

A SEARCH FOR LONG-LIVED
NEUTRALINOS DECAYING TO
DI-LEPTON DISPLACED VERTICES IN
PROTON-PROTON COLLISIONS AT
 $\sqrt{s} = 13 \text{ TeV}$

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of
Philosophy in the Graduate School of The Ohio State University

By

Zachary Pollock, B.S., M.S.

Graduate Program in Physics

The Ohio State University

2024

Dissertation Committee:

Dr. K.K Gan, Advisor

Dr. Antonio Boveia

Dr. Yuri Kovchegov

Dr. Fengyuan Yang



© Copyright by
Zachary Pollock
2024

ABSTRACT

A search for a long-lived neutral massive particle decaying to a pair of oppositely charged leptons ee , $e\mu$, $\mu\mu$ is presented using 140.1 fb^{-1} of pp collision data at center-of-mass energy of 13 TeV, collected with the ATLAS detector. The displaced leptons are required to form a vertex that is displaced from the primary pp collision and within the volume of the inner detector tracking system. The requirements of a minimum displacement of 2 mm and a minimum invariant mass 12 GeV effectively suppress backgrounds from Standard Model processes. The remaining backgrounds from cosmic ray muons and random track crossings are estimated using data-driven techniques to be less than one background event. No events containing a displaced di-lepton vertex were observed yielding upper limits for the production cross-section of two supersymmetric models that could produce a long-lived neutralino: pair production of gluinos $\tilde{g}$ and pair production of electroweakinos $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$. These are the first limits on the production cross-section for these long-lived neutralino models.

To my partner Matthew.

ACKNOWLEDGMENTS

The first thanks must go to Dr. Benjamin Cote and Dr. Rachel Rosten for being there and helping every step of the way. Solving problems with you has been one of my favorite parts of grad school.

Thank you to a few specialists at CERN: Dr. Zachary Marshall for helping to get the long-lived neutralino MC samples working and Dr. Rodney Walker for the invaluable help with getting the event-mixing procedure to run on the distributed computing grid.

Thank you to Dr. Bora Tar and Aaron Woyshville for all the incredible work and support (both technical and emotional) during the opto-board production.

Thank you to Becca, Brian, Sagan, Daisy, Lauren, Rachel, Fran, and Emma for all the group fitness dance classes at the RPAC, one of the only things that kept me sane for many weeks during grad school.

Thank you to my parents, my brother Tyler and sister-in-law Kayla, and their kids Louie, Ellie, Abby, and Calvin, for their continued love and support.

The biggest thanks to my partner Dr. Matthew Wilmot. I absolutely could not have done this without you.

Finally, thank you to my advisor Dr. K.K. Gan for the continuous guidance throughout this process. I know that our time together has made me a better scientist, a better human, and I am extremely grateful.

VITA

August 10, 1994 Born
Wright-Patterson Air Force Base, OH
2016 B.S. Physics,
Minors in Mathematics and Computer
Science,
Miami University, Oxford, OH
2019 M.S. Physics,
The Ohio State University, Columbus, OH
2016-2017 Graduate Fellow,
The Ohio State University, Columbus, OH
2017-2019 Graduate Teaching Associate,
The Ohio State University, Columbus, OH
2019-present Graduate Research Associate,
The Ohio State University, Columbus, OH

Fields of Study

Major Field: Physics, High Energy Physics

Studies in:

Beyond the Standard Model searches	K.K. Gan
Optoboard production	K.K. Gan

Table of Contents

	Page
Abstract	ii
Dedication	iii
Acknowledgments	iv
Vita	v
List of Figures	ix
List of Tables	xii
List of Abbreviations	xiv

Chapters

Introduction	1
1 The Standard Model and Supersymmetry	3
1.1 The Standard Model	3
1.1.1 Fundamental Particles	3
1.1.2 The Strong Interaction	4
1.1.3 The Electroweak Interaction	5
1.1.4 Electroweak Symmetry Breaking	5
1.1.5 Known Limitations of the Standard Model	6
1.2 Supersymmetry	7
1.2.1 Benefits of SUSY	8
1.2.2 Field Content of the Minimal Supersymmetric Model	9
1.2.3 Supersymmetry Breaking	9
1.2.4 R -Parity Violation	11
1.2.5 Simplified SUSY Models	12
2 The Large Hadron Collider and the ATLAS experiment	13
2.1 The Large Hadron Collider	13
2.2 The ATLAS experiment	16
2.2.1 ATLAS Coordinate System	16
2.2.2 The Inner Detector	18
2.2.3 The Calorimeters	22
2.2.4 The Muon Spectrometer	25
2.2.5 Toroidal Magnets	27
2.2.6 Trigger System	27

3	Object Reconstruction in the ATLAS experiment	29
3.1	Reconstruction of Tracks in the Inner Detector	29
3.1.1	Standard Track Reconstruction	30
3.1.2	Large Radius Track Reconstruction	31
3.2	Vertex Reconstruction	32
3.2.1	Primary Vertex Reconstruction	32
3.2.2	Secondary Vertex Reconstruction	33
3.3	Lepton Identification	37
3.3.1	Electron Reconstruction and Identification	37
3.3.2	Muon Reconstruction and Identification	38
4	Data and Simulated Samples	40
4.1	Data Samples	40
4.2	Simulated Samples	41
4.2.1	Signal MC Samples	41
4.2.2	Standard Model samples	46
5	Signal Selection	47
5.1	Event Selection	47
5.1.1	Cosmic Ray Muon Veto	48
5.1.2	Triggers	48
5.1.3	Filters	49
5.2	Lepton Selection	50
5.2.1	Signal Electron Requirements	51
5.2.2	Signal Muon Requirements	51
5.3	Vertex Selection	53
5.4	Signal Acceptance and Efficiencies	54
5.4.1	Cutflows	54
5.4.2	Lepton Efficiencies	55
5.4.3	Signal Reconstruction Efficiency	57
5.4.4	Overall Signal Efficiency	57
6	Background Estimation	67
6.1	Cosmic Ray Background	67
6.2	Random Track Crossing Background	67
6.2.1	Concept	68
6.2.2	Procedure	69
6.2.3	Calculation of the Estimate	71
6.2.4	Validations	72
6.2.5	Signal Region Background Estimate	75
6.3	Systematic Uncertainties	75
7	Scale Factors and Uncertainties	79
7.1	Lepton Identification Scale Factors and Uncertainties	79
7.2	Trigger Scale Factors and Uncertainties	81
7.3	LRT and VSI Scale Factors and Uncertainties	83
7.4	General MC Modeling	89

7.5	Pileup Modeling in MC	89
7.6	Other Sources of Systematic Uncertainty	89
7.7	Total Systematic Uncertainty	91
8	Results	94
8.1	Statistical Methods	94
8.2	Upper Limits on Model Cross-Sections	97
8.3	Comparison to Other SUSY Searches	98
9	Conclusion	110
	Bibliography	111
	Appendices	
A	Validation of Track Shifting for Event Mixing	122
B	Validation of Lifetime Reweighting	127

List of Figures

Figure		Page
1.1	The fundamental particles of the Standard Model.	4
1.2	First-order loop corrections to Higgs propagator	7
2.1	Overall view of the LHC	14
2.2	Run 2 Integrated Luminosity and Pileup	15
2.3	Cut-away view of ATLAS detector	17
2.4	Cut-away view of the Inner Detector	19
2.5	Detailed quarter-view of Inner Detector layers	20
2.6	Schematic of the ATLAS calorimetry system	23
2.7	Schematic of the ATLAS Muon Spectrometer	25
3.1	Defining Track Parameters	30
3.2	LRT reconstruction efficiency	32
3.3	Steps in in the <code>VrtSecInclusive</code> algorithm	33
3.4	Examples of requirements applied to track hit patterns based on the location of the displaced vertex position.	36
4.1	Feynman diagrams for the SUSY MC signal models	42
4.2	Truth-level kinematic distributions for the gluino MC signal samples	44
4.3	Truth-level kinematic distributions for the electroweakino MC signal samples	45
5.1	The distribution of $ \phi_1 - \phi_2 $ vs. $\sum \eta$ for potential cosmic muon pairs	48
5.2	Identification efficiencies for electrons and muons using standard and modified working points	52
5.3	Signal cutflows for the gluino-produced $\tilde{\chi}_1^0$ model	55
5.4	Signal cutflows for the electroweakino-produced $\tilde{\chi}_1^0$ model	56
5.5	Lepton tracking efficiency, reconstruction efficiency, and identification efficiency for the gluino model	58
5.6	Lepton tracking efficiency, reconstruction efficiency, and identification efficiency for the electroweakino model	59
5.7	Vertex-level acceptance, efficiency, and signal efficiency for the gluino model	60
5.8	Vertex-level acceptance, efficiency, and signal efficiency for the electroweakino model	61

5.9	Signal efficiency as a function of truth R_{xy} , p_T , η , ϕ , z , and μ for the gluino model	62
5.10	Signal efficiency as a function of truth R_{xy} , p_T , η , ϕ , z , and μ for the electroweakino model	63
5.11	Signal efficiencies as a function of decay length ($c\tau$) shown for multiple $\tilde{\chi}_1^0$ masses in the gluino model	65
5.12	Signal efficiencies as a function of decay length ($c\tau$) shown for multiple $\tilde{\chi}_1^0$ masses in the electroweakino model	66
6.1	Muon pair $\Delta R_{\cos}$ below the cosmic ray veto	68
6.2	Diagram of random track crossing background procedure	71
6.3	Track-track DV kinematics in $t\bar{t}$ MC	74
6.4	Track-track DV kinematics in 2017 data	76
7.1	Scale factors for the modified electron identification working point	80
7.2	Scale factors for the modified Loose muon working point	81
7.3	Scale factors for the HLT_g50_loose trigger	82
7.4	Scale factors for the HLT_g140_loose trigger	83
7.5	Scale factors for the HLT_mu60_0eta105_msonly trigger	84
7.6	Reconstructed K_S yields plotted against multiple kinematic variables	86
7.7	Reconstructed K_S yields as a function of R_{xy} for DVs made of ST/ST, ST/LRT, and LRT/LRT tracks	87
7.8	Scale factors for LRT/VSJ reconstruction as a function of R_{xy}	88
7.9	Pileup distributions before and after pileup reweighting	90
7.10	Total systematic errors for the gluino model	92
7.11	Total systematic errors for the electroweakino model	93
8.1	Observed and expected limits on production cross-section at the 95% CL for the gluino model with $m_{\tilde{g}} = 1500$ GeV	99
8.2	Observed and expected limits on production cross-section at the 95% CL for the gluino model with $m_{\tilde{g}} = 2000$ GeV	100
8.3	Observed and expected limits on production cross-section at the 95% CL for the gluino model with $m_{\tilde{g}} = 2500$ GeV	101
8.4	Observed and expected limits on production cross-section at the 95% CL for the electroweakino model with $m_{\tilde{\chi}_1^0} = 100$ GeV	102
8.5	Observed and expected limits on production cross-section at the 95% CL for the electroweakino model with $m_{\tilde{\chi}_1^0} = 300$ GeV	103
8.6	Observed and expected limits on production cross-section at the 95% CL for the electroweakino model with $m_{\tilde{\chi}_1^0} = 500$ GeV	104
8.7	Observed and expected limits on production cross-section at the 95% CL for the electroweakino model with $m_{\tilde{\chi}_1^0} = 700$ GeV	105
8.8	Observed and expected limits on production cross-section at the 95% CL for the electroweakino model with $m_{\tilde{\chi}_1^0} = 900$ GeV	106
8.9	Observed and expected limits on production cross-section at the 95% CL for the electroweakino model with $m_{\tilde{\chi}_1^0} = 1100$ GeV	107

8.10	Observed and expected limits on production cross-section at the 95% CL for the electroweakino model with $m_{\tilde{\chi}_1^0} = 1300$ GeV	108
A.1	Distributions of signal DVs before and after testing the track-shifting in the event-mixing procedure	124
A.2	Distributions of signal DV tracks before and after testing the track-shifting in the event-mixing procedure	125
B.1	A closure test of the lifetime reweighting procedure where one lifetime sample is excluded at a time	128

List of Tables

Table	Page
1.1 Supermultiplets of the MSSM	10
3.1 Comparison of track requirements for standard and large radius tracking algorithms.	31
3.2 Comparison of track preselection requirements for primary and secondary vertexing algorithms	34
3.3 List of VSI requirements for DVs and related tracks.	35
4.1 Gluino MC sample mass points with their cross-sections.	43
4.2 Electroweakino MC sample mass points and cross-sections.	46
5.1 Triggers used to select events in DRAW_RPVLL	49
5.2 Offline filters used to select muon, photon, and electron candidates	50
5.3 Signal event-level selection criteria.	50
5.4 Signal electron definitions.	51
5.5 Signal muon definitions.	53
5.6 Vertex level selection criteria.	54
6.1 Number of track-track DV candidates observed and predicted in $t\bar{t}$ MC and 2017 DAOD_SUSY15 data	74
6.2 Number of DV candidates predicted in each year of Run 2 data due to random track crossing	77
6.3 Final estimated background from random track crossings	78
7.1 K_S vertex level requirements and lepton requirements used for calculating LRT/VSI reconstruction scale factors and systematic uncertainties	85
8.1 Expected yield of ee , $e\mu$, and $\mu\mu$ vertices for the gluino model	95
8.2 Expected yield of ee , $e\mu$, and $\mu\mu$ vertices for the electroweakino model	95
8.3 Excluded $\tilde{\chi}_1^0$ lifetimes for the gluino-production model	98
8.4 Excluded $\tilde{\chi}_1^0$ lifetimes for the electroweakino-production model	99

A.1	Numbers of DV candidates observed and predicted for the validation of track-shifting in the event-mixing procedure	126
-----	--	-----

LIST OF ACRONYMS

ALICE	A Large Ion Collider Experiment
AMSB	anomaly-mediated supersymmetry breaking
ASIC	application-specific integrated circuit
ATLAS	A Toroidal LHC ApparatuS
BSM	Beyond the Standard Model
CERN	European Centre for Nuclear Research
CFF	Common Format File
CL	confidence level
CMS	Compact Muon Solenoid
CSC	Cathode Strip Chamber
CTP	Central Trigger Processor
DoF	degrees of freedom
DV	displaced vertex
E-Cal	Electromagnetic Calorimeter
EM	electromagnetic
EWSB	electro-weak symmetry breaking
F-Cal	forward calorimeter
FSR	final-state radiation
GRL	GoodRunsList
GSF	Gaussian-sum-filter
H-Cal	Hadronic Calorimeter
HEC	Hadronic End-cap Calorimeter
HLT	High Level trigger
IBL	Insertable B-layer
ID	Inner Detector
IP	Interaction Point
ISR	initial-state radiation
IR	Interaction Region
L1	Level 1
LAr	Liquid Argon
LEP	Large Electron–Positron Collider
LHC	Large Hadron Collider
LHCb	LHC-beauty
LLP	long-lived particle
LRT	Large Radius Track

LSP	lightest supersymmetric particle
MC	Monte Carlo simulation
MDT	Monitored Drift Tube
MET	missing transverse energy
MPI	multiple parton interactions
MS	Muon Spectrometer
MSSM	Minimal Supersymmetric Standard Model
mSUGRA	minimal supergravity
NLL	next-to-leading logarithmic
NLO	next-to-leading order
PDF	parton distribution function
PSB	Proton Synchrotron Booster
PS	Proton Synchrotron
PV	primary vertex
QCD	quantum chromodynamics
ROI	Region of Interest
RPC	Resistive Plate Chamber
RPV	R -parity conservation
RPV	R -parity violation
SF	scale factor
SPS	Super Proton Synchrotron
SCT	semiconductor tracker
SM	Standard Model
ST	Standard Track
SUSY	supersymmetry
TGC	Thin Gap Chamber
TRT	Transition Radiation Tracker
VCSEL	vertical-cavity surface-emitting laser
VSI	<code>VrtSecInclusive</code>
WP	working point

INTRODUCTION

The Standard Model (SM) of particle physics is the culmination of decades of advancement of scientific theories and experiments and successfully describes interactions of elementary particles. Its most notable achievement was the prediction in 1964 of the Higgs boson [1–6] that was discovered in 2012 [7, 8]. Despite its achievements, various phenomena demonstrate that the SM is incomplete. One proposal for physics Beyond the Standard Model (BSM) that attempts to explain some of these deficiencies is supersymmetry (SUSY). SUSY is a principle included in many models that postulates that each SM particle has a supersymmetric partner whose spin differs by $\frac{1}{2}$; SM fermions have a boson superpartner and SM bosons have a fermion superpartner. Despite the well-founded motivations, no evidence for SUSY has not been found to date.

As SUSY remains unconfirmed, experiments should expand their searches to more exotic signatures. For example, some specific SUSY theories with R -parity violating couplings (see Section 1.2.4) predict particles that are “long-lived.” While most particles created in high energy collisions decay promptly, i.e. before traversing a measurable distance in a particle detector, long-lived particles (LLPs) have longer lifetimes. If LLPs are produced in high energy collisions and travel several mm to hundreds of mm before decaying, their decays should be observable using current particle detectors like ATLAS (A Toroidal LHC ApparatuS). If no evidence of such particles is found, the search will provide limits on parameters for new BSM theories.

The analysis described in this dissertation searched for an LLP that decays into two leptons and a neutrino. The common origin of the two leptons (the location of the LLP decay) is reconstructed as a displaced vertex (DV), which is *displaced* from the initial pp collision. A significant advantage of this analysis is that background from SM processes is strongly suppressed by the displacement and invariant mass requirements. The only backgrounds are from cosmic ray muons and tracks randomly crossing to form DVs.

In Chapter 1, the foundations of the SM are discussed, followed by the fundamentals of SUSY theories. Chapter 2 describes the Large Hadron Collider (LHC) and the ATLAS experiment used to collect data for the search. Methods for track, lepton, and displaced vertex reconstruction in ATLAS are detailed in Chapter 3. Chapter 4 discusses the datasets

of recorded and simulated collision events that were used to search for di-lepton displaced vertices. The signal selections on events, leptons, and vertices are presented in Chapter 5, and the background estimates are described in Chapter 6. Chapter 7 describes details of the various corrections applied to simulated data to account for imperfect modeling and also discusses sources of systematic uncertainty. Finally, the results of the search and the extracted upper limits on cross-sections for the two models investigated are summarized in Chapter 8.

Chapter 1

THE STANDARD MODEL AND SUPERSYMMETRY

The basic theory and motivation for the analysis in this thesis (hereby called “this analysis”) are described here. Section 1.1 covers the SM of particle physics and some of its known limitations. Section 1.2 describes supersymmetry, a popular theoretical extension of the SM which addresses some of those limitations and may produce a decay signature that is searched for in the analysis described in later chapters.

1.1 The Standard Model

The SM [9] of particle physics is a very successful theory that describes the fundamental particles that make up the universe and their interactions. The SM is a quantum field theory described by the gauge symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. These symmetry groups describe three of the four fundamental forces in physics. Quantum chromodynamics (QCD), or the strong interaction, is described by the $SU(3)_C$ symmetry group and the unified electromagnetic and weak interactions are described by the $SU(2)_L \otimes U(1)_Y$ symmetry group. The fourth fundamental force, gravity, does not currently have a formulation in the SM. The SM is notable for its success at predicting new particles that would be later discovered. For example, the top quark [10] and the Higgs boson [7, 8] were each predicted by the SM and discovered years later.

1.1.1 Fundamental Particles

There are two types of fundamental particles in the SM: fermions and bosons. The fermions, which are spin- $\frac{1}{2}$, comprise leptons and quarks, shown on the left side of Figure 1.1. Leptons (green) include the charged leptons, e.g. electrons, and the neutral neutrinos. Quarks (pink) are the primary constituent particles of matter, and have up- and down-types with electrical charges $+\frac{2}{3}e$ and $-\frac{1}{3}e$ respectively. There are three generations of fermions where rest mass increases with generation. The bosons, shown on the right side of Figure 1.1, have integer

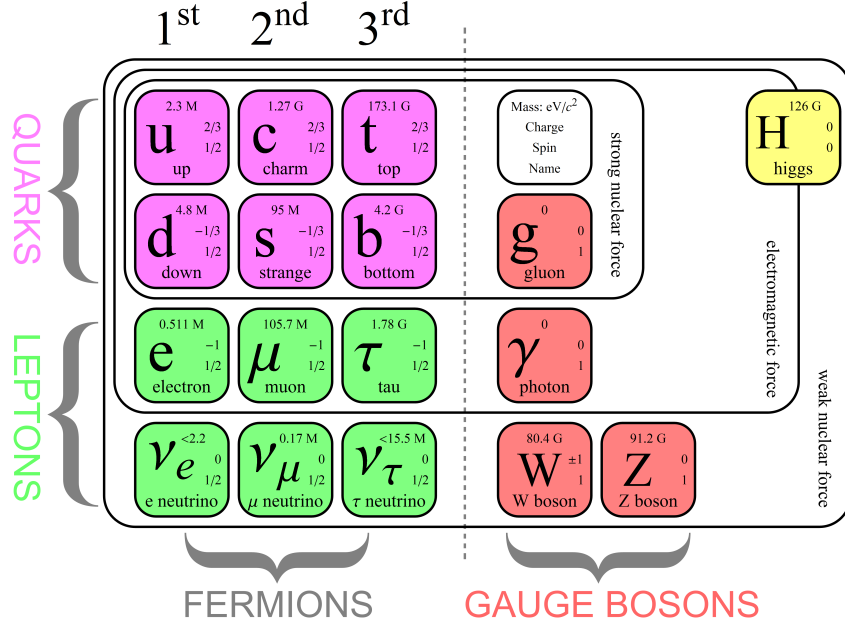


Figure 1.1: The fundamental particles of the Standard Model [11]. The Higgs mass was first measured as 126 GeV [7, 8], but has since been measured with more precision to be 125.11 ± 0.11 GeV [12].

spin. The spin-1 bosons (red) are responsible for mediating the fundamental forces between fermions. The spin-0 Higgs boson (yellow) is a special case; it arises from the electroweak symmetry breaking (see Section 1.1.4) necessary for the $W^\pm$ and Z bosons to have mass.

1.1.2 The Strong Interaction

The strong interaction is described by QCD, a non-abelian gauge group $SU(3)_C$. The C refers to color, the charge of the strong interaction, conveniently denoted as red, green, or blue (or anti-red, anti-green, anti-blue for antiparticles). The only fermions that participate in strong interactions are the quarks, but due to color confinement [13] they only exist in bound states of multiple quarks called hadrons that are color neutral. Mesons (e.g. pions and kaons) are hadrons composed of a quark and an anti-quark with opposite color charges, and baryons (e.g. protons and neutrons) are hadrons composed of three quarks (or three anti-quarks) with one charge of each color¹.

The $SU(3)_C$ gauge group generates eight gauge fields, corresponding to eight massless gluons. Due to the non-Abelian nature of the $SU(3)_C$ gauge group, the gluons carry color charge and are self-interacting. The ability to self-interact leads to QCD being very strong

¹“Color” in QCD is not related to colors in the visible spectrum of light, yet it is useful as a metaphor because when red, green, and blue light are combined they produce “colorless” white light, analogous to color charges in a baryon.

at small distances e.g. within a proton. At high energies the strong interaction becomes weaker, allowing them to interact as free particles, a characteristic known as asymptotic freedom [14]. This allows quarks and gluons to interact individually at high-energy particle colliders (see Chapter 2), although color confinement means that any individual quarks or gluons produced in the collision will immediately hadronize into colorless mesons or baryons.

1.1.3 The Electroweak Interaction

At high energies (like the early universe or at high energy colliders), the weak force and the electromagnetic force unify to act as one “electroweak” force. The $SU(2)_L \otimes U(1)_Y$ group describes the unified weak and electromagnetic interaction. The charges related to these symmetry groups are the third component of the weak isospin I_3 and the weak hypercharge Y , from which the familiar electrical charge can be calculated via:

$$Q = I_3 + \frac{Y}{2}. \quad (1.1)$$

The weak interaction is a chiral theory, meaning its interactions with left-handed and right-handed particles are different. The left-handed fermions form doublets in $SU(2)_L$ with $I_3 = \pm\frac{1}{2}$, while the right-handed fermions are singlets with $I_3 = 0$. Right-handed neutrinos have not been observed [15] and are therefore not included in the SM [9]. The weak interaction is notable for being the only interaction that mediates flavor change, including decays from leptons to neutrinos, changing the flavor of quarks, or changing the fermion generation.

The electroweak interaction has four generators, three $W_\mu^i (i = 1, 2, 3)$ for $SU(2)_L$ and one B_μ for $U(1)_Y$, with separate gauge coupling constants g_W and g_Y . These W_μ^i are not identically the $W^\pm$ shown in Figure 1.1; the next section will discuss the relationship between the four generators and the physical gauge bosons.

1.1.4 Electroweak Symmetry Breaking

The local gauge symmetries in the SM as described so far would necessitate the $W^\pm$ and Z bosons be massless to preserve the local gauge invariance. Some extra mechanism must be present to preserve local gauge invariance while also giving the $W^\pm$ and Z bosons the masses that are observed in nature. The Higgs mechanism [1, 2] achieves this by adding an additional complex scalar $SU(2)_L$ doublet ϕ called the Higgs field. The Higgs field couples with the electroweak fields of $SU(2)_L \otimes U(1)_Y$ and can self-interact.

The Higgs field and its self-interactions allow the SM Lagrangian to be gauge invariant overall, but the ground state of the Higgs field is not invariant under $SU(2)_L \otimes U(1)_Y$ because of its non-zero vacuum expectation value. This is known as electro-weak symmetry breaking (EWSB) because the Higgs field breaks the symmetry of the weak gauge group $SU(2)_L \otimes U(1)_Y$ but is still invariant under the remaining subgroup $U(1)_Q$ that describes

electromagnetic interactions. Three of the four degrees of freedom (DoF) from the complex scalar doublet are absorbed by the $W^\pm$ and Z bosons, leaving the Higgs field with one DoF. The result of EWSB is that excitation of the Higgs field is a massive, neutral spin-0 boson known as the Higgs boson. The Higgs boson was discovered in 2012 [7, 8], validating the predictions of EWSB and hence the SM.

Because of the Higgs mechanism, the generator fields of $SU(2)_L \otimes U(1)_Y$, W_μ^i and B_μ mix into mass eigenstates:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \pm W_\mu^2) \quad (1.2)$$

$$Z_\mu = \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu \quad (1.3)$$

$$A_\mu = \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu \quad (1.4)$$

where θ_W is the Weinberg angle, which depends on the $SU(2)_L \otimes U(1)_Y$ gauge couplings as:

$$\sin \theta_W = \frac{g_W}{\sqrt{g_W^2 + g_Y^2}}. \quad (1.5)$$

These mass eigenstates correspond to the remaining SM gauge bosons; $W_\mu^\pm$ are the charged $W^\pm$ bosons, Z_μ is the neutral Z boson, and A_μ is the massless photon γ . The fermions also gain their masses via interactions with the Higgs field, but via Yukawa couplings, which are free parameters of the SM.

1.1.5 Known Limitations of the Standard Model

Despite all the successes of the SM, there are some phenomena that it currently does not explain, such as the remaining fundamental force of gravity [16], neutrino oscillations [17], and dark matter [18]. Other limitations are not unexplained phenomena per se, but are more like coincidences that seem “unnatural” to occur without some underlying mechanism. One example, dubbed the hierarchy problem, will be discussed further.

A hierarchy problem in general occurs when the order of some parameters are vastly different with no theoretical explanation. The relevant example in particle physics is the fact that gravity is $\mathcal{O}(10^{24})$ times weaker than the weak interaction. Because the strength of a gravitational interaction is related to a particle’s mass and therefore it’s coupling to the Higgs field, an equivalent expression of this hierarchy problem is why the Higgs mass is so much lower than the Planck scale.

The Higgs boson receives quadratically divergent contributions to its mass from all particles that couple to it. Consider the one-loop correction to the Higgs propagator shown in Figure 1.2. The leading-order correction to the Higgs boson mass m_h due to a fermion

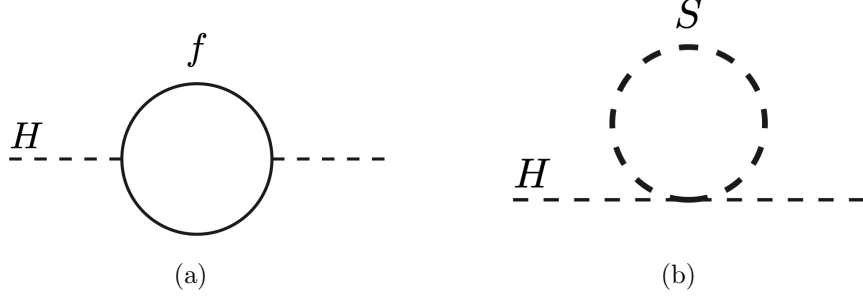


Figure 1.2: Examples of a first-order loop correction to the Higgs propagator due to (a) a fermion loop and (b) a scalar boson loop [19].

loop is:

$$\Delta m_{h,f}^2 = -\frac{|\lambda_f^2|}{8\pi^2}(\Lambda + \dots) \quad (1.6)$$

where λ_f is the Higgs coupling to the fermion ($\lambda_f \propto m_f$) and Λ is the cutoff energy where the SM is no longer valid. If that cutoff energy is taken to be in the Planck scale, $\mathcal{O}(10^{28}$ eV), then this correction to the Higgs mass would also be on the Planck scale. A correction of this order would be present for every massive fundamental particle. The sum of many Planck scale corrections happening to almost entirely cancel out, resulting in the observed Higgs boson mass of 125.11 ± 0.11 GeV [12], would require “fine-tuning” of the Higgs boson mass. While possible that all these masses happen to cancel out coincidentally, the fine-tuning seems unlikely to have occurred without some underlying mechanism. An elegant solution to the hierarchy problem would be supersymmetry, which is described in the next section.

1.2 Supersymmetry

Supersymmetry (SUSY) is a principle used in many theories for physics BSM which posits a symmetry between bosons and fermions in addition to the SM symmetries. Each boson has a supersymmetric partner fermion and each fermion has a supersymmetric partner boson. Each supersymmetric partner has all the same quantum numbers as the original particle except for spin, which is changed by $\frac{1}{2}$. SUSY is a promising extension of the SM because it can address several of the current limitations in the SM including the hierarchy problem, dark matter, and neutrino masses (see Section 1.2.1).

Because SUSY as a principle describes an entire class of theoretical models, it is helpful to limit this discussion to what is relevant to the subsequent search for LLPs. Focus will be on the simplest model that incorporates SUSY into the SM, known as the Minimal

Supersymmetric Standard Model (MSSM) [19]. The MSSM practically doubles² the number of elementary particles compared to the SM by introducing a SUSY partner to every SM quark, lepton, and gauge boson. The boson superpartners of the SM fermions receive an *s*-prefix to denote the relation to the original SM particle, e.g. sfermion, squark, smuon. The fermion superpartners of the SM bosons receive a *-ino* suffix, e.g. gluino, wino, higgsino. Additionally, a tilde ($\tilde{}$) is used to denote the superpartner, e.g. a muon μ and a smuon $\tilde{\mu}$.

There are some gauge-invariant and renormalizable interaction terms that can be added to the MSSM potential that would violate baryon number conservation and/or lepton number conservation. If both types of such interactions were allowed, then the proton could decay quickly via processes like $p \rightarrow \pi^0 + e^+$. Given experimental evidence that the lifetime of the proton is at least $\mathcal{O}(10^{34})$ years [20], *R*-parity is introduced to prevent the proton from decaying. *R*-parity is an additional discrete symmetry added to some SUSY models including the MSSM [19], defined as:

$$P_R = (-1)^{3(B-L)+2s}, \quad (1.7)$$

where B is baryon number, L is lepton number, and s is the spin of the particle. All SM particles have *R*-parity of +1 and all SUSY particles would have *R*-parity of -1. If *R*-parity is conserved, then the lightest supersymmetric particle (LSP) cannot decay to SM particles.

1.2.1 Benefits of SUSY

One of the primary benefits of SUSY is that it can solve the hierarchy problem introduced in Section 1.1.5. For the quadratically divergent correction to the Higgs boson mass from a fermion loop in Eq. 1.6, the corresponding contribution for a bosonic loop is:

$$\Delta m_{h,b}^2 = \frac{|\lambda_b|}{8\pi^2}(\Lambda + \dots) \quad (1.8)$$

where the difference in sign between Eq. 1.6 and Eq. 1.8 is due to spin statistics. If there is an unbroken symmetry between fermions and bosons, then $|\lambda_f^2| = |\lambda_b|$ and these divergent corrections exactly cancel [21]. Similarly, the fermion superpartners of the SM bosons would cancel out their contributions. Thus, instead of “unnatural” fine-tuning to cancel out large contributions to the Higgs mass, SUSY provides an elegant underlying mechanism.

SUSY can also produce a promising dark matter candidate. Particle dark matter is a theoretical BSM particle that interacts with SM gravitationally, but not electromagnetically [22]. If *R*-parity is conserved and the LSP cannot decay to SM particles, the LSP would be an excellent dark matter candidate.

²Adding SUSY to the SM technically more than doubles the number of elementary particles because it requires two Higgs doublets, as explained further in Section 1.2.2.

1.2.2 Field Content of the Minimal Supersymmetric Model

The field content of the MSSM is summarized in Table 1.1. Similar to how fermions transforming under $SU(2)_L \otimes U(1)_Y$ are placed in doublets where a gauge transformation changes one particle into the other, SM particles and their superpartners can be placed in “supermultiplets” where the supersymmetric operator Q switches between fermions and bosons.

Q commutes with every SM gauge group generator, which implies that right- and left-handed fermions have separate superpartners because they transform differently under electroweak gauge transformations. Note that the right- or left-handedness descriptors on the sfermions do not relate to their own helicity (sfermions have 0 spin), but that of their SM superpartner. The left-handed quark and lepton doublets are placed in a supermultiplet with the left-handed squark and slepton doublet, respectively and the right-handed quark and lepton singlets are placed in a supermultiplet with the right-handed squark and slepton singlets, respectively. Maintaining the massless neutrino assumption from the SM, right-handed neutrinos do not exist in the SM and therefore do not have a supersymmetric partner. Each sfermion has the same coupling to the SM gauge bosons as its superpartner, i.e. a $\tilde{u}_L^i$ couples to a $W^\pm$ boson while a $\tilde{u}_R^{i*}$ does not.

The supersymmetric potential requires two Higgs field complex doublets H_u and H_d . These are necessary in the MSSM for both the up and down type fermions (i.e. fermions with hypercharge $Y = \frac{1}{2}$ and $Y = -\frac{1}{2}$) to acquire mass via Yukawa couplings while keeping the superpotential holomorphic [23]. The four Higgs complex scalars H_u^+ , H_u^0 , H_d^0 , and H_d^- are labelled by a subscript for the type of fermion for which it generates mass and a superscript for its electrical charge. These four Higgs scalars have superpartners $\tilde{H}_u^+$, $\tilde{H}_u^0$, $\tilde{H}_d^0$, and $\tilde{H}_d^-$ called the higgsinos. Each Higgs doublet is placed in a supermultiplet with its corresponding higgsino doublet.

The gauge bosons are placed in supermultiplets with their superpartners the gauginos. The gauginos transform under every gauge transformation the same as the SM gauge bosons, so no special treatment of chirality is necessary. The gluon, W_μ^a , and B_μ fields have partners called gluinos, winos, and binos, respectively. Were supersymmetry to remain unbroken, EWSB would cause the W_μ^a and B_μ fields to form mass eigenstates the same way as in the SM, with a massive zino ($\tilde{Z}_0$) and a massless photino ($\tilde{\gamma}$).

1.2.3 Supersymmetry Breaking

An unbroken supersymmetry would imply that both members of each supermultiplet have the same mass; however, no SUSY particles have been observed yet, so their masses must be higher than their SM partners. Thus supersymmetry must be a broken symmetry. The symmetry is expected to be spontaneously broken [19], that is, that the Lagrangian is invariant under supersymmetry while a vacuum expectation value is not.

Table 1.1: Supermultiplets of the MSSM, with $i = 1, 2, 3$ for the three fermion generations, $a = 1, \dots, 8$ for the eight gluons, and $b = 1, 2, 3$ for the three $SU(2)_L$ generator fields [19].

Supermultiplet	Spin-0 Sfermions	Spin- $\frac{1}{2}$ Fermions
Q_i	$\begin{pmatrix} \tilde{u}_L^i & \tilde{d}_L^i \end{pmatrix}$	$\begin{pmatrix} u_L^i & d_L^i \end{pmatrix}$
$\bar{U}_i$	$\tilde{u}_R^{i*}$	$u_R^{i\dagger}$
$\bar{D}_i$	$\tilde{d}_R^{i*}$	$d_R^{i\dagger}$
L_i	$\begin{pmatrix} \tilde{\nu}^i & \tilde{\ell}_L^i \end{pmatrix}$	$\begin{pmatrix} \nu^i & \ell_L^i \end{pmatrix}$
$\bar{E}_i$	$\tilde{\ell}_R^{i*}$	$\ell_R^{i\dagger}$
Supermultiplet	Spin-0 Higgs fields	Spin- $\frac{1}{2}$ Higgsino fields
H_u	$\begin{pmatrix} H_u^+ & H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ & \tilde{H}_u^0 \end{pmatrix}$
H_d	$\begin{pmatrix} H_d^0 & H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 & \tilde{H}_d^- \end{pmatrix}$
Supermultiplet	Spin-1 gauge fields	Spin- $\frac{1}{2}$ gaugino fields
G^a	g_μ^a	$\tilde{g}^a$
W^b	W_μ^b	$\tilde{W}^b$
B	B_μ	$\tilde{W}$

If the solution to the hierarchy problem described in Section 1.2.1 is to be maintained, then the relationship between coupling for a particle/sparticle pair must be maintained. This restriction leads to so-called “soft” symmetry breaking, where the effective Lagrangian can be written as:

$$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{soft} \quad (1.9)$$

where $\mathcal{L}_{SUSY}$ contains all the gauge and Yukawa interactions and preserves SUSY invariance and $\mathcal{L}_{soft}$ contains the symmetry-breaking mass terms for the SUSY particles. If the largest mass term in $\mathcal{L}_{soft}$ is denoted as m_{soft} , then the remaining corrections to the Higgs boson mass must be of the form:

$$\Delta m_{h,f}^2 = m_{soft}^2 \left[\frac{\lambda}{16\pi^2} \ln(\Lambda/m_{soft} + \dots) \right] \quad (1.10)$$

where λ is the corresponding dimensionless couplings describing the particle/sparticle pair of interest. If Λ is of the order of the Planck mass and $\lambda \sim 1$, then the mass of new SUSY particles should not be much higher than ~ 1 TeV [19, 24] or else it would require additional fine-tuning. Particles in that mass range should be accessible at the LHC, which is a major motivator to search for SUSY there.

When supersymmetry is broken, the SUSY particles with the same quantum numbers will mix to form mass eigenstates. The neutral gauginos $\widetilde{W}^0$ and $\widetilde{B}^0$ will mix with the neutral higgsinos $\widetilde{H}_u^0$ and $\widetilde{H}_d^0$ to form four mass eigenstates $\widetilde{\chi}_1^0$, $\widetilde{\chi}_2^0$, $\widetilde{\chi}_3^0$, and $\widetilde{\chi}_4^0$, called the neutralinos. The charged gauginos $\widetilde{W}^\pm$ and charged higgsinos $\widetilde{H}_u^\pm$ and $\widetilde{H}_d^\pm$ mix to form the charginos, labelled $\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_2^\pm$. For both neutralinos and charginos, the lower index corresponds to its mass rank, i.e. $\widetilde{\chi}_1^0$ is the lightest neutralino. The neutralinos and charginos are often collectively referred to as the electroweakinos. The gluinos are charged only under the $SU(3)_C$ color charge, so they do not mix with other SUSY particles.

One notable aspect of SUSY symmetry breaking in the MSSM is the addition of “SM” Higgs mass eigenstates. The two complex scalar Higgs doublets have eight degrees of freedom. Following symmetry breaking, three are absorbed by the gauge bosons to generate the $W^\pm$ and Z^0 boson masses, leaving five degrees of freedom for Higgs masses. These lead to five mass eigenstates: neutral scalars h and H (the lighter of which, h , must be the Higgs boson observed at the LHC), two charged scalars H^+ and H^- , and a pseudo-scalar field A .

1.2.4 R -Parity Violation

As discussed briefly in Section 1.2.1, requiring conservation of R -parity is necessary to prevent proton decay if both lepton- and baryon-violating interactions are present in the superpotential. If **only** one of either lepton- or baryon-violating terms are allowed, then R -parity will no longer be conserved, but consistency with the observed proton lifetime is maintained. These scenarios are known as models with R -parity violation (RPV).

Violation of R -parity conservation has multiple implications for the LSP, depending on its coupling. Most importantly, the LSP can now decay, but only to SM particles. This would still allow for the LSP to be a dark matter candidate, but only if the lifetime is close to the age of the universe and the RPV coupling of the LSP is $\sim \mathcal{O}(10^{-12})$ [25]. The other case, where the lifetime is short enough to produce decays in detectors at particle colliders, is where this dissertation will focus. In this case, the lifetime of the LSP would be too short for it to be a feasible dark matter candidate. It would, however, now be a potential explanation for neutrino masses and oscillations if lepton number (and not baryon number) conservation is violated [25]. The prospective lepton number violating terms in the superpotential are:

$$W_{\Delta L=\pm 1} = \kappa^i L_i H_u + \lambda^{ijk} L_i L_j \bar{E}_k + \lambda'^{ijk} L_i Q_j \bar{D}_k \quad (1.11)$$

where κ and the λ s are the bilinear and trilinear couplings and i , j , and k are generation indices. Neutrino mass contributions could originate from either (or both) of (1) tree-level contributions of neutrino/neutralino mixing from the bilinear couplings and (2) loop-level contributions from the trilinear couplings λ and λ' .

The analysis in this dissertation will focus on a long-lived neutralino $\tilde{\chi}_1^0$ as the LSP which decays via RPV couplings to two leptons and a neutrino. The leptons in the final state are required to be electrons or muons, so the coupling of interest is λ^{12k} , following the notation in [26]. If the coupling λ^{12k} is small, the lifetime of the $\tilde{\chi}_1^0$ may be large enough to decay with macroscopic displacement but still be reconstructed within the ATLAS detector.

1.2.5 Simplified SUSY Models

No searches at high energy particle colliders have produced evidence of SUSY to date. As such, SUSY still encompasses a wide set of theories that could produce many types of experimental signatures. A set of “simplified models” [27] were created to group SUSY theories by their experimental signature. For example, the decay of a gluino to two quarks and an neutralino: $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$. This decay may occur via:

- A direct three-body decay: $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$
- A cascade decay via a chargino: $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^\pm \rightarrow q\bar{q}(W^\pm\tilde{\chi}_1^0)$
- A cascade decay via a neutralino: $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0 \rightarrow q\bar{q}(Z^0\tilde{\chi}_1^0)$

The final state of these gluino decays includes two quarks and a neutralino, which will produce two jets and missing transverse energy in the detector (see Chapter 3). Unless it includes the decay products of the $W^\pm$ or Z^0 , the experimental signature of the three decay models would be the same. Because differences in kinematics due to the $W^\pm$ or Z^0 are unlikely to change the optimization of the signal region, these decay models are grouped together as one “simplified model.”

As stated previously, the charginos $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ and the neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ are mixtures of the supersymmetric partners of the Higgs fields called higgsinos and the electroweak gauge fields called winos and binos. The proportions of these fields mixings depend on the mechanism for supersymmetry breaking and are therefore still undetermined. Different models may predict, for example, that the lightest neutralino is more “higgsino-like,” more “wino-like,” or more “bino-like” [28]. For instance, minimal supergravity (mSUGRA) [29–31] predicts a bino-like $\tilde{\chi}_1^0$ LSP, anomaly-mediated supersymmetry breaking (AMSB) [32, 33] predicts a wino-like LSP, and “natural SUSY” [34, 35] predicts a higgsino-like $\tilde{\chi}_1^0$ LSP. Adding RPV scenarios to any of these specific theories would allow for the long-lived $\tilde{\chi}_1^0$ decay searched for in this analysis. Following the framework of simplified SUSY models, the nature of mixing of the electroweakinos that decay to the $\tilde{\chi}_1^0$ LSP is treated as a free parameter; it neither affects the final state leptons nor is it probed by the final state leptons. As such, the charginos and neutralinos are simply referred to as electroweakinos.

Chapter 2

THE LARGE HADRON COLLIDER AND THE ATLAS EXPERIMENT

2.1 The Large Hadron Collider

The LHC is the largest and most energetic particle accelerator in the world, and is located at the European Centre for Nuclear Research (CERN) campus outside of Geneva, Switzerland [36]. The accelerator is built in the tunnel of the decommissioned Large Electron–Positron Collider (LEP) [37], a circular tunnel 27 km in circumference and about 100 meters underground, crossing between the border of Switzerland and France. An overall view of the LHC is shown in Figure 2.1.

Most of the time, the LHC accelerates counter-rotating beams of protons to collide them at high energy. There are also occasionally specialized runs that accelerate lead ion beams, called “heavy ion” runs, with proton-lead (p -Pb) or lead-lead (Pb-Pb) collisions.

The protons accelerated at the LHC originate from hydrogen gas. The hydrogen atoms are stripped of their electrons and the remaining protons are accelerated through a series of smaller accelerators including a linear accelerator (LINAC2), the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS) [38]. The proton beams are then injected into the main LHC ring, where two particle beams travel in opposite directions around the ring. A series of superconducting magnets, operating at a maximum temperature of 1.9 K, is used to accelerate the proton beams further. The accelerator was designed to accelerate protons up to an energy of 7 TeV each, producing a center-of-mass energy ($\sqrt{s}$) of 14 TeV. Due to problems with the magnet system in 2008 [39], the LHC did not operate at its full design energy for many years. During Run 1 (2010 – 2013), the LHC was operated at $\sqrt{s} = 7$ TeV for the first two years and $\sqrt{s} = 8$ TeV after that. The data used in this dissertation was collected in 2015-2018, called Run 2, from pp collisions at $\sqrt{s} = 13$ TeV. At the start of Run 3 in 2022, the LHC achieved its highest operating energy so far, with $\sqrt{s} = 13.6$ TeV, but that new data is beyond the scope of this dissertation.

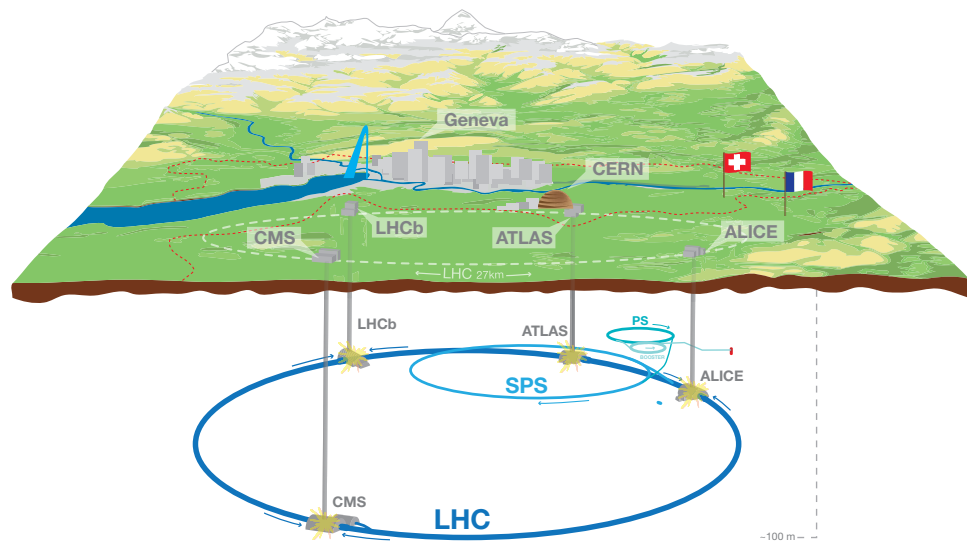


Figure 2.1: Rendition of the LHC with its underground detector experiments [40].

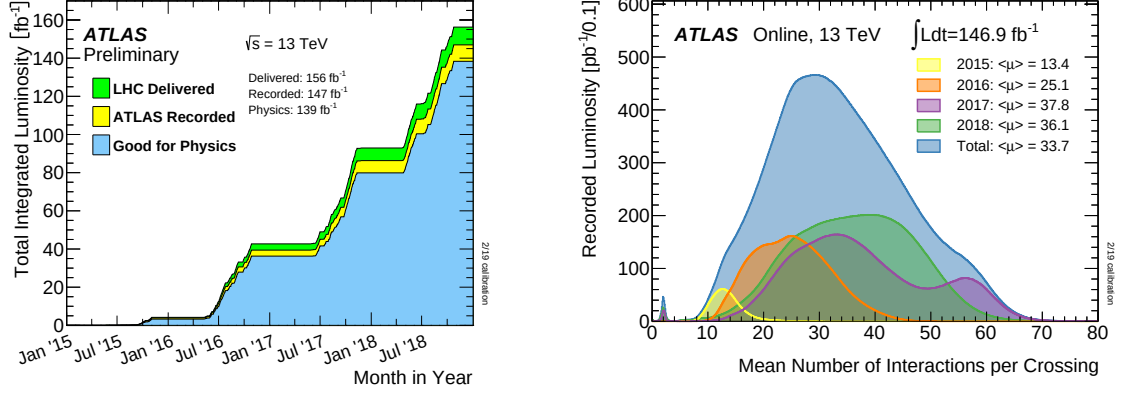


Figure 2.2: (Left) Total integrated luminosity delivered by the LHC (green), recorded by ATLAS (yellow), and certified as good for physics analysis by ATLAS (blue) [42]. (Right) Mean number of interactions per crossing for each year in Run 2, with the total, luminosity-weighted average for all years shown in blue [42].

The prediction of the number of events of interest produced by the LHC is characterized by the “instantaneous luminosity” ($\mathcal{L}$). The number of expected events per unit time is:

$$\frac{dN}{dt} = \mathcal{L} \times \sigma \quad (2.1)$$

where σ is the cross-section of the process of interest. The cross-section describes the probability that the process will occur, and is typically given in units of barns, $b = 10^{-24} \text{ cm}^2$. Integrating the above equation over time yields the total number of events:

$$N = \int \mathcal{L} dt \times \sigma = \mathcal{L}_{int} \times \sigma \quad (2.2)$$

where the integrated luminosity $\mathcal{L}_{int}$ can be considered as the total amount of data delivered by the LHC.

The LHC was designed to have a peak instantaneous luminosity of $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, although improvements to the proton beam parameters have achieved a peak instantaneous luminosity of $2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The total integrated luminosity delivered by the LHC during Run 2 was 159 fb^{-1} , while 140 fb^{-1} were recorded and certified as good for physics by ATLAS [41]. The timeline of integrated luminosity over Run 2 is shown in Figure 2.2.

The beams in the LHC are comprised of bunches of protons spaced by 25 ns intervals. The average number of protons per bunch during Run 2 was 1.2×10^{11} . Because there are so many protons, each time a pair of bunches collides, there are multiple pp interactions. The interaction of interest is a “hard” scattering that has a large momentum transfer and creates energetic particles; however, most of these pp interactions involve small amounts of momentum transfer, as if the protons are glancing off each other, and are called “soft”

scattering. All pp interactions other than interaction of interest (i.e. the one producing the highest momentum transfer) are classified as “pileup.” Detector signals from pileup collisions create confusion in the event of interest. Pileup is quantified as the time-averaged mean number of pp interactions per bunch crossing, $\langle\mu\rangle$, the distributions of which for Run 2 are shown in Figure 2.2.

There are eight Interaction Regions (IRs) around the accelerator where the beams can be steered into collisions. Four of these points are in caverns that are home to the primary experiments at the LHC: ATLAS, CMS (Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment), and LHCb (LHC-beauty). ATLAS and CMS are large, general-purpose particle detectors [43, 44]. These two detectors independently discovered the Higgs boson in 2012 [7, 8]. ALICE is a specialized detector designed to detect the particles created from heavy ion collisions, specialized runs where the LHC accelerates and collides heavy ions instead of the usual protons [45]. LHCb is another specialized detector designed to study the bottom quark, including CP violation [46]. The data for this dissertation was collected using ATLAS. The next section, 2.2, will discuss the design and operation of the various detector subsystems within ATLAS, with a special focus on the Inner Detector.

2.2 The ATLAS experiment

The ATLAS detector is the largest particle detector ever built at a collider, with a height of 25 m, length of 44 m, and weight of 7000 tons [43]. The cylindrical detector has forward/backward symmetry around the Interaction Point (IP) and provides nearly 4π solid angle coverage.

The sub-detectors can be grouped in two types: trackers, designed to measure the trajectory of a particle with minimum perturbation of its momentum (i.e. minimum loss of energy), and calorimeters, designed to measure the total energy of a particle by stopping it completely. The detector subsystem closest to the beamline is the Inner Detector (ID), which measures the trajectory of charged particles. Surrounding the ID are two calorimeter systems, which nominally stop all particles except for muons and neutrinos. Surrounding all of those are the muon trackers and toroidal magnet systems, known as the Muon Spectrometer (MS). Each of these systems is designed with a cylindrical “barrel” region that is coaxial to the beamline and two “end-cap” (disk) regions that are normal to the beamline. A schematic of these systems is shown in Figure 2.3.

2.2.1 ATLAS Coordinate System

ATLAS utilizes a specific coordinate system that is also used throughout this dissertation. The origin is defined to be the nominal interaction point, with the beamline along the $\hat{z}$ -direction. Specifically, the $+z$ -axis points from the IP to side-A of the detector, which is the

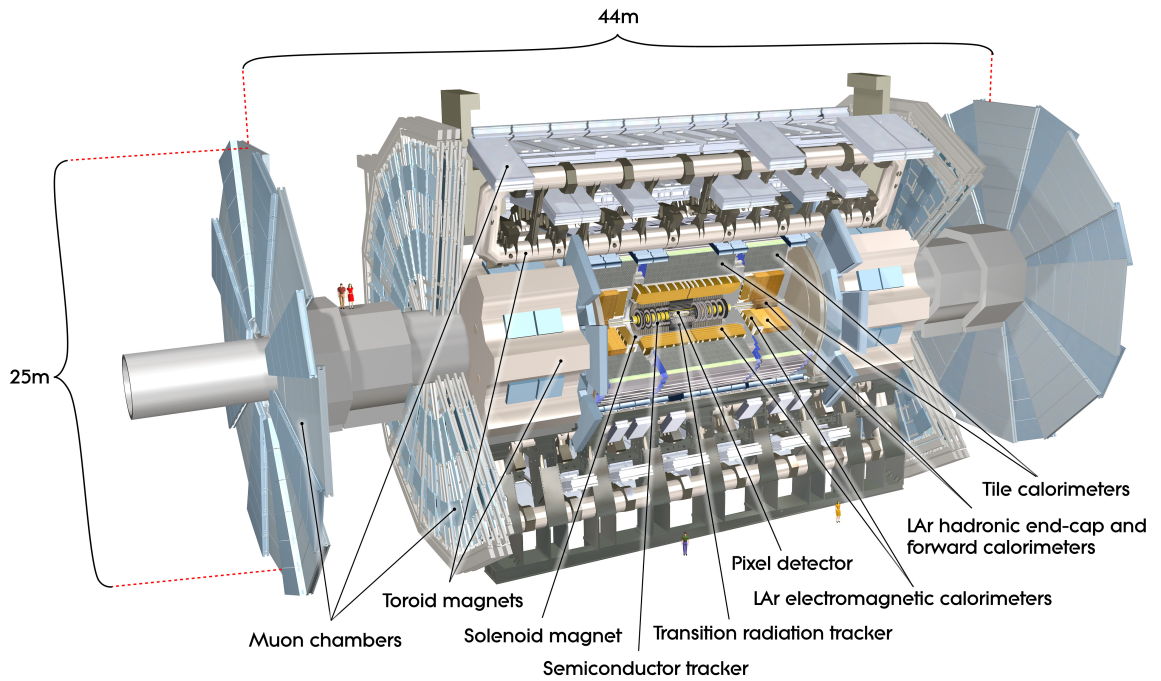


Figure 2.3: A cut-away view of the ATLAS detector indicating subsystems [43]. Two humans are shown on the left side for scale.

side closer to Geneva. The $+\hat{x}$ -direction points towards the center of the LHC accelerator ring, and the $+\hat{y}$ -direction points vertically up toward the Earth's surface. The standard angular radial coordinates ϕ and θ are used, where ϕ is the angle measured from the $+x$ -axis in the x - y plane and θ is the angle measured from the $+z$ -axis.

It is unlikely that the center-of-mass frame of the particles colliding is the same as the lab frame of the detector, because the individual quarks and gluons have a fraction of the proton momentum. It is therefore convenient to use coordinates that are Lorentz invariant under boosts³ along the z -axis. The rapidity of a particle with energy E and momentum p_z along the z -axis is defined as:

$$y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c}. \quad (2.3)$$

It fulfils the requirement of being Lorentz invariant but its usefulness is limited because its direction in space depends on the energy of the particle. Instead, the pseudorapidity η is used, where

$$\eta = -\ln \frac{\theta}{2}, \quad (2.4)$$

which is approximately the same as rapidity in the massless or relativistic ($m \ll E$) limit. The pseudorapidity can therefore be used instead of the polar angle θ to describe direction in the detector, with $\eta = \pm\infty$ along the $\pm z$ -axis and $\eta = 0$ in the transverse plane. The angular separation between two objects, $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, is also invariant under Lorentz boosts in the z -direction. Other useful quantities to characterize an event are the momentum and energy in the transverse plane (x - y), because the total transverse momentum before the collision is zero. The transverse momentum is defined as $p_T = |p| \sin \theta$. A particle is typically characterized by the parameters (p_T, η, ϕ) because these are all independent of the Lorentz boost in the z -direction under the massless or ultrarelativistic assumption.

2.2.2 The Inner Detector

The innermost subdetector closest to the beamline is the ID, which tracks charged particles with $|\eta| < 2.5$. “Tracking” is the process of reconstructing the trajectory of a particle in the detector and is described further in Section 3.1.

The ID comprises three different tracker systems, as shown in Figure 2.4. Closest to the beamline is the pixel tracker with the highest spatial resolution. Surrounding the pixel detector is the semiconductor tracker (SCT), which uses strips to reduce cost while maintaining good r - ϕ resolution. Surrounding the SCT is the Transition Radiation Tracker (TRT), which uses drift tubes to provide more space-point measurements to measure the momentum of the charged particle more precisely. These trackers are designed to provide

³“Boosts” refers to a Lorentz transformation in the direction of interest. It is often used to refer to the kinetic energy of particle, where a more boosted particle has higher kinetic energy.

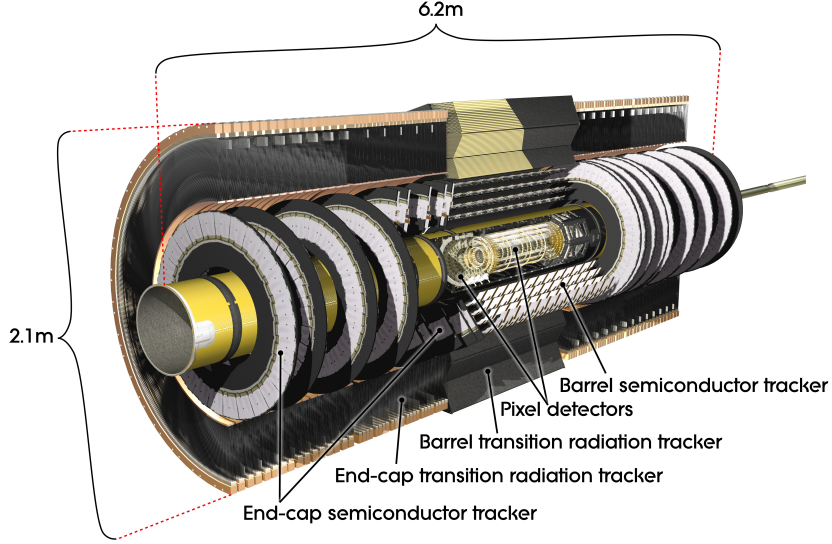


Figure 2.4: Cut-away view of the subsystems of the inner tracking detector [43].

excellent spatial resolution close to the beamline and precise momentum measurements, allowing for reconstruction of both individual track particles and vertices. Figure 2.5 shows the arrangement of layers in each of these subsystems in detail, which will be useful for discussions of secondary vertex reconstruction in Section 3.2.2.

The ID is surrounded by a superconducting solenoid. The solenoid is a coil with 1154 turns and is 2.5 m in diameter and 5.8 m in length. The solenoid provides a 2 T magnetic field that bends charged particles in the ID, allowing for measurements of the particles momenta.

The Pixel Tracker

The pixel tracker utilizes 80.4 million silicon pixel sensors in the region $|\eta| < 2.5$ for precise spatial resolution next to the beamline. Each pixel is a $250\ \mu\text{m}$ thick n-type silicon semiconductor. When a charged particle passes through the pixel, it creates electron-hole pairs that under an applied electric field create an electric signal that registers as a “hit”. The pixels are arranged in four layers in the barrel region and three layers in each end-cap. Three of these layers were original to ATLAS, with the fourth and innermost layer, the Insertable B-layer (IBL) [47], being added during the shutdown between Runs 1 and 2. Each pixel in these outer three layers has an area of $50\ \mu\text{m} \times 400\ \mu\text{m}$, giving a spatial resolution of $10\ \mu\text{m}$ in the $R\text{-}\phi$ plane and $115\ \mu\text{m}$ in z . The pixels in the IBL are smaller, with an area of $20\ \mu\text{m} \times 200\ \mu\text{m}$ and spatial resolution of $8\ \mu\text{m}$ in the $R\text{-}\phi$ plane and $40\ \mu\text{m}$ in z . This fine resolution at small radii is vital for precise reconstruction of decay vertices for b -hadrons or

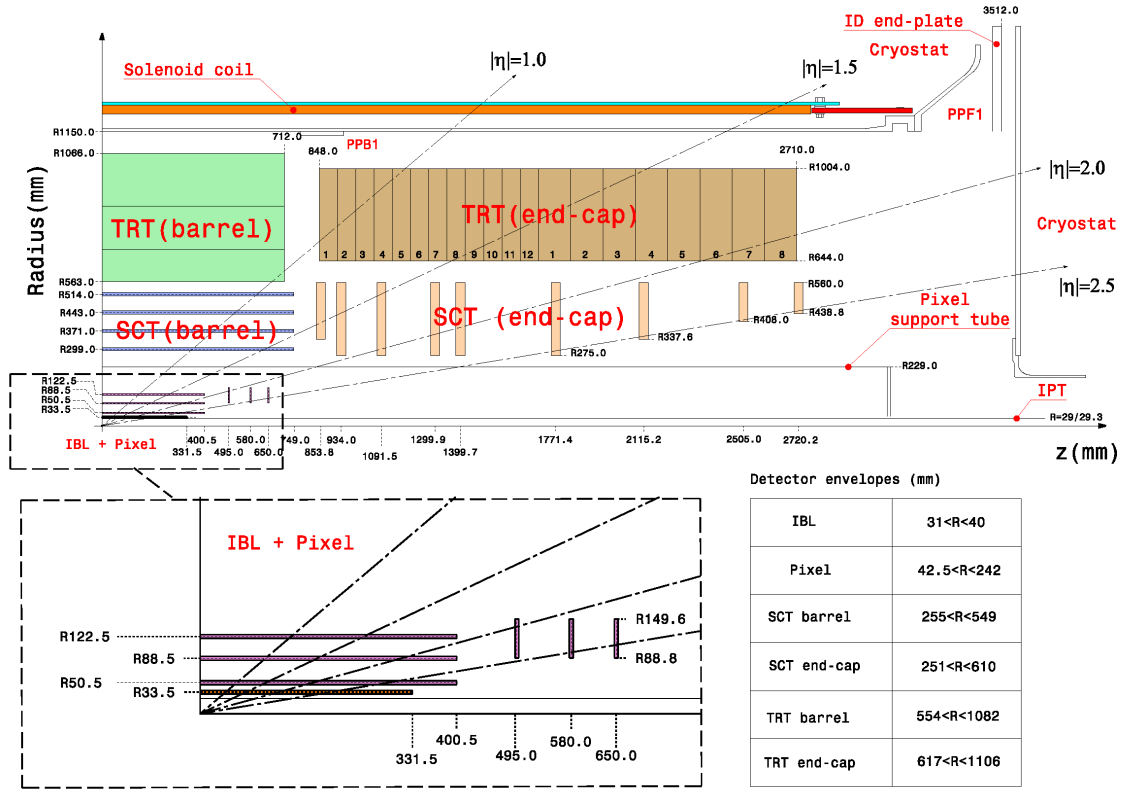


Figure 2.5: A quarter-view of the layout of the ATLAS inner tracking detector, including the additional IBL detector layer, shown in the R - z plane [47]. The top shows the entire ID, and the bottom shows the pixel subsystem enlarged for more detail.

exotic LLPs.

Opto-boards

Each of the subsystems of ATLAS has its sundry service systems that provide structural support, power, and control and read-out capabilities. Most of these support systems are beyond the scope of this dissertation, but are detailed in the various ATLAS Technical Design Reports [48–56]. One component involved in read-out for the pixel detector is called an “opto-board,” [57] which is of particular note because a significant fraction of the author’s time in graduate school was invested in the construction and testing of its components.

The detector readout must be processed quickly, but computers cannot be placed in or near the detector because the high radiation levels would damage them. The opto-boards convert the electrical signals from the detector to fiber-optic signals that are transmitted to the computing room and vice versa. The former is achieved using vertical-cavity surface-emitting laser (VCSEL) arrays and the latter is achieved with PIN diode arrays.

Some opto-boards from the previous production cycle had VCSELs that ceased emitting light after being installed in ATLAS, so extensive quality assurance testing was performed on each VCSEL. These tests included a minimum optical output power, a maximum percentage change of the turn-on current after a 24 hour burn-in at 100° C, and a maximum percent change after burn-in of the voltage required to reach 6 mA of current. The final test was to check for a shift in wavelength of the optical spectra from before to after burn-in, as the spectrum in the previous VCSELs was observed to shift to higher wavelengths before ceasing optical output. This author performed quality assurance on over 1000 VCSELs and mounted both passive components and custom application-specific integrated circuit (ASIC) chips on over 400 opto-boards. As of the date of submission for this dissertation, none of the new VCSELs on the new opto-boards have lost functionality after being installed.

The Semiconductor Tracker

The SCT uses silicon semiconductors like the pixel detector, but the smallest unit is a strip instead of a pixel. This design choice is a compromise, where less precise position resolution is acceptable further away from the IP in order to decrease costs, the number of readout channels, and material interactions. The SCT and pixel detector are often grouped together and called the Si detectors. Each SCT sensor has 768 parallel strips with a pitch of 80 μm that are 64 mm in length. Two of these sensors are wire-bonded together to make a total strip length of 128 mm (126 mm active [43]). The SCT module consists of two of these sensor pairs that are attached top and bottom to 380 μm -thick thermal pyrolytic graphite and rotated by 40 mrad to give a two-dimensional position measurement in each module. The barrel consists of 2112 such modules arranged in four concentric layers, with the strips

parallel to the beam axis. Each end-cap consists of 988 modules arranged in nine disks, with the strips arranged radially from the beam axis. The spatial resolution is $17\text{ }\mu\text{m}$ in r - ϕ and $580\text{ }\mu\text{m}$ in z (r) in the barrel (end-caps)⁴ [51].

The Transition Radiation Tracker

The outermost sub-detector of the ID is the TRT, which covers $|\eta| < 2.0$. Unlike the pixel and SCT subsystems, the TRT uses drift tubes (“straws”) as the detecting element. Each straw has a gold-plated tungsten wire in the center as the anode and is filled with a 70%/27%/3% Xe/CO₂/O₂ gas mixture. A traversing charged particle ionizes the gas, creating electron/ion pairs. The electrons drift to the anode, producing an electrical signal that is read out. The tubes are 4 mm in diameter and have a length of 144 (37) cm for the barrel (end-caps). In the barrel, 50,000 straws are arranged parallel to the beam axis, providing position information in the r - ϕ plane only. In the end-caps, there are 320,000 straws arranged radially, also providing position information in the r - ϕ (or z - ϕ ⁴) plane. The resolution of the TRT straws in both regions is $130\text{ }\mu\text{m}$. A track will nominally have 36 TRT hits, except in the transition region between the barrel and end-caps at $0.8 < |\eta| < 1.0$, where it will have 22 hits. The larger number of hits, combined with the longer distance over which the track’s curvature is measured, allow for more precise momentum measurements in the TRT than the Si trackers.

An additional feature of the TRT allows for better identification of electrons via transition radiation. The straws are surrounded by polypropylene fibers (barrel) or foil (end-caps). When a charged particle passes between a material boundary, it can release high-energy photons as x-rays, which are also absorbed by the gas mixture in the straws, producing an amplified signal. Transition radiation is dependent on the Lorentz factor of the charged particle, so a low-mass charged particle with a high Lorentz factor (i.e. an electron) will produce a much larger signal, allowing for enhanced identification.

2.2.3 The Calorimeters

The calorimetry system in ATLAS is designed to stop and thereby measure the energy of a particle. All calorimeters in ATLAS are “sampling” calorimeters with alternating layers of passive, absorbing material and active material. The traversing particle interacts with the dense absorbing material which causes a shower of particles, which enter into the active material and create a signal. The term “sampling” refers to the fact that the energy measured is a fraction of the total energy of the incident particle, as some is lost in the passive material. ATLAS uses two types of calorimeters: the Liquid Argon (LAr) calorimeters and the tile calorimeter. The tile calorimeter are used in the barrel region

⁴Note the change in coordinate from z in the barrel to r in the end-caps. In the end-cap region, $\hat{r} \rightarrow \hat{z}$ as $|\eta| \rightarrow \infty$.

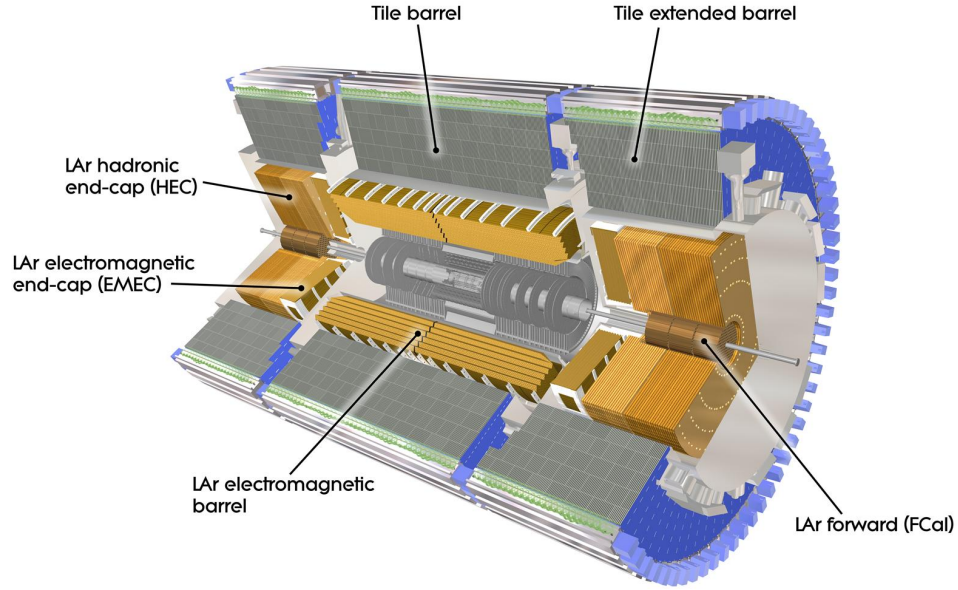


Figure 2.6: A cut-away view of ATLAS showing the electromagnetic and hadronic calorimetry subsystems [43].

for the Hadronic Calorimeter (H-Cal), while LAr calorimeters are used in both the H-Cal end-caps and the Electromagnetic Calorimeter (E-Cal). A diagram of the E-Cal and H-Cal subsystems is shown in Figure 2.6.

The Electromagnetic Calorimeter

The inner of the two calorimetry systems is the E-Cal, designed to stop electrons and photons. The barrel covers $|\eta| < 1.475$ while the end-caps cover $1.375 < |\eta| < 3.2$. The E-Cal uses lead plates as the absorbing material, with LAr as the active detector medium. When the electron or photon interacts with the material, it produces bremsstrahlung or a e^+e^- pair, respectively. The process repeats for the resulting electrons and photons, producing an electromagnetic (EM) shower. The layers of absorbers and electrodes are arranged in an accordion geometry, allowing for complete coverage in ϕ without any gaps between modules. The first layer of the E-Cal is finely segmented with a resolution of $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$, which is useful to distinguish photons that don't leave tracks in the ID. The second layer is the thickest, to collect the most energy deposit possible, but has lower resolution of $\Delta\eta \times \Delta\phi = 0.05 \times 0.025$. The third layer is the coarsest, capturing the tail of high energy EM showers and estimating the energy of particles that escape the E-Cal. The depth of each of these layers is measured in terms of the radiation length X_0 , which

is the mean length of material that causes an electron to lose all but $1/e$ of its energy via bremsstrahlung or $7/9$ of the mean free path for pair production by a high-energy photon. The three barrel layers in the E-Cal have a nominal depth of ~ 4 , 16 , and $2 X_0$ respectively. Additionally, in the region $|\eta| < 1.8$ there is a presampler detector—just the active medium with no passive medium to induce a shower—to measure the energy of any particles that shower before reaching the calorimeter [49].

The Hadronic Calorimeter

The H-Cal surrounds the E-Cal to cover the region $|\eta| < 4.9$. Heavier particles like hadrons have a lower Lorentz factor and minimally interact with the E-Cal, thus the H-Cal was designed to stop and measure the energy deposits from all hadronic particles.

The H-Cal uses scintillating tile calorimeters in the barrel. In the end-caps, two different LAr subsystems are used: the Hadronic End-cap Calorimeter (HEC) and the forward calorimeter (F-Cal). Hadronic calorimeters operate by the same principles as electromagnetic calorimeters. The incident hadron will interact with the absorber material and cause a hadronic cascade (or shower) of particles in the active material, which measures their total energy. The reconstruction of a shower is called a jet, which nominally describes all the daughter particles originating from one hadron entering the H-Cal. The depth of hadronic calorimeters is measured in terms of the interaction length (λ), which is the mean length a hadronic particle travels before interacting with a nucleus in the medium. The choices of absorbing material, active material, and size are a compromise between maximizing the interaction lengths and minimizing the size and cost of construction.

The tile calorimeters [50] are sampling calorimeters like the LAr calorimeters, but use iron as the passive medium and plastic scintillator tiles as the active medium. The tile calorimeters consist of a barrel covering $|\eta| < 1.0$ and two “extended barrels” covering $0.8 < |\eta| < 1.7$. In each of these subsystems, there are three radial readout layers, each consisting of multiple alternating layers of iron and scintillators. The incident particle produces light in the scintillators, which is fed to photomultiplier tubes by wavelength-shifting fibers, producing the electrical signal. The resolution is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the first two layers and 0.2×0.1 in the last layer. The three layers have a total depth of $\sim 6.4 \lambda$ in the barrel and $\sim 7.4 \lambda$ in the extended barrel.

The HEC extends the barrel region to cover $1.5 < |\eta| < 3.2$. The HEC uses copper plates as the passive material and LAr as the active material. It has two wheels in each end-cap, each consisting of 32 wedge-shaped modules. Each wheel has two layers, providing four layers of coverage in each end-cap.

The F-Cal in $3.1 < |\eta| < 4.9$ is designed to cover the more forward, higher energy particles. The first of its three layers is optimized for stopping EM particles, and uses copper as the passive material and LAr as the active material. The other two layers are

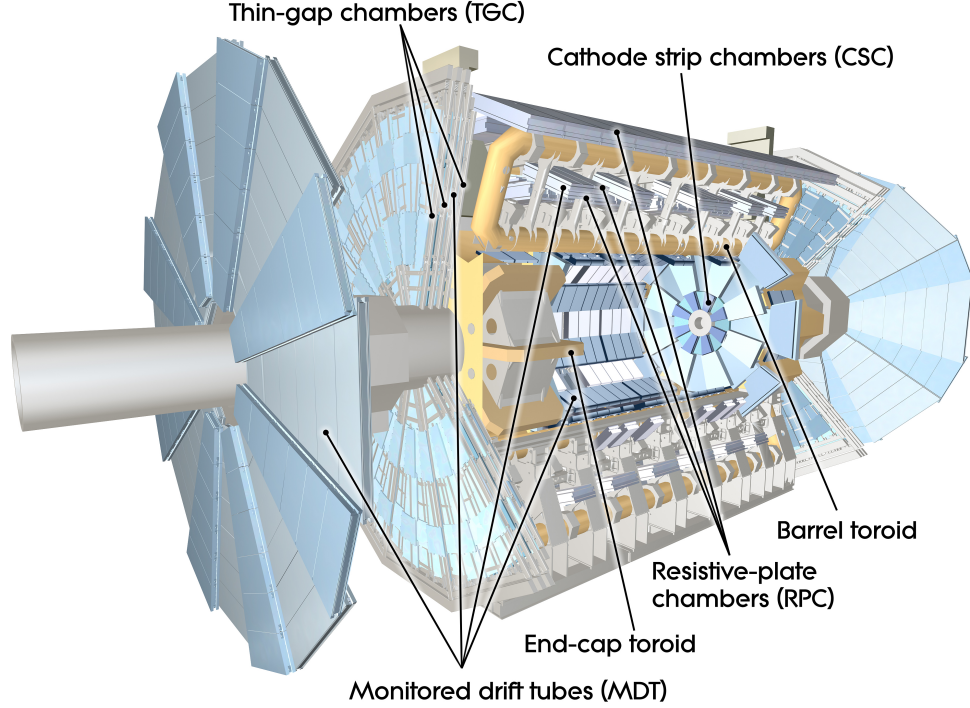


Figure 2.7: The subsystems of the ATLAS Muon Spectrometer [43].

optimized for stopping hadrons, using tungsten as the passive material and LAr as the active material.

2.2.4 The Muon Spectrometer

The outermost subdetector of ATLAS is the MS [58]. Because muons interact primarily electromagnetically and the likelihood for a lepton to bremsstrahlung is inversely proportional the mass of the lepton squared, muons are large unaffected when traversing the ID and calorimeters, necessitating additional detector systems. The MS is comprised of separate subsystems to achieve precision tracking and triggering on muons, as well as the toroid magnet system to bend the trajectory of the muons. The tracking subsystem consists of the Monitored Drift Tube (MDT) chambers and the Cathode Strip Chambers (CSCs), while the triggering subsystem uses both the Resistive Plate Chambers (RPCs) and the Thin Gap Chambers (TGCs). These subsystems are shown in Figure 2.7.

Muon Precision Tracking Chambers

The primary tracking instruments in the MS are the MDT chambers. There are three layers of tracker modules in both the barrel and the end-caps, of which all are comprised

of MDT chambers except for the innermost layer in the end-caps, which are made of the CSCs, which will be discussed later. Each MDT is a 30 mm diameter drift tube with a tungsten-rhenium anode wire in the center, and is filled with a 93%/7% Ar/CO₂ gaseous mixture. They operate under the same principles as the TRT, as described in Section 2.2.2, using the drift time for the electrons to reach the anode to calculate the distance of closest approach. Each MDT module is composed of two multi-layers of three or four layers of tubes. Each multilayer independently measures and reconstructs a partial muon track segment used in later muon reconstruction. The spacing of the tubes, combined with the drift time measurements, results in a resolution of 80 μm for a single tube and 35 μm for the combined MDT module.

The innermost tracking layer in the end-caps ($2.0 < |\eta| < 2.7$) uses a different technology due to the much higher particle flux. The CSCs can operate at a flux up to 1,000 Hz/cm², as opposed to the 150 Hz/cm² for the MDTs. The CSCs are multiwire proportional chambers with anode wires and cathode strips, filled with an 80%/20% Ar/CO₂ mixture. The cathode strips are segmented both parallel and perpendicular to the anode wires. Each end-cap is a wheel with eight large and eight smaller chambers, each with four CSC layers. The CSCs provide four measurements of (η, ϕ) per incident track, with a resolution of (60 $\mu\text{m} \times 5$ mm). Note that in the MS muon tracks are bent in the η - ϕ plane, motivating finer resolution in η .

Muon Trigger Chambers

The muon trigger chambers consist of the RPCs in the barrel and the TGCs in the end-caps, both with fast readout for triggering. The RPCs provide three layers of coverage in the region $|\eta| < 1.05$. Each RPC layer consists of two electrode plates separated by 2 mm, with the gap filled with a C₂H₂F₄-based gaseous mixture. The read-out strips on the two electrodes are orthogonal to each other, providing a measurement in both ϕ and η/z . The RPCs are positioned either directly inside or directly outside a MDT layer, adding six additional measurements per muon to those measured by the precision-tracking chambers at a spatial resolution of 10 mm and a time resolution of 1.5 ns. The two inner RPC layers trigger on three of four hits for a low- p_T threshold, while the outer RPC layer requires one of two hits for high- p_T trigger thresholds.

The TGCs provide the muon triggers in the end-caps, in the region $1.05 < |\eta| < 2.4$, as well as extending measurements in the non-bending ϕ coordinate up to $|\eta| < 2.7$. The TGCs are multiwire proportional chambers filled with 55%/45% CO₂/n-C₅H₁₂, operating under the same principles as the CSCs. There are four layers of TGC wheels in each end-cap, each with a time resolution of 4 ns and a spatial resolution in $(r \times \phi)$ of (2-6 mm $\times$ 3-7 mm).

2.2.5 Toroidal Magnets

Finally, interwoven in the same space as the MS tracking and triggering subsystems are the large toroidal magnets that give ATLAS its name. There is one larger toroid encompassing the barrel region and two smaller toroids for the end-caps. The barrel toroid is 25.4 m in length, with an inner/outer diameter of 9.4/20.1 m. The end-cap toroids are 5.0 m in length, with an inner/outer diameter of 1.65/10.7 m. Both types of toroids are comprised of eight identical coils made of a Niobium-Titanium alloy, each with 120 (barrel) or 116 (end-cap) turns per coil. These toroids combined provide a magnetic field of ~ 0.5 T in the barrel region and ~ 1 T in the end-caps for bending muon tracks. The toroid magnets can be seen interwoven with the MS in Figure 2.3.

2.2.6 Trigger System

The LHC collides proton bunches at a rate of 40 MHz, and has $\mathcal{O}(10^8)$ readout channels. It is implausible to record every interaction, either in terms of data read-out speed or data storage memory. ATLAS uses its trigger and data acquisition system to decide which interactions (or “events”) to save in order to keep the readout rate to ~ 1 kHz. The trigger system uses a multi-stage process including hardware-based triggers called the Level 1 (L1) triggers, and software-based triggers including the High Level triggers (HLT).

Level 1 Triggers

The L1 trigger system uses coarse data from the MS (L1Muon) and both calorimeters (L1Calo). This raw detector data can be used to trigger on leptons, photons, jets, and large missing transverse energy. Each event is fed to a buffer, and the Central Trigger Processor (CTP) decides within $2.5 \mu\text{s}$ whether to pass the event to the next trigger step. Additionally, the L1 triggers define Regions of Interest (ROIs), certain geometrical volumes in η and ϕ in the detector where further investigation by the HLTs is warranted. The L1 triggers reduce the readout rate of the detector to 100 kHz.

High Level Triggers

The second level of triggers, known as the High Level triggers (HLT), are software based. Each event flagged by a L1 trigger undergoes preliminary reconstruction of physics objects (jets, tracks, etc.), combining full granularity data for each of the L1-identified ROIs and reconstructed ID tracks. Which reconstruction is performed depends on which L1 trigger or triggers selected the event, e.g. muon triggers do not usually reconstruct jets. The HLT framework allows for finer specificity in which events are saved by selecting certain physics objects or combinations thereof. If an event passes an HLT, the event is sent to the CERN Tier-0 computing facility for full offline reconstruction (as described in Section 3)

and permanent storage. The HLT framework reduced the rate of saved events to ~ 1.2 kHz during Run 2, which corresponds to delivering 1.2 GB/s to permanent storage.

Chapter 3

OBJECT RECONSTRUCTION IN THE ATLAS EXPERIMENT

Reconstruction is the term for the process of combining raw detector signals to determine which physics objects most likely produced each signal. Raw detector output like hits in the ID or energy deposits in the calorimeters can be combined to form tracks or jets, respectively. Certain objects including jets (hadronic showers), missing transverse energy (MET) (a measure of the imbalance of detected transverse momentum), and tau leptons have their own complex reconstruction methods, but are not used in this dissertation, and so will not be discussed further. The standard processes for reconstructing tracks and vertices are optimized for particles originating from the IP, so secondary algorithms that target displaced decays are needed. Both the standard and secondary algorithms are described here for both tracking and vertexing. Additionally, the reconstruction of a physics object like a track does not give enough information to determine what type of charged particle produced that track. That extra step is the “identification” process and is described for electrons and muons in Sections 3.3.1 and 3.3.2 respectively.

3.1 Reconstruction of Tracks in the Inner Detector

As described in Section 2.2.2, a charged particle will leave a trail of raw detector signals called “hits” along its trajectory in the ID. A “track” refers to that reconstructed trajectory. Reconstructing a track from the hits can be thought of as “connecting the dots.” In practice, however, the sheer number of tracks in each event poses significant challenges, requiring complex pattern recognition algorithms. A track is defined by five parameters d_0 , z_0 , ϕ , θ , and $\frac{q}{p}$, as shown in Figure 3.1. These parameters are defined with respect to the perigee [59], which is the point of closest approach to the primary vertex (PV). PVs are further discussed in Section 3.2.1. The impact parameters d_0 and z_0 are the signed distance from the perigee to the PV in the transverse plane and along the beamline, respectively. The azimuthal angle ϕ and the polar angle θ give the direction of the track momentum at the

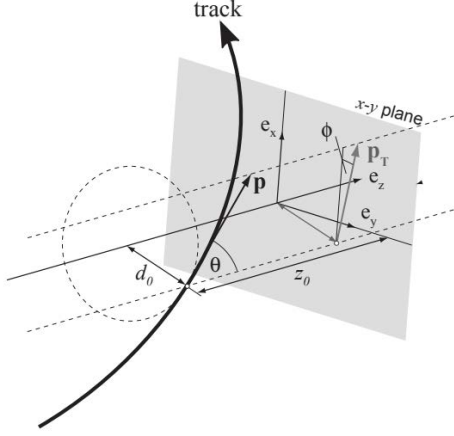


Figure 3.1: An example track with its five defining parameters d_0 , z_0 , ϕ , θ , and $\frac{q}{p}$ [60].

perigee. The last parameter, $\frac{q}{p}$ provides both the sign of the track charge and the magnitude of the track momentum, which is calculated from the tracks curvature.

3.1.1 Standard Track Reconstruction

Standard track (ST) reconstruction is achieved with two independent algorithms, first “inside-out” then “outside-in.”

The initial track reconstruction is performed “inside-out”, starting from clusters of silicon hits (pixel and SCT) to create the collection of 3-D space-points where a charged particle interacted with a layer of active material [61]. These space-points are then combined to form track seeds. The track seeds are rejected if the initial estimation of their momentum and impact parameters does not fulfil the requirements listed in Table 3.1. Notable to a search involving displaced leptons is that track seeds with a projected $d_0 > 10$ mm will not be reconstructed. The track seeds are then combined using the combinatorial Kalman filter [62], which requires that at least one hit in the added space-point cluster be compatible with the track seed. A trajectory is fit to each of the track candidates using a χ^2 method. At this point, there are many track candidates with many overlapping hits, so the track candidates are fed to ambiguity-solving algorithms that assign shared hit clusters to tracks based on a scoring system that gives higher weight to tracks with high momentum, low number of holes⁵, and low χ^2 per degree of freedom, χ^2/n_{dof} . Finally, the track candidates are extrapolated into the TRT to find compatible hits [61]. If the quality of the χ^2/n_{dof} for the fit is not improved with the addition of the TRT hits, the track is saved only using the Si hits.

⁵A hole is a missing hit in a sensor where a hit is expected in a layer based on the particle’s trajectory.

Table 3.1: Comparison of track requirements for standard and large radius tracking algorithms.

Reconstruction Phase	Requirement	Standard	Large Radius
Forward tracking	Min. p_T (MeV)	500	900
	Max. η	2.7	5.0
	Max. d_0 (mm)	10	300
	Max. z_0 (mm)	250	1500
Ambiguity Solving	Min. unshared Si hits	6	5
	Max. shared Si modules	1	2
	Min. Si hits	7	7
	Seed extension	Combinatorial	Sequential
Backtracking	Min. p_T (MeV)	1000	–
	Max. d_0 (mm)	100	–

A second, “outside-in” algorithm is run, which starts from from stand-alone TRT track segments in ROIs defined by the E-Cal [60]. The algorithm extrapolates these TRT track seeds inwards into the Si detectors by attempting to associate any Si hit clusters that remain unused by the inside-out algorithm. The later steps (i.e. Kalman algorithm combination, ambiguity-solving, and χ^2 fitting) are the same as for the “inside-out” algorithm. The “outside-in” algorithm increases the reconstruction efficiency of tracks from displaced decays. A displaced track may fail the first “inside-out” algorithm due to missing Si hits, but can still be reconstructed when starting from the TRT hits. Relevant requirements in the “inside-out” (forward tracking), ambiguity-solving, and “outside-in” (backtracking) phases of standard tracking are listed in Table 3.1.

3.1.2 Large Radius Track Reconstruction

Standard track reconstruction is optimized for particles originating from the IP, with a reconstruction efficiency of $\sim 90\%$ [61]. Due to the previously mentioned impact parameter requirements, the reconstruction efficiency for displaced tracks decreases precipitously as d_0 increases. Even for “outside-in” tracking starting from the TRT, reconstruction efficiency decreases precipitously for tracks with displacement greater than ~ 20 mm [63]. A secondary track reconstruction algorithm was developed to increase reconstruction efficiency for these so-called Large Radius Tracks (LRTs).

The LRT algorithm uses a similar process to the “inside-out” process for standard tracking described above using hits not used by any STs. The most notable difference in the method is the loosening of impact parameters d_0 and z_0 to 300 mm and 1500 mm respectively. A comparison of track requirements for ST and LRT is shown in Table 3.1.

Tracks from both LRT and ST are used as the input for the vertexing algorithms de-

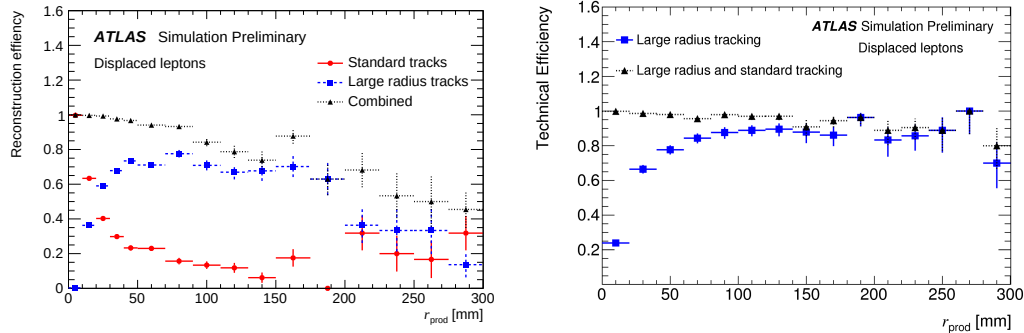


Figure 3.2: Reconstruction efficiency and technical efficiency (see text) of displaced leptons vs. r_{prod} [63]. “Leptons” here refers to electrons and muons, but not taus.

scribed in Section 3.2. The gain in sensitivity to tracks with large impact parameters is crucial to this analysis. The large increase in reconstruction efficiency is evident in Figure 3.2. The remaining inefficiencies at large r_{prod} —the radius at which the decay into the lepton occurred—can arise from several factors including algorithmic inefficiencies, the non-hermicity of the detector at larger radii, and interactions with detector material. A “technical efficiency” was defined to separate the algorithmic inefficiencies from other factors that could not be controlled. The technical efficiency only includes particles that, based on their geometry and decay position, could produce enough hits in pixel or SCT modules to be reconstructed by either ST or LRT. The high technical efficiency ($> 85\%$ for all production radii) shows that the LRT is successfully reconstructing these displaced leptons [63].

3.2 Vertex Reconstruction

A “vertex” describes a point that two or more tracks originate from, presumably the location of a particle interaction or decay. The primary reconstruction strategy, described in Section 3.2.1, is optimized for vertices close to the beamline. For analyses targeting displaced decays, a secondary vertex reconstruction algorithm, **VrtSecInclusive** (VSI) is utilized. Because it is critical for this analysis, particularly for the background estimate described in Section 6.2, the VSI algorithm is described in detail in Section 3.2.2.

3.2.1 Primary Vertex Reconstruction

The PV in an event is the location where the most energetic hard-scattering pp collision occurred. The location of this PV is determined using the ID tracks, which must pass the preselection requirements listed in Table 3.2 [64]. The algorithm uses an iterative annealing procedure, where all tracks are given a weight that decreases over iterations if



Figure 3.3: Steps in in the `VrtSecInclusive` algorithm

the compatibility with the vertex is poor, while tracks with good compatibility retain a high weight. After the vertex position is calculated, tracks that are incompatible with the vertex are removed and used to attempt to find another vertex. This process is repeated until there are no more tracks or no more vertices with two or more tracks can be formed. The vertex with the highest Σp_T^2 is defined as the PV for the event, and all other vertices are classified as pileup interactions.

3.2.2 Secondary Vertex Reconstruction

An LLP with a decay vertex significantly displaced from the beamline will not be reconstructed by the primary vertexing algorithm. The VSI [65] attempts to reconstruct such displaced vertices. “Secondary vertex” and “displaced vertex” are equivalent terms for the same object; DV will be used in this dissertation for consistency.

Reconstruction of DVs is crucial for analysis of BSM long-lived particles, but is also used for reconstructing B -hadron decays. The steps in the VSI algorithm are illustrated in Figure 3.3. This analysis used the default configuration of the VSI so that no additional dataset processing is needed beyond a standard ATLAS derivation (see Section 4.1).

Track Preselection

The first step in the VSI is selecting the ID tracks to be used for DV reconstruction, as using all tracks in each event would be computationally infeasible. The collection of tracks available to be used includes both STs (see Section 3.1.1) and LRTs (see Section 3.1.2). The track preselection requirements are listed in Table 3.2. Almost all selection criteria are much looser than in the primary vertexing algorithm; however, one notable additional requirement is that the tracks cannot be associated with any PV in the event. This is to ensure that the potential vertex is from the decay of an LLP and not from poorly reconstructed tracks originating from the PV. These preselection requirements are optimized to reduce computational memory and time requirements while maintaining the DV reconstruction efficiency.

Table 3.2: Comparison of track requirements for primary and secondary vertexing algorithms [64, 65].

Requirement	Primary	Secondary
Min. p_T (MeV)	500	1000
Max. d_0 (mm)	4	–
Max. z_0 (mm)	1000	–
Max. z_0 significance	5	–
Max. track χ^2/n_{dof}	–	50
Min. Pixel hits	1	0
Min. SCT hits	4	2 (6 if 0 Pixel hits and $p_T < 20$ GeV, 7 if 0 Pixel hits and $p_T > 20$ GeV)
Max. shared Si hits	–	2
Min. TRT hits	–	1 (0 if Pixel hits ≥ 2 , 20 if $p_T < 20$ GeV and $ \eta < 1.7$)
PV association	–	Not PV associated

Two-track Vertex Finding

The next step in the VSI algorithm is forming seed vertices consisting of two tracks. The algorithm first attempts to form a vertex from each pair of tracks in the event (e.g. if there are 8 preselected tracks in the event, then $\frac{8*7}{2} = 28$ potential seed vertices would be considered). Then a series of selection criteria are applied to reject incompatible track pairs, as defined in Table 3.3. The algorithm performs a fast fit to find the position of the potential DV, then applies requirements both to the DV and to the tracks based on the DV’s position.

The DV’s position vector $\vec{r}_{DV}$ (measured with respect to the PV) and total momentum vector $\vec{p}_{DV}$, the sum of the momentum vectors of the two constituent tracks, must be pointing in approximately the same direction to be consistent with the decay of an LLP originating from the PV. This is applied via the requirement $\frac{\vec{r}_{DV} \cdot \vec{p}_{DV}}{\|\vec{p}_{DV}\|} > -20$ mm, which imposes a stricter requirement on the relative directions for DV positions further from the PV. Similar requirements are imposed on the tracks individually using the ϕ coordinate of their momenta.

Additionally, there are strict requirements on the “hit pattern” of each track, as illustrated in Figure 3.4. The hit pattern is a string of booleans corresponding to each tracking layer that records whether a hit is present in that layer. Each track is extrapolated back towards the beamline, and the position where it would intersect with a tracking layer is calculated. Any hits on tracking layers “inside” of the DV position ($r < r_{DV}$) are forbidden. A hit on the next tracking layer “outside” the DV position ($r > r_{DV}$) is required. Any tracking layers outside the DV position beyond the first are allowed but not required.

Table 3.3: List of VSI requirements for DVs and related tracks.

Algorithm Step	Requirement
2-track compatibility	≥ 1 track with $d_0 > 2$ mm DV $\chi^2/n_{dof} < 5$ DV $r_{xy} < 563$ mm $\cos(\phi_{DV} - \phi_{trk}) > -0.8$ $\frac{\vec{r}_{DV} \cdot \vec{p}_{DV}}{\ \vec{p}_{DV}\ } > -20$ mm Track HitPatternTight
Vertex Merging	$\ \vec{r}_{DV,1} - \vec{r}_{DV,2}\ < 10\sigma(\vec{r}_{DV,1} - \vec{r}_{DV,2})$ $\ \vec{r}_{DV,1} - \vec{r}_{DV,2}\ < 1$ mm
Track association	Track $p_T > 1000$ MeV Track $\chi^2/n_{dof} < 5$ $ \vec{r}_{DV} > 2$ mm Track $\sigma(d_{0,DV}) < 5$ Track $\sigma(z_{0,DV}) < 5$ New DV $\chi^2/n_{dof} < 20$ Track HitPatternOuterOnly

These selection criteria select tracks consistent with originating from the DV. For example, if a track has hits in the detector that occur inside of the DV (i.e. *before* the particle decay forming the DV occurred) then that track is unlikely to have originated from the DV. The application of requirements on the hit pattern both to the inside and outside of the DV location is referred to as **HitPatternTight**, while applying on the requirements to the outside of the DV location is **HitPatternOuterOnly**, as referenced in Table 3.3.

The ID tracking system is not perfect, and the VSI accounts for changes in its functionality by changing the hit pattern requirements. Specifically, some ID tracking modules may malfunction and be disabled during one run of data taking, but may be recovered during the next run. The VSI uses a map of disabled ID modules specific to the run during which the event was recorded. If there is a disabled module where for one of the tracks a hit would be forbidden, it cannot be determined that there was no hit and so the track and its associated seed DV are rejected. If there is a disabled module in the tracking layer just outside of the DV where a hit is required, that hit requirement is treated as satisfied and the track and its associated seed DV are otherwise kept.

N-track Vertex Finding

After all compatible two-track seed DVs have been found, there can be ambiguities if one track belongs to multiple seed DVs. The next step of the algorithm is to combine multiple seed DVs, which it does if all tracks in each seed DV are compatible (i.e. form a two-track

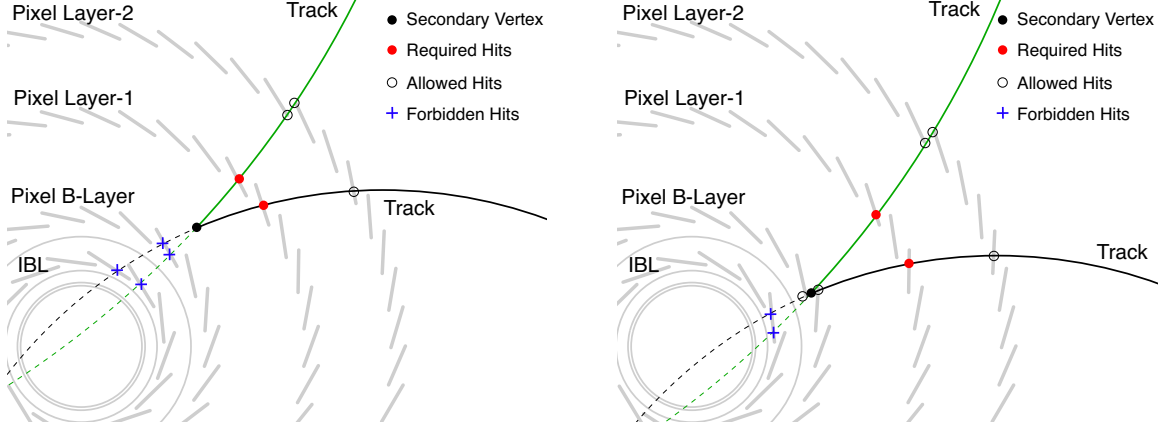


Figure 3.4: Examples of requirements applied to track hit patterns based on the DV location within the Pixel detector [65]. (a) The DV is in between the B-Layer and Layer-1. Hits are forbidden in the inner layers (i.e. IBL and B-layer) and a hit is required in the next layer (i.e. Layer-1). (b) The DV is located in the vicinity of the B-layer and consequently has loosened requirements on hits in that layer. Hits in that layer are allowed but not required and a hit is required on the next layer outside the DV (i.e. Layer-1).

seed DV) with all other tracks in the other seed DVs. For example, say there are 5 tracks in an event labelled A , B , C , D , and E and that the list of two-track seed DVs includes AB , BC , AC , and DE . Seed DVs AB , BC , and AC would be combined and refit to form a single vertex ABC with three tracks, while seed DV DE would remain separate. For more details on this process, see Reference [65].

After combining seed vertices, there may still be individual tracks that are a part of multiple vertices. Following the above example, if compatible seed DVs included AB and BC , but not AC , then the three seed DVs would not be combined and track B would still belong to multiple seed DVs. At this point, the quality of the track's fit to each DV is calculated and the track is only kept as part of the DV with the best χ^2/n_{dof} .

Vertex Merging

A single LLP can produce multiple separate DVs, especially in the case of an LLP decaying to hadronic showers. The next step in the VSI algorithm is to combine vertices that are geometrically close to each other to attempt to reconstruct a single vertex for the initial parent particle. Two vertices are merged if the distance between them is less than 10σ , where σ is the uncertainty on the difference between the two vertex positions. Additionally, if the distance between any two DV is less than 1 mm, the vertices are forced to be merged. All merged vertices are refit using all the tracks from the original separate vertices.

Track Attachment

Finally, the VSI attempts to attach any track that did not pass preselection to the reconstructed DVs. A track may be a part of a displaced vertex even if it does not pass all the quality criteria to be used as a seed for a DV, especially if it is part of a high multiplicity decay like a jet. All tracks in the event that did not pass preselection are considered, with the only additional requirements on the track being $p_T > 1$ GeV and $\chi^2/n_{dof} < 5$. Each track is tested for compatibility to each vertex, starting with the vertex with the highest track multiplicity. If the significance (i.e. value/uncertainty) of the track impact parameters d_0 and z_0 with respect to the DV is less than 5 and the track passes the hit requirement on the outer layers (i.e. a required hit on the next outer tracking layer), then the track is attached to the vertex and the vertex is refit. Each track can only be attached to one vertex. The information on such a track is saved with the track so that such “associated” tracks can be pruned later during an analysis if needed.

3.3 Lepton Identification

A “track” object by itself only identifies that there is a charged particle, but not what type of charged particle produced the track. The algorithms to identify if a reconstructed track is an electron or a muon are discussed below. “Reconstruction” as a lepton in this context refers to classifying the track as that type of lepton, while “identification” refers to classifying the quality of that lepton into one of multiple possible working points (WPs).

3.3.1 Electron Reconstruction and Identification

Electron reconstruction uses a combination of ID tracks and E-Cal energy deposits [66]. Photon reconstruction is closely related because photons and electrons produce similar electromagnetic showers in the E-Cal [67]. Seed clusters are created from energy deposits in the E-Cal with $E_T > 2.5$ GeV using a sliding-window algorithm [68]. Then ID tracks are checked for matching to the seed cluster. If a seed cluster has a matched ID track, it is classified as an electron. If there is not match, the seed cluster is classified as a photon⁶. This difference is particularly relevant to the triggers in this analysis because a highly displaced electron may have insufficient tracking information to be matched to a seed cluster and be treated as a photon by the trigger.

Once the combination of electron ID track and seed cluster is formed, the track is refitted to account for the electron’s energy loss via bremsstrahlung while traversing the material prior to the E-Cal. This refit, achieved using a Gaussian-sum-filter (GSF) technique [70], improves accuracy of track parameters such as d_0 .

⁶A photon may instead convert to e^+e^- before the E-Cal; if the conversion vertex is reconstructed and matched to the seed cluster, the cluster is classified as a photon [69].

Discriminators are used to classify the quality of an electron candidate against backgrounds with similar signatures like hadronic jets and material interactions—the aforementioned “identification” process. There are ~ 20 discriminating variables based on information from the ID, E-Cal, and H-Cal, including variables such as number of silicon track hits, EM shower width, and the ratio of cluster energy to track momentum. These discriminating variables are constructed using a likelihood-based method [67], which applies the product of a probability density function for each variable for both background and signal to determine the likelihood discriminator. Four standard electron identification WPs (*Strict*, *Medium*, *Loose*, and *VeryLoose*) are constructed from this likelihood discriminator, with some additional track requirements.

These additional track requirements reduce the efficiency of lepton identification for this analysis, specifically the small d_0 requirement eliminating displaced electrons. This analysis uses a modified WP derived from the *VeryLoose* WP, removing the d_0 and pixel hit requirements while keeping the overall silicon hit requirements.

3.3.2 Muon Reconstruction and Identification

Muons are reconstructed in the ID and the MS independently, then information from both detector systems is combined [71]. Muon tracks in the ID are reconstructed like all other tracks as described in Section 3.1. Muon track segments in the MS are reconstructed by combining hits from layers within a muon chamber. A loose fit is performed assuming that the trajectory of the muon is parabolic (a first-order approximation of how a muon bends in the magnetic field) and that the trajectory of the particle originates from the PV. Track segments are then combined with segments from other chambers, starting from the middle layer and attempting to add segments from the inner and outer layers. These muon track candidates must have at least two segments, except in the barrel-endcap transition region where only at least one high quality segment is required [72]. An overlap removal algorithm is applied, preventing track segments from being used in multiple track candidates (except if the two track candidates share two segments and then share no hits in the final chamber, assuming a highly collimated muon pair). A global χ^2 fit of the muon trajectory is then performed. Hits with large contributions to the χ^2 are removed and hits along the fit trajectory are added; after each step, the χ^2 fit is performed again.

Muon tracks from the MS are then combined with ID tracks. There are multiple combination methods resulting in muons of different quality. The description here will be limited to the **Combined** muons used in this analysis. **Combined** muons require both an ID and an MS track that are fully reconstructed. Each MS track is extrapolated to the ID and matched with any compatible ID tracks. Tracks are refit using information from both tracks, and some MS hits can be added or removed to improve fit quality. A second pass starts from the ID and extrapolates tracks to the MS. In this “Inside-Out” muon reconstruction, an

independently reconstructed MS track is not required, just three aligned MS hits. These “Inside-Out” muons are also classified as **Combined** muons.

Muon identification uses a cut-based method to define three typical WPs: *Loose*, *Medium*, and *Tight*. With increasingly stringent requirements, each collection is a subset of the next-loosest WP. All WPs apply quality requirements on silicon hits, including at least one pixel hit, at least five SCT hits, and no more than three pixel or SCT holes. These requirements severely diminish signal efficiency for the displaced muons in this analysis, so again modified WPs are used. This modified WP removes the requirements on pixel hits and pixel or SCT holes but maintains the requirements for SCT hits. This analysis uses a modified *Loose* WP to improve sensitivity to displaced muons, except for the tag-and-probe study in Section 7 which uses a modified *Medium* WP.

Chapter 4

DATA AND SIMULATED SAMPLES

The analysis described in this dissertation uses both real and simulated pp collisions. The real events recorded by the ATLAS detector are hereafter referred to as “data” while the simulated events are called Monte Carlo simulation (MC). A “dataset” or “sample” simply refers to any collection of events, either in data or MC. This analysis follows the high energy physics standard practice of developing the analysis on simulated datasets and “blinded” data (i.e. data excluding the final signal region). Blinding is used to reduce researcher bias by avoiding optimization of selection criteria to artificially enhance the signals. The data samples and simulated samples used in this analysis are described below.

4.1 Data Samples

The data events used in this analysis are from pp collisions at $\sqrt{s} = 13$ TeV recorded by ATLAS during Run 2. The total integrated luminosity recorded was 140.1 fb^{-1} as measured by the LUCID-2 detector [73] with an uncertainty of 0.83% [41]. Data events must be included in a `GoodRunsList` (GRL), a list of runs certified by ATLAS to be good for physics, which eliminates events from runs with a hardware or data-acquisition problem in the detector.

The datasets are processed in multiple steps designed to reduce file size. The first step is creating the `DRAW_RPVLL` data stream, which is designed for LLP searches. This data stream retains raw detector hit information for the special reconstruction for LLPs, so a trade off must be made to reduce file size. `DRAW_RPVLL` only saves events which pass one of the collection of triggers and filters used by several LLP analysis groups.

The next step (called a “derivation”) is to process the `DRAW_RPVLL` data stream with all the specialized reconstruction algorithms to target LLPs described in Sections 3.1.2 and 3.2.2. After this step, the raw detector hits are no longer needed, so the file size of the resulting `DAOD_RPVLL` is drastically reduced.

The dataset is further processed to select events from a shorter, more specialized list

of triggers and rerun some reconstruction algorithms. This DAOD_SUSY15 derivation is less computationally intensive than the previous derivation, allowing for multiple reruns with different analysis-specific parameters for reconstruction algorithms or new recommendations for WPs.

There are also datasets with different final derivations used for various studies, including DAOD_EGAM1 and DAOD_MUON1, which store extra information about high p_T leptons and are used in this analysis for the calculation of custom lepton scale factors (SFs) (see Section 7.1).

4.2 Simulated Samples

The principal simulated MC samples are the signal models, which are the theoretical models that are expected to result in a displaced di-lepton signal in the detector. A few other MC samples are employed for various studies in this analysis, as described in Section 4.2.2.

In both cases, there are many steps of simulation to make the simulated events emulate recorded collision data as closely as possible. First, the particle production and decay are generated using either known SM parameters or user-specified parameters (i.e. for the signal model). Then the interactions of the generated particles with the ATLAS detector are simulated, producing simulated detector hits. The same reconstruction and derivation algorithms as for recorded collision events (see Section 4.1) are then applied to the simulated samples. The information about the true identity of the generated particles from the first step is saved as “truth” information, allowing for calculation of reconstruction efficiency. There are three different versions called “campaigns” of each MC samples that correspond to different data-taking conditions over different years. The campaign mc16a emulates data recorded in 2015 and 2016, mc16d emulates data from 2017, and mc16e emulates data from 2018.

4.2.1 Signal MC Samples

SUSY Models

The theoretical models used in this analysis feature a long-lived, RPV neutralino $\tilde{\chi}_1^0$ that decays via a λ_{12k} coupling [26] into two leptons and a neutrino, resulting in the ee , $e\mu$, and $\mu\mu$ final states. The two models being investigated have different production processes for the neutralinos, as shown in Figure 4.1. For both models, the branching ratio of the neutralino decay was assumed to be 100% to increase the statistical power of the simulated events.

The first model implements the pair production of gluinos $\tilde{g}$, with the gluino decaying promptly as $\tilde{g} \rightarrow q\tilde{\chi}_1^0$. The long-lived $\tilde{\chi}_1^0$ decays via R -parity-violating couplings λ_{121} and λ_{122} into two charged leptons and a neutrino, as illustrated in Figure 4.1a. The quark products of the gluon decays ($\tilde{g} \rightarrow q\tilde{\chi}_1^0$) will produce four total jets and the final state

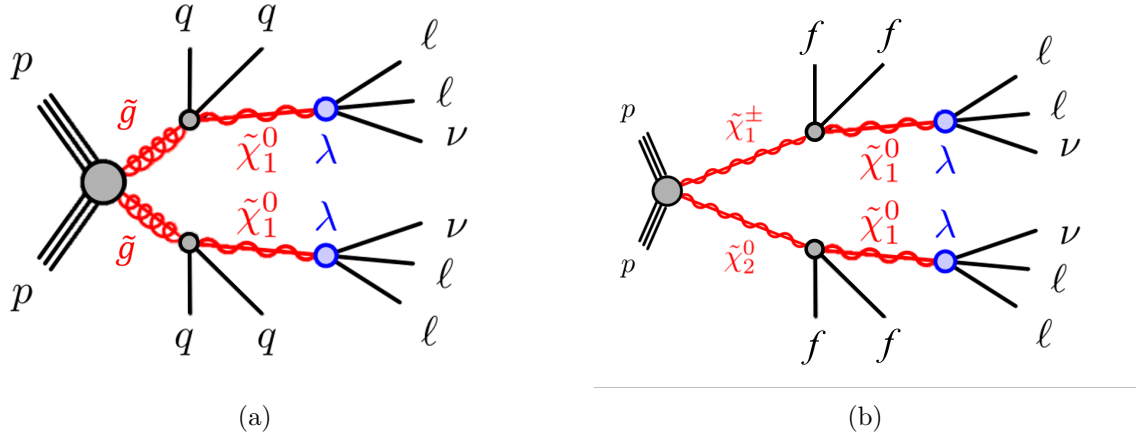


Figure 4.1: Feymann diagrams for two modes of $\tilde{\chi}_1^0$ production via: (a) gluino, (b) electroweakino $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$. Note that other electroweakino production modes are allowed, including some in which the $\tilde{\chi}_1^0$ is produced directly by the pp collision; in that case, the intermediate decay to $\tilde{\chi}_1^0$ and fermions is moot.

neutrinos will result in MET. In order for the search for a displaced di-lepton vertex to be as model-independent as possible to allow for reinterpretation into novel theoretical models, the jets and MET information are not used in the analysis.

The second model implements pair production of electroweakinos. These two parent particles can be any combination of the lightest neutralino $\tilde{\chi}_1^0$, the next-to-lightest neutralino $\tilde{\chi}_2^0$, and the lightest chargino $\tilde{\chi}_1^\pm$, except for the $\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0\tilde{\chi}_2^0$ channels that are suppressed due to the weak coupling. If $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$ is produced, they decay promptly via $\tilde{\chi} \rightarrow f\tilde{\chi}_1^0$. The $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^0$ are all essentially mass degenerate; the masses of the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are set to be 1 GeV higher than the mass of the $\tilde{\chi}_1^0$ to allow for the prompt decays. Again, the fermion products of the intermediate decay of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are not used as analysis objects to keep this analysis as model-independent as possible.

SUSY Signal Samples

In both production models, the parent particles are generated and decayed by MADGRAPH [74] interfaced with PYTHIA8 [75] using the NNPDF23L0 tuned parameters [76] for the parton distribution function (PDF). For easier comparison to detector geometry, the lifetime of the $\tilde{\chi}_1^0$ is reported in units of mm using $c\tau$. The values of $c\tau$ range from 10 to 1000 mm, following the convention of the ATLAS SUSY-RPVLL subgroup. The neutralino decay rates are set to be equal for $\tilde{\chi}_1^0 \rightarrow ee\nu$, $\tilde{\chi}_1^0 \rightarrow e\mu\nu$, and $\tilde{\chi}_1^0 \rightarrow \mu\mu\nu$, allowing for only one sample to be produced per mass-lifetime point.

The signal grid for the gluino model spans three gluino masses, five neutralino masses,

Table 4.1: Gluino MC sample mass points with their cross-sections. All mass points are generated at five $\tilde{\chi}_1^0$ lifetimes ($c\tau$): 10, 30, 100, 300, and 1000 mm. All samples are generated with 20000 events at each lifetime.

$m_{\tilde{g}}$ (GeV)	$m_{\tilde{\chi}_1^0}$ (GeV)	Cross-Section (fb)
1500	100	15.7 ± 2.4
1500	500	15.7 ± 2.4
1500	1000	15.7 ± 2.4
1500	1200	15.7 ± 2.4
2000	100	1.01 ± 0.20
2000	500	1.01 ± 0.20
2000	1000	1.01 ± 0.20
2000	1700	1.01 ± 0.20
2500	100	0.0768 ± 0.0211
2500	500	0.0768 ± 0.0211
2500	1000	0.0768 ± 0.0211
2500	2200	0.0768 ± 0.0211

and five neutralino lifetimes. The neutralino masses range from 50 to 1000 GeV, with an additional “heavy” mass point, where $m_{\tilde{\chi}_1^0} = m_{\tilde{g}} - 300$ GeV. Sixty MC samples have been produced, listed in Table 4.1 with their cross-sections. The cross-sections calculations include the resummation of soft-gluon emission at next-to-leading logarithmic (NLL) accuracy, matched to next-to-leading order (NLO) supersymmetric QCD corrections [77].

The signal grid for the electroweakino model spans seven mass choices for the degenerate electroweakinos and the same five lifetime choices as for the gluino-production model. Thirty-five MC samples have been produced, listed in Table 4.2 with their cross-sections. The production cross-sections are computed at NLO plus NLL precision in a limit of mass-degenerate higgsino $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^0$ with all the other sparticles assumed to be heavy and decoupled [78, 79].

A select subset of kinematic distributions are shown for the long-lived neutralino, electron children, and muon children in Figure 4.2 for the gluino production mode and in Figure 4.3 for the electroweakino production mode. The p_T and η of the gluino-produced $\tilde{\chi}_1^0$ are quite insensitive to the $\tilde{\chi}_1^0$ mass while the p_T of the electroweakino-produced $\tilde{\chi}_1^0$ increases with $\tilde{\chi}_1^0$ mass since its parent mass is nearly degenerate and, therefore, the p_T is close to that of its parent’s. The η distribution of the lepton children from the gluino-produced $\tilde{\chi}_1^0$ are relatively insensitive to the $\tilde{\chi}_1^0$ mass. The electroweakino-produced $\tilde{\chi}_1^0$ lepton children, however, are slightly more forward for lower $\tilde{\chi}_1^0$ mass. Independent of the $\tilde{\chi}_1^0$ production mechanism, one notable feature is the large number of low- p_T electrons. These are dominated by electrons from bremsstrahlung, but because they originate from the $\tilde{\chi}_1^0$ decay and can be reconstructed as electrons, they are important to include and analyze.

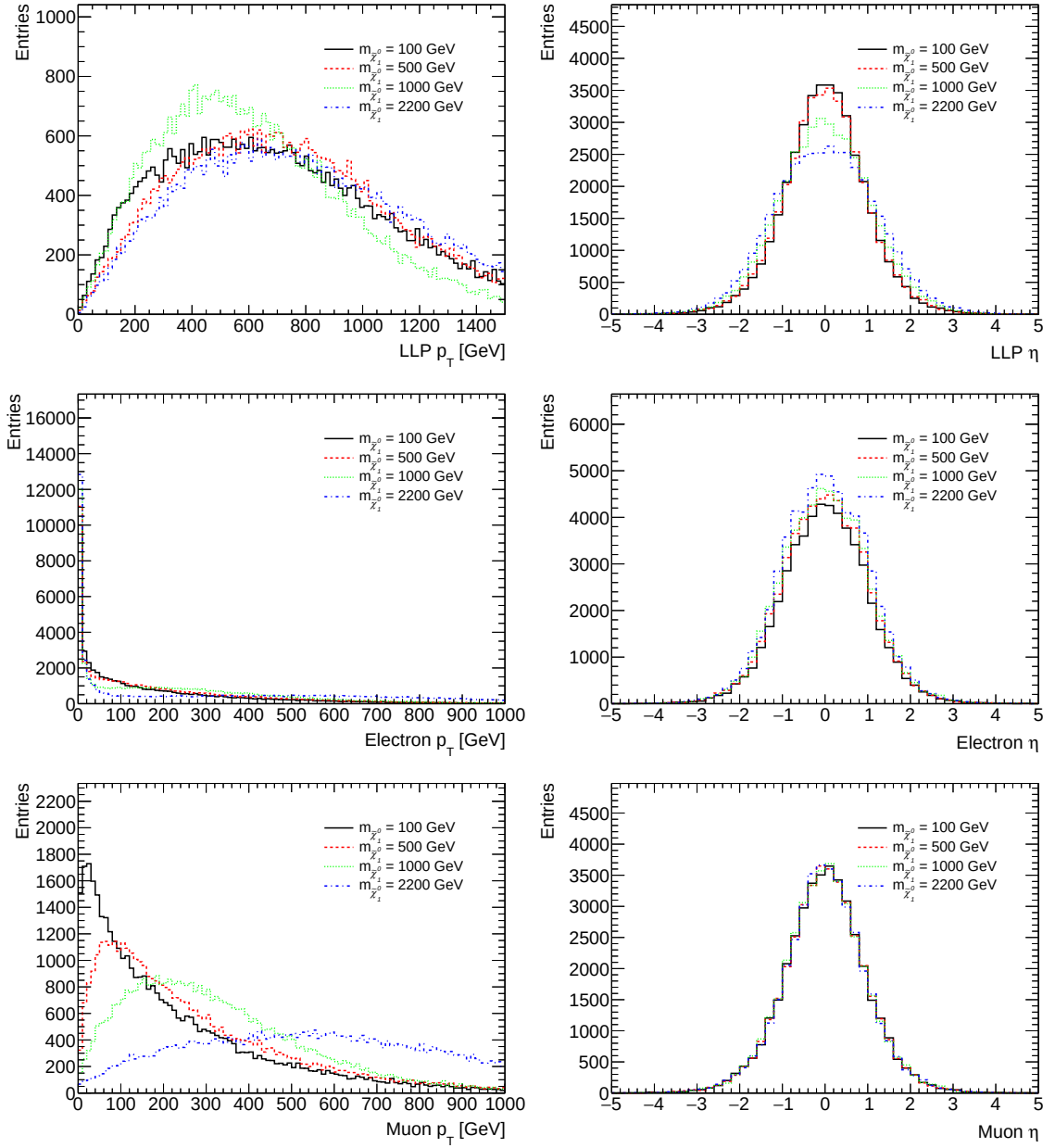


Figure 4.2: Truth-level p_T (left) and η (right) distributions for the LLP $\tilde{\chi}_1^0$ (top), electrons (middle) and muons (bottom) for a set of gluino-produced $\tilde{\chi}_1^0$ mc16d samples with a gluino mass of 2500 GeV and $\tilde{\chi}_1^0$ decay length ($c\tau$) of 10 mm and mass of 100, 500, 1000, and 2200 GeV.

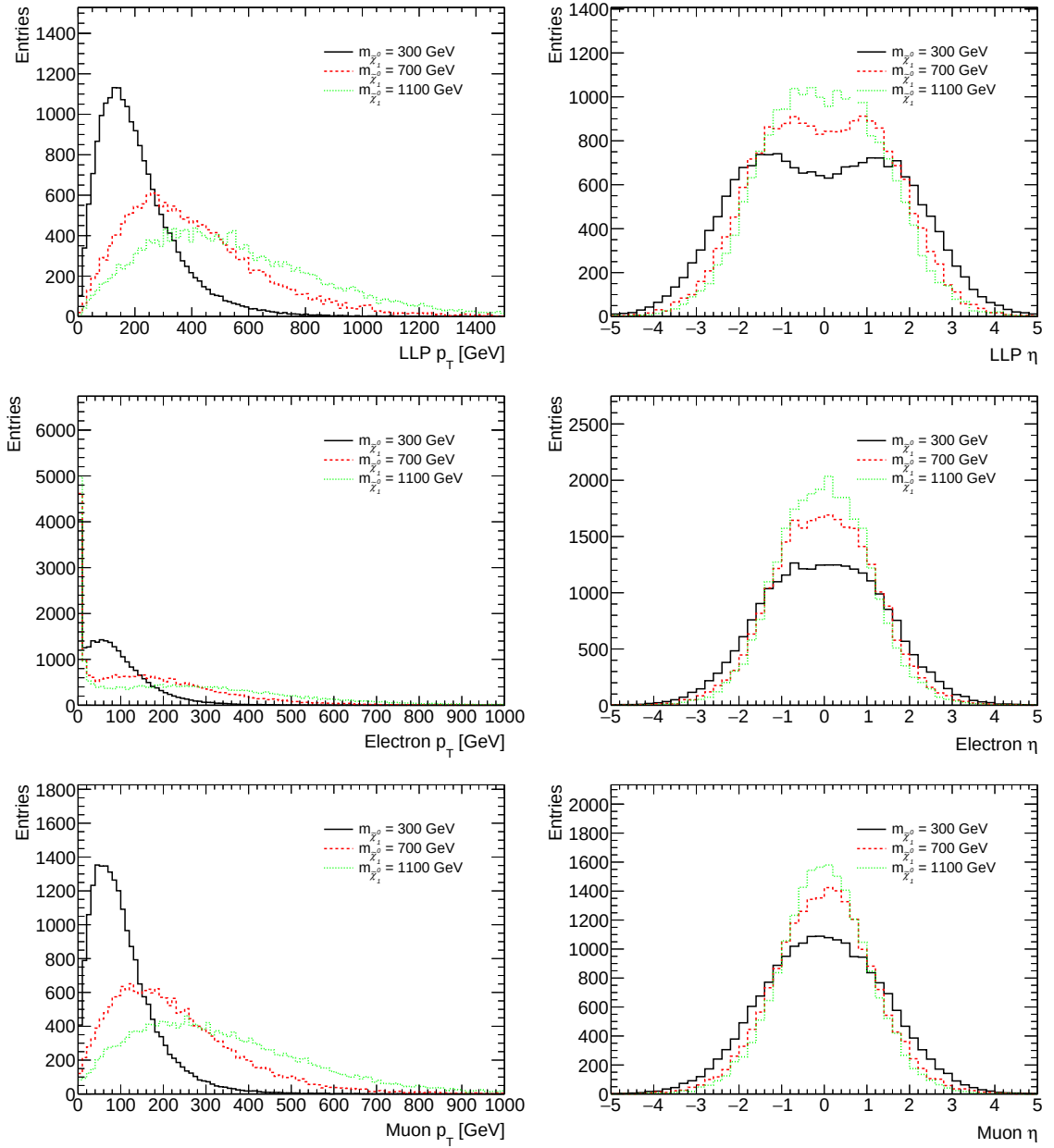


Figure 4.3: Truth-level p_T (left) and η (right) distributions for the LLP $\tilde{\chi}_1^0$ (top), electrons (middle) and muons (bottom) for a set of electroweakino-produced $\tilde{\chi}_1^0$ mc16d samples with a $\tilde{\chi}_1^0$ mass of 300, 700, and 1100 GeV and decay length ($c\tau$) of 1000 mm. Note that the 300 GeV statistics have been scaled down to the number of events produced for the other two mass points.

Table 4.2: Electroweakino MC sample mass points and cross-sections. All mass points are generated at five $\tilde{\chi}_1^0$ lifetimes ($c\tau$): 10, 30, 100, 300, and 1000 mm. The number of events generated per grid point vary by neutralino mass, as listed. In the case where two numbers of events are given, the first is for mc16a while the second is for both mc16d and mc16e, where the increase in number of events corresponds approximately to the increase in luminosity for the years these MC samples are intended to simulate.

$m_{\tilde{\chi}}$ (GeV)	Cross-Section (fb)	Events
100	16797 ± 603	40000/50000
300	285 ± 17	30000/40000
500	33.8 ± 2.7	10000
700	6.90 ± 0.68	10000
900	1.82 ± 0.20	10000
1100	0.538 ± 0.072	10000
1300	0.161 ± 0.020	10000

4.2.2 Standard Model samples

A few SM MC samples are used in this analysis for various studies. As will be discussed in Section 6, the backgrounds are estimated from data (i.e. recorded collision) samples, so not many SM MC samples are needed. One $t\bar{t}$ sample with 20 million events is used for validation of the event-mixing background estimate procedure (see Section 6.2). The sample is generated using POWHEG+PYTHIA8 [75, 80] using the NNPDF23L0 [81] tuned parameters for the PDF and is a subset of the general $t\bar{t}$ production, selecting events with high p_T leptons.

The other SM MC samples are for $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$, produced in the DAOD_EGAM1 and DAOD_MUON1 derivations, respectively. These samples are used for studies of the trigger and lepton identification SFs (see Chapter 7).

Chapter 5

SIGNAL SELECTION

The final signal region for this analysis is an event with a DV consisting of two⁷ leptons (i.e. di-lepton), separated into ee , $e\mu$, and $\mu\mu$ channels. Throughout this chapter, “lepton” will be understood to include electrons and muons but exclude taus. This analysis used a straightforward cut-and-count approach, with the same requirements applied to signal and background. The requirements reduce the background from SM processes to less than one event (see Chapter 6). This section details the selections used, starting with event selection in Section 5.1, followed by signal lepton selection in Section 5.2, and finally signal vertex selection in Section 5.3.

5.1 Event Selection

Before any selection is imposed on leptons or vertices, events must satisfy some basic requirements, as listed in Table 5.3. As mentioned in Section 4.1, events must have been recorded during a luminosity block present in a GRL; however, some problematic events may still be present if the error was short enough to not justify eliminating the whole luminosity block. Event cleaning removes these remaining problematic events that were tagged during reconstruction as having a problem in the LAr calorimeters, tile calorimeters, or SCT, or having incomplete or corrupted data. The event must have at least one PV with $|z_{PV}| < 200$ mm.

Finally, events must pass the cosmic ray muon veto and then pass one of the triggers and its corresponding filter. The DAOD.RPVLL data stream includes triggers and filters not used in this analysis. To isolate the events relevant to this analysis, events must pass one of the three triggers and its corresponding filter described in Sections 5.1.2 and 5.1.3, respectively.

⁷If more than two leptons are present in a DV, the DV will be categorized into all relevant channels. For example, an $e\mu_1\mu_2$ DV would be assigned to both the $\mu\mu$ channel with the signal selections imposed on the two muons and the $e\mu$ channel (twice) with the signal selections imposed on the electron and each muon—i.e. $\mu_1\mu_2$, $e\mu_1$, and $e\mu_2$ are all considered as DV candidates.

5.1.1 Cosmic Ray Muon Veto

Cosmic rays are high energy particles from outer space that interact with the Earth’s atmosphere, producing mainly pions that decay to muons, which can reach ATLAS in the underground cavern. A cosmic ray muon incident on ATLAS may be reconstructed as a pair of back-to-back muons with their reconstructed “production” vertex being highly displaced. Because the “top” muon will be reconstructed as moving opposite to its true direction, its charge will be opposite to its true charge (and therefore opposite to the charge of the bottom muon).

There is no official ATLAS software to reject cosmic ray events, so this analysis devised a custom requirement to reject this background. The geometry of the muons being back-to-back is utilized for the cosmic veto; two back-to-back muons will have $\eta_1 + \eta_2 \approx 0$ and $|\phi_1 - \phi_2| \approx \pi$. This can be seen in the high number of events in that area in Figure 5.1.

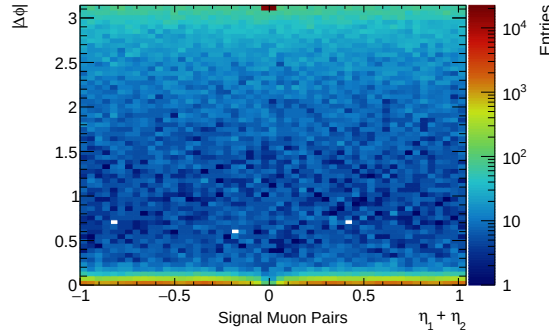


Figure 5.1: The distribution of $|\phi_1 - \phi_2|$ vs. $\sum \eta$ for potential cosmic muon pairs in Run 2 data, shown for events that passed the trigger and filter requirements.

The cosmic veto rejects events that include a pair of muons with:

$$\Delta R_{\text{cos}} = \sqrt{(|\phi_1 - \phi_2| - \pi)^2 + (\eta_1 + \eta_2)^2} < 0.01. \quad (5.1)$$

The ΔR_{cos} requirement effectively removes events with a cosmic ray and rejects less than 1% of the signal MC events. The remaining background from cosmic rays after applying this veto will be discussed in Section 6.1.

5.1.2 Triggers

The HLT trigger used in this analysis are listed in Table 5.1. Most muon and electron HLTs use standard tracking information and therefore are unlikely to trigger on displaced leptons (see Section 3.1.1). This analysis uses a single-muon trigger that only uses MS information

Table 5.1: HLTs used to select events in DRAW_RPVLL. Two HLTs are listed for the diphoton trigger; the first was used in 2015 and 2016 and the second was used in 2017 and 2018. In the cases where the p_T requirement listed is higher than that in the trigger, the threshold used in the DRAW_RPVLL filters in Table 5.2 is used for consistency and to simplify the calculation of SFs.

Description	HLT Trigger	Requirement
Single Muon	HLT_mu60_0eta105_msonly	One object with $p_T > 60$ GeV and $ \eta < 1.05$
Single Photon	HLT_g140_loose	One object with $p_T > 160$ GeV
Di-photon	HLT_2g50_loose (HLT_2g50_loose_L12EM20VH)	Two objects with $p_T > 60$ GeV

(with no requirements from ID information) to reconstruct the muon, allowing it to be used to trigger on displaced muons. The single muon trigger requires a muon with $p_T > 60$ GeV and $|\eta| < 1.05$.

Triggering on displaced electrons is less straightforward. Photon triggers are based on electromagnetic showers in the E-Cal, which are produced from both electrons and photons. Because a displaced electron track may not be reconstructed by standard tracking, the displaced electron may be reconstructed as a photon (see Section 3.3.1). Photon triggers are used to select events with electrons without any requirements on the electron’s ID track. There is a single photon trigger that requires one e/γ object with $p_T > 160$ GeV and a di-photon trigger that requires two e/γ objects with $p_T > 60$ GeV.

Bandwidth limitations required changing the threshold the L1 trigger seed to the di-photon trigger in 2017. The p_T threshold of this L1 trigger is far below the p_T threshold of the HLT, so any difference at the HLT level is negligible.

5.1.3 Filters

In addition to the HLTs, there are event filters designed to further target displaced leptons, which are listed in Table 5.2. These filters are used to select events for further processing through the computationally intensive LRT and VSI by requiring the triggering electron or muon to have $|d_0| > 2.0$ mm.

The filter passed must correspond to the trigger that is passed. The p_T thresholds for each filter are either at or higher than the thresholds used in the trigger to ensure that the object’s p_T is in the range where the trigger is highly efficient.

Again, photons are accepted in lieu of electrons because highly displaced electrons may be misidentified as photons before the LRT algorithm is run.

There are no identification requirements imposed on the electrons or muons, allowing

Table 5.2: Offline filters used to select muon, photon, and electron candidates. *The $|d_0|$ requirement is imposed only on **Combined** muons.

Filter	Object 1	p_T [GeV]	$ \eta $	$ d_0 $ [mm]	Object 2	p_T [GeV]	$ \eta $	$ d_0 $ [mm]
μ	μ	> 60	< 1.07	$> 2.0^*$				
γ	γ (loose)	> 160	< 2.5	–	γ (loose)	> 10	< 2.5	–
					e	> 10	< 2.5	> 2.0
					μ	> 10	< 2.5	$> 2.0^*$
e	e	> 160	< 2.5	> 2.0				
$\gamma\gamma$	γ (loose)	> 60	< 2.5	–	γ (loose)	> 60	< 2.5	–
ee	e	> 60	< 2.5	> 2.0	e	> 60	< 2.5	> 2.0
$e\gamma$	e (loose)	> 60	< 2.5	–	γ (loose)	> 60	< 2.5	–
$e\gamma$	e	> 60	< 2.5	> 2.0	γ (loose)	> 60	< 2.5	–

Table 5.3: Signal event-level selection criteria.

GoodRunsList
Event cleaning
$ z_{PV} < 200$ mm
Trigger filter
Cosmic veto

them to be more displaced. The single exception is the case of an $e\gamma$ pair; if the electron does not have $d_0 > 2.0$ mm, it may still pass the filter if it satisfies the Loose electron WP. The photons are required to satisfy the Loose photon WP. The single e/γ filter requires two objects if the first object is initially identified as a photon; the second object can be a displaced electron, a displaced muon, or another photon. Single photon events are copious [82], so requiring at least two objects at the filter level maintains disk space usage at a reasonable level.

Additionally, the $d_0 > 2.0$ mm displacement requirement is only applied to **Combined** muons. Other muon types may pass the filter without this requirement; however, because the signal lepton requirements used in this analysis require muons to be **Combined** muons, the $d_0 > 2.0$ mm is effectively applied to all muons of interest.

5.2 Lepton Selection

The first signal requirement on the reconstructed vertex is that it contain at least two signal leptons, so the requirements for signal electrons and signal muons are described here.

Table 5.4: Signal electron definitions.

GSF track $p_T > 10$ GeV
GSF track $ \eta < 2.47$
Bad cluster removal
No crack veto
Modified VeryLoose identification WP
Pass overlap removal

5.2.1 Signal Electron Requirements

The signal electron requirements are listed in Table 5.4. While the regular ID track kinematics are used in the secondary vertex reconstruction and therefore the final vertex invariant mass requirement, the electron GSF track kinematics are used for the signal electron requirements, namely $p_T > 10$ GeV and $|\eta| < 2.47$. Additionally, the electron is vetoed if one of its clusters is in a bad E-Cal module (i.e. loss of high voltage supply to the module). Measurements in the calorimeter “crack” region between the barrel and the end-caps have limited precision, so electrons in the range $1.37 < |\eta| < 1.52$ are vetoed.

The electrons must satisfy the modified *VeryLoose* WP described in Section 3.3.1. Electrons must also pass an overlap removal algorithm designed to only allow each ID track to be matched to one physics object. Typically, for electrons this entails keeping the electron with the highest p_T . The combination of reconstructing tracks using LRT and identifying tracks with the modified WP significantly increases the identification efficiency for electrons, as shown in Figure 5.2. For truth electrons with $d_0 > 20$ mm, the LRT greatly increases the identification efficiency, particularly for electrons with $d_0 > 50$ mm when the modified WP is also applied. For truth electrons that were correctly reconstructed as an electron, the modified WPs are highly efficient, with the efficiency only decreasing at $d_0 \sim 250$ mm.

5.2.2 Signal Muon Requirements

The signal muon requirements are listed in Table 5.5. The most important requirement is that the muon is **Combined**. As discussed in Section 3.3.2, **Combined** muons have both ID and MS track segments that match when extrapolated. If a hadron produces an ID track and then decays to a muon that produces an MS track, these tracks can be matched to form one **Combined** “muon.” The fit for such fake **Combined** muons will be poor due to differences in trajectory between the hadron and its daughter muon. The contributions from such fake **Combined** muons, as well as from an ID track matching with an uncorrelated MS track, are suppressed by requiring the joint ID+MS fit satisfy $\chi^2/n_{dof} < 10$.

Most other requirements for muons are similar to those for electrons. The $p_T > 10$ GeV

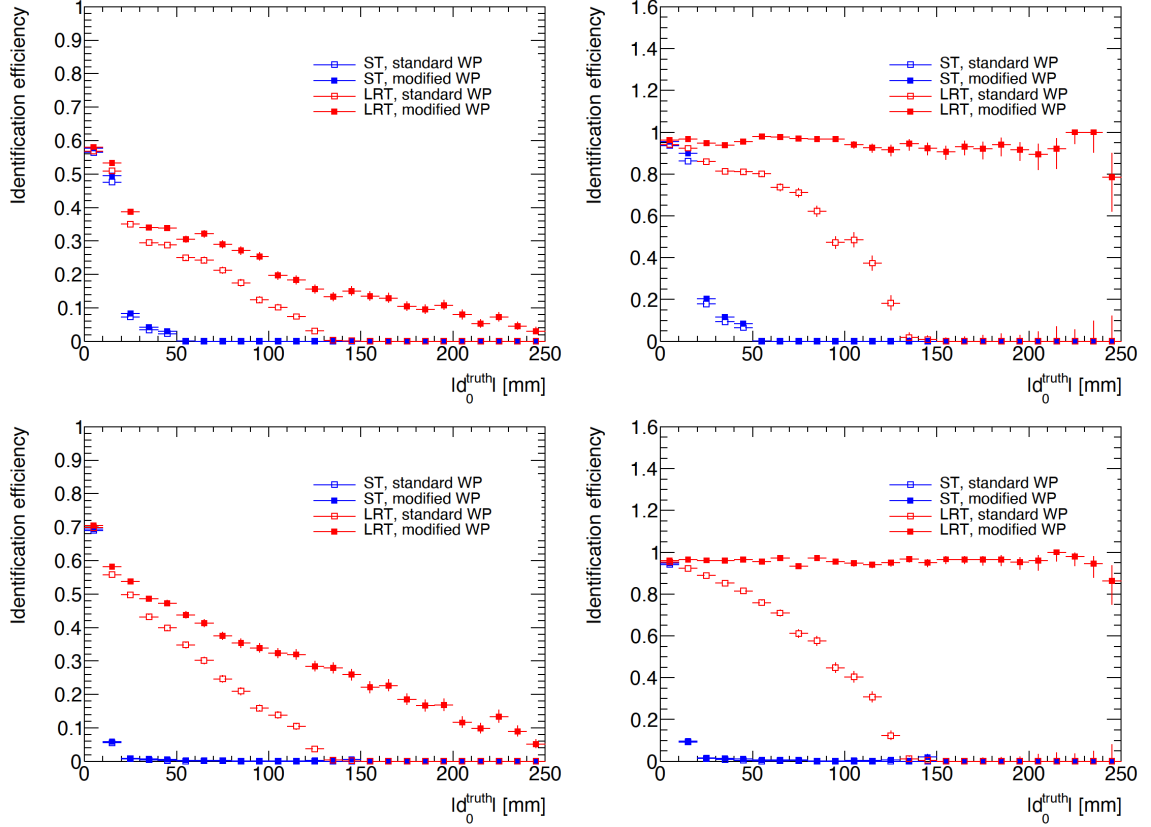


Figure 5.2: Identification efficiencies for electrons (top) and muons (bottom) reconstructed by ST and LRT for standard and modified WPs. A combined set of electroweakino-produced $\tilde{\chi}_1^0$ mc16e samples with a $\tilde{\chi}_1^0$ mass of 500 GeV and all lifetimes ($c\tau$) was used. The plots on the left show the efficiency for a truth lepton passing acceptance requirements to pass the identification WP while the plots on the right represent the efficiency for a lepton that has been successfully reconstructed as an electron/muon to then pass the identification WP. Therefore the left identification efficiencies are with respect to the truth signal leptons while the right are with respect to the correctly reconstructed leptons.

Table 5.5: Signal muon definitions.

ID track $p_T > 10$ GeV
ID track $ \eta < 2.5$
Modified Loose identification WP
Combined
Pass overlap removal
Combined muon $\chi^2/n_{dof} < 10$

requirement is the same and the η requirement is slightly looser at $|\eta| < 2.5$, both of which are applied to the muon ID track. The overlap removal follows a similar process, with the additional stipulation that if an ID track matched to both an electron and a muon, the muon is kept and the electron is rejected. The muon also has to satisfy the modified *Loose* WP described in Section 3.3.2 that removes the Pixel hit requirement. The effects of the modified WP and LRT on signal muon identification efficiencies are illustrated in Figure 5.2. For muons with $d_0 > 10$ mm, the LRT increases the identification efficiency significantly, particularly for muons with $d_0 > 50$ mm when the modified WP is also applied. For truth muons that were correctly reconstructed as a muon, the modified WPs are highly efficient, with the efficiency only decreasing slightly at $d_0 \sim 250$ mm.

5.3 Vertex Selection

Vertex selection criteria are listed in Table 5.6. The first set of requirements are on the vertex object itself, followed by requirements on the pair of constituent leptons.

First the DV position is required to be in the fiducial region, $R_{xy} < 300$ mm and $|z| < 300$ mm. The former requirement corresponds to the region where the VSI imposes missing hit requirements on ID tracks. The latter requirement, together with the track requirement on η , ensures that all signal tracks traverse multiple SCT layers. The DV is required to be more than 2 mm displaced from any PV in the transverse plane to suppress prompt SM backgrounds. The fit of the DV is required to be of good quality, $\chi^2/n_{dof} < 5$.

There are two requirements on the DV position that remove ambiguities arising from detector effects. First, DVs that are produced via interactions with non-active detector material (e.g. structural supports) should be discarded. The most common type of material interaction is a photon conversion to e^+e^- , so DVs are vetoed using maps of detector material [83–86] for the ee and $e\mu$ channels. While photon conversion to $\mu^+\mu^-$ is possible, it is so much less likely than e^+e^- that the material veto is not applied to the $\mu\mu$ channel. Second, DVs located within an ID module that was determined to be inactive when the event was recorded [87] are also vetoed. Vetoing on these maps is applied to both data and MC for consistency.

Table 5.6: Vertex level selection criteria.

$R_{xy} < 300 \text{ mm}, z < 300 \text{ mm}$
$R_{xy} > 2 \text{ mm}$
$\chi^2/n_{dof} < 5$
Material map veto (for ee and $e\mu$ channels)
Disabled module veto
Two signal leptons (see Tables 5.4– 5.5)
Trigger matching
Filter matching
Opposite charge leptons
$m_{\ell\ell} > 12 \text{ GeV}$

Finally requirements are imposed on the DV’s constituent lepton pair. The leptons must satisfy the HLT and filter requirements described in Sections 5.1.2 and 5.2 to ensure that these requirements were not accidentally satisfied by other leptons not in the signal DV. To make sure the two leptons are the decay products of a neutral LLP, the two leptons are required to be of opposite electric charge. Finally, the invariant mass of the pair of leptons must be above 12 GeV in order to suppress higher mass SM Υ resonances.

5.4 Signal Acceptance and Efficiencies

The signal efficiencies can be separated into acceptance and efficiency to better understand the sources of loss of efficiency. Following standard ATLAS nomenclature, “acceptance” is the fraction of simulated DVs that pass the kinematic and geometric signal selection based on truth information. The “efficiency” is then the fraction of DVs passing the truth-level acceptance that were reconstructed and passed the full analysis signal selection. The “signal efficiency” is then the product of acceptance and efficiency—the fraction of simulated DVs that pass the full analysis signal selection. There are various weights applied to simulated events to correct for imperfect modeling in MC; when applied to efficiencies, these weights are called scale factors (SFs). All efficiency distributions presented below include the SFs and systematic uncertainties discussed in Chapter 7 while the cutflows use the unweighted events.

5.4.1 Cutflows

Cutflow plots are presented in this section to show the loss of events as a function of the analysis selection criteria. Figure 5.3 presents an example of the truth-matched vertex level cutflows for a gluino-produced $\tilde{\chi}_1^0$ with a gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 500 GeV for decay lengths ($c\tau$) of 10, 100, and 1000 mm. Figure 5.4 shows the corresponding

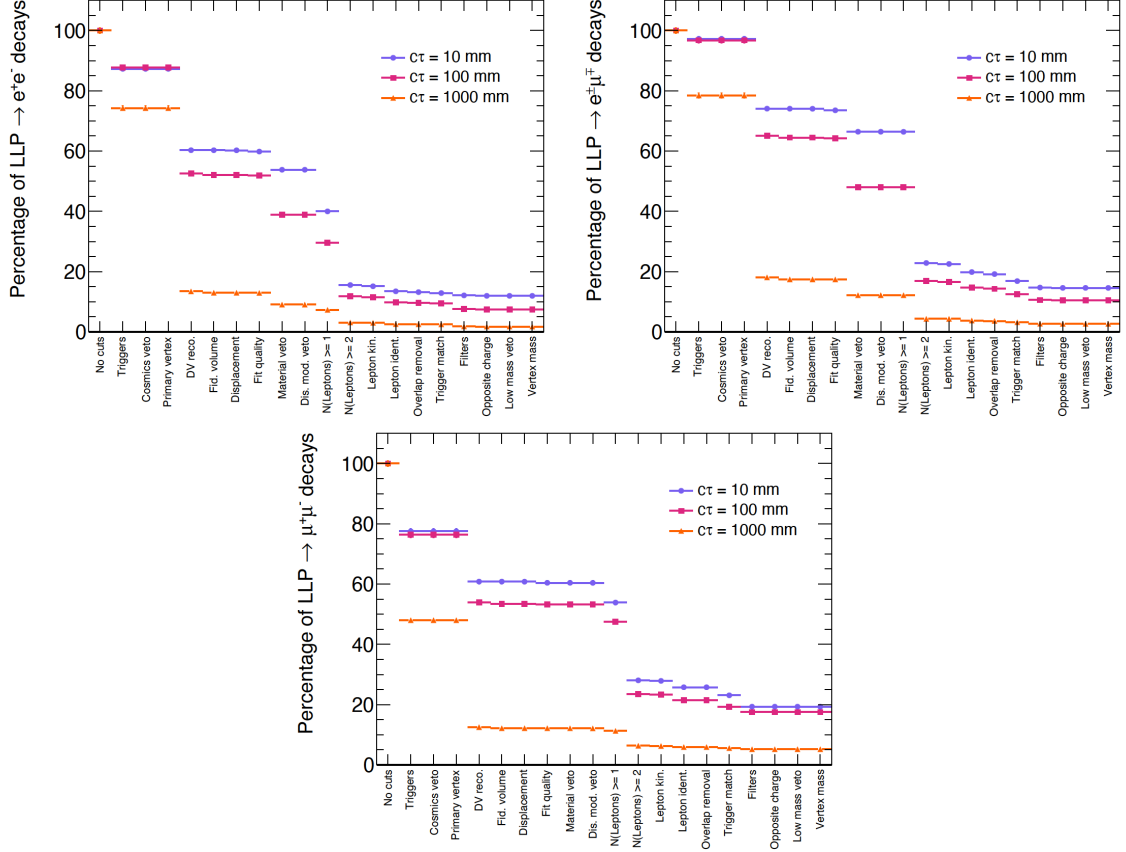


Figure 5.3: Percentage of gluino-produced $\tilde{\chi}_1^0$ decays passing each requirement in the signal cutflow for the ee (top left), $e\mu$ (top right), and $\mu\mu$ (bottom) decay modes for a set of $\tilde{g}\tilde{g} \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ mc16a samples with a gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 500 GeV and decay length ($c\tau$) of 10, 100, and 1000 mm.

cutflows for an electroweakino-produced $\tilde{\chi}_1^0$ with the same mass and decay lengths ($c\tau$). For all lifetimes, the primary losses in efficiency are due to the DV reconstruction and the lepton signal requirements. The material veto has a significant impact on the ee and $e\mu$ channels, although this effect is less severe for the samples with $c\tau$ of 10 mm, as neutralinos decay before encountering more detector material.

5.4.2 Lepton Efficiencies

The tracking efficiency, lepton reconstruction efficiency, and lepton identification efficiency are shown in Figures 5.5 and 5.6.

As expected, the tracking efficiency decreases as lepton d_0 and z_0 increase and is the most significant detriment to signal lepton efficiency. For muons, the reconstruction efficiency is remarkably independent of d_0 and number of Pixel hits due to using MS information for

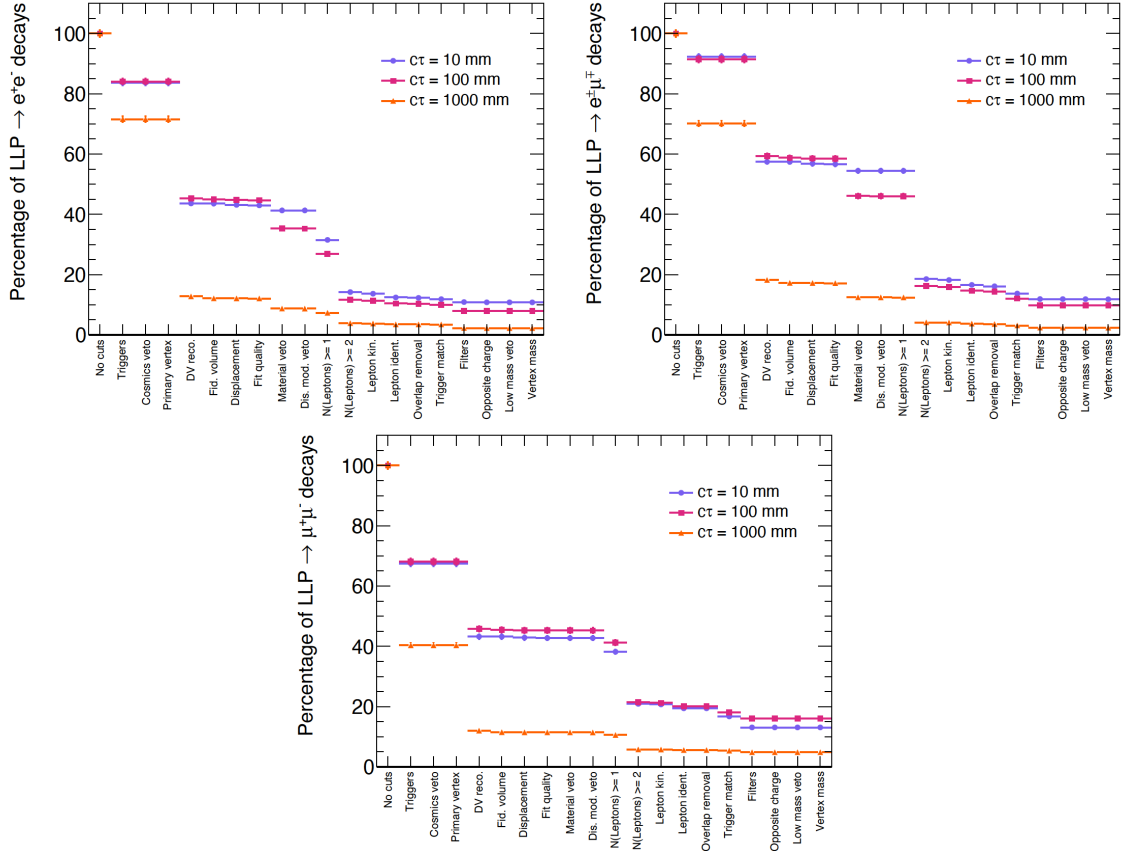


Figure 5.4: Percentage of electroweakino-produced $\tilde{\chi}_1^0$ decays passing each requirement in the signal cutflow for the ee (top left), $e\mu$ (top right), and $\mu\mu$ (bottom) decay modes for a set of electroweakino-produced $\tilde{\chi}_1^0$ mc16a samples with a $\tilde{\chi}_1^0$ mass of 500 GeV and decay length ($c\tau$) of 10, 100, and 1000 mm.

reconstruction. For electrons, the reconstruction efficiency degrades slightly as d_0 increases. Additionally, the reconstruction efficiency is notably lower if there are zero Pixel hits. This is likely due to the similar E-Cal signatures of electrons and photons; if an electron has no Pixel hits, it is more likely to be reconstructed as a photon. Finally, the identification efficiency is high and independent of d_0 and number of Pixel hits for both electrons and muons, indicating that the modified WPs from Sections 3.3.1 and 3.3.2 are highly efficient.

5.4.3 Signal Reconstruction Efficiency

The acceptances, efficiencies, and total signal efficiencies are shown in Figures 5.7 and 5.8 as a function of R_{xy} and p_T of the truth $\tilde{\chi}_1^0$ for the gluino-produced and the electroweakino-produced models, respectively, for a decay length ($c\tau$) of 100 mm.

It is evident that there is a loss of acceptance for low p_T and loss of efficiency for large R_{xy} . This is expected since low momentum LLPs are less likely to generate high p_T signal leptons that can pass the triggers and filters before the reconstruction stage. Similarly, reconstruction efficiency decreases with increasing decay length as there are insufficient hits for track and vertex reconstruction.

5.4.4 Overall Signal Efficiency

The signal efficiencies are shown in Figures 5.9 and 5.10 for the gluino-produced and electroweakino-produced models, respectively, for various kinematic variables. As expected, for both models, the signal efficiencies are highest at intermediate R_{xy} and z close to zero, with decreasing efficiency as $|\eta|$ or $|z|$ increases.

Lifetime Extrapolation

Finally, the signal efficiencies can be extrapolated to different decay lengths ($c\tau$). For practicality reasons, only five lifetime points were created for each signal mass point. Any distribution can be extrapolated from one generated lifetime to another lifetime by applying weights to lifetime bin based on how many LLPs would have decayed in that bin if the sample were generated with that different lifetime. The weight of an event in bin i of a distribution of the number of decays in time for a sample generated with lifetime τ_{gen} when reweighting to a target lifetime τ_{target} is given by:

$$w_i = \frac{\tau_{\text{gen}}}{\tau_{\text{target}}} e^{-\left(\frac{1}{\tau_{\text{target}}} - \frac{1}{\tau_{\text{gen}}}\right)t_i}, \quad (5.2)$$

where t_i is the central value of the lifetime bin i .

The signal efficiency (acceptance $\times$ efficiency) is extrapolated over the lifetime range 1 mm to 10,000 mm. To reduce statistical error, the extrapolations from the five generated

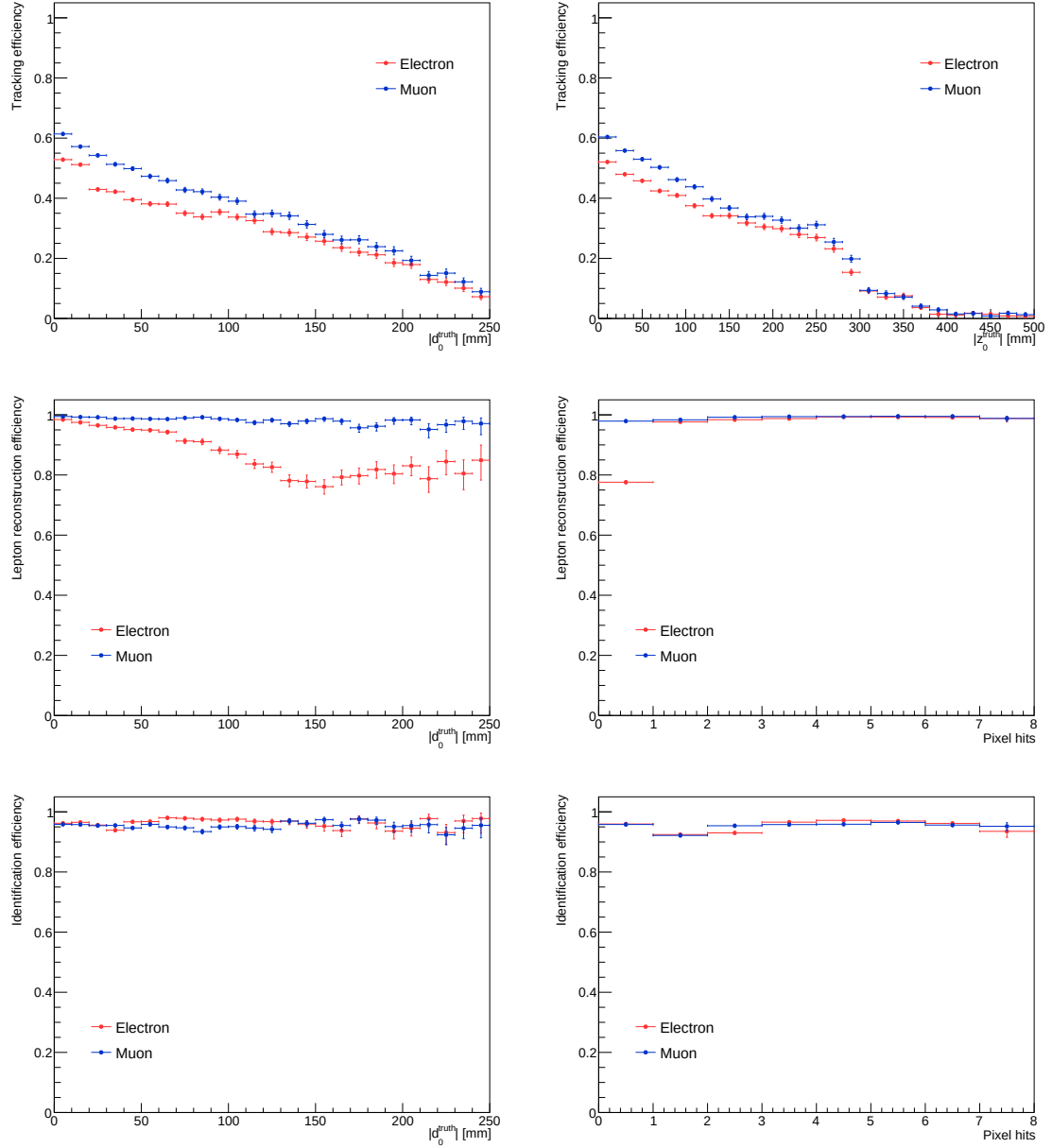


Figure 5.5: Lepton efficiencies for gluino-produced $\tilde{\chi}_1^0$ mc16a samples with a $\tilde{g}$ mass of 2000 GeV, a $\tilde{\chi}_1^0$ mass of 1000 GeV and all decay lengths ($c\tau$): tracking efficiency (top), lepton reconstruction efficiency (middle) for reconstructed tracks, and identification efficiency (bottom) for reconstructed leptons (see text) as function of the truth signal leptons' d_0 (left) and number of Pixel hits for truth-matched tracks (right). The number of Pixel hits is not available for truth signal leptons that are not reconstructed and, so, tracking efficiency is given as a function of z_0 instead.

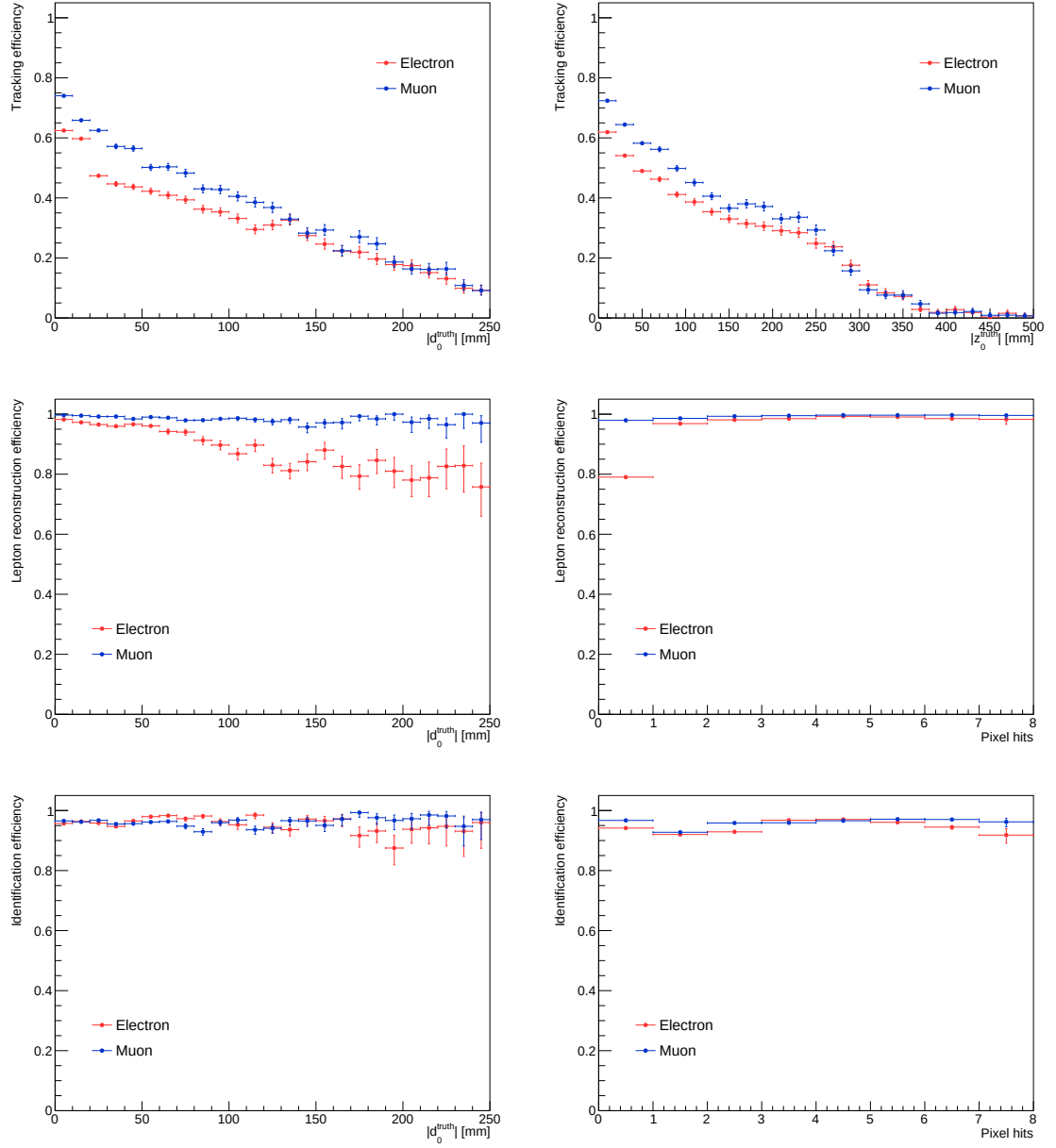


Figure 5.6: Lepton efficiencies for electroweakino-produced $\tilde{\chi}_1^0$ mc16a samples with a $\tilde{\chi}_1^0$ mass of 700 GeV and all decay lengths ($c\tau$): tracking efficiency (top), lepton reconstruction efficiency (middle) for reconstructed tracks, and identification efficiency (bottom) for reconstructed leptons (see text) as function of the truth signal leptons' d_0 (left) and number of Pixel hits for truth matched tracks (right). This information is not available for truth signal leptons that are not reconstructed and, so, tracking efficiency is given as a function of z_0 instead.

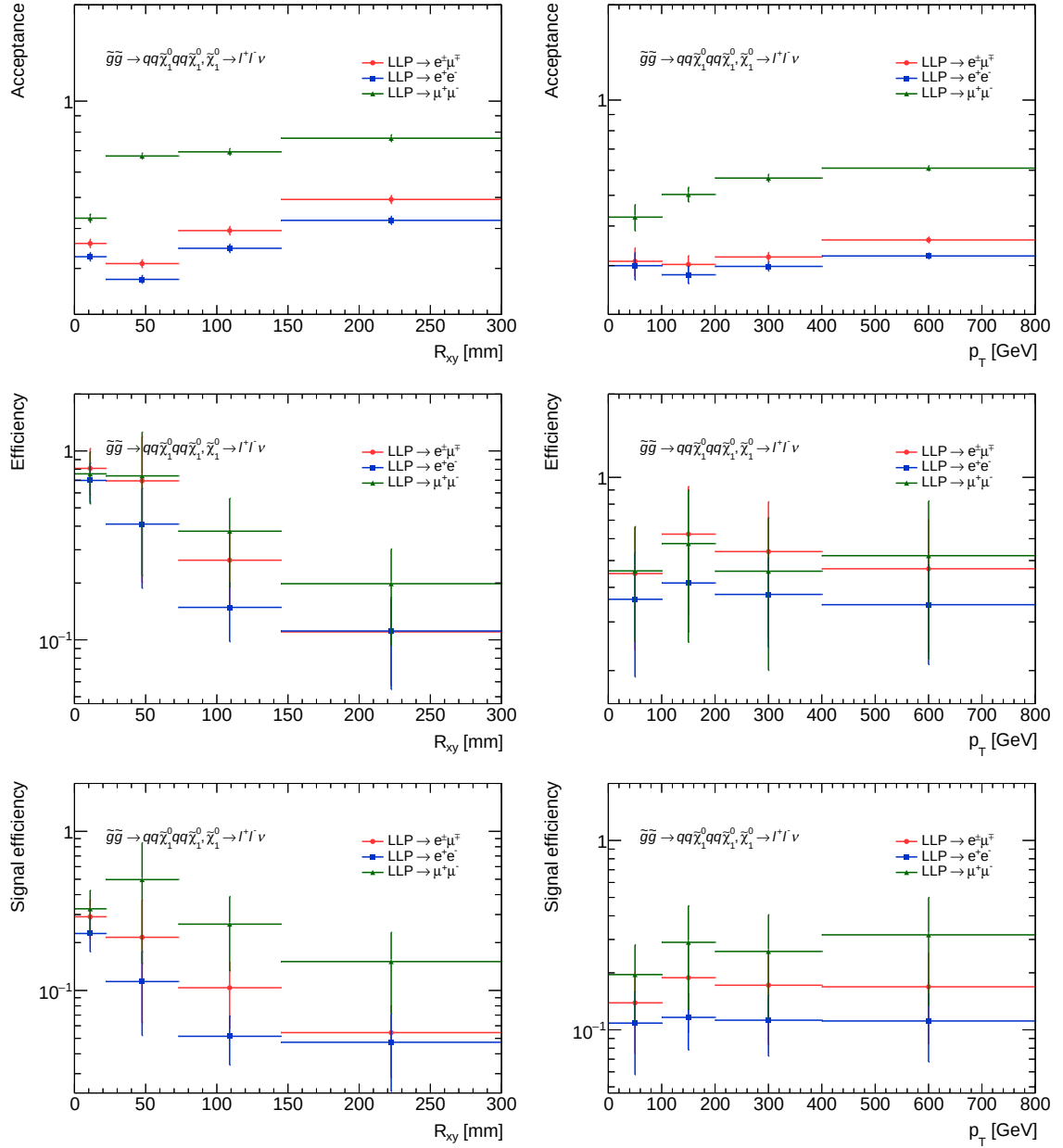


Figure 5.7: Vertex-level acceptance (top), efficiency (middle) and total signal efficiency (bottom) as a function of truth R_{xy} (left) and p_T (right) for the three decay modes of the gluino-produced $\tilde{\chi}_1^0$ mc16a samples with a gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 500 GeV and decay length ($c\tau$) of 100 mm.

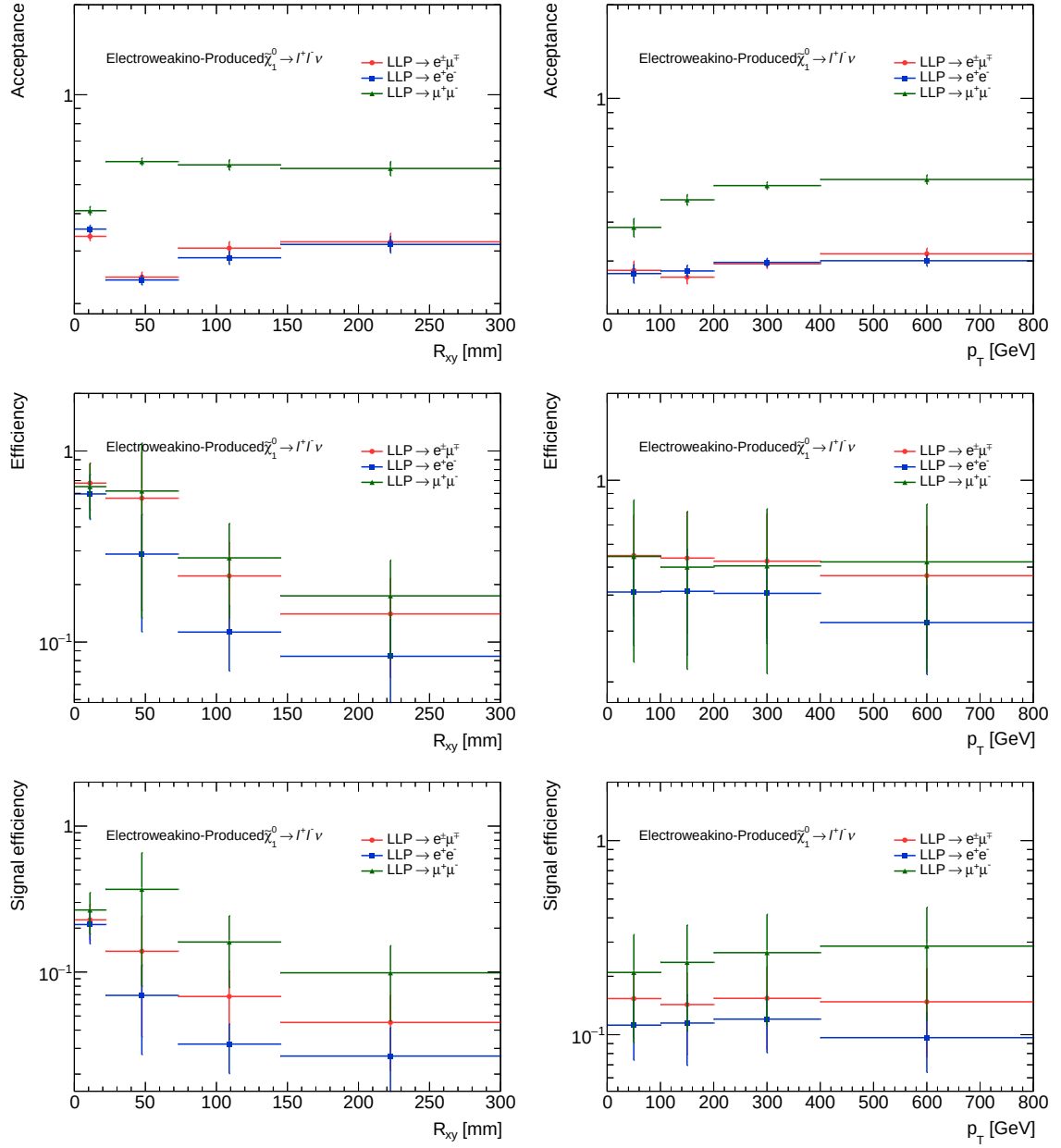


Figure 5.8: Vertex-level acceptance (top), efficiency (middle) and total signal efficiency (bottom) as a function of truth R_{xy} (left) and p_T (right) for the three decay modes of the electroweakino-produced $\tilde{\chi}_1^0$ mc16a samples with a $\tilde{\chi}_1^0$ mass of 500 GeV and decay length ($c\tau$) of 100 mm.

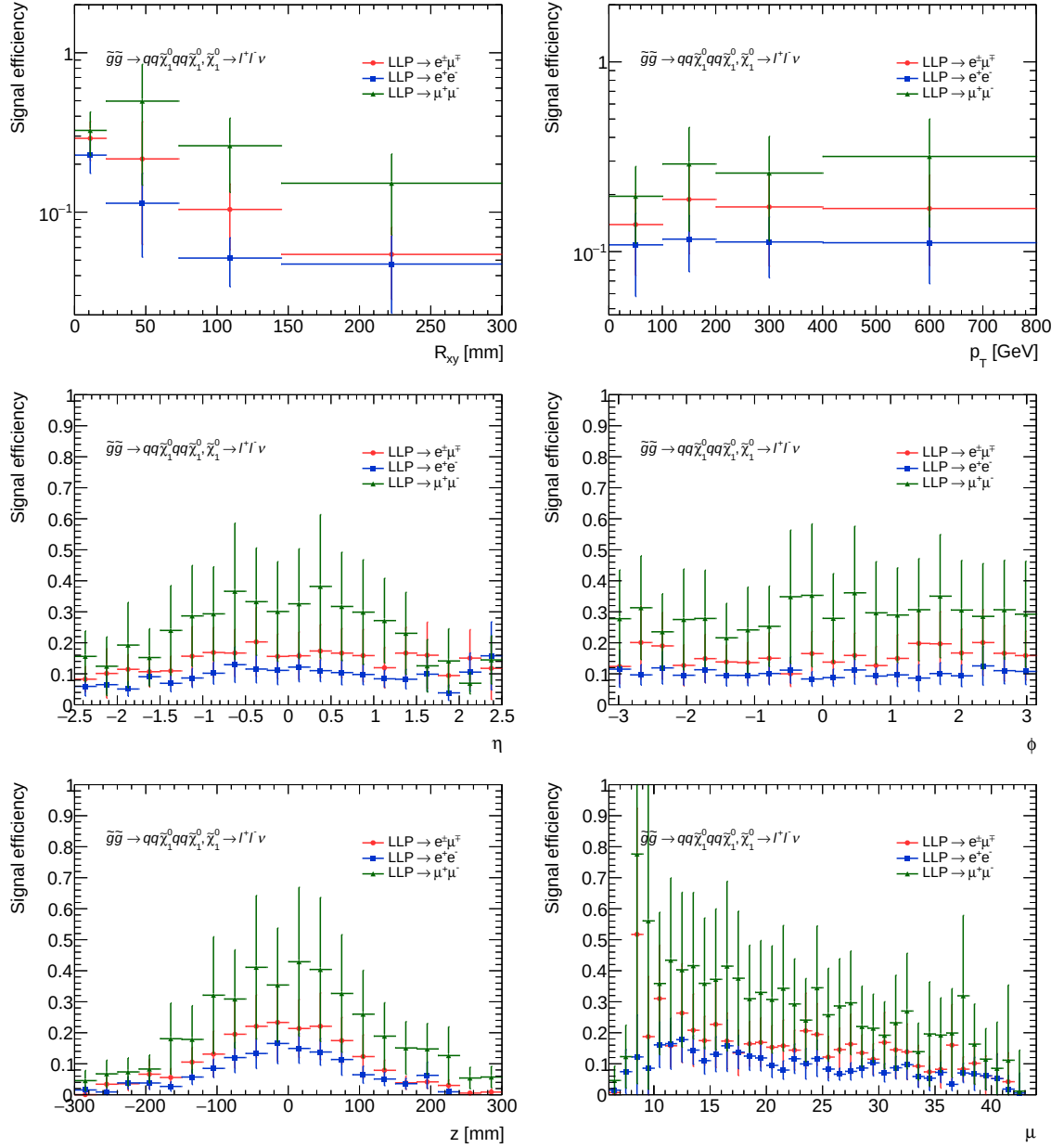


Figure 5.9: Vertex-level signal efficiency as a function of truth R_{xy} (top left), p_T (top right), η (middle left), ϕ (middle right), z (bottom left), and μ (bottom right) for the three decay modes of the gluino-produced $\tilde{\chi}_1^0$ mc16a samples with a gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 500 GeV and decay length ($c\tau$) of 100 mm.

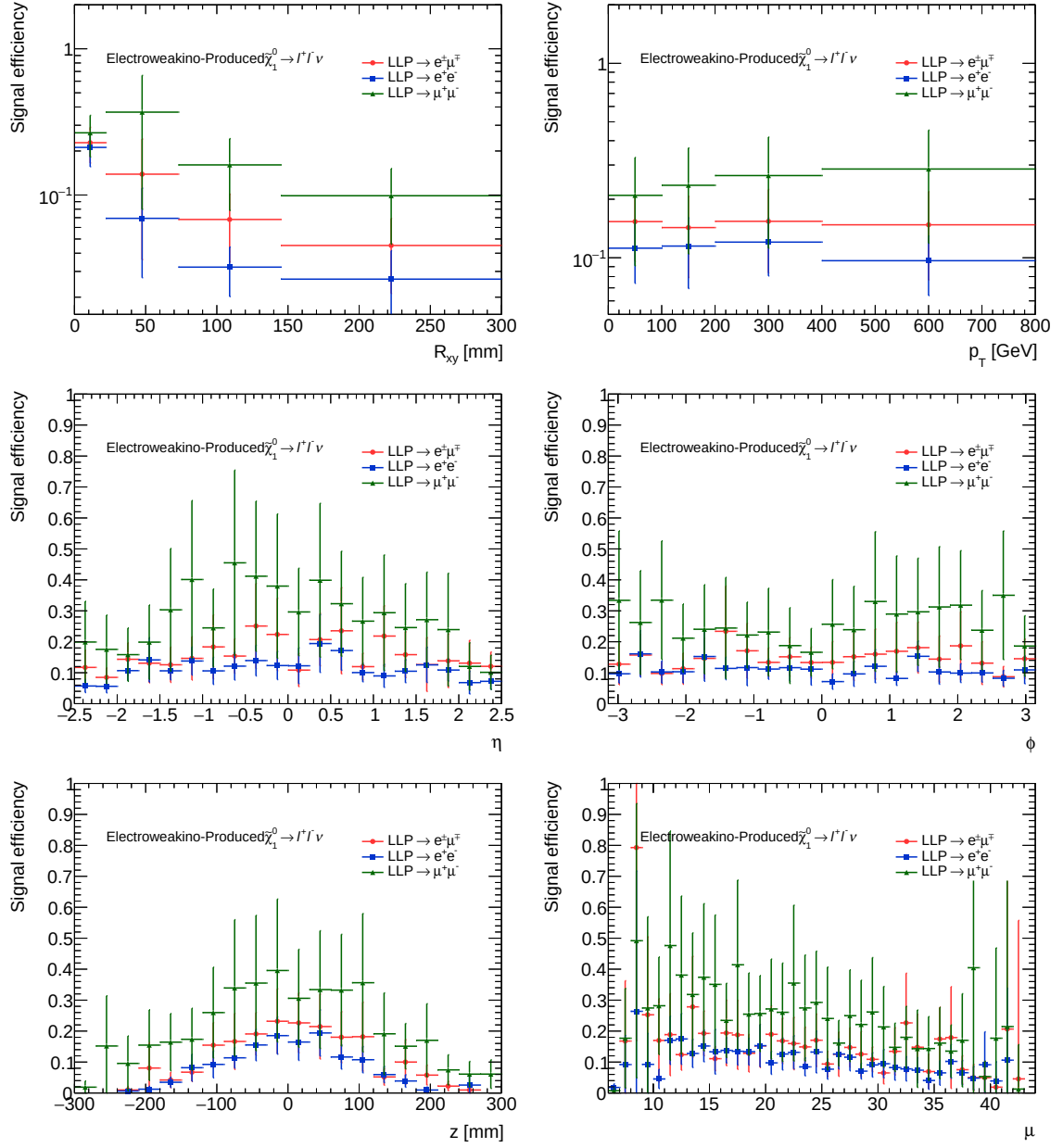


Figure 5.10: Vertex-level signal efficiency as a function of truth R_{xy} (top left), p_T (top right), η (middle left), ϕ (middle right), z (bottom left), and μ (bottom right) for the three decay modes of the electroweakino-produced $\tilde{\chi}_1^0$ mc16a sample with a $\tilde{\chi}_1^0$ mass of 500 GeV and decay length ($c\tau$) of 100 mm.

lifetimes are combined. A validation of the lifetime reweighting procedure can be found in Appendix B. The final signal efficiency after lifetime reweighting is shown in Figures 5.11 and 5.12.

The final signal efficiencies are shown as both the probability for an MC vertex to be a signal vertex (i.e. vertex-level) and the probability that an MC event has a signal vertex (i.e. event-level). The event-level efficiencies are higher because there are two LLP decays in each MC event, so there are two chances to reconstruct a signal DV.

As expected, the signal efficiency for the gluino-produced samples is highest within the ID, with the peak occurring at higher decay lengths ($c\tau$) for higher $\tilde{\chi}_1^0$ masses. The signal efficiency is significantly lower for the sample with $\tilde{\chi}_1^0$ mass of 100 GeV because the lower mass results in fewer signal leptons that satisfy the p_T requirement of the filter.

Similarly, the signal efficiency for the electroweakino-produced samples is highest for decays lengths between ~ 10 and ~ 100 mm, corresponding decays within the ID volume. The mass dependence is notably different, with higher $\tilde{\chi}_1^0$ masses not peaking at significantly different decay lengths. The lowest $\tilde{\chi}_1^0$ mass point is remarkably inefficient, partially because (as seen in the gluino samples) the lower mass results in fewer LLP decay leptons satisfying the filter requirements. Specifically for the electroweakino-produced samples, the particle that decays to the $\tilde{\chi}_1^0$ is approximately mass-degenerate with the $\tilde{\chi}_1^0$ itself ($\Delta m = 1$ GeV). Consequently, the kinetic energy the $\tilde{\chi}_1^0$ receives from the decay is minimal when compared to the gluino samples with the same neutralino mass. The most significant source of energy for the decay leptons is from the mass of the $\tilde{\chi}_1^0$, producing very few decay leptons that satisfy the filter p_T requirements.

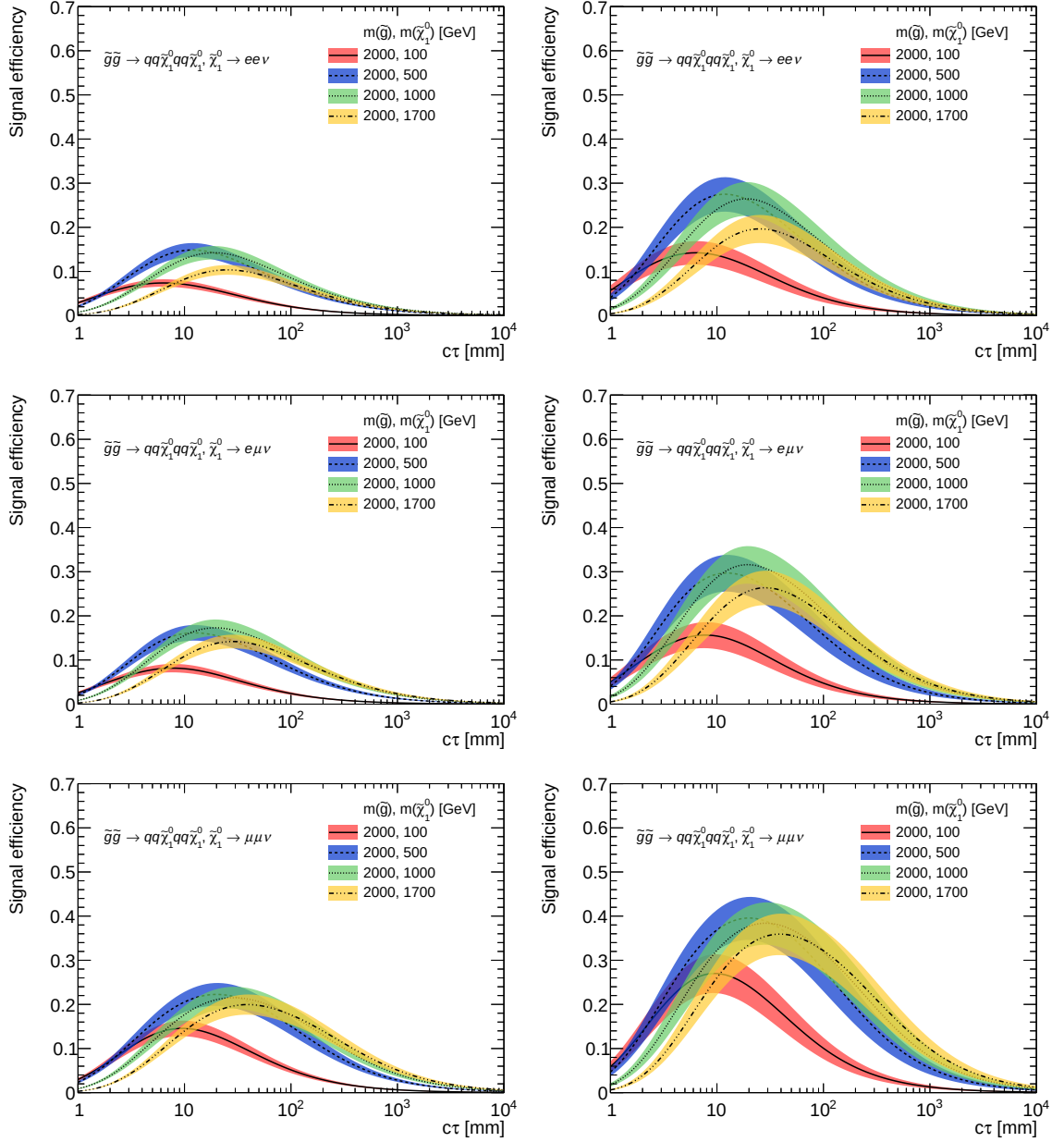


Figure 5.11: Vertex-level (left) and event-level (right) efficiencies as a function of decay length ($c\tau$) for the gluino-produced $\tilde{\chi}_1^0$ samples from all MC campaigns with a gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 100, 500, 1000, or 1700 GeV decaying to $ee\nu$ (top), $e\mu\nu$ (middle), and $\mu\mu\nu$ (bottom) final states. The colored bands represent the total uncertainties.

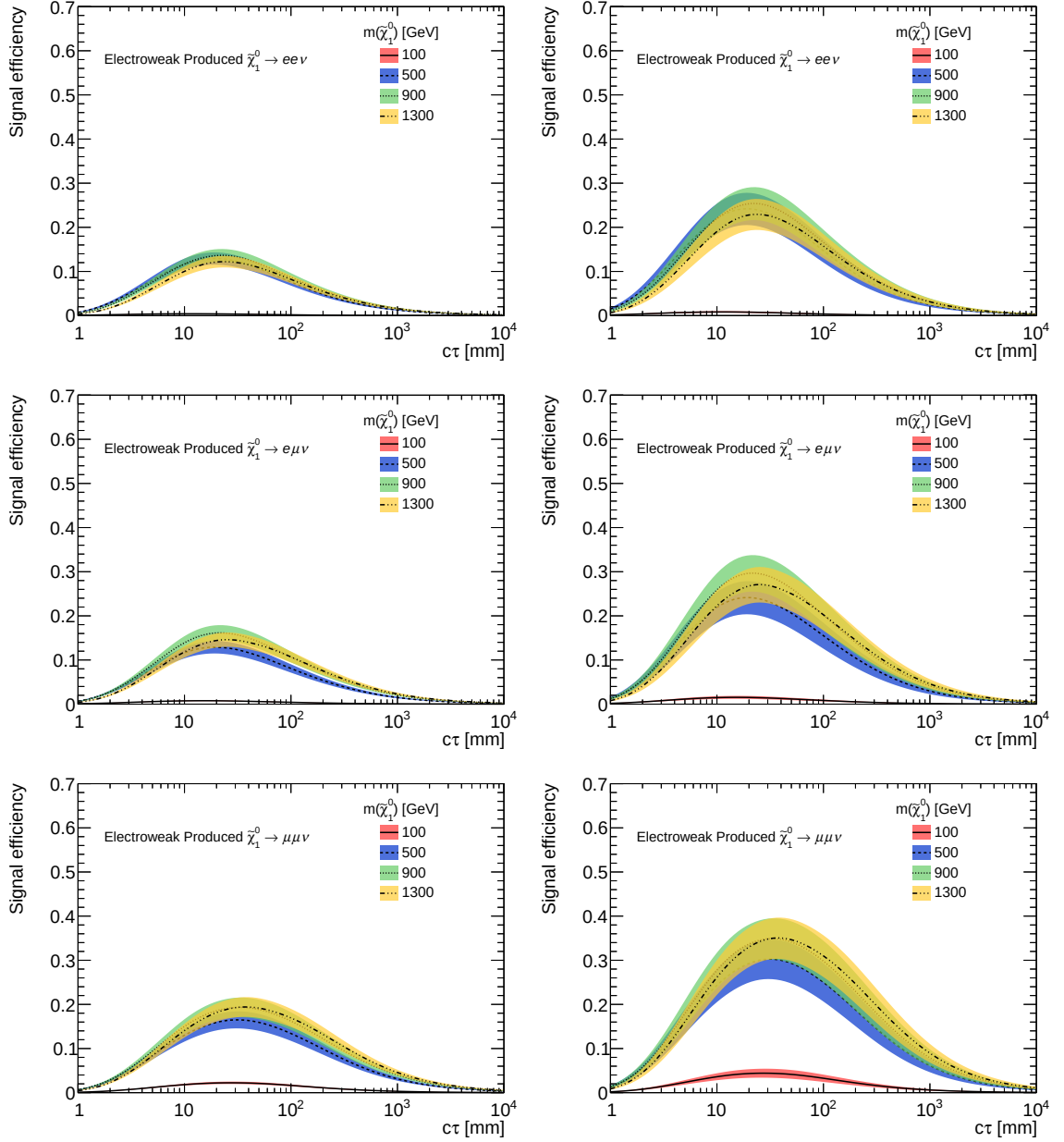


Figure 5.12: Vertex-level (left) and event-level (right) efficiencies as a function of decay length ($c\tau$) for the electroweakino-produced $\tilde{\chi}_1^0$ samples from all MC campaigns with a $\tilde{\chi}_1^0$ mass of 100, 500, 900, or 1300 GeV decaying to $ee\nu$ (top), $e\mu\nu$ (middle), and $\mu\mu\nu$ (bottom) final states. The colored bands represent the total uncertainties.

Chapter 6

BACKGROUND ESTIMATION

One of the advantages of this analysis is that the background contributions from any SM processes are negligible. The combination of the 2 mm displacement and 12 GeV invariant mass requirements effectively removes contributions from all meson decays and material interactions [88]. The remaining two contributions are from cosmic ray muons and random track crossing, both of which predict a background of less than one event. The background estimates for both contributions are calculated using data.

6.1 Cosmic Ray Background

As briefly described in Section 5.1, events with cosmic ray muons are strongly suppressed by vetoing any event with $\Delta R_{\text{cos}} < 0.01$ (see Eq. 5.1). The remaining background is estimated by fitting the ΔR_{cos} distribution in the veto region ($\Delta R_{\text{cos}} < 0.01$) and extrapolating into the signal region, as shown in Figure 6.1. The distribution is fit with an exponential function starting at 0.0012, just above the peak; other starting points yield somewhat larger (i.e. worse) χ^2/n_{dof} . The integral of the fit function in the signal region ($\Delta R_{\text{cos}} > 0.01$) yields a background estimate of 0.00 ± 0.04 events for Run 2. The actual value of the integral is 3.6×10^{-8} , many orders of magnitude smaller than the uncertainty on that value.

It was discovered that track associated with a low-quality reconstructed muon may fulfil the signal requirements for an electron. Thus, the cosmic veto is also applied to $e\mu$ pairs. The same method cannot be used to estimate this background because there are only two $e\mu$ pairs with $\Delta R_{\text{cos}} < 0.01$ in Run 2. Instead, the ratio of $e\mu$ pairs to $\mu\mu$ pairs in this region, $2/1837$ is used as a scale factor relative to the $\mu\mu$ background estimate. The resulting background estimate for the $e\mu$ signal region is $0 \pm 4 \times 10^{-5}$ vertices.

6.2 Random Track Crossing Background

Lepton tracks not originating from the PV vertex have a small probability of randomly crossing to produce a DV that passes all signal criteria. This probability is very low, but

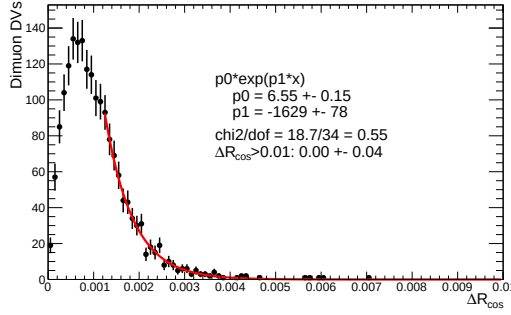


Figure 6.1: The ΔR_{cos} distribution of muon pairs below the cosmic ray veto in the Run 2 data. The red line shows the exponential fit, which starts at 0.0012.

is actually the largest source of background due to the low background from cosmic muons and the lack of any SM background. This random crossing probability and the resulting background prediction are estimated by forming “toy”⁸ events composed of randomly chosen tracks from different events. Thus, this procedure is also referred to as “event-mixing.” Because the VSI uses ID tracks to reconstruct DVs, the focus of this section is on the track object rather than the lepton. All tracks can be assumed to be associated with a lepton unless otherwise noted.

6.2.1 Concept

The steps involved in estimating this background are outlined as follows:

- Randomly choose two tracks from a track library gathered from data
- Randomly choose a PV from a library of PV coordinates gathered from data
- Shift the geometric location of the tracks to maintain their original impact parameters with respect to their original PVs, now with respect to the new PV
- Rerun the VSI algorithm on the track pairs (Section 3.2.2)
- If a vertex is reconstructed, apply the full selection criteria of the analysis

The probability of a signal vertex from random track crossings (p_{ring}) is then the ratio of signal vertices formed ($N_{\text{vtx}}^{\text{mixed}}$) to track pairs provided to the VSI ($N_{\text{pairs}}^{\text{mixed}}$). The actual application of this strategy faced several challenges:

⁸Toy events are events which are not fully simulated starting from hadronic collisions, and are a common tool for quickly creating a large number of events with a desired feature.

- Validating the strategy with MC requires a very large sample containing enough leptons and events to form a sufficient number of good vertices via random crossings to calculate the “real” probability.
- Validating the strategy with data requires investigating a region other than the signal region, or else the data would not be appropriately blinded.
- Running the actual algorithms is incredibly CPU and time intensive.

The challenge of identifying an MC sample with sufficient numbers of crossed leptons is addressed with a $t\bar{t}$ MC sample that selected events with a di-lepton final state; however, statistics are still inherently limited for the di-lepton displaced vertex signal region because the $t\bar{t}$ sample only models the SM processes that the signal region was designed to eliminate. To solve both this and the challenge of validating in data without prematurely unblinding, an additional validation region is used, where tracks not identified as leptons are included in the event-mixing procedure. Because the VSI algorithm does not impose any identification requirements on the tracks it uses to form DVs, this region is used to validate the event-mixing strategy in both MC (to significantly increase statistics) and data (to avoid unblinding the signal region). The challenge of time and CPU requirements is partially addressed via various algorithmic optimizations such as ensuring the invariant mass of the track pair would be in the signal region before running the VSI algorithm; however, the final procedure remains CPU- and time-intensive simply due to the high statistics necessary to observe random crossings. Every aspect of the event-mixing process has to compromise between (1) recreating mixed events as close to real events as possible with high statistics and (2) keeping time and memory requirements at a reasonable level.

6.2.2 Procedure

The procedure for the event-mixing is diagrammed in Figure 6.2. Tracks are extracted from ntuples⁹ which contained all analysis-relevant track information that were produced from the DAOD_SUSY15 derivation. This includes all track information used in both the VSI and the analysis selections, and also the lepton information used in the analysis selections if there was a lepton associated with the track. To reduce file sizes and CPU usage, leptonic tracks are only retained if they satisfy the analysis criteria to be a signal lepton (see Tables 5.4 and 5.5). When using tracks that are not identified as leptons for validations (see Section 6.2.4), the minimum requirement between signal electrons and signal muons is applied, specifically $|\eta| < 2.47$ and $p_T > 10$ GeV.

⁹“Ntuples” are a data structure where only analysis-relevant variables are stored for each event. This data format makes file sizes significantly smaller and allows considerably faster computational processing.

Once the candidate tracks are selected, the instructions are created to specify which randomly-selected tracks and primary vertices are to be combined into each newly-created, “mixed” toy event. The requirements placed on the track assignments are:

- Each toy event contains one PV, which is randomly selected from the same input dataset that the tracks come from.
- Each toy event contains two randomly selected tracks.
- The two tracks do not come from the same input event.
- Each possible combination of the two original events (that the two tracks came from) can only be used once.
- Each track is used a maximum of N times. This was set to $N = 5$ for the validations using non-leptonic tracks and $N = 10$ for the background estimate using leptons.

Choosing tracks (and PVs) from the same or adjacent luminosity blocks ensures that the tracks were recorded under similar conditions, e.g. pileup, disabled modules. Using two tracks per event was a choice made to match our signal region and to avoid complications with later steps of the VSI such as vertex merging and extra track attachment. Any impact of this choice is negligible because $< 1\%$ of data events have more than one signal DV. The maximum number of times to reuse a track was chosen to use every available track but keep the number of events created at a reasonable level.

The instructions for which input tracks go into which created event are added to the ntuples containing all the information on the candidate tracks. The resulting file is referred to as the Common Format File (CFF).

The CFF is then processed by the standard `DAOD_SUSY15` derivation, which reruns the VSI to reconstruct DVs. The only modifications to the VSI are those necessary to change the input track and PV collections to come from the input ntuples. This derivation process requires including a data “host file” to provide the event container that the derivation software iterates over. None of the original particles and vertices from the host file are retained. For each toy event, the CFF instructs the derivation software which tracks and which PV to pull from the ntuples. The tracks are inserted into the toy event using the track information stored in the ntuples and shifted so that the track’s d_0 and z_0 with respect to the PV are preserved.

Producing the `DAOD_SUSY15` derivation includes rerunning the VSI algorithm, so producing `DAOD_SUSY15` derivations of the mixed events ensures that the same version of the VSI software was used on the toy events as on real events. This was a deliberate choice that was weighed against the increased processing time necessary. Rerunning the full VSI algorithm ensures that the complex algorithm is recreated faithfully. A simulacrum of the

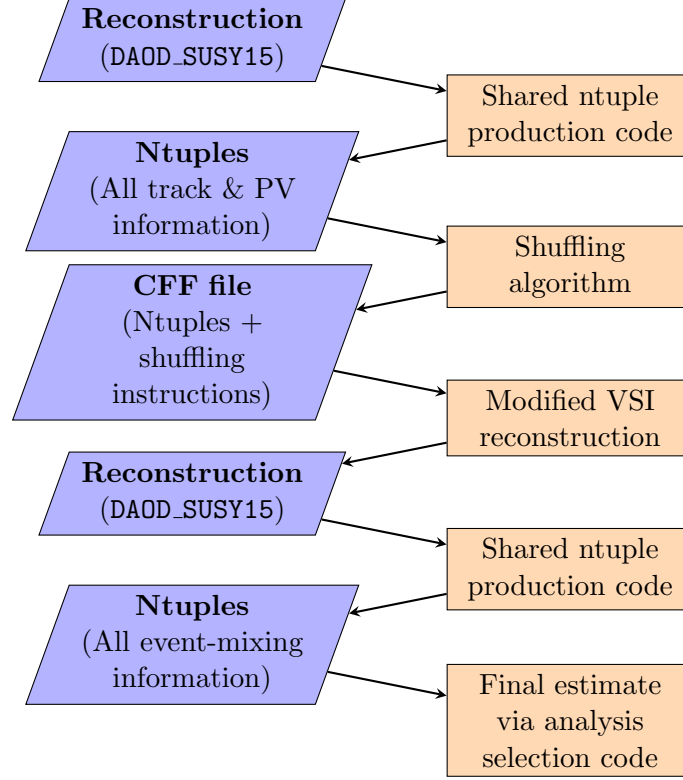


Figure 6.2: A diagram of the steps involved in estimating the random track crossing background, where the left column describes each file type and the right column describes the code used.

VSI could have been created that would have run faster, but it would be exceedingly difficult to account for the many obscure parts of the algorithm that are not user-specified. For example, some values like the disabled module map are automatically determined by the luminosity block containing the event. The choice was made to prioritize fidelity to the original reconstruction at the expense of longer processing times.

Ntuples are created from this derivation output using the same method as before. The analysis selection is performed on these ntuples. If a vertex that satisfies all signal vertex selection requirements (see Table 5.6) is found, a background DV is counted.

6.2.3 Calculation of the Estimate

The formula used to calculate the background estimate is:

$$N_{vx} = N_{pairs}^{obs} \times p_{xing} = N_{pairs}^{obs} \times \frac{N_{vtx}^{mixed}}{N_{pairs}^{mixed}}. \quad (6.1)$$

The last piece needed to estimate the background is the number of observed candidate track-pairs in the original input dataset, N_{pairs}^{obs} . A pair of tracks is defined as a “candidate” pair if the two tracks are found in the same event, both tracks pass the signal lepton selection, and the pair of tracks passes one of the analysis filters (see Table 5.2). Therefore, if an event contains more than two tracks, there will be multiple candidate-pairs in that event (e.g. three candidate tracks form three candidate pairs, four candidate tracks form six candidate pairs, etc.). Because there can be multiple candidate pairs in actual events, using only one candidate pair per mixed toy event might result in the possibility of under-counting events that have multiple signal DVs. In the validation region using non-leptonic tracks, less than 1% of events containing a signal DV have multiple signal DVs, so the single candidate pair method is appropriate.

As mentioned above, the set of two tracks has to pass one of the filters listed in Table 5.2 to be considered a candidate pair. This requirement ensures the event-mixing signal selection is as close as possible to the signal selection in the main analysis without having to simulate the triggers for the mixed events. For the case of a candidate pair including a track not identified as a lepton, the track must pass the filter kinematic and d_0 requirements, i.e. the lepton identification requirements of the filter are ignored.

The number of candidate track-pairs in data (N_{pairs}^{obs}) is counted. The probability that two tracks will randomly form a displaced vertex (p_{xing}) is calculated from the mixed events. The background estimate is then that crossing probability applied to the observed candidate pairs, as in Eq. 6.1.

6.2.4 Validations

Given the complexity of the event-mixing procedure and the use of assumptions and parameters set by other tools and algorithms, a validation procedure was developed for each major step of the event-mixing procedure.

Recreating the Derivation Framework

The first validation was a closure test verifying that despite the extra complex steps in the procedure, the DAOD_SUSY15 derivation was recreated faithfully. No shuffling or shifting of tracks was performed for this validation. A signal MC sample was used for its high number of signal DVs. The number of signal DVs was the same whether processed by the central DAOD_SUSY15 derivation or the event-mixing framework, indicating complete closure.

Shifting Tracks

The next validation looked for effects of the track-shifting procedure. This validation was also run without mixing tracks from different events, but added the new, randomly selected

PV to the toy event and shifted all the tracks to maintain d_0 and z_0 with respect to the new PV. This was not a closure test—because their hit patterns are not recalculated, tracks may fail a hit pattern requirement after shifting if a different hit pattern is expected in the new location. For example, a track’s new location may have a disabled module in the layer just inside the DV and therefore fail the track hit pattern requirement. However, it is expected that most vertices will still be reconstructed due to the high efficiency of track and vertex reconstruction within the Pixel detector. Again, a SUSY signal MC sample was used for efficiency. The results of this validation, summarized in Appendix A, show a slight deficit ($\sim 1\text{--}3\%$, depending on the MC sample used) in the expected number of vertices being reconstructed.

Mixing Events using MC samples

Validating that the predicted number of random track crossings is consistent with the actual number is more challenging, even in MC. Actual *random* lepton crossings in MC samples, signal or otherwise, are too rare to produce statistics sufficient to estimate the background with reasonable precision. This was, in fact, the original motivator for creating toy events. Non-lepton random track crossings are more common and may be used to validate whether the calculated probability for vertex formation matches the observed probability in a given MC sample, due to the fact that the VSI does not require any lepton identification on tracks. Hence the requirement that tracks be identified as leptons is relaxed for this validation, but retain all other requirements. A resulting DV would be in one of our validation channels, forming a “track-track” DV.

The first column of Table 6.1 shows results from event-mixing procedure in the $t\bar{t}$ MC sample. Figure 6.3 shows kinematic distributions for signal DVs in the unmixed $t\bar{t}$ MC and mixed events for the “track-track” channels. In the $t\bar{t}$ MC, comprising almost 20 million events, zero signal DVs were observed in the ee , $\mu\mu$, and $e\mu$ channels, as expected. Additionally, there was only one DV each in the “track-muon” and “track-electron” channels, so this validation focused on only the “track-track” channel.

Within the limited statistics, the mixed events reproduce the general shape of kinematics of the unmixed events. The number of track-track vertices predicted by the event-mixing procedure is 2639 ± 482 vertices. There were 3037 vertices observed in the unmixed events. The resulting discrepancy is an underestimation of 13.1%, just within the statistical error.

Non-Leptonic Track Results in Data

In data, the first validation used the track-track, track-muon, and track-electron channels. Again, the statistics in the track-muon and track-electron channels were too low to produce a conclusive validation. Results from the event-mixing procedure for the track-track channel

Table 6.1: Number of track-track DV candidates observed and predicted in $t\bar{t}$ MC and 2017 DAOD_SUSY15 data. With respect to DV category, “track” refers to tracks not identified as leptons. The predicted number of vertices is obtained using the number of seed pairs in the data N_{pairs}^{obs} and the average crossing probability p_{xing} via Eq. 6.1.

	$t\bar{t}$ MC	2017 DAOD_SUSY15 data
N_{pairs}^{obs}	6.95×10^9	4.22×10^{11}
Mixed candidate-track pairs	7.90×10^7	3.88×10^9
Mixed signal DVs	30	1192
Avg. crossing probability	$(3.80 \pm 0.69) \times 10^{-7}$	$(3.07 \pm 0.09) \times 10^{-7}$
Predicted vertices	2639 ± 482	$(1.30 \pm 0.04) \times 10^5$
Observed vertices	3037	1.14×10^5

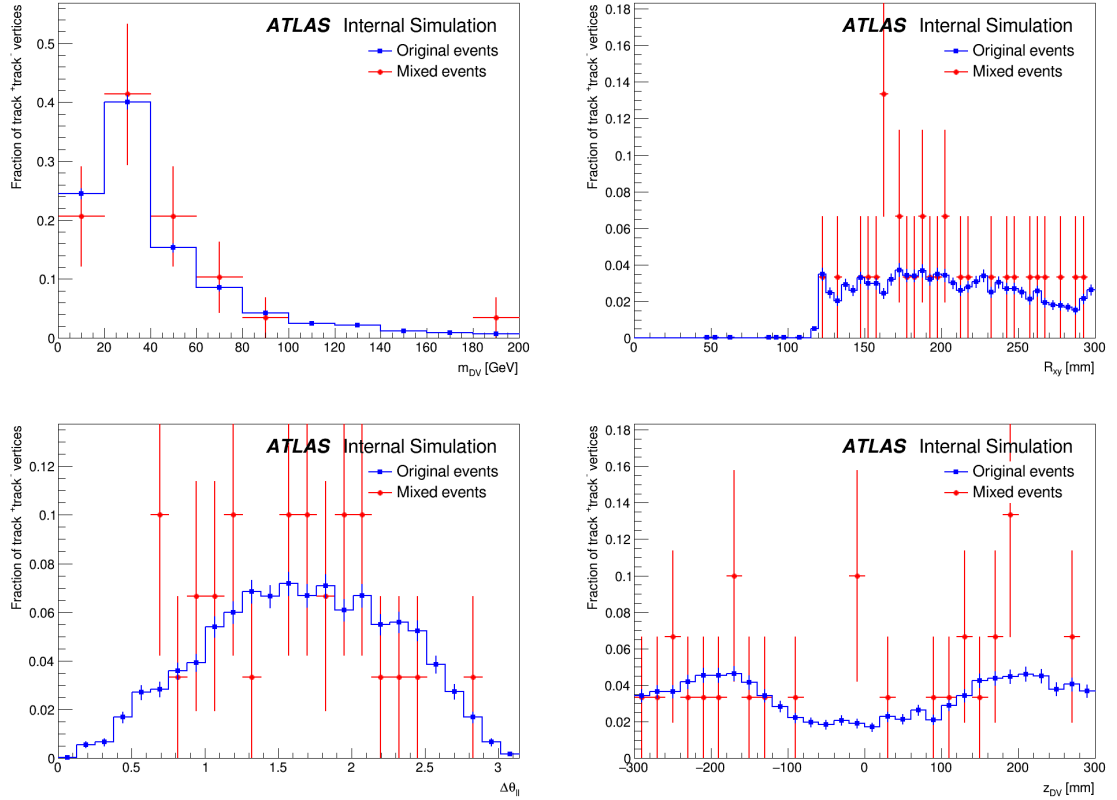


Figure 6.3: Number of accepted “signal” track-track DVs as a function of DV mass (top-left), DV transverse decay position (top-right), opening angle between the DV’s tracks (bottom-left), and DV z -position (bottom-right), shown for both the original (blue) events and the mixed events (red). The distributions are for track-track vertices using the $t\bar{t}$ MC dataset.

are shown in the second column of Table 6.1. Kinematic distributions for signal DVs in the unmixed 2017 data and mixed events are shown in Figure 6.4.

There is quite good agreement between the distributions of unmixed and mixed events, albeit with somewhat limited statistics. The sharp rise in the number of DVs with transverse displacement above ~ 120 mm in Figures 6.3 and 6.4 is a result of the hit requirements imposed by the VSI. The location of the step corresponds to the radius of the outermost Pixel layer, 122.5 mm. Any DV reconstructed at a lower radius has strict hit requirements: no hits on layers with smaller radii than the DV position and a required hit on the next layer with a larger radius than the DV. Essentially, this means that DVs with $R_{xy} \gtrsim 122$ mm have a simple requirement of no Pixel hits, which is easier to satisfy.

The number of track-track vertices predicted by the event-mixing procedure is $(1.30 \pm 0.04) \times 10^5$ (statistical error only), and there were 113535 track-track vertices observed. This suggests the event-mixing method can give a reasonable estimate of the random track crossing background. The 14.2% discrepancy between mixed events and observed events in the track-track channel, combined in quadrature with the statistical error from the validation, is used as the systematic error for the background estimate. The combined uncertainty on the random-track-crossing background estimate is 14.6%.

6.2.5 Signal Region Background Estimate

Table 6.2 shows the results of the event-mixing procedure using leptons, separated by data-taking year. Because the number of mixed and unmixed seeds scale with luminosity, the final background estimated is calculated by summing over the four years. The final background estimates for each channel, including the statistical and systematic uncertainty, are listed in Table 6.3.

The relative difference in crossing probability between the vertex types is consistent with expectations based on the missing hit requirement in the VSI (see Figure 3.4). Because E-Cal clusters with missing hits in the ID are more likely reconstructed as photons, reconstructed displaced electrons are less likely than reconstructed displaced muons to have the missing ID hits required by the VSI.

6.3 Systematic Uncertainties

The background estimates for both cosmic ray muons and random track crossings are calculated using data, so applying SFs due to mismodeling in MC is not necessary. Systematic uncertainties associated with the fit to the cosmic ray distribution are estimated by varying the bin size, fit starting point, and fit function, then comparing to the nominal value. All fit variations yield an estimate of zero background events. The systematic uncertainties calculated from these tests are many orders of magnitude smaller than the statistical uncer-

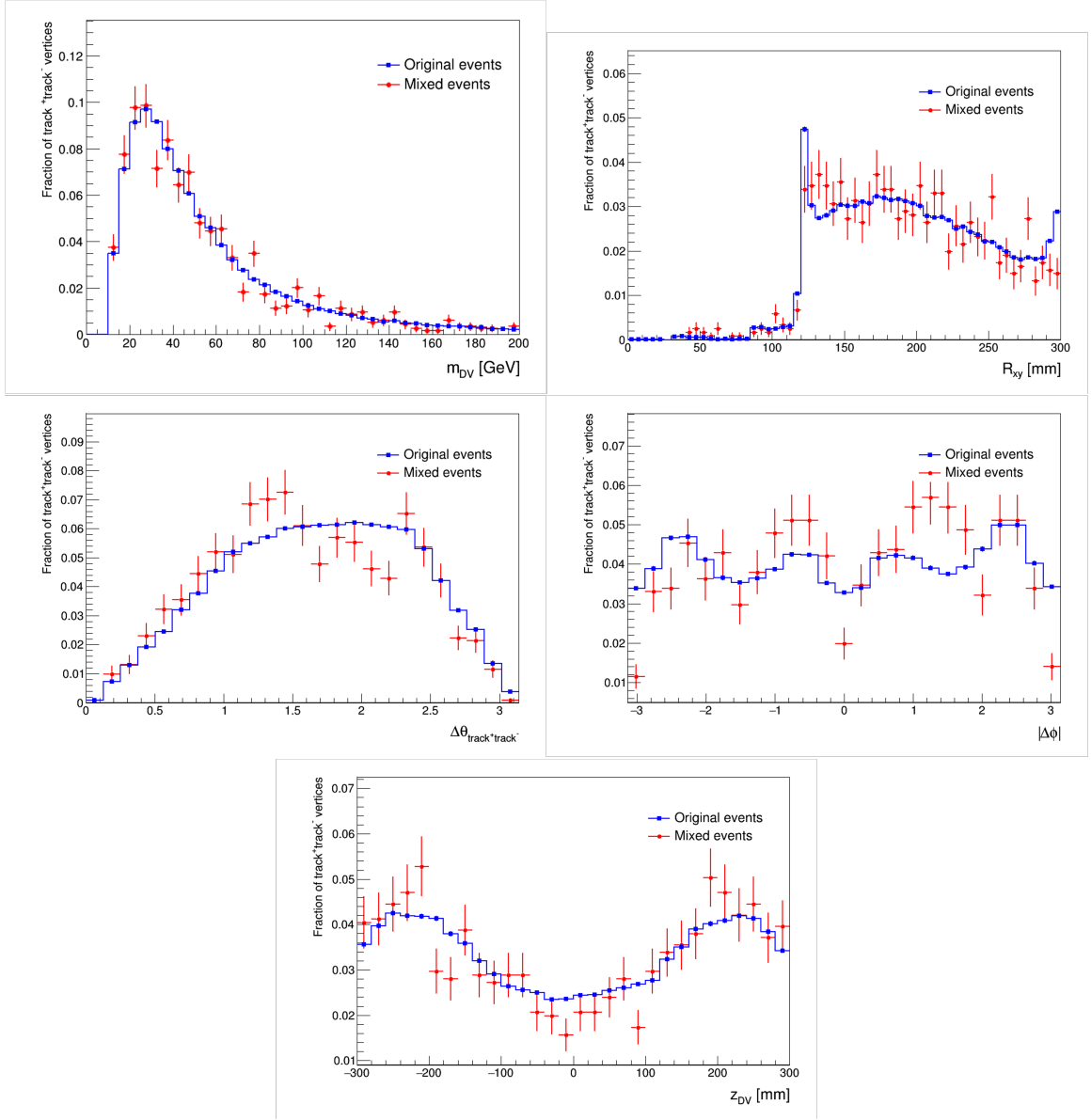


Figure 6.4: Number of accepted “signal” track-track DVs as a function of DV mass (top-left), DV transverse decay position (top-right), opening angle between DV’s tracks (middle-left), the difference between the track’s ϕ (middle-right), and DV z -position (bottom), shown for both the original (blue) events and the mixed events (red). The distributions are for track-track vertices using 2017 DADO_SUSY15 data.

Table 6.2: Number of displaced vertex candidates predicted in each year of Run 2 data. The predicted number of vertices is obtained using the number of seed pairs in the data N_{pairs}^{obs} and the average crossing probability p_{xing} via Eq. 6.1.

2015			
	ee	$e\mu$	$\mu\mu$
N_{pairs}^{obs}	714	230	3731
Mixed candidate pairs	4.01×10^5	1.32×10^5	1.89×10^5
Mixed signal DVs	0	0	1
Average p_{xing}	0	0	$(5.30 \pm 5.30) \times 10^{-6}$
Predicted DVs	0	0	$(1.98 \pm 1.98) \times 10^{-2}$
2016			
	ee	$e\mu$	$\mu\mu$
N_{pairs}^{obs}	1.64×10^4	4.33×10^2	2.57×10^4
Mixed candidate pairs	9.46×10^6	1.05×10^6	1.62×10^6
Mixed signal DVs	2	0	6
Average p_{xing}	$(2.11 \pm 1.50) \times 10^{-7}$	0	$(3.69 \pm 1.51) \times 10^{-6}$
Predicted DVs	$(3.47 \pm 2.45) \times 10^{-3}$	0	$(9.48 \pm 3.87) \times 10^{-2}$
2017			
	ee	$e\mu$	$\mu\mu$
N_{pairs}^{obs}	3.37×10^4	5.86×10^2	5.43×10^3
Mixed candidate pairs	1.00×10^7	9.30×10^5	1.44×10^6
Mixed signal DVs	3	3	15
Average p_{xing}	$(3.00 \pm 1.73) \times 10^{-7}$	$(3.22 \pm 1.86) \times 10^{-6}$	$(1.04 \pm 0.27) \times 10^{-5}$
Predicted DVs	$(1.01 \pm 0.58) \times 10^{-2}$	$(1.89 \pm 1.09) \times 10^{-3}$	$(5.65 \pm 1.46) \times 10^{-2}$
2018			
	ee	$e\mu$	$\mu\mu$
N_{pairs}^{obs}	4.70×10^4	7.41×10^2	6.74×10^3
Mixed candidate pairs	3.69×10^7	1.36×10^6	1.99×10^6
Mixed signal DVs	7	7	17
Average p_{xing}	$(1.89 \pm 0.71) \times 10^{-7}$	$(5.14 \pm 1.94) \times 10^{-6}$	$(8.53 \pm 2.07) \times 10^{-6}$
Predicted DVs	$(8.91 \pm 3.37) \times 10^{-3}$	$(3.81 \pm 1.44) \times 10^{-3}$	$(5.74 \pm 1.39) \times 10^{-2}$
Total			
	ee	$e\mu$	$\mu\mu$
N_{pairs}^{obs}	9.79×10^4	1.78×10^3	4.16×10^4
Mixed candidate pairs	5.68×10^7	3.47×10^6	5.25×10^6
Mixed signal DVs	12	10	39
Average p_{xing}	$(2.11 \pm 0.61) \times 10^{-7}$	$(2.88 \pm 0.91) \times 10^{-6}$	$(7.43 \pm 1.19) \times 10^{-6}$
Predicted DVs	$(2.07 \pm 0.60) \times 10^{-2}$	$(5.13 \pm 1.62) \times 10^{-3}$	$(3.09 \pm 0.49) \times 10^{-1}$

Table 6.3: Final estimated background from random track crossings for Run 2.

Channel	Background Estimate	Stat. Error	Syst. Error
ee	0.0207	0.0060	0.0030
$e\mu$	0.00513	0.00162	0.00075
$\mu\mu$	0.309	0.049	0.044

tainty in each test, so the systematic uncertainty is negligible. The systematic uncertainty for the random track crossing is calculated by combining in quadrature the 14.2% difference between the prediction and the observed number of DVs in the track-track validation region and the 3.1% statistical error to yield a systematic error of 14.6%.

Chapter 7

SCALE FACTORS AND UNCERTAINTIES

MC does not perfectly simulate detector response and operating conditions. The process of reweighting involves applying weights so that distributions in MC reproduce data. When reweighting to correct efficiencies, these weights are known as SFs:

$$SF = \frac{\epsilon_{data}}{\epsilon_{MC}} \quad (7.1)$$

These SFs are corrective weights that can be applied to the events overall or to individual objects such as a single lepton in the event. Many of these SFs are common to all ATLAS analyses, but because this analysis uses displaced leptons with custom WPs, the standard lepton and trigger SFs cannot be used. The procedure for calculating the custom SFs, together their associated systematic uncertainties, is discussed in this chapter. Finally, all other sources of systematic uncertainties are noted. In general, most systematic uncertainties are calculated by varying a relevant parameter and taking the difference between the alternate and the nominal signal efficiency.

7.1 Lepton Identification Scale Factors and Uncertainties

There are standard lepton identification SFs produced by ATLAS for each standard WP that are calculated using prompt leptons reconstructed by the standard tracking algorithm. This analysis uses displaced leptons which may be reconstructed by LRT and are identified using custom identification WPs, so those standard SF are not appropriate. The same tag-and-probe method used to calculate the standard SFs was followed, and is described briefly here.

A tag-and-probe procedure uses a well-understood signature to identify a pair of particles, the tag and the probe. The tag is identified with strict criteria, and the probe so named because it is used to probe the efficiency of interest. For this analysis, the Z boson decaying to pairs of leptons is the well-understood process used to produce the collection of tag and probe lepton pairs. The tag lepton is well-identified with a strict WP, while the

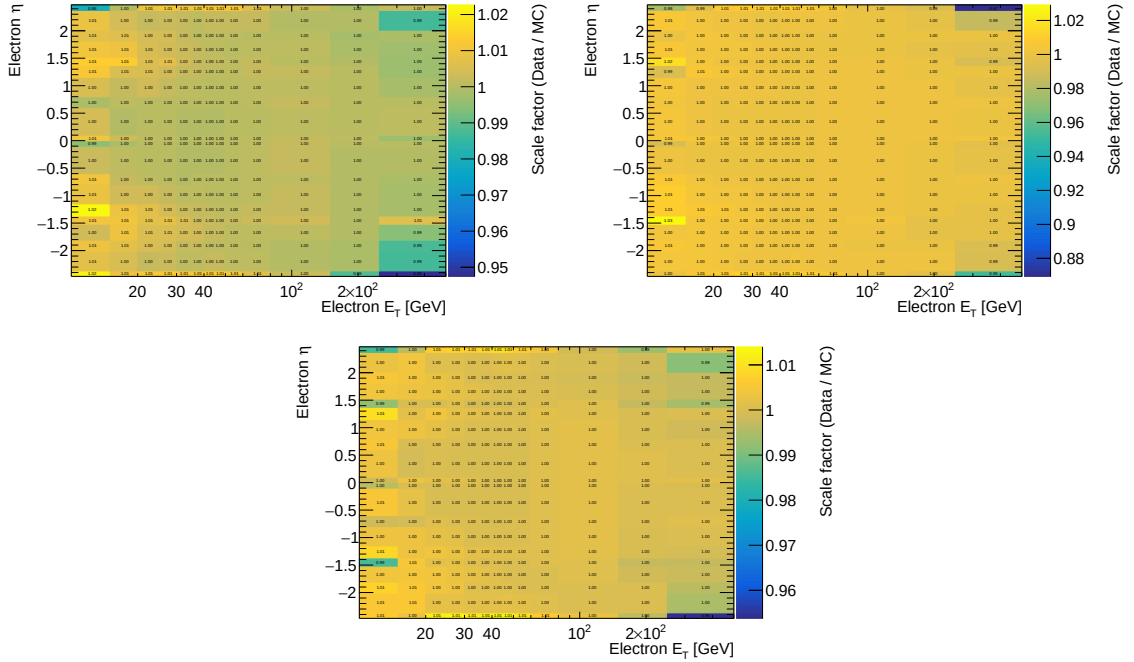


Figure 7.1: Scale factors for the modified electron identification WP, as a function of the probe E_T and η extracted from a comparison of 2015/2016 data and mc16a (top), 2017 data and mc16d (middle), and 2018 data and mc16e (bottom).

probe has very loose selection criteria (e.g. is identified as the any quality). Because the invariant mass of the lepton pair is required to be in the Z mass peak, the tag and probe can be assumed with high confidence to be a lepton/anti-lepton pair resulting from a Z decay. This produces a collection of probe leptons to calculate the efficiency of interest. For this analysis, the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ MC mentioned in Section 4.2.2 were used to compare with the corresponding processes in data (see Section 4.1). Details of the tag-and-probe procedure for calculating lepton identification SFs, including tag and probe selections, background discrimination, and normalization, can be found in Reference [89]. Note that the use of prompt $Z \rightarrow ll$ decays to study these scale factors is acceptable because the lepton identification efficiency is largely independent of d_0 , as shown in Figures 5.5 and 5.6.

The lepton identification SFs are shown in Figure 7.1 for electrons and Figure 7.2 for muons. For electrons, the scale factor is ~ 1.0 for most of the η/E_T region. The minimum value is ~ 0.90 for electrons with high E_T and $|\eta|$ close to 2.5 and the maximum is ~ 1.2 for electrons in the barrel/end-cap crack region. For muons, the scale factor is ~ 1.0 except for η close to 0, which corresponds to a physical gap in MS coverage that allows technical services to reach inner ATLAS subsystems [43].

Two sources of systematic uncertainty in the lepton identification SFs have been inves-

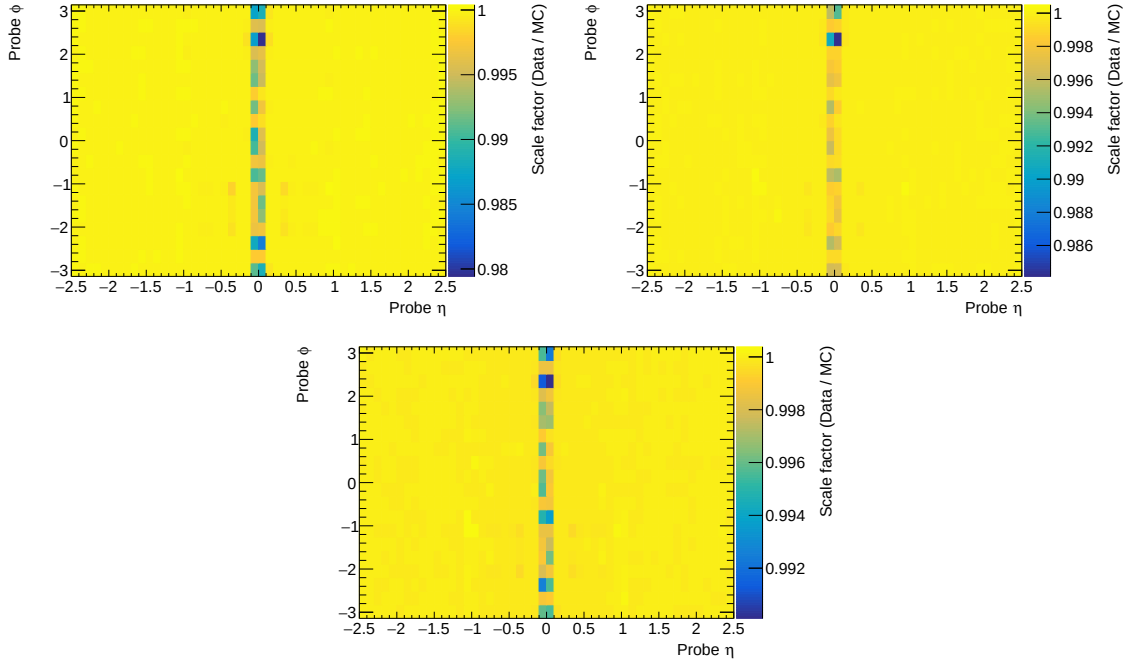


Figure 7.2: Scale factors for the modified **Loose** muon WP as a function of the probe η and ϕ extracted from a comparison of 2015/2016 data and mc16a (top), 2017 data and mc16d (middle), and 2018 data and mc16e (bottom).

tigated. For the ideal tag-and-probe pair, the calculated efficiencies should only depend on the properties of the probe; they should be independent of the tag selection criteria and the mass window around the Z boson mass. The systematic uncertainty from each source is estimated by measuring the difference in signal efficiency after varying those parameters. These components are added in quadrature to yield the total systematic uncertainty of $\sim 1\%$.

7.2 Trigger Scale Factors and Uncertainties

As with the lepton identification SFs, there are standard trigger SFs that are produced for prompt leptons, with displaced leptons excluded by d_0 and Pixel hit requirements. The photon triggers used were chosen specifically to trigger on displaced electrons and the muon trigger uses MS information only to trigger on displaced muons. These differences, combined with the modified lepton WPs, excludes the use of the standard trigger SFs. Therefore, the trigger SFs are also recalculated following the same standard tag-and-probe procedure as in Section 7.1, using the same $Z \rightarrow ll$ samples.

The SFs are calculated for each of the three HLTs separately. When using the tag-and-probe method with $Z \rightarrow ll$, the efficiency can only be determined for one daughter lepton

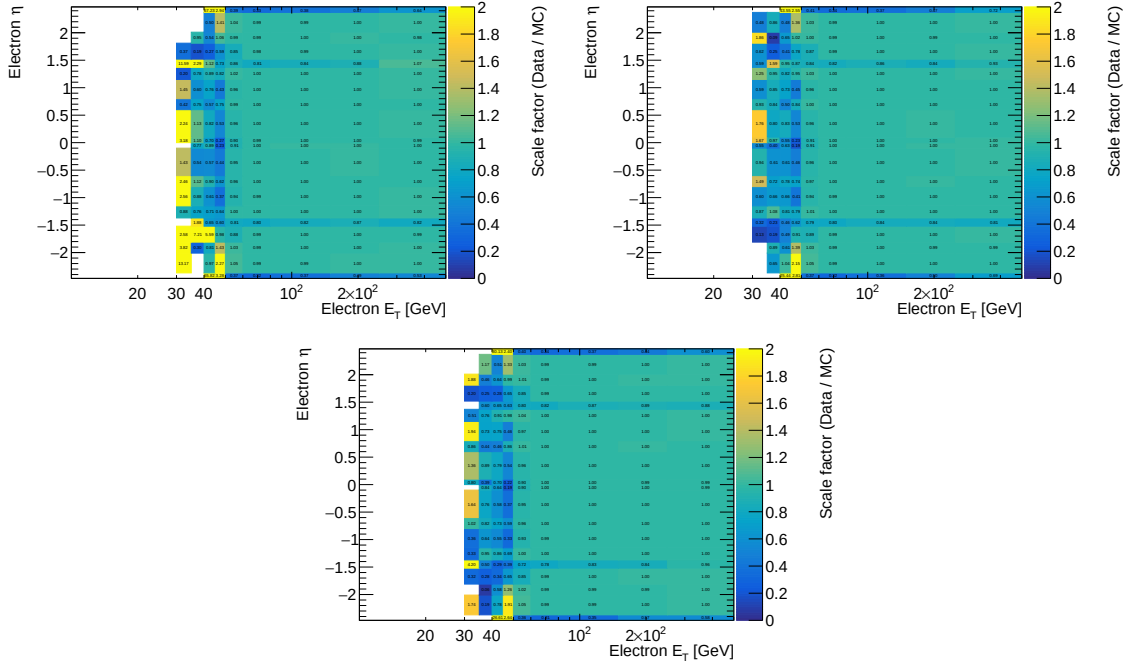


Figure 7.3: Scale factors for the `HLT_g50_loose` trigger, as a function of the probe E_T and η extracted from a comparison of 2015/2016 data and mc16a (top), 2017 data and mc16d (middle), and 2018 data and mc16e (bottom).

(the probe) because the other must be used as the tag. Therefore, when considering the di-photon trigger, the SFs are calculated for the single photon trigger with the same p_T threshold: `HLT_g50_loose`. For events passing the di-photon trigger, the scale factors for the two electrons in the ee pair are combined multiplicatively.

The SFs for each MC period are shown in Figures 7.3 and 7.4 for `HLT_g50_loose` and `HLT_g140_loose` respectively. The SFs are also ~ 1.0 , with a notable deviation in the barrel/end-cap crack region, similar to the lepton identification SFs. The electrons in this region are vetoed by the analysis selection and therefore have no effect on the signal region. The region with $p_T < 60$ GeV shows larger SF variation for `HLT_g50_loose`, but because filter requirements for the di-photon trigger require triggering particles have $p_T > 60$ those variations do not affect the signal region. The systematic uncertainties are also estimated by varying the tag requirements and varying the Z boson mass window. Added in quadrature, these systematic uncertainties are $\sim 0.1\%$ and $\sim 0.2\%$ for the di-photon and single photon triggers, respectively.

The SFs for each MC period are shown in Figure 7.5 for `HLT_mu60_0eta105_msonly`. The same method from calculating the muon identification SFs systematic uncertainties was used here, yielding uncertainties of $\sim 1\%$.

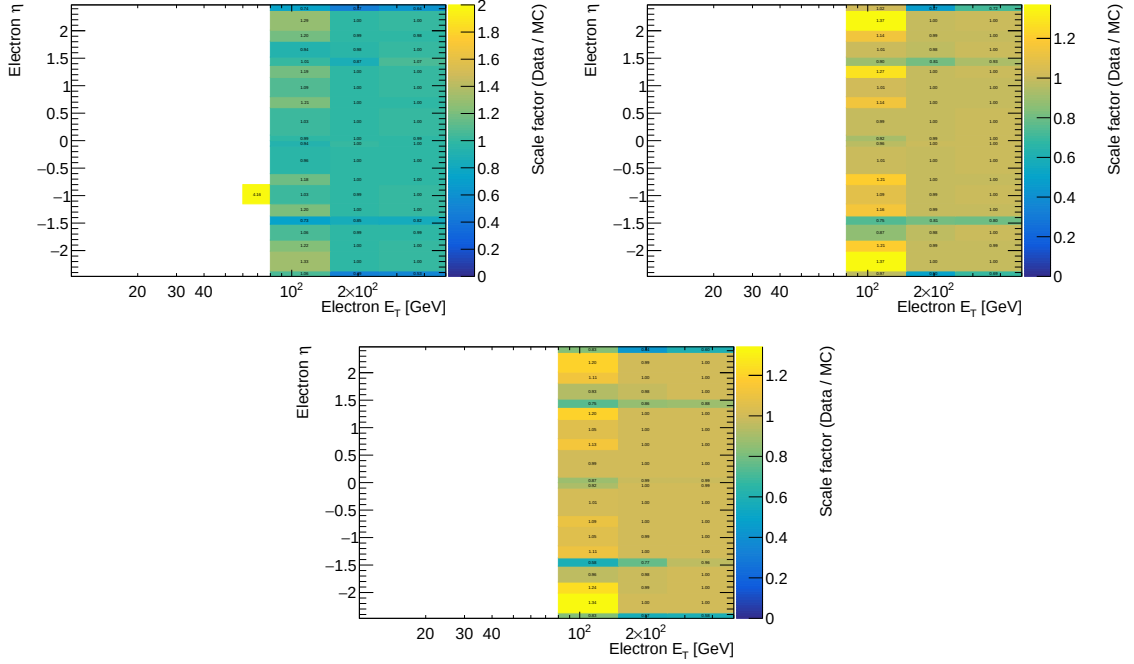


Figure 7.4: Scale factors for the `HLT_g140_loose` trigger, as a function of the probe E_T and η extracted from a comparison of 2015/2016 data and mc16a (top), 2017 data and mc16d (middle), and 2018 data and mc16e (bottom).

7.3 LRT and VSI Scale Factors and Uncertainties

The last set of custom SFs calculated for this analysis are due to imperfect modeling of the LRT and VSI reconstruction algorithms (see Sections 3.1.2 and 3.2.2) performance in MC. The systematic uncertainty on these SFs is the dominant uncertainty in this analysis. Whether a track is reconstructed by ST or LRT depends on multiple factors—the most important of which is d_0 —that the simulation may not emulate perfectly; the same is true for the VSI algorithm reconstructing DVs. The decay $K_S \rightarrow \pi^+ \pi^-$ provides a decent sample for studying these differences. The kinematics of the K_S are quite different from those of the LLP; however, the long lifetime ($c\tau = 26.8$ mm) has large overlap with the signal region and hence K_S provides an adequate sample for the study.

The same dilepton-filtered $t\bar{t}$ sample used for event-mixing validations (see Section 6.2.4) was used to study reconstruction of K_S . Because the K_S is long-lived, its decay products can be reconstructed by either ST or LRT. The reconstructed vertex can therefore consist of two ST tracks, two LRT tracks, or one of each. SFs and systematic uncertainties are calculated for each of these three DV types.

Because the mass of the K_S is much smaller than that of the signal LLPs, the same signal selections cannot be applied. The signal selections applied to K_S are listed in Table 7.1.

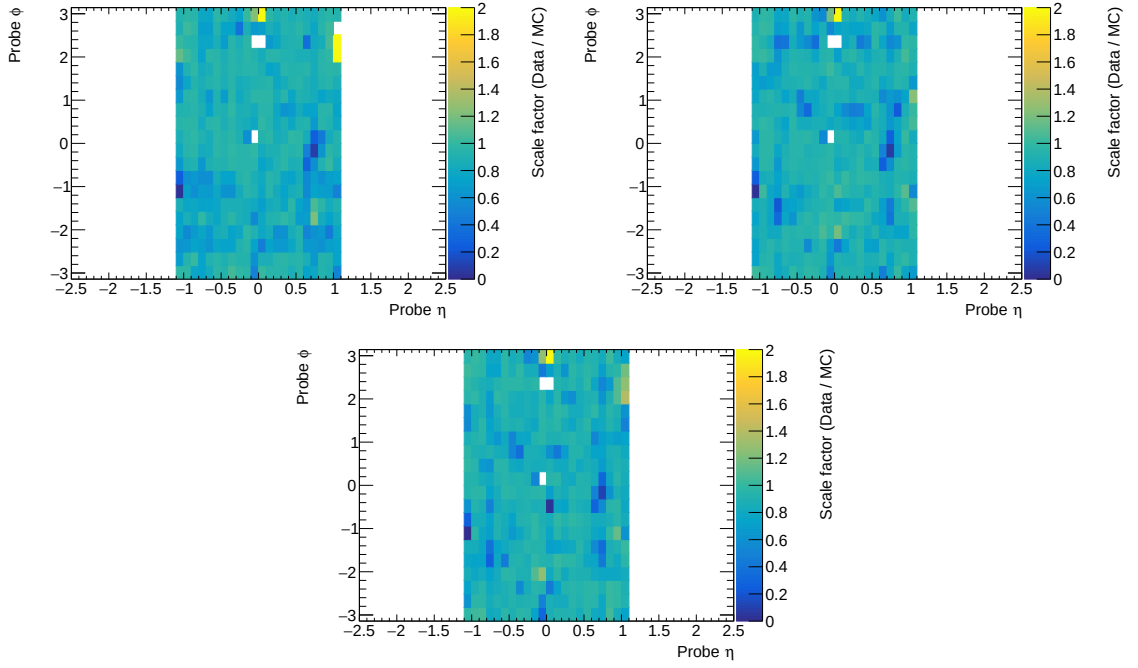


Figure 7.5: Scale factors for the `HLT_mu60_0eta105_msonly` trigger as a function of the probe η and ϕ extracted from a comparison of 2015/2016 data and mc16a (top), 2017 data and mc16d (middle), and 2018 data and mc16e (bottom). Only probes with $p_T > 60$ GeV are considered.

Table 7.1: K_S vertex level requirements and lepton requirements used for calculating LRT/VSI reconstruction SF and systematic uncertainties.

K_S Vertex Selections
Opposite charge
$470 \text{ MeV} < m_{\pi\pi} < 530 \text{ MeV}$
$ \Delta z_0 < 2 \text{ mm}$
Decay length $> 15 \text{ mm}$
Lepton Selections
$p_T > 10 \text{ GeV}$
$ \eta < 2.5$

Many vertex-specific selections detailed in Section 5.3 are still applicable, but are modified as motivated by literature focusing on K_S [90] to select K_S vertices. The lepton identification selections detailed in Section 5.2 are not applicable; only the kinematic requirements on p_T and η are kept.

The p_T spectrum of the K_S is known to be poorly modeled [91], so the ST/ST K_S p_T spectrum is adjusted to reproduce the data after sideband subtraction (380–440 and 560–620 MeV), assuming a linear background near the K_S mass peak. The same adjustment (scale factor binned in p_T) is then applied to the ST/LRT and LRT/LRT samples. Figure 7.6 shows the K_S decay kinematic distributions after this p_T scaling. The remaining discrepancies in the transverse decay length (R_{xy}) and three-dimensional decay length (ℓ) distributions are attributed to systematic errors in the LRT/VSI reconstruction. These discrepancies show different trends over different MC campaigns, so the SFs and systematic uncertainties are calculated for each campaign separately.

The K_S radial distribution is binned to loosely align with the tracking layers. The K_S yield in MC is normalized to the data to compare trends of the kinematics, where the normalization factor is calculated by normalizing the first bin of the ST/ST distribution, where the tracking and vertexing are both assumed to be well-modeled. The same normalization factor is applied to the ST/LRT and LRT/LRT distributions. These normalized distributions are shown in Figure 7.7. Because there are no entries in the first three bins of the LRT/LRT distribution and no entries in the first two bins of the ST/LRT, a linear fit of the scale factor in the five larger bins is calculated. The SFs for these empty bins is extrapolated from this linear fit. The ST/ST distribution matches this linear fit well, indicating that a linear function is a reasonable description of the dependence of the scale factor on R_{xy} .

The resulting SFs are shown in Figure 7.8. The SFs are typically less than one and decrease with increasing R_{xy} , suggesting that the MC overestimates the tracking efficiency, the vertexing efficiency, or both—especially at larger displacements. They can be as low as

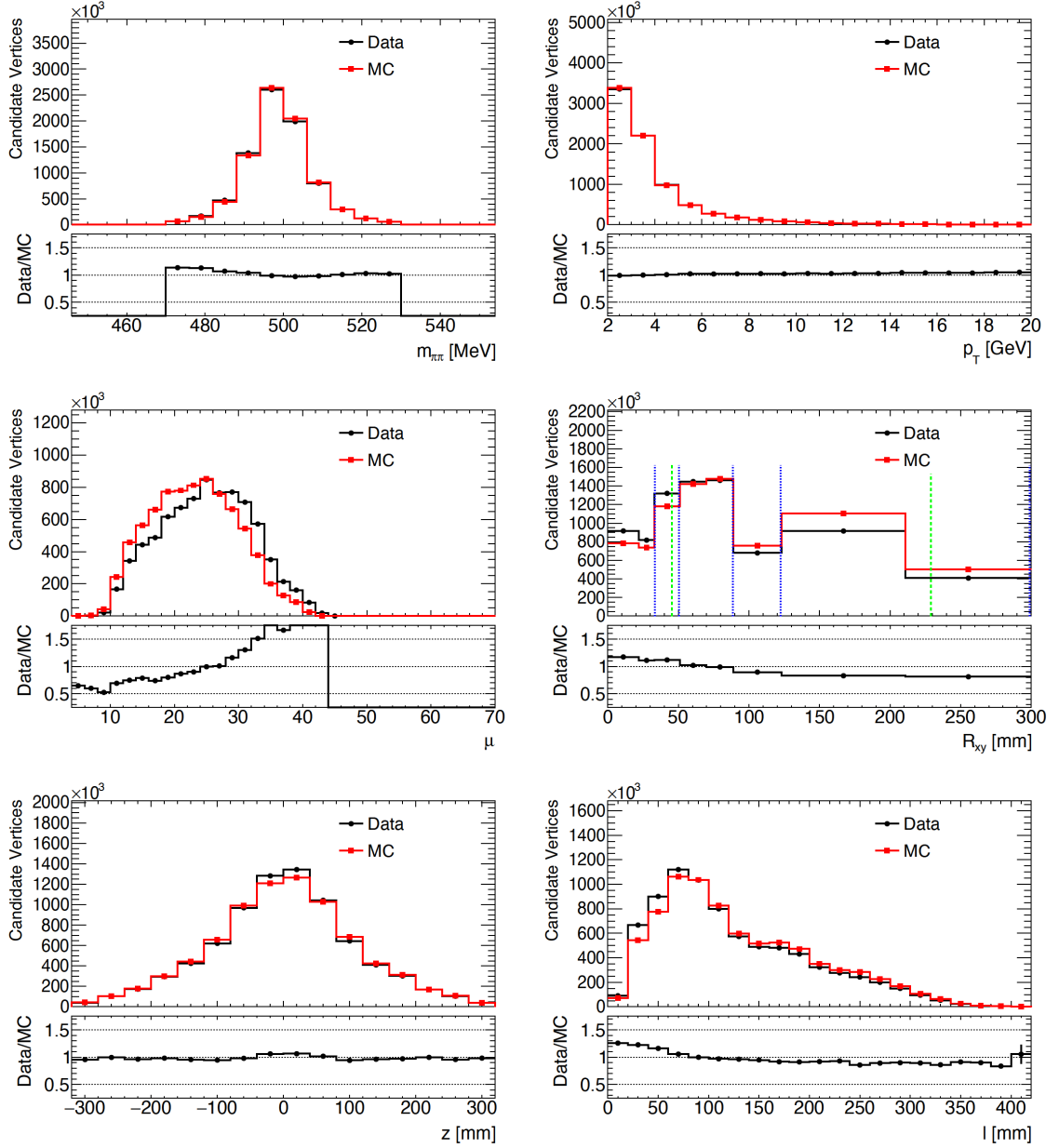


Figure 7.6: Reconstructed K_S yields after p_T scaling for mc16a $t\bar{t}$ and combined 2015 and 2016 data for $\pi\pi$ invariant mass (top left), p_T (top right), pileup (middle left), R_{xy} (middle right), z (bottom left), and l (bottom right). For the radial distribution, the blue dashed lines indicate the four Pixel layers and the first layer of SCT. The green dotted lines indicate the Inner Support Tube (45.5 mm) and Pixel Support Tube (229 mm).

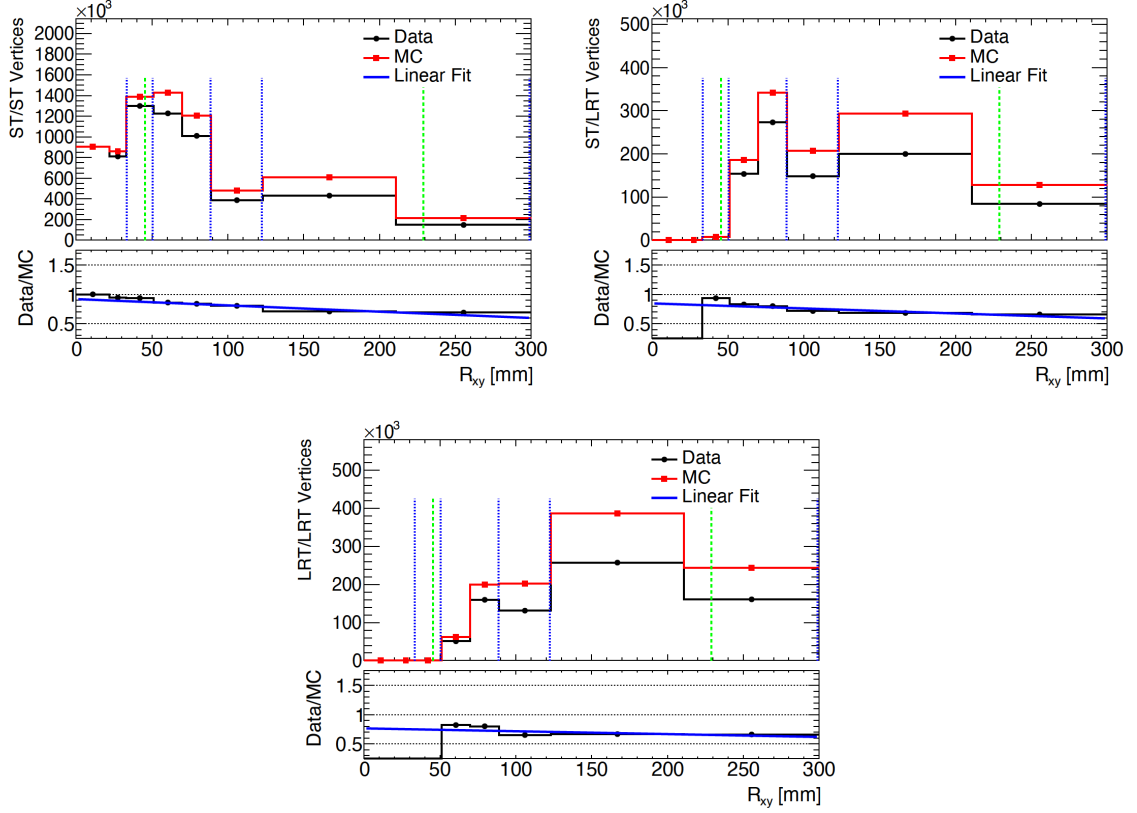


Figure 7.7: Reconstructed K_S yields as a function of R_{xy} for mc16a $t\bar{t}$ and combined 2015 and 2016 data with the three different vertex types, ST/ST (top left), ST/LRT (top right), and LRT/LRT (bottom). The data to MC scale factor is used to estimate the systematic error for LRT/VSI. The line shows the linear fit to the scale factor, which uses the five larger radial bins to extrapolate into the three smaller radial bins (see text). Only statistical errors are shown.

0.6 for ST/ST vertices at large R_{xy} ; however, the small SFs have limited impact because the statistics are significantly higher for ST/ST DVs with smaller decay length ($c\tau$), where the SFs are much closer to 1.

The systematic uncertainty is calculated by using an alternate normalization, normalizing to the total number of ST/ST in MC to data instead of just the first bin of the R_{xy} distribution. The systematic uncertainty of standard tracking is well understood, $\lesssim 1.7\%$ [92], which is added in quadrature to the uncertainty from using the alternate normalization. The resulting systematic uncertainties are 14.0% for mc16a, 11.7% for mc16d, and 6.1% for mc16e.

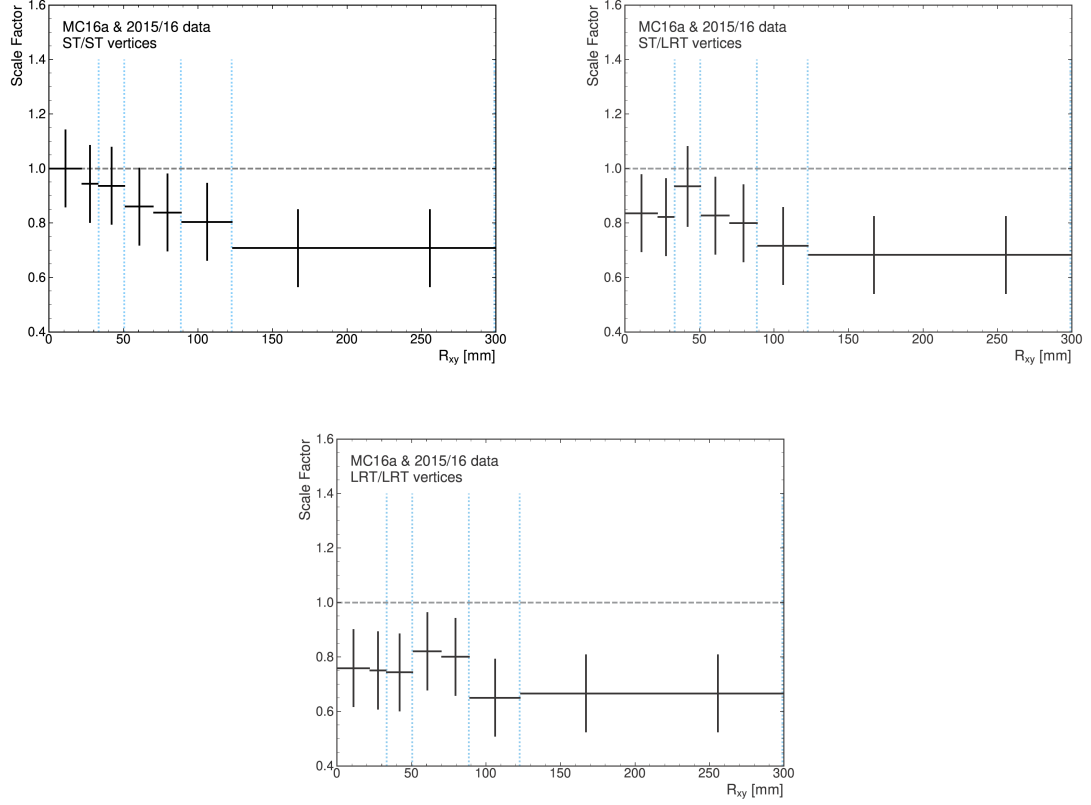


Figure 7.8: Scale factors as a function of R_{xy} for mc16a $t\bar{t}$ and combined 2015 and 2016 data with the three different vertex types, ST/ST (top left), ST/LRT (top right), and LRT/LRT (bottom). The error bars correspond to the combined statistical and systematic uncertainties.

7.4 General MC Modeling

There are multiple sources of systematic uncertainty originating from MC modeling that are not specific to this analysis. The kinematic distribution of the quarks and gluons inside a proton, and therefore how they interact in a pp collision, is characterized by the parton distribution function (PDF). The PDF used in the MC generation is Madgraph tuned parameters NNPDF23L0 [76], which specifies a certain set of PDFs. The intra-PDF uncertainty is calculated by varying the PDF parameters within the NNPDF23L0 tuned parameters during the MC event generation. The inter-PDF uncertainty is calculated by using alternate PDFs. In both cases, the effect on the final signal efficiency is low. The maximum uncertainty across all MC samples was 5% for intra-PDF variation and 1.4% for inter-PDF variation. In both cases, that maximum is conservatively applied to all signal MC samples.

Varying the choice of factorization and normalization scales during MC generation produces an uncertainty of $\sim 0.34\%$, which is assumed to be negligible.

Initial-state radiation (ISR) refers to one of the initial partons radiating a photon or a gluon prior to the pp collision while final-state radiation (FSR) refers to any of the particles created in the collision radiating a photon or gluon. These phenomena, along with having multiple parton interactions (MPI) in a single event, can affect the event kinematics and the frequency of additional radiated particles in a MC event. Variations due to these three effects are applied to events in the fiducial region at truth-level, following the standard technique for ATLAS SUSY searches. The uncertainty from these three effects is combined, with the largest deviation of 3% being conservatively applied to all signal MC samples.

7.5 Pileup Modeling in MC

The pileup distributions used in MC are estimated before data-taking begins. Once the distributions in collision data are measured, weights are applied to events in MC so that the pileup distribution more closely match that of the corresponding data-taking period [93]. The procedure reproduces the distributions of pileup in data to reasonable fidelity, as shown in Figure 7.9. The associated uncertainty obtained by varying the pileup weights is $\sim 2\text{--}3\%$.

7.6 Other Sources of Systematic Uncertainty

The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [41], measured primarily using the LUCID-2 detector [73], complemented by measurements using the ID and calorimeters. The uncertainties on the theoretical cross-sections of the signal MC samples as reported in Tables 4.1 and 4.2 include uncertainties in the PDF, scale and normalization, and strong coupling constant [77–79].

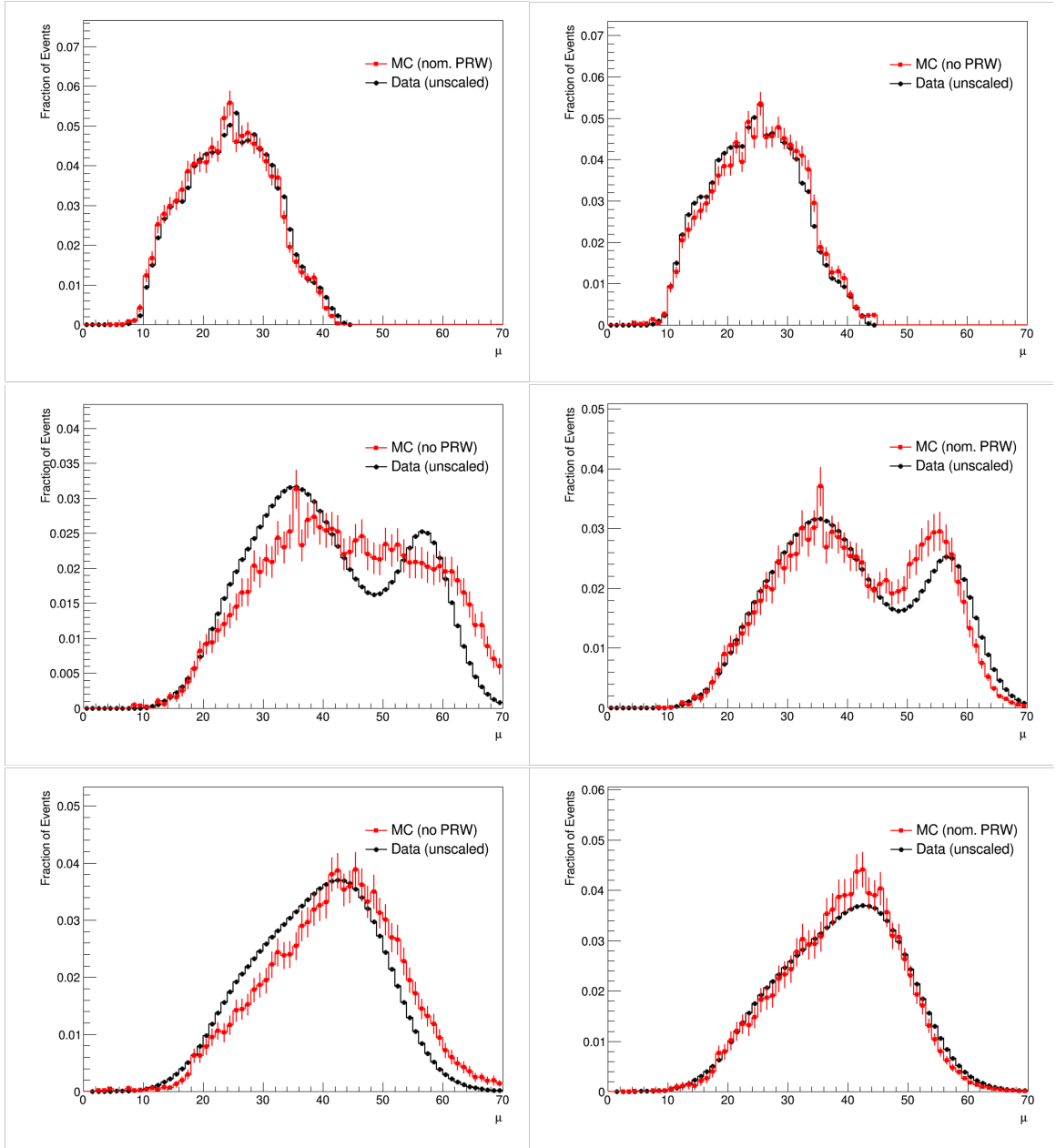


Figure 7.9: Number of pileup vertices in data and in MC without (left) and with (right) pileup reweighting. The top row compares mc16a with 2015 and 2016 data, the middle row compares mc16d with 2017 data, and the bottom row compares mc16e with 2018 data.

The systematic uncertainty due to lifetime reweighting is calculated from the difference between the efficiency for one MC sample with a particular lifetime and the efficiency extrapolated from the other four samples with different lifetimes but the same mass. The procedure is explained in more detail in Appendix B. The systematic uncertainty due to lifetime reweighting is 2%.

7.7 Total Systematic Uncertainty

The total systematic uncertainty is calculated from adding in quadrature the uncertainty from all sources discussed in this chapter. Figures 7.10 and 7.11 show the total uncertainty as a function of decay length ($c\tau$) for the gluino-produced and electroweakino-produced samples, respectively. The uncertainty due to the LRT/VSI scale factors is the dominant uncertainty, with other contributions being notable only at the lowest lifetimes studied. The event-level uncertainties are higher than the vertex-level efficiencies because the event-level efficiency is calculated from two DVs instead of one DV. The dip in uncertainty between decay lengths of 10 mm and 100 mm is due to higher signal efficiency in that region, which reduces the uncertainty propagated from the vertex level efficiency.

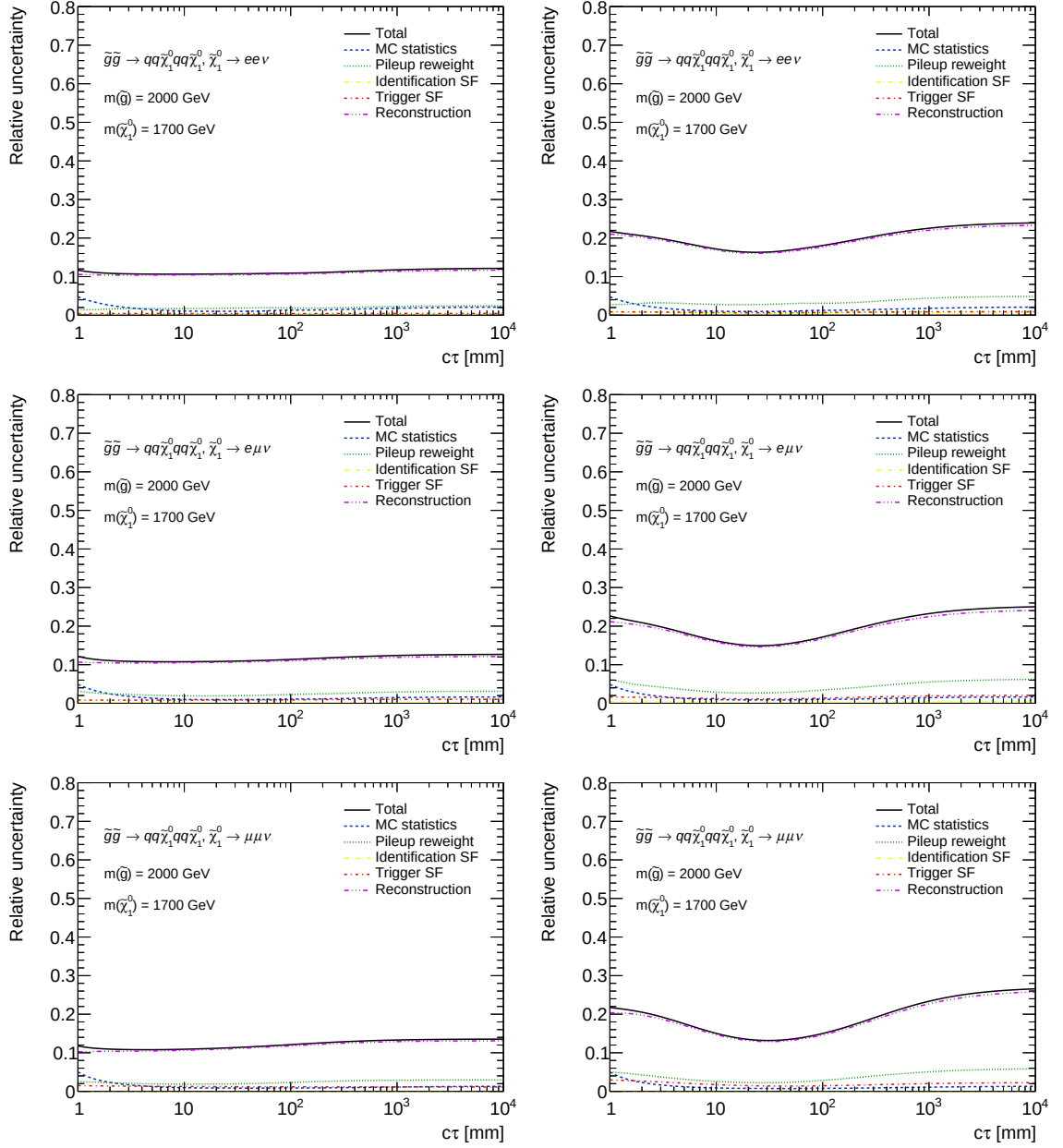


Figure 7.10: Systematic errors at the vertex-level (left) and event-level (right) as a function of decay length ($c\tau$) for the gluino-produced $\tilde{\chi}_1^0$ (mc16a+mc16d+mc16e) samples with a gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 1700 GeV with $\tilde{\chi}_1^0$ decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states.

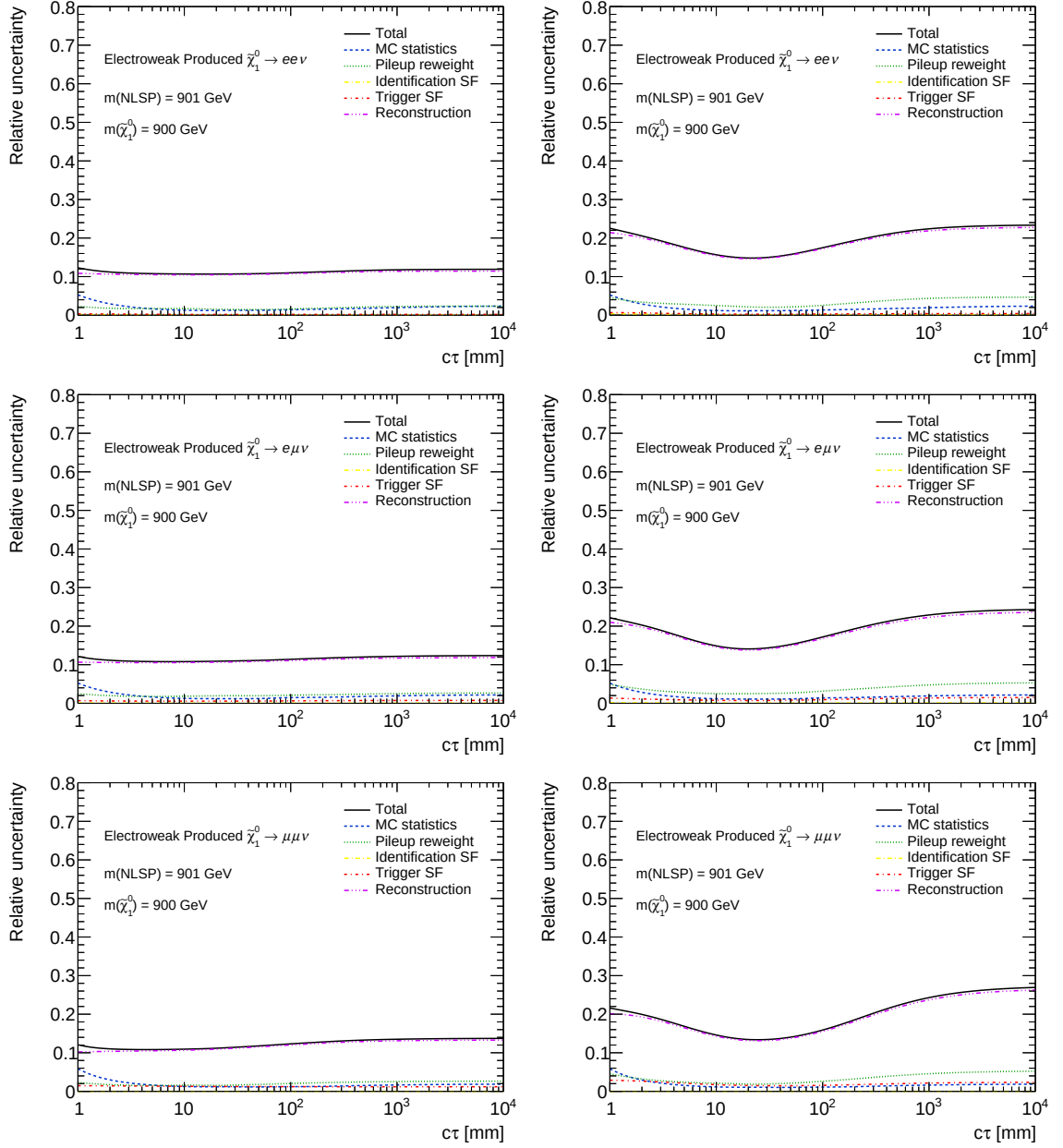


Figure 7.11: Systematic errors at the vertex-level (left) and event-level (right) as a function of decay length ($c\tau$) for the electroweakino-produced $\tilde{\chi}_1^0$ (mc16a+mc16d+mc16e) samples with a $\tilde{\chi}_1^0$ mass of 900 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states.

Chapter 8

RESULTS

There were zero signal events observed in Run 2 data. This is disappointing for the author to not discover new physics during graduate school, but new limits can be set on the cross-section of the models studied.

For a specific theoretical cross-section of a gluino/electroweakino at a particular mass in the SUSY models studied, Eq. 2.2 yields the expected number of events produced in 140.1 fb^{-1} of pp collisions. The expected number of events detected depends on the signal efficiency discussed Section 5.4.4, which is dependent on the LLP lifetime. Tables 8.1 and 8.2 show the expected number of signal events for the gluino-production and electroweakino-production model, respectively. A bigger difference between the expected and observed numbers of events results in more stringent limits on the production cross-section. For example, with a background of less than one event and zero observed events, stronger limits will be set on the production cross-section of a 1500 GeV $\tilde{g}$ than a 2500 GeV $\tilde{g}$.

It should be noted that the models themselves are not excluded entirely, but rather a region of parameter space for the model is excluded. There could be an LLP decaying to displaced, di-lepton vertices with a lifetime excluded by this study of these particular SUSY models, but it must be produced with a cross-section that is less than the modeled theoretical cross-section. The result of this search will be presented as the “upper limit” on the cross-section, which is the maximum cross-section that could produce zero signal events at the 95% confidence level (CL).

8.1 Statistical Methods

To determine the upper limit based on the number of expected signal events, the number of observed events, and associated uncertainties, two hypotheses are considered. The signal-plus-background hypothesis is that events originate from both signal and background; i.e. $n_{\text{exp}} = \mu s + b$, where b is the number of background events, s is the number of signal events, and μ is the “signal strength.” The signal strength is the parameter of interest; it scales

Table 8.1: Expected yield of ee , $e\mu$, and $\mu\mu$ vertices for gluino-produced $\tilde{\chi}_1^0$ with $c\tau$ of 10, 100, and 1000 mm.

Mass (GeV)		ee Yield (Events)			$e\mu$ Yield (Events)			$\mu\mu$ Yield (Events)		
$\tilde{g}$	$\tilde{\chi}_1^0$	10	100	1000	10	100	1000	10	100	1000
		mm	mm	mm	mm	mm	mm	mm	mm	mm
1500	100	300	98	12	340	110	14	570	250	34
1500	500	610	330	55	630	370	64	760	650	140
1500	1000	510	380	74	590	480	100	640	710	200
1500	1200	460	370	71	550	470	100	610	710	200
2000	100	19	5.7	0.7	22	6.7	0.8	38	14	1.8
2000	500	39	19	3.1	42	22	3.6	52	39	7.9
2000	1000	34	23	4.4	41	30	6	46	45	12
2000	1700	22	20	3.9	29	29	6.6	37	45	14
2500	100	1.4	0.4	0.05	1.6	0.5	0.06	2.8	1	0.1
2500	500	2.8	1.3	0.2	3.2	1.6	0.3	4.1	2.9	0.5
2500	1000	2.7	1.5	0.3	3.2	2	0.4	3.7	3.4	0.8
2500	2200	1.2	1.2	0.2	1.8	1.9	0.5	2.6	3.5	1.1

Table 8.2: Expected yield of ee , $e\mu$, and $\mu\mu$ vertices for electroweakino-produced $\tilde{\chi}_1^0$ with $c\tau$ of 10, 100, and 1000 mm.

Mass [GeV]		ee Yield (Events)			$e\mu$ Yield (Events)			$\mu\mu$ Yield (Events)		
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	$\tilde{\chi}_1^0$	10	100	1000	10	100	1000	10	100	1000
		mm	mm	mm	mm	mm	mm	mm	mm	mm
101	100	19000	8400	1100	35000	20000	3200	85000	77000	14000
301	300	5900	3500	570	5500	3600	680	7700	7700	1800
501	500	1000	700	120	1000	730	140	1200	1200	290
701	700	220	160	29	250	190	36	260	270	69
901	900	56	42	8.1	65	51	10	70	75	20
1101	1100	15	12	2.3	18	16	3.4	21	24	6.6
1301	1300	4.3	3.5	0.7	5	4.6	1	5.9	7	2

the number of signal events. The branching ratio to signal decays is assumed to be 100%, and therefore μ functionally scales the cross-section. The background-only hypothesis is that any events originate solely from background sources, i.e. $n_{\text{exp}} = b$, which is equivalent to the signal strength μ being set to zero. To calculate the 95% CL, a p -value must be calculated for each of these hypotheses.

The calculation of the p -value begins with the probability of observing n_{obs} events given a signal strength μ , known as the probability density function. It is described by a Poisson distribution with mean $n_{\text{exp}} = \mu s + b$:

$$P(n_{\text{obs}}|\mu) = \frac{(\mu s + b)^n}{n!} e^{-(\mu s + b)} := \text{Pois}(n_{\text{obs}}|n_{\text{exp}}) \quad (8.1)$$

This is also known as the likelihood function $L(\mu)$.

To account for the uncertainties on both s and b inherent to real-world particle physics experiments, “nuisance parameters” are introduced to the likelihood function:

$$L(\mu, \theta) = \text{Pois}(n_{\text{obs}}|n_{\text{pred}}) \cdot \text{Gaus}(\Theta_s|\theta_s, \sigma_s) \cdot \text{Gaus}(\Theta_b|\theta_b, \sigma_b), \quad (8.2)$$

where Gaus is the probability of observing Θ_s signal (Θ_b background) events for a Gaussian distribution with mean θ_s (θ_b) and width σ_s (σ_b).

The question of whether the number of observed events is compatible with either hypothesis is quantified using the one-sided profile-likelihood test statistic:

$$q_\mu = \begin{cases} -2 \ln \lambda(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu, \end{cases} \quad (8.3)$$

where $\lambda(\mu)$ is the profile likelihood ratio,

$$\lambda(\mu) = \frac{L(\mu, \hat{\theta}_\mu)}{L(\hat{\mu}, \hat{\theta})}. \quad (8.4)$$

The variables $\hat{\mu}$ and $\hat{\theta}$ in the denominator are the maximum likelihood estimates, which are the values of μ and θ that globally maximize the likelihood function. The $\hat{\theta}_\mu$ variables in the numerator are the “profiled” θ values that maximize the likelihood function for a *specific* μ .

The high energy physics standard for the threshold of the test statistic q_μ is a CL of 95% [94], corresponding to a p -value of less than 0.05. The p -value of the test statistic for the signal-plus-background hypothesis is:

$$p_\mu = P(q_\mu \geq q_\mu^{\text{obs}}|\mu, \theta) = \int_{q_\mu^{\text{obs}}}^{\infty} f(q_\mu, \theta) dq_\mu. \quad (8.5)$$

The p -value for the background-only hypothesis is then calculated via:

$$1 - p_b = P(q_\mu \geq q_\mu^{\text{obs}} | 0, \theta) = \int_{q_0^{\text{obs}}}^{\infty} f(q_0, \theta) dq_0 \quad (8.6)$$

One method of determining the threshold, typically denoted $\text{CL}_{\text{s+b}}$, is to calculate the value of μ for which $p_\mu < 0.05$. This method has the downside of rejecting models where the number of observed events is far below the expected background, even if the sensitivity to the model is arbitrarily low. To not artificially exclude all models just because the observed number of events is lower than the background, physics analyses at the LHC use a modified frequentist approach called CL_s [94], where:

$$\text{CL}_\text{s} = \frac{1 - \text{CL}_{\text{s+b}}}{1 - \text{CL}_\text{b}} = \frac{p_\mu}{p_{\mu=0}} = \frac{p_\mu}{1 - p_b}. \quad (8.7)$$

In this formulation, larger deviation from the background will result in larger p_b -values and larger CLs, preventing inappropriate exclusions.

To solve the multiple integrals in the formulas above, the standard asymptotic method [95] cannot be used because its assumptions are not valid when the signal is very low. Instead, the problem is solved numerically using “toy” pseudo-experiments. In each toy experiment, a value for each of the nuisance parameters (i.e. systematic uncertainties) is randomly selected from its assumed-Gaussian distribution. A range of μ values are tested with ten thousand toy experiments each, allowing for numerical determination of the maximum likelihood estimates $\hat{\mu}$ and $\hat{\theta}$, the profiled $\hat{\theta}_\mu$, and therefore the profile likelihood ratio in Eq. 8.4. The upper limit of the cross-section is then the highest value of μ that cannot be excluded at the 95% CL.

8.2 Upper Limits on Model Cross-Sections

Figures 8.1-8.3 show the limits on the cross section for gluino pair production at the gluino masses studied. Figures 8.4-8.10 show the limits on the cross section of production of mass-degenerate pairs of $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$. The lifetimes that are excluded for the theoretical cross-section are listed in Tables 8.3 and 8.4.

For all gluino and neutralino masses studied, the upper limit on the cross-section of gluino pair production is $\mathcal{O}(1) \text{ fb}^{-1}$ at decay lengths ($c\tau$) of 1 mm, improves to as low as $\mathcal{O}(10^{-1}) \text{ fb}^{-1}$ for intermediate decay lengths, and then increases back to $\mathcal{O}(1) \text{ fb}^{-1}$ at large decay lengths. As the gluino mass increases, the limits on the cross-section remain about the same while the theoretical cross-section decreases, reducing the range of excluded lifetimes. The theoretical cross-section for pair production of the lightest gluino mass considered, 1000 GeV, is excluded for all lifetimes studied. At the highest gluino mass considered, 2500 GeV, only a small range of lifetimes was excluded. For each gluino mass, the upper-limit on

Table 8.3: Excluded $\tilde{\chi}_1^0$ lifetimes for the gluino-production model, assuming 100% branching ratio to leptons for the $\tilde{\chi}_1^0$ decay. The threshold for exclusion is the theoretical cross-sections listed in Table 4.1. A value of 1 (10000) mm means that the theoretical cross-section was excluded at the minimum (maximum) decay length ($c\tau$) considered.

$\tilde{g}$ mass (GeV)	$\tilde{\chi}_1^0$ mass (GeV)	ee Excluded $c\tau$ (mm)	$e\mu$ Excluded $c\tau$ (mm)	$\mu\mu$ Excluded $c\tau$ (mm)
1500	100	1—4000	1—4700	1—6800
1500	500	1—10000	1—10000	1—10000
1500	1000	1—10000	1—10000	1—10000
1500	1200	1—10000	1—10000	1—10000
2000	100	1—210	1—250	1—580
2000	500	1—1000	1—1200	1—2700
2000	1000	1.2—1500	1.1—2100	1.1—4270
2000	1700	1.8—1330	1.7—2390	1.6—5440
2500	100	-	-	-
2500	500	-	5.7—25	4.2—94
2500	1000	-	7.4—41	5.7—150
2500	2200	-	-	12—180

the cross-section is more stringent (smaller) for lighter neutralino masses at smaller decay lengths, while at larger decay lengths heavier neutralino masses produce more stringent (smaller) upper-limits on the cross-section. This is consistent with higher mass neutralinos having higher signal efficiency in general due to having more energetic decay leptons, but often having lower signal efficiency due to having a larger decay length.

For all neutralino masses studied in the electroweakino production model (except for 100 GeV), the upper limits of the cross section are $\mathcal{O}(1) \text{ fb}^{-1}$ at decay lengths ($c\tau$) of 1 mm, improve to $\mathcal{O}(10^{-1}) \text{ fb}^{-1}$ for intermediate decay lengths, and increase back to $\mathcal{O}(1) \text{ fb}^{-1}$ at longer decay lengths. The upper limits on the cross-section at 100 GeV are an order of magnitude larger (weaker) due to the significantly lower signal efficiency; however, because the theoretical cross-section is even larger, all lifetimes are excluded. The theoretical cross-section is lower for higher neutralino masses. All lifetimes are excluded for neutralino masses up to 700 GeV; for higher neutralino masses, smaller lifetime ranges are excluded.

8.3 Comparison to Other SUSY Searches

Many analyses have searched for SUSY using gluino or electroweakino models [96–99]; however, most of these analyses assume prompt decays. Even the inclusion of RPV couplings does not always induce some particles to be long lived, so many RPV searches still assume prompt decays [100–105]. The inclusion of LLPs in the model makes comparison to most of these analyses difficult because this search is analyzing a different phase space.

Table 8.4: Excluded $\tilde{\chi}_1^0$ lifetimes for the electroweakino-production model, assuming 100% branching ratio to leptons for the $\tilde{\chi}_1^0$ decay. The threshold for exclusion is the theoretical cross-sections listed in Table 8.4. A value of 1 (10000) mm means that the theoretical cross-section was excluded at the minimum (maximum) decay length ($c\tau$) considered.

$\tilde{\chi}_1^0$ mass (GeV)	ee Excluded $c\tau$ (mm)	$e\mu$ Excluded $c\tau$ (mm)	$\mu\mu$ Excluded $c\tau$ (mm)
100	1—10000	1—10000	1—10000
300	1—10000	1—10000	1—10000
500	1—10000	1—10000	1—10000
700	1—10000	1—10000	1—10000
900	1.1—2900	1—3800	1—7500
1100	2.0—737	1.7—1200	2.2—2400
1300	5.2—150	4.4—250	5.7—610

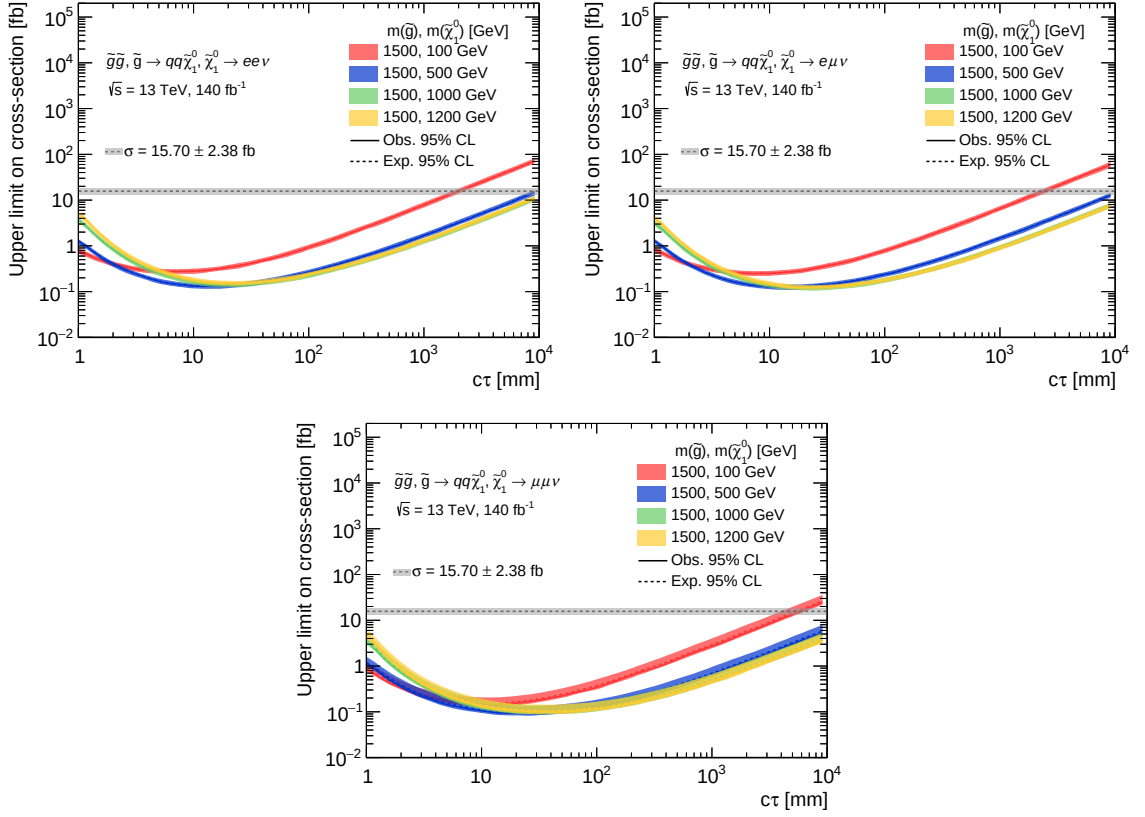


Figure 8.1: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the gluino-produced $\tilde{\chi}_1^0$ with a gluino mass of 1500 GeV and $\tilde{\chi}_1^0$ masses of 100, 500, 1000, and 1200 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of gluinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

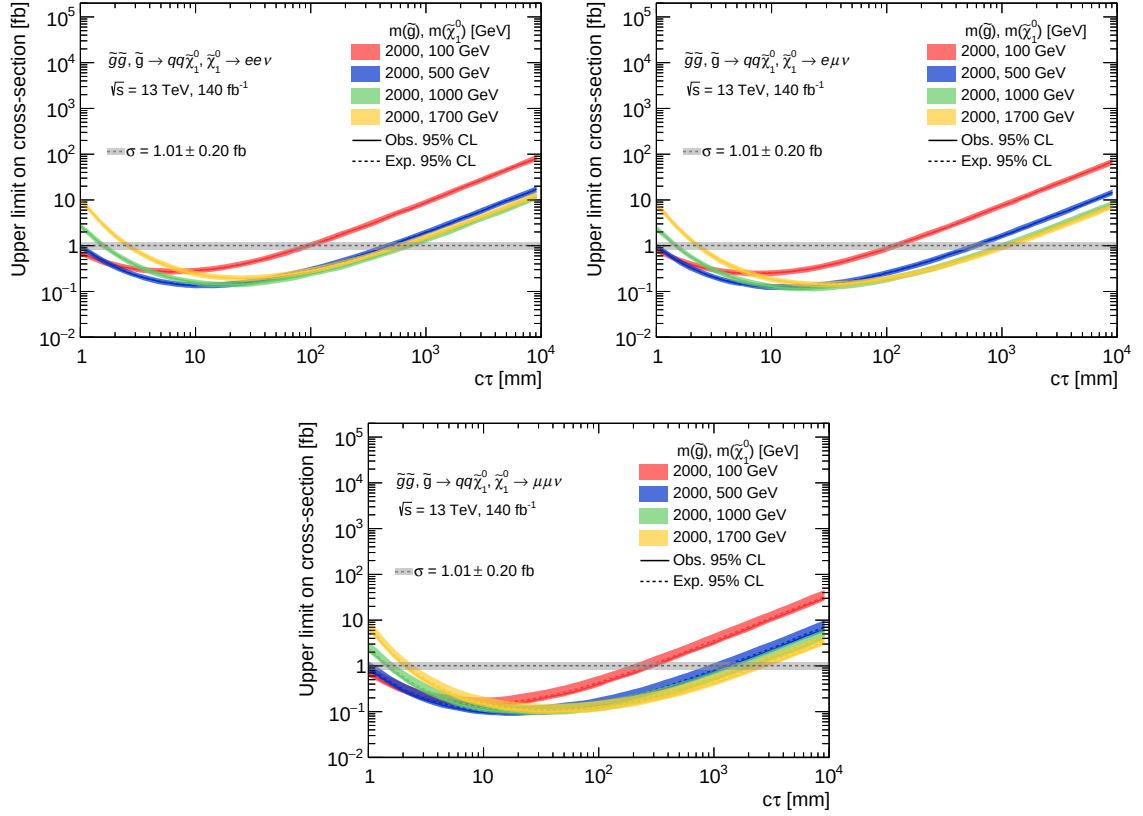


Figure 8.2: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the gluino-produced $\tilde{\chi}_1^0$ with a gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ masses of 100, 500, 1000, and 1700 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of gluinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

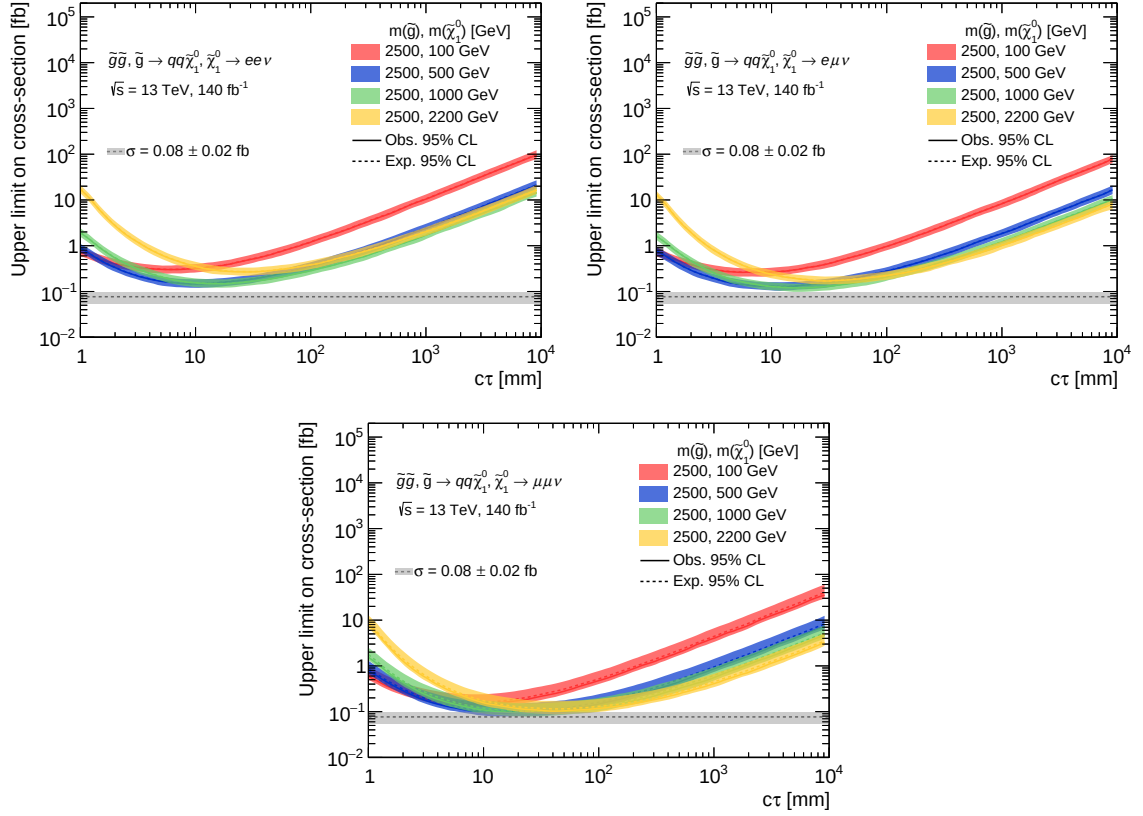


Figure 8.3: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the gluino-produced $\tilde{\chi}_1^0$ with a gluino mass of 2500 GeV and $\tilde{\chi}_1^0$ masses of 100, 500, 1000, and 2200 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of gluinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

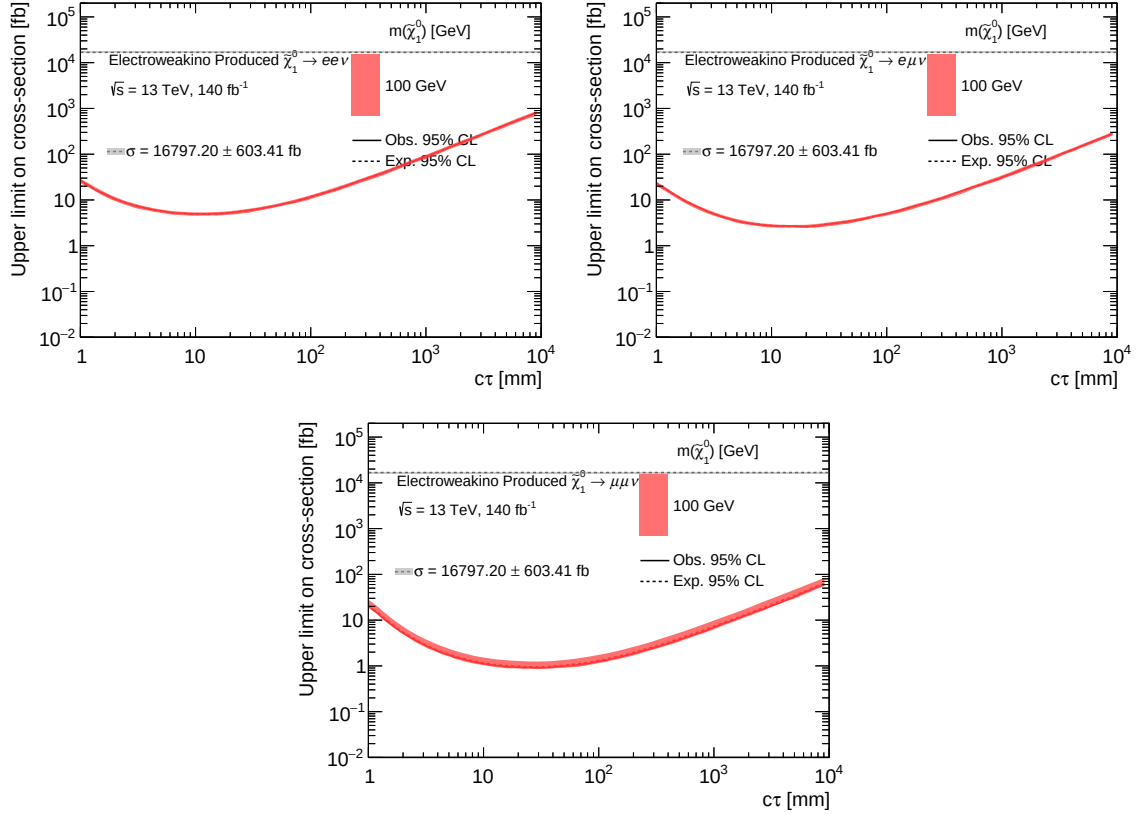


Figure 8.4: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the electroweakino-produced $\tilde{\chi}_1^0$ with a mass of 100 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of electroweakinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

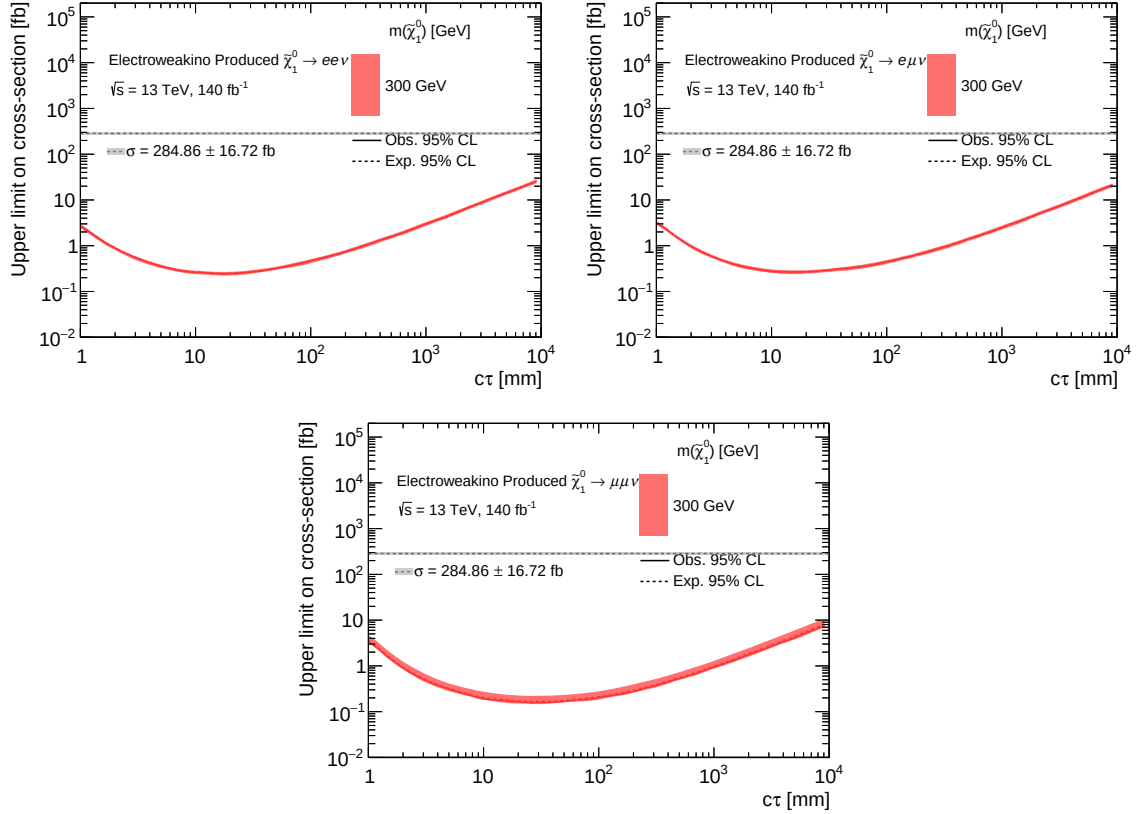


Figure 8.5: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the electroweakino-produced $\tilde{\chi}_1^0$ with a mass of 300 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of electroweakinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

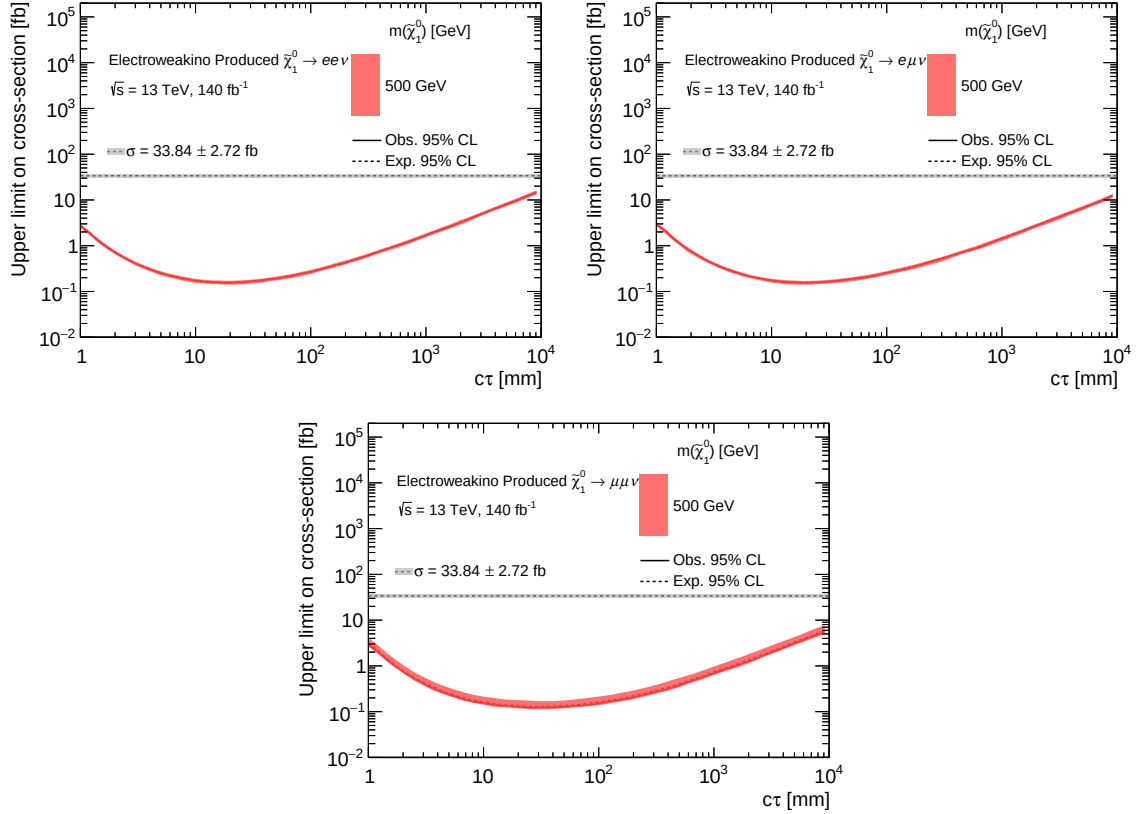


Figure 8.6: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the electroweakino-produced $\tilde{\chi}_1^0$ with a mass of 500 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of electroweakinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

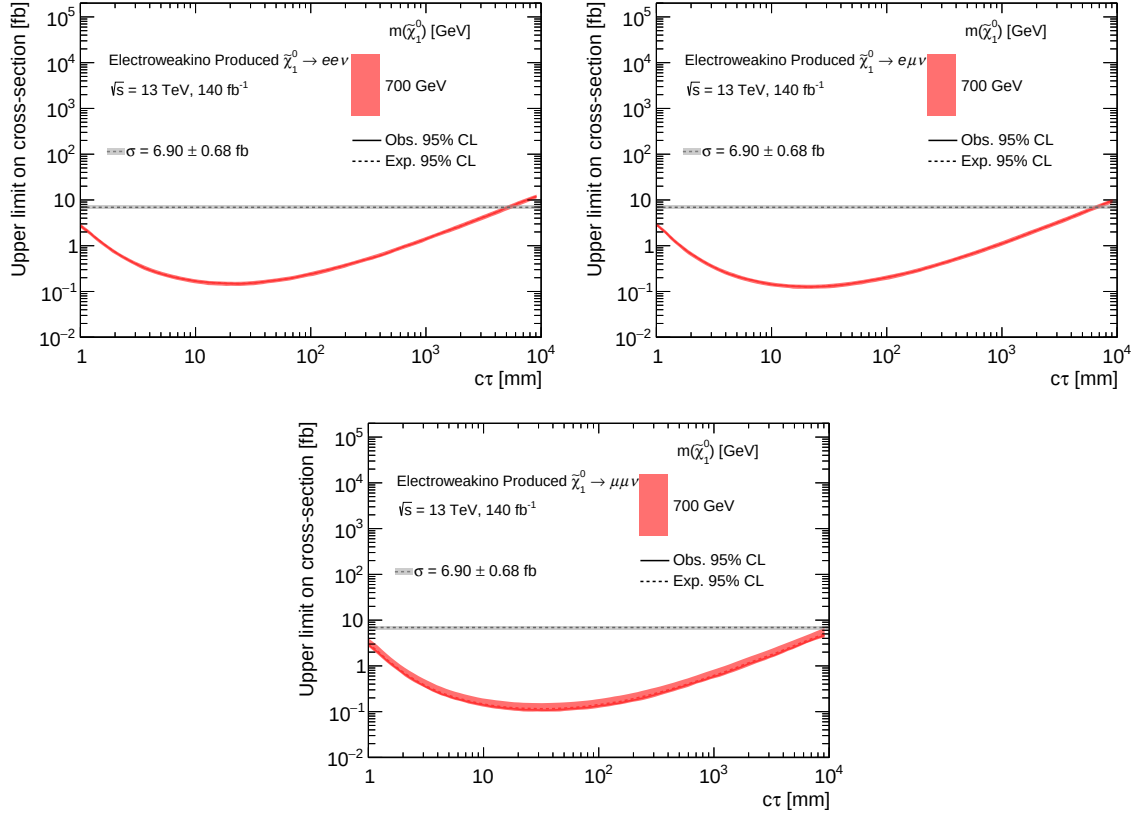


Figure 8.7: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the electroweakino-produced $\tilde{\chi}_1^0$ with a mass of 700 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of electroweakinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

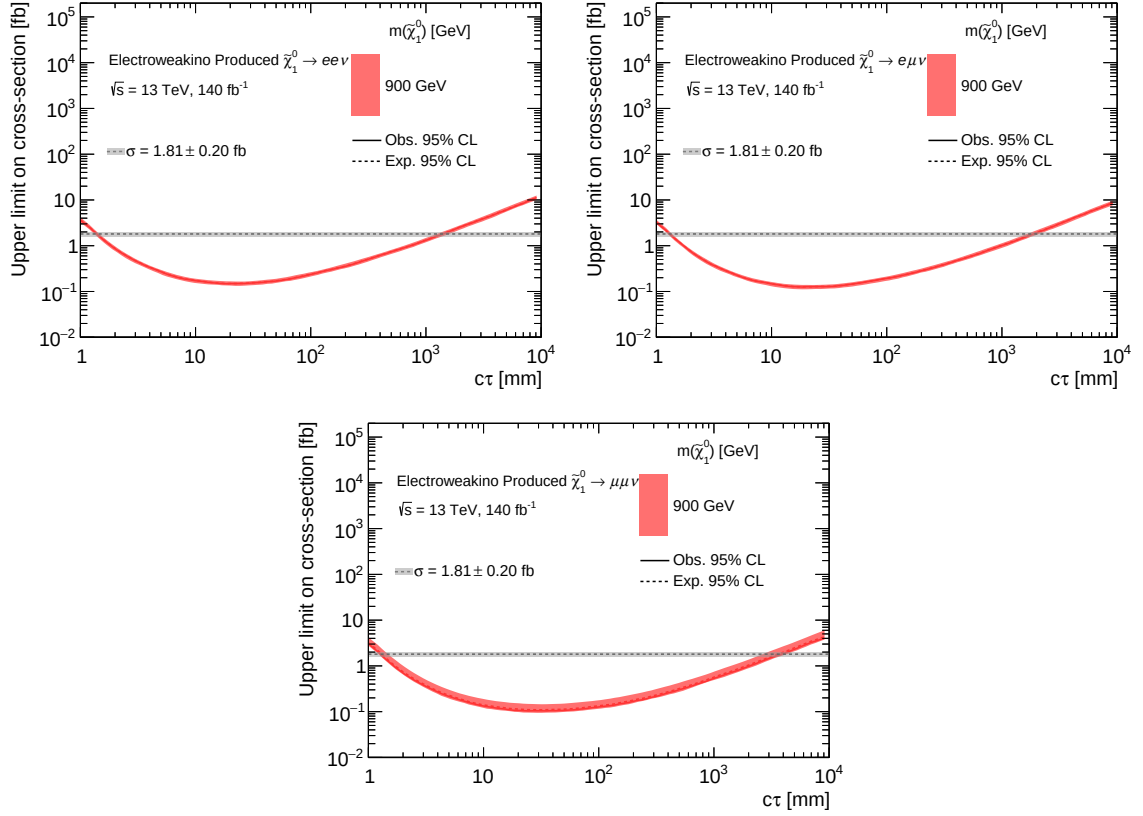


Figure 8.8: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the electroweakino-produced $\tilde{\chi}_1^0$ with a $\tilde{\chi}_1^0$ mass of 900 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of electroweakinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

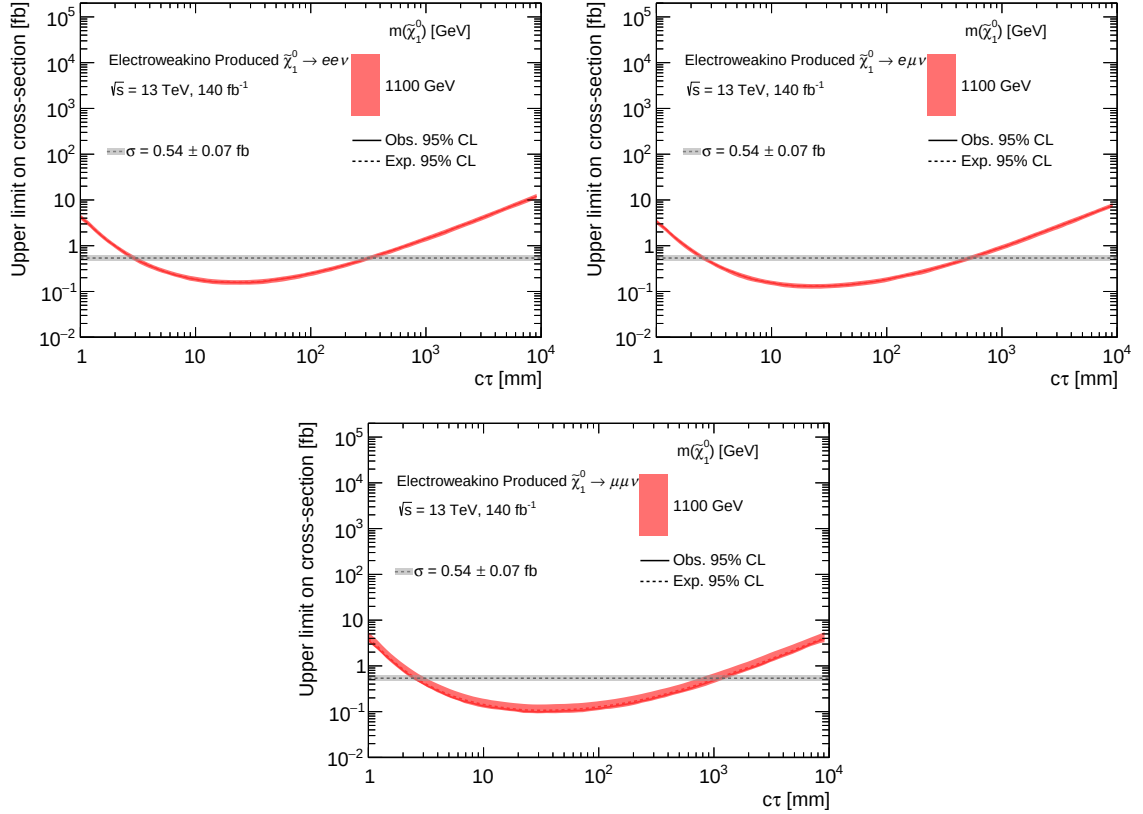


Figure 8.9: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the electroweakino-produced $\tilde{\chi}_1^0$ with a mass of 1000 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of electroweakinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

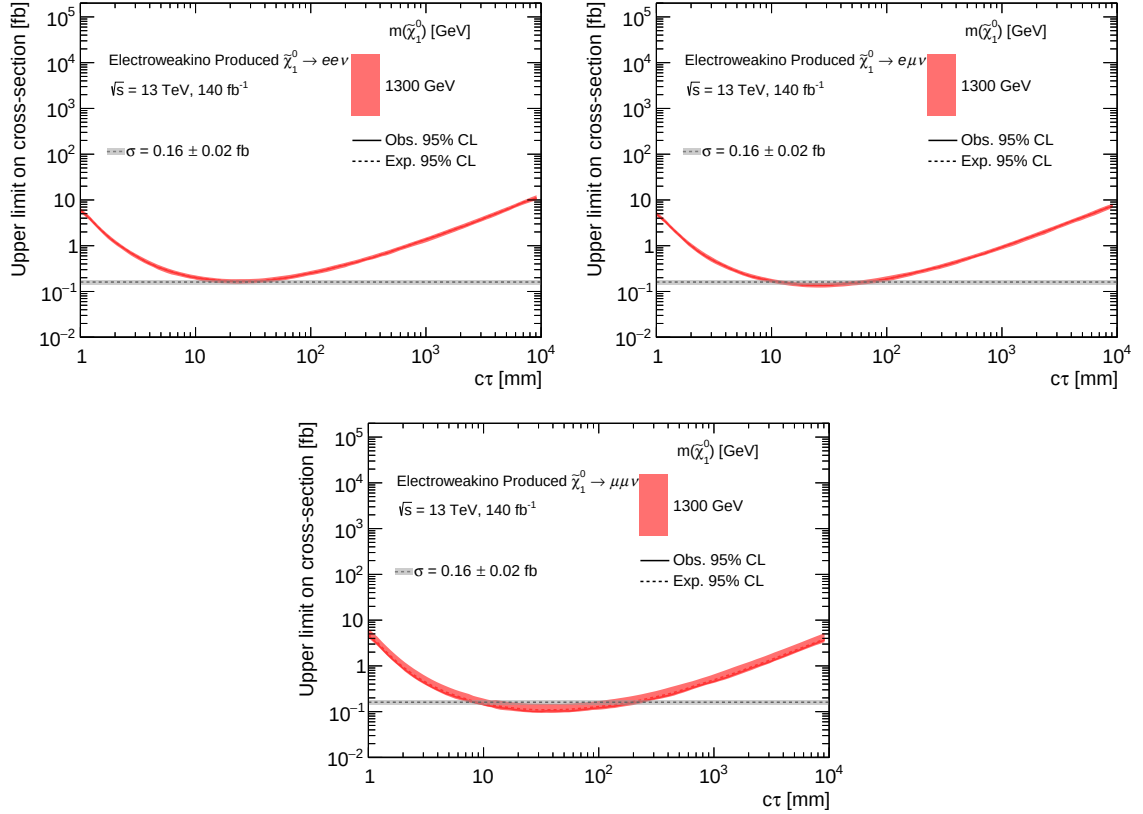


Figure 8.10: Observed and expected limits on production cross-section at the 95% CL as a function of decay length ($c\tau$) for the electroweakino-produced $\tilde{\chi}_1^0$ with a mass of 1300 GeV decaying to $ee\nu$ (top left), $e\mu\nu$ (top right), and $\mu\mu\nu$ (bottom) final states. The cross-section is for the pair production of electroweakinos with both neutralinos decaying into the leptonic decay mode of interest, with at least one of the decays detected. The colored bands represent the total uncertainty.

Nevertheless, there are searches for SUSY with displaced decays. Neutral LLP searches in ATLAS include: a search for isolated displaced leptons with no requirement that they form vertices [106], a search for a DV and a prompt lepton in the same event [107], a search for delayed di-electron and di-photon vertices reconstructed using only calorimeter information [108], and a search for displaced jets [109]. Most relevant is a previous version of this analysis with similar signal selections that was performed on 32.8 fb^{-1} of data collected in 2015 and 2016, using somewhat different benchmark models [110].

Similar searches in CMS include: a search displaced dilepton vertices in the inner tracking volume of the CMS detector using Run 1 data [111], a search for displaced leptons using Run 1 data [112]. Most comparable to this search is an analysis that uses early Run 3 data to search for displaced di-muon vertices [113].

None of these searches include both of the defining parameters of the this analysis's models: (1) a long-lived neutralino with (2) gluino or electroweakino production. Many of the models assume the gluino or electroweakino is long-lived and the neutralino LSP is stable, so there is no direct comparison to their limits. The most relevant models with the neutralino as the long-lived particle were used in the search for a DV and a prompt lepton [107] and the previous iteration of this analysis [110]. The former used a model with the decays of a W boson, not directly from the production of a more massive SUSY particle. The previous version of this analysis used a model with pair production squarks instead of gluino or electroweakino production. Nevertheless, the new limits are approximately three times lower for SUSY particles of similar masses, as expected due to the increase in integrated luminosity. This analysis also covers a wider range of masses including higher masses, therefore the limits for these mass points are the first limits set by experiment.

This lack of overlap between analyses is not a surprise. The field of high energy physics wants to cover as many experimental signatures as possible [114] given that there is no firm prediction for how evidence of SUSY would manifest. Just as this analysis does not include jets or MET in the signal region, many SUSY analyses aim to make the experimental signature as model-independent as possible to allow for results to be reinterpreted in the context of new models. For example, this search has already been interpreted for a separate long-lived Z' model [89] that does not involve SUSY. Public data such as HEPData [115] are specifically designed for high energy theorists to test existing models and develop new models based on results from searches like this one. The data from this search will be published in HEPData so that it can be used to test other theoretical models.

Chapter 9

CONCLUSION

This dissertation has presented the search for displaced di-lepton vertices in the inner tracking detector in ATLAS. No such vertices were observed. Results were interpreted for RPV SUSY models of a long-lived neutralino that was produced via gluino pair production or electroweakino pair production. There are some improvements that could be implemented to enhance sensitivity in order to further improve these limits (or discover new particles), some of which have already been implemented for LHC Run 3. There is a new di-muon trigger using only MS information with a p_T threshold of 60 GeV, significantly lower than the single muon p_T threshold of 160 GeV used in this analysis. Similarly, the DV-reconstruction algorithm that is fundamental to this analysis has been improved, decreasing the background by an order of magnitude for decay lengths ($c\tau$) larger than 100 mm. This may allow the signal selection for this analysis to be loosened, increasing signal efficiency.

While no evidence of SUSY has been found by LHC experiments, additional searches should be pursued. Every experimental signature that is excluded gets the field of particle physics closer to the goal of finding an experimentally verified BSM theory that explains the parts of the universe that are still not understood.

BIBLIOGRAPHY

- [1] P. W. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, Phys. Rev. Lett. **13** (16 1964) 508, URL: <https://link.aps.org/doi/10.1103/PhysRevLett.13.508> (cit. on pp. 1, 5).
- [2] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, Phys. Rev. Lett. **13** (9 1964) 321, URL: <https://link.aps.org/doi/10.1103/PhysRevLett.13.321> (cit. on pp. 1, 5).
- [3] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, Phys. Lett. **12** (1964) 132, URL: <https://cds.cern.ch/record/641590> (cit. on p. 1).
- [4] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, *Global Conservation Laws and Massless Particles*, Phys. Rev. Lett. **13** (20 1964) 585, URL: <https://link.aps.org/doi/10.1103/PhysRevLett.13.585> (cit. on p. 1).
- [5] P. W. Higgs, *Spontaneous Symmetry Breakdown without Massless Bosons*, Phys. Rev. **145** (4 1966) 1156, URL: <https://link.aps.org/doi/10.1103/PhysRev.145.1156> (cit. on p. 1).
- [6] T. W. B. Kibble, *Symmetry Breaking in Non-Abelian Gauge Theories*, Phys. Rev. **155** (5 1967) 1554, URL: <https://link.aps.org/doi/10.1103/PhysRev.155.1554> (cit. on p. 1).
- [7] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Physics Letters B **716** (2012) 1, URL: <https://doi.org/10.1016%2Fj.physletb.2012.08.020> (cit. on pp. 1, 3, 4, 6, 16).
- [8] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Physics Letters B **716** (2012) 30, URL: <https://doi.org/10.1016%2Fj.physletb.2012.08.021> (cit. on pp. 1, 3, 4, 6, 16).
- [9] C. Burgess and G. Moore, *The Standard Model: A Primer*, Cambridge University Press, 2006 (cit. on pp. 3, 5).

- [10] S. Abachi et al., *Observation of the Top Quark*, Physical Review Letters **74** (1995) 2632, ISSN: 1079-7114, URL: <http://dx.doi.org/10.1103/PhysRevLett.74.2632> (cit. on p. 3).
- [11] M. Lubej, *Standard Model*, 2015, URL: <https://www.physik.uzh.ch/groups/serra/StandardModel.html> (visited on 06/01/2024) (cit. on p. 4).
- [12] G. Aad et al., *Combined Measurement of the Higgs Boson Mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ Decay Channels with the ATLAS Detector Using $\sqrt{s} = 7, 8$, and 13 TeV pp Collision Data*, Phys. Rev. Lett. **131** (25 2023) 251802, URL: <https://link.aps.org/doi/10.1103/PhysRevLett.131.251802> (cit. on pp. 4, 7).
- [13] K. G. Wilson, *Confinement of quarks*, Phys. Rev. D **10** (8 1974) 2445, URL: <https://link.aps.org/doi/10.1103/PhysRevD.10.2445> (cit. on p. 4).
- [14] D. J. Gross and F. Wilczek, *Ultraviolet Behavior of Non-Abelian Gauge Theories*, Phys. Rev. Lett. **30** (26 1973) 1343, URL: <https://link.aps.org/doi/10.1103/PhysRevLett.30.1343> (cit. on p. 5).
- [15] M. DREWES, *THE PHENOMENOLOGY OF RIGHT HANDED NEUTRINOS*, International Journal of Modern Physics E **22** (2013) 1330019, ISSN: 1793-6608, URL: <http://dx.doi.org/10.1142/S0218301313300191> (cit. on p. 5).
- [16] V. A. Kostelecký, *Gravity, Lorentz violation, and the standard model*, Phys. Rev. D **69** (10 2004) 105009, URL: <https://link.aps.org/doi/10.1103/PhysRevD.69.105009> (cit. on p. 6).
- [17] M. H. Ahn, S. Aoki, H. Bhang, et al., *Indications of Neutrino Oscillation in a 250 km Long-Baseline Experiment*, Phys. Rev. Lett. **90** (4 2003) 041801, URL: <https://link.aps.org/doi/10.1103/PhysRevLett.90.041801> (cit. on p. 6).
- [18] D. Clowe et al., *A Direct Empirical Proof of the Existence of Dark Matter**, The Astrophysical Journal **648** (2006) L109, URL: <https://dx.doi.org/10.1086/508162> (cit. on p. 6).
- [19] S. P. MARTIN, “A SUPERSYMMETRY PRIMER”, *Advanced Series on Directions in High Energy Physics*, WORLD SCIENTIFIC, 1998 1, URL: http://dx.doi.org/10.1142/9789812839657_0001 (cit. on pp. 7–10).
- [20] K. Abe et al., *Search for proton decay via $p \rightarrow e^+ \pi^0$ and $p \rightarrow \mu^+ \pi^0$ in 0.31 megaton-years exposure of the Super-Kamiokande water Cherenkov detector*, Phys. Rev. D **95** (1 2017) 012004, URL: <https://link.aps.org/doi/10.1103/PhysRevD.95.012004> (cit. on p. 8).
- [21] I. J. R. Aitchison, *Supersymmetry in Particle Physics. An Elementary Introduction*, Cambridge University Press, 2007, ISBN: 978-0-511-61925-0 (cit. on p. 8).

- [22] G. Bertone, D. Hooper, and J. Silk, *Particle dark matter: evidence, candidates and constraints*, Physics Reports **405** (2005) 279, URL: <https://doi.org/10.1016/j.physrep.2004.08.031> (cit. on p. 8).
- [23] E. Witten, *Dynamical breaking of supersymmetry*, Nuclear Physics B **188** (1981) 513, ISSN: 0550-3213, URL: <https://www.sciencedirect.com/science/article/pii/0550321381900067> (cit. on p. 9).
- [24] R. Barbieri and G. F. Giudice, *Upper Bounds on Supersymmetric Particle Masses*, Nucl. Phys. B **306** (1988) 63 (cit. on p. 10).
- [25] R. Barbier et al., *R-Parity-violating supersymmetry*, Physics Reports **420** (2005) 1, ISSN: 0370-1573, URL: <http://dx.doi.org/10.1016/j.physrep.2005.08.006> (cit. on p. 11).
- [26] H. K. Dreiner et al., *The ABC of RPV: classification of R-parity violating signatures at the LHC for small couplings*, JHEP **07** (2023) 215, arXiv: 2306.07317 [hep-ph] (cit. on pp. 12, 41).
- [27] D. Alves et al., *Simplified models for LHC new physics searches*, Journal of Physics G: Nuclear and Particle Physics **39** (2012) 105005, ISSN: 1361-6471, URL: <http://dx.doi.org/10.1088/0954-3899/39/10/105005> (cit. on p. 12).
- [28] A. Canepa, T. Han, and X. Wang, *The Search for Electroweakinos*, Annual Review of Nuclear and Particle Science **70** (2020) 425, ISSN: 1545-4134, URL: <https://www.annualreviews.org/content/journals/10.1146/annurev-nucl-031020-121031> (cit. on p. 12).
- [29] A. H. Chamseddine, R. Arnowitt, and P. Nath, *Locally Supersymmetric Grand Unification*, Phys. Rev. Lett. **49** (14 1982) 970, URL: <https://link.aps.org/doi/10.1103/PhysRevLett.49.970> (cit. on p. 12).
- [30] R. Barbieri, S. Ferrara, and C. Savoy, *Gauge models with spontaneously broken local supersymmetry*, Physics Letters B **119** (1982) 343, ISSN: 0370-2693, URL: <https://www.sciencedirect.com/science/article/pii/0370269382906852> (cit. on p. 12).
- [31] L. Ibáñez, *Locally supersymmetric SU(5) grand unification*, Physics Letters B **118** (1982) 73, ISSN: 0370-2693, URL: <https://www.sciencedirect.com/science/article/pii/0370269382906049> (cit. on p. 12).
- [32] L. Randall and R. Sundrum, *Out of this world supersymmetry breaking*, Nuclear Physics B **557** (1999) 79, ISSN: 0550-3213, URL: [http://dx.doi.org/10.1016/S0550-3213\(99\)00359-4](http://dx.doi.org/10.1016/S0550-3213(99)00359-4) (cit. on p. 12).

- [33] T. Gherghetta, G. F. Giudice, and J. D. Wells, *Phenomenological consequences of supersymmetry with anomaly induced masses*, Nuclear Physics B **559** (1999) 27, ISSN: 0550-3213, URL: [http://dx.doi.org/10.1016/S0550-3213\(99\)00429-0](http://dx.doi.org/10.1016/S0550-3213(99)00429-0) (cit. on p. 12).
- [34] L. J. Hall, D. Pinner, and J. T. Ruderman, *A natural SUSY Higgs near 125 GeV*, Journal of High Energy Physics **2012** (2012), ISSN: 1029-8479, URL: [http://dx.doi.org/10.1007/JHEP04\(2012\)131](http://dx.doi.org/10.1007/JHEP04(2012)131) (cit. on p. 12).
- [35] H. Baer, V. Barger, P. Huang, A. Mustafayev, and X. Tata, *Radiative Natural Supersymmetry with a 125 GeV Higgs Boson*, Phys. Rev. Lett. **109** (16 2012) 161802, URL: <https://link.aps.org/doi/10.1103/PhysRevLett.109.161802> (cit. on p. 12).
- [36] L. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001 (cit. on p. 13).
- [37] *LEP design report*, Report, By the LEP Injector Study Group, CERN, 1983, URL: <https://cds.cern.ch/record/98881> (cit. on p. 13).
- [38] O. S. Brüning et al., *LHC Design Report*, CERN Yellow Reports: Monographs, CERN, 2004, URL: <https://cds.cern.ch/record/782076> (cit. on p. 13).
- [39] M. Bajko et al., *Report of the Task Force on the Incident of 19th September 2008 at the LHC*, tech. rep., CERN, 2009, URL: <https://cds.cern.ch/record/1168025> (cit. on p. 13).
- [40] C. Service graphique, *Overall view of the LHC. Vue d'ensemble du LHC*, (2014), General Photo, URL: <https://cds.cern.ch/record/1708849> (cit. on p. 14).
- [41] ATLAS Collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, (2022), arXiv: 2212.09379 [hep-ex] (cit. on pp. 15, 40, 89).
- [42] ATLAS Collaboration, *Luminosity Public Results Run 2*, <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2>, URL: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2> (visited on 05/06/2024) (cit. on p. 15).
- [43] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003 (cit. on pp. 16, 17, 19, 21, 23, 25, 80).
- [44] CMS Collaboration, *The CMS Experiment at the CERN LHC*, JINST **3** (2008) S08004 (cit. on p. 16).
- [45] T. A. Collaboration, *The ALICE experiment at the CERN LHC*, Journal of Instrumentation **3** (2008) S08002, URL: <https://dx.doi.org/10.1088/1748-0221/3/08/S08002> (cit. on p. 16).

- [46] T. L. Collaboration, *The LHCb Detector at the LHC*, Journal of Instrumentation **3** (2008) S08005, URL: <https://dx.doi.org/10.1088/1748-0221/3/08/S08005> (cit. on p. 16).
- [47] B. Abbott et al., *Production and integration of the ATLAS Insertable B-Layer*, JINST **13** (2018) T05008, arXiv: 1803.00844 [physics.ins-det] (cit. on pp. 19, 20).
- [48] ATLAS Collaboration, *ATLAS Calorimeter Performance: Technical Design Report*, ATLAS-TDR-1; CERN-LHCC-96-040, 1996, URL: <https://cds.cern.ch/record/331059> (cit. on p. 21).
- [49] ATLAS Collaboration, *ATLAS Liquid Argon Calorimeter: Technical Design Report*, ATLAS-TDR-2; CERN-LHCC-96-041, 1996, URL: <https://cds.cern.ch/record/331061> (cit. on pp. 21, 24).
- [50] ATLAS Collaboration, *ATLAS Tile Calorimeter: Technical Design Report*, ATLAS-TDR-3; CERN-LHCC-96-042, 1996, URL: <https://cds.cern.ch/record/331062> (cit. on pp. 21, 24).
- [51] ATLAS Collaboration, *ATLAS Inner Detector: Technical Design Report, Volume 1*, ATLAS-TDR-4; CERN-LHCC-97-016, 1997, URL: <https://cds.cern.ch/record/331063> (cit. on pp. 21, 22).
- [52] ATLAS Collaboration, *ATLAS Inner Detector: Technical Design Report, Volume 2*, ATLAS-TDR-5; CERN-LHCC-97-017, 1997, URL: <https://cds.cern.ch/record/331064> (cit. on p. 21).
- [53] ATLAS Collaboration, *ATLAS Magnet System: Magnet Project Technical Design Report, Volume 1*, ATLAS-TDR-6; CERN-LHCC-97-018, 1997, URL: <https://cds.cern.ch/record/338080> (cit. on p. 21).
- [54] ATLAS Collaboration, *ATLAS Barrel Toroid: Magnet Project Technical Design Report, Volume 2*, ATLAS-TDR-7; CERN-LHCC-97-019, 1997, URL: <https://cds.cern.ch/record/331065> (cit. on p. 21).
- [55] ATLAS Collaboration, *ATLAS End-Cap Toroids: Magnet Project Technical Design Report, Volume 3*, ATLAS-TDR-8; CERN-LHCC-97-020, CERN, 1997, URL: <https://cds.cern.ch/record/331066> (cit. on p. 21).
- [56] ATLAS Collaboration, *ATLAS Central Solenoid: Magnet Project Technical Design Report, Volume 4*, ATLAS-TDR-9; CERN-LHCC-97-021, CERN, 1997, URL: <https://cds.cern.ch/record/331067> (cit. on p. 21).
- [57] K. K. Gan et al., *Design, production, and reliability of the new ATLAS pixel opto-boards*, JINST **10** (2015) C02018, URL: <https://cds.cern.ch/record/2158936> (cit. on p. 21).

- [58] ATLAS Collaboration, *ATLAS Muon Spectrometer: Technical Design Report*, ATLAS-TDR-10; CERN-LHCC-97-022, CERN, 1997, URL: <https://cds.cern.ch/record/331068> (cit. on p. 25).
- [59] P. F. Åkesson et al., *ATLAS Tracking Event Data Model*, tech. rep., CERN, 2006, URL: <https://cds.cern.ch/record/973401> (cit. on p. 29).
- [60] ATLAS Collaboration, *ATLAS Track Reconstruction – General Overview*, <https://atlassoftwaredocs.web.cern.ch/trackingTutorial/idooverview/>, URL: <https://atlassoftwaredocs.web.cern.ch/trackingTutorial/idooverview/> (visited on 05/12/2024) (cit. on pp. 30, 31).
- [61] ATLAS Collaboration, *Performance of the ATLAS track reconstruction algorithms in dense environments in LHC Run 2*, The European Physical Journal C **77** (2017) 673, URL: <https://doi.org/10.1140%2Fepjc%2Fs10052-017-5225-7> (cit. on pp. 30, 31).
- [62] R. Frühwirth, *Application of Kalman filtering to track and vertex fitting*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **262** (1987) 444, ISSN: 0168-9002, URL: <https://www.sciencedirect.com/science/article/pii/0168900287908874> (cit. on p. 30).
- [63] *Performance of the reconstruction of large impact parameter tracks in the ATLAS inner detector*, tech. rep., CERN, 2017, URL: <https://cds.cern.ch/record/2275635> (cit. on pp. 31, 32).
- [64] K. Grimm et al., *Primary vertex reconstruction at the ATLAS experiment*, tech. rep. 4, CERN, 2017, URL: <https://cds.cern.ch/record/2253428> (cit. on pp. 32, 34).
- [65] *Performance of vertex reconstruction algorithms for detection of new long-lived particle decays within the ATLAS inner detector*, tech. rep., CERN, 2019, URL: <https://cds.cern.ch/record/2669425> (cit. on pp. 33, 34, 36).
- [66] M. Aaboud, G. Aad, B. Abbott, and D. C. Abbott, *Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton-proton collision data at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **79** (2019) 639, arXiv: 1902.04655, URL: <https://cds.cern.ch/record/2657964> (cit. on p. 37).
- [67] G. Aad, B. Abbott, D. C. Abbott, A. Abed Abud, and K. Abeling, *Electron and photon performance measurements with the ATLAS detector using the 2015-2017 LHC proton-proton collision data*, JINST **14** (2019) P12006, arXiv: 1908.00005, URL: <https://cds.cern.ch/record/2684552> (cit. on pp. 37, 38).

- [68] W. Lampl et al., *Calorimeter Clustering Algorithms: Description and Performance*, tech. rep., CERN, 2008, URL: <https://cds.cern.ch/record/1099735> (cit. on p. 37).
- [69] M. Aaboud, G. Aad, B. Abbott, O. Abdinov, and B. Abeloos, *Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016*, Eur. Phys. J. C **79** (2019) 205, arXiv: 1810.05087, URL: <https://cds.cern.ch/record/2643391> (cit. on p. 37).
- [70] ATLAS Collaboration, *Improved electron reconstruction in ATLAS using the Gaussian Sum Filter-based model for bremsstrahlung*, tech. rep. ATLAS-CONF-2012-047, CERN, 2012, URL: <https://cds.cern.ch/record/1449796> (cit. on p. 37).
- [71] G. Aad, B. K. Abbott, B. Abbott, and D. C. Abbott, *Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV*, Eur. Phys. J., C **81** (2021) 578, arXiv: 2012.00578, URL: <https://cds.cern.ch/record/2746302> (cit. on p. 38).
- [72] G. Aad et al., *Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s}=13$ TeV. Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s}=13$ TeV*, Eur. Phys. J. C **76** (2016) 292, arXiv: 1603.05598, URL: <https://cds.cern.ch/record/2139897> (cit. on p. 38).
- [73] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, JINST **13** (2018) P07017 (cit. on pp. 40, 89).
- [74] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, Journal of High Energy Physics **2014** (2014), ISSN: 1029-8479, URL: [http://dx.doi.org/10.1007/JHEP07\(2014\)079](http://dx.doi.org/10.1007/JHEP07(2014)079) (cit. on p. 42).
- [75] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, Computer Physics Communications **191** (2015) 159, ISSN: 0010-4655, URL: <http://dx.doi.org/10.1016/j.cpc.2015.01.024> (cit. on pp. 42, 46).
- [76] R. D. Ball et al., *Parton distributions with QED corrections*, Nucl. Phys. B **877** (2013) 290, arXiv: 1308.0598, URL: <https://cds.cern.ch/record/1566755> (cit. on pp. 42, 89).
- [77] C. Borschensky et al., *Squark and gluino production cross sections in pp collisions at $\sqrt{s} = 13, 14, 33$ and 100 TeV*, The European Physical Journal C **74** (2014), ISSN: 1434-6052, URL: <http://dx.doi.org/10.1140/epjc/s10052-014-3174-y> (cit. on pp. 43, 89).

- [78] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, *Gaugino production in proton-proton collisions at a center-of-mass energy of 8 TeV*, JHEP **10** (2012) 081, arXiv: 1207.2159 [hep-ph] (cit. on pp. 43, 89).
- [79] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, *Precision predictions for electroweak superpartner production at hadron colliders with RESUMMINO*, Eur. Phys. J. C **73** (2013) 2480, arXiv: 1304.0790 [hep-ph] (cit. on pp. 43, 89).
- [80] S. Frixione, P. Nason, and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, Journal of High Energy Physics **2007** (2007) 070, ISSN: 1029-8479, URL: <http://dx.doi.org/10.1088/1126-6708/2007/11/070> (cit. on p. 46).
- [81] R. D. Ball et al., *Parton distributions for the LHC run II*, Journal of High Energy Physics **2015** (2015), ISSN: 1029-8479, URL: [http://dx.doi.org/10.1007/JHEP04\(2015\)040](http://dx.doi.org/10.1007/JHEP04(2015)040) (cit. on p. 46).
- [82] M. Aaboud et al., *Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Journal of High Energy Physics **2016** (2016), ISSN: 1029-8479, URL: [http://dx.doi.org/10.1007/JHEP06\(2016\)059](http://dx.doi.org/10.1007/JHEP06(2016)059) (cit. on p. 50).
- [83] ATLAS Collaboration, *Study of the material of the ATLAS inner detector for Run 2 of the LHC*, Journal of Instrumentation **12** (2017) P12009, URL: <https://dx.doi.org/10.1088/1748-0221/12/12/P12009> (cit. on p. 53).
- [84] K. F. Di Petrillo et al., *Search for long-lived, massive particles in events with a displaced vertex and muon in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, tech. rep. ATL-COM-PHYS-2018-1138, CERN, 2018, URL: <https://cds.cern.ch/record/2633973> (cit. on p. 53).
- [85] ATLAS Collaboration, *Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Phys. Rev. D **97** (5 2018) 052012, URL: <https://link.aps.org/doi/10.1103/PhysRevD.97.052012> (cit. on p. 53).
- [86] M. Aoki et al., *Search for long-lived, massive particles in events with a displaced vertex and multiple jets in $\sqrt{s} = 13$ TeV collisions with the ATLAS detector*, tech. rep. ATL-COM-PHYS-2021-1049, CERN, 2021, URL: <https://cds.cern.ch/record/2792409> (cit. on p. 53).
- [87] M. Backhaus, *The upgraded Pixel Detector of the ATLAS Experiment for Run2 at the Large Hadron Collider*, tech. rep. ATL-INDET-PROC-2015-015, CERN, 2016, URL: <https://cds.cern.ch/record/2110260> (cit. on p. 53).

- [88] D. Krauss, “Search for long-lived particles decaying to oppositely charged lepton pairs with the ATLAS experiment at $\sqrt{s} = 13$ TeV”, PhD thesis, 2019, URL: <https://cds.cern.ch/record/2712393> (cit. on p. 67).
- [89] B. Cote, “A search for long-lived neutral particles decaying to oppositely charged lepton pairs in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, Presented 20 Nov 2023, Ohio State U., 2023, URL: <https://cds.cern.ch/record/2882651> (cit. on pp. 80, 109).
- [90] S. H. Oh and C. Wang, *Kshort and Lambda Production In Jets from pp Collisions at 7 TeV Center-of-Mass Energy.*, tech. rep. ATL-COM-PHYS-2014-1258, CERN, 2014, URL: <https://cds.cern.ch/record/1951024> (cit. on p. 85).
- [91] J. C. Burzynski et al., *Search for Higgs boson decays to long-lived scalar particles in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, tech. rep. ATL-COM-PHYS-2020-129, CERN, 2020, URL: <https://cds.cern.ch/record/2711218> (cit. on p. 85).
- [92] *Early Inner Detector Tracking Performance in the 2015 data at $\sqrt{s} = 13$ TeV*, tech. rep. ATL-PHYS-PUB-2015-051, CERN, 2015, URL: <https://cds.cern.ch/record/2110140> (cit. on p. 87).
- [93] W. Buttinger, *Using Event Weights to account for differences in Instantaneous Luminosity and Trigger Prescale in Monte Carlo and Data*, tech. rep. ATL-COM-SOFT-2015-119, CERN, 2015, URL: <https://cds.cern.ch/record/2014726> (cit. on p. 89).
- [94] A. L. Read, *Presentation of search results: the CLs technique*, Journal of Physics G: Nuclear and Particle Physics **28** (2002) 2693, URL: <https://dx.doi.org/10.1088/0954-3899/28/10/313> (cit. on pp. 96, 97).
- [95] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, The European Physical Journal C **71** (2011) 1554, URL: <https://doi.org/10.1140/epjc/s10052-011-1554-0> (cit. on p. 97).
- [96] ATLAS Collaboration, *A statistical combination of ATLAS Run 2 searches for charginos and neutralinos at the LHC*, tech. rep., CERN, 2024, arXiv: 2402.08347, URL: <https://cds.cern.ch/record/2889204> (cit. on p. 98).
- [97] A. Hayrapetyan et al., *Combined search for electroweak production of winos, binos, higgsinos, and sleptons in proton-proton collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. D **109** (2024) 112001, arXiv: 2402.01888, URL: <https://cds.cern.ch/record/2888264> (cit. on p. 98).

- [98] ATLAS Collaboration, *The quest to discover supersymmetry at the ATLAS experiment*, tech. rep., CERN, 2024, arXiv: 2403.02455, URL: <https://cds.cern.ch/record/2890693> (cit. on p. 98).
- [99] A. Hayrapetyan et al., *Searches for pair-produced multijet resonances using data scouting in proton-proton collisions at $\sqrt{s} = 13$ TeV*, tech. rep., CERN, 2024, arXiv: 2404.02992, URL: <https://cds.cern.ch/record/2894460> (cit. on p. 98).
- [100] ATLAS Collaboration, *Search for supersymmetry in events with four or more charged leptons in 139 fb1 of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Journal of High Energy Physics **2021** (2021), ISSN: 1029-8479, URL: [http://dx.doi.org/10.1007/JHEP07\(2021\)167](http://dx.doi.org/10.1007/JHEP07(2021)167) (cit. on p. 98).
- [101] ATLAS Collaboration, *Search for supersymmetry in events with four or more leptons in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, Phys. Rev. D **90** (5 2014) 052001, URL: <https://link.aps.org/doi/10.1103/PhysRevD.90.052001> (cit. on p. 98).
- [102] ATLAS Collaboration, *Search for R-parity-violating supersymmetry in a final state containing leptons and many jets with the ATLAS experiment using $\sqrt{s} = 13$ proton-proton collision data*, The European Physical Journal C **81** (2021), ISSN: 1434-6052, URL: <http://dx.doi.org/10.1140/epjc/s10052-021-09761-x> (cit. on p. 98).
- [103] A. Collaboration, *A search for R-parity-violating supersymmetry in final states containing many jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, 2024, arXiv: 2401.16333 [hep-ex], URL: <https://arxiv.org/abs/2401.16333> (cit. on p. 98).
- [104] ATLAS Collaboration, *Search for pair production of squarks or gluinos decaying via sleptons or weak bosons in final states with two same-sign or three leptons with the ATLAS detector*, Journal of High Energy Physics **2024** (2024), ISSN: 1029-8479, URL: [http://dx.doi.org/10.1007/JHEP02\(2024\)107](http://dx.doi.org/10.1007/JHEP02(2024)107) (cit. on p. 98).
- [105] ATLAS Collaboration, *Search for trilepton resonances from chargino and neutralino pair production in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Phys. Rev. D **103** (11 2021) 112003, URL: <https://link.aps.org/doi/10.1103/PhysRevD.103.112003> (cit. on p. 98).
- [106] ATLAS Collaboration, *Search for displaced leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Phys. Rev. Lett. **127** (2020) 051802, arXiv: 2011.07812 [hep-ex] (cit. on p. 109).

- [107] ATLAS Collaboration, *Search for Heavy Neutral Leptons in Decays of W bosons using a dilepton displaced vertex in $\sqrt{s} = 13$ pp Collisions with the ATLAS Detector*, Physical Review Letters **131** (2023), ISSN: 1079-7114, URL: <http://dx.doi.org/10.1103/PhysRevLett.131.061803> (cit. on p. 109).
- [108] ATLAS Collaboration, *Search in diphoton and dielectron final states for displaced production of Higgs or Z bosons with the ATLAS detector in $\sqrt{s} = 13$ TeV pp collisions*, Phys. Rev. D **108** (2023) 012012, arXiv: 2304.12885 [hep-ex] (cit. on p. 109).
- [109] ATLAS Collaboration, *Search for neutral long-lived particles that decay into displaced jets in the ATLAS calorimeter in association with leptons or jets using pp collisions at $\sqrt{s} = 13$ TeV*, tech. rep., CERN, 2024, URL: <https://cds.cern.ch/record/2904294> (cit. on p. 109).
- [110] ATLAS Collaboration, *Search for displaced vertices of oppositely charged leptons from decays of long-lived particles in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Lett. B **801** (2020) 135114, arXiv: 1907.10037 [hep-ex] (cit. on p. 109).
- [111] CMS Collaboration, *Search for long-lived particles that decay into final states containing two electrons or two muons in proton–proton collisions at $\sqrt{s} = 8$ TeV*, Phys. Rev. D **91** (2015) 052012, arXiv: 1411.6977 [hep-ex] (cit. on p. 109).
- [112] CMS Collaboration, *Search for Displaced Supersymmetry in Events with an Electron and a Muon with Large Impact Parameters*, Phys. Rev. Lett. **114** (2015) 061801, arXiv: 1409.4789 [hep-ex] (cit. on p. 109).
- [113] C. Collaboration, *Search for long-lived particles decaying to final states with a pair of muons in proton-proton collisions at $\sqrt{s} = 13.6$ TeV*, 2024, arXiv: 2402.14491 [hep-ex] (cit. on p. 109).
- [114] J. Alimena et al., *Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider*, Journal of Physics G: Nuclear and Particle Physics **47** (2020) 090501, ISSN: 1361-6471, URL: <http://dx.doi.org/10.1088/1361-6471/ab4574> (cit. on p. 109).
- [115] E. Maguire, L. Heinrich, and G. Watt, *HEPData: a repository for high energy physics data*, Journal of Physics: Conference Series **898** (2017) 102006, ISSN: 1742-6596, URL: <http://dx.doi.org/10.1088/1742-6596/898/10/102006> (cit. on p. 109).

Appendix A

VALIDATION OF TRACK SHIFTING FOR EVENT MIXING

The second validation of the event mixing method described in Section 6.2.4 was a test to validate the shifting of the tracks, which is performed to maintain the d_0 and z_0 of each track with respect to its original PV.

A set of signal MC events were processed by the event-mixing pipeline, but with no actual event-mixing. Instead of randomly selecting tracks and placing them in pairs in a toy event, all selected tracks from the input event are passed to the toy event; the only differences from the original event are that (1) tracks that do not satisfy the requirements of the VSI are not included and (2) a PV from the input dataset is randomly selected for the toy event and all tracks are shifted with respect to that new PV. The event is then processed through the modified DADO_SUSY15 derivation as in the standard event mixing procedure.

If the procedure works, there should be minimal difference in the number of signal DVs between the original event and the toy event that has been through the remaining steps in the event-mixing procedure. There are several reasons a DV might pass or fail depending on its position within the detector, including:

- the DV or tracks moving in or out of the analysis's fiducial region
- the DV moving into or out of a disabled module of the Pixel detector
- the DV movement leading to different hit pattern requirements for tracks
- tracks traversing or not traversing a disabled module
- the DV moving to a different region of the detector, which changes the pixel hit requirements imposed by the VSI on its constituent tracks

As in Section 6.2.2, tracks associated to leptons that do not pass the signal lepton selection criteria are not included in the pool of available tracks for the event mixing. As

with the other validations performed, non-lepton identified tracks that pass all signal lepton selection criteria (except lepton ID and quality) are saved and passed to the VSI.

The dataset used for this validation was a signal MC dataset, chosen because it is more efficient to test reconstruction when a sample is rich in signal DVs. Specifically, the gluino-produced SUSY sample with 2 TeV gluino mass, 100 GeV neutralino mass, and 10 mm neutralino lifetime ($c\tau$) was used. Kinematic distributions for the signal DVs are shown in Figure A.1 and those for signal tracks (whether lepton identified or not) are shown in Figure A.2. The results of this test are shown in Table A.1. Because all selected tracks are copied from the original event, the number of observed track pairs does not change; therefore, multiplying the crossing-probability by the number of observed tracks pairs to calculate the prediction is equivalent to simply counting the signal vertices in the “mixed” events. In these plots, “mixed” refers to events or DVs that have been processed through the event-mixing pipeline, although no event mixing has been performed.

As expected, the new distributions reproduce the original distributions, but not with the perfect accuracy seen in the validation where no shifting took place. The tracks are shifted to maintain d_0 and z_0 with respect to the PV, so the decay position, which is measured with respect to the PV, is maintained; however, the standard calculation of d_0 and z_0 are measured with respect to the beamspot (i.e. not the PV). There is some small variation in track d_0 and z_0 measurements after the shifting corresponding to the variation in PV location with respect to the beamspot. Table A.1 also shows that the perfect reproduction from the validation without shifting has been compromised. The procedure underestimates the observed number of DVs by $\sim 1\%$ in the channels with good statistics (ee , $e\mu$, $\mu\mu$), and matches well with the observations in the other channels, albeit with low statistics.

All the DVs that were either not reproduced or were reconstructed only in the shifted events were investigated to understand the cause. All observed differences were the result of one of the scenarios listed above.

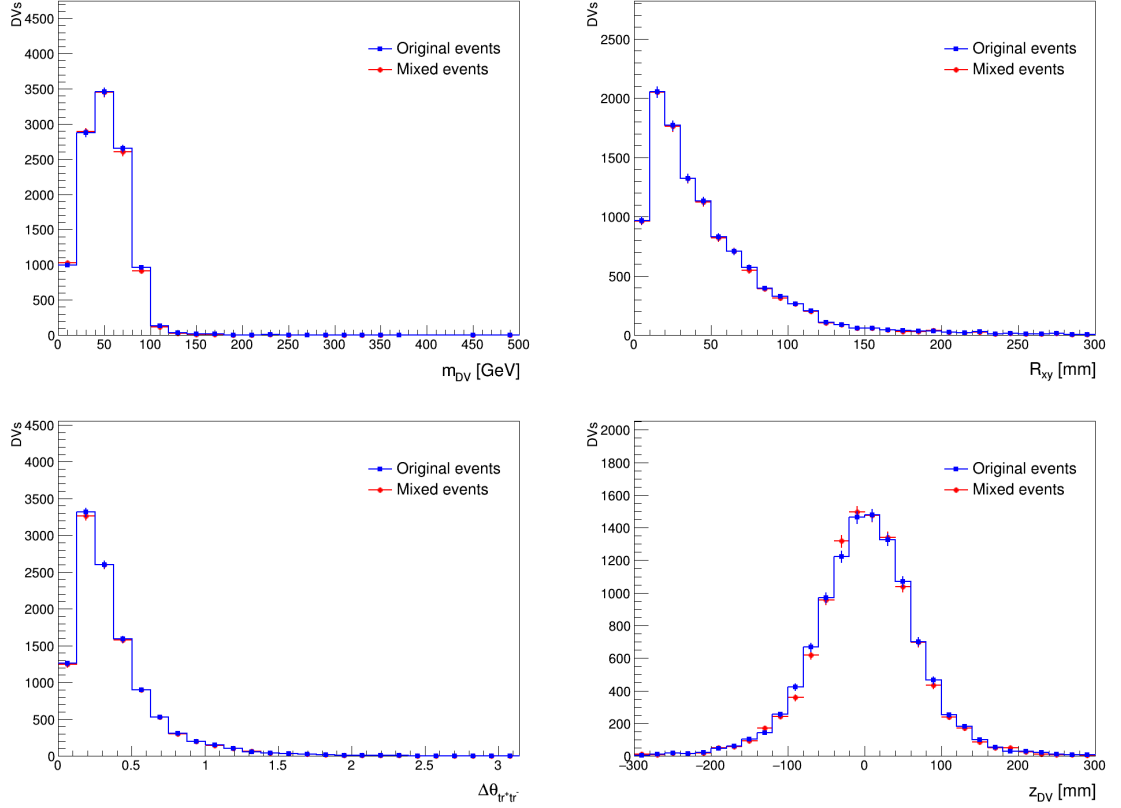


Figure A.1: Number of accepted signal DVs as a function of DV mass (top-left), DV transverse decay position (top-right), opening angle between the DV’s tracks (bottom-left) and DV z decay position (bottom-right), shown for both the original events (blue) and the “mixed” events (red) from the test validating the track-shifting procedure in the event-mixing. The distributions are for the gluino-produced $\tilde{\chi}_1^0$ MC dataset with gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 100 GeV and decay length ($c\tau$) of 10 mm.

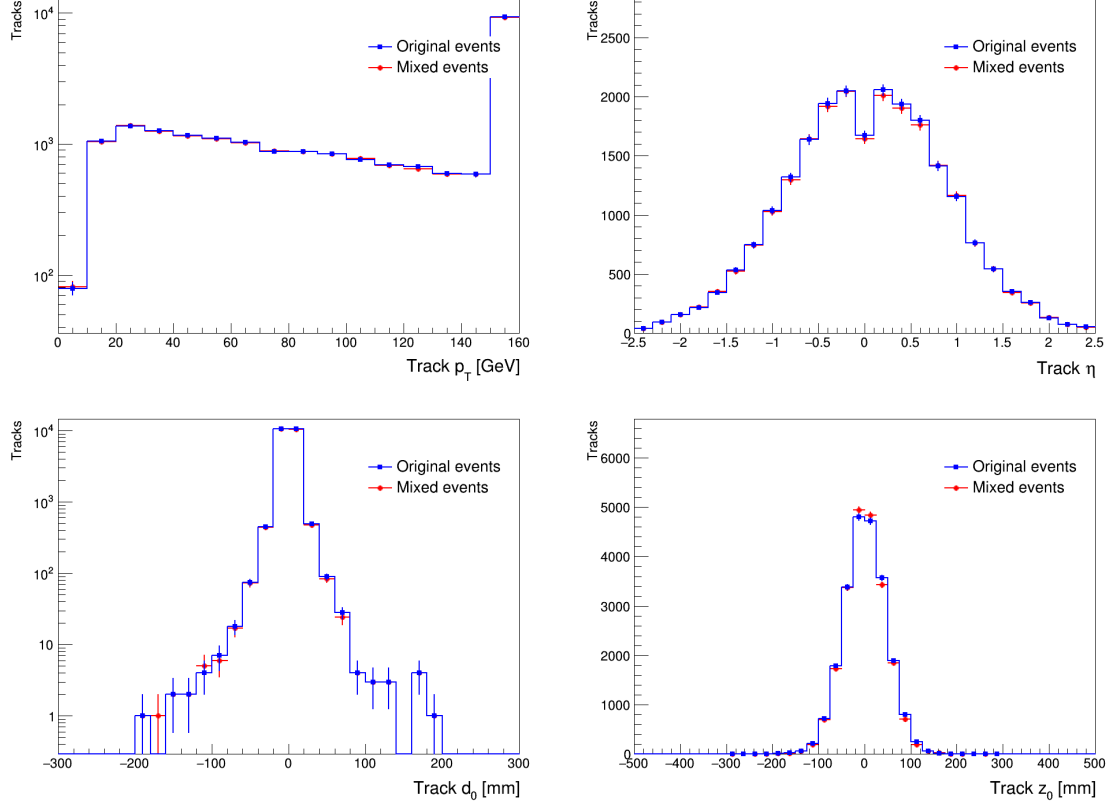


Figure A.2: Number of tracks that are constituents of an accepted signal DV as a function of track p_T (top-left), η (top-right), d_0 (bottom-left), and z_0 (bottom-right), shown for both the original events (blue) and the “mixed” events (red) from the test validating the track-shifting procedure in the event-mixing. The distributions are for the gluino-produced $\tilde{\chi}_1^0$ MC dataset with gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 100 GeV and decay length ($c\tau$) of 10 mm.

Table A.1: Number of displaced vertex candidates observed and predicted in the gluino-produced $\tilde{\chi}_1^0$ MC dataset with gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 500 GeV and decay length ($c\tau$) of 100 mm. In the DV category, “track” refers to tracks not identified as leptons. The predicted number of vertices is obtained using the number of seed pairs in the data N_{pairs}^{obs} and the average crossing probability p_{xing} via Eq. 6.1.

	ee	$e\mu$	$\mu\mu$
N_{pairs}^{obs}	3.58×10^5	4.24×10^5	1.35×10^5
“Crossing Probability”	6.41×10^{-3}	7.74×10^{-3}	3.75×10^{-2}
Predicted vertices	2298	3285	5142
Observed vertices	2326	3318	5094
	track- e	track- μ	track-track
N_{pairs}^{obs}	9.46×10^6	6.00×10^6	7.83×10^7
“Crossing Probability”	2.09×10^{-5}	3.65×10^{-5}	3.96×10^{-7}
Predicted vertices	198	219	29
Observed vertices	200	215	28

Appendix B

VALIDATION OF LIFETIME REWEIGHTING

If the lifetime reweighting procedure is valid, the signal efficiency for a MC sample generated at a given lifetime should be consistent with the signal efficiency at that lifetime from the combination of the five extrapolated samples with different lifetimes. The first plot in Figure B.1 demonstrates good agreement for the five lifetimes.

The reweighting procedure is further tested by comparing the efficiency of one sample at a particular lifetime to that calculated by combining the four other samples of different lifetimes. The rest of the plots in Figure B.1 show the results of the lifetime reweighting method with one lifetime sample removed. The efficiency of each sample removed still is consistent with the efficiency of the combined distribution at the corresponding lifetime. The difference between the extrapolated efficiency and the efficiency of the single lifetime signal sample is used to calculate the systematic uncertainty of the method. Those differences are collected for each model, mass, and lifetime point and histogrammed. A Gaussian fit to that distribution of differences gives a mean of $(-1.34 \pm 0.56)\%$, so a systematic uncertainty of 2% is used to be conservative.

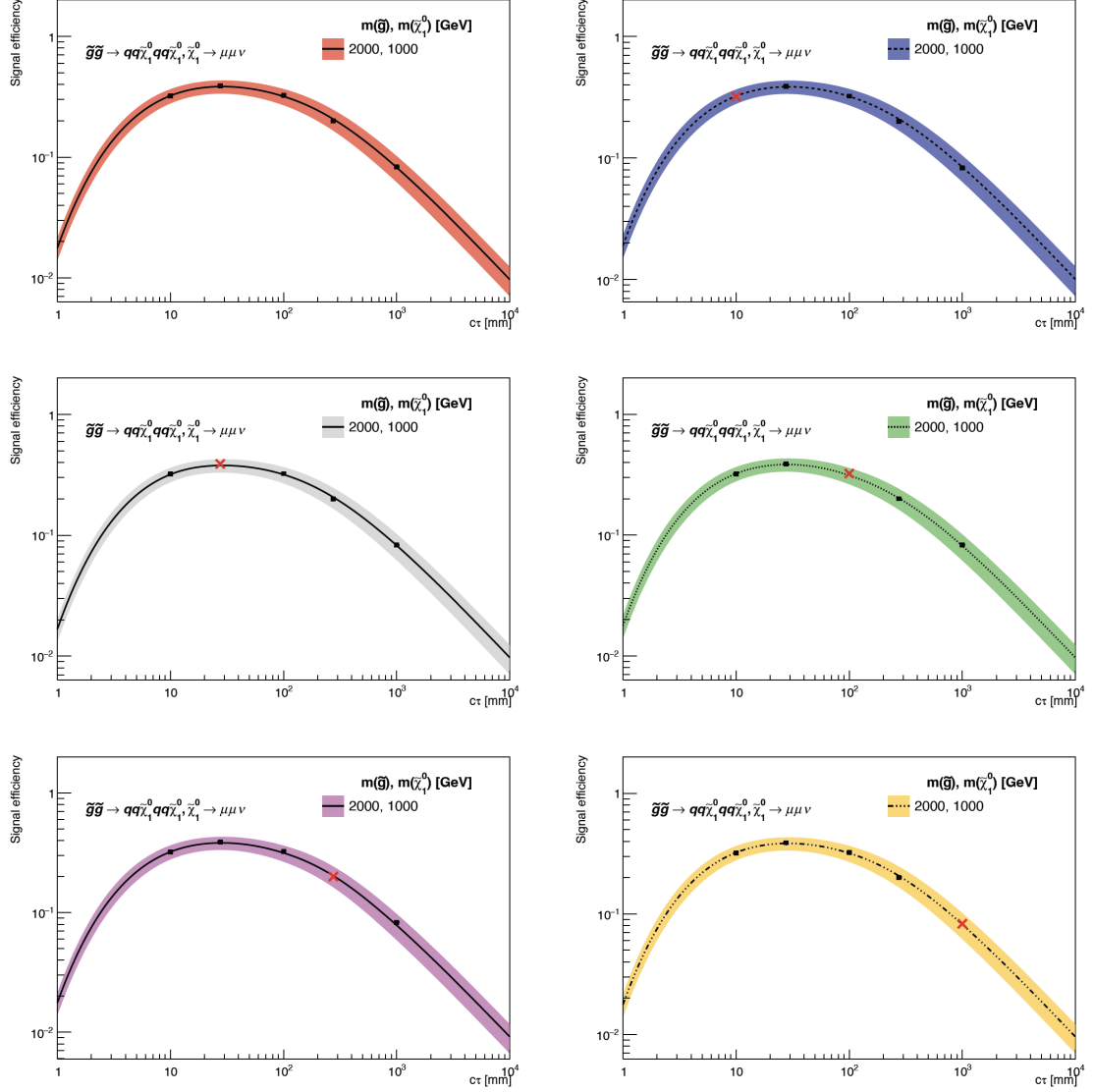


Figure B.1: A closure test comparing extrapolated and generated $A \cdot \epsilon$, when one of the generated lifetimes is not used in the extrapolation. The black points correspond to the generated samples while the red $\times$ indicated the efficiency sample removed for that lifetime. Plots were produced using the gluino-produced $\tilde{\chi}_1^0$ (mc16a+mc16d+mc16e) samples with a gluino mass of 2000 GeV and $\tilde{\chi}_1^0$ mass of 1000 GeV.