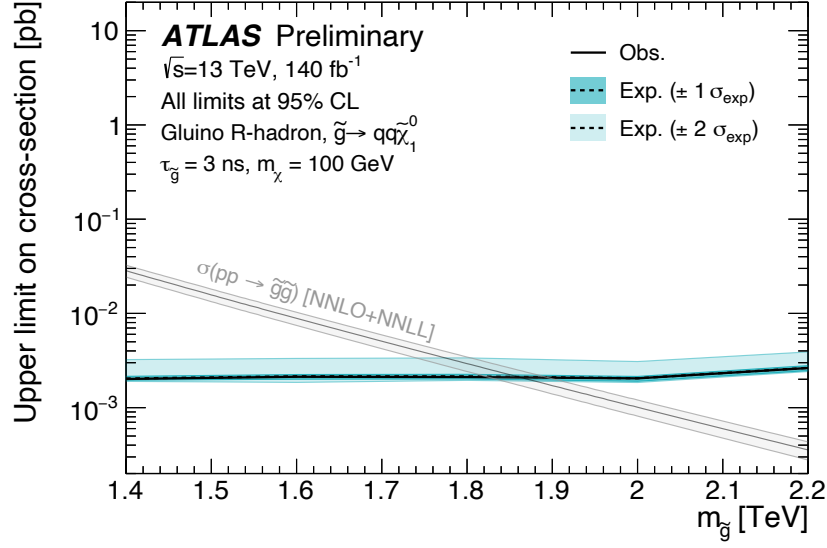
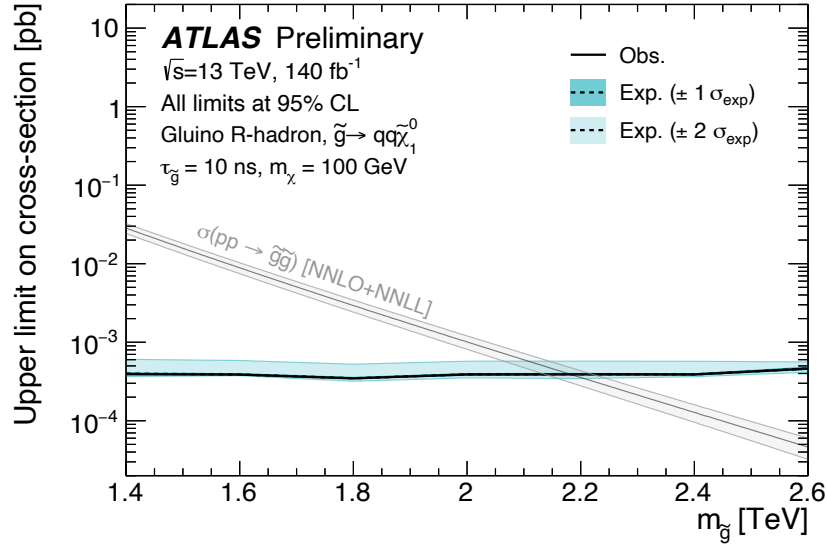


Figure 9.12: A comparison of the limits placed on sleptons in three searches. The expected and observed limits placed in the search described in this thesis are shown in teal dashed and solid lines, respectively. The purple contours show the limits placed in the previous iteration of this search, described in [26], which used ionization energy measured in the ATLAS silicon pixel detector as the sole measure of particle speed. The blue contours represent the limits placed by a search for displaced leptons, described in [28], which targeted sleptons of a lower mass and lifetime range than the search presented here [2].

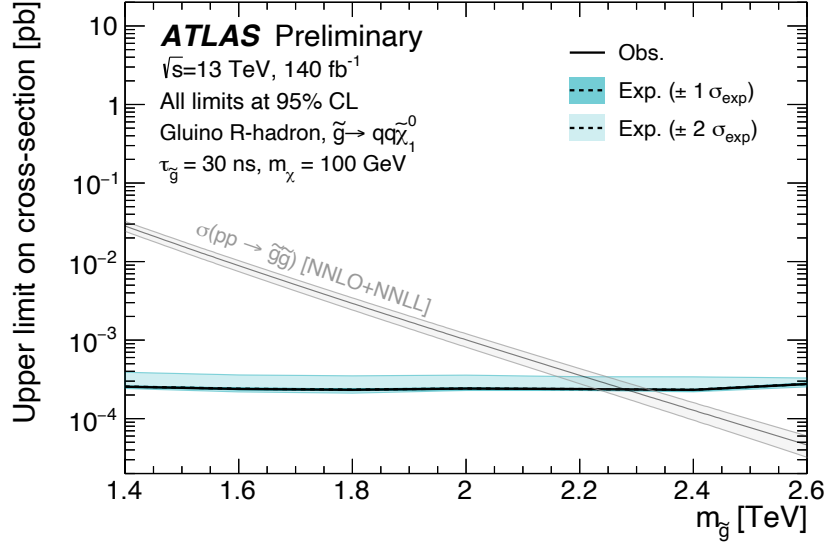


(a) 3ns R-hadron

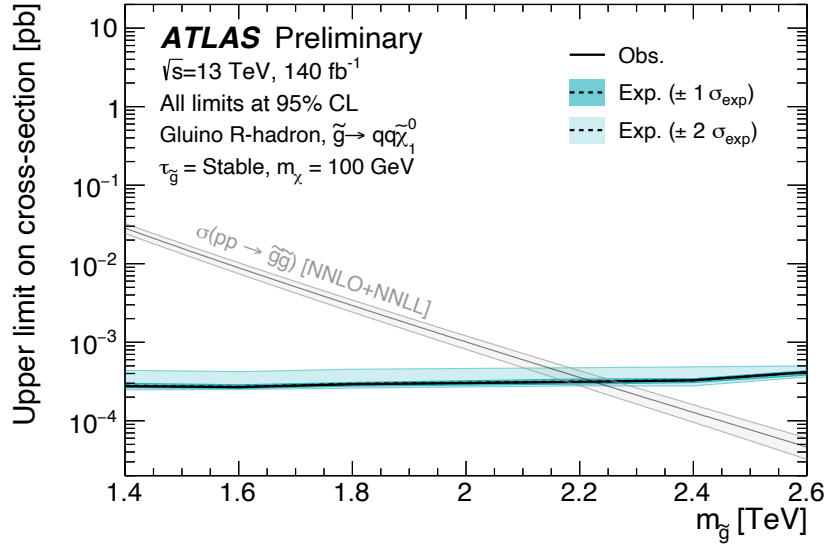


(b) 10ns R-hadron

Figure 9.13: 95% CL upper limits on the production cross section of R-hadrons ($m_\chi=100$ GeV) of lifetimes 3 and 10ns as a function of mass. The cross section predicted by the simplified model is shown in a gray line. The expected upper cross-section limit in the background-only hypothesis is shown in the dashed line. The limit extracted from the observed data is shown in the solid black line. The teal bands represent the 1 and 2 σ bounds on the upper limit [2].

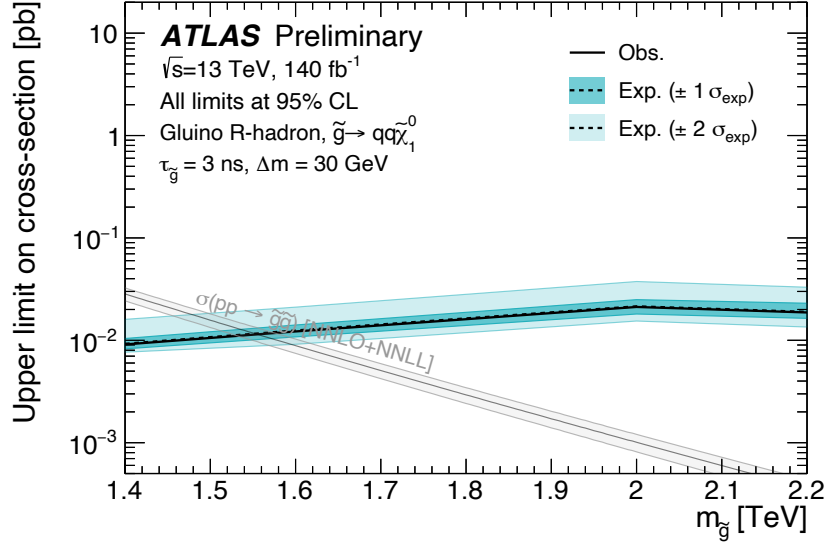


(a) 30ns R-hadron

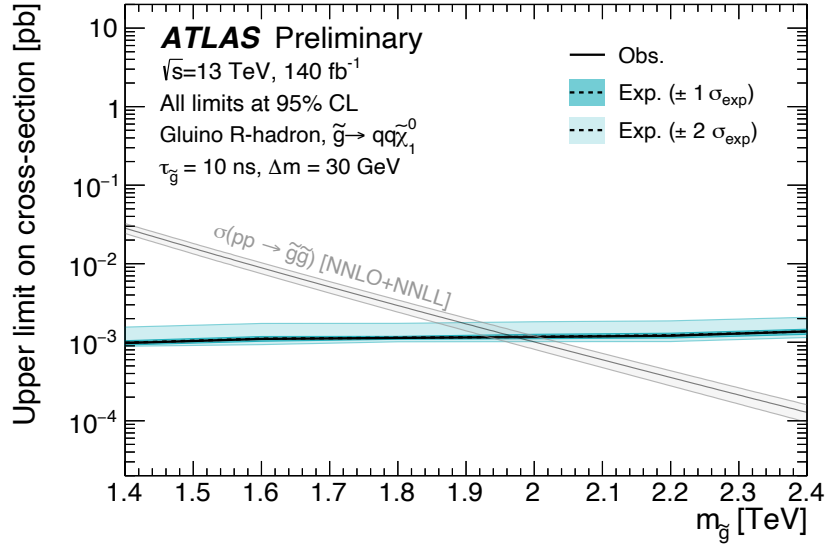


(b) Stable R-hadron

Figure 9.14: 95% CL upper limits on the production cross section of R-hadrons ($m_\chi=100$ GeV) of lifetimes 30ns and stable as a function of mass. The cross section predicted by the simplified model is shown in a gray line. The expected upper cross-section limit in the background-only hypothesis is shown in the dashed line. The limit extracted from the observed data is shown in the solid black line. The teal bands represent the 1 and 2 σ bounds on the upper limit [2].



(a) 3ns R-hadron



(b) 10ns R-hadron

Figure 9.15: 95% CL upper limits on the production cross section of R-hadrons ($m_{\tilde{g}} - m_{\tilde{\chi}} = 30 \text{ GeV}$) of lifetimes 3 and 10ns as a function of mass. The cross section predicted by the simplified model is shown in a gray line. The expected upper cross-section limit in the background-only hypothesis is shown in the dashed line. The limit extracted from the observed data is shown in the solid black line. The teal bands represent the 1 and 2 σ bounds on the upper limit [2].

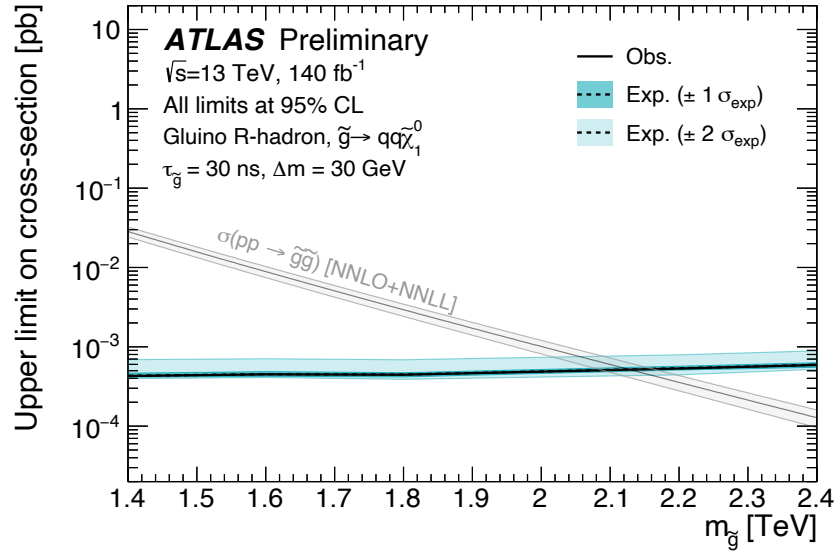
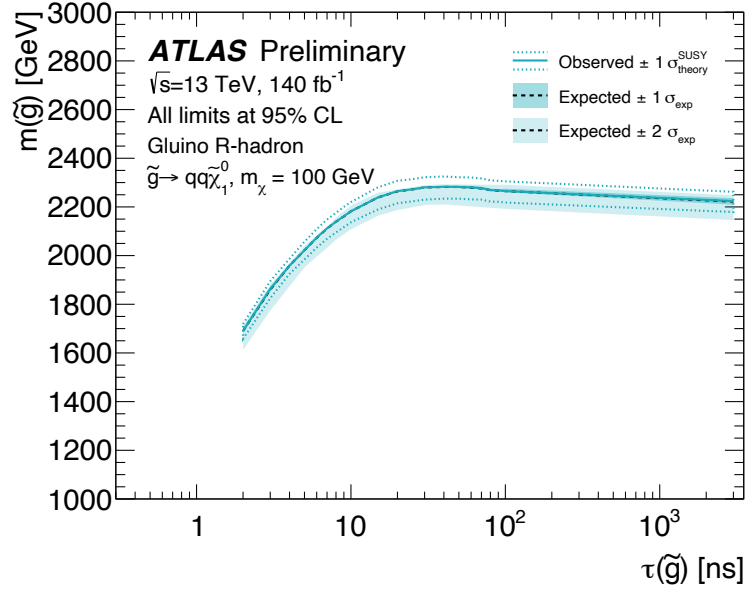
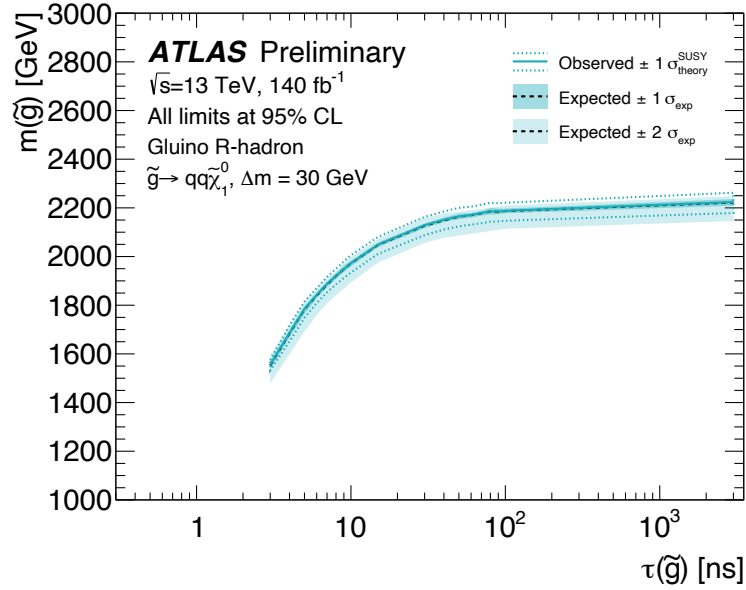


Figure 9.16: 95% CL upper limits on the production cross section of R-hadrons ($m_{\tilde{g}} - m_{\tilde{\chi}} = 30 \text{ GeV}$) of lifetime 30ns as a function of mass. The cross section predicted by the simplified model is shown in a gray line. The expected upper cross-section limit in the background-only hypothesis is shown in the dashed line. The limit extracted from the observed data is shown in the solid black line. The teal bands represent the 1 and 2 σ bounds on the upper limit [2].



(a) R-hadrons ($m_\chi=100$ GeV)



(b) R-hadrons ($m_{\tilde{g}}-m_\chi=30$ GeV)

Figure 9.17: Limit contours in the 2D mass-lifetime plane for (a) R-hadrons ($m_\chi=100$ GeV) and (b) R-hadrons ($m_{\tilde{g}}-m_\chi=30$ GeV). The black dashed line shows the expected limit. The solid teal line shows the observed limit. The teal bands represent the 1σ and 2σ uncertainty ranges. For a given lifetime, masses below the limit contour are excluded [2].

10

Conclusion

A search for heavy, charged, long-lived particles was conducted in 140 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton-proton collision data collected by the ATLAS experiment. Ionization energy loss measured in the silicon pixel tracker and time-of-flight measured in the hadronic calorimeter were used to look for slow-moving particles at high momenta, which is a signature for new long-lived particles that are heavy. This analysis was designed to be particularly sensitive to particles of masses on the order of

100s of GeV.

The ionization energy loss measurements and time-of-flight measurements were used to reconstruct two masses for particles passing the Signal Region selection criteria. The background mass distributions were predicted using a data-driven approach. Overall, 5.1 ± 0.5 background tracks were expected to appear in the Signal Region and 9 tracks were observed in data. Deviations in the observed mass distributions relative to the predicted background mass distributions were searched for within mass windows. Data was found to agree with the background-only expected yields within a significance of 2σ . Results were interpreted in supersymmetric models that predict heavy, charged, long-lived sleptons and R-hadrons.

A detailed study of the 9 tracks appearing in the Signal Region is in progress. Future work includes interpreting results in terms of supersymmetric models predicting the existence of long-lived charginos.

Appendix

Removed, May 15, 2021.

References

- [1] ATLAS Collaboration, Dario Barberis, Andrea Coccaro, Tomas Davidek, Jana Faltova, Anne Winifred Fortman, Melissa Franklin, Claudia Gemme, Alexis Elizabeth Mulski, Marija Glisic, Millie Mae Healy, Laura Jeanty, Elliot Lipeles, Hideyuki Oide, Katherine Pachal, Karri Folan Di Petrillo, Simone Pagan Griso, Stefano Passaggio, Tadeas Petru, Martina Ressegotti, Leonardo Rossi, Ismet Siral, Alexander Naip Tuna, Abraham Kahn, and Aaron Stephen White. Search for heavy, long lived charged particles with large specific ionisation and low-beta in 139 fb^{-1} of pp collisions at $\sqrt{s} = 13 \text{ TeV}$ using the ATLAS experiment. Technical report, CERN, Geneva, 2023. URL <https://cds.cern.ch/record/2850697>. Supporting Note for ANA-SUSY-2022-12.
- [2] Search for heavy, long lived charged particles with large specific ionisation and low-beta in 140 fb^{-1} of p-p collisions at $\sqrt{s} = 13 \text{ TeV}$ using the ATLAS experiment. Technical report, CERN, Geneva, 2023. URL <https://cds.cern.ch/record/2870112>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-044>.
- [3] R. L. Workman et al. Review of Particle Physics. *PTEP*, 2022:083C01, 2022. doi: 10.1093/ptep/ptac097.
- [4] Q. R. Ahmad et al. Measurement of the rate of $\nu_e + d \rightarrow p + p + e^-$ interactions produced by ^8B solar neutrinos at the sudbury neutrino observatory. *Phys. Rev. Lett.*, 87:071301, Jul 2001. doi: 10.1103/PhysRevLett.87.071301. URL <https://link.aps.org/doi/10.1103/PhysRevLett.87.071301>.
- [5] Y. Fukuda et al. Evidence for oscillation of atmospheric neutrinos. *Physical Review Letters*, 81(8):1562–1567, aug 1998. doi: 10.1103/physrevlett.81.1562. URL <https://doi.org/10.1103/PhysRevLett.81.1562>.
- [6] Alessandro Strumia and Francesco Vissani. Neutrino masses and mixings and..., 2010. URL <https://arxiv.org/abs/hep-ph/0606054>.

- [7] S. F. Novaes. Standard Model: An Introduction, 2000. URL <https://arxiv.org/abs/hep-ph/0001283>.
- [8] Mary K. Gaillard, Paul D. Grannis, and Frank J. Sciulli. The standard model of particle physics. *Rev. Mod. Phys.*, 71:S96–S111, Mar 1999. doi: 10.1103/RevModPhys.71.S96. URL <https://link.aps.org/doi/10.1103/RevModPhys.71.S96>.
- [9] J. Barranco. Some standard model problems and possible solutions. *Journal of Physics: Conference Series*, 761(1):012007, oct 2016. doi: 10.1088/1742-6596/761/1/012007. URL <https://dx.doi.org/10.1088/1742-6596/761/1/012007>.
- [10] Lawrence Lee, Christian Ohm, Abner Soffer, and Tien-Tien Yu. Collider searches for long-lived particles beyond the standard model. *Progress in Particle and Nuclear Physics*, 106: 210–255, may 2019. doi: 10.1016/j.pnpnp.2019.02.006. URL <https://doi.org/10.1016%2Fj.pnpnp.2019.02.006>.
- [11] Katherine Garrett and Gintaras Duda. Dark matter: A primer. *Advances in Astronomy*, 2011:1–22, 2011. doi: 10.1155/2011/968283. URL <https://doi.org/10.1155%2F2011%2F968283>.
- [12] Vera C. Rubin. Dark matter in spiral galaxies. *Scientific American*, 248(6):96–109, 1983. ISSN 00368733, 19467087. URL <http://www.jstor.org/stable/24968923>.
- [13] Stephen P. Martin. A Supersymmetry Primer. In *Perspectives on Supersymmetry*, pages 1–98. World Scientific, jul 1998. doi: 10.1142/9789812839657_0001. URL https://doi.org/10.1142%2F9789812839657_0001.
- [14] M. Tanabashi et al. Review of particle physics. *Phys. Rev. D*, 98:030001, Aug 2018. doi: 10.1103/PhysRevD.98.030001. URL <https://link.aps.org/doi/10.1103/PhysRevD.98.030001>.
- [15] G.F. Giudice and R. Rattazzi. Theories with gauge-mediated supersymmetry breaking. *Physics Reports*, 322(6):419–499, dec 1999. doi: 10.1016/S0370-1573(99)00042-3. URL <https://doi.org/10.1016%2Fs0370-1573%2899%2900042-3>.
- [16] Lisa Randall and Raman Sundrum. Out of this world supersymmetry breaking. *Nuclear Physics B*, 557(1-2):79–118, sep 1999. doi: 10.1016/S0550-3213(99)00359-4. URL <https://doi.org/10.1016%2Fs0550-3213%2899%2900359-4>.

- [17] Gian F Giudice, Riccardo Rattazzi, Markus A Luty, and Hitoshi Murayama. Gaugino mass without singlets. *Journal of High Energy Physics*, 1998(12):027–027, dec 1998. doi: 10.1088/1126-6708/1998/12/027. URL <https://doi.org/10.1088%2F1126-6708%2F1998%2F12%2F027>.
- [18] G.F. Giudice and A. Romanino. Erratum to: “split supersymmetry” [nucl. phys. b 699 (2004) 65]. *Nuclear Physics B*, 706(1-2):487, jan 2005. doi: 10.1016/j.nuclphysb.2004.11.048. URL <https://doi.org/10.1016%2Fj.nuclphysb.2004.11.048>.
- [19] Nima Arkani-Hamed and Savas Dimopoulos. Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC. *Journal of High Energy Physics*, 2005(06):073–073, jun 2005. doi: 10.1088/1126-6708/2005/06/073. URL <https://doi.org/10.1088%2F1126-6708%2F2005%2F06%2F073>.
- [20] Generation and Simulation of R -Hadrons in the ATLAS Experiment. Technical report, CERN, Geneva, 2019. URL <http://cds.cern.ch/record/2676309>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-019>.
- [21] SUSY March 2023 Summary Plot Update. Technical report, CERN, Geneva, 2023. URL <https://cds.cern.ch/record/2852738>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2023-005>.
- [22] Daniele Alves et al. Simplified models for LHC new physics searches. *Journal of Physics G: Nuclear and Particle Physics*, 39(10):105005, sep 2012. doi: 10.1088/0954-3899/39/10/105005. URL <https://doi.org/10.1088%2F0954-3899%2F39%2F10%2F105005>.
- [23] Cristiano Alpigiani et al. Recent progress and next steps for the MATHUSLA LLP detector, 2023. URL <https://arxiv.org/abs/2203.08126>.
- [24] Martin Bauer, Oleg Brandt, Lawrence Lee, and Christian Ohm. Anubis: Proposal to search for long-lived neutral particles in CERN service shafts, 2019. URL <https://arxiv.org/abs/1909.13022>.
- [25] M. Aaboud et al. Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the atlas detector. *Phys.*

- Rev. D*, 97:052012, Mar 2018. doi: 10.1103/PhysRevD.97.052012. URL <https://link.aps.org/doi/10.1103/PhysRevD.97.052012>.
- [26] ATLAS Collaboration. Search for heavy, long-lived, charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the atlas experiment and the full run 2 dataset, 2022. URL <https://arxiv.org/abs/2205.06013>.
- [27] Georges Aad et al. Search for long-lived charginos based on a disappearing-track signature using 136 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Eur. Phys. J. C*, 82(7):606, 2022. doi: 10.1140/epjc/s10052-022-10489-5. URL <https://cds.cern.ch/record/2799061>. Comments: 51 pages in total, author list starting page 35, 9 figures, 8 tables, published in EPJC. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-19/>.
- [28] Georges Aad et al. Search for displaced leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector. *Phys. Rev. Lett.*, 127(5):051802, 2021. doi: 10.1103/PhysRevLett.127.051802. URL <https://cds.cern.ch/record/2744332>. 29 pages in total, author list starting page 14, 2 figures, 1 table, submitted to PRL. All figures including auxiliary figures are available at <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-14>.
- [29] Gian F. Giudice, Matthew McCullough, and Daniele Teresi. dE/dx from boosted long-lived particles. *Journal of High Energy Physics*, 2022(8), aug 2022. doi: 10.1007/jhep08(2022)012. URL <https://doi.org/10.1007%2Fjhep08%282022%29012>.
- [30] Ana Lopes and Melissa Loyse Perrey. FAQ-LHC The guide. 2022. URL <https://cds.cern.ch/record/2809109>.
- [31] Oliver Sim Brüning, Paul Collier, P Lebrun, Stephen Myers, Ranko Ostojic, John Poole, and Paul Proudlock. *LHC Design Report*. CERN Yellow Reports: Monographs. CERN, Geneva, 2004. doi: 10.5170/CERN-2004-003-V-1. URL <https://cds.cern.ch/record/782076>.
- [32] Joao Pequeno. Computer generated image of the whole ATLAS detector. 2008. URL <https://cds.cern.ch/record/1095924>.
- [33] Malte Backhaus. The upgraded Pixel Detector of the ATLAS Experiment for Run2 at the Large Hadron Collider. Technical report, CERN, Geneva, 2016. URL <https://cds.cern.ch/record/2110260>.

- [34] Track Reconstruction Performance of the ATLAS Inner Detector at $\sqrt{s} = 13$ TeV. Technical report, CERN, Geneva, 2015. URL <https://cds.cern.ch/record/2037683>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2015-018>.
- [35] Vertex Reconstruction Performance of the ATLAS Detector at " $\sqrt{s} = 13$ TeV". Technical report, CERN, Geneva, 2015. URL <https://cds.cern.ch/record/2037717>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2015-026>.
- [36] dE/dx measurement in the ATLAS Pixel Detector and its use for particle identification. Technical report, CERN, Geneva, 2011. URL <https://cds.cern.ch/record/1336519>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-016>.
- [37] G. Lindstrom et al. Radiation hard silicon detectors developments by the RD48 (ROSE) Collaboration. *Nucl. Instrum. Meth. A*, 466:308–326, 2001. doi: 10.1016/S0168-9002(01)00560-5.
- [38] G Aad et al. ATLAS pixel detector electronics and sensors. *JINST*, 3:P07007, 2008. doi: 10.1088/1748-0221/3/07/P07007. URL <https://cds.cern.ch/record/1119279>.
- [39] H. Pernegger. The Pixel Detector of the ATLAS experiment for LHC Run-2. *Journal of Instrumentation*, 10:C06012, 2015. doi: 10.1088/1748-0221/10/06/C06012. URL <https://dx.doi.org/10.1088/1748-0221/10/06/C06012>.
- [40] B. Abbott et al. Production and Integration of the ATLAS Insertable B-Layer. *JINST*, 13(05):T05008, 2018. doi: 10.1088/1748-0221/13/05/T05008. URL <https://cds.cern.ch/record/2307576>. 90 pages in total. Author list: ATLAS IBL Collaboration, starting page 2. 69 figures, 20 tables. Published in Journal of Instrumentation. All figures available at: <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2018-001>.
- [41] *ATLAS inner detector: Technical Design Report, 1*. Technical design report. ATLAS. CERN, Geneva, 1997. URL <https://cds.cern.ch/record/331063>.

- [42] G Aad et al. Operation and performance of the ATLAS semiconductor tracker in LHC Run 2. *JINST*, 17:P01013, 2022. doi: 10.1088/1748-0221/17/01/P01013. URL <https://cds.cern.ch/record/2780336>. All figures including auxiliary figures are available at <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SCTD-2019-01>.
- [43] A Abdesselam and T Akimoto. The Barrel Modules of the ATLAS SemiConductor Tracker. Technical report, CERN, Geneva, 2006. URL <https://cds.cern.ch/record/974073>.
- [44] Morad Aaboud et al. Performance of the ATLAS Transition Radiation Tracker in Run 1 of the LHC: tracker properties. Performance of the ATLAS Transition Radiation Tracker in Run 1 of the LHC: tracker properties. *JINST*, 12:P05002, 2017. doi: 10.1088/1748-0221/12/05/P05002. URL <https://cds.cern.ch/record/2253059>. 45 pages in total, author list starting page 29, 23 figures, 0 tables, submitted to JINST, All figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/IDET-2015-01>.
- [45] The ATLAS Collaboration. Trt performance results from 13 tev collision data (2015/2016). <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/TRT-2016-001/>, . Accessed: 2023-02-28.
- [46] E. Hines. Performance of particle identification with the atlas transition radiation tracker, 2011. URL <https://arxiv.org/abs/1109.5925>.
- [47] The ATLAS Collaboration. The atlas experiment at the cern large hadron collider. *Journal of Instrumentation*, 3(08):S08003, aug 2008. doi: 10.1088/1748-0221/3/08/S08003. URL <https://dx.doi.org/10.1088/1748-0221/3/08/S08003>.
- [48] Joao Pequenaio. Computer Generated image of the ATLAS calorimeter. 2008. URL <https://cds.cern.ch/record/1095927>.
- [49] Morad Aaboud et al. Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data. Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data. *Eur. Phys. J. C*, 76(12):666, 2016. doi: 10.1140/epjc/s10052-016-4507-9. URL <https://cds.cern.ch/record/2158117>. 44 pages plus author list (61 pages total), 19 figures, 2 tables, submitted to Eur. Phys. J. C, All figures including auxiliary figures are available at <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2013-04/>.

- [50] *ATLAS tile calorimeter: Technical Design Report*. Technical design report. ATLAS. CERN, Geneva, 1996. doi: 10.17181/CERN.JRBJ.7O28. URL <https://cds.cern.ch/record/331062>.
- [51] Georges Aad et al. Performance of the ATLAS RPC detector and Level-1 muon barrel trigger at $\sqrt{s} = 13$ TeV. Performance of the ATLAS RPC detector and Level-1 muon barrel trigger at $\sqrt{s}=13$ TeV. *JINST*, 16:P07029, 2021. doi: 10.1088/1748-0221/16/07/P07029. URL <https://cds.cern.ch/record/2753039>. 63 pages in total, author list starting page 48, 42 figures, 4 tables, published in JINST. All figures including auxiliary figures are available at <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/MDET-2019-01>.
- [52] *ATLAS muon spectrometer: Technical Design Report*. Technical design report. ATLAS. CERN, Geneva, 1997. URL <https://cds.cern.ch/record/331068>.
- [53] Georges Aad et al. Operation of the ATLAS trigger system in Run 2. *JINST*, 15(10):P10004, 2020. doi: 10.1088/1748-0221/15/10/P10004. URL <https://cds.cern.ch/record/2725146>. 60 pages in total, author list starting page 44, 19 figures, 3 tables, submitted to JINST, All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TRIG-2019-04/>.
- [54] G. Aad et al. Performance of the missing transverse momentum triggers for the ATLAS detector during run-2 data taking. *Journal of High Energy Physics*, 2020(8), aug 2020. doi: 10.1007/jhep08(2020)080. URL <https://doi.org/10.1007%2Fjhep08%282020%29080>.
- [55] T Cornelissen, M Elsing, I Gavrilenko, W Liebig, E Moyse, and A Salzburger. The new ATLAS track reconstruction (NEWT). *J. Phys.: Conf. Ser.*, 119:032014, 2008. doi: 10.1088/1742-6596/119/3/032014. URL <https://cds.cern.ch/record/1176900>.
- [56] Azriel Rosenfeld and John L. Pfaltz. Sequential operations in digital picture processing. *J. ACM*, 13(4):471–494, oct 1966. ISSN 0004-5411. doi: 10.1145/321356.321357. URL <https://doi.org/10.1145/321356.321357>.
- [57] M. Aaboud et al. Performance of the ATLAS Track Reconstruction Algorithms in Dense Environments in LHC run 2. *Eur. Phys. J. C*, 77(10):673, 2017. doi: 10.1140/epjc/s10052-017-5225-7. URL <https://cds.cern.ch/record/2261156>. 44 pages in total, author list starting page 28, 17 figures, 1 table, submitted to EPJC, All figures including auxiliary figures are available at <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2015-08/>.

- [58] R. Frühwirth. Application of kalman filtering to track and vertex fitting. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 262(2):444–450, 1987. ISSN 0168-9002. doi: [https://doi.org/10.1016/0168-9002\(87\)90887-4](https://doi.org/10.1016/0168-9002(87)90887-4). URL <https://www.sciencedirect.com/science/article/pii/0168900287908874>.
- [59] G. Aad et al. Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ tev. *The European Physical Journal C*, 76(5), may 2016. doi: 10.1140/epjc/s10052-016-4120-y. URL <https://doi.org/10.1140%2Fepjc%2Fs10052-016-4120-y>.
- [60] The ATLAS Collaboration. Beamspotpublicresults,run 2 25ns pp collisions, $\sqrt{s} = 13$ tev. <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BeamSpotPublicResults>, . Accessed: 2023-03-09.
- [61] Performance of primary vertex reconstruction in proton-proton collisions at $\sqrt{s} = 7$ TeV in the ATLAS experiment. Technical report, CERN, Geneva, 2010. URL <https://cds.cern.ch/record/1281344>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2010-069>.
- [62] R Frühwirth, Wolfgang Waltenberger, and Pascal Vanlaer. Adaptive Vertex Fitting. Technical report, CERN, Geneva, 2007. URL <https://cds.cern.ch/record/1027031>.
- [63] Georges Aad et al. Muon reconstruction and identification efficiency in ATLAS using the full Run 2 *pp* collision data set at $\sqrt{s} = 13$ TeV. *Eur. Phys. J., C*, 81:578, 2021. doi: 10.1140/epjc/s10052-021-09233-2. URL <https://cds.cern.ch/record/2746302>. 64 pages in total, author list starting page 42, auxiliary material starting at page 59, 34 figures, 3 tables. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/MUON-2018-03/>.
- [64] Georges Aad et al. Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s}=13$ TeV. . *Eur. Phys. J. C*, 76:292, 2016. doi: 10.1140/epjc/s10052-016-4120-y. URL <https://cds.cern.ch/record/2139897>. Comments: 27 pages including cover page plus author list (45 pages total), 12 figures, 3 tables, submitted to Eur. Phys. J. C. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2015-10/>.

- [65] Georges Aad et al. Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1. Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1. *Eur. Phys. J. C*, 77:490, 2017. doi: 10.1140/epjc/s10052-017-5004-5. URL <https://cds.cern.ch/record/2138166>. Comments: 64 pages plus author list + cover page (87 pages in total), 41 figures, 3 tables, submitted to EPJC. All figures including auxiliary figures are available at <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2014-07/>.
- [66] Matteo Cacciari, Gavin P Salam, and Gregory Soyez. The anti- k_t jet clustering algorithm. *Journal of High Energy Physics*, 2008(04):063–063, apr 2008. doi: 10.1088/1126-6708/2008/04/063. URL <https://doi.org/10.1088%2F1126-6708%2F2008%2F04%2F063>.
- [67] Georges Aad et al. Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Eur. Phys. J. C*, 81(8):689, 2021. doi: 10.1140/epjc/s10052-021-09402-3. URL <https://cds.cern.ch/record/2722869>. 73 pages in total, author list starting page 57, 31 figures, 2 tables, submitted to Eur. Phys. J. C. All figures including auxiliary figures are available at <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/JETM-2018-05>.
- [68] The ATLAS Collaboration. Jet energy resolution in 2017 data and simulation. <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/JETM-2018-005/>, . Accessed: 2023-03-14.
- [69] The ATLAS Collaboration. Tagging and suppression of pileup jets with the ATLAS detector. Technical report, CERN, Geneva, 2014. URL <https://cds.cern.ch/record/1700870>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-018>.
- [70] Morad Aaboud et al. Performance of missing transverse momentum reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV. *Eur. Phys. J. C*, 78(11):903, 2018. doi: 10.1140/epjc/s10052-018-6288-9. URL <https://cds.cern.ch/record/2305380>. 66 pages in total, author list starting page 50, 19 figures, 2 tables, published in EPJC, All figures including auxiliary figures are available at <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/PERF-2016-07/>.

- [71] M. Aaboud et al. Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton–proton collision data at $\sqrt{s} = 13$ tev. *The European Physical Journal C*, 79(8), aug 2019. doi: 10.1140/epjc/s10052-019-7140-6. URL <https://doi.org/10.1140%2Fepjc%2Fs10052-019-7140-6>.
- [72] The ATLAS Collaboration. Reconstruction, Identification, and Calibration of hadronically decaying tau leptons with the ATLAS detector for the LHC Run 3 and reprocessed Run 2 data. Technical report, CERN, Geneva, 2022. URL <https://cds.cern.ch/record/2827111>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-044>.
- [73] G. Aad et al. Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton-proton collision data. *Journal of Instrumentation*, 14(12): P12006–P12006, dec 2019. doi: 10.1088/1748-0221/14/12/p12006. URL <https://doi.org/10.1088%2F1748-0221%2F14%2F12%2FP12006>.
- [74] Ann Miao Wang. A search for long-lived particles with large ionization energy loss in the ATLAS silicon pixel detector using 139 fb¹ of $\sqrt{s} = 13$ TeV *pp* collisions, 2021. URL <https://cds.cern.ch/record/2845662>. Presented 2021.
- [75] H. Maccabee. Fluctuations of energy loss by heavy charged particles in matter. Technical report, 1966. URL <https://escholarship.org/uc/item/85n0b989>.
- [76] The ATLAS Collaboration. Search for heavy, long-lived, charged particles with large ionisation energy loss in pp collisions at $s = \sqrt{13}$ tev using the atlas experiment and the full run 2 dataset. <http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-42/>, . Accessed: 2023-03-03.
- [77] Gunnar Lindström. Radiation damage in silicon detectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 512(1):30–43, 2003. ISSN 0168-9002. doi: [https://doi.org/10.1016/S0168-9002\(03\)01874-6](https://doi.org/10.1016/S0168-9002(03)01874-6). URL <https://www.sciencedirect.com/science/article/pii/S0168900203018746>. Proceedings of the 9th European Symposium on Semiconductor Detectors: New Developments on Radiation Detectors.
- [78] Georges Aad et al. Searches for heavy long-lived sleptons and R-Hadrons with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV. *Phys. Lett. B*, 720:277–308, 2013. doi:

- 10.1016/j.physletb.2013.02.015. URL <https://cds.cern.ch/record/1492197>.
Comments: 33 pages plus author list and cover (55 pagestotal), 18 (42) figures, 9 tables,
submitted to Physics Letters B, All figures including auxiliary figures will be available at
<http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2012-01/>.
- [79] M Volpi. Minimum bias physics with ATLAS. Technical report, CERN, Geneva, 2013. URL <https://cds.cern.ch/record/1639610>.
- [80] Tomas Davidek. Performance and calibration of the atlas tile calorimeter. *Instruments*, 6(3), 2022. ISSN 2410-390X. doi: 10.3390/instruments6030025. URL <https://www.mdpi.com/2410-390X/6/3/25>.
- [81] Stefanie Morgenstern. ATLAS LAr Calorimeter Performance in LHC Run-2. Technical report, CERN, Geneva, 2019. URL <https://cds.cern.ch/record/2627619>.
- [82] S Baron, T Mastoridis, J Troska, and P Baudrenghien. Jitter impact on clock distribution in LHC experiments. *JINST*, 7:C12023, 2012. doi: 10.1088/1748-0221/7/12/C12023. URL <https://cds.cern.ch/record/1608681>.
- [83] The ATLAS Collaboration. ATLAS experiment - public results: Approved detector reference figures and schematics. <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedDetectorReferenceFiguresAndSchematics>, . Accessed: 2023-05-09.
- [84] E Fullana, J Castelo, V Castillo, C Cuenca, A Ferrer, E Higón, C Iglesias, A Munar, J Poveda, A Ruiz-Martinez, B Salvachúa, C Solans, R Teuscher, and J Valls. Optimal Filtering in the ATLAS Hadronic Tile Calorimeter. Technical report, CERN, Geneva, 2005. URL <https://cds.cern.ch/record/816152>.
- [85] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *Journal of High Energy Physics*, 2014(7), jul 2014. doi: 10.1007/jhep07(2014)079. URL <https://doi.org/10.1007%2Fjhep07%282014%29079>.
- [86] Torbjörn Sjöstrand, Stefan Ask, Jesper R. Christiansen, Richard Corke, Nishita Desai, Philip Ilten, Stephen Mrenna, Stefan Prestel, Christine O. Rasmussen, and Peter Z. Skands. An

- introduction to pythia 8.2. *Computer Physics Communications*, 191:159–177, 2015. ISSN 0010-4655. doi: <https://doi.org/10.1016/j.cpc.2015.01.024>. URL <https://www.sciencedirect.com/science/article/pii/S0010465515000442>.
- [87] ATLAS Pythia 8 tunes to 7 TeV data. Technical report, CERN, Geneva, 2014. URL <https://cds.cern.ch/record/1966419>. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2014-021>.
- [88] David J. Lange. The evtgen particle decay simulation package. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 462(1):152–155, 2001. ISSN 0168-9002. doi: [https://doi.org/10.1016/S0168-9002\(01\)00089-4](https://doi.org/10.1016/S0168-9002(01)00089-4). URL <https://www.sciencedirect.com/science/article/pii/S0168900201000894>. BEAUTY2000, Proceedings of the 7th Int. Conf. on B-Physics at Hadron Machines.
- [89] S. Agostinelli et al. Geant4—a simulation toolkit. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 506(3):250–303, 2003. ISSN 0168-9002. doi: [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8). URL <https://www.sciencedirect.com/science/article/pii/S0168900203013688>.
- [90] G. Aad et al. The ATLAS simulation infrastructure. *The European Physical Journal C*, 70(3):823–874, sep 2010. doi: [10.1140/epjc/s10052-010-1429-9](https://doi.org/10.1140/epjc/s10052-010-1429-9). URL <https://doi.org/10.1140%2Fepjc%2Fs10052-010-1429-9>.
- [91] The ATLAS Collaboration. Feynman diagrams. <https://feynman.docs.cern.ch/>, . Accessed: 2023-03-21.
- [92] James Catmore, Paul Laycock, Eirik Gramstad, Thomas Gillam, Jack Cranshaw, Nurcan Ozturk, and Graeme Stewart. A New Petabyte-scale Data Derivation Framework for ATLAS. Technical Report 7, CERN, Geneva, 2015. URL <https://cds.cern.ch/record/2016628>.
- [93] Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. Asymptotic formulae for likelihood-based tests of new physics. *The European Physical Journal C*, 71(2), feb 2011. doi: [10.1140/epjc/s10052-011-1554-0](https://doi.org/10.1140/epjc/s10052-011-1554-0). URL <https://doi.org/10.1140%2Fepjc%2Fs10052-011-1554-0>.

- [94] A L Read. Presentation of search results: the CLs technique. *Journal of Physics G: Nuclear and Particle Physics*, 28(10):2693, sep 2002. doi: 10.1088/0954-3899/28/10/313. URL <https://dx.doi.org/10.1088/0954-3899/28/10/313>.



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