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Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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SEARCH FOR LONG-LIVED, WEAKLY INTERACTING PARTICLES THAT DECAY TO DISPLACED HADRONIC JETS IN PROTON-PROTON COLLISIONS AT $\sqrt{s} = 8$ TEV WITH THE ATLAS DETECTOR

A Dissertation Presented

by

PREEMA PAIS

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

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ABSTRACT

SEARCH FOR LONG-LIVED, WEAKLY INTERACTING PARTICLES THAT DECAY TO DISPLACED HADRONIC JETS IN PROTON-PROTON COLLISIONS AT $\sqrt{s} = 8$ TEV WITH THE ATLAS DETECTOR

SEPTEMBER 2016

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Directed by: Professor Benjamin Brau

Many new physics models predict the existence of neutral, weakly interacting, long-lived particles that can decay within the detector volume, producing a distinctive experimental signature. A search is performed for a pair of such particles, using proton-proton collision data at $\sqrt{s} = 8$ TeV collected by the ATLAS detector in 2012, corresponding to a total integrated luminosity of 20.3 fb$^{-1}$. Novel techniques are developed for the reconstruction of displaced decays to hadronic jets in the inner tracking detector and muon spectrometer. No significant deviation is found from the number of background events expected from Standard Model processes. The data are interpreted in terms of Hidden Valley scenarios with a $Z'$ boson mediator.
This dissertation presents the first results for a heavy $Z'$ boson decaying to displaced hadronic jets.
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INTRODUCTION

The Standard Model of particle physics describes the interactions of fundamental particles via the electromagnetic, weak, and strong forces, and has been extensively tested over the last forty years. However, a number of unresolved theoretical and experimental issues remain. Measurements of rotation curves of galaxies indicate that the universe contains a significant amount of matter that is currently invisible to us, possibly because the constituent particles are massive and require large amounts of energy to produce, or because they interact very weakly with visible matter. Further evidence for this dark matter comes from gravitational lensing studies, which estimate galactic cluster masses from distortions in background light due to gravitational fields.

A number of theoretical models have been proposed that include weakly-interacting massive particles. Some of these models predict the existence of particles with long lifetimes. These particles cannot be directly detected, and travel distances ranging between a few millimeters and several meters before decaying to Standard Model particles, making for a distinctive experimental signature.

The Large Hadron Collider (LHC) is a proton-proton collider near Geneva, Switzerland, designed to reach collision energies of $\sqrt{s} = 14$ TeV in order to perform further tests of Standard Model predictions and probe the existence of new physics models that may result in experimental signatures in this energy range. This dissertation details a search for a pair of long-lived particles using data collected by the ATLAS detector, one of two general purpose detectors at the LHC.

This document is structured as follows: Chapter 1 provides a brief overview of the Standard Model and the physics of proton-proton colliders, and then describes
a set of theoretical models that predict long-lived particles. Chapter 2 contains a brief overview of the Large Hadron Collider (LHC), and describes the design and performance of the components of the ATLAS detector. Chapter 3 describes the standard techniques used to identify particles and reconstruct their trajectories from the signals they produce in the detector, focusing on algorithms used to reconstruct the trajectories of charged particles as they traverse through the detector volume. Chapter 4 describes the dataset used in the analysis, and provides a description of the techniques used to simulate theoretical models and the detector signatures they are expected to produce.

In Chapter 5, new techniques to reconstruct the trajectories of long-lived particles decaying in the ATLAS inner detector are discussed, and their performance on simulation and data is studied. Chapter 6 describes a set of custom algorithms used to reconstruct decays in the ATLAS muon spectrometer, and details their performance in simulation and data. Chapter 7 presents an analysis that searches for a pair of such displaced decays, using 20.3 fb$^{-1}$ of $\sqrt{s} = 8$ TeV collision data collected by the ATLAS detector in 2012.

The analysis presented in this dissertation has been published by the ATLAS Collaboration [1], with additional detail provided in an ATLAS internal note [2], from which parts of this thesis are adapted.
CHAPTER 1
THEORETICAL BACKGROUND

This chapter begins with an overview of the Standard Model of particle physics (Section 1.1), and then uses concepts of Quantum Chromodynamics (QCD) to describe the physics of proton-proton collisions (Section 1.2). Section 1.3 discusses some limitations of the Standard Model, and motivates the search for new physics models. Sections 1.4 and 1.5 describe Hidden Valley and Supersymmetry scenarios characterized by final states with long-lived particles.

1.1 The Standard Model

The Standard Model (SM) [3, 4, 5] is a relativistic quantum field theory that describes the known fundamental particles and their interactions via the electromagnetic, weak, and strong forces. The fourth fundamental force, gravity, is not currently included in the Standard Model. Figure 1.1 shows the constituent particles of the SM and their properties; there are twelve fermion (matter) particles and their corresponding anti-fermions, four types of gauge bosons ($W^\pm, Z$, and the gluon), and the recently discovered Higgs boson.

Standard Model fermions are spin 1/2 particles that are subdivided into two types: leptons and quarks. There are three generations of fermions - particle masses increase with each generation, but the electric charge remains the same. Visible matter is predominantly composed of the first generation of fermions (electrons and electron neutrinos, and up and down quarks that form protons and neutrons).
Each generation of leptons consists of a particle with electric charge $-1$ (and the corresponding anti-lepton with charge $+1$), and its neutrino. Neutrinos in the Standard Model are considered to be massless, and are left-handed (their anti-particles have opposite helicity). In ascending order of mass, the three lepton flavors are the electron, muon, and tau; this lepton flavor is conserved during decays. Charged leptons interact via the electroweak force, but the electrical neutral neutrinos can interact only via the weak force.

Quarks are fermions that carry fractional electric charge (either $\pm \frac{2}{3}e$ or $\pm \frac{1}{3}e$). There is a positively (negatively) charged quark in each generation; they are named up (down), charm (strange), and top (bottom) quarks. They interact with each other via the strong force, and therefore also carry a color charge (red, green, or blue) that can be positive or negative. Quarks can also interact with other particles via the electromagnetic or weak interactions.
The gauge bosons are spin-1 particles that mediate the electromagnetic, weak, and strong interactions. The photon ($\gamma$) is a massless particle with no electric charge that mediates the interaction of all electrically charged particles (electromagnetic force). The field theory that describes these interactions is known as Quantum Electrodynamics, and its theoretical predictions have been found to be in excellent agreement (within a few parts per billion) with experimental tests. The electromagnetic interaction has a very long range due to the massless nature of the photon.

The weak force is mediated by three gauge bosons that couple only to left-handed fermions: the $W^\pm$ bosons mediate interactions between charged fermions, while the neutral $Z$ boson can interact with charged and electrically neutral fermions. The relatively high mass of the bosons due to spontaneous electroweak symmetry breaking limits the range of the weak force (hence the name); particles decaying via these mediators can therefore have longer lifetimes than those decaying via the other fundamental forces. A striking characteristic of the weak interaction is that it allows both parity violation and does not conserve the flavor of quarks in the interaction. These properties are seen in the beta-decay of a neutron to a proton, electron and anti-neutrino. This decay can occur because one of the $d$-quarks in the neutron decays to a $u$-quark and a $W^-$, which then decays to an electron and electron anti-neutrino.

The strong force is responsible for binding quarks together to form hadrons, and also keeps protons and neutrons bound together in nuclei. It is described by quantum chromodynamics (QCD), and will be discussed in more detail in Section 1.1.2. The massless, color-charged gluons act as mediators for the strong force.

1.1.1 Electroweak Symmetry Breaking and the Higgs Mechanism

A theory combining the electromagnetic and weak interactions into a single $SU(2)_L \times U(1)_Y$ symmetric gauge invariant theory was developed by Glashow [6], Weinberg [7] and Salam in the 1960’s. However, the lagrangian for the electroweak model includes
only massless gauge bosons. Englert and Brout \[8\], Higgs \[9\], and Guralnik, Hagen and Kibble \[10\] proposed a mechanism in which the weak bosons acquire mass via spontaneous symmetry breaking. It introduces an $SU(2)_L$ doublet of scalar fields, $\Phi$, also known as the Higgs field, resulting in a new classical potential:

$$V(\phi) = -\mu^2 \phi^4 + \lambda (\phi^4)^2$$

(1.1)

This potential, shown in Figure 1.2, has a minimum value at $\sqrt{\frac{\mu^2}{\lambda}}$, known as the vacuum expectation value, which breaks the electroweak symmetry.

The Higgs field can be expanded around its minimum, giving one real scalar field, the Higgs boson, and three complex terms that are the longitudinal components of the gauge bosons. The SM fermions acquire their masses from the Yukawa couplings with the Higgs field. Mixing between the electroweak bosons yields the weak and electromagnetic bosons. The mass hierarchy in the SM is given by the strength of the coupling to the Higgs field.

### 1.1.2 Quantum Chromodynamics

Quantum chromodynamics (QCD) is a non-abelian gauge theory that describes the interactions of quarks and gluons under the strong force. It is described by an
SU(3) ‘color’ symmetry, which imparts a color charge to quarks and gluons (red, green or blue). Quarks have a single color charge, while gluons carry both a color charge and a (different) anti-color charge; gluons can therefore interact with themselves and other gluons. Quarks in nature only exist in color-neutral bound states known as hadrons, such that the net color charge of the hadron is zero; this phenomenon is called color confinement. Hadrons composed of two quarks (q̅q) are known as mesons, while hadrons composed of three quarks (such as the proton and neutron) are called baryons. QCD cross-section calculations can yield infinite values (divergences) due to the massless gluons. A renormalization is applied, which effectively cancels these infinities. One effect of this renormalization is that the strong coupling constant $\alpha_S$ is not constant, but is a function of the square of the momentum transfer $Q$ (i.e. is a ‘running’ coupling constant):

$$\alpha_S(Q^2) = \frac{\alpha_S(\mu_R^2)}{1 + \alpha_S(\mu_R^2)\beta_0 \log(Q^2/\mu_R^2)}$$  

(1.2)

Here, $\mu_R$ is the renormalization scale, and the $\beta_0$ function is negative because of gluon self-interaction. Hence, at low values of $Q^2$ (corresponding to large distances), the coupling constant is very large. Therefore, the energy needed to separate a quark from a nucleon is much higher than the energy needed to produce a $q\bar{q}$ pair, and thus free quarks cannot exist. At very high $Q^2$, $\alpha_S$ is small - this phenomenon is known as asymptotic freedom. Some experimental consequences of confinement and asymptotic freedom will be discussed in the next section.

### 1.2 Proton-Proton Collisions

Results from Deep Inelastic Scattering (DIS) experiments of a lepton off a nucleon show that the quark-parton model description of the proton as a composite of three non-interacting ‘valence’ quarks ($uud$) is not adequate at the high collision energies of the LHC. The nucleon structure can instead be thought of as three valence quarks,
plus a ‘sea’ of (virtual) $q\bar{q}$ pairs from the gluons binding the nucleon together. The parton content of the protons are described by Parton Distribution Functions, or PDFs [11]. These give the probability of one parton carrying a fraction $x$ of the total momentum (in terms of $Q^2$) of the proton. Figure 1.3 shows next-to-leading order MSTW PDFs for two values of $Q^2$. At low momentum, the nucleon structure starts to resemble the quark-parton model description of three non-interacting quarks. At higher $Q^2$ values, it is observed that the number of $q\bar{q}$ pairs increases, with each parton carrying a smaller fraction of momentum $x$.

The Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations [12] model these sea quark interactions with perturbation theory to evolve the parton densities as a function of $Q^2$; the dependence on the PDF on $x$ is extracted from data.

Figure 1.4 is a schematic of a proton-proton collision; in general, this consists of a high-momentum (hard) parton-parton scatter, and multiple processes from the scattering of the remaining partons:
Parton showering and hadronization: Outgoing partons from a hard scatter initially radiate gluons (analogous to the emission of photons in electromagnetic radiation), which then emit quarks and gluons, forming a cascade (parton shower). At this stage, the distance scale is still small enough that this process can be approximated with perturbative QCD calculations. As the partons in the shower move further apart, due to confinement, they bind together to form hadrons. Various simplified models have been developed to describe this non-perturbative process. One example is the color string model, in which the field between partons is characterized as a gluonic string. As the partons move further apart, the ‘string’ stretches, increasing its potential, until it breaks apart via formation of a quark-antiquark pair.

Multiple Particle Interactions: Since protons are composed of three quarks, it is possible for more than one parton-parton scatter to occur in a single proton-proton collision. In general, these multiple scattering events will consist of one hard (high energy) collision, and one or more soft (low energy) collisions.
• **Initial and Final State Radiation:** In a parton-parton hard-scatter, it is possible for either of the incoming partons to radiate a photon or gluon - this is known as *initial state radiation*. Similarly, the outgoing partons in a collision can also emit a photon or gluon, known as *final state radiation*. In most cases, the radiated gluons are low-energy (‘soft’) and collinear, and are included in the structure of one of the hard-scatter jets, but it is possible for emission of high energy gluons to occur, leading to the formation of a separate, high momentum jet at the interaction point.

• **Beam Remnant:** When protons collide at high energy, one parton from each proton undergo a hard scatter. Protons are color-neutral bound states, and so when they lose a parton, they become remnants with a non-zero color charge. Since QCD requires that quarks be bound in color-neutral states, these proton remnants are unstable. Additionally, a color neutral proton that has taken part in a hard scatter (via emission of a gluon, for example) may undergo a recoil from momentum conservation of the collision, and this can cause a quark to be scattered from the proton, resulting in a non color-neutral state. This remaining part of the proton is called the beam remnant, and in both cases, due to the QCD requirement that quarks be bound in color-neutral states, will undergo hadronization.

The additional collision activity outside of the hard scatter (multiple particle interactions, ISR, FSR, and beam remnant) is collectively known as the *underlying event*.

1.3 **Beyond the Standard Model**

The Standard Model has proven very successful at describing the interactions of fundamental particles, and its predictions have been rigorously tested over the
last few decades. However, there are both experimental observations and theoretical arguments that suggest that the Standard Model does not provide a complete explanation of matter in our Universe, but could be a low-energy approximation of a more fundamental theory. Some of these issues are detailed below:

- The Standard Model by construction excludes the gravitational force. At energy scales being probed today, the gravitational force is much weaker than the electroweak or strong forces, and therefore no observed effect would be seen. However, it is hypothesized by theories of quantum gravity that at energy scales around the Planck mass, the Standard Model would not be valid.

- The scales of the weak and gravitational forces are very different - this is known as the hierarchy problem. A manifestation of this problem can be seen in the one-loop corrections to the Higgs mass. These corrections are of the order of the cutoff scale squared ($\Lambda^2$), and would require fine-tuning of the order of $10^{34}$ to keep the Higgs mass stable.

- Studies of the rotation curves of galaxies [14] indicate the presence of a large amount of matter that is not visible to telescopes. The presence of this ‘dark matter’ is also indicated by anomalous effects in the gravitational lensing of light through galaxy clusters, and more recently, by estimations of the total baryonic matter in the universe from anisotropies in the cosmic microwave background (CMB). Many extensions to the Standard Model predict the existence of weakly interacting massive particles (WIMPs) that could be likely candidates for this dark matter.

- Observations of the red-shift of galaxies indicate that the universe is expanding more rapidly than expected assuming that the standard model of cosmology is accurate. The increased expansion can be explained by the existence of a cosmological constant. This cosmological constant is usually equated to the
vacuum energy in quantum field theory. However, the value of the cosmological constant (estimated from galactic red-shift) is many many orders of magnitude smaller than the predicted value of the vacuum energy.

- The Higgs mechanism does not give mass to left-handed neutrinos; neutrinos in the Standard Model are therefore massless. However, neutrino oscillations observed by measuring solar and atmospheric neutrino fluxes [15] explicitly require that neutrinos have non-zero mass. Various solutions have been proposed to solve this, the simplest of which include Majorana neutrinos and heavy sterile right-handed neutrinos. However, additional new physics models with heavy right-handed neutrinos could also include new physics at high energy scales.

- The Standard Model cannot explain the huge asymmetry between baryonic and anti-baryonic matter.

- There has been no experimental observation of $CP$ violation in QCD, even though there is no theoretical motivation for $CP$ conservation in strong interactions.

Many extensions to the Standard Model (SM) have been introduced to solve one (or more) of these open questions. A number of these models predict the existence of weakly-coupled, electrically neutral particles. These include Twin Higgs models [16], gauge mediated symmetry breaking [17, 18], and ‘unparticle models’ [19, 20]. Some of these models include a ‘hidden sector’ that couples to the SM. These hidden sectors may be responsible for dark matter, could introduce new patterns for electroweak symmetry breaking [21], and may also play important roles in astrophysics and cosmology [22]. The remaining sections in this chapter describe two sets of such models used in this analysis: ‘Hidden Valley’ scenarios, and Stealth Supersymmetry.
1.4 Hidden Valley Scenarios

In the Hidden Valley (HV) scenario, a nearly-hidden sector with non-trivial dynamics that contains light particles (the ‘v-sector’) is appended to the Standard Model, with a mediator (or mediators) that has charge under both sectors (Figure 1.5). This mediator can be any neutral particle or combination of particles, including the $Z'$, $Z$, or Higgs bosons, neutrinos, neutralinos, etc. A barrier, such as the high mass of the mediator, weak couplings, or small mixing angles, prevents the production of these v-particles at low energies. At typical energies reached at the LHC, v-particle production may be possible and even copious through decay of the mediator.

In certain classes of models, some v-hadrons may be stable and invisible under the Standard Model, but other v-particles can decay to SM particles. In the set of classes studied here, the hidden sector contains light stable v-hadrons, which are all pseudoscalar and/or scalar mesons with comparable masses. Due to helicity suppress-
sion, these v-hadrons decay mainly to heavy-flavour pairs $b\bar{b}$, $\tau\bar{\tau}$) via the mediator. Due to the barrier, these decaying v-particles have long lifetimes, and this leads to the possibility of decay vertices that are displaced from the interaction point (IP).

In one set of models considered, the $Z'$ acts as a mediator between the two sectors, and decays to many v-hadrons, which then decay predominantly to $b\bar{b}$ pairs and other v-hadrons. This analysis also studies the reconstruction of decay vertices of long-lived particles in a scalar boson-mediated model, where the scalar boson decays to two long-lived v-particles.

1.4.1 $Z'$ Decays via a Hidden Sector

Consider an extension to the Standard Model with a $SU(n)_v \times U'(1)$ gauge group, and mediators $\phi$ and $Z'$. The $U'(1)$ symmetry is spontaneously broken by a scalar expectation value $\langle \phi \rangle$; this results in a massive $Z'$ boson (with a mass of the order of a few TeV). This $Z'$ can be produced from $q\bar{q}$ collisions, and if it has a charge under the v-sector, can decay to v-quarks ($Q$). These v-quarks then emit v-gluons in a process analogous to parton showering. The v-quarks and v-gluons hadronize to form v-hadrons. These v-hadrons can either be stable and invisible within the detector volume, or can decay into Standard Model particles. The decay lifetimes depend on various model parameters. The $Z'$ decay to a hidden valley sector is a particularly interesting case since the high mass-scale of the $Z'$ allows for a high-multiplicity final state. The $Z'$ can decay to multiple v-hadrons which then either decay (promptly or with a long lifetime), or are stable and invisible within the detector volume. This can lead to events with significant variability in multiplicity and kinematics.

To simplify the simulation of v-quark showering and hadronization, we consider a case where the SM extension is given by a $SU(3)_v \times U'(1)$ gauge group. Here, the v-sector is a clone of QCD, with two light flavors, scaled up by a constant factor. The v-hadron spectrum is also just the QCD spectrum scaled by a constant factor with a
Figure 1.6: The $Z'$ decaying to $v$-quarks, which then emit $v$-gluons, and undergo confinement to form $v$-hadrons. Some $v$-hadrons are stable, whereas others decay to SM particles [23]

spectrum of the $v$-hadrons that is identical, up to an overall multiplicative rescaling, to the spectrum of QCD hadrons. In a model with two light flavor $v$-quarks $U$ and $D$, the $v$-hadrons $\pi^0_v$ (neutral $v$-charge) and $\pi^+_v, \pi^-_v$ (charged pions, neutral under the standard model) form a $v$-isospin triplet, and are long-lived. There is also a $v$-nucleon doublet (the $v$-nucleons are stable and invisible). Other heavier $v$-hadrons ($\Delta_v, \rho_v$) decay rapidly into these $v$-pions and $v$-nucleons.

The $\pi^0_v$ has a wavefunction $U\bar{U} - D\bar{D}$, and the breaking of total $v$-isospin allows a decay via the $Z'$ to a pair of fermions ($f\bar{f}$) (the dominant decays being to $b\bar{b}$).

For $m_{\pi_v} \gg m_{Z'}$, the width of the $\pi^0_v$ is

$$\Gamma \sim (3 \times 10^{15} s^{-1}) \left( \frac{f^2 m_{\pi_v}}{(200 \text{ GeV})^3} \right) \left( \frac{10 \text{ TeV}}{m_{Z'}/g'} \right)^4$$  \hspace{1cm} (1.3)

For $m_{\pi_v} \ll m_{Z'}$,

$$\Gamma \sim (6 \times 10^9 s^{-1}) \left( \frac{f^2 m_{\pi_v}}{(20 \text{ GeV})^7} \right) \left( \frac{10 \text{ TeV}}{m_{Z'}/g'} \right)^4$$  \hspace{1cm} (1.4)

This analysis studies a variation of this model, in which the $D$-quark is unstable, and the lifetime of the lightest $D\bar{U}$ $v$-meson ($\pi^+_v$) is a free parameter, although much longer than the $\pi^0_v$ lifetime. The $\pi^\pm_v$ can therefore decay to heavy-flavor $f\bar{f}$ or $f\bar{f}\pi^0_v$. Because of the Yukawa coupling, the $\pi^0_v$ decays predominantly to heavy fermions, $b\bar{b}$,
and $\tau^+\tau^-$ in the ratio 85:5:8. The relatively heavy mass of the $Z'$ leads to a final state with multiple $\pi^0_v$ and $\pi^\pm_v$, and so has multiple prompt and displaced $b\bar{b}$ pairs.

1.4.2 Scalar $\Phi$ Boson as a Communicator

Another class of hidden sector models include a Standard Model scalar boson $\Phi$ that mixes with $\Phi_v$, its hidden sector counterpart. The hidden sector scalar boson $\Phi_v$ can decay to a pair of $v$-quarks. Due to the relatively low mass of the hidden sector scalar, the $v$-quarks then hadronize to two $\pi_v$ particles that can decay back to SM particles. Here, as with the $Z'$ scenario, the $\pi_v$ decays predominantly to heavy fermions, $b\bar{b}$. The branching ratio of this decay mode can be a few percent up to 100% and it is therefore interesting to focus both on the mass window where a new boson consistent with the SM Higgs particle was recently found and to other mass regions, which have been excluded by traditional analyses. A schematic diagram of the decay chain is shown in Figure 1.7.

1.5 Supersymmetry

Another extension to the Standard Model, called Supersymmetry [24], is a symmetry that relates fermions to bosons. Supersymmetry (SUSY) postulates that all SM fermions have a superpartner boson, and vice-versa, with sets of fermions and bosons grouped into supermultiplets. Fermion superpartners are named after their SM boson
counterparts, with a suffix -ino added, while boson superpartners renamed by adding a prefix s- to the SM partner name. SUSY particles (sparticles) are expected to have the same mass and charge as their SM partners; since these sparticles have not yet been observed, their masses must be larger than their respective SM partners, which indicates that supersymmetry is a broken symmetry. Supersymmetry introduces a new quantum number called R-parity, which is defined as:

\[ P_R = (-1)^{(3B−L+2s)} \]  

where \( B \) is baryon number, \( L \) is lepton number, and \( s \) is the particle’s spin. All SM particles have even R-parity (R = 1), while SUSY particles are R-parity odd (R = -1).

If R-parity is conserved, the lightest supersymmetric particle (LSP) will not be allowed to decay to SM particles, and is thus stable. These stable, weakly-interacting LSPs make for attractive dark matter candidates. Supersymmetry also offers a solution to the hierarchy problem by introducing loop effects that cancel out the divergences, and can also enable the unification of the SM coupling constants.

1.5.1 Stealth Supersymmetry

Stealth supersymmetry (Stealth SUSY) models [25, 26] are a subclass of SUSY models that conserve R-parity, but do not have large imbalances in transverse momentum. This can occur in models with low-scale SUSY breaking, with a weakly-interacting hidden sector appended. If SUSY is broken at a low scale, the lightest SM super-partner (LVSP) can decay to a gravitino, which is stable and contributes to missing energy. If a hidden sector of weakly-interacting particles with an approximately supersymmetric spectrum is included in this SUSY scenario, the LVSP can decay into a hidden sector field \( \tilde{S} \). The LVSP then decays to its scalar superpartner \( G \) and a gravitino \( \tilde{G} \). The scalar superpartner can decay into standard model states.
The mass splitting $\delta M$ between $S$ and $\tilde{S}$ is small, due to the low-scale SUSY breaking. Due to the small mass splitting, the gravitino produced is soft, and so the process has very little missing transverse momentum.

The model used in this analysis involves the addition of a hidden (stealth) sector singlet chiral superfield $S$ at the electroweak scale, which has a superpartner singlino $\tilde{S}$. The singlino is long-lived, and decays to its superpartner singlet ($S$) plus a gravitino $\tilde{G}$.

In addition to the singlet, this $SY\bar{Y}$ model adds two additional fields, $Y$ and $\bar{Y}$, that provide couplings to the singlet and singlino at one loop order. The superpotential is given by:

$$W = \frac{m}{2} S^2 + \lambda Y\bar{Y} + m_Y Y\bar{Y}$$

(1.6)

where $m$ and $m_Y$ are the supersymmetric masses. Once the $Y$ and $\bar{Y}$ have been integrated out, the effective decay process is $\tilde{g} \rightarrow \tilde{S}g$ (prompt), $\tilde{S} \rightarrow S\tilde{G}$ (not prompt), and $S \rightarrow gg$ (prompt), as shown in Figure 1.8. This results in one prompt gluon jet and two displaced gluon jets per gluino.

The singlet decays promptly to SM gluon jets. The decay chain is shown in Figure 1.8. Due to the small mass splitting, there is no phase space for the gravitino to carry
significant momentum, and the event has very little missing transverse momentum. High-scale SUSY breaking can also be consistent with small $\delta M$ and Stealth SUSY, though this more complex model is not considered in this search.

The decay width (and, consequently, the lifetime) of the singlino is determined by both the mass splitting $\delta M$ and the SUSY breaking scale $F$ [25]:

$$\Gamma_{\tilde{S} \to \tilde{G}} \sim \frac{m_{\tilde{S}}(\delta M)^4}{\pi F^2}.$$ 

The SUSY breaking scale $F$ is not a fixed parameter - at certain values of $F$, the resulting singlino lifetime is such that it may travel an appreciable distance through the detector, leading to a significantly displaced vertex. Since R-parity is conserved, each event would necessarily produce two long-lived gluinos.
CHAPTER 2

THE ATLAS EXPERIMENT AT THE LHC

This chapter describes the design and performance of the Large Hadron Collider (Section 2.1) and the ATLAS detector (Section 2.2), which collected the data used in this analysis.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [27, 28, 29] is a proton-proton collider housed in a 27 km long tunnel (formerly used by the LEP experiment) located 100 m beneath
the France-Switzerland border, at the European Organization for Nuclear Research (CERN), Switzerland. It is the highest energy and highest luminosity collider to date, designed to collide protons at a center of mass energy \( (\sqrt{s}) \) of 14 TeV. The LHC started producing collisions in 2010, at center-of-mass energies of \( \sqrt{s} = 900 \) GeV and 7 TeV; 7 TeV collisions were continued in 2011. For the 2012 data-taking period, the LHC operated at \( \sqrt{s} = 8 \) TeV. In 2015, the LHC recorded the first-ever collisions at a center-of-mass energy of 13 TeV.

Figure 2.1 illustrates the LHC accelerator system. Hydrogen atoms are passed through an electric field at a duoplasmotron source, which removes their electrons. The resulting protons are then injected into a linear accelerator (LINAC2) where they are accelerated to an energy of 50 MeV. The linear accelerator uses radio-frequency cavities and accelerates the protons in bunches. These proton bunches then enter the Proton Synchrotron Booster (PSB), a system of four superimposed circular rings, where they are accelerated to 1.4 GeV. Next, they are cycled through the Proton Synchrotron (PS), where they reach an energy of 25 GeV. In the final step before injection into the LHC, protons are accelerated up to 450 GeV by the Super Proton Synchrotron (SPS). A set of dipole magnets are used to transfer the bunches between the synchrotron rings.

The LHC is a synchrotron accelerator ring with a double beam pipe structure. A system of over 1200 superconducting twin-bore dipole magnets is responsible for bending the beam along the circular ring. The dipole magnets are maintained at a temperature of 1.8 K for operation, using a superfluid helium cooling system. Radio-frequency (RF) cavities are used to accelerate the beams from 450 GeV to 7 TeV. The system operates at 400 MHz, and provides up to 16 MV at a beam energy of 7 TeV. The cavities are also used to maintain the bunch structure of the beams. The LHC is designed to circulate 2808 proton bunches spaced 25 ns apart, with a longer \textit{abort gap} of 3 \( \mu \)s occurring periodically in order to protect the accelerator system when
beams are transferred in and out of the rings. Additional systems of magnets are used to keep the beam focused and stabilized. Incoming proton bunches are squeezed in the transverse direction to increase the rate of collisions in a single bunch-crossing (in-time pile-up). The number of circulating bunches can also be increased, which leads to an increased probability of collisions from different bunches being recorded in the same event window by the detector (out-of-time pile-up). Figure 2.2 shows the mean number of interactions per bunch crossing for 2012 data.

![Recorded Luminosity](image)

Figure 2.2: The mean number of interactions per bunch crossing for data recorded by the ATLAS detector in 2012.

An important measure of the operation of an accelerator is its instantaneous luminosity, defined as:

\[
\mathcal{L} = \frac{N_b^2 n_b^2 f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F
\]  

(2.1)

where \(N_b\) is the number of particles per bunch, \(n_b\) is the number of bunches per beam, \(f_{\text{rev}}\) is the frequency of revolution, \(\gamma_r\) is the relativistic Lorentz factor, \(\epsilon_n\) is the transverse beam emittance, which is a measure for the spread of particles in the beam, \(\beta^*\) is a measure for the beam width in the transverse direction, and \(F\) is a geometric reduction factor due to the crossing angle at the interaction point. The LHC is designed to operate at an instantaneous luminosity of \(10^{34}\) s\(^{-2}\)cm\(^{-1}\). Figure
2.3 shows the peak luminosity recorded by the ATLAS detector in 2010, 2011, and 2012. The integrated luminosity is calculated as $L = \int \mathcal{L} dt$; the LHC delivered an integrated luminosity of 5 fb$^{-1}$ at $\sqrt{s} = 7$ TeV in 2011, and 23 fb$^{-1}$ at $\sqrt{s} = 8$ TeV in 2012.

Figure 2.3: The peak luminosity as a function of time provided by the LHC in 2010, 2011, and 2012

Figure 2.4 shows the four points along the LHC ring where proton-proton collisions occur, and where the following primary detectors are stationed: ATLAS (A Large Toroidal LHC Apparatus) [30] and CMS (Compact Muon Solenoid) [31] are general purpose detectors designed to perform SM measurements and searches for new physics; LHCb [32] aims to study CP violation and the properties of $B$ mesons; the ALICE (A Large Ion Collision Experiment) detector [33] is designed to study heavy ion collisions.

2.2 The ATLAS Detector

The ATLAS detector is a multipurpose particle detector at the Large Hadron Collider (LHC) at CERN. It is forward-backward symmetric, with a $4\pi$ solid angle coverage, and is designed for a broad range of physics searches and measurements. It consists of a cylindrical barrel centered around the beam pipe, and two endcap wheels situated at each end of the barrel. Figure 2.5 shows a computer-generated image of the
Figure 2.4: An illustration of the layout of the LHC including the four major collision detectors.

ATLAS detector layout and its sub-detector components. It primarily uses tracking sub-detectors to measure the trajectory of charged particles, and calorimeters that are designed for particle energy measurements. Traveling radially outward from the beam pipe, a particle traversing the ATLAS detector would pass through the Inner Detector (Section 2.2.1), the Calorimeter system (Section 2.2.2), and the Muon Spectrometer (Section 2.2.3); these will be described in detail in this section.

ATLAS utilizes a right-handed coordinate system, with the \( x \)-axis pointing towards the centre of the LHC ring, the \( y \)-axis perpendicular to the plane of the LHC tunnel (with the positive \( y \)-direction pointing upwards), and the \( z \)-axis in the direc-
tion of the beam. Cylindrical coordinates are commonly used due to the detector geometry. The azimuthal angle $\phi$ is measured in the $x$-$y$ plane and increases in the clockwise direction when looking in the positive $z$-direction, with $\phi = 0$ set at the $x$-axis. The polar angle $\theta$ is measured from the positive $z$-axis, and is related to the pseudo-rapidity $\eta$ using the relation $\eta = -\ln \tan(\theta/2)$. Transverse components of particle measurements (such as $p_T$, the transverse momentum) are defined to be in a direction perpendicular to the beam axis.

2.2.1 The Inner Detector

The Inner Detector (ID) consists of a cylindrical barrel (Figure 2.6) and two end-cap wheels (Figure 2.7), designed to measure the trajectories of charged particles within $\eta = 2.5$. It comprises a pixel tracker, a SemiConductor Tracker (SCT), and a Transition Radiation Tracker (TRT), immersed in a 2 T axial magnetic field from
a central solenoid. It is designed for precision tracking and primary interaction vertex measurements, and therefore achieves a high momentum resolution ($\Delta p_T/p_T \sim 0.04\%$) and spatial resolution (15 $\mu$m transverse impact parameter resolution).

The pixel tracker consists of three concentric cylindrical layers in the barrel region, and three disks in each endcap. It is the closest detector to the beam pipe; and is designed to provide the best possible resolution for reconstruction of the primary interaction point and precise measurements of the outgoing particle momenta. Due to the close distance to the beam pipe, particles emanating from the primary interaction (the hard-scatter collision) are not yet well-separated spatially, and a high granularity is needed to precisely measure particle trajectories. Each layer is comprised of sensor modules made from silicon pixels; the minimum pixel size is $50 \times 400 \ \mu$m$^2$, and there are approximately 80.4 million readout channels in total. Charged particles passing

Figure 2.6: An illustration of the ATLAS inner detector barrel being crossed by a high-energy particle (trajectory shown as a red line).
through these charge-depleted silicon sensors create electron-hole pairs, which are separated by an applied electric field. The electron charge is then collected on the silicon surface. These signals can also be produced by electronic noise, and so a minimum ‘time-over-threshold’ is implemented. Multiple neighboring pixels can have a signal that surpasses the threshold; the signals from these pixels are clustered to form a single ‘hit’. The pixel modules have a resolution of 10 \( \mu \text{m} \) in \( r - \phi \) and 115 \( \mu \text{m} \) in \( z \) in the barrel, and 10 \( \mu \text{m} \) in \( r - \phi \) and 115 \( \mu \text{m} \) in \( z \) in the endcaps.

Figure 2.7: An illustration of the ATLAS inner detector endcap being crossed by two high-energy particles (trajectories shown as a red line).

The SCT consists of four cylindrical layers in the barrel and nine disk layers in each of the endcaps. SCT modules consist of double-sided silicon strip detectors that are crossed by each track, and are used to complement information from the pixel detector by providing precise momentum measurements. Each strip is 80 \( \mu \text{m} \) wide and 12 cm long; strips are positioned parallel to the beam direction in the barrel, and are arranged radially around the beam line in the endcaps. Charge deposition in the SCT modules occurs via the same way as in the pixel modules. However, the strips can only measure an \( r \)-coordinate (or \( z \)-coordinate) - pairs of strip detectors are bonded together back-to-back, displaced by a small (40 mrad) stereo angle, in
order to provide a single three-dimensional measurement. The resolution of barrel
SCT measurements is 17 µm in the r-ϕ plane and 580 µm in the z-direction; endcap
measurements have a resolution of 17 µm in the r − ϕ plane and 580 µm in the
r-direction in the endcaps.

The TRT consists of 4 mm diameter straw tubes filled with a Xe-based gas mix-
ture, and with a central wire held at a high voltage. The tubes, measuring 144 cm
in length, are arranged in up to 73 concentric layers parallel to the beam pipe in the
barrel and radially in the endcaps. Charged particles passing through the straw tubes
interact with the gas mixture and create ionization electrons that drift toward the
central wire. This drift time is measured and converted to a drift radius measurement
with a resolution of 170 µm. Since the ionization electrons do not provide informa-
tion about where along the tube length the ionization occurred, the TRT provides
two-dimensional measurements (r − ϕ in the barrel and z − ϕ in the endcaps). How-
ever, the large number of close hits are used to aid pattern recognition for particle
trajectory reconstruction. The TRT is also used to aid in electron identification via
the detection of transition radiation photons in the gas mixture of the straw tubes.

2.2.2 Calorimeters

The ATLAS calorimeter system, shown in Figure 2.8, consists of a electromagnetic
calorimeter designed to produce electromagnetic particle showers (electrons and pho-
tons) and hadronic calorimeters that produce showers of hadronic particles (primarily
charged and neutral pions). Both calorimeters are sampling calorimeters, constructed
using alternating layers of absorbers that stop particles and initiate showers, and ac-
tive material that detects the showers. The calorimeter system covers up to |η| < 4.9,
and is hermetic in ϕ.

The Electromagnetic (EM) Calorimeter uses liquid argon (LAr) active material
and lead plate absorbers. The barrel extends to a range of |η| < 1.475; the endcaps
are comprised to two wheels that together have coverage in the range $1.375 < |\eta| < 3.2$. The crack region between $1.375 < |\eta| < 1.52$ consists of additional material for instrumentation and cooling of the inner detector. The calorimeter constituents are arranged in an accordion geometry, as shown in Figure 2.9, to ensure full coverage in the $\phi$-direction. Electromagnetic particles passing through the calorimeter will interact with the lead absorber and produce an initial shower of particles. The liquid argon is kept at a high voltage, and so the showers initiate ionization, and the resulting charge is collected.

The EM calorimeter barrel consists of three layers - the first layer is highly segmented in $\eta$ (with a granularity of $0.003 \times 0.098$ in $\Delta\eta \times \Delta\phi$) and is used to provide a measurement of the shower position. The second layer is less granular ($0.025 \times 0.025$ in $\Delta\eta \times \Delta\phi$), but has the highest amount of material and collects the majority of the energy deposited by the shower. The third layer is segmented with a granularity of $0.05 \times 0.025$ in $\Delta\eta \times \Delta\phi$, and is used to collect the tails of the shower. The first wheel
Figure 2.9: A schematic of the ATLAS electromagnetic calorimeter, illustrating the accordion geometry of the lead layers.

of the LAr endcaps also has fine granularity in $\eta$; the second wheel is more coarsely granulated. A pre-sampler consisting of a thin active layer of LAr is placed before the first barrel layer (for $|\eta| < 1.8$), in order to correct for energy losses occurring from particle interactions with material before reaching the EM calorimeter.

The barrel hadronic calorimeter utilizes plastic scintillator tiles as active material, alternated with steel absorber tiles. It consists of a central barrel ($|\eta| < 0.8$) and two extended barrels ($0.8 < |\eta| < 1.7$). The tiles are oriented radially around the beam pipe and grouped into modules, which then form projective towers in $\eta$. Particles interact with the plastic to produce scintillator light, which is collected via optical fibers and fed into photomultiplier tubes in each tower. The first two calorimeter layers have a granularity of $0.1 \times 0.1$ in $\Delta \eta \times \Delta \phi$. The third layer has a granularity of $0.2 \times 0.2$ in $\Delta \eta \times \Delta \phi$. 


The endcap hadronic calorimeters use LAr as active material and copper plates as absorbers; they are designed to operate in the increased radiation environment of the forward region. There are two wheels in each endcap, each with two sampling layers. The forward calorimeter provides coverage up to the pseudo-rapidity range $|\eta| < 4.9$, and is made of copper/tungsten plates, with LAr as the active material.

### 2.2.3 The Muon Spectrometer

![Muon Spectrometer Diagram](image_url)

Figure 2.10: A schematic of the muon spectrometer with barrel MDT chambers shown in green, and endcap MDT chambers shown in blue. The RPCs are stationed around the middle and outer barrel layers, and the TGC chambers are located in the endcaps (pink). The CSCs (yellow) are located in the high eta region of the first endcap layer.

The Muon Spectrometer (MS) is the outermost part of the ATLAS detector, and is comprised of multiple sub-detectors with tracking and trigger chambers for identification of muons and measurements of their momentum and charge. A system of three large air-core toroids (one in the barrel, two in the endcaps) provides the magnetic field for the MS. The spectrometer consists of a barrel and two endcaps;
chambers in the barrel are arranged in three concentric layers at radii of $r = 5$ m, 7.5 m, and 10 m. Endcap chambers are arranged in three wheels perpendicular to the beam line at $|z| = 7.4$ m, 14 m, and 21.5 m, as shown in Figure 2.10. The trigger system consists of Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs), and enables trigger capabilities up to $|\eta| = 2.7$. Muon Drift Chambers (MDTs) and Cathode Strip Chambers (CSC’s) are used for precision tracking, and provide momentum measurements for particles within $|\eta| < 2.4$.

![Figure 2.11: An cross-sectional view of the muon spectrometer barrel, with MDT chambers in green ...](image)

The Muon Drift Tube (MDT) system includes chambers composed of drift tubes with a 30 mm diameter. The tubes are filled with an Ar/CO$_2$ gas mixture and contain a central wire kept at a voltage of 3080 V. Charged particles passing through the MDTs ionize the gas mixture, and the ionization electrons drift towards the
central wire. The drift radius resolution for the MDTs is approximately 80 μm. As with the TRT in the inner detector, measurements in the MDT are two-dimensional, with low precision due to the long length of the tubes. Each chamber consists of two multilayers, each of which contains 3-4 rows of drift tubes. The multilayers are separated by a distance ranging between 6.5 mm and 317 mm. MDT chambers in the barrel are located around the eight toroid magnet coils, as seen in Figure 2.11. In the endcaps, MDT chambers are placed either before or after the endcap toroid, and thus are located outside of the magnetic field.

The Cathode Strip Chambers (CSCs) are multiwire proportional chambers with cathode strip readouts, located in the high |η| region (> 2.0) in the endcaps; they are designed to be able to operate in detector regions with high readout. A central wire is kept at a relative potential of 1900 V. One cathode has strips placed orthogonal to the anode, and provides a measurement in η. The second cathode has strips oriented parallel to the anode wire to provide measurements in φ. The position of a charged particle hit is obtained by interpolation between the charges on adjacent strips, and has a resolution of 60 μm.

The Resistive Plate Chambers (RPCs) provide trigger capabilities and a measurement of the φ position for muons passing through the barrel. RPCs consist of two parallel resistive plates separated by a 2 mm gas gap filled with C₂H₂F₄. Charged particles passing through an RPC ionize the gas, and the initial ionization electrons are multiplied into an avalanche by a 4-5 kV/mm electric field. Orthogonal metal strips located outside each chamber read out the signal in (η, φ).

The Thin Gap Chambers (TGCs) provide trigger capability and φ measurements for muons passing through the endcaps. The TGCs are a type of multi-wire proportional chamber filled with a gas mixture of 55% CO₂ and 45% n-pentane. Readout strips perpendicular to the wires are located outside the chambers, and together with
the chamber wires provide a two-dimensional measurement. The TGCs have a spatial resolution that allows for improved separation between hits from muons and photon and neutron background, which is much higher in the end caps (as compared to the barrel).

### 2.2.4 The Magnet System

The ATLAS magnet system consists of a central solenoid and three outer toroids. Charged particles passing through these magnetic fields have a helical trajectory, which can be used to measure their momenta, and determine the sign of their charge.

The solenoid magnet surrounds the inner detector, and is 2.5 m in diameter and 5.3 m in length. It produces a 2 T magnetic field that bends the trajectories of particle traversing the inner detector in the $r$-$\phi$ plane. The magnetic field is inhomogenous in the forward (high $\eta$) regions.

The magnetic field for the muon spectrometer is provided by a system of three toroids which causes bending primarily in the $r$-$z$ plane. The barrel system consists of eight superconducting coils extending radially from 4.7 m to 10.0 m, and measuring 25.0 m in length along the $z$-axis. It produces a $\sim$0.5 T magnetic field. The two endcap toroids, each with eight superconducting coils, are placed at each end of the barrel and generate a field of $\sim$1 T. They have a length of 5.0 m, an inner bore of 1.65 m, and an outer diameter of 10.7 m.

### 2.2.5 Luminosity Detectors

**LUCID** (Luminosity measurement using Cerenkov Integrating Detector) is the primary detector for luminosity measurements. It consists of two stations (one in each endcap region) situated at $z = \pm 17$ m, each with twenty aluminum tubes oriented radially around the beam line. Each tube is 1.5 m long and has a diameter of 15 mm, and is filled with $C_4F_{10}$. Charged particles passing through the gas emit Cerenkov radiation, which is then collected by photomultiplier tubes (PMTs). The amount
of radiation produced is proportional to the number of charged particles, and so the
detector is capable of providing a flux measurement and the instantaneous luminosity.

2.2.6 Trigger and Data Acquisition (TDAQ) System

At the LHC, proton bunches cross (collide) at a rate of 40 MHz, with each bunch
crossing producing on average 20 inelastic proton-proton collisions in 2012, corre-
sponding to a collision rate of 400 MHz. It is not feasible to process and record all
these collision events given current computing technology. The ATLAS trigger sys-
tem is designed to reduce the event rate to a reasonable level by selecting only events
of interest to physics analyses. Events are processed in three stages: Level 1, Level
2, and Event Filter (EF). Each stage uses information from a larger percentage of
detector to successively reduce the event rate. On average, only one out of \(~200,000
events are processed and stored for analysis.

The Level 1 trigger [34] is a hardware-based trigger that has 2 \(\mu s\) to make a
decision during data-taking. Taking into account the time delays due to signal trans-
mission through the system, the actual trigger decision has to be made in \(~0.5 \mu s\).
The decision is made using coarse-granularity information from the RPCs and TGCs
in the muon system, and the electromagnetic and hadronic calorimeters. Trigger ob-
jects at Level 1 include electromagnetic clusters, jets, hadronic tau decays, missing
transverse momentum, total scalar energy, and muons. The calorimeter trigger system
(L1Calo) searches for high-\(p_T\) objects in ‘trigger towers’ (cells in a \(\Delta \eta \times \Delta \phi = 0.1 \times 0.1\)
region). The Level 1 muon (L1Muon) trigger system searches for coincident hits in
two RPC (barrel) or TGC (endcaps) respectively in a \(\Delta \eta \times \Delta \phi = 0.2 \times 0.2\) ‘road’.
The approximate curvature of the muon object trajectory is computed from these
coincident hits to obtain a \(p_T\) measurement. The output from the Level 1 trigger
sub-systems is sent to the Central Trigger Processor (CTP); if the event passes any
Level 1 trigger criteria, an accept signal is sent to all sub-detectors. The L1 trigger system reduces the event rate to a maximum of $\sim 75$ KHz.

The Level 2 trigger is a software-based trigger that makes a decision on whether to accept an event based on full detector readout in ‘Regions of Interest’ (RoI). These RoI are detector regions in $\eta$ and $\phi$ associated to high $p_T$ objects that triggered a positive Level 1 decision. Detector readout from all sub-systems in the RoI are used to make a Level 2 decision, and so a version of the inner detector track reconstruction algorithms is run at this stage. Calibration is applied to trigger objects - this includes basic $b$-jet identification, separation of electrons from photons using track-matching, and refinements to $E_T^{\text{miss}}$. The event rate is reduced to $\sim 3.5$ KHz at this stage.

The Event Filter (EF) is the final stage of the trigger system; it runs offline reconstruction algorithms on the full detector readout data. It takes a few seconds to
run and reduces the event rate to 200 - 400 Hz. The Level 2 and EF systems together comprise the High-Level Trigger (HLT) [35].
CHAPTER 3
OBJECT RECONSTRUCTION

A particle traversing various sub-systems of the ATLAS detector can interact with detector material and create raw signals, which are then converted to a set of measurements of the particle’s properties. Charged particles interact with detector layers in the inner detector and muon spectrometer, from which the particle trajectory (a ‘track’) can be reconstructed. Electromagnetic and hadronic particles will also interact with material in calorimeter cells to produce particle cascades (‘showers’). Particles in these showers can interact with active calorimeter layers, leading to energy deposits in calorimeter cells.

Figure 3.1 shows a wedge-shaped cross section of the ATLAS detector, and illustrates the experimental signatures produces by particles passing through detector material, the reconstruction of which will be discussed in this chapter. Particles emerge from the initial proton-proton collision (interaction point, or IP), and then traverse through various sub-detectors. All charged particles produce tracks (Section 3.1) in the inner detector. Muons (Section 3.4) typically traverse through the entirety of the detector, and so produce tracks in the muon spectrometer as well. Electrons and photons (Section 3.2) both deposit almost all of their energy in the electromagnetic calorimeter. Electrons also produce an inner detector track, whereas electrically neutral photons do not. Jets (Section 3.3) deposit their energy in the electromagnetic and hadronic calorimeters. Tau-leptons (Section 3.5) primarily decay hadronically, and so produce set of tracks in the inner detector, as well as energy deposits in the calorimeter. Certain particles such as neutrinos do not interact with detector mate-
rial, but their presence can be inferred from an overall momentum imbalance in the event, known as missing transverse energy ($E_{\text{miss}}$, Section 3.6).

The experimental signatures studied in this analysis are characterized by the presence of a large number of tracks, jets, and in some cases, significant $E_{\text{miss}}$. Reconstructed photons, electrons, tau leptons and muons are not explicitly required or studied in these events, but do contribute to the calculation of the overall momentum imbalance.

Figure 3.1: A schematic illustrating the experimental signature of various particles produced at the primary interaction point (at the bottom of the diagram), which then traverse through the ATLAS detector volume.
3.1 Track and Primary Vertex Reconstruction

Charged particles leave detector signals, or ‘hits’, as they pass through layers of the inner detector. Since the inner detector is immersed in a magnetic field, these hits can be used to obtain the parameters of the helical trajectory of the particle. Pattern recognition algorithms make use of high precision measurements obtained using the silicon detectors and the high number of close-by hits in the TRT to reconstruct tracks in the full acceptance range ($|\eta| < 2.5$) of the inner tracker. These tracks are then used to find the primary interaction point. Track and vertex reconstruction in ATLAS [36, 37] consists of three main parts: a pre-processing to convert raw pixel and SCT data into three-dimensional co-ordinates and TRT timing data into calibrated drift circles; the main track-finding stage; and a post-processing to find primary vertices, and subsequently vertices from photon conversions and secondary interactions.

3.1.1 Space Point Formation

Hit information from the silicon detectors is converted to three-dimensional co-ordinates known as ‘space points’, in order to be used for track finding. Each hit in the pixel detector provides a two-dimensional local measurement on the module surface, and this measurement in combination with the module position provides a space point. For SCT modules, a precise measurement is given only in a direction orthogonal to the strip, and so a single SCT hit provides only two spatial co-ordinates. However, since the SCT structure consists of back-to-back modules separated by a stereo angle, a combination of measurements from the two modules is used to construct the space point. A charged particle produced at the primary interaction point will typically cross three pixel and eight SCT layers (four double-layers), and will typically have seven silicon space points on a track.

A charged particle passing through a TRT drift tube will create ionization electrons. The time taken for the electrons to drift to the wire anode at the center of the
tube is measured, and this measurement is then converted to a drift radius. Since the drift time does not tell us where along the tube length the hit occurred, a TRT hit will only provide a two-dimensional measurement. Straw tubes in the barrel are arranged parallel to the beam line, and measurements are given in the $r - \phi$ plane. In the endcap wheels, the straw tubes are arranged radially, and so measurements are given in the $z - \phi$ plane.

### 3.1.2 Track Finding

The primary track finding procedure is known as ‘inside-out’ tracking, and is designed to reconstruct tracks originating from the IP. It starts with a track seed formed from silicon space points, which is then extrapolated outwards into the TRT to form a track candidate. A subsequent complementary tracking step uses TRT hits to form track segments, which are then back-extrapolated to pick up silicon hits. This method is particularly useful for the reconstruction of tracks produced by particles from secondary interactions.

Reconstructed tracks in ATLAS are parametrized at the point of closest approach to the nominal beam pipe ($z$-axis), using five perigee parameters, illustrated in Figure 3.2:

- $q/p$, the magnitude of the charge of the particle divided by its’ momentum.

- $\phi_0$, the azimuth angle, calculated with respect to the $x$-axis in the $x - y$ plane at the point of closest approach, and measured in the range $\phi_0 \in [-\pi, \pi]$.

- $\theta_0$, the polar angle, calculated with respect to the $z$-axis in the $r - z$ plane, and measured in the range $\theta_0 \in [0, \pi]$.

- $d_0$, the transverse impact parameter, defined as the signed distance to the beam pipe at the point of closest approach. $d_0$ is positive if $\phi - \phi_0 = \frac{\pi}{2} + 2n\pi, \; n \in \mathbb{Z}$, where $\phi$ is the azimuthal angle to the perigee position.
• \( z_0 \), the longitudinal impact parameter, defined as the \( z \)-coordinate of the track at the point of closest approach

Initial track parameters may be estimated at the early pattern recognition stage, but the final estimates of the track parameters are performed by the track fitting algorithms. At later stages of reconstruction (vertex finding, for example), track parameters can be re-calculated with respect to primary or secondary vertices, or with respect to scattering surfaces.

![Figure 3.2: Illustration of the track perigee parameters in the \( x - y \) and \( r - z \) planes.](image)

3.1.2.1 Inside-out Track Reconstruction

Initial track seeds are created from sets of three silicon space points; each space point must originate from a unique silicon detector layer. ATLAS silicon pattern recognition [38] can create seeds using one of three combinations: three pixel space points, two pixel and one SCT space points, or three SCT space points\(^1\). Since the primary purpose of the standard track finding procedure is to reconstruct tracks

\(^1\)A fourth possible combination, one pixel and two SCT space points, is not implemented in ATLAS track finding.
originating from the IP, only seeds created using the three pixel and first SCT layers are used. Additionally, minimum requirements on the momentum and transverse impact parameter are implemented to pre-select seeds. These requirements are listed in Table 3.1. At this stage, these parameters are estimated assuming a perfect helical track model in a constant magnetic field. If the track produced by the three seeds is projected onto the transverse plane, it forms a circular trajectory described by the transverse impact parameter $d_0$, the azimuthal angle $\phi$, and the transverse momentum $p$, shown in Figure 3.3. In the presence of a magnetic field with strength $B$, the radius of the trajectory is given by:

$$\rho[mm] = \frac{p_T[GeV]}{3 \cdot 10^{-4} \times q[e] \times B[T]}$$ \hspace{1cm} (3.1)

The transverse impact parameter is calculated at the point where the circular trajectory intersects the line between the center of the circle $(c_x, c_y)$ and the center of the reference frame:

$$d_0[mm] = \sqrt{x_0^2 + y_0^2} - \rho$$ \hspace{1cm} (3.2)

The clusters used to form these seeds are input into a Kalman filtering algorithm [39], which follows an iterative process to obtain. First, a set of detector elements are found along the trajectory of the initial seed (road-building), for which measurements to be associated to the track can be searched for. Then, starting with the parameters of the initial seed, the algorithm extrapolates the track to calculate the track parameters and covariance matrix at the next measurement surface. The predicted value and nearest actual hit are both used to update the track parameters at the measurement surface, and this hit is added to the track candidate. This procedure is performed iteratively at every measurement surface, and allows for good recognition of outlier
measurements based on their large contribution to the fit $\chi^2$. Only a fraction of small fractions of silicon track seeds lead to a final track candidate.

Since the initial seeding process leads to a large number of track candidates, some of which may be constructed from hits from multiple particles (‘fake’ tracks), may have few associated hits (incomplete tracks), or may have a large number of hits shared with other track candidates. To reject these fake or poorly reconstructed tracks, the silicon track-candidates go through an ambiguity solving procedure. The tracks are first refit using a detailed detector material description. Track candidates are then assigned a score to preferentially select tracks with a high number of total hits contributing to the parameter estimation, with precision hits from the pixel sub-detector weighted more highly than less-precise information. Hits shared between two
tracks are usually reassigned to the track with a higher score \(^2\), and the other track is then refitted and given a new score. Tracks with ‘holes’ (missing measurements on a detector element traversed by the track) are also assigned a penalty. Candidates with fewer than seven silicon hits, or with a final score below a certain value are not processed further. The remaining tracks are extended into the TRT using a road finding approach. The full set of selection criteria implemented at various stages of silicon-seeded track finding is listed in Table 3.1.

3.1.2.2 Outside-in Track Reconstruction

Tracks from secondary vertices which occur after the first few material layers of the inner detector (such as \(K^0_S\) decays, or photons which produce \(e^+e^-\) pairs) may not have enough silicon hits to produce a space point seed. Additionally, tracks may be overshadowed by hits from additional collisions in the events (pile-up) have a may not survive the strict requirements at the ambiguity-solving stage. A second stage of track-finding, known as ‘outside-in’ tracking, is used to reconstruct these tracks from hits not used in the inside-out tracking step. This approach starts with the construction of a TRT segment. Assuming tracks with transverse momentum greater than 500 GeV originating near the primary interaction region, an initial straight line pattern finder known as the Hough Transform [40] is used. This algorithm transforms hits from the \(r - \phi\) plane into the parameter space of the straight line (Hough Space) to look for a local maximum. This is done for several slices of the TRT detector, to minimize the number of overlaying segments. The line patterns found are converted to track segments using a Kalman fitter-smoother formalism, and extrapolated back into the silicon region to pick up unused SpacePoint objects, using the Kalman filtering process. The set of selection criteria during segment finding and track extrapolation

\(^2\)Tracks that fulfill all other selection criteria are allowed to have one shared hit

45
Table 3.1: Selection criteria used for track reconstruction.

are listed in Table 3.1 - since these tracks can originate at a distance from the IP, they are allowed to have larger values of \( d_0 \), and fewer silicon hits.

### 3.1.3 Primary Vertex Reconstruction

The set of reconstructed tracks are used to reconstruct primary vertices, points near the IP from which multiple tracks emerge. A subset of the Inner Detector tracks are first selected as input to the vertex algorithms, using the following criteria:

- \( p_T > 150 \text{ MeV} \)
- \( |d_0| < 4 \text{ mm} \)
- \( \sigma(d_0) < 5 \text{ mm} \)
- \( \sigma(z_0) < 10 \text{ mm} \)
- at least one pixel hit
- at least 4 SCT hits
- at least 6 pixel and SCT hits
The track parameters $d_0$ and $z_0$ are re-calculated with respect to the reconstructed beam spot [41]. The impact parameter significances $\sigma(d_0)$ and $\sigma(z_0)$ represent the uncertainties estimated by the track fit.

Primary vertices are then constructed from these pre-selected tracks using an iterative vertex finding method. Selected tracks are input into a vertex seed finder, which looks for a global maximum in the $z$-coordinate to create an initial seed, calculated at the point of closest approach to the beam spot. An adaptive vertex fitter uses the seed and nearby tracks to compute a vertex position. This algorithm is a robust $\chi^2$-based fitter which weights track measurements based on the contribution to the overall vertex $\chi^2$ (and therefore progressively down-weights outlying track measurements). The compatibility of a given track with the vertex is expressed as a $\chi^2$ with two degrees of freedom. Tracks more than $7\sigma$ away from a vertex are used to seed a new vertex, and the above procedure repeats until no additional vertices are found. This corresponds to a rather loose selection of $\chi^2 > 49$, intended to minimize the splitting of vertices due to outlying track measurements. The beam spot parameters are also used to constrain the vertex fit, which serves to remove far outliers in the longitudinal directions, and thus differentiates the signal vertex from tracks from pileup. The vertex with the highest average track $p_T$ is considered the signal primary vertex, while other reconstructed vertices are associated with pileup.

### 3.2 Electron and Photon Reconstruction

Electrons and photons traversing the electromagnetic calorimeter produce cascades of particles by interacting with the detector material. Showers produced by electrons will also be associated to a track in the inner detector, while showers produced by photons in the calorimeter are narrower and isolated from track activity. Photons produced at the IP can also decay to an $e^+e^-$ pair before entering the
calorimeter, in which case the energy clusters produced can be associated to tracks from a conversion vertex.

### 3.2.1 Electron Reconstruction

Electron reconstruction [42] is seeded by clusters with transverse energy $> 2.5$ GeV in a $3 \times 5$ window in $\eta \times \phi$ in the electromagnetic calorimeter. This seed cluster region of interest must then be matched to an ID track. If there are no tracks found using standard pattern recognition (Section 3.1.2), a modified pattern recognition algorithm is used for any track seed with a $p_T > 1$ GeV which is within the cluster region of interest. This algorithm is also based on the Kalman filter-smoother technique, but additionally accounts for possible bremsstrahlung effects by allowing a maximum of 30% energy loss at each material surface traversed by the track. Matched tracks are then refit with an optimized electron track fitter, for a better estimate of electron track parameters.

The energy clusters for these electron-candidates are then remade using a $3 \times 7$ ($5 \times 5$) window in $\eta \times \phi$ in the barrel (endcap). Selection criteria are implemented on final electron-candidate objects in order to reject background from hadronic jets and photon conversions. Since the majority of energy from an electron should be deposited in a relatively narrow volume in the electromagnetic calorimeter, requirements are made on the maximum amount of energy found in the first layer of the hadronic calorimeter (‘hadronic leakage’), and the shower width in the strip and middle layers of the calorimeter. Additionally, the electron track is required to have a minimum number of pixel hits and small transverse parameter to ensure that the track originated at the primary interaction point.

### 3.2.2 Photon Identification

Photon reconstruction and identification [43] is seeded in the same way as electron reconstruction, using energy clusters in towers of $3 \times 5$ cells in the second layer of the
electromagnetic calorimeter. These seeds are then matched to reconstructed inner
detector tracks. If a cluster has no associated tracks with $p_T > 1$ GeV within a
$\Delta R$ cone of 0.3 from the cluster barycenter $^3$, it is considered an unconverted photon
candidate. As showers from photons traversing the calorimeter should have a narrower
width than those from electrons, the final clusters for unconverted photon candidates
are remade in a $3 \times 5$ window $\eta \times \phi$ in the barrel. In the endcaps, a $5 \times 5$ window is
used.

Seed clusters with associated tracks are initially considered electron candidates. A
modified vertex-finding algorithm is run as part of post-processing after track recon-
struction, which takes into account the massless nature of photon-conversion vertices
[44]. If the matched electron-candidate track is associated with a conversion vertex,
the object is considered a conversion photon candidate. If the conversion is highly
asymmetric (i.e. where either the electron or positron is produced at very low energy),
the second track may not be reconstructed. Tracks which pass the selection criteria
for conversions, but are not used to fit a conversion vertex are used to construct these
‘single-track’ conversion candidates. The final energy measurement for conversion
photon candidates is performed in a slightly wider $3 \times 7$ ($5 \times 5$) window in the barrel
(endcaps), to account for energy dispersion from both the electron and positron.

3.3 Jet Reconstruction

A jet can loosely be defined as a collimated set of particles produce by hadroniza-
tion of quarks and gluons. These quarks and gluons can be emitted from the initial
proton-proton collision, be produced via $W, Z$, or Higgs boson decays, or in the case
of this analysis, be produced due to decays of long-lived particles to SM partons.

$^3$The barycenter of a cluster is the sum of the four-vectors of the contributing clusters, assuming
zero mass for each of the constituents
Jet reconstruction algorithms are used to associate particles (or their corresponding detector signatures) to a jet object. From a theoretical perspective, a well behaved jet algorithm fulfills the following criteria:

- It should be **infrared safe** - the result of jet finding is not affected by the presence or absence of additional infinitely soft particles between two constituent particles of the jet.
- It should be **collinear safe**, in that the reconstruction of a jet is unchanged if a particle is split into two collinear particles.
- It reconstructs the same hard process regardless of whether it received partons, particles, or calorimeter objects as input.

The main jet algorithm used by ATLAS is the anti-$k_t$ algorithm [45]. The anti-$k_t$ algorithm is a successive recombination algorithm which is both infrared and collinear safe. It iteratively combines pairs of input objects $(i, j)$ based on a variable $d_{ij}$ that considers both the distance between them, and their relative transverse momenta:

\[
d_{ij} = (p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{(\Delta R_{ij}^2)}{R^2}
\]  

\[
d_{iB} = p_{T,i}^{-2}
\]  

(3.3)  

(3.4)

Here, $\Delta R_{ij} = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ is the angular separation between the objects in $\eta - \phi$ space, $d_{iB}$ is the transverse momentum of object $i$ with respect to the beam line, and $R$, known as the distance parameter, is a characteristic parameter of the algorithm that characterizes the size of the jet object. The quantities $d_{ij}$ and $d_{iB}$ are calculated for all pairs of input objects, and the minimum $d_{\text{min}}$ is found. If $d_{\text{min}}$ is a $d_{ij}$, the pair of objects are combined into a single new object (with a summed
four-momenta and updated angular distance). All \( d_{ij} \) and \( d_{iB} \) are re-calculated, and the process is repeated for this new set of objects. If the minimum value is a \( d_{iB} \), the object \( i \) is considered a jet and removed from the input list, and the process is repeated for the remaining objects until no input objects remain. Therefore, low \( p_T \) objects from the input collection are successively grouped around nearby higher \( p_T \) objects until a jet is formed, and objects with a high enough \( p_T \) will be considered jets by themselves. An added benefit of this algorithm is that the jets produced are fairly conical in shape. The distance parameter \( R \) describes the radius of this cone.

The input to jet reconstruction [46] is a set of four-momenta and spatial coordinates, and these can be partons (theoretical jet reconstruction), particles, or their resulting detector signals. Particles produced by hadronization of quarks and gluons can be charged, so a jet typically creates tracks in the inner detector. However, most constituent particles will deposit a majority of their energy in the calorimeter, and so topological calorimeter clusters ('topoclusters') are used as input for jet-finding. These topoclusters are three-dimensional groups of calorimeter cells that are designed to represent the energy deposition from a particle shower development in the calorimeter. One of the challenges for calorimeter-based jet finding is the suppression of any effects due to electronic noise from the calorimeter readout system. The noise threshold \( \sigma_{noise} \) is measured from calorimeter energy deposition during data-taking runs when there is no beam. The initial seed for cluster formation is a calorimeter cell with a high signal-to-noise ratio, \( E_{cell} > 4\sigma_{noise} \). Neighboring cells with an energy \( E_{cell} > 2\sigma_{noise} \) are iteratively added to the cluster. In a final step, all cell surrounding the neighbor cells are added to the cluster. The formation of topoclusters are includes a step where initial topoclusters are split if they contain local energy maxima; the local maxima are used as seeds for the formation of new topoclusters. The topoclusters are defined as zero mass objects with their energy \( E \) equal to the sum of the energy
of all constituent cells, and a four momentum calculated from the energy-weighted barycenter \((\eta, \phi)\):

\[
\begin{align*}
p_0 &= E \\
px &= E \cdot \frac{\cos \phi}{\cosh \eta} \\
py &= E \cdot \frac{\sin \phi}{\cosh \eta} \\
 pz &= E \cdot \tanh \eta
\end{align*}
\]

(3.5) (3.6) (3.7) (3.8)

The topoclusters are then input into the anti-\(k_t\) algorithm for jet finding. The final jet four-momentum is calculated by adding the four-momenta of any constituent topoclusters.

### 3.3.1 Jet Quality Criteria

Jet-like signatures can occur in the calorimeter from electronic noise, and energy deposition from cosmic rays or beam halo muons. A set of quality criteria [47] are determined from calorimeter and jet variables to discriminate against such ‘fake’ jets:

- **FMax**, the maximum fraction of energy in a single calorimeter layer.
- **HECf**: The fraction of the jet’s energy contained in the hadronic endcap calorimeter.
- **HECQ**: The fraction of hadronic endcap calorimeter cells with a Q-factor greater than 4000.
- **NegativeE**: The negative energy contained in the jet.
- **Timing**: The average jet time weighted by the cell energy, is calculated from the cell timing. The cell time is defined as the time a signal is recorded in a calorimeter cell, with respect to the bunch crossing time.
- The jet EM fraction (EMf), the fraction of the jet’s energy which is contained in the electromagnetic calorimeter.

- LArQ: The fraction of energy from LAr cells with a Q-factor greater than 4000. The Q-factor is defined as $\sum_{\text{samples}}(a_i^{\text{meas}} - a_i^{\text{pred}})^2$, where $a_i^{\text{meas}}$ and $a_i^{\text{pred}}$ are the measured and predicted pulse shapes used to reconstruct the cell energy.

- chf: The jet charge fraction, which is defined as the ratio of the sum of track $p_T$ associated with the jet to the calibrated jet $p_T$.

For jets reconstructed in the 2012 dataset, the following requirements were applied as selection criteria:

- HECf > 0.50 and HECQ > 0.50
- HECf > 1−HECQ
- NegativeE > 60 GeV
- Timing > 10 ns
- EMf > 0.90 and LArQ > 0.8 and $|\eta| < 2.8$
- FMax > 0.99 and $|\eta| < 2.0$
- EMf > 0.95 and chf < 0.05 and $|\eta| < 2.0$
- EMf < 0.05 and chf < 0.10 and $|\eta| < 2.0$
- EMf < 0.05 and $|\eta| < 2.0$

A jet is labeled ‘bad’ if it fails any of the above criteria.

Jets that pass through the electromagnetic calorimeter crack region are identified and labeled ‘ugly’ based on the following selection criteria:
• The TileGap calorimeter covers the transition region between the barrel and endcap calorimeters. The fraction of jet energy contained in the TileGap is required to be > 50% of the total jet energy.

• The fraction of the jet energy from extrapolation into dead cells > 50% of the total jet energy; dead cells are those flagged as problematic during data quality checks.

These quality criteria are designed to select well-reconstructed jets originating at the IP. This analysis studies theoretical models which include jets that are not produced at the primary interaction point. Jets from long-lived particles that decay at the end of the electromagnetic calorimeter (ECal) will have all their energy deposited in the hadronic calorimeter. In this case, the final two ‘bad’ jet flags, which veto jets with less than 5% of their energy in the ECal, would remove jets from potential signal events. Therefore, for this analysis, a jet is considered ‘good’ if it has $p_T > 20$ GeV, is within $|\eta| < 4.5$, and is neither ‘bad’ nor ‘ugly’ (with the final two ‘bad’ jet criteria not considered).

3.3.2 Jet Energy Scale

The ATLAS calorimeters are ‘non-compensating’ - they have an accurate response to particles from electromagnetic showers, but have a lower response to hadronic showers. Raw signals from calorimeter cells are first calibrated at the electromagnetic scale; jet finding algorithms are run on these clusters to produce electromagnetic (EM) jets. A correction needs to be applied to obtain the true hadronic energy scale, known as jet energy scale. The initial energy of the EM jet also needs to be corrected to account for various detector and reconstruction effects:

• Particles from the hadronic shower may escape the detector acceptance (‘leakage’).
- Part of the hadronic shower may occur in inactive regions of the calorimeters, leading to a loss in total jet energy.

- If the energy deposition in some calorimeter cells is below a certain threshold, the cells are not used in jet finding, leading to a loss in signal jet energy.

In order to obtain a reconstructed jet energy as close as possible to the true jet energy, the EM+JES calibration scheme is applied, consisting of the following steps:

- Pileup offset correction: Energy deposits in the calorimeter from products of multiple proton-proton collisions can be added to a true jet by the jet reconstruction algorithms. A correction is calculated from collision data events by first computing the additional energy in a $(\Delta \eta \times \Delta \phi) = 0.1 \times 0.1$ region as a function of the jet pseudo rapidity $\eta$ and the number of primary vertices $N_{PV}$ in the event, and then multiplying the energy by the average number of calorimeter towers.

- Jet origin correction: Jet algorithms use the geometric center of the detector as a reference for calculation of jet angular variables. The true origin of jets, the primary vertex, can be quite displaced from the detector center. The new jet direction is obtained by re-calculating the angular distribution of the constituent topoclusters with respect to the primary interaction point, and then summing to obtain the new jet direction.

- Jet energy and $\eta$ correction: The final step of the calibration scheme uses truth-matched jets in a simulated sample without pileup (since this is corrected for separately) to compute correction factors designed to return the jet energy as close to the truth values as possible. The EM-scale jet energy response is calculated by taking the ratio of reconstructed and true jet energy values for truth-matched jets.
3.4 Muon Reconstruction

The reconstruction of muons [48, 49] utilizes information obtained from both the muon spectrometer and inner detector to reconstruct the muon’s trajectory.

- **Standalone muons**: Straight-line segments are reconstructed in each muon station, and these are then combined using a road-building algorithms. MS tracks are reconstructed using a global fit on hits from combined segments. These standalone tracks are then extrapolated back towards the beam line to obtain the final track parameters. The back-extrapolation accounts for scattering effects and energy loss in the calorimeters, using estimates based on the amount of detector material crossed by the track, and calorimeter energy measurements along the track. Standalone muon reconstruction is particularly useful in the region $2.5 < |\eta| < 2.7$, since ID tracks are not reconstructed for particles with $\eta > 2.5$. Standalone tracks in the muon system can also be produced by muons from in-flight decays of pions and kaons, and possibly also exotic neutral particle decays.

- **Segment-tagged muons**: Muon-object candidates can also be formed by associating inner detector tracks to muon track segments via extrapolation. This method is primarily useful for reconstructing low-$p_T$ muons, since the large curvature of the particle’s trajectory would make reconstruction of a full muon standalone track unlikely.

- **Calorimeter-tagged muons**: ID tracks associated with energy deposits in the calorimeter can also be tagged as a muon candidate. This method is used to gain acceptance in the region $|\eta| < 0.1$, which is not instrumented in the MS, and it optimized for high $p_T$ muons ($25 \text{ GeV} < p_T < 100 \text{ GeV}$).

- **Combined muons**: A combined muon track can be formed by associating an inner detector track with a muon standalone track that has been extrapolated
back into the calorimeters (accounting for energy loss). Tracks are paired using a match $\chi^2$, defined as the difference between the track parameters weighted by the combined covariance matrix. The final track parameters are obtained either from a refit of the combined track, or from a statistical combination of the two tracks.

3.5 $\tau$-lepton Reconstruction

$\tau$ leptons decay hadronically to a tau neutrino and neutral pions (rarely kaons) about 65% of the time. These hadronic $\tau$ decays tend to have fewer tracks and a narrower calorimeter shower as compared to QCD jets. The reconstruction of taus [50] is performed only for their hadronic decay modes, as leptonic tau decays (to a neutrino plus an electron or muon) are almost impossible to distinguish from reconstructed electrons and muons from the primary interaction point.

A dedicated reconstruction algorithm which utilizes information from both the inner detector and calorimeters is used to reconstruct and identify hadronic tau ($\tau_{\text{had-vis}}$) decays. It is seeded from reconstructed jet-objects (described in 3.3) with a $p_T > 10$ GeV and $|\eta| < 2.5$. A new $\tau_{\text{had-vis}}$ axis is calculated using clusters within $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.2$ of the jet-object barycenter. Inner detector tracks with $p_T > 1$ GeV and $d_0 < 1.0$ mm within a $\Delta R = 0.2$ cone are then associated with the $\tau_{\text{had-vis}}$ objects.

Further selection criteria based on the calorimeter shower shape and track variables, as well as isolation criteria, are implemented to distinguish these tau-object candidates from QCD jets.

3.6 Missing Transverse Momentum

In proton-proton collisions at the LHC, incoming protons travel along the beam line (i.e. along the $z$-axis) and so have no transverse momentum. Due to conservation
of momentum, the outgoing particles of the collision should have zero momentum in the transverse plane. An imbalance in the transverse momentum between the initial and final states could indicate the presence of particles (neutrinos, predicted exotics particles) that do not interact with detector material, and therefore pass through the detector without leaving an experimental signature. Indirect detection of particles such as neutrinos is very important both for SM signatures that include a $W$ boson decaying to a lepton plus neutrino, and for signatures predicted by certain supersymmetry models, which include hypothesized particles that do not have any charge under the SM. In this analysis, certain models include a large number of displaced decays per collision, and some of these decays could occur outside the detector volume, leading to a sizeable imbalance in the transverse momentum.

The missing transverse momentum is defined as the negative momentum balance in the transverse plane. Experimentally, the momentum of charged particles produced in collisions can easily be measured, since they leave tracks in the ID or MS. For neutral particles, the energy deposition in the calorimeters to calculate their contribution to the transverse momentum. Therefore, a term representing the energy imbalance in the event, known as missing transverse energy, or $E_T^{\text{miss}}$, is calculated [51] by summing all contributions from calorimeter energy deposits, and the momentum of particles detected in the muon system. The hermetic coverage of the calorimeters (including the very forward regions) is useful to capture the maximum possible energy deposition from particles. It is also necessary to account for gaps in calorimeter coverage, dead regions, and noise in the calorimeters, since these can all lead to ‘fake’ $E_T^{\text{miss}}$.

The components of $E_T^{\text{miss}}$ are:

$$E^{\text{miss}}_{x(y)} = E^{\text{miss,calo}}_{x(y)} + E^{\text{miss,}\mu}_{x(y)}$$  \hspace{1cm} (3.9)

The magnitude of the missing transverse momentum ($E_T^{\text{miss}}$) and its azimuthal coordinate $\phi^{\text{miss}}$ can be calculated as follows:
\[ E_T^{\text{miss}} = \sqrt{E_x^{\text{miss}} + E_y^{\text{miss}}} \]  \hspace{1cm} (3.10)

\[ \phi^{\text{miss}} = \arctan(E_x^{\text{miss}}, E_y^{\text{miss}}) \]  \hspace{1cm} (3.11)

The contribution to \( E_T^{\text{miss}} \) from the calorimeter is calculated by summing the transverse energy of all reconstructed objects that leave energy deposits in the calorimeter, as well as topoclusters not associated to any reconstructed object:

- \( E_{x(y)}^{\text{miss},e}, E_{x(y)}^{\text{miss},\gamma}, E_{x(y)}^{\text{miss},\tau} \), the calorimeter cluster energies from electron, photon, and hadronically decaying \( \tau \)-leptons respectively.

- \( E_{x(y)}^{\text{miss,jets}} \), the contribution from jets with \( p_T > 7 \text{ GeV} \).

- \( E_{x(y)}^{\text{miss,SoftTerm}} \) is the contribution from topological clusters that are not associated with any reconstructed object. The inclusion of contribution from topoclusters (as opposed to individual calorimeter cells) allows for the inclusion of significant calorimeter energy deposition not associated with a reconstructed object, while suppressing contributions from noise in the calorimeter cells.

- \( E_{x(y)}^{\text{miss,\mu}} \) is the sum of energy deposited by muons in the calorimeter.

The negative sum of the cell energies for each term is calculated by:

\[ E_{x,y}^{\text{miss,term}} = - \sum_{i=1}^{N_{\text{term}}} E_i \sin \theta_i \cos \phi_i \]  \hspace{1cm} (3.12)

\[ E_{x,y}^{\text{miss,term}} = - \sum_{i=1}^{N_{\text{term}}} E_i \sin \theta_i \sin \phi_i \]  \hspace{1cm} (3.13)
where $E_i$, $\theta_i$, and $\phi_i$ are the energy, polar angle, and azimuthal angle of the cell respectively.

In the muon system, the contribution to missing transverse momentum is calculated using the sum of transverse momentum for all tracks from combined muons within $|\eta| < 2.5$, and standalone muons for $2.5 < |\eta| < 2.7$. The combined muon requirement drastically reduces the contribution from fakes from jets that punch through the calorimeter.

Since muons also deposit energy in the calorimeter, the calorimeter muon term ($E_{miss,calo,\mu}^{x(y)}$) is calculated differently depending on whether the muon is isolated\(^4\) from jets in the event. The $p_T$ of isolated muons is determined from the combined track parametrization, so no contribution is made to the calorimeter $E_{miss,calo,\mu}^{x(y)}$ term. For non-isolated muons, the MS after calorimeter energy loss is used, and therefore the contribution to the calorimeter term is also counted. Additionally, in inactive regions of the muon spectrometer ($|\eta| \sim 1.2$), the contribution from segment-tagged muons is considered.

\(^4\)An isolated muon is defined as being at least $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} > 0.3$ from a reconstructed jet.
CHAPTER 4
DATA AND MONTE CARLO SAMPLES

4.1 Data

This analysis uses a dataset with a total integrated luminosity of 20.3 fb$^{-1}$, recorded by the ATLAS detector in 2012. This represents 92% of the data delivered to ATLAS by the LHC in 2012, and 95% of the data recorded by ATLAS during 2012 (Figure 4.1). The data are recorded in luminosity blocks, which correspond to approximately one minute of data-taking. During data-taking, certain sub-detectors may encounter problems like noise bursts, power trips, and gas leaks, while other sub-detectors continue to run optimally. A record of the data quality is maintained for each sub-detector by assigning quality flags (‘good’, ‘bad’, or ‘unknown’) in every lumi-block. A standard ‘Good Runs List’ (GRL) is created, consisting of all lumi-block numbers where the data quality was confirmed as ‘good’. Data events used in this analysis are required to pass this GRL requirement; this excludes any data-taking periods where a minimum percentage of detector sub-systems were not operating optimally. The uncertainty on the integrated luminosity is obtained from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012, following the methodology detailed in [52]. For the 2012 data run, this uncertainty was calculated to be 2.8%.

Events from this dataset are selected with a trigger that requires a minimum threshold of 110 GeV for the highest-$E_T$ jet and 75 GeV of $E_{T}^{\text{miss}}$; this trigger is
Figure 4.1: The total integrated luminosity as a function of time delivered by the LHC (green), recorded by ATLAS (yellow), and with data quality declared ‘good’ (blue) in 2012.

called the $EF_{j110 \ a4tchad \ xe75 \ tclcw}$ trigger$^1$. Events from Standard Model QCD processes are the dominant background for this analysis. This analysis employs data-driven techniques for estimating expected backgrounds; a sample of QCD events in data is selected using a set of single jet triggers with various thresholds. For the $Z'$ search, two control samples are selected using single-jet triggers with $E_T$ thresholds at 110 GeV ($EF_{j110 \ a4tchad}$) and 280 GeV ($EF_{j280 \ a4tchad}$). A third single-jet trigger with a minimum jet $E_T$ of 220 GeV ($EF_{j220 \ a4tchad}$) was used to select a control sample for vertex reconstruction studies for Scalar boson and Stealth SUSY benchmark samples. Since the cross-sections of processes with low-energy jets are orders of magnitude higher than those with relatively high-energy jets, pre-scale factors are applied to triggered events to limit the number of low-energy jets stored. These scale factors are listed in Table 4.1.

$^1$EF denotes event-filter level trigger selection criteria. The $a4tchad$ label indicates that the jet is reconstructed using the anti-$k_t$ algorithm with a cone radius of 0.4 using topological clusters calibrated at the hadronic scale. The $tclcw$ label indicates that the $E_T^{\text{miss}}$ is calculated from topological clusters calibrated with local cluster weighting calibration scheme.
<table>
<thead>
<tr>
<th>Offline pre-scale</th>
<th>Minimum jet $E_T$ [GeV]</th>
<th>Maximum jet $E_T$ [GeV]</th>
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<td>1</td>
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</tbody>
</table>

Table 4.1: Offline pre-scale factors applied to dijet data events according to the leading jet $E_T$.

4.2 Monte Carlo Samples

Simulated data events are produced in order to study hypothesized signal processes as well as known Standard Model processes. These events are produced in three steps: *generation* of the underlying hard scatter events; *simulation* of the detector response to the generated physics processes; and *digitization* of the simulated energy deposits into electronic signals. The output of the final digitization step is designed to be identical in format to the electronic signals recorded by the detector during data-taking; the reconstruction algorithms described in Chapter 3 are then applied to these signals to obtain ‘reconstructed’ data usable for analyses.

4.2.1 Event Generation

Generation refers to the production of final state primary particles for specified physics processes using Monte Carlo methods to numerically calculate parton showering and matrix elements.

This analysis studies a $Z'$-mediated Hidden Valley scenario with two heavy flavors, described in Section 1.4.1; the $\pi^0_v$ particles decay promptly, while the $\pi^\pm_v$ are long-lived.

The $Z'$-mediated Hidden Valley events are simulated in a two-step process. In the first step, a combination of **Pythia6** [53] subroutines is used to simulate $Z'$ production and decay to hidden-sector particles, using a scaled-up version of QCD
The simulated hidden sector has three colors, two flavors and confinement scale $\Lambda_{v}$. This sector is analogous to three-color two-flavor QCD, with all masses and dimensional quantities scaled up (relative to QCD) by a constant factor $R$ ($R = \Lambda_{v}/\Lambda_{QCD}$, where $\Lambda_{QCD}$ is the QCD confinement scale). The v-pions have mass $m_{\pi_{v}} = m_{\pi} R$, where $m_{\pi}$ is the physical pion mass. The stable nucleons have similarly scaled-up masses - the iso-singlet pseudoscalar of 2-flavor QCD ($\eta_{v}$) has its mass set to $m_{\eta} R$. Then, the simulation of the decay of a $Z'$ boson with mass $M$ into hidden sector particles proceeds as follows:

- The production of v-quarks ($Q$) via the $Z'$ ($qq \rightarrow Z' \rightarrow QU$) is simulated based on the PYTHIA6 routine for $qq \rightarrow Z' \rightarrow f \bar{f}$.

- The v-quark parton showering and hadronization are then simulated by first scaling down the energy of the $QU$ system to $E = E_{0}/R$ (where $E_{0}$ is the true energy of the system), simulating QCD showering and hadronization for a $q \bar{q}$ system (with 2 flavors), and then scaling up the final state particles by a factor of $R$ to get v-hadrons at the original energy scale.

The standard library of particles used by PYTHIA6 and other Monte Carlo event generators does not include v-pions, and so it is necessary to use surrogates in order to simulate the generation and decay of the v-pions. The neutral pseudo-scaler $H_{0}$ is found in some two Higgs-doublet MSSM models, and is coupled to the $A_{0}$ particle, which then decays predominantly to heavy fermions. Since this closely represents the decay of the $\pi_{v}^{\pm}$ to SM fermions ($\pi_{v}^{\pm} \rightarrow \pi_{v}^{0} \rightarrow f \bar{f}$), the $H_{0}$ and $A_{0}$ are used as proxies for the $\pi_{v}^{0}$ and $\pi_{v}^{\pm}$ respectively. The mass and lifetime parameters of the proxy particles are modified to generate the benchmark samples used in this analysis.

In the second step, the decay of the resulting $\pi_{v}$ to SM partons, and their showering, hadronization and decay, are simulated using PYTHIA8 [54]. The resulting final states consist of Standard Model hadrons and leptons, as well as v-hadrons that
are neutral under the Standard Model (and are therefore stable and invisible). The inputs to the generator are the $Z'$ mass, the $\pi^0$ mass, and the $\pi_\nu$ lifetimes. The other $\nu$-hadron masses are calculated by scaling up QCD by the factor $R$. The couplings of the $Z'$ to $u$ and $d$ quarks are fixed at Pythia6 default values.

The decay of a Scalar boson via a hidden sector (described in Section 1.4.2) is also not implemented in Pythia8; as with the $Z'$ generation, parameters of existing processes and particles are modified to generate this signal process. The $H_0 \rightarrow A_0 A_0$ and $A_0 \rightarrow f\bar{f}$ processes are used to model the decay of the Scalar boson to two $\pi^0_\nu$, and the consequent $\pi^0_\nu$ decay to fermion pairs, respectively.

Stealth SUSY events are generated in a two-step process using the Madgraph5 [55] and Pythia8 generators. The production of long-lived singlinos from gluino pairs and their subsequent decay to gluons are simulated using a modified version of minimal supersymmetry processes implemented in Madgraph5; the gluon showering, hadronization and decay, as well as other SM processes in the signal events, are simulated with Pythia8.

4.2.2 Detector Simulation

The Geant4 [56] toolkit is used to simulate the interactions of event generator particles with detector material. It requires a detailed modeling of the detector geometry; this is done by combining simulations of sub-volumes of different shapes (representing different detector chambers and layers) into the full ATLAS geometric volume. The calculated physics processes due to material interactions are used to create a set of expected energy depositions in the detector volume (‘hits’). The simulation is designed to resemble conditions of the actual detector as closely as possible, and includes detailed magnetic field maps as well as a record of data-taking conditions (dead channels, misalignment of detector chambers, calibrations, voltage levels) when performing these calculations.
4.2.3 Digitization and Reconstruction

The digitization step first converts the raw energy depositions from simulation into electronic inputs (voltage or time measurements) from detector readout units. Simulated hits from minimum bias triggered events are added to the signal process hits to simulate effects from cavern background, beam gas, and beam halo. The behavior of the actual detector readout system is then emulated, and a set of processed measurements are created. The digitization stage also adds in modeled electronic noise from the detector readout system. These hits are then input into the same standard reconstruction algorithms used for data events.

4.2.3.1 Simulation of Zero-bias Overlay Monte Carlo Samples

Standard MC sample production simulates pile-up by overlaying a simulated minimum bias event on the signal event; this procedure does not properly account for detector effects due to cavern background and other sources of detector noise. This can be seen in distributions of background hits in the muon spectrometer, which are studied in \((\eta, \phi)\) regions with no calorimeter activity. Selected events must pass a single jet trigger with an energy threshold at 360 GeV \((EF_j^{360_{\text{etchad}}})\), and the two highest \(p_T\) jets are required to be back-to-back \((|\Delta\phi| > 2.14)\). For each event, a random \((\eta, \phi)\) is chosen. If there are no jets with \(E_T > 25\) GeV within a \(\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}\) cone of radius 1.6 around the \((\eta, \phi)\) axis, the number of MDT hits within \(\Delta R < 0.6\) of the \((\eta, \phi)\) axis is recorded. Figure 4.2 compares this distribution for data and simulation; the standard minimum-bias overlay method significantly underestimates the amount of background MDT hits as compared to data. Pile-up interactions in data are recorded using a zero-bias trigger; for this analysis, signal and background MC hard processes are overlaid with with zero-bias data events. These events correctly represent backgrounds found in real data, as shown in Figure 4.2. The remaining discrepancy between data and zero-bias overlay simulation is likely
due to the overlay procedure, which converts the digital measurement of zero bias events to an estimated electrical pulse in the detector and re-digitizes the event after adding the hard MC process.

![Figure 4.2: Cavern background average number of MDT hits within a $\Delta R < 0.6$ cone as a function of $\eta$.](image)

4.2.4 Signal Monte Carlo Samples

A range of MC samples have been produced for the $Z'$, Scalar boson, and Stealth SUSY models. Each Scalar boson and $Z'$ sample includes different $Z'$, Scalar boson, and $\pi_\nu$ masses and different $\pi_\nu$ proper lifetimes. Stealth SUSY samples were produced with different $\tilde{g}$ masses and $\tilde{S}$ lifetimes. The simulated benchmark samples are listed in Tables 4.2 – 4.4.

The proper lifetime values are chosen to maximize the number of decays in the entire ATLAS detector volume. The parametrization at leading order used for the proton parton distribution function (PDF) for the Scalar boson and $Z'$ simulations is MSTW 2008 [11], while CTEQ6L1 [57] is used for Stealth SUSY simulation. The signal MC simulation samples contain 400,000 events per sample.
4.2.5 QCD Monte Carlo Simulated Samples

Standard Model QCD MC samples are used in this analysis to characterize vertex reconstruction in the muon spectrometer (in the absence of sufficient statistics from
### Table 4.5: QCD dijet samples

<table>
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</tr>
</thead>
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</tr>
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</table>

QCD data events), and to study differences in the performance of custom reconstruction algorithms in data and simulation. The samples are generated using Pythia8, in eight separate slices (named JZXW, with X ranging from zero to seven) based on the leading anti-$k_T$ truth jet $p_T$ of the event. Each slice contains $\sim$1.5 million generated events. The slices are selected such that the $p_T$ spectrum is fairly flat, so that all $p_T$ bins have sufficient statistics. The cross-section for QCD dijet production falls rapidly as a function of leading jet $p_T$. A scale factor is applied to events from each JZXW slice to obtain the continuous jet $p_T$ spectrum:

$$\text{scale factor} = \frac{\text{event weight} \times \text{filter efficiency} \times \text{cross-section} \times \text{luminosity}}{\text{total number of events}} \quad (4.1)$$

Table 4.5 lists the $p_T$ ranges for each MC sample, along with the filter efficiency and relative cross-section.

#### 4.2.6 Pileup Correction

Figure 4.3 (a) shows the $\langle \mu \rangle$ distribution in the entire 2012 dataset, overlay MC simulated samples, and standard MC simulated samples, and Figure 4.3 (b) compares the number of primary vertices reconstructed as a function of $\langle \mu \rangle$. Since the overlay MC simulation is produced using zero-bias events in data, there is much
better agreement between overlay MC simulation and data (as compared to standard MC simulation). The slight difference between the overlay MC samples and data \( \langle \mu \rangle \) distributions is due to the fact that the overlay method used zero-bias events from a partial dataset of 2012 collisions (corresponding to two-thirds of the total dataset). A per-event weight is applied to match the overlay MC distribution to the \( \langle \mu \rangle \) distribution in data.

Figure 4.3: (a) Number of interactions per bunch crossing for all events in 2012 data, overlay MC, and standard MC (b) Number of primary vertices as a function of \( \langle \mu \rangle \) for 2012 data, and one MC benchmark sample.
CHAPTER 5
DISPLACED VERTICES IN THE INNER DETECTOR

Particles from new physics scenarios described in Chapter 2 can have proper lifetimes such that they decay throughout the detector volume. The ability to detect decays in the silicon region of the inner detector enables sensitivity to a wide range of particle lifetimes.

5.1 Signatures of Displaced Hadronic Decays in the Inner Detector

Tracks from displaced decays in the silicon detector region ($50 \text{ mm} < r < 550 \text{ mm}$) are characterized by large impact parameters and fewer silicon hits than primary tracks. The default silicon-seeded track finding algorithms (Section 3.1) are designed to reconstruct tracks originating from the primary interaction point; strict requirements are implemented during track seeding and ambiguity-solving in order to suppress fake track reconstruction from combinatorics. A maximum allowed impact parameter of 10 mm is implemented for silicon track seeds, which is increased to 100 mm for back-tracking with TRT segments. The seeds are also required to have at least one pixel hit, and are less likely to be used to create tracks if they are missing hits in the first pixel layer (b-layer), or have few total silicon hits. Due to these constraints, tracks originating from vertices outside the beam pipe ($r = 48 \text{ mm}$) are unlikely to be reconstructed using standard algorithms, and tracks from decay vertices occurring after the final pixel barrel layer ($r = 122 \text{ mm}$) will not be reconstructed. It is therefore necessary to develop new techniques to reconstruct these large radius tracks.
5.2 Reconstruction of Tracks with Large Impact Parameters

After the reconstruction of standard tracks is completed, a collection of hits that are not associated to any track remains. Tracks from decay vertices outside the beam pipe are unlikely to be reconstructed during the standard track-finding stage; events with these decays will have many unassociated hits.

A second iteration of silicon-seeded track finding uses a modified tracking algorithm to reconstruct tracks with large impact parameters from unassociated hits. Seeds are created from pixel and SCT hits, with larger allowed impact parameters. The ambiguity solving procedure is also modified to allow seeds with no silicon hits in the first few detector layers to be selected for track finding. The closer a vertex is to the end of the silicon region, the more likely that its tracks will have a high fraction of shared hits, as tracking information from the SCT will only be available for a short distance after the vertex, where the tracks are not yet well-separated; the maximum number of shared hits allowed is therefore increased.

The final default and modified requirements are listed in Table 5.1, with the transverse and longitudinal impact parameters denoted by $d_0$ and $z_0$, respectively. A minimum $p_T$ requirement is introduced to reduce the processing time needed for these algorithms, since tracks from displaced decays studied in this analysis generally have a $p_T > 1$ GeV. The maximum allowed values for $d_0$ and $z_0$ are chosen to maximize acceptance at this initial track reconstruction stage. Figure 5.1 compares the impact parameter distributions of the default and modified tracking collections. The modified reconstruction stage produces many tracks with large impact parameters.

5.3 Displaced Vertex Reconstruction

Secondary decay vertices are reconstructed using techniques based on the ATLAS primary vertex algorithm described in Section 3.1.3. Pre-selected tracks are used as input for a vertex seed finder to create clusters of tracks, which are then fit to obtain
<table>
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<td>1 GeV</td>
</tr>
<tr>
<td>maximum $d_0$</td>
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<td>500 mm</td>
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<td>maximum $z_0$</td>
<td>320 mm</td>
<td>1000 mm</td>
</tr>
<tr>
<td>minimum number of silicon hits</td>
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<td>2</td>
</tr>
<tr>
<td>maximum number of shared hits</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.1: Default and modified criteria for track finding.

![Transverse and Longitudinal impact parameter distributions](image)

Figure 5.1: (a) Transverse and (b) Longitudinal impact parameter distributions for tracks reconstructed with default and loosened requirements for a benchmark sample with $m_{Z'} = 1$ TeV, $m_{\rho} = 50$ GeV, and $\pi_v c\tau = 0.5$ m.

candidate vertices. The primary vertex finder is designed to minimize the splitting of vertex candidates, and attempts to group together as many tracks as possible (with outlying tracks down-weighted for the vertex fit). This feature is particularly useful for reconstructing displaced decays to $b$-quarks, since the products of $b$-hadronization can be displaced, and tracks from the decay chain do not always point back to the initial decay vertex.

5.3.1 Track Selection for Vertex Finding

First, a collection of tracks to be used for vertex finding is created from the combined set of default and modified tracks. The maximum allowed values for impact parameters $d_0$ and $z_0$ are loosened to 500 mm and 1000 mm respectively, in order
to retain maximum acceptance at the reconstruction stage. If $d_0$ is large and the error on $d_0$ remains small, the $d_0$ significance (defined as $d_0/\sigma(d_0)$) will be large, and thus no upper limit is placed on this parameter. Tracks selected for displaced vertex reconstruction are required to have a minimum transverse impact parameter to remove tracks from primary and pile-up interactions. A study comparing three different choices for the minimum $d_0$ cut on tracks (2 mm, 5 mm or 10 mm) is described in Appendix A. Tracks from displaced decays well within the beam pipe ($r < 30$ mm) can have tracks with $d_0 < 10$ mm; requiring a minimum $d_0$ of 10 mm results in a loss of efficiency in this region, compared to a less conservative requirement of $d_0 > 2$ mm. However, the $d_0 > 10$ mm requirement also decreased the total background due to pileup tracks by almost two orders of magnitude, and so this value was chosen for the analysis. As with track reconstruction, requirements on the number of pixel, SCT, and total silicon hits are relaxed. The majority of tracks used to reconstruct displaced vertices are created by the large-radius track finding method, and so have a minimum of seven silicon hits. The minimum number of silicon hits required is set at four to include tracks reconstructed by back-extrapolating TRT segments (Section 3.1). Finally, the fit quality $\chi^2$ requirement for the tracks is relaxed slightly. Table 5.2 compares the track selection for primary vertex finding and displaced vertex finding.

5.3.2 Vertex Reconstruction

Tracks that pass the selection criteria described above are input into an iterative vertex finding algorithm. First, a vertex seed finder is used to group tracks into clusters based on the minimum distance between tracks, creating a set of seed vertex candidates. A $\chi^2$ vertex fitter is used to form initial vertex candidates from the track

---

1SCT-only tracks seeds will have the fewest number of silicon hits. Track seeding requires three space points (and therefore six SCT hits), with an additional hit to constrain pattern recognition.

2The distance of closest approach is calculated between two tracks at a time.
clusters. Tracks found to be incompatible with the vertex position are removed and used to create another vertex seed, and the vertex is then refit. This procedure is performed iteratively until all remaining tracks used in the fit are compatible with the vertex position. The constraint that the reconstructed vertex must be compatible with the beam spot position is removed.

This tool was developed primarily to reconstruct decays of neutral, long-lived particles. It was observed that some reconstructed vertices had associated tracks with hits at a smaller radius than the decay vertex radial position. In Figure 5.2 (a), the position of the first hit on a track associated to the vertex as a function of the position of the vertex is shown for one $Z'$ benchmark MC sample. Entries below the diagonal indicate the presence of tracks with a hit in a detector layer before the vertex position. This can be caused by the decay of a charged particle, or by a track from the IP passing in front of a true neutral decay vertex. The vertex finding algorithm was modified to remove such tracks and refit the vertex. The track is then returned to the collection of tracks available for seeding other vertices. Figure 5.2 (b) shows the same distribution after the method is implemented; none of the reconstructed vertices have tracks with hits before the vertex. For the $Z'$ MC benchmark samples used in this analysis, 7–10% of truth-matched vertices had more than 1 in 5 tracks

<table>
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<td>$d_0/\sigma(d_0)$</td>
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<tr>
<td>$z_0/\sigma(z_0)$</td>
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<td>removed</td>
</tr>
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<td>$\min$ Si hits</td>
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<td>4</td>
</tr>
<tr>
<td>$\min$ Pixel hits</td>
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<td>0</td>
</tr>
<tr>
<td>$\min$ SCT hits</td>
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<td>2</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>3.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.2: Track selection criteria used for primary and displaced vertex reconstruction.
with a hit before the vertex position, and so this procedure does not have a large impact on the vertex reconstruction efficiency.

Figure 5.2: Position of the first hit on a track associated to a vertex, versus the position of the vertex (a) before and (b) after removing tracks with a hit before the vertex position for all truth-matched vertices reconstructed in a sample with \( m_{Z'} = 1 \) TeV, \( m_{\pi_v} = 50 \) GeV, and \( \pi_v c \tau = 0.5 \) m.

A second displaced vertex reconstruction algorithm (RPVDispVrt) \cite{58} was tested on signal MC simulation and data. This algorithm is based on an inclusive secondary vertex finder; it starts by forming two-track vertices, and then merges nearby tracks to form high track-multiplicity vertices. A detailed description of this alternate method and a comparison of the performance of the two algorithms on data and signal MC simulated samples can be found in Appendix B. The method used in this analysis was found to have a higher vertex reconstruction efficiency for all signal benchmarks, with the improvement more noticeable for samples with low mass long-lived particles. It should be noted that the background rate of the method used in this analysis is slightly higher.

Reconstructed vertices in the silicon barrel (\(|\eta| < 1.5\)) and endcap (\(1.5 < |\eta| < 2.5\)) regions are considered for this analysis. Vertices must also be within the fiducial region \( r < 275 \) mm and \(|z| < 840 \) mm. In signal MC samples, reconstructed vertices are considered truth-matched to simulated \( \pi_v \) decay vertices if the reconstructed vertex
is within 5 mm of the simulated vertex, and contains at least two tracks that have
been truth-matched (at hit level) to truth tracks from the $\pi_\nu$ decay. Position residuals
in $x$, $y$ and $z$ are shown for truth-matched reconstructed vertices in Figure 5.3 for
$Z'$ benchmark MC samples. Good agreement is observed between the reconstructed
and true vertex positions. The vertex resolution is $\sim 200 \mu$m in $x$ and $y$, and 500
$\mu$m in $z$. Pull distributions for truth-matched vertices with at least 5 tracks are
shown in Figure 5.4. The vertex position uncertainties for displaced decays to $b\bar{b}$
pairs in $x$, $y$, and $z$ are underestimated by factors of $1.4 - 1.8$. This underestimation
occurs because particles produced in the $b$ decay chain can be quite displaced from
the $\pi_\nu$ decay vertex, and the vertex reconstruction algorithm assumes that tracks
from all these decays come from a single vertex when estimating the vertex position
uncertainty. Similar results are obtained for all other $Z'$ and Scalar boson benchmark
samples. Long-lived singlinos in the Stealth SUSY benchmark samples decay to gluon
jets, where decay products originate from a single vertex; the widths of the vertex
pull distributions are therefore closer to unity (in the range $1.1 - 1.4$).

5.4 Good Vertex Criteria

The modifications to standard reconstruction relax selection criteria designed to
suppress the reconstruction of fake tracks and vertices. The modified algorithms also
reconstruct real vertices from hadronic interactions with detector layers. Selection cri-
teria have been developed to reject vertices from interactions with detector material,
poorly reconstructed vertices that result from random track crossings, and vertices
produced by a track passing close to a displaced $K_S$ or $\Lambda$ decay.

A significant fraction of background vertices are due to hadronic interactions with
material layers in the silicon detector regions. In order to remove this background,
vertices reconstructed within detector material are rejected using a silicon detector
material map [58]. The material map for the barrel region was constructed from a
Figure 5.3: The (a) x, (b) y, and (c) z residuals for the $Z'$ benchmark samples

combination of simulated detector geometry and hadronic interactions with detector material reconstructed in 2011 and 2012 minimum bias data. A transverse slice of this barrel material map is shown in Figure 5.5. Veto regions for pixel support structures in the endcaps were mapped using hadronic interactions in 2010 minimum bias data and MC.

This material veto is implemented with an algorithm that calculates the distance between a vertex and the closest material layer as described in a simulated detector layout. For vertices in the pixel (barrel and endcaps) layers, the vertex position is transformed into the local coordinates of the closest pixel module, and a 3-D veto is applied on the module shape. Vertices consistent with having originated in a material
Figure 5.4: The (a) x, (b) y, (c) z, and (d) r vertex pulls for a benchmark sample with \( m_{Z'} = 1 \) TeV, \( m_{\pi^0} = 50 \) GeV, and \( \pi^0 \rightarrow c\tau = 0.5 \) m with Gaussian fits indicated by the red curves.

Layer within their position uncertainties are selected based on a variable \( d/\sigma \), defined as the distance to the closest material layer divided by the vertex position uncertainty. With well estimated uncertainties, a value of \( d/\sigma \geq 3 \) would be a natural choice. However, the pull distributions indicate that the vertex position uncertainties are underestimated by a factor of two. Vertices with \( d/\sigma < 6 \) are therefore considered to be consistent with originating from material layers, and are rejected.

A requirement of fit \( \chi^2 \) probability > 0.001 is used to remove poorly reconstructed vertices. To further optimize the selection criteria for signal, a background sample is chosen such that its events have characteristics similar to events selected for analysis,
Figure 5.5: Regions of detector material (in color) in an x-y slice of the barrel, mapped using a combination of detailed detector geometry simulation, and hadronic material interactions reconstructed in data (taken from [58]).

Figure 5.6: (a) Track multiplicity and (b) angular distance ($\Delta R$) to the closest jet for vertices reconstructed in a set of signal MC benchmark samples and in a background dataset.
but with minimal contamination from signal events. Dijet events in data are selected by requiring a good IP (> 3 tracks with $p_T > 1$ GeV) from events passing single jet triggers at various thresholds. The $p_T$ threshold of the chosen single jet control region trigger is selected such that jets in the control region have similar characteristics ($p_T$, $\eta$, $\phi$) to those in the signal region.

$Z'$ signal events contain multiple jets and significant $E_T^{\text{miss}}$, while scalar boson and Stealth SUSY signal events are characterized by low $E_T^{\text{miss}}$ (and in the case of the Scalar boson, few medium $p_T$ jets). Therefore, different control regions are chosen for $Z'$ signal vertices and stealth SUSY (and scalar boson) signal vertices; the remaining selection criteria are also optimized separately for these two sets of signal samples. Two control regions selected with jet triggers at $E_T$ thresholds of 110 GeV and 280 GeV (EF_j110_a4tchad and EF_j280_a4tchad) are used to optimize selection criteria for vertices reconstructed in $Z'$ benchmark samples. $Z'$ signal events are characterized by high $E_T^{\text{miss}}$, and so a further requirement of $E_T^{\text{miss}} < 75$ GeV minimizes the number of signal-like events in the control region. Control regions for scalar boson and Stealth SUSY contain lower $p_T$ jets on average, and were also chosen with a single jet trigger.

Background vertices, both from material interactions and from random intersections of tracks, have on average a much lower track multiplicity than signal vertices, as seen in Figure 5.6 (a). Since the long-lived particles studied in this analysis all decay to hadronic jets, a significant fraction of the reconstructed vertices lie within a $\Delta R$ cone of the $\pi_\nu$ jet cone axis as shown in Figure 5.6 (b). The jets used in this study are required to pass the criteria stated in Section 3.3.

The metric $S/\sqrt{B}$ is used to select appropriate requirements on the track multiplicity (Figure 5.7) and size of the $\Delta R$ cone (Figure 5.8), where $S$ and $B$ are the

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3The dependence of the rate of reconstruction of background vertices was studied as a function of $E_T^{\text{miss}}$, and no significant dependence of the fake rate on $E_T^{\text{miss}}$ was found.
Figure 5.7: ID vertex reconstruction significance ($S/\sqrt{B}$) as a function of the number of tracks per vertex for various signals. The four signals are (a) low mass Scalar boson, (b) stealth SUSY benchmark samples, (c) $Z'$, and (d) high mass Scalar boson benchmarks samples. The background sample is di-jet data passing a single-jet trigger. The chosen values for the minimum number of tracks per vertex is $\geq 5$ ($\geq 7$) for the Scalar boson and stealth SUSY ($Z'$) benchmark samples.

A final selection criteria is chosen such that a good compromise is made between signal acceptance and background discrimination for the majority of benchmark samples. The maximum $S/\sqrt{B}$ for track multiplicity is highly correlated with LLP mass - reconstructed vertices in the $Z'$ benchmark samples are required to have at least seven associated tracks, while the lighter LLP masses of some Scalar boson benchmark samples result in a selection requirement of at least five tracks associated...
Figure 5.8: ID vertex reconstruction significance ($S/\sqrt{B}$) as a function of the $\Delta R$ between the ID vertex and the closest jet for various signals. The four signals are (a) low mass Scalar boson, (b) stealth SUSY, (c) $Z'$, and (d) high mass Scalar boson benchmark samples. The background sample is di-jet data passing a single-jet trigger. The chosen values for the $\Delta R$ between the ID vertex and the closest jet is $< 0.4$ for the Scalar boson and stealth SUSY ($Z'$) benchmark samples.

The size of the $\Delta R$ cone that gives the maximum $S/\sqrt{B}$ value also varies by benchmark sample; vertices selected for the $Z'$ and Scalar boson analyses are required to be within a $\Delta R$ cone of 0.6 or 0.4 from the center of a jet, respectively.

The final selection criteria are summarized in Table 5.3. The effect on the efficiency of applying the criteria to signal MC is shown in Figure 5.9. Tracks from decays of long-lived particles with higher $p_T$ and mass are more likely to be reconstructed, and
Table 5.3: Vertex selection criteria for vertices reconstructed in the ID.

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<td>$&gt; 0.001$</td>
<td>$&lt; 0.6$</td>
<td>$\geq 7$</td>
</tr>
<tr>
<td>Scalar boson</td>
<td>$\geq 6$</td>
<td>$&gt; 0.001$</td>
<td>$&lt; 0.4$</td>
<td>$\geq 5$</td>
</tr>
</tbody>
</table>

Figure 5.9: Effect on the signal efficiency after applying all the cuts for good vertices in the ID for three $Z'$ samples and three Scalar boson benchmark samples.

so benchmarks with heavier long-lived particles (or particles with higher average $p_T$) will have a higher efficiency after selection criteria are applied.

5.5 Vertex Reconstruction Efficiency

Figures 5.10, 5.11, 5.12, 5.13 show the ID vertex reconstruction efficiencies for the $Z'$, Stealth SUSY, and low and high-mass Scalar boson benchmark samples, respectively. Reconstructed vertices in MC benchmark samples are considered ‘good’ if they are pass the selection criteria described above. The efficiency is defined as the fraction of simulated displaced decays that are associated with a good reconstructed vertex that pass the selection criteria. The vertex reconstruction efficiency is correlated with the $\pi_v$ mass, since vertices from heavier long-lived particle decays will have a higher number of tracks.
Figure 5.10: ID Vertex reconstruction efficiency for $Z'$ samples with (a) $c\tau = 0.5$ m (b) $c\tau = 1.5$ m. Note that the vertex reconstruction efficiency as a function of the decay radial position is independent of mean proper lifetime, and so the efficiencies for the $Z'$ benchmark samples at $c\tau = 0.5$ m and 1.5 m are nearly identical for the same mass points.

Figure 5.11: ID Vertex reconstruction efficiency for stealth SUSY samples with (a) $m_{\tilde{g}} = 110, 250, \text{ and } 500$ GeV and (b) $m_{\tilde{g}} = 800$ and 1200 GeV.

Track reconstruction in the endcaps produces a non-negligible amount of combinatorial background, particularly from SCT-only seeds. Furthermore, the detector material map in the endcaps has higher position uncertainties due to the difficulty in selecting a low-background set of hadronic interactions vertices in this region. To check if these fake tracks cause a significant amount of background vertices, the
Figure 5.12: ID Vertex reconstruction efficiency for low-mass Scalar boson benchmark samples with (a) $m_\Phi = 100$ GeV, (b) $m_H = 125$ GeV, and (c) $m_\Phi = 140$ GeV.

signal vertex reconstruction efficiency as well as the reconstruction rate in data is checked separately for the endcap regions. Figures 5.14 show the reconstruction efficiency for vertices passing selection criteria in a set of simulated signal benchmark samples as a function of $z$. The contribution to the background from the endcaps was evaluated from 5 $fb^{-1}$ of data collected in 2012. Events that pass the signal $EF_{J110 \_a4tchad_xe75_tclw}$ trigger and have two reconstructed vertices (with loosened selection criteria, to increase background statistics) are counted. A slightly higher background rate was observed when the endcap regions were included. How-
Figure 5.13: ID Vertex reconstruction efficiency for high-mass Scalar boson benchmark samples with (a) $m_\Phi = 300$, and 600 GeV, and (b) $m_\Phi = 900$ GeV.

5.6 Data-Monte Carlo Comparison

A dijet control sample is used to understand differences in tracking and vertex reconstruction efficiencies between MC simulation and data. There are no known
long-lived particles that decay to hadronic jets in the Standard Model; $K_S^0$ vertices are used to study differences in track reconstruction with the modified algorithms. A $K_S^0 \to \pi^+\pi^-$ decay produces a two-track vertex that can be identified (with a low fake rate) using topological selection criteria.

Dijet events in data were selected from 6 fb$^{-1}$ of data collected in the first half of 2012. Dijet events in MC samples were selected from MC dijet JZ2W-JZ6W samples. In both data and simulation, a primary vertex with four or more tracks and two good jets with an opening angle of $|\Delta\phi| > 2.14$ are required. Figure 5.15 shows the momentum distribution for $K_S^0$ reconstructed in each simulated sample separately compared with the data in the barrel and endcaps. The shape of the momentum distribution is similar for all MC samples up to 20 GeV, and in order to maximize the statistics available from MC simulation, the $K_S^0$ distributions are added together without applying the scale factors described in Section 4.2.5.

![Figure 5.15](image-url)

Figure 5.15: The momentum distribution for $K_S^0$ reconstructed in data and in MC JZXW slices (a) in the barrel and (b) in the endcaps.

Two-track candidate vertices with a non-zero flight distance are selected by requiring that each track has $p_T > 0.1$ GeV and at least 2 silicon hits (to remove TRT-only tracks). Vertices that have a position consistent with originating from detector mate-
rial regions are excluded. A set of topological requirements are made on the vertices to select final $K^0_S$ candidates:

- The vertex fit $\chi^2 \geq 15$.
- Transverse flight distance (defined from the IP) $\geq 4$ mm
- The pointing angle $\theta$ between the candidate vertex momentum vector and the flight vector must satisfy $\cos \theta \geq 0.999$

Figures 5.16 and 5.17 show the distribution of the invariant mass of the selected two track candidates. The $K^0_S$ signal peak is fit with a double-gaussian function, where the means of the two constituent gaussian functions are constrained to be equal. This function has a good $\chi^2$/nDoF performance, and is stable for distributions in various detector regions. The combinatorial background is fit with a second-order polynomial. In order to minimize the combinatorial background in the signal region (within $3\sigma$ of the mass peak), parameter distributions from vertices reconstructed in the sideband regions (between $6\sigma$ and $9\sigma$) are subtracted from signal $K^0_S$ parameter distributions.

The vertex and track parameters for the $K^0_S$ vertices that pass all selection criteria are compared. Figure 5.18 shows the distributions in data and MC, as well as their pulls $^4$, for track $p_T$ and $d_0$, number of pixel hits on track, and number of silicon hits on track. All track variables show good agreement between data and simulation. Figure 5.19 compares the $p_T$, $P$ and vertex fit $\chi^2$ for $K^0_S$ reconstructed vertices; the distributions for $K^0_S$ decay vertices reconstructed in MC simulated samples are representative of those from data.

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$^4$The pull for a parameter $y$ is defined as: $(y_{data} - y_{MC})/\sqrt{\sigma^2_{data} + \sigma^2_{MC}}$
Figure 5.16: The mass distribution for $K_0^0$ reconstructed in data in the (a) barrel and (b) endcaps.

Figure 5.17: The mass distribution for $K_S^0$ reconstructed in MC JZXW slices in the (a) barrel and (b) endcaps.
Figure 5.18: Comparison of $K_S^0$ track (a) $p_T$, (b) $d_0$, (c) number of pixel hits and (d) number of SCT hits for reconstructed in dijet data and simulation. The data-MC pull distributions are shown below each comparison plot.
Figure 5.19: Comparison of (a) $p_T$, (b) $P$ and (c) fit $\chi^2$ for reconstructed $K_S^0$ vertices in dijet data and simulation. The data-MC pull distributions are shown below each comparison plot.
CHAPTER 6
DISPLACED VERTICES IN THE MUON SPECTROMETER

The muon spectrometer (MS) provides trigger and precision tracking capabilities for charged particles that pass through the calorimeters. Weakly-interacting particles with a long enough lifetime could decay towards the end of the calorimeters or in the muon spectrometer, producing detectable particle showers. The muon spectrometer has good acceptance for a wide range of lifetimes due to its large volume. Additionally, the low multiple scattering of charged particles makes the muon spectrometer well-suited for reconstruction of vertices with many tracks.

6.1 Signatures of Displaced Hadronic Decays in the Muon Spectrometer

Final state particles from $b\bar{b}$ decays have low momentum; if the decay occurs before the last layer of the hadronic calorimeter, the particles will be stopped by calorimeter material, and will not enter the muon spectrometer. Thus, detectable decay vertices are located between the tile calorimeter and the second layer of the muon spectrometer. A typical $\pi_v$ decay to a $b\bar{b}$ pair produces on average $\sim 10$ charged hadrons and $\sim 5$ neutral pions. In the MS, each charged hadron produces $\sim 20 - 25$ MDT hits, similar to a muon traversing the detector. However, a large number of additional hits are caused by electromagnetic showers from the neutral pions interacting with detector material. Figure 6.1 shows the number of MDT and RPC/TGC hits in events with a single $\pi_v$ decay. The MDT and trigger systems average $\sim 1000$ hits per event, a
Figure 6.1: Number of (a) MDT hits, and (b) RPC/TGC trigger hits in events with a $\pi_\nu$ decay in the MS barrel or endcaps.

majority of which are within a $\Delta R = 0.6$ cone of the $\pi_\nu$ decay. This high hit multiplicity poses a challenge to the standard muon segment finding algorithms, which were designed to reconstruct muon tracks in a relatively clean environment.

6.2 Tracklet Reconstruction

A new algorithm [59] has been developed to reconstruct trajectories of low $p_T$ particles in the busy environment characteristic of events with $\pi_\nu$ decays. The algorithm first reconstructs straight-line segments from a single MDT multi-layer containing at least three MDT hits, using a minimum $\chi^2$ fit. Segments with a $\chi^2$ probability greater than 5% are retained for track reconstruction. A typical simulated signal event contains $\sim 500$ such segments. Since a charged particle passing through all three stations would produce $\sim$six segments (two per chamber), and there are on average 10 charged particles in a $\pi_\nu$ decay, most of the initial reconstructed segments are fake. The large spatial separation between the two multilayers inside a single MDT chamber is utilized to reject fake segments and create segment pairs from charged hadrons.
Segments from the two multilayers in a single chamber are matched using two parameters illustrated in Figure 6.2: $\Delta b$, defined as the distance of closest approach between the pair of segments at the middle plane of the MDT chamber, and $\Delta \alpha$, the angle between the two segments. The matched segment pairs are known as tracklets. Requirements are placed on the maximum allowed values for $\Delta \alpha$ and $\Delta b$ during tracklet reconstruction (separately in the barrel and endcaps). Segment pairs in the barrel are refit as straight-line tracklets if their $|\Delta \alpha| < 12$ mrad. In the endcaps, due to the lack of a magnetic field, all tracklets with at least 6 MDT hits are refit as a straight line segment. In the case of barrel chambers, $\Delta \alpha$ is a measure of the bend angle inside the chamber, which can be used to measure the $p_T$ of the particle.

Figure 6.3 shows distributions for $\Delta b$ vs. $\Delta \alpha$ for tracklets reconstructed in the barrel and endcaps; the low diffuse background is due to the incorrect pairing of segments. The fraction of fake tracklets reconstructed is estimated from the $\Delta b$ distribution, shown for a set of signal benchmarks in Figure 6.4. The combinatorial background in the side-bands are fit to a straight line, which is then extrapolated to
the signal region. The fake rate is the fraction of tracklets under the background fit in the signal region, calculated to be 25% in the barrel and 5% in the endcaps\textsuperscript{1}.

\textsuperscript{1}The lower fake rate in the endcaps is due to the straight line refit.
6.3 Vertex Reconstruction

The muon spectrometer barrel is immersed in a magnetic field, and so reconstructed barrel tracklets have an associated momentum measurement. Endcap tracklets are fit as straight lines, with no measured momentum. Therefore, different algorithms are needed to reconstruct vertices in the barrel and endcaps.

6.3.1 Vertex Reconstruction in the MS Barrel

A cone algorithm is used to create clusters of tracklets. The algorithm is seeded by a single tracklet and searches for the cone of radius $\Delta R = 0.6$ (originating at the IP) that contains the maximum number of tracklets. The $\theta$ line-of-flight is computed from the IP to the centroid of the tracklet cluster. Since MDT hits are measured in two coordinates, each tracklet is assigned the $\phi$ coordinate of the chamber center, directed radially outward, and the average $\phi$ value is computed. The $\phi$ line-of-flight is then defined as the average position of all RPC hit $\phi$ measurements in a cone of $\Delta R = 0.6$ centered around these $(\theta, \phi)$ line-of-flight coordinates. The difference between the reconstructed line-of-flight and true $\pi_v$ line-of-flight is shown in Figure 6.6. The tracklets are then mapped onto the $r$-$z$ plane defined by the reconstructed line-of-flight, and back-extrapolated using the full magnetic field map to a set of lines between $r = 3.5$ m to $r = 7.0$ m, parallel to the $z$-axis. Figure 6.5 illustrates the tracklets and lines in the $r$-$z$ plane. The lines are spaced equally along the line-of-flight, with the distance between two adjacent lines being $25$ cm. This results in an increase in the number of lines as the $\eta$ of the line-of-flight increases. Each tracklet will thus be extrapolated by a constant distance along the line-of-flight, ensuring that the vertex reconstruction is consistent for different $\pi_v \eta$. The vertex $z$-position is calculated as the barycenter of the tracks, and a vertex $\chi^2$ probability is calculated using this $z$-position. If the probability is greater than $5\%$, the tracklet with the largest contribution to the $\chi^2$ probability is removed, and the new $z$-barycenter and $\chi^2$ probability
are calculated. This procedure is performed iteratively until a vertex with at least three tracklets and a $\chi^2$ probability less than 5% is found. The position residuals in $r$ and $z$ for reconstructed vertices are shown in Figure 6.7. Since this analysis tool has been developed for a search for new physics signatures, it is optimized to increase the vertex finding efficiency at the expense of reconstructed vertex resolution.

Figure 6.5: An illustration of the vertex reconstruction technique employed in the barrel muon spectrometer, shown for a simulated $\pi_\nu$ decay from the MC benchmark sample $m_H = 140$ GeV, $m_{\pi_\nu} = 20$ GeV.

6.3.2 Vertex Reconstruction in the MS endcaps

The endcap vertex reconstruction begins with the clustering of tracklets using the same cone algorithm utilized in the barrel; the line-of-flight is then calculated using the $\theta$ position of the tracklets, and average $\phi$ position of TGC hits within a $\Delta R = 0.6$ cone. Due to the lack of a magnetic field in the endcaps, the tracklets are then back-extrapolated as straight lines, as shown in Figure 6.8. The linear parametrization of the tracklets is input into a least squares regression fit to obtain an initial vertex position. If the furthest tracklet has a distance of closest approach more than 30 cm away from the vertex position, it is removed, and a new vertex position is calculated.
Figure 6.6: Angular difference between the long-lived particle true and reconstructed lines-of-flight for various benchmark samples.

This is done iteratively until the distance between the farthest tracklet and the vertex is less than 30 cm.

Figure 6.9 shows the position resolution of the reconstructed vertices in the MS endcaps. The position of the vertex is systematically shifted towards smaller values of $r_{\text{reco}}$ because of the lack of tracklet momentum and charge measurements. Vertices reconstructed in the endcaps also have worse resolution compared to those reconstructed in the barrel.
6.4 Good Vertex Criteria

Particles from jets that punch through the hadronic calorimeter can leave hits in the muon spectrometer. Hits from these punch-through jets in QCD events are the primary source of background for displaced tracklet and vertex reconstruction. Detector noise and hits from cosmic rays can also result in ‘fake’ vertices reconstructed in the muon spectrometer.

A set of selection criteria are applied to vertices used in this analysis to reject background events while retaining signal efficiency. The signal acceptance is optimized with respect to simulated QCD dijet background. Background events are required to...

Figure 6.7: Difference between the $R$ coordinate (left) and $z$ coordinate (right) of the reconstructed vertex and the true decay position for decays in the MS barrel for various benchmark samples.
pass the \( EF_{j360\_a4tchad} \) trigger, and the two highest-\( p_T \) jets must be separated by an angle \( |\Delta \phi| > 2.14 \). The metric \( S/\sqrt{B} \) is used to optimize the selection, where \( S \) and \( B \) are the fraction of signal and background events that survive a particular requirement. In cases where the \( S/\sqrt{B} \) distribution has a plateau (instead of a maximum), the final selection criteria is chosen where the \( S/\sqrt{B} \) begins to level off, in order to maximize signal acceptance.

Jets that punch through the calorimeter have significantly fewer hits in the muon system than signal displaced decays, as illustrated in Figures 6.10 and 6.11. A minimum number of MDT and RPC/TGC hits is required to remove the majority of punch-through jet background. A maximum number of MDT hits is also applied to remove background vertices caused by coherent noise bursts in the MDT system.

Jets in QCD events originate from the primary interaction; vertices in these events should also be associated to tracks and jets that originate at the IP. Requirements that vertices be isolated with respect to ID tracks and jets are applied. Figures 6.12 and 6.13 show the efficiency distribution as a function of the \( \sum p_T \) of nearby ID tracks,
in the barrel and endcaps, respectively. In the ID, there must be no high $p_T$ ID tracks ($p_T > 5$ GeV) in a $\Delta R = 0.6$ cone around the MS vertex, and the sum of low-$p_T$ ID tracks in this cone must be less than 10 GeV. The cone around the MS vertex must also not contain any calorimeter jets with $E_T > 30$ GeV with $\log_{10}(E_{\text{HAD}}/E_{\text{EM}}) < 0.5$. 

Figure 6.9: Difference between the $R$ coordinate (left plots) and $z$ coordinate (right plots) of the reconstructed vertex and the true decay position for decays in the MS endcaps for various benchmark samples.
Figure 6.10: The number of MDT hits in a cone of $\Delta R < 0.6$ around a displaced decay or punch-through jet in the barrel for (a) $Z'$, and (b) stealth SUSY benchmark samples.

Figure 6.11: The number of MDT hits in a cone of $\Delta R < 0.6$ around a displaced decay or punch-through jet in the endcaps for (a) $Z'$, and (b) stealth SUSY benchmark samples.

The full set of selection criteria for good MS vertices are listed in Table 6.1. Additional signal, background, and efficiency distributions for all selection criteria variables are listed in Appendix C.

After all selection criteria are applied, approximately 60 – 70% (40 – 60%) of reconstructed signal vertices are kept in the Scalar boson ($Z'$) samples, and 60% of
Figure 6.12: MS vertex reconstruction efficiency in the barrel as a function of the maximum $\sum p_T$ of nearby tracks for (a) $Z'$, and (b) stealth SUSY benchmark samples.

Figure 6.13: MS vertex reconstruction efficiency in the endcaps as a function of the maximum $\sum p_T$ of nearby tracks for (a) $Z'$, and (b) stealth SUSY benchmark samples.

signal vertices are retained in stealth SUSY samples. The exact percentage varies (moderately) based on the benchmark sample under consideration.

6.5 Vertex Reconstruction Efficiency

The efficiency for MS vertex reconstruction is defined as the fraction of truth-matched simulated $\pi_v$ decays in the MS fiducial volume that have a reconstructed
Table 6.1: Summary of good MS vertex criteria requirements in barrel and endcap regions.

<table>
<thead>
<tr>
<th>Description</th>
<th>Barrel Cut</th>
<th>Endcap Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of MDT hits</td>
<td>(300 \leq n\text{MDT} &lt; 3000)</td>
<td>(300 \leq n\text{MDT} &lt; 3000)</td>
</tr>
<tr>
<td>Number of RPC/TGC hits</td>
<td>(n\text{RPC} \geq 250)</td>
<td>(n\text{TGC} \geq 250)</td>
</tr>
<tr>
<td>High (p_T) track isolation</td>
<td>(\Delta R &lt; 0.3)</td>
<td>(\Delta R &lt; 0.6)</td>
</tr>
<tr>
<td>(\Sigma p_T) for nearby tracks</td>
<td>(\Sigma p_T &lt; 10 \text{ GeV})</td>
<td>(\Sigma p_T &lt; 10 \text{ GeV})</td>
</tr>
<tr>
<td>Jet isolation within</td>
<td>(\Delta R &lt; 0.3)</td>
<td>(\Delta R &lt; 0.6)</td>
</tr>
</tbody>
</table>

Figure 6.14: Effect on the signal efficiency after applying all the cuts for good vertices in the MS for (a) low-mass Scalar boson samples, (b) high-mass Scalar boson samples, (b) \(Z'\) samples, and (c) stealth SUSY samples.

vertex satisfying all of the criteria described above. Figure 6.15 shows the efficiency for reconstructing a vertex in the MS barrel and endcaps for the \(Z'\) benchmark samples.
Figure 6.15: (a),(b) Efficiency for reconstructing a vertex for $\pi_v$ decays in the MS barrel as a function of the radial position for different $Z'$ benchmark samples. (c),(d) Efficiency for reconstructing a vertex for $\pi_v$ decays in the MS endcaps as a function of the $|z|$ position for different $Z'$ benchmark samples.

The vertex reconstruction efficiency for $\pi_v$ in the barrel decreases significantly between the end of the calorimeter region ($r \sim 4\,\text{m}$) and the middle station ($r \sim 7\,\text{m}$), due to a corresponding decrease in spatial separation between the decay products. Because there is no magnetic field in the region in which endcap tracklets are reconstructed, the vertex reconstruction algorithm has different constraints in the endcaps. Consequently, the endcap vertex reconstruction has a higher efficiency but is also more likely to construct random background.
6.6 Data-Monte Carlo Comparison

Data and overlay MC simulated events are compared in order to study the differences in tracklet and vertex reconstruction between real and simulated data. This study uses a sample of QCD dijets that punch through the calorimeter and shower in the MS. The punch-through jet sample consists of events in the MS that contain both low-energy photons and charged hadrons.

Dijet events in data and simulation are selected with the $EF_{j360\_a4tchad}$ trigger, and are additionally required to have at least four IP tracks with $p_T > 1$ GeV. The two highest-$p_T$ jets are required to be approximately back-to-back ($|\Delta \phi| > 2.14$) and pass the jet quality criteria described in Section 3.3. Punch-through jets are selected from leading or sub-leading jets that are located in the 'punch-through region' of the calorimeter ($0.7 < |\eta| < 1.0$ or $1.5 < |\eta| < 1.7$), and have $E_T^{\text{miss}} > 30$ GeV within $|\Delta \phi| < 0.6$ of the jet axis.

![Fractional occupancy of MDT chambers](image)

Figure 6.16: Average fractional occupancy of chambers as a function of $\Delta R$ between the center of the MDT chamber and the punch-through jet’s axis (for the dijet data samples) or the $\pi_\nu$ decay position (for signal MC samples). Only punch-through jets with a minimum of 250 MDT hits are considered.

The detector signature of punch-through jets is compared to signatures produced by signal $\pi_\nu$ decays using the fractional occupancy of the MDT tubes per MDT
chamber. The fractional occupancy of a chamber is defined as the number of MDT hits observed divided by the total number of MDT tubes for a given chamber. Figure 6.16 shows the occupancy of MC signal $\pi_v$ decays that occur within the MS for two benchmark Scalar boson models. The fractional occupancy for punch-through jets is similar to that of signal events, and so can be used to characterize differences in vertex reconstruction between data and MC. The decay products of a heavier $\pi_v$ will have higher energy jets and a larger opening angle; this contributes to the long tail of the signal sample with $m_{\pi_v} = 40$ GeV (compared to the $m_{\pi_v} = 10$ GeV sample).

![Figure 6.16: Occupancy of MC signal $\pi_v$ decays](image)

Figure 6.17: Probability of finding a certain minimum number of MDT hits in a cone of $\Delta R < 0.6$ due to cavern background as a function of $\eta$.

A single muon passing through the detector, in combination with cavern background, can potentially mimic a punch-through jet. An upper limit on the number of misclassified punch-through jets is estimated from dijet data $^2$. This probability is calculated by counting the minimum number of MDT hits in a cone of $\Delta R < 0.6$ as a function of the cone axis’ $\eta$, for events that have no jets with $E_T > 25$ GeV within $\Delta R < 1.6$ of the cone axis. Figure 6.17 displays this probability as a function of the

$^2$Since the $E_T^{\text{miss}}$ requirement will not typically be met, the actual rate is overestimated.
cone $\eta$. The data sample contains 3 million dijet events passing the single jet trigger; the probability of finding at least 220 MDT hits in the barrel is $3.0 \times 10^{-5}$ and the probability of finding at least 220 MDT hits in the endcaps is $3.8 \times 10^{-5}$.

A single muon would contribute $\sim 30$ additional hits; a total requirement of at least $> 250$ MDT hits is therefore implemented. All three million dijet MC events are assumed to satisfy the punch-through jet’s $E_{\text{T}}^{\text{miss}}$ requirement, in order to estimate an upper limit on the number of jets that are incorrectly considered punch-through jets as a result of a single muon combined with cavern background MS hits. This results in $(3 \text{ million events}) \times (1 \text{ jet per event}) \times (3.0 \times 10^{-5}) = 90$ events in the barrel and $(3 \text{ million events}) \times (1 \text{ jet per event}) \times (3.8 \times 10^{-5}) = 114$ events in the endcaps. This number is negligible compared to the data sample, which contains 3216 (3551) punch-through jets in the barrel (endcaps). It is therefore concluded that the cavern background does not significantly contaminate the selected punch-through jet samples if a requirement of at least 250 MDT hits in the barrel or endcaps is implemented.
CHAPTER 7
ANALYSIS

This analysis describes a search for a $Z'$-mediated Hidden Valley scenario with hidden sector particles ($\pi_\nu$) that decay to hadronic jets, performed with 20.3 fb$^{-1}$ of data collected by the ATLAS detector in 2012. Some of these particles have long lifetimes and travel through part of the detector volume before decaying, making for a very distinctive experimental signature. Algorithms for vertex reconstruction in the inner detector (Chapter 5) and muon spectrometer (Chapter 6) are used to reconstruct displaced decay vertices. Figure 7.1 shows the fraction of $\pi_\nu$ decays in the fiducial volume of each sub-detector for a benchmark sample with $m_{Z'} = 2$ TeV and $m_{\pi_\nu} = 50$ GeV. The combination of vertex reconstruction tools in the inner detector and muon spectrometer maximizes the signal acceptance for a large range of particle proper lifetimes. The analysis considers events with two reconstructed displaced decay vertices (two inner detector vertices, two muon spectrometer vertices, or one in each sub-system) - the two-vertex requirement serves as a powerful discriminator against background from mis-reconstructed vertices.

$Z'$ signal events contain multiple prompt and displaced decays to $b\bar{b}$ pairs; prompt decays and displaced decays occurring before the electromagnetic calorimeter will both give rise to reconstructed jets. Since these events can contain many long-lived $\pi_\nu$ (an average of $\sim 4$ in the case of the $m_{Z'} = 2$ TeV and $m_{\pi_\nu} = 50$ benchmark sample), there is a significant probability that one or more of these particles will escape the calorimeter volume and contribute to the missing transverse energy ($E_T^{\text{miss}}$) of the event. Signal events are therefore characterized by multiple jets and substantial $E_T^{\text{miss}}$. 
Figure 7.1: Fraction of $\pi_v$ decays occurring in various ATLAS sub-detector volumes as a function of mean proper lifetime for the $Z'$ benchmark with $m_{Z'} = 2$ TeV and $m_{\pi_v} = 50$ GeV.

Figure 7.2 shows the $p_T$ of the leading jet for all $Z'$ events. The reconstructed $E_T^{\text{miss}}$ is shown in Figure 7.3. The average $E_T^{\text{miss}}$ is higher for benchmarks with higher $\pi_v$ proper lifetime, due to the increased probability for a $\pi_v$ to decay after the calorimeters.

Figure 7.2: Leading jet $p_T$ distributions for $Z'$ benchmark samples with (a) $c\tau = 0.5$ m and (b) $c\tau = 1.5$ m

Another distinguishing feature of $Z'$ events is the possibility of more than two decays within the detector volume. The number of $\pi_v$ per event decaying in the
Figure 7.3: $E_{T}^{\text{miss}}$ distributions for $Z'$ benchmark samples with (a) $c\tau = 0.5$ m and (b) $c\tau = 1.5$ m.

inner detector fiducial volume is shown as a function of lifetime in Figure 7.4 (a), and the average $\pi_\nu$ per event at each lifetime is shown in Figure 7.4 (b). At very short lifetimes, there is a high probability that events have more than two detectable vertices in the inner detector, which increases the sensitivity for this region of phase space.

Figure 7.4: (a) Number of decays in the ID vertex reconstruction fiducial volume as a function of $c\tau$ and (b) Average number of displaced decays in the ID fiducial volume as a function of $c\tau$. 
7.1 Trigger and Event Selection

A single jet plus $E_T^{\text{miss}}$ trigger with a jet $E_T$ threshold of 110 GeV and an $E_T^{\text{miss}}$ threshold of 75 GeV ($EF_{j100\_a4tchad\_x075\_tclcw}$, also referred to as the jet + $E_T^{\text{miss}}$ trigger in this chapter), described in 4.1, has a high efficiency for the signal samples used in this analysis. Offline selection criteria are determined from the trigger turn-on dependence of the leading jet $p_T$ and the $E_T^{\text{miss}}$ of the event, both of which are shown in Figure 7.5. These distributions show the fraction of events passing the trigger as a function of the leading jet $p_T$ and the $E_T^{\text{miss}}$ in $Z'$ signal MC samples. The criteria $p_T \geq 120$ GeV and $E_T^{\text{miss}} \geq 200$ GeV are selected such that the trigger efficiency is constant beyond these values. The efficiency on the plateau for the trigger jet $p_T$ requirement is less than one because events with a high $p_T$ jet may not satisfy the $E_T^{\text{miss}}$ requirement. Conversely, the $E_T^{\text{miss}}$ plateau is reached at 200 GeV, and most events with high $E_T^{\text{miss}}$ also have at least one high $p_T$ jet.

Figure 7.5: Trigger turn-on curves for the jet+$E_T^{\text{miss}}$ trigger for (a) leading jet $p_T$ and (b) $E_T^{\text{miss}}$.

Table 7.1 lists the number of events that survive the online trigger and offline jet $p_T$ and $E_T^{\text{miss}}$ requirements. The $Z'$ benchmark with $m_{Z'} = 1$ TeV and $m_{\pi_v} = 50$ GeV has fewer long-lived $\pi_v$ per event due to the relatively light mass of the $Z'$, and so the probability of a $\pi_v$ escaping the calorimeters and contributing substantially to the
Table 7.1: Selection efficiency after applying trigger and offline jet $p_T$ requirements for the $Z'$ benchmarks

$E_T^{\text{miss}}$ is low. All benchmarks have a lower trigger efficiency at a proper lifetime of $c\tau = 0.5$ m for the same reason. The benchmark samples with $m_{Z'} = 2$ TeV have higher efficiencies due to the high multiplicity of $\pi_v$ (for the benchmark with $m_{\pi_v} = 50$ GeV) or the relatively heavy mass of the $\pi_v$ (in the case of the benchmark with $m_{\pi_v} = 120$ GeV).

Events are required to have a good IP, with at least four tracks with $p_T > 1$ GeV. Events are also required to have two vertices in the inner detector or muon spectrometer that pass selection criteria described in Sections 5.4 and 6.4. These selection criteria are summarized below.

- Vertices reconstructed in the inner detector are required to satisfy the following criteria:
  - $d/\sigma > 6$, where $d/\sigma$ is the distance to the nearest material layer divide by the vertex position uncertainty.
  - Vertex fit $\chi^2$ probability $> 0.001$
- Number of tracks $> 7$
- $\Delta R(\text{vertex, jet}) < 0.6$, where $\Delta R$ is calculated between the vertex and the axis of the nearest jet.

- Reconstructed vertices in the muon spectrometer barrel are required to satisfy the following criteria:
  - Number of MDT hits $300 < n_{MDT} < 3000$
  - Number of RPC hits $n_{RPC} > 250$
  - No tracks within $\Delta R 0.3$
  - Track $\Sigma p_T < 10$ GeV
  - No jet within $\Delta R 0.3$

- Reconstructed vertices in the muon spectrometer endcaps are required to satisfy the following criteria:
  - Number of MDT hits $300 < n_{MDT} < 3000$
  - Number of TGC hits $n_{TGC} > 250$
  - No tracks within $\Delta R 0.6$
  - Track $\Sigma p_T < 10$ GeV
  - No jet within $\Delta R 0.6$

Table 7.2 lists the number of signal benchmark events that pass the trigger requirements, and also have two reconstruction vertices that satisfy selection criteria. The benchmark sample with a $Z'$ of mass 2 TeV, and a $\pi_v$ of mass 50 GeV has on average $\sim 4$ displaced decays per event, and so has the highest acceptance for displaced vertex reconstruction.
Table 7.2: Number of events that pass each consecutive event selection requirement, and final signal acceptance for all $Z'$ benchmark samples.

<table>
<thead>
<tr>
<th>$m_{Z'}$ = 1 TeV</th>
<th>$m_{Z'}$ = 2 TeV</th>
<th>$m_{Z'}$ = 2 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\tau_\nu}$ = 50 GeV</td>
<td>$m_{\tau_\nu}$ = 50 GeV</td>
<td>$m_{\tau_\nu}$ = 120 GeV</td>
</tr>
<tr>
<td>$cT_{\tau_\nu} = 0.5$ m</td>
<td>$cT_{\tau_\nu} = 0.5$ m</td>
<td>$cT_{\tau_\nu} = 0.5$ m</td>
</tr>
<tr>
<td>Processed Events</td>
<td>357739</td>
<td>376977</td>
</tr>
<tr>
<td>Trigger</td>
<td>130586</td>
<td>262828</td>
</tr>
<tr>
<td>min. Jet $p_T$ and min. $E_T^{miss}$</td>
<td>50362</td>
<td>160133</td>
</tr>
<tr>
<td>Two good vertices (total)</td>
<td>907</td>
<td>3963</td>
</tr>
<tr>
<td>(ID+ID / ID+MS / MS+MS)</td>
<td>13 / 381 / 513</td>
<td>252 / 1337 / 2374</td>
</tr>
<tr>
<td>Acceptance (%)</td>
<td>0.25%</td>
<td>1.05%</td>
</tr>
<tr>
<td>$cT_{\tau_\nu} = 1.5$ m</td>
<td>$cT_{\tau_\nu} = 1.5$ m</td>
<td>$cT_{\tau_\nu} = 1.5$ m</td>
</tr>
<tr>
<td>Processed Events</td>
<td>309919</td>
<td>261025</td>
</tr>
<tr>
<td>Trigger</td>
<td>158367</td>
<td>200554</td>
</tr>
<tr>
<td>min. Jet $p_T$ and min. $E_T^{miss}$</td>
<td>68466</td>
<td>132118</td>
</tr>
<tr>
<td>Two good vertices (total)</td>
<td>1500</td>
<td>4906</td>
</tr>
<tr>
<td>(ID+ID / ID+MS / MS+MS)</td>
<td>7 / 197 / 1296</td>
<td>49 / 677 / 4180</td>
</tr>
<tr>
<td>Acceptance (%)</td>
<td>0.48%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

7.2 Systematic Uncertainties

The trigger and vertex reconstruction efficiencies are derived from Monte Carlo simulated samples, and systematic uncertainties based on corrections applied to the simulation are calculated in this section.

7.2.1 Inner Detector Vertex Reconstruction

The primary contribution to the uncertainty on the vertex reconstruction is inherent to the use of simulation to model both the detector response and subsequent track and vertex reconstruction. Other contributions arise from corrections applied to simulated samples: pileup reweighing and jet energy scale corrections. The PDF uncertainty also contributes to the total systematic uncertainty.
7.2.1.1 Differences in Reconstruction Between Data and Simulation

Signal vertices are reconstructed from hadronic decays, and so are characterized by high track-multiplicity vertices. Since there are no long-lived particles in the Standard Model that decay to hadronic jets, the reconstruction uncertainty is obtained in a two-step process. First, the difference in tracking efficiency between data and MC simulation for tracks with large impact parameters is determined from $K^0_S$ decays (Section 5.6). The $K^0_S$ yield as a function of vertex position is obtained from data and MC simulation. The decay position distributions for data and MC samples are scaled by the number of $K^0_S$ vertices inside the beampipe for each sample respectively, to correct for differences in the total $K^0_S$ yield between data and simulation. The scaled decay position distributions for data and MC in the barrel and endcaps are illustrated in Figure 7.6; Figure 7.7 shows the data-MC ratio of these normalized yields. The weighted averages of the yield ratios are $0.99 \pm 0.03$ in the ID barrel, and $1.01 \pm 0.05$ in the endcaps. The weighted averages are consistent with one in both cases, and so the statistical uncertainty, 3% in the barrel and 5% in the endcaps, is taken as the systematic uncertainty on the $K^0_S$ reconstruction efficiency. Because each of the two tracks contribute to $K^0_S$ vertex reconstruction, the $K^0_S$ reconstruction efficiency is proportional to the square of the track efficiency. A per-track uncertainty is then calculated using the following equation:

\[
\frac{\text{data/MC deviation in } K^0_S \text{ reconstruction}}{1 - \epsilon_{data}/\epsilon_{MC}} = 1 - (\text{ratio of track reco. uncertainty in data and MC})^2
\]

The above equation is inverted to obtain systematic uncertainties of 2% and 3% for track reconstruction in the barrel and endcaps, respectively.
Figure 7.6: The $K^0_S$ lifetime distribution normalized by the $K^0_S$ yield inside the beam pipe (a) in the barrel and (b) in the endcaps.

Figure 7.7: The ratio of data to MC of the normalized lifetime yield (a) in the barrel and (b) in the endcaps. The red line, the weighted average value across all bins, shows the data-MC scale factor.

To propagate the per-track uncertainty to the vertex reconstruction, 2% of barrel tracks and 3% of endcap tracks are randomly removed from signal MC samples during track selection for vertex finding. This method is based on the assumption that the primary contribution to the vertex reconstruction uncertainty from data and simulation differences is the corresponding uncertainty at the track reconstruction stage. The weighted average of the ratio of the reconstruction efficiency with and without
tracks removed is taken as the systematic uncertainty on the vertex reconstruction efficiency, and ranges from 2.1% to 2.5% for the simulated benchmark samples.

7.2.1.2 Pileup Re-weighting

The increased luminosity delivered by the LHC in 2012 also meant a significant increase in the number of simultaneous proton-proton collisions (pileup). Increased pileup leads to a denser tracking environment (many more detector hits), which is an additional challenge for track pattern recognition.

Figure 7.8 (a) shows the efficiency for one $Z'$ benchmark sample ($m_{Z'} = 1$ TeV, $m_{\pi_v} = 50$ GeV, and $c\tau_{\pi_v} = 1.5$ m) for different ranges of number of interactions per bunch crossing for vertices (⟨$\mu$⟩) passing all selection criteria. As expected, the vertex reconstruction efficiency is significantly lower in events with higher pileup. The right panel shows the purity for all vertices for low and high pileup. The increase in pileup causes an increase in the number of non-matched vertices with two or three tracks, due to random combinations from a higher number of reconstructed tracks.

Figure 7.8: (a) Vertex reconstruction efficiency for all vertices passing good vertex criteria, and (b) number of non truth-matched vertices with at least 5 tracks for a $Z'$ benchmark sample with $m_{Z'} = 1$ TeV, $m_{\pi_v} = 50$ GeV, and $c\tau_{\pi_v} = 1.5$ m
Since the overlay MC signal samples were produced with a subset of the full 2012 dataset, the simulated datasets are re-weighted to match the $\langle \mu \rangle$ distribution in the full 2012 dataset, following the method stated in Section 4.2.6. A comparison of the efficiency before and after the re-weighting procedure is applied is shown in Figure 7.9 (a). To evaluate the systematic uncertainty from this re-weighting procedure, the $\langle \mu \rangle$ distribution in the MC samples is shifted up and down by the total statistical uncertainty. The difference in the efficiency is calculated for each benchmark model, and the difference from the default efficiency is taken as the systematic uncertainty. Figure 7.9 (b) shows the weighted average of the ratio of the default and modified (pileup down-shifted) reconstruction efficiency for one benchmark sample. The re-weighting procedure contributes an uncertainty of $\sim 0.1\%$.

![Figure 7.9: (a) Vertex reconstruction efficiency for all vertices passing good vertex criteria in default and pileup re-weighted events, and (b) weighted average of the ratio of default and shifted events in a $Z'$ benchmark sample with $m_{Z'} = 1$ TeV, $m_{\pi_v} = 50$ GeV, and $c\tau_{\pi_v} = 0.5$ m](image)

### 7.2.1.3 Jet Energy Scale (JES) Calibration

The jet energy scale (JES) calibration applied to reconstructed jets in simulation has an associated uncertainty, described in Section 3.3. Selection criteria applied to ID vertices requires association with a jet; the effect of the JES uncertainty on vertex
reconstruction is given by shifting the $p_T$ of all reconstructed jets up/down by their relative uncertainties. The maximum difference in vertex reconstruction efficiency from the nominal is taken as the systematic, and is found to be between 0.4% and 0.6% percent for the benchmark samples.

### 7.2.1.4 Parton Distribution Functions

The final contribution to the systematic uncertainty on vertex reconstruction arises from the application of parton distribution functions (PDFs) to simulation; this includes uncertainties inherent to the PDF, as well as uncertainties based on the choice of PDF used in simulation. Events are weighted up or down according to the PDF used for a set of three different PDFs, and the systematic uncertainty is assigned as the difference with respect to the default efficiency. For the $Z'$ benchmarks, this value is $\sim 0.3%$

All of the contributions to the systematic uncertainties described above are added in quadrature. Other possible sources of systematic uncertainty are negligible compared to the uncertainty related to the track and vertex reconstruction. Table 7.3 summarizes the ID vertex reconstruction systematic uncertainties for signal MC.

<table>
<thead>
<tr>
<th>$m_{Z'}$ [TeV]</th>
<th>$m_{\pi}$ [GeV]</th>
<th>Track reco.</th>
<th>Pileup</th>
<th>JES</th>
<th>PDF</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>2.4%</td>
<td>&lt;0.1%</td>
<td>0.6%</td>
<td>0.3%</td>
<td>2.5%</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>2.5%</td>
<td>0.1%</td>
<td>0.4%</td>
<td>0.3%</td>
<td>2.6%</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>2.1%</td>
<td>&lt;0.1%</td>
<td>0.4%</td>
<td>0.3%</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

Table 7.3: Summary of ID vertex systematic uncertainties for the $Z'$ benchmark samples.

### 7.2.2 Muon Spectrometer Vertex Reconstruction

The primary source of systematic uncertainty is the modeling in simulation of hadronic showers in the muon spectrometer. Other contributions to the total systematic uncertainty include pileup, JES, and ISR.
7.2.2.1 Differences in Reconstruction Between Data and Simulation

The difference in reconstruction of showers in the MS are studied by comparing punch-through jets in data and simulation (Section 6.6). The method used to calculate reconstruction systematic uncertainty is analogous to the method for ID track and vertex reconstruction. First, distributions of number of tracklets found within a $\Delta R < 0.6$ cone of a punch-through jet are compared in data and MC. Figure 7.10 shows the distribution of number of tracklets from punch-through activity in the MS. The weighted average of the ratio of the yield in data and MC, shown in Figure 7.11, is $0.96 \pm 0.05$ in the barrel and $0.89 \pm 0.05$ in the endcaps. Systematic uncertainties in tracklet finding of 5% and 11% are assigned to the barrel and the endcaps respectively.

The systematic uncertainty of tracklet reconstruction is propagated to MS vertex reconstruction by randomly removing tracklets with a probability equal to the tracklet reconstruction uncertainty. The weighted average of the ratio of the efficiency with and without tracklets removed is the systematic uncertainty for each MC signal sample. The resulting uncertainties range between 5% and 7%.

![Figure 7.10: The number of tracklets found within $\Delta R < 0.6$ of the jet axis (a) in the barrel and (b) in the endcaps.](image)
7.2.2.2 Additional Contributions

The effect of pileup re-weighting, JES calibration uncertainty, and the PDF uncertainty on the MS vertex reconstruction are calculated using the same procedures used for the ID vertex systematic uncertainties. Shifting the $\langle \mu \rangle$ distributions in MC simulation up and down by the statistical uncertainties changes the acceptance of MS vertices by up to 0.3%. MS vertices are required to be isolated from jet activity in the calorimeter; uncertainties on the JES calibration can affect the acceptance of this requirement. When the energy of each jet is increased or decreased by its JES uncertainty, the acceptance rate of MS vertices changes by up to 0.2%. Jets from initial state radiation can also affect the isolation criteria. The jet energy is fluctuated by 5% to account for ISR uncertainty, which changes the acceptance rate of MS vertices by up to 0.3%. Weighting the events as a consequence of the PDF uncertainty results in MS vertex acceptance changes of up to 0.3%.

Other potential sources of systematic uncertainty are negligible compared to the uncertainty related to the vertex reconstruction, and are summarized in Tables 7.4 and 7.5. The dominant uncertainty is due to inherent differences of the simulation.

Figure 7.11: The ratio of data to MC distributions on number of tracklets found within $\Delta R < 0.6$ of the jet axis (a) in the barrel and (b) in the endcaps.
from data. The total systematic uncertainty of reconstructing a vertex is found by adding in quadrature the contributions of all of the above systematic uncertainties.

<table>
<thead>
<tr>
<th>$m_{Z'}$ (TeV)</th>
<th>$m_{\pi_v}$ (GeV)</th>
<th>Track reco.</th>
<th>Pileup</th>
<th>ISR</th>
<th>JES</th>
<th>PDF</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>6.8%</td>
<td>&lt;0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>6.8%</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>7.0%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.2%</td>
<td>7.0%</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>6.6%</td>
<td>&lt;0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.2%</td>
<td>6.6%</td>
</tr>
</tbody>
</table>

Table 7.4: Summary of MS vertex systematic uncertainty in the barrel for the $Z'$ benchmark samples.

<table>
<thead>
<tr>
<th>$m_{Z'}$ (TeV)</th>
<th>$m_{\pi_v}$ (GeV)</th>
<th>Track reco.</th>
<th>Pileup</th>
<th>ISR</th>
<th>JES</th>
<th>PDF</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>6.3%</td>
<td>&lt;0.1%</td>
<td>0.3%</td>
<td>0.2%</td>
<td>0.1%</td>
<td>6.3%</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>6.6%</td>
<td>0.1%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>0.2%</td>
<td>6.6%</td>
</tr>
<tr>
<td>2</td>
<td>120</td>
<td>5.2%</td>
<td>0.1%</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.3%</td>
<td>5.2%</td>
</tr>
</tbody>
</table>

Table 7.5: Summary of MS vertex systematic uncertainty in the endcaps for the $Z'$ benchmark samples.

### 7.2.3 Trigger Uncertainty

The jet + $E_T^{\text{miss}}$ trigger and corresponding selection criteria on reconstructed jets and $E_T^{\text{miss}}$ also include corresponding uncertainties (JES calibration uncertainties, for example). Since the trigger efficiency is dependent on the $\pi_v$ mean proper lifetime, a method is utilized to extrapolate the events selection efficiency to arbitrary proper lifetimes. This method will be described in Section 7.4. The uncertainty on the number of selected events associated with this extrapolation procedure was found to be significantly higher than the effect of jet and $E_T^{\text{miss}}$ reconstruction uncertainties; the contribution from object reconstruction is considered negligible, and not included in the analysis.
7.3 Expected Background

In order to estimate the expected number of background events, it is necessary to quantify the frequency with which the ID and MS vertex algorithms reconstruct vertices for non-signal events (known as ‘fake’ vertices). The frequency of fake vertex reconstruction is estimated from data events. Calculating the fake rate from data has a few advantages - systematic uncertainties associated with the use of simulated datasets can be avoided, and statistical uncertainties are smaller because there are relatively few simulated events of the dominant background processes. The control regions used to obtain the ID and MS vertex fake rates are listed in Tables 7.6.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Control 1</th>
<th>Control 2</th>
<th>Control 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>Low $p_T$ IDvx fake rate</td>
<td>High $p_T$ IDvx fake rate</td>
<td>MSvx fake rate</td>
</tr>
<tr>
<td>Offline sel.</td>
<td>jet $E_T \lessgtr 110$ GeV</td>
<td>jet $E_T \lessgtr 280$ GeV</td>
<td>minBias</td>
</tr>
<tr>
<td></td>
<td>120 GeV &lt; jet $p_T$ &lt; 300 GeV $E_T^{miss} &lt; 75$ GeV</td>
<td>jet $p_T \geq 300$ GeV $E_T^{miss} &lt; 75$ GeV</td>
<td>N/A</td>
</tr>
<tr>
<td>Vertices</td>
<td>1 IDvx</td>
<td>1 IDvx</td>
<td>1 MSvx</td>
</tr>
</tbody>
</table>

Table 7.6: Analysis control regions.

7.3.1 ID Vertex Reconstruction Fake Rate

Modifications to the standard vertex reconstruction routine relax selection criteria designed to suppress the reconstruction of fake vertices from poorly reconstructed tracks. Furthermore, real processes such as a cosmic ray passing close to ID tracks produced by a jet can mimic the displaced decay of a heavier particle, producing a cluster of tracks that may be fitted as a vertex within the jet cone. Control regions in data are used to measure the rate at which the these mis-reconstructed vertices are produced in the inner detector. The vertex reconstruction rate is slightly proportional to the $p_T$ of the jet; it is therefore necessary to calculate the vertex reconstruction rate using a background sample that has a similar jet $p_T$ spectrum to events selected...
for the analysis. The control sample is split into two regions based on the leading jet $p_T$, and a separate fake rate is calculated for each region. Events with a leading jet $p_T$ between 120 GeV and 300 GeV are selected using the $EF_{j110,a4tchad}$ single jet trigger (control region 1). The $EF_{j280,a4tchad}$ trigger is used to obtain adequate statistics for selected events with leading jet $p_T > 300$ GeV (control region 2). The background sample should also not contain potential signal events; all selected events are therefore required to have $E_T^{\text{miss}} < 75$ GeV to minimize contamination from signal events.

Figure 7.12: For vertices reconstructed in selected dijet events in 2012 data: the number of tracks in the vertex (left), and the vertex fit probability (right)

Figure 7.13: For vertices reconstructed in selected dijet events in 2012 data: the r-z position (left), and distance to material (right)
A collection of jets passing the quality criteria described in Section 3.3 is made from events passing these requirements, and vertices reconstructed within these jet cones are studied. Figures 7.12 and 7.13 show the number of tracks per vertex, vertex fit probability, vertex $r$-$z$ position, and distance to nearest material in units of the vertex position uncertainty for vertices reconstructed in selected dijet events in 2012 data within $\Delta R = 0.6$ of a good jet. Reconstructed vertices are primarily low track-multiplicity vertices from random track crossings within the jet cone (Figure 7.12 (a)), and vertices from interactions with detector material (the peak at zero in Figure 7.13 (b)).

<table>
<thead>
<tr>
<th>Selected events</th>
<th>Average jets per event</th>
<th>'Good' vertices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control region 1</td>
<td>4,402,360</td>
<td>3.38</td>
</tr>
<tr>
<td>Control region 2</td>
<td>4,120,600</td>
<td>4.08</td>
</tr>
</tbody>
</table>

Table 7.7: The number of events passing selection, the average number of jets per event, and the number of vertices found after applying good vertex criteria for the control regions.

Figure 7.14: Probability of reconstruction a ‘good’ ID vertex within the $\Delta R$ cone of a jet for leading and non-leading jets in 2012 data control region.
Jets associated to vertices passing the ID good vertex criteria (considered fake vertices) are counted in data. Table 7.7 shows the number of events selected, the average number of jets per event, and the number of vertices found passing the good vertex criteria for the two control regions. The vertex reconstruction probability increases with an increase in jet $p_T$, and leading jets have a slightly lower average vertex fake rate than non-leading jets. In control region 1, the leading jet fake rate in 2012 data is calculated to be $(4.3 \pm 3.1) \times 10^{-6}$ in selected events with a leading jet $p_T$ in the ranges $120 - 300$ GeV. There were no non-leading jets associated with fake vertices in this data sample (due to low event statistics). Since the non-leading jet fake rate is slightly higher than the leading jet fake rate, a scale factor is computed from the higher $p_T$ control region by dividing the non-leading and leading jet fake rates above 300 GeV. This scale factor is then applied to the leading jet fake rate in control region 1 to obtain a corresponding fake rate for non-leading jets. Figure 7.14 shows the fake rate for leading and non-leading jets as a function of the jet $p_T$ for leading and non-leading jets in both control regions. These fake vertex probabilities are then applied separately for all leading and non-leading jets in events selected for the analysis.

### 7.3.2 MS Vertex Reconstruction Fake Rate

To measure the probability of randomly reconstructing an MS vertex, $P(\text{MSVTX})$, a sample of events passing a minimum bias trigger is selected, and the fraction of events that contain a good, reconstructed MS vertex is determined. Such events with a single vertex are assumed to be fake vertices not due to displaced decays. Signal events can contaminate this control region; this would lead to an overestimate in the fake vertex reconstruction probability, and would therefore yield a conservative value for the number of expected two-vertex background events.
In the 2012 dataset, zero events that contained a good MS vertex were found out of 6,168,200 events. Since the number of events is large and the per-event probability of observation is low, the Poisson approximation of the binomial distribution is taken as the 95% confidence interval. The Poisson distribution gives the probability \( P \) of making \( n \) observations in a trial with a mean number of observations per trial \( \mu \) by the equation \( P(n; \mu) = \frac{\mu^n e^{-\mu}}{n!} \). If zero events are observed in a test, a confidence interval of 95% on \( \mu \) is given by \( P(0, \mu) = \mu^0 e^{-\mu}/0! = 0.05 \), from which \( \log 0.05 = 2.9957 \approx 3 \). From this, the best estimate of \( P(MSVTX) \) is zero, and the true value of \( P(MSVTX) \) is less than \( 3/6,168,200 = 4.86 \times 10^{-7} \) at the 95% confidence level.

As a cross-check, the probability of reconstructing a vertex in data events passing the \( EF_{j360,4tchad} \) trigger is also calculated. The probability was found to be \( 42/(1.43 \times 10^7) = (2.9 \pm 0.5) \times 10^{-6} \), which is about a factor of six greater than the estimate calculated from minimum bias events.

### 7.3.3 Expected Background Events

Data events studied in this analysis are required to have two reconstructed vertices in any of three configurations: MS+MS, MS+ID, and ID+ID vertices. In all cases listed below, the expected background is calculated only from the subset of events that pass the signal trigger requirement.

#### 7.3.3.1 ID Vertex + ID Vertex

The estimated number of background ID+ID events is the probability of selecting two jets in a event multiplied by their vertex fake rates, summed over all selected events passing the event selection:

\[
N_{Fake}(\text{trig, 2 IDvtx}) = \sum_{i} P_{2 \text{ ID Vertices}}(nJets_i),
\]

where
\[ P_{2 \text{ ID Vertices}}(n_{\text{Jets}_i}) = \sum_{n_{\text{Jets}} \geq 2} \frac{{n_{\text{Jets}} \choose n_{\text{IDs}}}}{n_{\text{Jets}}} \times (P_{\text{ID,reco}})^{n_{\text{IDs}}} \times (1 - P_{\text{ID,reco}})^{n_{\text{Jets}} - n_{\text{IDs}}} \]

\[ \approx \left( \frac{n_{\text{Jets}}}{2} \right) \times (P_{\text{ID,reco}})^2. \]

The expected number of events is calculated to be \( N_{\text{Fake}}(\text{trig, 2 IDvtx}) = (1.8 \pm 0.4) \times 10^{-4} \).

### 7.3.3.2 ID Vertex + MS Vertex

To estimate the number of background ID + MS events, the number of events passing the signal event selection that also have a good reconstructed MS vertex is multiplied by the probability of finding a fake ID vertex in the event.

\[ N_{\text{Fake}}(\text{trig, 1 IDvtx, 1 MSvtx}) = \sum_{\text{ID trig+MSVx events}} n_{\text{Jet}_i} \times P_{\text{ID,reco}}. \]

There are 29 events passing the \( Z' \) event selection criteria that also have a good reconstructed MS vertex. The per-jet ID vertex reconstruction rates described in section 7.3.1 are applied to jets from these 29 events, and the expected number of events obtained is \( N_{\text{Fake}}(\text{trig, 1 MSvtx, 1 IDvtx}) = (5.5 \pm 0.9) \times 10^{-4} \).

The expected number of background events for this final state topology can also be calculated by counting the number of events which pass event selection and have a good ID vertex, and then multiplying by the probability of finding a fake MS vertex. There are 29 events with a good MS vertex, out of 544,781 total events selected with the \( \text{jet+}\not{E}_T \) trigger, which gives a probability of \((5.3 \pm 1.0) \times 10^{-5}\). There are 6 events with a good ID vertex, and so we obtain an expected background yield of \((3.3 \pm 0.7) \times 10^{-4}\).

### 7.3.3.3 MS Vertex + MS Vertex

To estimate the number of background MS + MS events, the number of events passing event selection with an MS vertex is multiplied by the probability of finding an additional, random MS vertex in the event.
\[ N_{\text{Fake}}(\text{trig}, 2 \text{ MSvtx}) = \sum_i P(\text{MSVTX}). \]

There are 29 events passing the \(Z'\) event selection criteria with a reconstructed MS vertex, 23 of which are reconstructed in the barrel and 6 in the endcaps. The number of fake events passing the \(Z'\) selection criteria is predicted to be less than \(29 \cdot 4.86 \times 10^{-7} = 1.4 \times 10^{-5}\) at the 95% confidence level.

### 7.4 Expected Signal

A toy model is used to evaluate the expected number of signal events for an arbitrary lifetime without running full simulation for each lifetime. Samples of two million events are generated with Pythia8 (using the procedure described in Section 4.2.1) for each benchmark in order to sample the long-lived particle’s momenta for a large number of events. The toy model is then run for mean proper lifetimes between 0 and 1 m in 0.25 cm steps, 1 m and 11 m, in 2.5 cm steps, and then 11 m and 100 m in 25 cm steps.

For each mean proper lifetime, the time to decay for each long-lived particle is calculated by sampling a random number from the exponential distribution governing the particle’s decay probability, shown in equation 7.1. Its decay position in the detector is then calculated using the generated momentum.

\[
P(t) = \exp(-t/\gamma) \tag{7.1}\]

The probabilities of an event satisfying the jet plus \(E_T^{\text{miss}}\) trigger, reconstructing an ID vertex, and reconstructing an MS vertex are used to evaluate an overall probability of an event passing the selection criteria. The vertex reconstruction probability as a function of decay radius for a given mass benchmark is constant; the reconstruction efficiencies obtained in Sections 5.5 and 6.5 can be applied to \(\pi_v\) decays at a given radius for any proper lifetime. The \(Z'\) search uses a single jet plus \(E_T^{\text{miss}}\) trigger and
offline requirement to select events and events in the $Z'$ scenario contain multiple $\pi_v$ with varying decay lengths. The trigger efficiency is therefore dependent on the $\pi_v$ proper lifetime $\tau$, and a method has been devised. Truth and reconstructed distributions from signal MC benchmark samples are compared separately for jet $p_T$ and $E_T^{\text{miss}}$ to obtain probability density functions. These functions are then used to smear the truth distributions and obtain reconstructed jet $p_T$ and $E_T^{\text{miss}}$ distributions for each toy model.

To obtain the probability of an event passing the single jet requirement of the trigger, the truth $\pi_v$ are compared to reconstructed jet distributions in the signal MC benchmark samples. Reconstructed jets are matched to truth $\pi_v$, taking into consideration a maximum distance of $\Delta R = 0.4$. The ratio of the $p_T$ of the reconstructed jet to the matched $\pi_v$ are considered in the interval $[0, 2.5]$. Since this ratio is $p_T$-dependent, the distributions are obtained separately for eight $p_T$ regions. The ratio distributions are then fit using a triple gaussian function - one gaussian for the central peak, another to incorporate long tails, and the final to accommodate for asymmetry. An example of one of the ratio distributions as well as its overlaid fit function can be seen in Figure 7.15 (a). These fit functions are used as probability density functions to obtain reconstructed object distributions by means of an inverse transform sampling. The fit functions are validated by comparing the $p_T$ distributions of the actual reconstruction objects to the smeared truth objects for the official MC benchmark samples.

A similar procedure is used to calculate the probability of an event passing the $E_T^{\text{miss}}$ portion of event selection. The reconstructed event $E_T^{\text{miss}}$ (MET_RefFinal) is compared to the vector sum of the $E_T$ of $\pi_v$ that decay outside of the detector volume in signal MC benchmark samples. In order to quantify the jet reconstruction inefficiency in the final layers of the hadronic calorimeter, the ratio of the sum of reconstructed jet $E_T$ to the sum of truth $\pi_v$ $E_T$ is formed as a function of the decay.
position. The distribution of this ratio has a central value near one for decays well inside the detector volume. However, this ratio drops to zero in the final section of the hadronic calorimeter as is illustrated by Figure 7.15 (b). In order to account for the drop, the ratio is fit linearly in the drop-off region. Then, the vector sum of $E_T$ for $\pi_v$ decaying in the drop-off region is calculated, scaled based on the inefficiency fit, and finally added to the truth event $E_T^{\text{miss}}$. The ratio of the reconstructed $E_T^{\text{miss}}$ to truth $E_T^{\text{miss}}$ is calculated for each event. As with the jet trigger probability, these ratios are obtained for eight $E_T^{\text{miss}}$ kinematic regions, which are then fit in the range $[0, 2.5]$. The resulting fit functions are used to generate the $E_T^{\text{miss}}$ smearing for the toy models. Validation is performed by comparing the $E_T^{\text{miss}}$ distributions for reconstruction objects and smeared truth objects in officially simulated samples.

The smearing described above is then performed on the toy MC samples for both jet $p_T$ and $E_T^{\text{miss}}$, and each event is checked to see whether it will pass both the jet $p_T$ and $E_T^{\text{miss}}$ requirements of event selection. For each of the three signal mass points validation is achieved by comparing the lifetime dependent trigger efficiency obtained from the toy MC samples with the trigger efficiency obtained from the reconstructed

Figure 7.15: (a) Reconstructed Jet $p_T/\text{truth } \pi_v p_T$ distribution as well as fit function (see text for details) produced for the $Z' = 2$ TeV $\pi_v = 120$ GeV benchmark sample. (b) Jet $E_T/\pi_v E_T$ distribution as a function of decay position in $r$ for the $Z' = 2$ TeV, $\pi_v = 120$ GeV benchmark sample.
benchmark samples (two lifetimes per mass point). Further validation is achieved by producing the probability density functions from a benchmark sample of a given lifetime (for each of the three mass points) and then performing the smearing on the other benchmark sample associated with the same mass points but a different lifetime. A systematic uncertainty of 15% is assigned to this method, based on the maximum discrepancy between predicted and reconstructed trigger efficiencies. The event selection acceptance as a function of lifetime is shown for the three Z' benchmarks in Figure 7.16.

The expected number of signal events is evaluated as a function of πν proper lifetime from generator-level simulated samples. Two million ‘toy’ events are generated for each point in a range of lifetimes: in increments of 0.025 m between cτ = 0.001 m and cτ = 10.0001 m, and then in increments of 0.25 m until cτ = 100.0001 m. At each lifetime point, a random decay position for each long-lived particle is obtained by sampling from an exponential distribution, f(t) = exp -1/βγcτ. Their physical decay positions in the detector are then calculated using the stored 4-momenta. The

Figure 7.16: Acceptance as a function of lifetime for signal events that pass the trigger emulation and have a jet p_T > 120 GeV and a E_T^{miss} > 200 GeV
smearing procedure described above is used to calculate the ‘reconstructed’ jet $p_T$ and $E_T^{\text{miss}}$ and determine whether the toy event will pass minimum jet $p_T$ and $E_T^{\text{miss}}$ requirements. Due to reconstruction and selection criteria, vertices in the MS will have a minimum separation of $\Delta R > 1.0$, while vertices in the higher-granularity ID will be separated by $\Delta R > 0.4$. Vertex reconstruction efficiencies are therefore applied to all long-lived $\pi_v$ in events that satisfy any of the following criteria:

- **MS** - MS event candidates must have at least two $\pi_v$ in the MS Barrel or Endcap regions which are separated by $\Delta R > 1.5$
- **MS** - ID event candidates must have at least two $\pi_v$ in the MS or ID (Barrel or Endcap) regions which are separated by $\Delta R > 1.5$
- **ID** - ID event candidates must have at least two $\pi_v$ in the MS or ID (Barrel or Endcap) regions which are separated by $\Delta R > 0.4$

‘Good’ toy events must pass the trigger requirement and have at least two ‘reconstructed’ vertices in the final state topologies considered. The final number of expected signal events is computed at each lifetime by scaling the fraction of good events by the production cross-section times integrated luminosity to obtain the number of expected signal events in $20.3 fb^{-1}$ of data.

The effect of all systematic and statistical uncertainties of the efficiency histograms are each considered individually. As an example, consider the topology with an ID vertex, and MS vertex in the barrel (BMS-ID). There are three systematic uncertainties that must be taken into account: trigger, barrel MS vertex, and ID vertex. For the $m_{Z'} = 1 \text{ TeV}$, $m_{\pi_v} = 50 \text{ GeV}$ sample these values are 9%, 6.9%, and 3.4%, respectively. Each time a selection criterion is considered, the random probability is also compared against the criterion plus (and minus) its systematic uncertainty, and plus (and minus) its statistical uncertainty, applied for one criterion at a time. The combined effect of the uncertainties on the total number of two vertex events are
added in quadrature. The 2.8% systematic uncertainty on the integrated luminosity is not added at this stage, but is included in the limit setting step.

### 7.5 Results

#### 7.5.1 Observed Number of Events

The analysis event selection plus two vertex requirement were applied to 20.3 $fb^{-1}$ of data collected in 2012. 614,762 events were selected with the jet + $E_T^{\text{miss}}$ trigger, that also had at least one jet with $p_T > 120$ GeV, and $E_T^{\text{miss}} > 2002$ GeV. The number of selected jets per event, and the $p_T$ distribution of the jets, are shown for these pre-selected events in Figure 7.17. Figure 7.18 (a) shows the track multiplicity for all reconstructed vertices in the inner detector. The predominant background is combinatorial, as seen by the high number of two-track vertices. Seven events have a ID vertex that satisfies the selection criteria used for this analysis. The distribution of the angular distance $\Delta R$ between a muon spectrometer vertex and the nearest jet is shown in Figure 7.18 (b). Most of the reconstructed muon vertices are produced in association with jets, and are excluded by the selection criteria applied. 23 vertices in the muon spectrometer pass the selection criteria.

No events with two reconstructed vertices are found among events selected by the jet + $E_T^{\text{miss}}$ trigger, consistent with the expected number of background events for this dataset. A comparison of the expected background with observed number of events for each final state (2 ID vertices, 2 MS vertices, one in each detector sub-system) is listed in Table 7.8.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Topology</th>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet + $E_T^{\text{miss}}$</td>
<td>ID+ID</td>
<td>$(1.8 \pm 0.4) \cdot 10^{-4}$</td>
<td>0</td>
</tr>
<tr>
<td>Jet + $E_T^{\text{miss}}$</td>
<td>ID+MS</td>
<td>$(5.5 \pm 0.9) \cdot 10^{-4}$</td>
<td>0</td>
</tr>
<tr>
<td>Jet + $E_T^{\text{miss}}$</td>
<td>MS+MS</td>
<td>$&lt; 1.4 \cdot 10^{-5}$</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 7.8: Number of events predicted and observed for different final-state topologies.
7.5.2 Limit Setting

In the absence of signal events being observed, upper limits are set on the $\sigma \times \text{BR}$ for all benchmark samples using a modified frequentist method, also known as the $\text{CL}_s$ method [60] to obtain the probability of an observation in data given a single hypothesis. The $\text{CL}_s$ value is defined as the ratio of two frequentist probabilities $\text{CL}_{s+b} / \text{CL}_b$, and is a measure of the probability that the observed data is compat-
ible with a signal plus background hypothesis. Here, $\text{CL}_{s+b}$ is the probability of an observation given a signal plus background hypothesis, while $\text{CL}_b$ is the observation probability given a background-only hypothesis. The signal strength is parametrized in terms of the cross section ($\sigma$) times branching ratio. The systematic uncertainties are propagated to derive the corresponding uncertainties in the number of expected signal events, and are then included as nuisance parameters through their effect on the mean of the Poisson functions and through convolution with their assumed Gaussian distributions.

The limit is calculated for a chosen lifetime, and then extrapolated to a range of lifetimes using the number of expected events as a function of the lifetime obtained with the toy simulation described in 7.4.

### 7.5.3 Limits and Results

Exclusion limits for the $Z'$ benchmarks are shown in Figure 7.19. The black solid line represents the observed limit (which coincides with the expected limit in all cases). ±1σ and ±2σ uncertainty bands are denoted in green and yellow respectively. Figure 7.20 compares the observed limits for three benchmark samples. The probability of having two decays in the ID fiducial volume increases rapidly at small proper lifetimes, which results is good exclusion power in that region of parameter space. This effect is particularly evident for the benchmark sample $m_{Z'} = 2$ TeV, $m_{\pi_v} = 50$ GeV, where the high multiplicity of long-lived $\pi_v$ results in a high number of expected events for $c\tau < 0.3$ m.
Figure 7.19: Expected and observed 95% CL limits on $\sigma \times \text{BR}$ as a function of the $\pi$' proper lifetime for $m_{Z'} = 1$ and 2 TeV and $m_{\pi'} = 50$ and 120 GeV.
Figure 7.20: Observed 95% CL limits on $\sigma \times \text{BR}$ for the $Z'$ samples.
CHAPTER 8
CONCLUSIONS

A search was performed for a pair of neutral, weakly interacting, long-lived particles decaying within the ATLAS detector volume. This search used 20.3 fb$^{-1}$ of proton-proton collision data collected by the ATLAS detector in 2012, at a collision center of mass energy of $\sqrt{s} = 8$ TeV. Displaced decays to hadronic jets in the inner tracking detector and muon spectrometer were reconstructed using custom techniques developed for this analysis. The search was performed for three different topologies: two decays occurring in the inner detector, two decays occurring in the muon spectrometer, or one decay reconstructed in each detector sub-system. In all cases, no events were observed, and thus no significant deviation is found from expected Standard Model processes.

The data were interpreted in terms of Hidden Valley scenarios with a $Z'$ boson mediator. The exclusion limits presented here are the first search results for a heavy $Z'$ boson decaying to displaced hadronic jets.
APPENDIX A

MINIMUM TRACK $d_0$ REQUIREMENT FOR ID VERTEX RECONSTRUCTION

A minimum transverse impact parameter ($d_0$) requirement is applied during track selection for vertex finding in order to remove tracks from primary and pileup activity, which constitute the majority of reconstructed tracks. A comparison was performed using three minimum $d_0$ values (2 mm, 5 mm, and 10 mm), to find the best balance between signal acceptance and background rates for vertex reconstruction.

Figure A.1 shows the efficiency for one $Z'$ benchmark sample ($m_{Z'} = 1$ TeV, $m_{\pi_v} = 50$ GeV, and $c\tau_{\pi_v} = 0.5$ m) for the three different requirements. The left panel shows the reconstruction efficiency for all vertices, and the right panel shows the efficiency for vertices with at least five tracks; a more conservative $d_{0\text{min}}$ requirement decreases the reconstruction efficiency in the pre-pixel region, but the $d_0 > 2$ mm requirement leads to a lower reconstruction efficiency at higher radius. This can be explained by studying the vertex track multiplicity at different vertex radial positions. Figures A.3 and A.4 show the track multiplicity as a function of the vertex radial position for all vertices and truth-matched vertices respectively. The looser requirement of $d_0 > 2$ mm adds in a large number of low $d_0$ tracks to the collection for vertex-finding, and so the majority of vertices are reconstructed near the IP, most of which are combinatorial background. Since the primary vertex algorithm allows tracks to be loosely associated to a vertex (albeit down-weighted), some tracks from more displaced decays are also associated to these ‘fake’ vertices. Therefore, the $d_0 > 2$ mm sample has a slightly lower efficiency through the rest of the silicon region. Figure A.2 shows the number of non truth-matched vertices per truth vertex in signal
MC simulation for all vertices (left panel) and vertices with at least five tracks (right panel). The number of non-matched vertices with at least five tracks in the pre-pixel region is an order of magnitude higher for samples with $d_0 = 2 \text{ mm}$ or $5 \text{ mm}$.

![Graph](image1.png)

**Figure A.1:** Vertex reconstruction efficiency for a $Z'$ benchmark sample with $m_{Z'} = 1 \text{ TeV}$, $m_{\tau\nu} = 50 \text{ GeV}$, and $c\tau_{\tau\nu} = 0.5 \text{ m}$ for (a) all vertices, and (b) vertices with at least five tracks.

![Graph](image2.png)

**Figure A.2:** Vertex reconstruction rate for non-matched vertices for a $Z'$ benchmark sample with $m_{Z'} = 1 \text{ TeV}$, $m_{\tau\nu} = 50 \text{ GeV}$, and $c\tau_{\tau\nu} = 0.5 \text{ m}$ for (a) all vertices, and (b) vertices with at least five tracks.

The reconstruction background rate in data was calculated using events selected from a subset of the 2012 data. The number of vertices reconstructed per event
Figure A.3: Track multiplicity as a function of vertex radial position for all vertices reconstructed in a $Z'$ benchmark sample with $m_{Z'} = 1\,\text{TeV}$, $m_{\pi_v} = 50\,\text{GeV}$, and $c\tau_{\pi_v} = 0.5\,\text{m}$ for a minimum $d_0$ requirement of (a) 10 mm and (b) 2 mm.

Figure A.4: Track multiplicity as a function of vertex radial position for truth-matched vertices reconstructed in a $Z'$ benchmark sample with $m_{Z'} = 1\,\text{TeV}$, $m_{\pi_v} = 50\,\text{GeV}$, and $c\tau_{\pi_v} = 0.5\,\text{m}$ for a minimum $d_0$ requirement of (a) 10 mm and (b) 2 mm.

(Figure A.5) is much higher for the $d_0 = 2\,\text{mm}$ and $d_0 = 5\,\text{mm}$ samples. After a material veto is applied, the fraction of vertices remaining with high track multiplicity increases significantly as the impact parameter cut is loosened (Figure A.5). The lower minimum $d_0$ criteria also leads to a much larger fraction of background vertices
reconstructed in the pre-pixel region, and a slightly higher fraction of vertices with a very low fit probability (Figure A.6).

Figure A.5: (a) Number of vertices reconstructed, and (b) fraction of vertices as a function of track multiplicity for 2012 signal stream data.

Figure A.6: Fraction of vertices as a function of (a) vertex radial position and (b) vertex fit probability for 2012 signal stream data.

Considering vertices in the barrel and endcap regions, the background rates are:

- $0.192 \pm 0.003$ vertices/event for $d_0 = 2$ mm,
- $0.051 \pm 0.002$ vertices/event for $d_0 = 5$ mm, and
• 0.0023 ± 0.0003 vertices/event for \( d_0 = 10 \) mm.

The drop in background rate for vertex reconstruction using tracks with \( d_0 > 10 \) mm outweighs the loss in efficiency in the pre-pixel region. To cope with the high pileup environment in 2012 data-taking, the conservative requirement of \( d_0 > 10 \) mm is the better choice, and was utilized in this analysis.
APPENDIX B

ID VERTEX RECONSTRUCTION WITH THE RPVDispVrt ALGORITHM

A study was performed to compare the vertex reconstruction algorithm used in this analysis with the RPVDispVrt algorithm that also reconstructs displaced vertices. This vertex finder starts by constructing all possible two-track vertices with a vertex $\chi^2 < 5$. Vertices with tracks that have hits between the vertex position and the interaction point (IP) are rejected, and tracks are required to have hits in the first detector layer after the vertex. Higher track-multiplicity vertices are then formed by merging nearby two-track seeds. An iteration over the tracks for each vertex is performed, starting with the track with the largest $\chi^2$ relative to the vertex. If the relative $\chi^2$ satisfies the condition $\chi^2 > 6$, the track is removed, and the vertex is reconstructed with the remaining tracks. The algorithm also checks the significance of the distance between two vertices sharing each track (defined as the ratio of the distance and the error in the distance); if this distance significance is less than three, the tracks associated with them are combined to reconstruct one vertex. These iterations are performed until no two vertices share the same tracks. In a final step, adjacent vertices with a distance separation of less than 1 mm are merged and refitted.

Figure B.1 compares the vertex reconstruction efficiency of the two algorithms for a $Z'$ benchmark sample ($m_{Z'} = 1$ TeV, $m_{\pi_v} = 50$ GeV, $c\tau_{\pi_v} = 0.5$m). The reconstructed vertices are truth-matched to simulated vertices: they must be within 5 mm of a simulated vertex and contain at least two tracks that are truth-matched to tracks from the simulated vertex at hit the level. The left panel of Figure B.1
shows the efficiency for reconstructing vertices containing at least four tracks, while the right panel is for vertices with at least five tracks.

Figure B.1: Vertex reconstruction efficiency for \( Z' \) samples with \( \Delta r_{\pi v} \) of 0.5m for vertices with (a) at least four tracks (b) at least 5 tracks

The efficiencies of the two reconstruction algorithms are also compared after applying the material veto. The resulting efficiencies are shown in Fig. B.2. Both before and after applying the ID material veto, the efficiency of the modified primary vertex reconstruction algorithm is significantly greater for vertices with four or more tracks.

Figure B.2: Vertex reconstruction efficiency for \( Z' \) samples with \( \Delta r_{\pi v} \) of 0.5m for vertices with (a) at least four tracks (b) at least 5 tracks that pass the material veto
The background rate is checked on a subset of the 2012 dataset, with events selected using the single jet + $E_T^{\text{miss}}$ trigger (~30,000 events). Before applying any requirements on reconstructed vertices, it was observed that RPVDispVrt reconstructs many more vertices overall than the modified primary vertex reconstruction algorithm. However, the majority of these vertices are two-track vertices and do not pass vertex selection criteria. In order to retain enough events to make a comparison of background reconstruction rates, a modified version of the vertex selection criteria with a less stringent track multiplicity requirement (at least five tracks associated to the vertex) is used.

Considering only vertices in the ID barrel, the background rates are:

- 0.00063 ± 0.00014 vertices/event for the modified primary vertex algorithm
- 0.00040 ± 0.00011 vertices/event for RPVDispVrt

Considering vertices in the ID barrel and endcaps, the background rates are:

- 0.00097 ± 0.00017 vertices/event for the modified primary vertex algorithm
- 0.00055 ± 0.00011 vertices/event for RPVDispVrt

This corresponds to $S/\sqrt{B}$ values of 6.09 ± 0.69 and 3.89 ± 0.55 for the modified primary vertex reconstruction and RPVDispVrt, respectively. The background rate obtained for the modified primary vertex algorithm is between two and three standard deviations greater than the background rate found using the RPVDispVrt tool. However, the analysis requirement of two reconstructed vertices passing selection criteria per event provides additional background discrimination, and therefore the increase in the background rate is outweighed by the substantial increase in signal efficiency. The modified primary vertex reconstruction algorithm also has a significantly faster processing time of approximately 0.5 seconds per event, compared to more than 4 seconds per event for the RPVDispVrt tool, and is therefore a more appropriate choice for the signal benchmarks and datasets studied in this thesis.
In this appendix, $S/\sqrt{B}$ distributions (where $S$ and $B$ are the fraction of vertices in signal and background events respectively) are shown for all selection criteria applied to vertices in the MS. A set of three $Z'$, three Stealth SUSY, and six Scalar boson benchmark signals are used for the study.

Figure C.1: MS vertex reconstruction efficiency in the barrel as a function of the minimum number of RPC hits for various signals. The signals are (a) Scalar boson and (b) $Z'$ benchmark samples. The background is MC di-jet events. The chosen value for the minimum number of RPC hits is $\geq 250$. As a consequence of these distributions and to improve performance, an internal cut of nRPC $\geq 200$ was added to the MS vertexing algorithm in the endcaps. Stealth SUSY was added after this cut was implemented, so a corresponding distribution for stealth SUSY is not shown here.
Figure C.2: MS vertex reconstruction efficiency in the endcaps as a function of the minimum number of TGC hits for various signals. The signals are (a) Scalar boson and (b) $Z'$ benchmark samples. The background is MC di-jet events. The chosen value for the minimum number of TGC hits in the endcaps is $\geq 250$. As a consequence of these distributions, an internal cut of $n_{\text{TGC}} \geq 200$ was added to the MS vertexing algorithm before a similar study was made for the stealth SUSY.
Figure C.3: MS vertex reconstruction efficiency in the barrel as a function of $\Delta R$ for the high-$p_T$ track isolation requirement for various signals. The signals are (a) Scalar boson, (b) high mass Scalar boson, (c) $Z'$, and (d) stealth SUSY benchmark samples. The background is MC di-jet events. The chosen value for the high-$p_T$ track isolation requirement in the barrel is $\Delta R < 0.3$. 
Figure C.4: MS vertex reconstruction efficiency in the endcaps as a function of ΔR for the high-p_T track isolation requirement for various signals. The signals are (a) Scalar boson, (b) high mass Scalar boson, (c) Z', and (d) stealth SUSY benchmark samples. The background is MC di-jet events. The chosen value for the high-p_T track isolation requirement in the endcaps is ΔR < 0.6.
Figure C.5: MS vertex reconstruction efficiency in the barrel as a function of the maximum $\sum p_T$ of nearby tracks for various signals. The signals are (a) Scalar boson, (b) high mass Scalar boson, (c) $Z'$, and (d) stealth SUSY benchmark samples. The background is MC di-jet events. The chosen value for the maximum $\sum p_T$ of nearby tracks in the barrel is $\sum p_T < 10$ GeV.
Figure C.6: MS vertex reconstruction efficiency in the endcaps as a function of the maximum $\sum p_T$ of nearby tracks for various signals. The signals are (a) Scalar boson, (b) high mass Scalar boson, (c) $Z'$, and (d) stealth SUSY benchmark samples. The background is MC di-jet events. The chosen value for the maximum $\sum p_T$ of nearby tracks in the endcaps is $\sum p_T < 10$ GeV.
Figure C.7: MS vertex reconstruction efficiency in the barrel as a function of ∆R for the jet isolation requirement for various signals. The signals are (a) Scalar boson, (b) high mass Scalar boson, (c) Z', and (d) stealth SUSY benchmark samples. The background is MC di-jet events. The chosen value for the jet isolation in the barrel is ∆R < 0.3.
Figure C.8: MS vertex reconstruction efficiency in the endcaps as a function of ∆R for the jet isolation requirement for various signals. The signals are (a) Scalar boson, (b) high mass Scalar boson, (c) Z’, and (d) stealth SUSY benchmark samples. The background is MC di-jet events. The chosen value for the jet isolation in the endcaps is ∆R < 0.6.
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