

# Searches for long-lived supersymmetric particles with a disappearing track signature in Run 2 at the ATLAS experiment and development of ATLAS ITk tracking software



UNIVERSITY OF  
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Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by

**James Leslie Smith**

Department of Physics  
Oliver Lodge Laboratory  
University of Liverpool

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# Declaration

I hereby confirm this work is my own, except where other works are referenced. This work has not previously been submitted to any institute, including this one. This thesis does not exceed the relevant word count.

*James Leslie Smith*





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*For Nana and Papa*

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# Glossary

**AMSB** Anomaly-Mediated Supersymmetry Breaking. xii, xv, xvii, 2, 27–30, 106–108, 131

**API** Application Programming Interface. xvii, 133, 134

**ATLAS** A Torodial LHC ApparatuS. vii, xii–xiv, xvi, xvii, xxi, xxiv, 2–4, 20, 21, 29, 31–36, 41, 46–52, 54, 55, 57–61, 67–70, 75, 77, 78, 83, 88, 93, 95, 106, 108, 109, 129–134, 143, 152, 157, 196, 199, 205, 206, 214, 215, 219, 220

**BDT** Boosted Decision Tree. xviii, xix, 65, 93, 101–103, 161, 167–170

**BSM** Beyond Standard Model. 2, 21, 24, 69, 132

**BT** Barrel Toroid. xiv, 49, 58

**C/A** Cambridge/Aachen. 93

**CERN** European Organisation for Nuclear Research. xiii, 46, 47

**CKM** Cabibo-Kobayashi-Maskawa. 15, 16

**CL** Confidence Level. xvi, xvii, 125, 129–131, 220

**CMB** Cosmic Microwave Background. 37, 38

**CMS** Compact Muon Solenoid. xii, 21, 47, 67, 195

**CR** Control Region. xvi, xix, 113–121, 125, 180

**CS** Central Solenoid. xiv, 49, 50, 58

**CSC** Cathode Strip Chamber. 57

**CST** Calo Soft Term. 96

**DIS** Deep Inelastic Scattering. 67

**DM** Dark Matter. 106

**DNN** Deep Neural Network. 93

**ECal** Electromagnetic Calorimeter. xiv, 49, 54–56, 94

**ECT** End-Cap Toroid. xiv, 49, 58

**EMEC** Electromagnetic End-Cap. 55

**EWSB** Electroweak Symmetry Breaking. 25, 31

**FCal** Forward Calorimeter. 54

**FCC** Future Circular Collider. 48, 133

**FPGA** Field-Programmable Grid Array. 59

**FSR** Final-State Radiation. 123

**GMSB** Gauge-Mediated Supersymmetry Breaking. 27, 28

**GRL** Good Run List. 181

**GSW** Glashow-Salam-Weinberg. 16

**GUT** Grand Unified Theory. 21

**HCal** Hadronic Calorimeter. 49, 53, 54, 56, 57

**HEC** Hadronic Endcap. 56, 58

**HGTD** High-Granularity Timing Detector. xx, 199, 201

**HL-LHC** High-Luminosity LHC. xxiv, 4, 46–48, 133, 196, 199, 202, 212, 217, 220

**HLT** High-Level Trigger. 59, 62, 63, 65, 202, 203

**HST** Hubble Space Telescope. xiii, 38

**HTT** Hardware-based Tracking for the Trigger. 203

**IBL** Insertable B-Layer. 50, 51, 89, 213

**ID** Inner Detector. xiii, xiv, xx, xxi, 2, 33, 48–50, 52, 58, 95, 96, 196, 199, 200, 204, 214, 216, 218

**ISR** Initial-State Radiation. 106, 107, 123

**ITk** New Inner Tracker. xx, xxi, xxiv, 4, 48, 196–200, 204–206, 210, 214, 216, 218

**JER** Jet Energy Resolution. 93

**JES** Jet Energy Scale. 54, 93

**JVT** Jet-to-Vertex Tagger. 93

**L0** Level 0. xxvii, 203

**L0Calo** Level 0 (L0) Calorimeter trigger. 203

**L0Muon** L0 Muon trigger. 203

**L1** Level 1. xxvii, 59, 62, 110, 202, 203

**L1Calo** Level 1 (L1) Calorimeter trigger. 59

**L1Muon** L1 Muon trigger. 59

**LAr** liquid argon. xiv, 54–56, 199, 202

**LEP** Large Electron-Positron Collider. xii, 29, 152

**LGAD** Low-Gain Avalanche Detector. 199

**LHC** Large Hadron Collider. xxii, 2–4, 24, 31, 39, 46–49, 51, 53, 60, 62, 66, 67, 70, 132, 134, 205, 219, 220

**LHE** Les Houches Event. 133

**LLP** Long-Lived Particle. xiii, 32, 33, 35, 132, 219

**LO** Leading-Order. 67–69, 76

**LRT** Large-Radius Tracking. 86, 87, 89

**LS1** Long Shutdown 1. 47, 50

**LS2** Long Shutdown 2. xx, 47, 196, 199, 202, 203

**LS3** Long Shutdown 3. xx, 47, 196, 197, 199, 202, 203

**LSP** Lightest Supersymmetric Particle. xvi, xvii, 25, 28, 30–32, 39, 129, 130, 152, 219

**LUCID** LUminality Cherenkov Integrating Detector. 60, 61

**MACHO** Massive Compact Halo Object. 39

**MC** Monte-Carlo. 57

**MDT** Muon Drift Tube. 57, 202

**ME** Matrix Element. 67–69



**ML** Machine Learning. xix, 101, 167, 169

**MLT** Maximum Likelihood Theorem. 98

**MOND** Modified Newtonian Dynamics. 38

**MPI** Multiple Parton Interactions. 65, 68

**MS** Muon Spectrometer. 49, 57, 63, 95

**MSSM** Minimal Supersymmetric Standard Model. xxii, xxviii, 3, 25–28, 219

**MSTrack** Muon Spectrometer Track. xix, 82, 87, 95, 118, 119, 171, 172, 174

**MVA** Multi-Variate Analysis. 101

**NLL** Negative-Log-Likelihood. 98

**NLL** Next-to-Leading-Log. xxi, 212

**NLO** Next-to-Leading-Order. xxi, 67, 69, 76, 123, 212

**NN** Neural Network. 101

**NNLO** Next-to-Next-to-Leading-Order. 67

**NP** Nuisance Parameter. 99–101

**NSW** New Small Wheel. 196, 202

**PDF** Parton Distribution Function. xxi, 65–67, 123, 212

**PDF** Probability Distribution Function. 98–100

**PLM** Profile Likelihood Method. 99

**PMSB** Planck-Scale-Mediated Supersymmetry Breaking. 27

**pMSSM** Phenomenological Minimal Supersymmetric Standard Model (MSSM). xviii, 3, 31, 132, 152–154, 220

**PMT** Photo-Multiplier Tube. 39, 56, 60

**POI** Parameter of Interest. 99, 100

**PS** Parton Shower. 67, 68

**PS** Proton Synchrotron. 46

**PSB** Proton Synchrotron Booster. 46

**PV** Primary Vertex. xv, 86, 93, 95, 108, 109

**QCD** Quantum Chromodynamics. xii, 8, 11, 13, 14, 72

**QED** Quantum Electrodynamics. xii, 8, 11–14, 16

**QFT** Quantum Field Theory. 8, 10, 11, 13

**RDO** Raw Data Object. 70

**ROD** Read-Out Device. 61

**ROI** Region of Interest. 59, 79, 83, 84

**RPC** Resistive Plate Chamber. 57, 202

**SCT** Silicon Tracker. xiv, xxi, xxiv, 49, 51, 52, 61, 78–81, 83, 84, 89, 108, 110, 113, 114, 118, 136, 155, 167, 195, 199, 204–206, 214, 242, 243

**SPG** Single Particle Gun. 75, 171, 172

**SPS** Super Proton Synchrotron. 46

**SR** Signal Region. xvii, xxiii, 125, 137–141, 143, 145, 146, 149

**sTGC** Small-Strip Thin Gap Chamber. 202

**SUSY** Supersymmetry. xii, xiii, 2, 3, 23–25, 27, 28, 30–32, 34, 39, 106, 132, 152, 219

**SV** Secondary Vertex. 167

**TDAQ** Trigger & Data Acquisition. xx, 49, 59, 202, 203

**TGC** Thin Gap Chamber. 57, 202

**TLA** Trigger-Level Analysis. 203

**TMS** Truth-Matching Score. xix, 161, 178–180, 243

**TRT** Transition Radiation Detector. xiv, 49, 51–53, 79, 113, 114, 167, 242, 243

**TST** Track Soft Term. 95, 96

**UE** Underlying Event. 68

**VEV** Vacuum Expectation Value. 19, 20, 26, 28

**VR** Validation Region. 114, 125

**WIMP** Weakly-Interacting Massive Particle. xiii, 39, 42, 106, 219

**WLS** Wavelength-Shifting. 56



# Chapter 1

## Introduction

15 years of analysis of proton-proton collisions at the Large Hadron Collider (LHC) have shown the Standard Model to be a complete, robust and highly accurate theory, with the discovery of the Higgs boson perhaps being the crowning achievement of the experimental programme so far. However, the Standard Model fails to explain cosmological observations such as dark matter, and has open questions such as the naturalness and hierarchy problems, and the lack of a method for generating neutrino masses.

Many new hypotheses, collectively known as Beyond Standard Model (BSM) hypotheses, have been proposed to provide solutions to some or all of these open questions. Some, such as Supersymmetry (SUSY), provide complete symmetric extensions to the Standard Model, whereas others offer minimal extensions in order to explain individual phenomena such as dark matter. However, extensive searches with the ATLAS experiment exploring a range of detector signatures and final states have failed to provide any significant discovery. Therefore, searches for new, unconventional signatures are required.

One such signature is the *disappearing track* signature, inspired by the Anomaly-Mediated Supersymmetry Breaking (AMSB) SUSY model. This signature is generated by models with a heavy charged particle that decays to a stable, neutral particle which is almost the same mass as the charged parent. This neutral particle is a dark matter candidate. Because of the small mass difference between the two particles ( $< 1 \text{ GeV}$ ), the phase space is severely restricted, allowing only a low-momentum pion to be produced along with the dark matter candidate and generating a relatively long lifetime for the parent particle between  $0.01 \text{ ns}$  and  $10 \text{ ns}$ , allowing it to travel  $\mathcal{O}(\text{cm})$  before decaying. This results in a detector signature of a short *tracklet* of three or four hits in the ATLAS Inner Detector (ID), leading to either nothing (known as *missing energy*), or a very low-momentum *soft* track.

This thesis is organised as follows:

**Part I** provides the theoretical basis of this thesis, and a review of current findings. This part is split into Chapter 2 which explores the Standard Model, and Chapter 3, which explores SUSY and the hypothesis of dark matter, as well as a short review of exclusion limits of a selection of SUSY and dark matter models. Whilst the text of these chapters is original work, this is a review of existing material. All sources used have been cited.

**Part II** explores the experimental techniques used in this thesis. It begins with Chapter 4 which provides a detailed overview of the LHC and ATLAS, and their configuration during the collection of the datasets used in this thesis. Again, no new work is presented here, as this chapter is a review of the state and performance of the ATLAS detector during the collection of the datasets used in this thesis. Chapter 5 provides an overview of these datasets, a review of the techniques used to simulate samples for comparison with the experimental datasets, and the simulated Monte Carlo datasets compared against the experimental datasets. The first two sections are reviews, however the generation and validation of samples for the second analysis is original work. Finally, Chapter 6 details the definitions used for the reconstructed physics objects such as tracks and electrons, and how this reconstruction is performed. This chapter also details the statistical techniques used in this thesis. This chapter is largely also a review of the definitions and techniques used in the analyses, although the efficiency and resolutions of the pixel tracklets and associated soft tracks are original work.

Finally, **Part III** covers the data analysis performed in the search for disappearing tracks, and forms the core work of this thesis. Chapter 7 presents the first search for disappearing tracks using the Run-2 dataset, searching for tracklets formed of four hits. The author joined this analysis when it was at a mature stage, so only limited contributions were made - essentially a number of cross-checks relating to the selection and triggers. The first section introducing the analysis is original work, whereas due to the limited involvement the remaining sections are a reproduction from the publication of the analysis [1] of which the author of this thesis was a co-author, with minor editorial changes to fit with the thesis. Chapter 8 covers the development of material to aid the reinterpretation of this analysis in the context of other models. It also presents an overview of the Phenomenological MSSM (pMSSM) scan which used this material to exclude a large number of SUSY models. Other than the initial review of the reinterpretation tools and the review of the pMSSM scan, this chapter is entirely original work written by the author, but a reproduction of previously published auxillary material to the first paper [1]. Chapter 9 presents a second search for disappearing tracks using the same Run-2 dataset, but with new reconstruction techniques to enable the reconstruction of shorter, three-hit tracklets, and the reconstruction of the low momentum pion from the chargino decay. It also presents updated analysis approaches to improve sensitivity. At the

time of writing this analysis is still work-in-progress, however it is at a mature-enough stage that preliminary sensitivity estimates can be made. Other than the scattered background estimates, this work was entirely performed by the author. All writing in this chapter is original work. Finally, Chapter 10 first provides an overview of the ATLAS upgrade programme in preparation for High-Luminosity LHC (HL-LHC), before detailing work on the development of improved particle tracking software which is better suited to the new geometry of the New Inner Tracker (ITk). This chapter then concludes with an overview of how changes in future runs of the LHC will impact the search for disappearing tracks and uses this to provide an outlook for the coming decade of this analysis. Other than the first two sections which form a review of the ATLAS upgrade program, and some plots used to support the sensitivity projections at HL-LHC, this chapter is also original work by the author, and written by the author.







Part I

Theory

## Chapter 2

# The Standard Model

The Standard Model is a mathematical framework which successfully models almost all currently-known particle physics phenomena. It provides accurate predictions for three generations of leptons and quarks, four gauge bosons, one scalar boson, and three forces. The predictions have been extensively tested and verified. Despite this success, the Standard Model fails to provide explanations for phenomena such as dark matter, and contains open questions such as the hierarchy problem. The Standard Model is a composite Quantum Field Theory (QFT), comprised of Quantum Electrodynamics (QED), Quantum Chromodynamics (QCD), and the weak interaction. In this chapter, a phenomenological overview of the Standard Model is given in Section 2.1 before the mathematical formalism of QED, QCD, and the weak force and electroweak unification is given in Sections 2.2, 2.3, and 2.4. The unified electroweak force must be broken to produce the separate electromagnetic and weak forces; the mechanism for this and the Higgs boson that arises from it is discussed in Section 2.5. Finally, the open question in the Standard Model are discussed in Section 2.6.

### 2.1 Overview & Particle Content

The Standard Model describes three fundamental forces: the strong, weak and electromagnetic forces. It also describes 17 fundamental particles, split into two families, bosons (which have an integer spin) and fermions (which have a half-integer spin). A graphical representation of these particles is given in Figure 2.1.

Ordinary matter is comprised of fermions, which can be further categorised into leptons which can interact via the electromagnetic and/or weak forces; and quarks which can additionally interact via the strong force, producing composite particles known as mesons (comprised of two quarks) and hadrons (comprised of three quarks). Rare composite particles with four quarks (known as *tetraquarks*) [3, 4] and five quarks (known as pentaquarks) [5, 6] are also possible. Quarks (shown in purple in Figure 2.1) can be further categorised into three doublets of up- and down-type quarks, which have a charge of  $+2/3$  and  $-1/3$  respectively. These doublets are

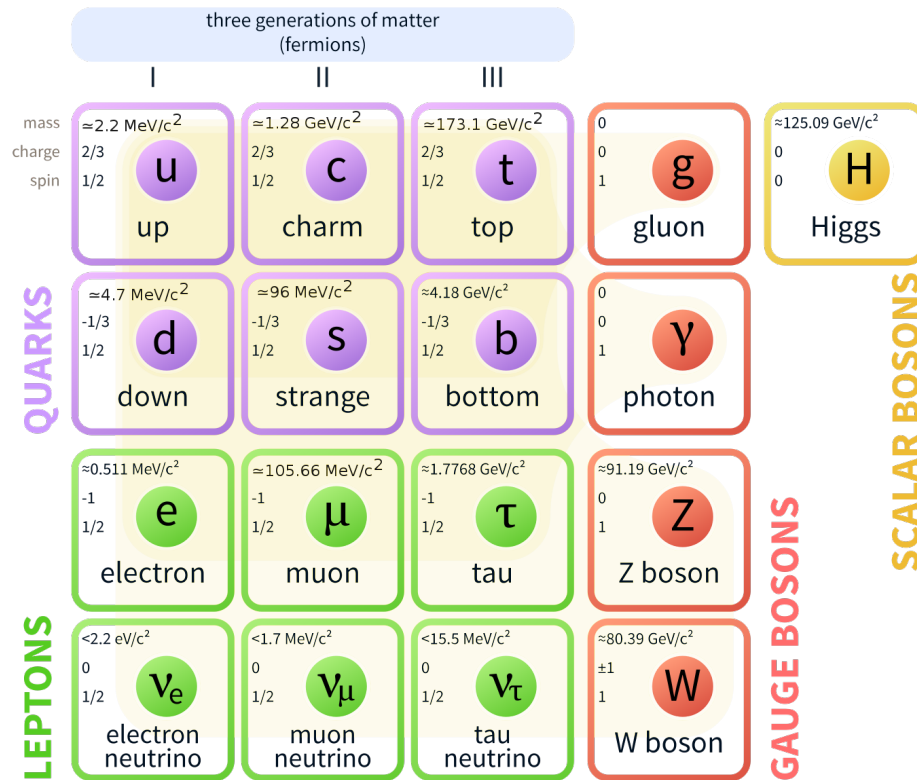


Figure 2.1: A graphical representation of the standard model of particle physics. Quarks are shown in purple, leptons in green, gauge bosons in red and the Higgs scalar boson in yellow. Reproduced from [2].

also known as *generations*. Quarks gain a colour charge from their interactions with the strong force, which can have a value of ‘red’, ‘green’ or ‘blue’, with antiquarks having opposite values (‘anti-red’, etc.). Leptons (shown in green in Figure 2.1) are also split into doublets of charged leptons and neutrinos. Charged leptons, such as electrons, are massive and have a charge of  $-1$ . Neutrinos have zero charge and, under the Standard Model, zero mass, although recent observations of neutrino oscillation have shown that neutrinos do have a small mass, with an upper limit of  $1.1\text{ eV}$  [7].

The gluon, photon, W and Z bosons, shown in red in Figure 2.1, are known as *vector* or *gauge* bosons, and act as force mediators. The gluon acts as the mediator for the strong force, the photon for the electromagnetic, and the W and Z bosons for the weak force. The gauge bosons have spin-1, the photon and gluon are massless, and the W-boson is charged. The Higgs boson, shown in yellow in Figure 2.1, is the only scalar boson, with spin-0. The Higgs boson and the Higgs field are responsible for symmetry breaking, ultimately allowing other particles to have mass.

Mathematically the Standard Model is described by a QFT formed from *groups*. A mathematical group  $G$  is defined as a set of objects and an operation which have the following properties and definitions [8]:

- Closure: for any two elements  $a, b$  of a group  $G$ , the product of these elements  $a \cdot b$  is also contained in the group
- Associativity: when multiplying any three elements  $a, b$  and  $c$  of a group  $G$ , the result is independent of the order of multiplication ( $a, b, c \in G$ :  $(a \cdot b) \cdot c \equiv a \cdot (b \cdot c)$ )
- Identity: there exists an identity element  $I$  which, when multiplied with any element  $a$ , results in  $a$  ( $I \cdot a \equiv a \cdot I \equiv a$ )
- Inverse: for each element  $a$  of a group  $G$  there exists an inverse element  $a^{-1}$  which, when multiplied with  $a$ , results in the identity element  $I$  ( $a \cdot a^{-1} \equiv a^{-1} \cdot a \equiv I$ )
- Generator: there exists a subset of elements of a group from which all elements of the group can be generated by repeated application of the group's operator
- Commutation: the commutator between any two elements  $a, b$  of a group  $G$  is defined as  $[a, b] = (a \cdot b - b \cdot a)$

*Abelian* groups can be defined as groups where the commutators between all pairs of elements is zero, and such groups have  $n^2$  generators. *Non-Abelian* can also be defined in contrast to Abelian groups, and such groups have  $n^2 - 1$  generators. *Unitary* groups  $U(n)$  are the set of square matrices  $n \times n$ , and *special unitary* groups  $SU(n)$  are the subset of  $U(n)$  with a determinant of 1.

The Standard Model, and much of physics, relies heavily on symmetries. Noether's theorem [9] demonstrates that for all symmetries (defined as a transformation under which the equations of motion of a system are unchanged) there is a conserved quantity. Examples of this include energy being conserved as a result of transformations in time, and momentum being conserved as a result of transformations in linear space. In terms of quantum mechanics, a transformation independent of space-time, known as a *global* transformation, can be described as a phase transformation

$$\varphi \rightarrow \varphi' = e^{i\alpha} \varphi \quad (2.1)$$

$$\bar{\varphi} \rightarrow \bar{\varphi}' = e^{-i\alpha} \bar{\varphi} . \quad (2.2)$$

Transformations that vary depending on the space-time co-ordinates such as

$$\varphi(x) \rightarrow \varphi' = e^{i\alpha(x)} \varphi(x) \quad (2.3)$$

$$\varphi(x) \rightarrow \bar{\varphi}' = e^{-i\alpha(x)} \bar{\varphi}(x) \quad (2.4)$$

are known as *local* or *gauge* transformations.

The Standard Model is comprised of QED, which describes electromagnetism and electric charge, and QCD, which describes the strong force, gluons, and colour charge. QED and QCD are combined to form the Standard Model, represented by the product of the component groups

$$\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y \quad (2.5)$$

where  $\text{SU}(3)_C$  represents the QCD strong interactions and colour charge with three *colours* of gluons,  $\text{SU}(2)_L$  represents the electroweak interactions, introducing two bosons ( $W^\pm$ ,  $Z^0$ ), and  $\text{U}(1)_Y$  represents electromagnetic interactions and hypercharge (Y) (defined as the sum of strangeness, charm, bottomness, topness and baryon number) and introduces one boson, the photon.

## 2.2 Quantum Electrodynamics (QED)

QED was one of the first major QFTs to be developed and widely accepted in particle physics. It successfully describes the electromagnetic interaction and relates the fermions to the photon by addressing the gauge invariance of the Dirac equation. QED is a  $\text{U}(1)$  symmetry, resulting in  $1^2 = 1$  mediator, the photon.

The Lagrangian for QED begins with the Dirac Lagrangian for free particles

$$\mathcal{L}_{\text{Dirac}} = \bar{\varphi} (i\gamma^\mu \partial_\mu - m) \varphi \quad (2.6)$$

where particle fields are represented by the 4-component Dirac spinors  $\varphi$ ,  $\gamma^\mu$  are the 4-dimensional Dirac matrices, and  $m$  is the particle mass. The Dirac equation is invariant under global transformations like those in Equation 2.2, as the two exponential added by the transformation are not affected by the space-time derivative in the Dirac Lagrangian, and cancel each other resulting in the original Lagrangian. However, The Dirac Lagrangian is not locally invariant, as the transformation of  $\varphi$  would be affected by the space-time derivative  $\partial_\mu$ .

This can be resolved by replacing the space-time derivative  $\partial_\mu$  with the *covariant* derivative  $D_\mu$ , which is defined as

$$D_\mu \varphi(x) = (\partial_\mu + ieA_\mu) \varphi(x) \quad (2.7)$$

and introduces a 4-vector field  $A_\mu$ , which transforms as

$$A_\mu \rightarrow A'_\mu = A_\mu - \frac{1}{e} \partial_\mu \alpha(x) \quad (2.8)$$

and allows the covariant derivative to transform as

$$D_\mu \varphi(x) \rightarrow D'_\mu \varphi'(x) = D'_\mu e^{i\alpha(x)} \varphi(x) \quad (2.9)$$

$$= (\partial_\mu + ieA'_\mu) e^{i\alpha(x)} \varphi(x) \quad (2.10)$$

$$= (\partial_\mu + ieA_\mu - i\partial_\mu \alpha(x)) e^{i\alpha(x)} \varphi(x) \quad (2.11)$$

$$= \partial_\mu \left[ e^{i\alpha(x)} \varphi(x) \right] + \left( e^{i\alpha(x)} \varphi(x) \right) (ieA_\mu - i\partial_\mu \alpha(x)) \quad (2.12)$$

$$= e^{i\alpha(x)} (\partial_\mu \varphi(x) + i\varphi(x) \partial_\mu \alpha(x) + ieA_\mu \varphi(x) - i\varphi(x) \partial_\mu \alpha(x)) \quad (2.13)$$

$$= e^{i\alpha(x)} (\partial_\mu + ieA_\mu) \varphi(x) \quad (2.14)$$

$$= e^{i\alpha(x)} D_\mu \varphi(x) \quad (2.15)$$

proving the covariance. The 4-vector field  $A_\mu$  has field equations

$$\partial^2 A^\nu - \partial^\nu (\partial_\mu A^\mu) = J^\nu \quad (2.16)$$

where  $J^\nu$  is the field current, which relates to Maxwell's equations and is the conserved quantity predicted by Noether's theorem.

Using the Feynman slash notation ( $\not{\partial} = \gamma^\mu \partial_\mu$ ,  $\not{D} = \gamma^\mu D_\mu$ ,  $\not{A} = \gamma^\mu A_\mu$ ) and the result from Equation 2.15 ( $D_\mu \varphi(x) \rightarrow D'_\mu \varphi'(x) = e^{i\alpha(x)} D_\mu \varphi(x)$ ), the local transformation of the Dirac Lagrangian now follows as:

$$i\bar{\varphi} \not{D} \varphi - m\bar{\varphi} \varphi \rightarrow i\bar{\varphi}' \not{D}' \varphi' - m\bar{\varphi}' \varphi' = ie^{-i\alpha} \bar{\varphi} e^{i\alpha} \not{D} \varphi - me^{-i\alpha} \bar{\varphi} e^{i\alpha} \varphi \quad (2.17)$$

$$= i\bar{\varphi} \not{D} \varphi - m\bar{\varphi} \varphi \quad (2.18)$$

The term  $i\bar{\varphi} \not{D} \varphi$  can be expanded to  $i\bar{\varphi} \not{\partial} \varphi - \bar{\varphi} e \not{A} \varphi$ . The second term couples the particle fields ( $\varphi, \bar{\varphi}$ ) and the vector field  $A$  with the coupling constant  $e$ . The particle fields corresponds to the fermions  $f, \bar{f}$ , the vector field to the photon  $\gamma$ , and the coupling constant to the electric charge. This defines a vertex shown in Figure 2.2. The strength of the interaction increases with momentum transfer and at small distances, and is therefore known as a running coupling.

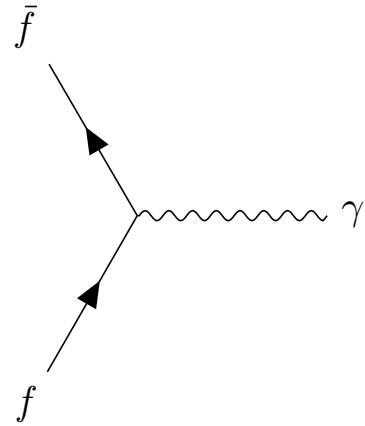


Figure 2.2: The electromagnetic vertex predicted by QED.

To form the complete QED Lagrangian  $\mathcal{L}_{\text{QED}}$ , the Dirac Lagrangian  $\mathcal{L}_{\text{Dirac}}$  must be combined with the kinetic term

from Maxwell's equations  $\mathcal{L}_{\text{EM}}$  to give

$$\mathcal{L}_{\text{QED}} = \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{EM}} \quad (2.19)$$

$$\mathcal{L}_{\text{QED}} = \bar{\varphi} (i\not{D} - m) \varphi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \quad (2.20)$$

where  $F_{\mu\nu}$  is the electromagnetic field tensor, defined as  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ .

## 2.3 Quantum Chromodynamics (QCD)

QCD builds on the discoveries of QED, providing a QFT and Lagrangian describing the strong force, the colour charge that the force depends on, and the gluons that mediate it. Unlike QED, QCD is a SU(3) symmetry, and therefore has  $(3^2 - 1) = 8$  mediators. The gluons exchange a particular colour charge, and therefore have colours and anti-colours such as 'red-antigreen' or 'antiblue-red', which form the first six mediators. Directly exchanging a single colour such as 'red-antired' is forbidden, but a superposition is possible so a representation of the final two mediators is  $\frac{(r\bar{r}-g\bar{g})}{\sqrt{2}}$  and  $\frac{(r\bar{r}+g\bar{g}-2b\bar{b})}{\sqrt{6}}$ . Additionally, the non-abelian nature of special unitary groups results in self-interacting mediators. QCD again begins from the Dirac Lagrangian and introduces a covariant derivative, this time defined as

$$D_i^\mu j \equiv \partial^\mu \delta_{ij} - ig_s t_{ij}^a G^{a\mu} \quad (2.21)$$

where  $\delta_{ij}$  is the Kronecker delta<sup>1</sup>,  $g_s$  is the strong coupling constant,  $t^a = \lambda^a/2$  are the SU(3) group generators where  $\lambda^a$  are the Gell-Mann matrices, and  $G^a$  are the gluon gauge fields. With this derivative and the base Dirac Lagrangian, the QCD Lagrangian can be written as

$$\mathcal{L}_{\text{QCD}} = \bar{\varphi}_j (i\gamma_\mu \partial^\mu \delta_{ij} - m\delta_{ij}) \varphi_i - g_s (\bar{\varphi}_j \gamma_\mu t_{ij}^a \varphi_i) G^{a\mu} \quad (2.22)$$

where the quarks are indexed  $1 \rightarrow 3$  by  $i$  and  $j$ , and the gluons are indexed  $1 \rightarrow 8$  by  $a$ . Like in QED, the second term in Equation 2.22 allows a quark  $\varphi_i$  and anti-quark  $\bar{\varphi}_j$  of the same flavour ( $i = j$ ) to form a vertex with one of the eight gluons.

The full QCD Lagrangian can be constructed with the gluon field kinetic term and the result from Equation 2.22 using Feynman slash notation as

$$\mathcal{L}_{\text{QCD}} = \bar{\varphi}_j (i\not{D}_{ij} - m) \varphi_i - \frac{1}{4} G_a^{\mu\nu} F_{\mu\nu}^a \quad (2.23)$$

Expanding  $G_a^{\mu\nu} F_{\mu\nu}^a$  yields the three- and four-gluon self-interactions. The Feynman vertices from QCD are shown in Figure 2.3

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<sup>1</sup> $\delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$

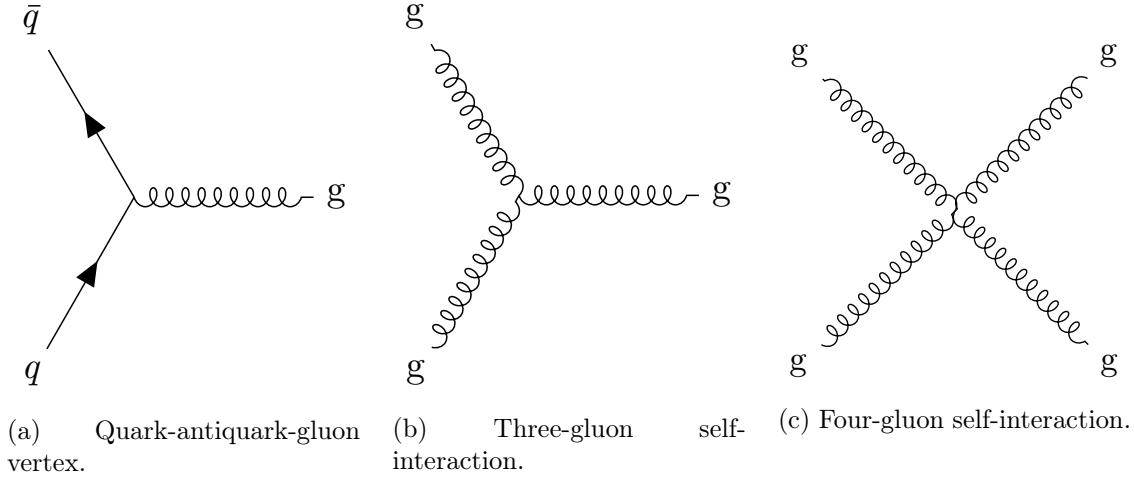


Figure 2.3: The three Feynman vertices predicted by QCD, including quark-gluon interactions and gluon self-interactions.

Like QED, the QCD coupling constant  $\alpha_s$  depends on the momentum transferred in the interaction,  $Q^2$  in the function

$$\alpha_s(Q^2) = \frac{2\pi}{\beta_0 \ln Q^2/\Lambda_{\text{QCD}}^2} \quad (2.24)$$

where  $\beta_0 = 11 - \frac{2}{3}n_{\text{flavours}}$  and  $\Lambda_{\text{QCD}}^2$  is the energy at which quarks and gluons hadronise, known as the *hadronisation scale*. As opposed to the interaction strength from QED, the QCD interaction strength clearly decreases as the momentum transfer increases. When the interaction strength is sufficiently small quarks and gluons can be treated as free particles and highly accurate perturbative calculations using a series expansion can be employed. In these calculations each successive term corresponds to additional vertices and complexities in the Feynman diagrams. In the higher-order diagrams the internal loops cause *ultraviolet* divergences from the perturbative calculation, which requires  $\alpha_s$  to be calculated at a *renormalisation scale*  $\mu_R$ , typically set to the Z-boson mass.

In the limit  $Q^2 \rightarrow \Lambda_{\text{QCD}}^2$  the coupling constant  $\alpha_s$  tends to infinity. This means as the distance over which the interaction takes place increases, the potential energy stored in the interaction also increases. Eventually, this reaches the point where it is energetically favourable to create a new pair of strong-interacting particles, analogous to stretching a spring to breaking point, where the stored spring potential energy exceeds the energy required to break the spring into two smaller springs. This has the effect that quarks and gluons can never exist as individual free particles, and can only be found in colour-neutral bound states. These bound states can exist as a quark-antiquark pair (mesons) or larger groups of quarks and antiquarks (hadrons,



tetraquarks, pentaquarks).

## 2.4 The Weak Interaction & Electroweak Unification

The third and final force introduced in the Standard Model is the weak interaction. The weak interaction follows an  $SU(2)$  symmetry and operates between *left-handed* fermions only. The handedness of a particle is determined by the particle's *chirality*. Chirality is an intrinsic property of a particle, connected to a particle's *helicity*, which it is equivalent to in the high-energy limit. Helicity is defined as the projection of a particle's spin vector onto the momentum vector – if the spin projection is in the same direction as the momentum vector the particle is said to be right-handed; if the spin projection and momentum are in opposite directions then the particle is said to be left-handed. For massless particles the helicity is Lorentz-invariant. Chirality is mathematically defined via the  $\gamma^5$  operator, which has a value of  $+1$  for right-handed particles and  $-1$  for left-handed particles.

As the weak interaction is a  $SU(2)$  symmetry it predicts  $(2^2 - 1) = 3$  mediators:  $W_\mu^1$ ,  $W_\mu^2$  and  $W_\mu^3$ . A new vector quantum number *isospin* ( $I$ ) is also introduced, along with the third component of isospin,  $I_3$ . Left-handed fermions  $f_L$  and right-handed anti-fermions  $\bar{f}_R$  have an isospin of  $I = 1/2$  and can form isospin doublets, whereas right-handed fermions  $f_R$  and left-handed anti-fermions  $\bar{f}_L$  have an isospin of  $I = 0$  and form isospin singlets. Two weak isospin doublets can be defined with this quantum number,

$$\begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad (2.25)$$

where  $\nu_L$  are neutrinos (left-handed only),  $\ell_L$  are left-handed leptons, and  $u_L$  and  $d_L$  are up- and down-type left-handed quarks. Both doublets have an isospin of  $I = 1/2$ , and the top fermions in the doublets have a third component of isospin of  $I_3 = +1/2$  whereas the bottom fermions have  $I_3 = -1/2$ . For composite particles, the third component can be defined as

$$I_3 = \frac{1}{2} (n_u - n_d), \quad (2.26)$$

where  $n_u$  and  $n_d$  are the number of up and down quarks in the particle respectively.

The ability for left-handed fermions to form isospin doublets allows for a change in quark flavour within a generation (e.g.  $u \rightarrow d$  or  $s \rightarrow c$ ). Additionally, the weak interaction allows for inter-generational flavour changes via the Cabibo-Kobayashi-Maskawa (CKM) matrix [10,

11], defined as

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (2.27)$$

where  $|V_{ij}|$  are the components of the CKM matrix, which are proportional to the probability of transition from quark  $i$  to quark  $j$ ,  $q'$  are the down-type weak isospin doublets, and  $q$  are the down-type mass eigenstates.

As the weak force mediates interactions involving the exchange of electric charge, it is possible to unify the weak interaction and QED into a single *electroweak* interaction. This is necessary to ensure the fermions in the weak interaction are the same as the fermions in the QED interactions. This is known as the Glashow-Salam-Weinberg (GSW) mechanism [12–14]. Here, an overall  $SU(2)_L \times U(1)_Y$  symmetry is formed. This introduces a weak *hypercharge*  $Y$ , defined using the electric charge and third isospin component as  $Y \equiv 2(Q - I_3)$ . Below a unification energy of approximately 246 GeV, the separate QED and weak interactions are sufficient to describe the phenomena observed, but above this energy a single interaction occurs. The electroweak interaction features four mediators, the familiar  $W^\pm$ ,  $Z^0$  and  $\gamma$ . The weak boson  $Z^0$  and electromagnetic boson  $\gamma$  are formed from a mixing of the  $B$  and  $W_3$  fields via the weak mixing angle  $\theta_W$ , which is performed as the rotation

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos(\theta_W) & \sin(\theta_W) \\ -\sin(\theta_W) & \cos(\theta_W) \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix} \quad (2.28)$$

. The  $W^\pm$  bosons are found by a complex combination of the  $W_1$  and  $W_2$  bosons,

$$W^\pm = \frac{1}{\sqrt{2}} (W_1 \mp iW_2) \quad (2.29)$$

For this combined electroweak interaction a new covariant derivative can be defined:

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + \frac{i}{2}g\vec{\sigma} \cdot \vec{W}_\mu + ig'\frac{Y}{2}B_\mu \quad (2.30)$$

in which the  $SU(2)$  symmetry is represented in the second term with the  $\vec{W}$  gauge fields corresponding to the  $W^{1 \rightarrow 3}$  bosons with the coupling  $g$ , and the  $U(1)$  coupling represented by the third term with the  $B$  gauge field corresponding to the  $B$  boson with the coupling  $g'$ , and  $\vec{\sigma}$  are the  $2 \times 2$  Pauli matrices.  $g$  and  $g'$  also define the weak mixing angle  $\theta_W = g'/g$ . Three fermion-boson vertices are available, along with three electroweak boson self-coupling vertices due to the non-abelian nature of the symmetry. These vertices are shown in Figure 2.4.

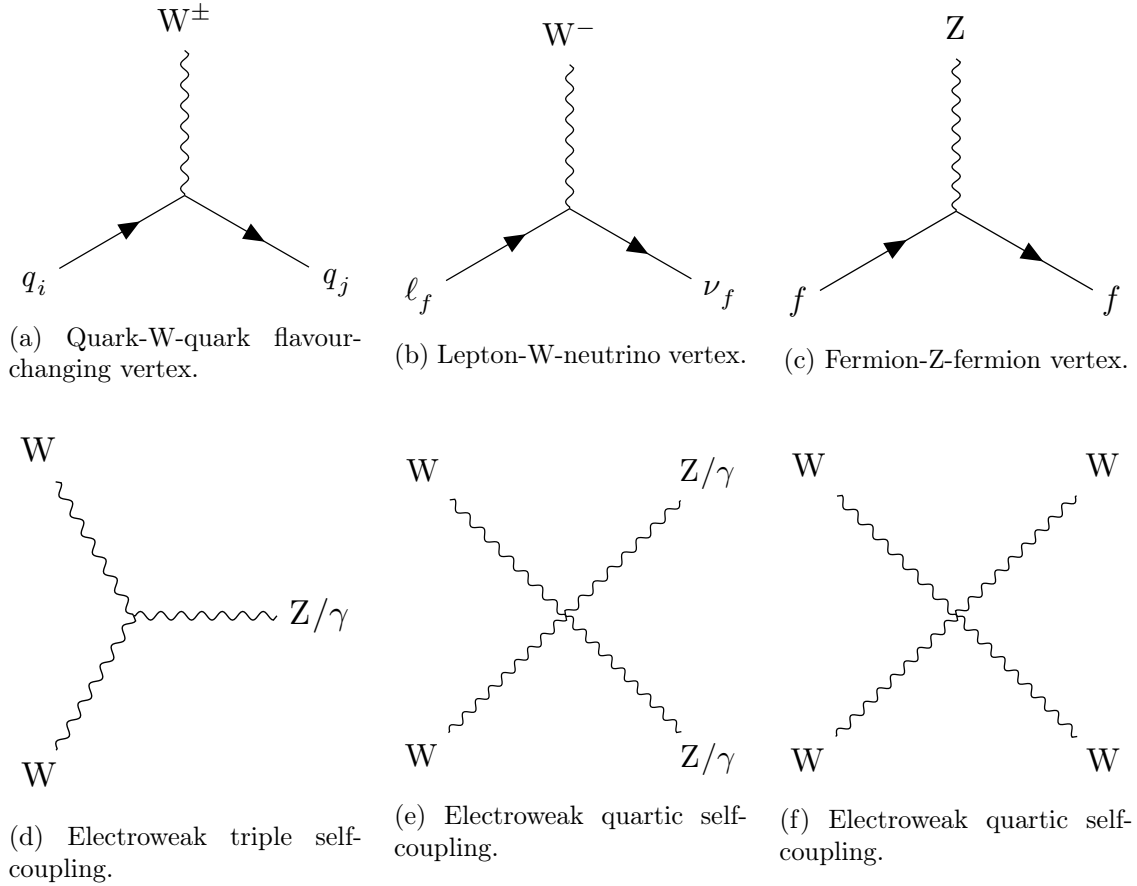


Figure 2.4: The six Feynman vertices predicted by electroweak theory, including three fermion-boson interactions and three boson self-interactions.

To ensure gauge-invariance the  $W^{1 \rightarrow 3}$  and B bosons must be massless. To demonstrate this, we can attempt to include a mass term in the Lagrangian to replace the previous  $m\bar{\varphi}\varphi$ . As only left-handed fermions couple to the interaction, projection operators ( $P_L$ ,  $P_R$ ) can be defined to separate out the left- and right-handed components:

$$P_L = \frac{1}{2} (1 - \gamma^5) \quad P_R = \frac{1}{2} (1 + \gamma^5) \quad (2.31)$$

where

$$\gamma^5 = \begin{bmatrix} 0 & \mathbb{I}_2 \\ \mathbb{I}_2 & 0 \end{bmatrix} \quad (2.32)$$

and  $\mathbb{I}_2$  is the 2x2 identity matrix. These projection operators can be used to expand the fermion field to

$$\varphi = P_L \varphi + P_R \varphi = \varphi_L + \varphi_R \quad (2.33)$$

and in turn develop a mass term of

$$m\bar{\varphi}\varphi = \bar{\varphi}_R \varphi_L + \bar{\varphi}_L \varphi_R \quad (2.34)$$

. As the (electro)weak interaction only couples with the first term in the expanded mass term, the two halves of the mass term will transform differently and break gauge invariance. This is resolved with the Higgs mechanism.

## 2.5 The Higgs Mechanism

To provide the mass terms to the electroweak interaction while allowing gauge invariance, a new mechanism to break the electroweak symmetry is required. This is achieved by the Higgs mechanism [15, 16], which introduces an additional SU(2) doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^- \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2.35)$$

which is comprised of complex scalar fields  $\phi$ . The Higgs doublet has quantum numbers of  $I = 1/2$  and  $Y = 1$ , and when using the covariant derivative  $D_\mu$  defined in Equation 2.30 the Higgs field gains the Lagrangian

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger D_\mu \Phi - V(\Phi) \quad (2.36)$$

where  $V$  is the Higgs field potential, defined as

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (2.37)$$

in which the  $\mu^2$  term can be designated as the mass term, and the  $\lambda$  term as the self-interaction term. Assuming a  $\lambda > 0$ , which is required to provide a lower bound for the potential and ensure a ground state exists, this potential takes a parabolic potential in the case  $\mu^2 > 0$  and a ‘mexican hat’ or ‘wine bottle’ shape in the case  $\mu^2 < 0$ , shown in Figure 2.5. Equation 2.37 has two sets of minimal solutions – a trivial local minima where there is no field ( $\phi^+ = \phi^- = 0$ ), and in the wine-bottle ( $\mu^2 < 0$ ) case an infinite set of global minima where

$$\phi = v = \sqrt{\frac{\mu^2}{\lambda}} \quad (2.38)$$

where  $v$  defines the Vacuum Expectation Value (VEV). These two forms of the Higgs potential, which change at  $\mu = 0$ , lead to the  $SU(2) \times U(1)$  electroweak symmetry breaking to the  $U(1)$  electromagnetic symmetry and the  $SU(2)$  weak symmetry.

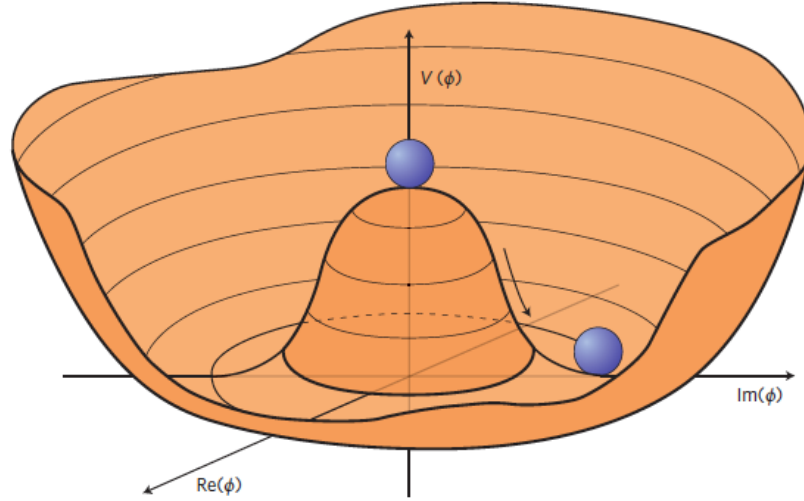


Figure 2.5: The Higgs field potential as a function of the vacuum expectation value, showing the characteristic ‘mexican hat’ or ‘wine bottle’ shape. [17]

By defining  $\phi_{1,2,4} = 0$ ,  $\phi_3 = v^2$ , the Higgs doublet becomes

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.39)$$

, or

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix} \quad (2.40)$$

when expanded around the neutral Higgs field  $H$ , which ensures the remaining field current is neutral and the electromagnetic symmetry is unbroken. When the Higgs field is introduced and a full electroweak Lagrangian using the covariant  $D_\mu$  from Equation 2.30 is defined, the quadratic term

$$(D_\mu \Phi)^\dagger D_\mu \Phi = \frac{1}{2} (\partial_\mu H)^2 + \frac{g^2 v^2}{4} W_\mu^+ W^{\mu-} + \frac{1}{8} (g^2 + g'^2) v^2 Z_\mu Z^\mu \quad (2.41)$$

from the Lagrangian can be isolated and identified as mass terms for the  $W^\pm$  and  $Z$  bosons, which allows a derivation of their masses as

$$m(W) = \frac{gv}{2} = \frac{e_0 v}{2 \cos(\theta_W)} \quad m(Z) = \frac{v}{2} \sqrt{g^2 + g'^2} = \frac{m(W)}{\cos(\theta_W)} \quad (2.42)$$

where  $e_0$  is the photon's coupling constant,  $e_0 = g \sin(\theta_W)$ . The VEV is related to the Fermi constant  $G_F$  as  $v^2 = G_F \sqrt{2}$ , leading to an approximate value of 246 GeV, and fixing the boson masses. It is also possible to isolate a mass term for the Higgs boson from the Lagrangian, which leads to

$$m(H) = 2v\sqrt{2\lambda} \quad (2.43)$$

, the best measurement of which is  $125.11 \pm 0.11$  GeV by the ATLAS collaboration combining multiple measurements of  $H \rightarrow \gamma\gamma$  and  $H \rightarrow 4\ell$  interactions [18]. A range of Higgs boson mass measurements is shown in Figure 2.6.

The Higgs boson also generates the fermion masses as well as the boson masses, with the fermion masses related to their coupling strength to the Higgs field, defined by the Yukawa interaction

$$g_f \bar{\psi}_L \phi \psi_R \quad (2.44)$$

where  $g_f$  is the Yukawa coupling and determined experimentally for each fermion. The fermion mass can then be found as

$$m_f = g_f \frac{v}{\sqrt{2}}. \quad (2.45)$$

The interaction in Equation 2.44 also raises the possibility of oscillations between left- and right-handed fermions.

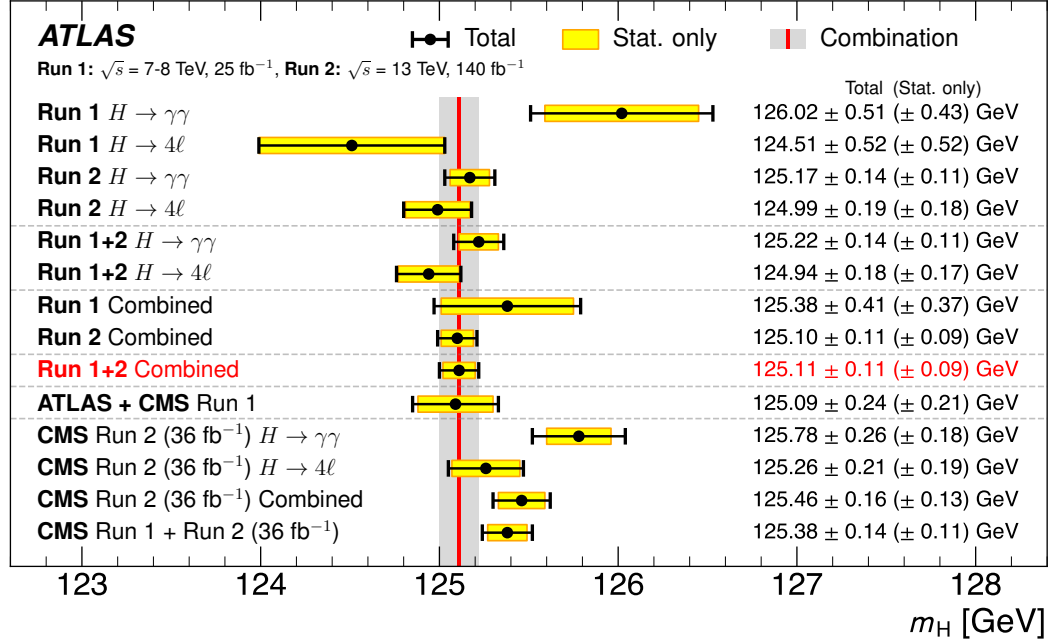


Figure 2.6: A history of measurements of the Higgs boson mass by the ATLAS and Compact Muon Solenoid (CMS) collaborations. Reproduced from [18].

## 2.6 Motivations for Physics Beyond the Standard Model

The Standard Model has had incredible success, providing the first self-consistent model that describes all observed forces and particles. The Standard Model also delivers the most accurate prediction known, the anomalous magnetic dipole moment of the electron, which has a prediction of  $0.001\,159\,652\,181\,61\,(23)$  [19] and a measurement of  $0.001\,159\,652\,180\,62\,(12)$  [20], an accuracy of more than one in ten billion. However, there are a number of open questions in the Standard Model which motivate new, Beyond Standard Model (BSM) physics.

As demonstrated in Section 2.4, it is possible to unify the electromagnetic and weak forces. It is therefore natural to wonder if the strong force can also be unified with the other forces. Such a theory would be known as a Grand Unified Theory (GUT). This is defined as finding a value of momentum transfer  $Q$  where the coupling constants of the three interactions converge. However, attempts to do so fail, as shown in Figure 2.7 – while any two of the  $SU(3)$ ,  $SU(2)$  and  $U(1)$  couplings converge, at no point do all three converge.

Oscillations between neutrino flavours have been widely observed at a number of neutrino observatories. Left- and right-handed Dirac fermions interact with the Higgs boson to acquire their masses, however neutrinos do not have right-handed partners, so cannot acquire mass in this way. Therefore, a new BSM mechanism is required to provide neutrino masses. A

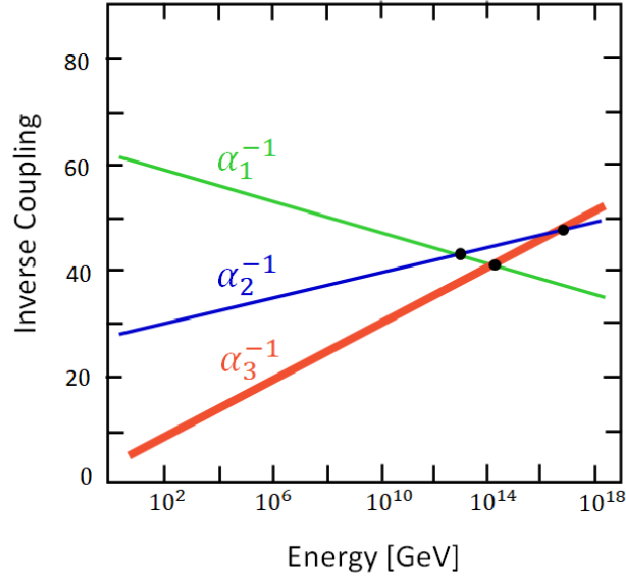


Figure 2.7: A depiction of the running coupling constants of the electromagnetic ( $\alpha_1$ ), weak ( $\alpha_2$ ) and strong ( $\alpha_3$ ) interactions, and how there is no point at which all three intersect. [21]

popular solution is the *see-saw* mechanism [22], which proposes extremely heavy (GUT-scale) right-handed neutrinos to provide a mechanism for neutrino masses, keep the right-handed neutrinos out of the sensitivity range of published results, and resolve the unbalanced nature of tiny neutrino masses compared with other particles in the Standard Model.

It is widely desired that physical models have as few free parameters as possible, so that the theory is motivated by mathematics and logical consequences rather than *fine-tuning* of parameters to match reality. This is known as the *naturalness* of a theory. An analogy is that, with sufficient terms, a polynomial can match an observed distribution of some variable perfectly, but does not necessarily relate at all to the underlying mechanism producing that distribution. The Standard Model contains at least 25 free parameters, and more if mixing angles between neutrino mass states are included. Many of these values have to be very carefully “chosen” to produce the stable universe we inhabit. One solution to this is that there are infinite universes with all possible parameter values, and through a form of survivorship bias we inhabit a universe with a particular combination of these. This is also known as the anthropic principle.

An extension of the naturalness problem is the *hierarchy* problem, which is when a theory requires large corrective factors to match reality, often leading to large differences in scale from the rest of the theory. Several examples exist in the Standard Model. The leading example is the corrections to the Higgs boson mass. The mass of the observed Higgs boson is



dependent on the bare mass and corrections from higher-order loop diagrams. For most other particles, these loop corrections are small compared to the bare mass of the particle. For the Higgs, this can be found as

$$m^2(\text{H}) = m_{\text{bare}}^2(\text{H}) + \delta m^2(\text{H}) \approx 2\mu^2 - \frac{|g_f|^2}{8\pi^2} \Lambda_p^2 \quad (2.46)$$

where  $\Lambda_p$  is the Planck scale and is considered to be the cut-off energy for virtual particle corrections. This corrective factor is therefore  $\mathcal{O}(10^{30})$  times the observed Higgs mass. This is part of a larger hierarchy problem, caused by the difference in scale between the electroweak ( $\mathcal{O}(10^2)$  GeV) and gravitational (Planck) scales ( $\mathcal{O}(10^{19})$  GeV), which makes unification between the interactions unlikely.

Perhaps the most significant open question in the Standard Model is the lack of explanation for dark matter. Dark matter is an unknown, gravitationally-attractive particle that is common throughout the universe, but does not interact electromagnetically. However, beyond this specification nothing is known about dark matter, such as the spin or production mechanism. There exists a broad range of hypothetical candidates for dark matter, ranging in mass from fractions of an eV up to several solar masses. The evidence for particulate dark matter from cosmological observations is very strong, including the rotation curves of galaxies and the distribution of mass during galactic collisions. Dark matter, the evidence for it, and an overview of the leading explanations is covered in detail in Section 3.2, along with SUSY, a class of models capable of elegantly resolving many of the open questions in the Standard Model.

## Chapter 3

# Beyond the Standard Model

As described at the end of Chapter 2, despite the great success of the Standard Model, there are phenomena such as dark matter and neutrino masses that remain unexplained, and conceptual problems such as naturalness and the hierarchy problems. There are many proposed solutions to some or all of these issues. As the Standard Model is extremely accurate for what it does predict, most of these solutions seek to extend the Standard Model, rather than replace it altogether. One of the most popular classes of BSM hypotheses is supersymmetry, which introduces a new symmetry to the Standard Model, potentially resolving all issues described in Section 2.6. The general principles of SUSY, a minimal SUSY model, and a mechanism for the breaking of the SUSY symmetry are discussed in Section 3.1, along with the current exclusion limits from major experiments.

As Section 3.1 will discuss, while SUSY is very well motivated mathematically and has the potential to resolve many outstanding issues in particle physics, 14 years of LHC operation and analysis has failed to discover any significant evidence for SUSY, and results from other experiments and observations have significantly constrained the feasible parameter space for SUSY models. Another approach is to attempt to solve problems such as dark matter individually. Dark matter, its evidence, and a range of possible explanations are discussed in Section 3.2 along with the current exclusion limits.

### 3.1 Supersymmetry

Supersymmetry introduces an extension to the Standard Model in the form

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{SUSY} \tag{3.1}$$

and the symmetry

$$Q |\text{boson}\rangle = |\text{fermion}\rangle \quad (3.2)$$

$$Q |\text{fermion}\rangle = |\text{boson}\rangle \quad (3.3)$$

where  $Q$  is a new operator also introduced by SUSY [23]. Through this extension all Standard Model particles gain a *superpartner*, different in spin by  $1/2$ . Fermion superpartners (now spin-0 bosons) follow the naming convention of adding an ‘s’ to the beginning of their name – for example, an electron’s superpartner is a *selectron*, and a quark becomes a *squark*. This ‘s’ is short for scalar. Boson superpartners (now spin- $1/2$  fermions) have ‘-ino’ appended to their names – for example, the Higgs boson becomes a *higgsino*, and a gluon becomes a *gluino*. In equations and Feynman diagrams, superpartners are commonly denoted with a tilde ( $\sim$ ) above the symbol – for example, a selectron is represented by  $\tilde{e}$ , and a stop quark is represented by  $\tilde{t}$  [23].

As with all symmetries, SUSY also introduces a conserved quantity,  $R$ -parity, defined as

$$R = (-1)^{3(B-L)+2S} \quad (3.4)$$

where  $B$  is the baryon number,  $L$  is the lepton number and  $S$  is the spin [24]. The  $R$ -parity is defined such that Standard Model particles have an  $R$ -parity of  $+1$ , whereas SUSY particles have a value of  $-1$ . If this is a conserved quantity, this will have the effect that all SUSY particles must decay to at least one other SUSY particle, thereby forcing the Lightest Supersymmetric Particle (LSP) to be stable as there are no lighter SUSY particles to decay to. If the LSP is neutral it therefore forms a dark matter candidate [25, 26]. It is worth noting however that some SUSY formulations allow for limited amounts of  $R$ -parity violation.

### 3.1.1 Minimal Supersymmetric Standard Model

The MSSM is, as the name suggests, the minimal extension to the Standard Model that is consistent with the observations of the Standard Model. Within the MSSM [27, 28], the particles are organised into *chiral* and *gauge super-multiplets*. The chiral super-multiplets contain a Standard Model fermion and the corresponding boson superpartner. The gauge super-multiplets contain the pre-Electroweak Symmetry Breaking (EWSB) massless Standard Model gauge bosons and the corresponding fermion *gaugino* superpartners. The chiral and gauge super-multiplets are shown in Tables 3.1 and 3.2 respectively. Additionally, the spin- $3/2$  gravitino is added as a superpartner for a hypothetical particle mediator of gravity, the spin-2 graviton.

Electroweak symmetry breaking in the MSSM proceeds in a similar way to the Standard Model, described in Section 2.5. However, an extended Higgs sector is required with two

| Super-multiplet Name      | Symbol    | Spin-0                      | Spin-1/2                        | $SU(3)_C \times SU(2)_L \times U(1)_Y$ |
|---------------------------|-----------|-----------------------------|---------------------------------|----------------------------------------|
| (s)quarks                 | Q         | $(\tilde{u}_L \tilde{d}_L)$ | $(u_L d_L)$                     | $(3, 2, \frac{1}{6})$                  |
| ( $\times 3$ generations) | $\bar{u}$ | $\tilde{u}_R^*$             | $\tilde{u}_R^\dagger$           | $(\bar{3}, 1, -\frac{2}{3})$           |
|                           | $\bar{d}$ | $\tilde{d}_R^*$             | $\tilde{d}_R^\dagger$           | $(\bar{3}, 1, \frac{1}{3})$            |
| (s)leptons                | L         | $(\tilde{\nu} \tilde{e}_L)$ | $(\nu e_L)$                     | $(1, 2, -\frac{1}{2})$                 |
| ( $\times 3$ generations) | $\bar{e}$ | $\tilde{e}_R^*$             | $\tilde{e}_R^\dagger$           | $(1, 1, 1)$                            |
| Higgs(inos)               | $H_u$     | $(H_u^+ H_u^0)$             | $(\tilde{H}_u^+ \tilde{H}_u^0)$ | $(1, 2, +\frac{1}{2})$                 |
|                           | $H_d$     | $(H_d^0 H_d^-)$             | $(\tilde{H}_d^0 \tilde{H}_d^-)$ | $(1, 2, -\frac{1}{2})$                 |

Table 3.1: The chiral super-multiplets of the MSSM.

| Super-multiplet Name | Spin-1/2                    | Spin-1      | $SU(3)_C \times SU(2)_L \times U(1)_Y$ |
|----------------------|-----------------------------|-------------|----------------------------------------|
| gluino, gluon        | $\tilde{g}$                 | $g$         | $(8, 1, 0)$                            |
| wino, W-boson        | $\tilde{W}^\pm \tilde{W}^0$ | $W^\pm W^0$ | $(1, 3, 0)$                            |
| bino, B-boson        | $\tilde{B}^0$               | $B^0$       | $(1, 1, 0)$                            |

Table 3.2: The gauge super-multiplets of the MSSM.

Higgs doublets. These doublets correspond to the two chiral super-multiplets  $H_u$  and  $H_d$ , and have weak isospin  $I = \pm 1/2$ . These doublets generate four Higgs eigenstates,  $\tilde{H}_u^+$ ,  $\tilde{H}_u^0$ ,  $\tilde{H}_d^0$  and  $\tilde{H}_d^-$  which mix to five mass states,  $h^0$ ,  $H^0$ ,  $A^0$  and  $H^\pm$  where  $h^0$  is the discovered Standard Model Higgs particle. The two Higgs doublets gain separate VEVs  $v_u$  and  $v_d$ ,

$$\langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix} \quad \langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix} \quad (3.5)$$

which can be related to each other as

$$v_u^2 + v_d^2 = v^2 = \frac{2m^2(Z)}{g^2 + g'^2} \quad (3.6)$$

with the ratio of the two VEVs left as a free parameter characterised by  $\beta$ , defined as

$$\tan \beta = \frac{v_u}{v_d} \quad (3.7)$$

After electroweak symmetry breaking, the higgsinos and gauginos mix into observable mass eigenstates. The neutral higgsinos and gauginos mix to form four electrically-neutral *neutrali-*

$nos$ , and the charged higgsinos and gauginos mix to form two *charginos*. These are denoted by their mass, with the lightest neutralino and chargino denoted as  $\tilde{\chi}_1^0$  and  $\tilde{\chi}_1^\pm$  respectively, and the heaviest as  $\tilde{\chi}_4^0$  and  $\tilde{\chi}_2^\pm$  respectively. The neutralino mass term from the Lagrangian is given as

$$-\frac{1}{2} \left( \vec{\psi}^0 \right)^T \mathbf{M}_{\tilde{\chi}^0} \vec{\psi}^0 \quad (3.8)$$

where  $\vec{\psi}^0$  is the set of neutral higgsinos and gauginos  $(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$  and  $\mathbf{M}_{\tilde{\chi}^0}$  is the neutralino mixing matrix

$$\mathbf{M}_{\tilde{\chi}^0} = \begin{bmatrix} M_1 & 0 & -\cos \beta \sin \theta_W m_Z & \sin \beta \sin \theta_W m_Z \\ 0 & M_2 & \cos \beta \cos \theta_W m_Z & -\sin \beta \cos \theta_W m_Z \\ -\cos \beta \sin \theta_W m_Z & \cos \beta \cos \theta_W m_Z & 0 & -\mu \\ \sin \beta \sin \theta_W m_Z & -\sin \beta \cos \theta_W m_Z & -\mu & 0 \end{bmatrix} \quad (3.9)$$

where  $M_1$ ,  $M_2$  and  $\mu$  are the bino, wino and higgsino mass terms respectively. The chargino mass term is defined similarly as

$$-\frac{1}{2} \left( \vec{\psi}^\pm \right)^T \mathbf{M}_{\tilde{\chi}^\pm} \vec{\psi}^\pm \quad (3.10)$$

where  $\vec{\psi}^\pm$  is the set of charged higgsinos and gauginos  $(\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$  and  $\mathbf{M}_{\tilde{\chi}^\pm}$  is the chargino mixing matrix

$$\mathbf{M}_{\tilde{\chi}^\pm} = \begin{bmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{bmatrix} \quad \mathbf{X} = \begin{bmatrix} M_2 & \sqrt{2} \sin \beta m(W) \\ \sqrt{2} \sin \beta m(W) & \mu \end{bmatrix} \quad (3.11)$$

As we do not observe SUSY particles at the same mass as their Standard Model partners, the symmetry introduced by SUSY must be a broken symmetry. In the MSSM supersymmetry breaking is simply added as a spontaneous soft term [29] in the Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}} \quad (3.12)$$

It is necessary for the breaking mechanism to take place in a hidden sector, as it is not possible to contain it within the MSSM as described. There are several methods to communicate this hidden-sector breaking to the MSSM. Three popular methods for achieving this are Planck-Scale-Mediated Supersymmetry Breaking (PMSB), Gauge-Mediated Supersymmetry Breaking (GMSB) and AMSB.

PMSB proposes that the breaking of supersymmetry occurs via gravity, and therefore takes

place at energies approaching the Plank scale. GMSB extends the gauge groups in the MSSM with an additional sector which is communicated to the Standard Model via heavy messengers [30–32]. AMSB proposes additional dimensions and allows for an anomalous violation of symmetries such as SUSY [33, 34]. AMSB is used to provide a model for the analyses discussed in the thesis, so will be covered in greater detail.

### 3.1.2 Anomaly-Mediated Supersymmetry Breaking

As described above, AMSB proposes a supersymmetry breaking mechanism that utilises ‘Weyl anomalies’ in higher dimensions to break the symmetry and communicate these to our observable dimensions [23, 33, 34]. A minimal AMSB model can be defined by four free parameters:

- the gravitino mass ( $m_{3/2}$ )
- the scalar mass ( $m_0$ )
- the ratio of the Higgs VEVs ( $\tan \beta$ )
- the sign of the higgsino mass ( $\text{sgn } \mu$ )

It is possible to relate the gaugino masses to the coefficient of their renormalisation group  $b$ :

$$-\frac{b_i g_i}{16\pi^2} m_{3/2} \quad (3.13)$$

where  $i = 1, 2, 3$  indexes the gauge groups  $U(1)$ ,  $SU(2)$  and  $SU(3)$ ,  $b_i = (-33/5, -1, 3)$  are the normalisation coefficients, and  $g_i$  are gauge couplings.

In this ‘pure’ form of AMSB the bino, wino and gluino masses are approximately related as  $M_1 : M_2 : M_3 \approx 3 : 1 : 7$  and the LSP is wino-like. This model is henceforth referred to as the *pure-wino* model. When the higgsino mass  $\mu$  is large, the chargino and neutralino masses become degenerate at tree-level, and the mass splitting between these particles is dominated by electroweak loop corrections. This splitting is calculated in Reference [35] at the two-loop level and found to be 160 to 165 MeV above a neutralino mass of 250 GeV, shown in Figure 3.1.

As there is only a small mass splitting between the chargino and neutralino and the neutralino is the LSP and therefore stable, the chargino dominantly decays into the neutralino and a low-momentum pion. This process is shown in Figure 3.3(a). The decay width, and subsequently the charging lifetime, of the chargino at a particular mass splitting  $\Delta m \left( \tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right)$  can be found by

$$\frac{1}{\tau} \approx \Gamma \left( \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm \right) = \frac{2G_F^2}{\pi} \cos^2(\theta_c) f_\pi^2 \Delta m \left( \tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right)^3 \sqrt{1 - \frac{m_{\pi^\pm}^2}{\Delta m \left( \tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right)^2}} \quad (3.14)$$

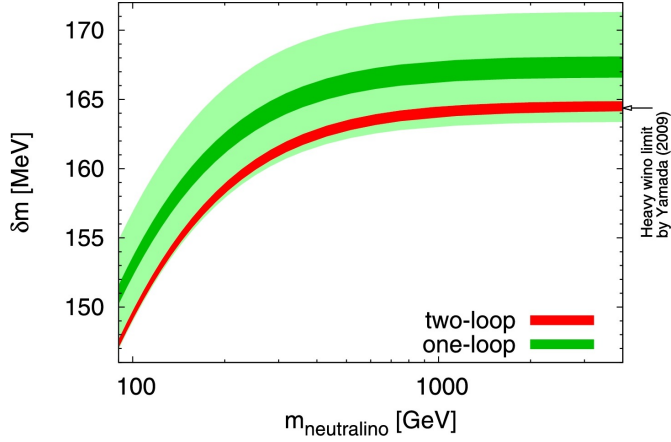


Figure 3.1: The difference in mass between the chargino and neutralino in the pure-wino model as a function of the neutralino mass, as found in [35].

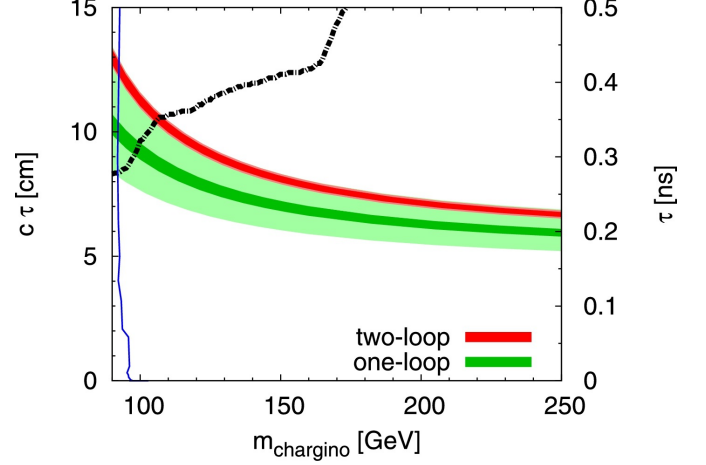


Figure 3.2: The chargino lifetime in the pure-wino model as a function of the chargino mass, as found in [35]. The blue line to the left is the limit from the Large Electron-Positron Collider (LEP) collider experiments, and the dashed black line is the Run-1 ATLAS limit.

where  $G_F$  is the Fermi constant,  $\theta_c$  is the Cabibbo angle,  $f_\pi \approx 130 \text{ MeV}$  is the pion decay constant and  $m_{\pi^\pm} = 139.6 \text{ MeV}$  is the charged pion mass. The chargino lifetime is shown as a function of the chargino mass in Figure 3.2

From the ratio of  $M_3/M_2 = \sim 7$  given above, in the pure-wino AMSB model the gluino has a high mass, and due to the choice of a large value of  $m_0$  all sfermions become decoupled from the gauginos. This yields a mass spectrum similar to that shown in Figure 3.4, but at higher masses – this figure shows an excluded model with a chargino mass similar to a Standard Model higgs mass.

It is also possible to generate charginos through a strong process [37]. At suitable values of the higgsino mass  $\mu$  and heavy Higgs mass  $m_A$  there can be a Higgs-higgsino radiative loop contribution  $L$  which takes the form

$$L = \mu \sin 2\beta \frac{m_A^2}{|\mu|^2 - m_A^2} \ln \frac{|\mu|^2}{m_A^2} \quad (3.15)$$

and is included in the gaugino masses as

$$M_1 = \frac{g_1}{16\pi^2} (11m_{3/2} + L) \quad (3.16)$$

$$M_2 = \frac{g_2}{16\pi^2} (m_{3/2} + L) \quad (3.17)$$

$$M_3 = \frac{g_3}{16\pi^2} (-3m_{3/2}) \quad (3.18)$$

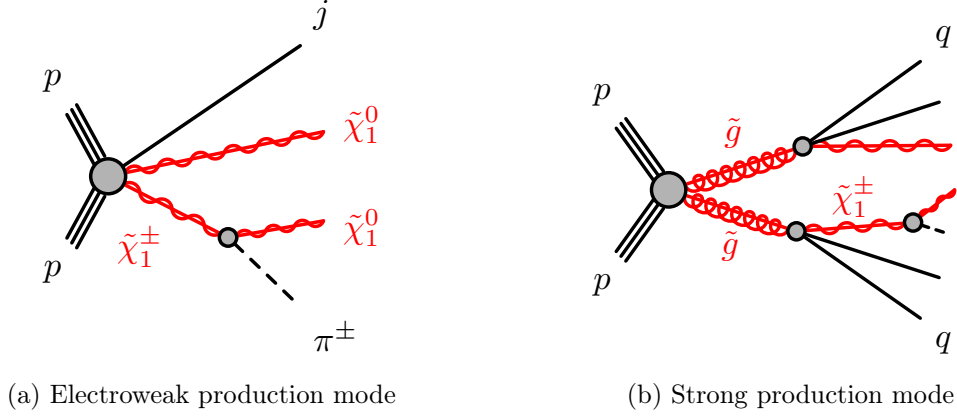


Figure 3.3: Feynman diagrams for the production of charginos and neutralinos from the AMSB model.

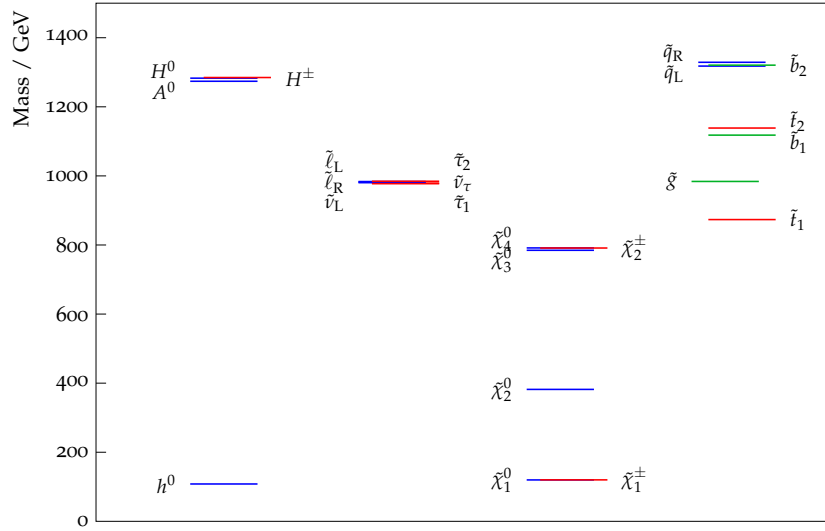


Figure 3.4: The mass spectrum of SUSY particles in an AMSB model with parameters of  $m_{3/2} = 32$  TeV,  $m_0 = 1$  TeV,  $\tan \beta = 5$ , and  $\mu > 0$ . This model is strongly excluded, and models considered in this thesis have squarks and sleptons at much higher masses of multiple TeV. Reproduced from [36].

If  $L$  becomes large the gluino becomes the principal component of the LSP, and a strong production mechanism like that in Figure 3.3(b) becomes possible.

Finally, a pure-higgsino model can be motivated via naturalness arguments [38–40]. In the limit of large  $\tan \beta$ , a naturalness condition can be defined as

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2 \quad (3.19)$$



where if the SUSY particles are heavy and the EWSB is to happen at the electroweak energy scale (as in the Standard Model), the terms on the right hand side of Equation 3.19 must be *fine-tuned* to balance. However, if the higgsino mass  $\mu$  is naturally small and the heavy higgs mass  $m_{H_u}$ , dominated by the stop and gluino masses at the one- and two-loop levels, can be larger. In a pMSSM-like model, the mass splitting between the lightest charginos and neutralinos depends on the wino, bino and higgsino masses  $(M_1, M_2, \mu)$  as shown in Equations 3.9 and 3.11. If  $M_1 = M_2 \approx 1 \text{ TeV}$  and  $\mu = 150 \text{ GeV}$ , the mass splitting can be  $\mathcal{O}(10 \text{ GeV})$ , and at higher values of  $M_1, M_2$  reduces to  $\mathcal{O}(100 \text{ MeV})$ .

In the limit of a pure-higgsino chargino (totally decoupled wino and bino masses), the difference in mass between the lightest and next-to-lightest neutralinos  $\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_2^0)$  vanishes, but a small difference between the lightest neutralino and chargino  $\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm)$  remains, which is dominated by one-loop corrections in virtual photon and Z exchanges. This chargino-neutralino mass splitting can be found by

$$\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm) = \frac{\alpha}{2} m_Z f\left(\frac{m_\chi^2}{m_Z^2}\right) \quad (3.20)$$

where

$$f(r) = \frac{\sqrt{r}}{\pi} \int_0^1 \left[ (2-x) \ln \left[ 1 + \frac{x}{r(1-x)^2} \right] \right] dx \quad (3.21)$$

is the loop function [41]. In the limit of a large value of  $\mu$ , the mass splitting is approximately 355 GeV, and decreases as  $\mu$  also decreases. At  $\mu = 100 \text{ GeV}$  the mass splitting is approximately 260 GeV.

The pure-higgsino chargino lifetime can be approximately determined from the mass splitting and pion mass by

$$c\tau_\chi [\text{mm}] \approx 7 \times \left[ \left( \frac{\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm)}{340 \text{ MeV}} \right)^3 \sqrt{1 - \frac{m_\pi^2}{\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm)^2}} \right]^{-1} \quad (3.22)$$

which yields lifetimes of 0.03 to 0.07 ns ( $c\tau = 9$  to 21 mm) and distances of flight with a typical gamma factor of  $\gamma = 5$  decay radii of  $\mathcal{O}(10)$  are possible [38].

### 3.1.3 ATLAS Searches & Current Limits

A large range of searches for supersymmetric particles are conducted at ATLAS.

In many simplistic SUSY models that the LHC was expected to be sensitive to, the SUSY particles would rapidly decay to the LSP, which as discussed earlier in this chapter is stable

if  $R$ -parity is conserved, and neutral in the case of a neutralino LSP, making it an excellent dark matter candidate [25, 26]. In such cases, the experimental signature would be Standard Model particles or jets recoiling from this LSP. As the LSP leaves no detector signature, it is only detectable by its missing energy. As there are no particles moving in the transverse plane of the detector before a collision, the transverse momenta of all particles after a collision must sum to zero, if momentum is conserved. However, not all particles are reconstructable, so the negative vector sum of the transverse momenta can be associated with these particles. Analyses that search for these signatures are known as MET+X searches, for example MET+Jets or MET+Photons.

Other models can predict SUSY particles that have lifetimes that are long enough to interact with the detectors in the experiment before decaying, or if invisible decay to detectable particles within the experiment. These are known as Long-Lived Particles (LLPs). Common detector signatures are displaced vertices or particles, where an undetectable SUSY particle travels through part of the detector before decaying to detectable particles, and disappearing tracks, where a detectable SUSY particle travels through part of the detector before decaying to undetectable particles. These LLP signatures and others are shown in Figure 3.5.

A summary of recent searches for various SUSY models at ATLAS can be seen in Figure 3.6, and for models predicting LLPs in Figure 3.7. Note that there is overlap between these summaries, and they include the results that form part of this thesis. Searches for disappearing track signatures produced by the models described in Section 3.1.2 published prior to the work in this thesis are shown in Figure 3.8. These limits are at significantly lower masses than other searches shown in Figure 3.6, highlighting the ample uncovered phase space.

## 3.2 Dark Matter

As described in Section 2.6, dark matter is perhaps the most significant question in modern particle physics. A wide range of complementary astrophysical observations show an unexplained gravitational attraction in the universe that is extremely likely to be caused by undiscovered massive particles. However, these observations simply suggest the existence of a massive particle that does not, or only weakly, interacts via the strong or electroweak forces; no restrictions are placed on spin, mass or production mechanism. Therefore, there exists a huge range of hypotheses with particles ranging in mass from a fraction of an eV to the order of solar masses.

In this section a brief overview of some of the observational evidence for dark matter is first discussed in Section 3.2.1, before a selection of hypotheses are discussed in Section 3.2.2 and the current exclusion limits in Section 3.2.3.

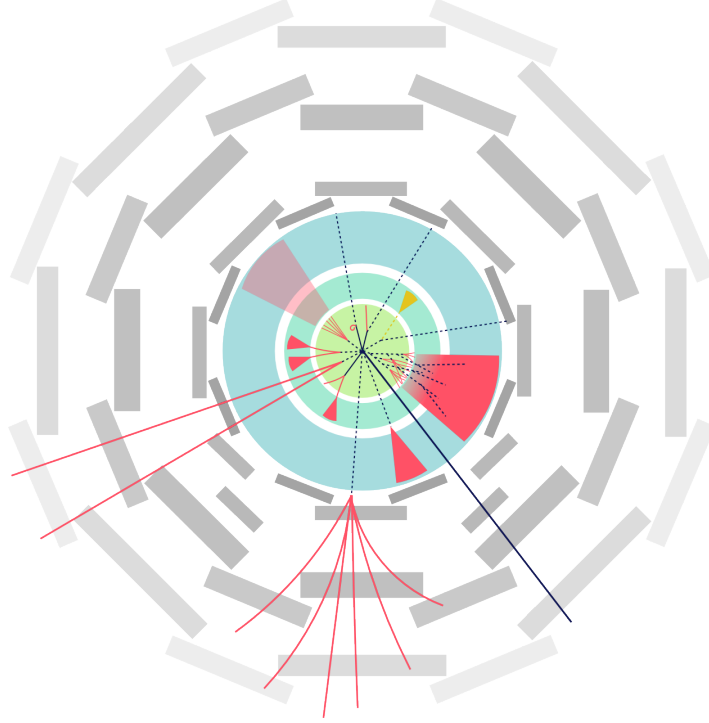


Figure 3.5: A selection of LLP signatures searched for by the ATLAS experiment [42]. Working clockwise from the top there are disappearing and kinked track signatures, displaced photons, emerging jets from LLPs gradually decaying to Standard Model particles, detector-stable LLPs, post-calorimeter hadronic decays, and various leptonic and hadronic LLP decays within the ID.

### 3.2.1 Evidence for Dark Matter

Some of the first experimental evidence that suggested the existence of dark matter was the study of the orbital velocities of stars within galaxies as a function of their radius from the centre of the galaxy. An example of this is shown in Figure 3.9, demonstrating the effect of dark matter. Early research in the middle of the 20<sup>th</sup> Century suggested discrepancies between the rotation curves predicted using the visible mass in a galaxy and the observed rotation curves, but the evidence was not conclusive. Using new telescopes in the 1970s, it was possible to conduct new, accurate surveys of many galaxies. This data was presented in 1980 and conclusively showed that, after the galactic core, the orbital speed of stars in a galaxy is approximately constant with respect to radius [47]. This can only be explained by additional ‘dark’ matter, or that the effect of gravity varies across the galaxy.

The Bullet cluster, shown in Figure 3.10, is a system of two galaxy clusters that collided 150 million years ago from Earth’s perspective. During this collision, the hot gas in the galaxies contained in the two clusters interacted and slowed, and gained shock waves. Due to these interactions and shock waves, the gas is hot enough to emit x-rays, which can be imaged by

# ATLAS SUSY Searches\* - 95% CL Lower Limits August 2023

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

| Model                | Signature                                                                | $\int \mathcal{L} dt \text{ [fb}^{-1}\text{]}$ | Mass limit | Reference                       |
|----------------------|--------------------------------------------------------------------------|------------------------------------------------|------------|---------------------------------|
| Inclusive Searches   | $q\bar{q}, \bar{q} \rightarrow q\bar{q} \ell^0$<br>$E_{T}^{\text{miss}}$ | 140                                            | 1.0        | 2010.14293                      |
|                      | mono-jet<br>$E_{T}^{\text{miss}}$                                        | 140                                            | 0.9        | 2102.10874                      |
|                      | $0 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.85       | 2010.14293                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 2.3        | 2010.14293                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.15-1.95  | 2101.01629                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 2.2        | 2204.13072                      |
| 3rd gen. squarks     | $0 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.15       | 2008.06032                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.97       | 2008.06032                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.15       | 2008.06032                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 2.45       | 2008.06032                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.25       | 2008.06032                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.25       | 2008.06032                      |
| EW                   | $0 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.68       | 2101.12527                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.13-0.85  | 2101.12527                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.23-1.35  | 1908.03122                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.25       | 2103.08169                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.05       | 2004.14060, 2012.03799          |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.4        | 2012.03799, ATLAS CONF-2023-043 |
| Long-lived particles | $0 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.55       | 2108.07665                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.85       | 1905.01649                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.067-1.18 | 2102.10874                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.86       | 2006.05880                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.96       | 2006.05880                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.205      | 2108.07665                      |
| RPV                  | $0 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.42       | 2108.07665                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.34       | 2108.07665                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.7        | 2108.07665                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.26       | 2108.07665                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.55       | 2108.07665                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.45-0.93  | 2108.07665                      |
| RPV                  | $0 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.77       | 2204.13072                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.66       | 2201.00472                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.21       | 2201.00472                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 2.05       | 2205.06013                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 2.2        | 2205.06013                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.34       | 2011.07812                      |
| RPV                  | $0 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.36       | 2011.07812                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.625      | 2205.06013                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.05       | 2205.06013                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.95       | 2205.06013                      |
|                      | $1 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 1.6        | 2205.06013                      |
|                      | $2 e, \mu$<br>$E_{T}^{\text{miss}}$                                      | 140                                            | 0.55       | 2205.06013                      |

Figure 3.6: Summary of recently published exclusion limits from searches for SUSY at ATLAS as of August 2023 [43]

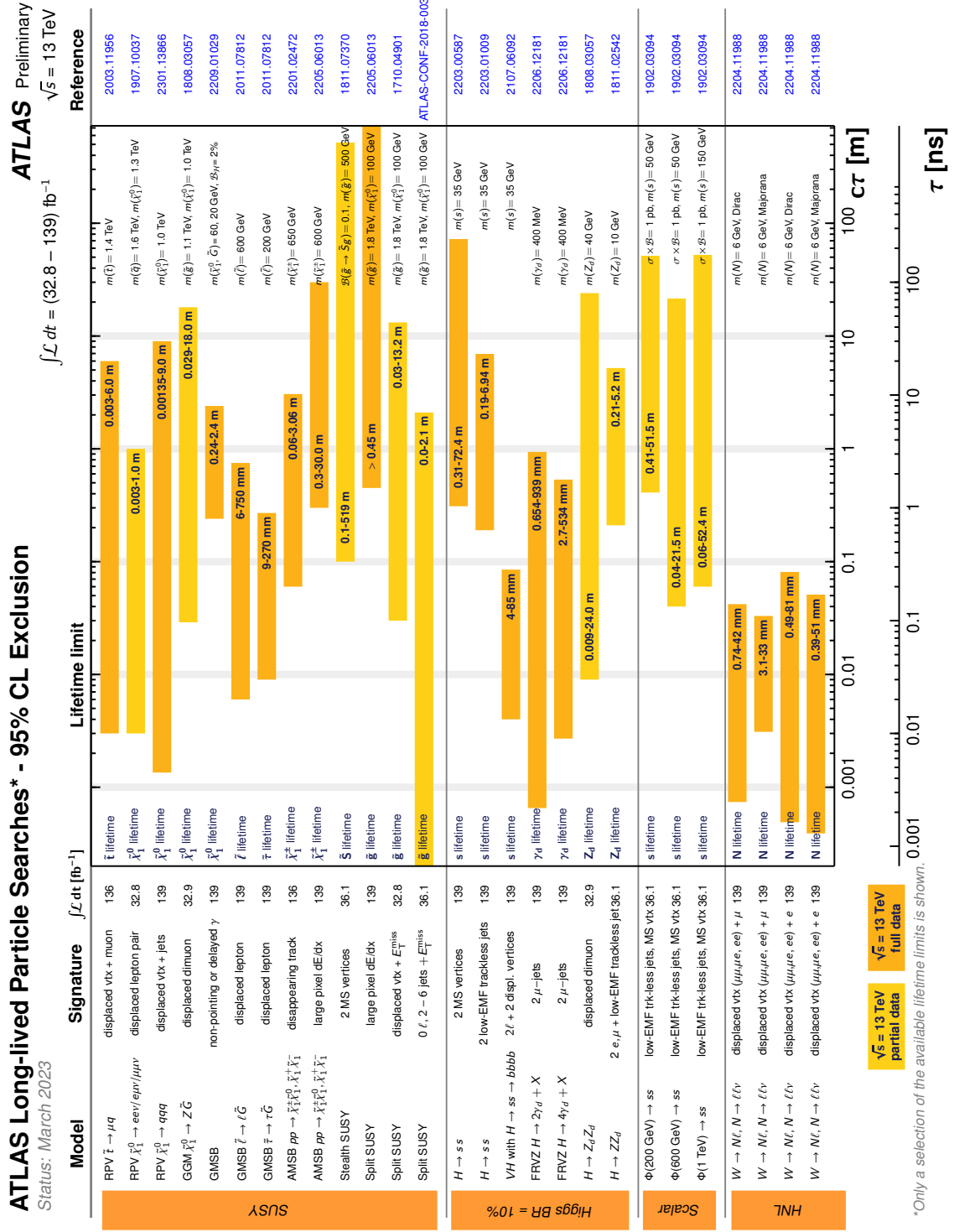
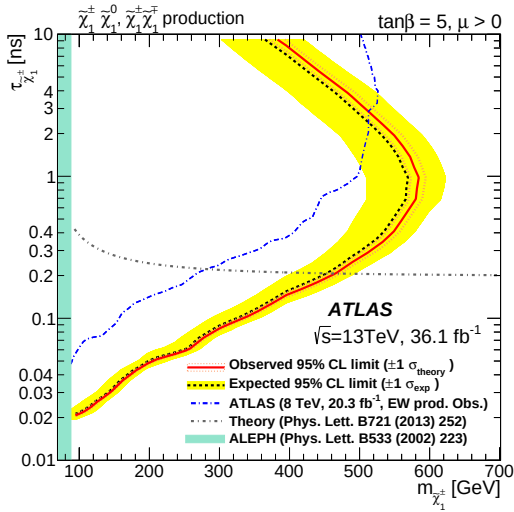
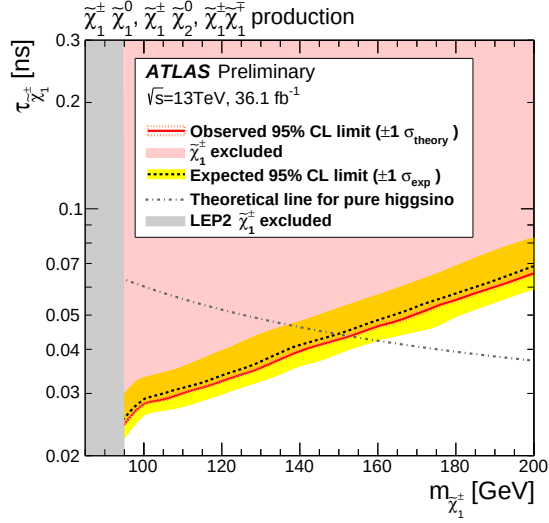


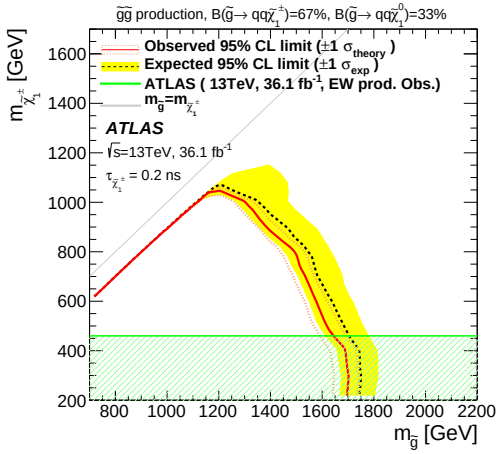
Figure 3.7: Summary of recently published exclusion limits for searches for LLPs at ATLAS as of March 2023 [44]



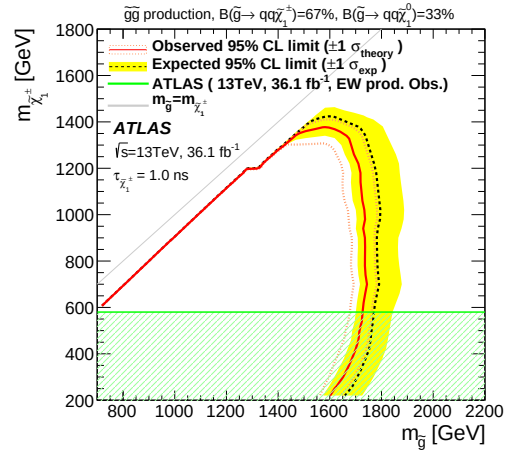
(a) Electroweak production of pure-wino charginos.



(b) Electroweak production of pure-higgsino charginos.



(c) Strong production of pure-wino charginos with a lifetime of 0.2 ns.



(d) Strong production of pure-wino charginos with a lifetime of 1.0 ns.

 Figure 3.8: Exclusion limits from the search for disappearing tracks with  $36 \text{ fb}^{-1}$  of  $pp$  collisions at ATLAS. [45, 46]

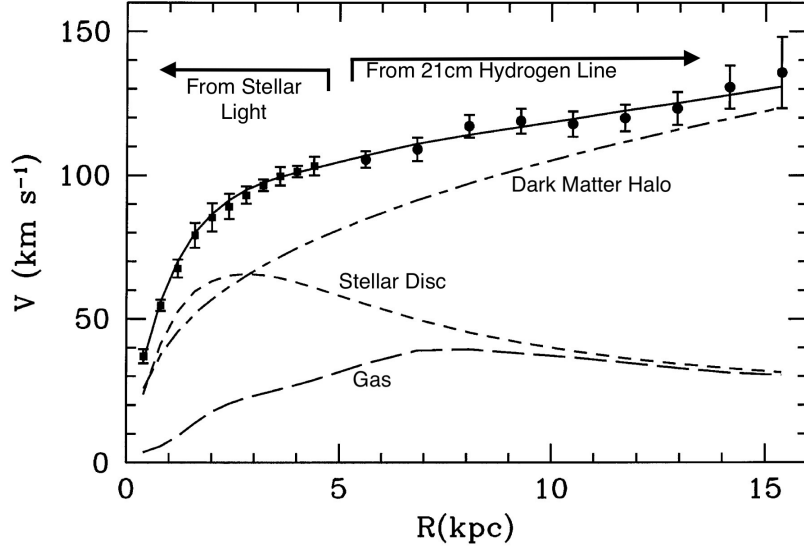


Figure 3.9: Measurements of the orbital velocities of stars in the M33 galaxy, along with estimations of the contributions from the stellar disc, visible gas and the dark matter halo, showing good agreement with data. Modified from [48].

space telescopes, confirming the collision. Observations of gravitational lensing can be used to estimate the mass density across the clusters. When compared to the x-ray data, it is clear that the mass density is not correlated with the visible matter [49, 50]. This suggests that the majority of the mass is dark matter, and as it is only weakly interacting continued through the collision unimpeded. This forms very strong evidence for the particulate nature of dark matter.

Another piece of evidence for dark matter are the anisotropies in the Cosmic Microwave Background (CMB). The early universe consisted of hot mixtures of photons, protons, electrons in a plasma, and dark matter. This ordinary matter plasma prevented the free movement of photons, resulting in an opaque universe. As the universe expanded and cooled, the protons and electrons recombined into atoms, and the photons could then travel freely. These photons are now in the microwave spectrum and provide a near-uniform background across the sky, known as the CMB. Small variations in the CMB exist due to variations in density in the early universe. The strength of these variations is related to the proportions of ordinary and dark matter. Various surveys of the CMB have been performed, most notably by the WMAP and Planck space telescopes. Measurements from Planck estimate the matter in the universe is 84.5% dark matter and 15.5% ordinary matter [52].

### 3.2.2 Explanations for Dark Matter

Due to the minimal criteria set for dark matter by existing cosmological observations, there exists a vast range of viable explanations for dark matter.

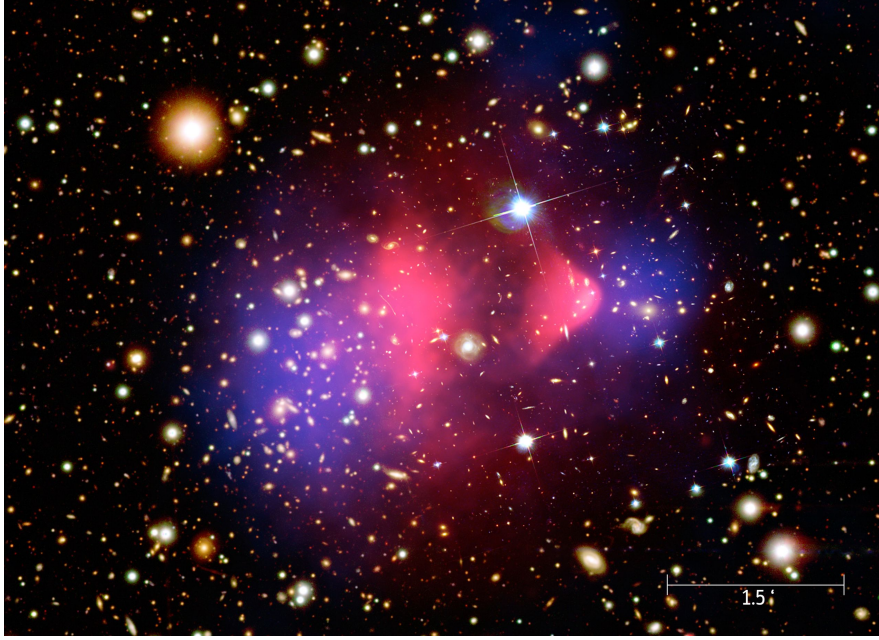


Figure 3.10: The Bullet Cluster. Shown are visible-light observations from the Hubble Space Telescope (HST) (stars and galaxies), x-ray data from Chandra (red-pink) showing the bow-wave-like shocks from the cluster collision, and a mass map from gravitational lensing data (blue). The separation between mass and visible matter is due to the weakly interacting dark matter. [51]

After the early evidence above was published, an alternative proposal to the dark matter hypothesis of Modified Newtonian Dynamics (MOND) was proposed in 1983 [53], and has since been developed into niche subfield. MOND hypotheses propose that the conventional rules of Newtonian dynamics do not apply at a galactic scale, and a modified version typically in the form

$$F = ma \mu \left( \frac{a}{a_0} \right) \quad (3.23)$$

applies instead, where  $a_0$  is a new fundamental constant and  $\mu(x)$  is a new *interpolating* function that allows for consistency with current observations. Whilst MOND has some success in explaining early evidence such as the rotation curves of galaxies, MOND theories often struggle to explain other evidence for dark matter such as the collisions of galaxies [49–51, 54], variations in the CMB [55], and the formation of galactic structures [56], among other flaws. The observation of gravitational waves and the measurements of their speed being equal to the speed of light also ruled out large swathes of MOND theories [57]. In general, MOND theories may explain a selection of these pieces of evidence, but not all.

Perhaps the most intuitive explanation for dark matter is a single new, heavy particle that is



very weakly-interacting - the Weakly-Interacting Massive Particle (WIMP). Motivated by the current lack of observations of dark matter at collider experiments, a dark matter candidate must either be out of the range of masses that can be produced at current colliders, very weakly interacting such that an insignificant quantity has been produced, or a combination of both. From the observed thermal relic density of dark matter, a preferred mass range for a WIMP is  $\mathcal{O}(100 \text{ GeV})$  to  $\mathcal{O}(10 \text{ TeV})$ . In R-parity-conserving SUSY models, the LSP exactly meets these criteria, a phenomenon known as the WIMP miracle. Recent observations by the Fermi telescope provide a mild ( $2\sigma$ ) preference for a higgsino-like particle around the thermal higgsino mass of  $\sim 1 \text{ TeV}$  and cross section [58]. However, extensive searches at the LHC have failed to find significant evidence for SUSY, although certain models such as the pure-higgsino models above still provide compelling candidates.

Alternate particulate explanations for dark matter also exist, including very light particles such as Axions, and very heavy ‘particles’ such as Massive Compact Halo Objects (MACHOs).

### 3.2.3 Current Limits

The most impactful limits of WIMP-like dark matter come from direct detection experiments. These typically function with a large volume of a natural scintillator such as liquid argon, surrounded by sensitive detectors such as Photo-Multiplier Tubes (PMTs). When a WIMP passes through the detector, it will extremely rarely collide elastically with a nucleon, which will scintillate. By placing the detector inside a low-background moderator such as a deep mine under a mountain, the background rate can be very low. The best current limits for spin-independent and spin-dependent interaction cross-sections are shown in Figure 3.11 and 3.12 respectively. These also show the *neutrino floor* - an irreducible background where the detector is dominated by interactions from astronomical or solar neutrinos, and orders of magnitude larger detectors are needed to progress. At this point, searches from colliders will be even more important.

As well as SUSY searches detailed earlier, it is also possible to search for dark matter at the LHC via various simplified models. These include models with simplified s-channel Spin-1 and Spin-0 mediators, with limits shown in Figure 3.13, and Higgs-portal models where the Higgs weakly couples to dark matter, shown in Figure 3.14. These exclusion limits highlight how collider searches can be very competitive with direct detection results when appropriate models are considered.

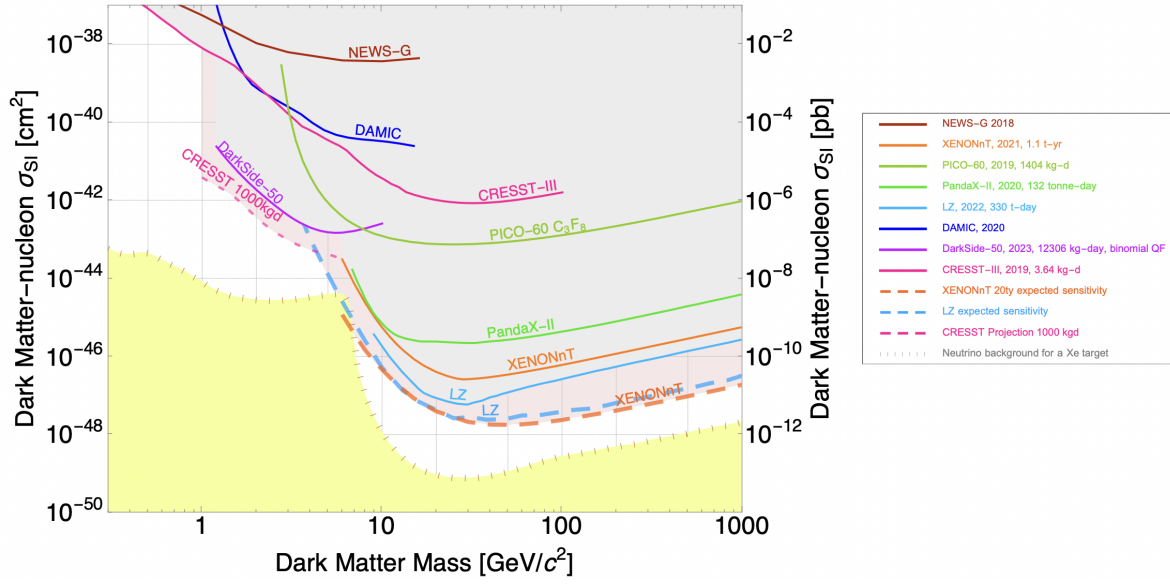
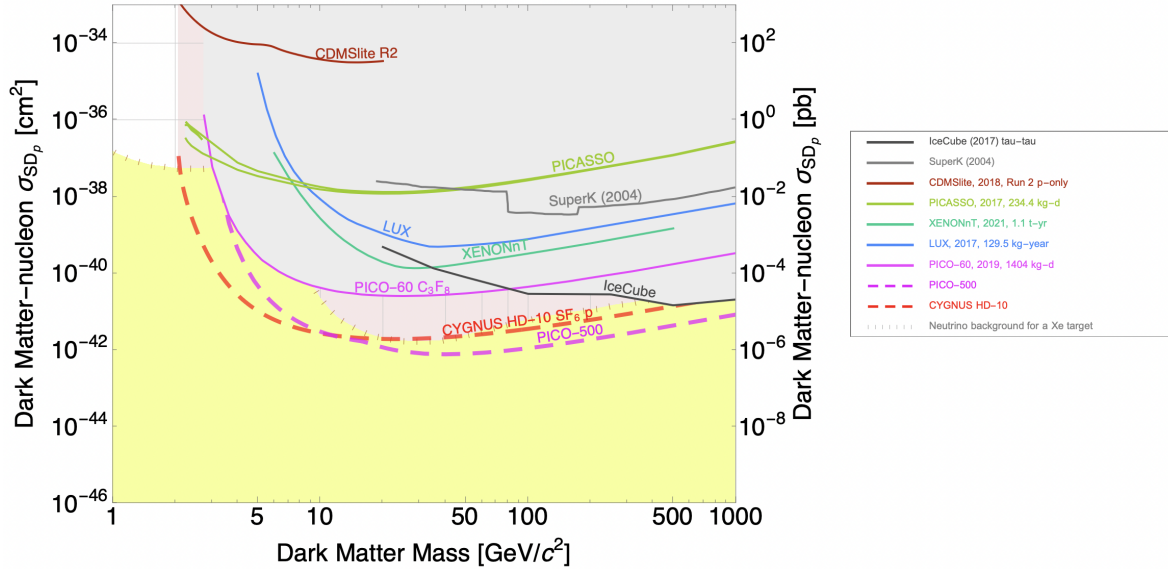
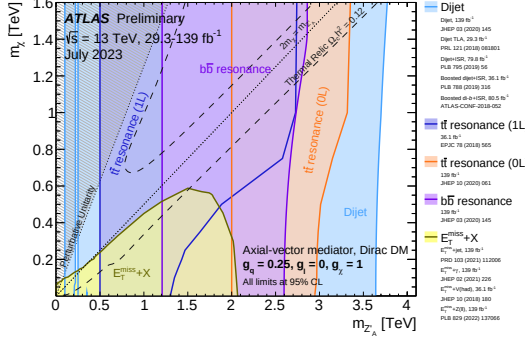


Figure 3.11: Spin-independent nucleon-WIMP interaction limits from various current (solid line) and future (dashed line) direct detection, as well as the neutrino floor, below which sensitivity is significantly reduced. Produced using the Dark Matter Limit Plotter [59]. [60–71]

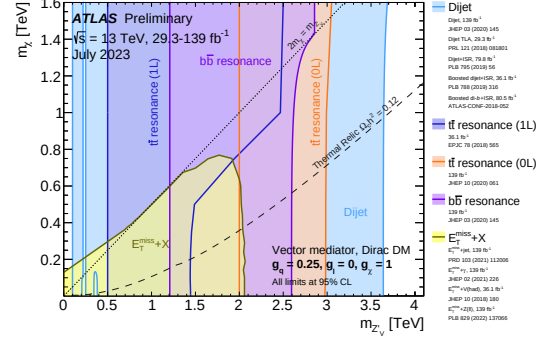


All Nuclear Recoil limits are scaled to a local dark matter density of  $0.3 \text{ GeV}/c^2$

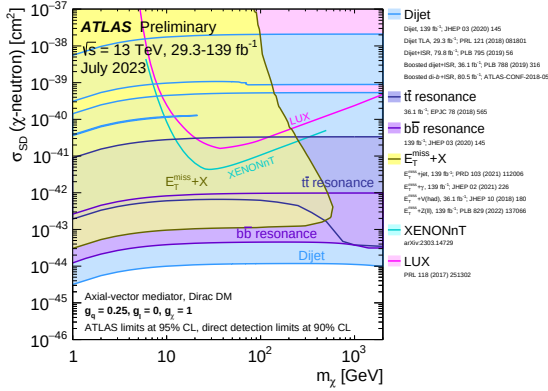
Figure 3.12: Spin-dependent proton-WIMP interaction limits from various current (solid line) and future (dashed line) direct detection, as well as the neutrino floor, below which sensitivity is significantly reduced. Produced using the Dark Matter Limit Plotter [59]. [61, 71–79]



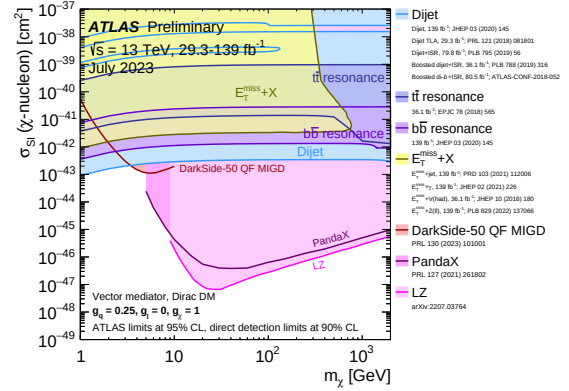
(a) Regions excluded in a mediator mass - dark matter mass plane in leptophobic axial-vector mediator simplified model.



(b) Regions excluded in a mediator mass - dark matter mass plane in leptophobic vector mediator simplified model.



(c) Comparison of the spin-dependent WIMP-neutron cross-section limits from the excluded regions in 3.13(a) with direct detection experiments.



(d) Comparison of the spin-dependent WIMP-neutron cross-section limits from the excluded regions in 3.13(b) with direct detection experiments.

Figure 3.13: Regions excluded by various ATLAS searches interpreted in either a leptophobic axial-vector mediator simplified model (3.13(a), 3.13(c)), or a leptophobic vector mediator simplified model (3.13(b), 3.13(d)). In both models a dark matter coupling of  $g_\chi = 1$ , a quark coupling of  $g_q = 0.25$ , and no lepton coupling is assumed. Reproduced from [80].

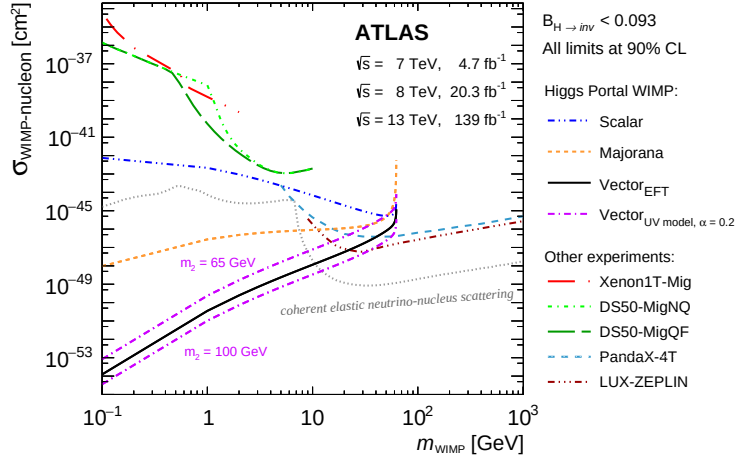


Figure 3.14: Interpretation of the Higgs-to-invisible combination search into Higgs portal models hypothesising various WIMP candidates, and comparison to spin-independant direct detection results. Reproduced from [80].





# Part II

## Experiment

## Chapter 4

# The LHC and the ATLAS Experiment

The LHC is a proton-proton circular accelerator and collider located at European Organisation for Nuclear Research (CERN) in Geneva. The LHC is the most powerful proton collider in the world, with a design beam energy of 7 TeV and a collision centre-of-mass energy of 14 TeV. Data about these collisions is collected using the ATLAS experiment, one of two general-purpose experiments at the LHC. This chapter outlines the design and operation of the LHC and the ATLAS

### 4.1 The Large Hadron Collider (LHC) and the CERN Accelerator Complex

The CERN accelerator complex is responsible for delivering high-energy protons and heavy ions to the LHC and other experiments based at CERN. This is performed with a chain of particle accelerators, each increasing the beam energy. The various accelerators, experiments and other facilities in the complex are shown in Figure 4.1.

The proton beam begins by ionising hydrogen gas and accelerating the resulting protons with the Linac2 linear accelerator to 50 MeV. The Linac3 linear accelerator is used to produce heavy ion beams such as lead for specialist LHC runs, and for dedicated experiments. Since 2020, in preparation for HL-LHC, the Linac4 linear accelerator has replaced Linac2. Linac4 accelerates hydrogen anions to 160 MeV, providing greater beam intensities and reduced losses at injection.

The proton beam is then injected into the Proton Synchrotron Booster (PSB) and accelerated to 1.4 GeV. The beam is also organised into bunches, packets of protons spaced 25 ns apart. The proton beam is then injected into the Proton Synchrotron (PS) where it is accelerated to 25 GeV, and finally, the Super Proton Synchrotron (SPS) where it is further accelerated to 450 GeV. The beam is now ready for injection into the LHC.



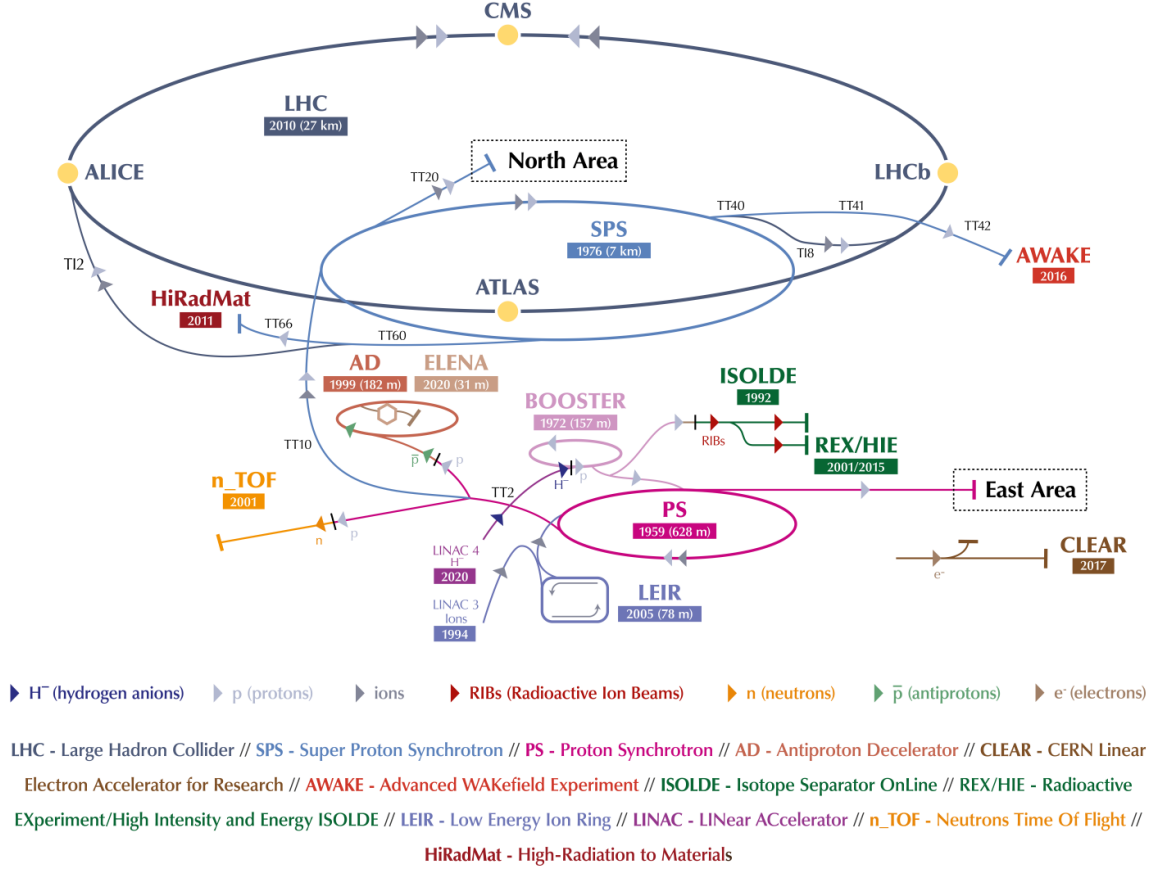


Figure 4.1: The CERN accelerator complex as of 2023. [81]

The LHC [82] is a hadron collider capable of accelerating protons and other ions to very high energies (currently 6.5 TeV) and colliding them at four experiments located around the LHC, the general purpose ATLAS and CMS experiments, and the more specialised ALICE and LHCb experiments. The LHC is a 27 km superconducting circular collider situated at CERN, Geneva, and supported by a number of linear and circular colliders.

The operation of the LHC is split into ‘Runs’, which are separated by Long Shutdowns, where maintenance and upgrades to the LHC and the experiments can take place. Run-1 was between 2009 and 2013, and used 3.5 TeV and 4 TeV proton beams. This was followed by Long Shutdown 1 (LS1) between 2013 and 2015. Run-2 took place between 2015 and 2018, and used 6.5 TeV proton beams, with ATLAS collecting a total of  $139 \text{ fb}^{-1}$  of good collisions. The analyses featured in Chapters 7 and 9 used the Run-2 dataset. Long Shutdown 2 (LS2) took place between 2018 and 2022 to allow for accelerator and experiment upgrades to support HL-LHC. Run-3 began in 2022 with 6.8 TeV beams and an increased peak instantaneous luminosity. Run-3 is scheduled to continue until 2025 and will be followed by Long Shutdown 3 (LS3)

where more accelerator and experiment upgrades for HL-LHC will be implemented, including the ATLAS ITk upgrade. HL-LHC is scheduled to begin in 2029 with Run-4 of the LHC. Successive runs are tentatively planned to take place in the 2030s and 2040s in parallel to the construction of the Future Circular Collider (FCC).

In order to achieve high integrated luminosities, multiple collisions happen simultaneously along the detector during a bunch crossing. This is known as *pileup*, and whilst it is highly beneficial for the increased number of collisions, it can lead to objects being reconstructed in other events and an increase of pileup-dependent backgrounds. Pileup is quantified as the mean number of collisions per bunch crossing,  $\mu$ . During Run-2 the average pileup was  $\mu = 35$ , with a distribution shown in Figure 4.2. Dedicated LHC beam fills are performed each year with a lower pileup for highly sensitive analyses that require it, and this can be seen as a small bump around  $\mu = 2$ .

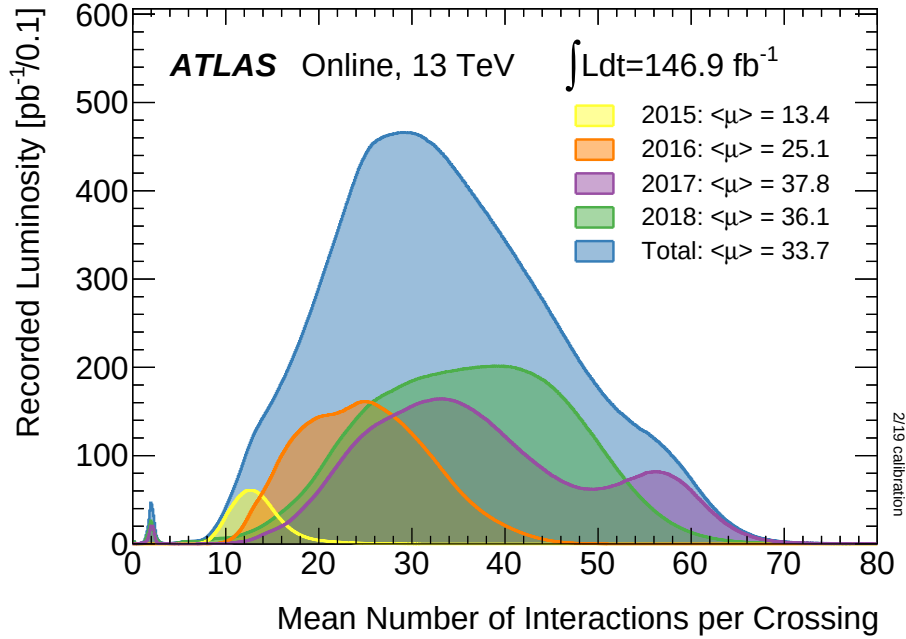


Figure 4.2: The average number of collisions per bunch crossing in each year of data-taking during Run 2 at ATLAS [83]

The previous and future LHC runs and their properties can be seen in Table 4.1.

## 4.2 The ATLAS Experiment

The ATLAS experiment [84] is one of two general-purpose detectors at the LHC, tasked with observing and investigating the products of high energy proton-proton collisions at the LHC. The ATLAS experiment is the largest at the LHC, measuring 44 m long and 25 m wide and weighing over 7000 tons. ATLAS contains four major detector systems, the ID,

| Run           | Years                  | Beam Energy   | Integrated Luminosity             | Average Pileup          |
|---------------|------------------------|---------------|-----------------------------------|-------------------------|
| Run-1         | 2011-2012              | 2011: 3.5 TeV | 2011: $5.2 \text{ fb}^{-1}$       | 2011: $\mu = 9.1$       |
|               |                        | 2012: 4 TeV   | 2012: $21.7 \text{ fb}^{-1}$      | 2012: $\mu = 20.7$      |
| Run-2         | 2015-2018              | 6.5 TeV       | $146.9 \text{ fb}^{-1}$           | $\mu = 33.7$            |
| Run-3         | 2022-2025              | 6.8 TeV       | 2022-2023: $70.4 \text{ fb}^{-1}$ | 2022-2023: $\mu = 44.6$ |
|               |                        |               | Expected: $250 \text{ fb}^{-1}$   | Expected: $\mu = 55$    |
| Run-4 & Run-5 | 2029-2032<br>2035-2038 | 7 TeV         | $3000 \text{ fb}^{-1}$            | $\mu > 200$             |

Table 4.1: The data-taking runs of the LHC and the conditions during the runs. Information for data-taking after 2023 is expected. Information for Run-3 is preliminary.

Electromagnetic Calorimeter (ECal), Hadronic Calorimeter (HCal) and Muon Spectrometer (MS) systems. A magnetic field surrounds the detector systems to allow the differentiation of charged particles [85]. This is generated by the Central Solenoid (CS) which surrounds the ID and provides a 2 T magnetic field [86], and the Barrel Toroid (BT) and End-Cap Toroid (ECT) which provide a 0.5 to 1 T field for the MS [87, 88]. The data from these detectors is read out with the Trigger & Data Acquisition (TDAQ) system. An overview of ATLAS is shown in Figure 4.3.

The geometry of the ATLAS detector is defined with a cartesian coordinate system with the origin in the centre of the detector, the  $x$ -axis pointing radially out of the LHC ring, the  $y$ -axis pointing vertically upwards out of the earth, and the  $z$ -axis along the beam line such that the three axes form a right-handed coordinate system. A cylindrical coordinate system is also commonly used, defined by a radius  $r$  from the beamline and azimuthal angle  $\phi$  around the  $z$ -axis, which maintains the same definition as the cartesian system. The pseudo-rapidity  $\eta$  is also used, and defined as  $\eta = -\ln(\theta/2)$ , where  $\theta$  is the polar angle from the  $z$ -axis, such that a vector in the  $x$ - $y$  plane has a pseudo-rapidity of 0, and a vector along the  $z$ -axis has a pseudo-rapidity of  $\infty$ .

#### 4.2.1 Inner Detector

Moving from the inside out, the ID is the first detector system [90, 91]. It is responsible for tracking the path of charged particles and using these tracks to locate the interaction points along the beamline. The ID is comprised of three main subdetectors: the pixel detector, the Silicon Tracker (SCT) and the Transition Radiation Detector (TRT). A tracking detector has to be the innermost component, as particle calorimetry is a destructive process. Additionally, as little material as possible must be used in the ID to minimise the amount of particles being absorbed or scattered before the calorimeters. A cutaway diagram of the whole ID is shown

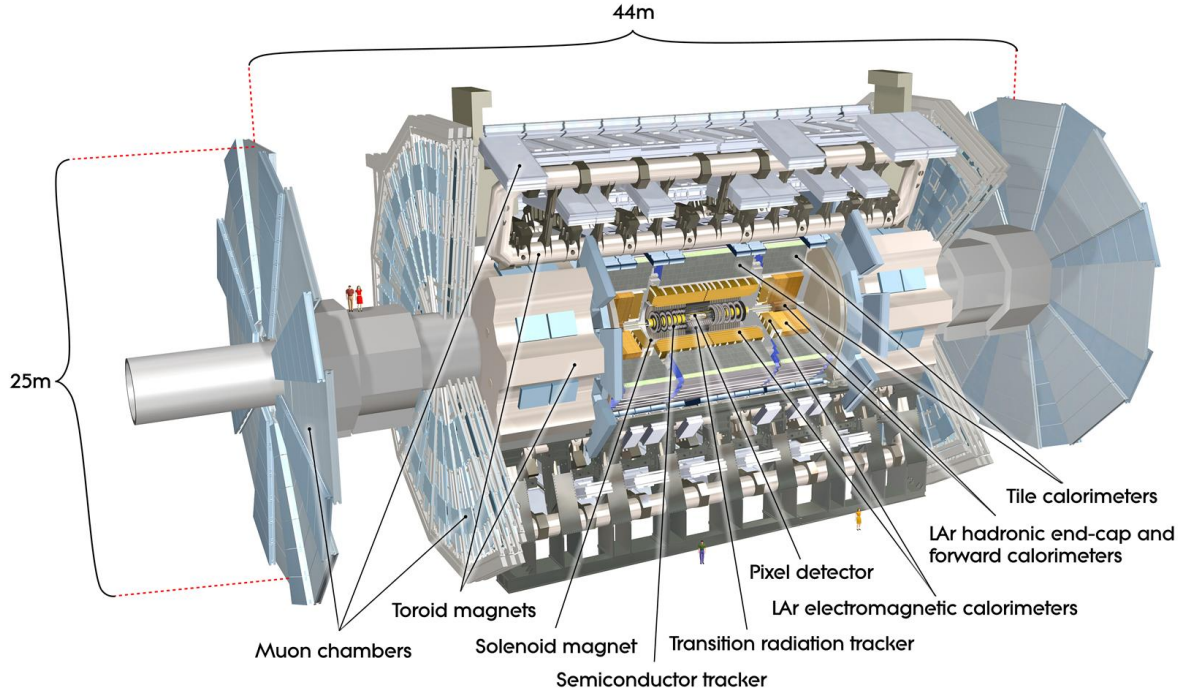


Figure 4.3: The ATLAS experiment. [89]

in Figure 4.4, and a cross-sectional view of the barrel section in the transverse plane is shown in Figure 4.5.

The ID is surrounded by a 2 T magnetic field generated by CS. This is orientated along the beamline, such that particles curve in the transverse plane inside the ID. This allows for accurate transverse momentum measurements.

#### 4.2.1.1 Pixel Detector

As the name suggests, the pixel detector [90, 91, 94–96] uses silicon pixels for high-resolution tracking close to the beam line. Silicon pixels are comprised of a p-n junction, which generates a depletion region when a bias voltage is applied. When a charged particle passes through the depletion region electron-hole pairs are generated, which can be read out as a signal.

Originally there were three pixel barrel layers at 50.5, 88.5 and 122.5 mm from the  $z$ -axis; in 2014 during LS1 a fourth layer, known as the Insertable B-Layer (IBL) [95, 96], was installed at a radius of 33.3 mm from the  $z$ -axis. These layers cover a volume of  $|\eta| < 2.6$ . Additionally, there are three endcaps on each side, orientated in the transverse plane at the end of the barrels for additional high- $\eta$  coverage. The endcap layers are located at  $|z| = 495, 580$  and  $650$  mm, and extend from a radius of 88.8 mm to 149.6 mm.

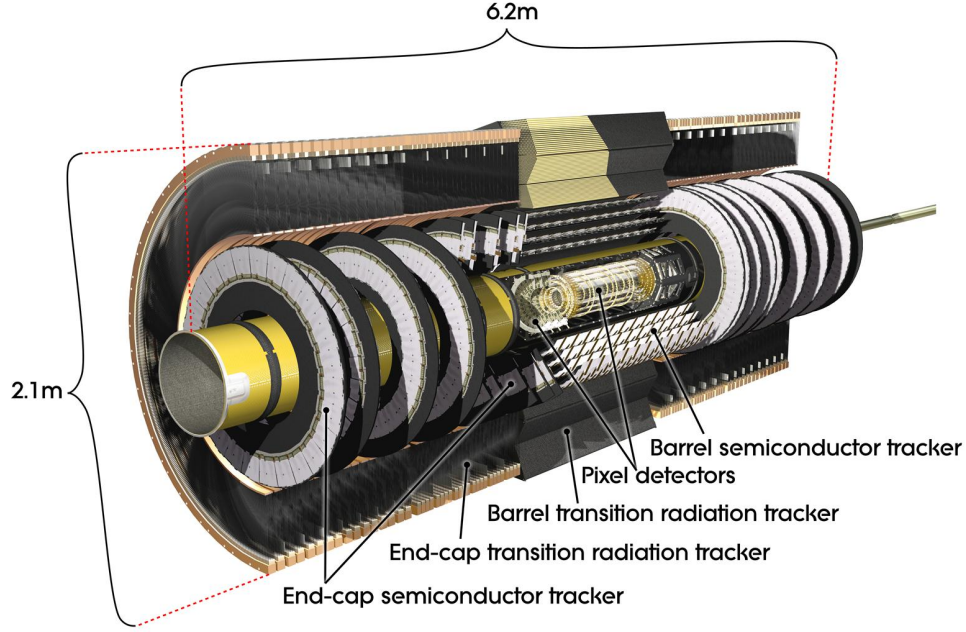


Figure 4.4: The ATLAS inner detector comprised of three major sub-detectors, the pixel, SCT and TRT detectors. [92]

The IBL uses  $50\text{ }\mu\text{m} \times 250\text{ }\mu\text{m}$  pixels, whereas  $50\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$  pixels are used elsewhere. The barrel pixels are orientated with the long side along the  $z$ -axis. The IBL modules have a transverse ( $r-\phi$ ) resolution of  $8\text{ }\mu\text{m}$ , and a longitudinal ( $z$ ) resolution of  $40\text{ }\mu\text{m}$ . The barrel (endcap) modules have a transverse resolution of  $10\text{ }\mu\text{m}$ , and a longitudinal (radial) resolution of  $115\text{ }\mu\text{m}$ .

The pixel detector comprises 1968 modules – 224 IBL modules, 1456 barrel modules and 288 endcap modules. Together, the pixel detector has almost  $10^8$  readout channels.

The pixel detector is vital not just for obtaining accurate particle tracks, but also for reliably determining the primary interaction vertex, essential for resolving one event from another in the high-pileup conditions at the LHC.

#### 4.2.1.2 Semiconductor Tracker (SCT)

The SCT is of a similar design to the pixel detector but uses cheaper silicon strips, necessary due to the SCT's vastly greater surface area [90, 91]. As the name suggests, silicon strip modules are segmented into strips  $80\text{ }\mu\text{m}$  in width, rather than the grid of a pixel module. Two layers of strips overlapping with a small angular offset allow for a two-dimensional measurement. This also means a strip module provides two hits.

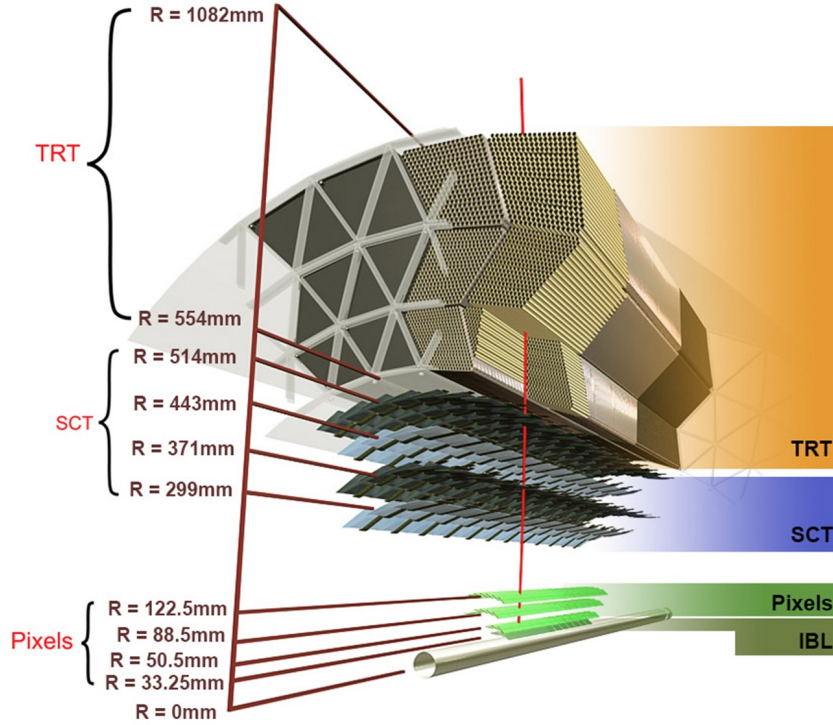


Figure 4.5: A cross-section in the transverse plane of the barrel section of the ID during Run-2, showing the beam pipe, the pixel and SCT barrel layers, and the TRT. [93]

The SCT is comprised of four barrel layers at 299, 371, 443 and 514 mm from the  $z$ -axis, and nine end-caps on each side at  $|z| = 853.8$  to 2720.2 mm from the ATLAS origin. The barrel section has 2112 modules, and the endcap section has 1976 modules. The SCT barrel strips are orientated along the beamline to provide a high resolution in the  $\phi$  direction, allowing for precise measurements of a track's curvature. The barrel (endcap) modules have a longitudinal resolution of  $580\text{ }\mu\text{m}$  and a transverse (radial) resolution of  $17\text{ }\mu\text{m}$ .

The SCT provides a similar role to the pixel detector, allowing for precise tracking of charged particles with almost complete coverage over the ATLAS experiment.

#### 4.2.1.3 Transition Radiation Tracker (TRT)

The TRT is a straw-tube tracking detector, and the final sub-detector of the ID. Straw-tube detectors use a thin metal tube filled with a gas and a central wire. A high voltage is applied between the wire and the tube. When a charged particle passes through the tube the gas along the track is ionised, and the charges drift to the wire. This creates an analogue signal which can be read out. The timing of the signal can provide information about the path through the tube. The tubes can also be surrounded by polymer fibres and foils. As highly-relativistic

particles pass from the polymer materials to the straws transition radiation can be emitted. The probability of transition radiation being emitted is proportional to  $\gamma = E/m$ , providing information about the mass of the particle that can be used for identification.

The straw tubes used in the TRT are comprised of 4 mm diameter Kapton tubes containing a 31  $\mu\text{m}$  diameter gold-plated tungsten wire and a 70% xenon, 27% carbon dioxide and 3% oxygen gas mixture. A 1.5 kV potential difference is applied to the Kapton tube, with the central wire grounded.

The TRT is organised into a barrel section of  $|z| < 712 \text{ mm}$  and  $563 \text{ mm} < r < 1066 \text{ mm}$ , and an endcap section of  $848 \text{ mm} < |z| < 2710 \text{ mm}$  and  $644 \text{ mm} < r < 1004 \text{ mm}$ . The barrel section contains approximately 50,000 straws, and the endcap section approximately 320,000 straws. An average track will gain 36 TRT hits.

### 4.2.2 Calorimetry

Particle calorimeters are responsible for measuring the energy and momentum of particles entering them. Sampling calorimeters are the most common form of calorimeter at the LHC experiments. Sampling calorimeters consist of interspaced layers of a dense, moderating material such as lead, and layers of a scintillating material such as argon or plastic scintillator. The moderator layers trigger particle interactions and showers, and the scintillator layers produce a signal from the products of the absorber layers proportional to the energy deposited. Typically a moderator layer will be placed once every radiation length  $X_0$ , defined as the average length over which only  $1/e$  of an electron's energy remains after passing through that material. This length is different for each material.

The design of a calorimeter depends on the target particles. Photons and electrons only undergo electromagnetic interactions (pair production of electrons and positrons for photons and bremsstrahlung of photons for electrons), whereas hadrons can also interact via the strong force, causing lighter hadrons, pions and leptons to be produced. These pions can also decay electromagnetically to two photons. The photons in the electromagnetic interactions have a mean free path of  $\frac{9}{7}X_0$ . However, the strong interactions have a longer mean interaction length, so deeper calorimeters are required. Hadronic particle decays produce jets of particles beginning near the interaction point. These are composite objects involving particle tracks, EM showers and hadronic showers. The composition of a jet is approximately 65% charged hadrons, 25% photons, and 10% neutral hadrons. 75% of the jet is measured in the HCal, where the hadronic energy resolution is poorer.

As with all detectors, the measurements made by a calorimeter are not perfect. The uncer-



tainty in the measurement of a particle's energy can be given as

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad (4.1)$$

where  $a$  is the stochastic term, including statistical contributions,  $b$  is the noise term, including contributions that are fundamentally random, and  $c$  is the constant term which includes systematic contributions. Due to the different interaction methods and calorimeter designs, hadrons and photons/electrons have different energy resolutions. A typical sampling ECal might have a resolution of  $\frac{5-20\%}{\sqrt{E}} \oplus 0.5\%$ , whereas a typical sampling HCal might have a resolution of approximately  $\frac{50-100\%}{\sqrt{E}} \oplus 5\%$ . [97]

Additionally, not all of the initial particle's energy will be deposited in the calorimeter. Some products may be below the detection threshold of the calorimeter; some particles such as neutrinos may be invisible to the calorimeter and some of the shower may extend beyond the calorimeter. A Jet Energy Scale (JES) is used to calibrate the energy measured by the calorimeter so that it is accurate to the energy of the incident particle.

ATLAS has multiple ECal and HCal systems to ensure acceptance of a range of particle interactions and accurate energy measurements. A Forward Calorimeter (FCal) system also provides acceptance at high pseudorapidities. These are shown in Figure 4.6. The ECal system sits closer to the interaction point and uses a liquid argon (LAr) and lead sampling calorimeter. The HCal systems sit outside the ECal. The barrel HCal uses scintillating plastic tile and steel plate sampling calorimeter. The endcap HCals use a LAr and lead system similar to the ECal. The FCals also use LAr designs but with varying materials.

#### 4.2.2.1 Electromagnetic Calorimeter

The ECal is responsible for observing photons and electrons in an electromagnetic shower. It can also observe any charged particle passing through it. The ECal is organised into a barrel section and endcaps. The barrel covers radius of 1.15 to 2.25 m ( $24X_0$ ) up to  $|\eta| < 1.5$ , and the endcaps cover a depth of  $3.7 \text{ m} < |z| < 4.25 \text{ m}$  for pseudo-rapidities between 1.375 and 3.2. The endcaps are split into outer and inner rings at  $|\eta| = 2.5$ .

The ECals use lead moderators made into an 'accordion' geometry to maximise the number of interactions [99]. These are interspaced with LAr, and a strong potential difference is applied between the lead layers. As a charged particle passes through the LAr it ionises the argon and the resulting charges drift to the lead layers due to the potential difference, and a signal is read out. An additional presampler is placed inside the ECal barrel and in front of the endcaps, and consists of a 11 mm LAr layer with interwoven electrode grids to read out the signal.



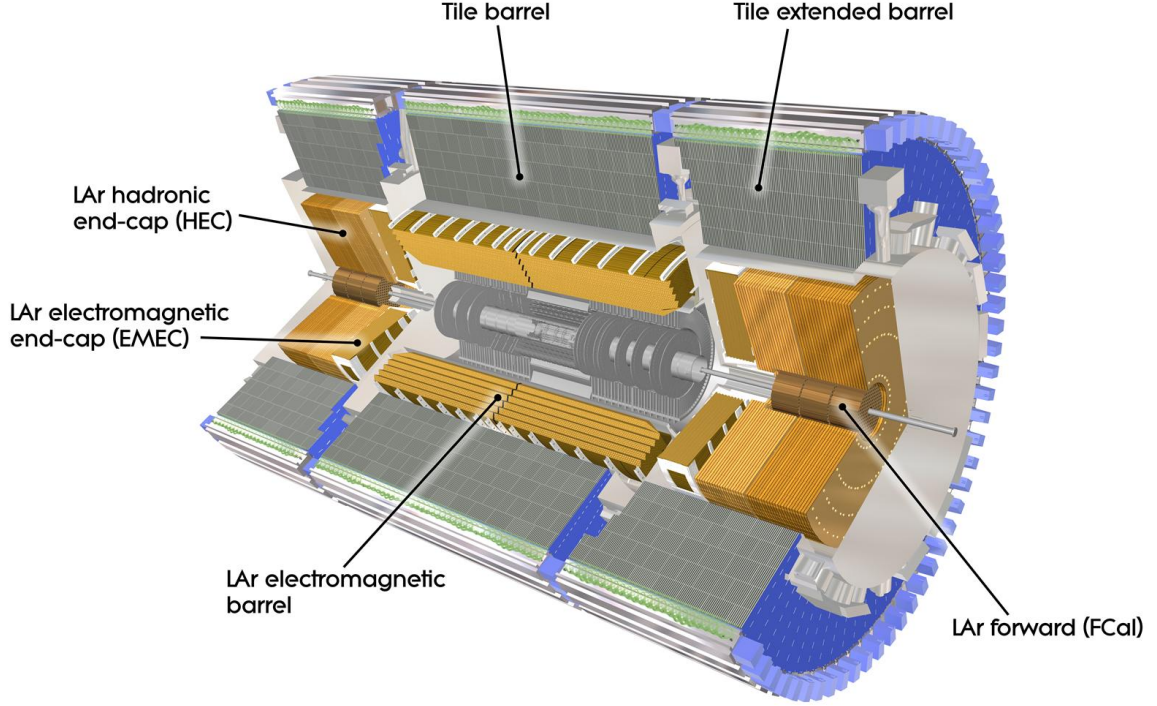


Figure 4.6: The ATLAS calorimeter systems surrounding the inner detector. [98]

The ECal barrel is segmented into layers of towers for readout. These towers are shown in Figure 4.7. The first layer is formed of thin strips  $4.3 X_0$  deep, and filling a solid angle of  $\Delta\phi \times \Delta\eta = 0.098 \times 0.0031$ . The second layer forms the majority of the LAr barrel, and is  $16 X_0$  deep and segmented into sections covering a solid angle of  $\Delta\phi \times \Delta\eta = 0.0245 \times 0.025$ . The final layer is  $2 X_0$  deep and formed of sections twice as wide in  $\Delta\eta$ .

The Electromagnetic End-Caps (EMECs) are segmented similarly to the the barrel ECal. The first layer consists of strips around  $4.4 X_0$  deep with a pseudorapidity granularity  $\Delta\eta$  between 0.003125 and 0.1, and a polar granularity  $\Delta\phi$  of 0.1. This is followed by a deep layer of  $\Delta\phi \times \Delta\eta = 0.025 \times 0.025$  cells for the outer ring and  $\Delta\phi \times \Delta\eta = 0.01 \times 0.01$  cells for the inner ring, and a final thinner layer with  $\Delta\phi \times \Delta\eta = 0.025 \times 0.05$  for the outer ring only.

The ECal was built to achieve an energy resolution of

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{170 \text{ MeV}}{E(\text{MeV})} \oplus 0.7\% \quad (4.2)$$

, when parameterised with Equation 4.1.

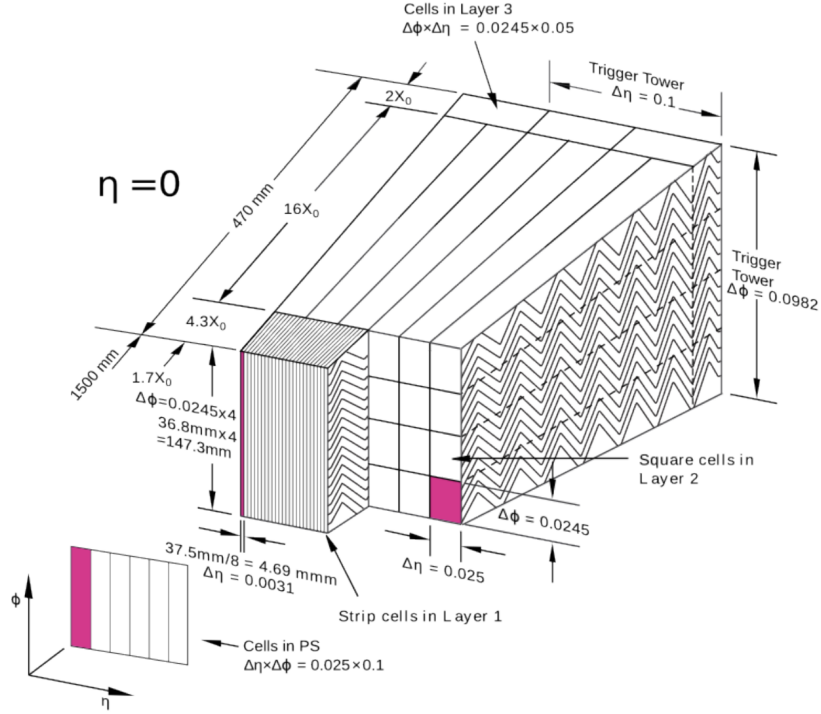


Figure 4.7: Schematic showing the structure and segmentation of readout cells of the LAr barrel calorimeters for the ECal.

#### 4.2.2.2 Hadronic Calorimeter

The HCal is responsible for causing and observing hadronic jets. The HCal has different designs for the barrel and endcaps. The barrel HCal, also known as the tile calorimeter, uses steel absorber plates interspaced by plastic scintillator tiles, read out with Wavelength-Shifting (WLS) fibre leading to PMTs [100]. The Hadronic Endcap (HEC) uses a LAr design similar to the ECal but with a copper moderator instead of lead.

The tile calorimeter covers an area of  $|\eta| < 1.7$  and  $2.2 \text{ m} < |r| < 3.72 \text{ m}$ , split into a central barrel and two extended barrels, as shown in Figure 4.6. The HEC covers a range of  $1.5 < |\eta| < 3.2$ . The barrel HCals are segmented into three layers, the first two with a granularity of  $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$  and the final of  $0.2 \times 0.1$ . The endcaps have four layers, each with a granularity of  $0.1 \times 0.1$  for  $1.5 < |\eta| < 2.5$  and  $0.2 \times 0.2$  for  $2.5 < |\eta| < 3.2$ .

The barrel HCals achieves a pion energy resolution of

$$\frac{\sigma_E}{E} = \frac{48.6\%}{\sqrt{E}} \oplus 2.46\% \quad (4.3)$$

, whereas the endcap HCals achieve a pion energy resolution of

$$\frac{\sigma_E}{E} = \frac{70.6\%}{\sqrt{E}} \oplus 5.8\% \quad (4.4)$$

### 4.2.3 Muon Detectors

As long-lived, minimally-ionising leptons, muons pass through the whole ATLAS experiment without causing a jet or an electromagnetic shower. To allow accurate observation and identification of muons, a dedicated muon tracker is used, known as the Muon Spectrometer (MS) [101]. The MS covers a range of  $|\eta| < 2.7$ , and is capable of observing any charged particle escaping the calorimeters. The MS is comprised of four types of detector: the Muon Drift Tubes (MDTs), the Cathode Strip Chambers (CSCs), the Resistive Plate Chambers (RPCs) and the Thin Gap Chambers (TGCs). The Monte-Carlo (MC) and its subdetectors are shown in Figure 4.8.

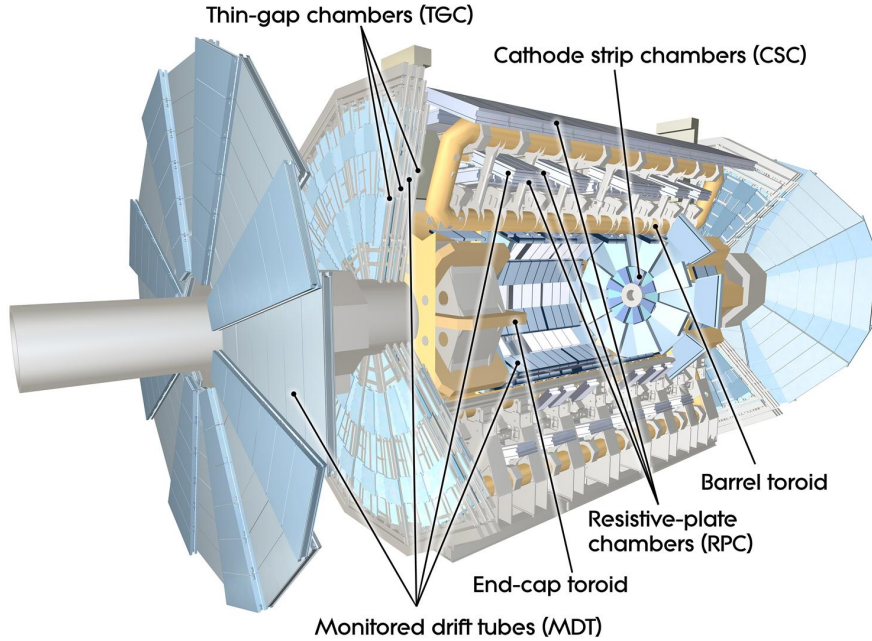


Figure 4.8: The Muon Spectrometer system and sub-detectors.

Found throughout the MS, the MDTs provides the primary track measurements, with CSCs used instead on the innermost layers at high pseudo-rapidities above 2.0. Triggering is performed in the barrel using RPCs and the endcaps using TGCs, up to a pseudo-rapidity of  $|\eta| < 2.4$ .

#### 4.2.4 Magnets

To extract momentum information from particle tracks, a strong magnetic field is required to provide a curvature in the tracks which can be measured. The ATLAS magnet system [85, 102] comprises of three sub-systems: the CS [86], the BT [87], and the ECT [88]. These are shown in a cut-away style in Figure 4.9.

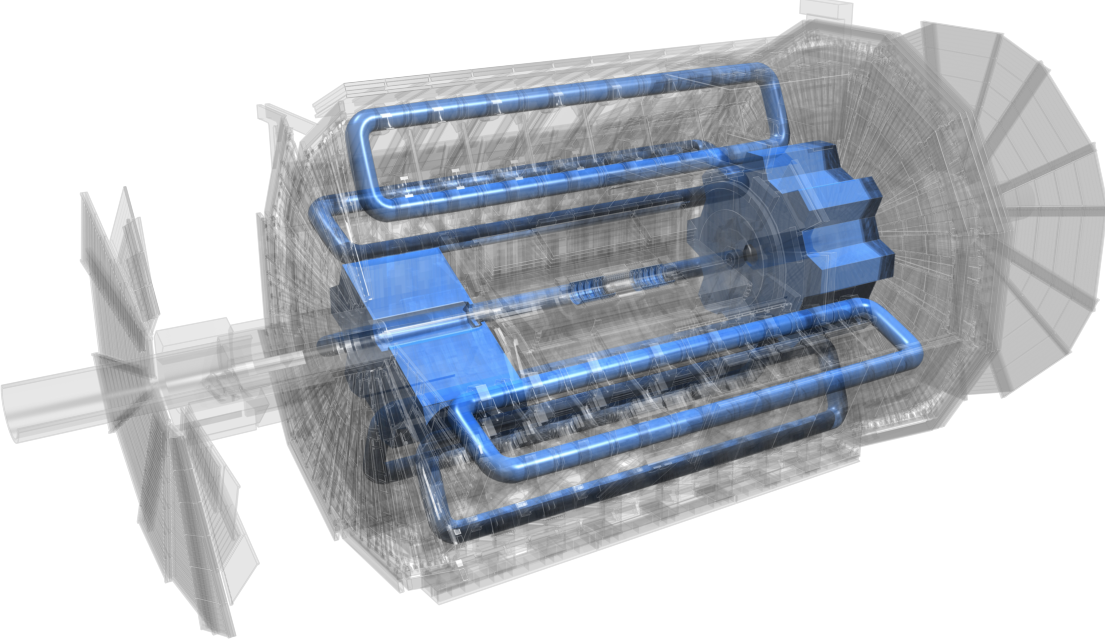


Figure 4.9: A cut-away view showing the ATLAS magnet system, consisting of the CS [86], the BT [87], and the ECT [88]. These are shown in a cut-away style in Figure 4.9.  
[103]

The CS is the innermost magnet, has a barrel shape, and surrounds the ID. The CS provides a 2 T magnetic field to the ID, peaking at 2.6 T on the casing of the solenoid. The CS measures 5.8 m in length, has an outer diameter of 2.56 m and a thickness of 4.5 cm [86, 102].

The BT are eight loop-shaped toroid magnets inside the muon systems [87, 102]. Each is 25.3 m in length and have an outer diameter of 20.1 m. The BT sub-system together contains 100 km of superconducting wire, operating at 20.5 kA. The BT works in tandem with the two ECTs which sit between the HEC and the muon wheels [88, 102]. Each ECT contains eight toroid coils 5 m in length. Both the BT and the ECT generate a 4 T field at their casings, and up to a 3.5 T field throughout the experiment. The toroids are primarily intended to provide a momentum measurement for particles passing through the muon systems.

### 4.2.5 Triggers & Data Acquisition

Proton bunch crossings occur at ATLAS every 25 ns, giving an interaction rate of 40 MHz. A typical event in ATLAS uses 1.3 MB of storage, giving a theoretical bandwidth of up to  $52 \text{ TB s}^{-1}$  – clearly unfeasible to store and process with currently-available technology. Therefore, a Trigger & Data Acquisition (TDAQ) system is required to select events of interest from this stream and reduce the data rate to a manageable level. [104]

During Run-2, the TDAQ system consisted of the hardware-based L1 trigger and the software-based High-Level Trigger (HLT) [105]. The L1 trigger is encoded on Field-Programmable Grid Arrays (FPGAs) to enable it to process data in real time up to a maximum event rate of 100 kHz, without requiring slow buffer storage. The L1 trigger is also split into two systems, the L1 Calorimeter trigger (L1Calo) and the L1 Muon trigger (L1Muon). L1Calo uses coarse data from the calorimeter trigger towers ( $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$  in the central region) and can identify preliminary electron/photon, tau and jet candidates, and produce information using these candidates such as vector sums of transverse energy. L1Muon takes input from the muon trigger systems discussed in Section 4.2.3 and forms muon candidates from coincident signals compatible with a muon from the interaction point. The L1 trigger then selects events using quantities constructed from L1Calo and L1Muon information, such as object multiplicities, sums of transverse energy and geometrical quantities such as angular separation between objects. The L1 trigger also defines Regions of Interest (ROIs) in  $\eta$ - $\phi$  space, which contain potentially interesting physics signatures that should be investigated in the HLT.

The HLT uses more complex algorithms running in software on conventional CPUs. It processes events selected by the L1 trigger and incorporates much more detailed and granular calorimeter information than the L1 trigger, and also includes tracking information from the inner detector within the ROIs. This information is used to perform an event reconstruction similar to the full offline reconstruction, which allows for triggers dedicated to specific signatures such as flavour-tagged jets and long-lived particles, as well as more accurate global variables such as missing transverse energy.

## Chapter 5

# Data & MC Simulation

In order to design and optimise the analysis, it is vital to have accurate simulated Monte Carlo samples modelling a range of signal hypotheses, and high-quality samples modelling various Standard Model processes which can be used to aid the development of the background estimations. In this chapter, the experimental dataset used in the analysis and its properties are first described. The techniques used to produce samples modelling this dataset are then explained before the choice of samples produced is described and their validation is shown. As described in the Introduction the first two sections in this Chapter are a review of the Run-2 dataset, and the general techniques used in simulating events with Monte Carlo techniques, and present no original work. Sections 5.3 to 5.5 presents the simulated signal and background samples used in the analyses in this thesis. The samples used in the first analysis with four pixel hits were produced by other members of the team so are simply described here. The samples used in the second analysis with three or four pixel hits were produced and validated by the author.

### 5.1 Data

The analyses included in this thesis used data collected in the second experimental run of the LHC (Run-2). This took place between 2015 and 2018, with  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The ATLAS detector collected  $(140.1 \pm 1.2) \text{ fb}^{-1}$  of  $pp$  collisions which are considered “good for physics”, and henceforth referred to as the full Run-2 dataset. The integrated luminosity of this dataset as Run-2 progressed is shown in Figure 5.1. The analysis presented in Chapter 7 used an older integrated luminosity estimate of  $(139.0 \pm 1.7) \text{ fb}^{-1}$  for the full Run-2 dataset.

The online luminosity measurements (those made in real-time as the data is collected) are made by Luminosity Cherenkov Integrating Detector (LUCID) [106]. LUCID measures the amount of radiation produced by the proton bunches as they travel along the beampipe, which can be used to infer the luminosity of the bunch. LUCID consists of PMTs connected to quartz fibres or windows, which act as the Cherenkov medium. The quartz windows also have a small

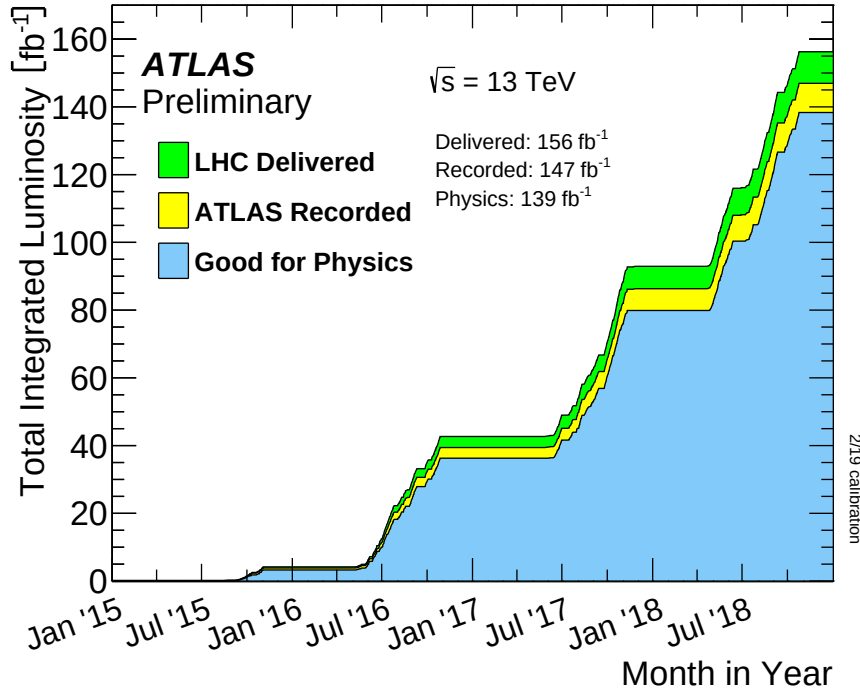


Figure 5.1: The cumulative integrated luminosity of  $pp$  collisions delivered to ATLAS, recorded by ATLAS and marked "good for physics" during Run-2. [83]

amount of  $^{207}\text{Bi}$  deposited on them, which is used for continuous calibration over the operation of LUCID. The integrated luminosity can also be measured offline by the Z-counting method, where the number of  $Z \rightarrow \ell\ell$  interactions is measured, and the luminosity per time period is calculated. This method can provide smaller uncertainties, as well as a cross-check of the online luminosity measurements.

Both analyses presented in this thesis use a subset of the full Run-2 dataset. During some parts of Run-2 datataking period, a number of SCT Read-Out Devices (RODs) were not operating correctly. Due to the importance of the SCT in vetoing tracklets which extend into the SCT, the data-taking periods in which the SCT suffered from this defect were excluded. This reduced the available integrated luminosity by 2.0%, to  $(136.3 \pm 1.7) \text{ fb}^{-1}$  for the analysis presented in Chapter 7, and to  $(137.3 \pm 1.1) \text{ fb}^{-1}$  for the analysis presented in Chapter 9.

Multiple  $pp$  collisions happen simultaneously along the beamline during each bunch crossing – this is known as *pileup*. The distribution of the recorded luminosity as a function of the number of simultaneous collisions for each data-taking year is shown in Figure 5.2.



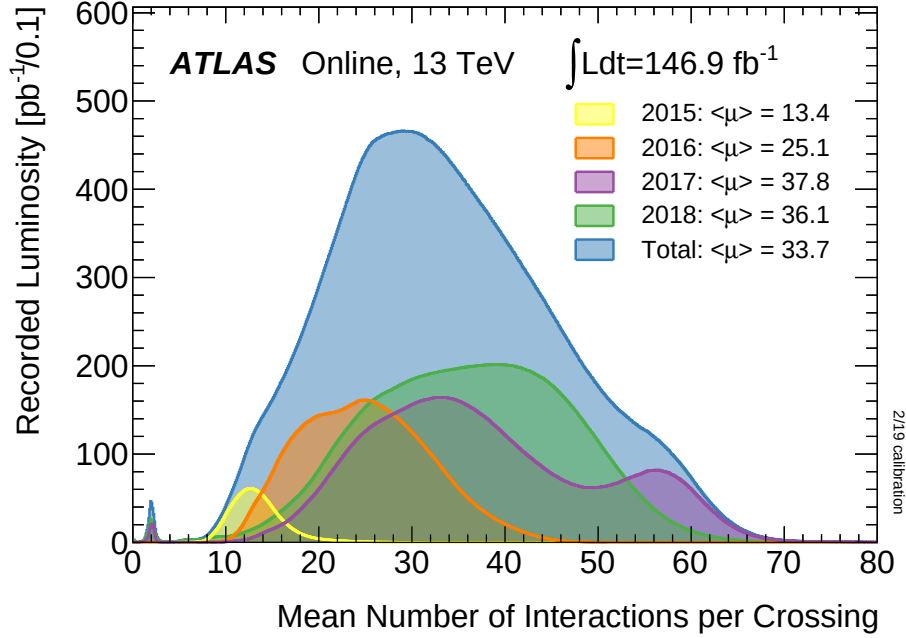


Figure 5.2: The integrated luminosity recorded as a function of the pileup for each data-taking year in Run-2. [83]

### 5.1.1 Triggers

As described in Section 4.2.5, due to the very high rate of collisions in the LHC algorithms known as *triggers* are needed to select which collisions to store. The trigger system comprises Level 1 (L1), a hardware-based trigger system with fixed algorithms using simplistic objects, and the High-Level Trigger (HLT), a software-based system with flexible and more advanced algorithms using objects similar to those used in the analyses. The analyses presented in this thesis use triggers that depend on both of these systems.

The primary triggers used in the analyses presented in this thesis are the transverse missing energy (MET) triggers. Various MET triggers exist for use in different data-taking periods where the beam conditions and the subsequent demands on the trigger system can vary. The MET triggers are itemised in Table 5.1. These MET triggers can use a variety of algorithms. First, the MET can be calculated using the objects available in the L1 trigger system, or a variety of algorithms in the HLT trigger system. In this thesis, the algorithms used include:

- the `mht` algorithm, a simple sum over the transverse energy of all jets;
- the `pufit` algorithm, where a missing energy vector is calculated from objects assigned to the primary vertex, and corrections are calculated for pileup-induced effects, which are required to sum to 0 and be uniform over the detector;
- the `cell` algorithm, a simple sum over all calorimeter cells with significant energy de-



| Trigger                     | MET Cut                                                                                     | Data Periods |
|-----------------------------|---------------------------------------------------------------------------------------------|--------------|
| HLT_xe70_mht                | $> 70 \text{ GeV}$ (HLT mht)                                                                | 2015 D-J     |
| HLT_xe90_mht_L1XE50         | $> 90 \text{ GeV}$ (HLT mht)<br>$> 50 \text{ GeV}$ (L1)                                     | 2016 A3-D3   |
| HLT_xe100_mht_L1XE50        | $> 100 \text{ GeV}$ (HLT mht)<br>$> 50 \text{ GeV}$ (L1)                                    | 2016 D4-F1   |
| HLT_xe110_mht_L1XE50        | $> 110 \text{ GeV}$ (HLT mht)<br>$> 50 \text{ GeV}$ (L1)                                    | 2016 F2-L11  |
| HLT_xe110_pufit_L1XE55      | $> 110 \text{ GeV}$ (HLT pufit)<br>$> 55 \text{ GeV}$ (L1)                                  | 2017 B1-D5   |
| HLT_xe110_pufit_L1XE50      | $> 110 \text{ GeV}$ (HLT pufit)<br>$> 50 \text{ GeV}$ (L1)                                  | 2017 D6-K6   |
| HLT_xe110_pufit_xe70_L1XE50 | $> 110 \text{ GeV}$ (HLT pufit)<br>$> 70 \text{ GeV}$ (HLT cell)<br>$> 50 \text{ GeV}$ (L1) | 2018 B-C5    |
| HLT_xe110_pufit_xe65_L1XE50 | $> 110 \text{ GeV}$ (HLT pufit)<br>$> 65 \text{ GeV}$ (HLT cell)<br>$> 50 \text{ GeV}$ (L1) | 2018 C5-Q2   |

Table 5.1: Missing transverse energy triggers used in each data-taking period in Run-2

posits.

The efficiency of the trigger varies over the phase space, and for each trigger. Typically this is characterised by very low efficiency in events with less than approximately 100 GeV of missing transverse energy, a steep sigmoidal curve in the trigger threshold region between 100 and 200 GeV, and very high efficiency above the threshold. This is known as a turn-on curve, and can be seen as a function of  $E_T^{\text{miss}}$  in Figure 5.3. The efficiency can also depend on the transverse momentum of the highest-transverse-momentum (*leading*) jet, separate to the effect from the  $E_T^{\text{miss}}$ . This can be seen in Figure 5.4. These efficiencies were measured using  $Z \rightarrow \mu^+ \mu^-$  events as these have independent triggers, can be reconstructed with high efficiency, and the minimally-ionising nature of the muons provides a clean proxy for the MET as there are few associated calorimeter deposits.

Other triggers were also used in this thesis, including single-lepton triggers. These identify events containing a candidate electron or muon, and were used in  $Z \rightarrow e^+ e^-$  and  $Z \rightarrow \mu^+ \mu^-$  event selections respectively. These are HLT triggers that are seeded from a region of interest of calorimeter deposits or MS track seeds, from which a candidate lepton object is built. Various quality criteria can be chosen, which can be higher quality and more selective at the cost of efficiency (*tight*) or varying quality and more inclusive (*loose*).

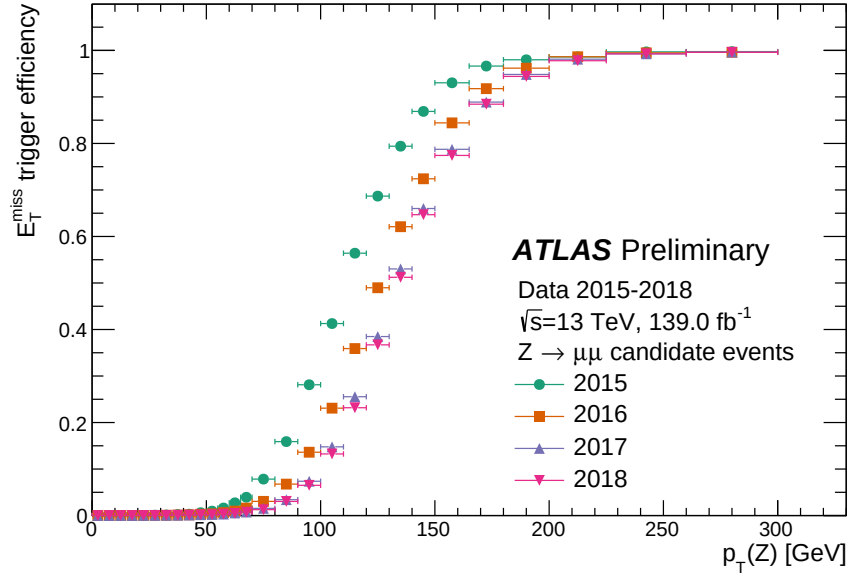


Figure 5.3: The efficiency of the missing transverse momentum triggers used in each year of Run-2 as a function of the missing transverse momentum, using the muon-subtraction method.

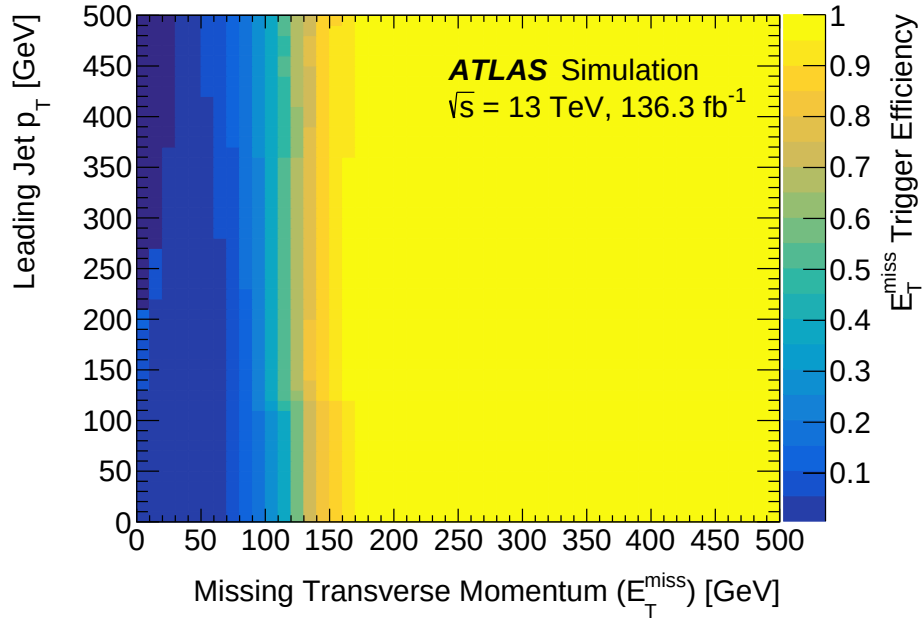


Figure 5.4: The average efficiency of the missing transverse momentum triggers parameterised by reconstructed missing and leading jet transverse momentum.

For Run-3, a dedicated disappearing track trigger is used [107]. This identifies events that

contain pixel tracklet candidates reconstructed from rejected HLT track seeds by utilising a combination of Boosted Decision Trees (BDTs). It significantly improves event acceptance below the MET trigger threshold, as shown in Figure 5.5

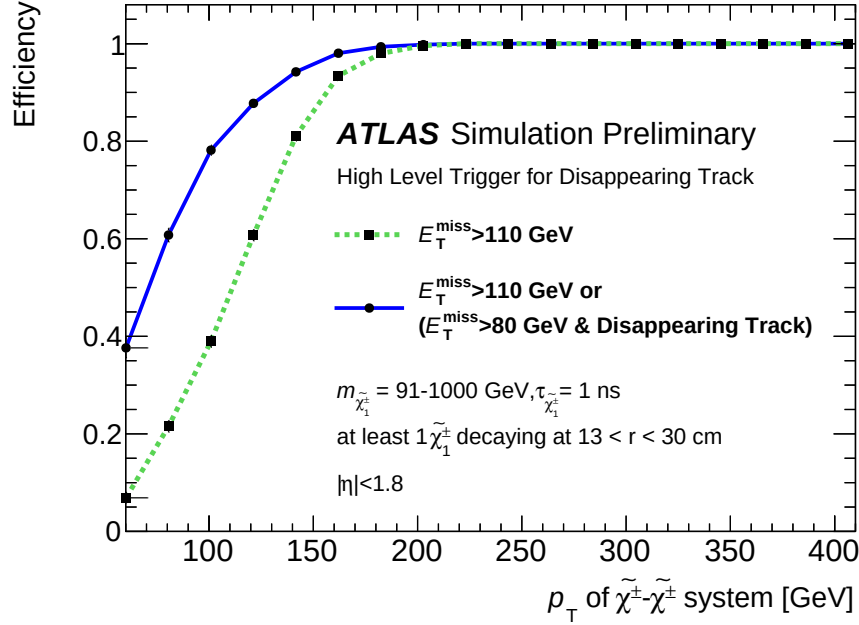


Figure 5.5: The improved performance of the Run-3 dedicated disappearing track trigger compared to the existing MET triggers. [107]

## 5.2 Monte Carlo Generation, Simulation & Reconstruction

When generating simulated samples, there are a series of calculations that must be completed. These include generating the simulated event, simulating the material interactions and detector response, and finally reconstructing physics objects from this response. Each stage is performed by a separate program within the ATHENA software package, and many of the stages make use of external programs which are standardised across much of the particle physics community.

### 5.2.1 Event Generation

The Monte Carlo event generation consists of multiple stages. First, the matrix element describing the target physics process must be calculated using a set of Parton Distribution Functions (PDFs), which is then used to simulate the hard-scatter events. The parton shower can then be calculated, which adds the initial- and final-state radiation. Finally, the hadronisation and Multiple Parton Interactions (MPI) can be added. These stages can be seen in Figure 5.6.

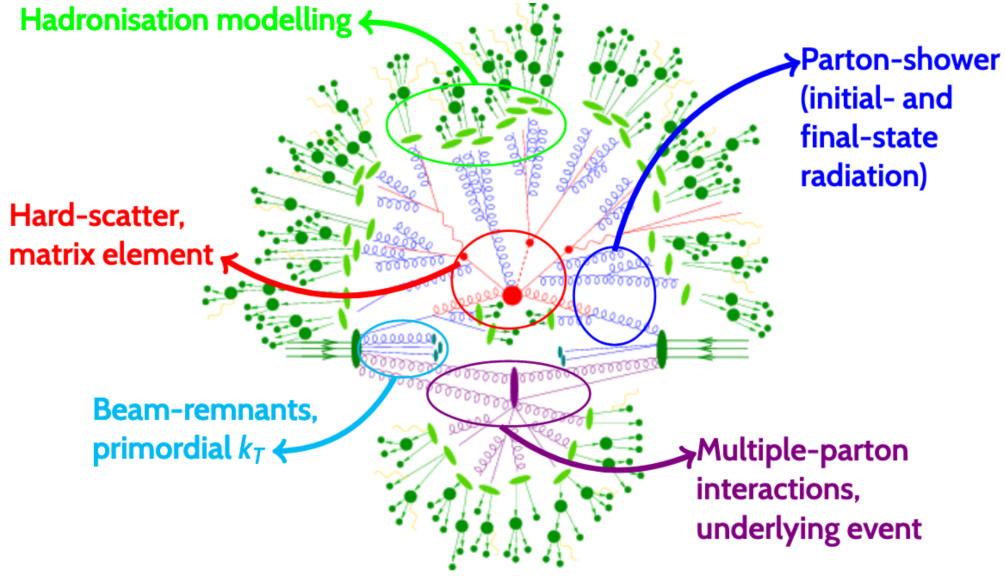


Figure 5.6: An example of a  $pp$  event simulated with Monte Carlo techniques. The various components of the simulated event are labelled.

The simulation of hadron collisions can be challenging due to the composite nature of hadrons, which are comprised of an ever-changing sea of quarks and gluons, together known as partons. In hadron collisions such as those occurring at the LHC, the interactions of these partons can be factorised into longer-distance hard-scatter interactions and the short-distance interactions governed by the PDFs. The cross-section of the hadron interaction can then be calculated as

$$\sigma = \sum_{i,j} \underbrace{\int dx_1 f_i(x_1, \mu^2) \int dx_2 f_j(x_2, \mu^2)}_{\text{PDF}} \underbrace{\sigma_{ij}(Q^2)}_{\text{Hard Scatter}} \quad (5.1)$$

where the two phenomena are separated by the energy scale  $\mu_F$ , known as the factorisation scale. The matrix element calculation is used to model the cross-section above the energy scale, whereas the PDFs are used below this scale, along with parton showering. This shows how it is possible to calculate each component of the event separately, with different tools or techniques. A brief discussion of how each component is calculated will now follow.

### Parton Distribution Functions (PDFs)

At the high energies of the LHC, the collisions happen between the constituent partons, rather than the whole proton. Partons are comprised of the *valance* quarks that define a particular hadron (for a proton,  $uud$ ), as well as *sea* quarks, which are pairs of virtual quarks and antiquarks that are constantly being created and annihilated within the proton. Partons also include the gluon content of the hadron.

Due to the varied parton content within a given hadron, it is clear that it cannot be assumed

which partons will interact in a collision. PDFs represent the probability that a given parton will be found in the hadron, dependent on the Bjorken scaling variable  $x$  and the energy scale  $Q^2$ .

PDFs are calculated with fits to experimental Deep Inelastic Scattering (DIS) data, including those from the ATLAS and CMS experiments, as well as other current and previous experiments globally. PDFs can be provided to various degrees of precision, including Leading-Order (LO), Next-to-Leading-Order (NLO) and for select samples Next-to-Next-to-Leading-Order (NNLO).

### Hard Scatter and Matrix Element

The Hard Scatter represents the physics of interest in the Monte Carlo simulation. In the hard scatter individual partons from the incident hadrons interact and produce a specified final state. This is the highest-energy process in the hadron collision.

In the hard scatter calculation the Feynman diagrams for the desired process are computed to the desired precision. For LO simulations, the Feynman diagrams are computed at tree level with two vertices, with the matrix element proportional to the square of the strong coupling constant,  $\mathcal{M} \propto g_s^2$ . For NLO simulations, now the norm at the LHC, the Feynman diagrams are computed at loop level, and the matrix element is proportional to the cube of the strong coupling constant,  $\mathcal{M} \propto g_s^3$ .

Particles resulting from the hard scatter interaction are not necessarily stable. Later stages of the event simulation continue the simulation of these particles through further decays and interactions.

### Parton Showering

Only the core physics process is contained in the hard scatter – to produce the rest of the event as seen in reality, further steps must be taken to propagate the hard scatter to a stable final state, and model the other parton collisions happening in parallel.

The Parton Shower (PS) process propagates the immediate result of the hard scatter through to the hadronisation stage, converting the small final state from the Matrix Element (ME) to a more complex one with a large number of partons. This covers an energy scale starting from  $Q^2$  and continuing to the hadronisation scale  $\Lambda_{\text{QCD}}$ , approximately 200 MeV. The PS calculation is performed by requiring the partons to emit quarks and gluons. These can also be low-momentum (*soft*) or co-linear. This is sequentially performed until every parton reaches the hadronisation energy scale.

Extra care must be taken when the final states include multiple partons, which is common when the ME is calculated above LO. As an example, final states including  $n$  jets can be generated either by calculating a ME with  $n$  partons in the final state and applying the PS as normal, or by generating events with  $n - 1$  partons and requiring an additional parton emission in the PS. These approaches can have overlap, which is accounted for using matching and merging algorithms to prevent double-counting.

## Hadronisation

At the hadronisation energy scale  $\Lambda_{\text{QCD}}$ , colour-confinement begins, and all partons must be combined into colour-neutral hadrons. This process is known as the hadronisation stage. There are two popular methods of achieving hadronisation; the *Lund string* model [108] and the *cluster* model.

The Lund string model utilises the colour-confinement property of quarks. It models the strong potential between a quark and an antiquark as a string, with the potential energy proportional to the length of the string. As the distance between the quarks increases, it eventually becomes energetically favourable for the string to break and a new quark and antiquark to be generated.

The cluster model forces the gluons to split into colourless groups following an independent, invariant mass distribution. The higher-mass, unstable hadrons formed from these groups are then decayed via Standard Model processes until stable hadrons are formed.

## Multiple Parton Interactions (MPI)

Only the highest-energy partons are considered in the hard scatter calculation – as hadrons are being collided there are also interactions between the other partons in the event, known as Multiple Parton Interactions (MPI). The result of the MPI is known as the Underlying Event (UE). This is modelled by applying perturbative corrections to the hard scatter known as tunings. The two primary tunings used by ATLAS are the A14 and A3 tunings.

## Event Generators

The various stages of the event generation can be performed in a range of *event generators*. Some generators are capable of several of these stages or even complete event generation; others are designed to perform specific calculations or are designed around specific processes. Where appropriate, the output of one generator after a given stage can be used as the input to the following stage in another generator, although care must be taken to ensure suitable matching and merging algorithms are used to prevent double counting between the two programs. This is achieved by the application of event weights.

The event generators used in this thesis are:

- **SHERPA** – A complete event generation program capable of NLO precision for events with two or less partons, and LO precision for four or less partons. SHERPA’s parton showering is performed at NLO, and matched with the hard scatter output. In this thesis SHERPA is used for samples modelling processes involving vector boson decays. [109, 110]
- **MADGRAPH5\_aMC@NLO** – A multi-purpose NLO ME generator. The output must be interfaced into a parton showering program such as PYTHIA8. MADGRAPH5\_aMC@NLO is used in this thesis for samples modelling processes involving BSM processes, specifically chargino production. [111, 112]
- **POWHEG** – A multi-purpose NLO ME generator. The output must be interfaced into a parton showering program such as PYTHIA8. POWHEG is used in this thesis for samples modelling processes involving top quarks. [113–116]
- **PYTHIA8** – A LO program for performing the parton showering, hadronisation and underlying event modelling using the A14 tune. In this thesis PYTHIA8 is used in the samples with MEs produced by MADGRAPH5\_aMC@NLO and POWHEG. [117–119]
- **EVTGEN** – EVTGEN improves the modelling of the decays of certain hadrons including b-hadrons and CP-violating decays. In this thesis EVTGEN is used in the samples that also use PYTHIA8. [120]
- **PARTICLEGUN** – Rather than model complete events using physical processes, PARTICLEGUN generates individual particles or simple final states with user-defined kinematic distributions. An example is generating events with only a single electron, with a uniform momentum distribution. It is used to study the reconstruction and detector responses to specific particles.

### 5.2.2 Simulation

Once the event has been generated, the detector response can be simulated. This is achieved using the GEANT4 toolkit and a precise description of the material and sensitive elements in the ATLAS experiment [121].

GEANT4 defines all materials in the detector in *logical volumes* and simulates the effects of each particle passing through the detector, such as material interactions, scattering, and energy deposition and ionisation.

GEANT4 contains a precise description of the shape and position of every element of the ATLAS detector, and the properties of the material each element is made from, such as density.

This includes sensitive elements such as silicon sensors, as well as cabling, steel support structures, and the air or other environmental gasses the detector sits in.

The position of many of the detector elements is measured using *cosmics* runs, where the ATLAS experiment collects data when there is no beam from the LHC, so cosmic muons can be measured. Due to their high energy and minimally-ionising nature, these will produce long, clean tracks through the detector. The individual sensor hits can be used to calibrate the position of the sensor.

The output of the GEANT4 program is a simulation of the raw signals produced by each sensor, such as the currents from a straw tube detector. This can be stored in the same Raw Data Objects (RDOs) used to store the output from the real ATLAS detector, which can then be passed through the same reconstruction software chain as the experimental data.

### 5.2.3 Reconstruction

Event reconstruction is then performed using ATHENA, using the same workflow as experimental data. Special reconstruction techniques not used in generic samples can be enabled, including the tracklet and associated soft track reconstruction, secondary vertexing and more. Chapter 6 discusses these techniques in greater detail.

To model the effect of event pileup, minimum-bias events are also simulated and overlayed onto the event. These are simulated inelastic  $pp$  collisions. An event weight is also calculated to correct the pileup distribution to match that observed during each data-taking period.

## 5.3 Signal Samples

### 5.3.1 Disappearing Tracks with 4 Hits

For the first analysis, which searched for tracklets with four hits only and is presented in Chapter 7, the primary set of signal samples modelled a pure-wino hypothesis. Samples were generated using MADGRAPH5\_aMC@NLO v2.6.2, PYTHIA8 v8.230, and EVTGEN v1.6.0. A small set of samples were generated with chargino masses at 100 GeV intervals between 100 GeV and 1 TeV, and lifetimes of 0.2 ns, 1.0 ns, 4.0 ns and 10.0 ns. Other lifetimes can be accessed by re-weighting the existing samples event-by-event, as the physics of a particle is determined in the hard-scatter, and is independent of the particle's lifetime. A weight can be found by using the ratio of the distributions of the populations at the two lifetimes, given as

$$w\left(\tau_{\tilde{\chi}_1^\pm}\right) = \prod_i^{n_{\tilde{\chi}_1^\pm}} \left[ \frac{t_0}{\tau_{\tilde{\chi}_1^\pm}} \exp\left(-t_i \left(\frac{1}{\tau_{\tilde{\chi}_1^\pm}} - \frac{1}{t_0}\right)\right) \right] \quad (5.2)$$



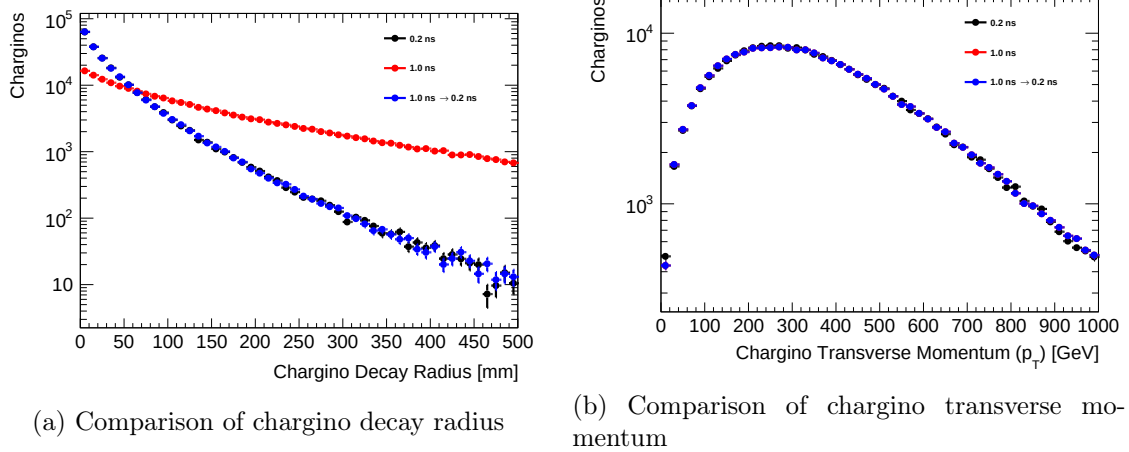


Figure 5.7: Validation plots comparing a chargino sample generated with a proper lifetime of 0.2 ns to a sample with a proper lifetime of 1.0 ns which has been reweighted to 0.2 ns using Equation 5.2.

where  $w$  is the event weight to be applied,  $\tau_{\tilde{\chi}_1^\pm}$  is the target lifetime,  $t_0$  is the proper lifetime,  $t_i$  is the lifetime of the  $i^{\text{th}}$  chargino in the event, and  $n_{\tilde{\chi}_1^\pm}$  is the number of charginos in the event. This method can also improve statistical uncertainties by using a long-lifetime region with high acceptance to model a short-lifetime region with low acceptance. A comparison of a sample with a proper lifetime of 0.2 ns to a sample with a proper lifetime of 1.0 ns which has been reweighted to 0.2 ns is shown in Figure 5.7

A small number of samples modelling the pure-higgsino hypothesis were also produced for research and development purposes, primarily to confirm their similarity to the pure-wino samples. As the decay products of the chargino were not investigated in this analysis, the kinematics of pure-wino and pure-higgsino samples with the same chargino mass and lifetime were essentially identical, and the pure-higgsino yields could be found by renormalising the samples by the appropriate cross-section.

### 5.3.2 Disappearing Tracks with 3 or 4 Hits and an Associated Pion

For the second analysis in this thesis, which searched for tracklets with three or four pixel hits and is presented in Chapter 9, separate pure-wino and pure-higgsino signal sample sets were produced. This was necessary because of the different chargino-neutralino mass splittings between the two models. The pure-wino model has a mass splitting of approximately 120 MeV, whereas the pure-higgsino model has a mass splitting of approximately 350 MeV. This provides extra momentum for the pion that results from the chargino decay, and therefore significantly different kinematics for this low-momentum pion.

The software suite used to produce the signal samples was also updated to a more recent software package, using MADGRAPH5\_aMC@NLO v2.9.9, PYTHIA8 v8.306, and EVTGEN v1.7.0, necessary to maintain compatibility with the latest versions of the analysis software, ATHENA. The samples were validated by comparing several generator-level and reconstructed quantities to the samples at the same chargino masses and lifetimes from the previous analysis. A comparison of a selection of these quantities for a pure-higgsino and a pure-wino sample can be seen in Figures 5.8 and 5.9 respectively, where all distributions agree within statistical uncertainties, with the exception of the nominal Monte Carlo generator event weight, shown in Figures 5.8(f) and 5.9(f). The weight distributions are the same but stretched horizontally, so when normalised by the sum of weights they are functionally identical.

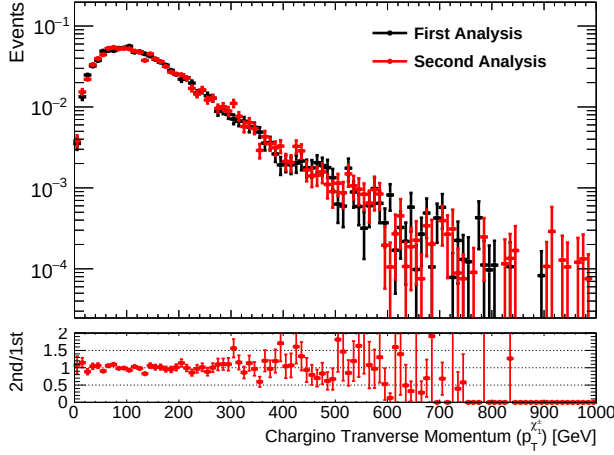
The initial signal sample sets were designed to follow the observed limits on chargino lifetimes and masses from the first analysis, and extend beyond these in the regions expected to be explored with this analysis, such as shorter lifetimes. Samples were generated at lifetimes of 0.02 ns, 0.04 ns, 0.2 ns, 1.0 ns, 4.0 ns and 10.0 ns, and select masses ranging from 100 GeV to 1 TeV at 100 GeV intervals, depending on their lifetime. Additional samples were also generated for the pure-higgsino model at 250 GeV 0.04 ns and 200 GeV 0.03 ns for the study and development of the low-momentum pion selection, and for a more precise understanding of the expected limits for the chargino observation. Between ten thousand and ten million events were generated at each point, depending on the expected chargino acceptance calculated during the development of the reinterpretation material for the first analysis, which is discussed in detail in Section 8. A detailed breakdown of the number of events generated for each sample can be found in Appendix A.2.1.

## 5.4 Background Samples for a Search for Disappearing Tracks With 4 Hits

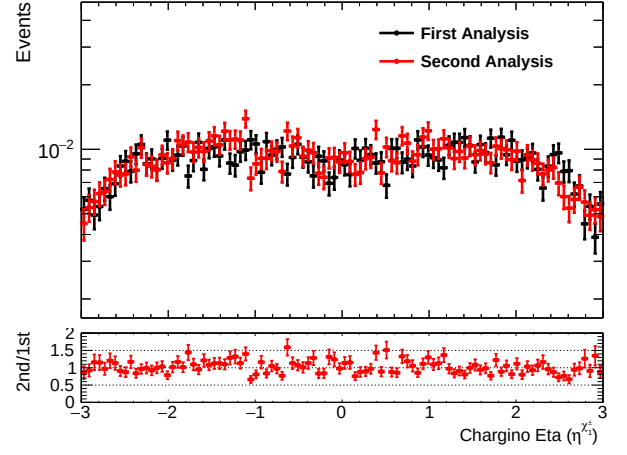
A large range of samples were generated to support the development of the background estimates for the search for disappearing tracks with four hits, which is presented in Chapter 7. Most of these samples model  $W^\pm \rightarrow \ell^\pm \nu_\ell$ ,  $Z \rightarrow \ell\ell$  and  $Z \rightarrow \nu\nu$  processes, as well as other samples involving top quark decays and QCD interactions. These were generated using SHERPA v2.2.1, with the exception of the top quark samples which were generated using POWHEG and showered in PYTHIA8 v8.230.

## 5.5 Background Samples for a Search for Disappearing Tracks With 3 or 4 Hits and an Associated Pion

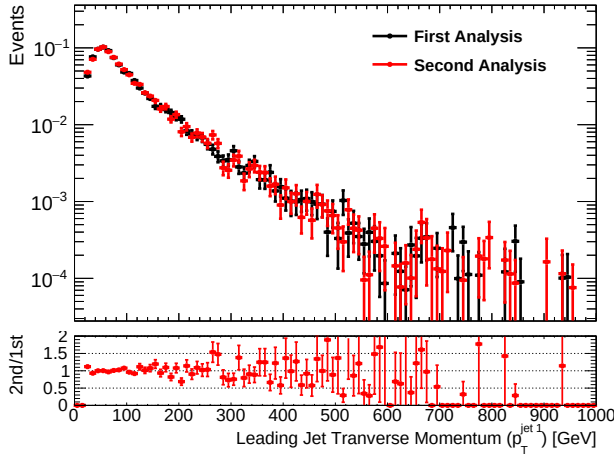
A range of simulated samples were also produced to study the background processes and develop the background estimation methods for the search for disappearing tracks with three



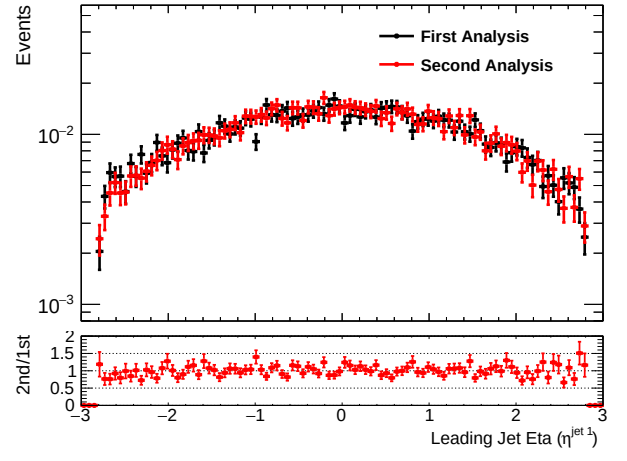
(a) Generator-level chargino transverse momentum



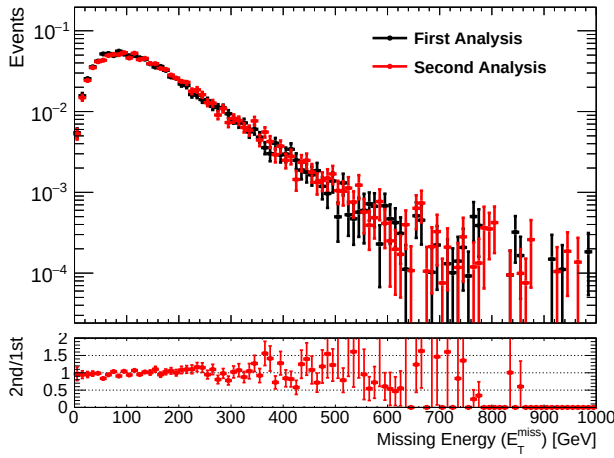
(b) Generator-level chargino pseudo-rapidity



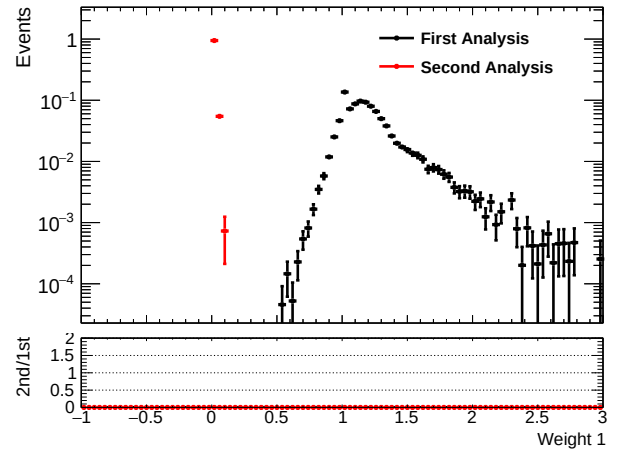
(c) Generator-level leading jet transverse momentum



(d) Generator-level leading jet pseudo-rapidity

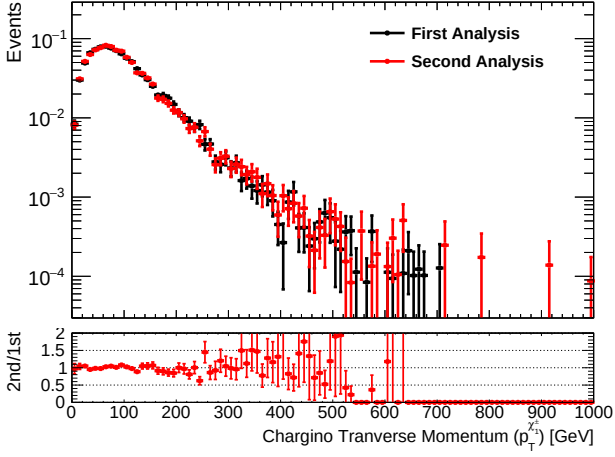


(e) Generator-level missing transverse momentum

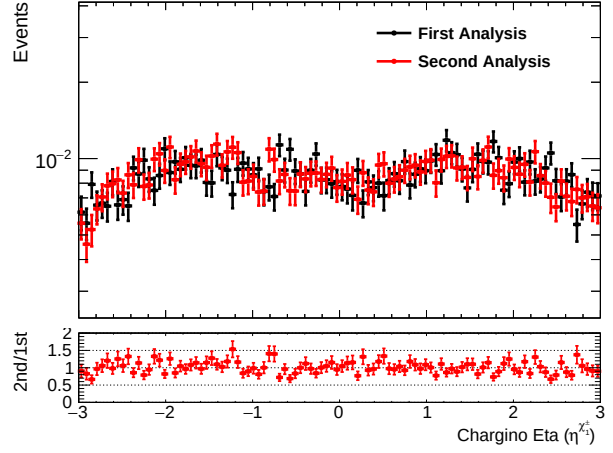


(f) Nominal Monte Carlo generator event weight

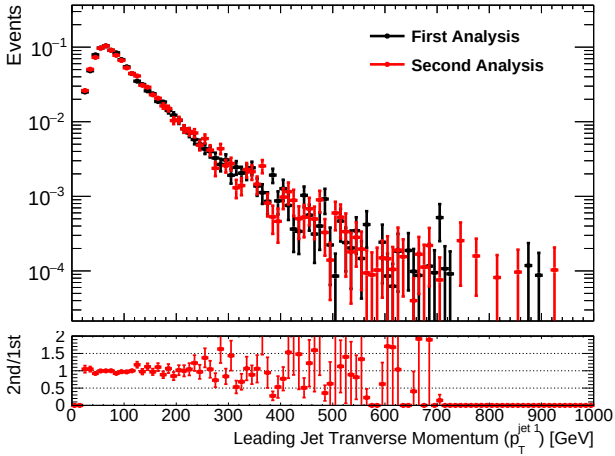
 Figure 5.8: Validation plots comparing various variables in old and new pure-higgsino samples (160 GeV, 0.2 ns,  $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^0$ )



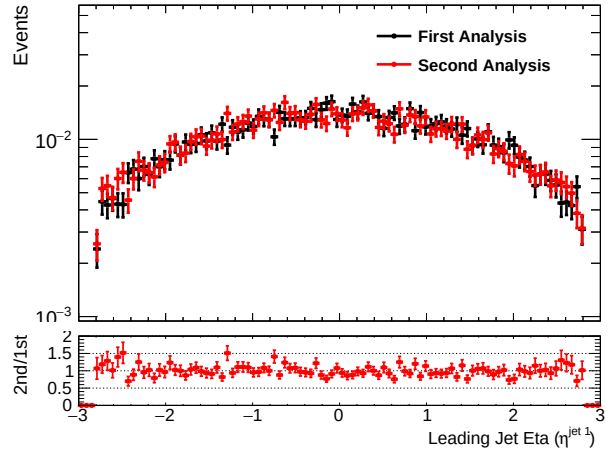
(a) Generator-level chargino transverse momentum



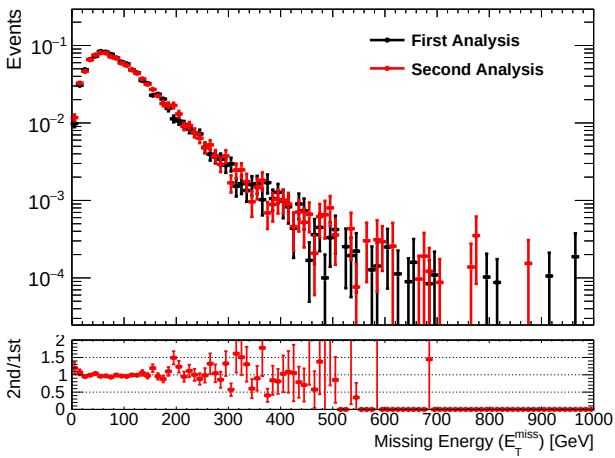
(b) Generator-level chargino pseudo-rapidity



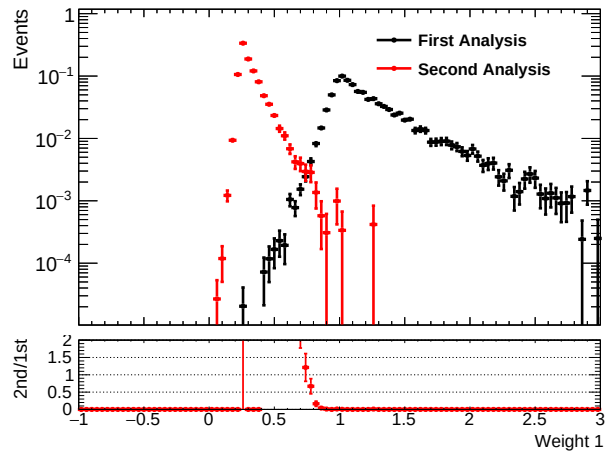
(c) Generator-level leading jet transverse momentum



(d) Generator-level leading jet pseudo-rapidity



(e) Generator-level missing transverse momentum



(f) Nominal Monte Carlo generator event weight

 Figure 5.9: Validation plots comparing various variables in old and new pure-wino samples (90.7 GeV, 0.2 ns,  $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ )

or four hits and an associated low-momentum pion, which is presented in Chapter 9. These include samples modelling Single Particle Gun (SPG) and the production of a vector boson in association with one or more jets (V+Jets).

### 5.5.1 Single Particle Gun Samples

A range of simple samples was produced to understand the behaviour of tracklets caused by the scatter of specific Standard Model particles. These samples do not represent a physical event or process – instead, the desired particle is generated from nothing at the centre of the detector with a certain momentum and direction. These are known as *Single Particle Gun* samples.

Four samples were produced, with positively- and negatively-charged pions, muons and neutrinos respectively. The two pion samples were for the study of the scattered hadron background, the muon sample for the study of the scattered lepton background, and the neutrino sample for the study of the combinatorial fake background.

These samples were generated using the ATLAS-specific PARTICLEGUN generator, detailed in Section 5.2.1. The neutrino samples were produced such that the neutrinos have a constant transverse momentum of 50 GeV. The pion samples were produced such that the pions have a transverse momentum spectrum following exponential decrease between 5 GeV and 2000 GeV. The electron sample was produced with a transverse momentum spectrum that empirically approximates that seen in the ATLAS detector. It is comprised of a flat baseline plus two Fermi-Dirac distributions, specifically

$$y = 0.005 - \frac{1}{\exp\left(\frac{x-0.5}{0.1}\right) + 1} + \frac{1}{\exp\left(\frac{x-200}{20}\right) + 1} \quad (5.3)$$

which was then used to generate electrons with transverse momenta between 0 and 3 TeV.

### 5.5.2 V+Jets Samples

A range of samples modelling events involving the decay of a vector boson in association with one or more jets were produced to more completely model background events in the experimental dataset, known as *V+Jets* samples. These include  $W^\pm \rightarrow \tau^\pm \nu_\tau$ ,  $Z \rightarrow \mu^+ \mu^-$  and  $Z \rightarrow \nu \bar{\nu}$  processes, produced with up to six jets. The  $W^\pm \rightarrow \tau^\pm \nu_\tau$  sample was used to study hadronic scatters from the tau decay, as well as fake tracks in an event topology similar to the signal topology. The  $Z \rightarrow \mu^+ \mu^-$  sample was used to study muon scattering rates, as well as a control region to develop and test background estimates. Finally, the  $Z \rightarrow \nu \bar{\nu}$  sample was used to study fake tracklets and pileup effects, as there is no hard-scatter process in this sample for scattered tracks from the primary vertex.

These V+Jets samples were generated using SHERPA v2.2.11. As described in Section 5.2.1, SHERPA will produce events with zero to two jets at NLO, and events with three to six jets at LO.

The V+Jets samples were produced in slices for easier dataset management, and to allow other groups to be able to work with only the slices relevant to their analyses. These slices are based on the quark flavour producing the jets in the sample, specifically either filtering or vetoing charm- and beauty-tagged jets. The slices available are c-veto + b-veto, c-filter + b-veto, and b-filter. As shown in Figure 5.10, together these are inclusive of the whole phase space.

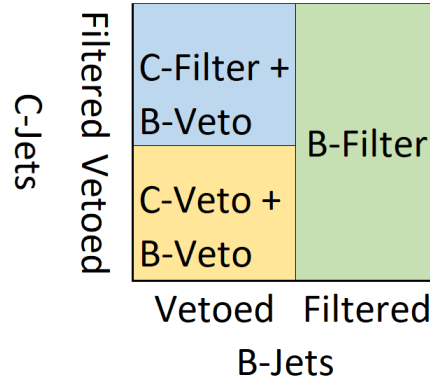


Figure 5.10: The slicing strategy for the V+Jets samples. Samples are sliced based on c- and b-Jet vetos and filters.

## Chapter 6

# Physics Object Definitions, Event Reconstruction

Despite the wishes of particle physicists, particle detectors do not produce perfect, unambiguous signals for every particle passing through. Particles may cause multiple overlapping signals in different detectors. These signals may be weak, or similar to that of another type of particle. *Physics objects* must be defined to collect the signals from a given particle and form a set of these particles with high efficiency and purity. The reconstruction of these objects is performed within the ATHENA software package. This chapter describes the techniques used to reconstruct objects from detector signals, and the object definitions used in the analyses presented in this thesis. As described in the Introduction, this chapter is a detailed review of reconstruction techniques used in the analyses in this thesis, including specific techniques previously developed for use exclusively in this analysis. While these techniques are not original work they are key for understanding the analyses, and the resolution and efficiency plots presented in Section 6.1 are original work.

### 6.1 Charged Particle Tracking

One of the most fundamental objects used in ATLAS is a *track*, the reconstructed trajectory of a charged particle. Fundamentally, a track is a collection of measurements made from individual charged particle hits read out from the inner detector. A variety of track reconstruction algorithms and track types are available in ATHENA for use in physics analyses, many of which are used in the analyses presented in this thesis. This includes standard track objects, short tracklets using fewer hits, muon-spectrometer tracks, and low-momentum tracks associated to a pixel tracklet. These are explained in detail below.

### 6.1.1 Standard Track Reconstruction

Standard tracks are produced from the primary track reconstruction algorithm [122]. They can be used as stand-alone physics objects, or as part of higher-level objects such as electrons or muons.

The majority of tracks reconstructed from ATLAS data use an *inside-out* approach. To construct a track, hits are first recorded from individual pixel cells or SCT strips, and adjacent hits are clustered together. A position measurement, known as a *space-point*, is formed from a pixel cluster or a pair of SCT clusters. Each measurement along a particle track can be completely defined by five parameters – the transverse and longitudinal separation between the primary vertex and the track perigee (known as the impact parameters  $d_0$  and  $z_0$  respectively), the angle of the track relative to the beamline at the perigee in  $\theta$  and  $\phi$ , and the charge-over-momentum  $q/p$ , which is proportional to the track curvature. This can be seen graphically in Figure 6.1.

The primary tracking algorithm then begins by creating a *seed track* of three space points. Very loose criteria such as impact parameters are placed on the track seeds to reject low-quality seeds, and improve computation time. The tracking algorithm extends this seed track by searching for compatible space-points found on modules that are near the trajectory of the seed. By only considering certain modules, the computational complexity is again significantly reduced. A combinatorial Kalman filter is used to select space-points, which simultaneously searches inwards and outwards, and attempts to smooth the track trajectory as more space-points are added. If suitable space-points cannot be found, the seed is discarded.

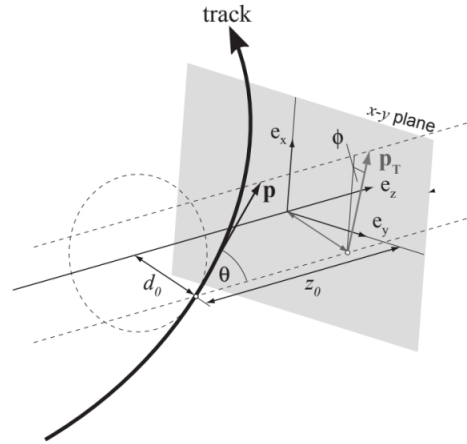


Figure 6.1: Track parameter definitions as used in the ATLAS Experiment. Shown are the impact parameters  $d_0$  and  $z_0$ , the polar and azimuthal angles  $\phi$  and  $\theta$ , and the track momentum  $p$ .

In the particle-dense environment of the inner detector, it is possible to construct multiple plausible tracks from a set of space-points. An *ambiguity resolver* is used to reject low-quality track candidates. This stage scores candidates on a number of criteria, with the number of hits shared with other tracks being a key variable. Where possible, large clusters compatible with multiple tracks are split using a neural-network-based algorithm to keep the number of shared hits low. Once all compatible hits have been collected, a track can then be fitted to this collection of hits using a global  $\chi^2$  method.



The track can optionally be extended to include any compatible TRT hits. A Kalman filter is again used to collect TRT hits in a region along the track trajectory, and the new collection is refitted. Additionally, an outside-in approach can also be used, where track seeds are formed in the TRT in ROIs defined by calorimeter activity, and then extrapolated into the silicon detectors to form full tracks.

Standard tracks reconstructed in ATHENA require at least 500 MeV of transverse momentum, a pseudo-rapidity  $|\eta|$  less than 2.5, at least seven silicon hits<sup>1</sup>, no more than two missing silicon hits along the track, no more than one missing pixel hit along the track, and no more than one shared module<sup>2</sup> with other tracks. Other physics objects such as electrons may apply additional criteria.

### 6.1.2 Pixel Tracklets

As standard tracks require the reconstructed particle to have passed through the pixel detector and the majority of the SCT, particles with lab-frame lifetimes less than approximately 1.5 ns would not be reconstructed, causing a blind spot to potential new physics. To enable the analyses presented in Chapters 7 and 9, an additional track reconstruction algorithm was developed to reconstruct tracks shorter than standard tracks, known as tracklets.

The tracklet reconstruction algorithm functions in a similar way to the standard tracking algorithm but only considers silicon hits not used by the standard tracking algorithm. This reduces the computation time and the number of erroneous (fake) tracklets, which are primarily caused by random combinations of hits from multiple unrelated particles. To be able to reconstruct short-lived particles, fewer hits are required for tracklets than for standard tracks. In the analysis presented in Chapter 7 tracklets were required to have four pixel hits only, and up to one SCT hit. In the analysis presented in Chapter 9 this was expanded to allow tracklets with three or four pixel hits to allow a broader range of particle lifetimes to be studied. Two new reconstruction techniques were also introduced for the tracklets used in the analysis presented in Chapter 9 – vertex constraints and SCT hit filters.

The vertex constraint improves the tracklet’s transverse momentum and angular resolutions by identifying the nearest hard-scatter vertex to the tracklet and updating the tracklet’s defining parameters such that the tracklet passes through this vertex. This effectively acts as an additional hit and increases the lever arm of the tracklet, significantly improving the resolu-

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<sup>1</sup>Pixel modules are single-sided and contribute one hit each. SCT modules are double-sided and contribute two hits each, as described in Section 4.2.1.

<sup>2</sup>Defined as the sum of the number of pixel hits shared with other tracks, and the number of SCT hits shared with other tracks divided by two.

tions. This is most noticeable for the transverse momentum resolution of three-layer tracklets. The improved transverse momentum resolution can be seen in Figure 6.2, and the improved pseudo-rapidity and angular resolution can be seen in Figures 6.3 and 6.4 respectively.

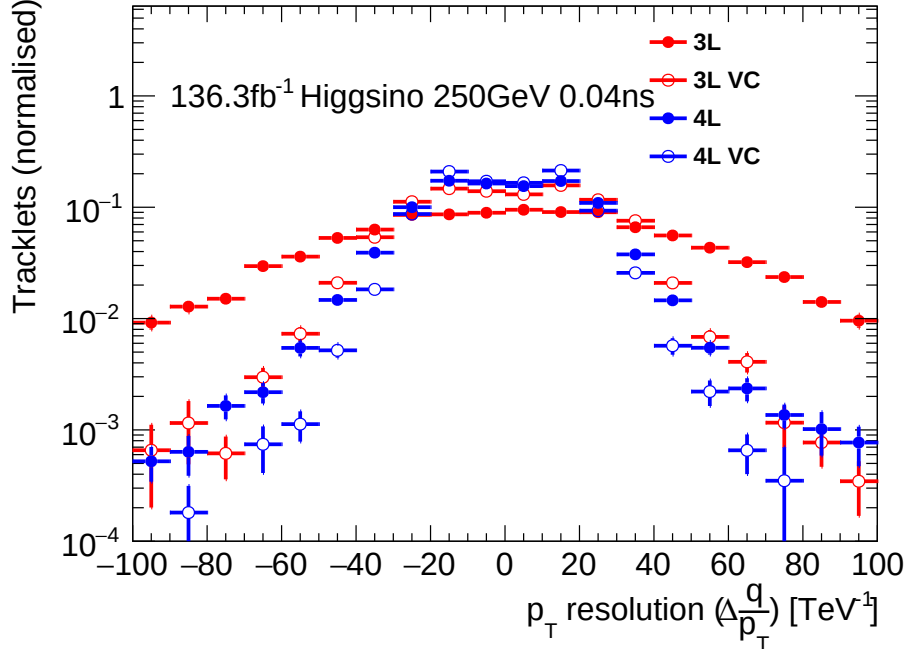


Figure 6.2: Transverse momentum resolutions of three- and four-layer tracklets reconstructed from 250 GeV 0.04 ns pure-higgsino charginos, with and without the use of a vertex constraint.

Often, spurious SCT hits can be mistakenly associated to a pixel tracklet, leading to the tracklet being vetoed. The SCT hit filter reduces this inefficiency by filtering spurious SCT hits. During the tracklet extension stage, if the penultimate hit is on a pixel layer any single SCT hits are removed, reducing the effect of attaching single fake SCT hits to four-layer pixel tracklets. Additionally, when the last two hits are from the SCT, they are required to be on the same layer, reducing further extension into the SCT. The SCT hit filter improves pixel tracklet reconstruction by over 40%, whilst rejecting less than 5% of tracklets truly extending into the SCT.

Tracklets are required to pass a number of quality criteria to reduce the number of fake tracklets mis-reconstructed from unrelated combinations of hits. For pixel tracklet candidates to be accepted, they must have a transverse momentum of at least 5 GeV, a pseudo-rapidity of  $|\eta| \leq 2.2$ , a longitudinal impact parameter of  $|z_0| \leq 250 \mu\text{m}$  and a transverse impact parameter of  $|d_0| \leq 10 \mu\text{m}$ . Additionally in the analysis presented in Chapter 9 a filter of  $|z_0 \sin \theta| \leq 5 \text{ mm}$  was applied during the data reconstruction to reduce the computational complexity.

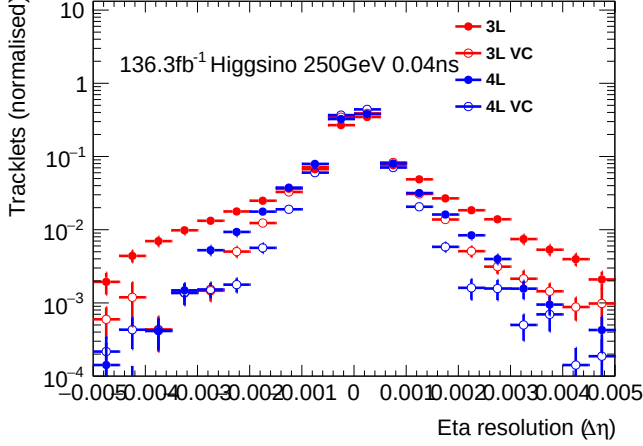


Figure 6.3: Pseudo-rapidity resolutions of three- and four-layer tracklets reconstructed from 250 GeV 0.04 ns pure-higgsino charginos, with and without the use of a vertex constraint.

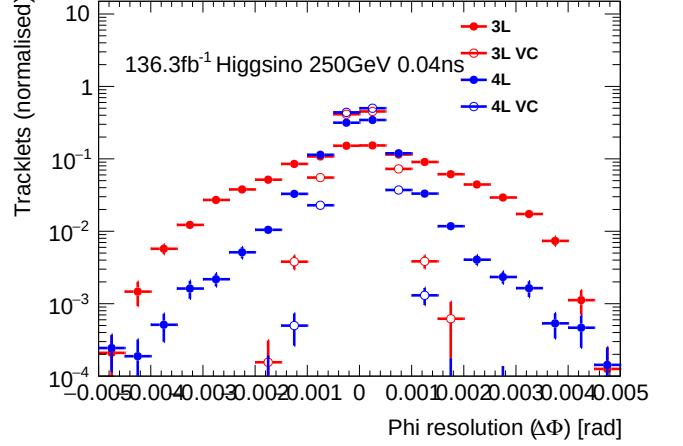


Figure 6.4: Polar angle resolutions of three- and four-layer tracklets reconstructed from 250 GeV 0.04 ns pure-higgsino charginos, with and without the use of a vertex constraint.

An offline selection is also applied to tracklets before accepting them into a signal region, in order to suppress background contributions and ensure good-quality tracklets. The requirements are listed below.

- The tracklet is required to have high transverse momentum, generally above 20 GeV and above 60 GeV for the signal region.
- The tracklet is required to be in the most sensitive part of the barrel region, with a pseudo-rapidity of  $0.1 < |\eta| < 1.9$ .
- The tracklet is required to fulfil the disappearing condition. For the analysis presented in Chapter 7, this is formed from the numbers of hits and layers, specifically:
  - At least four pixel hits from at least four pixel layers
  - No SCT hits
  - No missing hits (*holes*)
  - No outlying, spoilt or ganged pixel hits
  - At least 1 B-Layer pixel hit

. In the analysis presented in Chapter 9, the hits are required to fall on specific layers by use of a hitpattern, detailed in Appendix B.1. This also easily allows for separate three- and four-layer signal regions.

- The tracklet is required to be close to the primary vertex, defined by  $|\sigma_{d_0}| = |d_0/\text{err}(d_0)| \leq 1.5$ , and  $|z_0 \sin(\theta)| \leq 0.5$  mm for the analysis presented in Chapter 7 and  $|z_0 \sin(\theta)| \leq 0.2$  mm for the analysis presented in Chapter 9

- The tracklet is required to be well isolated from other tracks and calorimeter objects.
  - Track isolation is measured with a track isolation variable, defined by summing the transverse momenta of all tracks within a cone of  $\Delta R < 0.4$ <sup>3</sup> of the tracklet that have a transverse momenta of more than 1 GeV. The isolation variable is then normalised by the tracklet’s transverse momentum. The normalised track isolation variable is required to be less than 4%.
  - Calorimeter isolation is measured with a calorimeter isolation variable, defined by the sum of the transverse energy of all topological calorimeter clusters (see Section 6.3) within  $\Delta R < 0.2$  of the tracklet. The calorimeter isolation variable is required to be less than 5 GeV.
- The tracklet is required to be well-fitted, with a fit quality requirement of  $(\chi^2, \text{ndf}) > 0.1$ .
- The tracklet is required to be separated from other objects in the event, specifically with a  $\Delta R > 0.4$  from all jets with more than 50 GeV of transverse momentum, all electrons and muons, and all Muon Spectrometer Tracks (MSTracks) with more than 10 GeV of transverse momentum.
- If more than one tracklet is reconstructed, only the tracklet with the highest transverse momentum is considered. For the analysis presented in Chapter 9 three-layer tracklets are only considered if there is no good four-layer tracklet.

These requirements are common to both analyses presented in this thesis unless otherwise stated.

The number of tracklets simulated and reconstructed as a function of decay radius are shown in Figure 6.5 over the whole inner detector for both analyses.

### 6.1.3 Associated Soft Tracks

Many proposed long-lived particles gain their long lifetimes from having a small difference in mass to their primary decay product. This gives a limited decay phase space where the only other products are light particles such as charged pions with low momentum. When the long-lived particle decays within the tracking detector, it can be possible to reconstruct the light, low-momentum decay products [125]. These are known as associated soft tracks. In the case of the pure-higgsino charginos considered in the analysis presented in Chapter 9 the pions resulting from the chargino decay typically have between 250 MeV and 350 MeV of transverse momentum.

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<sup>3</sup> $\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\theta^2}$

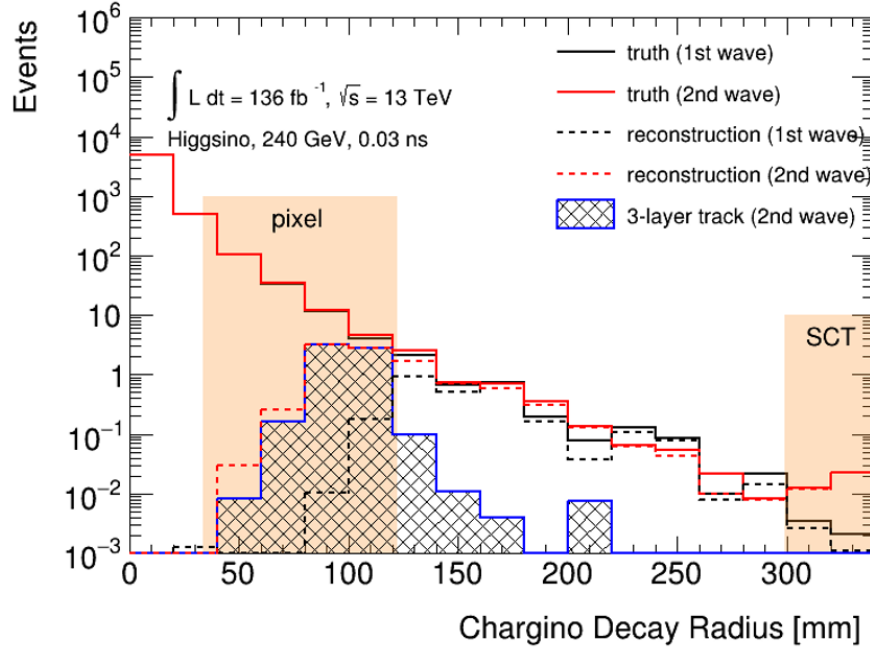


Figure 6.5: Tracklet reconstruction efficiency for three- and four-layer tracklets reconstructed from 240 GeV 0.03 ns pure-higgsino charginos. ‘First Wave’ refers to the analysis searching for tracklets with four pixel hits only, presented in Chapter 7, whereas ‘Second Wave’ refers to the analysis presented in Chapter 9. ‘Truth’ refers to the decay radii of the charginos simulated, and ‘reconstruction’ refers to the charginos successfully reconstructed as tracklets. ‘3-layer track’ shows the contribution to the second-wave reconstruction exclusively from tracklets with three pixel hits, and the ‘reconstruction (2nd wave)’ line is inclusive of this. [123, 124]

Like other specialist tracking algorithms used by the ATLAS experiment, the associated soft track algorithm uses hits left over from the standard tracking algorithm to reduce the complexity of the algorithm. Additionally, as the soft tracks of interest are only produced from long-lived particles reconstructed as tracklets, the soft tracks are only reconstructed in an ROI around a suitable tracklet. This also means that the two algorithms (pixel tracklets and associated soft tracks) can be performed sequentially and do not compete for hits.

The tracklets defining the ROI are required to have at least 20 GeV of transverse momentum, at least three pixel hits and zero SCT hits. They are also required to be isolated from other tracks or tracklets using the same track isolation variable defined in Section 6.1.2, but considering all tracks and tracklets with more than 500 MeV of transverse momentum, rather than the previous 1 GeV. The parent tracklet is required to have a normalised isolation variable of less than 10%. These tracklet criteria significantly reduce the impact of low-momentum hadrons producing jets, which would cause a large increase in processing time. The tracklets

are also ranked by the smallest transverse impact parameter  $d_0$ , so priority is given to tracklets from the hard-scatter interaction.

The soft track seeds are then formed from SCT hits within the ROI around the candidate tracklet. The ROI is defined as a cone of  $\Delta R < 0.8$  around the tracklet, beginning from the beam-spot center. Soft track seeds are formed from at least three SCT hits found within this cone. The resulting seed is required to have a transverse momentum of at least 200 MeV, a transverse impact parameter relative to the last pixel hit of the tracklet  $|d_0^{\text{pix}}| < 150$  mm and a longitudinal impact parameter relative to the last pixel hit of the tracklet  $|z_0^{\text{pix}}| < 1000$  mm.

These seeds can then be extended into full candidate soft tracks using SCT hits in the ROI along the seed's trajectory. For the final soft track to be accepted, at least six SCT hits are required, with no more than two hits shared with other tracks and no more than two missing SCT hits.

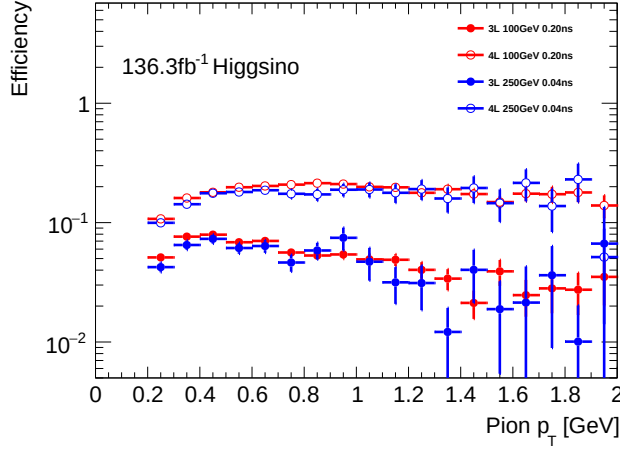
The reconstruction efficiency of the low-momentum pions produced by chargino decays can be defined as the ratio of the number of reconstructed soft tracks linked to a generator-level low-momentum pion with a chargino parent, over the number of such pions within acceptance. The pion acceptance is the set of requirements for the low-momentum pion to be considered for reconstruction at all, namely that the parent chargino was successfully reconstructed (defined as there being a reconstructed tracklet linked to a generator-level chargino), and that the pion has a transverse momentum of at least 200 MeV.

The efficiency is generally good in a region where the soft track has a moderate amount of transverse momentum ( $p_T^{\text{soft}} \gtrsim 350$  MeV), a small impact parameter relative to the last pixel hit of the parent tracklet ( $|d_0^{\text{pix}}| \lesssim 100$  mm), and was produced between the pixel and SCT detectors ( $88.5 \text{ mm} < r_{\text{prod}}^{\text{soft}} < 122.5 \text{ mm}$ ). Reconstruction efficiency gradually decreases with increasing pileup, but the efficiency remains high below  $\mu \simeq 35$ . These parameterised efficiencies can be seen in Figure 6.6.

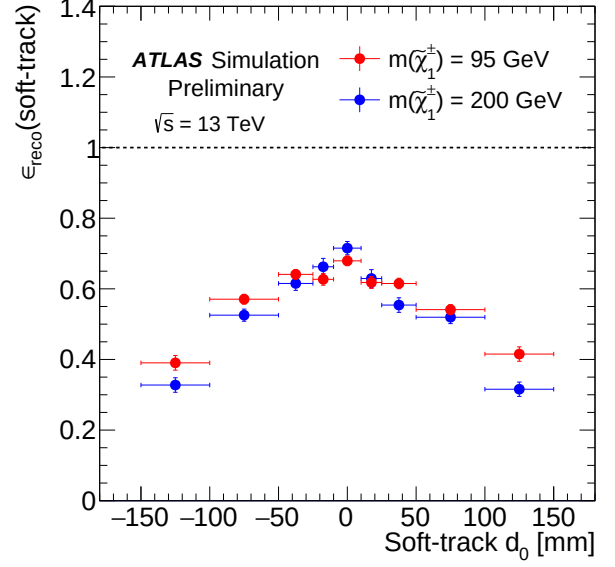
The soft track transverse momentum resolution, impact parameter resolution relative to the primary and secondary vertices, and angular resolution. This can be seen in Figure 6.7, Figures 6.8 and 6.9, and Figures 6.10 and 6.11 respectively.

#### 6.1.4 Large Radius Tracking (LRT)

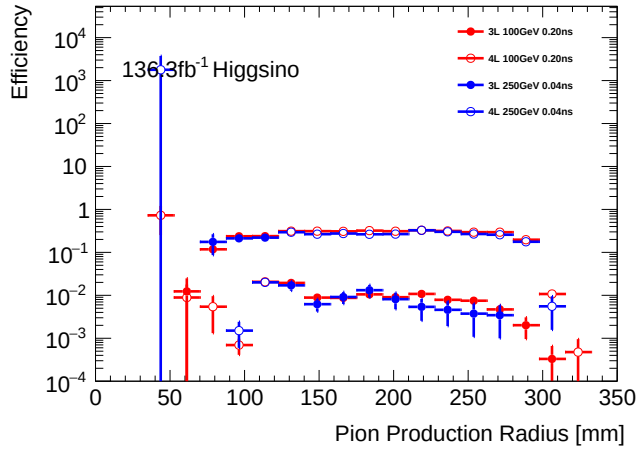
Long-lived particles such as charginos may decay to detectable products within the inner detector volume. However, these decay products would not be reconstructed by the standard tracking algorithm as this is focused on tracks from the hard-scatter vertex. In the reprocessed Run-2 dataset, used in the analysis presented in Chapter 9, a new, additional track reconstruc-



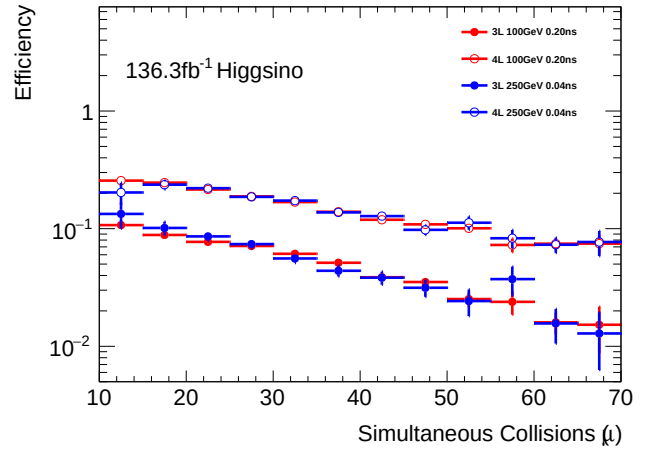
(a) Reconstruction efficiency as a function of pion transverse momentum ( $p_T$ )



(b) Reconstruction efficiency as a function of pion impact parameter with respect to the chargino ( $|d_0^{\text{pix}}|$ ). Reproduced from [125].



(c) Reconstruction efficiency as a function of pion production radius ( $r_{\text{prod}}^{\text{soft}}$ )



(d) Reconstruction efficiency as a function of event pileup

Figure 6.6: Reconstruction efficiency of low-momentum pions produced from a chargino decay.

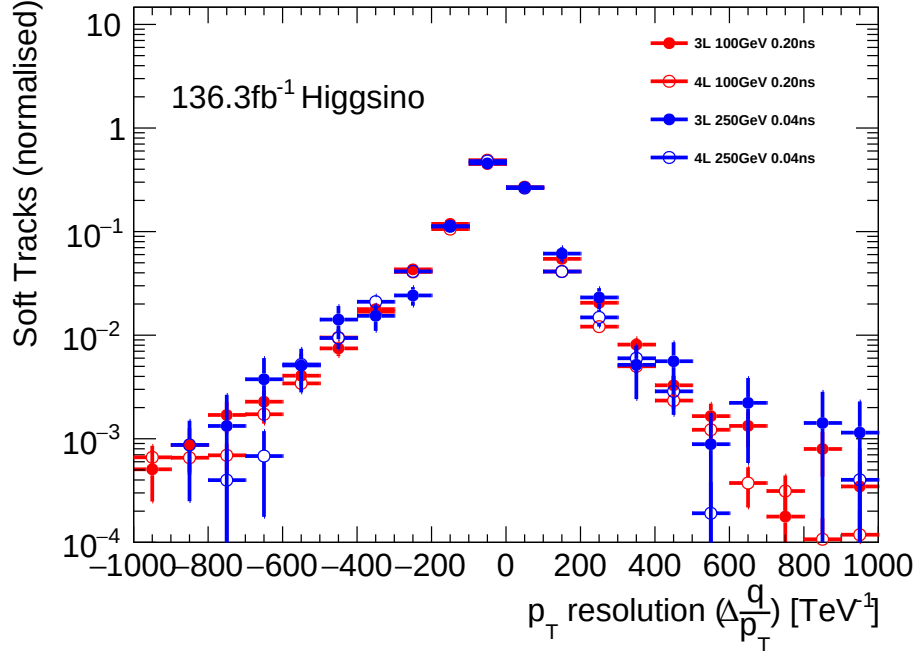


Figure 6.7: Transverse momentum resolution of soft tracks reconstructed from pions produced by decays of pure-higgsino charginos.

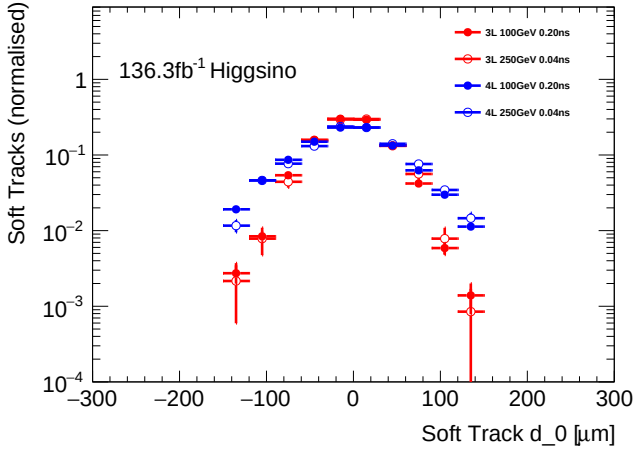


Figure 6.8: Transverse impact parameter resolution relative to the Primary Vertex (PV) of soft tracks reconstructed from pions produced by decays of pure-higgsino charginos.

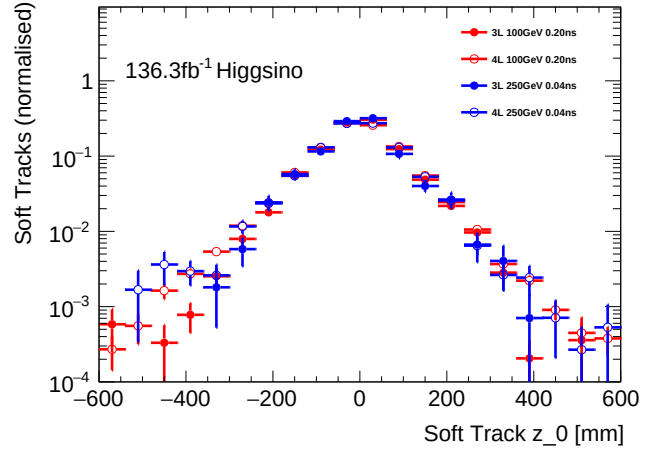


Figure 6.9: Longitudinal impact parameter resolution relative to the PV of soft tracks reconstructed from pions produced by decays of pure-higgsino charginos.

tion algorithm was used to identify such decay products. These tracks have a perigee from the primary vertex that is at a much higher radius than standard tracks – this tracking algorithm is therefore known as *Large-Radius Tracking (LRT)* [126].

Like the tracklet algorithm discussed in Section 6.1.2, this algorithm is similar to the standard



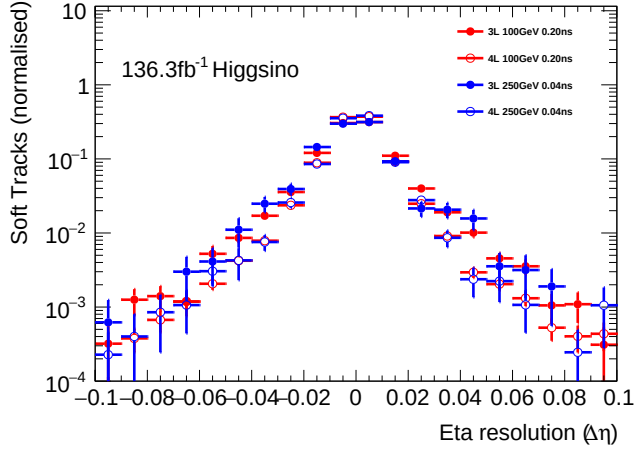


Figure 6.10: Pseudo-rapidity resolution of soft tracks reconstructed from pions produced by decays of pure-higgsino charginos.

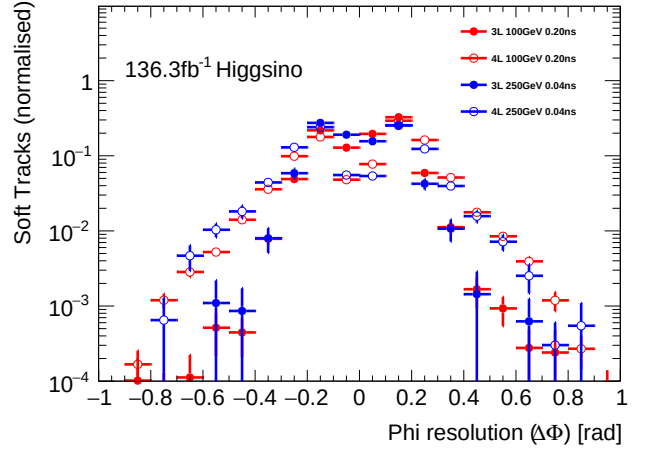


Figure 6.11: Azimuthal angle resolution of soft tracks reconstructed from pions produced by decays of pure-higgsino charginos.

tracking algorithm but uses hits left-over after the reconstruction of the standard tracks. It has significantly relaxed impact parameter requirements. The requirement on longitudinal impact parameter  $|z_0|$  is relaxed from  $|z_0| < 250$  mm to  $|z_0| < 1500$  mm, and the requirement on radial impact parameter  $|d_0|$  is relaxed from  $|d_0| < 10$  mm to  $|d_0| < 300$  mm. The requirement of the maximum pseudo-rapidity  $|\eta|$  is also relaxed from  $|\eta| < 2.7$  to  $|\eta| < 5.0$ , and the maximum allowed number of shared silicon modules is increased from one to two.

The Large-Radius Tracking (LRT) algorithm allows greatly improved track reconstruction efficiency above a radius of 10 mm from the primary vertex. This can be seen in Figure 6.12.

In the context of this thesis, LRT tracks are considered as candidate soft pions alongside standard tracks and tracks reconstructed by the dedicated soft track reconstruction described in Section 6.1.3.

### 6.1.5 Muon Spectrometer Tracks

Due to their minimally-ionising nature, muons will pass through the calorimeter largely unimpeded, allowing for additional tracking to be performed in dedicated muon spectrometers described in Section 4.2.3 [127]. Each muon spectrometer station reconstructs short, straight-line segments. Compatible segments can be combined into a track, with loose requirements set to be compatible with the interaction point. Once a set of segments is identified, a complete fit can be performed including the expected curvature due to the magnetic field and expected interactions with the detector material. Outlying hits are discounted and unused hits along the track are included, and the fit is recalculated using the updated set of hits. The resulting MTrack can be accessed by itself or used to construct combined muon objects as described

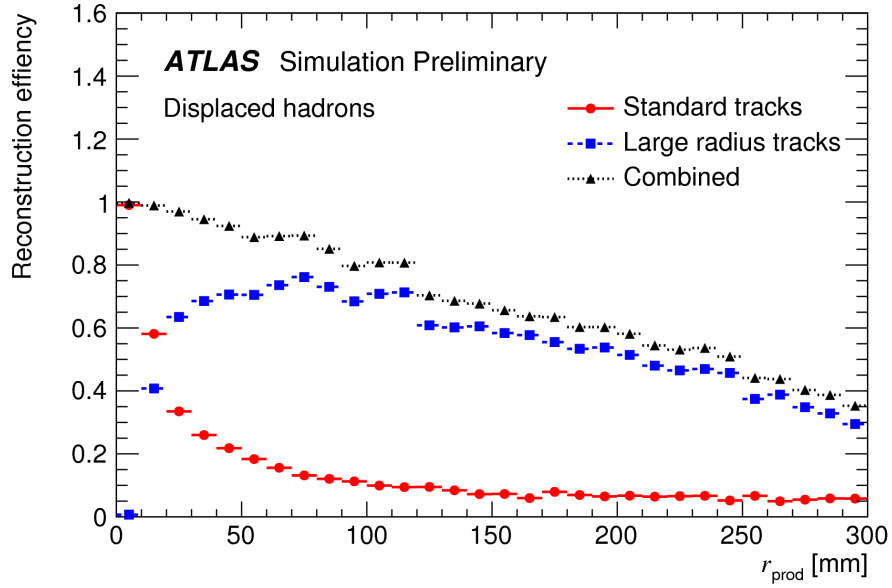


Figure 6.12: Reconstruction efficiency of hadrons as a function of their production radius for standard and large-radius tracks. Reproduced from [126].

in Section 6.4.2.

## 6.2 Vertexing

Vertexing is the process of identifying the point at which a set of tracks or objects originate, known as a vertex. This can be a primary vertex, an approximation of the hard scatter interaction, or a secondary vertex, where a particle decayed within the ATLAS experiment to detectable products, and the vertex is a reconstruction of the decay position [128].

### 6.2.1 Primary Vertices

For the primary vertex, good-quality standard tracks extending through most or all of the silicon inner detectors with few missing hits are used as the input. The vertex fit begins with determining a seed position. In the transverse plane, this is taken as the centre of the beam-spot, which is measured during data-taking every 10 minutes. The mode of the longitudinal impact parameter with respect to the beamspot for all tracks is taken as the longitudinal component of the seed position.

This seed position and the set of tracks terminating from the beamspot region are used as inputs to the vertex fitting. Tracks are iteratively added to the vertex, and the best-fit position for the vertex is recalculated. Tracks which are less compatible with the updated vertex are

then down-weighted, and tracks more than  $7\sigma$  from the estimated vertex position are removed from the vertex. This procedure is repeated until all tracks have been considered. The vertex is then considered final, and the associated tracks are removed from the set.

The whole procedure can then be performed again to find additional vertices by calculating the seed position from the remaining tracks. Multiple vertices can be identified in an event. The primary vertex is defined as the vertex with the largest square sum of the transverse momentum of associated tracks,  $\sum_{\text{tracks}} p_T^2$ . Other vertices are defined as pileup vertices.

### 6.2.2 Secondary Vertices

Many secondary vertexing algorithms are available within ATHENA which target different signatures including flavour-tagging of jets, displaced vertices generated by the decays of long-lived invisible particles, and crucially for the analysis presented in Chapter 9, decays of pixel tracklets [125].

The vertexing algorithm targeting the decays of pixel tracklets attempts to fit a decay vertex between a tracklet identified using the algorithm in Section 6.1.2, and any suitable track, which can be a standard track (Section 6.1.1), a soft track associated to a tracklet (Section 6.1.3), or an LRT (Section 6.1.4). First, a selection is applied to the candidate parent tracklet, and the candidate child tracks. The candidate parent tracklet is required to meet the following criteria:

- The tracklet is required to have a transverse momentum of at least 10 GeV.
- The tracklet is required to have an absolute pseudo-rapidity  $|\eta|$  of less than 2.1.
- The tracklet is required to have hits in at least three pixel layers, a hit in the IBL, and no SCT hits.
- The tracklet is required to be close to the primary vertex, defined as  $z_0 \sin(\theta) < 0.5$  mm.
- The tracklet is required to be either a three-layer or a four-layer tracklet, as defined by a `hitpattern`<sup>4</sup>.

The candidate child track is required to meet the following criteria:

- The track must not be associated with the primary vertex.
- The track must have a transverse momentum of at least 200 MeV.
- The track must not have any hits in the inner-most two pixel layers, and no more than two pixel hits in total. The track must also have at least 6 SCT hits.

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<sup>4</sup>See Appendix B.1. A three-layer tracklet has a `hitpattern` of 7, whereas a four-layer tracklet has a `hitpattern` of 15.

- The angular separation between the candidate parent tracklet and child track  $\Delta R_{(\text{parent}, \text{child})}$  is required to be less than 1.5.

A vertex can then be fitted between the parent and child tracks by approximating the equations of motion of each particle with a first-order Taylor expansion in terms of charge-over-momentum. A *fast* fit is first performed without considering correlations between the vertex position and the track momenta. The result of the fast fit is used as an initial position for the full fit where the correlation is considered.

The candidate vertices then also have a selection applied to them before being accepted. The vertices are required to meet the following criteria:

- The vertex must have a good quality of fit, defined as a  $\chi^2/\text{ndf}$  of less than 10.
- The vertex must be located at a radius from the beamline between 85 mm and 300 mm.

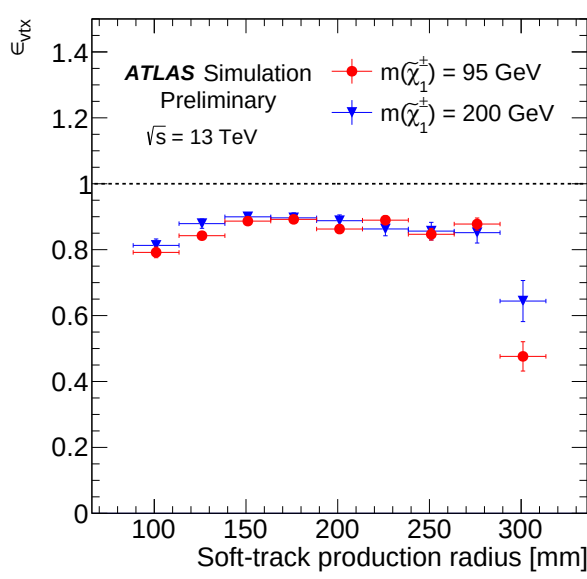
The parent and child tracks are then decorated with the impact parameters with respect to the secondary vertex.

The vertex is then optionally extended to include multiple child tracks. The candidate child tracks are extrapolated to the previously calculated vertex, and if the transverse and longitudinal impact parameters with respect to this vertex are both less than 15 mm then the candidate child is added to the vertex. Once all child tracks have been found, the vertex is refitted and the impact parameters for the parent and child tracks are updated.

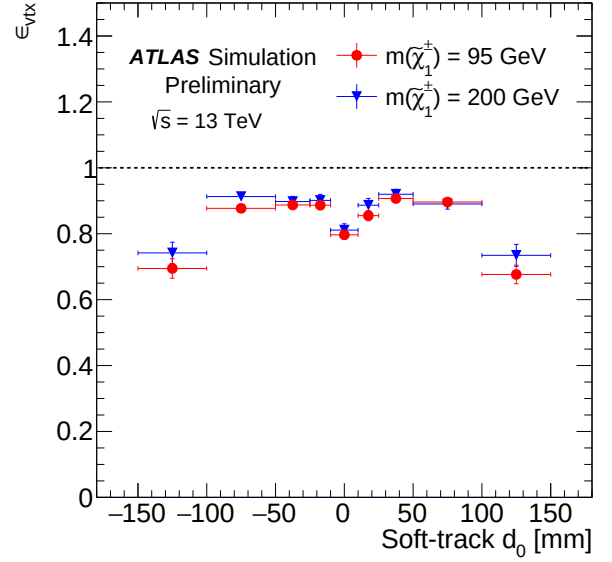
A vertex reconstruction efficiency can be defined as the number of reconstructed vertices (given that both the incoming and outgoing particle were truth-linked to a truth-level chargino and pion respectively) over the number of truth-level vertices (given that both the chargino and resulting pion were reconstructed). By this metric, the secondary vertex reconstruction generally achieves good efficiency in excess of 90%, as shown in Figure 6.13. Small drops in efficiency can be seen when the vertex has a very small or large radius from the beamline (Figure 6.13(a)), when the reconstructed pion has a very small or large transverse impact parameter with respect to the primary vertex (Figure 6.13(b)), and when the reconstructed pion has a small opening angle from the parent tracklet (Figure 6.13(c)).

### 6.3 Jets

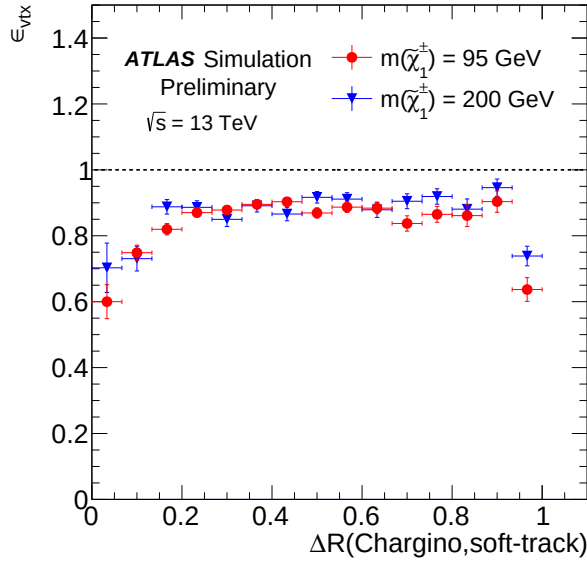
As described in Section 2.3, the results of the proton collision rapidly undergo hadronisation, producing highly-collimated jets of particles. When these jets reach the calorimeter systems they undergo successive material interactions and particle decays, producing showers of particles, which along with any inner detector tracks form the observable part of a jet. The



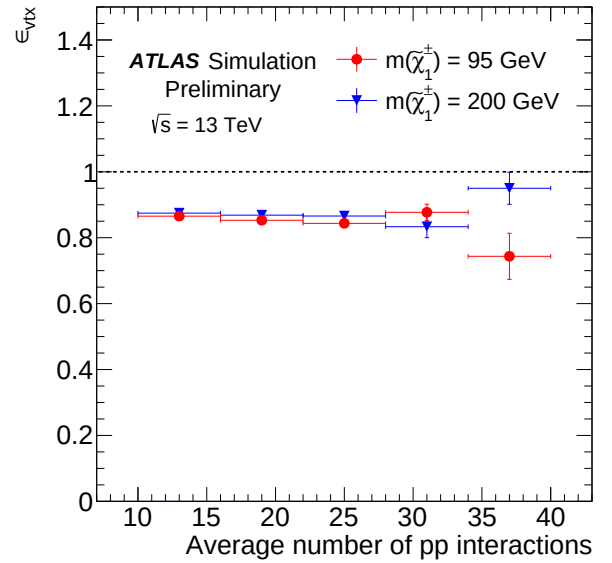
(a) Reconstruction efficiency as a function of truth-level pion production radius



(b) Reconstruction efficiency as a function of the pion's transverse impact parameter with respect to the primary vertex



(c) Reconstruction efficiency as a function of the opening angle between the parent chargino and child pion



(d) Reconstruction efficiency as a function of event pileup

Figure 6.13: Reconstruction efficiency of secondary vertices fitted to the decay of charginos producing low-momentum pions. Reproduced from [125].

interactions of jets with the calorimeter are described in greater detail in Section 4.2.2.

The calorimeters produce an energy reading from each calorimeter cell. The primary measurement of a jet relies on identifying which measurements in the calorimeter were caused by the same jet, and grouping these cells together. This process is known as *clustering*, and numerous algorithms are available to achieve this.

The oldest jet clustering algorithms used cone-based methods where a calorimeter cell (usually the highest energy) is taken as a seed, and calorimeter cells within a fixed cone of  $\Delta R$  around the seed are clustered together. The cone-based methods are computationally efficient and use a simple geometrical motivation, but lack infra-red and co-linear safety – two theoretical guidelines that ensure the reproducibility of jet clustering algorithms. Infra-red safety is the principle that adding or removing low-momentum particles or cells, such as those formed from the underlying event or pile-up collisions, should not affect the overall jet formation. Co-linear safety is the principle that splitting a high-momentum particle or cell into two co-linear particles or cells should not affect the resulting jet. The cone-based algorithms fail both these criteria as the seed ordering is  $p_T$ -sensitive, and low-momentum cells can cause the jet axis to be distorted.

An alternative method is recursive recombination. This functions by combining particles or cells with the smallest distance parameter between them, until a specified maximum distance  $R$  is reached. Recursive recombination algorithms use the same basic formulas for this process. The distance parameter between  $i$  and  $j$  is defined as

$$d_{i,j} = \min \left( p_{T,i}^{2n}, p_{T,j}^{2n} \right) \frac{\Delta R_{i,j}^2}{R^2} \quad (6.1)$$

where  $p_{T,i}$  and  $p_{T,j}$  are the transverse momenta of the  $i^{\text{th}}$  and  $j^{\text{th}}$  particles or cells,  $\Delta R$  is the distance between the two particles and takes the usual definition of  $\Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2}$ , and  $n$  is a parameter of the clustering algorithm with a value of -1, 0 or +1. The distance parameter for two particles is compared to

$$d_{i,B} = p_{T,i}^{2n} \quad (6.2)$$

using the same parameter definitions as Equation 6.1.

The recursive recombination algorithms compute the distance parameter for all particles  $j$  within a cone of  $\Delta R$  around the seed particle  $i$ . These particles are then ordered by the distance parameter, with the smallest first. Particles with  $d_{i,j} < d_{i,B}$  are added to the jet and removed from the set  $\{i, j\}$ . Once the jet is complete ( $d_{i,j} > d_{i,B}$  or no particles remain),

the jet is considered final and  $i$  is removed. The process continues until no particles remain. All jets produced from this technique are infra-red and co-linear safe, but the process can be much more computationally intensive than cone-based algorithms.

Three main types of recursive recombination algorithms exist: the classic  $k_t$  algorithm which defines  $n = 1$ , the Cambridge/Aachen (C/A) algorithm which defines  $n = 0$ , and the anti- $k_t$  algorithm which defines  $n = -1$ . The classic  $k_t$  algorithm builds jets from the lowest-momentum components first, and jets reconstructed with this algorithm can be sensitive to components caused by the underlying event or pileup, and can result in varying jet shapes. The C/A algorithm depends only on distance between objects and is useful for studying jet sub-structures, but can have some dependence on low-momentum components. The anti- $k_t$  algorithm produces stable jets and works from the highest-momentum particles first [129].

In ATLAS in order to reduce the effect of detector noise, calorimeter cells above a base noise energy ( $\sigma_{noise}$ ) are first grouped into topological clusters (*topo-clusters*) [130]. Seed cells are required to have an energy  $E > 4\sigma_{noise}$ . Adjacent cells, either in the same calorimeter layer or in adjacent layers and overlapping in  $\eta - \phi$  space, which have an energy  $E > 2\sigma_{noise}$  are iteratively added to the cluster. The resulting clusters are then split to ensure all clusters have only one maxima. The topo-clusters are then used as the input to the jet algorithms.

All jets need to be calibrated to account for detector effects with the JES, and the resolution of the calorimeter with the Jet Energy Resolution (JER). This is described in detail in Section 4.2.2. The Jet-to-Vertex Tagger (JVT) is also used to suppress jets from pileup events using a likelihood calculated from the fraction of the jet's transverse momentum arising from the PV. Typically this is required to be greater than 0.59, and is around 92% efficient.

It is possible to identify jets that originate from heavy quark flavours (c- or b-quarks) from other jets in a process known as flavour-tagging. This is useful as b-hadrons can have relatively long lifetimes (around a picosecond) and travel several millimetres before decaying. This means that the jet is slightly displaced from the PV. The b-tagging algorithm used in ATLAS is formed from BDT classifiers and Deep Neural Networks (DNNs).

For the analyses presented in Chapters 7 and 9, jets are reconstructed from topo-clusters [131] using the anti- $k_t$  algorithm [129, 132] with a radius parameter of  $R = 0.4$ . Jets are required to have a transverse momentum of at least 20 GeV and a pseudo-rapidity of  $|\eta| < 2.8$ . In order to reduce contributions from pile-up jets, all jets with  $|\eta| < 2.5$  and a transverse momentum less than 60 GeV are required to satisfy the JVT [133] requirements. Events containing b-tagged jets are vetoed.

## 6.4 Leptons and Photons

### 6.4.1 Electrons and Photons

Electrons and photons are primarily reconstructed with the ECal. When reaching the ECal, both particles will produce a shower of photons and electron-positron pairs, which in turn produce more particles until their energy drops below the threshold of the calorimeter. As charged particles, electrons will also produce an inner detector track. As neutral particles, photons will not generate a track, however they can interact with the detector material and produce electron-positron pairs in a process known as photon conversion. Therefore, the reconstruction of electrons and photons have many shared aspects [134].

Reconstruction of an ECal shower uses topo-clusters built in a similar way to those used for jet reconstruction, as discussed in Section 6.3. The ECal layers are segmented into a  $200 \times 256$  grid of  $(\eta, \phi)$ , and the clusters are built into towers by summing the clusters at the same  $(\eta, \phi)$  grid point. Seeds are then built by summing towers in a  $3 \times 5$  sliding window, and accepting the seed if the summed energy  $E_T$  is greater than 2.5 GeV. Extrapolated inner detector tracks within  $|\Delta\eta| < 0.05$  and  $-0.10 < \Delta\phi < 0.05$  of a seed are associated, and together with the seed are considered as electron candidates. Seeds without an associated track are considered photon candidates. The energy of the candidates is found by extending the seed to a  $3 \times 7$   $(\eta, \phi)$  cluster for the barrel region ( $|\eta| < 1.37$ ), or a  $5 \times 5$   $(\eta, \phi)$  cluster for the endcap region ( $1.52 < |\eta| < 2.47$ ).

Electron candidates are accepted using a likelihood discriminant which takes tracking and calorimetry information as inputs. Several working points are available depending on the requirements of the analysis, which provide different levels of electron purity whilst trading off selection efficiency. For the analyses presented in Chapters 7 and 9 a **Loose** working point was used, with an efficiency of approximately 93% for 40 GeV prompt electrons. The electron candidates are also required to have a transverse momentum greater than 10 GeV, and a pseudo-rapidity  $|\eta|$  less than 2.47. Isolation criteria are also applied. An isolation variable constructed from the transverse energy of tracks within a cone of size  $\Delta R = 0.4$  around the electron candidate, normalised by the electron's transverse energy, is required to be less than 15%, and a similar variable constructed from topo-clusters instead of tracks is required to be less than 20%.

Photon candidates are selected based on calorimetry variables, and the shape of the shower in the ECal. While photons are not used as objects in the analyses presented in Chapters 7 and 9, they are used as an input to the missing transverse momentum calculation discussed in Section 6.5.



### 6.4.2 Muons

Muons leave energy deposits throughout the ATLAS detectors. Muon reconstruction begins with MSTracks, which are described in Section 6.1.5. The trajectory of the MSTrack is extrapolated into the inner detector in an attempt to find a compatible ID track. If a compatible track is found, the hits from both tracks are combined and refitted into a new track. Energy deposit information from the calorimeters is also used. The resulting object is known as a combined muon. Such muons are required to satisfy the **Medium** quality requirements described in [127] and have at least 10 GeV of transverse momentum, and a pseudo-rapidity  $|\eta|$  less than 2.7. Combined muons used in the analyses presented in Chapters 7 and 9 are required to originate from the PV, with impact parameters of  $|z_0 \sin \theta| < 0.5$  mm, and  $|d_0/\sigma_{d_0}| < 3$ .

A stand-alone or MS-only muon is a muon object where a compatible ID track could not be found, and is constructed using the information from the MSTrack only. Other than basic quality criteria and a minimum requirement of 10 GeV of transverse momentum, no other selections are made on stand-alone muons.

## 6.5 Missing Transverse Energy (MET, $E_T^{\text{miss}}$ )

As the ATLAS detector provides near-complete solid-angle coverage, it is possible to assess the energy and momentum conservation of the event. Some energy released by the  $pp$  collision will not be captured, either due to inefficiencies in object reconstruction, or because it is not possible to reconstruct some particles with the ATLAS experiments, such as neutrinos. This *missing energy* can also be a powerful signature of new physics such as dark matter candidates.

Due to the composite nature of  $pp$  collisions, it is not possible to accurately determine what fraction of the proton's constituents were involved in the collision. Additionally, there can be contributions from pileup collisions along the experiment and other beam-induced backgrounds. For these reasons, it is not possible to determine the total missing energy. However, in the transverse plane the total energy before a collision is zero, so a transverse missing energy can be determined by simply taking a negative vector sum of all reconstructed objects, plus a soft term, as shown in Equation 6.3 [1, 135].

$$E_T^{\text{miss}} = \left| \vec{p}_T^{\text{miss}} \right| = - \sum \vec{p}_T^\mu - \sum \vec{p}_T^e - \sum \vec{p}_T^\gamma - \sum \vec{p}_T^\tau - \sum \vec{p}_T^{\text{jets}} - \sum \vec{p}_T^{\text{soft}} \quad (6.3)$$

Physics objects are primarily used in the  $E_T^{\text{miss}}$  calculation as unlike raw signals such as topoclusters they are calibrated, providing better energy resolution. A *soft* (low-momentum) term is also included to account for the energy reconstructed but not associated with a physics object. The primary definition is the Track Soft Term (TST), a sum of the transverse momenta of all tracks not associated with a physics object. The soft tracks included in the TST are

required to meet the following requirements.

- The track passed **TightPrimary** standard track definition.
- The track has a moderately-low transverse impact parameter significance  $|\sigma_{d_0}| = |d_0/\text{err}(d_0)| \leq 1.5$ .
- The track is moderately close to the interaction point  $|z_0 \sin(\theta)| \leq 3.0 \text{ mm}$
- For a track isolated from other tracks, either
  - the sum of the transverse energy of calorimeter clusters within a  $\Delta R < 0.1$  of the track normalised by the track's transverse momentum  $E_T^{\text{clus10}}/p_T^{\text{track}} < 0.1$ , and the normalised uncertainty in charge-over-momentum  $|\sigma^{(q/p)}/q/p| < 0.1$ , or
  - $E_T^{\text{clus10}}/p_T^{\text{track}} > 0.65$  and  $|\sigma^{(q/p)}/q/p| < 0.4$ .
- For a track *not* isolated from other tracks, the sum of the transverse energy of calorimeter clusters within a  $\Delta R < 0.1$  of the track normalised by track's transverse momentum plus the sum of the transverse momentum of all tracks within  $\Delta R < 0.2$  of the track being considered,  $E_T^{\text{clus10}}/(p_T^{\text{track}} + p_T^{\text{cone20}}) > 0.6$ , or the track's transverse momentum over the track's transverse momentum plus the sum of the transverse momentum of all tracks within  $\Delta R < 0.2$  of the track being considered,  $p_T^{\text{track}}/(p_T^{\text{track}} + p_T^{\text{cone20}}) < 0.6$ .

Pixel tracklets are not included in the TST, to allow the  $E_T^{\text{miss}}$  to be dominated by the neutralino, and because of the poor transverse momentum resolution of pixel tracklets. An alternative soft term is the Calo Soft Term (CST), which is the sum of the transverse momenta of calorimeter clusters, but this is not routinely used as it is strongly dependent on pileup.

## 6.6 Overlap Removal

It is possible for multiple overlapping physics objects to be reconstructed from the same particle. For example, an electron can produce track, electron and jet objects. An overlap removal procedure is applied to reduce double-counted particles, which is vital for an accurate event reconstruction [1]. The overlap removal is performed in the following order:

- For an ID track shared by two electron objects, the lower- $p_T$  electron is removed.
- For an ID track shared by an electron object and a muon object, if the muon has calorimeter deposits associated with bremsstrahlung radiation the muon is removed, otherwise the electron is removed.
- Jets within  $\Delta R < 0.2$  of an electron are removed
- Electrons and muons within  $\Delta R < \min\left(0.4, 0.04 + \frac{10 \text{ GeV}}{p_T^\mu}\right)$  of a remaining jet are removed

- Muons either ghost-associated with or within  $\Delta R < 0.2$  of a jet with three or more tracks are removed.

## 6.7 Statistical Techniques

### 6.7.1 Monte-Carlo Approximations

Frequently, physical processes cannot be analytically modelled so statistical approaches must be used instead. Monte Carlo methods make use of random sampling to derive accurate approximations from carefully designed situations. A simple example is using a Monte Carlo approach to approximate the value of  $\pi$  by randomly choosing points on a plane. By defining the plane to extend over  $-1 < x < 1$  and  $-1 < y < 1$ , and overlaying a circle of radius 1 centered at the origin of the plan, the ratios of the area of the circle to the area of the square is equal to  $\pi/3$ :

$$\frac{A_{\text{circle}}}{A_{\text{square}}} = \frac{\frac{4}{3}\pi r^2}{4r^2} = \frac{\pi}{3} \quad (6.4)$$

A Monte Carlo approximation of  $\pi$  can then be found by randomly distributing points across the plane (for example, by throwing darts) and taking the number of points within the circle over the total number of points, and multiplying by 3. An example of this is shown in Figure 6.14.

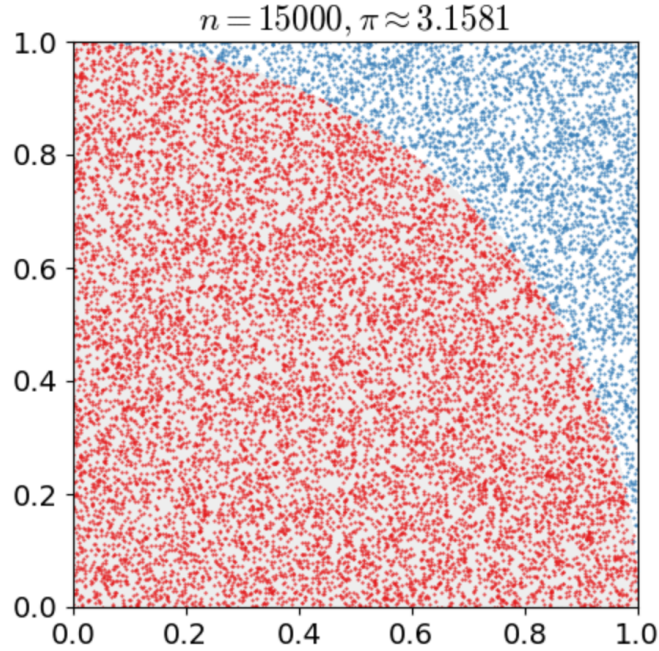


Figure 6.14: An example of using a Monte Carlo approach to approximate the value of  $\pi$  by comparing the number of randomly distributed points within the circle to the total number of points. [136].

It is essential to ensure that Monte Carlo generators are truly random and without bias, otherwise the result will not be accurate. In the above example, if this was performed by throwing darts at the plane, a source of bias would be introduced by the human tendency to aim at the center of the target, increasing the proportion of the points within the circle and increasing the observed value of  $\pi$ .

### 6.7.2 Likelihoods, Fits and $\text{CL}_s$

A Probability Distribution Function (PDF) represents the probability of a given measurement of a variable  $x$ . Integrating a PDF gives the probability for a measurement  $X$  to be within the range integrated over. A subset of PDFs (known as parametric PDFs) can be fully described with a finite set of parameters  $\theta$ . The shape of a PDF  $\mathcal{P}(x_i; \theta_i)$  is determined by the variables  $x_i$  and the parameters  $\theta_i$ , and can be determined by sequential estimation.

For an  $n$ -dimensional PDF  $\mathcal{P}(x_{1 \rightarrow n}; \theta_{1 \rightarrow k})$  with  $k$  parameters, the parameters  $\theta_{1 \rightarrow k}$  can be estimated with an *estimator*  $\hat{\theta}_{1 \rightarrow k}$ . A confidence interval can be assigned to the estimator,  $\mathcal{P}(\theta_a < \hat{\theta} < \theta_b) = \alpha$ . An estimator can be determined with the Maximum Likelihood Theorem (MLT), which requires the PDF to be formulated as the likelihood

$$\mathcal{L}(\theta_{1 \rightarrow n}; x) = \prod_{i=1}^N \mathcal{P}(x; \theta_{1 \rightarrow n}) \quad (6.5)$$

where  $N$  represents the region to be considered. Estimators are then assigned that maximise Equation 6.5, equivalent to maximising the probability of the parameters producing the observed data. Analytical solutions are rare, so an evaluation of the likelihood around the parameter space is more commonly performed to minimise the Negative-Log-Likelihood (NLL)  $(-\ln \mathcal{L})$  [137].

The estimators are assumed to be Gaussian, which allows a variance  $\hat{\sigma}_\theta$  to be calculated from the covariance of  $\mathcal{L}$  around the maximum. The covariance matrix  $\sum_{i,j}^{-1}$  is related to the NLL with

$$\begin{aligned} -2\Delta \ln \mathcal{L} &= -2 \left( \ln \mathcal{L}(\theta) - \ln \mathcal{L}(\hat{\theta}) \right) \\ &= \sum \left[ \theta_i - \hat{\theta}_i \right] \sum_{i,j}^{-1} \left[ \theta_i - \hat{\theta}_j \right] \end{aligned} \quad (6.6)$$

and relates the contours of the estimator variances  $\sigma_\theta$  to confidence intervals around the maximum. For a single parameter likelihood, the contours about  $\hat{\theta}$  in the region  $-2\Delta \ln \mathcal{L} < 1$  define a 68% confidence interval. The estimator can then be quoted as  $\hat{\theta} \pm \hat{\sigma}_\theta$ , although this includes statistical uncertainties only.

To consider systematic variations, the PDF must be re-parameterised. A Parameter of Interest (POI)  $\mu$  is defined along with other Nuisance Parameters (NPs) which represent systematic sources of uncertainty. NPs can be categorised as Type-I if they can be constrained by the dataset and otherwise Type-II. An example of a Type-I NP could be a background normalisation factor, whereas a Type-II NP could be a model assumption. Type-I NPs will improve by adding more data to the dataset whereas Type-II NP are independent. A Type-I NP can be assessed with a control sample  $y$  and a new likelihood profiled for a fixed  $\mu$ ,

$$\begin{aligned}\mathcal{L}(\mu, \theta) &= \mathcal{L}_\mu(\mu, \theta) \mathcal{L}_\theta(\theta) \mathcal{L}(x, y; \mu, \theta) \\ &= \mathcal{L}_\mu(x; \mu, \theta) \mathcal{L}_\theta(y; \theta)\end{aligned}\tag{6.7}$$

which can be maximised with respect to the NP for the fixed value of  $\mu$ . This can then be repeated for all NPs yielding a likelihood depending only on  $\mu$ . This is the Profile Likelihood Method (PLM).

In particle physics this is commonly performed with a histogram comprised of a signal and a background content. Considering such a histogram  $N$  with  $i$  bins, the expected content per bin can be defined as  $E[n_i] = \mu s_i + b_i$ , where  $\mu$  is a signal strength parameter between 0 and 1, and  $s_i$  and  $b_i$  are the probability of the signal and background content of the  $i^{\text{th}}$  bin, defined as

$$s_i = s_{\text{total}} \int_i f_s(x; \theta s) dx \tag{6.8}$$

$$b_i = b_{\text{total}} \int_i f_b(x; \theta b) dx \tag{6.9}$$

where  $f_s$  and  $f_b$  are the signal and background PDFs and  $s_{\text{total}}$  and  $b_{\text{total}}$  are the total number of signal and background events predicted from Monte Carlo. A likelihood function for this histogram can be found as the product of the Poisson probabilities for all bins,

$$\mathcal{L}(\mu, \theta) = \prod_{j=1}^N \frac{(\mu s_j + b_j)^{n_j}}{n_j!} \exp\{- (\mu s_j + b_j)\} \tag{6.10}$$

As before, to assess Type-I NPs the likelihood in Equation 6.10 can be modified to separate the POI from the NPs, and a control sample can be introduced. In this case, this takes the form of a histogram  $M$  with  $k$  bins which is (mostly) pure in the process related to the target uncertainty. The expected contents  $m_k$  of each bin of this histogram can be given by  $E[m_k] = u_k \theta$  where  $u_k$  is the PDF describing the control sample, parameterised by the set  $\theta$ . By using a new likelihood specifically for the NPs and profiling the likelihood for a each

parameter at a fixed  $\mu$ , the histogram  $M$  constrains the NPs. The Poisson probabilities

$$\prod_{k=1}^M \frac{u_k^{m_k}}{m_k!} \exp\{-u_k\} \quad (6.11)$$

from the NPs then contribute to Equation 6.10.

To make a statistically meaningful statement with the results of an analysis, a hypothesis and a test statistic  $q$  using the likelihoods above must be defined. The outcome of this test is a  $p$ -value representing the compatibility with the null (background-only) hypothesis. A frequentist approach using the  $\text{CL}_s$  method is typically used in particle physics to make statements on exclusion or observations. This derives confidence levels using the test statistic PDFs defined as

$$q = -2 \ln \frac{\mathcal{L}(s+b)}{\mathcal{L}(b)} \quad (6.12)$$

where a positive value of  $q$  can be interpreted as background-like, a negative value as signal-plus-background-like, and a value near zero as having insufficient statistical power to make a statement. The confidence levels calculated from the test statistic for the background-only hypothesis are labelled  $\text{CL}_b$ , the signal-plus-background hypothesis  $\text{CL}_{s+b}$  and an estimation of the confidence level for the signal-only hypothesis  $\text{CL}_s$  [138].

When calculating the  $\text{CL}_{s+b}$ , there is an edge case where if both the signal and background fluctuate down from the expected values a signal hypothesis can be erroneously excluded with high confidence. This can be avoided by using a modified  $\text{CL}_s$  defined as

$$\text{CL}_s(\mu) = \frac{p_\mu}{1 - p_b} = \frac{\text{CL}_{s+b}}{\text{CL}_b} \quad (6.13)$$

. Additionally, a profiled likelihood ratio is commonly used as the test statistic, defined as

$$\tilde{q}_\mu = \begin{cases} -2 \ln \frac{\mathcal{L}(\mu, \hat{\hat{\theta}}(\mu))}{\mathcal{L}(0, \hat{\hat{\theta}}(0))} & \hat{\mu} < 0 \\ -2 \ln \frac{\mathcal{L}(\mu, \hat{\hat{\theta}}(\mu))}{\mathcal{L}(\mu, \hat{\hat{\theta}})} & 0 \leq \hat{\mu} \leq \mu \\ q_0 = 0 & \hat{\mu} > \mu \end{cases} \quad (6.14)$$

which tends towards a  $\chi^2$  distribution with one degree of freedom. In Equation 6.14  $\hat{\hat{\theta}}$  represents the fitted values of the NPs at a fixed value of  $\mu$ , the POI (signal strength) which is in this case defined as the ratio of the observed cross-section over the expected (background-only) cross-section.  $\hat{\mu}$  and  $\hat{\theta}$  are fitted with free-floating NPs and  $\mu$ . The numerator of Equation 6.14 ( $\mathcal{L}(\mu, \hat{\hat{\theta}}(\mu))$ ) is a conditional maximum-likelihood estimator of  $\theta$  maximised by  $\hat{\hat{\theta}}$  for a fixed

$\mu$ , and the denominator is the unconditional function where  $\hat{\mu}$  and  $\hat{\theta}$  are the estimators.

Using the test statistic  $p$ -values can be assigned to the hypotheses. For the null (background-only) hypothesis the  $p$ -value is found by

$$1 - p_b = \int_{q_0^{\text{obs}}}^{\text{inf}} f\left(\tilde{q}_\mu | 0, \theta_0^{\text{obs}}\right) d\tilde{q}_\mu \quad (6.15)$$

, whereas for the alternative (signal-plus-background) hypothesis the  $p$ -value is found by

$$p_\mu = \int_{q_\mu^{\text{obs}}}^{\text{inf}} f\left(\tilde{q}_\mu | \mu, \theta_\mu^{\text{obs}}\right) d\tilde{q}_\mu \quad (6.16)$$

. In Equations 6.15 6.16,  $\theta^{\text{obs}}$  are the fitted NPs and  $f$  are the sampling functions. Calculating the expected significance for a hypothesis requires the use of computationally-expensive Monte Carlo simulations. The complexity of this can be reduced by using an asymptotic formula. This requires the use of an artificial *Asimov* dataset, defined such that the estimators produced match the true values.

### 6.7.3 Multi-Variate Analysis & Machine Learning

Machine Learning (ML), and more widely Multi-Variate Analysis (MVA), are a set of statistical techniques that allow a program to identify features in a dataset rather than relying on human intuition. In particle physics they are commonly used to classify data and separate signal from background with greater significance than traditional cuts. Two of the most commonly-used techniques in particle physics are BDTs and Neural Networks (NNs), which are described below. Throughout this thesis any work using these techniques is performed within the TMVA package within ROOT [139].

#### 6.7.3.1 Boosted Decision Trees

Decision trees are a series of sequential cuts used to categorise an input (such as an event or a tracklet) into two or more categories. Individually a decision tree will be a poor classifier, but many trees can be trained in parallel to create a *forest*, which can extract small features of the dataset.

A BDT is trained using a labelled dataset (such as signal and background datasets generated using Monte Carlo) where the individual items have already been categorised. Any number of variables can be chosen by the user to be used in the classifier. The BDT algorithm begins by randomly choosing cuts on a subset of these variables, and constructing these into a tree.

The effectiveness of a particular cut is commonly determined using the Gini index, defined as

$$G = p(1 - p), \quad p = \frac{S}{S + B} \quad (6.17)$$

where  $p$  is the purity of the sample resulting from the cut for the desired classification, defined as the number of signal items  $S$  over the total number of items  $S + B$ . Multiple cuts are added to the tree until either the result is pure in a given classification, less than a certain fraction of the initial events remain after a cut, or the maximum number of successive cuts (*tree depth*) is reached. A *response*  $R_T$  for an input to a given tree  $T$  can then be defined as +1 if classified as signal, and -1 if classified as background, or in the case of multiple classifications +1 if classified as that outcome and 0 if not. An overall response for a forest can subsequently be defined as  $R = \frac{1}{N_T} \sum_{i=1}^{N_T} R_i$ .

A single tree will typically perform poorly, frequently misclassifying inputs. This is performed by using a boosting algorithm, which up-weights inputs that are frequently misclassified and retrain them. One of the most commonly used boosting algorithms is ADABOOST. ADABOOST first defines a *error rate*,

$$E_T = \frac{\sum_{i=1}^{\text{misclassified}} w_i}{\sum_{j=1}^{\text{all}} w_j} \quad (6.18)$$

where  $E_T$  is the error rate of a given tree  $T$ , and  $w_i$  is the weight applied to the  $i^{\text{th}}$  item in the input dataset. When fewer events are misclassified the error rate will be smaller. ADABOOST then defines a *boosting rate*,

$$\alpha_T = \frac{1 - E_T}{E_T} \quad (6.19)$$

and uses this and a user-defined *learning rate*  $\beta$  to iteratively calculate weights for every input in the dataset using

$$w_i^{t+1} = w_i^t \alpha_i^\beta \quad (6.20)$$

.  $\alpha^\beta$  must be greater than or equal to one to ensure that weights are increased for misclassified inputs. Otherwise, the value of  $\beta$  can be chosen by the user to dictate the learning process – a higher value of  $\beta$  causes larger increases or decreases of a weight in each iteration, which can lead to faster training at the cost of instability. To then use the weights in the BDT training the definition of purity used in Equation 6.17 is modified to

$$p = \frac{\sum_{i=1}^S w_i}{\sum_{j=1}^{S+B} w_j} \quad (6.21)$$



, where  $S$  and  $B$  are the number of Signal and Background events respectively. Finally, the response is modified to account for the weights, reducing the impact of trees that frequently misclassify weights:

$$R = \frac{1}{N_T} \sum_{i=1}^{N_T} R_i \ln \alpha_i \quad (6.22)$$

BDTs are typically easy and quick to train, and deliver good performance compared to other techniques, although some others will outperform BDT when well optimised. BDTs are also *white-box* algorithms, where the inner workings of the algorithm can be observed, such as individual trees or the performance and relative contribution each input variable.



## Part III

# Searches for Disappearing Tracks

## Chapter 7

# Search for pixel tracklets with 4 hits

The analysis presented in this chapter searches for pixel tracklets with four pixel hits only, and a disappearing signature in association with an Initial-State Radiation (ISR) jet. This improved on a previous search for the same signature at ATLAS by using the full Run-2 dataset ( $136.3 \text{ fb}^{-1}$  instead of the previous  $36.1 \text{ fb}^{-1}$ ), and introducing a calorimeter isolation requirement for pixel tracklets, significantly suppressing the scattered standard model particle background. Two theoretical models were used as the target of this analysis, a minimal AMSB model generating pure-wino charginos, and a simplified SUSY model generating pure-higgsino charginos. Two production modes were explored for the pure-wino AMSB model, an electroweak production (shown in Figure 7.1(a)) and a strong production (shown in Figure 7.1(b)), each with dedicated signal regions. The analysis is also applicable to a wide range of SUSY and Dark Matter (DM) models, specifically those providing a WIMP candidate. To aid the future probing of these models by third parties, multiple methods of reinterpreting this search were also developed, building on techniques provided for the previous disappearing track search.

This chapter begins with a discussion in Section 7.1 of the detector signature that was searched for in this analysis, and the associated experimental backgrounds to this signature, which is original work. This is followed in Sections 7.2 through 7.5 by a partial reproduction of the paper in which this analysis was published, where the event selection, background estimation, systematic uncertainty estimation and results are discussed. As discussed in the Introduction to this thesis, there was limited involvement in this analysis by the author due to joining the analysis when it was at a mature stage, so only minor edits have been made to the reproduced content of the paper to fit the context and flow of this thesis. The author was a contributor to this analysis, performing selection efficiency comparisons and general debugging, as well as producing and validating the reinterpretation material discussed in the following Chapter (8).

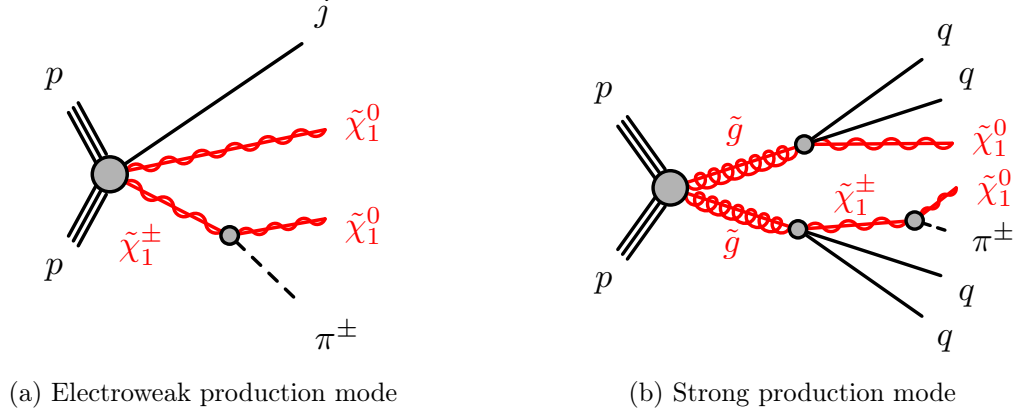


Figure 7.1: Feynman diagrams for the production of charginos and neutralinos from the AMSB model.

## 7.1 Detector Signature and Backgrounds

As discussed in Section 3.1.2, the charginos that are the target of this analysis gain their long lifetimes from the small decay phase space they have due to a small difference between their mass and that of their decay product. For the pure-wino AMSB model, the inverse decay time is expressed by the formula for the decay width for the  $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$  process,

$$\frac{1}{\tau} \approx \Gamma \left( \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm \right) = \frac{2G_F^2}{\pi} \cos^2(\theta_c) f_{pi}^2 \Delta m \left( \tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right)^3 \sqrt{1 - \frac{m(\pi^\pm)^2}{\Delta m \left( \tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right)^2}} \quad (7.1)$$

which shows how the decay width depends on the difference in mass between the lightest chargino and neutralino they decay into (*chargino-neutralino mass splitting*,  $\Delta m \left( \tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \right)$ ), as well as the Fermi constant ( $G_F$ ), the Cabibbo angle ( $\theta_c$ ), the pion decay constant ( $f_{pi} \approx 130$  MeV) and the charged pion mass ( $m(\pi^\pm) = 139.6$  MeV).

Calculations of the chargino-neutralino mass splitting for the pure-wino AMSB model were made in [35] at the two-loop level, shown in Figure 7.2, and when used with Equation 7.1 allow the chargino lifetime as a function of chargino mass to be calculated, shown in Figure 7.3.

As shown in Figure 7.3, in most situations the chargino decay distance ( $c\tau$ ) is approximately five to six centimetres, which is equivalent to a lifetime of around 0.2 ns. This analysis requires the track to have four pixel hits, and the fourth pixel layer is located at a radius of 12.25 cm, requiring the chargino to be significantly boosted. This boost is provided by an ISR jet in the event.

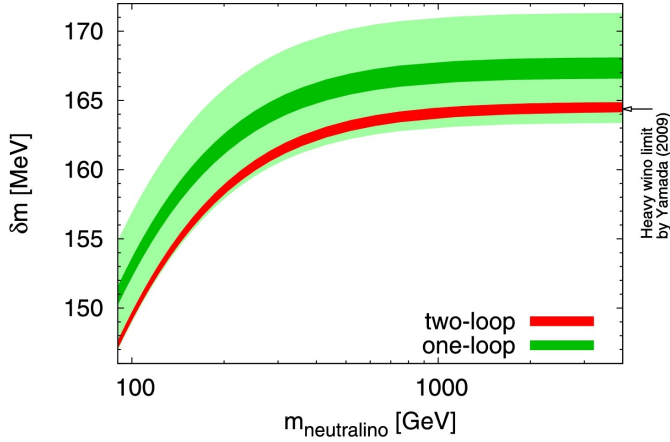


Figure 7.2: The difference in mass between the chargino and neutralino (*mass splitting*,  $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ ) in the pure-wino model as a function of the neutralino mass, as found in [35].

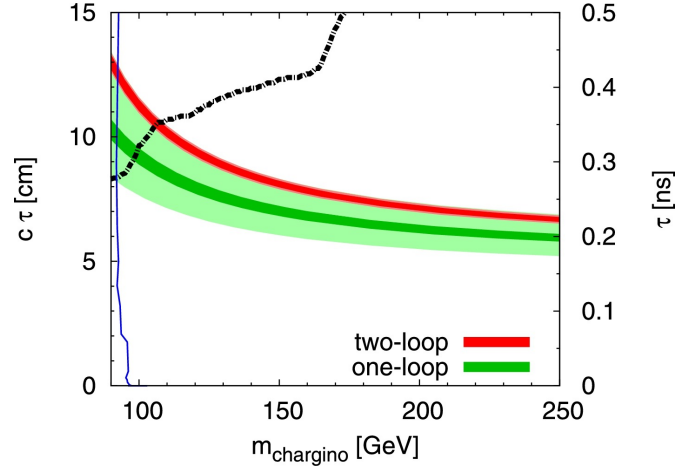


Figure 7.3: The chargino lifetime in the pure-wino model as a function of the chargino mass, as found in [35].

A similar situation exists for the pure-higgsino model, but with larger mass splittings and correspondingly-shorter chargino lifetimes. Depending on the chargino mass, the chargino-neutralino mass splitting is 280 to 360 MeV, leading to proper lifetimes from 0.048 to 0.026 ns, equivalent to travelling 7 to 14 mm. This, along with cross-sections approximately  $1/4$  that of the pure-wino AMSB case, makes the pure-higgsino case extremely challenging to search for.

After decaying between the fourth pixel layer and the SCT, the chargino decays to a neutralino and a pion. Due to the small chargino mass splitting shown in Figure 7.2, there is only enough excess energy for a very low momentum pion, which cannot be reconstructed in the ATLAS detector. As the neutralino is of course invisible to the ATLAS detector, the resulting signature is a short track leading to nothing but missing transverse momentum (as defined in Section 6.5) – this is known as the *disappearing track* signature, shown in Figure 7.4 in the red tracklet.

Whilst there are no Standard Model processes that result in a disappearing track signature, there are a number of experimental backgrounds which are also shown in Figure 7.4. The dominant background is the *combinatorial fake* background, which is shown in Figure 7.4 in orange, counter-clockwise from the red signal tracklet. The inner detector is a very high radiation environment, with a large number of very low-momentum particles from both the  $pp$  interaction at the PV, and from the neighbouring  $pp$  interactions. Random, unrelated combinations of these particles can score groups of pixel hits that can, by chance, be reconstructed as a track pointing towards the PV. This is known as a *fake track*, as it does not correspond to any individual real particle. In general, this background can be reduced by requiring that

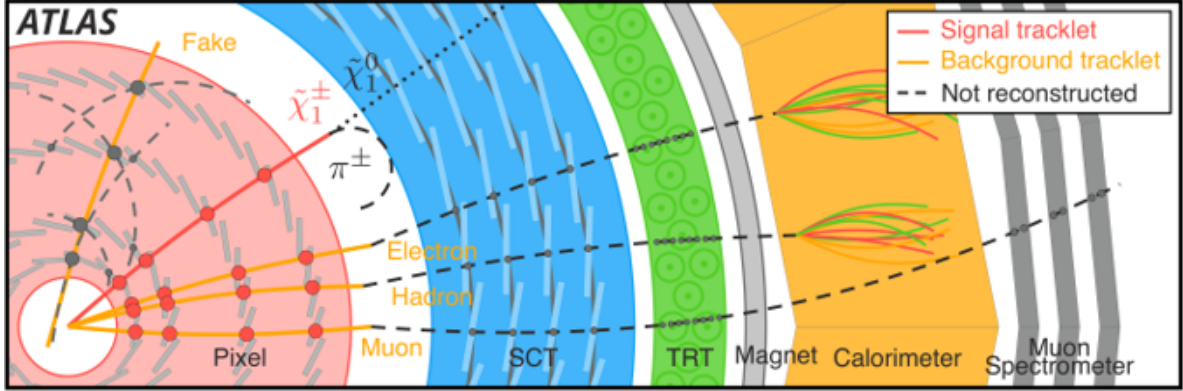


Figure 7.4: The detector signature of the disappearing tracklet signal and backgrounds. Shown on a logarithmic scale is a slice of the ATLAS detector in the transverse plane. Shown in red is the disappearing track signal tracklet caused by a chargino, scoring four pixel hits before decaying to a low momentum pion and an undetectable neutralino. Counter-clockwise from the signal track in orange is the fake combinatorial background, and clockwise from the signal tracklet in orange are the scattered background tracklets. Reproduced from [1].

the track is well-fitted, and has small impact parameters to the PV<sup>1</sup>.

The other class of backgrounds to the disappearing track signature are scattered Standard Model particles, which are shown in Figure 7.4 in orange, clockwise from the red signal tracklet. These are where common Standard Model particles, such as muons or pions, pass through the pixel layers as normal, before scattering off of some object, such as sensitive material, support structures or simply air. The particle after the scatter is then not reconstructed, so the only track is a well-fitted tracklet. The majority of these scattered particles are hadrons, primarily pions and some kaons. This is due to their abundance in the detector, and the lepton veto applied in the signal region selection. There is also a sub-dominant background from scattered muons and leptons. These scattered tracks are generally well-fitted like a signal chargino tracklet would be. However, the scattered particle will often leave a signature elsewhere the detector, such as forming a jet for hadrons, leaving calorimeter cell deposits for electrons and hadrons, or forming a track in the muon spectrometer for muons. The background can therefore be reduced by requiring that the candidate tracklet is well-separated from reconstructed physics objects, that the sum of the energy of the calorimeter clusters near the track is low, and that there are no reconstructed leptons in the event.

<sup>1</sup>The impact parameters are defined as separation between the point of closest approach to the PV, and the PV, both along and tangential to the beam line. See Section 6.1 for more information

## 7.2 Triggers and Signal region selection

Signal events for this analysis are characterised by a distinctive signature composed of a disappearing track and large missing transverse momentum. The disappearing-track criteria are implemented by vetoing pixel tracklets with any SCT hits or significant calorimeter energy along their trajectory as described in the previous section. Signal regions are designed to target the electroweak and strong production models shown separately in Figure 7.1.

A common preselection is applied to all events selected for the signal regions. Events are required to contain at least one high-momentum jet with  $p_T > 100 \text{ GeV}$  and satisfy the  $E_T^{\text{miss}}$  trigger requirements described in Section 5.1.1. In events containing multiple pixel tracklets satisfying all of the quality criteria described in Section 6, the tracklet with the highest transverse momentum is chosen. In order to reduce contributions from backgrounds such as top-pair and  $W/Z + \text{jets}$  production, events are vetoed if they contain any electron or muon candidates.

In this analysis, the  $E_T^{\text{miss}}$  trigger efficiency is measured in data and used instead of the efficiency of the simulated trigger. In order to evaluate the  $E_T^{\text{miss}}$  trigger efficiency for signal-like events, a control sample consisting of data events with exactly one muon, with  $p_T > 27 \text{ GeV}$ , matched to the single-muon trigger is used. Muon candidates are not included as visible objects in the hardware-based L1  $E_T^{\text{miss}}$  trigger, so  $W \rightarrow \mu\nu$  events, which have a signature similar to that of signal events, can be used to assess the trigger performance. In order to select events consistent with a  $W \rightarrow \mu\nu$  decay, events are required to have  $30 \text{ GeV} < m_T < 100 \text{ GeV}$ , where  $m_T$  is the transverse mass defined by

$$m_T = \sqrt{2p_T^\mu E_T^{\text{miss}} [1 - \cos \Delta\phi(\mu, E_T^{\text{miss}})]}. \quad (7.2)$$

The  $E_T^{\text{miss}}$  trigger efficiency is calculated by dividing the number of these events passing the  $E_T^{\text{miss}}$  trigger by the total number of these events. The efficiencies depend on the trigger thresholds used during a given data-taking period, and all plateau at  $E_T^{\text{miss}}$  values above  $200 \text{ GeV}$ . In the signal regions, where the  $E_T^{\text{miss}}$  requirements are greater than  $200 \text{ GeV}$  or  $250 \text{ GeV}$  as described below, the trigger efficiency is nearly 100%. The efficiencies are determined in bins of  $E_T^{\text{miss}}$  with widths of  $10 \text{ GeV}$ .

In order to factor out efficiency differences between data and simulation, all simulated-signal predictions use the efficiencies measured in data. For selections with  $E_T^{\text{miss}}$  below  $200 \text{ GeV}$ , such as those for the control and validation regions described in Section 7.3.1, the event selection efficiency is significantly impacted by the trigger efficiency turn-on. The efficiency differences between data and simulation do not affect the background estimations because the efficiencies are based on data satisfying the same  $E_T^{\text{miss}}$  trigger requirements, and the contamination of



the control regions by signal events is expected to be small.

Signal regions are designed for the electroweak and strong production modes. For the signal regions targeting the electroweak (strong) production mode, the offline missing transverse momentum is required to be greater than 200 GeV (250 GeV). The two signal regions are not orthogonal. The higher  $E_T^{\text{miss}}$  requirement is found to be optimal for the strong production channel, due to the large Lorentz boost of the neutralinos produced in the decay of a heavy gluino. Additionally, the strong production signal region requires at least three jets with  $p_T > 20$  GeV. In order to reduce contributions from processes for which fake instrumental  $E_T^{\text{miss}}$  can be produced by jet mismeasurements, the azimuthal angle  $\Delta\phi_{\min}^{\text{jet}-E_T^{\text{miss}}}$ , defined as the smallest of the  $\phi$  direction differences between the missing transverse momentum and each of the four highest- $p_T$  jets with  $p_T > 50$  GeV, is required to be greater than 1.0 (0.4) for the electroweak (strong) production signal regions. The signal region selection criteria are summarised in Table 7.1.

The transverse momentum distribution of the selected pixel tracklets is fitted to estimate the backgrounds and sensitivity to the signals. Since the signal is characterised by a high-momentum chargino, the majority of the signal events contain a high- $p_T$  pixel tracklet. For the model-independent interpretation of the results, the pixel tracklet is required to have  $p_T > 60$  GeV as shown in Section 7.5.

| Signal region                                                                                      | Electroweak production | Strong production |
|----------------------------------------------------------------------------------------------------|------------------------|-------------------|
| Number of electrons and muons                                                                      | 0                      |                   |
| Number of pixel tracklets                                                                          | $\geq 1$               |                   |
| $E_T^{\text{miss}}$ [GeV]                                                                          | $> 200$                | $> 250$           |
| Number of jets ( $p_T > 20$ GeV)                                                                   | $\geq 1$               | $\geq 3$          |
| Leading jet $p_T$ [GeV]                                                                            | $> 100$                | $> 100$           |
| Second and third jet $p_T$ [GeV]                                                                   | –                      | $> 20$            |
| $\Delta\phi_{\min}^{\text{jet}-E_T^{\text{miss}}}$ (up to 4 <sup>th</sup> jet with $p_T > 50$ GeV) | $> 1.0$                | $> 0.4$           |

Table 7.1: Signal region selection for electroweak and strong production channels. Entries with ‘–’ indicate that no requirement is placed on the variable.

Table 7.2 shows the expected number of signal events, normalised to  $136 \text{ fb}^{-1}$ , satisfying the selections of the electroweak and strong production channels. The electroweak and strong production signals assume  $m_{\tilde{\chi}_1} = 600$  GeV and  $(m_{\tilde{g}}, m_{\tilde{\chi}_1}) = (1.4, 1.1)$  TeV respectively. Unless otherwise indicated, the wino LSP model is assumed for the benchmark signal points. The dominant inefficiency in the pixel tracklet selection arises from the requirement that the track-

let can be reconstructed, and thus has propagated at least to the fourth pixel layer at a radius of 122.5 mm. Such a requirement implies that charginos have a significant Lorentz boost. The overall acceptance and efficiency for those benchmark signal points in the case of a chargino lifetime of 0.2 ns are 0.74% (1.5%) and 40% (37%), respectively, for the electroweak (strong) production channel. The acceptance is calculated by counting the number of events passing the event selection in Table 7.1 at generator level. Additionally, at least one chargino is required to have a decay radius after the fourth pixel layer ( $r > 122.5$  mm) and before the first SCT layer or end-cap ( $r < 299$  mm,  $|z| < 934$  mm), transverse momentum greater than 60 GeV, its pseudorapidity  $0.1 < |\eta| < 1.9$ , and an angular separation of  $\Delta R > 0.5$  for the four highest  $p_T$  jets with transverse momentum greater than 50 GeV. The efficiency term accounts for any additional effects at reconstructed level, including the trigger and pixel tracklet reconstruction inefficiencies.

| Signal production channel<br>$\tau_{\tilde{\chi}_1}$           | Electroweak production |                 | Strong production |                 |
|----------------------------------------------------------------|------------------------|-----------------|-------------------|-----------------|
|                                                                | 0.2 ns                 | 1.0 ns          | 0.2 ns            | 1.0 ns          |
| $E_T^{\text{miss}}$ trigger                                    | $770.8 \pm 6.8$        | $775.3 \pm 5.2$ | $3177 \pm 22$     | $3177 \pm 22$   |
| Lepton veto                                                    | $769.4 \pm 6.8$        | $774.2 \pm 5.2$ | $3165 \pm 22$     | $3165 \pm 22$   |
| $E_T^{\text{miss}} > 200$ GeV                                  | $394.5 \pm 5.2$        | $390.9 \pm 4.0$ | –                 | –               |
| $E_T^{\text{miss}} > 250$ GeV                                  | –                      | –               | $1852 \pm 17$     | $1852 \pm 17$   |
| Leading jet $p_T > 100$ GeV                                    | $389.7 \pm 5.2$        | $384.9 \pm 4.0$ | $1848 \pm 17$     | $1848 \pm 17$   |
| Third jet $p_T > 20$ GeV                                       | –                      | –               | $1834 \pm 17$     | $1834 \pm 17$   |
| $\Delta\phi_{\text{min}}^{\text{jet}-E_T^{\text{miss}}} > 1.0$ | $366.7 \pm 5.0$        | $362.3 \pm 3.9$ | –                 | –               |
| $\Delta\phi_{\text{min}}^{\text{jet}-E_T^{\text{miss}}} > 0.4$ | –                      | –               | $1578 \pm 16$     | $1578 \pm 16$   |
| Pixel tracklet selection ( $p_T > 60$ GeV)                     | $8.6 \pm 0.6$          | $27.3 \pm 0.8$  | $16.0 \pm 1.3$    | $105.0 \pm 3.3$ |

Table 7.2: Expected number of signal events after each of the selection requirements listed in Section 7.2 for the electroweak and strong production channels as well as for two different chargino lifetimes. Signal predictions are normalised to an integrated luminosity of  $136 \text{ fb}^{-1}$ . Errors are statistical only.

### 7.3 Background estimation

Backgrounds arise from several sources and can be classified into two categories: *charged-particle scattering* and *combinatorial fake* backgrounds. All backgrounds are estimated in a fully data-driven manner using an unbinned likelihood fit of background templates to the pixel tracklet  $p_T$  spectrum as described in Section 7.3.5. Background templates are derived from data for the charged-particle scattering and combinatorial fake backgrounds as described in Section 7.3.3 and 7.3.4, respectively. The likelihood fit is then performed simultaneously in background enriched Control Region (CR) and the signal region. Additional fits are performed with the validation regions in place of the signal region for the purpose of validating the background modelling. A schematic representation of the various background processes contributing to this analysis, as well as the expected signal signature, is shown in Figure 7.4.

The charged-particle scattering background arises primarily from events in which a lepton changes its direction after traversing the inner pixel layers, through interaction with the material or bremsstrahlung, so that its reconstructed track does not have any associated hits in the SCT and TRT detectors. The dominant underlying processes contributing to the scattering backgrounds are  $W \rightarrow \ell \nu$  and  $t\bar{t}$  production. Contributions from electrons, muons and charged hadrons are estimated separately. The latter includes all physics processes that generate a hadronic final state, such as jets originating from the hadronisation of quarks and gluons. Transfer factors, defined in Section 7.3.3, are measured in  $Z \rightarrow \ell\ell$  events and applied to the electron, muon and hadron CRs in order to estimate the relative compositions of the templates for the charged-particle scattering backgrounds. In the CR, a lepton or inner-detector track is used as a proxy for the pixel tracklet, and its momentum is smeared to match the pixel tracklet's transverse momentum as described in Section 7.3.2.

Combinatorial fake backgrounds arise from random combinations of unassociated pixel hits that are in close proximity and reconstructed into a pixel tracklet. The shape of the combinatorial fake background is estimated using the fake-enriched high- $|d_0|$  CRs described in Section 7.3.1. The relative contributions of the charged-particle scattering and combinational fake backgrounds are constrained in a combined fit as described in Section 7.3.5.

#### 7.3.1 Control and validation regions

In order to estimate scattering backgrounds, low- $E_T^{\text{miss}}$ , middle- $E_T^{\text{miss}}$ , and high- $E_T^{\text{miss}}$  CRs are defined. Events selected for the CRs must satisfy the  $E_T^{\text{miss}}$  trigger requirements detailed earlier in Section 7.2 and pass all kinematic selections of the signal regions except the pixel tracklet requirement. The pixel tracklet selection is replaced with a well-identified electron, muon or inner-detector track, in order to estimate contributions from electron, muon or hadron scattering backgrounds, respectively. The leading electron or muon is excluded from the cal-

culation of the missing transverse momentum, in order to reproduce the treatment of the pixel tracklets when calculating the offline  $E_T^{\text{miss}}$ . Energy deposited by electrons in the calorimeters may be included in the  $E_T^{\text{miss}}$  calculation via other objects in the event, but is treated in a similar manner for events with pixel tracklets or when electrons are excluded from the offline  $E_T^{\text{miss}}$  calculation. The low- and middle- $E_T^{\text{miss}}$  requirements are  $100 \text{ GeV} < E_T^{\text{miss}} < 150 \text{ GeV}$  and  $150 \text{ GeV} < E_T^{\text{miss}} < 200 \text{ GeV}$ , respectively. The high- $E_T^{\text{miss}}$  requirements are the same as for the signal region for which the backgrounds are being estimated:  $E_T^{\text{miss}} > 200 \text{ GeV}$  and  $E_T^{\text{miss}} > 250 \text{ GeV}$  for the electroweak and strong production signal regions, respectively. Events in the CRs are used to calculate the number of pixel tracklets from scattering processes as described in Section 7.3.3.

A high-purity control sample of fake pixel tracklets is obtained by applying the same kinematic selection requirements as in the signal regions, but with an inverted requirement of  $|d_0/\sigma(d_0)| > 10$  on the transverse impact parameter. Events selected for the fake-tracklet CR must satisfy the  $E_T^{\text{miss}}$  trigger requirements, but to increase the sample size no offline  $E_T^{\text{miss}}$  selection is applied. Events in the fake-tracklet CR are used to estimate the tracklet  $p_T$  shape and number of fake pixel tracklets in the signal regions as described in Section 7.3.4.

A low- $E_T^{\text{miss}}$  pixel-tracklet CR is used in the simultaneous fit described in Section 7.3.5. This CR has the same selection as the signal region, except for the  $E_T^{\text{miss}}$  requirement to enrich in background contributions. Validation Regions (VRs) defined in the context of the middle- $E_T^{\text{miss}}$  selection are used to validate the background model constructed for the fit. A low- $p_T$  pixel tracklet selection is used to validate the background predictions. In the low- $p_T$  VR, the pixel tracklet is required to have  $p_T < 60 \text{ GeV}$  in order to reduce the contamination from signal at high transverse momentum. In order to validate the fit results across the entire  $p_T$  spectrum in a region with low signal contamination, a middle- $E_T^{\text{miss}}$  calorimeter-based sideband validation region is used. The calorimeter sideband selection requires the pixel tracklet to have  $5 \text{ GeV} < E_T^{\text{topo cluster}} < 10 \text{ GeV}$ . The number of signal events in the control and validation regions is less than one quarter of the estimated background uncertainty.

A summary of the control and validation regions is shown in Table 7.3.

### 7.3.2 Smearing functions

The transverse momentum resolution of a track scales as  $\Delta p_T/p_T \propto 1/L_T^2$ , where  $L_T$  is the transverse length of the track. Since pixel tracklets have only pixel hits, they are significantly shorter than tracks with a full set of pixel, SCT and TRT hits, and thus the transverse momentum resolution of the pixel tracklets is significantly worse than that of full-length tracks. Therefore, the tracks in the CRs need to be smeared to match the pixel tracklet momentum resolution. Additionally, the tracklet  $q/p_T$  resolution that is measured using observed data

| Region                                                                                                                                     | $E_T^{\text{miss}}$ condition         | Track condition                                                                  |
|--------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------|----------------------------------------------------------------------------------|
| <b>Control regions</b>                                                                                                                     |                                       |                                                                                  |
| Electron                                                                                                                                   | $e$ -subtracted $E_T^{\text{miss}}$   | well-identified electron                                                         |
| Muon                                                                                                                                       | $\mu$ -subtracted $E_T^{\text{miss}}$ | well-identified muon                                                             |
| Hadron                                                                                                                                     | standard $E_T^{\text{miss}}$          | inner-detector track                                                             |
| Fake-tracklet                                                                                                                              | standard $E_T^{\text{miss}}$          | pixel tracklet with $ d_0/\sigma_{d_0}  > 10$                                    |
| <b>Low-<math>E_T^{\text{miss}}</math> control region (<math>100 \text{ GeV} &lt; E_T^{\text{miss}} &lt; 150 \text{ GeV}</math>)</b>        |                                       |                                                                                  |
| Low- $E_T^{\text{miss}}$                                                                                                                   | standard $E_T^{\text{miss}}$          | pixel tracklet                                                                   |
| <b>Middle-<math>E_T^{\text{miss}}</math> validation regions (<math>150 \text{ GeV} &lt; E_T^{\text{miss}} &lt; 200 \text{ GeV}</math>)</b> |                                       |                                                                                  |
| Low- $p_T$                                                                                                                                 | standard $E_T^{\text{miss}}$          | pixel tracklet with $p_T < 60 \text{ GeV}$                                       |
| Calorimeter sideband                                                                                                                       | standard $E_T^{\text{miss}}$          | pixel tracklet with $5 \text{ GeV} < E_T^{\text{topo cluster}} < 10 \text{ GeV}$ |

Table 7.3: Definitions of control and validation regions. The track condition corresponds to the modified selection on the pixel tracklet, or tracks used as a proxy for the pixel tracklet to estimate background processes. The table shows the treatment of the  $E_T^{\text{miss}}$  for the estimation of the scattering backgrounds. The electron, muon and hadron control regions are defined for each of the low-, middle- and high- $E_T^{\text{miss}}$  selections as described in the text.

samples is worse than that predicted by simulation, and measurements in data are used to correct those from simulation.

The  $q/p_T$  resolution has a strong dependence on the momentum of the track: at low momentum, multiple scattering effects are dominant, while at higher momentum the alignment of the detector can affect the resolution. Since a fit is applied to the shape of the pixel tracklet  $p_T$  spectrum, it is important to have a good description of the different components of the spectrum. The measured tracklet resolution in data is used to correct the shapes of the track  $p_T$  templates in the CRs, and additionally to correct the expected  $q/p_T$  resolution of the simulated-signal predictions to match the data.

Smearing functions are derived using  $Z \rightarrow \mu\mu$  and  $Z \rightarrow ee$  events. Events are required to satisfy the data quality criteria described in Section 5.1, and contain two opposite-sign, same-flavour leptons with an invariant mass between 81 GeV and 101 GeV. The transverse momenta of the leading and sub-leading leptons are required to be greater 25 GeV to satisfy the single lepton trigger requirements. A specialised track reconstruction configuration is then used to re-fit the leptons using pixel hits only, and the re-fitted leptons are used to derive a  $q/p_T$

smearing function with respect to the lepton four-momentum.

The  $\Delta(q/p_T)$  distribution is fitted using the **ExpGaussExp** function [140]:

$$f(z; \sigma, \alpha) = \begin{cases} \exp(\alpha(z + \alpha/2)) & (z < -\alpha) \\ \exp(-z^2/2) & (-\alpha < z < \alpha), \\ \exp(-\alpha(z - \alpha/2)) & (z > \alpha) \end{cases}, \quad (7.3)$$

$$z = \frac{\Delta(q/p_T) - \beta}{\sigma}, \quad (7.4)$$

where  $\alpha$  is a parameter that reflects the slope of the tail, and  $\beta$  and  $\sigma$  are parameters that control the mean and resolution, respectively, of the core of the distribution. The parameter  $\sigma$  has a significant  $p_T$  dependence, and parameters are measured in data for  $p_T > 25$  GeV using data collected with single lepton triggers. Below this threshold, the smearing functions are estimated using detector simulation for tracks with transverse momentum down to  $p_T = 10$  GeV. The parameters derived above  $p_T > 25$  GeV agree well between data and detector simulation up to a constant overall difference of approximately 10% across all track momenta. This difference is used to correct the parameters derived with the detector simulation for tracks with  $10 \text{ GeV} < p_T < 25 \text{ GeV}$ . The uncertainties on the  $\sigma$  and  $\alpha$  terms are 8.2% and 9.4% for muons and 8.4% and 11.5% for electrons, respectively. These uncertainties include statistical errors added together in quadrature with the maximum deviation of the smearing parameters across different data taking conditions. The  $p_T$ -dependent smearing function parameters derived for electrons and muons are shown in Table 7.4 along with their uncertainties. These values are used for the full data set.

### 7.3.3 Charged-particle background templates

Backgrounds arising from charged particles are estimated using a fully data-driven method. Transfer factors are derived using a  $Z \rightarrow \ell\ell$  tag-and-probe method. In this method, a good-quality tag electron or muon with  $p_T > 30$  GeV that is matched to any of the single-lepton triggers described in Section 5.1.1 is selected for analysis. Probe leptons are identified using clusters reconstructed from energy deposits in the calorimeters, a muon track reconstructed only in the muon spectrometer, or a high-quality inner-detector track, depending on the measurement as described below. Transfer factors are defined so as to represent the probability that a lepton is misidentified as a pixel tracklet and fulfils the full set of pixel tracklet selection criteria. They are used to scale the number of events in the electron or muon CRs defined in Table 7.3 to obtain an estimate of the number of events from charged-particle scattering in the signal regions.

All probe leptons are required to have  $p_T > 10$  GeV and  $|\eta| < 2.5$ . In order to select events

| Transverse momentum [GeV] | Muon                          |               | Electron                      |               |
|---------------------------|-------------------------------|---------------|-------------------------------|---------------|
|                           | $\sigma$ [TeV <sup>-1</sup> ] | $\alpha$      | $\sigma$ [TeV <sup>-1</sup> ] | $\alpha$      |
| $10 < p_T < 15$           | $17.0 \pm 1.4$                | $1.7 \pm 0.1$ | $20.9 \pm 1.8$                | $1.9 \pm 0.2$ |
| $15 < p_T < 20$           | $15.5 \pm 1.3$                | $1.7 \pm 0.1$ | $19.5 \pm 1.6$                | $1.9 \pm 0.2$ |
| $20 < p_T < 25$           | $14.9 \pm 1.2$                | $1.7 \pm 0.1$ | $18.3 \pm 1.5$                | $1.9 \pm 0.2$ |
| $25 < p_T < 35$           | $14.8 \pm 1.2$                | $1.7 \pm 0.1$ | $17.0 \pm 1.4$                | $1.9 \pm 0.2$ |
| $35 < p_T < 45$           | $14.2 \pm 1.2$                | $1.7 \pm 0.1$ | $15.4 \pm 1.3$                | $1.8 \pm 0.2$ |
| $45 < p_T < 60$           | $13.6 \pm 1.1$                | $1.6 \pm 0.1$ | $14.5 \pm 1.2$                | $1.7 \pm 0.2$ |
| $60 < p_T < 100$          | $13.4 \pm 1.1$                | $1.7 \pm 0.1$ | $13.9 \pm 1.2$                | $1.5 \pm 0.2$ |
| $100 < p_T$               | $13.2 \pm 1.1$                | $1.6 \pm 0.1$ | $14.0 \pm 1.2$                | $1.6 \pm 0.2$ |

Table 7.4: The  $p_T$ -dependent  $\sigma$  and  $\alpha$  smearing parameters for muons and electrons. The uncertainties include both statistical and systematic sources.

originating from  $Z \rightarrow \ell^\pm \ell^\mp$  decays, the probe lepton and tag lepton are required to have opposite-sign charges, and the invariant mass of the tag-and-probe pair is required to satisfy  $81 \text{ GeV} < m_{\text{tag,probe}} < 101 \text{ GeV}$ . For both the electron and muon transfer factors, the charge of the probe lepton is obtained from its associated track. Backgrounds in this measurement are accounted for by subtracting same-sign tag-and-probe pairs from the opposite-sign selection.

The templates for the shapes of electron scattering backgrounds are estimated by multiplying the number of events in the single-electron CR by a set of transfer factors. The electron transfer factors are factorised into two components: pixel tracklet and calorimeter isolation selections, and the final estimate is given by

$$f_e^{\text{SR}}(p_T; \sigma_e, \alpha_e) = N_{e,\text{signal}}^{\text{CR}}(p_T, \eta) \times \text{TF}_{\text{pixel-only}}^e(p_T, \eta) \times \text{TF}_{\text{calo-veto}}^e(p_T, \eta) \times f(z = z_{\text{ran}}; \sigma_e, \alpha_e) \quad (7.5)$$

where  $N_{e,\text{signal}}^{\text{CR}}$  is the number of events in the single-electron CR,  $\text{TF}_{\text{pixel-only}}^e$  is a transfer factor for an electron failing to satisfy the electron identification and being instead mistakenly categorised as a pixel tracklet, and  $\text{TF}_{\text{calo-veto}}^e$  is the transfer factor representing the probability for an electron track to be isolated from a calorimeter cluster. Additionally, the templates are smeared to account for the different momentum resolution of the full-length track and the pixel-tracklets by the  $f(z = z_{\text{ran}}; \sigma_e, \alpha_e)$  term. The smearing function depends on the electron smearing parameters  $\sigma_e$  and  $\alpha_e$  shown in Table 7.4, and is evaluated at a random value ( $z_{\text{ran}}$ ) using Equation 7.4.

In the pixel tracklet transfer-factor measurement, the probe lepton is a calorimeter cluster, and

the transfer factor  $\text{TF}_{\text{pixel-only}}^e$  is calculated as the number of probes matched to a pixel tracklet divided by the number of probes matched to an electron. An object is considered matched if  $\Delta R(\text{probe}, \text{object}) < 0.2$ . Both the pixel tracklet and the track matched to the electron must pass the requirements for the pixel tracklet defined in Section 6.1.2, without application of the disappearing-track condition for the electron. The calorimeter isolation transfer factor  $\text{TF}_{\text{calo-veto}}^e$  is calculated using a high-quality inner-detector track as the probe. The inner-detector track is required to satisfy the same quality criteria as the pixel tracklets, except that instead of meeting the disappearing-track condition, the track is required to have at least eight SCT hits. This measurement assesses the ratio of the number of inner-detector tracks passing the calorimeter isolation requirement,  $E_{\text{T}}^{\text{topo cluster}} < 5 \text{ GeV}$ , to the number failing this requirement. Both transfer factors are parameterised as a function of  $p_{\text{T}}$  and  $\eta$ . Detector simulations are used to correct for the change in the isolation transfer factor when the track selection requires at least eight SCT hits instead of imposing the disappearing-track condition. These simulation-based corrections can be up to  $\mathcal{O}(10^{-4})$  for tracks with  $p_{\text{T}} > 30 \text{ GeV}$ . However, since the isolation transfer factor is already very small in this region, these correction factors have a small impact on the resulting template and final results.

Since the electron and hadron scattering backgrounds have similar pixel tracklet  $p_{\text{T}}$  distribution shapes, the electron transfer factors are used to obtain templates for the hadron scattering backgrounds. The number of events in a single-inner-detector-track CR is used instead of  $N_{e,\text{signal}}^{\text{CR}}$  in Equation 7.5. Similarly to the electron  $\text{TF}_{\text{calo-veto}}^e$ , detector simulations are used to correct for track-length differences between the two CRs. Corrections are derived using simulated single-pion events for the hadron scattering backgrounds. The correction factors can range from approximately 10 to 100, but only have a marginal effect on the pixel tracklet  $p_{\text{T}}$  template shape. As the normalization of the hadron scattering backgrounds is extracted from the combined fit described in Section 7.3.5, these correction factors have a small impact on the resulting background prediction and final results.

Similarly to the electron measurement, the muon transfer factors are factorised into two components: pixel tracklets and those with no MSTrack association, and they are multiplied by the number of events in the single-muon CR to estimate the muon scattering background,

$$f_{\mu}^{\text{SR}}(p_{\text{T}}; \sigma_{\mu}, \alpha_{\mu}) = N_{\mu,\text{signal}}^{\text{CR}}(p_{\text{T}}, \eta, \phi) \times \text{TF}_{\text{pixel-only}}^{\mu}(p_{\text{T}}, \eta) \times \text{TF}_{\text{no MSTrack}}^{\mu}(\eta, \phi) \times f(z = z_{\text{ran}}; \sigma_{\mu}, \alpha_{\mu}) \quad (7.6)$$

where  $N_{\mu,\text{signal}}^{\text{CR}}$  is the number of events in the single-muon CR,  $\text{TF}_{\text{pixel-only}}^{\mu}$  is the transfer factor representing the probability for a muon to be misidentified as a pixel tracklet, and  $\text{TF}_{\text{no MSTrack}}^{\mu}$  is the transfer factor accounting for the probability that a muon with a good inner-detector track does not have an associated MSTrack. Similar to the electron template, the muon template is smeared using the  $\sigma_{\mu}$  and  $\alpha_{\mu}$  smearing parameters found in Table 7.4.



In the muon pixel-tracklet measurement, the probe lepton is a muon track reconstructed only in the muon spectrometer. The transfer factor  $\text{TF}_{\text{pixel-only}}^\mu$  is calculated in the same way as the electron pixel-tracklet transfer factor, but the denominator is the number of events where the probe is matched to a muon. The no-MS-track transfer factor  $\text{TF}_{\text{no MSTrack}}^\mu$  uses a high-quality inner-detector track as the probe. It represents the probability for an MSTrack not to be geometrically matched to an inner-detector track. In order to account for the detector geometry, the transfer factor is measured as a function of  $\eta$  and  $\phi$ . No significant  $p_T$  dependence is observed.

### 7.3.4 Combinatorial fake backgrounds

Fake tracklets are reconstructed from a combination of unassociated hits. These tracklets can have high transverse momentum and can mimic the signal. Since their  $d_0$  is broadly distributed, and the high- $p_T$  chargino tracks have good pointing resolution and originate from the primary interaction region, the high- $|d_0|$  sidebands can be used as a CR that is pure in fake tracklets. A pure fake-tracklet control sample is obtained by applying the same kinematic selection requirements as in the signal region, but without the offline  $E_T^{\text{miss}}$  selection, so as to increase the sample size, and with an inverted requirement of  $|d_0/\sigma(d_0)| > 10$  on the transverse impact parameter.

The  $p_T$  spectrum of mismeasured pixel tracklets in the fake-tracklet CR is modelled with the following functional form:

$$f_c(p_T; p_0, p_1) = \exp\left(-p_0 \cdot \log(p_T) - p_1 \cdot (\log(p_T))^2\right). \quad (7.7)$$

In order to remove any correlations between  $p_0$  and  $p_1$  in the fit described in Section 7.3.5, the parameters are rotated by an angle  $\theta$  and redefined as  $p_0 = p_0' \cos \theta - p_1' \sin \theta$  and  $p_1 = p_0' \sin \theta + p_1' \cos \theta$ . The  $\theta$  value is chosen such that the two parameters are uncorrelated, and is found to be  $\theta = -0.0973$ . The  $p_0$  and  $p_1$  parameters are determined in the combined fit described in Section 7.3.5. The parameter  $p_1'$  is found to be  $p_1' = 0.171 \pm 0.002$  in the signal regions of both channels, and  $p_0' = 1.172 \pm 0.113$  ( $0.996 \pm 0.110$ ) in the electroweak (strong) channel. The data and fitted fake background are shown in Figure 7.5 for the electroweak and strong production fake-tracklet CRs and show good agreement between the fit and the data.

### 7.3.5 Fitting procedure

The backgrounds are estimated by fitting the model below to the data in the high- $E_T^{\text{miss}}$  signal region or in each of the middle- $E_T^{\text{miss}}$  validation regions, simultaneously with the low- $E_T^{\text{miss}}$  and fake-tracklet CRs described in Section 7.3.1. The fit is performed using the likelihood function described in the following, where the likelihood function is described for the high- $E_T^{\text{miss}}$  signal region setup. For the validation region fits, the high- $E_T^{\text{miss}}$  signal region is replaced with the

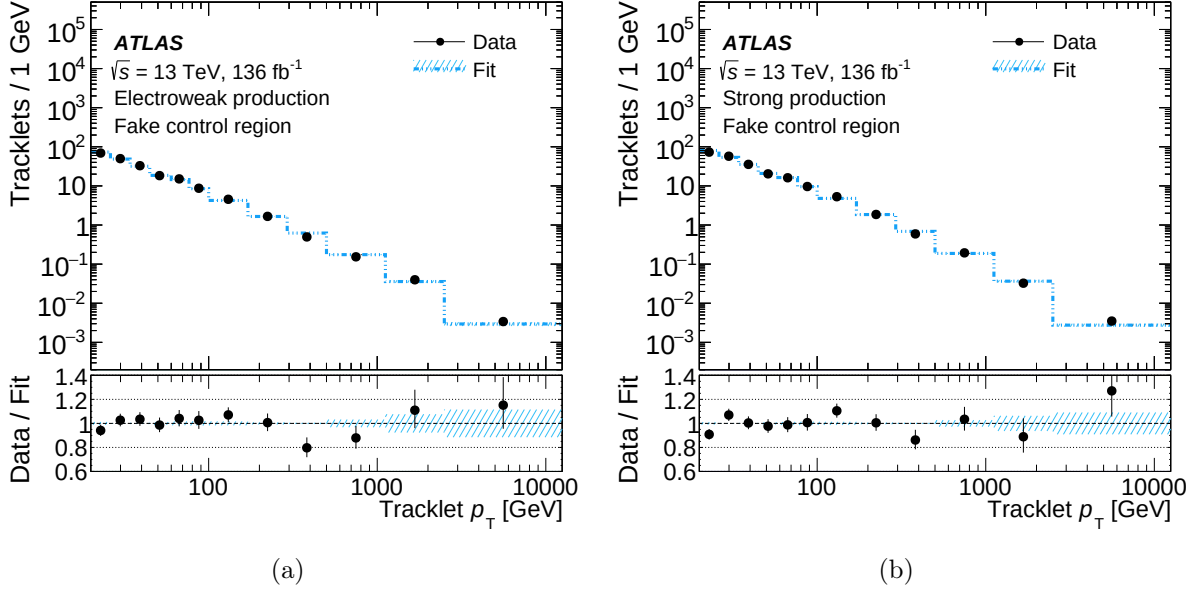


Figure 7.5: Fit in the fake-tracklet CR for (a) the electroweak production channel and (b) the strong production channel. The black points show data. The blue line and the hatched band show the fit function and its uncertainty. The bottom insert shows the ratio of the data to the fitted prediction.

corresponding validation region.

The likelihood function  $\mathcal{L}$  for the tracklet  $p_T$  in a sample of observed events ( $N_{\text{obs}}$ ) is defined as  $\mathcal{L} = \mathcal{L}_{\text{shape}} \times \mathcal{L}_{\text{shape}}^{\text{Fake CR}} \times \mathcal{L}_{\text{syst}}$ . The shape terms represent the probability to observe  $N_{\text{obs}}$  events in the low- $E_T^{\text{miss}}$  and high- $E_T^{\text{miss}}$  region. The  $\mathcal{L}_{\text{shape}}$  term is defined as:

$$\mathcal{L}_{\text{shape}} = \prod_R^{\text{low-/high-}E_T^{\text{miss}}} \mathcal{L}_{\text{shape}}^R, \quad (7.8)$$

with

$$\mathcal{L}_{\text{shape}}^R = \frac{\exp\left(-\sum_i^{s,e,\mu,h,c} n_i^R\right)}{N_{\text{obs}}^R!} \times \prod_{N_{\text{obs}}^R} \left( \sum_{i'}^{s,e,\mu,h} \left( n_{i'}^R \cdot f_{i'}^R(p_T; \sigma_{i'}, \alpha_{i'}) \right) + n_c^R \cdot f_c(p_T; p_0, p_1) \right). \quad (7.9)$$

The  $\mathcal{L}_{\text{shape}}^{\text{Fake CR}}$  term is defined as:

$$\mathcal{L}_{\text{shape}}^{\text{Fake CR}} = \frac{\exp\left\{\left(-n_c^{\text{Fake CR}}\right)\right\}}{N_{\text{obs}}^{\text{Fake CR}}!} \times \prod_{N_{\text{obs}}^{\text{Fake CR}}} \left( n_c^{\text{Fake CR}} \cdot f_c(p_T; p_0, p_1) \right). \quad (7.10)$$

Here  $s, e, \mu, h$  and  $c$  are subscripts of the signal process and the electron, muon, hadron and

combinatorial fake-tracklet backgrounds respectively;  $N_{\text{obs}}^R$  is the number of observed events in each of the fitted regions,  $R = \text{high-}E_{\text{T}}^{\text{miss}}$  or  $\text{low-}E_{\text{T}}^{\text{miss}}$  region;  $n_i^R$  is the estimated number of events of process  $i$  in region  $R$ ;  $\sigma_{i'}$  and  $\alpha_{i'}$  are the smearing parameters of process  $i'$ ;  $p_0$  and  $p_1$  are the parameters for the combinatorial fake-tracklet background fit described in Section 7.3.4;  $f_i$  is the charged-particle scattering background-shape template for process  $i$  described in Sections 7.3.3 and 7.3.2;  $n_c^R$  is the estimated number of combinatorial fake-tracklet events in region  $R$ . For region  $R = \text{low-}E_{\text{T}}^{\text{miss}}$ , the number of combinatorial fake-tracklet events ( $n_c^{\text{low-}E_{\text{T}}^{\text{miss}}}$ ) is a free parameter in the likelihood fit and extracted from the data. Using this, the number of combinatorial fake-tracklets in the  $\text{high-}E_{\text{T}}^{\text{miss}}$  region is calculated from:

$$n_c^{\text{high-}E_{\text{T}}^{\text{miss}}} = r_{\text{CD}} \cdot \exp(r_{\text{ABCD}}) \cdot n_c^{\text{low-}E_{\text{T}}^{\text{miss}}}, \quad (7.11)$$

with  $r_{\text{CD}}$  defined as:

$$r_{\text{CD}} = \frac{n_c^{\text{high-}E_{\text{T}}^{\text{miss}} \text{ Fake CR}}}{n_c^{\text{low-}E_{\text{T}}^{\text{miss}} \text{ Fake CR}}}, \quad (7.12)$$

and  $r_{\text{ABCD}}$  defined as:

$$r_{\text{ABCD}} = \ln \frac{n_c^{\text{high-}E_{\text{T}}^{\text{miss}}} / n_c^{\text{high-}E_{\text{T}}^{\text{miss}} \text{ Fake CR}}}{n_c^{\text{low-}E_{\text{T}}^{\text{miss}}} / n_c^{\text{low-}E_{\text{T}}^{\text{miss}} \text{ Fake CR}}}. \quad (7.13)$$

Here  $r_{\text{CD}}$  and  $r_{\text{ABCD}}$  are terms to constrain the combinatorial fake-tracklet background in the  $\text{high-}E_{\text{T}}^{\text{miss}}$  regions relative to that in the  $\text{low-}E_{\text{T}}^{\text{miss}}$  regions: the  $r_{\text{CD}}$  term is used for the  $\text{low-}E_{\text{T}}^{\text{miss}}$  control and  $\text{high-}E_{\text{T}}^{\text{miss}}$  signal region, while the  $r_{\text{ABCD}}$  term is used to constrain the extrapolation from the high  $d_0$  significance side fake enriched regions into the  $\text{low-}E_{\text{T}}^{\text{miss}}$  control and  $\text{high-}E_{\text{T}}^{\text{miss}}$  signal regions.

The likelihood  $\mathcal{L}_{\text{syst}}$  consists of a product of terms related to the systematic uncertainties in each background process and the signal process,  $\mathcal{L}_{\text{syst}} = \mathcal{L}_{\text{syst}}^s \times \mathcal{L}_{\text{syst}}^e \times \mathcal{L}_{\text{syst}}^\mu \times \mathcal{L}_{\text{syst}}^h \times \mathcal{L}_{\text{syst}}^c$ . Each likelihood component is defined as below:

$$\mathcal{L}_{\text{syst}}^s = G(\sigma_s; \bar{\sigma}_s, \Delta\sigma_s) \times G(\alpha_s; \bar{\alpha}_s, \Delta\alpha_s) \times \prod_R G(n_s^R; \bar{n}_s^R, \Delta n_s^R), \quad (7.14)$$

$$\mathcal{L}_{\text{syst}}^\mu = G(\sigma_\mu; \bar{\sigma}_\mu, \Delta\sigma_\mu) \times G(\alpha_\mu; \bar{\alpha}_\mu, \Delta\alpha_\mu) \times \prod_R G(n_\mu^R; \bar{n}_\mu^R, \Delta n_\mu^R), \quad (7.15)$$

$$\mathcal{L}_{\text{syst}}^e = G(\sigma_e; \bar{\sigma}_e, \Delta\sigma_e) \times G(\alpha_e; \bar{\alpha}_e, \Delta\alpha_e) \times \prod_R G(n_e^R; \bar{n}_e^R, \Delta n_e^R), \quad (7.16)$$

$$\mathcal{L}_{\text{syst}}^h = G(\sigma_h; \bar{\sigma}_h, \Delta\sigma_h) \times G(\alpha_h; \bar{\alpha}_h, \Delta\alpha_h), \quad (7.17)$$

$$\mathcal{L}_{\text{syst}}^c = G(r_{\text{ABCD}}; 1, \Delta r_{\text{ABCD}}), \quad (7.18)$$

where  $G(a; b, c)$  represents a unit Gaussian function of  $a$  with a mean of  $b$  and a standard deviation  $c$ . The expected value and the uncertainty of a variable  $x$  are represented by  $\bar{x}$  and

$\Delta x$  respectively.

The likelihood is maximised by minimising the negative log-likelihood function with the MINUIT [141] package in the ROOFIT framework [142]. The fit parameters are the normalisations of the hadron and combinatorial fake-tracklet backgrounds ( $n_h^R$  and  $n_c^R$ ), the  $p_0$  and  $p_1$  parameters of the function modelling the fake-tracklet transverse momentum distribution described in Section 7.3.4, and nuisance parameters. Each nuisance parameter represents a source of systematic uncertainty and is allowed to float in the fit with a Gaussian constraint. The statistical uncertainty of the transfer factors for electrons and muons is propagated into the final template.

## 7.4 Systematic uncertainties

Several sources of uncertainty are considered for this search, and these can be divided into uncertainties affecting the parameters in the background and signal fit model, and those affecting the expected signal yields.

### 7.4.1 Fit model uncertainties

Uncertainties in the normalisation of the electron and muon backgrounds are dominated by the statistical uncertainties in the transfer factors. The shape uncertainty in the hadron and charged-lepton backgrounds is dominated by uncertainties in the smearing functions. The pile-up condition is the largest source of uncertainty for the smearing function, especially for lower- $p_T$  tracklets. The pile-up uncertainty is evaluated by taking the difference between the nominal values of the smearing parameters and the values obtained from events with different pile-up conditions. This is done by splitting the dataset into data taken in low ( $\mu < 40$ ) and high ( $\mu > 40$ ) pile-up conditions, and the full parameter-value differences between the datasets with low and high pile-up are assigned as the systematic uncertainties of the  $p_T$ -dependent smearing parameters.

The uncertainties in  $r_{CD}$  and  $r_{ABCD}$  are obtained from statistical uncertainties in the control regions used to calculate these parameters. An additional uncertainty in the extrapolation of  $r_{ABCD}$  over  $d_0/\sigma(d_0)$  is obtained by evaluating  $r_{ABCD}$  using pixel tracklets with  $3 < |d_0/\sigma(d_0)| < 10$  for  $n_c^{\text{high-}E_T^{\text{miss}}}$  and  $n_c^{\text{low-}E_T^{\text{miss}}}$  in Equation 7.13. Since fake tracklets are the dominant backgrounds in the signal regions, variations of these parameters are the leading source of uncertainty in both the electroweak and strong production signal regions. Similarly, the  $p_0$  and  $p_1$  parameters are varied up and down by the statistical uncertainties obtained from the fit.

Table 7.5 summarises the effect of various sources of systematic uncertainty on the signal exclusion significance.

|                                                                 | Electroweak channel [%] | Strong channel [%] |
|-----------------------------------------------------------------|-------------------------|--------------------|
| $r_{\text{ABCD}}$                                               | 5.2                     | 0.9                |
| $r_{\text{CD}}$                                                 | 3.2                     | 0.6                |
| $\sigma$ parameter in signal $p_{\text{T}}$ smearing function   | 2.9                     | 0.1                |
| $\alpha$ parameter in signal $p_{\text{T}}$ smearing function   | 1.7                     | 0.2                |
| $p_0$ parameter in the fake background $p_{\text{T}}$ function  | 0.3                     | <0.1               |
| $p_1$ parameter in the fake background $p_{\text{T}}$ function  | 0.3                     | 0.2                |
| Normalisation of muon background                                | 0.6                     | <0.1               |
| Normalisation of electron background                            | <0.1                    | <0.1               |
| $\alpha$ parameter in muon $p_{\text{T}}$ smearing function     | <0.1                    | <0.1               |
| $\sigma$ parameter in muon $p_{\text{T}}$ smearing function     | <0.1                    | <0.1               |
| $\alpha$ parameter in electron $p_{\text{T}}$ smearing function | <0.1                    | <0.1               |
| $\sigma$ parameter in electron $p_{\text{T}}$ smearing function | <0.1                    | <0.1               |
| $\alpha$ parameter in hadron $p_{\text{T}}$ smearing function   | 0.5                     | 0.2                |
| $\sigma$ parameter in hadron $p_{\text{T}}$ smearing function   | 0.6                     | 0.2                |

Table 7.5: Effects of systematic uncertainties on the signal exclusion significance for a representative signal point with  $m(\tilde{\chi}_1^\pm) = 600$  GeV for the electroweak channel and  $m(\tilde{g}) = 1400$  GeV and  $m(\tilde{\chi}_1^\pm) = 1100$  GeV for the strong channel.

#### 7.4.2 Signal uncertainties

A breakdown of the systematic uncertainties for the expected number of signal events in the signal regions is shown in Table 7.6.

Theoretical uncertainties in the signal cross-section are estimated in a way similar to that for the previous result [45]. This is done by computing the changes in the cross-section when the renormalisation and factorisation scales, the choice of PDFs and the strong coupling constant,  $\alpha_s$ , are varied independently. Renormalisation and factorisation scales are varied by factors of 0.5 and 2 from their nominal value. The PDF uncertainty is estimated as the maximum of the uncertainty from the CTEQ6.6 [143] uncertainty band at 68% confidence level and the difference between the results for the CTEQ6.6 and MSTW2008 NLO PDF [144] sets. Each uncertainty is varied independently and their effects are added in quadrature. Uncertainties in the modelling of ISR and Final-State Radiation (FSR) are estimated by varying the renormal-

isation, factorisation and merging scales from 0.5 to 2 times their nominal values. Jet modelling uncertainties related to the energy scale and resolution, and jet vertex tagging uncertainty, are estimated by comparing simulated events and data as described in Ref. [131]. The pile-up modelling uncertainty is estimated by varying the number of collisions per bunch crossing in simulation by its uncertainty of 10% of the nominal value. The uncertainty in the  $E_T^{\text{miss}}$  soft-term modelling is considered by comparing data and simulated samples using  $Z \rightarrow \mu\mu + \text{jets}$  events as described in Ref. [131]. The uncertainty in the trigger efficiency modelling is small because it is measured from data as described in Section 7.2. Only the statistical uncertainty in the efficiency measurement is taken into account for the signal trigger efficiency uncertainty.

The uncertainty in the tracklet reconstruction efficiency is evaluated by comparing efficiencies for muons in the collision data and simulation. Events containing muons from Z boson decays are selected and muons are re-tracked using only pixel hits as described in Section 7.3.2. The efficiency is measured as the ratio of re-tracked pixel tracklets satisfying all of the tracklet quality and selection criteria to the total number of muon tracks. The difference between data and simulation is assigned as a systematic uncertainty.

|                                    | Electroweak channel [%]<br>$m(\tilde{\chi}_1^\pm) = 600 \text{ GeV}$ | Strong channel [%]<br>$m(\tilde{g}) = 1400 \text{ GeV}$<br>$m(\tilde{\chi}_1^\pm) = 1100 \text{ GeV}$ |
|------------------------------------|----------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| Cross-section                      | 7.6                                                                  | 14                                                                                                    |
| Initial/final-state radiation      | 8.4                                                                  | 5.1                                                                                                   |
| Jet energy scale                   | 2.3                                                                  | 1.5                                                                                                   |
| Jet energy resolution              | 0.6                                                                  | 0.3                                                                                                   |
| Jet vertex tagging efficiency      | <0.1                                                                 | <0.1                                                                                                  |
| Pile-up modelling                  | 0.7                                                                  | <0.1                                                                                                  |
| $E_T^{\text{miss}}$ soft term      | 0.4                                                                  | <0.1                                                                                                  |
| Trigger efficiency                 | 0.3                                                                  | 0.4                                                                                                   |
| Tracklet reconstruction efficiency | 5.9                                                                  |                                                                                                       |
| Luminosity                         | 1.7                                                                  |                                                                                                       |
| Total                              | 11                                                                   | 8.1                                                                                                   |

Table 7.6: Effects of systematic uncertainties on the signal yields for representative signal points with  $\tau(\tilde{\chi}_1^\pm) = 0.2 \text{ ns}$ . Each value is obtained by symmetrising the larger of the upward and downward deviations from the nominal signal yield. The effects of pixel tracklet efficiency and luminosity uncertainties are common to the two signal regions.

## 7.5 Results and interpretation

The transverse momentum spectra of the fitted pixel tracklets in the low- $E_T^{\text{miss}}$  CR, the calorimeter sideband and middle- $E_T^{\text{miss}}$  VRs, and the high- $E_T^{\text{miss}}$  Signal Region (SR) for the electroweak and strong production channels are shown in Figures 7.6 and 7.7, respectively. The measured spectra show agreement with the sum of all expected background. Examples of the expected-signal prediction with  $m(\tilde{\chi}_1^\pm) = 600 \text{ GeV}$  and  $\tau(\tilde{\chi}_1^\pm) = 0.2 \text{ ns}$  for the electroweak production channel, and with  $m(\tilde{g}) = 1400 \text{ GeV}$ ,  $m(\tilde{\chi}_1^\pm) = 1100 \text{ GeV}$  and  $\tau(\tilde{\chi}_1^\pm) = 0.2 \text{ ns}$  for the strong production channel are overlaid.

The numbers of events in the two middle- $E_T^{\text{miss}}$  validation regions after the background fits described in Section 7.3.5 are shown in Table 7.7. Good agreement between data and background predictions is observed in all validation regions. No significant excess above the background predictions is observed in the high- $E_T^{\text{miss}}$  signal regions, as shown in Table 7.8. The probability of a background-only experiment being more signal-like than observed ( $p_0$ ), its equivalent formulation in terms of the number of standard deviations ( $Z$ ), and the upper limit on the model-independent visible cross-section at 95% Confidence Level (CL) using the  $\text{CL}_s$  technique [145] are also shown in Table 7.8. For the evaluation of these model-independent quantities, the tracklet is required to have  $p_T > 60 \text{ GeV}$ .

|                | Electroweak channel    |                        | Strong channel         |                        |
|----------------|------------------------|------------------------|------------------------|------------------------|
|                | Calo. sideband         | Low $p_T$              | Calo. sideband         | Low $p_T$              |
|                | $p_T > 60 \text{ GeV}$ | $p_T < 60 \text{ GeV}$ | $p_T > 60 \text{ GeV}$ | $p_T < 60 \text{ GeV}$ |
| Fake           | $4.3 \pm 2.2$          | $5.5 \pm 1.5$          | $3.2 \pm 1.5$          | $3.5 \pm 1.0$          |
| Hadron         | $1.0 \pm 0.8$          | $23 \pm 6$             | $0.36 \pm 0.23$        | $13 \pm 4$             |
| Electron       | $0.8 \pm 0.5$          | $1.2 \pm 1.3$          | $0.29 \pm 0.20$        | $0.5 \pm 0.5$          |
| Muon           | $0.023 \pm 0.007$      | $0.25 \pm 0.06$        | $0.012 \pm 0.004$      | $0.129 \pm 0.032$      |
| Total Expected | $6.1 \pm 1.9$          | $29 \pm 5$             | $3.8 \pm 1.5$          | $17 \pm 4$             |
| Observed       | 5                      | 30                     | 3                      | 18                     |

Table 7.7: Expected and observed numbers of events and corresponding background predictions in the middle- $E_T^{\text{miss}}$  validation regions. The uncertainty in the total background prediction differs from the sum in quadrature of the individual components due to anti-correlation of fit parameters between the backgrounds.

Model-dependent exclusion limits at 95% CL are placed on the various signal models. The likelihood function is extended to contain both the signal and background components. The signal normalisation is the parameter of interest and is unconstrained in the fit.

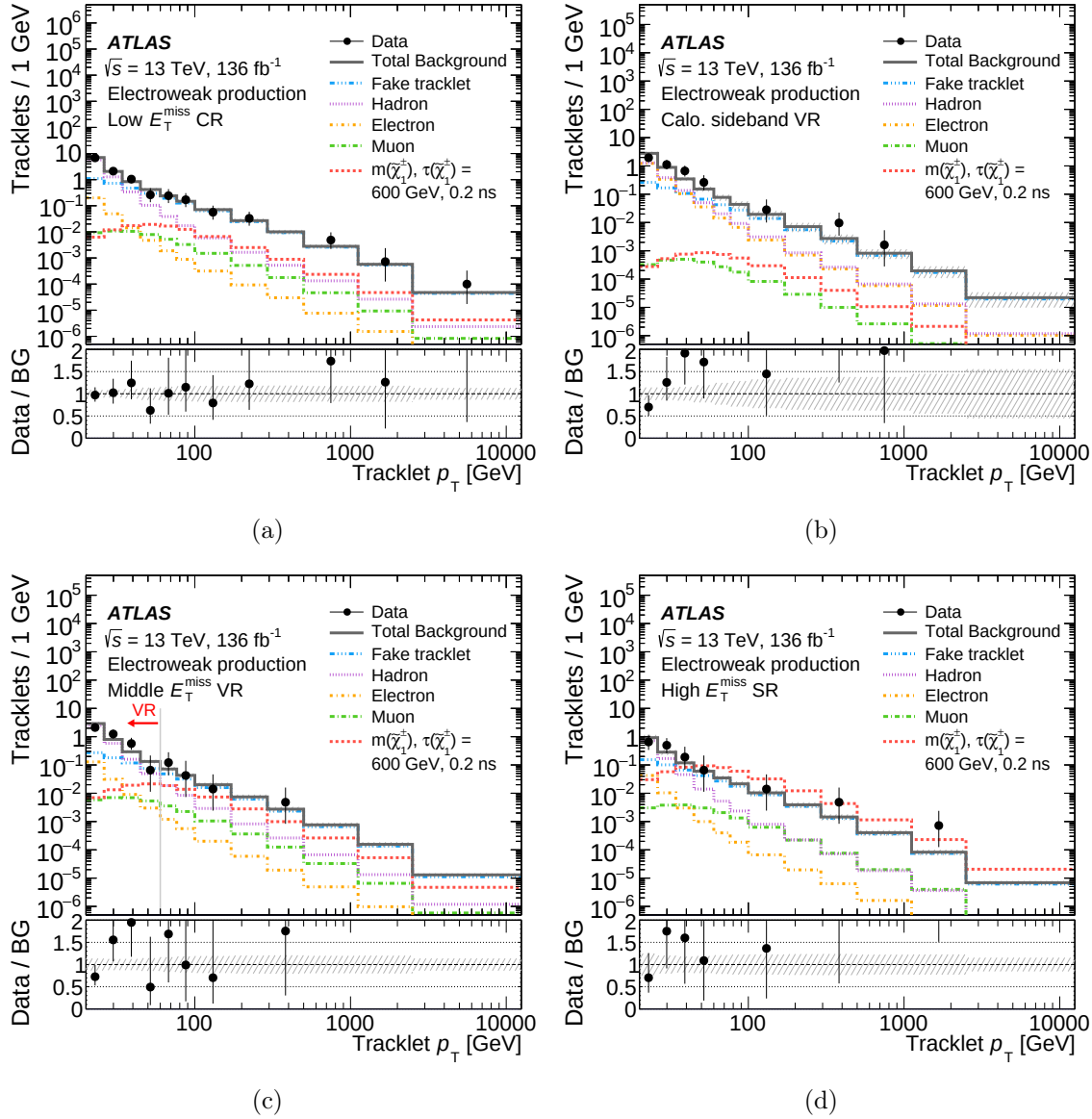


Figure 7.6: Pixel tracklet  $p_T$  spectrum fit results in the low-, middle- and high- $E_T^{\text{miss}}$  regions for the electroweak production channel. The fake-tracklet, hadron, electron and muon templates are fitted to observed data events in a background-only fit. An example of the expected-signal prediction with  $m(\tilde{\chi}_1^\pm) = 600 \text{ GeV}$  and  $\tau(\tilde{\chi}_1^\pm) = 0.2 \text{ ns}$  is overlaid in red. The last bin includes overflow entries. The bottom panel shows the ratio of data to the background-only prediction.



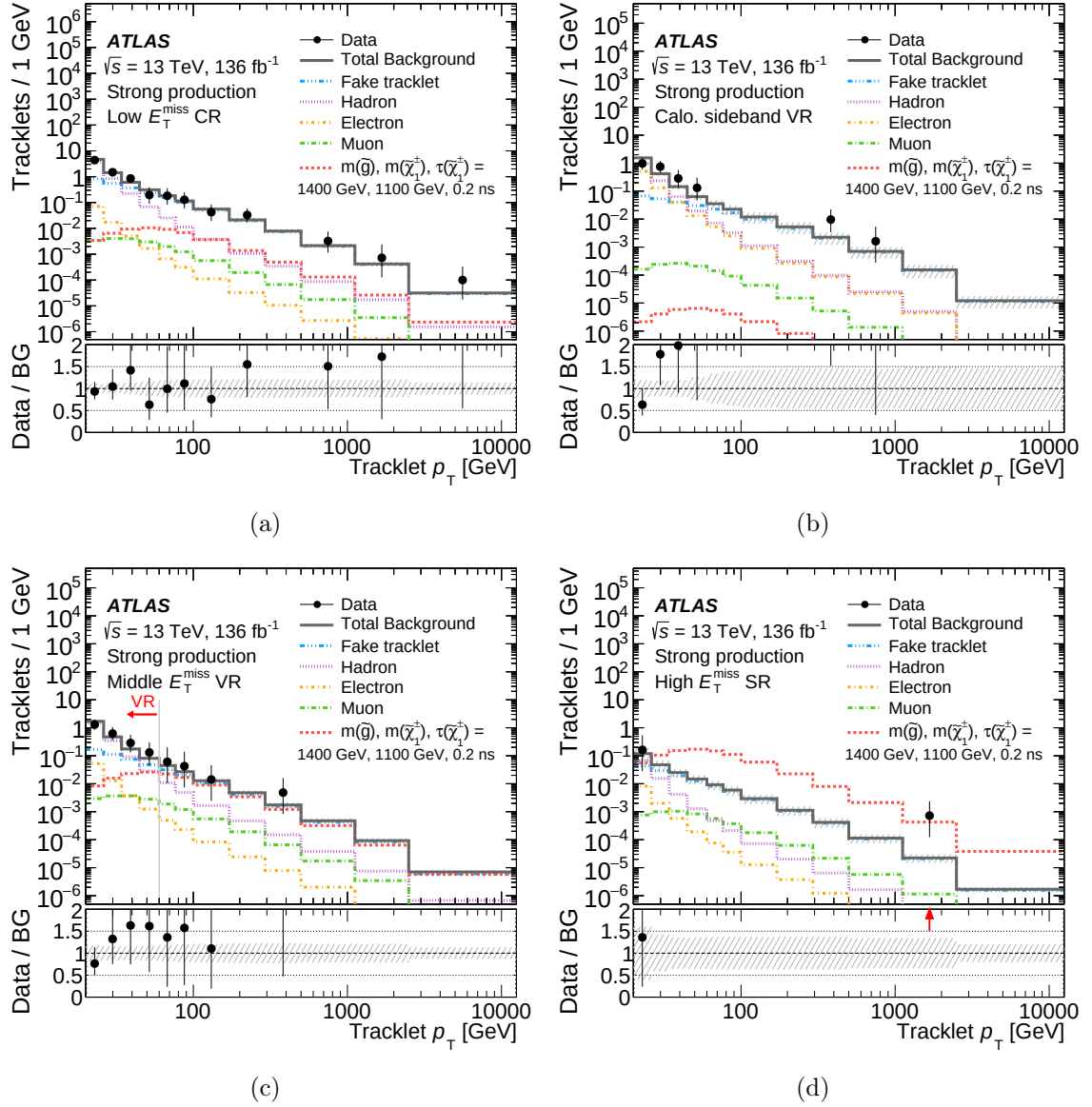


Figure 7.7: Pixel tracklet  $p_T$  spectrum fit results in the low-, middle- and high- $E_T^{\text{miss}}$  regions for the strong production channel. The fake-tracklet, hadron, electron and muon templates are fitted to observed data events in a background-only fit. An example of the expected-signal prediction with  $m(\tilde{g}) = 1400$  GeV,  $m(\tilde{\chi}_1^\pm) = 1100$  GeV and  $\tau(\tilde{\chi}_1^\pm) = 0.2$  ns is overlaid in red. The last bin includes overflow entries. The bottom panel shows the ratio of data to the background-only prediction. The arrow indicates a value outside of the range of the bottom inset.

|                                            | Electroweak channel       | Strong channel            |
|--------------------------------------------|---------------------------|---------------------------|
| Fake                                       | $2.6 \pm 0.8$             | $0.77 \pm 0.33$           |
| Hadron                                     | $0.26 \pm 0.13$           | $0.024 \pm 0.031$         |
| Electron                                   | $0.021 \pm 0.023$         | $0.004 \pm 0.004$         |
| Muon                                       | $0.17 \pm 0.06$           | $0.049 \pm 0.018$         |
| Total Expected                             | $3.0 \pm 0.7$             | $0.84 \pm 0.33$           |
| Observed                                   | 3                         | 1                         |
| $p_0$ (Z)                                  | 0.5 (0)                   | 0.38 (0.30)               |
| Observed $\sigma_{\text{vis}}^{95\%}$ [fb] | 0.037                     | 0.028                     |
| Expected $\sigma_{\text{vis}}^{95\%}$ [fb] | $0.038^{+0.014}_{-0.009}$ | $0.024^{+0.009}_{-0.003}$ |

Table 7.8: Expected and observed numbers of events and corresponding background predictions in the high- $E_T^{\text{miss}}$  signal regions with transverse momenta above 60 GeV. The uncertainty in the total background prediction differs from the sum in quadrature of the individual components due to anti-correlation of fit parameters between the backgrounds.

For the electroweak production of pure winos or pure higgsinos, the exclusion limits are shown as a function of the chargino lifetime and mass.

In the case of pure winos, the expected lower limit on the mass of a chargino with a lifetime of 0.2 ns is improved from 450 GeV in the previous search [45] to 680 GeV in this search, while a simple scaling from the integrated luminosity used in the previous search gives an expected mass limit of 530 GeV with the present integrated luminosity of  $136 \text{ fb}^{-1}$ . The observed limit excludes chargino masses up to 660 GeV as shown in Figure 7.8, in which the pure-wino lifetime is shown by the grey dashed line.

For pure higgsinos, chargino masses are excluded up to 210 GeV as shown in Figure 7.9. The lower sensitivity to higgsinos in comparison with winos is explained by two factors: the smaller production cross-section of higgsinos relative to the wino case, and the extremely short lifetime of the higgsinos.

For the strong production channels, the exclusion limits are set as a function of the lightest chargino’s mass and the gluino’s mass. The exclusion limits for charginos with lifetimes fixed to 0.2 ns and 1.0 ns are shown in Figure 7.10. The observed limits from the electroweak wino model in Figure 7.8 are shown by a green hatched line. Gluino masses below 2.1 TeV are excluded for a chargino mass of 300 GeV and a chargino lifetime of 0.2 ns.

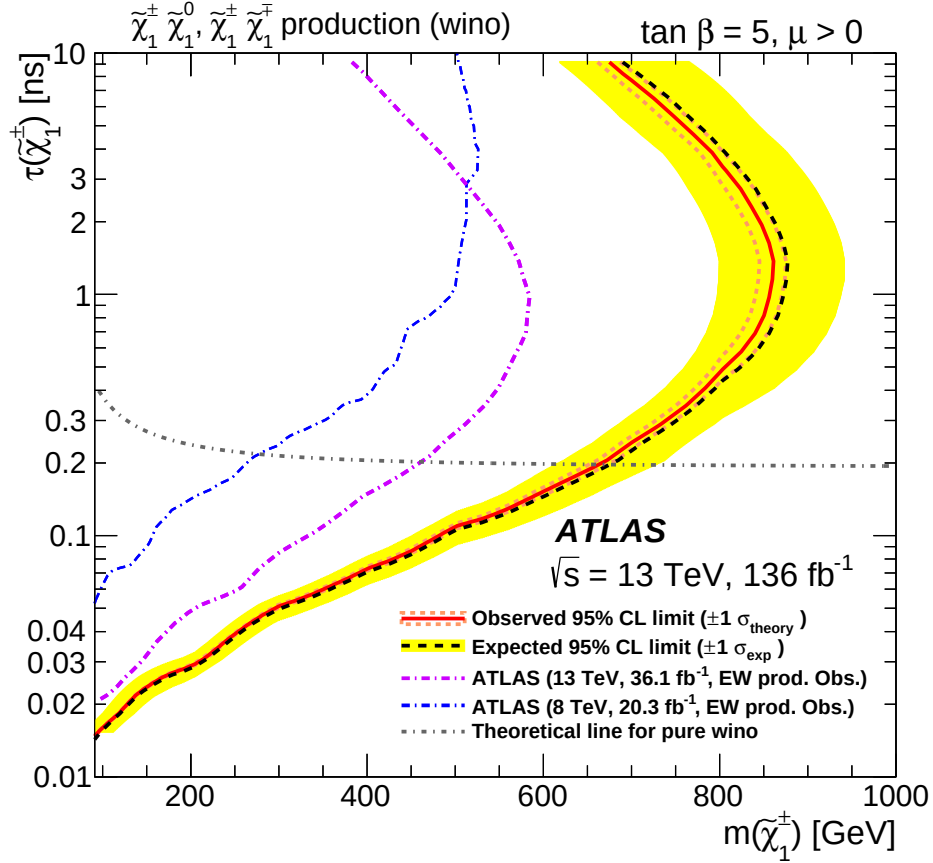


Figure 7.8: Exclusion limits at 95% CL obtained in the electroweak production channel with the pure-wino scenario. The limits are shown as a function of the chargino lifetime and mass. The black dashed line shows the median expected value, and the yellow band shows the  $1\sigma$  uncertainty band around the expected limits. The red line shows the observed limits and the red dotted lines show the  $1\sigma$  uncertainty from the signal cross-section. The blue and violet broken lines show the observed limits from the ATLAS results in References [45] and [146] respectively. The dashed gray line shows the predicted chargino lifetime in the almost pure wino-LSP scenario at the two-loop level [147].

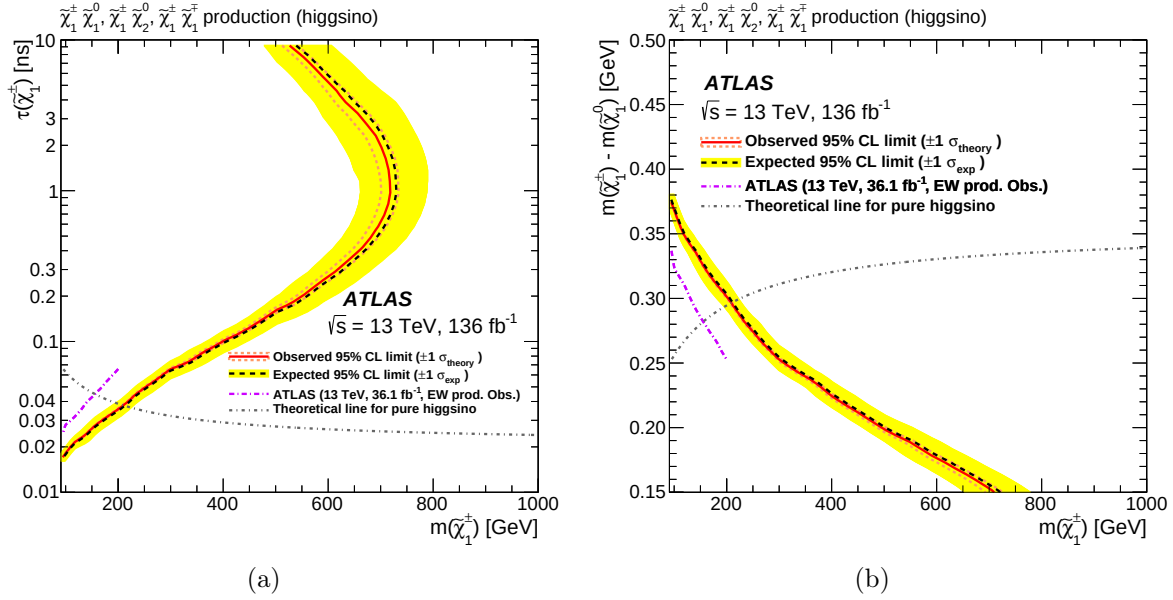


Figure 7.9: Exclusion limits at 95% CL obtained in the electroweak production channel with the pure-higgsino scenario. The limits are shown separately for the higgsino lifetime or mass splitting as a function of the chargino mass. The black dashed line shows the median expected value, and the yellow band shows the  $1\sigma$  uncertainty band around the expected limits. The red line shows the observed limits and the red dotted lines show the  $1\sigma$  uncertainty from the signal cross-section. The violet broken line shows the observed limits from the previous ATLAS result [46]. The dashed gray line shows the predicted chargino lifetime in the pure higgsino-LSP scenario [41].

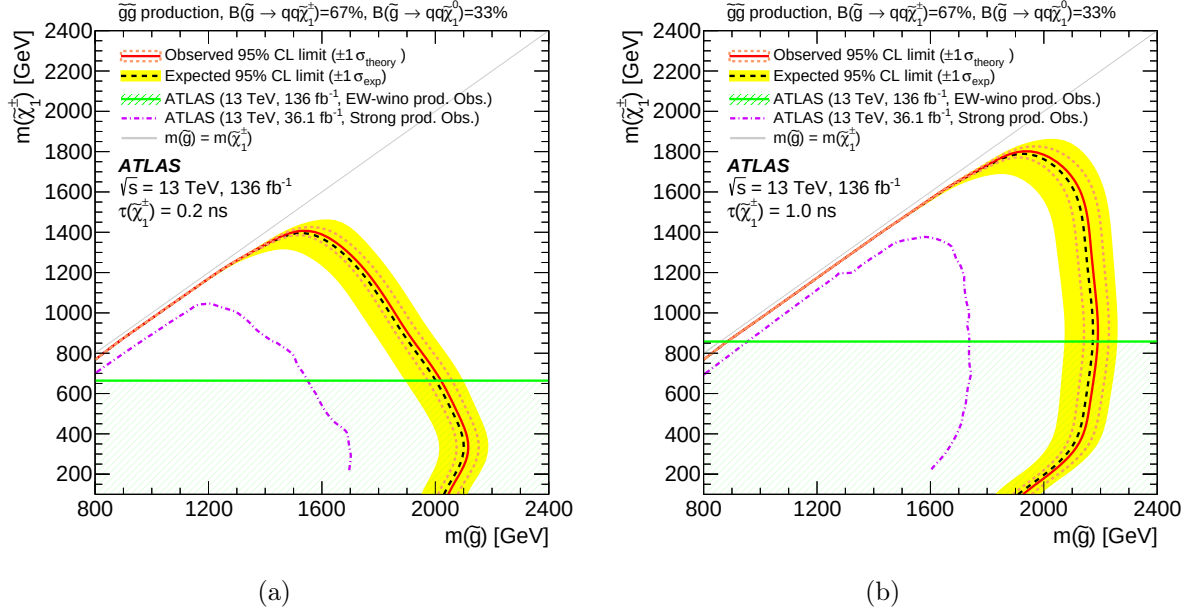


Figure 7.10: Exclusion limits at 95% CL obtained in the strong production channel. The limits are shown as a function of the lightest chargino's mass versus the gluino's mass, for chargino lifetimes of (a) 0.2 ns and (b) 1.0 ns. The black dashed line shows the median expected value, and the yellow band shows the  $1\sigma$  uncertainty around the expected limits. The red line shows the observed limits and the red dotted lines show the  $1\sigma$  uncertainty from the signal cross-section. The observed exclusion limits from this search in the direct electroweak wino production channel in the minimal AMSB model with (a)  $\tau_{\tilde{\chi}_1^\pm} = 0.2 \text{ ns}$  and (b)  $\tau_{\tilde{\chi}_1^\pm} = 1.0 \text{ ns}$  are overlaid in green. The violet broken line shows the observed limits from the previous ATLAS result [45].

## Chapter 8

# Reinterpretation of Physics Results

As described in Chapter 3, BSM theories such as SUSY often consist of a large range of models with different mechanisms and assumptions, predicting different particle phenomenology. Searches for new physics at modern experiments such as ATLAS typically search for only a small number of models to give context to the results of the search. However, a search may be applicable to a large range of models, or models that have not yet been defined by theorists. Reinterpretation is the process of establishing the sensitivity of an existing search result to models not considered in the original publication. Searches for LLPs, such as those discussed in Chapters 7 and 9, tend to be good targets for reinterpretation, as the searches are more motivated by experimental signatures rather than specific models, and the areas of phase-space targeted by LLP searches are usually uncovered by traditional searches.

Multiple techniques have been developed by both experimental physicists and theoreticians to enable the reinterpretation process. A selection of popular techniques is discussed in Section 8.1. The development and validation of novel reinterpretation materials for the analysis presented in Chapter 7 is described in Section 8.2. This is a reproduction of the auxiliary material published alongside [1], with minor changes to fit the context of this thesis. Finally, other searches by third parties reinterpreting this analysis are briefly discussed in Section ??, specifically a scan of pMSSM models performed by the ATLAS collaboration.

### 8.1 Methods of Result Reinterpretation

Multiple frameworks and methods are now routinely used by LHC and other collaborations to provide results to interested researchers. A selection of the most popular are detailed below, including the RECAST and SIMPLEANALYSIS frameworks, the HEPDATA database and statistical likelihoods.

#### RECAST

RECAST is an analysis preservation and reinterpretation framework which allows users to run new signal models through the published code of an analysis via an Application Programming Interface (API) [148]. An analysis is packaged within a docker container along with the software infrastructure necessary to support it. A user can then provide a set of Les Houches Event (LHE) files for a new signal model, and the RECAST API will process the full set and compare the signal yields to the background observation from the published results. New exclusion limits can then be defined. Collaborations which published the initial analysis can approve or withhold the results. An overview of this workflow is provided in Figure 8.1

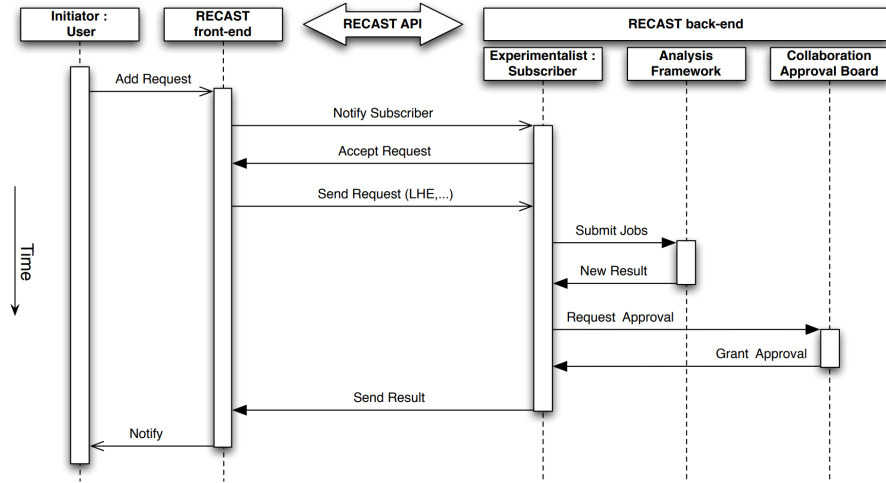


Figure 8.1: A schematic overview of the RECAST API showing how a researcher can submit a new signal model and receive results from the analysis framework. [148]

### SIMPLEANALYSIS

SIMPLEANALYSIS is a generator-level analysis framework for the reinterpretation of published analyses [149]. The concept is similar to RECAST, but much simpler as it does not attempt to use the original analysis code or reconstruct events. Originally developed as an internal ATLAS tool for HL-LHC and FCC sensitivity studies, it is now widely used for analysis preservation and reinterpretation. Experimental physicists provide a *selector*, a simple analysis script that defines signal regions (and optionally control and validation regions) with cuts on generator-level quantities. Quantities to be observed can be defined and plots can also be generated. Theoreticians then provide a sample generated from their model of interest, in either LHE format or ATLAS data formats. The theoretician can then run over any of the implemented analyses, which includes most recent ATLAS searches, and very quickly calculate event yields for each search which can be compared to published background yields.

SIMPLEANALYSIS includes the ability to smear the generator-level quantities, such as a particle's transverse momentum, to mimic the reconstructed version, and the inefficiencies associated.

SIMPLEANALYSIS also includes an emulation of the Run-2 and Run-4 ATLAS geometries, for studying future sensitivity. However, both of these features are internal to ATLAS.

### Likelihoods

Statistical likelihoods are produced internally for the vast majority of LHC searches [137, 150], via frameworks such as PYHF [151, 152] and HISTFITTER [153]. These encapsulate all parts of the statistical analysis including the yields and shapes of the background components and all statistical and systematic sources of uncertainty in a `json` object. This allows an interested researcher to calculate the yields and uncertainties of their signal models, and provide these as a *patch* which can be added to the provided `json` model and the confidence limits recomputed. The likelihoods are provided via HEPDATA.

### HEPDATA

Although not directly a reinterpretation technique, HEPDATA is vital to many reinterpretations. HEPDATA is a database of the data presented in plots and tables for publications [154]. As an example, the ROOT object representing an observed exclusion contour presented in a search paper can be directly provided, rather than estimating the contour from the image. Analysis code, such as a selector for SIMPLEANALYSIS, can also be provided, aiding other researchers in testing their models. An API is also provided in which records can be accessed within a program, allowing researchers to easily test their models against a wide set of searches.

## 8.2 Development of Novel Materials for Reinterpreting Searches for Disappearing Tracks

Three methods for the re-interpretation of the results published in this paper are outlined. The first method utilises the acceptance, efficiency and acceptance-times-efficiency maps in the mass-lifetime plane of the models explored in this paper. As such, this method is dependent on the model assumptions and is designed to be used for the re-interpretation of signals similar to those in this paper. For more model-independent re-interpretations, a second method is provided which factors out the model-dependent and reconstruction specific acceptance and efficiencies. This allows for the model dependencies to be replaced with the equivalent figures of the model of interest. The third method is a description of the analysis code using the SimpleAnalysis framework [155], which allows for individual events to be investigated.

### 8.2.1 Common material

To ease reinterpretation of the analysis, dedicated correction factors for the  $E_T^{\text{miss}}$  trigger and the tracklet transverse momenta smearing are provided below.



### 8.2.1.1 $E_T^{\text{miss}}$ trigger

The  $E_T^{\text{miss}}$  triggers have been parameterised as a function of  $E_T^{\text{miss}}$  and the leading jet  $p_T$ . They have then been averaged across the run periods. This is shown in Figure 8.2.

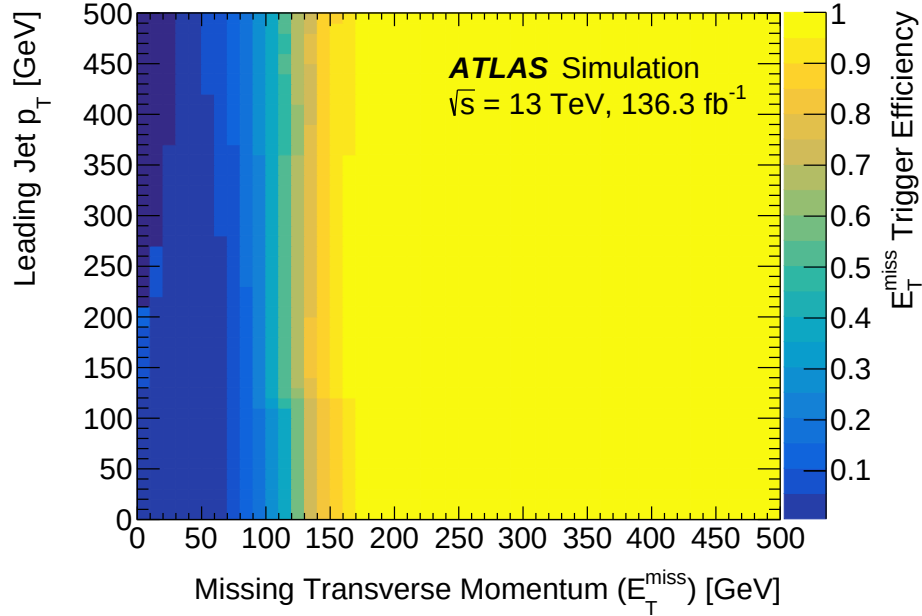


Figure 8.2: The trigger efficiency for reinterpretation, calculated using a weighted average over all run periods. It is parameterised as a function of  $E_T^{\text{miss}}$  and the leading jet  $p_T$ .

### 8.2.1.2 Tracklet $p_T$ smearing

As four-pixel-layer tracklets have a poor transverse momentum resolution due to the short lever arm (path length in the magnetic field), correct modelling of their momentum resolution is key to ensure the transverse momentum distributions in Monte Carlo simulations and measured data are comparable. Given the small number of measurements along the tracklet's trajectory, sensitivity to any errors in pattern recognition and any mis-modelling between Monte Carlo simulation and measured data is amplified.

Due to these effects, there are significant differences in the chargino transverse momentum resolution between Monte Carlo simulation and data. To account for this, at all points where the transverse momentum of a candidate tracklet is required, the smeared generator-level momentum is used. The generator-level chargino momentum is smeared using the functional form in Equation 7.4 and the electron smearing parameters in Table 7.4 in the paper.

### 8.2.1.3 Fiducial region

For the generator-level acceptance cuts, the fiducial region in which tracklets can be accepted is defined as the region in which a particle can pass through the outermost pixel barrel layer but not reach any SCT element (barrel or endcap). This region is also restricted to  $|\eta| > 0.1$  in the centre of the detector.

The fiducial region can then be defined through:

- charginos with a decay radius between 122.5 mm and 299 mm, and a pseudo-rapidity of  $0.1 < |\eta| < 1.649$  (tracks rejected by the first SCT barrel layer)
- charginos with a decay  $z$ -position less than 853.8 mm, and a pseudo-rapidity of  $1.649 < |\eta| < 1.658$  (tracks rejected by the first SCT endcap layer)
- charginos with a decay  $z$ -position less than 934 mm, and a pseudo-rapidity of  $1.658 < |\eta| < 1.9$  (tracks rejected by the second SCT endcap layer).

Charginos with a pseudorapidity greater than 1.9 are rejected as they do not hit the outermost pixel barrel layer. These definitions assume the charginos are produced at the origin of the detector.

## 8.2.2 Method 1 - event-level acceptance and efficiency in the mass-lifetime plane

The first and simplest reinterpretation method uses event-level acceptance and efficiency maps covering the signal model parameter space. The acceptance and efficiency maps are calculated for each signal point by dividing the number of events passing the signal region selection by the total number of events predicted by the model at that point (i.e. the cross-section times the luminosity). This method therefore includes any assumptions made about the signal model. The acceptance map is calculated on the basis of the generator-level information, by considering events which pass the event level selection in 7.1, and have at least one chargino which satisfies the requirements:

- chargino transverse momentum ( $p_T$ ) greater than 60 GeV,
- chargino pseudorapidity ( $\eta$ ) satisfying  $0.1 < |\eta| < 1.9$ ,
- chargino-jet conical separation ( $\Delta R_{min}(\tilde{\chi}_1^\pm, \text{Jet}_{1 \rightarrow 4, p_T > 50 \text{ GeV}})$ ) greater than 0.5,
- chargino decay radius is inside the fiducial volume defined in Section 8.2.1.3,

where  $\text{Jet}_{1 \rightarrow 4, p_T > 50 \text{ GeV}}$  refers to the four highest  $p_T$  jets with at least  $p_T > 50 \text{ GeV}$ . The efficiency map is then calculated by dividing the acceptance  $\times$  efficiency map by the acceptance map. The acceptance, efficiency and acceptance  $\times$  efficiency for benchmark signal points are

shown in Tables 8.1 and 8.2 for the electroweak and strong SRs respectively. These are used to compare the other reinterpretation methods.

Figures 8.3 and 8.5 show the chargino lifetime versus mass event-level acceptance  $\times$  efficiency maps for the electroweak wino and higgsino models respectively, in the electroweak SR. The strong production information is shown in Figure 8.7 for chargino lifetimes of 0.2 ns and 1.0 ns. The individual acceptance maps and efficiency maps are shown in Figures 8.4, 8.6, and 8.8, for the wino, higgsino and strong production models, respectively.

| Mass [GeV] | Lifetime [ns] | Acceptance $\times$ Efficiency | Acceptance            | Efficiency            |
|------------|---------------|--------------------------------|-----------------------|-----------------------|
| 400        | 0.2           | $2.87 \times 10^{-3}$          | $7.55 \times 10^{-3}$ | $3.80 \times 10^{-1}$ |
| 600        | 0.2           | $2.97 \times 10^{-3}$          | $7.40 \times 10^{-3}$ | $4.01 \times 10^{-1}$ |
| 600        | 1.0           | $9.49 \times 10^{-3}$          | $2.59 \times 10^{-2}$ | $3.66 \times 10^{-1}$ |
| 600        | 4.0           | $5.51 \times 10^{-3}$          | $1.64 \times 10^{-2}$ | $3.36 \times 10^{-1}$ |
| 600        | 10.0          | $2.80 \times 10^{-3}$          | $8.58 \times 10^{-3}$ | $3.27 \times 10^{-1}$ |
| 800        | 0.2           | $2.84 \times 10^{-3}$          | $6.93 \times 10^{-3}$ | $4.09 \times 10^{-1}$ |

Table 8.1: Acceptance, efficiency, and acceptance-times-efficiency values at the benchmark points for the electroweak wino SR.

| (Gluino, Wino) Mass [GeV] | Lifetime [ns] | Acceptance $\times$ Efficiency | Acceptance            | Efficiency            |
|---------------------------|---------------|--------------------------------|-----------------------|-----------------------|
| (1000, 900)               | 1.0           | $9.82 \times 10^{-3}$          | $3.27 \times 10^{-2}$ | $3.00 \times 10^{-1}$ |
| (1400, 1100)              | 0.2           | $5.53 \times 10^{-3}$          | $1.48 \times 10^{-2}$ | $3.74 \times 10^{-1}$ |
| (1400, 1100)              | 1.0           | $3.64 \times 10^{-2}$          | $1.02 \times 10^{-1}$ | $3.57 \times 10^{-1}$ |
| (1600, 500)               | 1.0           | $6.01 \times 10^{-2}$          | $1.73 \times 10^{-1}$ | $3.48 \times 10^{-1}$ |
| (1800, 900)               | 0.2           | $1.43 \times 10^{-2}$          | $4.26 \times 10^{-2}$ | $3.36 \times 10^{-1}$ |
| (1800, 900)               | 1.0           | $6.31 \times 10^{-2}$          | $1.79 \times 10^{-1}$ | $3.52 \times 10^{-1}$ |
| (2000, 1700)              | 1.0           | $3.45 \times 10^{-2}$          | $9.99 \times 10^{-2}$ | $3.45 \times 10^{-1}$ |
| (2200, 700)               | 1.0           | $6.49 \times 10^{-2}$          | $1.83 \times 10^{-1}$ | $3.55 \times 10^{-1}$ |

Table 8.2: Acceptance, efficiency, and acceptance-times-efficiency values at the benchmark points for the strong SR.

### 8.2.3 Method 2 - acceptance and efficiency components

In order to reduce the signal model dependency, a second method is presented which factors out the model-dependent factors into separate event- and tracklet-level acceptances and efficiencies. This allows these acceptances to be replaced by those calculated from a target model,

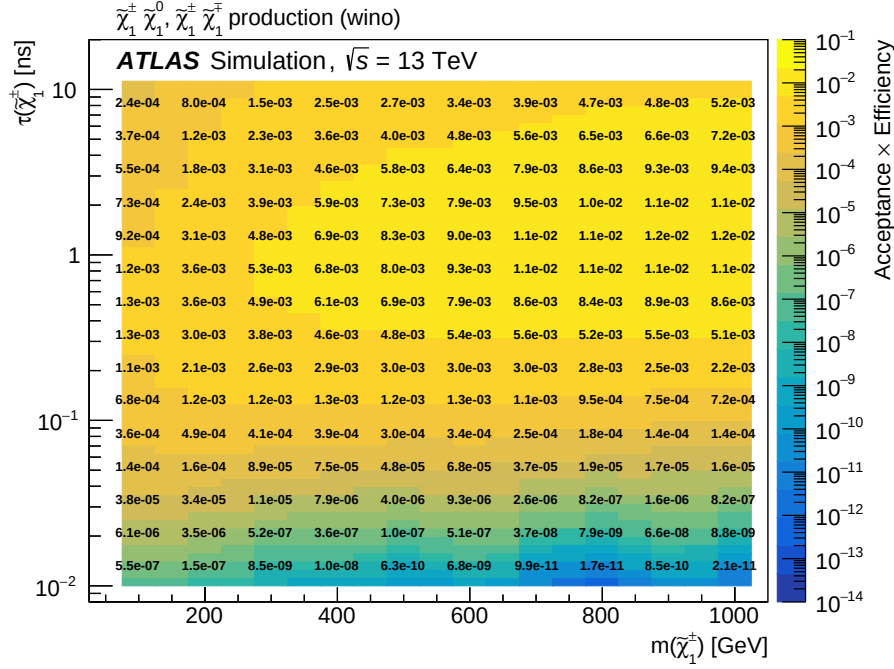


Figure 8.3: Event-level acceptance  $\times$  efficiency map for the wino model in the electroweak SR.

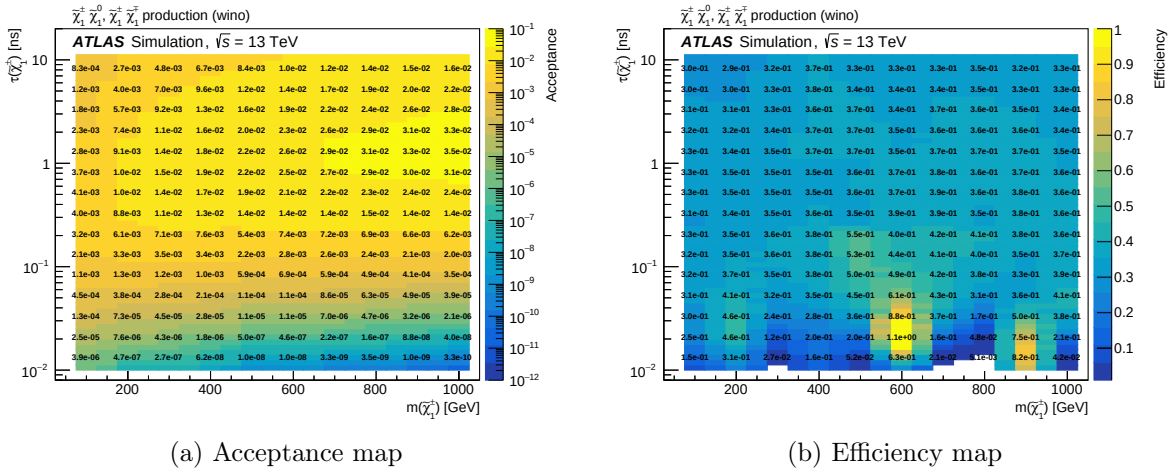


Figure 8.4: Individual event-level acceptance and efficiency maps for the wino model in the electroweak SR.

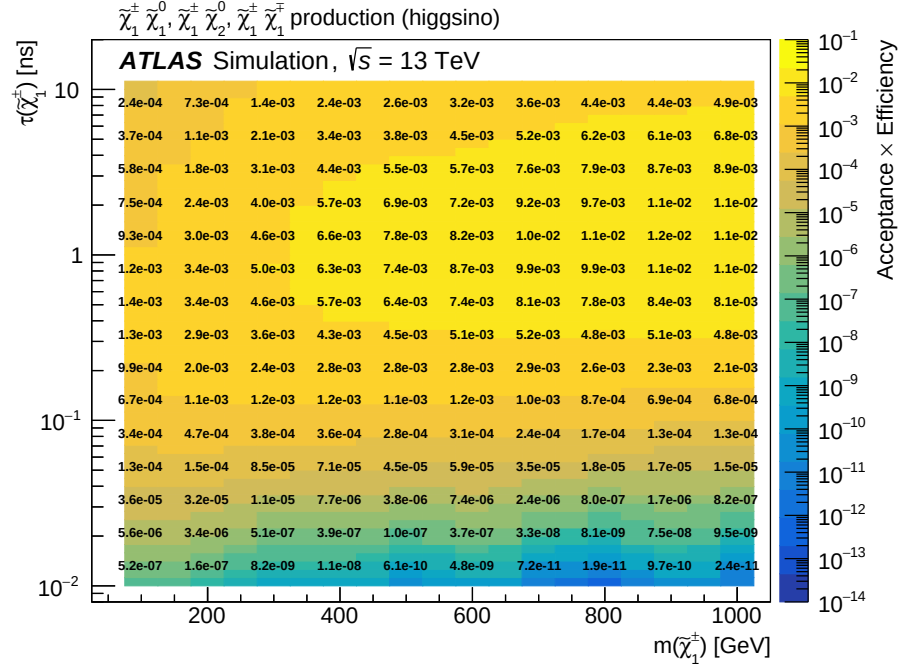
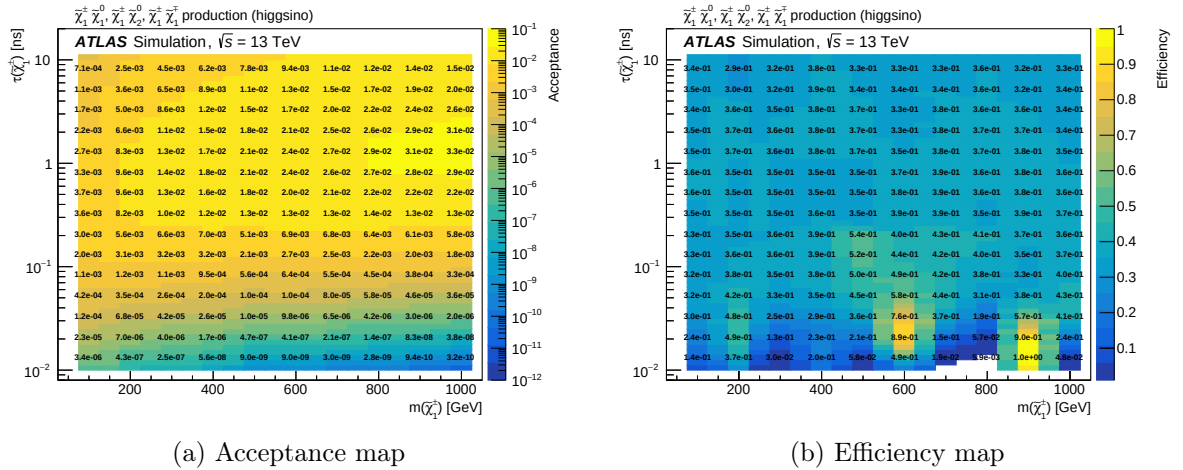


Figure 8.5: Event-level acceptance  $\times$  efficiency map for the higgsino model in the electroweak SR.



(a) Acceptance map

(b) Efficiency map

Figure 8.6: Individual event-level acceptance and efficiency maps for the higgsino model in the electroweak SR.

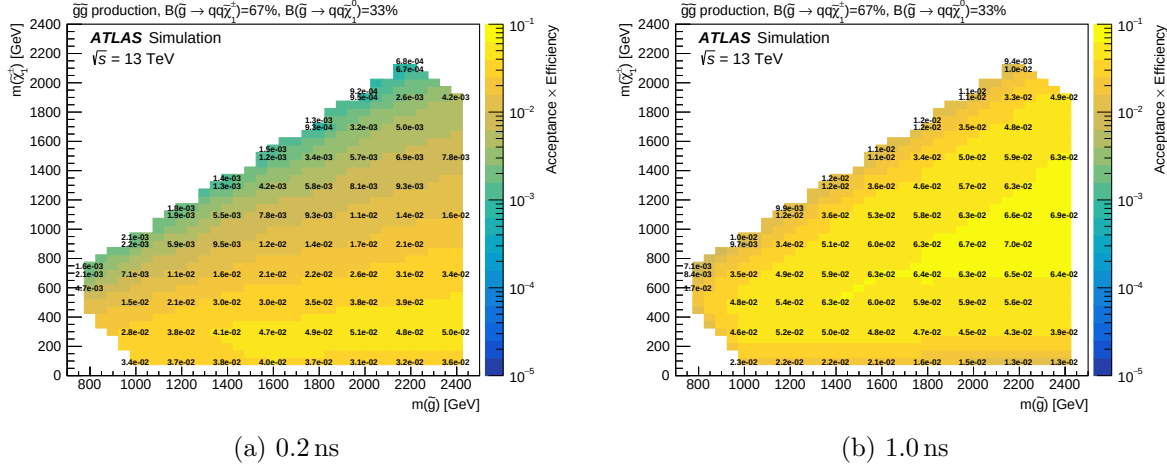


Figure 8.7: Event-level acceptance  $\times$  efficiency map for the gluino model in the strong SR.

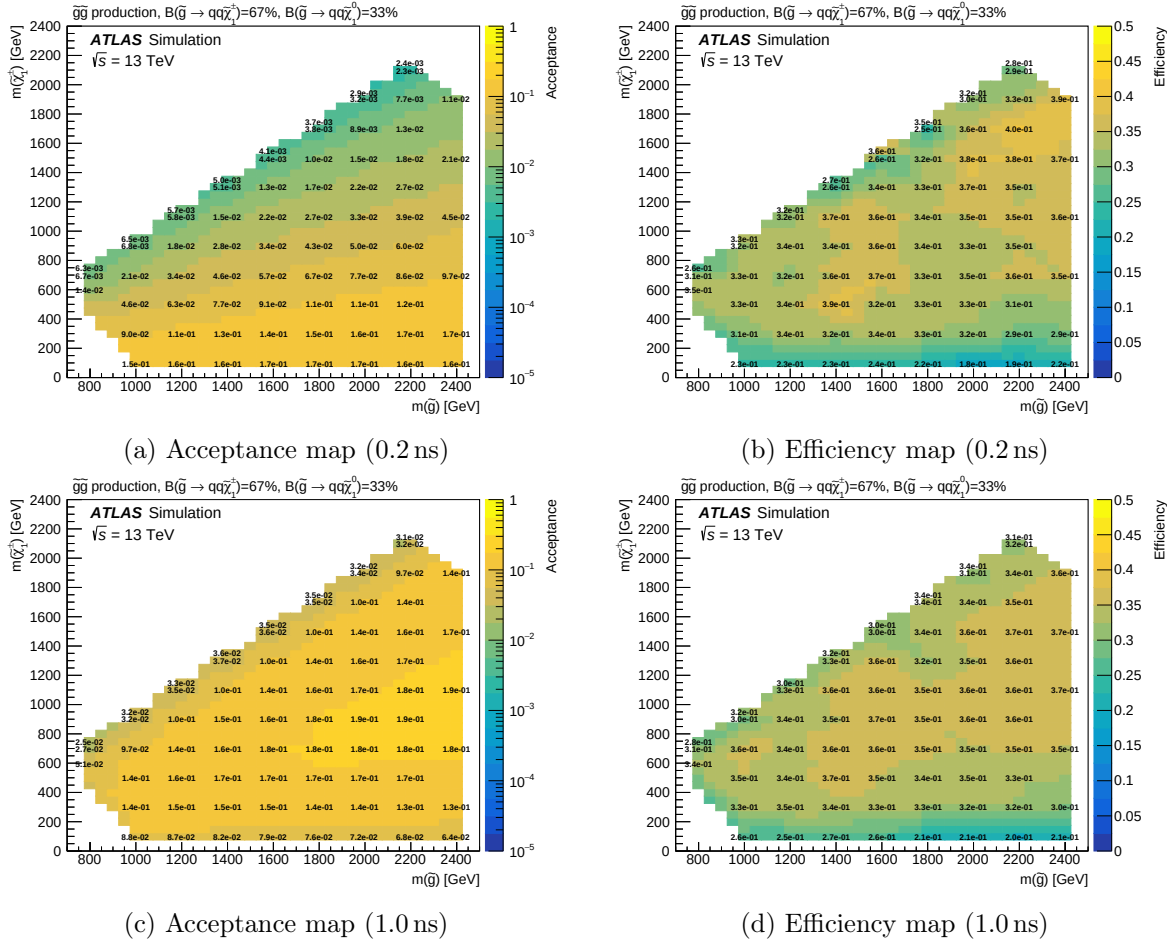


Figure 8.8: Individual event-level acceptance and efficiency maps for the gluino model in the strong SR.

and the event- and tracklet-level efficiencies can then be used to estimate how many of these events could be observed.

The following definitions are used for event- and tracklet-level acceptance and efficiency. For both the electroweak and strong production SRs, the object selection criteria and overlap removal described in Section 6.6 are applied.

### Event Acceptance ( $E_A$ )

For the electroweak SR, the numerator is defined as the number of generator-level events with:

- $E_T^{\text{miss}}$  greater than 200 GeV. The  $E_T^{\text{miss}}$  is calculated by summing information from all stable non-interacting particles including neutralinos.
- leading jet  $p_T$  greater than 100 GeV
- $E_T^{\text{miss}}$ -jet angular separation ( $\Delta\phi_{\min}(E_T^{\text{miss}}, \text{Jet}_{1 \rightarrow 4, p_T > 50 \text{ GeV}})$ ) greater than 1.0 rad
- lepton veto

For the strong SR, the numerator is defined as the number of generator-level events with:

- $E_T^{\text{miss}}$  greater than 250 GeV
- leading jet  $p_T$  greater than 100 GeV
- second- and third-leading jet  $p_T$  values greater than 20 GeV
- chargino-jet angular separation ( $\Delta\phi_{\min}(E_T^{\text{miss}}, \text{Jet}_{1 \rightarrow 4, p_T > 50 \text{ GeV}})$ ) greater than 0.4 rad
- lepton veto

The denominator is defined as the total number of generator events, calculated as the theoretical cross-section times by the measured luminosity. This means that the event acceptance is inclusive of any generator-level filters, such as the  $E_T^{\text{miss}} > 60 \text{ GeV}$  filter for the electroweak wino samples.

### Event Efficiency ( $E_E$ )

The numerator is defined to include the number of reconstruction-level events that pass the kinematic preselection in Table 7.1. This includes the trigger parameterisations. The denominator is defined as the number of events in the numerator of the event acceptance calculation. Due to the fact that this definition uses generator-level and reconstructed events, it is possible for this efficiency to be greater than unity.

### Tracklet Acceptance ( $T_A$ )

The numerator is defined to include the number of generator-level charginos with:

- $p_T$  greater than 20 GeV
- $0.1 < |\eta| < 1.9$
- chargino decay radius is inside the fiducial region, as defined in Section 8.2.1.3
- chargino-jet conical separation ( $\Delta R_{min}(\tilde{\chi}_1, \text{Jet}_{1 \rightarrow 4, p_T > 50 \text{ GeV}})$ ) greater than 0.5

The denominator is defined to include the number of generator-level charginos in the events considered (i.e. the cross-section times the luminosity times the number of charginos in that process times the generator efficiency). This ensures that the generator efficiency has not been considered multiple times.

### Tracklet Efficiency ( $T_E$ )

The numerator is defined to include the number of reconstruction-level tracks that pass the tracklet selection, in events that pass the appropriate event selection. The selections are defined in Section 6.1.2. This includes the dead-pixel-module scale factor and the use of a smeared transverse momentum taken from a generator-level chargino which corresponds to the tracklet. The denominator is defined as the number of tracklets in the numerator of the tracklet acceptance, times the event efficiency (this accounts for the difference between the generator-level acceptance, and the reconstructed-level event efficiency). Due to the fact that this definition uses generator-level and reconstructed events, it is possible for this efficiency to be greater than unity.

### Model-Independent Tracklet Efficiency ( $T_{60}$ )

The numerator is defined as the number of tracklets passing the efficiency selection with a smeared transverse momentum greater than 60 GeV. The denominator is defined as the number of tracklets in the numerator of the tracklet efficiency. This represents the fraction of tracklets with a smeared transverse momentum greater than 60 GeV, and helps to provide a more model-independent limit.

#### 8.2.3.1 Calculated values

The generator-level acceptances were calculated using SimpleAnalysis as described above. As the charginos are generated as stable and only decayed during the detector simulation, some charginos may mistakenly be clustered into a jet at generator level. Any jet containing a chargino as a constituent is removed.

The event-level acceptances and efficiencies, and tracklet-level acceptance and efficiencies for selected models are shown in Tables 8.3 and 8.4, and in Tables 8.5 and 8.6, for the electroweak and strong processes, respectively.



| Mass<br>[GeV] | Lifetime<br>[ns] | Event                            |                                  |
|---------------|------------------|----------------------------------|----------------------------------|
|               |                  | Acceptance ( $E_A$ )             | Efficiency ( $E_E$ )             |
| 400           | 0.2              | $(7.78 \pm 0.19) \times 10^{-2}$ | $(9.38 \pm 0.11) \times 10^{-1}$ |
| 600           | 0.2              | $(1.01 \pm 0.05) \times 10^{-1}$ | $(9.37 \pm 0.04) \times 10^{-1}$ |
|               | 1.0              | $(1.01 \pm 0.05) \times 10^{-1}$ | $(9.38 \pm 0.04) \times 10^{-1}$ |
|               | 4.0              | $(1.00 \pm 0.05) \times 10^{-1}$ | $(9.43 \pm 0.06) \times 10^{-1}$ |
|               | 10.0             | $(1.01 \pm 0.05) \times 10^{-1}$ | $(8.97 \pm 0.04) \times 10^{-1}$ |
| 800           | 0.2              | $(1.19 \pm 0.12) \times 10^{-1}$ | $(9.28 \pm 0.11) \times 10^{-1}$ |

Table 8.3: Calculated values for electroweak event acceptance and efficiency, as defined in Section 8.2.3. Uncertainties are statistical only.

| Mass<br>[GeV] | Lifetime<br>[ns] | Tracklet                           |                                    |                                  |
|---------------|------------------|------------------------------------|------------------------------------|----------------------------------|
|               |                  | Acceptance ( $T_A$ )               | Efficiency ( $T_E$ )               | $p_T > 60$ GeV ( $T_{60}$ )      |
| 400           | 0.2              | $(7.91 \pm 0.20) \times 10^{-2}$   | $(3.81 \pm 0.12) \times 10^{-1}$   | $(7.3 \pm 0.6) \times 10^{-1}$   |
| 600           | 0.2              | $(5.98 \pm 0.07) \times 10^{-2}$   | $(3.87 \pm 0.14) \times 10^{-1}$   | $(7.52 \pm 0.29) \times 10^{-1}$ |
|               | 1.0              | $(2.162 \pm 0.014) \times 10^{-1}$ | $(3.561 \pm 0.025) \times 10^{-1}$ | $(7.50 \pm 0.15) \times 10^{-1}$ |
|               | 4.0              | $(1.341 \pm 0.015) \times 10^{-1}$ | $(3.48 \pm 0.04) \times 10^{-1}$   | $(7.33 \pm 0.27) \times 10^{-1}$ |
|               | 10.0             | $(6.87 \pm 0.07) \times 10^{-2}$   | $(3.62 \pm 0.04) \times 10^{-1}$   | $(7.28 \pm 0.28) \times 10^{-1}$ |
| 800           | 0.2              | $(4.20 \pm 0.14) \times 10^{-1}$   | $(4.20 \pm 0.14) \times 10^{-1}$   | $(7.4 \pm 0.7) \times 10^{-1}$   |

Table 8.4: Calculated values for electroweak tracklet acceptance and efficiency, as defined in Section 8.2.3. Uncertainties are statistical only.

### 8.2.3.2 Usage

The calculated values in the previous section can be used for the purpose of re-interpreting the data in the context of a wide range of models. For models different than those explored in this paper, the acceptances should be computed for that model using the definitions outlined above, while the event- and tracklet-level efficiencies for the corresponding signal region should be used. The average efficiencies for the electroweak SR event- and tracklet-level efficiencies are  $0.9366 \pm 0.0032$  % and  $0.3747 \pm 0.0028$  %, respectively. For the strong SR, the efficiencies are  $0.893 \pm 0.004$  % and  $0.316 \pm 0.006$  % respectively. The uncertainties are statistical only. The 10.0 ns lifetime samples have been excluded from the above averages since a significant number of charginos are reconstructed by the standard ATLAS tracking, which has a performance that is different from that of the dedicated pixel-tracklet reconstruction. As such, the efficiencies are statistically different. For charged particles with proper lifetimes below 10.0 ns;

| Gluino Mass<br>[GeV] | Wino Mass<br>[GeV] | Lifetime<br>[ns] | Event                              |                                  |
|----------------------|--------------------|------------------|------------------------------------|----------------------------------|
|                      |                    |                  | Acceptance ( $E_A$ )               | Efficiency ( $E_E$ )             |
| 1000                 | 900                | 1.0              | $(1.200 \pm 0.021) \times 10^{-1}$ | $(9.04 \pm 0.22) \times 10^{-1}$ |
| 1400                 | 1100               | 0.2              | $(4.17 \pm 0.08) \times 10^{-1}$   | $(9.26 \pm 0.12) \times 10^{-1}$ |
| 1400                 | 1100               | 1.0              | $(4.22 \pm 0.08) \times 10^{-1}$   | $(9.27 \pm 0.12) \times 10^{-1}$ |
| 1600                 | 500                | 1.0              | $(6.81 \pm 0.06) \times 10^{-1}$   | $(8.63 \pm 0.09) \times 10^{-1}$ |
| 1800                 | 900                | 0.2              | $(6.90 \pm 0.35) \times 10^{-1}$   | $(8.76 \pm 0.09) \times 10^{-1}$ |
| 1800                 | 900                | 1.0              | $(6.89 \pm 0.35) \times 10^{-1}$   | $(8.76 \pm 0.09) \times 10^{-1}$ |
| 2000                 | 1700               | 1.0              | $(4.44 \pm 0.05) \times 10^{-1}$   | $(9.40 \pm 0.12) \times 10^{-1}$ |
| 2200                 | 700                | 1.0              | $(7.16 \pm 0.06) \times 10^{-1}$   | $(8.58 \pm 0.09) \times 10^{-1}$ |

Table 8.5: Calculated values for strong event acceptance and efficiency, as defined in Section 8.2.3. Uncertainties are statistical only.

the average values above are recommended, otherwise the 10.0 ns efficiencies should be used. The remainder of this section outlines the procedure for application of the efficiencies and acceptances.

The probability of having at least one reconstructed, selected tracklet with  $p_T > 20$  GeV in an event where  $N$  charginos are emitted can be calculated as:  $E_A \times E_E \times \left(1 - (1 - T_A \times T_E)^N\right)$  where  $E_A$  is the event acceptance,  $E_E$  is the event efficiency,  $T_A$  is the tracklet acceptance,  $T_E$  is the tracklet efficiency, respectively.

The acceptance ( $A_{M1}$ ) times efficiency ( $E_{M1}$ ) values shown in Section 8.2.2 can be recovered with

$$A_{M1} \times E_{M1} = E_A \times E_E \times \left[ \left(1 - (1 - T_A \times T_E)^2\right) \times \frac{\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)}{\sigma_{tot}} + (1 - (1 - T_A \times T_E)) \times \frac{\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^0)}{\sigma_{tot}} \right], \quad (8.1)$$

where  $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$  is the  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  cross-section at the chosen chargino mass and lifetime,  $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^0)$  is the  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  cross-section, and  $\sigma_{tot}$  is the sum of  $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$  and  $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^0)$ , respectively.

The term of Equation 8.1

$$\left(1 - (1 - T_A \times T_E)^2\right) \times \frac{\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)}{\sigma_{tot}},$$

gives the probability that either of the charginos in the  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  production are in the acceptance

| Gluino Mass<br>[GeV] | Wino Mass<br>[GeV] | Lifetime<br>[ns] | Tracklet                           |                                  |                                     |
|----------------------|--------------------|------------------|------------------------------------|----------------------------------|-------------------------------------|
|                      |                    |                  | Acceptance ( $T_A$ )               | Efficiency ( $T_E$ )             | $p_T > 60 \text{ GeV}$ ( $T_{60}$ ) |
| 1000                 | 900                | 1.0              | $(2.41 \pm 0.08) \times 10^{-1}$   | $(2.77 \pm 0.16) \times 10^{-1}$ | $(7.4 \pm 0.9) \times 10^{-1}$      |
| 1400                 | 1100               | 0.2              | $(2.94 \pm 0.13) \times 10^{-2}$   | $(3.37 \pm 0.27) \times 10^{-1}$ | $(7.2 \pm 1.1) \times 10^{-1}$      |
| 1400                 | 1100               | 1.0              | $(2.20 \pm 0.04) \times 10^{-1}$   | $(3.16 \pm 0.19) \times 10^{-1}$ | $(7.6 \pm 0.4) \times 10^{-1}$      |
| 1600                 | 500                | 1.0              | $(2.267 \pm 0.032) \times 10^{-1}$ | $(3.18 \pm 0.33) \times 10^{-1}$ | $(7.46 \pm 0.35) \times 10^{-1}$    |
| 1800                 | 900                | 0.2              | $(5.24 \pm 0.14) \times 10^{-2}$   | $(3.44 \pm 0.15) \times 10^{-1}$ | $(7.4 \pm 0.7) \times 10^{-1}$      |
| 1800                 | 900                | 1.0              | $(2.311 \pm 0.032) \times 10^{-1}$ | $(3.13 \pm 0.07) \times 10^{-1}$ | $(7.56 \pm 0.34) \times 10^{-1}$    |
| 2000                 | 1700               | 1.0              | $(2.01 \pm 0.04) \times 10^{-1}$   | $(3.04 \pm 0.1) \times 10^{-1}$  | $(7.7 \pm 0.4) \times 10^{-1}$      |
| 2200                 | 700                | 1.0              | $(2.298 \pm 0.031) \times 10^{-1}$ | $(3.19 \pm 0.07) \times 10^{-1}$ | $(7.51 \pm 0.34) \times 10^{-1}$    |

Table 8.6: Calculated values for strong tracklet acceptance and efficiency, as defined in Section 8.2.3. Uncertainties are statistical only.

region and are selected. The fraction  $\frac{\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)}{\sigma_{tot}}$  is approximately equal to  $\frac{1}{3}$ . Likewise, the term of Equation 8.1

$$(1 - (1 - T_A \times T_E)) \times \frac{\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^0)}{\sigma_{tot}},$$

gives the probability of the chargino in a  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  event being in the acceptance region and selected.

An example of this calculation for the  $m(\tilde{\chi}_1^\pm) = 600 \text{ GeV}$ ,  $\tau(\tilde{\chi}_1^\pm) = 4.0 \text{ ns}$  sample, with  $E_A = 0.100$ ,  $E_E = 0.943$ ,  $T_A = 0.1341$ ,  $T_E = 0.348$ ,  $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp) = 9.12 \text{ fb}$  and  $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_1^0) = 19.37 \text{ fb}$  gives

$$0.1 \times 0.943 \times \left[ \left( 1 - (1 - 0.1341 \times 0.348)^2 \right) \times 0.32 + (1 - (1 - 0.1341 \times 0.348)) \times 0.68 \right] = 0.00574$$

which agrees well with the acceptance-times-efficiency from Method 1.

The recovered acceptance-times-efficiency for a selection of signal samples is shown in Table 8.7 and compared to the values of acceptance-times-efficiency from Method 1. Good agreement is obtained throughout.

For the strong SR, the gluinos can decay according to  $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ ,  $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^-$  and  $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^+$ , with probability  $\frac{1}{3}$  for each. Therefore,  $\frac{4}{9}$  of the events will contain two charginos,  $\frac{4}{9}$  of the events will contain one chargino, and  $\frac{1}{9}$  of the events will not contain any charginos. The

| Mass<br>[GeV] | Lifetime<br>[ns] | Electroweak Acceptance $\times$ Efficiency |                                  |              |
|---------------|------------------|--------------------------------------------|----------------------------------|--------------|
|               |                  | Method 1                                   | Method 2                         | M2/M1 [%]    |
| 400           | 0.2              | $2.87 \times 10^{-3}$                      | $(2.88 \pm 0.27) \times 10^{-3}$ | $100 \pm 9$  |
| 600           | 0.2              | $2.97 \times 10^{-3}$                      | $(2.87 \pm 0.30) \times 10^{-3}$ | $97 \pm 10$  |
|               | 1.0              | $9.49 \times 10^{-3}$                      | $(9.4 \pm 0.7) \times 10^{-3}$   | $99 \pm 7$   |
|               | 4.0              | $5.51 \times 10^{-3}$                      | $(5.7 \pm 0.5) \times 10^{-3}$   | $104 \pm 9$  |
|               | 10.0             | $2.80 \times 10^{-3}$                      | $(2.95 \pm 0.24) \times 10^{-3}$ | $105 \pm 9$  |
| 800           | 0.2              | $2.84 \times 10^{-3}$                      | $(2.9 \pm 0.5) \times 10^{-3}$   | $101 \pm 18$ |

Table 8.7: Comparison of the Method 1 electroweak acceptance times efficiency values from Table 8.1 and the values calculated from Tables 8.3 and 8.4 using Equation 8.1. Errors are statistical only, and are propagated from Tables 8.3 and 8.4.

equation to recover an overall acceptance-times-efficiency then takes the form

$$A_{M1} \times E_{M1} = E_A \times E_E \times \left[ \left( 1 - (1 - T_A \times T_E)^2 \right) \times \frac{4}{9} + (1 - (1 - T_A \times T_E)) \times \frac{4}{9} \right] \quad (8.2)$$

where the parameters  $E_A$ ,  $E_E$ ,  $T_A$  and  $T_E$  take the same definitions as before. The recovered values of acceptance-times-efficiency for the selected strong SR samples are shown in Table 8.8.

| Gluino Mass<br>[GeV] | Wino Mass<br>[GeV] | Lifetime<br>[ns] | Strong Acceptance $\times$ Efficiency |                                  |              |
|----------------------|--------------------|------------------|---------------------------------------|----------------------------------|--------------|
|                      |                    |                  | Method 1                              | Method 2                         | M2/M1 [%]    |
| 1000                 | 900                | 1.0              | $9.82 \times 10^{-3}$                 | $(9.4 \pm 1.2) \times 10^{-3}$   | $95 \pm 13$  |
| 1400                 | 1100               | 0.2              | $5.53 \times 10^{-3}$                 | $(5.1 \pm 0.8) \times 10^{-3}$   | $92 \pm 14$  |
| 1400                 | 1100               | 1.0              | $3.64 \times 10^{-2}$                 | $(3.54 \pm 0.28) \times 10^{-2}$ | $97 \pm 8$   |
| 1600                 | 500                | 1.0              | $6.01 \times 10^{-2}$                 | $(5.5 \pm 0.8) \times 10^{-2}$   | $92 \pm 13$  |
| 1800                 | 900                | 0.2              | $1.43 \times 10^{-2}$                 | $(1.44 \pm 0.19) \times 10^{-2}$ | $101 \pm 13$ |
| 1800                 | 900                | 1.0              | $6.31 \times 10^{-2}$                 | $(5.7 \pm 0.6) \times 10^{-2}$   | $90 \pm 9$   |
| 2000                 | 1700               | 1.0              | $3.45 \times 10^{-2}$                 | $(3.33 \pm 0.24) \times 10^{-2}$ | $97 \pm 7$   |
| 2200                 | 700                | 1.0              | $6.49 \times 10^{-2}$                 | $(5.86 \pm 0.32) \times 10^{-2}$ | $90 \pm 5$   |

Table 8.8: Comparison of the Method 1 strong acceptance times efficiency values from Table 8.2 and the values calculated from Tables 8.5 and 8.6 using Equation 8.2. Errors are statistical only, and propagated from Tables 8.5 and 8.6.

### 8.2.4 Method 3 - SimpleAnalysis

SimpleAnalysis is a generator-level analysis preservation framework which can be used to generate reinterpretation material such as HEPData. SimpleAnalysis reads in generator-level objects and provides access to high-level analysis objects such as electrons and jets, at a variety of working points. However, lower-level objects such as tracks are not available. As the majority of this analysis requires information that is unavailable for these tracks, this has to be emulated by selecting generator-level charginos statistically using a reconstruction and selection probability map. The selection maps are parameterised in terms of the pseudorapidity and decay radius of the generator-level chargino.

The SimpleAnalysis code can be used to investigate individual events, as well as to calculate overall acceptance-times-efficiency values.

#### 8.2.4.1 Reconstruction and selection probability maps

To emulate the reconstruction and selection of charginos in SimpleAnalysis, the probability of a generator-level chargino being both reconstructed and selected needs to be parameterised. To achieve this, generator-level charginos contained in the Monte Carlo sample are compared with the number of tracklets found after a customised selection.

This selection begins with the same object definitions as described in Chapter 6, and the strong or electroweak reconstructed-level event selection. The denominator of the selection map is defined at this point as the number of generator-level charginos in these events. The numerator of the selection map is found by applying the reconstructed-level tracklet selection defined in Section 6.1.2, except the transverse momentum requirement, which can be applied in SimpleAnalysis. Figure 8.9 shows the tracklet reconstruction and selection probability maps for SimpleAnalysis. As the map is parameterised in terms of the generator-level chargino decay radius and pseudorapidity, a truth-matching requirement is also applied to the tracklet to retrieve the generator-level chargino that was reconstructed as the candidate tracklet. This truth matching uses a weighted hit-based calculation, wherein the weighted number of measurements associated with the simulated chargino's track divided by the weighted total number of all measurements on the track define a truth-matching score. A chargino is considered matched when this score is greater than 0.5. The chargino reconstruction and selection probability can then be defined as the number of truth-matched tracklets divided by the total number of generator-level charginos, in events which passed the event-level selections.

This process is performed for each of the pseudorapidity and decay radius bins to define the selection probability map. Furthermore, to improve the statistical uncertainties, the selection probability map is calculated by integrating over signal samples of different lifetimes and mass, as no significant dependence on these parameters was found.

#### 8.2.4.2 Usage

The provided SimpleAnalysis code returns information on whether a given generator-level event passes the signal-region selection in the paper. In the code, the decay radius and pseudorapidity of each generator-level chargino is used to retrieve a probability from the corresponding bin in the selection map. This is compared to a uniformly-distributed random number between 0 and 1; if the random number is less than the retrieved probability, the chargino is considered to have passed the reconstruction and selection and, once smeared, is represented by a tracklet.

#### 8.2.4.3 SimpleAnalysis validation and comparison

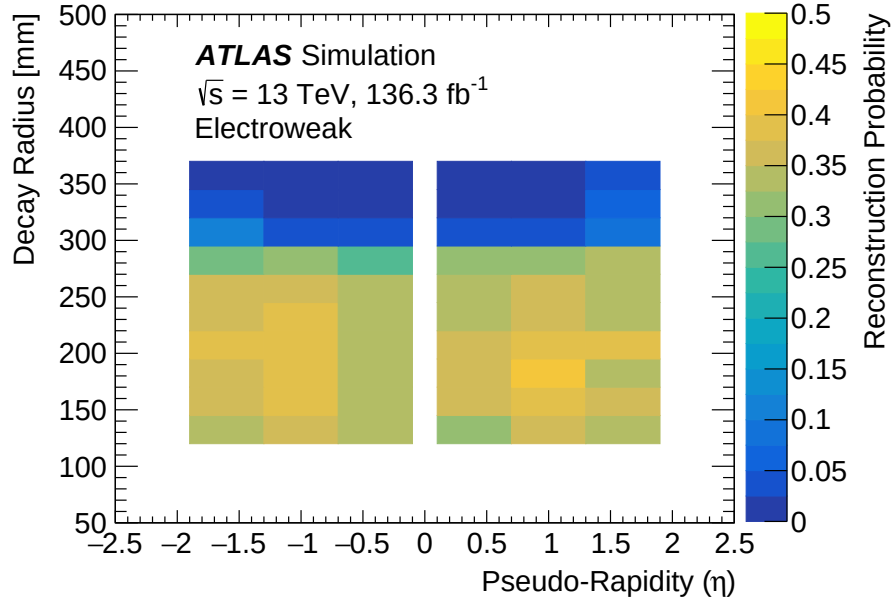
SimpleAnalysis uses standardised detector smearing to ensure that kinematic quantities such as  $E_T^{\text{miss}}$  have values similar to those observed in the simulated Monte Carlo samples. The effect of the smearing was assessed and found to have percent-level effects on the results.

To explore any difference between the SimpleAnalysis implementation and the main analysis, a cut-flow comparison for the 600 GeV 0.2 ns electroweak case was performed. Good agreement is found between the two approaches with the maximum difference of 7%. In addition, closure tests were performed on the selection maps using the generator-level information in the simulated Monte Carlo samples, and in these tests the emulation generally agrees to within a few percent, as shown in Table 8.9 and Table 8.11.

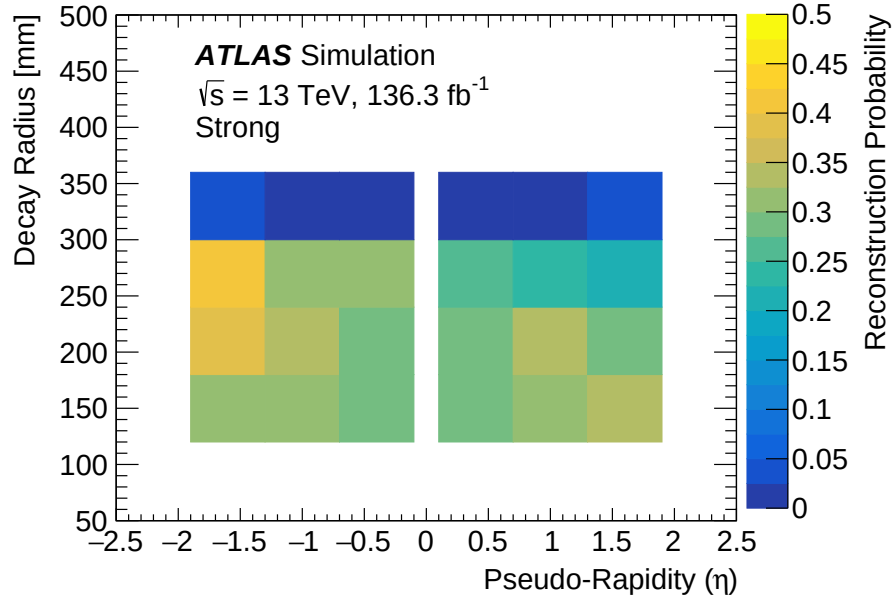
| Mass<br>[GeV] | Lifetime<br>[ns] | Electroweak Number of Events    |                                 |                  |
|---------------|------------------|---------------------------------|---------------------------------|------------------|
|               |                  | Full Analysis                   | Closure Test                    | Closure/Full [%] |
| 400           | 0.2              | $(6.94 \pm 0.29) \times 10^1$   | $(6.21 \pm 0.29) \times 10^1$   | 89.5             |
| 600           | 0.2              | $(1.119 \pm 0.021) \times 10^1$ | $(1.087 \pm 0.022) \times 10^1$ | 97.1             |
|               | 1.0              | $(3.72 \pm 0.04) \times 10^1$   | $(3.71 \pm 0.04) \times 10^1$   | 99.6             |
|               | 4.0              | $(2.25 \pm 0.04) \times 10^1$   | $(2.28 \pm 0.04) \times 10^1$   | 101.2            |
|               | 10.0             | $(1.153 \pm 0.021) \times 10^1$ | $(1.149 \pm 0.022) \times 10^1$ | 99.7             |

Table 8.9: Comparison of the number of signal events passed by the main analysis, and those passed using the selection maps in a closure test for the electroweak case, showing good agreement throughout.

Table 8.10 shows a comparison of the results of the SimpleAnalysis method with the Method 1 results from Table 8.1 for the electroweak case. This shows good agreement. Table 8.12



(a) The tracklet reconstruction and selection probability map for SimpleAnalysis for the electroweak SR.



s

(b) The tracklet reconstruction and selection probability map for SimpleAnalysis for the strong SR.

Figure 8.9: The tracklet reconstruction and selection probability maps for SimpleAnalysis. These parameterise the probability of a chargino being reconstructed and selected, excluding some kinematic requirements such as track transverse momentum, which are applied in the SimpleAnalysis program. These maps are parameterised as a function of the generator-level chargino pseudorapidity and decay radius.

shows a comparison of the results of the SimpleAnalysis method with the Method 1 results from Table 8.2 for the strong case.

| Mass<br>[GeV] | Lifetime<br>[ns] | Electroweak Acceptance $\times$ Efficiency |                                  |                 |
|---------------|------------------|--------------------------------------------|----------------------------------|-----------------|
|               |                  | Method 1                                   | Method 3                         | M3/M1 [%]       |
| 400           | 0.2              | $2.87 \times 10^{-3}$                      | $(3.12 \pm 0.13) \times 10^{-3}$ | $109 \pm 7$     |
| 600           | 0.2              | $2.97 \times 10^{-3}$                      | $(2.82 \pm 0.05) \times 10^{-3}$ | $94.9 \pm 2.7$  |
|               | 1.0              | $9.49 \times 10^{-3}$                      | $(9.79 \pm 0.1) \times 10^{-3}$  | $103.2 \pm 1.5$ |
|               | 4.0              | $5.51 \times 10^{-3}$                      | $(6.03 \pm 0.1) \times 10^{-3}$  | $109.4 \pm 2.8$ |
|               | 10.0             | $2.80 \times 10^{-3}$                      | $(3.06 \pm 0.05) \times 10^{-3}$ | $109.3 \pm 2.9$ |
| 800           | 0.2              | $2.84 \times 10^{-3}$                      | $(2.73 \pm 0.13) \times 10^{-3}$ | $96 \pm 7$      |

Table 8.10: Comparison of the Method 1 acceptance times efficiency values from Table 8.1 and the results of the SimpleAnalysis for the electroweak case.

| Gluino Mass<br>[GeV] | Wino Mass<br>[GeV] | Lifetime<br>[ns] | Strong Number of Events       |                               |                  |
|----------------------|--------------------|------------------|-------------------------------|-------------------------------|------------------|
|                      |                    |                  | Full Analysis                 | Closure Test                  | Closure/Full [%] |
| 1000                 | 900                | 1.0              | $(5.22 \pm 0.29) \times 10^2$ | $(5.85 \pm 0.33) \times 10^2$ | 112.1            |
| 1400                 | 1100               | 0.2              | $(1.99 \pm 0.15) \times 10^1$ | $(2.01 \pm 0.16) \times 10^1$ | 101.3            |
| 1400                 | 1100               | 1.0              | $(1.40 \pm 0.04) \times 10^2$ | $(1.36 \pm 0.04) \times 10^2$ | 97.7             |
| 1600                 | 500                | 1.0              | $(6.88 \pm 0.16) \times 10^1$ | $(6.79 \pm 0.17) \times 10^1$ | 98.7             |
| 1800                 | 900                | 0.2              | $(5.93 \pm 0.26) \times 10^0$ | $(5.65 \pm 0.28) \times 10^0$ | 95.3             |
| 1800                 | 900                | 1.0              | $(2.37 \pm 0.05) \times 10^1$ | $(2.41 \pm 0.06) \times 10^1$ | 101.7            |
| 2000                 | 1700               | 1.0              | $(4.73 \pm 0.14) \times 10^0$ | $(5.03 \pm 0.15) \times 10^0$ | 106.4            |
| 2200                 | 700                | 1.0              | $(2.92 \pm 0.06) \times 10^0$ | $(2.90 \pm 0.07) \times 10^0$ | 99.3             |

Table 8.11: Comparison of the number of signal events passed by the main analysis, and those passed using the selection maps in a closure test for the strong case, showing good agreement throughout.



| Gluino Mass<br>[GeV] | Wino Mass<br>[GeV] | Lifetime<br>[ns] | Strong Acceptance $\times$ Efficiency |                                    |                 |
|----------------------|--------------------|------------------|---------------------------------------|------------------------------------|-----------------|
|                      |                    |                  | Method 1                              | Method 3                           | M3/M1 [%]       |
| 1000                 | 900                | 1.0              | $9.82 \times 10^{-3}$                 | $(1.11 \pm 0.06) \times 10^{-2}$   | $113 \pm 9$     |
| 1400                 | 1100               | 0.2              | $5.53 \times 10^{-3}$                 | $(5.1 \pm 0.4) \times 10^{-3}$     | $91 \pm 11$     |
| 1400                 | 1100               | 1.0              | $3.64 \times 10^{-2}$                 | $(3.709 \pm 0.015) \times 10^{-2}$ | $101.9 \pm 0.6$ |
| 1600                 | 500                | 1.0              | $6.01 \times 10^{-2}$                 | $(5.85 \pm 0.14) \times 10^{-2}$   | $97.4 \pm 3.5$  |
| 1800                 | 900                | 0.2              | $1.43 \times 10^{-2}$                 | $(1.44 \pm 0.07) \times 10^{-2}$   | $100 \pm 7$     |
| 1800                 | 900                | 1.0              | $6.31 \times 10^{-2}$                 | $(6.110 \pm 0.034) \times 10^{-2}$ | $96.8 \pm 0.8$  |
| 2000                 | 1700               | 1.0              | $3.45 \times 10^{-2}$                 | $(3.63 \pm 0.11) \times 10^{-2}$   | $105 \pm 5$     |
| 2200                 | 700                | 1.0              | $6.49 \times 10^{-2}$                 | $(6.37 \pm 0.15) \times 10^{-2}$   | $98.2 \pm 3.4$  |

Table 8.12: Comparison of the Method 1 acceptance times efficiency values from Table 8.2 and the results of the SimpleAnalysis for the strong case.

### 8.3 Reinterpretation of Results from Searches for Disappearing Tracks

As discussed in Section 3.2 previous disappearing track searches have been widely reinterpreted into other models, particularly dark matter models. One of the major reinterpretations of the analysis presented in Chapter 7 is a scan of pMSSM models [156]. As described in Section 3.1.1 the pMSSM provides a minimal phenomenological description of SUSY models with 19 free parameters. This reinterpretation uses the disappearing track analysis along with other analyses and cosmological constraints to scan across all the parameters to set model-independent electroweak exclusion limits for pure-wino, pure-higgsino and pure-bino electroweakino hypotheses.

Models were generated at 20,000 randomly chosen points in the electroweak parameter space, and 437,500 points in the pure-bino dark matter parameter space. External constraints were applied, including the bounds on the dark matter relic density from the Planck observatory, and direct detection cross-sections from LZ and PICO-60. Additional constraints on the Higgs and W particle masses, the  $Z \rightarrow \text{inv.}$  and several B-hadron branching ratio bounds are applied. The models are then further refined by requiring the LSP to be the lightest neutralino, the chargino mass to be above the LEP exclusion limits and less than 1.2 TeV, and the total cross-section for the electroweak production of SUSY particles to be greater than  $7 \times 10^{-5}$  pb so that at least 10 signal events are expected in the Run-2 ATLAS dataset. 12,280 electroweak models and 8,897 pure-bino models pass these requirements.

250,000 events are then simulated for each model. These are tested for each analysis with SIMPLEANALYSIS, and the signal yields are saved as a json patch which is compared to preserved likelihoods using PYHF, and confidence limits are calculated. If this is between 0.001 and 0.1 a full detector-level simulation is performed, and the model is processed using RECAST for more accurate confidence limits. The model is then excluded if the confidence limit is less than 0.05. This process is shown schematically in Figure 8.10. The fraction of models excluded for each sparticle considered is shown in Figure 8.11.

The disappearing track analysis is particularly powerful for the pure-wino scan. In total 48.5% of considered models were excluded by ATLAS, of which 94% were excluded by the disappearing track analysis, as shown in Figure 8.12. However, only 2.3% of pure-higgsino models excluded by ATLAS were excluded by the disappearing track analysis. This is due to the low acceptance at the shorter lifetimes of pure-higgsino charginos. It is hoped that an analysis improved and optimised for short lifetimes such as the analysis presented in Chapter 9 will increase sensitivity to pure-higgsino models significantly and become a powerful contribution to parameter scans and other reinterpretations.

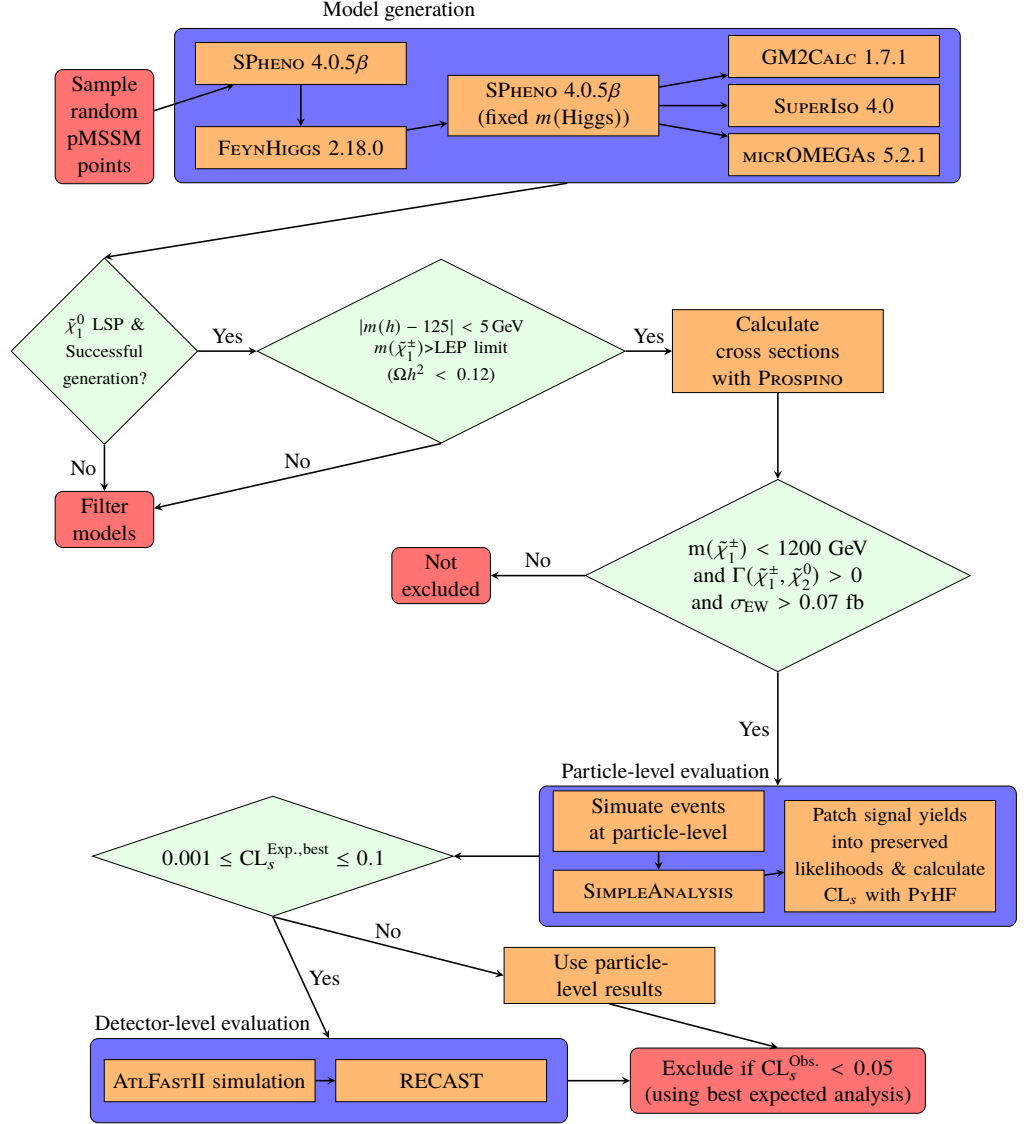
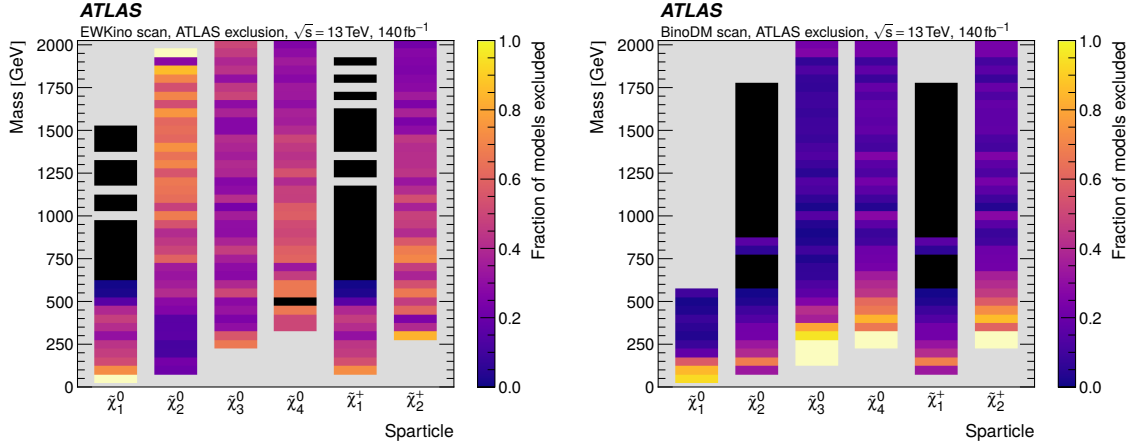
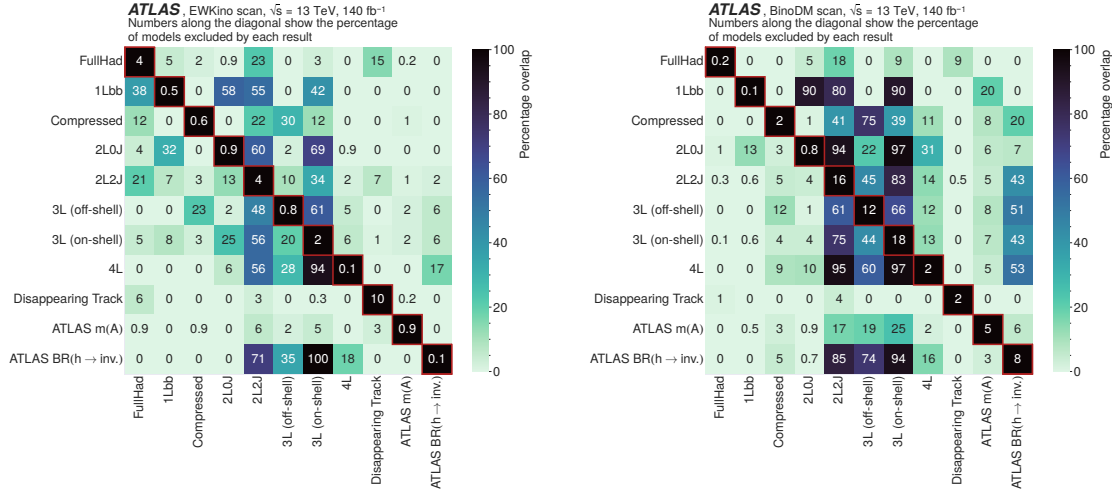


Figure 8.10: Flowchart describing the model generation, selection, and processing procedure for the pMSSM scan. Reproduced from [157].



(a) Fraction of considered electroweak-ino models excluded in the pMSSM scan. (b) Fraction of considered bino models excluded in the pMSSM scan.

Figure 8.11: Reproduction of Figure 15 from the pMSSM scan [157]. Fraction of models at different masses of sparticles excluded by the scan.



(a) Overlap between analyses when excluding bino models (b) Overlap between analyses when excluding bino models

Figure 8.12: Reproduction of Figure 14 from the pMSSM scan [157]. The overlap in models excluded between the analyses used in the scan is shown, highlighting the success of the disappearing track analysis.

## Chapter 9

# Search for pixel tracklets with 3 and 4 hits and a soft pion

The analysis presented in this chapter builds upon that presented in Chapter 7 to specifically target the pure-higgsino interpretation. In such scenarios, charginos have a proper lifetime of approximately 0.04 ns, hence sensitivity to shorter lifetimes must be enhanced. This is achieved by extending the target to signatures characterised by the presence of shorter tracklets reconstructed with just three pixel hits, instead of four hits as illustrated previously. However, such an approach leads to a substantial increase in the number of fake tracklets, as only three hits need to be close enough to each other to be reconstructed as a tracklet object, rather than four hits. The increase in fake tracklets is found to be approximately two orders of magnitude above the previous analysis estimates.

To mitigate this problem and reduce the rate of mis-reconstructed tracks, a low-transverse momentum (soft) pion is required to be reconstructed and associated to the tracklet. The new signal signatures are shown in Figure 9.1. As it is highly unlikely for a fake tracklet to have a high-quality soft track associated with it: this requirement reduces the fakes by over an order of magnitude. Additional suppression of the fake background is achieved by optimising the signal selection, specifically increasing the  $E_T^{\text{miss}}$  and leading jet requirements and narrowing the  $|z_0 \sin \theta|$  requirement.

Further reconstruction improvements were made in the analysis including a primary vertex constraint, which improves the momentum resolution by updating the track parameters to pass through the primary vertex, and a SCT hit filter, which improves tracklet reconstruction efficiency across the lifetime range by preventing tracklets having spurious SCT hits mistakenly associated with the tracklet and causing the tracklet to be rejected.

These new reconstruction techniques have been described in greater detail in Chapter 6, par-

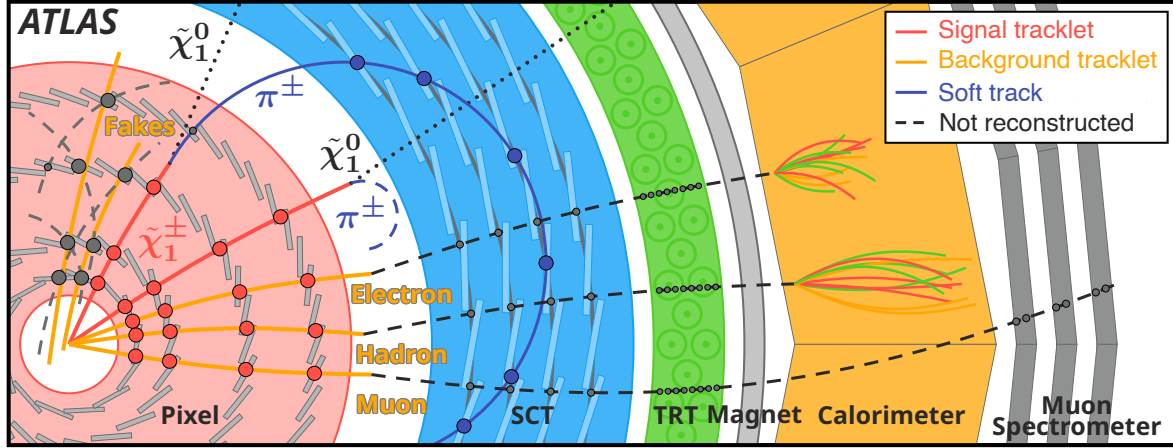


Figure 9.1: A depiction of the signal and background signatures involved in the updated disappearing track analysis. Working clockwise around the origin from the left, shown are three- and four-layer fake tracklets, a three-layer signal tracklet with a reconstructed soft pion, a four-layer signal tracklet with an unreconstructed soft pion, and four-layer scattered electrons, hadrons and muons. Note that any track, signal or background, can have three or four layers, and can also have an associated soft track. Modified from [1].

ticularly in Sections 6.1 and 6.2. The use and optimisation of these techniques and the development of signal regions using them is explained in this chapter, in Section 9.1.

The new reconstruction techniques and new signal regions require new background estimates to be developed, described in detail in Section 9.2. For the scattered particle backgrounds, a similar approach to the previous analysis (Section 7.3) was taken, where templates of the shape of the transverse momentum distribution of each type of particle are normalised to fit the observed data in a control region. This is described in Section 9.2.1. For this estimate, new scattering rates, transfer factors and Monte Carlo correction factors had to be derived for each signal region. This background estimate was developed by another member of the analysis team, but is included in this Thesis as it is essential for understanding the analysis.

For the combinatorial fake backgrounds, a new approach was taken, detailed in Section 9.2.2. It uses the assumption that fake tracklets are not dependent on the event topology, and are randomly pointing in the detector. A *sideband* to the signal region with very high fake tracklet purity was defined in a high- $|z_0 \sin \theta|$  region and used to measure the number of fake tracklets per mm of  $|z_0 \sin \theta|$  and then extrapolated to the signal region. The development of the fake background estimates was made more difficult by the very low statistics available to evaluate its impact for signal regions using four-layer tracklets or soft pions. This was solved by again using the assumption that fake tracklets are not dependent on the event topology, and extrapolating the fake estimates from the three-layer region using a scale factor.

Finally, preliminary results including expected exclusion limits are shown and discussed in Section 9.3. Due to the work-in-progress background estimates these results should be taken as a worst-case scenario. It should also be noted that the results in this Chapter only consider the  $pp \rightarrow \tilde{\chi}_1 \tilde{\chi}_1^0$  process that was simulated, and not the  $pp \rightarrow \tilde{\chi}_1 \tilde{\chi}_2^0$  process which will effectively double the number of signal events. The entire chapter is original writing, and with the previously-described exception of the discussion of the scattered particle background estimate in Section 9.2.1 this Chapter is entirely the work of the author.

## 9.1 Signal Region Selection

This analysis builds on the analysis presented in Chapter 7, with minor optimisation in the event and tracklet selections to take advantage of new features such as the primary vertex constraint and to reduce three-layer fake backgrounds. However, a new cut-based object definition and BDT-powered selection was defined for the soft pion objects, detailed in Section 9.1.3.

### 9.1.1 Event Selection

The disappearing track event selection is largely unchanged from the previous analysis. The only changes are a small increase in the  $E_T^{\text{miss}}$  selection, raised from 200 GeV to 220 GeV, and the leading jet  $p_T$  threshold, raised from 100 GeV to 150 GeV. These changes in  $E_T^{\text{miss}}$  and leading jet  $p_T$  thresholds were motivated by the need to suppress the substantially increased fake tracklet backgrounds in the three-layer signal regions. The effect of increasing  $E_T^{\text{miss}}$  and leading jet  $p_T$  thresholds on a 250 GeV 0.04 ns sample and a 100 GeV 0.04 ns sample compared to fake tracklets can be seen for three- and four-layer tracklet signal regions in Figure 9.2(b). The same can be seen for increasing the leading jet  $p_T$  threshold in Figure 9.2(a). For both of these, the fake background is found by replacing the tracklet  $|z_0 \sin \theta|$  requirement with  $2.5 \text{ mm} < |z_0 \sin \theta| < 5.0 \text{ mm}$ , which as described in Section 9.2.2 has a high purity of fake or poorly-reconstructed tracklets. The change in  $E_T^{\text{miss}}$  cut leads to an approximate 50% reduction in fake background for a cost of approximately 20% of signal events. The change in leading jet  $p_T$  leads to an approximate 10% reduction in fake background for a negligible cost in signal events.

These changes can be justified as the vast majority of the signal events have a leading jet  $p_T$  greater than 150 GeV, as a substantial boost from this jet is required for the chargino to be observable in ATLAS. This can be seen in Figure 9.3, where the  $E_T^{\text{miss}}$  and leading jet  $p_T$  cuts are relaxed and the events are plotted on a heatmap for the two benchmark signal samples, the V+Jets samples and the fake control region from data.

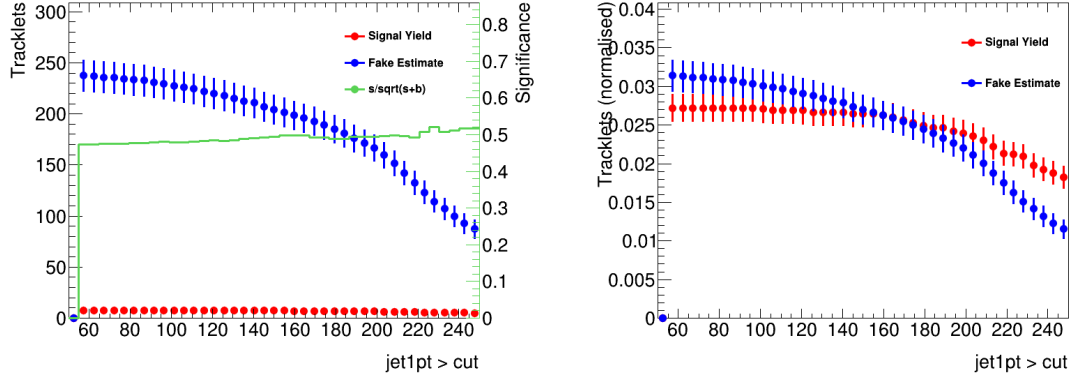
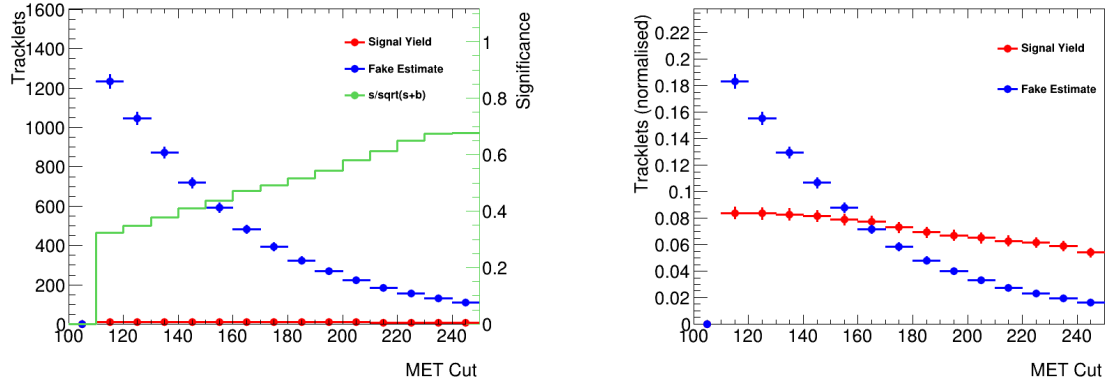

 (a) Increasing leading jet  $p_T$  cuts.

 (b) Increasing  $E_T^{\text{miss}}$  cuts.

Figure 9.2: A comparison of tightening various in an event selection applied to 250 GeV 0.04 ns sample .



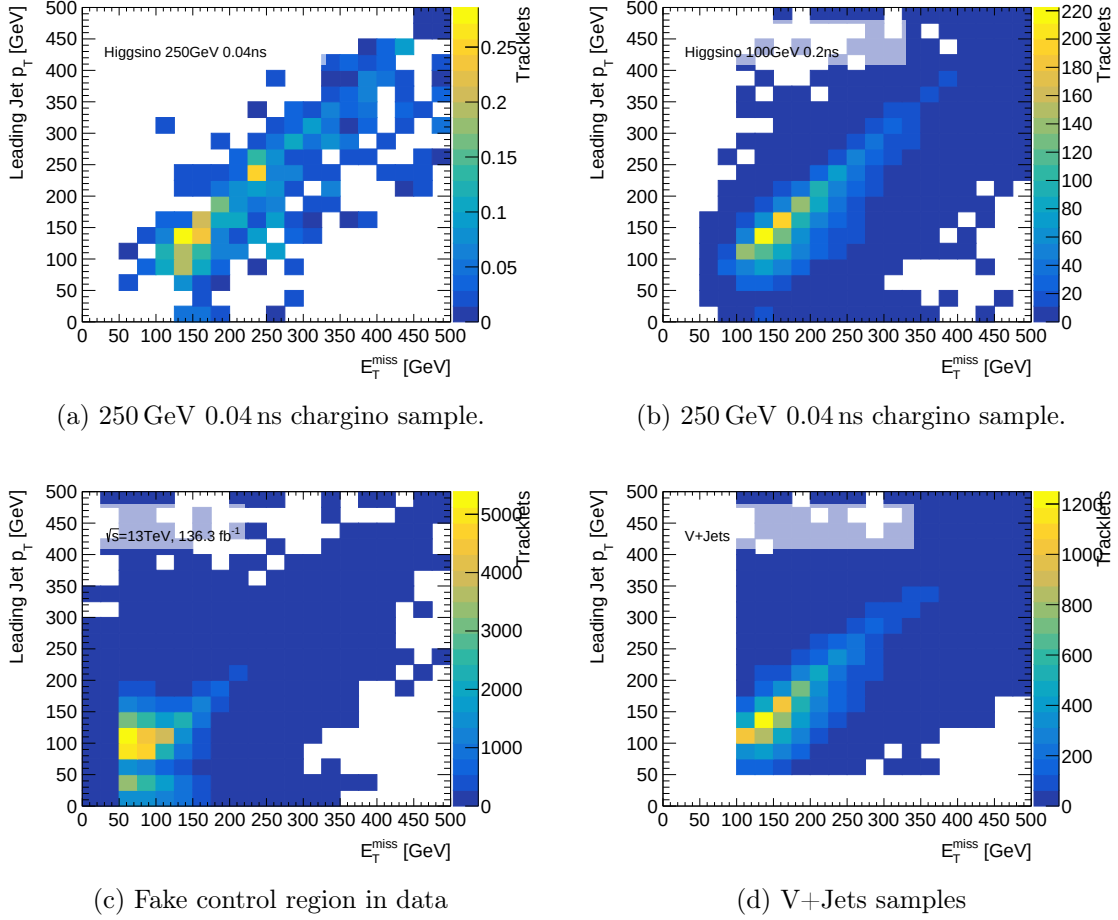


Figure 9.3:  $E_T^{\text{miss}}$  vs leading jet  $p_T$  for disappearing track events with three- or four-layer tracklets in (a) a SI250GeV 0.04 ns sample, (b) a 100 GeV 0.2 ns sample, (c) the fake control region in data, and (d) the V+Jets samples. The  $E_T^{\text{miss}}$  and leading jet  $p_T$  cuts were, replaced, but all other event and tracklet cuts were applied.

| Cut                                                                                     | 100 GeV 0.2 ns            |                           | 250 GeV 0.04 ns           |                           |
|-----------------------------------------------------------------------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
|                                                                                         | 3-Layer                   | 4-Layer                   | 3-Layer                   | 4-Layer                   |
| All Events                                                                              | $1.51 \times 10^6$        | $1.51 \times 10^6$        | $5.39 \times 10^4$        | $5.39 \times 10^4$        |
| Chargino reconstructed                                                                  | $3.86 \times 10^4$ (3%)   | $3.86 \times 10^4$ (2.6%) | $4.62 \times 10^1$ (0.1%) | $4.62 \times 10^1$ (0.1%) |
| Tracklet $p_T > 10$ GeV                                                                 | $3.86 \times 10^4$ (100%) | $3.86 \times 10^4$ (100%) | $4.62 \times 10^1$ (100%) | $4.62 \times 10^1$ (100%) |
| Tracklet $p_T^{\text{vc}} > 20$ GeV                                                     | $3.82 \times 10^4$ (99%)  | $3.82 \times 10^4$ (99%)  | $4.56 \times 10^1$ (99%)  | $4.56 \times 10^1$ (99%)  |
| $0.1 <  \eta^{\text{vc}}  < 1.9$                                                        | $3.23 \times 10^4$ (84%)  | $3.23 \times 10^4$ (84%)  | $4.12 \times 10^1$ (90%)  | $4.12 \times 10^1$ (90%)  |
| <b>hitPattern</b>                                                                       | $1.06 \times 10^4$ (33%)  | $1.82 \times 10^4$ (56%)  | $2.63 \times 10^1$ (64%)  | $1.30 \times 10^1$ (32%)  |
| Hit Quality                                                                             | $1.03 \times 10^4$ (98%)  | $1.74 \times 10^4$ (96%)  | $2.57 \times 10^1$ (98%)  | $1.24 \times 10^1$ (95%)  |
| Fit Quality $> 0.1$ (4-Layer)                                                           | -                         | $1.71 \times 10^4$ (98%)  | -                         | $1.20 \times 10^1$ (97%)  |
| $p_T^{\text{cone40}}/p_T^{\text{vc}} < 0.04$                                            | $9.73 \times 10^3$ (94%)  | $1.65 \times 10^4$ (97%)  | $2.48 \times 10^1$ (96%)  | $1.18 \times 10^1$ (99%)  |
| $\Delta R(\text{tracklet}, \text{jets}_{1 \rightarrow 4}^{p_T > 50 \text{ GeV}}) > 0.4$ | $9.73 \times 10^3$ (100%) | $1.65 \times 10^4$ (100%) | $2.48 \times 10^1$ (100%) | $1.18 \times 10^1$ (100%) |
| $\Delta R(\text{tracklet}, \text{MSTracks}) > 0.4$                                      | $9.64 \times 10^3$ (99%)  | $1.64 \times 10^4$ (99%)  | $2.46 \times 10^1$ (99%)  | $1.18 \times 10^1$ (99%)  |
| Calo-Veto: $E_T^{\text{topoclus20}} < 5$ GeV                                            | $9.57 \times 10^3$ (99%)  | $1.63 \times 10^4$ (99%)  | $2.44 \times 10^1$ (99%)  | $1.17 \times 10^1$ (99%)  |
| $d_0$ Significance $< 1.5$                                                              | $9.40 \times 10^3$ (98%)  | $1.56 \times 10^4$ (96%)  | $2.41 \times 10^1$ (99%)  | $1.10 \times 10^1$ (95%)  |
| $ z_0 \sin \theta  < 0.2$ mm                                                            | $8.82 \times 10^3$ (94%)  | $1.49 \times 10^4$ (95%)  | $2.25 \times 10^1$ (94%)  | $1.06 \times 10^1$ (96%)  |

Table 9.1: The tracklet selection and efficiencies for three- or four-layer tracklets from 250 GeV 0.04 ns and 100 GeV 0.2 ns pure-higgsino chargino samples, and V+Jets samples.

### 9.1.2 Tracklet Selection

Like the event selection described in Section 9.1.1, the tracklet selection in this analysis closely follows from the previous analysis in Chapter 7. Here, the tracklet transverse momentum  $p_T$ , pseudo-rapidity  $\eta$ , and azimuthal angle  $\phi$  are updated to use the vertex-constrained values. Additionally, the  $|z_0 \sin \theta|$  selection is lowered from 0.5 mm to 0.2 mm to reject fake tracklets. To support three-layer tracklets, the hit requirements are changed to use exclusively a three- or four-barrel-layer **hitPattern**, which is explained further in Appendix B.1. The efficiencies of the individual cuts in the selection are shown in Table 9.1.

### 9.1.3 Soft Track Selection

The soft pion reconstruction has not been previously used in an analysis, so the development of an object definition and selection was required. The selection is applied to soft tracks associated with reconstructed tracklets. The requirements for reconstruction and acceptance of the soft track are defined in Sections 6.1.3 and 6.2.2. To develop an object definition and selection, a definition of a signal and background soft pion is required. As shown in Figure 9.4, as many as 25 soft tracks can be associated to a tracklet reconstructed from a chargino. The signal

definition used henceforth is a reconstructed soft track which was linked to a truth pion with a good Truth-Matching Score (TMS) ( $> 0.5$ ), which is associated to a reconstructed tracklet which was linked to a chargino with a good score ( $> 0.75$ ). The background definition is any other associated soft track in the event.

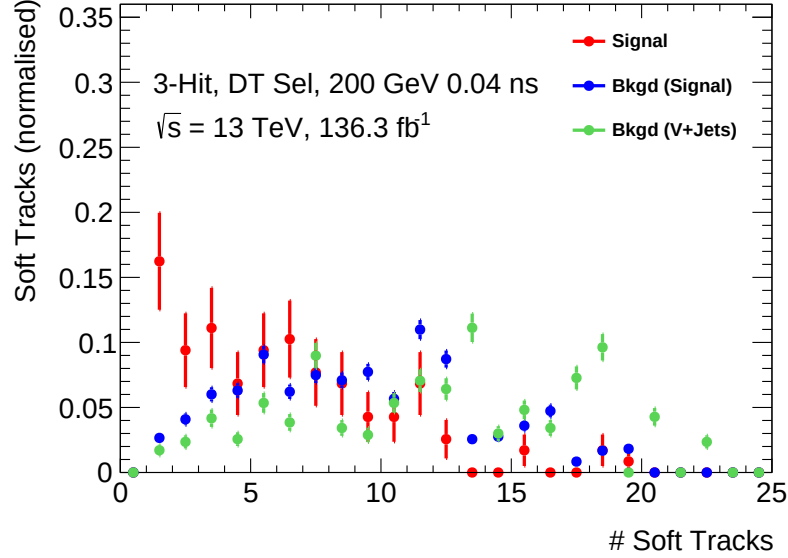


Figure 9.4: The number of reconstructed soft tracks associated with each reconstructed tracklet linked to a truth chargino in a sample of 200 GeV 0.04 ns pure-higgsino charginos.

To validate that this background definition is appropriate, a separate background of soft tracks associated with reconstructed tracklets in a range of V+Jets samples was also considered. As shown in Figure 9.4 this agrees well with the background from the signal samples.

These definitions can then be used to compare a range of quantities to define a selection. These comparisons are shown for a selection of quantities in Figures 9.5, 9.6, 9.7 and 9.8 for 200 GeV 0.04 ns and 100 GeV 0.2 ns pure-higgsino chargino samples respectively.

A cut-based selection was used as an initial object definition. These cuts are chosen by hand using the plots in Figures 9.5, 9.6, 9.7 and 9.8 to reject background soft tracks while preserving as much signal as possible, rather than to maximise significance or some other metric. This forms a ‘Loose’ definition. Future work could derive other working points with a range of signal purity and efficiency. The chosen cuts and the fraction of truth soft pions passing this selection are given in Table 9.2.

Following the cut-based object definition, a BDT was trained to act as a selection and to select the best soft track in the case multiple pass the selection. The same signal/background

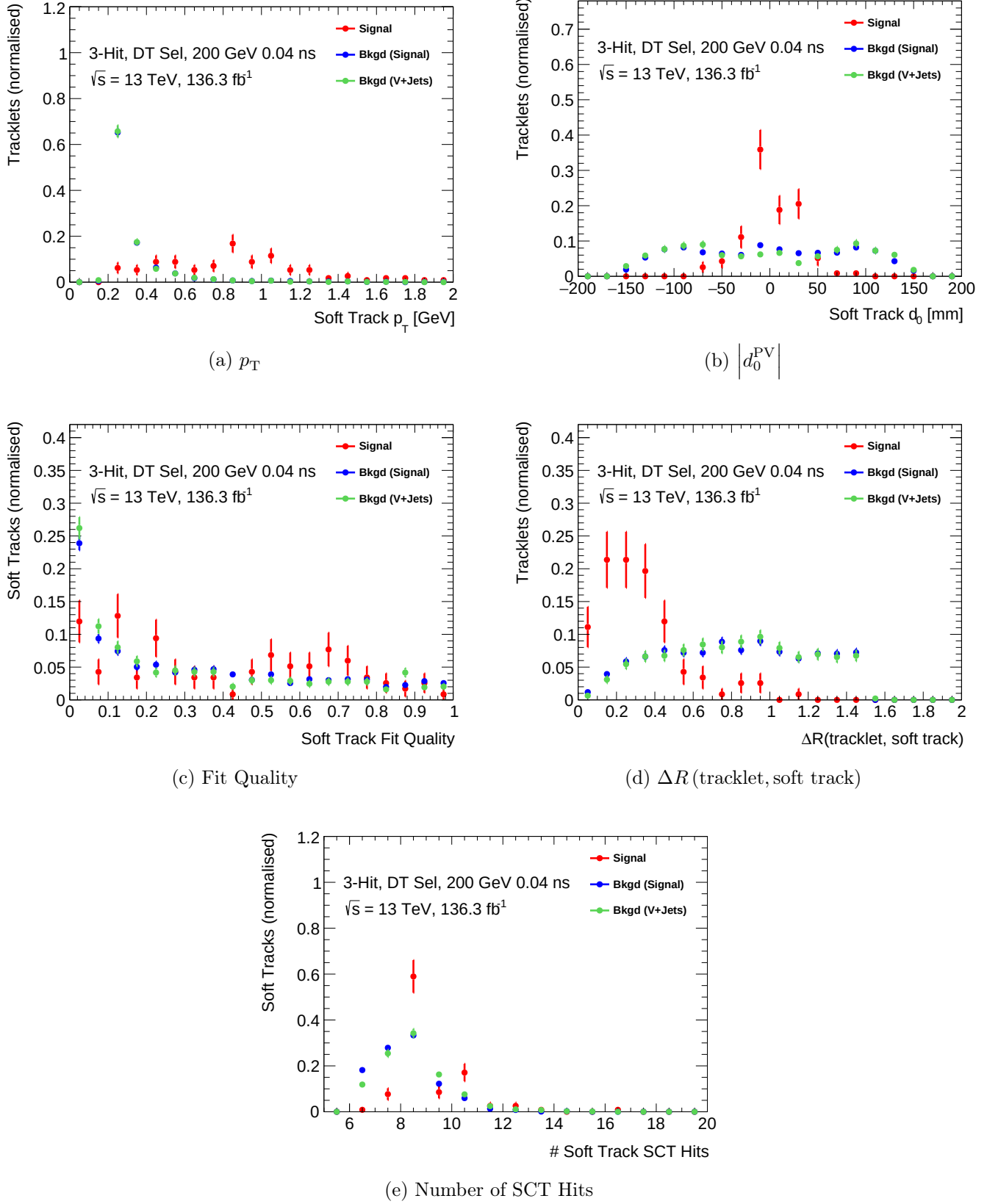


Figure 9.5: Comparison of various soft track quantities for signal and background soft tracks from three-layer tracklets in a 200 GeV 0.04 ns pure-higgsino signal sample.

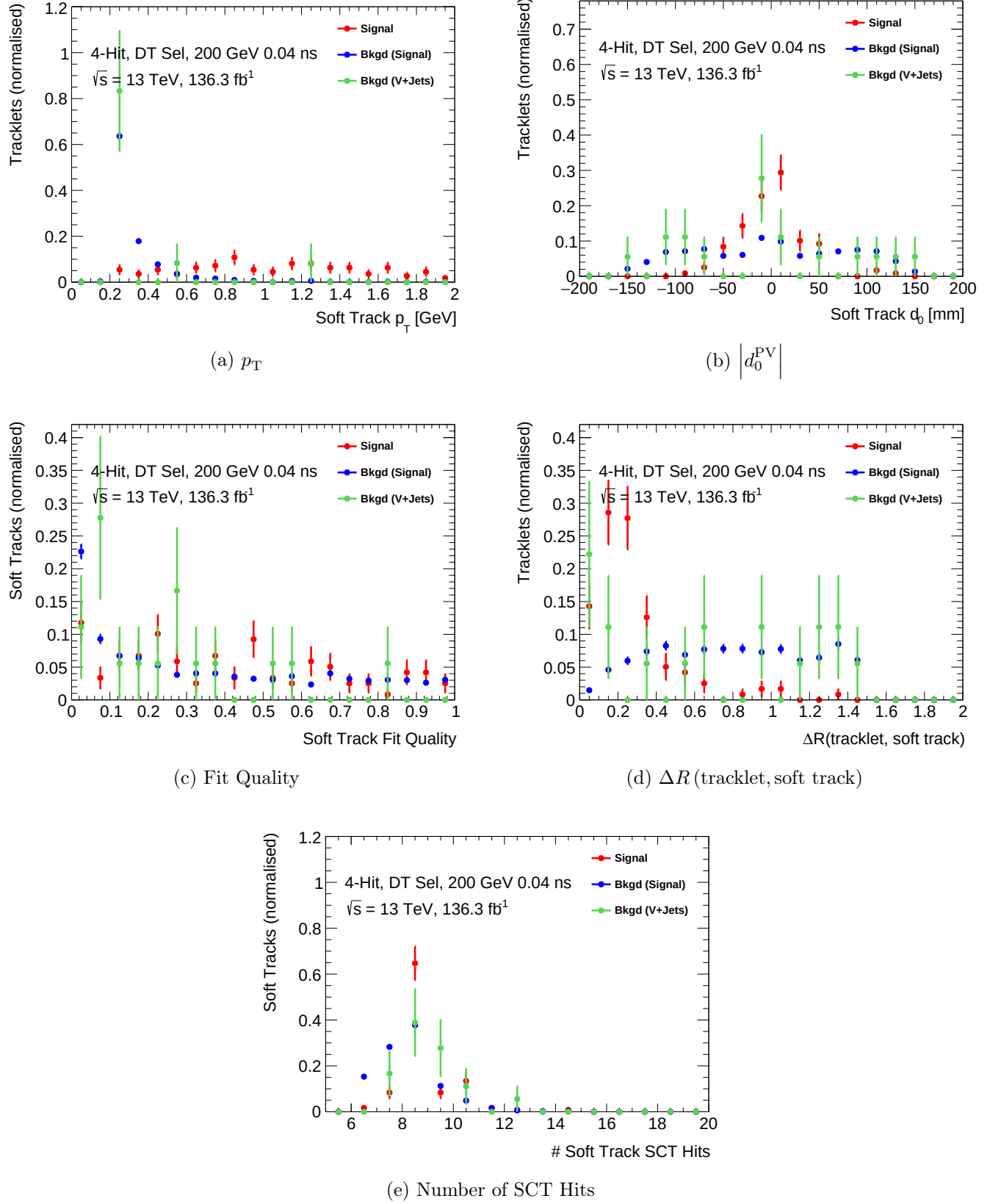


Figure 9.6: Comparison of various soft track quantities for signal and background soft tracks from four-layer tracklets in a 200 GeV 0.04 ns pure-higgsino signal sample.

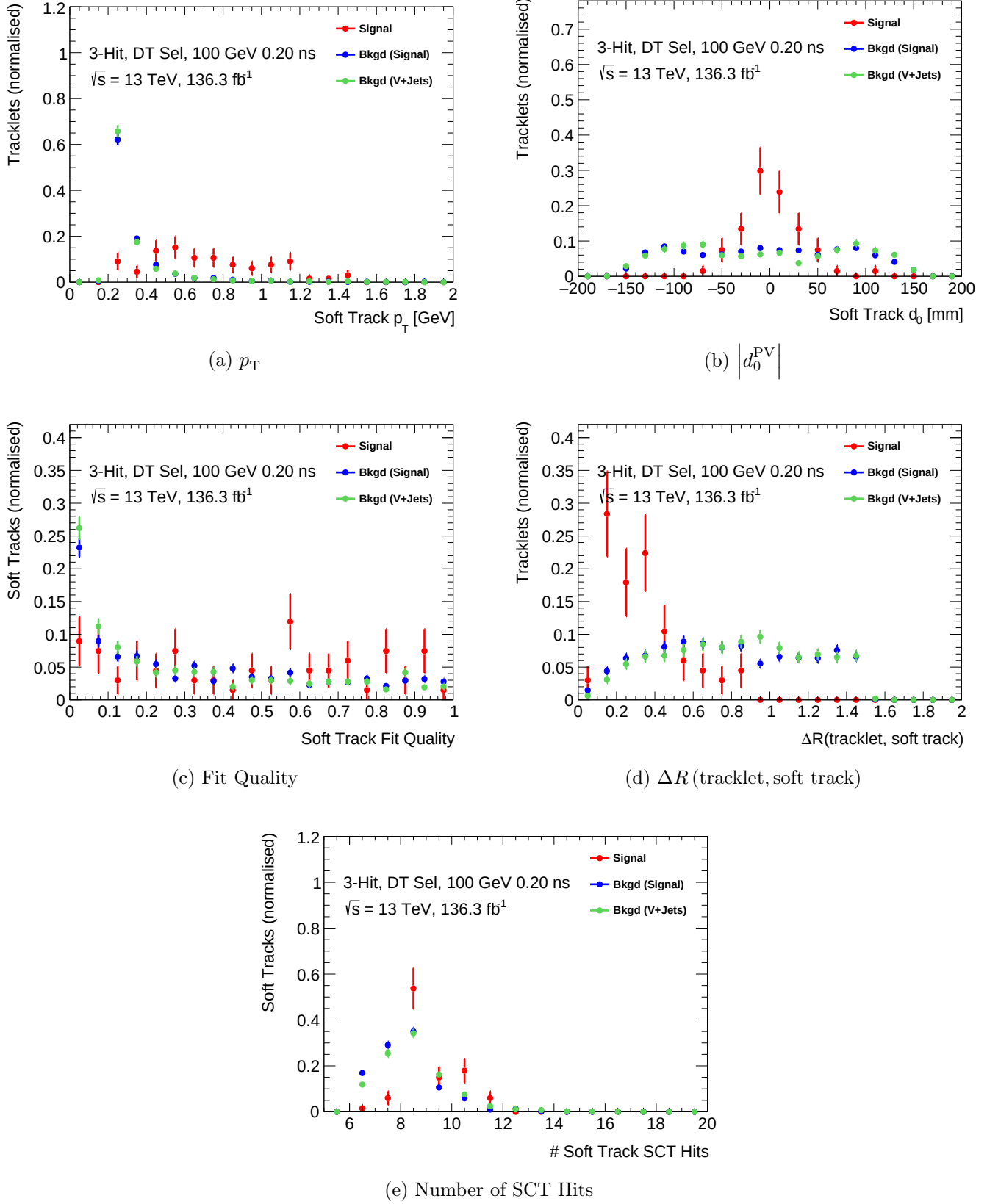


Figure 9.7: Comparison of various soft track quantities for signal and background soft tracks from three-layer tracklets in a 100 GeV 0.2 ns pure-higgsino signal sample.

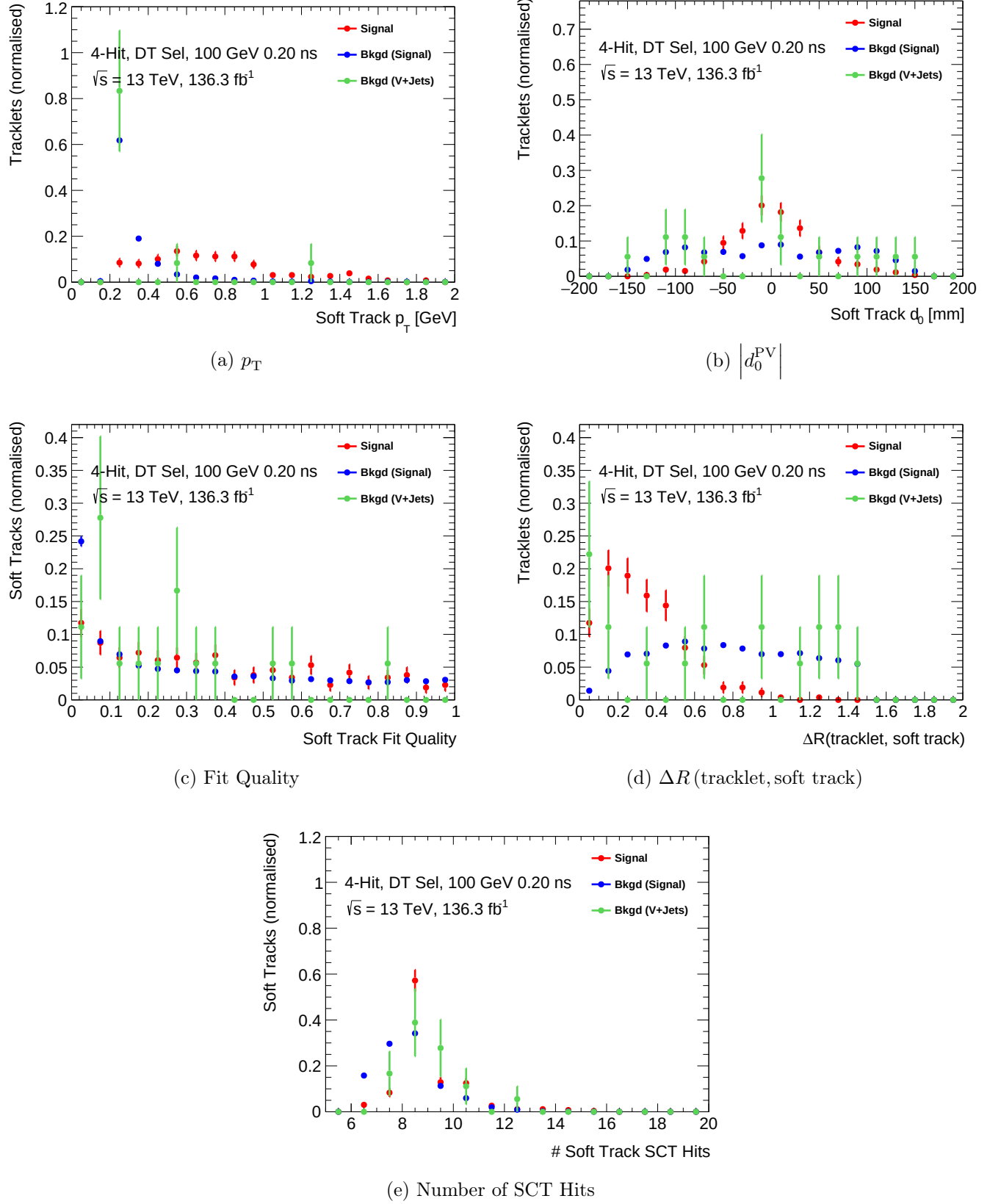


Figure 9.8: Comparison of various soft track quantities for signal and background soft tracks from four-layer tracklets in a 100 GeV 0.2 ns pure-higgsino signal sample.

| Cut                                                   | 100 GeV 0.2 ns            |                           | 250 GeV 0.04 ns           |                           |
|-------------------------------------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
|                                                       | 3-Layer                   | 4-Layer                   | 3-Layer                   | 4-Layer                   |
| All Events                                            | $1.51 \times 10^6$        | $1.51 \times 10^6$        | $5.39 \times 10^4$        | $5.39 \times 10^4$        |
| Chargino reconstructed                                | $4.58 \times 10^4$ (3%)   | $4.58 \times 10^4$ (3%)   | $4.67 \times 10^1$ (0%)   | $4.67 \times 10^1$ (0%)   |
| Pion reconstructed & associated                       | $7.10 \times 10^3$ (16%)  | $7.10 \times 10^3$ (16%)  | $1.04 \times 10^1$ (22%)  | $1.04 \times 10^1$ (22%)  |
| Soft Track $p_T > 300$ MeV                            | $6.18 \times 10^3$ (87%)  | $6.18 \times 10^3$ (87%)  | $1.01 \times 10^1$ (97%)  | $1.01 \times 10^1$ (97%)  |
| $ d_0^{\text{PV}}  < 75$ mm                           | $5.53 \times 10^3$ (89%)  | $5.53 \times 10^3$ (89%)  | $9.76 \times 10^0$ (97%)  | $9.76 \times 10^0$ (97%)  |
| $ z_0^{\text{PV}}  < 75$ mm                           | $3.76 \times 10^3$ (68%)  | $3.76 \times 10^3$ (68%)  | $8.76 \times 10^0$ (90%)  | $8.76 \times 10^0$ (90%)  |
| Fit Quality $> 0.05$                                  | $3.30 \times 10^3$ (88%)  | $3.30 \times 10^3$ (88%)  | $7.63 \times 10^0$ (87%)  | $7.63 \times 10^0$ (87%)  |
| # SCT Holes $< 2$                                     | $3.29 \times 10^3$ (100%) | $3.29 \times 10^3$ (100%) | $7.63 \times 10^0$ (100%) | $7.63 \times 10^0$ (100%) |
| # SCT Hits $> 6$                                      | $3.21 \times 10^3$ (98%)  | $3.21 \times 10^3$ (98%)  | $7.35 \times 10^0$ (96%)  | $7.35 \times 10^0$ (96%)  |
| $\Delta R$ (tracklet, soft track) $< 1.0$             | $3.21 \times 10^3$ (100%) | $3.21 \times 10^3$ (100%) | $7.35 \times 10^0$ (100%) | $7.35 \times 10^0$ (100%) |
| $\Delta\phi$ (tracklet, soft track) $< 0.7$           | $3.20 \times 10^3$ (100%) | $3.20 \times 10^3$ (100%) | $7.31 \times 10^0$ (99%)  | $7.31 \times 10^0$ (99%)  |
| 3-Layer or 4-Layer Parent                             | $8.61 \times 10^2$ (27%)  | $2.06 \times 10^3$ (64%)  | $4.22 \times 10^0$ (58%)  | $2.86 \times 10^0$ (39%)  |
| $88.5 \text{ mm} < r_{\text{SV}} < 122.5 \text{ mm}$  | $7.46 \times 10^2$ (87%)  | -                         | $3.84 \times 10^0$ (91%)  | -                         |
| $122.5 \text{ mm} < r_{\text{SV}} < 299.0 \text{ mm}$ | -                         | $1.93 \times 10^3$ (94%)  | -                         | $2.55 \times 10^0$ (89%)  |
| BDT Score $> -0.1$                                    | $7.32 \times 10^2$ (98%)  | $1.90 \times 10^3$ (99%)  | $3.80 \times 10^0$ (99%)  | $2.55 \times 10^0$ (100%) |

Table 9.2: The soft pion object definition and selection, and the efficiencies for soft pions from three- or four-layer tracklets for 250 GeV 0.04 ns and 100 GeV 0.2 ns pure-higgsino chargino samples, and for a group of V+Jets samples (Section 5.5.2).



definition was used as in the development of the object definition, and the BDT was trained on a range of samples covering 100 to 400 GeV and 0.02 to 0.2 ns. A large range of variables were considered by the BDT. In no particular order, these were:

- $p_T^{\text{soft}}$
- $\eta^{\text{soft}}$
- $\beta^{\text{soft}}$
- # Pixel Hits
- # SCT Hits
- # SCT Holes
- # SCT Outliers
- # SCT Shared Hits
- # TRT Hits
- Soft track fit quality
- Secondary Vertex (SV) fit quality
- Impact parameters ( $d_0^{\text{soft}}, z_0^{\text{soft}}$ )
- Impact parameter significances ( $\sigma(d_0^{\text{soft}})/d_0^{\text{soft}}, \sigma(z_0^{\text{soft}})/z_0^{\text{soft}}$ )
- $\Delta R(\text{tracklet}, \text{soft track})$

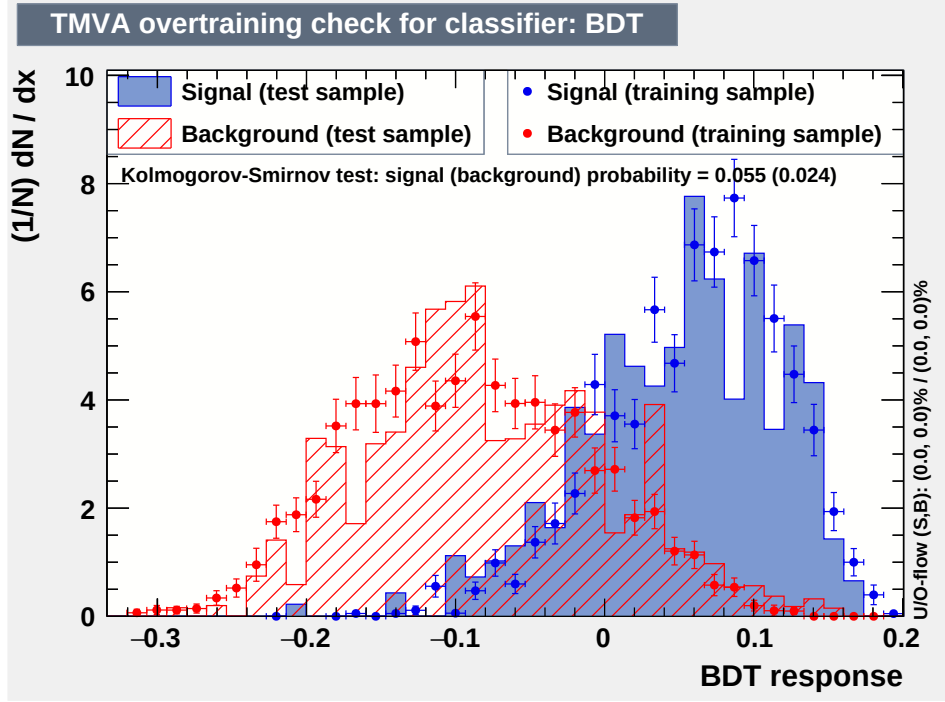
Separate BDTs were trained for soft pions associated with three-layer and four-layer tracklets. ADABOOST adaptive boosting was used for the BDT training, with a training factor of  $\beta = 0.4$ . 1500 trees were generated with a maximum depth of 3. A comparison of the training and test datasets is shown in Figure 9.9, and a comparison to other basic ML algorithms is shown in Figure 9.10. Use of the BDT to separate signal and background in two signal samples is shown in Figure 9.11. The overall effect of signal and background is included in Table 9.2.

#### 9.1.4 Signal Region Definitions

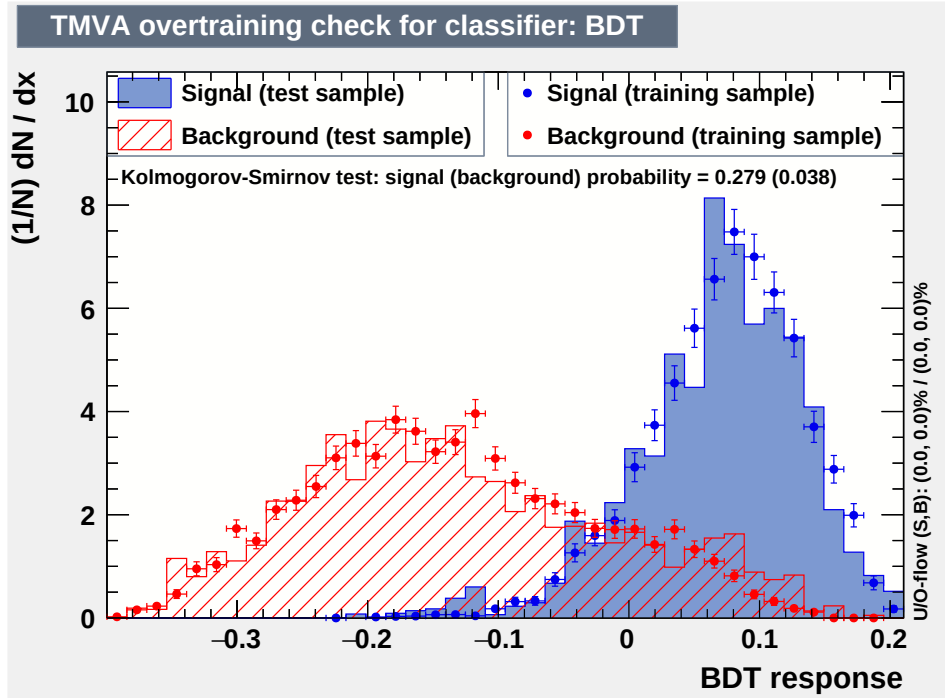
The event, tracklet and soft pion selections detailed above can then be used to define signal regions. All regions begin by requiring that the event selection is passed. A three- or four-layer tracklet is then required. It should be noted that the tracklet is required to have at least 60 GeV of transverse momentum, and a  $|z_0 \sin \theta|$  of less than 0.2 mm.

To ensure that the signal regions are orthogonal, if multiple tracklets are reconstructed a four-layer tracklet is preferentially chosen over any three-layer tracklets. Subsequently, if there are multiple four-layer tracklets, or no four-layer and multiple three-layer tracklets, the tracklet with the highest transverse momentum is chosen. The rationale for this is that fake tracklets are more likely to have three layers, and are more likely to have a low transverse momentum. Similarly, if multiple soft tracks pass the soft pion selection, the soft track with the highest BDT score is used. This way, only one tracklet and soft pion pair is considered per event.

From this, four signal regions can be defined. First, there can be orthogonal regions with three- or four-layer tracklets. Then, the region can either be inclusive of soft pions (**ThreeLayer** or **FourLayer**), or require a soft pion (**ThreeLayer+SP** or **FourLayer+SP**).

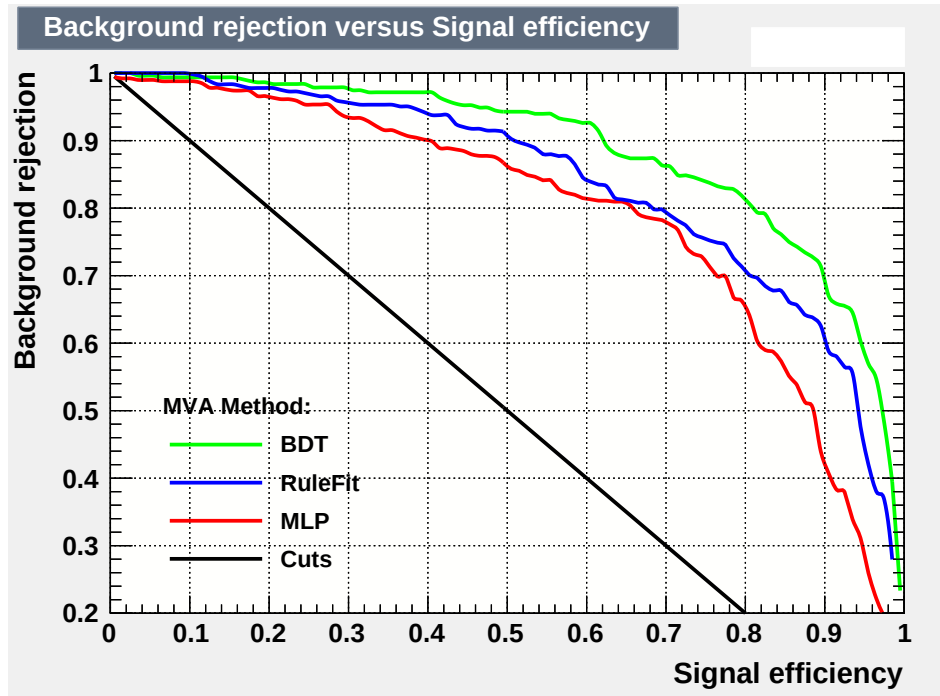


(a) Three-layer soft pion BDT.

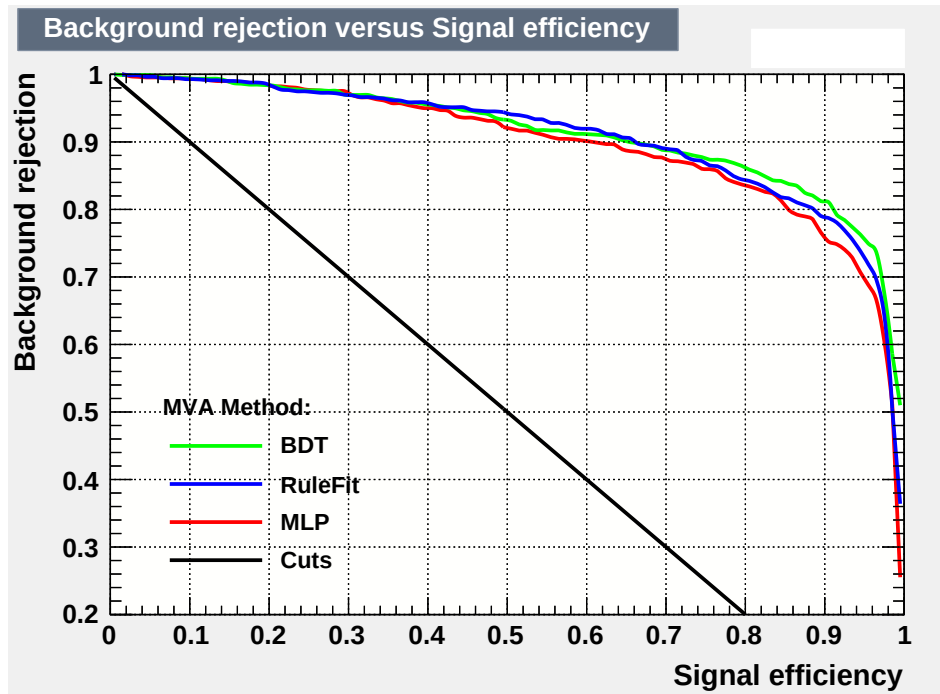


(b) Four-layer soft pion BDT.

Figure 9.9: A comparison of the BDT scores for training and test signal and background datasets for the three- and four-layer BDTs.

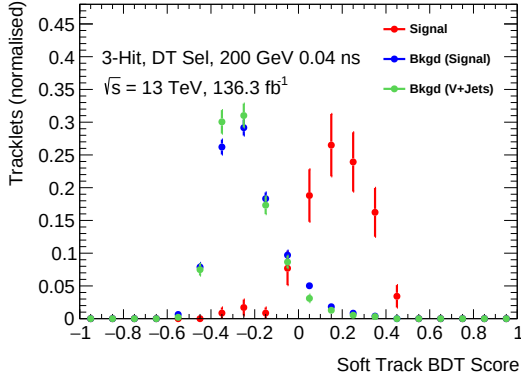


(a) Three-layer soft pion BDT.

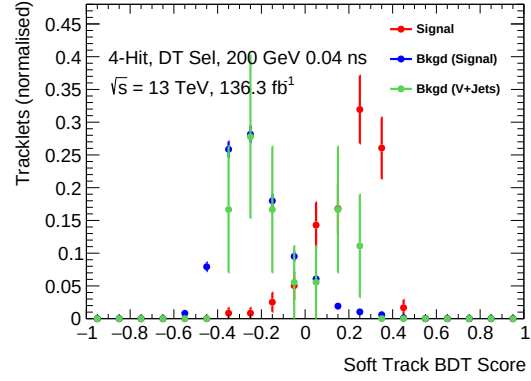


(b) Four-layer soft pion BDT.

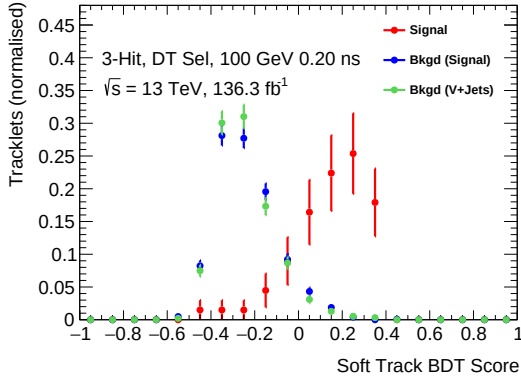
Figure 9.10: A comparison of the performance the three- and four-layer BDTs versus other basic ML algorithms.



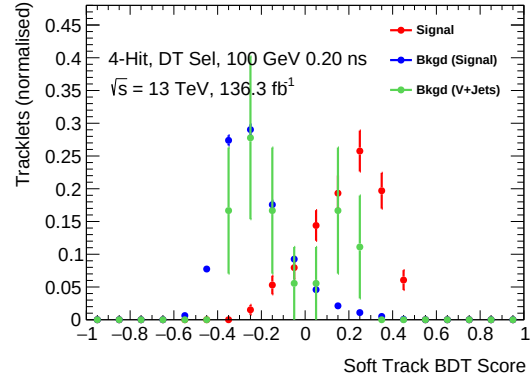
(a) Three-layer soft pion BDT applied to a 200 GeV 0.04 ns sample.



(b) Four-layer soft pion BDT applied to a 200 GeV 0.04 ns sample.



(c) Three-layer soft pion BDT applied to a 100 GeV 0.2 ns sample.



(d) Four-layer soft pion BDT applied to a 100 GeV 0.2 ns sample.

Figure 9.11: A comparison of the performance the three- and four-layer BDTs when applied to 200 GeV 0.04 ns sample (9.11(a) and 9.11(b)), and a 100 GeV 0.2 ns sample (9.11(c) and 9.11(d)).

## 9.2 Background Estimation

### 9.2.1 Scattered Particle Background

The scattered particle backgrounds use a similar approach to the first analysis, described in Section 7.3, but with some minor modifications. An overview is shown in Figure 9.12.

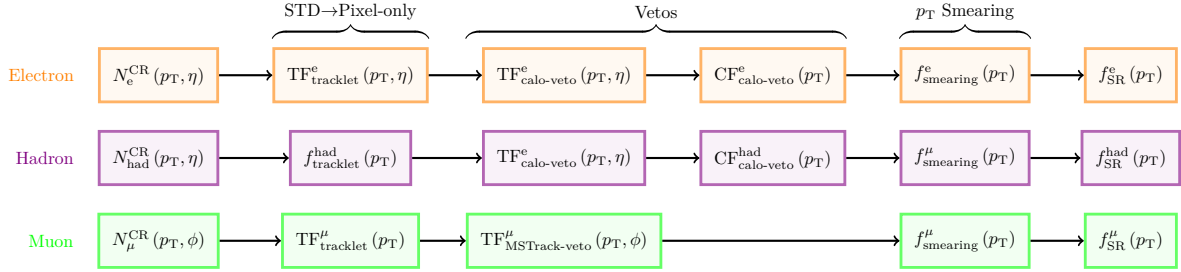


Figure 9.12: An overview of the method for producing the various scattered particle background predictions.

Standard tracks are first measured in a control region rich in the desired particle, and parameterised in  $p_T$  and  $\eta$  for hadrons or electrons, or  $p_T$  and  $\phi$  for muons. These control regions are unchanged from the previous analysis, but versions targeting three-layer tracklets are also defined. Various transfer factors are then applied to first encapsulate the probability of a particle scattering and being reconstructed as a tracklet, then to account for the effect of the calorimeter veto or MSTrack veto. Finally, a smearing function is applied to the  $p_T$  to mimic the  $p_T$  resolution of tracklets. All of these factors have to be calculated separately for each signal region including the new reconstruction techniques used, and are at the time of writing still a work-in-progress. The work included in this Section was performed by other members of the analysis team, but is included in this Thesis as it is essential to the analysis.

#### 9.2.1.1 Tracklet Transfer Factors

As in the first analysis, the lepton tracklet transfer factors are calculated with the Z-tag-and-probe method. In this method  $Z \rightarrow ee$  or  $Z \rightarrow \mu\mu$  events with a single high-quality *tag* lepton are identified. A calorimeter cluster or MSTrack compatible with being the other lepton from the Z decay is identified, and tracklets that can be associated with these objects are searched for. The ratio of these scattered Z-decay events to fully-reconstructed Z-decay events is taken as the scattering rate.

For the hadrons, no such pure control region is available in data so a transfer factor is found from Monte Carlo samples. The SPG Monte Carlo samples described in Section 5.5.1 are used to provide a pure sample of pions. Transfer factors similar to those used for the leptons are

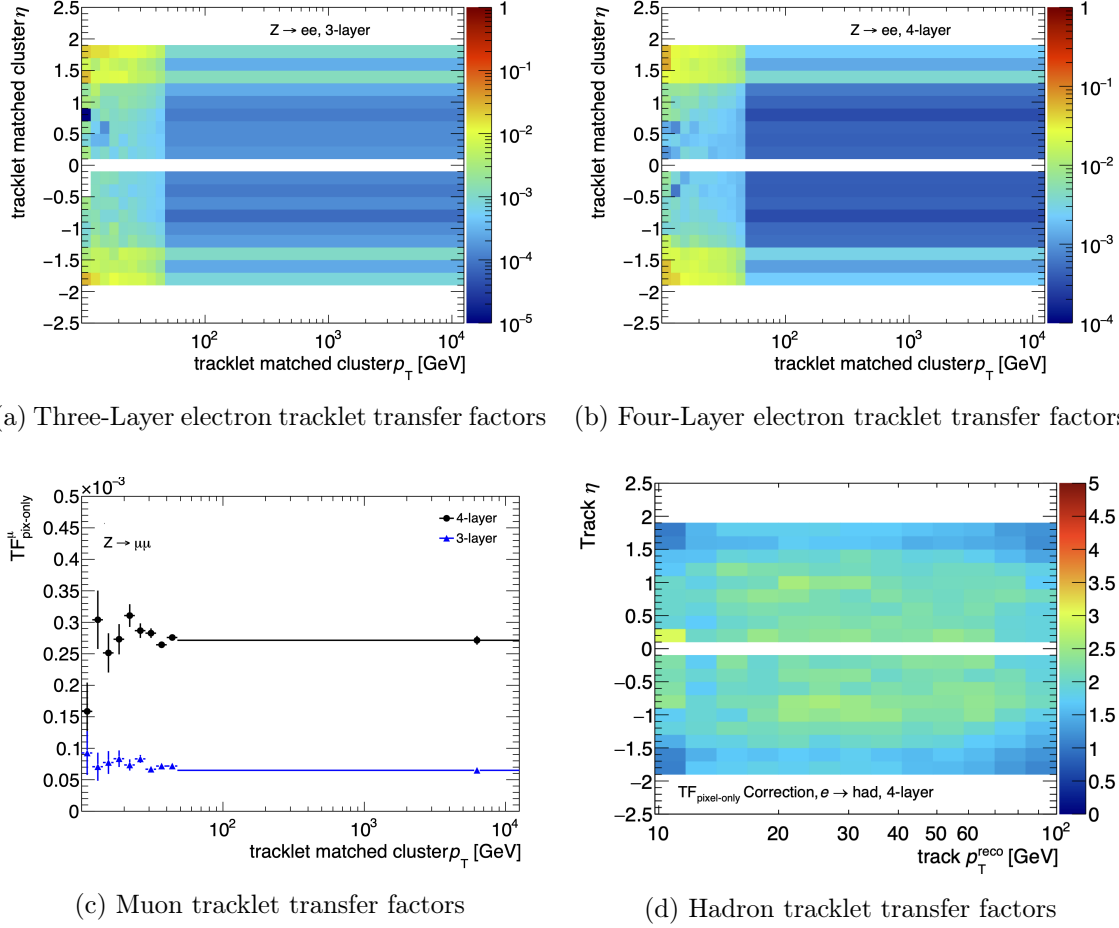


Figure 9.13: The tracklet transfer factors for each scattered particle background, measured using a Z-tag-and-probe method for leptons and estimated from Monte Carlo for hadrons.

then calculated. To account for the Monte Carlo–data differences, they are combined by

$$\text{TF}_{\text{tracklet}}^{\text{had}} = \text{TF}_{\text{tracklet}}^{\text{e, Z} \rightarrow \text{ee}} \times \frac{\text{TF}_{\text{tracklet}}^{\text{had, SPG}}}{\text{TF}_{\text{tracklet}}^{\text{e, SPG}}} \quad (9.1)$$

The tracklet transfer factors are shown in Figure 9.13, and tracklet + soft track transfer factors in Figure 9.14.

### 9.2.1.2 Veto Transfer Factors

As the initial samples of scattered particles are taken from a region with large calorimeter deposits near the track in order to enrich in electrons or hadrons, or near a MSTrack in order to enrich in muons, a transfer factor to a signal-region-like selection needs to be applied.

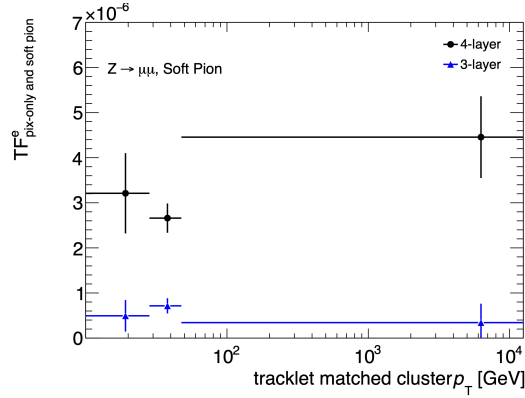
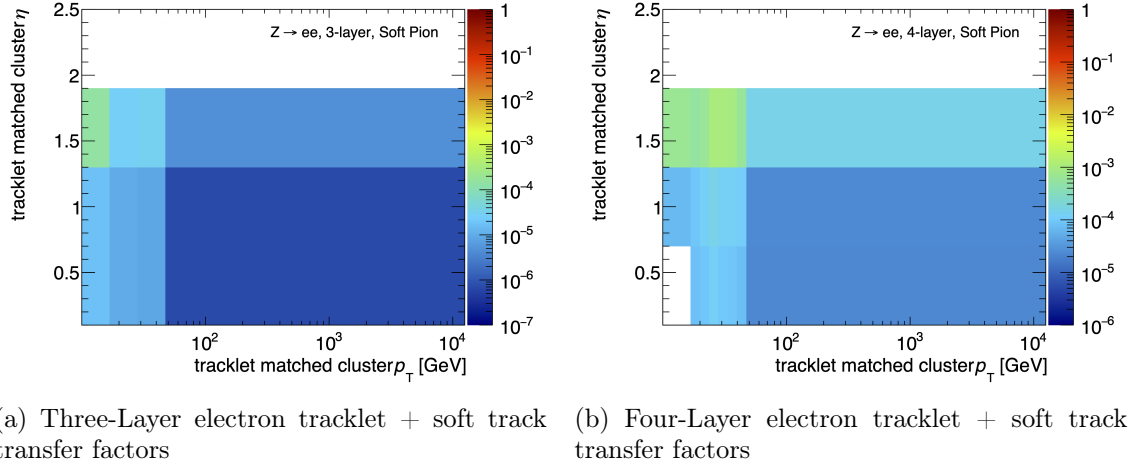


Figure 9.14: The tracklet + soft track transfer factors for each scattered particle background, measured using a Z-tag-and-probe method for leptons and estimated from Monte Carlo for hadrons. [123, 124]

For the hadrons and electrons, this *calo-veto* transfer factor is found from a  $Z \rightarrow ee$  region by taking the ratio of probe electron tracks with  $E_T^{\text{topoclus20}} < 10 \text{ GeV}$  over those with  $E_T^{\text{topoclus20}} > 10 \text{ GeV}$ , parameterised in  $p_T$  and  $\eta$ . This is shown in Figure 9.15. An additional correction factor is then applied to account for the differences in calorimeter deposits between hadrons and electrons, and the difference in calorimeter efficiency for standard and scattered particles. This is shown in Figure 9.17.

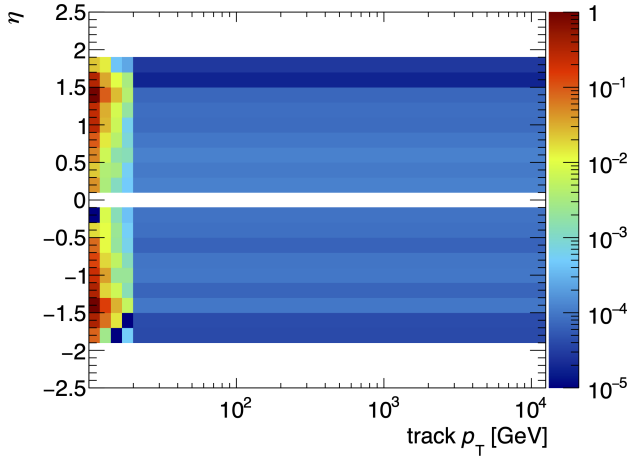


Figure 9.15: The calo-veto transfer factor. [123, 124]

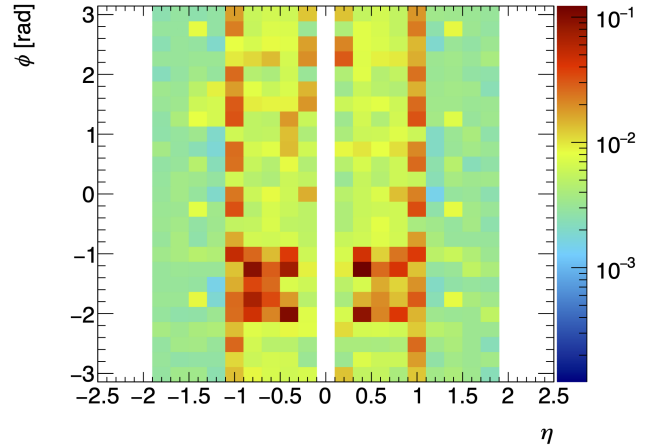


Figure 9.16: The MTrack-veto transfer factor. [123, 124]

For Muons, the MTrack-veto transfer factor is found by taking the ratio of tracks with no MTrack nearby over those with a MTrack nearby, parameterised in  $p_T$  and  $\phi$ . This transfer factor is shown in Figure 9.16.

### 9.2.1.3 Smearing Functions

As the pixel tracklets have significantly-poorer transverse momentum resolutions, it is necessary to smear the distributions of the standard tracks to match, after applying the transfer factors described above. These smearing functions were calculated by retracking well-reconstructed electrons or muons from data with pixel hits only. A function composed of a double-sided crystal ball and a Gaussian tail was fitted to the resulting  $\Delta q/p_T$  distributions. This equation is given in Appendix C. The fit was performed in slices of  $p_T$ , and the resulting fits are shown in Figure 9.18.

### 9.2.1.4 Normalisation & Results

As the electron and muon backgrounds have an absolute tracklet transfer factor calculated from a pure region, these estimates are also absolute. However, the the hadronic estimate



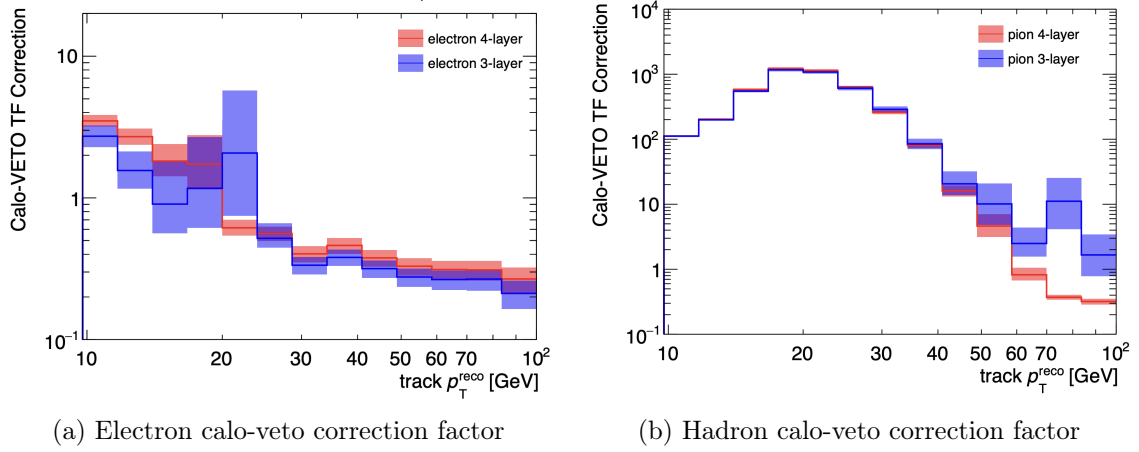
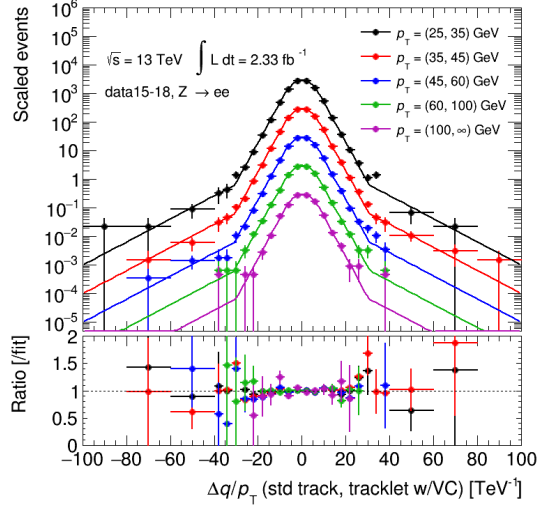
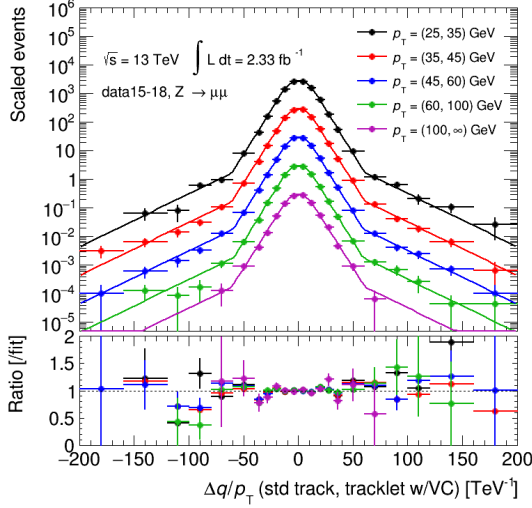


Figure 9.17: Calo-veto correction factors to account for the difference in calo-veto efficiency between standard tracks and tracklets, and for the difference between electron and hadron calorimeter activity. [123, 124]

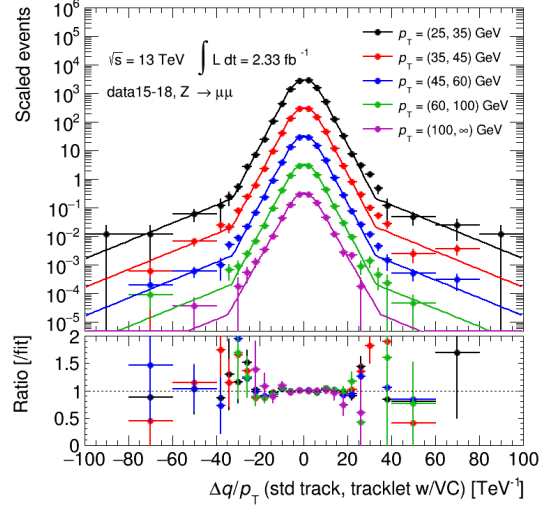
does not share this luxury, so the tracklet transfer function here only corrects the shape of the  $p_T$  distribution. Therefore, in the final fit the hadronic background shape is treated as a free-floating shape. To provide an initial estimate for the fit, the hadron shape is normalised to the lowest- $p_T$  bin. To validate this approach, the total background fit was performed in a low- and medium- $E_T^{\text{miss}}$  region with no calorimeter veto to enrich in scattered backgrounds. This is shown in Figure 9.19, where generally good agreement is shown, although there are deviations from the data that are still being understood at the time of writing.



(a) Smearing functions for four-layer tracklets derived from electrons

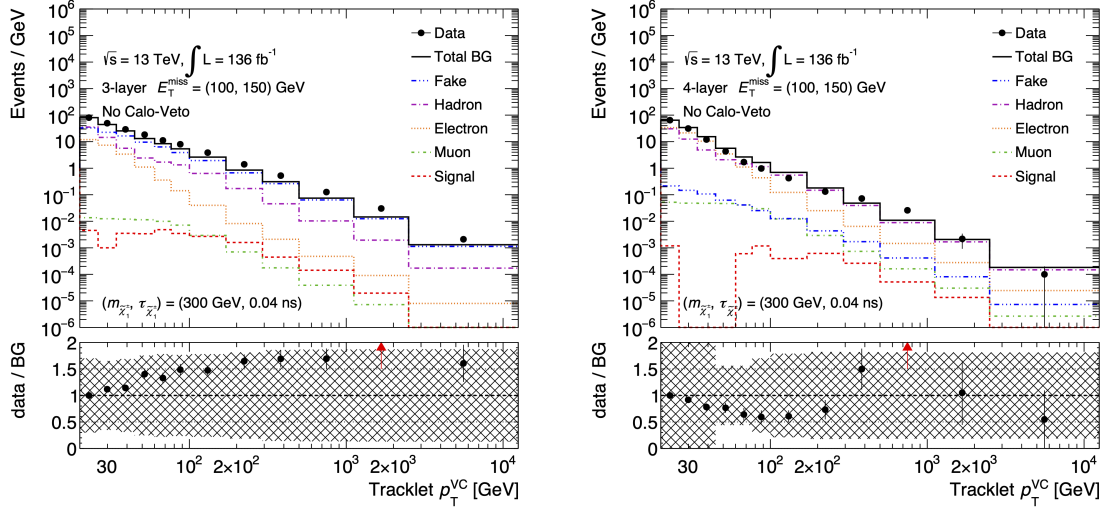


(b) Smearing functions for three-layer tracklets derived from muons



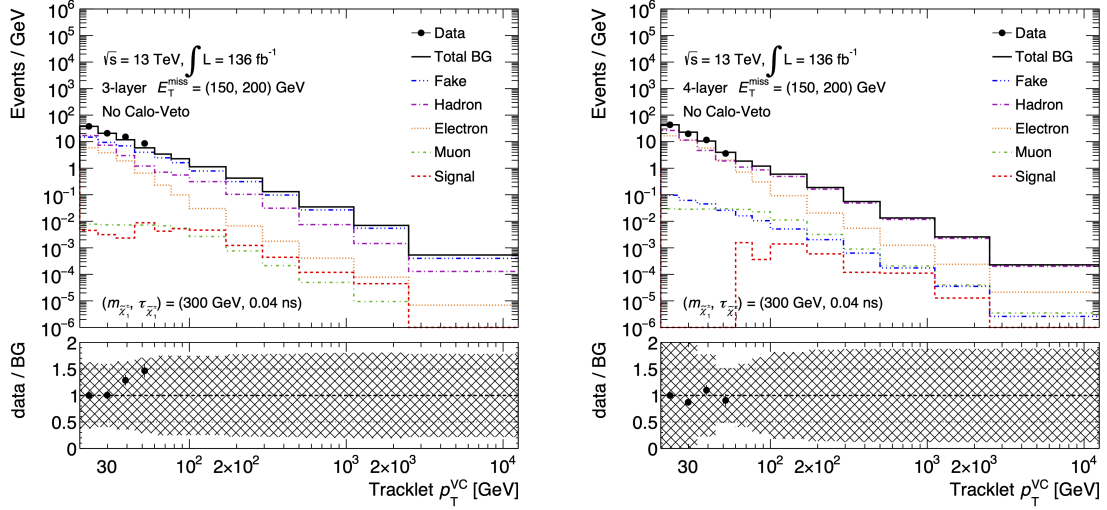
(c) Smearing functions for three-layer tracklets derived from muons

Figure 9.18: Smearing functions to approximate the  $p_T$  resolutions of pixel tracklets from standard tracks, calculated by fitting a double-sided crystal ball function plus a gaussian tail to retracked electrons or muons from  $Z \rightarrow \ell\ell$  events. [123, 124]



(a) Result of background fit in the three-layer low- $E_T^{\text{miss}}$  region without a calorimeter veto.

(b) Result of background fit in the four-layer low- $E_T^{\text{miss}}$  region without a calorimeter veto.



(c) Result of background fit in the three-layer mid- $E_T^{\text{miss}}$  region without a calorimeter veto.

(d) Result of background fit in the four-layer mid- $E_T^{\text{miss}}$  region without a calorimeter veto.

Figure 9.19: Background fits in low- and medium- $E_T^{\text{miss}}$  regions with no calorimeter veto, in order to validate the scatter background estimates. The signal sample shown is of higgsinos with a mass of 300 GeV and a lifetime of 0.04 ns.

### 9.2.2 Fake Tracklet Background

As discussed in Section 7.3.4, the previous approach used a  $p_T$  shape derived from a high- $d_0$ -significance control region, and fitted this shape along with shapes from the other backgrounds to match observations from the data. The fit resulting from this can be seen in Figure 9.20, reproduced from Section 7.3.4 and [1]. There were two concerns with this approach: the fake purity of the high- $d_0$ -significance control region, and the robustness of multiple floating fits of different  $p_T$  shapes to match the background. Figure 9.21 shows the  $d_0$  significance split by TMS (Appendix B.2) of truth-linked four-layer tracklets in a set of V+Jets samples, and shows a large number of tracklets with a perfect score in the high- $d_0$ -significance region, indicating a high chance of being a scattered particle. A new approach was pursued for the second analysis, using a high- $|z_0 \sin \theta|$  control region to gain an absolute fake estimate and extrapolate this prediction to the signal region.

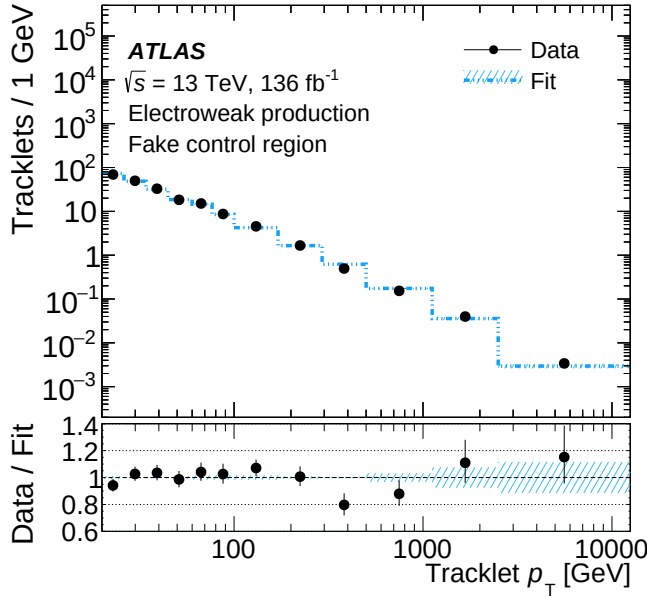


Figure 9.20: The fake background prediction from the first analysis. Reproduced from [1].

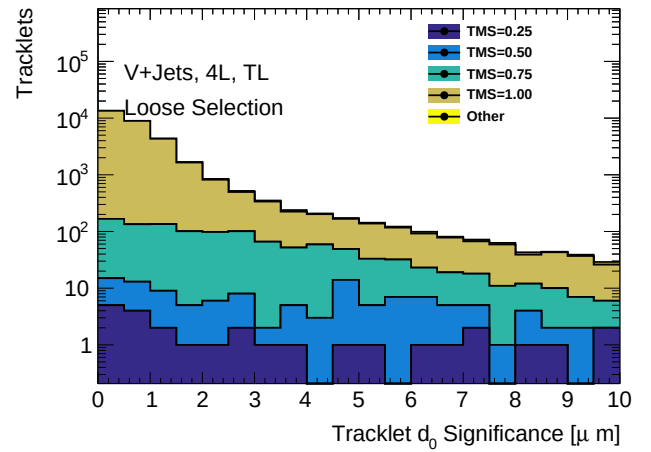


Figure 9.21: The  $d_0$  significance of truth-linked four-layer tracklets from a set of V+Jets samples, separated by TMS to show a large non-fake component in the fake control region at high- $d_0$ -significance.

This approach uses the assumption that a fake points in a random direction, and is independent of the event topology. In this case, a  $|z_0 \sin \theta|$  spectrum would have a large peak at low values of  $|z_0 \sin \theta|$  caused by well-reconstructed tracks from prompt particles, and a flat baseline across the whole spectrum from poorly-reconstructed or fake tracks. To validate this assumption, the  $|z_0 \sin \theta|$  spectrum must be assessed to define a fake control region, then prove that this control region is pure in fake tracklets, and finally prove that the  $p_T$  shape of the fake tracklets is independent of the control region definition.

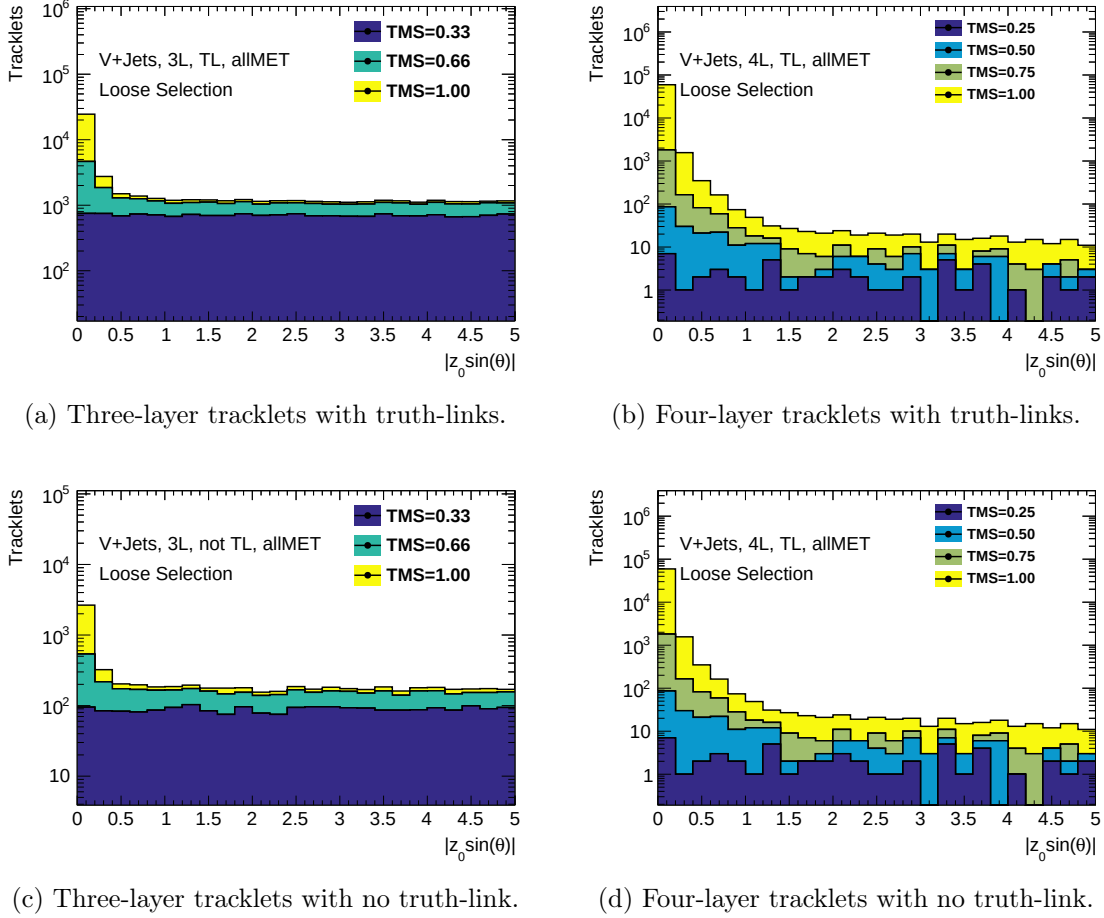


Figure 9.22: A comparison of the truth-link status and TMS of tracklets from a V+Jets background sample set. Figures 9.22(a) and 9.22(b) have a truth-link whereas Figures 9.22(c) and 9.22(d) do not.

### 9.2.2.1 $|z_0 \sin \theta|$ approach validation

To begin with testing the basic assumption that the fakes are evenly distributed in  $|z_0 \sin \theta|$  and that the high- $|z_0 \sin \theta|$  region is pure in fakes, the  $|z_0 \sin \theta|$  distribution is shown in Figure 9.22 for three- (left figures) and four-layer tracklets (right figures) and for tracklets with (top figures) and without links to truth particles (bottom figures). The  $|z_0 \sin \theta|$  distribution is only shown up to 5.0 mm due to a filter in the data derivation stage that reduces reconstruction efficiency past this point. From these figures, it can be seen that the distributions with the lowest TMS (most likely to be fake) are flat in  $|z_0 \sin \theta|$ , and that the distributions with a perfect TMS (most likely to be non-fake) are predominantly centrally distributed. A generous central region can then be defined as  $|z_0 \sin \theta| < 2.0$  mm to cover all possible non-fake contributions. The remainder can then be split into a small validation region ( $2.0 \text{ mm} < |z_0 \sin \theta| < 2.5 \text{ mm}$ ) and a large control region ( $2.5 \text{ mm} < |z_0 \sin \theta| < 5.0 \text{ mm}$ ).

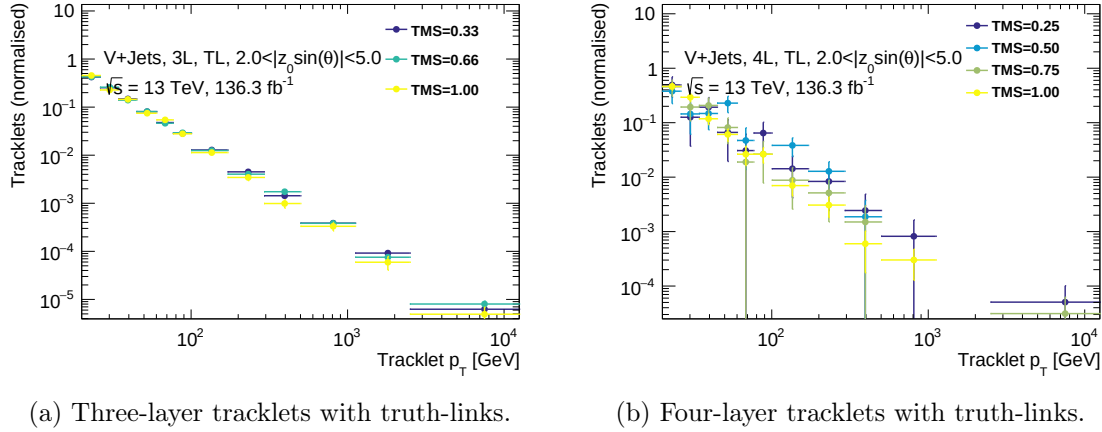


Figure 9.23: A comparison of the  $p_T$  of tracklets from a V+Jets background sample set in the fake CR with various TMS.

Next, it is important to verify that the  $p_T$  shape in the control region is independent of truth-link status and TMS. If it was not, then any contribution from the categories with a higher TMS would need to be understood and separated. Figure 9.23 shows the  $p_T$  shapes in the fake control region for three- (left figures) and four-layer tracklets (right figures) and for tracklets with (top figures) and without links to truth particles (bottom figures). No significant difference can be seen between the distributions, suggesting that the background in this control region can be taken as a single homogenous background.

Finally it is necessary to ensure that the  $p_T$  shapes are independent of the choice of  $|z_0 \sin \theta|$  region. If the  $p_T$  shape did change, it would be impossible to extrapolate this from the control region to the signal region. A comparison was made between the control region and validation region in data (Figure 9.24) and no significant difference in  $p_T$  shapes can be seen, meaning the fake shape can be safely extrapolated.

### 9.2.2.2 Fake extrapolation and scale factors

Now that the validity of the  $|z_0 \sin \theta|$  sideband approach has been shown, it can be used to derive estimates for the fake background in validation and signal regions. This is performed by measuring the tracklet  $p_T$  distribution in the fake control region, and scaling this by the ratio of the  $|z_0 \sin \theta|$  cuts in the regions. As the validation region has a  $|z_0 \sin \theta|$  cut of  $2.0 \text{ mm} < |z_0 \sin \theta| < 2.5 \text{ mm}$ , for the fake validation regions this scale factor is  $s_{\text{fake}}^{\text{VR}} = 0.5 \text{ mm} / 2.5 \text{ mm} = 0.2$  and for the signal regions the scale factor is  $s_{\text{fake}}^{\text{SR}} = 0.2 \text{ mm} / 2.5 \text{ mm} = 0.08$ .

The fake estimate was then made in the Run-2 dataset, with the results shown in Table 9.3). These results show good agreement in the validation regions within statistical uncertainty, and

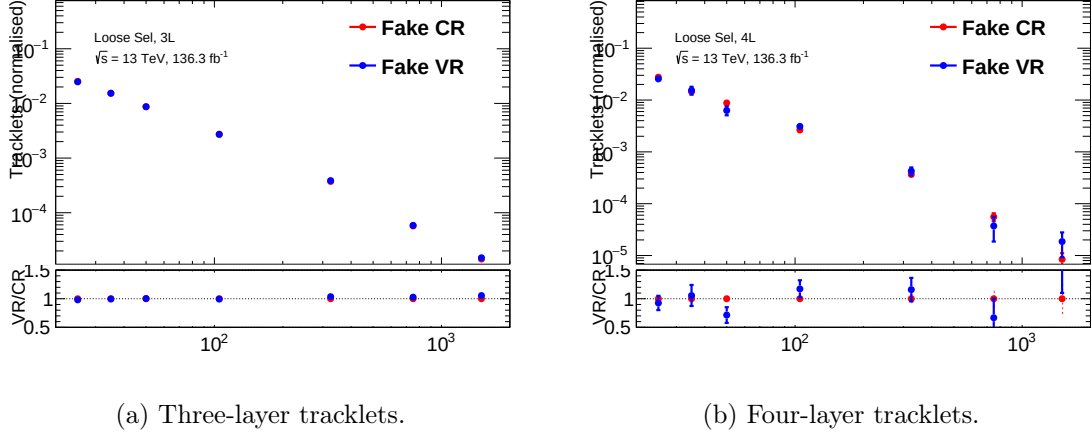


Figure 9.24: A comparison of the  $p_T$  shape of tracklets in the fake control and validation regions in the Run-2 dataset.

| Tracklet<br>Soft Pion | Three-Layer   |                | Four-Layer      |                 |
|-----------------------|---------------|----------------|-----------------|-----------------|
|                       | Inclusive     | Yes            | Inclusive       | Yes             |
| CR Measurement        | $2600 \pm 50$ | $93 \pm 10$    | $4.0 \pm 2.0$   | $2.0 \pm 1.4$   |
| VR Prediction         | $521 \pm 10$  | $18.6 \pm 1.9$ | $0.8 \pm 0.4$   | $0.40 \pm 0.28$ |
| VR Measurement        | $897 \pm 30$  | $23 \pm 5$     | $5.0 \pm 2.2$   | $0.0 \pm 0.0$   |
| SR Prediction         | $208 \pm 4$   | $7.4 \pm 0.8$  | $0.32 \pm 0.16$ | $0.16 \pm 0.11$ |

Table 9.3: Predicted and measured fake background yields for all selections for the Run-2 dataset

demonstrate the effectiveness of the soft-pion requirement at reducing the fake background. However, they are clearly hampered by large statistical uncertainties.

To resolve the issue with available statistics, an approach was developed where the fake estimate is made in the **Three-Layer** selection only, which has the highest available statistics for fake tracklets. A scale-factor is then calculated in an orthogonal high-statistics region between the **Three-Layer** selection and the target selection. The definition of this orthogonal region is not critical as the characteristics fake tracklet should be independent of the event selection. However, it will be necessary to demonstrate this independence, and the independence of the fake tracklet kinematics from the tracklet length and soft pion requirement. The scale-factors were calculated in either **lowMET** or  $Z \rightarrow \mu\mu$  regions. The **lowMET** region is similar to the disappearing track region, but with the  $E_T^{\text{miss}}$  and leading jet  $p_T$  cuts inverted with a small buffer, so that the region is defined with  $E_T^{\text{miss}} < 200 \text{ GeV}$  when  $p_T^{\text{jet } 1} > 100 \text{ GeV}$ , and no  $E_T^{\text{miss}}$  cut when  $p_T^{\text{jet } 1} < 100 \text{ GeV}$ . The  $Z \rightarrow \mu\mu$  region is defined as

- Event cleaning requirements and disappearing track Good Run List (GRL),

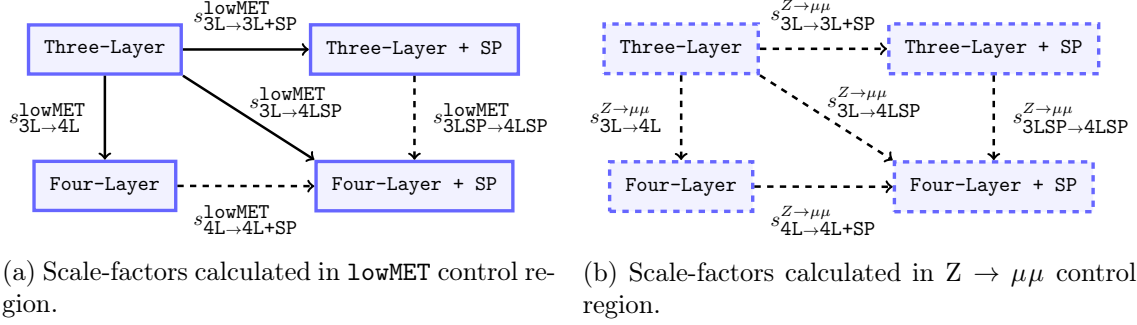


Figure 9.25: Diagrams showing how scale-factors are applied to the fake prediction **ThreeLayer** signal region to produce estimates for other signal regions. Scale-factors are a single number with an uncertainty. Solid items are used in the analysis, dashed items are used as a cross-check and to define systematic uncertainties.

- At least 2 good muons,
- Leading muon transverse momentum  $p_T^{\text{muon } 1} > 25 \text{ GeV}$ ,
- Sub-leading muon transverse momentum  $p_T^{\text{muon } 2} > 20 \text{ GeV}$ ,
- On-shell requirement:  $|m(\mu_1) + m(\mu_2) - 91 \text{ GeV}| < 10 \text{ GeV}$ ,
- At least one tracklet.

Assuming no tracklet  $p_T$  dependence from the choice of signal region selection, the scale-factor can be a single number, calculated by dividing the number of tracklets in the fake control region for the target selection by the number of tracklets in the fake control region for the **ThreeLayer** selection, in the chosen orthogonal region. As an example, the scale-factor to calculate the estimate for the **Three-Layer+SP** selection using the  $\text{lowMET}$  region is found as  $s_{3L \rightarrow 3L+SP}^{\text{lowMET}} = n_{3L+SP}^{\text{lowMET CR}} / n_{3L}^{\text{lowMET CR}}$ . Multiple scale-factors can be calculated using either orthogonal region, and going from the **ThreeLayer** selection to the target selection, or from another selection to the target selection. The application of these scale-factors is shown in Figure 9.25.

It is now necessary to test the assumptions of this extrapolation. First, it is necessary to show that the choice of orthogonal region has no affect on the fake tracklet  $p_T$ . This is shown by comparing the tracklet  $p_T$  in the fake control regions in each orthogonal region, shown in Figure 9.26. It is then necessary to demonstrate that the signal region selection does not affect the fake tracklet  $p_T$ . This is shown by comparing the tracklet  $p_T$  for three- four-layer tracklets with and without a reconstructed soft pion in the fake control region in each orthogonal region, shown in Figure 9.28 for the comparison of tracklet length, and Figure 9.30 for the comparison of soft pion requirement. For tracklets with a soft pion, the effect of the choice of tracklet length on the soft pion  $p_T$  is also assessed in Figure 9.29. All of these figures show that the



| Scale-Factor                | lowMET                           | $Z \rightarrow \mu\mu$           | Difference [%]    |
|-----------------------------|----------------------------------|----------------------------------|-------------------|
| $s_{3L \rightarrow 3L+SP}$  | $(4.16 \pm 0.07) \times 10^{-2}$ | $(3.54 \pm 0.15) \times 10^{-2}$ | $18 \pm 7$        |
| $s_{3L \rightarrow 4L}$     | $(2.98 \pm 0.18) \times 10^{-3}$ | $(2.7 \pm 0.4) \times 10^{-3}$   | $10^{+27}_{-20}$  |
| $s_{3L \rightarrow 4LSP}$   | $(6.5 \pm 0.9) \times 10^{-4}$   | $(4.3 \pm 1.6) \times 10^{-4}$   | $50^{+120}_{-60}$ |
| $s_{4L \rightarrow 4L+SP}$  | $(2.17 \pm 0.32) \times 10^{-1}$ | $(1.6 \pm 0.6) \times 10^{-1}$   | $40^{+110}_{-50}$ |
| $s_{3LSP \rightarrow 4LSP}$ | $(1.55 \pm 0.21) \times 10^{-2}$ | $(1.2 \pm 0.5) \times 10^{-2}$   | $30^{+120}_{-50}$ |

Table 9.4: Comparison of scale-factors for the fake extrapolation calculated in lowMET or  $Z \rightarrow \mu\mu$  orthogonal regions.

fake tracklet  $p_T$  shape is independent of these choices, within statistical uncertainty, and the extrapolation approach can be used.

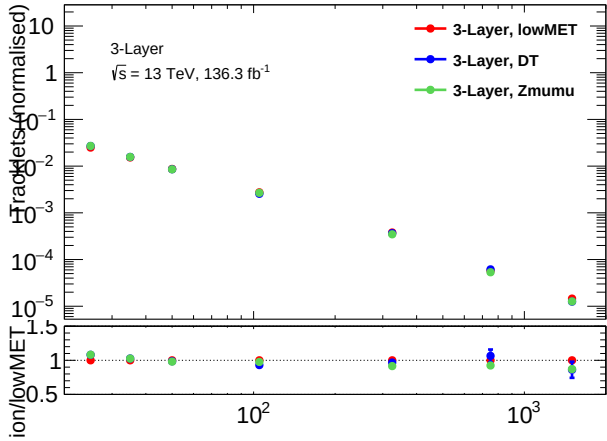


Figure 9.26: Comparison of three-layer tracklet  $p_T$  in the fake control region ( $2.5 \text{ mm} < |z_0 \sin \theta| < 5.0 \text{ mm}$ ) for the three control selections (DT, lowMET,  $Z \rightarrow \mu\mu$ ).

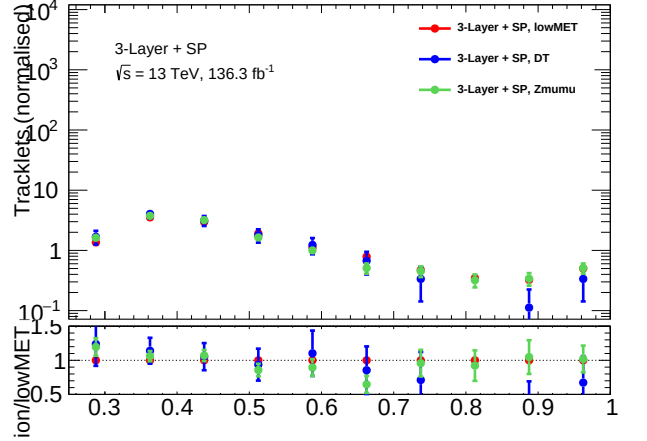
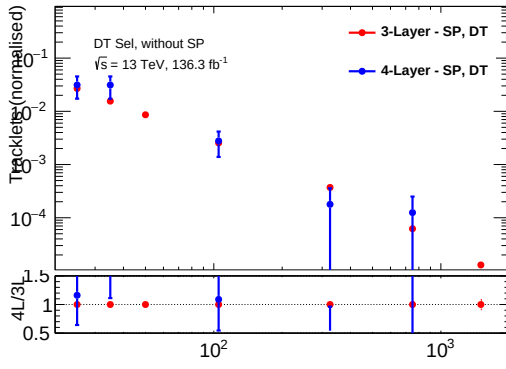
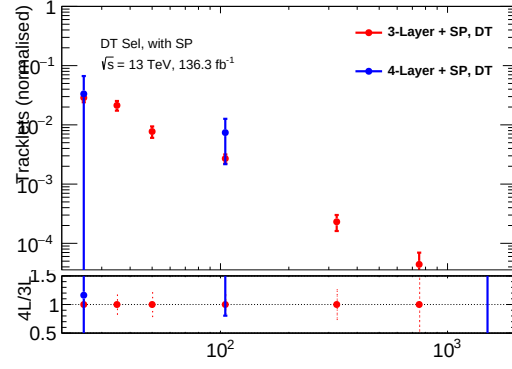


Figure 9.27: Comparison of three-layer soft track  $p_T$  in the fake control region ( $2.5 \text{ mm} < |z_0 \sin \theta| < 5.0 \text{ mm}$ ) for the three control selections (DT, lowMET,  $Z \rightarrow \mu\mu$ ).

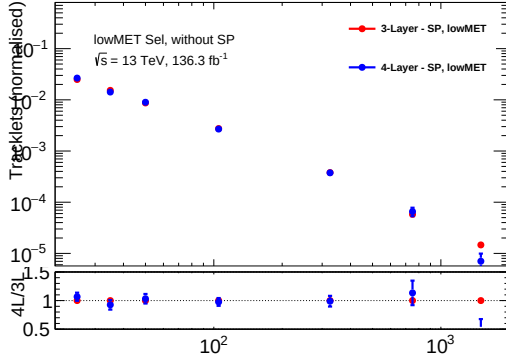
It is now possible to calculate scale-factors for the extrapolation. First, these are calculated in slices of  $E_T^{\text{miss}}$  and leading jet  $p_T$  for the two orthogonal regions, to check for any dependency. This is shown in Figure 9.31, and no dependency is observed. The final scale-factors for each selection are then shown in Table 9.4 for both the lowMET and  $Z \rightarrow \mu\mu$  orthogonal regions, and the difference between them. This difference can be averaged and halved as a gross approximation of the systematic uncertainty for the scale factors, approximately in the region of 10-20%.



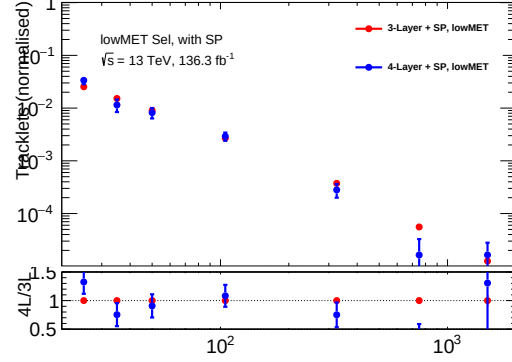
(a) Tracklets with no reconstructed soft pion, in the DT selection.



(b) Tracklets with a reconstructed soft pion, in the DT selection



(c) Tracklets with no reconstructed soft pion, in the lowMET selection.



(d) Tracklets with a reconstructed soft pion, in the lowMET selection

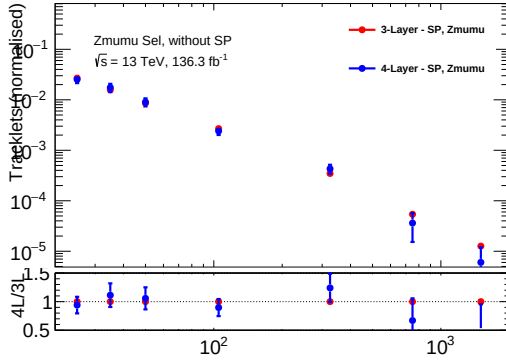
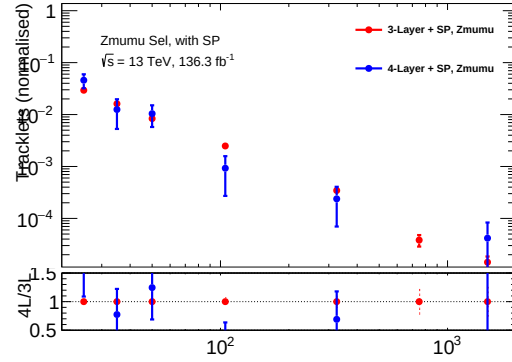
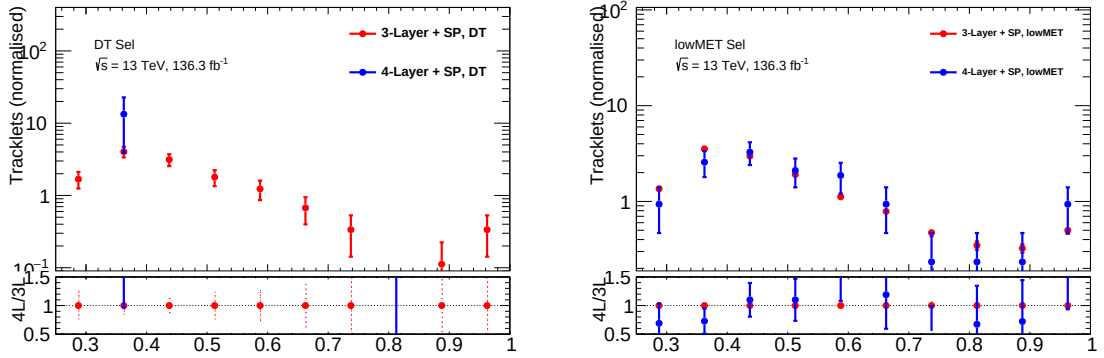
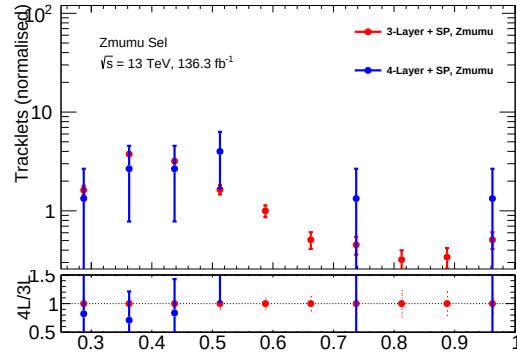

 (e) Tracklets with no reconstructed soft pion, in the  $Z \rightarrow \mu\mu$  selection.

 (f) Tracklets with a reconstructed soft pion, in the  $Z \rightarrow \mu\mu$  selection

 Figure 9.28: Comparison of tracklet  $p_T$  for different-length tracklets in the fake control region ( $2.5 \text{ mm} < |z_0 \sin \theta| < 5.0 \text{ mm}$ ) for the three control selections (DT, lowMET,  $Z \rightarrow \mu\mu$ ).

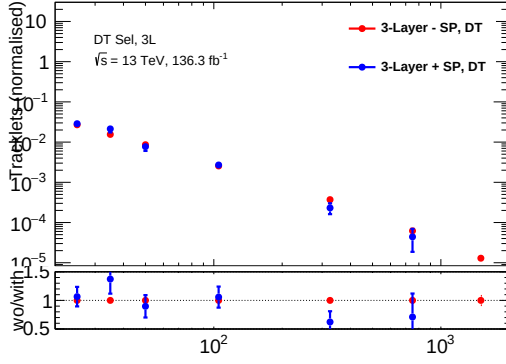


(a) Tracklets with a reconstructed soft pion, in the DT selection (b) Tracklets with a reconstructed soft pion, in the lowMET selection

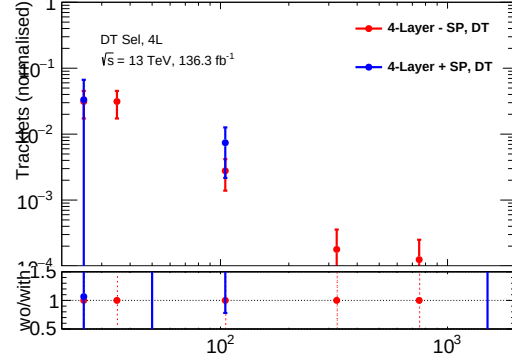


(c) Tracklets with a reconstructed soft pion, in the  $Z \rightarrow \mu\mu$  selection

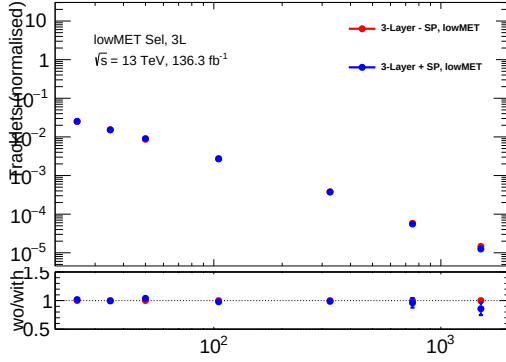
Figure 9.29: Comparison of soft track  $p_T$  for different-length tracklets in the fake control region ( $2.5 \text{ mm} < |z_0 \sin \theta| < 5.0 \text{ mm}$ ) for the three control selections (DT, lowMET,  $Z \rightarrow \mu\mu$ ).



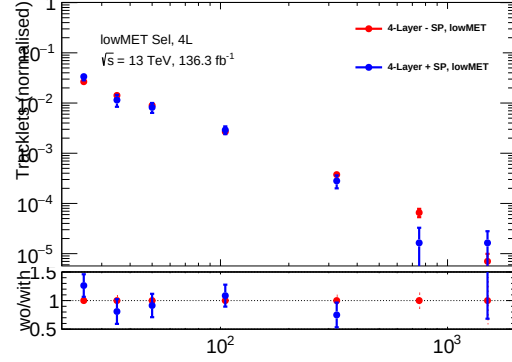
(a) Three-layer tracklets in the DT selection.



(b) Four-layer tracklets in the DT selection



(c) Three-layer tracklets in the lowMET selection.



(d) Four-layer tracklets in the lowMET selection

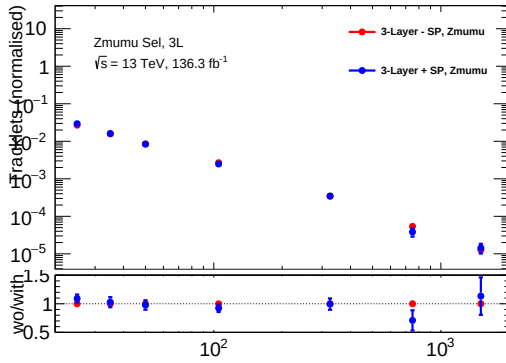
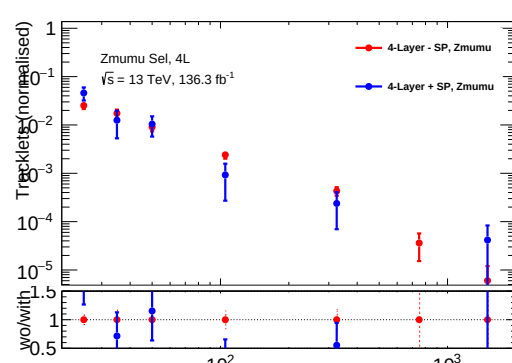
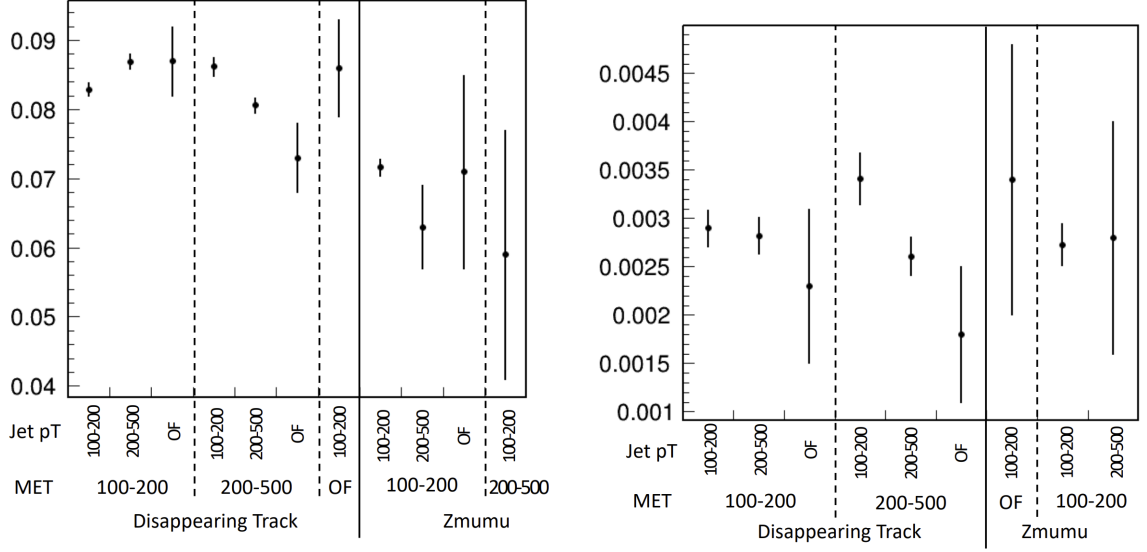
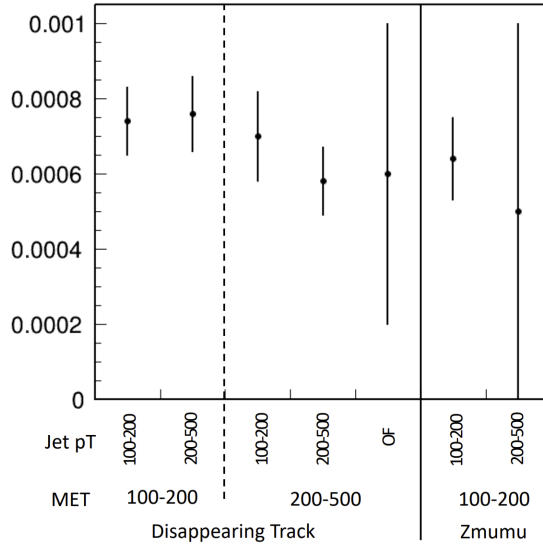

 (e) Three-layer tracklets in the  $Z \rightarrow \mu\mu$  selection.

 (f) Four-layer tracklets in the  $Z \rightarrow \mu\mu$  selection

Figure 9.30: Comparison of tracklet  $p_T$  with and without a soft pion in the fake control region ( $2.5 \text{ mm} < |z_0 \sin \theta| < 5.0 \text{ mm}$ ) for the three control selections (DT, lowMET,  $Z \rightarrow \mu\mu$ ).



(a) Three-Layer to Three-Layer+SP scale-factor.

(b) Three-Layer to Four-Layer scale-factor.



(c) Three-Layer to Four-Layer+SP scale-factor.

 Figure 9.31: Comparison of fake extrapolation scale-factors when calculated in varying selections and slices of  $E_T^{\text{miss}}$  and leading jet  $p_T$ .

| Tracklet  |                        | Three-Layer   |                 | Four-Layer        |                     |
|-----------|------------------------|---------------|-----------------|-------------------|---------------------|
| Soft Pion |                        | Inclusive     | Yes             | Inclusive         | Yes                 |
| CR        | lowMET                 | -             | $108.3 \pm 2.8$ | $7.76 \pm 0.20$   | $1.68 \pm 0.04$     |
|           | $Z \rightarrow \mu\mu$ | -             | $92 \pm 4$      | $6.96 \pm 0.32$   | $1.11 \pm 0.05$     |
|           | Measurement            | $2600 \pm 50$ | $93 \pm 10$     | $4.0 \pm 2.0$     | $2.0 \pm 1.4$       |
| VR        | lowMET                 | -             | $21.7 \pm 0.6$  | $1.55 \pm 0.04$   | $0.337 \pm 0.009$   |
|           | $Z \rightarrow \mu\mu$ | -             | $18.4 \pm 0.9$  | $1.39 \pm 0.06$   | $0.222 \pm 0.010$   |
|           | DT Sideband            | $521 \pm 10$  | $18.6 \pm 1.9$  | $0.8 \pm 0.4$     | $0.40 \pm 0.28$     |
|           | Measurement            | $897 \pm 30$  | $23 \pm 5$      | $5.0 \pm 2.2$     | $0.0 \pm 0.0$       |
| SR        | lowMET                 | -             | $8.66 \pm 0.22$ | $0.621 \pm 0.016$ | $0.1346 \pm 0.0035$ |
|           | $Z \rightarrow \mu\mu$ | -             | $7.37 \pm 0.34$ | $0.557 \pm 0.026$ | $0.089 \pm 0.004$   |
|           | DT Sideband            | $208 \pm 4$   | $7.4 \pm 0.8$   | $0.32 \pm 0.16$   | $0.16 \pm 0.11$     |

Table 9.5: Comparison of fake predictions and measurements for the fake control, validation and signal regions in the target selection either directly from the DT region or using predictions scaled from the **Three-Layer** selection using scale-factors calculated from the **lowMET** or  $Z \rightarrow \mu\mu$  regions. Uncertainties are statistical only.

### 9.2.2.3 Results and Normalisation

The final results for the fake estimate are then found by applying the scale-factors in Table 9.4 to the DT **Three-Layer** fake control region, and then finding the validation and signal region predictions as normal. This is compared to the measurements for these regions in Table 9.5, which shows good agreement in the validation region. The **lowMET**-extrapolation results are then used in the analysis.

To test that the fake predictions are accurate, a combined fit with the other backgrounds was made in low- $E_T^{\text{miss}}$  control region ( $100 \text{ GeV} < E_T^{\text{miss}} < 150 \text{ GeV}$ ) with a disappearing track selection including a calorimeter veto. The fake background was allowed to float, along with the hadron background described in Section 9.2.1. If the fake background is accurately calculated it would remain approximately the same after the fit. These regions before and after the fit are shown in Figure 9.32 for the low- $E_T^{\text{miss}}$  region. It is clear from this Figure that there is significant underestimate of the fake (or fake-like) background in the signal regions — the three-layer result is scaled up by approximately 1.8x and the four-layer result by 12.5x.

The tests shown earlier in Section 9.2.2.1 relied on the assumption that the  $|z_0 \sin \theta|$  spectrum was comprised of two components, a purely-combinatorial fake background which has a flat shape, and a scattered Standard Model particle background which has a gaussian peak centered at 0 mm. The tests shown in this Section show that the purely-combinatorial back-

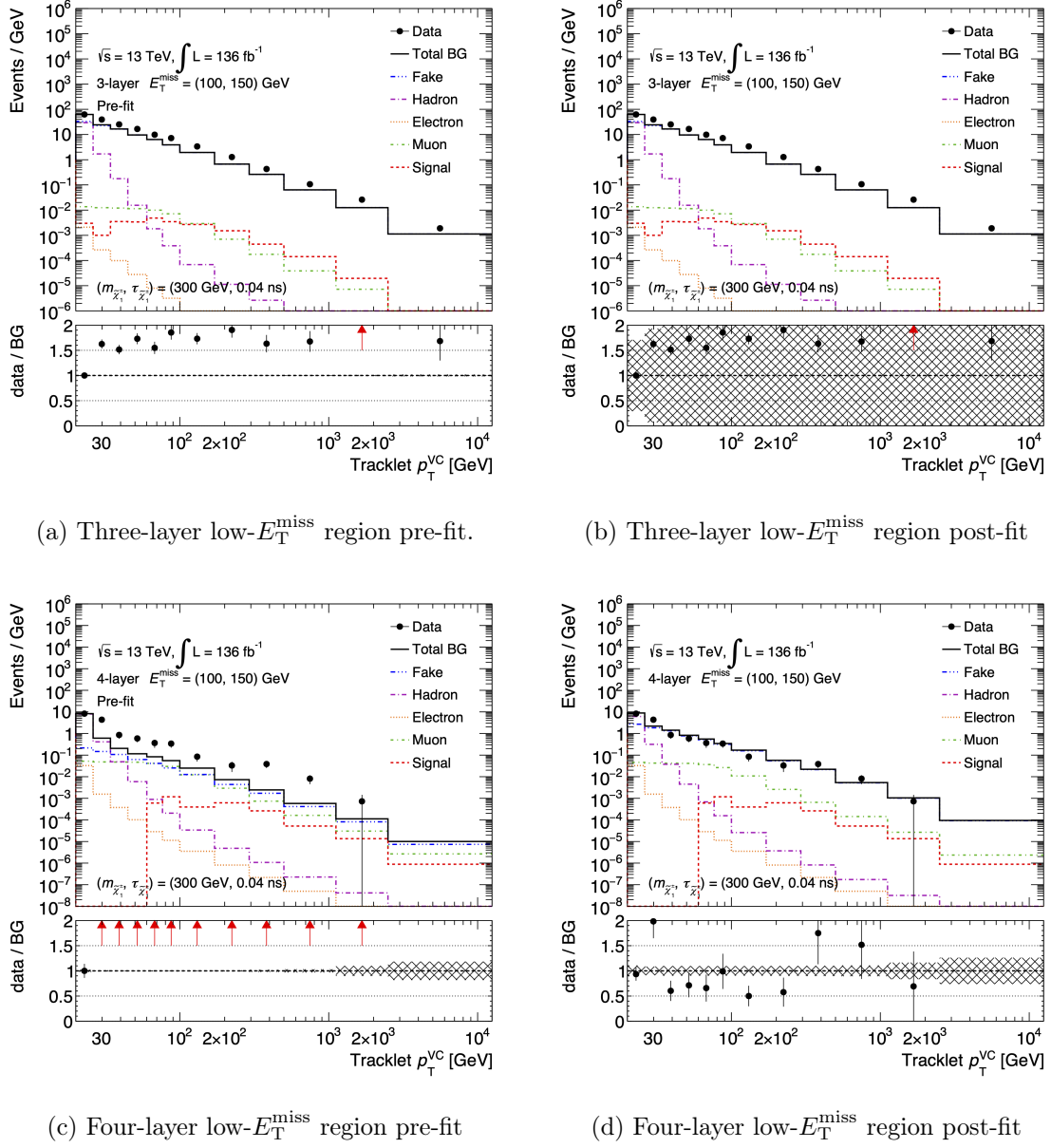


Figure 9.32: Comparison of low- $E_T^{\text{miss}}$  regions ( $100 \text{ GeV} < E_T^{\text{miss}} < 150 \text{ GeV}$ ) before and after a fit to data where the hadronic scatter and fake backgrounds are allowed to float freely. The signal sample shown is of higgsinos with a mass of 300 GeV and a lifetime of 0.04 ns.

ground is flat in  $|z_0 \sin \theta|$  and accurately predicted, but that there is a third class of background with a fake-like  $p_T$  shape, but centrally-distributed in  $|z_0 \sin \theta|$ . It is hypothesised that this is a *hybrid* fake track, where the majority of hits are from a real particle, but one or more is a fake hit mistakenly assigned to the tracklet. This is enough to distort the  $p_T$  shape to appear pure-fake-like, but the tracklet is still positioned close to the primary vertex due to most hits being from a real particle.

At the time of writing, studies are in progress to determine the best approach for estimating this background. As the  $p_T$  shapes are very similar (see Figure 9.23), this approach will likely involve estimating these backgrounds as one and scaling the shape from the purely-combinatorial fakes to account for the hybrid tracklets. It is possible that a control region could be defined with careful choices of variables derived from the track fit (the defining parameters  $(d_0, z_0, \phi, \theta, q/p)$  and their associated covariance matrix), or from the characteristics of fake tracks (more dominant at higher values of  $p_T$  and lower values of  $E_T^{\text{miss}}$ ). In this control region, if it is suitably pure in hybrids and fakes, the number of tracks per millimetre of  $|z_0 \sin \theta|$  in fake signal region ( $|z_0 \sin \theta| < 0.5 \text{ mm}$ ) could be divided by the fakes per millimetre in the flat control region to produce an additional scale factor.

For the purposes of this thesis we will proceed with the floating fit normalisation, as the fake shape is accurate.



| Component                | Three-Layer       | Three-Layer + SP | Four-Layer      |
|--------------------------|-------------------|------------------|-----------------|
| Fakes                    | $152.45 \pm 3.39$ | $7.27 \pm 0.70$  | $5.94 \pm 1.01$ |
| Hadrons                  | 0.00              | 0.00             | 0.00            |
| Electrons                | 0.00              | 0.00             | 0.00            |
| Muons                    | $0.32 \pm 0.02$   | 0.00             | $1.33 \pm 0.06$ |
| Total Background         | $152.77 \pm 3.39$ | $7.27 \pm 0.70$  | $7.27 \pm 1.01$ |
| Higgsino 250 GeV 0.04 ns | $5.35 \pm 0.30$   | $0.98 \pm 0.13$  | $3.59 \pm 0.24$ |

Table 9.6: Work-in-progress signal region predictions.

### 9.3 Results & Discussion

The backgrounds estimated in Sections 9.2.1 and 9.2.2 and the yields from the signal selections defined in Section 9.1 can now be combined, and the sensitivity of the analysis assessed. Due to the preliminary transfer factors for the scatter backgrounds discussed in Section 9.2.1 and the unresolved fake normalisation discussed in Section 9.2.2.3, the results presented in this section are work-in-progress, but still represent a useful approximation of the sensitivity of the analysis. A blinded region defined by

$$\begin{aligned}
 E_{\text{T}}^{\text{miss}} &> 150 \text{ GeV} \\
 \text{tracklet } p_{\text{T}} &> 60 \text{ GeV} \\
 \text{tracklet } |z_0 \sin \theta| &< 2.0 \text{ mm}
 \end{aligned}$$

is also applied to all plots to prevent unblinding the signal regions and biasing the analysis. Observed data within this region is not plotted.

Combined fits in low- $E_{\text{T}}^{\text{miss}}$  control region with and without the calorimeter veto have already been shown in Figures 9.19 and 9.32 in the development of the scattered and fake background estimates. Now, the mid- $E_{\text{T}}^{\text{miss}}$  control region can be used to verify that the backgrounds are correctly modelled. The backgrounds, observed data (blinded) and a 250 GeV 0.04 ns signal sample can be seen in Figure 9.33. These show acceptable agreement between observed data and the background prediction. The signal regions can also be plotted, shown in Figure 9.34. The results in the usable signal regions are shown in Table 9.6.

The sensitivity to pure-wino charginos can then be assessed for the whole sample set by calculating exclusion limits using a  $\text{CL}_s$  method, described in Section 6.13. These are shown for the pure-higgsino hypothesis in Figure 9.35.

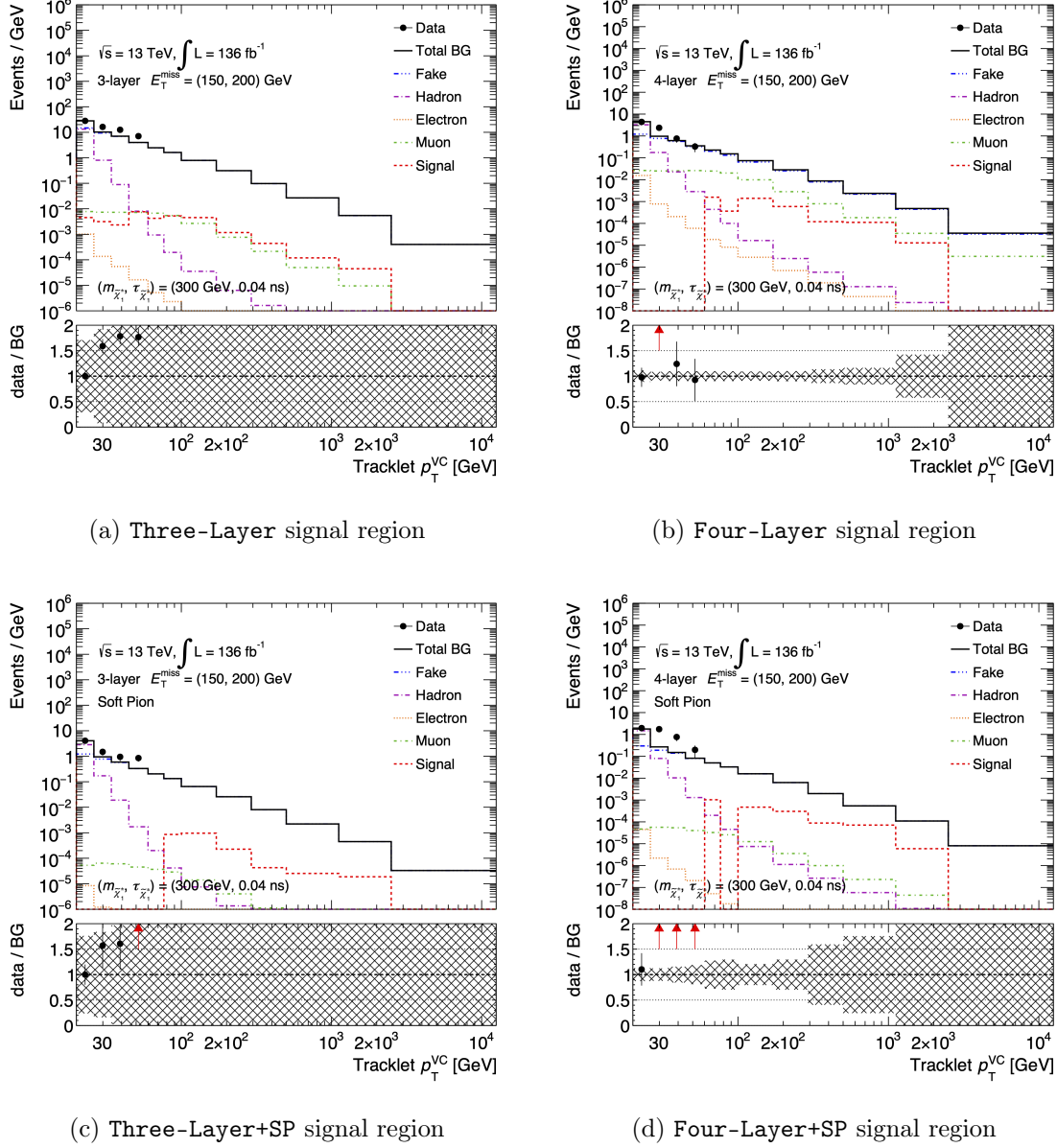


Figure 9.33: Tracklet  $p_T$  of estimated backgrounds, 300 GeV 0.04 ns signal and observed data in the  $150 \text{ GeV} < E_T^{\text{miss}} < 200 \text{ GeV}$  validation region.

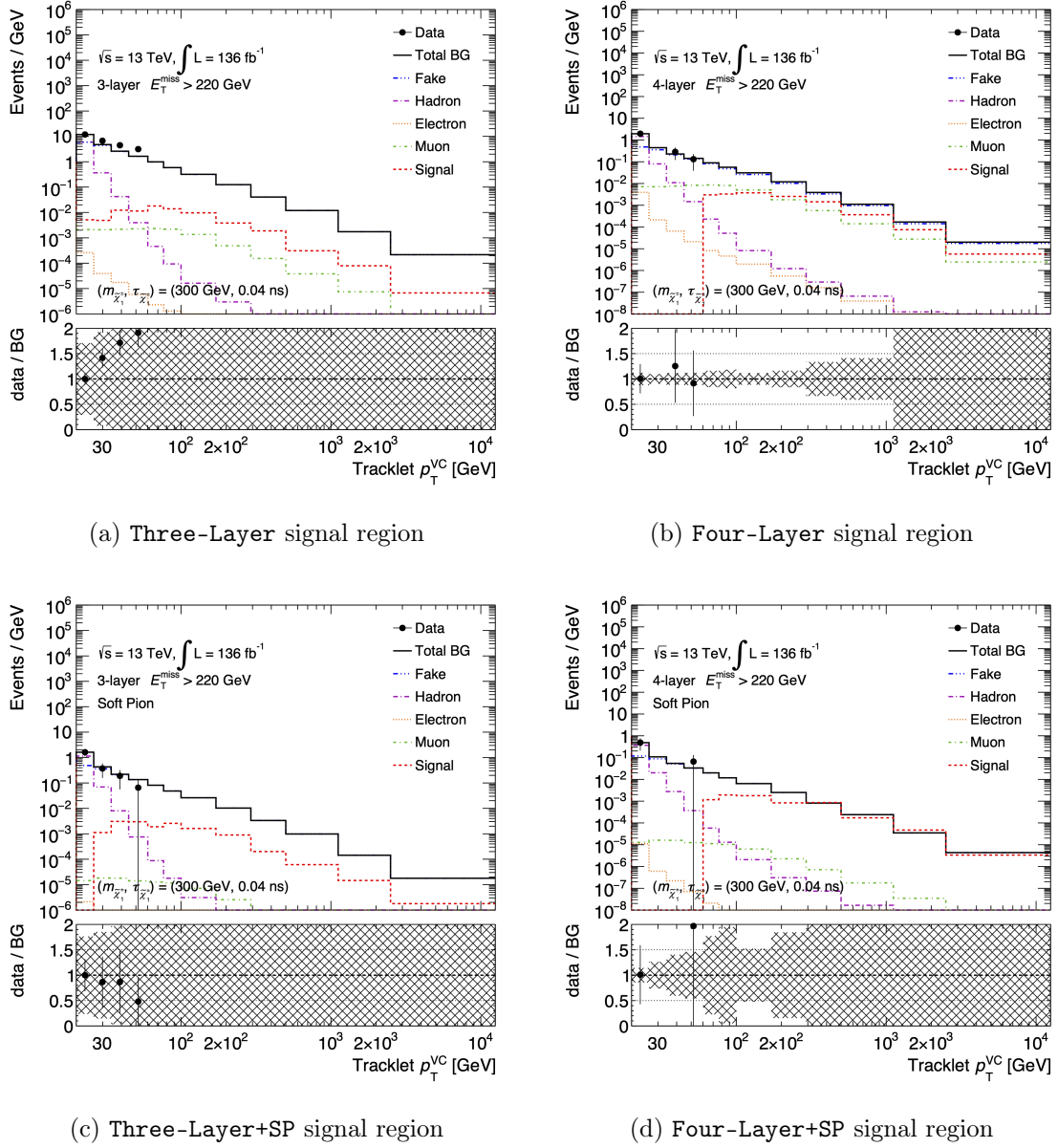
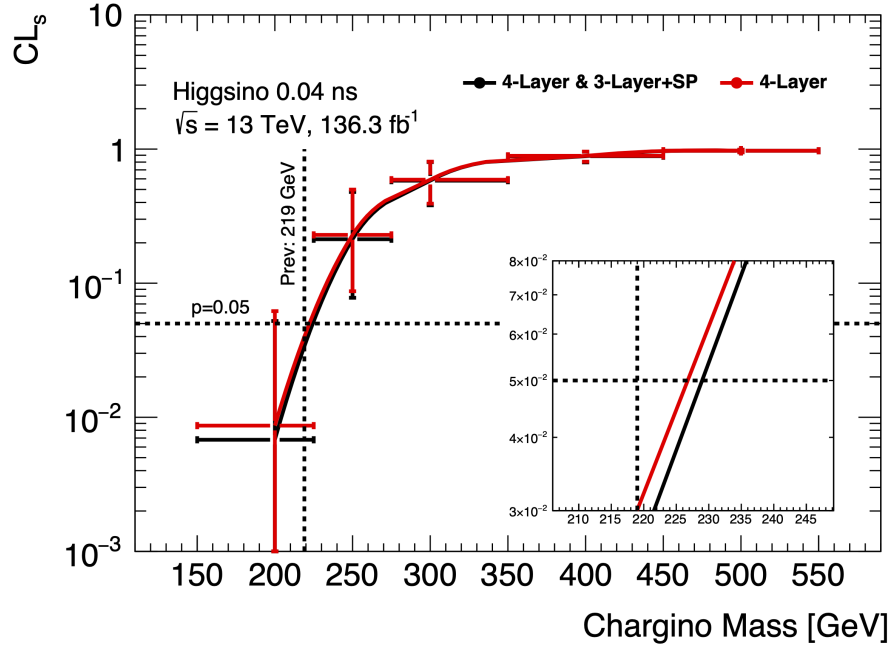
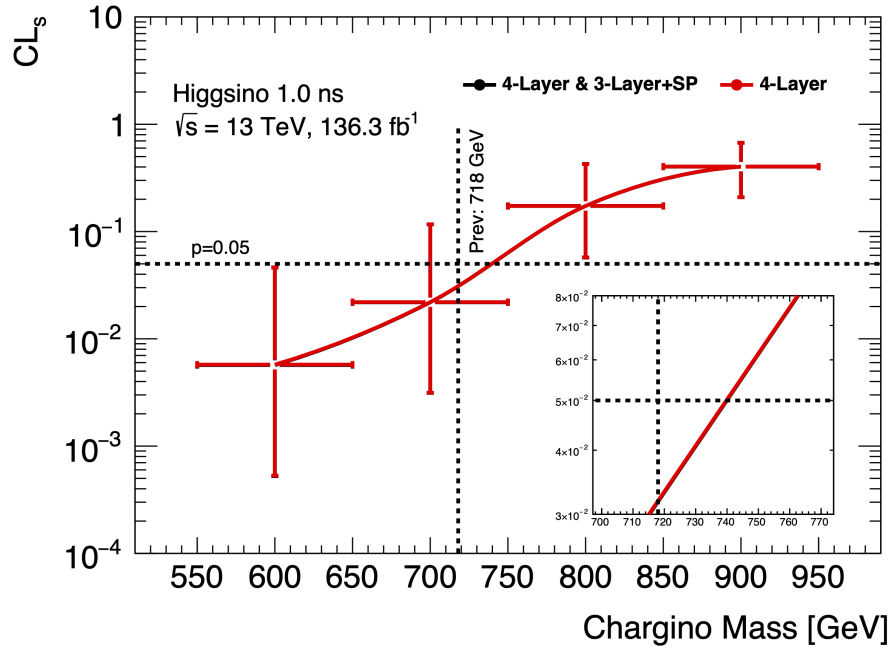


Figure 9.34: Tracklet  $p_T$  of estimated backgrounds, 300 GeV 0.04 ns signal and observed data in the  $E_T^{\text{miss}} > 220 \text{ GeV}$  signal region.



(a) 0.04 ns



(b) 1.0 ns

Figure 9.35: Expected exclusion limits for pure-higgsino charginos assuming a background-only hypothesis in the four-layer region only, and a combination of the four-layer and three-layer with soft track regions. Limits are shown at the expected pure-higgsino lifetime (0.04 ns, 9.35(a)) and at the most sensitive lifetime (1.0 ns, 9.35(b)). Shown also is the result from the previous analysis (dashed line).

The expected limits in Figure 9.35 show moderately-improved sensitivity to pure-higgsino charginos, with an expected exclusion of approximately 220 GeV, compared to 210 GeV from the previous analysis and 200 GeV from the most recent CMS result [158]. These figures show the gain in sensitivity is currently primarily driven by the improved **Four-Layer** signal regions, which benefit from an optimised selection and improved reconstruction efficiency from the SCT hit filter. The **Three-Layer+SP** signal region also contributes, although the poor signal yields from the low soft pion reconstruction efficiency limit the benefit from this additional region.

These limits are also a work-in-progress due to the open questions relating to the scatter background transfer factors and fake background normalisation discussed in Section 9.2. Resolving these issues may reduce the uncertainties in the background estimate, improving the performance of the analysis. The analysis also has poor signal yields, which are under investigation, and only the  $pp \rightarrow \tilde{\chi}_1 \tilde{\chi}_1^0$  process was considered – the  $pp \rightarrow \tilde{\chi}_1 \tilde{\chi}_2^0$  process provides approximately a doubling in signal yields. Finally, as the background estimation is not yet final a detail optimisation has not yet taken place - it is expected that the selections can be further optimised to improve signal yields and reduce background yields. Therefore, the limits presented above should be taken as a worst-case scenario. Together, these factors allow exclusion limits for pure-wino charginos in the range of 750 GeV and for pure-higgsino charginos in the range of 250 GeV or higher to be plausible, a very significant improvement in chargino sensitivity over the previous result without collecting new data.

## Chapter 10

# Upgrades & Future Outlook

The ATLAS experiment will undergo a major upgrade during LS3 in preparation for the beginning of the HL-LHC programme. The significantly increased luminosity will be partially provided by a significantly increased pileup, with more than two hundred simultaneous collisions. The ability to resolve these events from each other will be critical. Both the pileup and luminosity will also bring significantly increased radiation, which would destroy the existing inner detectors.

To cope with these challenges, an ambitious upgrade programme for the ATLAS experiment is in progress. An overview of this upgrade programme is given in Sections 10.1 to 10.2. The centrepiece of the upgrade programme is the New Inner Tracker ITk [159, 160], which will replace the ageing ID with a new, all-silicon tracker with improved resolution for pileup rejection, and improved radiation hardness. A timing detector [161] will be installed beyond the endcaps of the ITk to provide timing information to tracks, aiding in vertex location and flavour tagging. The trigger system will be expanded and simplified to accept the increased data collection [162–164]. Additionally, a new muon endcap wheel (New Small Wheel (NSW)) [165] which reduces the background rates in the muon system was already installed in LS2. Finally, a number of other upgrades will be made to the calorimeter systems [159, 166, 167] and muon systems [168].

New software will be required to use the new detectors, and this provides an opportunity for software improvements. A project was undertaken to convert the existing track reconstruction software from a cartesian co-ordinate system to a polar co-ordinate system which is better suited to the ITk endcap sensor geometry. This is described in Section 10.3, which is derived from an internal report on this work, [169].

The HL-LHC and ATLAS upgrade programmes will bring new opportunities and challenges to the disappearing track analysis. These are discussed in Section 10.4, along with approximate estimates of sensitivity improvements.

## 10.1 New Inner Tracker (ITk)

The ITk is an all-silicon tracking detector that is currently being constructed and is scheduled to be installed during LS3. The ITk detector is split into *Pixel* and *Strip* sub-detectors. The Pixel detector, comprised of pixel modules, sits inside the strip detector, covers a radius of  $1\text{ mm} < |r| < 2\text{ mm}$  and  $|z| < 999.9\text{ mm}$  ( $|\eta| < 4.0$ ). The Strip detector, comprised of silicon strips, covers a radius of  $1\text{ mm} < |r| < 2\text{ mm}$  and  $|z| < 999.9\text{ mm}$  ( $|\eta| < 2.7$ ). The layout of the ITk can be seen in Figure 10.1.[159, 160, 170, 171]

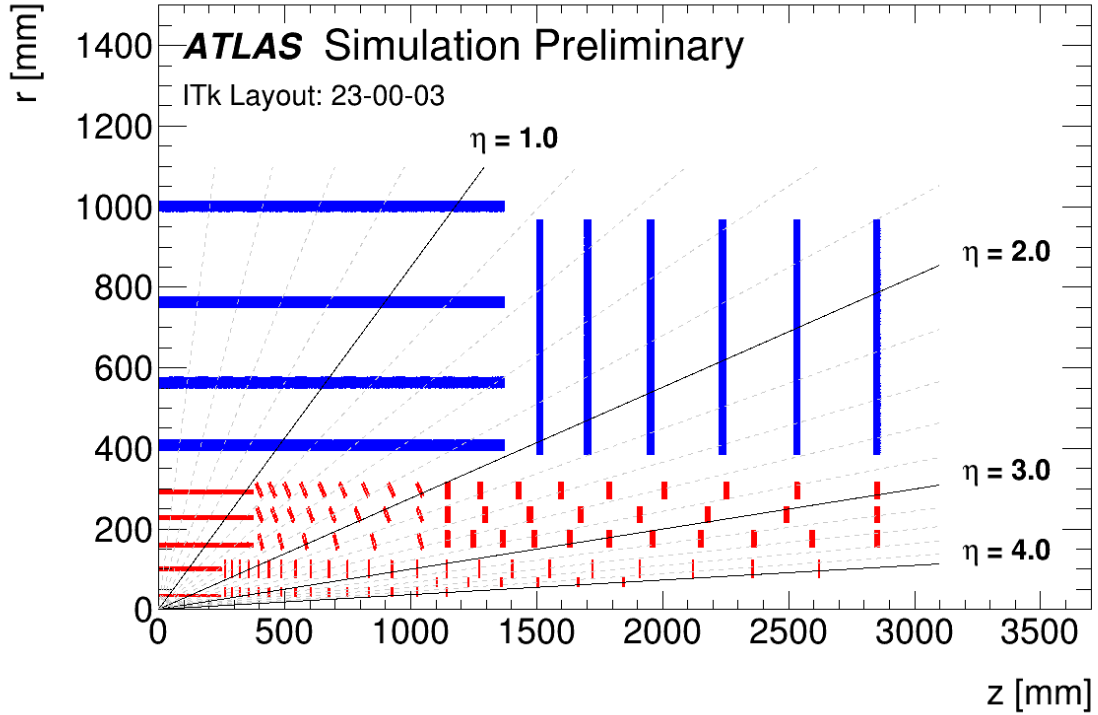


Figure 10.1: The layout of the ATLAS ITk, showing the pixel and strip sub-detectors.[170]

The ITk pixel detector, shown in detail in Figure 10.2, is comprised of a barrel section with modules either aligned parallel with respect to the beamline (*flat*) or at an angle with respect to the beamline (*inclined*), and an endcap section with modules in rings perpendicular to the beamline. The inclined and endcap modules are also staggered at various radii and  $z$  positions to maximise the number of hits per track whilst minimising the amount of material, both to reduce costs and minimise the effective depth of the detector in radiation lengths.

The pixel sensors are either  $20 \times 20\text{ mm}^2$  for the innermost barrel layer and two innermost endcap layers, or  $40 \times 40\text{ mm}^2$  elsewhere. The pitch of individual pixels in each sensor is either  $25 \times 100\text{ }\mu\text{m}^2$  in the innermost pixel barrel layer, or  $50 \times 50\text{ }\mu\text{m}^2$  elsewhere. The flat barrel

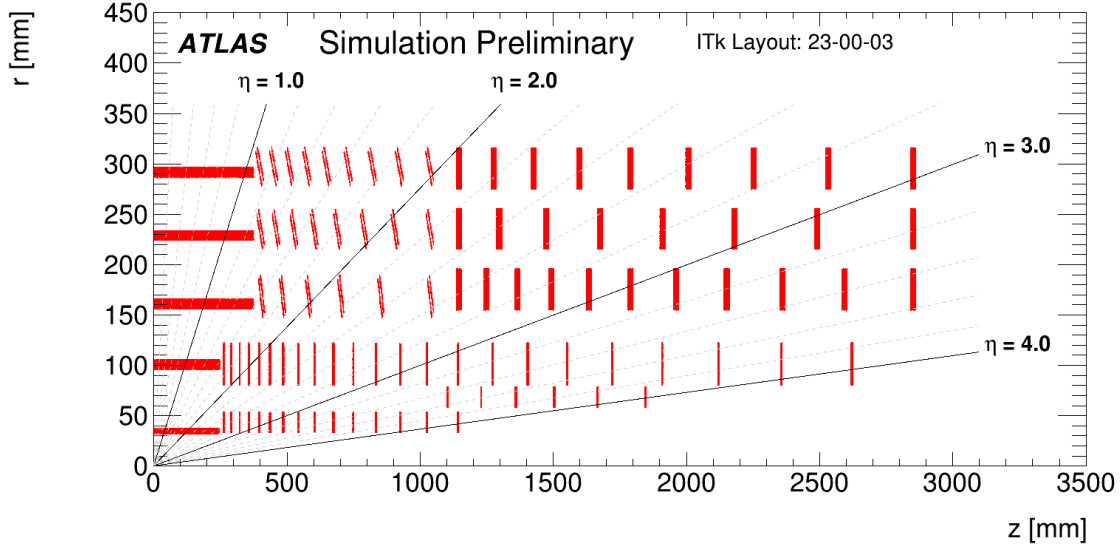


Figure 10.2: A zoomed-in view of the ITk detector showing the pixel sub-detector.[170]

| Endcap Layer | Radius [mm] | Length [mm]           | # Rings | # Sensors per Ring |
|--------------|-------------|-----------------------|---------|--------------------|
| 0            | 33.20       | $263 <  z  < 1142$    | 15      | 18                 |
| 0.5          | 58.70       | $1103 <  z  < 1846$   | 6       | 30                 |
| 1            | 80.00       | $263 <  z  < 2621$    | 23      | 20                 |
| 2            | 154.50      | $1145.5 <  z  < 2850$ | 11      | 32                 |
| 3            | 214.55      | $1145.5 <  z  < 2850$ | 8       | 44                 |
| 4            | 274.60      | $1145.5 <  z  < 2850$ | 9       | 52                 |

Table 10.1: Layout of the ITk pixel endcaps as shown in Figure 10.2 Modified from [170].

section consists of five layers at 34, 99, 160, 228 and 291 mm, with the innermost two layers extending to  $|z| = 245$  mm, and the remaining three extending to  $|z| = 372$  mm. The inclined section features modules at an inclination of 67, 58 or 55 degrees, working from the innermost to outermost rings. All layers of inclined rings are positioned between  $380 \text{ mm} < |z| < 1035 \text{ mm}$ . The innermost layer features six rings, the middle layer features eight rings, and the outermost layer features nine rings, with all rings formed of a pair of modules. Finally, the endcap rings are positioned in six layers, in an arrangement detailed in Table 10.1. [160, 170, 171]

The ITk strip detector consists of four double-sided barrel layers and six endcap disks. The four barrel layers are at radii of 399, 562, 762 and 1000 mm and all extend to  $|z| = 1372$  mm in length. The endcaps each cover a radius of  $385 \text{ mm} < r < 968 \text{ mm}$ , and are positioned along the beam axis at  $|z| = 1512, 1702, 1952, 2237, 2532$  and  $2850$  mm. The barrel sensors have



a strip pitch of  $75.5\mu\text{m}$  and are  $24.1\text{mm}$  long in the inner two layers and  $48.2\text{mm}$  long in the outer two layers. The layers feature pairs of sensors offset with a stereo angle of  $52\text{mrad}$ . The strip endcap sensors vary depending on their position to ensure an even distribution of strips. Endcap strips have pitches of  $69.9$  to  $80.7\mu\text{m}$  and lengths of  $15.1$  to  $60.2\text{mm}$ , positioned with stereo angles of  $40\text{mrad}$ . Notably, the strip endcaps are segments of an annulus, such that when properly rotated they form a perfect disc, whereas the previous SCT endcaps used trapezoidal modules that would not perfectly overlap, resulting in areas with reduced measurement precision. [159, 170, 171]

In simulations of muon tracking performance, the ITk achieves significantly improved impact parameter and transverse momentum resolutions and pileup management compared to the outgoing ID, whilst providing comparable reconstruction efficiency of standard tracks. Specifically, the uncertainty in the longitudinal and transverse impact parameters for  $100\text{GeV}$  muons is approximately  $60\%$  and  $25\%$  respectively of the Run-2 ID, and a relative transverse momentum resolution ( $p_T \times \sigma(q/p_T)$ )  $60\text{-}80\%$  of that provided by the Run-2 ID as shown in Figure 10.3 [170]. Additionally, as shown in Figure 10.4 the number of reconstructed tracks is proportional to the number of interactions in excess of 275 simultaneous interactions, whereas the Run-2 ID diverges above 60 simultaneous interactions indicating a large number of fake tracks being reconstructed. [170]

## 10.2 Other Upgrades

A number of other projects are part of the ATLAS upgrade programme, some installed in LS2 and already operational, and most to be installed during LS3 alongside the ITk.

The High-Granularity Timing Detector (HGTD) is a timing detector positioned between the ITk and the LAr calorimeter endcaps. An exploded view of one wheel of the HGTD can be seen in Figure 10.5. The HGTD is designed to provide timing information to forward tracks, with the goal of improving the vertex location and assignment of tracks and other objects to vertices. Each HGTD consists of two double-sided layers consisting of Low-Gain Avalanche Detector (LGAD) silicon modules measuring  $2 \times 4\text{cm}^2$ , which each contain two sensors each with a  $15 \times 15$  array of  $1.3 \times 1.3\text{mm}^2$ ,  $50\mu\text{m}$  thick pads. The detector can provide a per-track timing resolution of  $30$  to  $50\text{ps}$ . However, due to the forward position and proximity to the beampipe, the radiation damage to the HGTD is expected to be considerable, and the detector will need to be replaced potentially multiple times during HL-LHC. [161]

During the upgrade programme a significant fraction of the calorimeter electronics will be upgraded and replaced, largely to meet the demands of increased radiation and interaction rates. The LAr calorimeter has already received Phase-I upgrades during LS2, where the

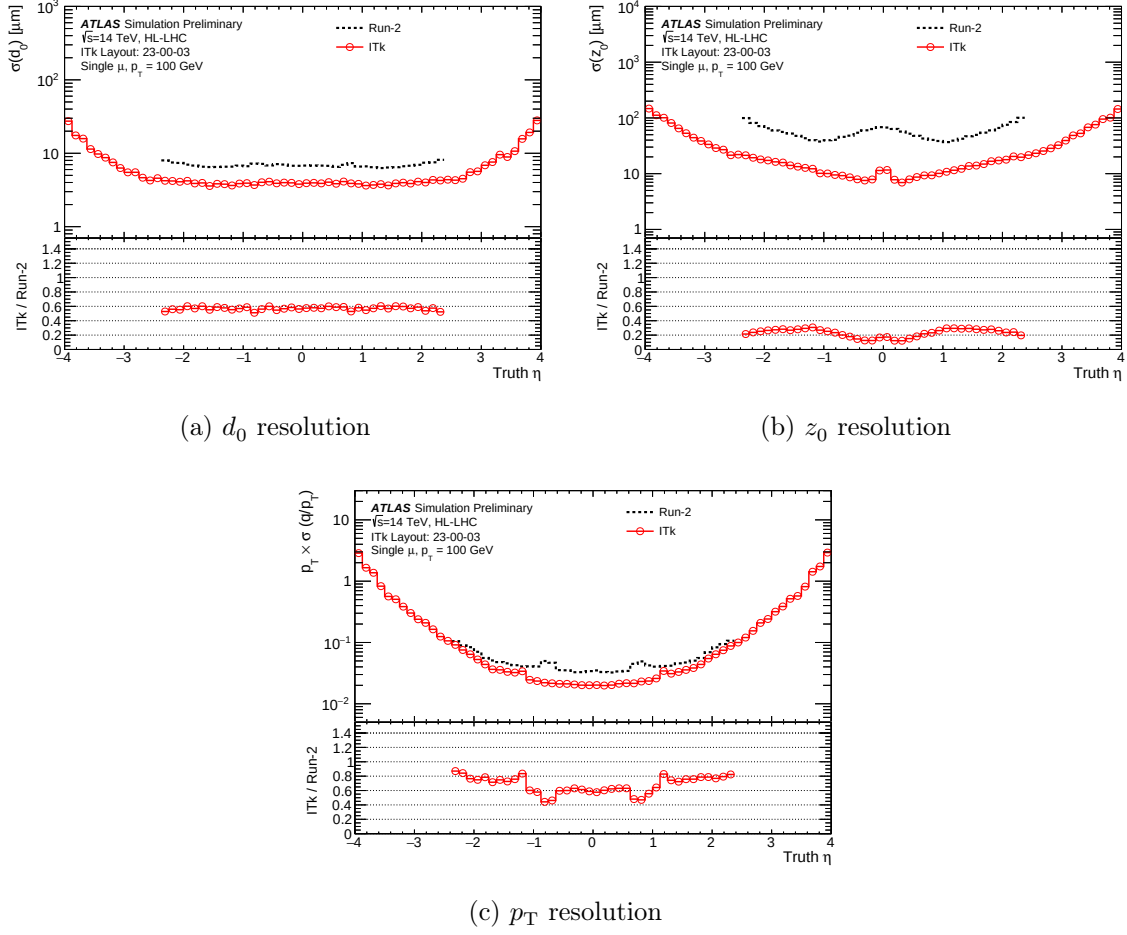


Figure 10.3: Comparison of track parameter resolutions for simulated 100 GeV muons detected in the ITk and Run-2 configuration of the ID. [170]

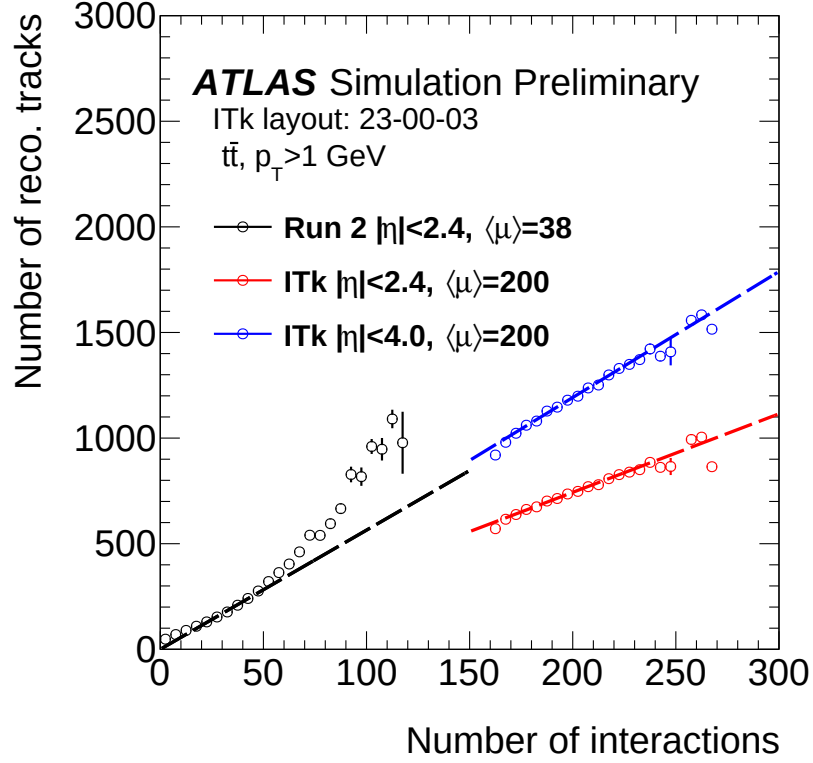


Figure 10.4: Comparison of the number of tracks with  $p_T > 100$  GeV in  $t\bar{t}$  events versus the pileup of in the event. Non-linear behaviour suggests the reconstruction of pileup-induced fake tracks. [170]

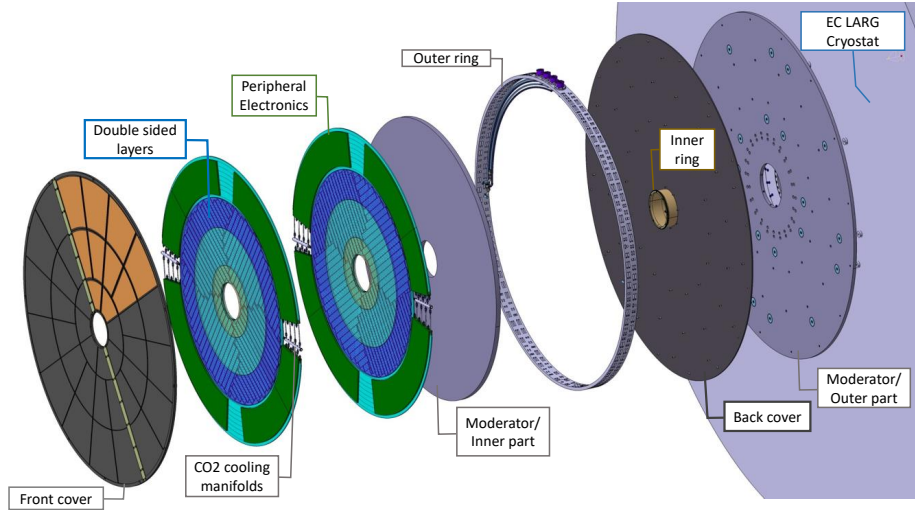


Figure 10.5: An exploded view of one wheel of the HGTD, showing . Reproduced from [161].

readout system was upgraded to allow for more granular *supercells*, rather than the previous  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  trigger towers described in Section 4.2.2.1. The readout and trigger

granularity now varies from layer-to-layer; the presampler and back layers (layers 0, 3) keep the previous  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  cell size, whereas the front and middle layers now have a  $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$  cell size [166]. During LS3 the LAr calorimeters will be upgraded again, with all original electronics used during Run-1 and Run-2 being replaced. This is to enable compatibility with the new TDAQ systems, to increase radiation hardness to be able to cope with the HL-LHC environment, and to increase the readout rate to cope with the HL-LHC luminosity [167]. The tile calorimeters (Section 4.2.2.2) are also receiving similar upgrades for the same reasons, including a complete replacement of all readout electronics [159].

The NSW was a significant upgrade of the muon system during LS2 [165]. The NSW is a replacement of the first station of the muon endcaps, known as the small wheels, to cope with the increased interaction rates and better reject false signals from the rest of the muon system (known as the big wheels). The replacement NSWs use a new design utilising two detector technologies, improved Small-Strip Thin Gap Chambers (sTGCs) and new Micro-Megas detectors. The sTGC detectors are optimised for trigger readout performance whereas the MicroMegas detectors are optimised for precision tracking, although both are capable of high-quality offline tracking. Importantly, the high precision of the NSW is able to confirm or reject track segments and candidate muons from the big wheels, depending on whether they are compatible with the primary vertices, reducing the trigger rate from the muon system which would otherwise overwhelm the TDAQ system in Run-3 and beyond.

The rest of the muon system (Section 4.2.3) will also receive comprehensive upgrades during LS3 [168]. The majority of the readout and TDAQ electronics for the RPC, TGC and MDT detectors will be replaced to ensure compatibility with the new TDAQ system and higher event rates. New MDT detectors with a smaller tube diameter will replace the existing MDTs in the innermost barrel layer, and additional RPC detectors will also be installed here. New TGC triplet detectors will replace old TGC doublet detectors in the barrel-endcap transition region to reduce the rate of false triggers from combinatorial fake signals. To support these changes, the power system will also be replaced to use modern components and deal with radiation damage.

The TDAQ system evolved substantially during LS2 and will again evolve during LS3. These changes are predominantly to support and make use of the new detectors installed in each long shutdown, increase the capability of the TDAQ system to deal with the significantly increased data and event rates, and enable new trigger algorithms to increase sensitivity to unconventional and uncovered signatures. During LS2 these were achieved by significantly expanding the computational capabilities of the HLT, increasing inputs from the calorimeter and muon systems to the L1 trigger system and using this to enable feature extraction in these regions, and introducing new algorithms to enable large-radius jets, better pileup corrections

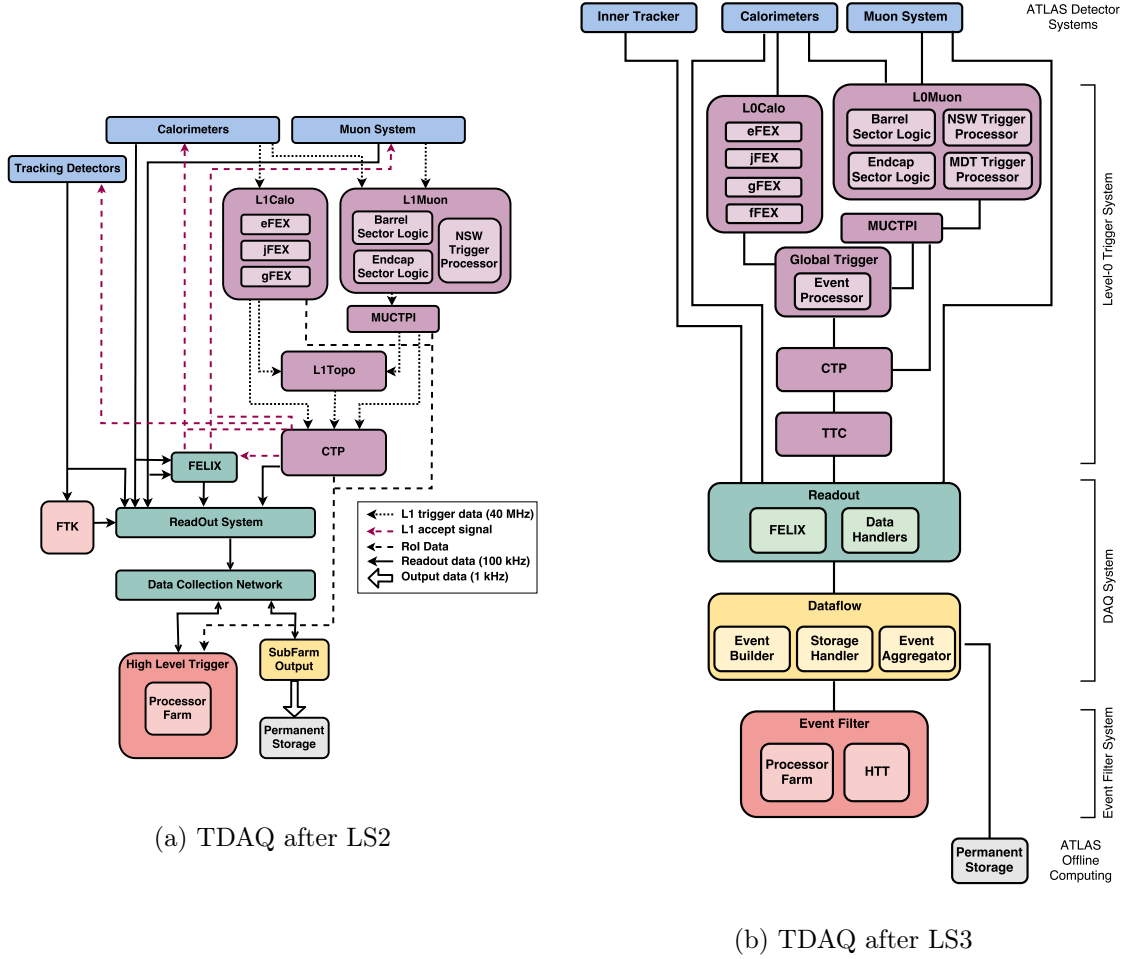


Figure 10.6: Schematics describing the TDAQ systems after the upgrades installed during LS2 (10.6(a)) and after the upgrades that will be installed during LS3 (10.6(b)). Reproduced from [163].

and new Trigger-Level Analyses (TLAs) and event building within the HLT. During LS3 these upgrades will also be achieved by expanding the feature extraction to include forward detectors, introducing a new L0 trigger system to replace the existing L1 system to further reduce the event rate which will be comprised of L0 Calorimeter trigger (L0Calo) and L0 Muon trigger (L0Muon) sub-systems, and leave open the possibility of a new L1 system in the future in case luminosity is higher than expected. A new Global Trigger system will replace the existing L1Topo trigger, and the Event Filter will be enhanced by the Hardware-based Tracking for the Trigger (HTT) system which is capable of regional and full-scan / global track reconstruction. An overview of the upgraded TDAQ systems is given in Figures 10.6.

### 10.3 Tracking Software in a Polar-Cylindrical Co-ordinate System

As discussed in Section 10.1, the old ID will be replaced with a new all-silicon inner detector, the ITk. In this detector, the strip endcaps will use a new design with modules shaped from sections of an annulus, compared to the old trapezoidal shape used in the SCT. Strip modules are used in pairs with a stereo angle offset between the two modules to allow precise 2D measurements. The trapezoidal SCT modules were rotated about their centre, which gives regions without overlap causing reduced measurement precision in these regions. The new ITk modules will be flipped about their radial axis, giving perfect overlap around the endcap ring. These module shapes and the overlap are compared in Figure 10.7.

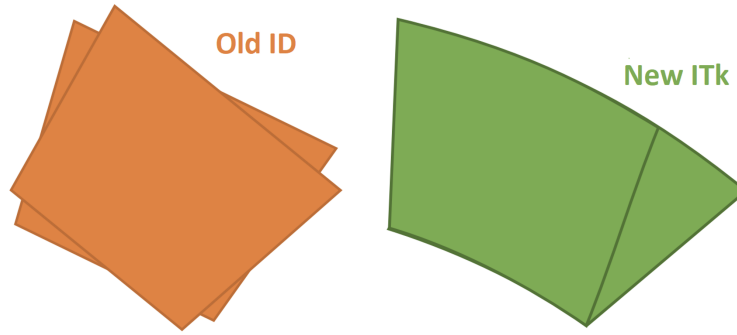


Figure 10.7: An illustrative comparison of the shape of a pair of ID SCT endcap modules and a pair of ITk Strip endcap modules. The modules have a stereo angle allowing 2D measurements. The ITk modules have perfect overlap whereas the SCT modules do not.

The SCT module shape is defined from the module origin  $O$ , which is a radius  $R$  from the beamline. The module has an opening angle  $\phi_w$  projected from the beamline, which when combined with inner and outer radii, defines the edges of the module. The edges are taken as straight lines between the points of intersection between the inner and outer radii and the projection of the opening angle. A local cartesian co-ordinate system can be constructed from the module origin  $O$  with the  $x$ -axis extending away from the beamline, the  $y$ -axis extending counter-clockwise, and the  $z$ -axis extending out of the module, parallel to the beamline, forming a right-handed co-ordinate system. This is shown in Figure 10.8. [90, 91, 172]

The endcap modules for the ITk Strip detector are also defined from the module origin  $O$  at a radius  $R$  from the beamline. However, the focus for the opening angle  $\phi_w$  is rotated away from the beamline around the module origin by the stereo angle  $\phi_S$  to a point  $f$ . This creates an asymmetric module. The inside and outside edges are also taken as the inner and outer radii, rather than straight lines. This is shown in Figure 10.9. A local cartesian co-

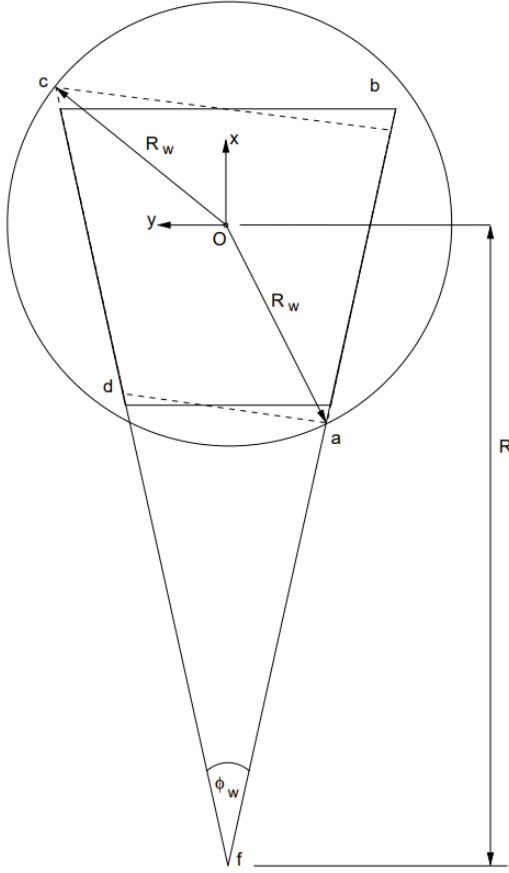


Figure 10.8: Definition of the trapezoidal modules used in the SCT endcaps [172].

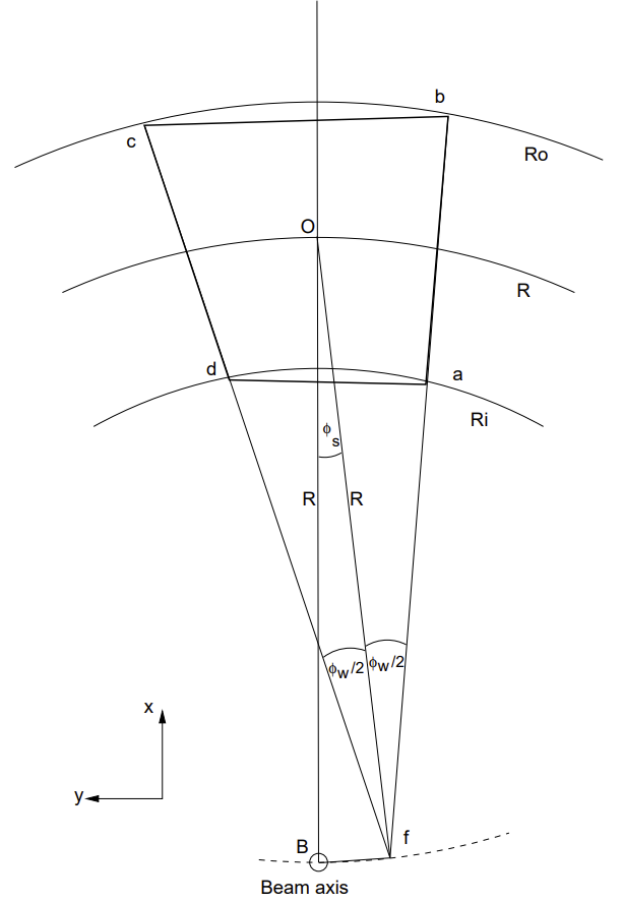


Figure 10.9: Definition of the annulus modules used in the ITk Strip endcaps [172].

ordinate system can be defined in the same way as the SCT modules. A *strip* frame can also be defined, centred at  $f$  with the  $x$ -axis passing through the module origin  $O$ , and the  $y$  axis 90 deg counter-clockwise from the  $x$ -axis around the  $z$ -axis which is parallel to the beamline, again forming a right-handed system. [172, 173]

A *global* frame is also used which is common to the whole of ATLAS. This can be cartesian or polar-cylindrical. The origin is taken as the centre of the experiment with the  $x$ -axis pointing towards the sky, the  $y$ -axis pointing radially out of the LHC ring, and the  $z$ -axis tangential to the beamline. The polar version shares the same origin and  $z$ -axis definition, and the polar angle is taken counter-clockwise from the cartesian  $x$ -axis. Finally, a *beam* frame is also used, with a similar definition to the global frame but translated along the  $z$ -axis such that the origin is in the same frame as the endcap module. A summary of the differences between all frames is given in Table 10.2.

Currently, the hits, clusters and other measurements in the SCT endcaps are computed and stored exclusively in cartesian co-ordinate systems. However, the annulus shape of the ITk

| Frame  | Origin                                      | $x$ -axis direction            |
|--------|---------------------------------------------|--------------------------------|
| Local  | Module origin ( $O$ )                       | Radially outward from beamline |
| Strip  | Module strip focus ( $f$ )                  | Through module origin          |
| Beam   | On the beamline, in plane of module ( $B$ ) | Skyward                        |
| Global | Centre of ATLAS                             | Skyward                        |

Table 10.2: Comparison of the various reference frames used for inner detector endcaps in ATLAS. Only the cartesian versions are defined here. For the trapezoidal SCT modules, the strip focus is on the beamline, so the strip and beam frames are identical.

strip endcap modules makes a polar representation more natural for many calculations. For example, the previous implementation of the ITk Strip endcap geometry software already performs a number of calculations using a polar system, such as determining co-ordinates given the index of a strip and a radius. Other parts of the reconstruction can be optimised, such as determining the covariance matrices for a measurement which involves a number of rotation operations which are computationally complex in the cartesian system but trivial in the polar frame.

### 10.3.1 Existing Implementation

In the Inner Detector software, a design class is created to represent each unique module shape. These are created using information from a geometry file, which specifies information such as the strip pitch, shape type and the physical dimensions of the module. The design class can then contain specialised methods for that shape, such as finding the ends of the strip associated with a hit. A new instance of each design object can be created for modules of the same type but different dimensions, for example each endcap ring. This object can then be rotated to form each module in an endcap ring.

An implementation for the ITk Strip endcap modules was previously developed and is contained in the `StripStereoAnnulusDesign`[174] design class, and provides both cartesian and polar methods where appropriate, although the polar methods were not called in normal use. These polar methods were extensively tested, and detailed `jupyter` notebook documentation was also previously developed [175].

The bounds of a module are defined by a `SurfaceBounds` object[176], which provides various methods such as testing if a given position is inside a given bound. There are separate cartesian (`AnnulusBounds` [177]) and polar (`AnnulusBoundsPC` [178]) implementations. Previously, an `StripStereoAnnulusDesign` object would only instantiate a cartesian `AnnulusBounds` object.



### 10.3.2 Integrating Polar Co-Ordinates

An important requirement is that any modifications to these objects cause no changes to external modules or methods, and lead to identical results. To separate the developments from the existing cartesian annulus implementation, a boolean was added to the geometry description file `sensors.gmx` [179] which can be set to `true` to enable the use of the polar implementation. [180, 181]

An example of the use of this boolean is in determining which type of `AnnulusBounds` to generate in the `AnnulusDesign` constructor. The `AnnulusDesign` class was modified to accept any `SurfaceBounds` object, from which both `AnnulusBounds` and `AnnulusBoundsPC` can inherit. Only the appropriate bounds object is created and stored, depending on the `usePC` variable.

### 10.3.3 Specialisation of `hitLocalToLocal`

Many of the polar methods within the `AnnulusDesign` class work exclusively in polar co-ordinates, and as such expect to be passed polar co-ordinates. However, the majority of ATHENA uses cartesian co-ordinates. Two options are available to resolve this: work in polar co-ordinates from the beginning when reading in data from disk, or redesign the polar methods such that they are transparent to external methods, reading in and returning cartesian co-ordinates and converting internally. The latter is simpler as it requires fewer modifications elsewhere in ATHENA, but would introduce significant overhead from repeated cartesian  $\longleftrightarrow$  polar conversions. Therefore, it was decided that the former should be pursued as far as feasible.

The conversion to polar is performed in the `hitLocalToLocal` method in the `SolidStateDetectorElementBase` class [182]. This method is responsible for converting co-ordinates from the frame of reference used in the output from the GEANT4 simulation stored on disk to that used in the ATHENA software. The conversion was modified to query the *Detector Shape* [183] of the design used in the detector element that the hit is part of. This shape is an `enum` which can be a `Box`, `Trapezoid`, `Annulus` or `Other`. A new `PolarAnnulus` shape was added that will be returned by the `AnnulusDesign` object when created in a polar frame. [184–186]

There are several places in ATHENA where the object shape is used to control whether or how to perform a rotation or transformation. In most cases, this is to differentiate the barrel modules (`Box`) from the endcap segments (`Trapezoid` or `Annulus`). Each of these points will need to be assessed to determine whether the transformation is still necessary, and the most efficient way to perform it. Some rotations, such as those relating to the covariance calculations, may be significantly simpler to perform in a polar co-ordinate system, or even unnecessary.

### 10.3.4 Co-ordinate frame conversions

There are many methods such as `cellIdOfPosition` [187] which use transformations between beam- and strip frames. In a cartesian system this transformation is straightforward. The beam frame is translated to the module origin, rotated by the stereo angle, and then the translation is reversed to the strip focus. Algebraically, this can be described as

$$\begin{pmatrix} x_{\text{SF}} \\ y_{\text{SF}} \end{pmatrix} = \begin{bmatrix} \cos(-\phi_s) & -\sin(-\phi_s) \\ \sin(-\phi_s) & \cos(-\phi_s) \end{bmatrix} \begin{pmatrix} x_{\text{BF}} - R \\ y_{\text{BF}} \end{pmatrix} + \begin{pmatrix} R \\ 0 \end{pmatrix} \quad (10.1)$$

where  $_{\text{SF}}$  and  $_{\text{BF}}$  indicate strip and beam frame respectively,  $\phi_s$  is the stereo angle, and  $R$  is the radius of the module origin.  $\cos(\pm\phi_s)$  and  $\sin(\pm\phi_s)$  can be pre-calculated for each module type, and therefore have only a limited impact on performance. All other operations are multiplications, additions and subtractions.

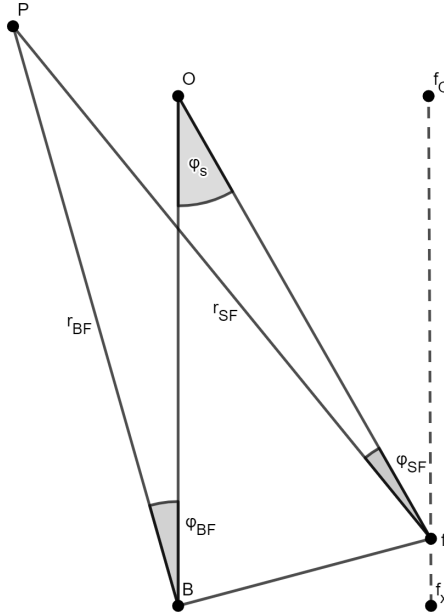


Figure 10.10: A simplified view of a point on a polar annulus module, for calculating a polar transform between the beam frame and the strip frame.

The polar equivalent to this is more complex. Figure 10.10 can be used to find the radius and angle in the strip frame, given the module properties and the beam-frame co-ordinates. In Figure 10.10,  $B$ ,  $f$  and  $O$  match the definitions from Figure 10.9, where  $B$  represents the beamline,  $f$  is the focus of the module and  $O$  is the module origin. The strip-frame radius  $r_{\text{SF}}$

can be found by

$$r_{\text{SF}} = \sqrt{r_{\text{BF}}^2 + \left(2R \left| \sin\left(\frac{\phi_s}{2}\right) \right| \right)^2 + 2r_{\text{BF}}2R \left| \sin\left(\frac{\phi_s}{2}\right) \right| \cos\left(\frac{\phi_s}{2}\right)} \quad (10.2)$$

and the strip-frame polar angle from

$$\phi_{\text{SF}} = \frac{\pi - \phi_S}{2} - \arcsin\left(\frac{r_{\text{BF}} \sin\left(\pi + \phi_{\text{BF}} - \frac{\phi_S}{2}\right)}{r_{\text{SF}}}\right) \quad (10.3)$$

However, there is an ambiguous case of the sine law, where two solutions are possible. This occurs in this derivation when

- $\angle \text{PBf} < \pi$
- $r_{\text{SF}} < r_{\text{BF}}$
- $r_{\text{SF}} > r_{\text{BF}} \sin(\angle \text{PBf})$

and this must be checked for every co-ordinate considered. Complete derivations are given in Appendix B.3.

Whilst it is possible that some optimisations could be made to the expressions for  $r_{\text{SF}}$  and  $\phi_{\text{SF}}$ , it is clear that there are significantly more steps than the cartesian case, using costly functions such as square roots, and trigonometric functions of values which cannot be precalculated.

An alternative strategy would be to convert the beam-frame position to polar co-ordinates, apply the cartesian transform, and convert back to polar. This can be expressed as

$$\begin{pmatrix} x_{\text{SF}} \\ y_{\text{SF}} \end{pmatrix} = \begin{bmatrix} \cos(-\phi_s) & -\sin(-\phi_s) \\ \sin(-\phi_s) & \cos(-\phi_s) \end{bmatrix} \begin{pmatrix} r_{\text{BF}} \cos(\phi_{\text{BF}}) - R \\ r_{\text{BF}} \sin(\phi_{\text{BF}}) \end{pmatrix} + \begin{pmatrix} R \\ 0 \end{pmatrix} \quad (10.4)$$

$$\begin{pmatrix} r_{\text{SF}} \\ \phi_{\text{SF}} \end{pmatrix} = \begin{pmatrix} \sqrt{x_{\text{SF}}^2 + y_{\text{SF}}^2} \\ \text{atan2}(y_{\text{SF}}, x_{\text{SF}}) \end{pmatrix} \quad (10.5)$$

where the square root can be optimised with the `std::hypot` function [188] and the `std::atan2` function [189] is an optimised function returning the tangent with checks for all quadrants.

### 10.3.5 Software Validation and Testing

The effect of the changes to ATHENA in the simulation and digitisation were tested by comparing the results of a sample of 100 GeV muons, which present an excellent case for testing

tracking as they reliably extend through the entire experiment. To test the event simulation, the modified version of ATHENA was compared to the latest nightly release, and the same event simulation file was used. The results were physically identical and ran in a comparable time. The same approach was also used to test the digitisation, and an existing analysis tool `RDOAnalysis.py` [190] was used to extract the results. To validate that there were no unintended changes to the existing cartesian workflow, the same comparison was also made but with the polar system disabled. In all of these tests, there are no differences in the results of each stage. The results of the digitisation are shown in Figure 10.11.

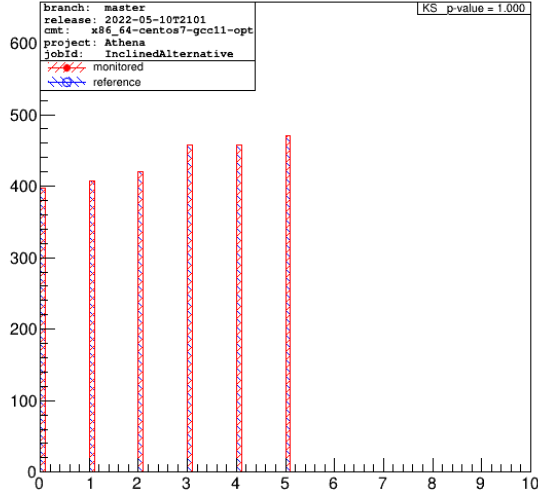
The performance of the changes was also investigated. This was performed using the Intel VTune tool, which can analyse the performance of individual method calls within a programme, and compare multiple runs. Overall, this showed approximately the same computation time for the simulation (0.2% quicker in the polar case, likely run-to-run variance) and slower performance for the digitisation (7.9% slower). This is expected as there are minimal calls to the modified files during the simulation, and additional calculations added in the conversion between strip and beam frames used in the digitisation, namely the conversion to a cartesian system to perform the frame conversion efficiently. The VTune results show that the dominant contribution to the slower performance is indeed the additional math library calls from the frame conversion, adding 66% of the extra time. The initial cost of the frame conversions is much higher, but it is offset by collecting the frame conversions in a single method rather than allowing other methods to implement their own version.

While the polar implementation so far has a significant performance cost, it is expected that this will allow for a significant gain in performance during event reconstruction, as this involves a significant number of rotations, especially in the calculation of the covariance matrices. These rotations are costly in a cartesian system, involving multiple calls to trigonometry functions, but trivial in a polar system, where the rotation simply needs to be added or subtracted from the previous angle.

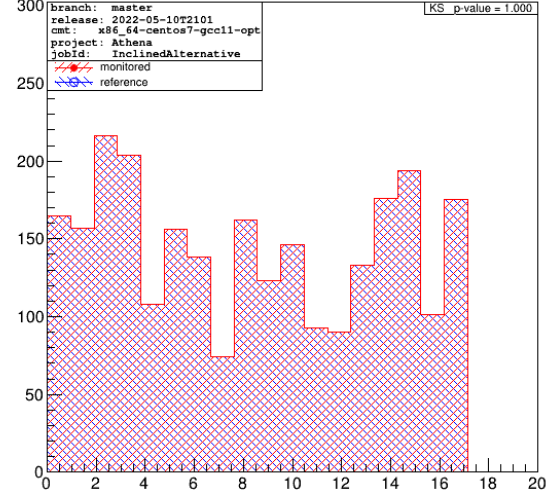
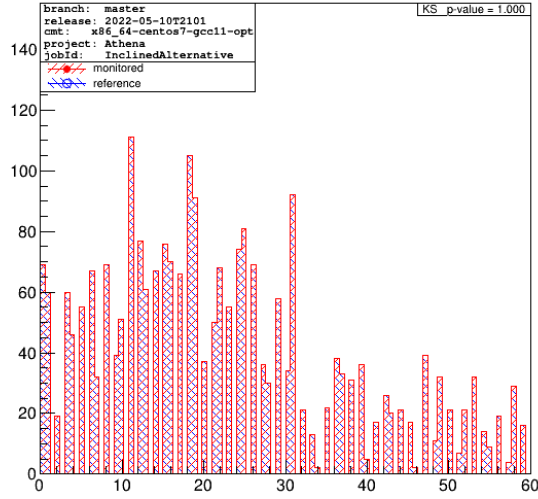
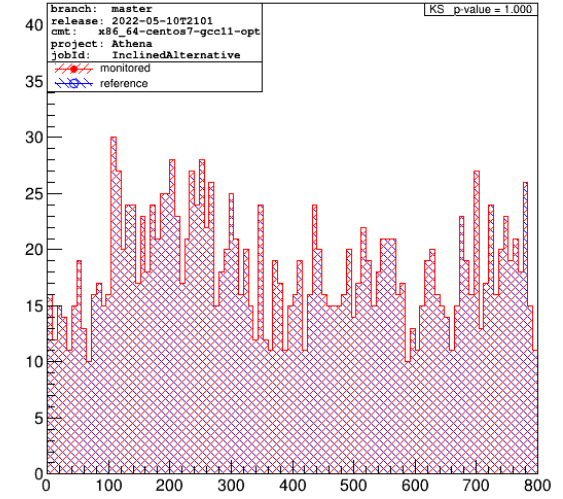
## 10.4 Future Prospects for Disappearing Tracks

As introduced in this Chapter, numerous changes taking effect in Run-3 and Run-4 are expected to have a significant impact on the disappearing track analysis. These include the increased centre-of-mass energy, the increased luminosity, the increased pileup, a new disappearing track trigger, and the ITk which will provide a new layout and improved resolution.

At the beginning of Run-3 the centre-of-mass energy in the proton collision was increased from  $\sqrt{s} = 13 \text{ TeV}$  to  $\sqrt{s} = 13.6 \text{ TeV}$ . For Run-4 and beyond it is expected that the collision energy will further increase to  $\sqrt{s} = 14 \text{ TeV}$ . These increased energies lead to a mildly-increased

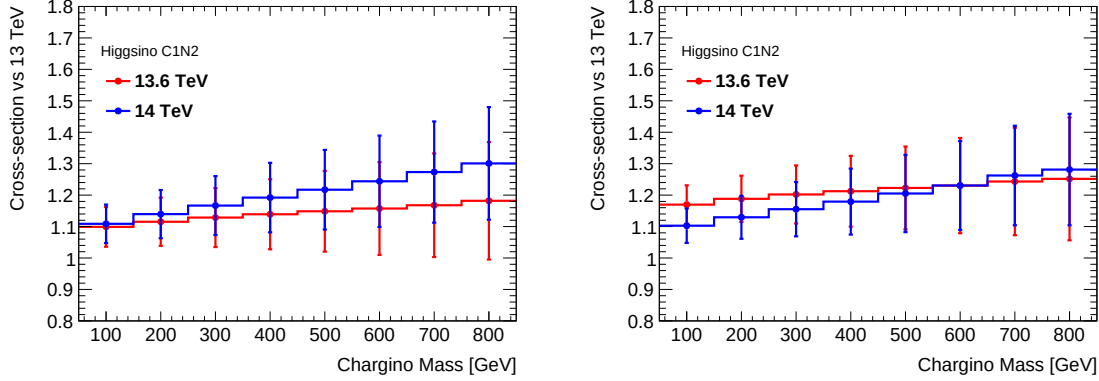


(a) Hits per endcap disk index

(b) Hits per endcap module *eta* index per disk(c) Hits per endcap module *phi* index per disk

(d) Hits per endcap strip index per module

Figure 10.11: The number of hits per endcap disk, module and strip after digitisation. The *reference* sample is the result of the unmodified nightly ATHENA release at the time of testing, and the *monitored* sample is the result of the modified ATHENA release using a polar co-ordinate system for the Strip endcaps. No difference is observed between the two samples. Note that the ‘eta’/‘phi’ module index is an index increasing in pseudo-rapidity or polar angle, not the actual position of the module.



(a) Comparison of cross-sections for a pure-wino  $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$  process.

(b) Comparison of cross-sections for a pure-higgsino  $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$  process.

Figure 10.12: Comparison of  $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$  production cross-sections at centre-of-mass energies of  $\sqrt{s} = 13.6$  TeV and  $\sqrt{s} = 14$  TeV against a centre-of-mass energy of  $\sqrt{s} = 13$  TeV. Cross-sections were collated by the LHC SUSY Cross-section Working Group [191]. The cross-sections were calculated using RESUMMINO [192, 193] assuming a mass-degenerate  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  and a decoupled sparticle spectrum.  $\sqrt{s} = 13$  TeV and  $\sqrt{s} = 14$  TeV cross-sections were calculated with RESUMMINO at NLO plus Next-to-Leading-Log (NLL) precision using an envelope of CTEQ6.6 and MSTW2008 PDFs [192, 194].  $\sqrt{s} = 13.6$  TeV cross-sections were taken directly from [193], where the PDF4LHC21 PDF was used.

cross-section for the chargino production channels. Cross-sections at centre-of-mass energies of  $\sqrt{s} = 13.6$  TeV and  $\sqrt{s} = 14$  TeV for the pure-wino and pure-higgsino  $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$  chargino production processes were provided by the LHC SUSY Cross-section Working Group [191] using the RESUMMINO tool. These cross-sections are compared to the equivalent cross-sections at  $\sqrt{s} = 13$  TeV in Figure 10.12. For pure-wino charginos, there is an increase of 15-20% in cross-sections at 600 to 900 GeV at 13.6 TeV and 35-45% for 1000 to 1200 GeV at 14 TeV. For pure-higgsino charginos, there is an increase of 15-25% in cross-sections at 300 to 500 GeV at 13.6 to 14 TeV.

As previously described in Table 4.1 in Section 4.1, the integrated luminosity is also expected to increase. The Run-3 integrated luminosity is expected to be  $250 \text{ fb}^{-1}$ , and the HL-LHC integrated luminosity is expected to be up to  $3000 \text{ fb}^{-1}$ . However, this increased luminosity is partially achieved by increased pileup, with the target Run-3 pileup being  $\mu = 55$ , and the HL-LHC pileup being in excess of  $\mu \geq 200$ . The fake background is strongly correlated with pileup, which will present a significant challenge. This linear trend can be seen clearly below in Figure 10.13, where the fake prediction from the analysis in Chapter 9 originating from the fake control region ( $2.0 \text{ mm} < |z_0 \sin \theta| < 5.0 \text{ mm}$ ) is compared to the total signal region

( $|z_0 \sin \theta| < 0.5 \text{ mm}$ ) in a low+mid  $E_T^{\text{miss}}$  selection ( $100 \text{ GeV} < E_T^{\text{miss}} < 200 \text{ GeV}$ ).

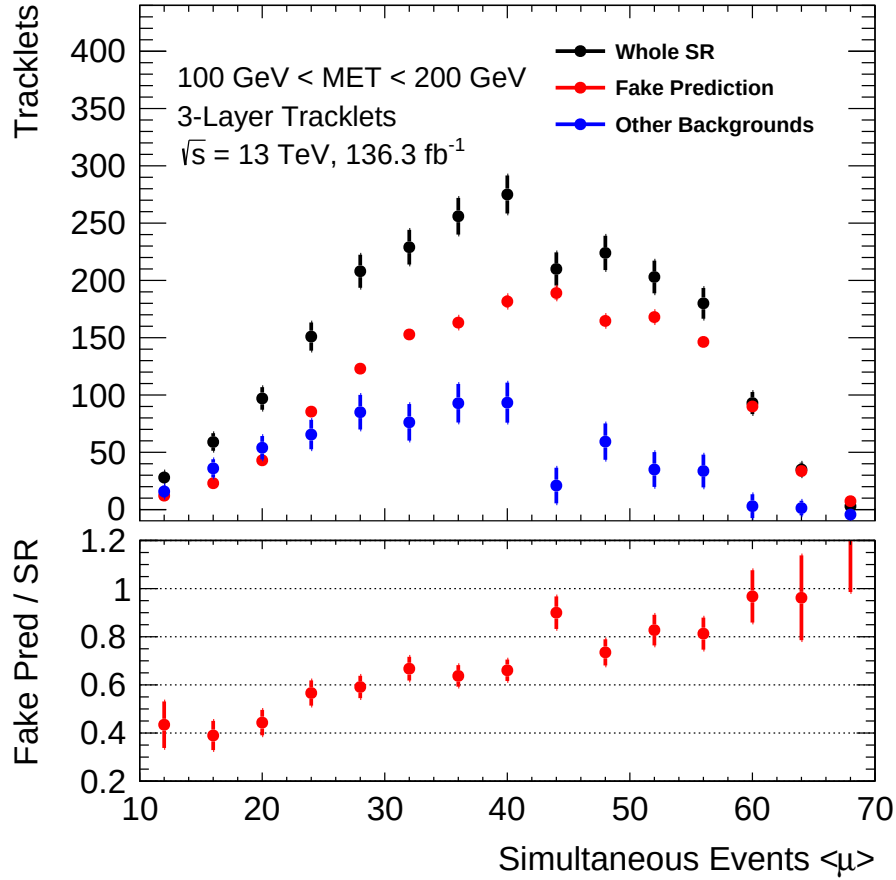


Figure 10.13: Comparison of the fake background prediction and observed events in a  $100 \text{ GeV} < E_T^{\text{miss}} < 200 \text{ GeV}$  selection as a function of the number of simultaneous events (pileup,  $\langle \mu \rangle$ ). A clear linear increase can be seen for fakes as a function of  $\langle \mu \rangle$ .

Bespoke disappearing track triggers were also introduced in Run-3. As described in the previous chapters, the disappearing track analysis uses the lowest-energy  $E_T^{\text{miss}}$  trigger, which has a turn-on curve around 190 GeV and reaches 100% acceptance at 200 GeV. The new disappearing track trigger, when used in a logical OR with the existing  $E_T^{\text{miss}}$  triggers, reduces the 100% acceptance threshold to 180 GeV or less. These improve acceptance of disappearing track events, but also increase the fake background, which increases at lower values of  $E_T^{\text{miss}}$  due to the increased pileup contribution.

As a heavy, charged particle, the chargino is expected to leave significant ionisation energy deposits in the pixel sensors. The pixel sensors, particularly those in the IBL, can measure the charge deposited in the sensor by a passing particle. This can help differentiate signal track-

lets from fake tracklets, which would not be expected to have a consistently-high ionisation energy deposition. This search is already performed in a separate ATLAS analysis searching for standard-length tracks with high  $dE/dx$  values. Early studies are underway to assess the feasibility of combining this  $dE/dx$  analysis with a Run-3 disappearing track analysis using the new bespoke trigger, which would allow a significant reduction in  $E_T^{\text{miss}}$  cut and a corresponding increase in signal acceptance while controlling the increase in fake tracklets.

As discussed earlier in this Chapter, the ITk presents a complete overhaul of the inner detector, on which the disappearing track analysis depends significantly. The outgoing ID has a large gap between the pixel and SCT barrel layers which provides a large volume to search within for chargino decays, whereas the ITk barrel has layers more evenly spread out, with the third and fourth barrel layers at a larger radius. This has the effect of shifting the sensitivity to longer lifetimes. The ITk geometry is also significantly more complex than the ID geometry with highly-granular inclined barrels and endcaps.

The Run-2 region is defined in the same way as in the analysis in Chapter 9, with a 3-hit region of  $|\eta| < 1.9$  and bounded by the third and fourth pixel barrel layers ( $88.5 \text{ mm} < r < 122.5 \text{ mm}$ ), and a 4-hit region also with  $|\eta| < 1.9$ , bounded by the fourth pixel barrel layer ( $r > 122.5 \text{ mm}$ ) and either the first SCT barrel layer ( $r < 299 \text{ mm}$ ,  $|z| < 749 \text{ mm}$ ) or the second SCT endcap layer ( $|z| < 749 \text{ mm}$ ,  $1.658 < |\eta| < 1.9$ ).

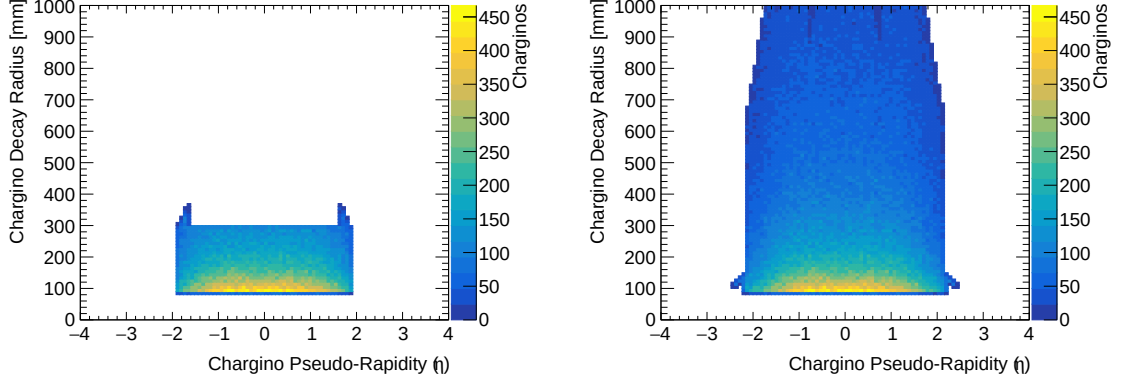
The possible Run-3 region is designed similarly but with expanded 3- and 4-hit regions to take advantage of increased fake rejection from analysis improvements, and the addition of 5-hit and 6+ hit regions for increased sensitivity at longer lifetimes. The 3-hit region was expanded to  $|\eta| < 2.2$  and the 4-hit to  $|\eta| < 2.5$ .

The possible Run-4 and beyond region was estimated from Figure 10.1 in segments of  $\Delta\eta = 0.05$  and  $\Delta r = 5 \text{ mm}$ . Pseudo-rapidity bounds for the 3-hit region were chosen at  $|\eta| < 2.2$  for 3-hits,  $|\eta| < 2.5$  for 4-hits,  $|\eta| < 3.0$  for 5-hits and  $|\eta| < 4.0$  for 6-hits and beyond.

Heatmaps of pure-wino chargino decays at a range of lifetimes using these definitions are shown in Figure 10.14.

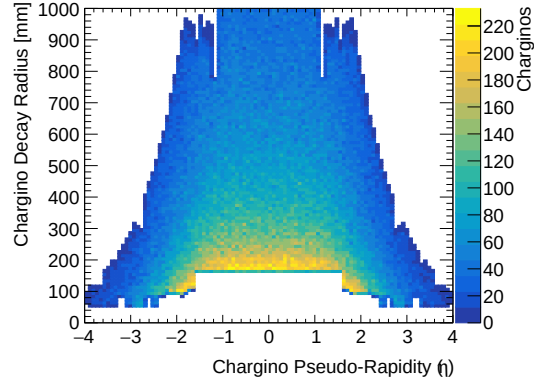
By simulating charginos with a range of proper lifetimes and counting the number of chargino decays within the fiducial definitions given above, the change in acceptance in each analysis as a function of lifetime can be estimated. This is shown in Figure 10.15. As expected, at short lifetimes the acceptance of the Run-2 and Run-3 analyses is similar due to the very similar three-hit region definitions. However, the additions of a five-hit analysis can significantly improve acceptance at medium and long lifetimes. However, in Run-4 and beyond acceptance at short lifetimes will be severely reduced due to the increase in barrel layer radius, although





(a) Estimated incidence of charginos of various rest-frame lifetimes in the  $\eta$ - $r$  plane as searched for using Run-2 data.

(b) Estimated incidence of charginos of various rest-frame lifetimes in the  $\eta$ - $r$  plane for a possible Run-3 search.



(c) Estimated incidence of charginos of various rest-frame lifetimes in the  $\eta$ - $r$  plane for a possible Run-4 search.

Figure 10.14: Estimated incidence of charginos of various rest-frame lifetimes in the  $\eta$ - $r$  plane for different ATLAS geometries.

there be a mild increase at long lifetimes.

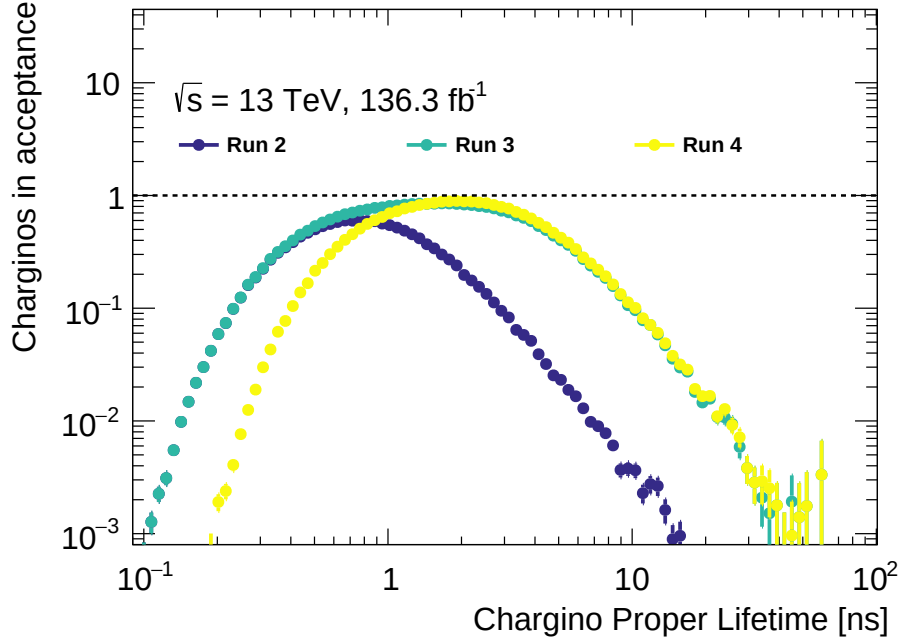


Figure 10.15: Estimated acceptance of charginos of various rest-frame lifetimes as searched for using Run-2 data, and possible future searches using Run-3 and Run-4 detector geometries

The ITk also presents an opportunity, in that the sensors are significantly improved compared to the outgoing ID, and the density and extent of the sensors is significantly improved. This means a given track(let) will have significantly more hits, and those hits will be significantly more accurate. This will reduce the rate of fake tracklets being reconstructed. For standard tracks, the fake reconstruction rate is expected to reduce by approximately 90%. This is shown in Figure 10.16, reproduced from [171]. Lacking specific studies, it is difficult to estimate the improvement for short tracklets, but this figure can be taken as an upper bound.

The assumptions made in this section can now be collated to provide an overall estimate of the change of sensitivity to disappearing tracks in the future. To target an improvement over the existing analysis, for pure-wino charginos a benchmark of 1200 GeV 0.2 ns is chosen. For pure-higgsino charginos, a 400 GeV 0.03 ns benchmark is chosen. These assumptions are collated in Table 10.3.

Improvements in sensitivity are estimated by using the expected signal and background yields from the analysis in Chapter 9 for each benchmark, modifying by the overall changes in yields shown in Table 10.3, and computing significances using the simple  $s/\sqrt{s+b}$ . For the pure-wino hypothesis, this leads to a 50% increase in sensitivity to 1000 GeV winos in Run-3, a 88%

|               | Run-3       |              |                  |
|---------------|-------------|--------------|------------------|
|               | Fake        | Wino 1 TeV   | Higgsino 400 GeV |
| Cross-section | -           | $1.15\times$ | $1.2\times$      |
| Luminosity    |             | $1.85\times$ |                  |
| Pileup        | $1.5\times$ | -            | -                |
| Acceptance    | -           | $1.1\times$  | $1\times$        |
| ITk Sensors   | -           | -            | -                |
| Total         | $2.8\times$ | $2.3\times$  | $2.2\times$      |

|               | Run-2 + Run-3 |             |                  |
|---------------|---------------|-------------|------------------|
|               | Fake          | Wino 1 TeV  | Higgsino 400 GeV |
| Cross-section | -             | $1.1\times$ | $1.15\times$     |
| Luminosity    |               | $3\times$   |                  |
| Pileup        | $1.3\times$   | -           | -                |
| Acceptance    | -             | $1.1\times$ | $1\times$        |
| ITk Sensors   | -             | -           | -                |
| Total         | $4\times$     | $3.6\times$ | $3.5\times$      |

|               | HL-LHC      |              |                  |
|---------------|-------------|--------------|------------------|
|               | Fake        | Wino 1 TeV   | Higgsino 400 GeV |
| Cross-section | $1.2\times$ | $1.35\times$ | $1.25\times$     |
| Luminosity    |             | $22\times$   |                  |
| Pileup        | $5\times$   | -            | -                |
| Acceptance    | -           | $0.4\times$  | $0.02\times$     |
| ITk Sensors   | $0.1\times$ | -            | -                |
| Total         | $11\times$  | $12\times$   | $0.5\times$      |

Table 10.3: Summary of assumptions for the change in fake and signal rates for 1 TeV 0.2 ns pure-wino charginos and 400 GeV 0.03 ns pure-higgsino charginos in hypothetical Run-3, Run-2 + Run-3 and HL-LHC analyses.

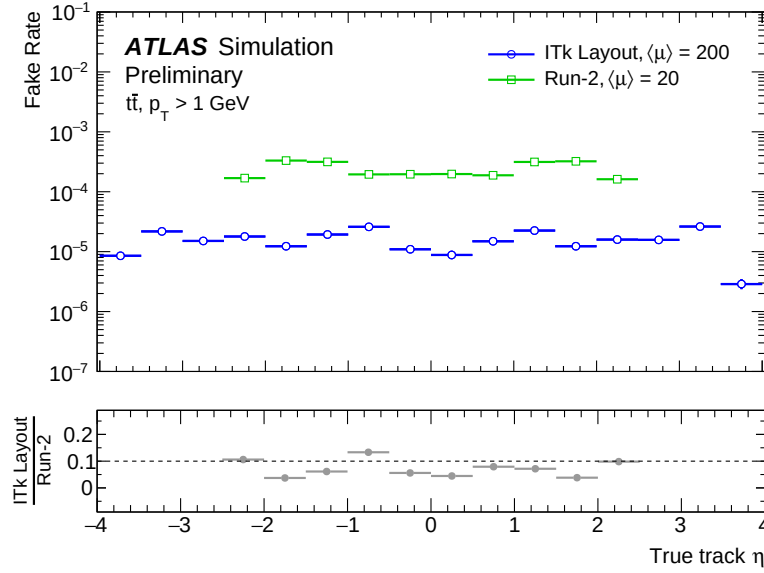


Figure 10.16: The reconstruction rate of fake tracks from  $t\bar{t}$  events in the ITk during Run-4 and in the ID during Run-2. [171]

increase in a combination of Run-2 and Run-3, and a 250% increase in Run-4. For the pure-higgsino hypothesis, Run-3 leads to a 45% increase in 400 GeV higgsinos and a 83% increase in a combination with Run-2, but a 70% decrease in sensitivity in Run-4 due to the unfavourable geometry.

Notably, the effect of analysis improvements such as the inclusion of  $dE/dx$  information and increased yields at low  $E_T^{\text{miss}}$  from the new trigger is neglected in these estimates, as the effect of these features in the context of an analysis is unknown. However, it is expected that these will lead to a significant reduction of background tracklets and increased acceptance of signal tracklets. The estimates given above therefore present a realistic worst case scenario for the future searches for disappearing tracks.

# Chapter 11

## Conclusion

This thesis has presented the case for multiple extensions to the Standard Model, in the form of SUSY and simpler models which seek to only provide a dark matter candidate, and how these models can produce a disappearing track signature in the ATLAS experiment. The theoretical case was made in Part I, first outlining the Standard Model and its successes in Chapter 2 before the open questions in particle physics and how SUSY and simplified dark matter models can provide a resolution to these questions was discussed in Chapter 3. In brief, the Standard Model is a highly-successful model of particle physics, which with the discovery of the Higgs boson became a complete theory. However, it does not provide explanations for many observed phenomena including matter-antimatter asymmetry and the existence of dark matter, as well as explaining why there is such a difference between the strength of different forces and why physical constants acquire the values they do. SUSY is a class of models that can resolve some or all of these issues. SUSY proposes a new symmetry between fermions and bosons - each Standard Model fermion gains a boson super-partner, and vice-versa. Minimal SUSY models (known as the MSSM) have been proposed, but the first two runs of the LHC have failed to discover any significant evidence of SUSY. New models with harder-to-discover signatures such as LLPs must therefore be considered. SUSY also provides excellent dark matter candidates, with the LSP expected to be heavy, neutral and stable in many SUSY models, with this dark matter candidate being known as a WIMP

Part II provided a detailed overview of how disappearing track signatures can be detected with the ATLAS experiment and the techniques necessary to search for them. Chapter 4 described the LHC and the ATLAS experiment, and their configuration during the collection of the data used in this thesis. Chapter 5 described this dataset, along with the simulated datasets used to develop the searches and produce exclusion limits, and the techniques used to simulate these datasets. Finally, Chapter 6 explained the reconstruction of the detector signatures in these datasets into physics objects and their performance. The statistical techniques used in the analysis of these objects was also explained.

The searches for a disappearing track signature with ATLAS were then presented in Part III. A first search exclusively for four-layer tracklets was presented in Chapter 7, which contains interpretations of the results for models with pure-wino charginos produced through strong and electroweak processes, and a model with pure-higgsino charginos produced through an electroweak process. Pure-wino charginos produced through an electroweak production mechanism were excluded at 95% CL up to 660 GeV at the theoretical lifetime of approximately 0.2 ns, and pure-higgsino charginos up to 210 GeV at a predicted lifetime of approximately 0.03 ns. As the disappearing track signature is a powerful general signature for the production of a dark matter candidate, detailed methods of reinterpretation were developed. These methods were detailed in Chapter 8, along with the use of these materials to rule out large fractions of the pMSSM parameter space.

A second search using the same dataset as the first but introducing four-layer tracklets and associated low-momentum tracks was presented in Chapter 9. This required the development of new object selections for the three-layer tracklets and associated soft tracks, and new background estimates. This analysis is ongoing at the time of writing, however preliminary results presented in this thesis already show an improvement of 10-25% in pure-higgsino expected exclusion limits over the previous analysis, with further room for optimisation.

Finally, the future prospects of the search for disappearing tracks with the ATLAS experiment were explored in Chapter 10. First, the ATLAS upgrade programme was discussed in detail, before describing software development work on the co-ordinate system used in the reconstruction of tracks in the strip endcap sensors. The effect of these upgrades and the beam conditions in future runs of the LHC were then discussed, showing the impact on the analysis in each future run. These show significant scope for improvement in exclusion limits during Run-3, although there will be challenges at HL-LHC due to the less favourable geometry and increased pileup. This demonstrates that the techniques used in this thesis for the first time will be essential for the viability of this search in the future.

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# Appendix A

## Monte-Carlo Datasets

### A.1 Dataset IDs

#### A.1.1 Second Wave Signal

### A.2 Events Generated

#### A.2.1 Second Wave Signal

|      | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    |
|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10.0 |        |        |        | 514828 | 514831 | 514834 | 514837 | 514840 | 514843 |
| 4.0  |        |        |        | 514810 | 514813 | 514816 | 514819 | 514822 | 514825 |
| 1.0  |        |        |        |        | 514795 | 514798 | 514801 | 514804 | 514807 |
| 0.2  | 514768 | 514771 | 514774 | 514777 | 514780 | 514783 | 514786 | 514789 | 514792 |
| 0.04 | 514750 | 514753 | 514756 | 514759 | 514762 | 514765 |        |        |        |
| 0.02 |        | 514744 | 514747 |        |        |        |        |        |        |

Table A.1: Higgsino  $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$  dataset IDs



|      | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    |
|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10.0 |        |        |        | 514827 | 514830 | 514833 | 514836 | 514839 | 514842 |
| 4.0  |        |        |        | 514809 | 514812 | 514815 | 514818 | 514821 | 514824 |
| 1.0  |        |        |        |        | 514794 | 514797 | 514800 | 514803 | 514806 |
| 0.2  | 514767 | 514770 | 514773 | 514776 | 514779 | 514782 | 514785 | 514788 | 514791 |
| 0.04 | 514749 | 514752 | 514755 | 514758 | 514761 | 514764 |        |        |        |
| 0.02 |        | 514743 | 514746 |        |        |        |        |        |        |

Table A.2: Higgsino  $pp \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^0$  dataset IDs

|      | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    |
|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10.0 |        |        |        | 514826 | 514829 | 514832 | 514835 | 514838 | 514841 |
| 4.0  |        |        |        | 514808 | 514811 | 514814 | 514817 | 514820 | 514823 |
| 1.0  |        |        |        |        | 514793 | 514796 | 514799 | 514802 | 514805 |
| 0.2  | 514766 | 514769 | 514772 | 514775 | 514778 | 514781 | 514784 | 514787 | 514790 |
| 0.04 | 514748 | 514751 | 514754 | 514757 | 514760 | 514763 |        |        |        |
| 0.02 |        | 514742 | 514745 |        |        |        |        |        |        |

Table A.3: Higgsino  $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^0$  dataset IDs

| $m(\tilde{\chi}_1^\pm)$ | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    | 1000   |
|-------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $m_{3/2}$               | 31.4   | 68     | 102.4  | 137.4  | 172.6  | 208    | 243.8  | 279.6  | 315.6  | 351.8  |
| 10.0                    |        |        |        |        |        | 514897 | 514899 | 514901 | 514903 | 514905 |
| 4.0                     |        |        |        |        |        | 514887 | 514889 | 514891 | 514893 | 514895 |
| 1.0                     |        |        |        |        |        |        | 514879 | 514881 | 514883 | 514885 |
| 0.2                     | 514859 | 514861 | 514863 | 514865 | 514867 | 514869 | 514871 | 514873 | 514875 | 514877 |
| 0.04                    | 514845 | 514847 | 514849 | 514851 | 514853 | 514855 | 514857 |        |        |        |

Table A.4: Wino  $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$  dataset IDs

| $m(\tilde{\chi}_1^\pm)$ | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    | 1000   |
|-------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $m_{3/2}$               | 31.4   | 68     | 102.4  | 137.4  | 172.6  | 208    | 243.8  | 279.6  | 315.6  | 351.8  |
| 10.0                    |        |        |        |        |        | 514896 | 514898 | 514900 | 514902 | 514904 |
| 4.0                     |        |        |        |        |        | 514886 | 514888 | 514890 | 514892 | 514894 |
| 1.0                     |        |        |        |        |        |        | 514878 | 514880 | 514882 | 514884 |
| 0.2                     | 514858 | 514860 | 514862 | 514864 | 514866 | 514868 | 514870 | 514872 | 514874 | 514876 |
| 0.04                    | 514844 | 514846 | 514848 | 514850 | 514852 | 514854 | 514856 |        |        |        |

Table A.5: Wino  $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0$  dataset IDs

|      | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    |
|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10.0 |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 4.0  |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 1.0  |        |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.2  | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.04 | 514750 | 514753 | 514756 | 514759 | 514762 | 514765 |        |        |        |
| 0.02 |        | 514744 | 514747 |        |        |        |        |        |        |

Table A.6: Number of Higgsino  $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$  events generated

|      | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    |
|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10.0 |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 4.0  |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 1.0  |        |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.2  | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.04 | 514750 | 514753 | 514756 | 514759 | 514762 | 514765 |        |        |        |
| 0.02 |        | 514744 | 514747 |        |        |        |        |        |        |

Table A.7: Number of Higgsino  $pp \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^0$  events generated

|      | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    |
|------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 10.0 |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 4.0  |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 1.0  |        |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.2  | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.04 | 514750 | 514753 | 514756 | 514759 | 514762 | 514765 |        |        |        |
| 0.02 |        | 514744 | 514747 |        |        |        |        |        |        |

Table A.8: Number of Higgsino  $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^0$  events generated

| $m(\tilde{\chi}_1^\pm)$ | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    | 1000   |
|-------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $m_{3/2}$               | 31.4   | 68     | 102.4  | 137.4  | 172.6  | 208    | 243.8  | 279.6  | 315.6  | 351.8  |
| 10.0                    |        |        |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 4.0                     |        |        |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 1.0                     |        |        |        |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.2                     | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.04                    | 514845 | 514847 | 514849 | 514851 | 514853 | 514855 | 514857 |        |        |        |

Table A.9: Number of Wino  $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$  events generated

| $m(\tilde{\chi}_1^\pm)$ | 100    | 200    | 300    | 400    | 500    | 600    | 700    | 800    | 900    | 1000   |
|-------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| $m_{3/2}$               | 31.4   | 68     | 102.4  | 137.4  | 172.6  | 208    | 243.8  | 279.6  | 315.6  | 351.8  |
| 10.0                    |        |        |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 4.0                     |        |        |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 1.0                     |        |        |        |        |        |        | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.2                     | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 | 30,000 |
| 0.04                    | 514844 | 514846 | 514848 | 514850 | 514852 | 514854 | 514856 |        |        |        |

Table A.10: Number of Wino  $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0$  events generated

## Appendix B

# Tracking

### B.1 Hitpattern

A `hitpattern` is a way of storing the information of which silicon layers and endcaps were used in a given track efficiently as a single variable. It takes the form of a binary bitset, with the lowest significance bit storing whether there was a hit in the first pixel barrel layer, the second bit storing whether there was a hit in the second pixel barrel layer, and so on. In order of increasing significance, the `hitpattern` stores the pixel barrel layers, the pixel endcap layers, the SCT barrel layers, the SCT endcap layers, and the TRT hits. The bitset is stored as a 32-bit unsigned integer to ensure sufficient memory allocation. Some examples are given in Table B.1.

| Description                                           | Binary Representation | Integer Representation |
|-------------------------------------------------------|-----------------------|------------------------|
| First 3 pixel barrel layers                           | 111                   | 7                      |
| First 3 pixel barrel layers, first pixel endcap layer | 10111                 | 23                     |
| First 4 pixel barrel layers                           | 1111                  | 15                     |
| First 4 pixel barrel layers, first SCT barrel layer   | 10001111              | 47                     |

Table B.1: Examples of track `hitpatterns` in binary and decimal integer representations. The binary representation is 32 bits; the preceding zeros have been neglected.

## B.2 Truth Linking

When reconstructing simulated Monte Carlo datasets, it is possible to link a reconstructed track to a truth-level particle with a truth link. The truth-level particle can come from the Monte Carlo event generation or from the detector simulation in GEANT4. This is performed by calculating a score known as the TMS. The TMS is defined by the ratio of hits that are shared in both the reconstructed track and a truth-level track, to the total number of hits in the truth-level track. Different weights are given to pixel, SCT and TRT hits, related to the expected number of hits in each detector. This is expressed as

$$\text{TMS} = \frac{10 \times N_{\text{shared}}^{\text{pix}} + 5 \times N_{\text{shared}}^{\text{SCT}} + 1 \times N_{\text{shared}}^{\text{TRT}}}{10 \times N_{\text{generator}}^{\text{pix}} + 5 \times N_{\text{generator}}^{\text{SCT}} + 1 \times N_{\text{generator}}^{\text{TRT}}} \quad (\text{B.1})$$

and the truth-level particle with the highest TMS score is linked.

## B.3 Frame Conversions

### B.3.1 Beam Frame to Strip Frame

Figure 10.10 can be used to find the radius and angle in the strip frame, given the module properties and the beam-frame co-ordinates. In Figure 10.10,  $B$ ,  $f$  and  $O$  match the definitions from Figure ??, where  $B$  represents the beamline,  $f$  is the focus of the module and  $O$  is the module origin. First, the cosine law can be used to find the strip-frame radius  $r_{\text{SF}}$  from the  $PBf$  triangle, using

$$r_{\text{SF}} = \overline{fP} = \sqrt{\overline{BP}^2 + \overline{Bf}^2 + 2 \overline{BP} \overline{Bf} \cos(\angle \text{PBf})} \quad (\text{B.2})$$

where the sides  $\overline{BP}$  and  $\overline{Bf}$ , along with the angle opposite  $r_{\text{SF}}$ ,  $\angle \text{PBf}$ , are used.  $\overline{BP}$  is the radius in the beam frame  $r_{\text{BF}}$ .  $\overline{Bf}$  can be found as

$$\overline{Bf} = \sqrt{\overline{Bf_x}^2 + \overline{Bf_y}^2} \quad (\text{B.3})$$

$$\overline{Bf} = \sqrt{(R \sin(\phi_s))^2 + (R(1 - \cos(\phi_s)))^2} \quad (\text{B.4})$$

$$\overline{Bf} = R \sqrt{\sin^2(\phi_s) + (1 - 2 \cos(\phi_s) + \cos^2(\phi_s))} \quad (\text{B.5})$$

$$\overline{Bf} = R \sqrt{2 - 2 \cos(\phi_s)} \quad (\text{B.6})$$

$$\overline{Bf} = 2R \sqrt{\frac{1}{2} (1 - \cos(\phi_s))} \quad (\text{B.7})$$

$$\overline{Bf} = 2R \left| \sin\left(\frac{\phi_s}{2}\right) \right| \quad (\text{B.8})$$

and  $\angle \text{PBf}$  can be found as

$$\angle \text{PBf} = \arctan\left(\frac{\overline{\text{ff}}_x}{\overline{\text{Bf}}_x}\right) \quad (\text{B.9})$$

$$\angle \text{PBf} = \arctan\left(\frac{R(1 - \cos(\phi_s))}{R \sin(\phi_s)}\right) \quad (\text{B.10})$$

$$\angle \text{PBf} = \arctan\left(\tan\left(\frac{\phi_s}{2}\right)\right) = \frac{\phi_s}{2} \quad . \quad (\text{B.11})$$

Together, these give

$$r_{\text{SF}} = \sqrt{r_{\text{BF}}^2 + \left(2R \left|\sin\left(\frac{\phi_s}{2}\right)\right|\right)^2 + 2r_{\text{BF}}2R \left|\sin\left(\frac{\phi_s}{2}\right)\right| \cos\left(\frac{\phi_s}{2}\right)} \quad (\text{B.12})$$

To find the strip frame polar angle, the angles about  $f$  can be analysed. Starting from

$$\pi = \angle \text{f}_\text{O} \text{f}_\text{O} + \angle \text{OfP} + \angle \text{PfB} + \angle \text{Bff}_x \quad (\text{B.13})$$

by using known variables,  $\angle \text{f}_\text{O} \text{f}_\text{O}$  can be replaced with  $\phi_S$ ,  $\angle \text{OfP}$  with  $\phi_{\text{SF}}$  and  $\angle \text{Bff}_x$  with  $\frac{\pi - \phi_S}{2}$ . For  $\angle \text{PfB}$  a sine law can be used to give

$$\frac{\overline{\text{BP}}}{\sin(\angle \text{PfB})} = \frac{\overline{\text{fP}}}{\sin(\angle \text{PBf})} \quad (\text{B.14})$$

$$\frac{r_{\text{BF}}}{\sin(\angle \text{PfB})} = \frac{r_{\text{SF}}}{\sin\left(\pi + \phi_{\text{BF}} - \frac{\phi_S}{2}\right)} \quad (\text{B.15})$$

$$\angle \text{PfB} = \arcsin\left(\frac{r_{\text{BF}} \sin\left(\pi + \phi_{\text{BF}} - \frac{\phi_S}{2}\right)}{r_{\text{SF}}}\right) \quad (\text{B.16})$$

which can then be used to find the strip-frame polar angle as

$$\pi = \phi_S + \phi_{\text{SF}} + \arcsin\left(\frac{r_{\text{BF}} \sin\left(\pi + \phi_{\text{BF}} - \frac{\phi_S}{2}\right)}{r_{\text{SF}}}\right) + \frac{\pi - \phi_S}{2} \quad (\text{B.17})$$

$$\phi_{\text{SF}} = \frac{\pi - \phi_S}{2} - \arcsin\left(\frac{r_{\text{BF}} \sin\left(\pi + \phi_{\text{BF}} - \frac{\phi_S}{2}\right)}{r_{\text{SF}}}\right) \quad (\text{B.18})$$

### B.3.2 Strip Frame to Beam Frame

A similar approach to the derivation of the beam-to-strip conversion can be used to derive the strip-to-beam conversion. Firstly, a cosine rule can be used to define the beam-frame radius as

$$r_{\text{BF}} = \overline{\text{BR}} = \sqrt{\overline{\text{fP}}^2 + \overline{\text{Bf}}^2 + 2\overline{\text{fP}}\overline{\text{Bf}}\cos(\angle \text{PfB})} \quad (\text{B.19})$$

which, as before, can be expanded using

$$\overline{\text{fP}} = r_{\text{SF}} \quad (\text{B.20})$$

and

$$\overline{\text{Bf}} = 2R \left| \sin\left(\frac{\phi_s}{2}\right) \right| \quad (\text{B.21})$$

.  $\angle \text{PfB}$  can be found as

$$\pi = \phi_S + \phi_{SF} + \angle \text{PfB} + \left( \frac{\pi}{2} - \frac{\phi_S}{2} \right) \quad (\text{B.22})$$

$$\angle \text{PfB} = \pi - \frac{\pi}{2} - \phi_S + \frac{\phi_S}{2} - \phi_{SF} \quad (\text{B.23})$$

$$\angle \text{PfB} = \frac{\pi}{2} - \frac{\phi_S}{2} - \phi_{SF} \quad (\text{B.24})$$

by inspecting the angles around f. The full equation for  $r_{\text{BF}}$  is then

$$r_{\text{BF}} = \overline{\text{BR}} = \sqrt{r_{\text{SF}}^2 + \left( 2R \left| \sin\left(\frac{\phi_s}{2}\right) \right| \right)^2 + 2 r_{\text{SF}} 2R \left| \sin\left(\frac{\phi_s}{2}\right) \right| \cos\left(\frac{\pi}{2} - \frac{\phi_S}{2} - \phi_{SF}\right)} \quad (\text{B.25})$$

The same sine law as the beam-to-strip conversion can be used to find the beam-frame polar angle

$$\frac{\overline{\text{BP}}}{\sin(\angle \text{PfB})} = \frac{\overline{\text{fP}}}{\sin(\angle \text{PBf})} \quad (\text{B.26})$$

$$\overline{\text{BP}} = r_{\text{BF}} \quad \overline{\text{fP}} = r_{\text{SF}} \quad (\text{B.27})$$

$$\angle \text{PfB} = \frac{\pi}{2} - \frac{\phi_S}{2} - \phi_{SF} \quad (\text{B.28})$$

$$\angle \text{PBF} = \frac{\pi}{2} - \frac{\phi_S}{2} + \phi_{\text{BF}} \quad (\text{B.29})$$

$$\frac{r_{\text{BF}}}{\sin\left(\frac{\pi}{2} - \frac{\phi_S}{2} - \phi_{SF}\right)} = \frac{r_{\text{SF}}}{\sin\left(\frac{\pi}{2} - \frac{\phi_S}{2} + \phi_{\text{BF}}\right)} \quad (\text{B.30})$$

$$\sin\left(\frac{\pi}{2} - \frac{\phi_S}{2} + \phi_{\text{BF}}\right) = \frac{r_{\text{SF}}}{r_{\text{BF}}} \sin\left(\frac{\pi}{2} - \frac{\phi_S}{2} - \phi_{SF}\right) \quad (\text{B.31})$$

$$\phi_{\text{BF}} = \frac{\phi_S}{2} - \frac{\pi}{2} + \arcsin\left(\frac{r_{\text{SF}}}{r_{\text{BF}}} \sin\left(\frac{\pi}{2} - \frac{\phi_S}{2} - \phi_{SF}\right)\right) \quad (\text{B.32})$$

## Appendix C

# Smearing Functions

The distribution of the  $\Delta q/$  is fitted in each region with the following function.

$$f = \begin{cases} C \exp \left[ \gamma z - \alpha \beta + \frac{\alpha^2}{2} + \beta \gamma \right], & z < -\beta \\ C \exp \left[ \alpha \left( z + \frac{\alpha}{2} \right) \right], & -\beta \leq z < -\alpha \\ C \exp \left[ -\frac{z^2}{2} \right], & -\alpha \leq z \leq \alpha \\ C \exp \left[ -\alpha \left( z - \frac{\alpha}{2} \right) \right], & \alpha < z \end{cases} \quad (\text{C.1})$$

$$z = \frac{x - \langle x \rangle}{\sigma} \quad (\text{C.2})$$

$$C = C_1 + C_2 + C_3 + C_4 \quad (\text{C.3})$$

$$C_1 = \sqrt{2\pi}\sigma \text{erf} \left[ \frac{\alpha}{\sqrt{2}} \right] \quad (\text{C.4})$$

$$C_2 = \frac{\sigma}{\alpha} \left\{ \exp \left[ -\frac{\alpha^2}{2} \right] - \exp \left[ -\alpha \beta + \frac{\alpha^2}{2} \right] \right\} \quad (\text{C.5})$$

$$C_3 = \frac{\sigma}{\gamma} \exp \left[ -\alpha \beta + \frac{\alpha^2}{2} \right] \quad (\text{C.6})$$

$$C_4 = \frac{\sigma}{\alpha} \exp \left[ -\frac{\alpha^2}{2} \right] \quad (\text{C.7})$$

The smearing function consists of the core crystal ball and one side exponential tail corresponding to the bad resolution of the charge-flipped pixel tracklets. The parameters for the  $< 25\text{GeV}$  region are not able to be evaluated by the fit of the data, thus, the parameter  $\sigma$  is evaluated by the fit with the function of the standard track and  $\alpha$  is used the same value as the  $= (25, 35)\text{GeV}$  for the moment.  $\beta$  and  $\gamma$  are decided by the tail only fit with all region inclusively due to the lack of statistics. However,  $\beta$  is updated by the threshold of the charge



flip following the equation when  $\beta$  is greater than the threshold.

$$\beta = \frac{1}{\sigma} \tag{C.8}$$