

IDENTIFYING ELECTRONS AND SEARCHING FOR ELECTROWEAK R-PARITY VIOLATING SUPERSYMMETRY AT ATLAS

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ABSTRACT

IDENTIFYING ELECTRONS AND SEARCHING FOR ELECTROWEAK R-PARITY VIOLATING SUPERSYMMETRY AT ATLAS

Lucas Macrorie Flores

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In this thesis a search for particles in the context of the theory of supersymmetry (SUSY) as well as algorithms for reconstructing and identifying electrons are detailed. The physics search was performed using 139 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton-proton collision data produced by the Large Hadron Collider (LHC) and collected by the ATLAS experiment during data taking periods in 2016, 2017, and 2018. Bare SUSY gives rise to baryon (B) and lepton (L) number violation which would lead to rapid proton decay and is therefore incomplete as we do not see this in nature. The “ $B - L$ MSSM” solves this elegantly by introducing a new local symmetry, $U(1)_{B-L}$, which accounts for the apparent strict conservation of both B and L at low energies as well as provides a method for generating neutrino masses and breaking SUSY. This model allows for the lightest supersymmetric particle (LSP) to decay into Standard Model particles giving rise to a rich phenomenology. One such signature is the decay of the SUSY partner of the W and charged Higgs bosons, $\tilde{\chi}_1^\pm$, into a final state with three charged leptons. This is a clean signature in which the invariant mass of the particle can be fully reconstructed. The search for this signature is the primary focus of this thesis. The second focus of this thesis is the developments and optimizations of the algorithms and software pertaining to the reconstruction and identification of electrons.

Contents

Acknowledgements	iii
Abstract	iv
Contents	v
List of Tables	x
List of Figures	xi
Preface	xv
1 Introduction	1
2 Theoretical Framework	2
2.1 Quantum Field Theory	2
2.2 The Standard Model	3
2.2.1 Quantum Chromodynamics	4
2.2.2 Electroweak Unification	4
2.2.3 Spontaneous Symmetry Breaking and the Higgs Mechanism	4
2.2.4 The Standard Model Lagrangian	5
2.3 Supersymmetry	6
2.3.1 R -parity	8
2.4 The $B - L$ Minimal Supersymmetric Standard Model	9
2.4.1 Phenomenology of a Broken $B - L$ Symmetry	11

3	LHC and the ATLAS Detector	14
3.1	The Large Hadron Collider	14
3.1.1	Magnets	15
3.1.2	Beams, Buckets, and Bunches	17
3.1.3	Pileup	19
3.2	The ATLAS Detector	19
3.2.1	The Inner Detector	20
3.2.1.1	Pixel Detector	21
3.2.1.2	Semiconductor Tracker	22
3.2.1.3	Transition Radiation Tracker	23
3.2.2	The Calorimeters	24
3.2.2.1	Liquid Argon Calorimeters	25
3.2.2.2	Tile Calorimeter	26
3.2.3	The Muon Spectrometer	27
3.3	Object Reconstruction and Identification	28
3.3.1	Electrons and Photons	29
3.3.2	Muons	29
3.3.3	Hadrons and Jets	30
3.3.4	Missing Transverse Energy	30
3.4	The Trigger System	31
4	These are Electrons: Identifying Electrons at ATLAS	33
4.1	Introduction	33
4.2	Electron-Efficiency Measurements	33
4.3	Topo-Cluster Reconstruction	34
4.4	Electron Candidate Reconstruction	34
4.4.1	Sliding-Window	35
4.4.2	Superclusters	36
4.4.3	Track Reconstruction	36
4.4.4	Electron specific track re-fit	37
4.4.5	Track-Cluster Matching	39
4.5	Electron Identification	40
4.5.1	The Electron Likelihood (LH)	40

4.5.2	LH Calorimeter Variables	42
4.5.3	LH Tracking Variables	43
4.5.4	LH Track-Cluster Matching Variables	44
4.5.5	Non-LH Variables	44
4.5.6	Constructing the pdfs	47
4.5.6.1	Binning in E_T and η	51
4.5.6.2	Smoothing: Adaptive Kernel Density Estimation (KDE)	52
4.5.7	Being Efficient in a Changing Environment	54
4.5.7.1	Pileup Dependence of Discriminating Variables	54
4.5.7.2	Alternative Pileup Measures: TRT Local Track Occupancy	58
4.5.8	Tuning the Electron LH	60
4.5.9	LH-Identification Operating Points	62
4.5.10	The Trigger Electron LH	62
4.5.10.1	Re-tuning the Trigger LH for Large Pileup Environments	63
5	An Exercise in Three Lepton Resonances	70
5.1	Analysis Introduction	70
5.1.1	Phenomenological Motivation	70
5.2	Analysis Strategy	75
5.2.1	Signal	75
5.2.2	Backgrounds	77
5.3	Simulated Data: Monte Carlo Generation	77
5.3.1	MC Specifications	78
5.4	Analysis Regions	79
5.4.1	Signal Regions	80
5.4.1.1	SR3 ℓ	80
5.4.1.2	SRFR	82
5.4.1.3	SR4 ℓ	84
5.4.2	Background Estimation and Validation	86
5.4.2.1	Handling Backgrounds: <i>fake</i> Leptons	87
5.4.2.2	Handling Backgrounds: WZ	88
5.4.2.3	Handling Backgrounds: ZZ	89
5.4.2.4	Handling Backgrounds: $t\bar{t}Z$	90

5.5	Statistical Treatment	93
5.5.1	Systematic Uncertainties	94
5.5.1.1	MC Statistics	95
5.5.1.2	Experimental Uncertainties	95
5.5.1.3	Theoretical Uncertainties	95
5.5.1.4	Fake Lepton Uncertainties	96
5.5.1.5	Normalization Uncertainties	96
5.5.2	Fit Configuration	97
5.5.3	Background-Only Fit	97
5.5.4	Model Independent Fit	99
5.5.5	Model Dependent Fit	99
5.6	Results	100
5.6.1	Model-Independent Limits on New Physics in Inclusive Regions	100
5.6.2	Mass Limits on $B - L$ RPV Production	102
5.6.3	Branching Ratio Limits on $B - L$ production	103
5.7	Analysis Preservation: Building Towards the “Do Analysis” Button	104
5.7.1	Analysis Preservation for the Trilepton Resonance Search	106
5.7.1.1	Preserving the Data	106
5.7.1.2	Preserving the Analysis	106
5.7.1.3	Workflow Authoring	107
6	Conclusion	110
	Appendices	111
A	Formulation of QFT	112
A.1	Formulation of QFT	112
B	Statistical Treatment	115
B.1	The Likelihood Function	115
B.2	Goodness of Fit: Maximum Likelihood Estimation	116
B.2.1	The Profile Likelihood	116
B.2.2	The Statistical Test: Profile Log Likelihood Ratio Test	117
B.2.3	The Asymptotic Regime	118

B.2.4	Building the Profile Likelihood: Pseudo-Experiments	119
B.2.5	Significance and the CL_s Method	119
C	Baseline Object Selection	121
C.0.1	Electron, Muon, and Jet Selection Summary Tables	121
C.0.2	Photon Selection	123
C.0.3	Missing energy	123
C.0.4	Overlap removal	123
D	Event Displays	124
	Bibliography	128

List of Tables

4.1	Type and description of the quantities used in the electron identification.	46
4.2	Summary of data-driven signal electron selection above 15 GeV.	50
4.3	Summary of data-driven signal electron selection below 15 GeV.	51
4.4	Summary of data-driven background electron selection.	52
4.5	Boundaries in absolute cluster pseudorapidity used to define the nine bins for the LH pdfs and LH discriminant requirements.	52
4.6	Boundaries in electron transverse energy used to define the seven bins for the LH pdfs and the twelve bins for LH discriminant requirements.	52
4.7	Trigger rates determined using a trigger emulation tool for four standard electron triggers for the three cases; using the nominal (old) LH TUNE, using the new updated LH TUNE, and using the new updated LH TUNE along with the new “ringer” fast calorimeter reconstruction algorithm.	69
5.1	Table of final states with a trilepton resonance from the chargino decay. Separate selection algorithms (two-leg or one-leg) are designed for final states where both or only one of the supersymmetric particles can be fully reconstructed from the detected particles.	76
5.2	Details of the MC simulation for each physics process	79
5.3	Kinematic selections for each region used in this analysis.	93
5.4	MC normalization factors for major backgrounds.	97
5.5	The observed yields and post-fit background expectations in SRFR, SR4 ℓ , and SR3 ℓ , shown inclusively and when the direct lepton from a $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ decay is required to be an electron or muon.	101
C.1	Summary of electron selection criteria. Signal criteria are applied on top of baseline criteria after overlap removal.	121
C.2	Summary of muon selection criteria. Signal criteria are applied on top of baseline criteria after overlap removal.	122
C.3	Summary of jet selection criteria. Signal criteria are applied on top of baseline criteria after overlap removal.	122

List of Figures

2.1	Particle content of the Standard Model both before and after spontaneous symmetry breaking. Also shown is an illustration of spontaneous symmetry breaking via the Higgs Mechanism	3
2.2	Particle content of the minimal supersymmetric standard model	7
2.3	The observed Higgs mass as a sum of the bare Higgs mass plus loop corrections.	8
2.4	The observed Higgs mass as a sum of the bare Higgs mass plus loop corrections now including contributions from SUSY particles. The large blue “+” sign from the stop loop illustrating the its effective cancellation with the top loop contribution with the red “-” sign.	8
2.5	Minimal SUSY $B - L$ Model particle content	10
2.6	Minimal SUSY $B - L$ Model particle content, pre- $B - L$ breaking	11
3.1	Accelerator complex at CERN	15
3.2	Diagram showing the cross-section of an LHC dipole magnet.	16
3.3	Cross-section of a model of the superconducting quadrupole magnet	16
3.4	Beam envelopes in the interaction region around point 1 (ATLAS) showing how the beam sizes are reduced in the last 60 m on each side of the interaction point following the squeeze.	17
3.5	Schematic of the Bunch Disposition around an LHC Ring for the 25 ns Filling Scheme	18
3.6	The luminosity-weighted distribution of the mean number of interactions per crossing for 2015-2018 pp collision data at 13 TeV centre-of-mass energy.	20
3.7	A Z candidate is reconstructed in a beam crossing with 24 additionally reconstructed vertices from minimum bias interactions.	21
3.8	A Z boson candidate is reconstructed in a beam crossing with 65 additionally reconstructed vertices from minimum bias interactions	21
3.9	General cut-away view of the ATLAS detector.	22
3.10	Illustration showing the ID systems being traversed by a charged track (red) of $p_T=10\text{GeV}$ in the barrel ($\eta = 0.3$).	23
3.11	Cut-away view of the ATLAS calorimeters. The LAr calorimeters are seen inside the hadronic Tile calorimeters	24
3.12	Illustration of the LAr calorimeter detailing the different granularities and radiation lengths of each layer	26
3.13	Illustration of the Tile Calorimeter	27
3.14	The muon spectrometer system.	28

3.15	Particle signatures for different particle types when traversing the ATLAS detector. . .	29
3.16	L1 and HLT trigger rates	32
4.1	Algorithm flow-chart for the electron and photon reconstruction.	35
4.2	Diagram of the superclustering algorithm for electrons and photons. Seed clusters are shown in red, satellite clusters in blue.	37
4.4	Depiction of an electron traversing the ATLAS detector. The TRT extends to $ \eta < 2.0$, and the SCT and pixel detectors out to $ \eta < 2.47$	41
4.6	Example distributions of the calorimeter variables R_{had1} , f_3 , $w_{\eta2}$, R_ϕ , R_η , E_{ratio} , and f_1	45
4.7	Example distributions of the calorimeter variables R_{had1} , f_3 , and f_1	47
4.8	Examples of distributions of tracking and track-cluster matching variables $ d_0/\sigma(d_0) $, $\Delta p/p$, eProbabilityHT, $\Delta\eta_1$, and $\Delta\phi_{\text{res}}$	48
4.9	Cartoon illustrating the TRT gas configurations used in 2015 (top), 2016 (middle), and 2017/2018 (bottom).	49
4.10	Cartoon of the middle cross-section of one side of the calorimeters and ID showing the η regions the LH is binned in.	53
4.11	The KDE method. In (a), an illustration of the advantage of the adaptive KDE pdf smoothing technique in regions with low statistics. In (b), an example of a variable distribution and its adaptive KDE-smoothed pdf	54
4.12	Electron variable distributions R_{had} and R_η showing high pileup's effect on the shapes of the distributions	55
4.13	Electron LH variables $n - 1$ ROC curve showing signal efficiency/background rejection response of LH when single variables are removed from the LH.	56
4.14	Illustration of the identification efficiency dependence of (a) signal and (b) background on n_{vtx} for the TIGHT operating point.	57
4.15	Example of the pileup correction used in Run-1 where the z-axis shows the number of entries in each bin.	58
4.16	The regions I, II, III, and IV illustrate the piece-wise transform described in Section 4.5.7.1	59
4.17	Signal (a) and background (b) identification efficiencies as a function of the nominal electron LH discriminant pileup measure n_{vtx} and the alternate variable local TRT track occupancy.	60
4.18	Example pdfs illustrating shift and width corrections applied to MC for discriminant tuning procedure	61
4.19	Pdfs of tracking and track-cluster matching variables eProbabilityHT, $\Delta\eta_1$, $\Delta\phi_{\text{res}}$, and the shower shape variables $w_{\eta2}$, R_{had} , and R_η	64
4.19	Pdfs of shower shape variables R_ϕ , E_{ratio} , f_1 , and f_3	65
4.20	Pdfs of tracking and track-cluster matching variables eProbabilityHT, $\Delta\eta_1$, $\Delta\phi_{\text{res}}$, and the shower shape variables $w_{\eta2}$, R_{had} , and R_η	66
4.20	Pdfs of shower shape variables R_ϕ , E_{ratio} , f_1 , and f_3	67
4.21	Efficiencies taken from a full data run reprocessed with Tier0 monitoring as a function of $\langle\mu\rangle$ and E_T produced for standard electron triggers that use the TIGHT (top), MEDIUM (middle), and VERYLOOSE (bottom) operating points. Three cases are compared: new offline LH TUNE numerator and new online LH TUNE denominator in black, old offline LH TUNE numerator and old online LH TUNE denominator in red, and new offline LH TUNE numerator and old online LH TUNE denominator in blue.	68
5.1	Diagrams of (a) $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ (b) production with at least one $\tilde{\chi}_1^\pm \rightarrow Z\ell \rightarrow \ell\ell\ell$ decay.	71
5.2	Plot of initial 100 million statistical trials of SUSY parameters and the subsequent filtering out of said points that do not satisfy necessary physical bounds.	72

5.3	histogram of the LSPs for the valid points of the statistical analysis	73
5.4	Theoretical production cross sections for selected standard model and SUSY in 13TeV proton collisions. The expected number of events produced for each process in 10 fb ⁻¹ of LHC data is shown on the right scale	74
5.5	The mass difference between the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ when the $\tilde{\chi}_1^0$ is the LSP and the $\tilde{\chi}_1^\pm$ the NLSP (a) and then again with the $\tilde{\chi}_1^\pm$ the LSP and the $\tilde{\chi}_1^0$ the NLSP (b)	75
5.6	Summary of several Standard Model total and fiducial production cross section measurements, corrected for branching fractions, compared to the corresponding theoretical expectations.	78
5.7	Signal region flow chart	81
5.8	Signal acceptance by process in SR3 ℓ	83
5.9	Signal acceptance by process in SRFR	84
5.10	Signal acceptance by process in SR4 ℓ	85
5.11	Expected yields from simulation for various background processes with (a) three leptons, four leptons (b) with and (c) without second boson candidate. Note that the kinematic requirements for the signal regions are not applied here.	86
5.12	Graphic depicting the orthogonality of the three lepton regions.	89
5.13	Expected yields of each background in CRWZ, VR E_T^{miss} and VR m_T^{min} , assuming 140 fb ⁻¹ . No normalization factors are applied.	90
5.14	Graphic depicting the orthogonality of the four lepton regions.	91
5.15	Expected yields of each background in CRZZ and VRZZ, assuming 140 fb ⁻¹ . No normalization factors are applied.	91
5.16	Expected distribution in simulation for background processes and signal processes of the angular separation between two b -tagged jets for events with three or more leptons (a) on a log scale where events without at least 2 b -jets have been assigned a value of 0.1, and (b) on a linear scale for events with at least 2 b -jets.	92
5.17	Expected yields of each background in CR $t\bar{t}Z$ and VR $t\bar{t}Z$, assuming 140 fb ⁻¹ . No normalization factors are applied.	92
5.18	The relative uncertainties in the post-fit SM background prediction as a function of $m_{Z\ell}$ from the background-only fit for the (top left) SRFR, (top right) SR4 ℓ , and (bottom) SR3 ℓ regions.	94
5.19	Distributions of the data and post-fit background in the CRs and VRs that are relevant in the extrapolation to the SRs (m_T^{min} in CRWZ and VR m_T^{min} , E_T^{miss} in CRWZ, E_T^{miss} in VR E_T^{miss} , $m_{ll,2}$ in CRZZ and VRZZ, and $\Delta R(b_1, b_2)$ in CR $t\bar{t}Z$ and VR $t\bar{t}Z$)	98
5.20	The observed data and the SM background expectation in the CRs (pre-fit) and VRs (post-fit).	99
5.21	The observed data and post-fit SM background expectation as a function of $m_{Z\ell}$ in SRFR, SR4 ℓ , and SR3 ℓ	102
5.22	Exclusion curves for the simplified model of $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production as a function of $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ mass and branching fraction to Z bosons.	103
5.23	Exclusion curves for the simplified model of $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production as a function of the branching fractions to Z and Higgs bosons.	105
5.24	Diagrammatic illustration of full step-by-step workflow of analysis procedure used for analysis reproduction and recasting. Explicit steps are <code>daod_to_ntup_mc16ade</code> , <code>ntup_to_HFtree</code> , and <code>HF_to_CLs</code> with inputs <code>dxaod_file_mc16a</code> , <code>dxaod_file_mc16d</code> , and <code>dxaod_file_mc16e</code> representing the three MC campaigns used in the analysis.	109
B.1	Cartoon of the Profile Likelihood.	117
B.2	Illustration of a test statistic distribution and an observed $q_{\mu_{sig}}$ with corresponding p -value.	118

D.1	Event display for data event in the SRFR signal region	125
D.2	Event display for data event in the SR4 ℓ signal region	126
D.3	Event display for data event in the SR3 ℓ signal region	127

Preface

Since at least high school I have been excited by the “*big questions*.” And it was particle physics where I found many of those questions were trying to be answered, endeavoring to probe the smallest and most fundamental constituents of reality in order to figure out how this all really works. The path then sort of took shape itself, as (for me) there was really only one game in town for experimental fundamental particle physics, the Large Hadron Collider (LHC). So after a stint working with heavy ions at a different collider in undergrad, I ultimately found myself at the University of Pennsylvania (Penn) pursuing a Ph.D. in experimental high energy particle physics on the ATLAS experiment (one of two general purpose detectors on the LHC). I started at Penn in 2015, which was an exciting time at the LHC as it was the end of a 2-year technical stop that prepared the machine for running at $1.6\times$ the energy of the LHC’s first run. The then CERN Director-General Rolf Heuer summarizes the excitement in the air prefacing the start of Run 2:

“With this new energy level, the LHC will open new horizons for physics and for future discoveries”

And I was lucky enough to take my first trip out to CERN the summer of 2015 for a few weeks during this time. It was certainly a memorable trip as I lost my wallet almost immediately as I was getting on my flight to Switzerland (I survived though).

The next two years I would spend living in Philadelphia, taking classes at Penn, and working on electron identification as a part of the electron/photon (e/γ) performance group on ATLAS. Initially I investigated a new variable that utilizes the occupancy of the transition radiation tracker (a sub-detector on ATLAS responsible for tracking particle trajectories) to better represent the noisy activity near an electron candidate in order for the electron identification algorithm (a likelihood based method) to remain efficient in very busy environments. After a study of this variable deemed

it comparable to the current standard, but with no clear advantage, it then became important to pivot to a re-optimization of the identification when enough Run 2 data became available, allowing the identification algorithm to become fully data-driven for the remainder of Run 2. This was ultimately the work that led to my authorship on ATLAS. I would continue on in an advisory role for electron ID in the group for some time after.

After several years spent working with some wonderful people in the e/γ group I then made the transition to analysis work in the beginning of 2018. I joined a fully Penn-driven analysis team, led by my advisor Evelyn Thomson, to look for new physics in the context of an R -parity violating supersymmetric model. My luck would continue and I would get to work with even more wonderful people on this team. Here I would work on developing regions where major backgrounds could be estimated, generating Monte Carlo (simulated data) signal samples for our model, determining signal acceptances for our analysis selection, and building a framework for the preservation and re-usability of our analysis.

It was also around this time (Aug. 2017) that I moved from Philadelphia out to CERN (Geneva, Switzerland more specifically) for what was then an unknown amount of time, but where I would ultimately spend the remainder of my Ph.D. Being able to be on-the-ground at CERN and live in the beautiful city of Geneva was an unforgettable experience and was where I met some life long friends.

Every experience I had during my time in graduate school I look back on fondly. These experiences have surely shaped who I am today and I will proudly bring their influences with me to whatever the next step is.

Lucas Macrorie Flores

California, November 2021

CHAPTER 1

Introduction

The field of elementary particle physics has been a burgeoning space of discovery since the development of particle accelerators in the 1950s. As accelerator technology advanced allowing for higher energy collisions more and more new particles were being discovered, contributing to what became known as the “particle zoo.” Fortunately this zoo was reined in with completion of the theory called the Standard Model (SM) in the 1970s. This theory reduced the number of actual elementary particles to a handful, filing most of the zoo into composite particles made from the elementary particles. Since its emergence in the 1970’s the SM has been remarkably successful as particle accelerator experiments have verified its predictions to great precision. And with the discovery of the Higgs boson by the ATLAS and CMS experiments at the European Organization for Nuclear Research (CERN) in 2012 the SM in its modern form was completed. However we know that that cannot be the entire story. Observed unexplained phenomena such as dark matter and unanswered question such as why the Higgs mass is so light demand there be physics beyond the Standard Model. And it is in this thesis where one approach for searching for new physics is described. This thesis is divided into four main chapters and is organised as follows. Chapter 2 describes the theoretical framework of the SM as well as an extension to that framework that would allow for new fundamental particles that would be accessible at high energy particle physics experiments such as the Large Hadron Collider (LHC) and its detectors. Chapter 3 then describes the LHC and its beam, ATLAS and its constituent subdetectors, and ATLAS’s methodology for reconstructing collision events and collecting data. Chapter 4 details the full procedure for reconstructing and identifying electrons at ATLAS and my contributions to that effort. And finally Chapter 5 describes a beyond the Standard Model search for a new fundamental particle via its decay into three charged leptons (electrons or muons) as motivated by an R -Parity violating supersymmetric model.

CHAPTER 2

Theoretical Framework

In this chapter the mathematical theoretical framework is presented in which the physical measurements and computational modeling will be interpreted in the subsequent chapters. For elementary particle physics this framework is Quantum Field Theory (QFT), a relativistically consistent quantum mechanics whose fundamental mathematical objects are fields instead of particles. Within the mathematical umbrella of QFT comes one of the most successful physical theories ever developed, the Standard Model (SM) of particle physics. While the success of the SM is undisputed, in its current form it can give no explanation for several big questions in physics. This invariably leads to extensions to the SM, known as beyond the standard model (BSM) physics, with one of the most important and attractive extensions known as Supersymmetry.

2.1 Quantum Field Theory

We won't go as far back as classical mechanics but there is good reason to take a step back to what Quantum Field Theory (QFT) *is*, as all of our current understanding of elementary particle physics is in the context of quantum field theories. That being said, there is no strict canonical definition of what QFT actually *is*, which might be why you don't see a section like this often in similar theses. Nevertheless we can gain enough handles in discussing it in relation to other physical theories. A common characterization is to sum up QFT as being the reconciliation of quantum mechanics (QM) with special relativity, which while true does not give us the full picture, as relativistic QM exists in the form of the Klein Gordon and Dirac equations, and it is also possible to form a non-relativistic QFT as well [1]. A potentially more discerning description would be that QFT, and not QM, allows for the description of systems with an infinite amount of degrees of freedom, i.e. fields. Of course

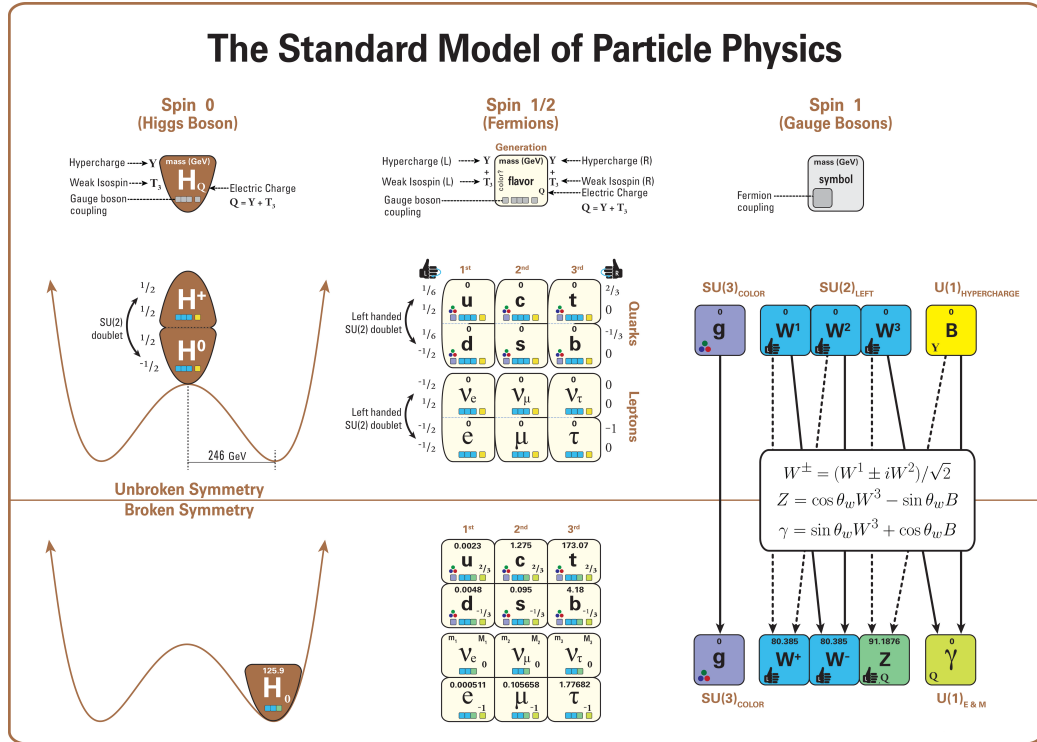


Figure 2.1: Particle content of the Standard Model both before and after spontaneous symmetry breaking. Also shown is an illustration of spontaneous symmetry breaking via the Higgs Mechanism [2]

this alone also falls just short as a classical field theory (relativistic or non-relativistic) is equipped for such a task as well. So the marriage of quantization, relativity, and field theory is all necessary in order to capture what makes QFT QFT. The Appendix A.1 has a brief review of the formulation of QFT and may be useful for readers before moving into the next section.

2.2 The Standard Model

Modern particle physics is generally interpreted in terms of the Standard Model (SM). The SM is a QFT which encapsulates our understanding of the electromagnetic, weak, and strong interactions. Noticeably missing of course is the force of gravity, which is described by Einstein's General Relativity (GR). Theories that reconcile GR and QFT belong to a topic that would take up its own library and shall not be discussed further as Gravity is so comparably small for our experiments in particle physics that it has no measurable effect and can be easily ignored. The SM obeys a set of

symmetries such that the theory belongs to the gauge unitary product group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \quad (2.1)$$

2.2.1 Quantum Chromodynamics

$SU(3)_C$ is the gauge symmetry group for the theory of the strong force, Quantum Chromodynamics (QCD), which defines the strong interaction between quarks and gluons. The strong force is mediated by the force carrying gluons, which each carry the color charges (red, green, blue) and anti-color charges (anti-red, anti-green, anti-blue), leading to a total of 9 possible states of gluons. However the special color singlet state, which would be indicative of a long range force like the photon, is not observed in nature and so only 8 physical color states are possible. Gluon-gluon interactions constrain the color fields to string-like objects called “flux tubes”, so that as two quarks are pulled apart there is a binding energy that increases linearly with their separation. At a large enough distance, it becomes energetically more favorable to pull a quark-antiquark pair out of the vacuum rather than increase the length of the flux tube. A phenomenon known as color confinement, this has a cascading effect of the two very energetically separating quarks pulling quark-antiquark pairs out of the vacuum along their journey (which also in turn can do the same), thereby forming hadrons is known as hadronization. This is an experimentally confirmed phenomenon showing up in particle detectors as large conical sprays or *jets* of particles.

2.2.2 Electroweak Unification

$SU(2)_L \times U(1)_Y$ is the gauge group for the theory of the Electroweak force. At high energies, the well known electromagnetic force and the weak nuclear force are unified into a single electroweak force. Composed of the four massless gauge vector bosons W_1, W_2, W_3 from the weak isospin (T) field and B from the weak hypercharge (Y) field, the $SU(2)$ Higgs doublet, and the nominal three generations of charged and neutral fermions. The particle content for this theory is illustrated in the upper half of Figure 2.1.

2.2.3 Spontaneous Symmetry Breaking and the Higgs Mechanism

We however do not live in a world with these particles - a very good thing or nuclear fusion reactions and radioactive decays would run much faster and stars and humans would not exist at all! We say that this electroweak symmetry is broken, and the Higgs mechanism was proposed as an explanation

that was confirmed 40 years later with the discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments at CERN. The Higgs mechanism occurs when any charged field (the Higgs field) at some critical temperature acquires a vacuum expectation value (vev) which induces spontaneous breaking of three out of four generators of $SU(2)_L \times U(1)_Y$. Due to electroweak symmetry breaking, the neutral boson from weak isospin and the hypercharge boson mix to form two different states: the massless photon that is the force carrier of the electromagnetic force; and the massive Z boson that is the neutral current of the weak force. The other two weak isospin bosons form the massive W^+ and W^- bosons that carry the electrically charged current of the weak force. The ratio of the W and Z boson masses is predicted by the theory, as are the couplings of the Z boson to quarks and leptons. These are experimentally confirmed to high precision. Figure 2.1 diagrammatically shows this symmetry breaking and the boson mixing that gives us the particle content that we observe in the world we live in today and is seen in the bottom half of the Figure.

2.2.4 The Standard Model Lagrangian

The full SM Lagrangian is as follows

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi) \quad (2.2)$$

Where some terms look familiar from our QFT exercises in Appendix A.1 and others not so much. It is useful here to break this down term by term.

1. $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$: This term is the scalar product of the field strength tensor $F_{\mu\nu}$ which contains the mathematical encoding of all force carrying interaction particles except the Higgs boson.
2. $i\bar{\psi}\not{D}\psi$: This term describes how these interaction particles interact with matter particles. The fields ψ and $\bar{\psi}$ describe (anti)quarks and (anti)leptons
3. $h.c.$: This term represents the ‘hermitian conjugate’ of the second term. The hermitian conjugate is necessary if arithmetic operations on matrices produce complex-valued ‘disturbances’. By adding h.c., such disturbances cancel each other out, thus the Lagrangian remains a real-valued function.
4. $\psi_i y_{ij} \psi_j \phi$: This term describes how matter particles couple to the Higgs field ϕ and thereby obtain mass. The entries of the Yukawa matrix y_{ij} represent the coupling parameters to the Higgs field, and hence are directly related to the mass of the particle in question. These parameters are not predicted by theory, but have been determined experimentally.

5. $h.c.$: See term 3, but here this term is really necessary, since term 4 is not self-adjoint.
6. $|D_\mu\phi|^2$: This term describes how the interaction particles couple to the Higgs field.
7. $-V(\phi)$: This term describes the potential of the Higgs field. Contrary to the other quantum fields, this potential does not have a single minimum at zero but has an infinite set of different minima. This makes the Higgs field fundamentally different and leads to spontaneous symmetry breaking.

2.3 Supersymmetry

It is well known however that the standard model of particle physics cannot account for all observed phenomena. Gravity, Dark Matter, and why the Higgs is so light, to name a few. For this we often look to *extend* the standard model to include more symmetries of nature. These symmetries often include new fundamental particles that can be observed in experiments like ATLAS. One such extension, *Supersymmetry* (SUSY), is seen as potential Swiss army knife of answers to several unanswered problems in physics. The idea here is that there is an explicit mathematical relationship, a symmetry, between fermions and bosons. Whereas in the SM these two types of particles though very similar, are not treated on that same footing as they are in SUSY. i.e. they really are two sides to the same coin in SUSY. Now the cool part is that when you introduce this symmetry you necessarily generate a doubling of all the fundamental particles described by the standard model. Each fermion now has a bosonic mirror, a *superpartner*, and equivalently each boson has a fermionic superpartner. For what is called the Minimal Supersymmetric Standard Model (MSSM), whereby we have supersymmetry with the fewest number of particles added to the standard model the particle content can be seen in Figure 2.2 (post-EWK symmetry breaking). Where we will also notice that in SUSY an additional $SU(2)$ Higgs doublet must be added¹. Supersymmetric fermions are called sfermions (squarks and sleptons) and supersymmetric gauge bosons are gauginos (Wino, Zino, gluino, Higgsino, and photino) and are all denoted with a the symbol of their standard partner with a tilde ($\tilde{X}$). Now this is an experimental physicist's dream as there are now a whole bunch of potential new particles to discover, but of course that's not what we observe in nature, i.e. we would have seen (in abundance!) superpartners at the same masses as their 'standard' partners' masses. This then means that the supersymmetry symmetry is broken. Fortunately for us this symmetry

¹Due to the Higgs superfield (SUSY quantum fields) not being holomorphic an additional Higgs doublet must be added in order to cancel anomalies and be able to generate mass for both the up and down type quarks.

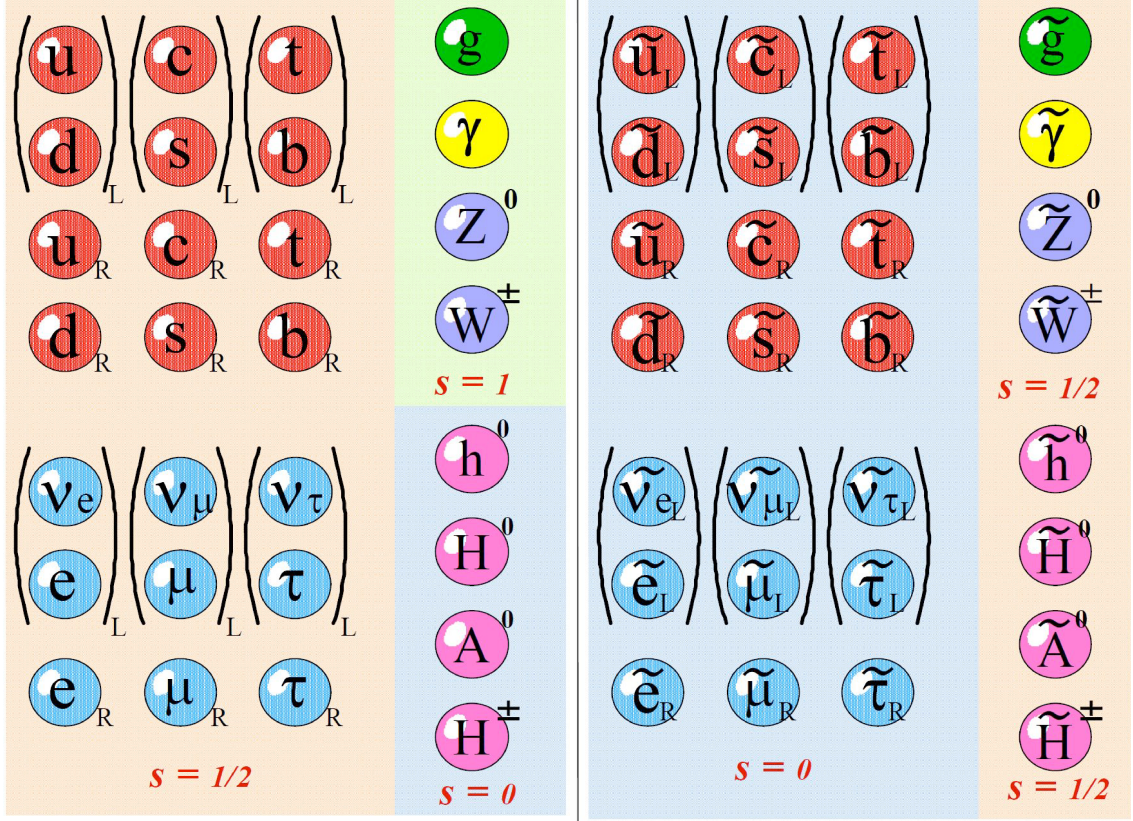


Figure 2.2: Particle content of the minimal supersymmetric standard model [3].

can be broken in such a way that the particle masses are large and observable at collider experiments (with sufficient energy).

We can now note how SUSY can address some of the unanswered questions in physics we listed in the beginning of this section. One of which it can explicitly address is known as the Hierarchy Problem, or as I put it before, “why is the Higgs so light.” The problem can be stated as follows: if the standard model is valid all the way up to the Planck scale, would expect the mass of the Higgs, due to the perturbative loop corrections seen in Figure 2.3, to be on the order of the Planck scale. We of course do not see this with the observed mass of 125 GeV of a SM like Higgs. With the addition of superpartners we find that a delicate cancellation occurs, where large loop corrections to the Higgs mass existed coming from the top quark (t) mass are now canceled by loop corrections arising from the stop quark ($\tilde{t}$) as is illustrated in Figure 2.4. Now, in order for the MSSM to solve the hierarchy problem in this way, we expect the characteristic mass scale of the supersymmetry breaking sector to be on the order of $m_{soft} = 1$ TeV. Therefore, it is reasonable to expect that masses

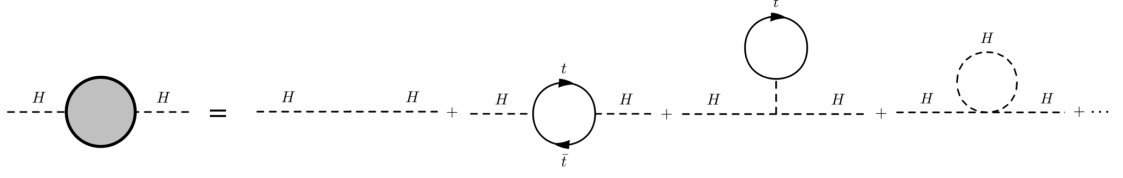


Figure 2.3: The observed Higgs mass as a sum of the bare Higgs mass plus loop corrections.

of the few lightest particles are approximately at the TeV scale and are potentially reachable at the LHC!

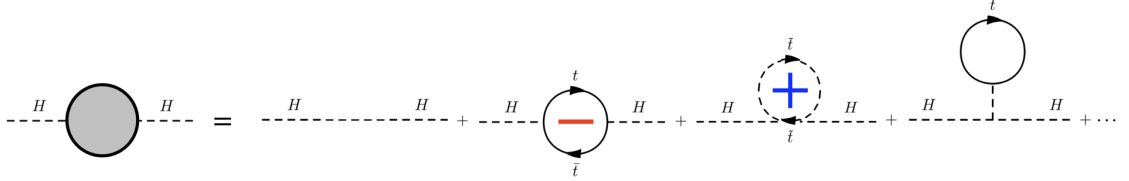


Figure 2.4: The observed Higgs mass as a sum of the bare Higgs mass plus loop corrections now including contributions from SUSY particles. The large blue “+” sign from the stop loop illustrating the its effective cancellation with the top loop contribution with the red “-” sign.

2.3.1 R -parity

Within the framework of the MSSM it is now possible to construct terms in the Lagrangian that violate Baryon (B) and Lepton number (L) to the tune that the proton would decay in approximately 10^{-2} seconds (for $\mathcal{O}(1)$ R -parity violating couplings, or if minimal flavor violation is assumed the lifetime can be extended to 1 year). We know of course that the proton does not rapidly decay (with lifetime bounds currently at 6×10^{39} years) and we also do not observe lepton number violation, so this problem must be addressed in the theory. A popular solution is to add in a discrete symmetry known as “ R -parity,” defined as the following,

$$P_R = (-1)^{3(B-L)+2S} \quad (2.3)$$

Where S is the spin of the particle. When R -parity is conserved at a vertex this forbids B and L violation entirely. This seems like a pretty reasonable thing to do, as B and L seem to be pretty much conserved as far as we can tell. Also this R -parity conserving solution (RPC) necessarily demands that the Lightest Supersymmetric Particle (LSP) be stable², which would give us a very convenient

²R=parity is also a measure for SUSYness, i.e. SUSY particles will always have $P_R = -1$ while SM particles will have $P_R = +1$

dark matter candidate. While this discrete symmetry does indeed accomplish its purpose, R -parity is, from a theoretical viewpoint, completely ad hoc, without any fundamental justification.

2.4 The $B - L$ Minimal Supersymmetric Standard Model

An alternative solution is obtained by simply postulating that the MSSM should be extended by a gauged $U(1)_{B-L}$ symmetry (of which R -parity is a discrete subgroup) which is spontaneously broken at some scale. This breaks L and, hence, $B - L$ symmetry. However, B remains unbroken and therefore proton decay continues to be suppressed below its present experimental bounds. However, the parameters of the $B - L$ MSSM must still be chosen so as to adequately suppress lepton number violating processes. This reproduces the exact MSSM particle spectrum with an additional three right handed neutrino chiral multiplets as well as a Z'_{B-L} (and its superpartner) from the broken symmetry. Below the scale of both spontaneous $B - L$ and SUSY breaking, the observable sector of this theory contains precisely the particle spectrum and gauge group of the Standard Model. This is known as the $B - L$ Minimal Supersymmetric Standard Model as described from the “bottom-up” approach. Also note that a “top-down” approach was shown to be possible in a series of papers [4–10] where this exact $B - L$ MSSM is recovered as the low energy theory of heterotic superstring/M-theory. The continuous $U(1)_{B-L}$ symmetry arising naturally as a consequence of the compactification of heterotic M-theory, which has long been known in a non-supersymmetric context to be the minimal extra gauging of the standard model that remains quantum mechanically anomaly free [11]. That is, the gauged $U(1)_{B-L}$ that arises in this context gives a “natural way” to suppress unwanted baryon and lepton number violating decays. For all of these reasons, *the $B - L$ MSSM appears to be the simplest possible phenomenologically realistic theory of heterotic superstring/M-theory; being exactly the MSSM with right-handed neutrino chiral supermultiplets and spontaneously broken R -parity* [12]. The post-EWKB particle content of the $B - L$ MSSM is illustrated in Figure 2.5. The gauge group for the $B - L$ MSSM is then

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \quad (2.4)$$

However, as discussed in detail in [8], it is equivalent and convenient to choose the gauge group to be

$$SU(3)_C \times SU(2)_L \times U(1)_{3R} \times U(1)_{B-L} \quad (2.5)$$

where $U(1)_{3R}$ is the canonical Abelian subgroup of $SU(2)_R$. It was shown in [8] that there is no kinetic mixing between the field strengths of $U(1)_{3R}$ and $U(1)_{B-L}$ at any momentum scale, and

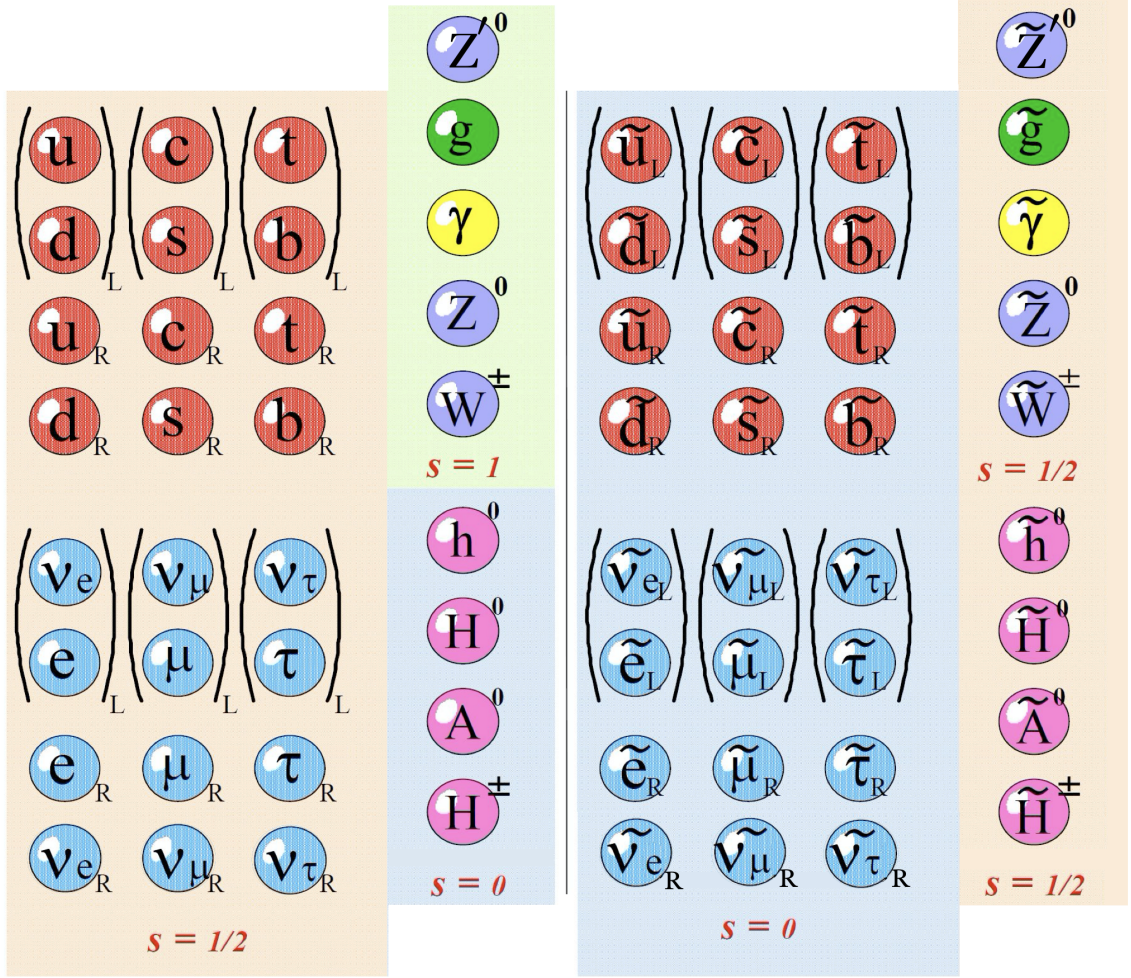
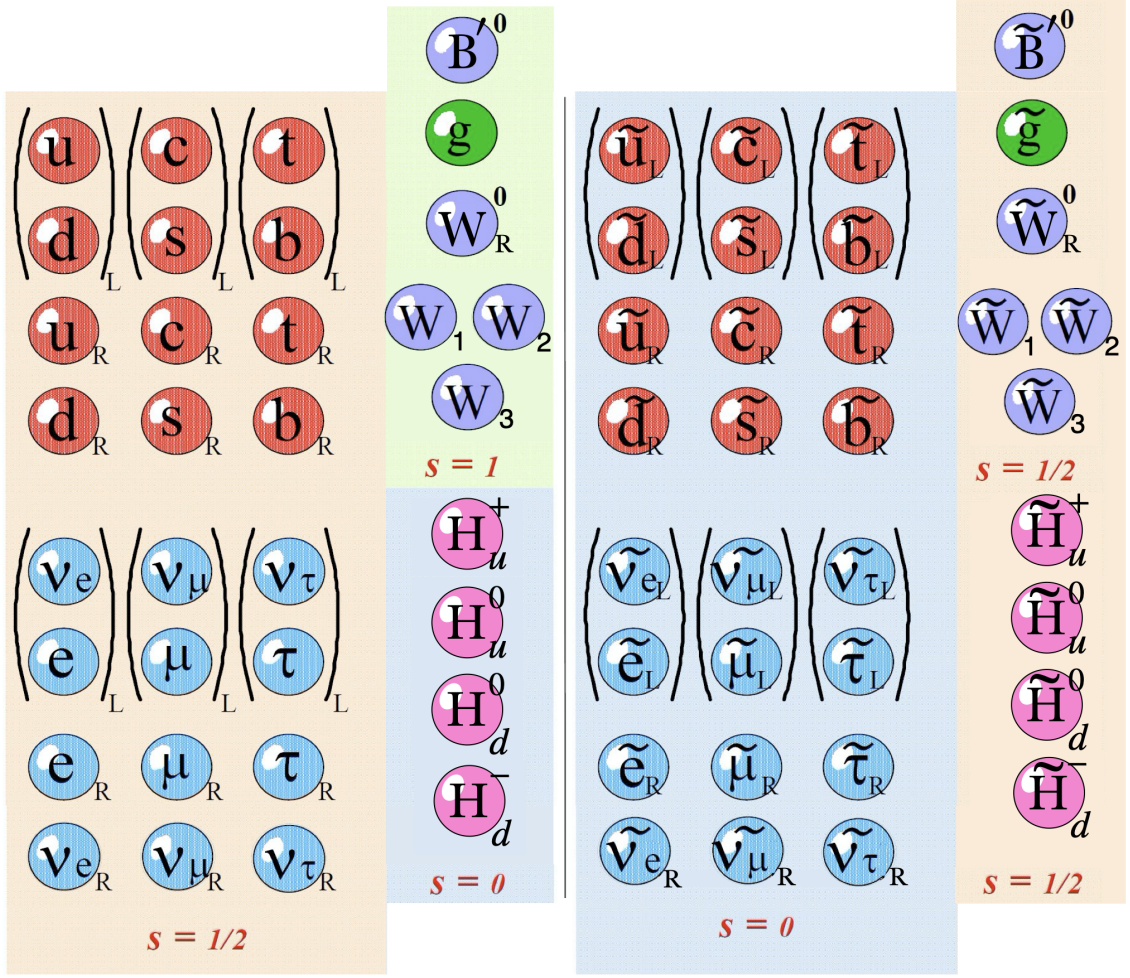


Figure 2.5: The post-EWKS particle content of the $B - L$ MSSM. Referring back to Figure 2.2 we note the addition of both right-handed neutrinos and sneutrinos. A Z' and its superpartner coming from the broken $U(1)_{B-L}$ symmetry are also added [13]

that this is the unique basis with this property. This vastly simplifies the solution of the RGEs and therefore the analyses done in the cited works work in this gauge group and so as to remain consistent the literature we will as well. The particle content corresponding to this gauge group is illustrated in Figure 2.6. Note the Blino (B'^0) and Rhino (W_R^0), corresponding to $U(1)_{B-L}$ and $U(1)_{3R}$ gauge symmetries respectively, in the Figure.

Figure 2.6: Minimal SUSY $B - L$ Model particle content, pre- $B - L$ breaking [13]

2.4.1 Phenomenology of a Broken $B - L$ Symmetry

In this theory the $U(1)_{B-L}$ symmetry can in principle be spontaneously broken by the right-handed sneutrino acquiring a non-vanishing vacuum expectation value (VEV). It was proven that this VEV could dynamically occur via radiative breaking in the $B-L$ MSSM using a full renormalization group (RG) analysis in [10]. Of course, the symmetry must be spontaneously broken at a scale sufficiently high to account for the fact that its associated massive vector boson Z'_{B-L} has, so far, not been observed.

A consequence of the breaking of $U(1)_{B-L}$ is the introduction of R -Parity violating terms, which will not significantly affect the mass eigenstates, *but do introduce mixing between the gauginos and*

the standard model charged leptons [11]. These mixings are central to this thesis as these are what allow for RPV decays and result in interesting signatures not well covered by standard SUSY searches at collider experiments. Continuing to work in the $SU(3)_C \times SU(2)_L \times U(1)_{3R} \times U(1)_{B-L}$ basis, the charged³ mixed mass eigenstates, called *charginos*, are related to the gauge eigenstates by unitary matrices $\mathcal{V}$ and $\mathcal{U}$ defined by

$$\begin{pmatrix} \tilde{\chi}_1^- \\ \tilde{\chi}_2^- \\ \tilde{\chi}_3^- \\ \tilde{\chi}_4^- \\ \tilde{\chi}_5^- \end{pmatrix} = \mathcal{U} \begin{pmatrix} \tilde{W}^- \\ \tilde{H}_d^- \\ e^- \\ \mu^- \\ \tau^- \end{pmatrix}, \quad \begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \\ \tilde{\chi}_3^+ \\ \tilde{\chi}_4^+ \\ \tilde{\chi}_5^+ \end{pmatrix} = \mathcal{V} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \\ e^+ \\ \mu^+ \\ \tau^+ \end{pmatrix} \quad (2.6)$$

Where the explicit values for the entries in $\mathcal{V}$ and $\mathcal{U}$ can be found in [11]. For the analogous neutral mass eigenstates, *neutralinos*, we have an even more complicated situation. First, it has been shown that mixing with the first- and second-family right-handed neutrino would lead to active sterile neutrino oscillations [11]. Unless and until there is more experimental evidence of such oscillations, we will assume that they do not exist. Therefore, the mixing with the first and second-family right-handed neutrinos is negligible and we include only mixing with the three families of left-handed neutrinos and the third-family right-handed neutrino [11]. The neutralinos are then related to the gauge eigenstates by unitary matrix $\mathcal{N}$ defined by

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \\ \tilde{\chi}_5^0 \\ \tilde{\chi}_5^0 \\ \tilde{\chi}_5^0 \\ \tilde{\chi}_5^0 \\ \tilde{\chi}_5^0 \\ \tilde{\chi}_5^0 \end{pmatrix} = \mathcal{N} \begin{pmatrix} \tilde{W}_R \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \\ \tilde{B}' \\ \nu_3^c \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \quad (2.7)$$

Where again the explicit values for the entries in $\mathcal{N}$ can be found in [11]. Now due to the relative smallness of the RPV couplings we expect RPV decays primarily coming from the LSP of the theory, as heavier charginos/neutralinos would prefer RPC decay channels. So it then becomes important to determine if the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^{04}$ are even likely candidates to be the LSP in the $B-L$ MSSM. An extensive

³electromagnetically

⁴The lightest chargino and neutralino state respectively

study involving the statistical scanning over all dimensionful parameters of the soft SUSY breaking terms was done in [11] and does motivate $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ as likely LSPs in the $B - L$ MSSM. This scan is discussed in more detail in Chapter 5 where additional experimental considerations are taken into account as well.

CHAPTER 3

LHC and the ATLAS Detector

3.1 The Large Hadron Collider

Located at the European Organization for Nuclear Research (CERN) near Geneva, Switzerland, the Large Hadron Collider (LHC) [14] is a circular particle accelerator made up of 27 kilometers of superconducting magnets and RF cavities a hundred meters beneath the Franco-Swiss countryside. The LHC is fed by a series of smaller accelerators, each subsequent accelerator increasing the energy of the particles by an order of magnitude or more. This impressive complex of accelerators is shown in Figure 3.1. A small bottle of hydrogen feeds a small fraction of its contents into a Duoplasmatron which ionizes the hydrogen into its constituent protons and electrons. The protons are then injected in Linac2 where they reach 50 MeV. Next they are passed on into the Booster, the Proton Synchrotron, and then the Super Proton Synchrotron, which accelerate the protons to an energy of 1.4 GeV, 25 GeV, and 450 GeV respectively. Finally they enter the LHC where the adjacent oppositely moving beams of protons are each accelerated to the highest energy of 6.5 TeV (99.9999991% the speed of light). The parallel beams meet at four crossing points along the LHC. The protons collide at these points with a center-of-mass energy of $\sqrt{s} = 13$ TeV. The actual operation energies were 7 TeV (2010-2011) and 8 TeV (2012) during Run-1, and 13 TeV during Run-2. The four independent physics experiments, A Large Ion Collider Experiment (ALICE) [15], A Toroidal LHC ApparatuS (ATLAS) [16], the Compact Muon Solenoid (CMS) [17], and the Large Hadron Collider beauty (LHCb) [18] exist at each collision point as seen in Figure 3.1.

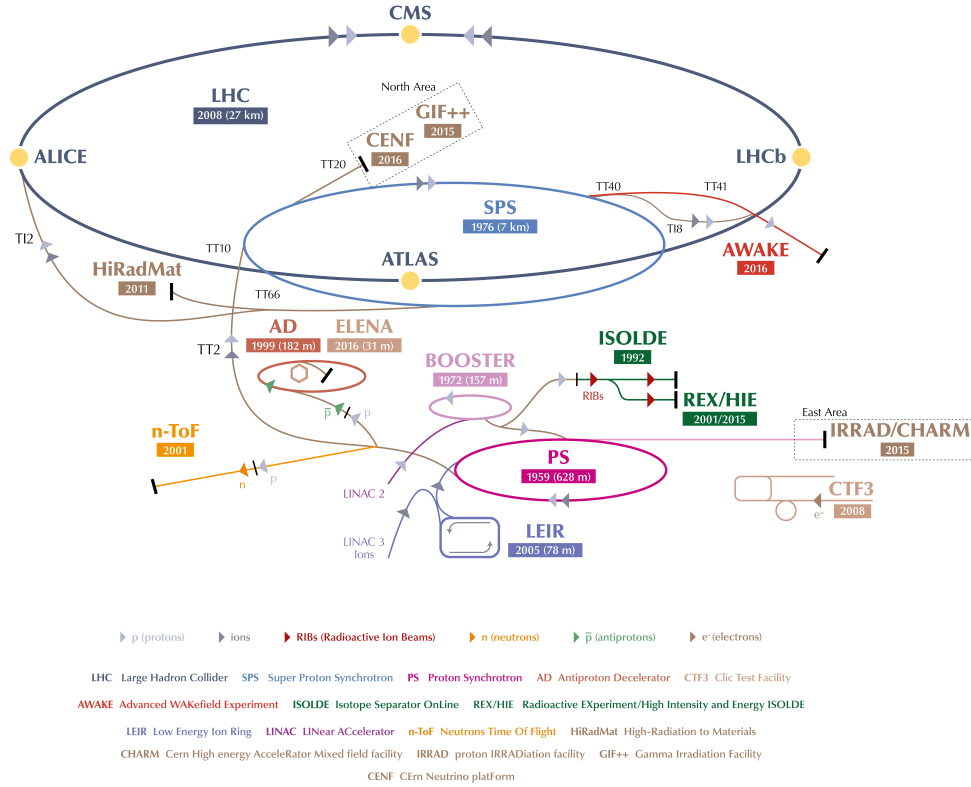


Figure 3.1: Accelerator complex at CERN [19]

3.1.1 Magnets

There are two primary types of magnets, the dipoles (bending magnets) and the quadrupoles (squeezing magnets). The 27 km LHC ring is filled with 1232 15 m long main superconducting dipole magnets and 392 main superconducting quadrupole magnets which bend and focus the the beam around the collider. With an additional 6000 correcting magnets proton beams are able to be steered in stable circular trajectory. The standard dipole cross-section schematic is shown in Figure 3.2a, detailing the anatomy of the dipole. Focusing in on the superconducting coils in Figure 3.2b, note there are two dipoles with magnetic fields in opposite directions. We can easily observe via the familiar right hand rule of the magnetic force law ($F = qv \times B$) that the oppositely circulating proton beams will be bent in the same direction in their path around the LHC ring. The quadrupole magnet cross-section is effectively identical to the dipole only now with a swap of the dipole superconducting coil configuration with that of the quadrupole configuration shown in Figure 3.3. The

LHC DIPOLE : STANDARD CROSS-SECTION

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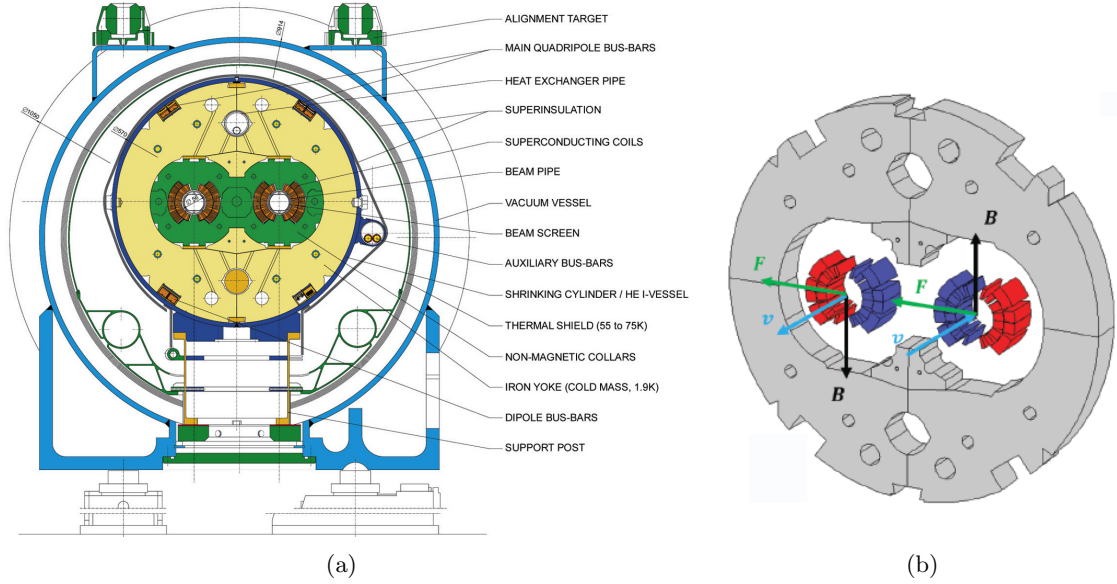


Figure 3.2: (a) Diagram showing the cross-section of an LHC dipole magnet with cold mass and vacuum chamber and (b) the polarity of the magnets with force diagrams depicting how oppositely same charges particles would be bent into the same circle [20] [21].

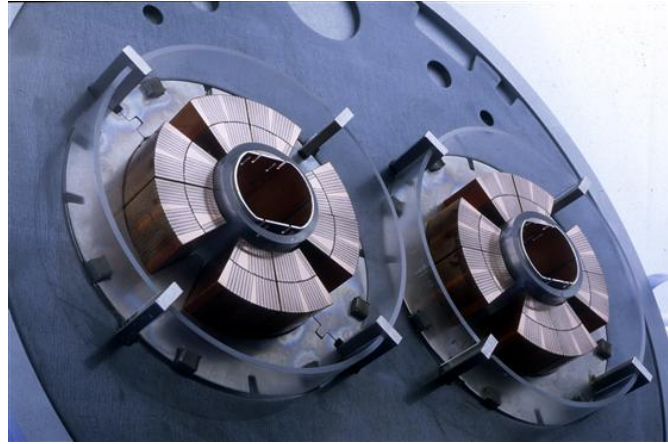


Figure 3.3: Cross-section of a model of the superconducting quadrupole magnet [22]

last set of magnets required are the low- β triplets, so-called due to their three quadrupole system that is used to focus the beams, and that it is the triplet's job to minimize the β -function, which is proportional to beam size, are located on either side of each of the four experiments. This system does a final squeeze on the beams, making them 12.5 times narrower – from 0.2 millimeters down

to 16 micrometers across, all the while simultaneously crossing the opposing beams at the center of the detectors. Figure 3.4 illustrates these low- β triplets at work as the beam sizes are drastically reduced in the last 60 m on each side of the interaction point. After colliding, the particle beams are separated again by dipole magnets.

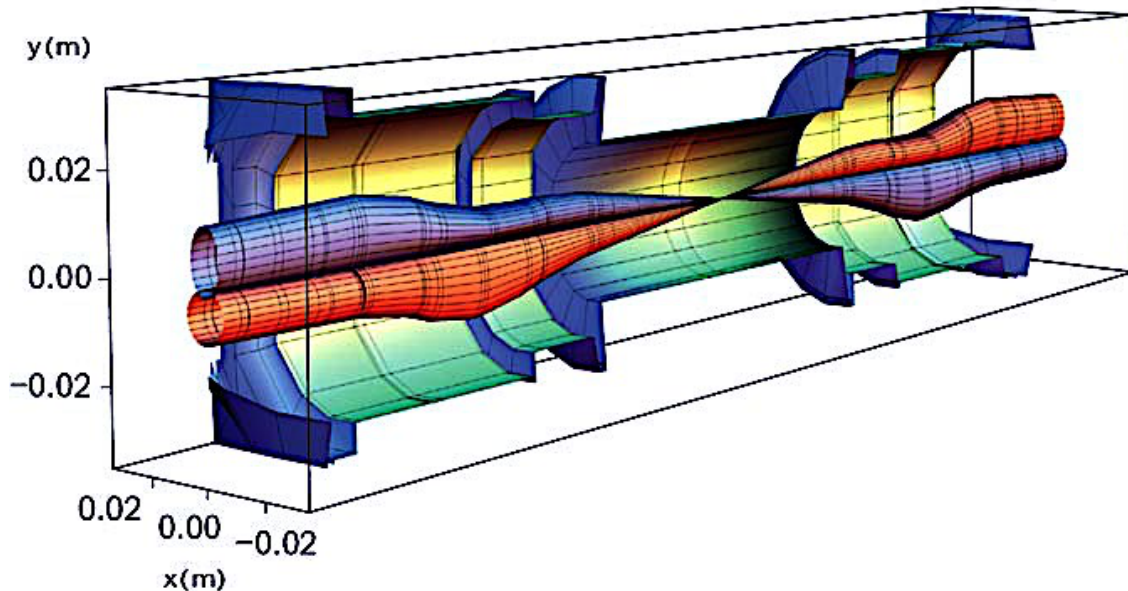


Figure 3.4: Beam envelopes in the interaction region around point 1 (ATLAS) showing how the beam sizes are reduced in the last 60 m on each side of the interaction point following the squeeze. Note the different transverse scale: the radius of the cut-away beam pipe is just 18 mm at the collision point. The clockwise beam is in blue and the anti-clockwise beam is in red [23]

3.1.2 Beams, Buckets, and Bunches

The proton beam structure consists of the base unit known as a “bunch” where each bunch is on the order of 10^{11} protons. A bunch is a direct consequence of the harmonics of the RF cavities. Given the revolution frequency of the protons and RF frequency the LHC has a total of 35640 harmonics. Each one of these harmonics is known as a “bucket” and is effectively a potential well for the protons in which a bunch *can* exist. So while in principle the LHC could accelerate 35640 bunches at a time per beam, practically this would result in a bunch spacing of 2.5 ns and the LHC’s diverting magnets would not have enough time to trigger and execute a beam dump (never mind the fact that it would make data taking an incredible challenge as it would light up our detectors like a Christmas tree even if we could!). These technical restrictions give rise to the

nominal proton beam at the LHC made up of 2808 bunches with 25 ns spacing (10 empty buckets spacing). Figure 3.5 shows a more detailed schematic of the 25 ns bunch structure. This amounts to $2808 \text{ bunches} \times 10^{11} \text{ protons} = 3 \cdot 10^{14} \text{ protons/beam}$, or $6 \cdot 10^{14} \text{ protons}$ for the two beams. From

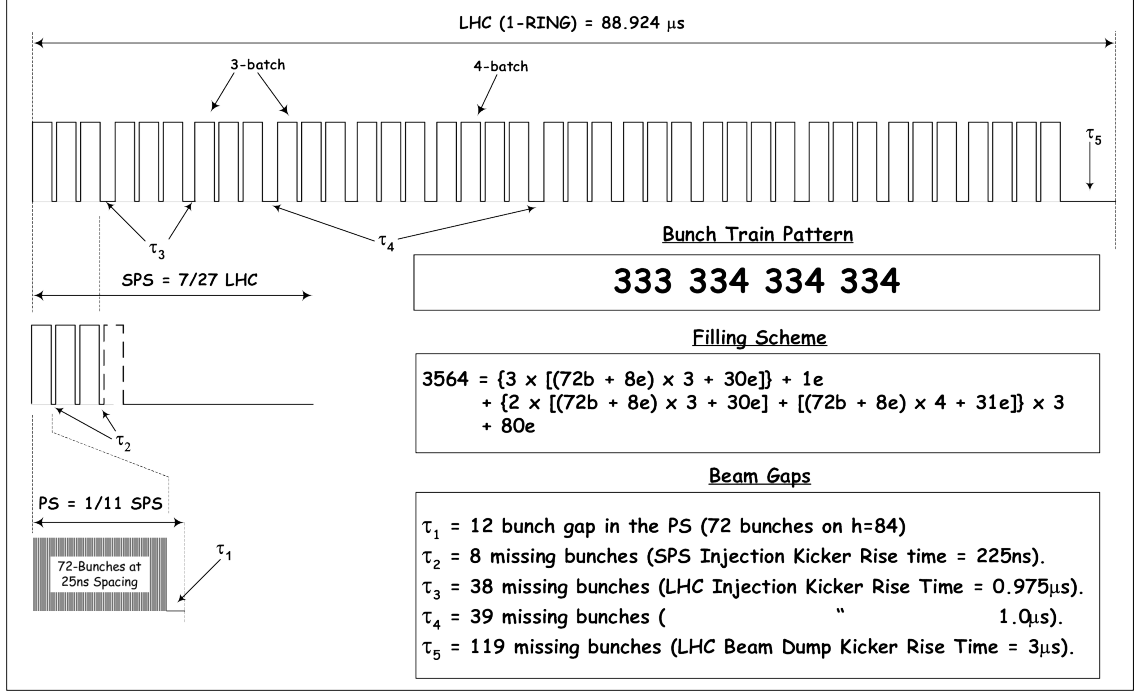


Figure 3.5: Schematic of the Bunch Disposition around an LHC Ring for the 25 ns Filling Scheme. We can recover the quoted number of bunches of 2808 in the text by sending the number of missing bunches, denoted with an “e” to zero ($e \rightarrow 0$) in the “Filling Scheme” calculation. Or equivalently adding up all the integers present in “Bunch Train Pattern” and multiplying by 72. [24]

September 2017 to the end of data-taking in 2017 this structure was modified to the “8 bunches” and “4 empty (slots)” spacing in order to mitigate excessive beam dumps caused by frozen particles of gas being detached from the inside of the beam pipe during a run. This resulted in a decrease of the number of bunches to 1920 but an actual *increase* in activity in the detector by the measure of the mean number of interactions per bunch crossing, $\langle \mu \rangle$. Where $\langle \mu \rangle$ corresponds to the mean of the Poisson distribution of the number of interactions per crossing calculated for each bunch. This is calculated from the instantaneous per bunch luminosity as $\mu = L_{\text{bunch}} \times \sigma_{\text{inel}} / f_r$ where L_{bunch} is the per bunch instantaneous luminosity, σ_{inel} is the inelastic cross section which is taken to be 80 mb for 13 TeV collisions, and f_r is the LHC revolution frequency. This bunch structure change was reflected in standard luminosity vs. $\langle \mu \rangle$ plot in Figure 3.6 as the infamous “double-hump” (Bactrian?) year

in purple. Each fill of the LHC with two proton beams last for 10 hours with stable beam conditions, i.e. a fill corresponds to a productive physics data collection period before the beam is depleted to the point that the bunch density becomes low enough that it becomes more favorable to dump the beam and re-fill for another run than to continue the current run.

3.1.3 Pileup

The number of interactions per bunch crossing is not only an important measure for data yield but also for the activity present in the detectors, as it directly influences physics analyses at almost every level. If the LHC were to be filled such that $\langle\mu\rangle = 1$ we would of course have very clean and straight forward detector signatures and this discussion would be moot. However the vast majority of potentially accessible processes at the LHC would be practically unattainable due to their extreme rarity, so the high rate of proton collisions is essential for modern collider particle physics analyses and the handling of many interactions is necessary. This additional activity to be handled is referred to as “pileup.” Figures 3.7 and 3.8 show ATLAS event displays for events with 25 and 66 reconstructed vertices, respectively, to demonstrate what these high pileup collisions look like in the ATLAS detector. So as one can easily imagine from these figures high pileup environments pose experimental difficulties for the detectors as the interaction of interest must be distinguished from all the other simultaneous collisions.

3.2 The ATLAS Detector

The ATLAS experiment is a general-purpose particle physics detector designed to observe particles produced in the high-energy pp and heavy-ion LHC collisions. It has a forward–backward symmetric cylindrical geometry and almost 4π coverage in solid angle. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis running along the beam line. The x-y plane is perpendicular to the beam line, and is referred to as the transverse plane. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward toward the earth’s surface. The detector half at positive z-values is referred to as the “A-side”, the other half the “C-side”. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The polar angle θ is defined as the angle from the positive z-axis. The polar angle is often reported in terms of pseudorapidity, defined as $\eta = -\ln[\tan(\frac{\theta}{2})]$. The inner tracking detector (ID) used for charged-particle tracking covers the pseudorapidity range $|\eta| < 2.5$ and consists of a silicon pixel detector, a silicon microstrip detector

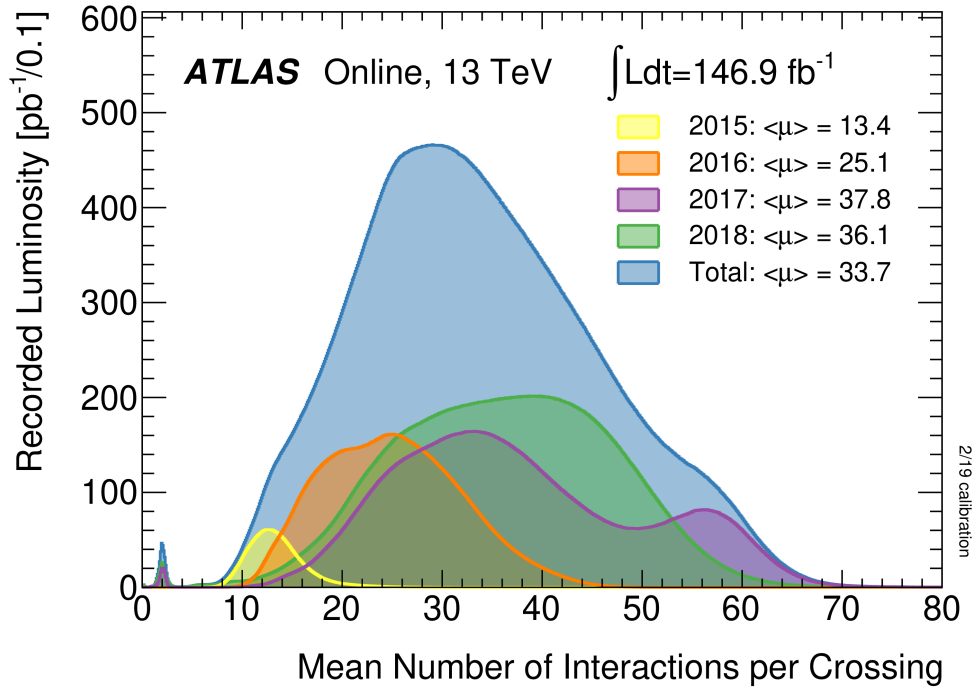


Figure 3.6: Shown is the luminosity-weighted distribution of the mean number of interactions per crossing for 2015-2018 pp collision data at 13 TeV centre-of-mass energy. All data recorded by ATLAS during stable beams is shown, and the integrated luminosity and the mean μ value are given in the figure. The luminosity shown represents the preliminary 13 TeV luminosity calibration for 2018, released in February 2019, that is based on van-der-Meer beam-separation scans [25].

(SCT), and a transition radiation tracker (TRT) in the range $|\eta| < 2.0$. The ID is immersed in a 2 Tesla axial magnetic field produced by a thin superconducting solenoid. Electromagnetic (EM) and hadronic calorimeters outside the solenoid cover the pseudorapidity range $|\eta| \leq 3.2$. A 4 Tesla toroid magnet then surrounds the calorimeters. Interleaved and surrounding the toroid barrel and endcap magnets are the muon spectrometers, covering $|\eta| \leq 2.7$. A two-level triggering system reduces the total data-taking rate to approximately 1 kHz from the bunch crossing rate of 40,000 kHz.

3.2.1 The Inner Detector

Surrounded by a superconducting solenoid producing a 2 Tesla magnetic field, the Inner Detector measures the trajectories of charged particles and is composed of three layers of tracking detectors.

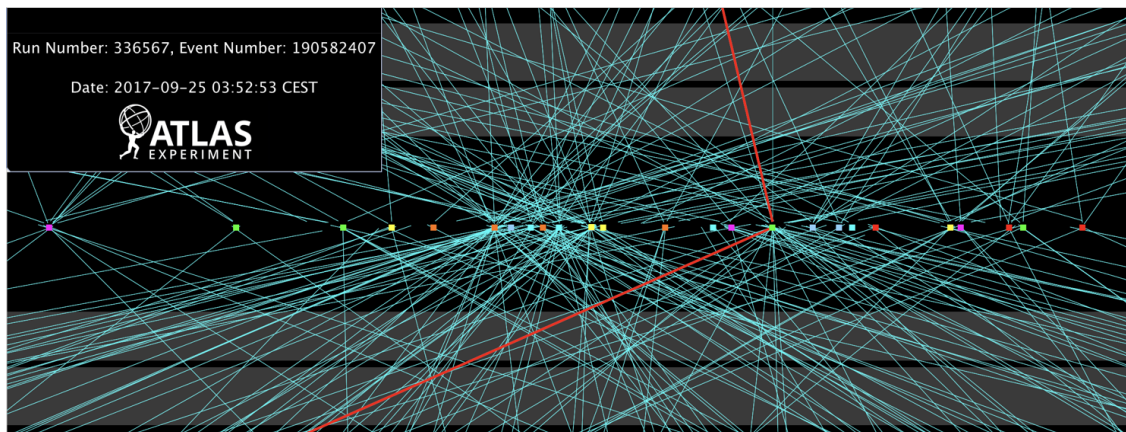


Figure 3.7: A display of a $Z \rightarrow \mu\mu$ candidate event from proton-proton collisions recorded by ATLAS with LHC stable beams at a collision energy of 13 TeV. The Z candidate is reconstructed in a beam crossing with 24 additionally reconstructed vertices from minimum bias interactions. The hard interaction vertex is represented by a green square from which the two muons (red tracks) are emerging. Tracks with $p_T > 500$ MeV are displayed [26].

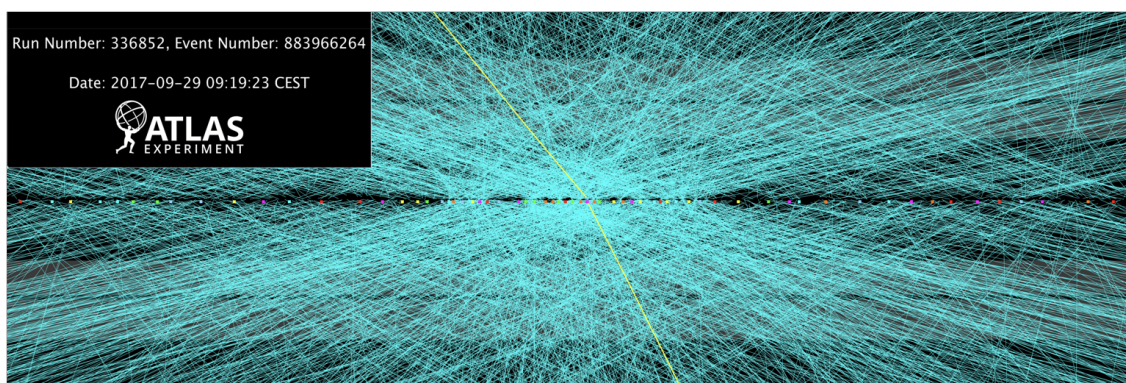


Figure 3.8: A display of a $Z \rightarrow \mu\mu$ candidate event from proton-proton collisions recorded by ATLAS with LHC stable beams at a collision energy of 13 TeV. The Z boson candidate is reconstructed in a beam crossing with 65 additionally reconstructed vertices from minimum bias interactions. The figure shows tracks with a cut on track p_T of 100 MeV [27].

3.2.1.1 Pixel Detector

The closest sub-detector system to the beam line, the Pixel Detector requires the finest sensor granularity of any sub-detector on ATLAS. Covering the η range of $|\eta| < 2.5$, the Pixel Detector is composed of four cylindrical barrel layers with 1736 sensor modules and three disk-shaped endcap layers with 288 modules. While the detector has just 1.9 m^2 of total active material with pixel sizes just $50 \times 400 \text{ } \mu\text{m}^2$ for the external layers and $50 \times 250 \text{ } \mu\text{m}^2$ for the innermost layer (IBL), The Pixel

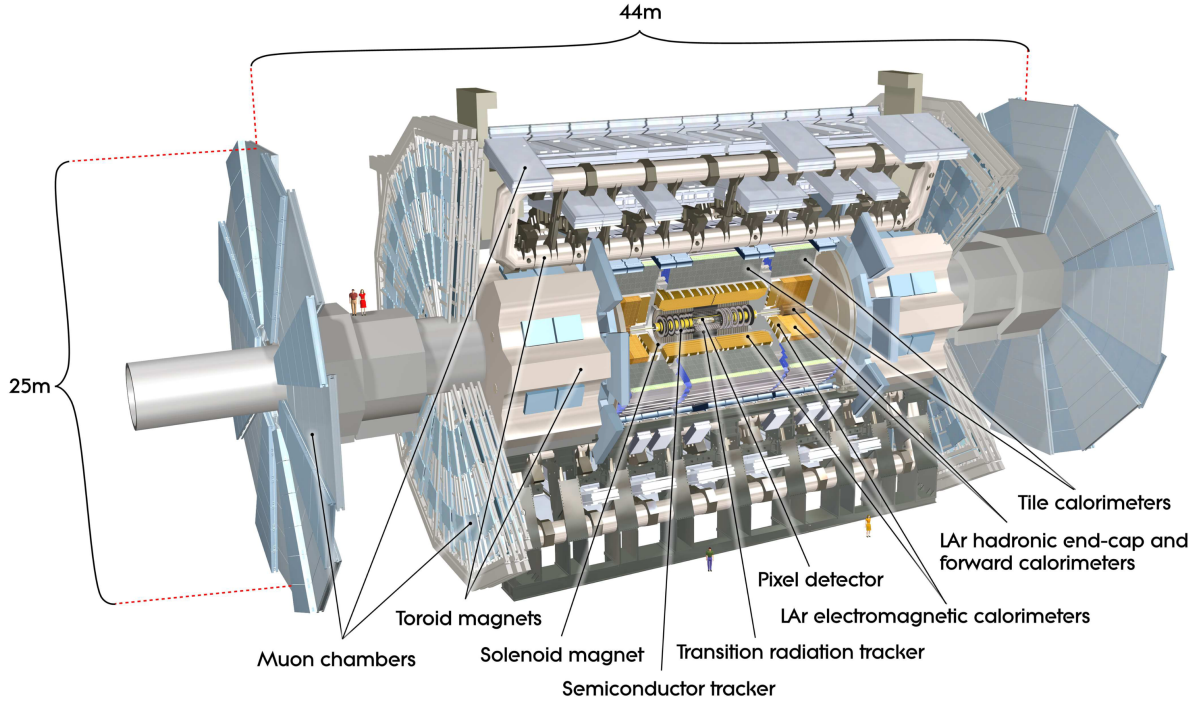


Figure 3.9: General cut-away view of the ATLAS detector [16].

Detector totals an impressive 92 million pixels (92 million electronic channels) [16]. The pixel sensors provide a resolution of $10\ \mu\text{m}$ in the transverse plane, and $115\ \mu\text{m}$ in the z direction (r direction) of the barrel (endcap) modules. An illustration in Figure 3.10 shows the barrel Pixel layers that reach just beyond 12 cm radially out from the beam line.

3.2.1.2 Semiconductor Tracker

The next detector is the Semiconductor Tracker, which uses the same basic technology as the Pixels, but the fundamental unit of silicon is a “strip.” Covering $|\eta| < 2.5$ the SCT consists of 4,088 two-sided modules and over 6 million implanted readout strips (6 million channels). The total instrumented area of 60 square meters of silicon is distributed over 4 cylindrical barrel layers and 18 planar endcap discs. Readout strips every $80\ \mu\text{m}$ on the silicon, allowing the positions of charged particles to be recorded to an accuracy of $17\ \mu\text{m}$ per layer (in the direction transverse to the strips). Thanks to stereo information from the strips, the resolution in the z (r) direction of the barrel (endcap) modules is $580\ \mu\text{m}$.

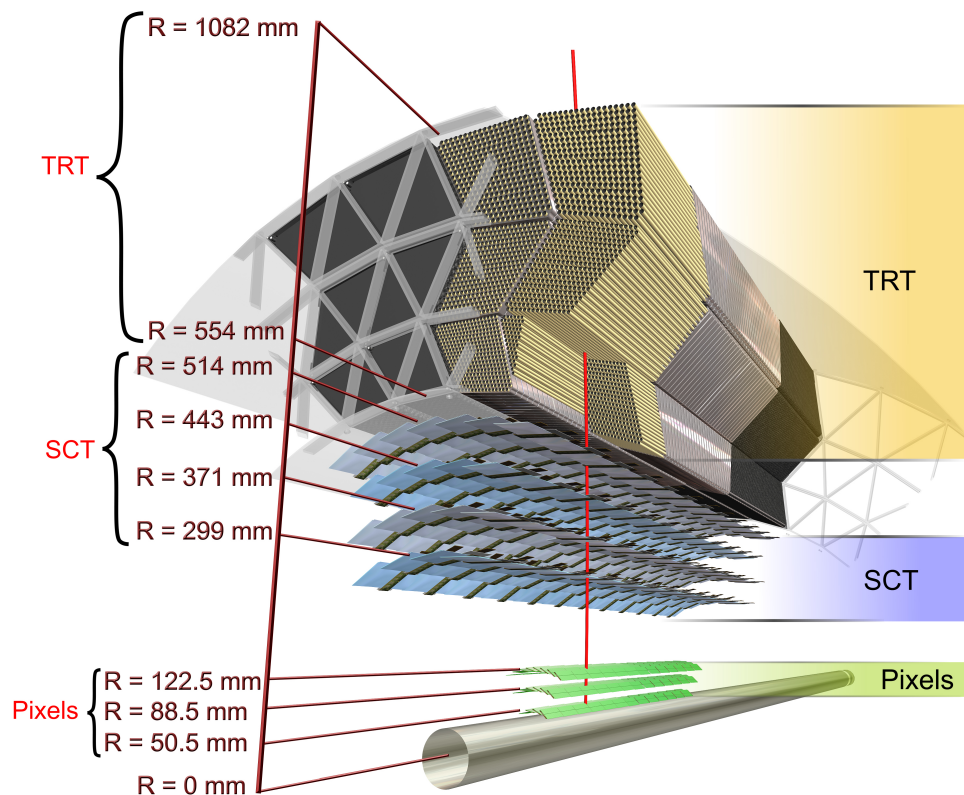


Figure 3.10: Illustration showing the ID systems being traversed by a charged track (red) of $p_T=10\text{GeV}$ in the barrel ($\eta = 0.3$). The track traverses successively the beam-pipe, the four cylindrical silicon-pixel layers (IBL included), the four cylindrical double layers of the barrel SCT, and approximately 36 axial straws contained in the barrel TRT modules within their support structure [28].

3.2.1.3 Transition Radiation Tracker

The Transition Radiation Tracker is the outermost and largest-by-volume system of the ID. At a volume of 12 m^3 the TRT consists of 350,000 small-radius (4 mm diameter) drift tubes called ‘straws.’ Each straw functions as a simple anode (a 0.03 mm diameter gold-plated tungsten wire at the center) and cathode (outer aluminium-coated kapton film) immersed in an ‘electrolyte’ (a Xe-based gas mixture). electrons drifting towards the anode. In the strong electric field close to the anode, avalanche multiplication leads to a signal on the anode wire. The TRT records if the signal on the wire above a low threshold every 3.25 ns. The maximum drift time (from ionization at the edge of the straw) is 60 ns. Transition radiation occurs for high energy electrons going through a polymer material between the straws. Expensive Xenon gas is used in the TRT since it has a higher

absorption cross section for these transition radiation X-rays than the much cheaper Argon. The transition radiation results in larger ionization and a larger pulse. The TRT records if the signal on the wire goes above a high threshold every 25 ns. Precision measurement of 130 microns (particle track to wire) are possible and the TRT provides electron identification information independent from the calorimeters.

3.2.2 The Calorimeters

ATLAS includes two types of calorimeter systems, the Liquid Argon calorimeter (LAr) and the Tile calorimeter (TileCal) for measuring electromagnetic and hadronic showers respectively. Together, these cover a region of $|\eta| < 4.9$. A cut away view of the calorimeter system can be seen in Figure 3.11.

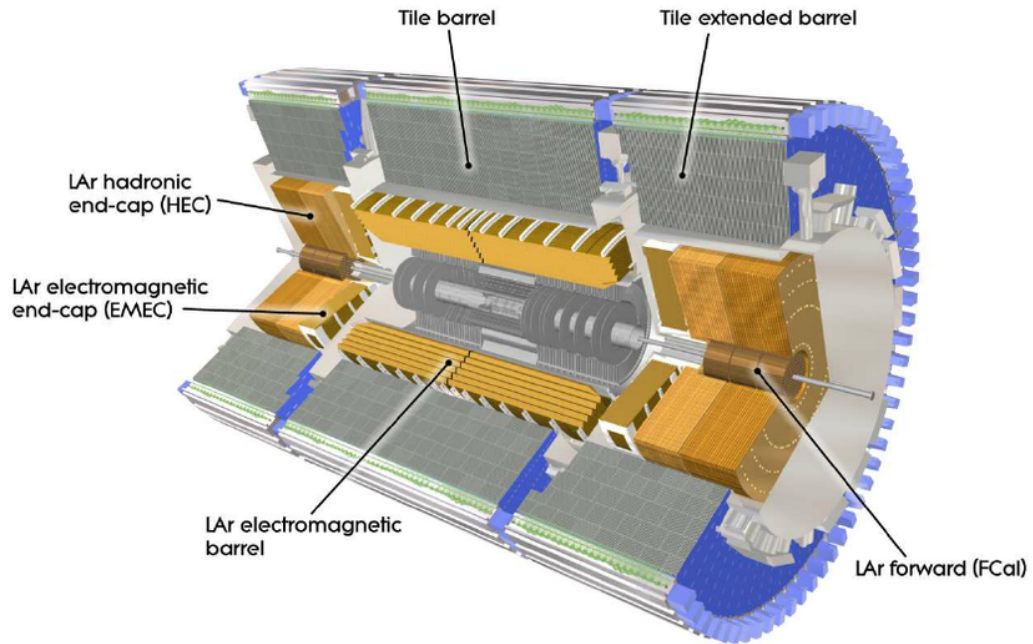


Figure 3.11: Cut-away view of the ATLAS calorimeters. The LAr calorimeters are seen inside the hadronic Tile calorimeters [16].

3.2.2.1 Liquid Argon Calorimeters

The EM calorimeter is a lead/liquid-argon (LAr) sampling calorimeter with an accordion geometry made up of layers of passive Pb absorber alternating with active liquid argon detector layers. As an electron or a positron or photon passes through the absorber the particle will cascade electromagnetically: photons produce electron-positron pairs and electrons/positrons will emit bremsstrahlung photon radiation; the daughter electrons, positrons, and photons also interact, resulting in a particle shower. Most of the energy will have been absorbed after traversing about 20 radiation lengths (X_0) of absorber (longitudinal depth). Note that lead has a radiation length of only 0.56 cm so the electromagnetic calorimeter is able to be rather compact at 53 cm (62 cm) deep in the barrel (endcap). The lateral width of the shower in a material is characterized by its Molière radius, the radius of a cone in which 90% of the shower energy is contained. Note that lead has a Molière radius of only 1.6 cm, so the energy deposits in the calorimeter from electrons, positrons, and photons have a very narrow width in the detector. This is a key for identification of electrons.

The calorimeter is divided into a barrel section (EMB) covering the pseudorapidity region $|\eta| < 1.475$, and two endcap sections (EMEC) covering $1.375 < |\eta| < 3.2$. The barrel and endcap calorimeters are immersed in three LAr-filled cryostats, and are segmented into three layers for $|\eta| < 2.5$. The layered and accordion structure of the LAr are illustrated in Figure 3.12, showing a section of the barrel LAr calorimeter. Layer 1 covers $|\eta| < 1.4$ and $1.5 < |\eta| < 2.4$, has a thickness of about 4.3 radiation lengths (X_0) and is finely segmented in the η direction, typically 0.003×0.1 in $\Delta\eta \times \Delta\phi$ in the EMB, to provide discrimination between electromagnetic showers initiated by a single electron or photon and those initiated by the two photons from the decay of a neutral pion [16]. Layer 2, which collects most of the energy deposited in the calorimeter by electromagnetic showers, has a thickness of about 17 X_0 and a granularity of 0.025×0.025 in $\Delta\eta \times \Delta\phi$ [16]. Layer 3, which has a granularity of 0.05×0.025 in $\Delta\eta \times \Delta\phi$ and a depth of about $2X_0$, is used to correct for leakage beyond the EM calorimeter for high-energy showers [16]. In front of the accordion calorimeter, a thin presampler layer (PS) covering the pseudorapidity interval $|\eta| < 1.8$, is used to correct for energy loss upstream of the calorimeter. The PS consists of an active LAr layer with a thickness of 1.1 cm (0.5 cm) in the barrel (endcap) and has a granularity of $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$. The transition region between the EMB and the EMEC, $1.37 < |\eta| < 1.52$, has a large amount of passive material (from cables and services to the inner detector) in front of the first active calorimeter layer ranging from 5 to almost $10X_0$ [16]. This section is instrumented with scintillators located between the barrel and endcap cryostats, and extending up to $|\eta| = 1.6$. Note that this transition region is

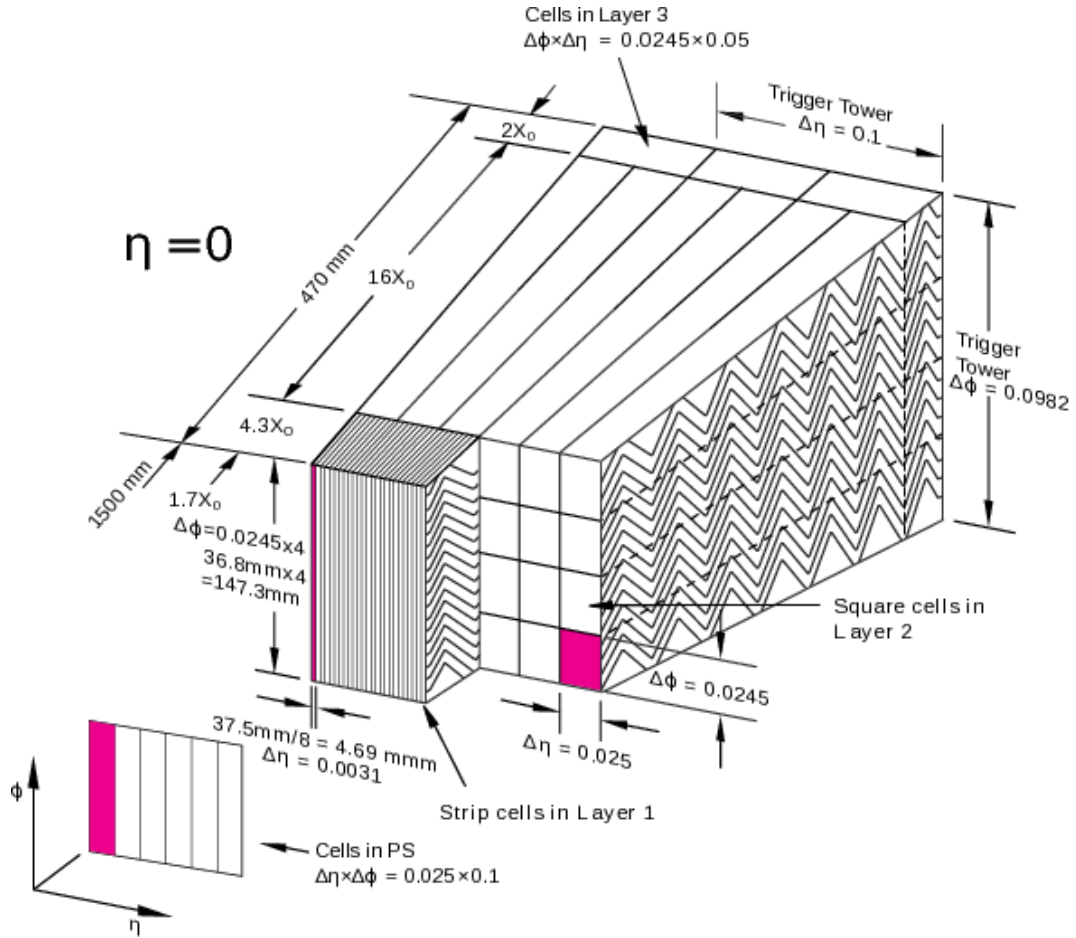


Figure 3.12: Illustration of the LAr calorimeter detailing the different granularities and radiation lengths of each layer [16].

specifically separated in the electron ID due to the lack of precise information available. This allows an analyzer to veto the region entirely which is common practice.

3.2.2.2 Tile Calorimeter

The main function of the Tile Calorimeter (TileCal) is to contribute to the energy reconstruction of the jets produced in the proton-proton interactions and, with the addition of the end-cap and forward calorimeters, to provide a good E_T^{miss} measurement [29]. The TileCal surrounds the EM calorimeter and extends radially from 2280 mm to radius of 4230 mm. It consists of three large segments in as can be seen in Figure 3.13. The middle segment consists of an alternating iron/scintillator material tile calorimeter with barrel coverage $|\eta| < 1.7$. The two outer segments, known as the hadronic

end cap (HEC), instead use copper for their absorber and LAr for the active material, spanning $1.5 < |\eta| < 3.2$. Figure 3.13 also illustrates the wedge based module structure of the TileCal. The acceptance is extended by two copper/LAr and tungsten/LAr forward calorimeters covering $3.1 < |\eta| < 4.9$, and hosted in the same cryostats as the EMEC.

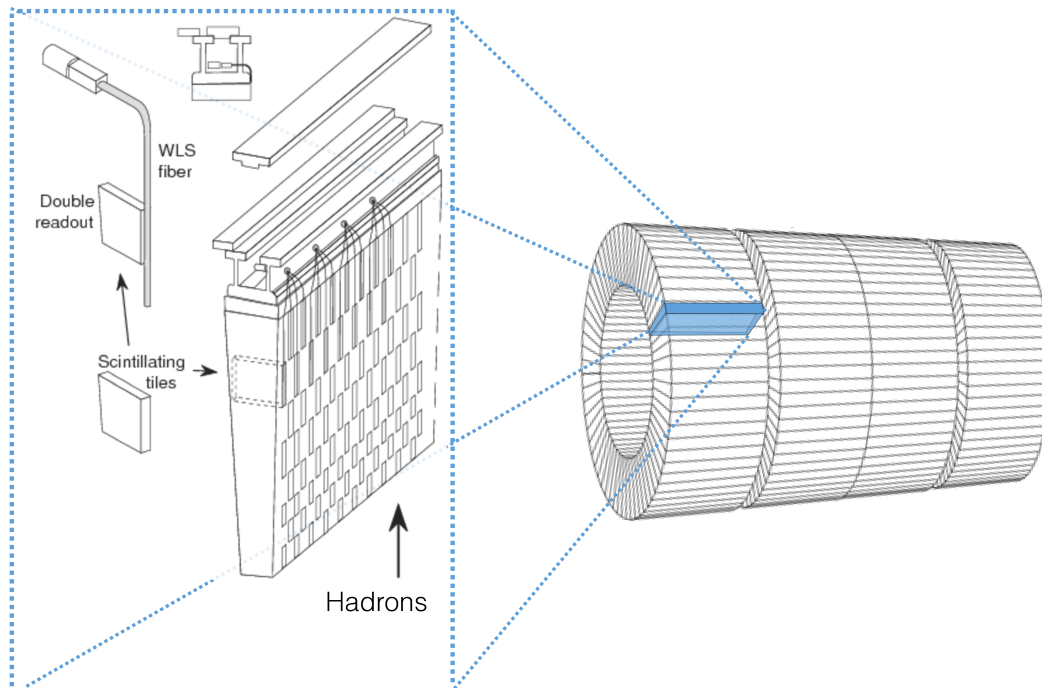


Figure 3.13: Illustration of the Tile Calorimeter showing its barrel and end cap segments along with a zoomed-in view of a wedge module diagramming the placement and orientation of the tiles and read out material for one of the HEC segments. Note for the barrel segment the tile orientation is such that its length dimension is along the z-axis instead.

3.2.3 The Muon Spectrometer

The Muon Spectrometer (MS), located beyond the calorimeters is the outermost subdetector of ATLAS and is shown in Figure 3.14. It consists of three large air-core superconducting toroid systems (two end cap and one barrel) with eight coils each, providing a magnetic field of ≈ 0.5 T [30]. The deflection of the muon trajectories in the bending plane of the magnetic field (the “precision coordinate”) is measured via hits in three layers of monitored drift tube (MDT) precision chambers

covering the region in pseudorapidity up to $|\eta| < 2.7$. In the innermost endcap wheels of the MS, cathode strip chambers (CSC) are used instead of MDTs in the region $2.0 < |\eta| < 2.7$ [30]. Three layers of resistive plate chambers (RPC) in the barrel ($|\eta| < 1.05$) and 3–4 layers of thin gap chambers (TGC) in the endcaps ($1.05 < |\eta| < 2.4$) provide the muon trigger, and also measure the muon trajectory in the non-bending coordinate of the toroid magnets (the “second coordinate”) [30]. In the Phase-I upgrade, during the second long shutdown (LS2), the Small Wheels will be replaced by the New Small Wheels (NSW) that use a small-strip TGC and Micro-Mesh Gaseous Structure chambers used for both triggering and precision tracking [30].

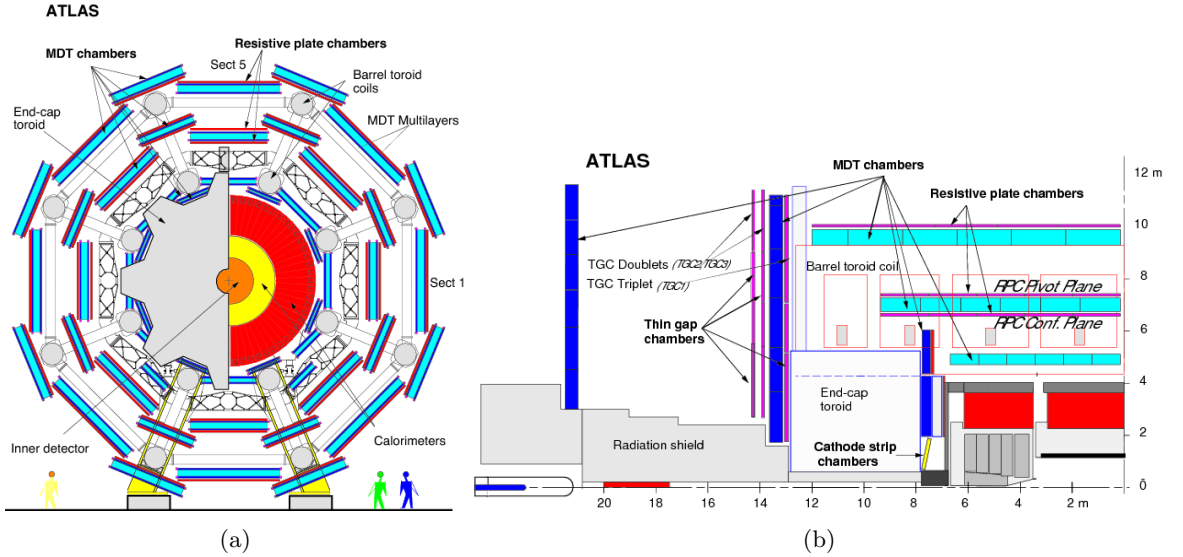


Figure 3.14: (a) A cross sectional view in the r - ϕ plane of the barrel layout of the muon spectrometer as well as the view (b) in the η - z plane depicting the MS endcap systems with the two outermost TGC systems also being known as the “wheels” [30].

3.3 Object Reconstruction and Identification

Now that the physical detectors have been described these individual physical detector read outs are translated into the representations of the physical particles that deposited the energy corresponding to those read outs. The four types of particles (electrons, photons, hadrons, muons) that can be directly detected at ATLAS are shown in Figure 3.15. Particles which do not interact with the detector and escape ATLAS entirely can be inferred by imposing conservation of momentum in the x - y plane. As the initial state partons inside the proton have negligible momenta transverse to the proton beams, conservation of momentum implies that the sum of the momenta of the final state

detected particles in the plane transverse to the proton beams should be zero, and any imbalance implies the presence of undetected particles like neutrinos.

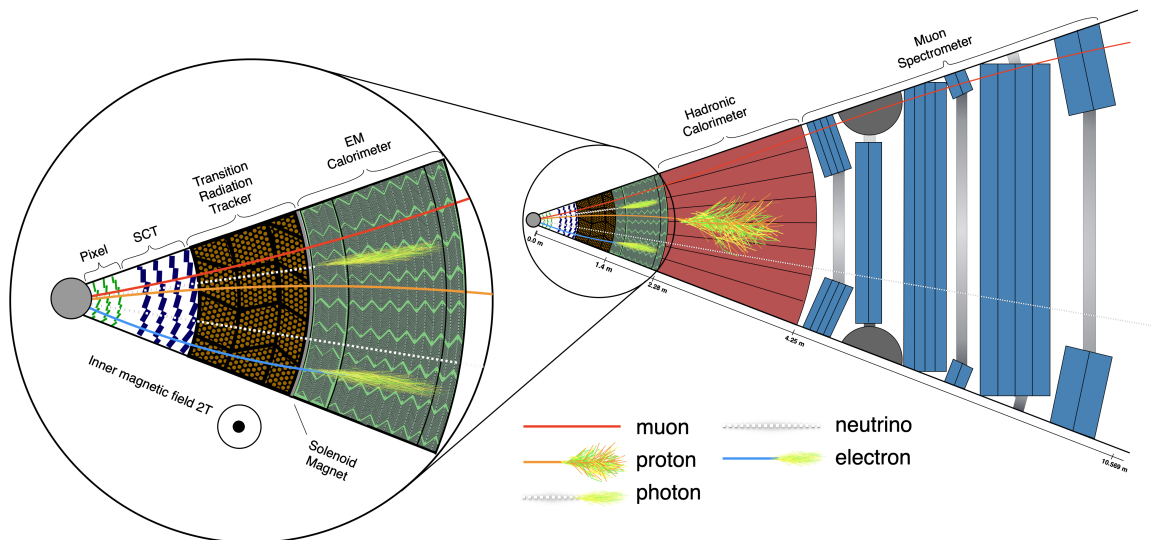


Figure 3.15: Particle signatures for different particle types when traversing the ATLAS detector in a radial direction.

3.3.1 Electrons and Photons

Electrons and photons are reconstructed from electromagnetic clusters deposited in the EM calorimeter layer. The EM clusters that can then be matched to charged particle tracks are then reconstructed electrons, and those that can't, photons. Further identification criteria are then used to distinguish electrons and photons from backgrounds. A detailed discussion of electron identification is given in Chapter 4.

3.3.2 Muons

Muon reconstruction is first performed independently in the ID and MS. The information from individual subdetectors is then combined to form the muon tracks that are used in physics analyses [31]. The combined reconstruction then proceeds in four different ways depending on the information available from each sub-detector [31]:

- *Combined (CB) muon*: track reconstruction is performed independently in the ID and MS, and a combined track is formed with a global refit that uses the hits from both the ID and

MS sub-detectors. An outside-in algorithm where hits in the MS are extrapolated into the ID is the primary method with an inside-out algorithm acting as a complimentary approach.

- *Segment-tagged (ST) muons*: a track in the ID is classified as a muon if, once extrapolated to the MS, it is associated with at least one local track segment in the MDT or cathode strip chambers (CSC).
- *Calorimeter-tagged (CT) muons*: a track in the ID is identified as a muon if it can be matched to an energy deposit in the calorimeter compatible with a minimum-ionizing particle.
- *Extrapolated (ME) muons*: the muon trajectory is reconstructed based only on the MS track and a loose requirement on compatibility with originating from the interaction point.

Overlaps between different muon types are resolved before producing the collection of muons used in physics analyses. When two muon types share the same ID track, preference is given to CB muons, then to ST, and finally to CT muons. The overlap with ME muons in the muon system is resolved by analyzing the track hit content and selecting the track with better fit quality and larger number of hits [31].

3.3.3 Hadrons and Jets

Jets were described from a theoretical stand point in Section 2.2.1. In ATLAS, jet reconstruction uses the energy clusters in the EM and hadronic calorimeters, as well as the reconstructed tracks from the ID from the charged particles in the jet. Jet reconstruction can follow several recombination algorithms, however the most widely used algorithm at ATLAS is the anti- k_t algorithm [32, 33]. At each step, the anti- k_t algorithm combines the pair of objects that have the smallest distance apart, where the distance is measured as the angular separation ($\sqrt{\Delta\phi^2 + \Delta\eta^2}$) between the objects multiplied by the minimum of the inverse of the E_T of either object. Note that the weighting by the inverse E_T gives rise to the “anti- k_t ” name and, more importantly, means that the combination process starts with the highest E_T cluster. This combination process stops when the angular separation between objects exceeds a user-specified cone radius R , which is usually 0.4 for most ATLAS analyses. The final combined object is called a jet.

3.3.4 Missing Transverse Energy

The missing transverse energy serves as a proxy for particles that do not interact with any detector element. In the x - y plane, transverse to the proton beams, the missing transverse momentum

points in the opposite direction to the total transverse momentum calculated from adding up the transverse momenta of the calibrated electrons, photons, muons, and jets, and any unclustered "soft" calorimeter deposits. The missing transverse energy is the magnitude of the missing transverse momentum vector.

3.4 The Trigger System

As discussed in Section 3.1.2, the nominal filling scheme results in a proton bunch spacing of 25 ns and so the collision rate is roughly 40 million events every second. Writing this much data to disk becomes intractable and impractical. Additionally most collisions produce physically uninteresting events coming from high cross section SM processes and as the gambit here at the LHC is to measure ultra rare processes there is no love lost. The goal then is to select the "most interesting" events to be saved at the highest rate possible. This is what is defined as the *Trigger*. Computational resources ultimately become the limiting factor (as physicists would keep every event if they could just to have them) resulting in an upper limit of 2000 events per second being able to be saved at ATLAS. ATLAS specifically has a two-level trigger system [34] used to select events. The first-level trigger is implemented in hardware (referred to often as "online" or Level 1 (L1)) and uses a subset of the detector information to reduce the accepted rate to a maximum of about 100 kHz. This is followed by a software-based trigger (referred to often as "offline" or the High Level Trigger (HLT)) that reduces the accepted event rate to 1 kHz on average, depending on the data-taking conditions. In Figures 3.16a and 3.16b the L1 and HLT trigger rates are shown for a typical fill in the 2018 data taking period. As is apparent in the figures the rate falls off rapidly over time during a fill, as the number of protons per bunch decreases and the emittance (transverse spread of protons) increases.

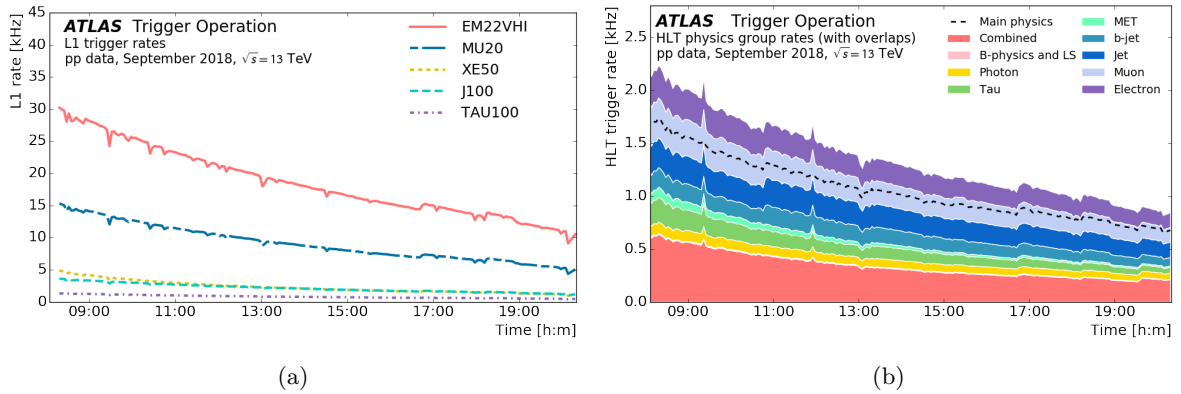


Figure 3.16: (a) L1 rates of some representative single-object trigger items, which have not been prescaled. These trigger items are based on such objects as electromagnetic clusters (EM), muon candidates (MU), jet candidates (J), missing transverse energy (XE) and tau candidates (TAU). The number in the trigger name denotes the trigger threshold in GeV. The letters following the threshold values refer to details of the selection: variable thresholds (V), hadronic isolation (H), and electromagnetic isolation (I). (b) HLT trigger rates for different targeted physics processes as a function of time. Each of the groups (colors) contains single-object and multi-object triggers. The combined group represents multiple triggers of different objects, as combinations of electrons, muons, taus, jets and missing transverse energy. Overlap between groups is only accounted for in the total main physics stream rate [35]

CHAPTER 4

These Are Electrons: Identifying Electrons at ATLAS

4.1 Introduction

The ATLAS detector was designed to identify electrons with high efficiency as electrons are important for many measurements, including measurements of the properties of the W and Z bosons, the Higgs boson, and the top quark, as well as for many searches for supersymmetric and exotic particles that decay to final states with electrons. I have contributed to performance studies and the development of improved algorithms used to identify electrons in the ATLAS “ e/γ ” (e-gamma) performance group. Through out this chapter electrons and photons may be spoken about together as they are effectively indistinguishable from the point of view of the EM Cal, but the primary focus will be electrons.

4.2 Electron-Efficiency Measurements

The job of performance groups at ATLAS is not only to develop, maintain and improve the algorithms that the vast majority of analyses will use to identify particles at ATLAS but also to provide data/MC correction factors for selection efficiencies related to the trigger, particle isolation, identification, and reconstruction. These factors are derived from the combination of efficiencies measured at every level along the chain leading to an analysis electron/photon object. In the electron and photon performance group, electron efficiencies are estimated directly from data using tag-and-probe methods. These methods select, from known resonances such as $Z \rightarrow ee$ or $J/\Psi \rightarrow ee$, unbiased samples of electrons (probes) by using strict selection requirements on the

second object (tags) produced from the particle’s decay. The events are selected on the basis of the electron–positron invariant mass. The efficiency of a given requirement can then be determined by applying it to the probe sample after accounting for residual background contamination. The combined total efficiency is then given by the following equation,

$$\epsilon_{total} = \epsilon_{EMclus} \times \epsilon_{reco} \times \epsilon_{id} \times \epsilon_{iso} \times \epsilon_{trig} = \frac{N_{cluster}}{N_{all}} \times \frac{N_{reco}}{N_{cluster}} \times \frac{N_{id}}{N_{reco}} \times \frac{N_{iso}}{N_{id}} \times \frac{N_{trig}}{N_{N_{iso}}}$$

The following sections will detail what goes into determining each numerator on the right most side of this equation with special attention paid to the electron identification and recent improvements.

4.3 Topo-Cluster Reconstruction

The topo-cluster reconstruction algorithm begins by forming proto-clusters in the EM and hadronic calorimeters using a set of noise thresholds in which the cell initiating the cluster is required to have $|\zeta_{cell}^{EM}| \geq 4$, where

$$\zeta_{cell}^{EM} = \frac{E_{cell}^{EM}}{\sigma_{noise,cell}^{EM}} \quad (4.1)$$

E_{cell}^{EM} is the cell energy at the EM scale and $\sigma_{noise,cell}^{EM}$ is the expected cell noise [36]. The expected cell noise includes the known electronic noise and an estimate of the pile-up noise corresponding to the average instantaneous luminosity expected. In this initial stage, cells from the presampler and the first LAr EM calorimeter layer are excluded from initiating proto-clusters, to suppress the formation of noise clusters. The proto-clusters then collect neighboring cells with significance $|\zeta_{cell}^{EM}| \geq 2$. Each neighbor cell passing the threshold of $|\zeta_{cell}^{EM}| \geq 2$ becomes a seed cell in the next iteration, collecting each of its neighbors in the proto-cluster. If two proto-clusters contain the same cell with $|\zeta_{cell}^{EM}| \geq 2$ above the noise threshold, these proto-clusters are merged. A crown of nearest-neighbor cells is added to the cluster independently on their energy. This set of thresholds is commonly known as ‘4-2-0’ topo-cluster reconstruction. Proto-clusters with two or more local maxima are split into separate clusters; a cell is considered a local maximum when it has $E_{cell}^{EM} > 500$ MeV, at least four neighbors, and when none of the neighbors has a larger signal.

4.4 Electron Candidate Reconstruction

An electron is defined as an object consisting of a cluster built from energy deposits in the calorimeter (supercluster) and a matched track (or tracks) to that cluster. Electron reconstruction in the central region of the ATLAS detector ($|\eta| < 2.47$) proceeds in the several steps illustrated in the flow-chart

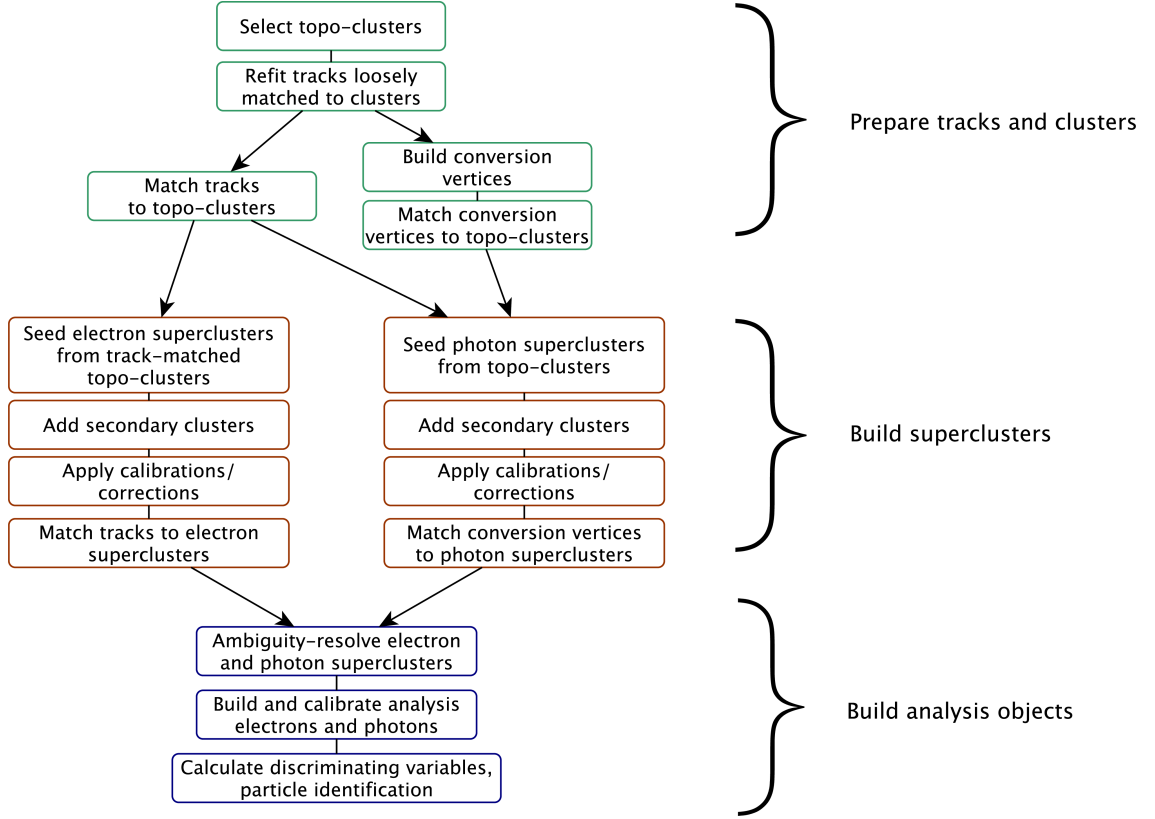


Figure 4.1: Algorithm flow-chart for the electron and photon reconstruction. [36]

in Figure 4.1. Note that EM clusters were determined using a “sliding-window” approach up until an improvement was implemented in 2018 in a move to a so-called “superclusters” based algorithm, which takes into account secondary satellite clusters created via bremsstrahlung and conversions originating from the incident electron or photon. To better understand the improvements, the sliding-window algorithm is described briefly first.

4.4.1 Sliding-Window

The $\eta \times \phi$ space of the EM calorimeter is divided into a grid of 200×256 elements (towers) of size $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$, corresponding to the granularity of the second layer of the EM calorimeter. For each element, the energy (approximately calibrated at the EM scale), collected in the first, second, and third calorimeter layers as well as in the presampler (only for $|\eta| < 1.8$, the region where the presampler is located) is summed to form the energy of the tower [36]. In the sliding-window approach a window with fixed size of 3×5 in units of 0.025×0.025 (in $\Delta\eta \times \Delta\phi$

space), corresponding to the granularity of the EM calorimeter middle layer, searches for longitudinal towers with total cluster transverse energy above 2.5 GeV [36]. The clusters are then formed around these seeds using a clustering algorithm that allows for duplicates to be removed [37]. The cluster kinematics are reconstructed using an extended window depending on the cluster position in the calorimeter, using 3×7 cells in the barrel and 5×5 cells in the endcap. The sliding window of size 3×5 then moves by 0.025 in either the η or ϕ direction to be centered on an adjacent tower, and the seed-cluster reconstruction process is repeated until this has been performed for every tower [36].

4.4.2 Superclusters

The fixed-sized cluster sliding-window algorithm described in the previous section has been replaced with an improved method using dynamic, variable-size clusters, called superclusters. While fixed-size clusters naturally provide a linear energy response and good stability as a function of pile-up, dynamic clusters change in size as needed to recover energy from bremsstrahlung photons or from electrons from photon conversions [36]. Improvements in the calibration techniques [38] ultimately freed the reconstruction from having to use fixed-size clusters, allowing the cluster to change in size dynamically. The reconstruction of electron and photon superclusters proceeds independently, each in two stages: in the first stage, EM topo-clusters are tested for use as seed cluster candidates, which form the basis of superclusters; in the second stage, EM topo-clusters near the seed candidates are identified as satellite cluster candidates, which may emerge from bremsstrahlung radiation or topo-cluster splitting. Satellite clusters are added to the seed candidates to form the final superclusters if they satisfy the necessary selection criteria [36].

4.4.3 Track Reconstruction

Track reconstruction proceeds in two steps: pattern recognition and track fit. The standard ATLAS pattern recognition uses the pion hypothesis for energy loss due to interactions with the detector material. This has been complemented with a modified pattern recognition algorithm which allows up to 30% energy loss at each intersection of the track with the detector material to account for possible bremsstrahlung. If a track seed (consisting of three hits in different layers of the silicon detectors) with a transverse momentum larger than 1 GeV can not be successfully extended to a full track of at least seven hits using the pion hypothesis and it falls within one of the EM cluster regions of interest⁵, a second pattern recognition attempt is performed using an electron hypothesis that

⁵For each seed EM cluster passing loose shower shape requirements of $R_\eta > 0.65$ and $R_{\text{had}} < 0.1$ (for the definition of these variables, see Table 4.1) a region of interest with a cone-size of $\Delta R = 0.3$ around the seed cluster barycenter

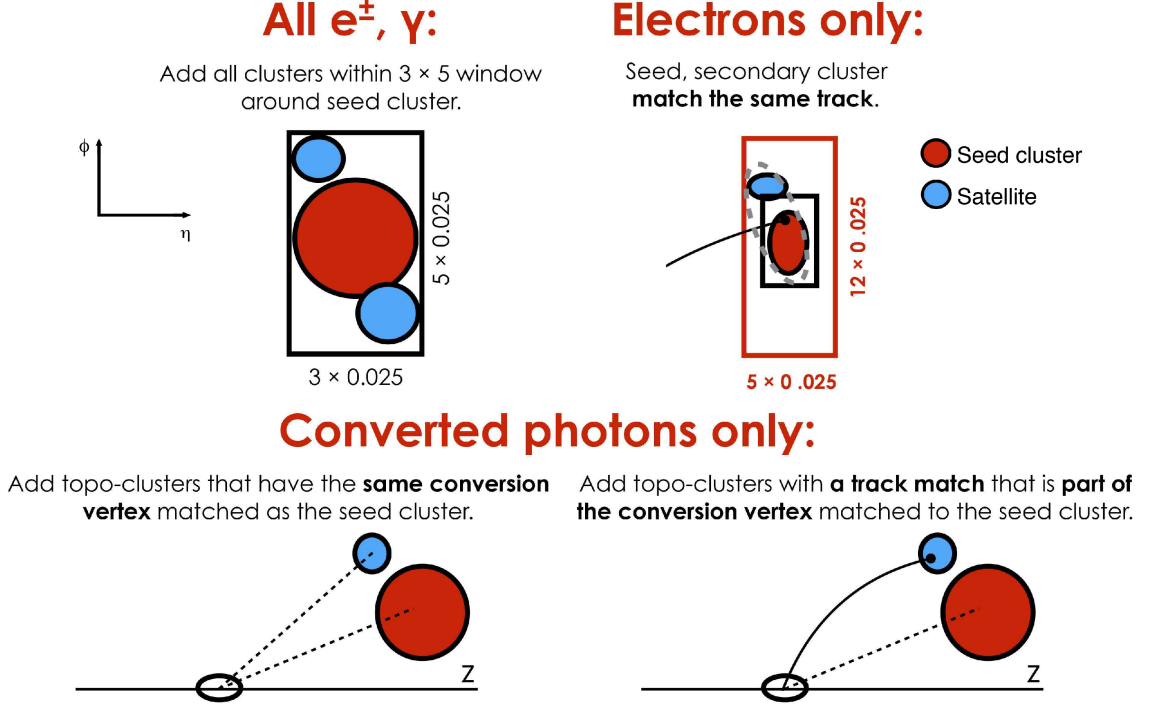


Figure 4.2: Diagram of the superclustering algorithm for electrons and photons. Seed clusters are shown in red, satellite clusters in blue [36].

allows for larger energy loss. Track candidates with $p_T > 400$ MeV are then fit either with the pion hypothesis or the electron hypothesis (according to the hypothesis used in the pattern recognition), using the ATLAS Global χ^2 Track Fitter [39]. If a track candidate fails the pion hypothesis track fit (for example, due to large energy losses), it is refit with the electron hypothesis. In this way, a specific electron-oriented algorithm has been integrated into the standard track reconstruction. It improves the performance for electrons and has minimal interference with the main track reconstruction.

4.4.4 Electron specific track re-fit

The obtained tracks are loosely matched to EM clusters using the distance in η and ϕ between the position of the track, after extrapolation, in the calorimeter middle layer and the cluster barycenter. This loose track-to-cluster match requires $|\eta_{\text{cluster}} - \eta_{\text{track}}| < 0.05$ and $0.10 < q \times (\phi_{\text{cluster}} - \phi_{\text{track}}) < 0.05$. This asymmetric condition for the matching in ϕ is designed to account for energy-loss due to

is defined.

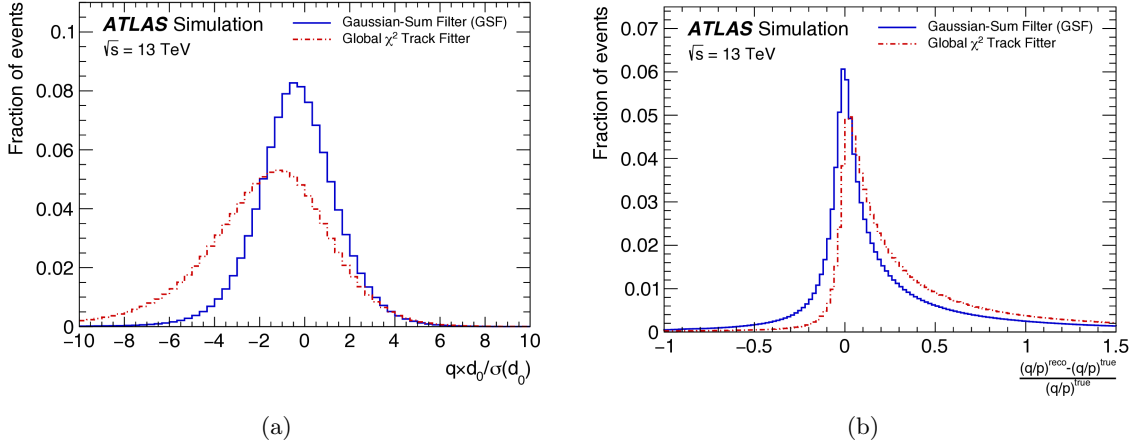


Figure 4.3: Comparisons between tracks fitted with the pion hypothesis (red) and tracks fitted with the GSF (blue) for the parameter $q \cdot |d_0 / \sigma(d_0)|$ (a) and for the relative difference of the ratio of the electron-candidate charge to its momentum, $(q/p)^{true}$, at the true generator value to the reconstructed value $(q/p)^{reco}$ (b) [41].

bremsstrahlung⁶. Tracks which satisfy this loose association to EM clusters and which have at least four precision hits are then refit using an optimised Gaussian Sum Filter (GSF) [40], which takes into account the non-linear bremsstrahlung effects. Radiative losses of energy lead to a decrease in momentum, resulting in increased curvature of the electron's trajectory in the magnetic field. When accounting for such losses via the GSF method, all track parameters relevant to the bending-plane are expected to improve. Such a parameter is the transverse impact parameter significance: d_0 divided by its estimated uncertainty $\sigma(d_0)$ [41]. Since the transverse impact parameter d_0 of conversions from bremsstrahlung photons is expected to be large and point opposite to the curvature of the track, the quantity is multiplied with the reconstructed electric charge q of the electron. Comparing $q \cdot |d_0 / \sigma(d_0)|$ in Figure 4.3a for tracks fitted with the pion hypothesis and tracks fitted with the GSF shows a clear improvement of the parameter for genuine electron tracks. Then in Figure 4.3b the relative difference of the ratio of the electron-candidate charge to its momentum, $(q/p)^{true}$, at the true generator value to the reconstructed value $(q/p)^{reco}$ is shown and the GSF method shows a clear sharper and better-centred distribution near zero with smaller tails [41].

⁶The presence of bremsstrahlung causes an asymmetry since the bremsstrahlung photon travels in a straight line to the calorimeter while the reduced energy electron (positron) will be deflected further by the magnetic field to positive (negative) ϕ . The cluster will contain the energy from both the bremsstrahlung photon and the electron/positron, so the position of the cluster will be systematically shifted to one side from the extrapolated track position.

4.4.5 Track-Cluster Matching

The matching of the track candidate to the cluster seed completes the electron reconstruction procedure. A similar matching as the one described in Section 4.4.4 for the re-fit track is done but with stricter conditions. Track-matching in ϕ is tightened to $-0.10 < \Delta\phi < 0.05$, keeping the original alternative requirement $-0.10 < \Delta\phi_{res} < 0.05$ the same [41]. If several tracks fulfill the matching condition, one track is chosen as the “primary” track. The choice is based on an algorithm using the cluster-track distance R calculated using different momentum hypotheses, the number of pixel hits and the presence of a hit in the first silicon layer [42]. Electron candidates which have no associated tracks with at least four hits in the pixel or SCT layers are removed from the collection of electron candidates and are considered to be photons. For the remaining objects, if the primary electron candidate track can be associated to a secondary vertex and has no pixel hits, then this object is classified as a photon, as well. Such an object is very likely to be from a photon conversion, and is thus removed from the collection of electron candidates. The criteria above are the only source of efficiency loss in the electron reconstruction step in case the electromagnetic cluster has been reconstructed. The remaining objects are considered as electron candidates for the remaining steps. A further classification is performed based on the electron candidate’s E/p , p_T , the presence of a pixel hit, and the secondary vertex information. This classification is used to determine whether the object is *only* considered as an electron candidate (unambiguous case) or if it is considered both in the collection of photon candidates and the collection of electron candidates (ambiguous cases) [41]. Candidates considered unambiguously as electrons have:

- A value of $E/p < 10$
- A track with at least one pixel hit and $p_T > 2$ GeV
- No secondary vertex matched
- *or* if a secondary vertex exists it fails one of the following criteria:
 - It is a double silicon vertex
 - Where several or none of the tracks have hits in the innermost pixel layer
 - The conversion is more than 40 mm separated from the secondary vertex

In all other cases the object is considered ambiguous. The classification into ambiguous objects is to keep a high reconstruction efficiency for *photons*. Most importantly, cases with $E/p > 10$

or $p_T < 2$ GeV are always ambiguous to avoid losing unconverted photons where a pileup track has been matched [41]. They are treated in the same way as the candidates solely classified as electrons. However, all supported identification criteria require a hit in the innermost pixel layer and therefore remove a class of electrons always classified as ambiguous. The electron cluster is then re-formed using 3×7 (5×5) longitudinal towers of cells in the barrel (endcaps) of the EM calorimeter. The energy of the clusters must ultimately be calibrated to the original electron energy. This is performed using multivariate techniques [43] based on simulated MC samples, and occurs at analysis-level, rather than during the reconstruction step. The four-momentum of the electrons is computed using information from both the final calibrated energy cluster and the best track matched to the original seed cluster. The energy is given by the final calibrated cluster, while the ϕ and η directions are taken from the corresponding track parameters with respect to the beam-spot [41].

4.5 Electron Identification

Further quality criteria, called ‘identification selections,’ are used to improve the purity of selected electron and photon objects. The identification of prompt electrons relies on a likelihood discriminant constructed from quantities measured in the inner detector, the calorimeter and the combined inner detector and calorimeter.

4.5.1 The Electron Likelihood (LH)

For use in the electron identification, the likelihood discriminant, effectively the test statistic in a modified likelihood ratio, is constructed by creating a set of probability distribution functions (pdfs) from a list of n electron identification variables with power for discriminating signal from background. From the product of these pdfs the likelihood, $\mathcal{L}_S$ ($\mathcal{L}_B$), for signal (background) can be formed as is seen in Equation 4.2 below.

$$\mathcal{L}_{S(B)}(\mathbf{X}) = \prod_{i=1}^n P_{S(B),i}(x_i) \quad (4.2)$$

$P_{S,i}(x_i)$ is the value of the signal pdf for quantity i at value x_i and $P_{B,i}(x_i)$ is the corresponding value of the background pdf. The signal is prompt electrons, while the background is the combination of jets that mimic the signature of prompt electrons, electrons from photon conversions in the detector material, and non-prompt electrons from the decay of hadrons containing heavy flavors. The quantities selected for the LH are mostly uncorrelated, and any residual correlations are neglected. The electron is given a score, or discriminant (or test statistic) value $d_{\mathcal{L}}$, based on the following

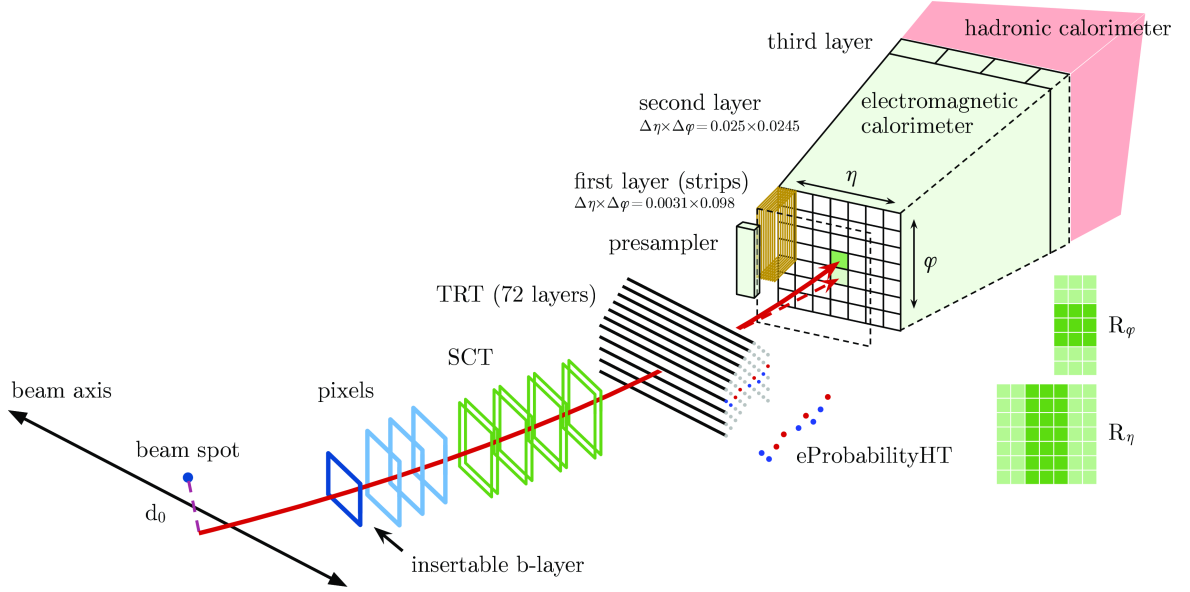


Figure 4.4: Depiction of an electron traversing the ATLAS detector. The TRT extends to $|\eta| < 2.0$, and the SCT and pixel detectors out to $|\eta| < 2.47$. Electron discriminating variables are described in Sections 4.5.2 to 4.5.4.

equation, which combines information from this entire variable set: For each electron candidate, a discriminant d_L is formed:

$$d_L = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_B}; \quad (4.3)$$

The electron LH identification is based on this discriminant. The discriminant d_L nominally has a sharp peak at unity (zero) for signal (background); this sharp peak makes it inconvenient to select operating points as it would require extremely fine binning. An inverse sigmoid function is used to transform the distribution of the discriminant of Equation 4.3:

$$d'_L = -\tau^{-1} \ln(d_L^{-1} - 1),$$

where the parameter τ is fixed to 15 [44]. As a consequence, the range of values of the transformed discriminant no longer varies between zero and unity. This transformation results in distribution will be positive and peak near unity for signal and will be negative and broad for background. Operating points are then defined by a chosen value of the transformed discriminant: electron candidates with values of d'_L larger than this value are considered signal. An example of the distribution of a transformed discriminant is shown in Figure 4.5a for prompt electrons from Z -boson decays and for background. This distribution illustrates the effective separation between signal and background encapsulated in this single quantity. By scanning over this distribution and computing the signal

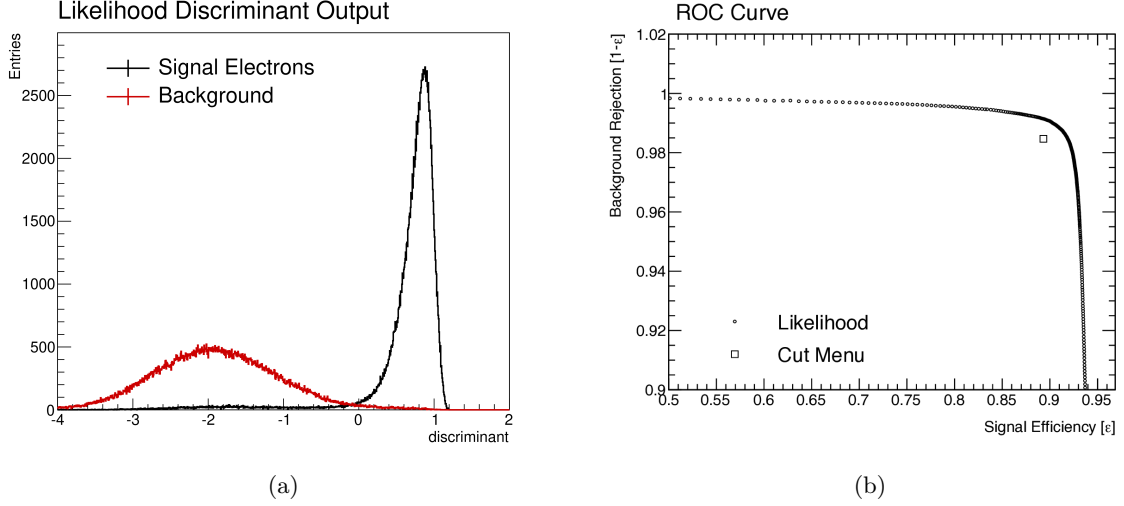


Figure 4.5: The transformed LH-based identification discriminant d'_L for reconstructed electron candidates with good quality tracks with $30 \text{ GeV} < E_T < 35 \text{ GeV}$ and $|\eta| < 0.6$. The black histogram is for prompt electrons in a $Z \rightarrow ee$ simulation sample, and the red (dashed-line) histogram is for backgrounds in a generic two-to-two process simulation sample. The histograms are normalised to unit area.

efficiency and corresponding background rejection for each sampled discriminant value the ROC curve in Figure 4.5b can be generated. Note that the most optimal values are in the top right corner of the curve. The power of this technique is derived from the choice of the discriminating variables, which make up three categories: those which describe the shape and magnitude of the electron's energy in the calorimeters, those which describe the trajectory of the electron through the tracking detectors, and those which describe the matching between the tracks and the calorimeter clusters.

4.5.2 LH Calorimeter Variables

Here the LH discriminating variables which characterize the shape and depth of the EM showers deposited in the EM and hadronic calorimeters by an electron are described. The variable R_{had1} is the ratio of E_T in the first layer of the hadronic calorimeter to the E_T in the EM calorimeter and is a measure of the energy leakage to the EM shower from the EM calorimeter to the hadronic calorimeter. R_{had1} is used to distinguish electrons and hadrons based on their shower depth. For isolated electrons, the shower is expected to be well-contained within the EM calorimeter and R_{had1} is expected to be centered very sharply around zero, while for background a long positive tail is expected. This distribution can be seen in Figure 4.6. Other depth ratio variables inside the EM calorimeter, f_1 and f_3 , seek to characterize the evolution of the shower as it traverses the EM

calorimeter. f_3 , is the ratio of the total energy in the EM calorimeter to the energy in the third layer. This variable encapsulates the expectation that an electron will deposit most of its energy in the first two layers of the EM calorimeter. As shown in the f_3 distribution in Figure 4.6 the signal peaks close to zero and has a broader width than R_{had1} . The variable f_1 is the ratio of the energy in the first layer of the EM calorimeter to the total energy in the calorimeter for the EM cluster of interest. While this variable is not expected to sharply peak at any specific value, features picked up by f_1 when used in conjunction with the entire suite of discriminating variables in the LH make it a powerful component. Its distribution for both signal and background is shown in Figure 4.6. The energy width variables $w_{\eta 2}$, R_ϕ , and R_η distinguish narrow electron showers from diffuse hadronic showers. The variable $w_{\eta 2}$ is designed to measure the lateral shower width of the object, defined as

$$w_{\eta 2} = \sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$$

The $w_{\eta 2}$ distribution for both signal and background is shown in Figure 4.7. The variable R_ϕ , the ratio of the energy of 3×3 cells over the energy in 3×7 cells centered at the electron cluster position handles the expectation that the cluster should have a narrow width in the ϕ direction. While R_η , the ratio of the energy of 3×7 cells over the energy in 7×7 cells centered at the electron cluster position, handles the expectation that the cluster should also have a narrow width in the η direction. Finally, E_{ratio} , the difference between the two largest maxima (if two maxima exist) in the finely segmented strips layer of the cluster, divided by the sum of the two maxima, is calculated to check for multiple incident particles. All of these variables are summarized in Table 4.1.

4.5.3 LH Tracking Variables

These are the variables that are associated with the tracking detectors and the track fit. The variable d_0 , the transverse impact parameter and $|d_0/\sigma(d_0)|$, the significance of the transverse impact parameter defined as the ratio of d_0 to its uncertainty, help to distinguish electrons prompt electrons from those from the semileptonic decay of long-lived heavy flavor hadrons. The $\Delta p/p$ variable is associated with the GSF track fit characterizes the track's energy loss due to bremsstrahlung and can help discriminate electrons from charged hadrons that do not lose as much energy in the ID. The TRT provides discrimination between electrons and heavier objects based on the principle of transition radiation. Charged particles with larger γ -factors (light particles, electrons being the lightest charged particle) radiate more photons than those with lower γ -factors (more massive particles like muons, charged pions, protons) when traversing the radiator foil inside the TRT. Those photons in turn induce high-threshold hits in the detector. In Run-1, only the ratio of high-threshold

hits to the total number of TRT hits along the reconstructed track, (F_{HT}), was used from the TRT as a signature of transition radiation to distinguish electrons from hadrons. However, beginning in 2012, leaks in the TRT gas system resulted in large losses of expensive xenon gas. To cope with this problem, the gas in some TRT modules was switched from xenon to argon, which is less expensive, beginning in the 2015 data taking period. More and more modules have been switched since. Figure 4.9 shows the gas configuration for both 2015, 2016, 2017, and 2018 data taking years for both the barrel and endcap layers. The use of argon gas leads to less transition radiation being produced and therefore a lower probability for a high-threshold hit as compared to xenon. To compensate for the subsequent loss of performance, a tool was developed to calculate a likelihood ratio between electrons and backgrounds based on the high threshold hit information. The TRT likelihood method uses the high-threshold probability of each TRT hit to construct a discriminant variable, referred to here as eProbabilityHT. The probability for each TRT hit to exceed the high level threshold depends on the straw gas type, the Lorentz factor γ calculated from the track p_T under a particle type hypothesis, the TRT occupancy local to the track, and the geometry: detector partition, straw layer, track-to-wire distance and the hit coordinates (z for the barrel and radius for the endcaps). The ratio of probabilities between the electron hypothesis and pion hypothesis is then this discriminating variable eProbabilityHT. These variables are summarized in Table 4.1.

4.5.4 LH Track-Cluster Matching Variables

Variables that describe the quality of the match between the track and the cluster can be used to distinguish electrons from primarily converted photons or charged hadrons. The variable $\Delta\eta_1$, is the $\Delta\eta$ between the cluster position in the first layer and the extrapolated track. The variable $\Delta\phi_{\text{res}}$, is the $\Delta\phi$ between the cluster position in the second layer of the EM calorimeter and the momentum-rescaled track, extrapolated from the perigee, times the charge q . These variables are summarized in Table 4.1.

4.5.5 Non-LH Variables

In addition to the LH decision which is a function of the multivariate product of the pdfs associated with the variables just described in previous Sections 4.5.2 to 4.5.4, there are several variables that are used directly as a selection criterion that the electron object must satisfy as well. The track quality criteria variables n_{Blayer} , n_{Pixel} , and n_{Si} refer to a required number of track hits in the B-layer, Pixel detector, and Silicon Strips detector respectively. The next two variables were implemented to

address inefficiencies of the LH at high p_T for the TIGHT operating point. These additional variables are E/p and w_{stot} , which are not included in the LH as pdfs due to their correlations with the other variables which are used, as well as concerns regarding their modeling in the MC (e.g. the resolution of E/p can degrade at high p_T , but this may not be properly represented in the MC, which would make it a sub-optimal variable to use as a pdf in the LH). These variables are summarized in Table 4.1 and appear in the table with a “C” in the “Usage” column.

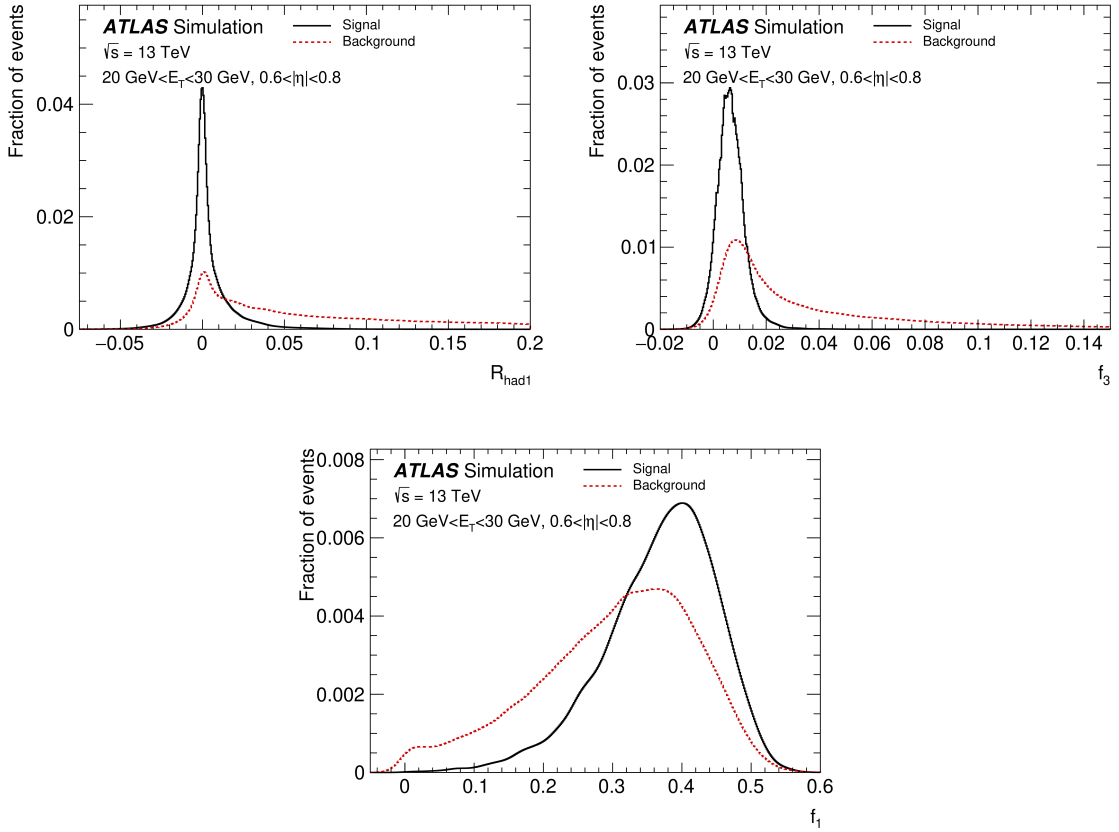


Figure 4.6: Example distributions of the calorimeter variables R_{had1} , f_3 , $w_{\eta 2}$, R_ϕ , R_η , E_{ratio} , and f_1 . Defined in Table 4.1 are shown for a typical E_T/η bin, $20 \text{ GeV} < E_T < 30 \text{ GeV}$ and $0.6 < |\eta| < 0.8$. The red-dashed distribution is determined from a background simulation sample and the black-line distribution is determined from a $Z \rightarrow ee$ simulation sample. These distributions are for reconstructed electron candidates before applying any identification. They are smoothed using an adaptive KDE and have been corrected for offsets or differences in widths between the distributions in data and simulation [41].

Table 4.1: Type and description of the quantities used in the electron identification. The columns labelled “Rejects” indicate whether a quantity has significant discrimination power between prompt electrons and light-flavor (LF) jets, photon conversions (γ), or non-prompt electrons from the semileptonic decay of hadrons containing heavy-flavor (HF) quarks (b - or c -quarks). In the column labelled “Usage,” an “LH” indicates that the pdf of this quantity is used in forming $\mathcal{L}_S$ and $\mathcal{L}_B$ (defined in Equation 4.2) and a “C” indicates that this quantity is used directly as a selection criterion. In the description of the quantities formed using the second layer of the calorimeter, 3×3 , 3×5 , 3×7 , and 7×7 refer to areas of $\Delta\eta \times \Delta\phi$ space in units of 0.025×0.025 .

Type	Description	Name	Rejects			Usage
			LF	γ	HF	
Hadronic leakage	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $ \eta < 0.8$ or $ \eta > 1.37$)	R_{had1}	x	x		LH
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \eta < 1.37$)	R_{had}	x	x		LH
Third layer of the EM calorimeter	Ratio of the energy in the third layer to the total energy in the EM calorimeter. This variable is only used for $E_T < 80$ GeV, due to inefficiencies at high E_T , and is also removed from the LH for $ \eta > 2.37$, where it is poorly modelled by the simulation.	f_3	x			LH
Second layer of the EM calorimeter.	Lateral shower width, $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, where E_i is the energy and η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells	$w_{\eta 2}$	x	x		LH
	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centered at the electron cluster position	R_ϕ	x	x		LH
	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster position	R_η	x	x	x	LH
First layer of the EM calorimeter	Shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, where i runs over all strips in a window of $\Delta\eta \times \Delta\phi \approx 0.0625 \times 0.2$, corresponding typically to 20 strips in η , and i_{max} is the index of the highest-energy strip, used for $E_T > 150$ GeV only	w_{stot}	x	x	x	C
	Ratio of the energy difference between the maximum energy deposit and the energy deposit in a secondary maximum in the cluster to the sum of these energies	E_{ratio}	x	x		LH
	Ratio of the energy in the first layer to the total energy in the EM calorimeter	f_1	x			LH
Track conditions	Number of hits in the innermost pixel layer	n_{Blayer}		x		C
	Number of hits in the pixel detector	n_{Pixel}		x		C
	Total number of hits in the pixel and SCT detectors	n_{Si}		x		C
	Transverse impact parameter relative to the beam-line	d_0		x	x	LH
	Significance of transverse impact parameter defined as the ratio of d_0 to its uncertainty	$ d_0/\sigma(d_0) $		x	x	LH
	Momentum lost by the track between the perigee and the last measurement point divided by the momentum at perigee	$\Delta p/p$	x			LH
TRT	Likelihood probability based on transition radiation in the TRT	eProbabilityHT	x			LH
Track-cluster matching	$\Delta\eta$ between the cluster position in the first layer and the extrapolated track	$\Delta\eta_1$	x	x		LH
	$\Delta\phi$ between the cluster position in the second layer of the EM calorimeter and the momentum-rescaled track, extrapolated from the perigee, times the charge q	$\Delta\phi_{\text{res}}$	x	x		LH
	Ratio of the cluster energy to the track momentum, used for $E_T > 150$ GeV only	E/p	x	x		C

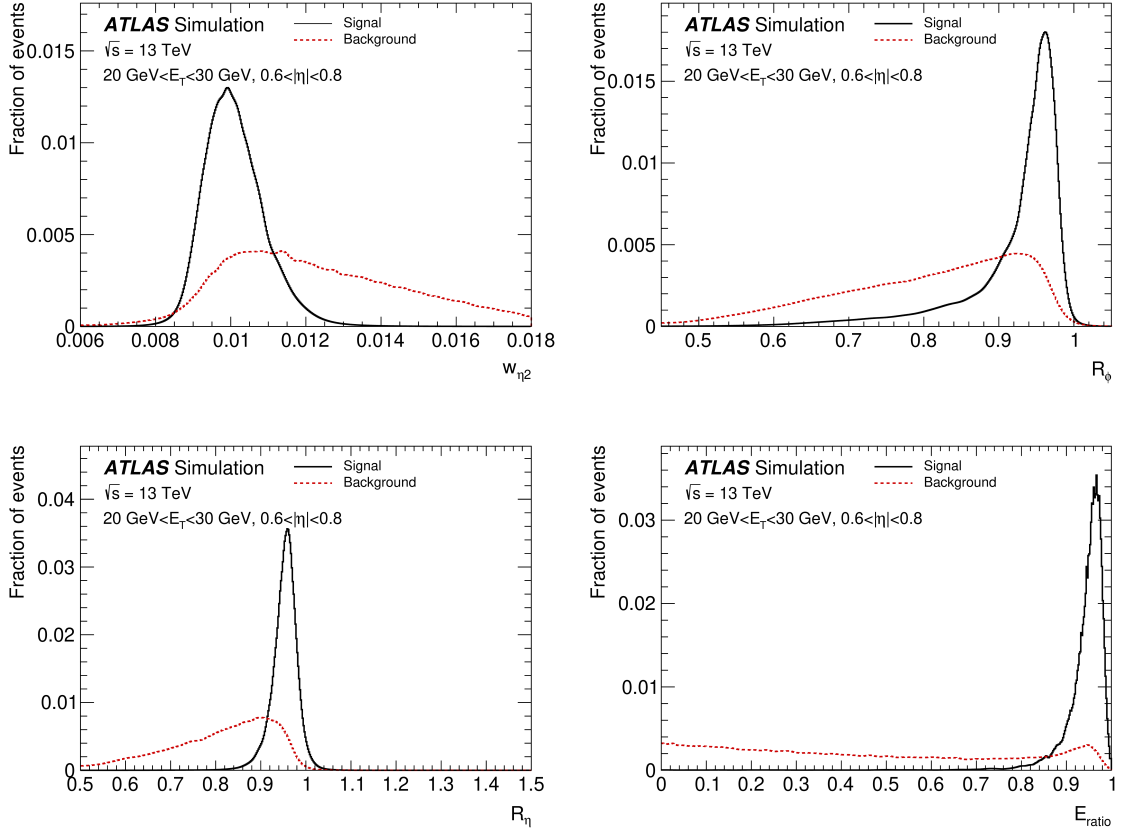


Figure 4.7: Example distributions of the calorimeter variables R_{had1} , f_3 , and f_1 . Defined in Table 4.1 are shown for a typical E_T/η bin, $20 \text{ GeV} < E_T < 30 \text{ GeV}$ and $0.6 < |\eta| < 0.8$. The red-dashed distribution is determined from a background simulation sample and the black-line distribution is determined from a $Z \rightarrow ee$ simulation sample. These distributions are for reconstructed electron candidates before applying any identification. They are smoothed using an adaptive KDE and have been corrected for offsets or differences in widths between the distributions in data and simulation [41].

4.5.6 Constructing the pdfs

During my time in the e/gamma group, I was one of the experts responsible for constructing the pdfs. There were lots of changes during Run-2, from MC-based pdfs used for 2015-16, data-driven pdfs used in the trigger in 2017, and data-driven pdfs used in both the trigger and offline in 2018. Many studies were required to check the performance of the electron identification. I will describe here the derivation of the data-driven pdfs. The signal pdfs are data-driven, using two samples. Signal electrons with $p_T > 15 \text{ GeV}$ are selected using a $Z \rightarrow ee$ tag-and-probe selection. Events are collected

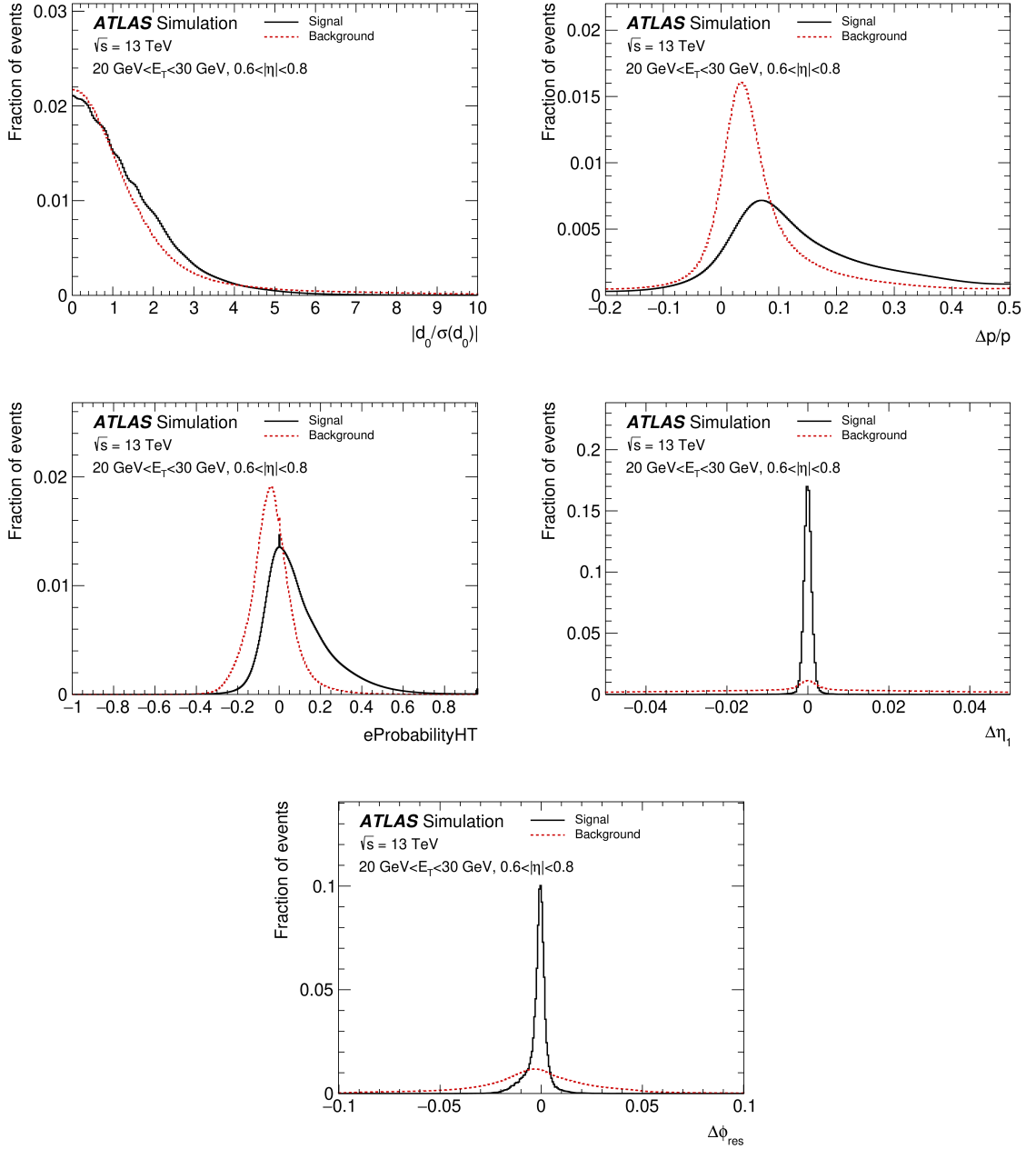


Figure 4.8: Examples of distributions of tracking and track-cluster matching variables $|d_0/\sigma(d_0)|$, $\Delta p/p$, eProbabilityHT , $\Delta \eta_1$, and $\Delta \phi_{\text{res}}$. All of which are defined in Table 4.1 and shown for $20 \text{ GeV} < E_T < 30 \text{ GeV}$ and $0.6 < |\eta| < 0.8$. The red-dashed distribution is determined from a background simulation sample and the black-line distribution is determined from a $Z \rightarrow ee$ simulation sample. These distributions are for reconstructed electron candidates before applying any identification. They are smoothed using an adaptive KDE and have been corrected for offsets or differences in widths between the distributions in data and simulation [41].

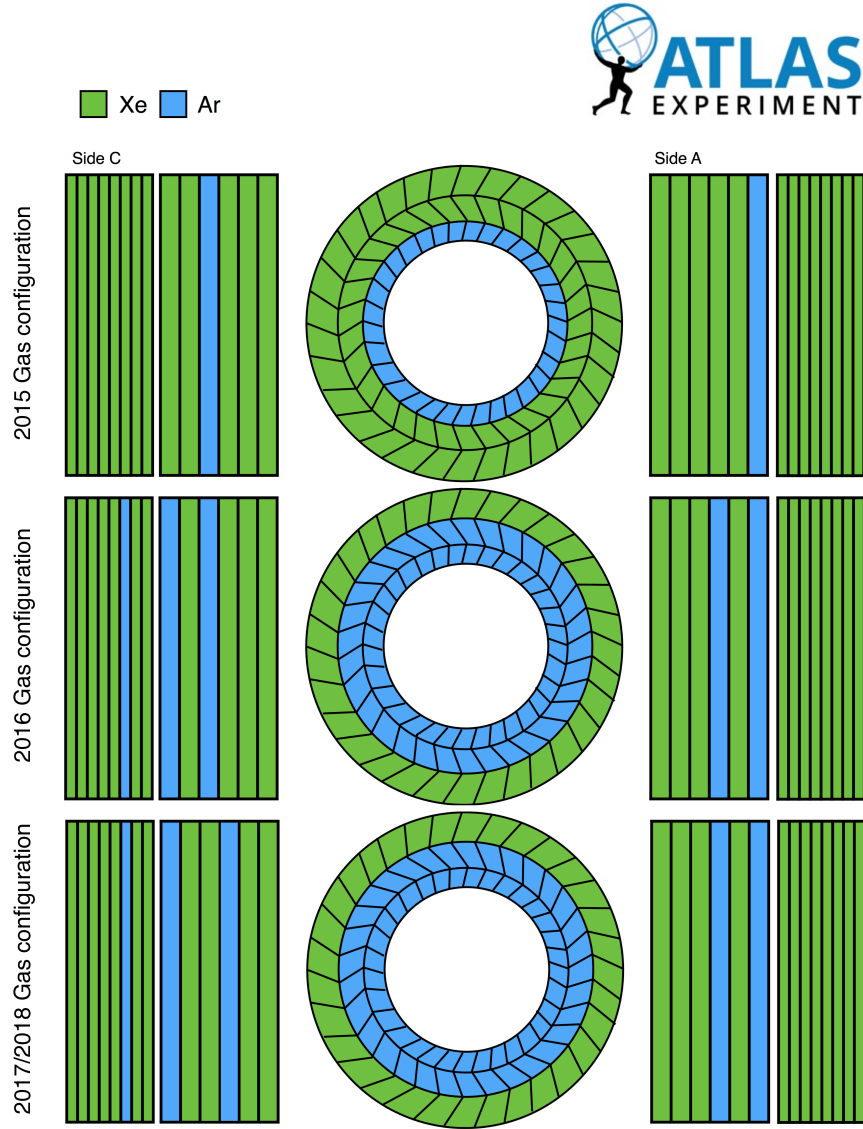


Figure 4.9: Cartoon illustrating the TRT gas configurations used in 2015 (top), 2016 (middle), and 2017/2018 (bottom). Note that the concentric circles represent the TRT barrel layers while the rectangles represent each of the TRT endcap wheels [45]

using the primary single electron triggers. The tag electrons must satisfy the TIGHT identification and have $p_T > 25$ GeV. The selected probe electrons must form an invariant mass with the tag which falls within 10 GeV of the Z mass. Additionally, the probes must satisfy the VERYLOOSE identification, which is required in order to reduce fake lepton background contamination in the sample of probes, without significantly biasing the distributions of the discriminating variables. Signal electrons with $p_T > 15$ GeV are selected using a J/ψ tag-and-probe selection. Events are collected using the secondary di-electron triggers. As with the $Z \rightarrow ee$ tag-and-probe selection, tag electrons must satisfy the TIGHT identification, but are only required to have $p_T > 4.5$ GeV. The probe electrons must form an invariant mass with the tag which falls within a 0.5 GeV window of the J/ψ mass and must satisfy the VERYLOOSE identification. Additionally, the tag and probe must be separated by $\Delta R > 0.1$ to avoid overlapping tag-probe pairs. A cut is also placed on the pseudo-proper time:

$$\tau = \frac{L_{xy} \cdot m^{J/\psi}}{p_T^{J/\psi}}, \quad \mathcal{L}_{xy} = \mathbf{L} \cdot \mathbf{p}_T^{J/\psi} / p_T^{J/\psi}$$

in order to remove the non-prompt J/ψ contribution coming from b-hadron decays [46]. These selections are summarized in Tables 4.2 and 4.3.

Selection for data-driven signal electron candidates above 15 GeV	
Single electron trigger fired	
Tag electron with $p_T > 25$ GeV	
Tag electron $ \eta < 1.37$ OR ($ \eta > 1.52$ AND $ \eta < 2.47$)	
Tag electron passes TIGHT identification	
$\Delta R(\text{tag electron, trigger electron}) < 0.10$	
Tag electron passes LAr object quality requirement	
Probe electron with $p_T > 15$ GeV	
Probe electron $ \eta < 2.47$	
Probe electron passes VERYLOOSE identification	
Probe electron passes LAr object quality requirement	
$80 \text{ GeV} < m_{e^+e^-} < 100 \text{ GeV}$	
Tag electron and probe electron have opposite electric charge	

Table 4.2: Summary of data-driven signal electron selection above 15 GeV.

Background events are collected using the prescaled single electron support triggers. These triggers require an electron to pass a p_T threshold, but do not apply any identification requirement at the HLT. Note that jets are frequently also reconstructed as electrons, due to the requirements imposed on the tracking hits and calorimeter energy deposition during the reconstruction stage. Thus, this sample primarily contains dijet events, which is the process with the largest production cross-section at the LHC. However, this is a very inclusive selection, and thus includes other processes

Selection for data-driven signal electron candidates below 15 GeV	
Di-electron trigger fired	
Tag electron with $p_T > 4.5$ GeV	
Tag electron $ \eta < 1.37$ OR ($ \eta > 1.52$ AND $ \eta < 2.47$)	
Tag electron passes TIGHT identification	
$\Delta R(\text{tag electron, trigger electron}) < 0.10$	
Tag electron passes LAr object quality requirement	
Probe electron with $p_T > 4.5$ GeV	
Probe electron $ \eta < 2.47$	
Probe electron passes VERYLOOSE identification	
Probe electron passes LAr object quality requirement	
$2.8 \text{ GeV} < m_{e^+e^-} < 3.3 \text{ GeV}$	
Tag electron and probe electron have opposite electric charge	
$\Delta R(\text{tag electron, probe electron}) > 0.10$	
$-1 < \tau < 0.2$	

Table 4.3: Summary of data-driven signal electron selection below 15 GeV.

as well. To reduce potential contamination from electroweak processes containing real, prompt electrons, the following requirements are applied:

- If $E_T^{\text{miss}} > 25$ GeV, veto the event (reduce contamination from $W \rightarrow e\nu$ decays)
- If $m_T > 40$ GeV, veto the event (reduce contamination from $W \rightarrow e\nu$ decays)
- If a second electron (which passes MEDIUM and has $p_T > 4$ GeV) exists in the event and forms an invariant mass within $70 \text{ GeV} < m_{e^+e^-} < 110 \text{ GeV}$, veto the event (reduce contamination from $Z \rightarrow ee$ decays). Note that no charge requirements are placed on these electrons, to suppress the (admittedly small) contamination from charge-flip $Z \rightarrow ee$ electrons

These selections are summarized in Table 4.4.

4.5.6.1 Binning in E_T and η

The shape of the discriminating variable distributions vary according to the detector geometry, whose features in η are dictated by the cylindrical nature of its barrel subdetectors, the transition to endcap detectors, the space dedicated to structure and services, and the amount of material before the calorimeters. The identification is split in η to account for these variations such that the discriminant variables have negligible variation within an η slice (for a constant E_T). The bin thresholds chosen are shown in Table 4.5 below and graphically depicted in Figure 4.10 where these geometry and material transitions can be seen explicitly. Variable distributions also vary as

Selection for data-driven background electron candidates	
Prescaled single electron supporting trigger fired	
Electron candidate with $p_T > 4$ GeV	
Electron candidate $ \eta < 2.47$	
Electron candidate has good track-quality ($n_{\text{Pixel}} \geq 1$, $n_{\text{Silicon}} \geq 7$)	
$\Delta R(\text{reco electron candidate, trigger electron}) < 0.10$	
Electron candidate passes LAr object quality requirement	
$E_T^{\text{miss}} < 25$ GeV	
$m_T < 40$ GeV	
$(70 \text{ GeV} < m_{e+e-} \parallel m_{e+e-} > 110 \text{ GeV})$ for events containing an additional MEDIUM electron	

Table 4.4: Summary of data-driven background electron selection.

a function of object E_T ; thus, the phase space is split further into E_T bins, typically in 5 GeV increments. The E_T bin thresholds used are shown in Tables 4.6. To avoid large discontinuities near E_T bin edges when using a finer granularity than what is shown in Table 4.6, a linear interpolation between neighboring E_T bins is used to extract an interpolated pdf value as well as an interpolated discriminant cut value.

Bin boundaries in $ \eta $									
0.0	0.6	0.8	1.15	1.37	1.52	1.81	2.01	2.37	2.47

Table 4.5: Boundaries in absolute cluster pseudorapidity used to define the nine bins for the LH pdfs and LH discriminant requirements.

Bin boundaries in E_T [GeV]													
pdfs	4.5	7	10	15	20		30	40					∞
Discriminant	4.5	7	10	15	20	25	30	35	40	45	80	150	∞

Table 4.6: Boundaries in electron transverse energy used to define the seven bins for the LH pdfs and the twelve bins for LH discriminant requirements.

4.5.6.2 Smoothing: Adaptive Kernel Density Estimation (KDE)

To first approximation, pdfs can be obtained by simply building a histogram of each variable using the signal and background samples as described in the previous section. However, logistical issues of bin granularity and limited statistics could adversely affect the performance of the likelihood. The electron likelihood should be constructed from pdfs containing only meaningful physical features. Random statistical fluctuations, particularly in the pdfs of likelihoods covering regions of η/E_T

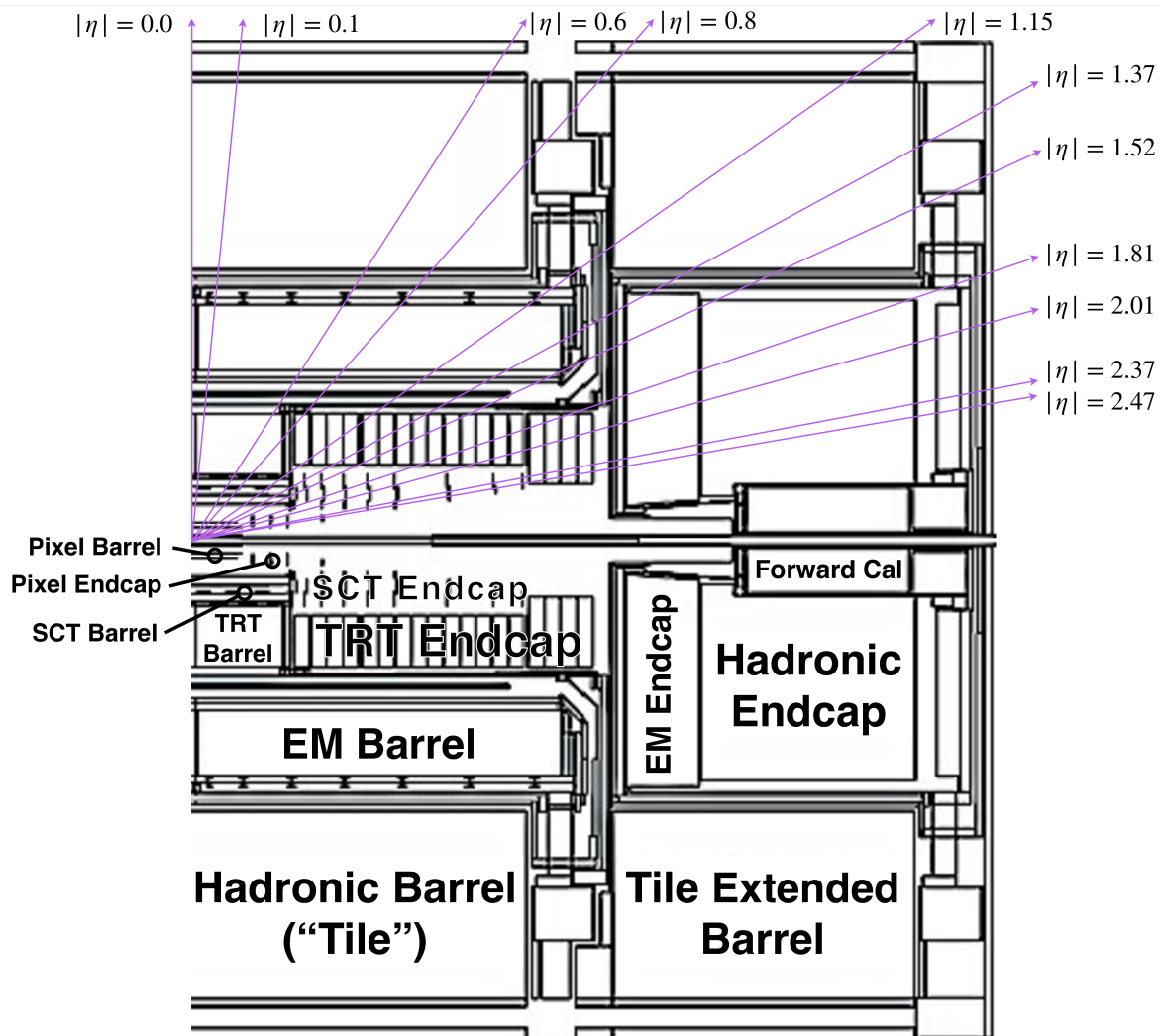


Figure 4.10: Cartoon of the middle cross-section of one side of the calorimeters and ID showing the η regions the LH is binned in.

where signal or background statistics are low, can cause suboptimal behavior, such as nearly identical electrons being assigned vastly different discriminant values. Likewise, the pdfs should be nonzero everywhere, to avoid undefined or unphysical results. Thus, raw histogram pdfs must be transformed to solve these issues. Adaptive kernel density estimation (KDE) is used to convert the histogrammed signal and background samples into pdf inputs for the likelihood. The KDE method smooths a variable distribution in the following manner: first, the value in each bin in the variable's distribution is treated as a δ -function. Each δ function then replaced by a "kernel" function (in this case a Gaussian distribution) with a tunable width parameter, and the collection of Gaussian distributions

are summed to form the final pdf. The adaptive KDE method follows the same procedure, but the Gaussian width parameter is increased in regions of low event yields as is illustrated in Figure 4.11a) [44]. The pdfs developed for the electron likelihood tool were created using the TMVA adaptive KDE tool. In practice, the tool uses very finely binned histograms to approximate the δ functions of an unbinned dataset, in order to increase the algorithm speed, without loss of performance. Figure 4.11b illustrates the adaptive KDE method at work in an example R_η distribution where we see nonphysical features being smoothed out by the method.

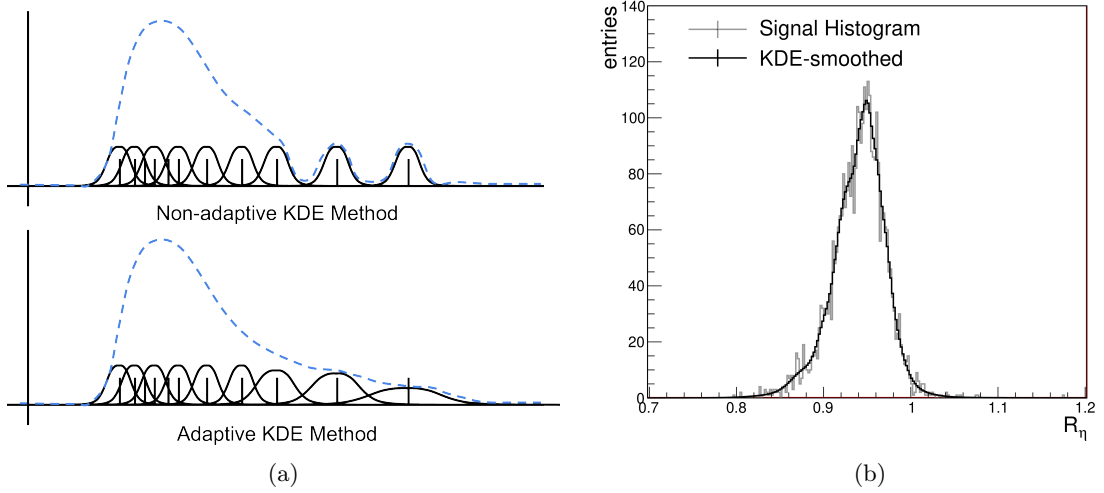


Figure 4.11: The KDE method. In (a), an illustration of the advantage of the adaptive KDE pdf smoothing technique in regions with low statistics. In (b), an example of a variable distribution and its adaptive KDE-smoothed pdf [47].

4.5.7 Being Efficient in a Changing Environment

During my time working in the e/gamma group, it was also important to adjust selection criteria to adapt to busier environments.

4.5.7.1 Pileup Dependence of Discriminating Variables

The wide range of pileup during Run 2 (see Figure 3.6) affects the discriminating variables used in the likelihood calculation. The hadronic leakage variable, R_{had} and the middle layer of the EM calorimeter variable, R_η , are the most affected by increases in pileup. The shapes of these variables become wider and more elongated as is shown in Figure 4.12. Thereby becoming more background shaped in a high pileup environment, hence reducing the discriminating power of these variables.

These two variables are among the most powerful, as shown in $n - 1$ likelihood studies Figure 4.13, and thus indispensable in the likelihood variable menu. The distributions of the remaining electron

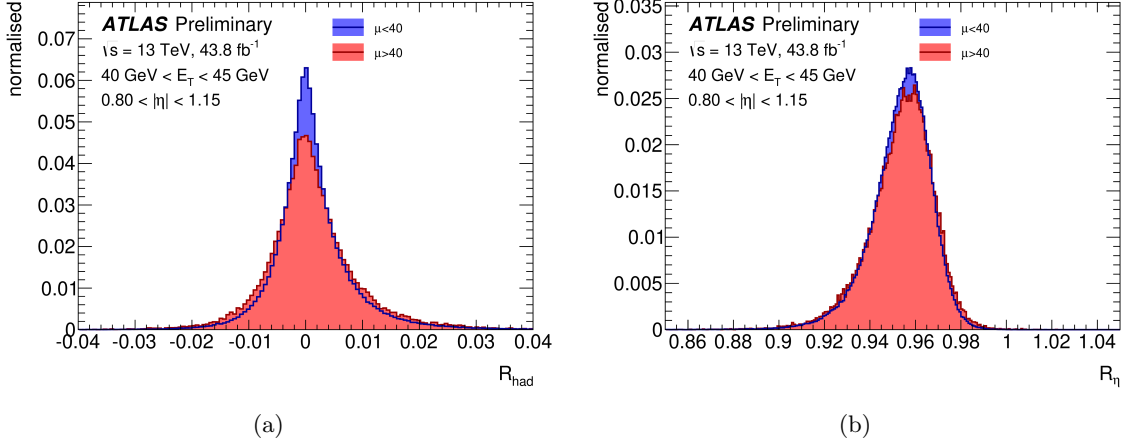


Figure 4.12: Electron variable distributions for the variables R_{had} and R_{η} are shown for electrons with $40 \text{ GeV} < E_T < 45 \text{ GeV}$ and $0.80 < |\eta| < 1.15$. They have been obtained from 43.8 fb^{-1} of data recorded in 2017 at $\sqrt{s} = 13 \text{ TeV}$ that were selected with $\mu > 40$ (red) or $\mu < 40$ (blue). Events were selected with a tag-and-probe method and applying a very loose selection on the likelihood discriminant used in the electron ID menu in order to reject contributions from background events.

discriminating variables are not largely affected by the increase in pileup. This effect corresponds to the likelihood discriminant being systematically *lower* in higher pileup conditions, leading to a negative efficiency slope as a function of the number of primary vertices, n_{vtx} .

In Run 1, this effect was corrected by making the discriminant cut linearly dependent on the number of vertices with the form $d(n_{\text{vtx}}) = d_{\mathcal{L}} - a \cdot n_{\text{vtx}}$ in each E_T/η bin. Introducing this discriminant dependence on n_{vtx} softens the resulting effect of n_{vtx} on the signal efficiency. It should be noted that the R_{had} and R_{η} distributions are broader in the background, and thus the background response is less dependent on n_{vtx} . As a result, correcting the signal efficiency causes the background to develop an n_{vtx} dependence, with worse rejection at higher n_{vtx} . This is illustrated by the black markers in Figure 4.14b. An additional correction is applied to balance these competing effects and is shown by the red markers in Figure 4.14. In the end, these n_{vtx} dependent cuts on the likelihood output are only applied for MEDIUM and TIGHT operating points. The dependence of the efficiency on the pile-up for the LOOSE and VERYLOOSE operating points were deemed to be small enough to not warrant a correction. However, this meant that on rare occasions, the operating points were not perfect subsets of one another, since MEDIUM and TIGHT could become looser than LOOSE for instance, as seen in Figure 4.15b. While this was typically a 10^{-5} effect or less, it was

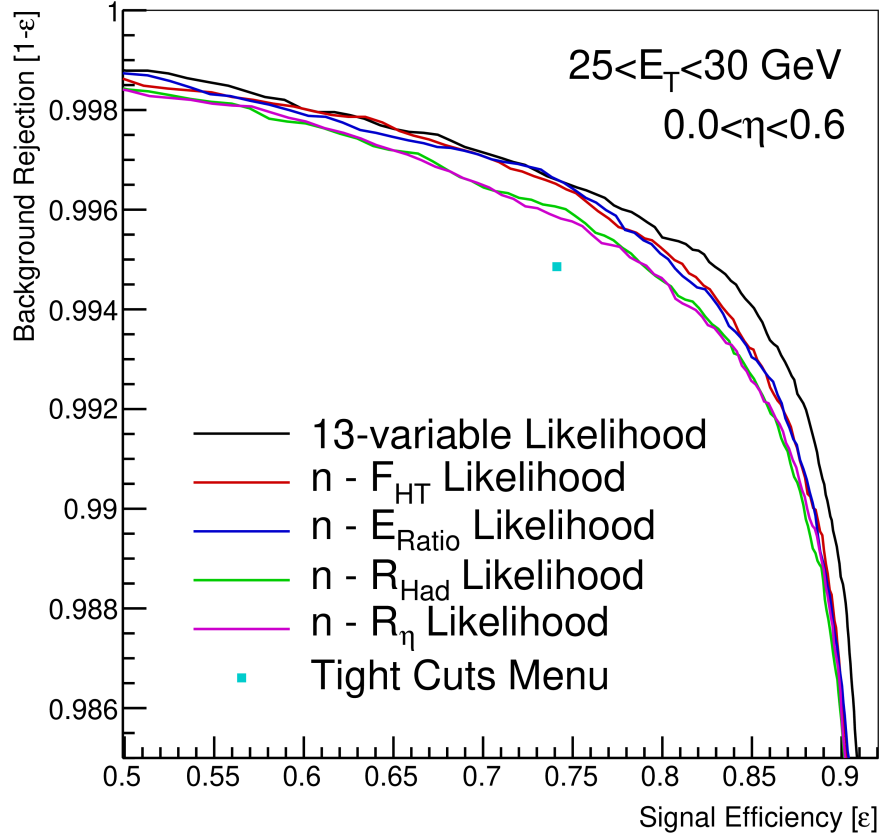


Figure 4.13: The $n - 1$ method used to optimize the choice of variables to use in the electron likelihood. Individual variables are removed from the nominal list of likelihood variables, and the likelihood recalculated to assess the relative power of each variable. The example shows the importance of F_{HT} , E_{ratio} , R_{had} and R_{η} ; the performance of the likelihood decreases when each is removed. The TIGHT cut-based operating point is shown for comparison [47].

not desirable to repeat this for Run-2.

A different strategy was employed in Run-2 to ensure that all of the tighter operating points are subsets of the looser operating points, for 2015. Rather than directly loosening the discriminant cut value, the pileup correction was put directly into the discriminant itself. In other words, the cut value used for each operating point is unaffected (the cuts do not change with pileup so they are subsets by construction), but with increasing pileup, the value of the discriminant changes instead. Mathematically, this is done as follows:

$$d_{TIGHT,new}(n_{vtx}) = d_{TIGHT,old} - a \cdot \max(n_{vtx}, n_{vtx,max}) \quad (4.4)$$

Where tight refers to the TIGHT operating point, so the result of a cut on $d_{TIGHT,new}(n_{vtx})$ is identical

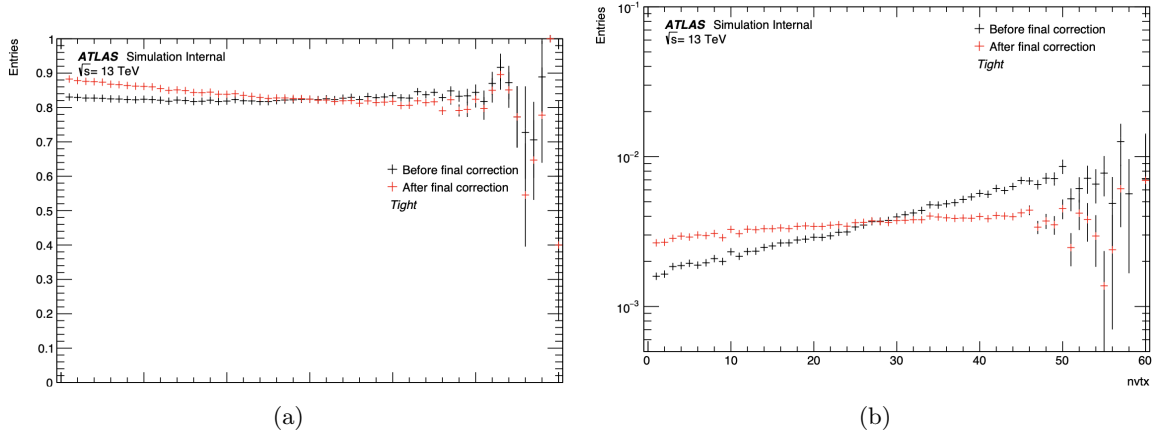


Figure 4.14: Illustration of the identification efficiency dependence of (a) signal and (b) background on n_{vtx} for the TIGHT operating point.

to the Run-1 pileup-corrected cut. To cut this off at some value of n_{vtx} , rather than to loosen the discriminant indefinitely, $n_{\text{vtx,max}}$ is defined as the largest value to use for the correction. As an example, if $n_{\text{vtx,max}} = 50$ (which it does for 2015, and increased to 100 in 2018), then the pileup correction used for all larger values of n_{vtx} will be identical, to avoid loosening the discriminant too much. This is illustrated for $n_{\text{vtx,max}} = 50$ as the solid blue line in Figure 4.15b. Then we define the new discriminant with a piece-wise function, continuous at each boundary condition, so:

$$d_{\text{new}}(n_{\text{vtx}}) =$$

$$\begin{cases} d, & d < d_{\text{VERYLOOSE}} & \text{(I)} \\ d_{\text{VERYLOOSE}} + (d - d_{\text{VERYLOOSE}}) \times \frac{d_{\text{TIGHT,old}} - d_{\text{VERYLOOSE}}}{d_{\text{TIGHT,new}} - d_{\text{VERYLOOSE}}}, & d_{\text{VERYLOOSE}} \leq d < d_{\text{TIGHT,new}} & \text{(II)} \\ d_{\text{TIGHT,old}} + (d - d_{\text{TIGHT,new}}) \times \frac{d_{\text{max}} - d_{\text{TIGHT}}}{d_{\text{max}} - d_{\text{TIGHT,new}}}, & d_{\text{TIGHT,new}} \leq d < d_{\text{max}} & \text{(III)} \\ d, & d_{\text{max}} \leq d & \text{(IV)} \end{cases}$$

Where $d_{\text{VERYLOOSE}}$ is the VERYLOOSE operating point where no pileup correction is desired, d_{max} is the largest discriminant value for which the transform should take place, which was chosen to be 2.0. This new method of pileup correction was found to perform similarly to the correction performed in Run-1, while fixing the effect of the operating points not being subsets of one another. One small difference this introduces is that LOOSE now depends on pileup (as VERYLOOSE is the reference point used for loose), but the correction is smallest for the looser operating points. Figure 4.16 illustrates how the phase space is carved out corresponding to the Roman numerals in the piece-wise equation above.

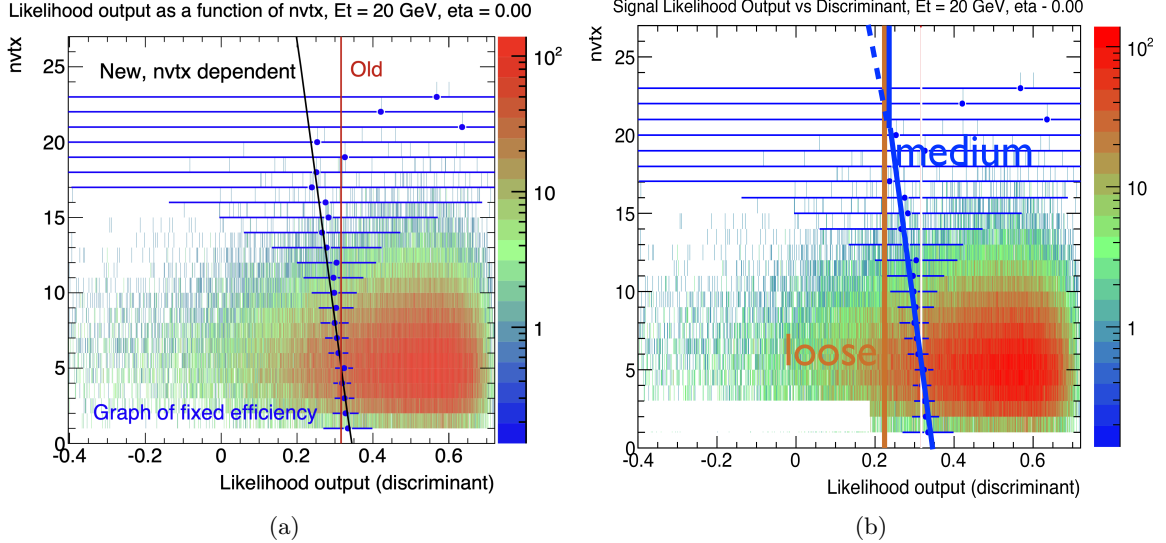


Figure 4.15: Example of the pileup correction used in Run-1 where the z-axis shows the number of entries in each bin. (a) Shows what a flat discriminant cut looks like and as well as a discriminant cut adjusted as a function of n_{vtx} to maintain a constant signal efficiency. (b) The blue dashed line shows that with large pileup, the MEDIUM operating point could be looser than the LOOSE operating point, so they are not perfect subsets. The solid blue line shows what is desired, namely, for MEDIUM to always be a subset of LOOSE.

4.5.7.2 Alternative Pileup Measures: TRT Local Track Occupancy

In an effort to better model the local pileup activity around an electron I investigated if parameterizing the pileup correction in terms of the newly available TRT local track occupancy variable, which measures activity around the electron, could provide improved performance in replacing the event-by-event offline measure of the number of primary vertices n_{vtx} . Additional motivation for the TRT local track occupancy lies in its availability *online* as well. As the availability of pileup measure information is limited online since event reconstruction is required to determine the number of primary vertices, n_{vtx} . The nominal replacement is the average number of collision vertices $\langle\mu\rangle$, measured online by a set of luminosity detectors (one dedicated detector LUCID, the Beam Conditions Monitor, and measurements from the Tile and Forward calorimeters and the ID) it is the average over all BCIDs in a Luminosity Block⁷ (one minute of data taking). The TRT local track occupancy could then mitigate inefficiencies arising from the use of different variables online and offline. The local TRT occupancy is measured in 192 regions (32 sectors in phi for the barrel, endcap A and endcap B regions on each side of the detector). For each track, the number of hits

⁷The time unit in which ATLAS luminosity data is recorded, an interval during which the luminosity is supposed to remain constant

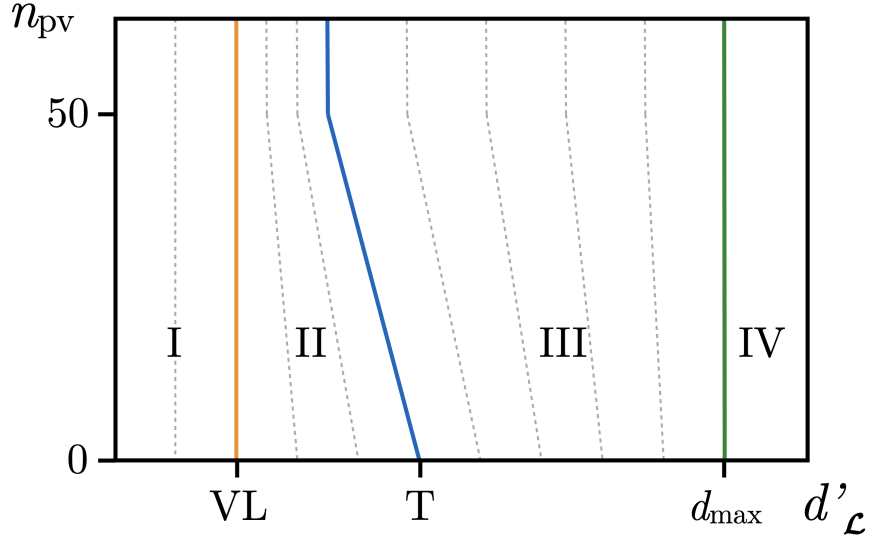


Figure 4.16: Sketch of the phase space carved out by the n_{vtx} dependant discriminant decisions which define the operating points TIGHT (blue line) and VERYLOOSE (orange line). The regions I, II, III, and IV illustrate the piece-wise transform described in this section [47].

in each region is weighted by the local TRT occupancy⁸ to calculate the local occupancy around the track. The TRT local track occupancy was implemented in the relevant software tools in the same manner as n_{vtx} and μ with several technical caveats. Firstly, the TRT acceptance only covers an $|\eta| < 2.01$ requiring the original measures to be used for the most forward two η bins. Second ‘silicon-only’ tracks are possible where no TRT hits are registered for the electron object leading to an undefined local track occupancy which not desirable, again the original measures are defaulted to in this special case. In Figure 4.17 the local track occupancy is compared to n_{vtx} in MC, both signal and background efficiencies are shown as a function of μ . At most an improvement of 1% is seen in signal efficiency for the TIGHT operating point, while in background an overall reduction in background rejection is seen, climbing to nearly a 10% loss in rejection power for large μ . This result can be understood as for signal the TRT Local track occupancy variable is correlated with pileup, so the signal efficiency improves slightly, but for background there is a stronger correlation with more activity from the other particles from a jet. While the TRT local track occupancy was attractive as a variable available online and offline, the increase in background efficiency was extremely unattractive as it would have increased the trigger rate.

⁸The occupancy is number of TRT straws which have a low-level hit within a validity gate divided by the total number of live TRT straws in the region considered

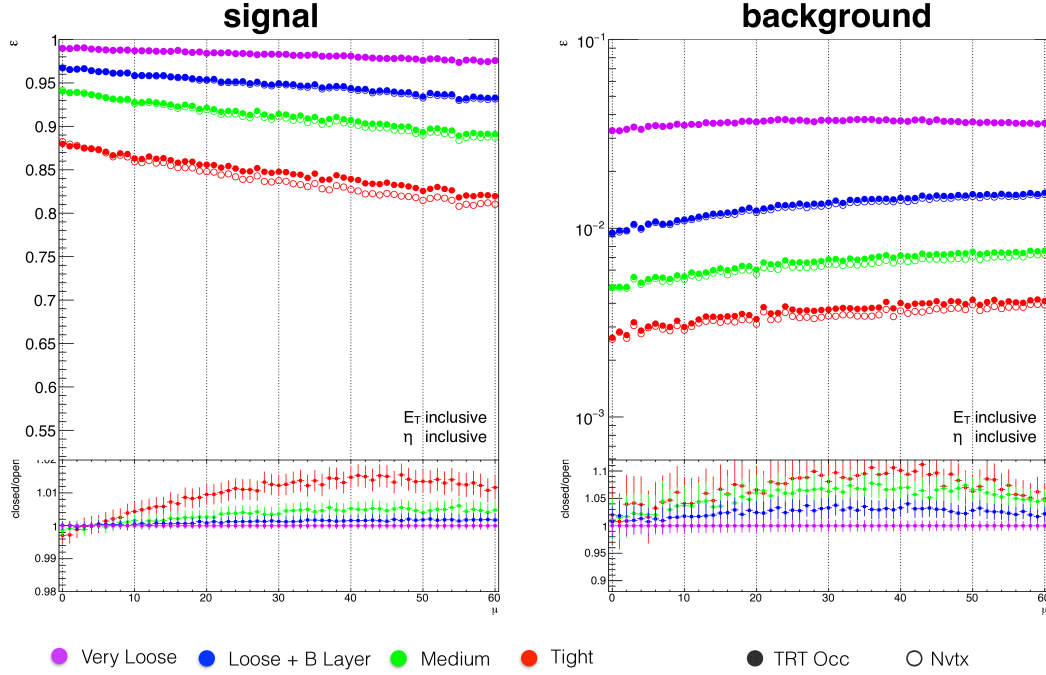


Figure 4.17: Signal (a) and background (b) identification efficiencies as a function of the nominal electron LH discriminant pileup measure n_{vtx} and the alternate variable local TRT track occupancy are shown for nominal LH menu TIGHT, MEDIUM, LOOSE, and VERYLOOSE operating points. In the bottom panels the efficiencies for the local TRT track occupancy to n_{vtx} is shown.

4.5.8 Tuning the Electron LH

A so-called “TUNE” is defined as a set of operating points all relying on the same set of pdfs. The defining of an operating point is then determined by tuning to a discriminant value that results in a desired identification efficiency. And just as kinematic bins are necessary for the pdfs, these are needed for the discriminant requirements as well. The $|\eta|$ and E_T bins used for the likelihood discriminant requirements are shown in Table 4.5 and the second row of Table 4.6 respectively. Note that fewer E_T bins are used for the pdfs than for the discriminant requirements; this is to allow for a smoother increase of electron efficiency with E_T than would otherwise occur. As a general improvement to the electron likelihood with respect to Run 1, an interpolation procedure was implemented to interpolate the pdfs and discriminant cut values between the E_T bins defined for the operating points. This procedure, first introduced for analysis of 2015–2016 data, allows for better continuity of electron identification efficiency as a function of E_T when using E_T bins that are finer than that used for the identification optimization (which have a bin width of 5 GeV or larger for $E_T > 10$ GeV). The discriminant tuning procedure is then done in each bin independently using

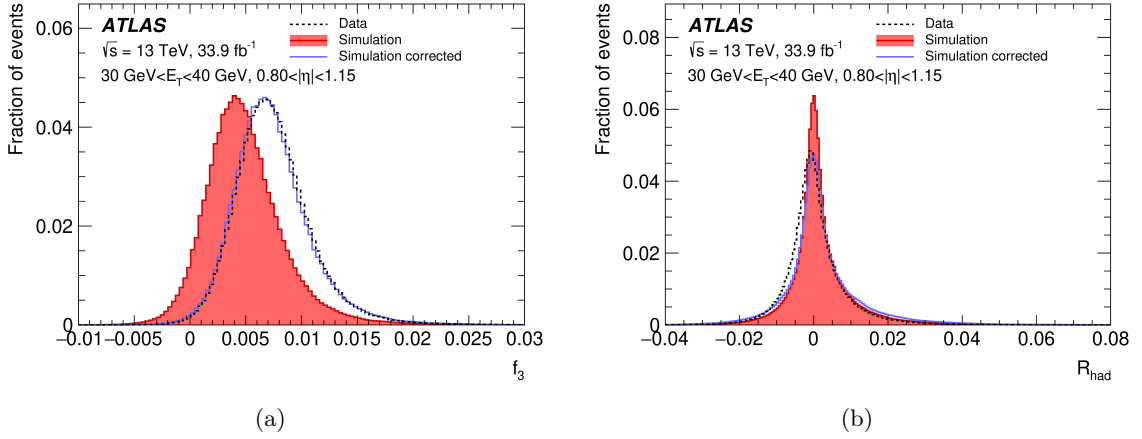


Figure 4.18: The f_3 (a) and R_{had} (b) pdf distributions in data and simulation for prompt electrons that satisfy $30 \text{ GeV} < E_T < 40 \text{ GeV}$ and $0.80 < |\eta| < 1.15$. The distributions for both simulation and data are obtained using the $Z \rightarrow ee$ tag-and-probe method. KDE smoothing has been applied to all distributions. The simulation is shown before (shaded histogram) and after (open histogram) applying a constant shift (f_3 , (a)) and a width-scaling factor (R_{had} , (b)). Although some $|\eta|$ bins of f_3 additionally have a width-scaling factor, this particular $|\eta|$ bin only has a constant shift applied.

MC, in order to get a pure enough sample of electrons, that are modified with data-to-simulation shift and width corrections. Examples of these corrections are illustrated in Figure 4.18

For a flat efficiency the procedure is fairly straight forward. A large MC sample of reco level electron objects are fed into the Electron LH in order to populate a discriminant distribution for a given bin, a discriminant cut value is then chosen such that a desired selection efficiency is achieved. This procedure becomes more nuanced when the discriminant loosening parameter, a , detailed in the previous section must be determined as well. For this case a two dimensional histogram in discriminant vs. n_{vtx} is populated and bin by bin in n_{vtx} the discriminant value most closely resulting in the desired efficiency is determined. These equi-efficiency discriminant values are then fit to a line to determine the slope, a . This is illustrated in Figure 4.15a with the blue points all corresponding to the desired efficiency and the black line the linear fit of those points. Now as illustrated in Figure 4.14a by the black markers the desired flat efficiency is achieved as a function of n_{vtx} as desired, however as discussed in the previous section this leads to a large n_{vtx} dependence in the background efficiency as seen in Figure 4.14b. This see-saw effect is then countered by by-hand iterations of reducing the slope a such that a relatively flat signal efficiency is retained while also ameliorating the strong n_{vtx} dependence in background, this is illustrated by the red markers in Figure 4.14.

4.5.9 LH-Identification Operating Points

As different ATLAS physics analyses desire different levels of electron signal efficiency and background rejection, several operating points are necessary. There are four levels of officially maintained and recommended TUNES designed to encompass a broad variety of analyses. These are the aforementioned VERYLOOSE, LOOSE, MEDIUM, and TIGHT operating points. Each corresponds to a more stringent requirement on the likelihood discriminant value than the one before it, and thus a larger background rejection (and correspondingly, a smaller signal efficiency). In addition to requirements on the discriminant value, all of the operating points also impose requirements on simple track quantities. LOOSE, MEDIUM, and TIGHT require at least two hits in the pixel detector and at least seven hits in the pixel and silicon strip detectors combined. Furthermore, MEDIUM and TIGHT also require a hit in the innermost pixel layer, which is useful for rejecting photon conversions. In cases where the innermost pixel layer is non-operational, the next-to-innermost pixel layer is used instead. A variation of the LOOSE operating point called LOOSEANDBLAYER also exists, which uses the same criteria as Loose but also adds the requirement of a hit in the innermost pixel layer. The VERYLOOSE operating point primarily exists for fake electron background estimation, and thus only requires a “good-quality” track, which is defined as at least one hit in the pixel detector (which need not be a hit in the innermost pixel layer) and at least seven hits in the pixel and silicon strip detectors combined.

4.5.10 The Trigger Electron LH

The time between a collision and the final ATLAS trigger decision is about 4 seconds. In order to meet this time requirement trigger reconstruction algorithms that are CPU-intensive must be altered with respect to their offline equivalents. In the case of the electron/photon reconstruction and identification algorithms this affects several inputs and techniques nominally used offline. The variable-sized supercluster algorithm described in Section 4.4.2 was not used online in Run-2. Neither is the GSF electron track refitting where instead the standard pion hypothesis track fitting must be used. As a result the quality of the track reconstruction degrades, impacting the resolution of the d_0 and $|d_0/\sigma(d_0)|$ tracking variables, as well as the trackcluster matching variables $\Delta\phi_{\text{res}}$ and $\Delta\eta_1$. The variable $\Delta p/p$ which is output by the GSF algorithm, is unavailable altogether at the HLT. During the reconstruction of electromagnetic clusters in the LAr calorimeter, some cell-energy-level corrections are not available online, such as the correction for transient changes in LAr high-voltage [48], or differ in implementation, such as the bunch crossing position-dependent pileup

correction [38, 49, 50].

4.5.10.1 Re-tuning the Trigger LH for Large Pileup Environments

Re-tuning the LH is desired when a change in data taking conditions could adversely effect the performance of the LH. In late 2017 during the historically high pileup runs it became urgent to re-optimize many recommendations as the μ for 2018 could be just as large (and potentially even larger). For reference listed below are is fill scheme for the middle part of 2017 data taking and it's resulting peak μ , as well as what the potential beam fill schemes for 2018 could be at the time (October 2017) and their expected maximum μ :

- 2017: 1.53×10^{34} with 1860 bunches $\rightarrow \mu=58$
- 2018: 2.0×10^{34} with 2550 bunches $\rightarrow \mu=56$
- 2018: 2.2×10^{34} ⁹ with 2550 bunches $\rightarrow \mu=61$
- 2018 (8b4e): 2.2×10^{34} with 1860 bunches $\rightarrow \mu=84$ (maybe even higher)

The e/γ Trigger working sub-group requested a re-tune of the Trigger LH to account for these potential large pileup environments expected in 2018. For this re-tune a set of official high- μ MC samples were generated with a μ -profile between 45-75. Additionally this re-tune allowed for the entire LH (both online and offline) to be completely data-driven with the implementation of low E_T data-driven pdfs¹⁰ for this TUNE. Data-driven pdfs were derived using the full 2017 data set. These pdfs, for both signal and background, are compared to the previous set of pdfs for high and low E_T in Figures 4.19 and 4.20 respectively.

High E_T pdfs in Figure 4.19 show very good agreement with the previous pdf set as well as an expected, with the exception of eProbabilityHT, systematic broadening of signal distributions due to the higher pileup data used to build the pdfs (2017 data vs. 2015-2016 data). The large differences for eProbabilityHT are due to a re-optimization of the eProbabilityHT (a likelihood itself) for an updated gas configuration. Low E_T pdfs in Figure 4.20 also show good agreement with several distributions showing narrower signal distributions. Note that here we are now comparing data pdfs (built of 2017 data) to MC pdfs with simple data-MC shift and width corrections applied and so we do expect differences coming from mis-modeling in MC. Via the discriminant tuning procedure described in Section 4.5.8 discriminant values are determined using the high- μ MC sample s.t.

⁹ 2.2×10^{34} is LHC's "limit" – cooling of inner triplets

¹⁰The low- E_T Trigger LH pdfs were MC based for Run 2 prior

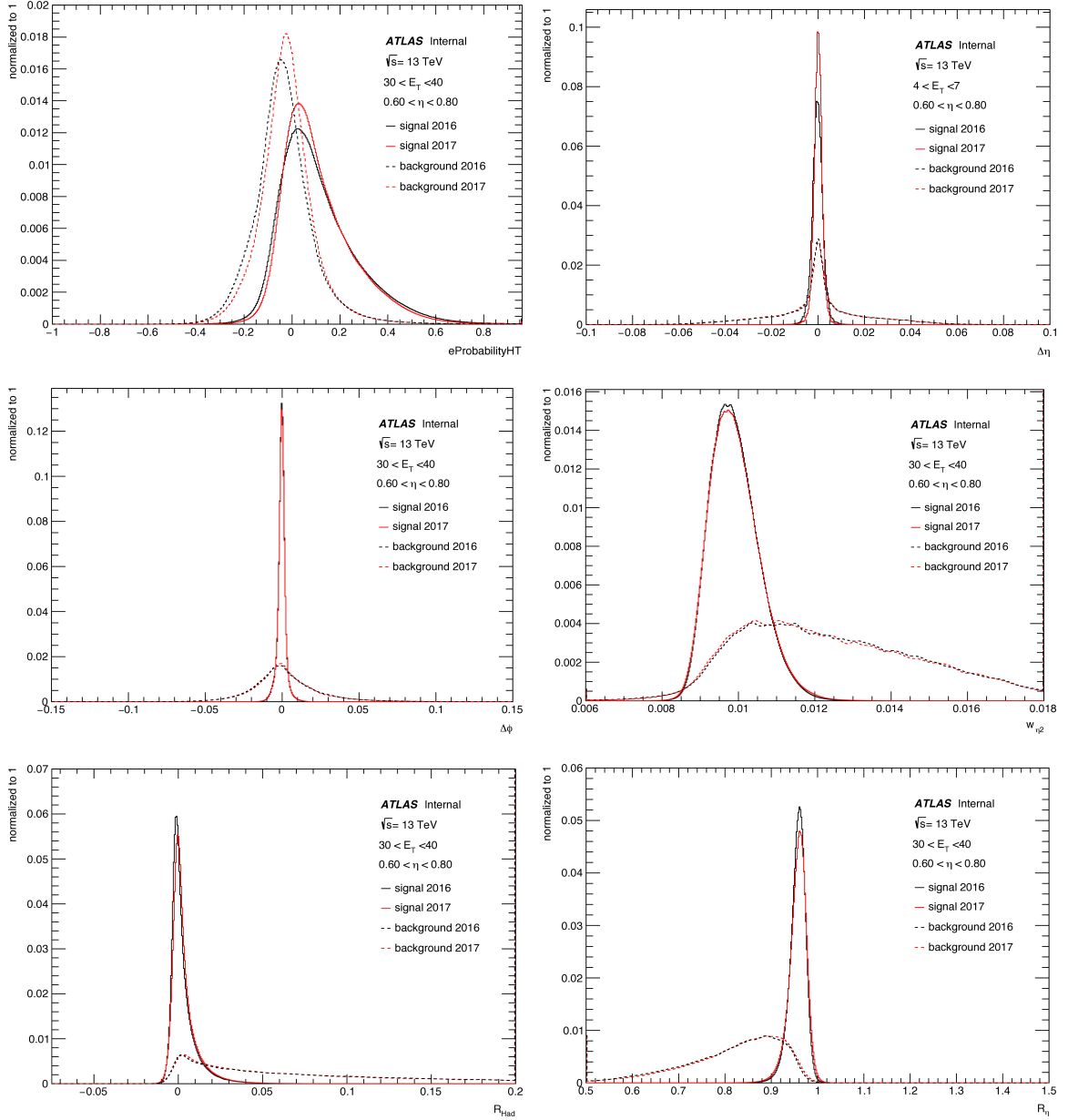


Figure 4.19: Pdfs of tracking and track-cluster matching variables $e\text{ProbabilityHT}$, $\Delta\eta_1$, $\Delta\phi_{\text{res}}$, and the shower shape variables $w_{\eta 2}$, R_{had} , and R_{η} . All of which are defined in Table 4.1 and shown for $30 \text{ GeV} < E_T < 40 \text{ GeV}$ and $0.6 < |\eta| < 0.8$. The solid line distributions are determined from a background simulation sample and the dashed-line distributions are determined from a $Z \rightarrow ee$ simulation sample. The black distributions are pdfs used in the trigger LH in 2016/2017 data taking years and the red are the pdfs developed for the 2018 year. These distributions are for reconstructed electron candidates before applying any identification. They are smoothed using an adaptive KDE and have been corrected for offsets or differences in widths between the distributions in data and simulation.

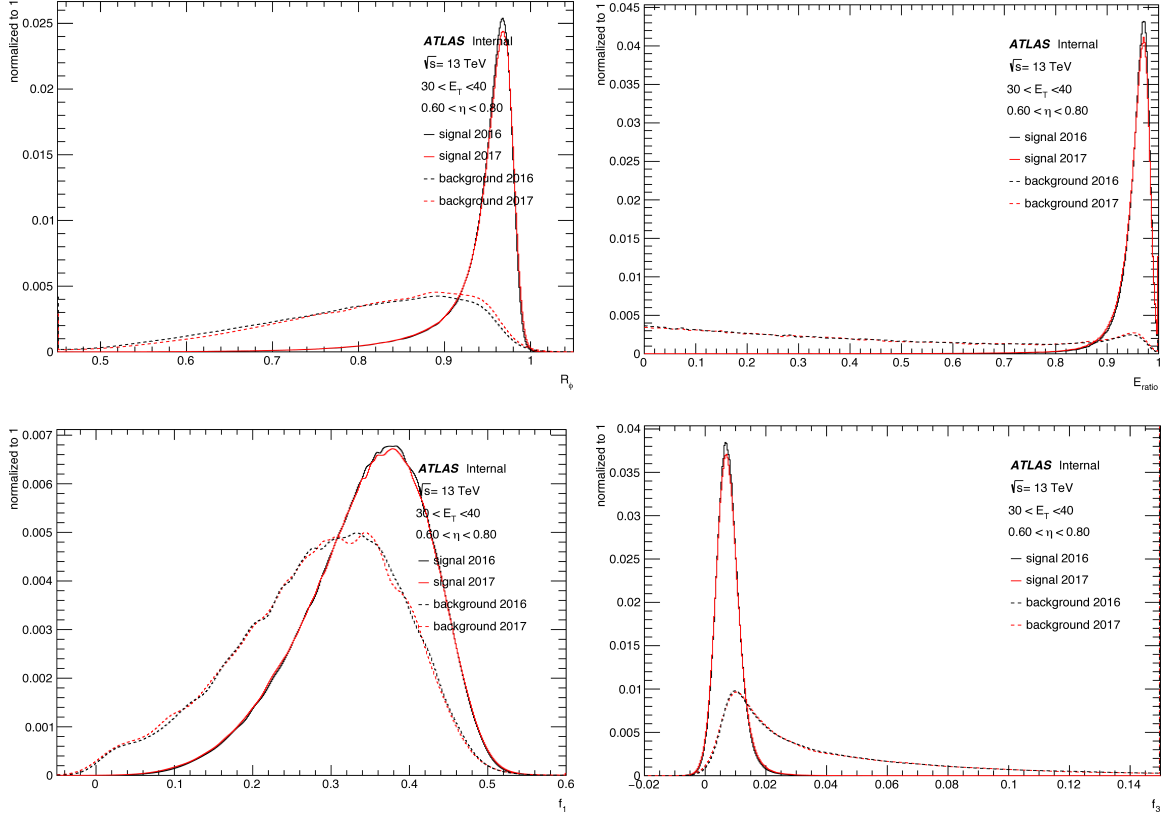


Figure 4.19: Pdfs of shower shape variables R_ϕ , E_{ratio} , f_1 , and f_3 . All of which are defined in Table 4.1 and shown for $30 \text{ GeV} < E_T < 40 \text{ GeV}$ and $0.6 < |\eta| < 0.8$. The solid line distributions are determined from a background simulation sample and the dashed-line distributions are determined from a $Z \rightarrow ee$ simulation sample. The black distributions are pdfs used in the trigger LH in 2016/2017 data taking years and the red are the pdfs developed for the 2018 year. These distributions are for reconstructed electron candidates before applying any identification. They are smoothed using an adaptive KDE and have been corrected for offsets or differences in widths between the distributions in data and simulation.

desired signal efficiencies are met. Additionally the $n_{vtx, \text{max}}$ (μ_{max} for Trigger LH) value described in Section 4.5.7.1, and illustrated in Figure 4.16, was increased from $\mu_{\text{max}} = 50$ to $\mu_{\text{max}} = 100$.

Trigger rates were determined using a trigger emulation tool for four standard electron triggers for the three cases, using the nominal (old) LH TUNE, using the new updated LH TUNE, and using the new updated LH TUNE along with the new “ringer” fast calorimeter reconstruction algorithm¹¹. These rates are shown in Table 4.7.

¹¹The ringer algorithm is a neural-network based fast-calorimeter reconstruction algorithm that uses all calorimeter layers, centered in a window around the cluster barycenter. Each ring is the collection of cells around the previous one. Ring value is the sum E_T of all cells of that ring. Achieves same signal efficiency as cut-based method but with a 50% reduction in CPU demand for the lowest unprescaled single electron trigger.

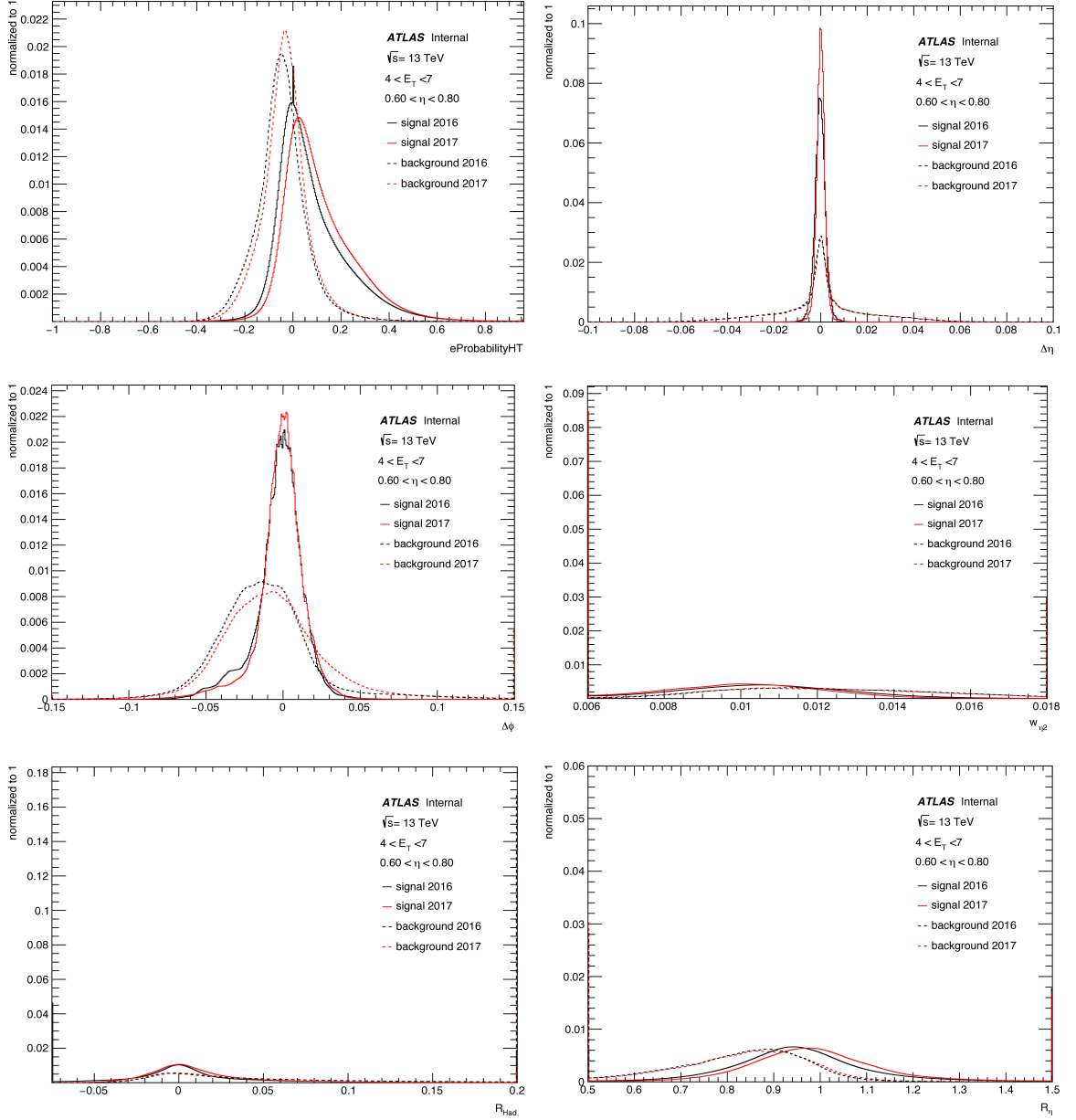


Figure 4.20: Pdfs of tracking and track-cluster matching variables $e\text{ProbabilityHT}$, $\Delta\eta_1$, $\Delta\phi_{\text{res}}$, and the shower shape variables $w_{\eta 2}$, R_{had} , and R_{η} . All of which are defined in Table 4.1 and shown for $4 \text{ GeV} < E_T < 7 \text{ GeV}$ and $0.6 < |\eta| < 0.8$. The solid line distributions are determined from a background simulation sample and the dashed-line distributions are determined from a $Z \rightarrow ee$ simulation sample. The black distributions are pdfs used in the trigger LH in 2016/2017 data taking years and the red are the pdfs developed for the 2018 year. These distributions are for reconstructed electron candidates before applying any identification. They are smoothed using an adaptive KDE and have been corrected for offsets or differences in widths between the distributions in data and simulation.

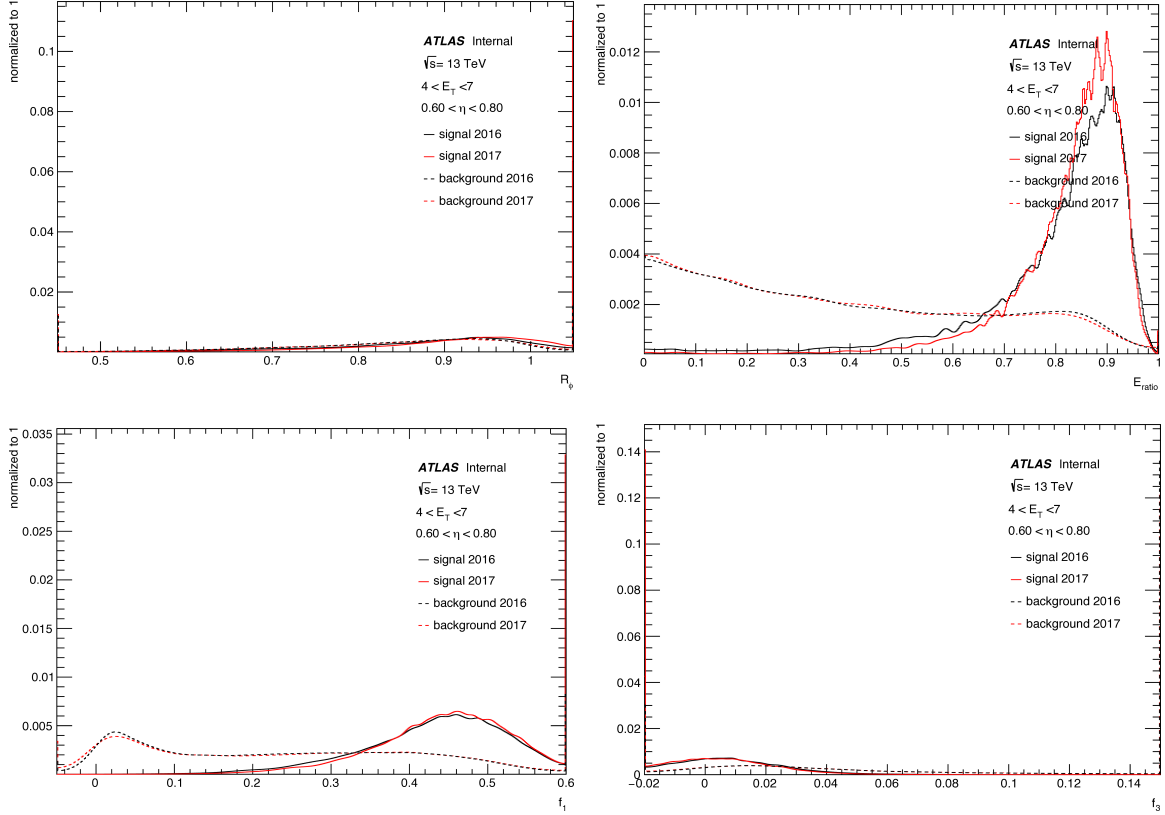


Figure 4.20: Pdfs of shower shape variables R_ϕ , E_{ratio} , f_1 , and f_3 . All of which are defined in Table 4.1 and shown for $4 \text{ GeV} < E_T < 7 \text{ GeV}$ and $0.6 < |\eta| < 0.8$. The solid line distributions are determined from a background simulation sample and the dashed-line distributions are determined from a $Z \rightarrow ee$ simulation sample. The black distributions are pdfs used in the trigger LH in 2016/2017 data taking years and the red are the pdfs developed for the 2018 year. These distributions are for reconstructed electron candidates before applying any identification. They are smoothed using an adaptive KDE and have been corrected for offsets or differences in widths between the distributions in data and simulation.

Small improvement expected with the new TUNE for electron triggers but all changes are within statistical uncertainties. No increase of rate expected with new TUNE. Efficiencies taken from a full data run reprocessed with Tier 0 monitoring were produced for standard electron triggers that use TIGHT, MEDIUM, and VERYLOOSE operating points are shown in Figure 4.21. Three cases are compared: new offline LH TUNE numerator and new online LH TUNE denominator in black, old offline LH TUNE numerator and old online LH TUNE denominator in red, and new offline LH TUNE numerator and old online LH TUNE denominator in blue.

The new online LH TUNE performed better than previous TUNE for all operating points with the

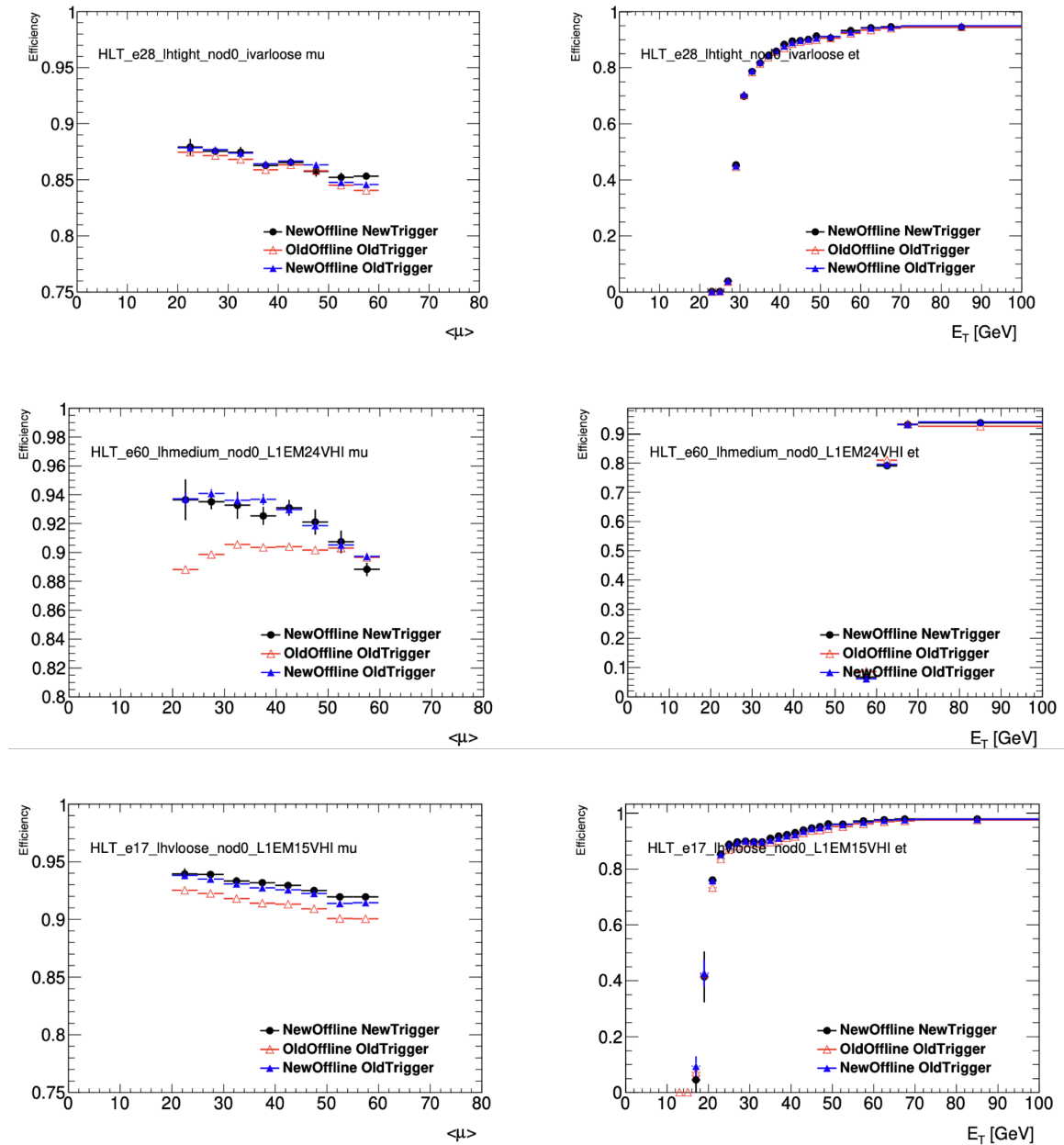


Figure 4.21: Efficiencies taken from a full data run reprocessed with Tier0 monitoring as a function of $\langle\mu\rangle$ and E_T produced for standard electron triggers that use the TIGHT (top), MEDIUM (middle), and VERYLOOSE (bottom) operating points. Three cases are compared: new offline LH TUNE numerator and new online LH TUNE denominator in black, old offline LH TUNE numerator and old online LH TUNE denominator in red, and new offline LH TUNE numerator and old online LH TUNE denominator in blue.

Trigger	Nominal Rate	Rate w/ new LH	Rate w/ new LH and Ringer
e26_lhtight_nod0_ivarloose	201 Hz	197 Hz	197 Hz
e28_lhtight_nod0_ivarloose	175 Hz	172 Hz	172 Hz
e60_lhmedium_nod0_L1EM24VHI	23.5 Hz	25.3 Hz	25.3 Hz
2e17_lhvloose_nod0_L12EM24VHI	12.5 Hz	12.3 Hz	12.5 Hz

Table 4.7: Trigger rates determined using a trigger emulation tool for four standard electron triggers for the three cases; using the nominal (old) LH TUNE, using the new updated LH TUNE, and using the new updated LH TUNE along with the new “ringer” fast calorimeter reconstruction algorithm.

exception of the MEDIUM operating point at high μ . While further investigation on this discrepancy was recommended, due to the short timeline associated with having a validated trigger menu in place before data taking, the decision was made to update all operating points except MEDIUM, which would retain the previous year’s version for the trigger LH (the blue triangle markers). This new Trigger LH TUNE was implemented in March 2018.

CHAPTER 5

An Exercise in Three Lepton Resonances

5.1 Analysis Introduction

The electron identification procedure just described in Chapter 4 leads nicely into the analysis portion of this thesis where those electrons are now used to look for new physics. New physics in the form of fundamental particles that require description beyond the Standard Model and ultimately would lead to a deeper understanding of our natural world. In this chapter we will describe just that, a search for a new fundamental particle by way of its decay into the fully visible final state of three charged leptons (a lot of which are electrons). This fully visible final state allows for the reconstruction of the particle's invariant mass which would rise resonantly above the estimated background if seen in the data. Figures 5.1a and 5.1b depict the the processes of interest that give rise to the resonance via the chargino decay, $\tilde{\chi}_1^\pm \rightarrow Z\ell^\pm \rightarrow \ell^\pm \ell^\mp \ell^\pm$.

5.1.1 Phenomenological Motivation

As alluded to in Chapter 2 the theoretical framework that is used to drive this search is the $B - L$ MSSM. Where in Chapter 2, the $B - L$ MSSM was strongly motivated, we now motivate a group of experimental signatures that are likely to be seen at the ATLAS experiment in the context of this model. Strong theoretical motivation comes from an extensive study involving the statistical scanning over all dimensionful parameters of the soft SUSY breaking terms [11]. A statistical analysis involving 100 million independent trials of these parameters is performed. Where the SUSY breaking scale is restricted to 1.5 TeV or below in order to ensure that the LHC would have sufficient energy to be able to produce the LSP. For the 100 million sets of randomly scattered initial conditions, it was found that 4,351,809 break $B - L$ symmetry with the Z'_{B-L} mass above the current lower bound of

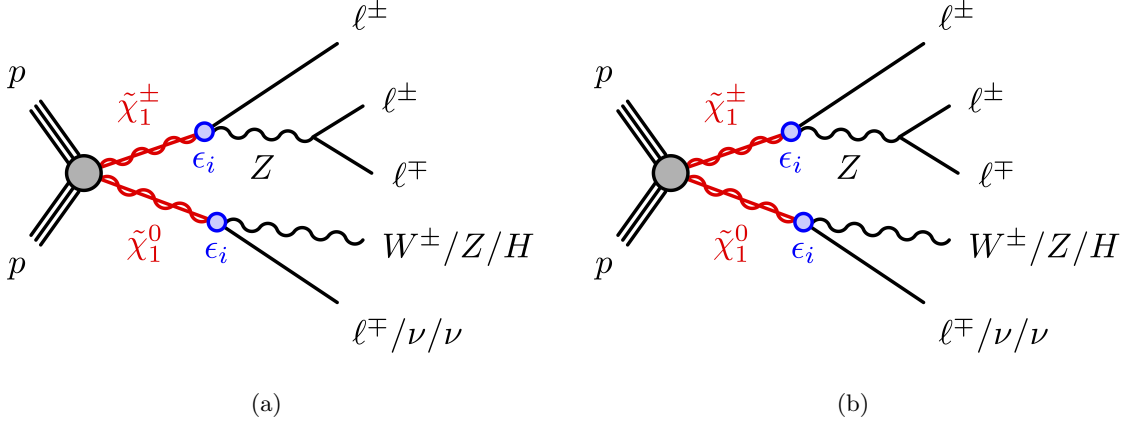


Figure 5.1: Diagrams of (a) $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ (b) production with at least one $\tilde{\chi}_1^\pm \rightarrow Z\ell \rightarrow \ell\ell\ell$ decay. The R-parity-violating coupling ϵ_i allows prompt $\tilde{\chi}_1^\pm$ decays into $Z\ell$, $H\ell$ or $W\nu$ and prompt $\tilde{\chi}_1^0$ decays into $W\ell$, $Z\nu$, or $H\nu$ [51].

$Z'_{B-L} = 4.1$ TeV. These are plotted as the green points in Figure 5.2. Running the Renormalization Group (RG) equations down to the EW scale, one finds that of these 4,351,809 appropriate $B-L$ initial points, only 3,142,657 break electroweak symmetry with the experimentally measured values for M_Z and M_W given in equation. These are shown as the purple points in Figure 5.2. Now applying the constraints that all sparticle masses be at or above their currently measured lower bounds [11], it was found that of these 3,142,657 initial points, only 342,236 are acceptable. These are indicated by cyan colored points in Figure 5.2. Finally, of these 342,236 points, only 67,576 also lead to the currently measured Higgs mass. That is, of the 100 million sets of randomly scattered initial conditions, 67,576 satisfy all present phenomenological requirements. These are referred to as the “valid” points. As discussed in detail in [9], the particle spectrum of each of the 67,576 valid black points is exactly determined by the computer code.

The identify of the highest supersymmetric particle (LSP) in the particle spectrum is particularly interesting when designing experimental searches. The identity of the LSP is shown in Figure 5.3 in terms of the number and percentage of the valid points that have that type of supersymmetric particle as the LSP. With the above assumptions for the model and constraints, we now have an effective probability for a given sparticle to be the LSP, a very interesting and useful result. There are of course experimental considerations to be made when analyzing this histogram that will in general re-weight one’s search motivations from Figure 5.3 for a given process. First is the relative production cross section of each sparticle at the LHC. Figure 5.4 shows us the production cross sections as a function of mass for various standard model and supersymmetric particles. The mostly

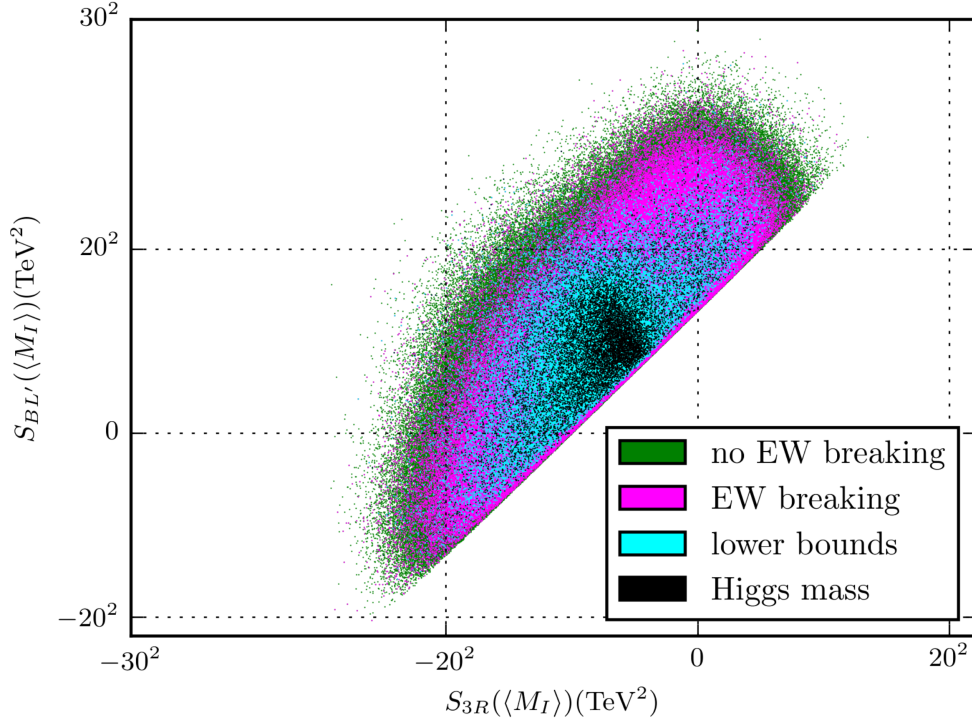


Figure 5.2: Plot of the 100 million initial data points for the analysis. The 4,351,809 green points lead to appropriate breaking of the $B - L$ symmetry. The 3,142,657 purple points also break the EW symmetry with the correct vector boson masses. The cyan points correspond to 342,236 also satisfy all lower bounds on the sparticle masses. Finally, as a subset of these 342,236 initial points, there are 67,576 valid black points which lead to the experimentally measured value of the Higgs boson mass [11].

bino-like neutralino ($\tilde{\chi}_B^0$) is the most probable LSP. However, if it is pure bino then it cannot be pair-produced directly and so the cross section is not even shown on Figure 5.4.

Sneutrinos or sleptons are the LSPs in about 10% of the valid model points. However, experimental searches with Run-2 data are also disfavored as these have a very small production cross section (cyan line in Figure 5.4). These will be left for future searches with more data in Run-3 or HL-LHC.

The mostly wino-like chargino or neutralino are the LSPs in about 10% of the valid model points. The experimental production cross sections for wino-type chargino-pair and chargino-neutralino pair production are large enough to allow for a feasible search with Run-2 data (green and magenta lines in Figure 5.4). Due to the relative smallness of the RPV coupling we expect the most probable RPV decays to be from the LSP, however if there is effective mass degeneracy between the LSP and

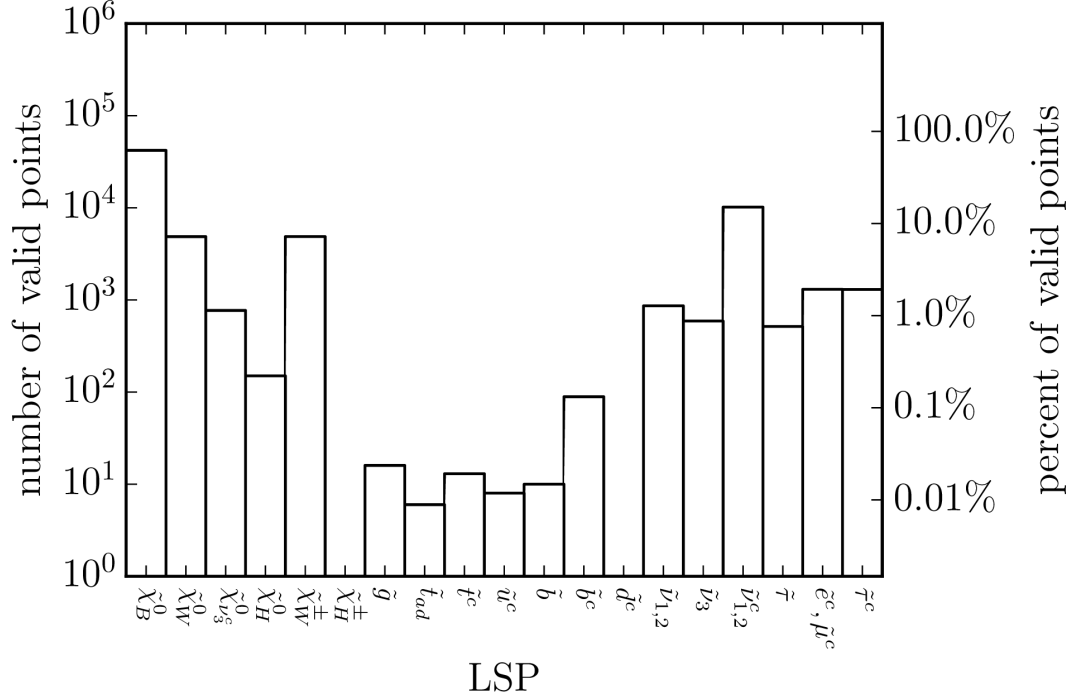


Figure 5.3: A histogram of the identity of the LSP for the 67,576 valid points. The left scale shows the number of valid points and the right scale shows the percent of valid points. Sparticles which did not appear as LSPs are omitted [12].

NLSP (a very small mass splitting), it is very reasonable to expect both the LSP and NLSP to both decay via RPV, i.e. all final states will be SM particles only. In Figure 5.5 where the mass values for the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ are for valid points in the scan in which the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\mp$ are either the LSP or NLSP we see mass splittings less than a GeV for cases where the $\tilde{\chi}_1^0$ is the LSP and $\tilde{\chi}_1^\pm$ the NLSP 5.5a and vice versa 5.5b. This shows the possibility of a search with sizable production cross sections from the sum of chargino-pair production and mass-degenerate chargino-neutralino production. Further, both the LSP and NLSP will have RPV decays due to the small size of their mass splitting. This will be the topic of the search described in this thesis. The remaining LSPs have a low probability but would be produced profusely through strong production processes. An earlier analysis by my adviser's group searched for pair production of a stop LSP with RPV decay [53] in early Run-2 data.

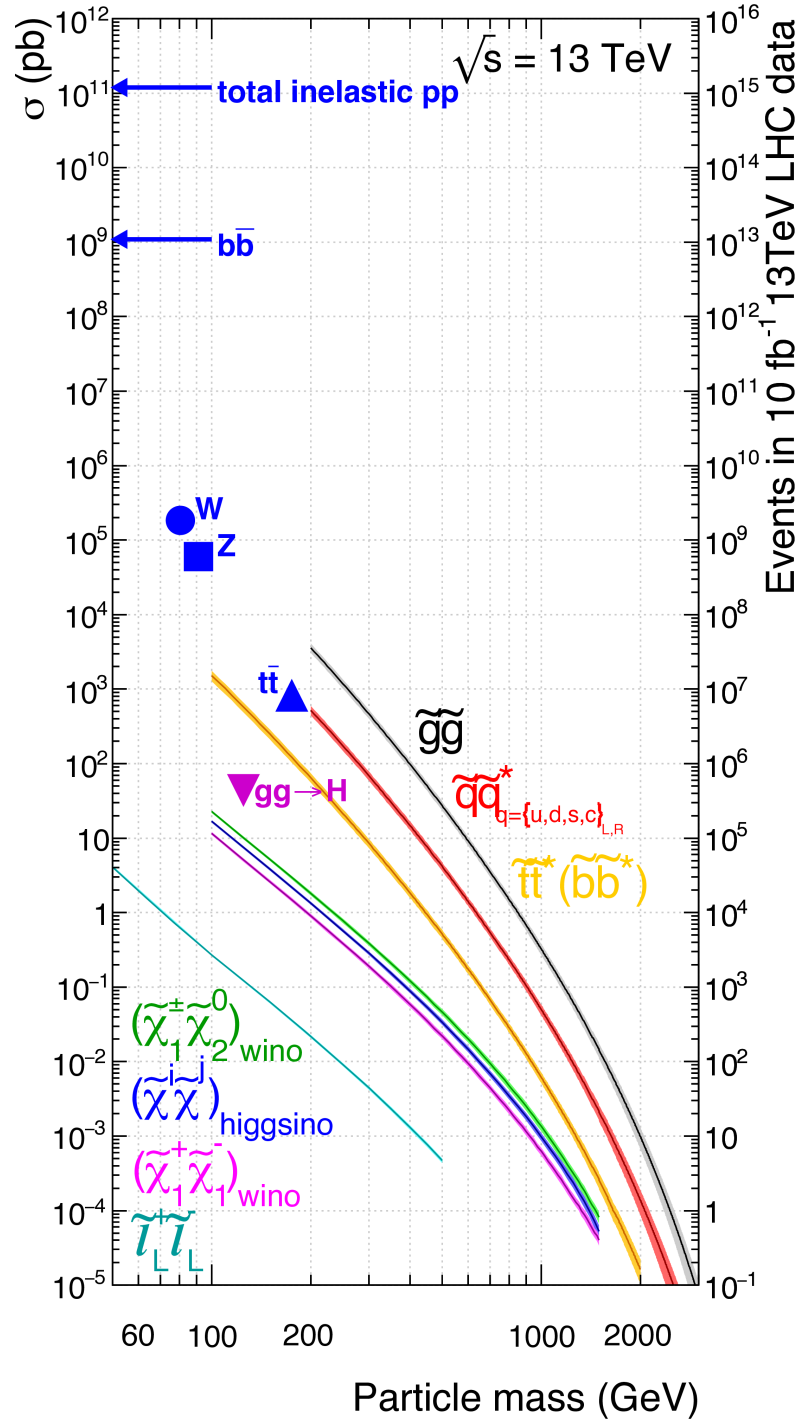


Figure 5.4: Theoretical production cross sections for selected standard model and SUSY in 13TeV proton collisions. The expected number of events produced for each process in 10 fb^{-1} of LHC data is shown on the right scale [52].

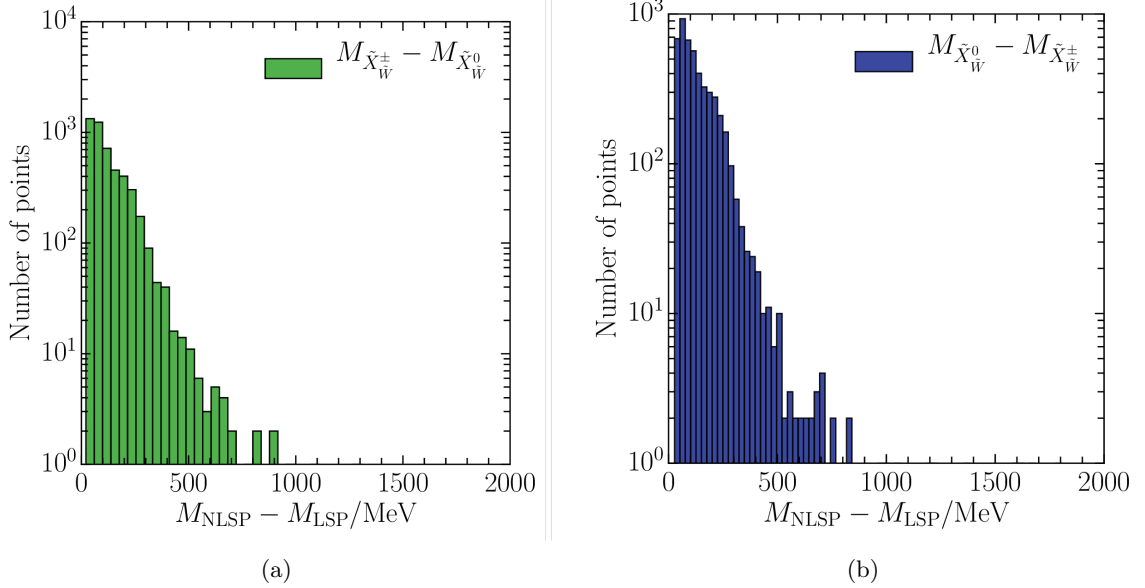


Figure 5.5: The mass difference between the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ when the $\tilde{\chi}_1^0$ is the LSP and the $\tilde{\chi}_1^\pm$ the NLSP (a) and then again with the $\tilde{\chi}_1^\pm$ the LSP and the $\tilde{\chi}_1^0$ the NLSP (b) [12].

5.2 Analysis Strategy

It has been just been shown that the signals in Figure 5.1 are phenomenologically well motivated from the stand point of the $B - L$ MSSM, as well as motivated experimentally in so far as it is possible with physical intuition and cross section calculations. We are now effectively invited to start to design the search strategy. It is very much worth noting that at this logical stage in the analysis the signal is further motivated by way of *sensitivity studies*. These are studies done using a simplified version of the analysis done on quickly generated simulated samples. This allows for a much more detailed assessment of signal sensitivity beyond cross section calculations. This is also a necessary requirement, and an important part of the process, for requesting official simulated data in the ATLAS collaboration. These studies will not be detailed here as their development are almost entirely contained in the full search strategy. It suffices to say that these studies showed that the expected sensitivity was very much large enough to not be deterred from this search in any way, and to actually be very much excited about in every way.

5.2.1 Signal

The strategy for this search revolves around being able to fully reconstruct the mass of the $\tilde{\chi}_1^\pm$ from its decay into a final state of three leptons, $\tilde{\chi}_1^\pm \rightarrow Z\ell \rightarrow \ell\ell\ell$. This points to the main discriminating

Table 5.1: Table of final states with a trilepton resonance from the chargino decay. Separate selection algorithms (two-leg or one-leg) are designed for final states where both or only one of the supersymmetric particles can be fully reconstructed from the detected particles.

Algorithm	Production	Decay	Final State
Two Leg	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$	$Z\ell Z\ell$	$\ell\ell\ell \ell\ell$
		$Z\ell H\ell$	$\ell\ell\ell jj\ell$
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^0$	$Z\ell W\ell$	$\ell\ell\ell jj\ell$
One Leg	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$	$Z\ell Z\ell$	$\ell\ell\ell \nu\nu\ell$
		$Z\ell H\ell$	$\ell\ell\ell WW\ell$
		$Z\ell W\nu$	$\ell\ell\ell jj\nu$
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^0$	$Z\ell Z\nu$	$\ell\ell\ell jj\nu$
		$Z\ell H\nu$	$\ell\ell\ell WW\nu$
		$Z\ell W\ell$	$\ell\ell\ell \ell\nu\ell$

variable, $m_{Z\ell}$, defined as the invariant mass of the leptonically decaying Z boson and the associated direct-lepton¹². Note that for the leptonic Z boson decay, we shift the measured dilepton invariant mass to the Z pole mass in order to reduce resolution effects. We redefine $m_{Z\ell}$ as

$$m_{Z\ell} : m_{Z\ell} - m_Z + 91.2 \text{ GeV} \quad (5.1)$$

Where ℓ here refers to only light leptons (electrons and muons) as we will not endeavour to reconstruct taus in this search. It is interesting to note here that when looking for terms in the $B - L$ MSSM Lagrangian that can lead to $\tilde{\chi}_1^\pm / \tilde{\chi}_1^0$ decays into SM particles that the term that is proportional to the photon exactly cancel. That is to say that the decay $\tilde{\chi}_1^\pm \rightarrow \gamma\ell$ vanishes. This leaves decays that involve only the massive gauge bosons and the Higgs and an associated direct-lepton (charged or neutral) to consider. Considering both chargino-pair and chargino-neutralino production, Table 5.1 shows the final states of interest that have at least one trilepton resonance from the chargino decay. The analysis regions will be defined later in this chapter. We also remain sensitive to other decays which may result in a leptonically decaying Z later in the decay chain, e.g. when the Higgs goes to ZZ in $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow H\ell H\ell$.

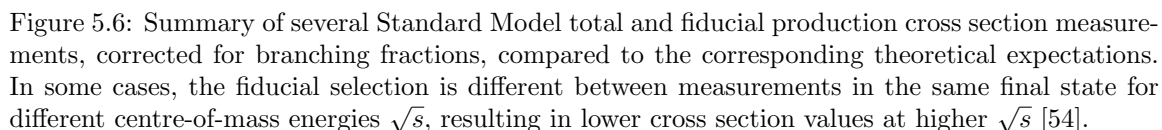
¹²lepton directly from the decay of the $\tilde{\chi}_1^\pm / \tilde{\chi}_1^0$

5.2.2 Backgrounds

The SM processes that are expected to contribute largely to this signal’s background are those that produce many leptons and contain a Z boson, these processes include WZ , ZZ , and $t\bar{t}Z$. Figure 5.6 shows a summary of several SM total and fiducial cross section measurements from ATLAS for four center-of-mass energies, $\sqrt{s}$, as well as their corresponding theoretical expectations. From this figure what is immediately obvious is all the very large backgrounds that, naively, we should not expect to have to deal with based on the the assumptions just made. i.e. we shouldn’t expect large contributions from any process to the left of VV in Figure 5.6. This assumption is of course built on absolute truth knowledge of all the SM processes final states and we will later see that this is not a very good assumption for a particular background. The strategy for handling these backgrounds in order to accurately estimate their yields in the signal regions in which we intend to make a statement about take on this particular form: *small* backgrounds will be directly estimated with Monte Carlo. The dominant backgrounds, WZ , ZZ , and $t\bar{t}Z$ will be estimated with dedicated control regions, to be described in detail in Sections 5.4.2.2, to 5.4.2.4, by way of data-MC normalization parameters for those background signatures contained in the full statistical fit that will be described in Section 5.5. The corrected estimation is then validated in dedicated validation regions before being propagated to the signal regions. The contribution from events with one or more misidentified or nonprompt (fake) leptons is separately estimated using a data-driven method to be described in Section 5.4.2.1.

5.3 Simulated Data: Monte Carlo Generation

To continue any further we must detail one of the most powerful, and the most essential, tools that an experimental particle physicist has at their disposal, simulated data by way of Monte Carlo (MC) experiments. Monte Carlo simulation is used to model the expected contributions of various SM processes as well the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ signal processes targeted by this search. The standard model MC samples form the basis of what will ultimately be the null hypothesis of the statistical test that will be used to evaluate against the data whether or not a discovery can be claimed. It also functions as a crucial tool to define and optimize event selection criteria and to estimate systematic uncertainties in the event yield predictions. MC simulation has three stages: First, event generation for each physics process (e.g. $pp \rightarrow WZ \rightarrow \ell\nu \ell\ell$) to predict the momenta of the final state particles; second, detector simulation to predict the response of the detector to these particles in terms of signals in the charged particle tracking detectors and energy deposits in the calorimeters; and third, the application of the same detector reconstruction algorithms used for the actual data to form the



5.3.1 MC Specifications

The generators and parameters used in the MC simulation samples for this analysis are summarized in Table 5.2. Signal samples were generated at masses between 100 GeV and 1500 GeV in steps of 50 GeV. Signals with masses below 100 GeV were not explored as they have been excluded by previous searches for charginos and neutralinos [55–61]. Signal events were generated with equal $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ branching fractions to each boson (W , Z , or Higgs bosons where kinematically accessible) plus a lepton (e , ν_e , μ , ν_μ , τ -lepton, or ν_τ) channel. In order to explore different assumptions for the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ branching fractions in the analysis, simulated events are reweighted appropriately, assuming that

Table 5.2: Details of the MC simulation for each physics process, including the event generator used for matrix element calculation, the generator used for the PS and hadronization, the PS parameter tunes, and the order in α_S of the production cross-section calculations.

Process	Event generator	PS and hadronization	PS tune	Cross section (in QCD)
Diboson, triboson, (Z +jets)	SHERPA 2.2	SHERPA 2.2	Default	NLO (NNLO)
$t\bar{t}W$, $t\bar{t}Z$, (Other top)	MADGRAPH5_aMC@NLO 2	PYTHIA 8	A14	NLO (LO)
$t\bar{t}$, (tW), [$t\bar{t}H$]	POWHEG-BOX v2	PYTHIA 8	A14	NNLO+NNLL (NLO+NNLL) [NLO]
Higgs: ggF, (VBF, VH)	POWHEG-BOX v2	PYTHIA 8	AZNLO	NNLO (NNLO+NNLL)
$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$, $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$	MADGRAPH 2.6	PYTHIA 8	A14	NLO+NLL

the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ branching fractions change in the same way. Generated signal events were required to have at least three leptons, two of which were associated with a Z boson. Hadronically decaying τ -leptons were not considered by this three-lepton requirement for the $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ events. The $\tilde{\chi}_1^\pm$ were also required to decay via a Z boson in the $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ events to increase the number of events with a trilepton resonance. The inclusive production cross sections were calculated assuming mass-degenerate, wino-like $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$, as predicted by the $B-L$ RPV model [11], and were calculated at NLO in QCD with next-to-leading-logarithmic (NLL) corrections to the soft-gluon terms [62–66]. The cross sections and their uncertainties were derived from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales [52]. The inclusive cross sections for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ ($\tilde{\chi}_1^\pm \tilde{\chi}_1^0$) production at a center-of-mass energy of $\sqrt{s}=13$ TeV range from 11.6 ± 0.5 (22.7 ± 1.0) pb for masses of 100 GeV to 0.040 ± 0.006 (0.080 ± 0.013) fb for masses of 1500 GeV. Events from all generators were propagated through a full simulation of the ATLAS detector [67] using GEANT4 [68] to model the interactions of particles with the detector. A parameterized simulation of the ATLAS calorimeter [67] was used for faster detector simulation of signal, tW , and $t\bar{t}H$ processes and was found to be in agreement with the full simulation. The effect of multiple interactions in the same and neighboring bunch crossings (pileup) was modeled by overlaying simulated minimum-bias events onto each hard-scattering event.

5.4 Analysis Regions

Events which meet a set of kinematic requirements are said to fall into a *region* of phase space carved out by those requirements. Three types of regions will be utilized in this analysis. Signal regions (SR) are regions that have high signal purity and are the regions to which physics statements

on the discovery or exclusion of supersymmetric particles will be made from the final statistical analysis. Control regions (CR) are regions high in purity of the major analysis backgrounds used for background estimation, this is described in more detail in Section 5.5. Validation regions (VR) are regions where the backgrounds estimated from the CRs can be thoroughly validated before unblinding the data in the SRs. Technical kinematic selections of baseline objects used in this analysis are detailed in Appendix C.

5.4.1 Signal Regions

The selection algorithm begins by filtering the events into two main categories, events where there are exactly three light leptons, with two of those leptons forming a same flavor opposite sign (SFOS) pair with an invariant mass consistent with the mass of the Z , and events with four or more light leptons where again there is at least one SFOS Z candidate. This first category defines the three lepton signal region (SR3 ℓ), the three leptons are assumed to be from the $\tilde{\chi}_1^\pm$ decay. The second category has four or more leptons and there is substantial ambiguity in assigning three of these leptons to the chone decay. If a second boson candidate can be formed, either from a hadronically decaying boson (i.e. $W \rightarrow jj$ or $H \rightarrow b\bar{b}$) or from a second leptonic Z this then defines the fully reconstructed signal region (SRFR), where both wino masses are reconstructed. If not, this defines our four lepton region (SR4 ℓ), where we still only have a single $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ being reconstructed, as in SR3 ℓ , but extra care must be taken in the correct assignment of leptons to optimize sensitivity. This selection algorithm is shown schematically in Figure 5.7.

5.4.1.1 SR3 ℓ

The signal region requires exactly three light leptons, two of which form a SFOS pair within the Z mass window of [81.2 GeV, 101.2 GeV]. If there are two SFOS sign candidates the candidate that is closest to the Z mass is chosen. The trilepton mass $m_{Z\ell}$ is then calculated. Events in SR3 ℓ are expected to exhibit a significant E_T^{miss} in final states where the other $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ decays has neutrinos in the final state, either directly for $\tilde{\chi}_1^\pm \rightarrow W\nu$ and $\tilde{\chi}_1^0 \rightarrow H\nu$ or $Z\nu$, or from the subsequent decay of the W , Z or Higgs boson. A requirement of $E_T^{\text{miss}} > 150$ GeV reduces contamination from SM processes with no neutrinos, particularly Z +jets events that include a *fake* lepton. The SM WZ process with fully leptonic decays is also a significant contributor to SR3 ℓ , and contains a single neutrino from the W decay. The measured E_T^{miss} is therefore representative of the p_T of the neutrino, and the transverse mass m_T of the W boson can be reconstructed from the p_T of the

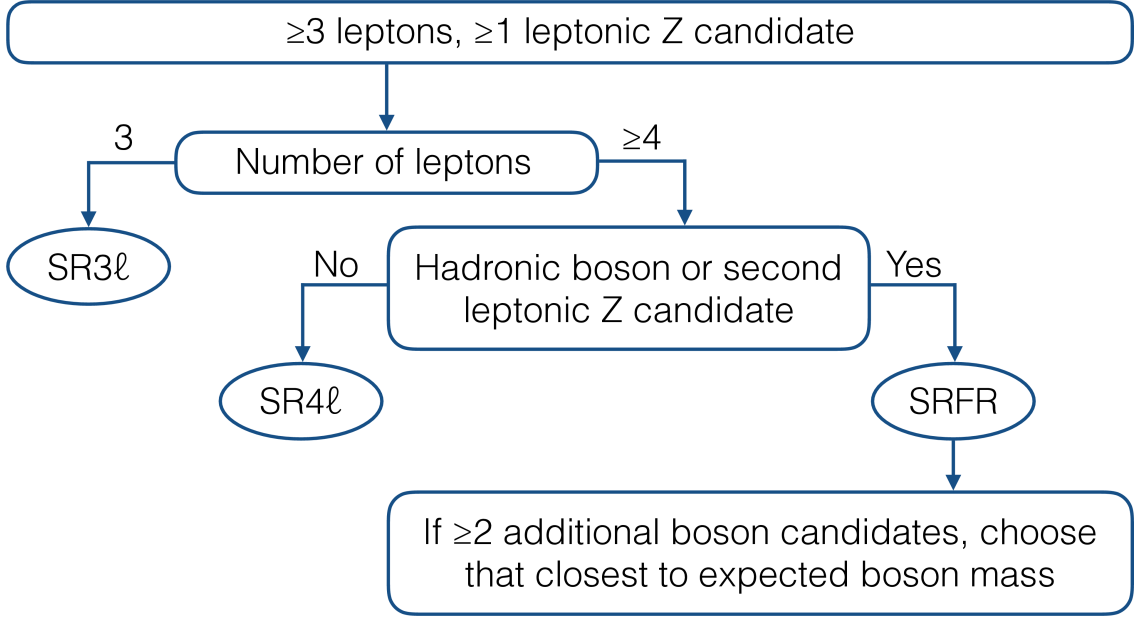


Figure 5.7: Flow chart of selection algorithm dictating separation of events in the three main signal regions [51]

lepton and the azimuthal separation $\Delta\phi$ between the lepton and p_T^{miss} , with

$$m_T(\ell, \nu) = \sqrt{2p_T^\ell E_T^{\text{miss}} [1 - \cos(\phi_\ell - \phi_{\text{miss}})]} \quad (5.2)$$

The m_T of a W boson has a kinematic edge at the W boson mass, and signal events in $\text{SR3}\ell$ usually produce lepton- E_T^{miss} pairings with a larger m_T . The minimum m_T of all lepton- E_T^{miss} pairings for which the other two leptons form a SFOS pair, defined as m_T^{min} , is required to be $m_T^{\text{min}} > 125$ GeV in $\text{SR3}\ell$. This definition allows WZ events to be rejected even if the incorrect SFOS pair was selected for the Z boson. Finally a cut in the angular separation between the highest p_T b -jets, $\Delta R(b_1, b_2) > 1.5$ is made to guarantee orthogonality to $t\bar{t}Z$ regions. This is discussed in greater detail in Section 5.4.2.4. The full definition of cuts for this region are shown in the region summary Table 5.3.

It is useful here to see how many events of a specific signal final state are accepted into the signal region when compared to the theoretically predicted number of events produced at the LHC for those processes. Composed of products of selections applied at every level of the analysis for a given mass and final state this acceptance is computed via Equation 5.3.

$$\mathcal{A}_{\text{SR}, i, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp} = \frac{n_{\text{SR}, i, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp}}{N_{\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp} \times F_{\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp}} \times \frac{\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp}}{\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp} + \sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_1^0}}, \quad \mathcal{A}_{\text{SR}, i, \tilde{\chi}_1^\pm \tilde{\chi}_1^0} = \frac{n_{\text{SR}, i, \tilde{\chi}_1^\pm \tilde{\chi}_1^0}}{N_{\tilde{\chi}_1^\pm \tilde{\chi}_1^0} \times F_{\tilde{\chi}_1^\pm \tilde{\chi}_1^0}} \times \frac{\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_1^0}}{\sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp} + \sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_1^0}} \quad (5.3)$$

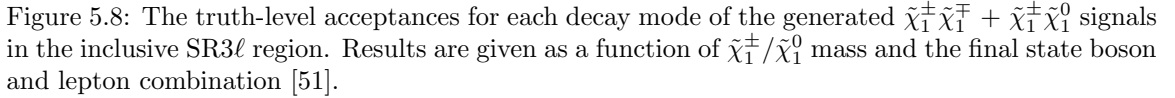
where the number of events selected in a signal region from a specific final state i in $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production is indicated by lower-case $n_{SR,i,\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp}$ and the *total* number of events generated for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production is indicated by $N_{\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp}$ ($\mathcal{O}(10^4)$), which is corrected by the filter efficiency (inverted) factor $F_{\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp}$ ($\mathcal{O}(10^2)$) determined by the MC generator in order to scale up to what would have been generated sans filters. The acceptance is then multiplied by the ratio of the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production cross section to the sum of the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production cross sections in order to show the relative importance of different final states from each production process. The similar formula for $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production is also shown. Finally, note that to find the number of events expected in a signal region from a specific final state, the corresponding acceptance factor can simply be multiplied by the total production cross section and the integrated luminosity.

Figure 5.8 shows the acceptances for each specific final state as a function of the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ mass from 100 GeV to 1200 GeV in steps of 50 GeV. Branching ratios to bosons are democratic as well as to each lepton flavor. The very first row with the label “All” row in the Figure is the total acceptance from all final states from both production processes. The acceptance for the three lepton signal region, SR3 ℓ , is shown in Figure 5.8. Having already explained that the top row is the total acceptance, note that approximately the upper third of the figure shows the acceptance for final states from the $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production process, while approximately the lower two-thirds shows the final states from the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production process. The largest acceptance for SR3 ℓ can indeed be seen to be from the final states that would be expected to have only three leptons ($Z\ell Z\nu$, $Z\ell H\nu$, $Z\ell W\nu$). The color scale is normalized to the largest acceptance from any single final state, which is 1.8×10^{-3} for the $\tilde{\chi}_1^\pm \tilde{\chi}_1^0 \rightarrow Z\ell Z\nu$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0 \rightarrow Z\mu Z\nu$ final states for a $\tilde{\chi}_1^\pm$ mass of 1200 GeV.

These figures are uploaded to the HEPData website associated with our analysis, which will allow reinterpretations in terms of future models.

5.4.1.2 SRFR

To target fully visible events, SRFR requires a fourth lepton and a second reconstructed Z , W , or Higgs boson. Pairs of jets are considered for the second boson if their invariant mass m_{jj} is consistent with that of a W or Z boson, with $71.2 < m_{jj} < 111.2$ GeV. If at least one of the jets is a b -jet, the m_{jj} requirement is loosened to $71.2 < m_{jj} < 150$ GeV to allow for Higgs boson decays. Additional SFOS lepton pairs are also considered for the second boson candidate in events with six or more leptons if their invariant mass is consistent with the Z boson mass, such that $81.2 < m_{\ell\ell} < 101.2$ GeV. If there are multiple candidates for the second boson, the pairing selected is that with


$$m_{Z\ell}^{\text{asym}} = \frac{|m_{Z\ell} - m_{\tilde{\chi},2}|}{m_{Z\ell} + m_{\tilde{\chi},2}} \quad (5.4)$$

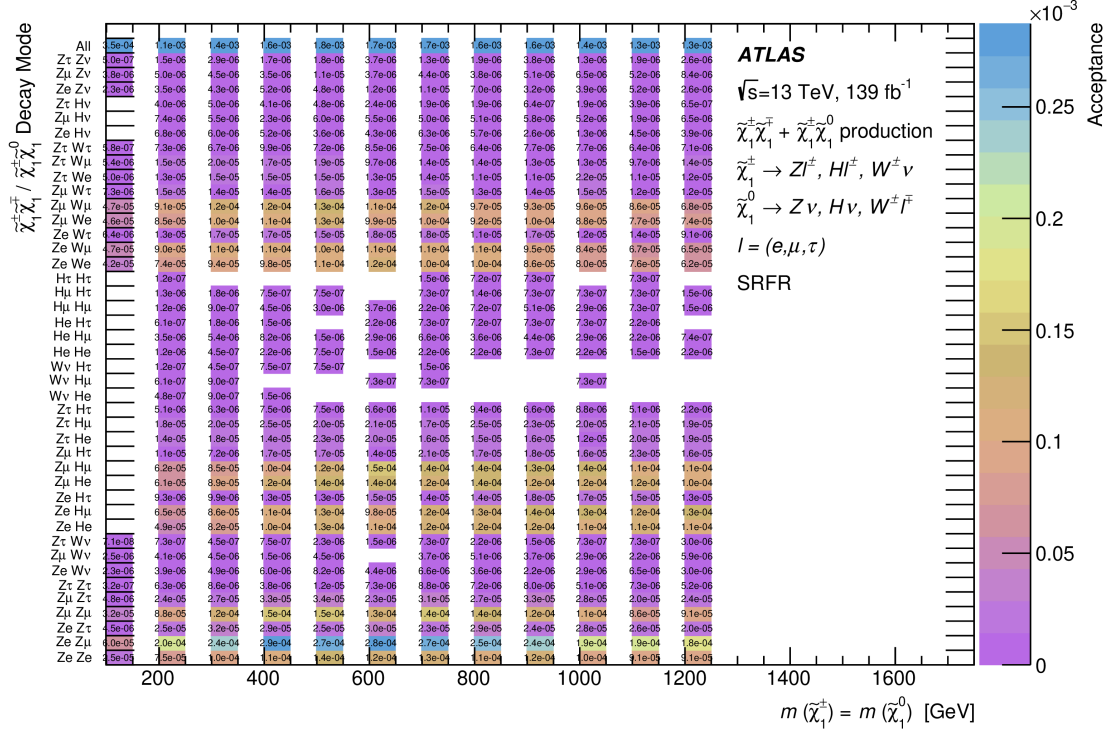


Figure 5.9: The truth-level acceptances for each decay mode of the generated $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ signals in the inclusive SRFR region. Results are given as a function of $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ mass and the final state boson and lepton combination [51].

Again a cut of $\Delta R(b_1, b_2) > 1.5$ is made to guarantee orthogonality to $t\bar{t}Z$ regions. The acceptance for SRFR is shown in Figure 5.9 and can be seen to be from the final states that are expected to have four or more leptons and two jets ($Z\ell W\ell$, $Z\ell H\ell$, $Z\ell Z\ell$). The color scale is normalized to the largest acceptance from any single final state, which is 0.29×10^{-3} for the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow Ze Z\mu$ final state for a $\tilde{\chi}_1^\pm$ mass of 400 GeV.

5.4.1.3 SR4 ℓ

The SR4 ℓ region targets events in which the decay of the second $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ includes one or more leptons but cannot be fully reconstructed, for example due to the presence of neutrinos in the final state. Events with four or more leptons that fail SRFR requirements are collected in SR4 ℓ . The optimal matching procedure to form the correct $m_{Z\ell}$ was found to be a combination of two separate methodologies that are chosen based on a threshold criterion value of L_T , the scalar sum of the p_T

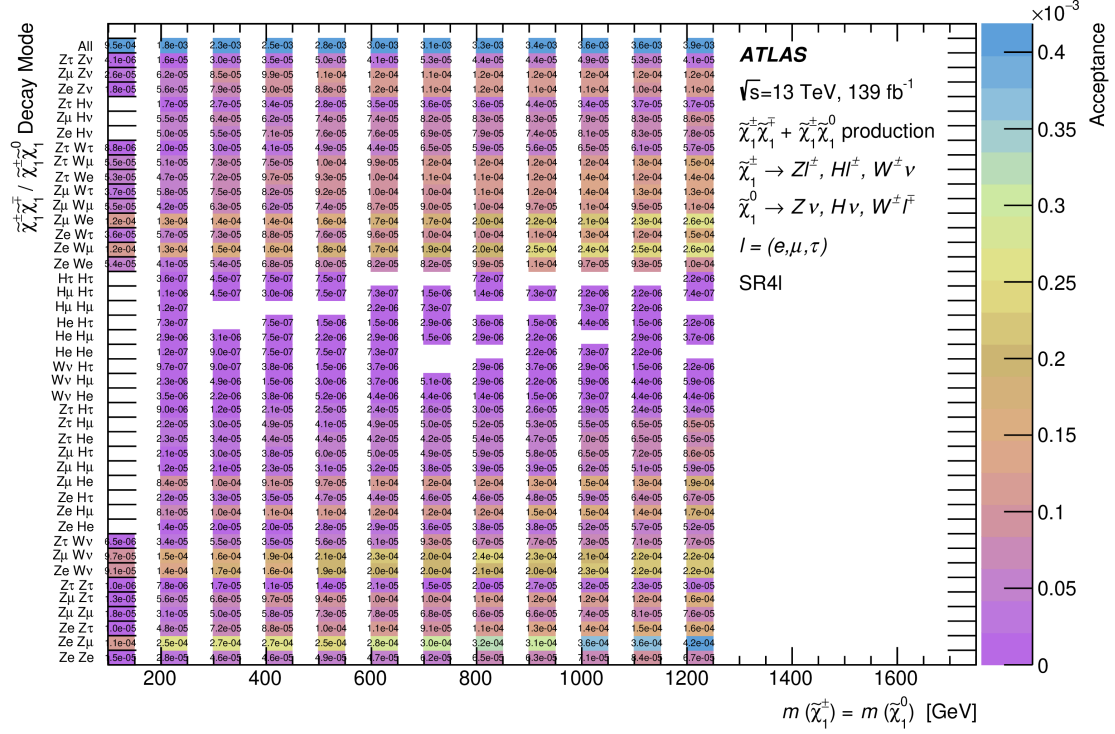


Figure 5.10: The truth-level acceptances for each decay mode of the generated $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ signals in the inclusive SR4 ℓ region. Results are given as a function of $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ mass and the final state boson and lepton combination [51].

of all the leptons in the event. Here L_T acts as a proxy for the $\tilde{\chi}_1^\pm$ mass. In the low mass regime where $L_T < 550$ GeV, the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ can often be produced with a sufficiently large momentum such that the charged lepton and Z boson are collimated, and $m_{Z\ell}$ is formed by choosing the lepton that is closest to the direction of the Z boson candidate, i.e. the lepton with the smallest ΔR to the Z boson. The second method targeting high-mass signals is used when $L_T \geq 550$ GeV, the $\tilde{\chi}_1^\pm$ decay products are often at a wide angle with respect to each other (back-to-back), and mispairings will produce a $m_{Z\ell}$ that is smaller than the $\tilde{\chi}_1^\pm$ mass. Therefore, the lepton that maximizes the reconstructed $m_{Z\ell}$ is chosen. Again a cut of $\Delta R(b_1, b_2) > 1.5$ is made to guarantee orthogonality to $t\bar{t}Z$ regions. The full definition of cuts for this region are shown in the region summary Table 5.3. The process specific acceptance plot in Figure 5.10 again shows good relative sensitivity to the wide range of final states with neutrinos. The color scale is normalized to the largest acceptance from any single final state, which is 0.42×10^{-3} for the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow Ze Z\mu$ final state for a $\tilde{\chi}_1^\pm$ mass of 1200 GeV.

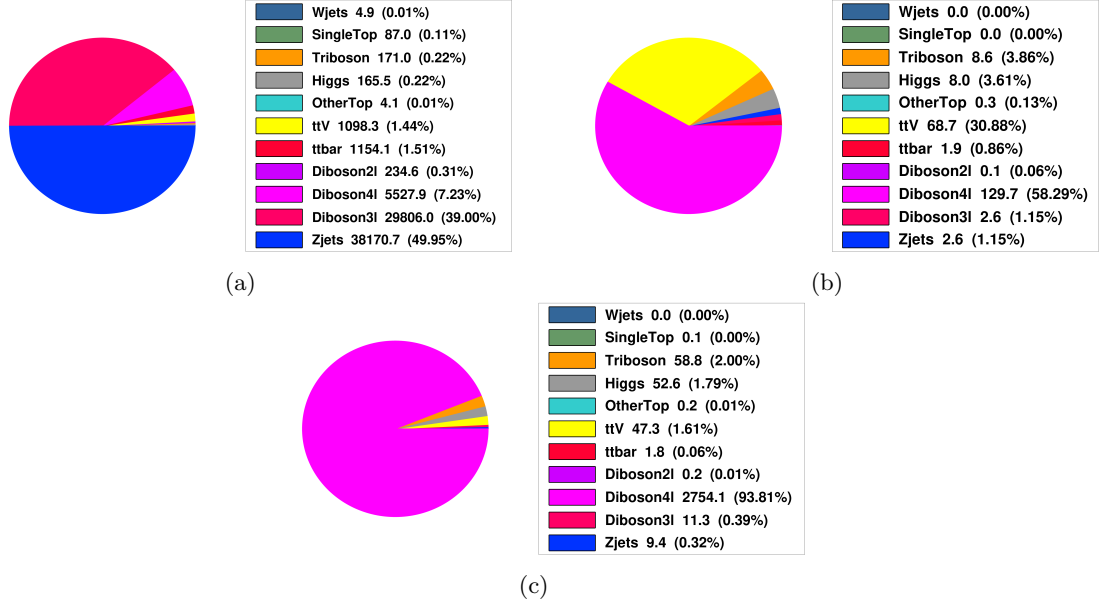


Figure 5.11: Expected yields from simulation for various background processes with (a) three leptons, four leptons (b) with and (c) without second boson candidate. Note that the kinematic requirements for the signal regions are not applied here.

5.4.2 Background Estimation and Validation

As cursorily stated in Section 5.3 the dominant backgrounds that contribute in the signal regions are WZ , ZZ , $t\bar{t}Z$, and Z +jets. Just how dominant is made clear from Figure 5.11, which shows the relative background contributions estimate from simulation for events with three leptons, and for events with four leptons with and without a second boson candidate. The additional region-specific kinematic requirements have not yet been applied here. Note that in this figure, the many diboson processes are classified by the number of charged leptons in the final state. Note that WZ is the dominant diboson process with three leptons (classified as **Diboson3l**), and ZZ is the dominant diboson process with four leptons (classified as **Diboson4l**). So in order to be confident in our ultimate background estimation it becomes pertinent to employ more robust techniques beyond simply taking yields directly from MC for these major players. The WZ , ZZ , and $t\bar{t}Z$ have Z bosons with leptonic decays and additional leptons, these are treated the same methodologically by way of dedicated orthogonal control and validation regions which are high in purity of the relevant background. The remaining large background, Z +jets, however is largely contributing by the misidentification of a jet as a lepton and is handled by a data-driven “fake factor” method.

5.4.2.1 Handling Backgrounds: *fake* Leptons

As it is required for all regions, the background estimate from fake-leptons will be described first. In this analysis *fake*-leptons or “*fakes*” are defined as misidentified prompt (light) leptons. Or in other words any event object that is identified as prompt light lepton that is *not* a prompt light lepton, is a *fake*. It is therefore important to determine the rate at which this misidentification occurs in all relevant kinematic regions. The most relevant sources for this analysis include the in-flight decays of heavy-flavor hadrons (HF) and misidentified light-flavor jets or in-flight decays of pions and kaons (LF). The pair production of two electrons from the conversion of a prompt photon (Conv) is also considered a *fake*-lepton process but makes a minor contribution. In this analysis the relevant *fake* processes (and their sources) are Z +jets (LF, HF) and $t\bar{t}$ (HF) in the three-lepton regions and WZ (LF) and ZZ (LF, Conv) in the four-lepton regions, with SRFR also having a large contribution from $t\bar{t}Z$ (HF). Due to the difficult MC modeling made by the many sources of fake-lepton processes, each of which is kinematically different and provides a relative contribution to the background estimate that is dependent on the analysis phase-space, the approach that is used for estimating this background is a data-driven fake-factor method.

To measure the *fake* factors, a region enriched in Z +jets type fake events is defined, CRFake. The CRFake region sets itself apart from other to-be-defined regions in that it is not directly included in the fit, but is used to derive the *fake*-lepton estimation in each analysis region. Events in this region are selected by requiring two signal leptons that form an SFOS pair and with an invariant mass within 10 GeV of the Z boson mass. One of the two signal leptons is required to have fired a single-lepton trigger, thus ensuring no selection bias from *fake* leptons. To enhance the Z +jets purity and reduce prompt-lepton event contamination from the WZ process, CRFake requires $E_T^{\text{miss}} < 30$ GeV and $m_T < 30$ GeV. A third, unpaired baseline lepton is also required in the event and is designated as the *fake* candidate. A requirement on the trilepton invariant mass of $m_{3\ell} > 105$ GeV reduces contamination from the $Z \rightarrow 4\ell$ process. This region is further split into so called nom-ID and anti-ID events. Where nom-ID refers to events in which the *fake* candidate passes all nominal lepton ID criteria, and anti-ID refers to events where the *fake* candidate passes all but at least one of three criteria: lepton ID requirements, isolation, or the impact parameter criteria. The expected contamination by prompt-lepton events from WZ and ZZ processes, as estimated from MC simulation, is subtracted from both populations so that they better represent the yields from *fake*-lepton sources. From these two types of events we can define our *fake* factors by Equation 5.5.

$$F(i) = \frac{N_{\text{ID, data}}(i) - N_{\text{ID, prompt MC}}(i)}{N_{\text{antiID, data}}(i) - N_{\text{antiID, prompt MC}}(i)} \quad (5.5)$$

Where the fake factor is parameterized as a function of specific kinematic quantity i . Several parameterizations were studied and the one best suited to this phase space was determined to be the variable p_T^{cone} , which is defined as the scalar sum of the lepton p_T and the track isolation p_T^{iso} , that is the scalar sum of the p_T of all the tracks in the given lepton’s isolation cone. In general, p_T^{cone} provides a better handle on the

momentum of the underlying jet giving rise to the fake/non-prompt lepton. Three p_T^{iso} working points are employed depending of flavor and lepton p_T as seen in Equation 5.6.

$$p_T^{\text{cone}} = \begin{cases} p_T + \text{ptvarcone20-TightTTVA_pt1000}, & \text{electron} \\ p_T + \text{ptvarcone30-TightTTVA_pt1000}, & \text{muon w/ } p_T < 50 \text{ GeV} \\ p_T + \text{ptcone20-TightTTVA_pt1000}, & \text{muon w/ } p_T > 50 \text{ GeV} \end{cases} \quad (5.6)$$

Applying the *fake* factors then involves defining an additional *anti-ID* region for each analysis region where the *fake* factors are to be applied. This region meets the exact conditions of its corresponding region with the exception that at least one signal lepton is replaced with an anti-ID lepton. The *fake* factor can then be applied to the anti-ID region to determine the *fake* estimate for the nominal region. The validation of the *fake* factors takes place in the orthogonal region of VRFake, an intermediate E_T^{miss} region designed as to move closer to the other analysis regions while maintaining Z +jets purity. The full region definition is given in the summary Table 5.3.

5.4.2.2 Handling Backgrounds: WZ

With the WZ process being the dominant background in the three lepton region, dedicated control and validation regions are designed to constrain its normalization, a method described later in Section 5.5. Natural discrimination for this background with a $W \rightarrow \ell\nu$ decay is provided by the missing transverse energy from the neutrino and a kinematic variable that targets the W boson mass. For this we look to m_T^{min} (Equation 5.7), which inherits from the standard definition of m_T in Equation 5.2, defined as the minimization of m_T when considering all leptons in the event while still always being able to form a SFOS pair.

$$m_T^{\text{min}} = \min(m_T(\ell_i, \nu)), \quad i = 1, 2, 3 \quad (5.7)$$

Where i indexes the three leptons. The m_T^{min} is chosen over the standard m_T as the main discriminator in the WZ regions because while the Z reconstruction efficiency is high ($>95\%$) for signal, the SM WZ background can have an off-shell Z and a selection which matches leptons to form a mass closest to the nominal Z pole mass may not choose the correct leptons from an off-shell Z . It was found that for signal m_T and m_T^{min} are often the same quantity as expected from the high reconstruction efficiency, but for background it is found that m_T^{min} is often much lower than m_T and is more consistent with the kinematic edge at the W mass. Again a cut of $\Delta R(b_1, b_2) > 1.5$ is made to guarantee orthogonality to $t\bar{t}Z$ regions. The full definition of cuts for the control region for WZ and two associated validation regions that check extrapolation in m_T^{min} and missing et are shown in the region summary Table 5.3 and illustrated in Figure 5.12. The expected yields in the control and validation regions for WZ are shown in Figure 5.13. The m_T^{min} and E_T^{miss} distributions are shown in Figure 5.20, where good agreement is seen between data and the post-fit background estimates.

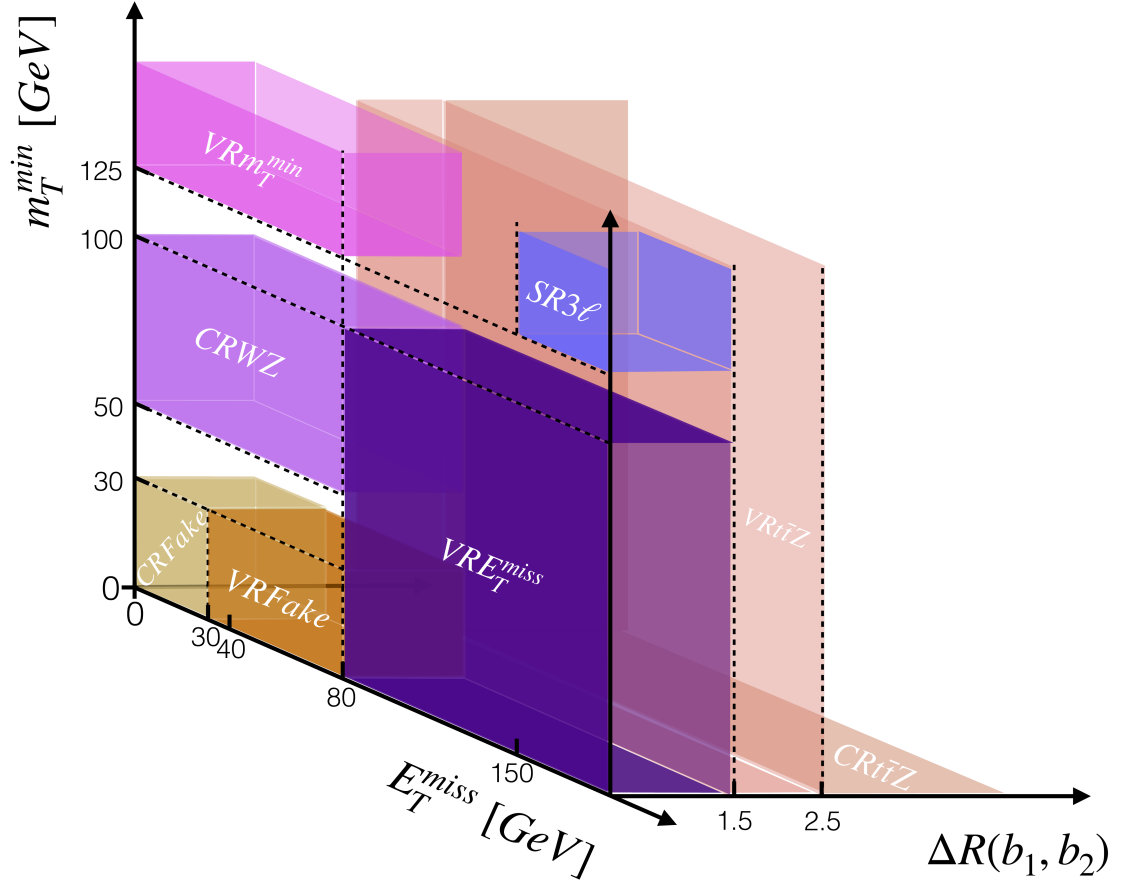


Figure 5.12: Graphic depicting the orthogonality of the three lepton regions. Boxes without a side are unbounded in that direction in that variable. The full region definitions are summarized in Table 5.3

5.4.2.3 Handling Backgrounds: ZZ

Regions designed to constrain ZZ , which dominates both the four lepton regions $SR4\ell$ and $SRFR$, are required to have two SFOS lepton pairs. This single requirement already gives a very pure ZZ region. The region is then further subdivided into CR and VR regions differentiated by the requirement on the mass window of the second reconstructed Z mass, $m_{l,2}$. The stricter requirement of the two is a window within 5 GeV of the Z mass which defines the control region $CRZZ$. For $VRZZ$ a looser window requirement is defined within 20 GeV, which does not include the $CRZZ$ window in order to maintain orthogonality. The expected yields in the control and validation regions for ZZ are shown in Figure 5.15. The $m_{l,2}$ distribution which contains both $CRZZ$ and $VRZZ$ can be seen in Figure 5.19d where good agreement is seen between data and the post-fit background estimates. Events for which one Z decays into a pair of τ -leptons that both

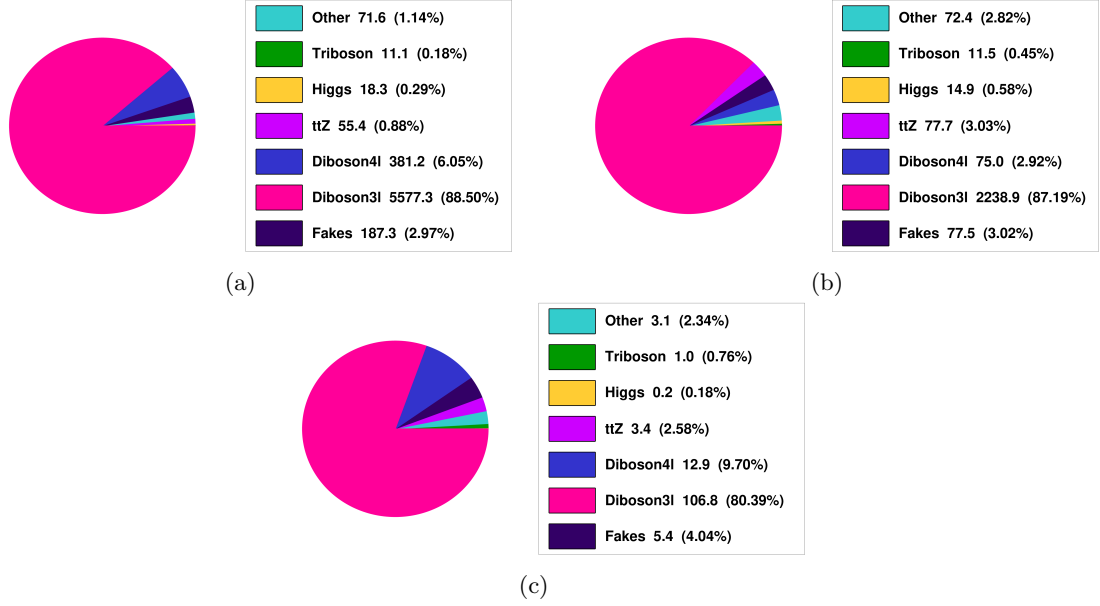


Figure 5.13: Expected yields of each background in $CRWZ$, VRE_T^{miss} and VRm_T^{min} , assuming 140 fb^{-1} . No normalization factors are applied.

then subsequently decay leptonically are included in this validation region. Good modeling in the three-lepton regions is also expected for such ZZ events when only one τ -lepton decays leptonically, although this process is strongly suppressed by the E_T^{miss} and m_T^{min} requirements. Again a cut of $\Delta R(b_1, b_2) > 1.5$ is made to guarantee orthogonality to $t\bar{t}Z$ regions. The full definition of cuts for this region are shown in the region summary Table 5.3 and illustrated in Figure 5.14.

5.4.2.4 Handling Backgrounds: $t\bar{t}Z$

The last dominant background, $t\bar{t}Z$, contributes via a leptonically decaying Z and two top quarks in which one or both decay leptonically. While $t\bar{t}Z$ is primarily a major background in SRFR the it is useful to construct the region such that it includes three lepton events as well in order to improve statistics in the region as well as to be able to extrapolate over number of leptons in the fit. Many variations of cuts on standard variables such as E_T^{miss} and b -jet multiplicity were studied but the underlying physics of $t\bar{t}$ decays, which heavily favor final states with two b -quarks, resulted in the best separation with reasonable CR purity and acceptable statistics. Thus, a requirement of $N_{b\text{-jet}} \geq 2$ is imposed along with a $4\ell 2Z$ veto in order to reduce contributions from ZZ . We can then go further by taking advantage of the expected large angular separation of the two b -quarks coming from $t\bar{t}$ to further purify the $t\bar{t}Z$ regions as well as to apply a blanket orthogonality requirement against all other regions. To get a handle on this separation the ΔR between the two highest $p_T b$ -tagged jets in the event is defined as the variable $\Delta R(b_1, b_2)$. Figure 5.16 shows the.

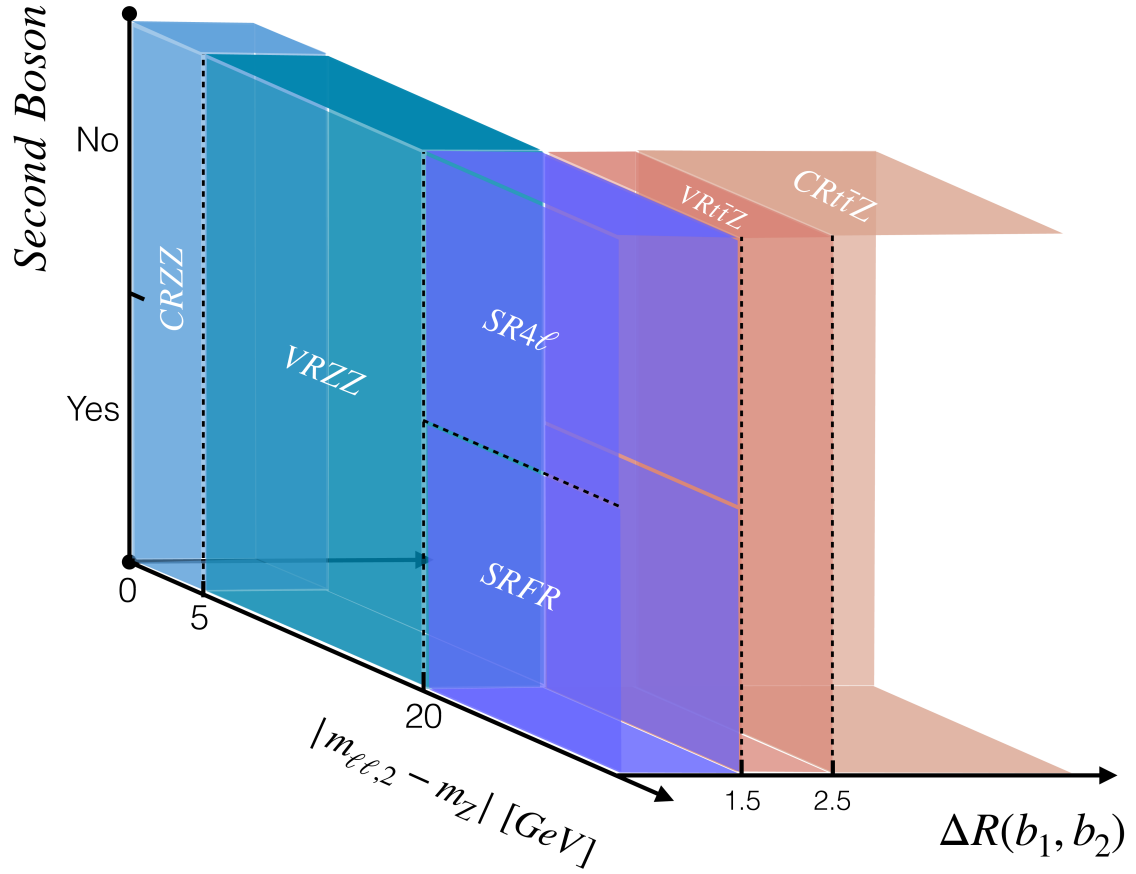


Figure 5.14: Graphic depicting the orthogonality of the four lepton regions. Boxes without a side are unbounded in that direction in that variable. The full region definitions are summarized in Table 5.3

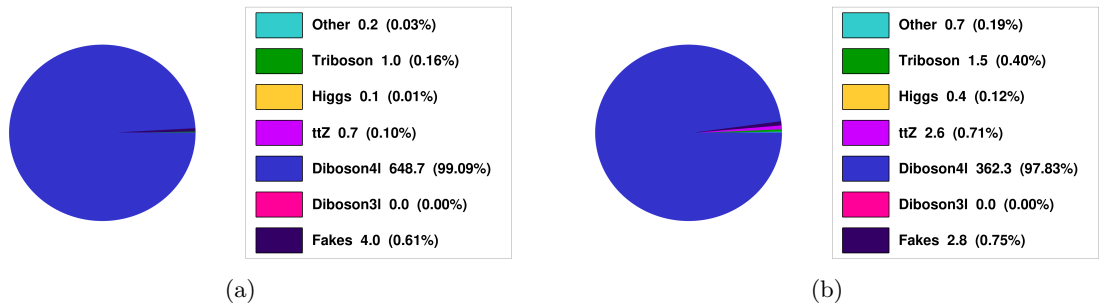


Figure 5.15: Expected yields of each background in CRZZ and VRZZ, assuming 140 fb^{-1} . No normalization factors are applied.

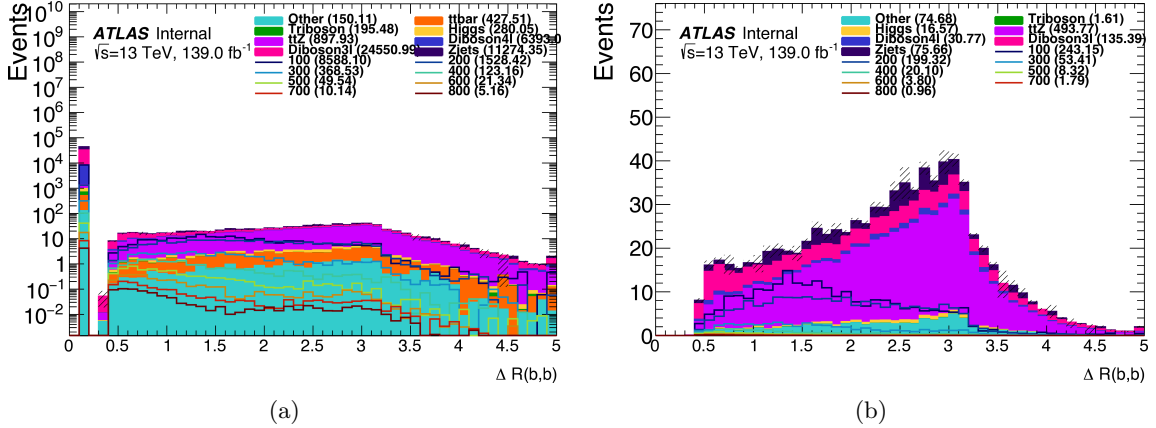


Figure 5.16: Expected distribution in simulation for background processes and signal processes of the angular separation between two b -tagged jets for events with three or more leptons (a) on a log scale where events without at least 2 b -jets have been assigned a value of 0.1, and (b) on a linear scale for events with at least 2 b -jets.

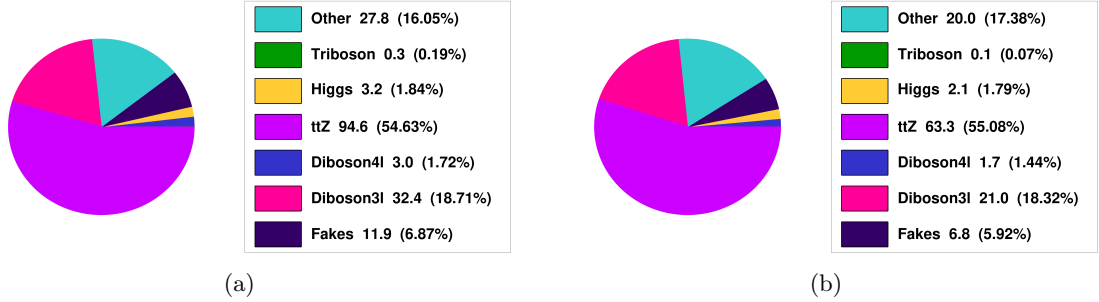


Figure 5.17: Expected yields of each background in $CRt\bar{t}Z$ and $VRt\bar{t}Z$, assuming 140 fb^{-1} . No normalization factors are applied.

expected distribution from background processes as well as a few representative signal points in $\Delta R(b_1, b_2)$ at pre-selection, i.e. the baseline selection with three or more leptons. From the linear plot in Figure 5.16b it is clear that $t\bar{t}Z$ events favor a large angular separation between b -jets and the peak at $\Delta R(b_1, b_2) \approx \pi$ is consistent with back-to-back production of $t\bar{t}$. The relative high purity of $t\bar{t}Z$ events through out this distribution invites us to compose a CR and VR. Cuts of $1.5 < \Delta R(b_1, b_2) \leq 2.5$ and $\Delta R(b_1, b_2) \geq 2.5$ were found to be optimal for $VRt\bar{t}Z$ and $CRt\bar{t}Z$ respectively. While the region of $\Delta R(b_1, b_2) \leq 1.5$ is reserved for all other regions and therefore imposes orthogonality everywhere. Yields in $VRt\bar{t}Z$ and $CRt\bar{t}Z$ are shown in Figure 5.17. The full definition of cuts for this region are shown in the region summary Table 5.3 and illustrated in Figures 5.12 and 5.14.

Region	N_{lep}	$N_{\text{b-jet}}$	$\Delta R(b, b)^\dagger$	$E_{\text{T}}^{\text{miss}}$ [GeV]	$m_{\text{T}}^{\text{min}}$ [GeV]	Second boson	$4\ell 2Z$; $ m_{\ell\ell} - m_Z $ [GeV]	$m_{Z\ell}$ asymmetry
SR3 ℓ	3	-	<1.5	>150	>125	-	-	-
CRWZ	3	-	<1.5	<80	[50,100]	-	-	-
VR $E_{\text{T}}^{\text{miss}}$	3	-	<1.5	>80	<100	-	-	-
VR $m_{\text{T}}^{\text{min}}$	3	-	<1.5	<80	>125	-	-	-
CRFake	3	-	<1.5	<30	<30	-	-	-
VRFake	3	-	<1.5	[30,80]	<30.	-	-	-
CR $t\bar{t}Z$	≥ 3	≥ 2	>2.5	>40	-	-	veto; <20	-
VR $t\bar{t}Z$	≥ 3	≥ 2	[1.5,2.5]	>40	-	-	veto; <20	-
SR4 ℓ	≥ 4	-	<1.5	>80*	-	No	veto; <20	-
SRFR	≥ 4	-	<1.5	-	-	Yes	veto; <20	< 0.1
CRZZ	4	-	<1.5	-	-	-	require; <5	-
VRZZ	4	-	<1.5	-	-	-	require; [5,20]	-

Table 5.3: Kinematic selections for each region used in this analysis. All regions require a SFOS pair of light leptons with an invariant mass between 81.2 GeV and 101.2 GeV and a third light lepton, the invariant mass of which ($m_{Z\ell}$) must be at least 90 GeV. The dagger ($\dagger$) indicates that this cut is only applied for events with at least 2 b-jets. The “second boson” requirement is shown to make the orthogonality between SR4 ℓ and SRFR explicit. This second boson is usually reconstructed from two jets, but it can also be reconstructed from two SFOS leptons, with an invariant mass requirement that changes depending on the objects used, as described in 5.4.1.2. This is distinct from the $4\ell 2Z$ criterion which only applies to a leptonic Z. The asterisk (*) in the SR4 ℓ $E_{\text{T}}^{\text{miss}}$ cut indicates that this cut is only applied for events with two pairs of SF leptons. This condition is also referred to as $E_{\text{T}}^{\text{miss,SF}}$.

5.5 Statistical Treatment

In order to make physics statements this analysis compares the goodness of fit of a statistical model to data via a fit based on a profile likelihood test statistic which is performed on all CRs and SRs simultaneously using the **HistFitter** package. This underlying statistical technique and the overall methodology is described in great detail in Appendix B.

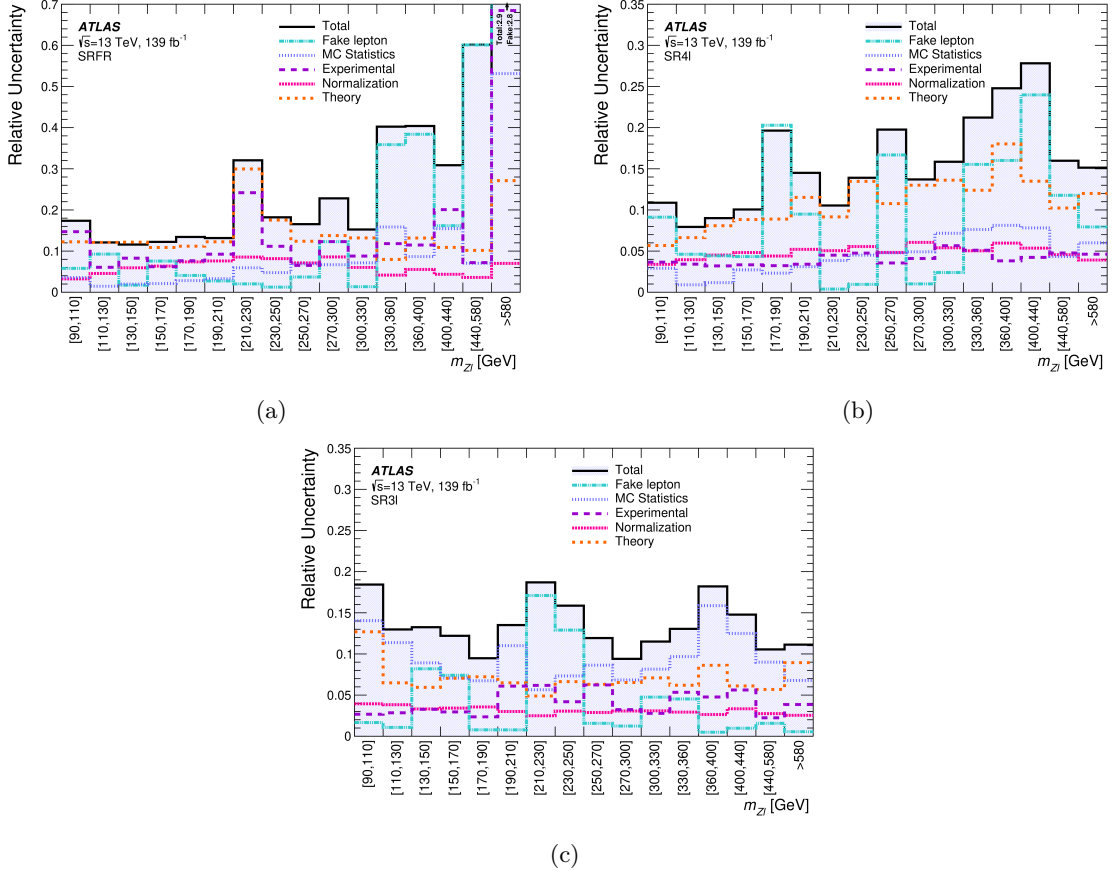


Figure 5.18: The relative uncertainties in the post-fit SM background prediction as a function of $m_{Z\ell}$ from the background-only fit for the (top left) SRFR, (top right) SR4 ℓ , and (bottom) SR3 ℓ regions. The $m_{Z\ell}$ binning (Eq. (B.1)) is the same as that used in the fit. Sources of uncertainty are grouped into experimental, theoretical, and MC statistical categories. Separate categories are provided for the *fake* backgrounds and for the normalization procedure of the major WZ , ZZ , and $t\bar{t}Z$ backgrounds. The individual uncertainties can be correlated and do not necessarily contribute in quadrature to the total uncertainty [51]

5.5.1 Systematic Uncertainties

Uncertainties in the expected signal and background yields account for the statistical uncertainties of the MC samples, the experimental systematic uncertainties in the detector measurements, and the theoretical systematic uncertainties of the MC simulation modeling. The uncertainties of the major backgrounds normalized in the CRs reflect the limited statistical precision of the CRs and the systematic uncertainties in the extrapolation to the signal regions, and an additional uncertainty in the normalization factor from the combined fit is included. Systematic uncertainties are treated as Gaussian nuisance parameters in the likelihood while the statistical uncertainties of the MC samples are treated as Poisson nuisance parameters. A

summary of the background uncertainties is shown in Figure 5.18. Individual uncertainties can be correlated or anti-correlated, for example between an uncertainty on a major background and the uncertainty on the CR-to-SR normalization procedure for that background. Bin-to-bin fluctuations in the uncertainty of the *fake* background estimation reflect the small anti-ID population and the conservative uncertainties applied when no anti-ID events are seen in the data. The effect of localized fluctuations in one SR is limited as all three SRs contribute to the overall sensitivity. A relative uncertainty of 2.9 is seen in the last $m_{Z\ell}$ bin of SRFR and is driven by a relative uncertainty of 2.8 in the *fake* estimation, reflecting the small post-fit background expectation. A breakdown of the types of uncertainties is given in the following sections

5.5.1.1 MC Statistics

The nominal statistical uncertainty on the number of MC events generated makes up this category.

5.5.1.2 Experimental Uncertainties

Experimental uncertainties in the detector measurements reflect the accuracy of the kinematic measurements of jets, electrons, muons, and E_T^{miss} . Varying the scale or resolution of the energy or p_T of objects within the uncertainties can cause the migration of events between $m_{Z\ell}$ bins or affect the inclusion of an event in an analysis region. The jet energy scale and resolution uncertainties [69, 70] are a large component of the experimental uncertainty. They are derived as a function of jet p_T and η and account for the flavor and pileup dependencies of the detector energy measurement. Similar scale and resolution uncertainties are included for electrons [36] and muons [71]. These per-object uncertainties are propagated through the E_T^{miss} calculation, with additional uncertainties accounting for the scale and resolution of the E_T^{miss} soft term [72]. Additional experimental uncertainties account for the mismodeling in MC simulation of observables related to the detection of leptons and jets. They include the efficiency of the triggering, identification, reconstruction, and isolation requirements of electrons [36] and muons [71]. They also include the identification and rejection of pileup jets by the jet vertex tagger [73] and the identification of b -jets by the flavor-tagging algorithm [74]. The experimental uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [75], obtained primarily using the luminosity measurements of the LUCID-2 detector [76]. Unless stated otherwise, each experimental uncertainty is treated as fully correlated across the analysis regions.

5.5.1.3 Theoretical Uncertainties

Each theoretical uncertainty is derived as the relative yield between an analysis region and a control region and is treated as uncorrelated across analysis regions. Theoretical uncertainties in the shape of the major diboson, triboson, and $t\bar{t}Z$ backgrounds are derived using MC simulation with varied generator parameters. For the other minor backgrounds a conservative 20% uncertainty is assumed. This value is larger than is

typically expected for the minor background processes and the choice has a negligible effect on the final results due to the small contributions of these backgrounds. Uncertainties due to the choice of QCD renormalization and factorization scales [77] are assessed by varying the relevant generator parameters up and down by a factor of two around the nominal values, allowing for both independent and correlated variations of the two scales but prohibiting anti-correlated variations. Each QCD variation is kept separate and is treated as correlated across analysis regions. An uncertainty of 1% due to the chosen value of the strong coupling constant α_S is assessed by varying α_S by ± 0.001 in the generator parameter settings. Uncertainties related to the choice of PDF sets, CT14NNLO [78] or MMHT2014NNLO [79], are derived by taking the envelope of the variation in event yield of 100 propagated uncertainties [80].

Additional theoretical uncertainties are assessed for the major backgrounds. These are related to assumptions made in the event generators and PS models, which can affect both the event kinematics and the cross section of the physics process. For the diboson backgrounds, the SHERPA parameters related to the PS matching scale and resummation scale are varied up and down by a factor of two around the nominal values, and an alternative recoil scheme is studied. For the $t\bar{t}Z$ background, the uncertainties in the hard scatter and in the PS are derived through a comparison with the SHERPA and MADGRAPH5_aMC@NLO +HERWIG7 predictions, respectively. Additional uncertainties in the amount of initial-state radiation (ISR) in the $t\bar{t}Z$ background are assessed by varying the related generator parameters.

For the signal samples, theoretical uncertainties in the cross section are applied, ranging from 4.5% at 100 GeV to 16% at 1500 GeV. Uncertainties related to the QCD scale, PS matching scale, and amount of ISR are derived by varying the related generator parameters of the A14 tune [81].

5.5.1.4 Fake Lepton Uncertainties

Alternative parameterizations to the nominal p_T^{cone} are used to define a systematic uncertainty due to the choice of p_T^{cone} [51]. The statistical uncertainty of each *fake* factor is propagated to an uncertainty in the yield. An uncertainty due to the prompt-lepton subtraction is estimated by varying the subtracted yields of the WZ and ZZ MC simulations up and down by 5%, corresponding to their cross-section uncertainties [82]. For any $m_{Z\ell}$ bin of an SR that does not have an anti-ID event, and therefore has a prediction of zero *fake*-lepton events, an uncertainty is applied corresponding to a yield of 0.32 *fake* events. This represents the largest *fake* estimate possible given a 1 sigma upward fluctuation in the anti-ID event yield.

5.5.1.5 Normalization Uncertainties

These are the uncertainties on the normalization factors $\mu_{t\bar{t}Z}$, μ_{WZ} , and μ_{ZZ} and are determined from the fit and dominated by the statistics in the control regions.

5.5.2 Fit Configuration

The **HistFitter** package [83], version 0.62.0, is used to perform the simultaneous fit of the control and signal regions. **HistFitter** is a flexible statistical tool used in many ATLAS SUSY analyses. For each process, a **ROOT** [84] tree is created containing all the kinematic quantities and weights used in the analysis. The signal, control, and validation regions are then defined within the **HistFitter** configuration file to select events which are to be considered.

5.5.3 Background-Only Fit

The first fit we will consider is the so called “background only fit.” This fit’s purpose is two fold, and takes on two different flavors as a result. The first flavor includes only the control regions, this is the very first fit done in order done to verify that the background prediction can model the data in the CRs and VRs, where the signal contamination in is negligible, such that the SRs can be unblinded. Once this initial fit is done, and an initial set of parameters estimated, the SRs are unblinded. Only after unblinding can the second flavor of the fit be performed. In this fit *both* CRs and SRs are all fit simultaneously in order to make physics statements. This fit results in the final values for the normalization factors which are shown in Table 5.4. For both flavors of this fit μ_{sig} in Equation B.2 is set to zero. For the CR only we of course take i to be $i = CRt\bar{t}Z, CRWZ, CRZZ$ and for the CR+SR fit i remains unchanged from Equation B.2. Several kinematic distributions are shown for the CRs and VRs post-fit in Figure 5.19. The data-MC agreement for the yields in the CRs (pre-fit) and VRs (post-fit) is shown in Figure 5.20. The data agree well with the post-fit background estimates in all validation regions, giving confidence in the validity of the post-fit background estimation in the SRs. A slight overestimation of almost 2σ is seen in VRE_T^{miss} , and no features are seen in the comparison of data and the post-fit background estimates in the $m_{Z\ell}$ (Figure 5.21) or E_T^{miss} (Figure 5.19c) distributions of VRE_T^{miss} . A minor excess of data over the background estimation of 1.3σ is seen in $VRt\bar{t}Z$, and good agreement is seen in the shape of the relevant $m_{Z\ell}$ (Figure 5.21) and $\Delta R(b_1, b_2)$ (Figure 5.19e) distributions.

μ_{WZ}	1.01 ± 0.03
μ_{ZZ}	1.12 ± 0.06
$\mu_{t\bar{t}Z}$	1.05 ± 0.18

Table 5.4: MC normalization factors for major backgrounds.

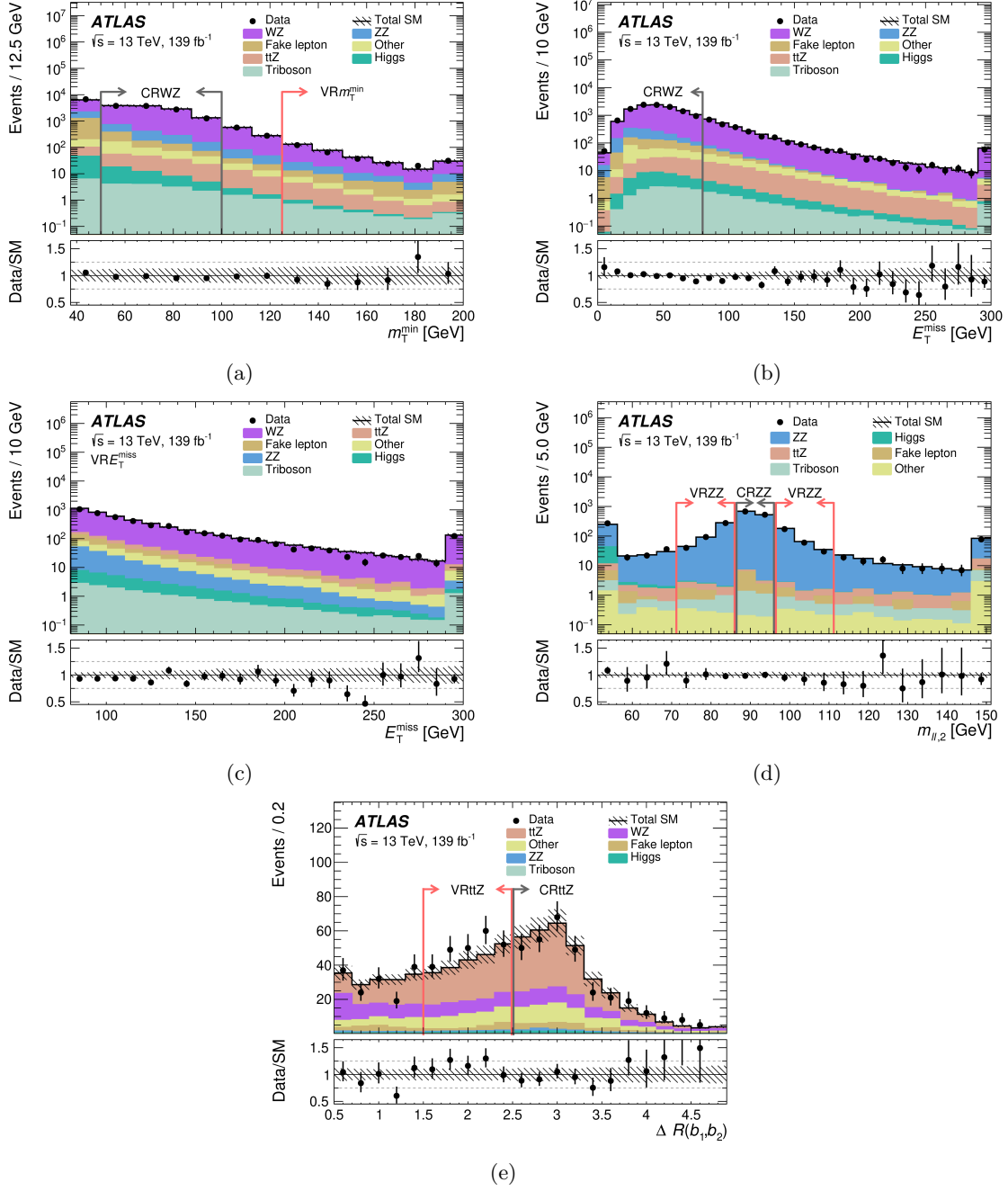


Figure 5.19: Distributions of the data and post-fit background in the CRs and VRs that are relevant in the extrapolation to the SRs, including (top left) $m_T^{\min}$ in CRWZ and VR $m_T^{\min}$, (top right) E_T^{miss} in CRWZ, (middle left) E_T^{miss} in VRE E_T^{miss} , (middle right) $m_{l,l,2}$ in CRZZ and VRZZ, and (bottom) $\Delta R(b_1, b_2)$ in CR ttZ and VR ttZ . Black (red) arrows indicate the CR (VR) selection on the variable shown, with all other region selections applied [51].

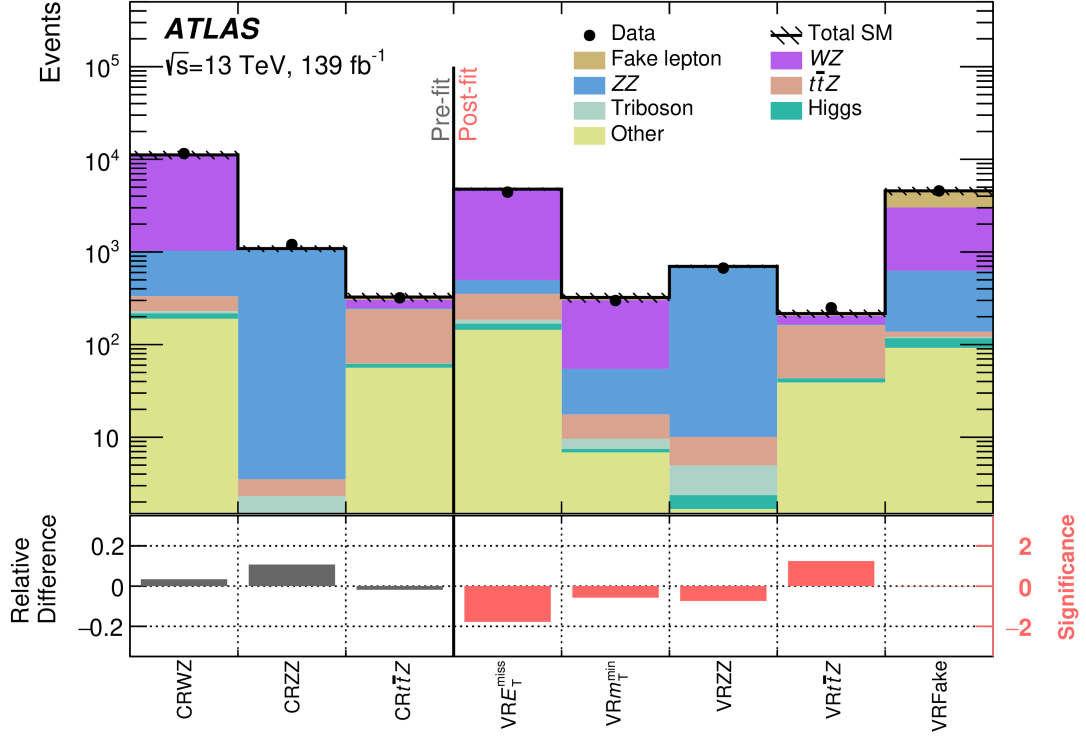


Figure 5.20: The observed data and the SM background expectation in the CRs (pre-fit) and VRs (post-fit). The “Other” category consists mostly of the tWZ , $t\bar{t}W$, and tZ processes. The hatched bands indicate the combined theoretical, experimental, and MC statistical uncertainties in the background prediction. The bottom panel shows the fractional difference between the observed data and expected yields for the CRs and the significance of the difference for the VRs, computed following the profile likelihood method described in Sections B.2 and B.2.2.

5.5.4 Model Independent Fit

This fit considers one SR at a time, to avoid any assumption on relative signal contributions across SRs and $m_{Z\ell}$ bins. Hence, this analysis has 48 discovery regions that are fit one-by-one in separate fits, corresponding to the 16 bins in each of the three SR types.

5.5.5 Model Dependent Fit

The second type of fit now includes the signal model contributions to the MC estimate. Each bin of the $m_{Z\ell}$ distribution in each SR is fit simultaneously. By re-weighting the truth decays of the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$, a scan over model branching ratio schemas, in addition to the nominal mass scan, is done to set limits for a large swath of model parameter space. The granularity and technical specifications of this scan is described in

detail in Section 5.6.3.

5.6 Results

The data are compared with the post-fit background expectations, derived from a background-only profile likelihood fit of all CRs and SRs simultaneously as described in Section 5.5, and no significant excess is observed. The VRs, shown in Figure 5.20, demonstrate good modeling of the post-fit background expectation in regions kinematically similar to the SRs and for a variety of observables, validating the background-estimation technique. The observed and expected numbers of events in SRFR, SR4 ℓ , and SR3 ℓ are given in Table 5.5 inclusively and separated by the lepton flavor (electron or muon) of what would be the direct lepton from the $\tilde{\chi}_1^\pm \rightarrow Z\ell$ decay. The background expectation and uncertainty are further split into contributions from each category of SM processes. Separate fits are performed for each flavor channel and for the inclusive channel, and therefore the predicted yields in the e and μ channels may not necessarily add to the inclusive yield. Note that for the SRFR region, the electron and muon channels impose the same flavor requirement on both direct leptons in the event, and so the yield in the SRFR $_e$ and SRFR $_\mu$ regions do not add to the inclusive SRFR region.

The $m_{Z\ell}$ distributions in each SR, with binning corresponding to that used in the fit, are shown in Figure 5.21. The SRs show good agreement in the shape of the $m_{Z\ell}$ distribution between data and the background prediction, with no significant localized excesses. Three example signals of mass 200, 500, and 800 GeV are included in these figures and peak strongly in their target $m_{Z\ell}$ bin for all three SRs, with the 800 GeV signal only visible in the last $m_{Z\ell}$ bin.

5.6.1 Model-Independent Limits on New Physics in Inclusive Regions

Via the model-independent fit procedure detailed in Section 5.5.4 and the modified frequentist CL_S technique described in Section B.2.5, upper limits are set on the possible visible cross sections of generic beyond-the-SM (BSM) processes in each $m_{Z\ell}$ bin of each SR. A generic BSM process is assumed to contribute only to the target $m_{Z\ell}$ bin. In this way no assumption is made concerning the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ branching fractions or $m_{Z\ell}$ shape of the BSM process. No uncertainties in the yield of the BSM process are considered, except for the luminosity uncertainty.

This procedure is repeated for each of the 16 $m_{Z\ell}$ bins in each of the three SRs, with only one SR bin considered for each fit. This differs from the nominal fit strategy which is performed using the three CRs and the 48 $m_{Z\ell}$ bins of the SRs simultaneously, though only minor differences from the significances shown in the bottom panel of Figure 5.21 are seen.

Table 5.5: The observed yields and post-fit background expectations in SRFR, SR4 ℓ , and SR3 ℓ , shown inclusively and when the direct lepton from a $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ decay is required to be an electron or muon. The “Other” category consists mostly of the tWZ , $t\bar{t}W$, and tZ processes. Uncertainties in the background expectation include combined statistical and systematic uncertainties. The individual uncertainties may be correlated and do not necessarily combine in quadrature to give the total background uncertainty.

Region	SRFR	SRFR _e	SRFR _{μ}	SR4 ℓ	SR4 ℓ_e	SR4 ℓ_μ
Observed yield	42	15	17	89	48	41
Expected background yield	39 ± 4	13.7 ± 2.0	15.7 ± 2.5	76 ± 6	35.8 ± 3.5	38.2 ± 2.8
WZ yield	—	—	—	—	—	—
ZZ yield	19 ± 4	7.1 ± 1.7	10.4 ± 2.4	20.9 ± 1.1	9.5 ± 0.6	11.2 ± 0.7
$t\bar{t}Z$ yield	12.2 ± 3.2	2.4 ± 0.7	3.0 ± 0.6	18 ± 6	9.1 ± 3.2	8.5 ± 1.6
Triboson yield	1.3 ± 0.4	0.25 ± 0.09	0.33 ± 0.12	12.2 ± 2.8	5.8 ± 1.4	6.0 ± 1.5
Higgs yield	2.6 ± 0.5	0.72 ± 0.17	1.17 ± 0.25	11.2 ± 2.0	5.3 ± 1.0	5.5 ± 1.1
Other yield	2.1 ± 0.5	0.25 ± 0.17	0.39 ± 0.16	7.9 ± 1.5	4.0 ± 0.8	3.5 ± 0.8
<i>Fake</i> yield	1.3 ± 0.8	3.0 ± 1.5	$0.5^{+0.6}_{-0.5}$	6.4 ± 2.5	2.1 ± 1.1	3.6 ± 1.7
Region	SR3 ℓ	SR3 ℓ_e	SR3 ℓ_μ			
Observed yield	61	28	33			
Expected background yield	54.9 ± 3.3	27.5 ± 2.2	27.4 ± 2.0			
WZ yield	33.6 ± 2.4	16.5 ± 1.7	17.3 ± 1.8			
ZZ yield	0.92 ± 0.27	0.11 ± 0.04	0.77 ± 0.24			
$t\bar{t}Z$ yield	7.5 ± 2.3	4.1 ± 1.3	3.4 ± 0.7			
Triboson yield	5.6 ± 1.5	2.7 ± 0.8	2.6 ± 0.7			
Higgs yield	0.51 ± 0.10	0.25 ± 0.06	0.23 ± 0.05			
Other yield	4.2 ± 0.8	2.0 ± 0.4	2.0 ± 0.4			
<i>Fake</i> yield	2.5 ± 1.2	1.8 ± 1.1	1.0 ± 0.8			

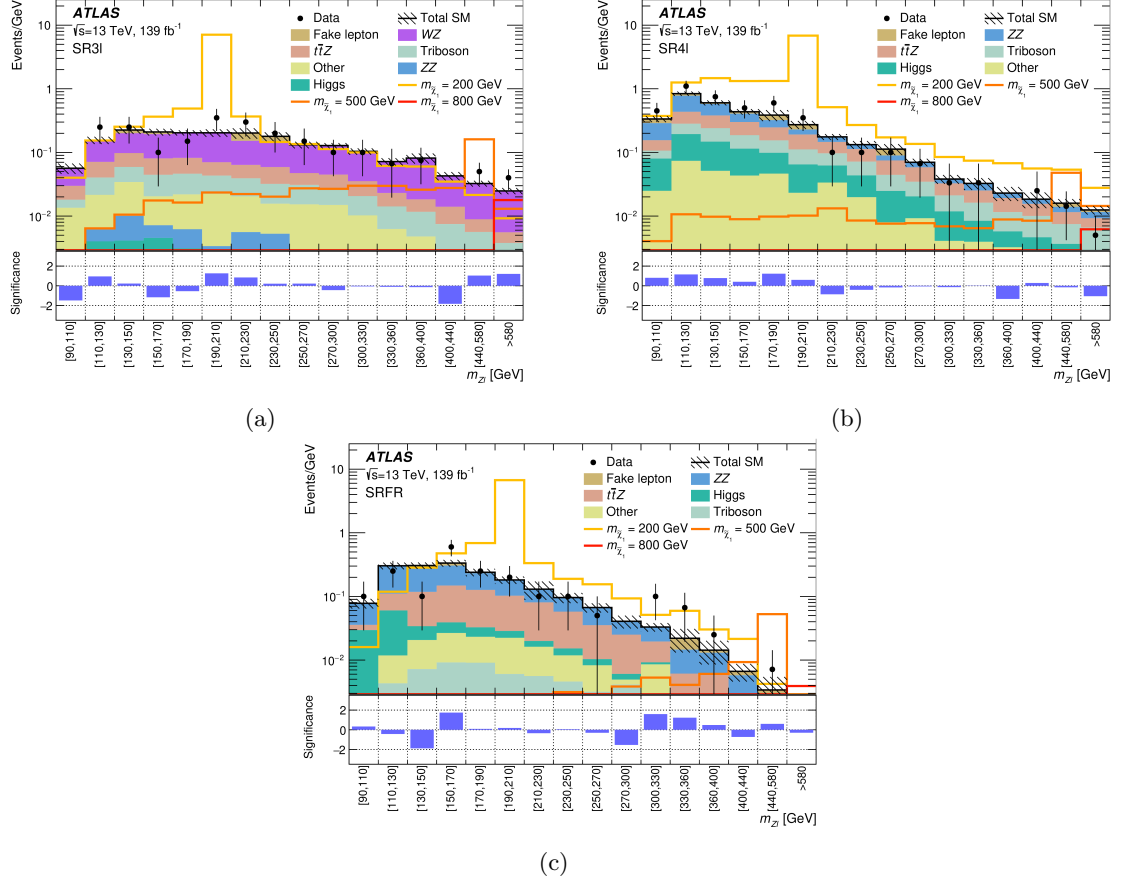


Figure 5.21: The observed data and post-fit SM background expectation as a function of $m_{Z\ell}$ in (top left) SRFR, (top right) SR4 ℓ , and (bottom) SR3 ℓ . The $m_{Z\ell}$ binning (Eq. (B.1)) is the same as that used in the fit and the yield is normalized to the bin width, with the last bin normalized using a width of 200 GeV. The “Other” category consists mostly of the tWZ , $t\bar{t}W$, and tZ processes. The hatched bands indicate the combined theoretical, experimental, and MC statistical uncertainties in the background prediction. The bottom panel shows the significance of the differences between the observed data and expected yields, computed following the profile likelihood method described in Ref. [85] [51].

5.6.2 Mass Limits on $B - L$ RPV Production

Exclusion limits on the generated SUSY $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ signal samples are derived at 95% confidence level (CL) through the profile log-likelihood ratio test using the CL_S prescription and performed with **HistFitter**. For each signal model, a simultaneous fit is performed to the control regions and the signal regions, fitting to the number of events passing each selection criteria. Each bin of the $m_{Z\ell}$ distribution in each SR is fit independently, so there are effectively 48 SRs being fit simultaneously. The modified frequentist CL_S technique is then used to determine the expected mass limit. The wino mass limit for the branching ratio

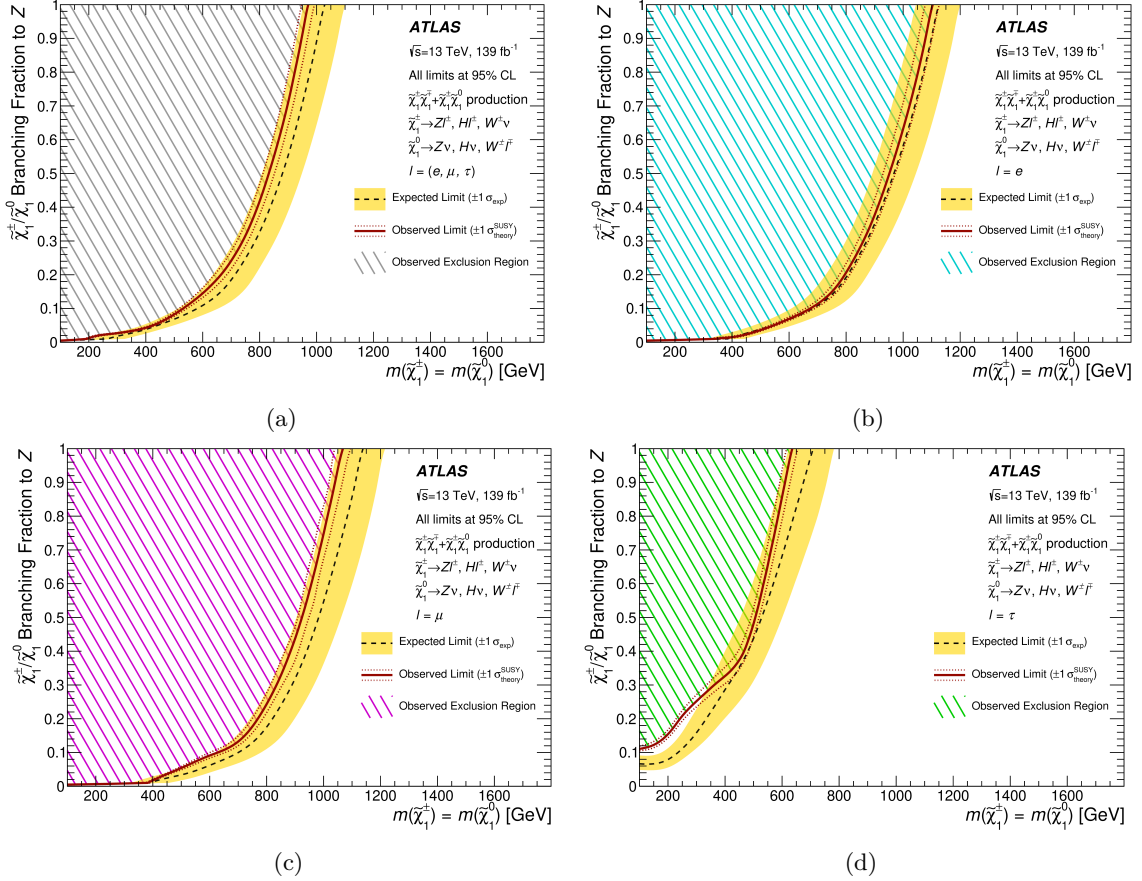


Figure 5.22: Exclusion curves for the simplified model of $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production as a function of $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ mass and branching fraction to Z bosons. Curves are derived separately when requiring that the charged-lepton decays of $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ are into (a) any leptons with equal probability, (b) electrons only, (c) muons only, or (d) τ -leptons only. The expected 95% CL exclusion (dashed black line) is shown with $\pm 1 \sigma_{\text{exp}}$ variations (shaded yellow band) from systematic and statistical uncertainties in the expected yields. The observed 95% CL exclusion (solid red line) is shown with $\pm 1 \sigma_{\text{theory}}^{\text{SUSY}}$ variations (dotted red lines) from cross-section uncertainties for the signal models. The phase-space excluded by the search is shown in the hatched regions. The sum of the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ branching fractions to W, Z, and Higgs bosons is unity for each point, and the branching fractions to W and Higgs bosons are chosen so as to be equal everywhere [51].

being tested is selected as the point where $\text{CL}_S = 0.05$. The mass points sampled are from 100 GeV to 1500 GeV in steps of 50 GeV.

5.6.3 Branching Ratio Limits on $B - L$ production

Since the charged and neutral winos in the $B - L$ model have several possible decays, limits are set as a function of the wino branching ratio. Signal events are reweighted according to the truth decay of the

wino to effectively set limits on each decay separately. A scan is performed over each charged lepton flavor (electron, muon, and τ -lepton) and over each possible boson type (Z , W , and higgs). The considered points in the lepton flavor scan are $(\text{BR}(\tilde{\chi}_1 \rightarrow Be), \text{BR}(\tilde{\chi}_1 \rightarrow B\mu), \text{BR}(\tilde{\chi}_1 \rightarrow B\tau)) = (1, 0, 0), (0, 1, 0), (0, 0, 1)$, and $(0.33, 0.33, 0.33)$, where B is a W boson for the $\tilde{\chi}_1^0$ scan, and can be either a Z or a Higgs for the $\tilde{\chi}_1^\pm$ scan. Then for each of these points, a finer granularity scan is performed over the possible boson types of the wino decay, steps of 10% for BR to Z and 20% for BR to H . Limits are set as a function of $\text{BR}(\tilde{\chi}_1^\pm \rightarrow H\ell)$ vs $\text{BR}(\tilde{\chi}_1^\pm \rightarrow Z\ell)$ for $\tilde{\chi}_1^\pm$ and $\text{BR}(\tilde{\chi}_1^0 \rightarrow H\nu)$ vs $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\nu)$ for $\tilde{\chi}_1^0$, separately for each considered wino-to-lepton branching ratio point. The $\text{BR}(\tilde{\chi}_1^\pm \rightarrow W\nu)$ and $\text{BR}(\tilde{\chi}_1^0 \rightarrow W\ell)$ are implicitly included on the respective 2D plots since the sum of the three BRs must equal 1. To increase sensitivity for the $\text{BR}(\tilde{\chi}_1 \rightarrow Be) = 100\%$ and $\text{BR}(\tilde{\chi}_1 \rightarrow B\mu) = 100\%$ scenarios in the lepton flavor scan, additional SR selections are applied on the flavor of the third lepton which is assumed to come directly from the $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_1^0$ decay (that which is assigned to the $Z\ell$ leg but not assigned to the Z). For $\text{BR}(\tilde{\chi}_1 \rightarrow Be) = 100\%$ limits, this lepton is required to be an electron, and for $\text{BR}(\tilde{\chi}_1 \rightarrow B\mu) = 100\%$ limits, this lepton is required to be a muon. SRFR events require that all leptons assigned directly to the $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_1^0$ decay (and not to a boson) must have the required flavor. This imposes the requirement that both winos decay to the same lepton flavor, as predicted in the $B-L$ model because the wino-to-lepton BR is dictated by the neutrino hierarchy and hence should be the same for charginos and neutralinos. SR4 ℓ events are agnostic to the fourth lepton flavor. The reasoning for this, as opposed to the agreement between the third and fourth leptons which is required in SRFR, is because in SR4 ℓ the fourth lepton can often come from the second boson decay and hence its flavor is random compared to the lepton directly from the wino decay. The other two points in the lepton flavor scan (fully tau and flavor democratic) allow all lepton flavors. Limits are set simultaneously for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production modes. This effectively imposes the assumption that the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ decay BRs are fully correlated, for both lepton and boson decays. Figures 5.22a to 5.22d show limits set in the plane of $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ branching fraction to the Z boson vs the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ mass, for each of the lepton flavor scenarios. The strongest exclusions come from $\text{BR}(\tilde{\chi}_1 \rightarrow Be) = 100\%$ and $\text{BR}(\tilde{\chi}_1 \rightarrow B\mu) = 100\%$ points in the scan as expected as light flavor leptons were only targeted in this analysis, sensitivity to the $\text{BR}(\tilde{\chi}_1 \rightarrow B\tau) = 100\%$ point comes from leptonic tau decays. Figures 5.23a to 5.23d show the limits set for the hypothesis of a $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ with a mass of 600 GeV to show the limits in the plane of the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ branching fraction to Higgs vs Z . The vertical nature of the limits shows the strong dependence (as expected) on the Z boson branching fraction and little dependence on the Higgs or W boson branching fraction.

5.7 Analysis Preservation: Building Towards the “Do Analysis” Button

One of the more interesting developments in this field in recent years is in the space of *Analysis Preservation* and the closely related *Recasting of Analyses*. The nominal way of preserving a scientific analysis such that it is effectively reproducible is by way of the tried and true method of publishing a paper, and, perhaps, a

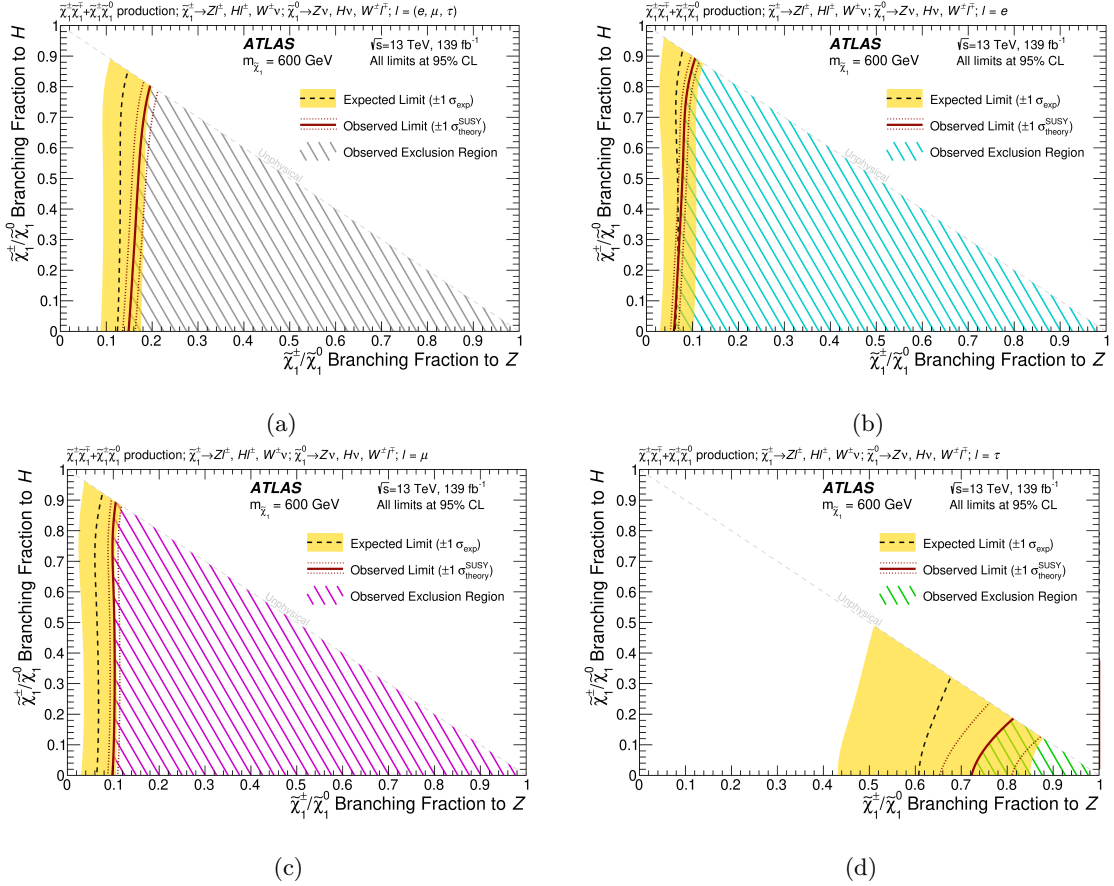


Figure 5.23: Exclusion curves for the simplified model of $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production as a function of the branching fractions to Z and Higgs bosons. Results are shown for the charged-lepton decays of $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ into (a) any leptons with equal probability, (b) electrons only, (c) muons only, and (d) τ -leptons only for the 600 GeV mass point. The expected 95% CL exclusion (dashed black line) is shown with $\pm 1 \sigma_{\text{exp}}$ variations (shaded yellow band) from systematic and statistical uncertainties in the expected yields. The observed 95% CL exclusion (solid red line) is shown with $\pm 1 \sigma_{\text{theory}}^{\text{SUSY}}$ variations (dotted red lines) from cross-section uncertainties for the signal models. The phase-space excluded by the search is shown in the hatched regions. [51].

linked collection of relevant data tables from that analysis. Now for many (most) fields this is still very much sufficient. But for anyone familiar with experiments such as ATLAS whose collaborations consist of thousands of scientists, hundreds of pieces of evolving software, hardware, and working point recommendations, the actual reproducibility of a single analysis becomes intractable. The resulting paper would ultimately become a list of various versions of internal pieces of software and this often legitimate information is lost in the final journal version of the paper because there is just too much information contained in the full analysis to be published. Fortunately as our experiments grow in complexity our technology grows too in power and capability. In recent years there have been tremendous strides in general software and computing

technology that allows for, on a user level, the ability to capture entire computing environments and analysis workflows in a relatively lightweight manner that can produce exact results seen in the the published paper. What we effectively have then is a custom piece of software built for a singular high energy physics analysis that can produce paper quality results with a single command. CERN’s specific efforts towards these goals take form in the CERN Analysis Preservation (CAP) [86] service and the REANA (**R**eusable **A**nalysis) platform [87]. While ATLAS has it’s own internal framework RECAST [88], which was developed closely along side REANA (and is compatible syntactically with only a few changes).

5.7.1 Analysis Preservation for the Trilepton Resonance Search

The process of preserving an analysis will be detailed in the context of this trilepton resonance search.

5.7.1.1 Preserving the Data

Actual data preservation is nothing new, raw data is of course preserved on tape at CERN and on disk at several tier 1 sites. But what people usually mean when talking about preserving data is the processed and analyzed data, i.e. the statistical results and supporting data. The efforts with this type of preservation for scattering experiments dates back to around 1975 with the advent of the Durham HepData Project, a database for results from particle physics experiments. The modern version was released in 2016 as HEPData [89] as a well indexed HEP results database with intuitive responsive data table visualizations. Whereas in the early days the project was driven from within in order to collect data from the experimentalists, additions to the database are now almost entirely community driven and is now regularly updated with results from the experimentalists themselves with support and review from the HEPData project. The HEPData space for this trilepton resonance search can be found here <https://www.hepdata.net/record/ins1831992> .

5.7.1.2 Preserving the Analysis

To preserve the actual analysis, in the most literal sense, the full underlying codebase that produces the final public results must be preserved. This can be as easy as just maintaining one’s analysis code on a version controlled repository. But where this runs into problems almost immediately is the tremendous burden on the developers to actually make the often incredibly complicated codebase usable, and understandable to future users (non-developers). This not only entails a necessarily detailed explanation of how to use the code but also an exhaustive list of its dependencies and libraries to ensure that it even works many years down the line, and you effectively have become a full fledged software developer. Fortunately, there is a nice way around a lot of this. A computational tool known as OS-virtualization by way of containers, most commonly referred to as just “containers.” Containers behave like a the more familiar virtual machine in many ways. The key difference from a virtual machine is that rather than creating a whole virtual operating system,

5.7. ANALYSIS PRESERVATION: BUILDING TOWARDS THE “DO ANALYSIS” BUTTON 07

containers need only the individual components required to operate the software of interest. This gives a significant performance boost and reduces the size of the application. They also operate much faster, as unlike traditional virtualization the process is essentially running natively on its host, just with an additional layer of protection around it. Containers have existed in some form for over a decade but really only gained traction in the computational world in 2013 when Docker released their containerization platform. Open-source and well maintained, Docker provided their own containers known as docker images, a registry to host those images, and created the Dockerfile, a simple file that contains all the commands to assemble an image. This combination made it incredibly easy to create images that anyone could run on any machine. To this end ATLAS has been Dockerizing its analysis platform Athena [90] (amongst an increasing number of other pieces of relevant software) since 2017, providing a large number of releases (stable versions of the software) readily available for use. Automatic containerization then becomes shockingly simple by way of continuous integration by including the aforementioned *Dockerfile* in your version controlled repository. For this analysis it looks like the following:

```
1 FROM atlas/analysisbase:21.2.78
2 ADD . /analysis/
3 WORKDIR /analysis/build
4 RUN source /home/atlas/release_setup.sh &&\
5     sudo chown -R atlas /analysis &&\
6     echo "ls"; ls &&\
7     echo "ls ../"; ls ../ &&\
8     echo "ls ../patch"; ls ../patch &&\
9     source ../patch/apply_patch.sh &&\
10    cmake ../source &&\
11    make -j4 &&\
12    bash -c "cd ../source/HistFitter && \
13        . setup.sh && cd src && make"
14 USER root
15 RUN sudo usermod -aG root atlas # Replace 'atlas' with the default user in your analysis image, if different
16 USER atlas.
```

Where in the first line is the Docker image of the specific release of the internal ATLAS software used for this analysis, then the remainder of the lines builds and sets up this release as well as all the local code contained in the repository in which the Dockerfile exists (and also applies a small very specific patch to some code contained in a submodule). This produces a new Docker image every time code is pushed to the repository using continuous integration.

5.7.1.3 Workflow Authoring

The next step known as *workflow authoring* and it effectively specifies a series of commands with a set of configurable inputs that will allow an end user to easily run the full analysis code that results in statistical statements (p -values/CLs values). Using the Markup type language YAML (or yadage), a human readable data-serialization language, external data file inputs can be passed in as variables, processed in one step, and have the step's output fed into the next step and so on. The first step in our framework can be seen

5.7. ANALYSIS PRESERVATION: BUILDING TOWARDS THE “DO ANALYSIS” BUTTON 08

below as an example of what this actually looks like in code, and can also be seen illustrated in Figure 5.24 as the first dashed line box as part of the full workflow.

```

1 daod_to_ntup_mc16ade:
2   process:
3     process_type: interpolated-script-cmd
4     interpreter: bash
5     script: |
6       source /recast_auth/getkrb.sh
7       source /home/atlas/release_setup.sh
8       source /analysis/build/*/setup.sh
9       cd /analysis
10      python ./source/xAODAnaHelpers/scripts/xAH_run.py -f --scanXRD --inputList --files {input_file_mc16a} --
          submitDir {submitDir_mc16a} --config source/BMinusLCharginoAnalysis/data/
          config_BMinusLChargino_AFII_mc16a.py direct
11      python source/BMinusLCharginoAnalysis/scripts/appendParsedNames.py --filelistpath {input_file_mc16a} --
          outputTrees {submitDir_mc16a}/data-tree/
12      python ./source/xAODAnaHelpers/scripts/xAH_run.py -f --scanXRD --inputList --files {input_file_mc16d} --
          submitDir {submitDir_mc16d} --config source/BMinusLCharginoAnalysis/data/
          config_BMinusLChargino_AFII_mc16d.py direct
13      python source/BMinusLCharginoAnalysis/scripts/appendParsedNames.py --filelistpath {input_file_mc16d} --
          outputTrees {submitDir_mc16d}/data-tree/
14      python ./source/xAODAnaHelpers/scripts/xAH_run.py -f --scanXRD --inputList --files {input_file_mc16e} --
          submitDir {submitDir_mc16e} --config source/BMinusLCharginoAnalysis/data/
          config_BMinusLChargino_AFII_mc16e.py direct
15      python source/BMinusLCharginoAnalysis/scripts/appendParsedNames.py --filelistpath {input_file_mc16e} --
          outputTrees {submitDir_mc16e}/data-tree/
16      mkdir {submitDir_all}
17      cp {submitDir_mc16a}/data-tree/* {submitDir_all}/
18      cp {submitDir_mc16d}/data-tree/* {submitDir_all}/
19      cp {submitDir_mc16e}/data-tree/* {submitDir_all}/
20      ls {submitDir_all}
21   publisher:
22     publisher_type: interpolated-pub
23     publish:
24       ntuple_mc16ade: '{submitDir_all}'
25     glob: true
26   environment:
27     environment_type: docker-encapsulated
28     image: gitlab-registry.cern.ch/atlassusy-bminusl/bminuslcharginoanalysis
29     imageTag: master
30     resources:
31       - kubernetes_uid: 500
32       - kerberos: true

```

Where you can see in line 28 the Docker image that was created by the Dockerfile shown previously is specified. Then lines 6–20 are the actual commands being run within this image environment which takes a very familiar form: set up environment with some scripts + run high level python script with various options. All things appearing in curly brackets (braces) are variable. From Figure 5.24 we also see the general structure of the analysis workflow, which is as follows:

- **daod_to_ntup_mc16ade** : Step taking data from a relatively general form, DOAD, and computing high level analysis quantities, creating a smaller data type containing only relevant analysis information.
- **ntup_to_HFtree** : Further slimming of data and reformatting for use in the statistical tool **HistFitter**.

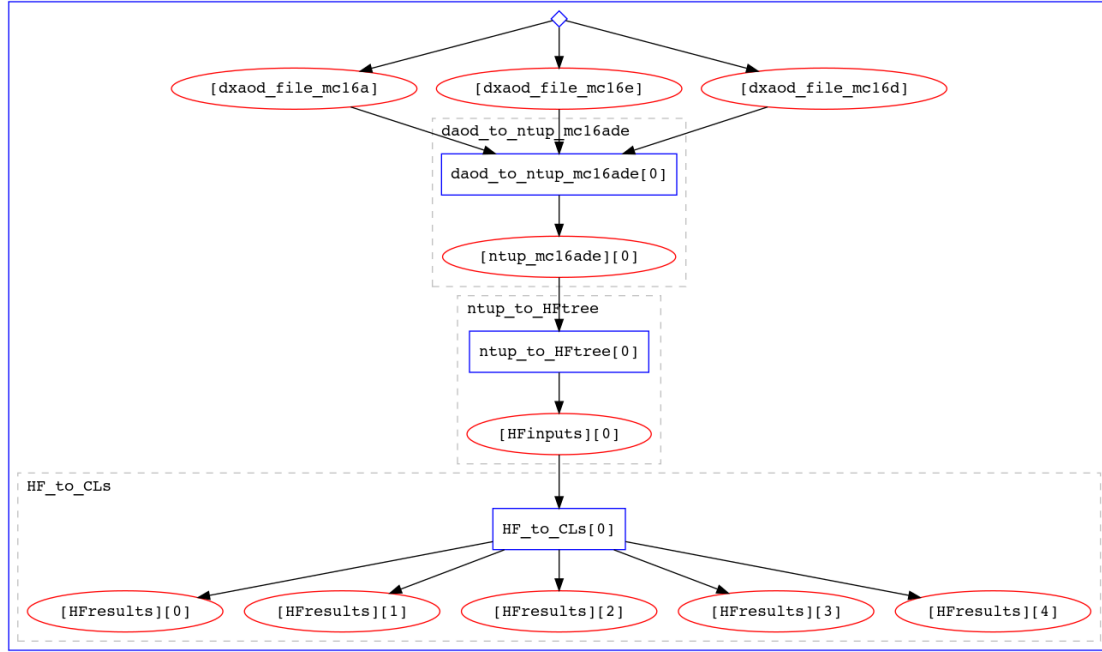


Figure 5.24: Diagrammatic illustration of full step-by-step workflow of analysis procedure used for analysis reproduction and recasting. Explicit steps are `daod_to_ntup_mc16ade`, `ntup_to_HFtree`, and `HF_to_CLs` with inputs `dxaod_file_mc16a`, `dxaod_file_mc16d`, and `dxaod_file_mc16e` representing the three MC campaigns used in the analysis.

- **HF.to.CLs** : Running the statistical machinery (**HistFitter**) that outputs the final statistical results.

This effectively allows us to run the entire analysis for a specified theory signal mass point for a specified branching ratio schema, with a single command. The first obvious use case is the ability to reproduce statistical results exactly. Second, is the ability to easily create a finer grained scan that goes beyond the reported statistics in the published paper in regions of parameter space that are of particular interest to the user. Thirdly, and most excitingly, this workflow builds a framework for a recasting of this analysis on other signal models, effectively allowing for the work done in constructing this analysis to be reused to make real publishable statistical statements about other theoretical models (most likely only those with a resonant three lepton final states).

CHAPTER 6

Conclusion

In this thesis we have discussed the theoretical framework that underpins our current understanding of elementary particle physics, the Standard Model, in Chapter 2. We also proposed the $B - L$ MSSM as a potential extension to the SM that provides a more natural way for R -parity conservation to be handled. The breaking of the $U(1)_{B-L}$ symmetry gives rise to R -parity violating couplings that allow for many interesting final states. Then the fantastical LHC device and the general purpose ATLAS detector which are well equipped to look for these particle signatures were described in Chapter 3. Much of the work in the e/γ performance group, including a detailed description of the electron likelihood identification technique and my contributions optimizing and developing working points used by the majority of ATLAS analyses, was detailed in Chapter 4. Then in the context of the $B - L$ MSSM we motivated $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ as likely LSPs. The signal $\tilde{\chi}_1^\pm \rightarrow Z\ell \rightarrow \ell\ell\ell$ via $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ productions was searched for in 139 fb^{-1} of proton-proton data collected at ATLAS. Search methodology and results of this analysis were presented in Chapter 5 and no statistically significant excess was seen. Limits were then set in the Mass vs. Branching Ratio to Z and Branching Ratio to Z vs. Branching Ratio to H planes, scanned over four lepton flavor branching ratio points. Finally we discuss analysis preservation/recasting and the techniques therein in the context of this analysis.

Appendices

APPENDIX A

Formulation of QFT

A.1 Formulation of QFT

I find it easiest, and maybe the most logically satisfying, to think of the formulation of QFT in terms of canonical quantization (or second quantization). Whereby the idea here is to retain the familiar form of the classical Hamiltonian (or Lagrangian) representation and then leap from a classical theory to a quantum one by promoting fundamental measurables of physical objects to operators and Poisson brackets to commutators. So more explicitly the steps are

1. Assume the quantum field Hamiltonian density has the same form as the classical field Hamiltonian density
2. Replace the classical Poisson brackets for conjugate property densities with commutator brackets (divided by $i\hbar$), i.e. $A \rightarrow \hat{A}$, $\{A, B\} \rightarrow \frac{1}{i\hbar}[\hat{A}, \hat{B}]$, where the “hatting” of the variables signifies the the classical field dynamical variables becoming quantum field non-commuting operators as a consequence of this imposition.

As an example we will quantize the most basic resulting QFT, scalar field theory. The classical scalar field, $\phi(x, t)$, takes in the position and time and produces the value of the field at that position and time. Classically, a scalar field is a collection of an infinity of oscillator normal modes. So the classical Lagrangian density describing an infinite number of coupled harmonic oscillators is written as

$$\mathcal{L}(\phi) = \frac{1}{2}(\partial_t \phi)^2 - \frac{1}{2}(\partial_x \phi)^2 - \frac{1}{2}m^2 \phi^2 - V(\phi) \quad (\text{A.1})$$

Where $V(\phi)$ is a potential term. The action is then,

$$S(\phi) = \int \mathcal{L}(\phi) dx dt = \int L(\phi, \partial_t \phi) dt$$

The canonical momentum can be obtained from the action via the Legendre transformation, and is found to be $\pi = \partial_t \phi$. The classical Hamiltonian is then,

$$H(\phi, \pi) = \int dx \left[\frac{1}{2} \pi^2 + \frac{1}{2} (\partial_x \phi)^2 + \frac{1}{2} m^2 \phi^2 + V(\phi) \right] \quad (\text{A.2})$$

Next we impose the canonical commutation relations at $t=0$ as follows

$$[\phi(x), \phi(y)] = 0, \quad [\pi(x), \pi(y)] = 0, \quad [\phi(x), \pi(y)] = i\hbar \delta(x - y)$$

The operators can then be generalized to any time t in the future by applying the time evolution operator $\mathcal{O}$,

$$\mathcal{O}(t) = e^{itH} \mathcal{O} e^{-itH}.$$

Where at this point a choice of $V(\phi)$ is required. For simplicity we will just consider the case of the free field with $V(\phi)=0$. It is useful to Fourier transform the fields,

$$\phi_k = \int \phi(x) e^{-ikx} dx, \quad \pi_k = \int \pi(x) e^{-ikx} dx.$$

It can then be identified that,

$$\phi_{-k} = \phi_k^\dagger, \quad \pi_{-k} = \pi_k^\dagger.$$

Expanding the Hamiltonian density in Equation A.2 in Fourier modes,

$$H = \frac{1}{2} \sum_{k=-\infty}^{\infty} \left[\pi_k \pi_k^\dagger + \omega_k^2 \phi_k \phi_k^\dagger \right], \quad (\text{A.3})$$

where $\omega_k = \sqrt{k^2 + m^2}$. We recognize this Hamiltonian as an infinite sum of classical oscillators ϕ_k , each one of which is quantized in the standard manner, so the free quantum Hamiltonian looks identical. It is the ϕ_k s that have become operators obeying the standard commutation relations, $[\phi_k, \pi_k^\dagger] = [\pi_k^\dagger, \phi_k] = i\hbar$ with all others vanishing. The Hilbert space of all these oscillators is constructed using creation and annihilation operators determined from these modes,

$$a_k = \frac{1}{\sqrt{2\hbar\omega_k}} (\omega_k \phi_k + i\pi_k), \quad a_k^\dagger = \frac{1}{\sqrt{2\hbar\omega_k}} (\omega_k \phi_k^\dagger - i\pi_k^\dagger),$$

Subtracting of the zero-point energy $\hbar\omega_k/2$ from the Hamiltonian in Equation A.3 in order to satisfy the condition that H must annihilate the vacuum and rewriting in terms of the creation/annihilation operators the Hamiltonian takes the form,

$$H = \sum_{k=-\infty}^{\infty} \hbar\omega_k a_k^\dagger a_k = \sum_{k=-\infty}^{\infty} \hbar\omega_k N_k \quad (\text{A.4})$$

where N_k may be interpreted as the number operator giving the number of particles in a state with momentum k . Now, commutation relations are useful only for quantizing bosons, for which the occupancy number of any state is unlimited. To quantize fermions, which satisfy the Pauli exclusion principle, anti-commutators

are needed. i.e. the relation $\{A,B\} = AB+BA$. When quantizing fermions, the fields are expanded into the creation and annihilation operators, $b_k^\dagger, b_k$, which satisfy

$$\{b_k, b_l^\dagger\} = \delta_{k,l}, \quad \{b_k, b_l\} = 0, \quad \{b_k^\dagger, b_l^\dagger\} = 0 \quad (\text{A.5})$$

All other fields can be quantized by a generalization of this procedure. Vector or tensor fields simply have more components, and independent creation and destruction operators must be introduced for each independent component. If a field has any internal symmetry, then creation and destruction operators must be introduced for each component of the field related to this symmetry as well. If there is a gauge symmetry, then the number of independent components of the field must be carefully analyzed to avoid over-counting equivalent configurations, and gauge-fixing may be applied if needed [91].

APPENDIX B

Statistical Treatment

The underlying statistical measure used in this analysis for comparing the goodness of fit of a statistical model to data is the *likelihood function*, a joint probability distribution of the sample viewed as a function of the parameters only. According to the likelihood principle proposition, the likelihood function contains all the evidence in a sample relevant to model parameters, given a statistical model. Constructing this likelihood function will thereby result in the full statistical model to be tested for this analysis.

B.1 The Likelihood Function

For experiments with a large number of independent discrete events, such as ATLAS, a Poisson distribution, $P(k; \lambda)$, is the valid probability distribution. Where k is the number of observed events and λ the expectation of the given model. Each analysis region included in the analysis will have a corresponding independent Poisson that forms the likelihood function. Regions included are the signal regions, SRFR, SR4 ℓ , and SR3 ℓ of which are further subdivided into bins of $m_{Z\ell}$, the primary discriminating variable discussed in Section 5.2.1, in order to maximize the discovery sensitivity to a resonance. The binning of the $m_{Z\ell}$ observable was optimized using simulated $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ signal samples with reconstructed mass resolutions of around 2%, and the optimized binning accounts for the predicted background expectation. Lower edges are set to

$$m_{Z\ell} = 90, 110, 130, 150, 170, 190, 210, 230, 250, 270, 300, 330, 360, 400, 440, \text{ and } 580 \text{ GeV}. \quad (\text{B.1})$$

The last bin has no upper edge and includes all events with $m_{Z\ell} > 580$ GeV. The same binning is used for all three SRs, facilitating the discovery of a trilepton resonance that would contribute to all SRs. This effectively results in $(3\text{SRs} \times 16 \text{ } m_{Z\ell} \text{ bins}) = 48$ independent signal regions. The three control regions, CRWZ, CR $t\bar{t}$ Z, and CRZZ are also included in the fit to better estimate the corresponding major backgrounds. The systematic uncertainties' probability distributions are modeled as Gaussians, $g(\theta_0, \theta)$, who's means and widths are determined by dedicated auxiliary measurements, θ_0 , collected by ATLAS performance groups.

The full statistical model is then written down as the Likelihood in Equation B.2.

$$\begin{aligned} \mathcal{L}(\boldsymbol{\theta}|k) &= \prod_i \frac{\lambda_i^{k_i} e^{-\lambda_i}}{k_i!} \times \prod_{sys} g(\boldsymbol{\theta}_0, \boldsymbol{\theta}), \quad \lambda_i = \mu_{sig} s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}) \\ i &= CRt\bar{t}Z, CRWZ, CRZZ, SR_0, SR_1, \dots, SR_{48} \\ \boldsymbol{\theta} &= (\mu_{t\bar{t}Z}, \mu_{WZ}, \mu_{ZZ}, NP_0, NP_1, \dots) \end{aligned} \tag{B.2}$$

Where $\boldsymbol{\theta}$ is the set of two types of parameters that will be allowed to float in the ultimate fit to the data. The first type are the *normalization factors*, derived from the yields of the three main background contributors $t\bar{t}Z$, WZ , and ZZ . And while the $t\bar{t}Z$, WZ , and ZZ yields are allowed to float in all regions in the fit the values of $\mu_{t\bar{t}Z}$, μ_{WZ} , and μ_{ZZ} will be determined by and large by the high purity/stats the dedicated control regions give us. The second type are known as *nuisance parameters*, and are degrees of freedom corresponding to the suite of systematic uncertainties included in the analysis and are constrained by their corresponding Gaussians. i is then the group of analysis regions to be fit simultaneously, the details of which is to be discussed in Sections 5.5.3 to 5.5.5. Three types of fits are required in order to both validate background estimations and to make model dependent and model independent physics statements and are detailed in Sections 5.5.3 to 5.5.5.

B.2 Goodness of Fit: Maximum Likelihood Estimation

The goodness of fit measure used is the powerful Maximum Likelihood Estimate (MLE), which is the method of estimating parameters of a probability distribution by maximizing its likelihood function so that under the assumed statistical model the observed data is most probable.

B.2.1 The Profile Likelihood

In physics analyses such as these, which many parameters must be estimated, reducing the parameters to only the parameters of interest by eliminating nuisance parameters becomes effectively essential in order to have a tractable problem. This is done via the procedure known as the *profile likelihood*. This amounts to concentrating the likelihood function for a subset of parameters by expressing the nuisance parameters as functions of the parameters of interest and then replacing them in the likelihood function. In this case a single parameter, μ_{sig} , the signal strength parameter, is the parameter of interest. Graphically the profile likelihood can be seen as a ridge for which the likelihood is maximized for values of μ_{sig} , with the maximum likelihood estimator then taking on $\boldsymbol{\theta} = \hat{\boldsymbol{\theta}}$ for a specific value of μ_{sig} . A cartoon of the profile likelihood is shown in Figure B.1.

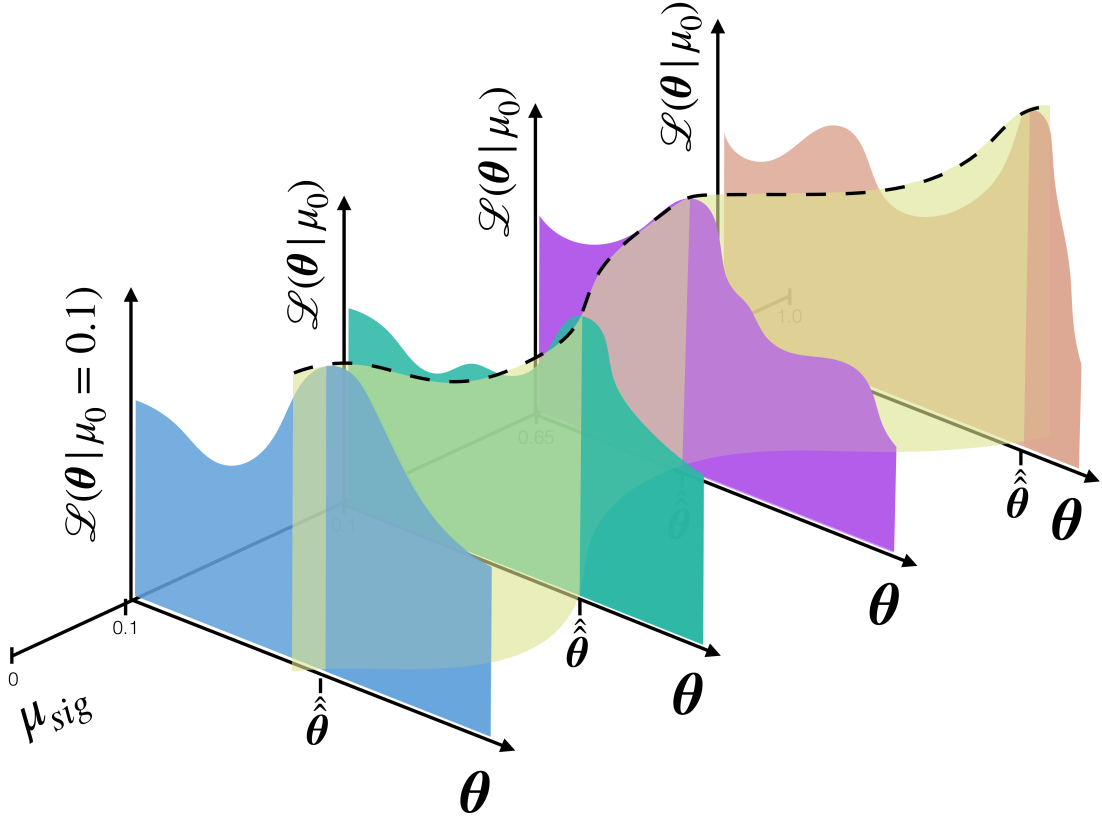


Figure B.1: Cartoon of the Profile Likelihood.

B.2.2 The Statistical Test: Profile Log Likelihood Ratio Test

In order to then assess the goodness of fit of two competing statistical models, i.e. some BSM signal models against the SM, the profile log likelihood ratio test is employed. Whereby the Neyman–Pearson lemma, the likelihood-ratio test has the highest power among all statistical test competitors for comparing two models, each of which has no unknown parameters. In general, for a statistical model Θ with subset Θ_0 the specified parameter set θ_0 in Θ_0 defines the null hypothesis H_0 . The alternative hypothesis θ_1 then exists in the complement parameter space Θ_0^c . The likelihood ratio test is then given by Equation B.3

$$q = -2 \ln \left[\frac{\mathcal{L}(\theta_0 | k)}{\mathcal{L}(\theta_1 | k)} \right] \quad (\text{B.3})$$

The profile log likelihood ratio test can then be written as:

$$q_{\mu_{sig}} = -2 \ln \left[\frac{\mathcal{L}(\mu_{sig}, \hat{\theta})}{\mathcal{L}(\hat{\mu}_{sig}, \hat{\theta})} \right] \quad (\text{B.4})$$

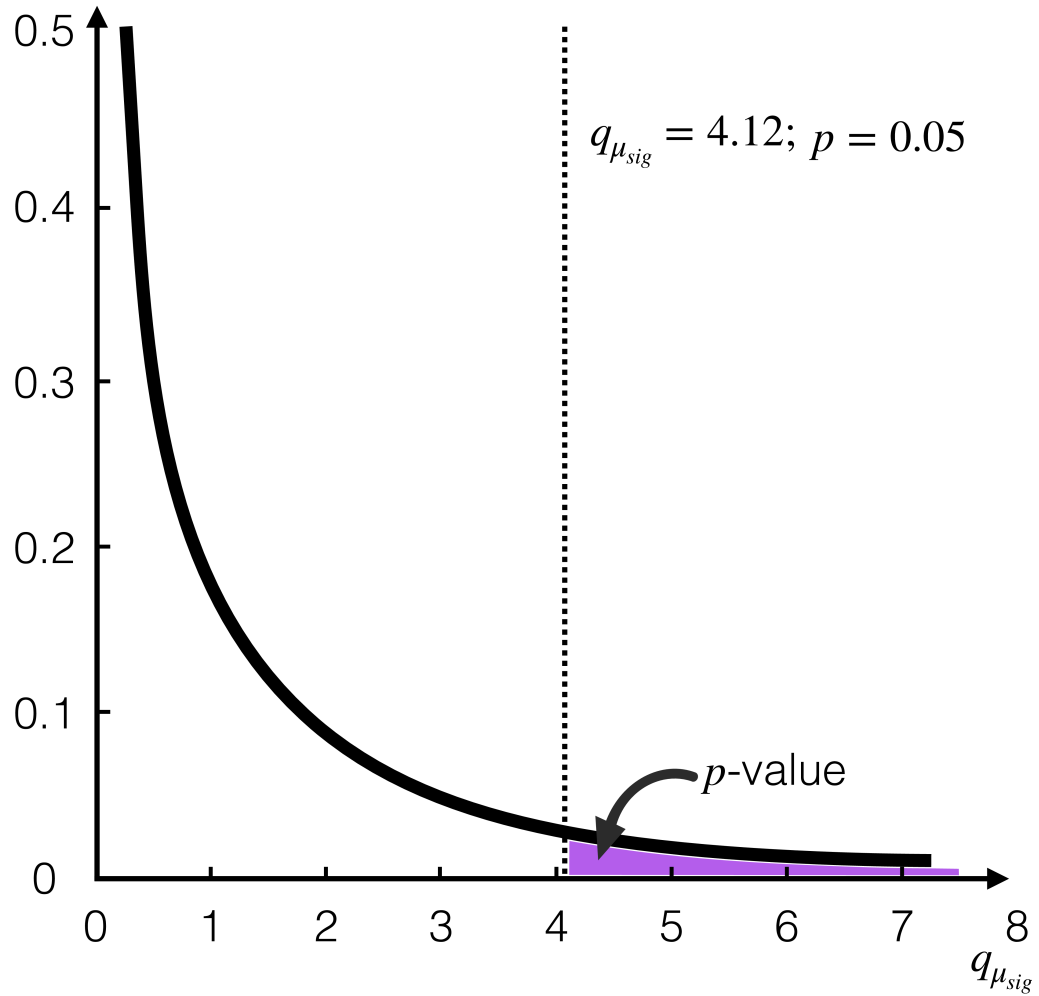


Figure B.2: Illustration of a test statistic distribution and an observed $q_{\mu_{sig}}$ with corresponding p -value as the purple area.

Where $\hat{\mu}_{sig}, \hat{\hat{\theta}}$ maximize the likelihood function and $\hat{\hat{\theta}}$ maximize the likelihood for the specific, fixed value of the signal strength as was detailed in the previous Section B.2.1. In this way a distribution of the test statistic q can be built up by scanning over $\hat{\mu}_{sig}, \hat{\hat{\theta}}$ values to which a significance, i.e. the p -value can be attained. Figure B.2 illustrates the distribution of $q_{\mu_{sig}}$ and it's relation to the p -value.

B.2.3 The Asymptotic Regime

The profile likelihood is constructed in two ways in this analysis. First, the *asymptotic method* is employed in the regime of a relatively large number of statistics, typically for event counts $O(10)$ and larger, Wilk's theorem states that the distribution of the test statistic, q , asymptotically approaches the chi-squared

distribution under the null hypothesis [92]. The logic follows that asymptotically, $\mathcal{L}(\boldsymbol{\theta}|k)$ is gaussian, and then

$$\mathcal{L} = \exp \left[-\frac{1}{2} \left(\frac{\mu - \hat{\mu}}{\sigma_\mu} \right)^2 \right] \Rightarrow q_{\mu_0} = \left(\frac{\mu_0 - \hat{\mu}}{\sigma_\mu} \right)^2, \quad \hat{\mu} \sim G(\mu_0, \sigma_\mu) \Rightarrow q_0 \sim \chi^2(n_{dof} = 1)$$

In this asymptotic regime $\mathcal{L}$ becomes independent of the values of the auxiliary measurements. As a result, when using this procedure, the p-value obtained from the hypothesis test is robust, and generally will not undercover.

B.2.4 Building the Profile Likelihood: Pseudo-Experiments

In the regime where the number of events is fewer than $O(10)$, and the distributions are not assumed to take on their asymptotic form, the profile likelihood must be constructed using Monte Carlo methods. In this “toy Monte Carlo” approach one generates pseudo-experiments in which the number of events in each channel i , the values of the discriminating variable, $m_{Z\ell}$, for each of those events, and the auxiliary measurements (global observables), $\boldsymbol{\theta}_0$, are all randomized according to $\mathcal{L}(\boldsymbol{\theta}|k)$ (Eq. B.2). By doing this many times one can build an ensemble of pseudo-experiments (generating a test statistic distribution) and evaluate the necessary integrals.

B.2.5 Significance and the CL_s Method

In the event that no significant excess is seen above the SM, limits are set on new physics. The prescription used to set these limits is known as the *CL_s Method*. Given the test statistic distribution $f(\tilde{q}_\mu|\mu, \hat{\boldsymbol{\theta}}(\mu, \text{obs}))$, determined from either pseudo-experiments or asymptotics, both described in previous sections, the following p -value is used to quantify consistency with the hypothesis of a signal strength of μ (μ_{sig}).

$$p_\mu = \int_{\tilde{q}_{\mu, \text{obs}}}^{\infty} f(\tilde{q}_\mu|\mu, \hat{\boldsymbol{\theta}}(\mu, \text{obs})) d\tilde{q}_\mu \quad (\text{B.5})$$

Now a standard 95% confidence-level, one-sided frequentist confidence interval (upper limit) is obtained by solving for $p'_{\mu_{up}} = 5\%$. For downward fluctuations the upper limit of the confidence interval can be arbitrarily small, though it will always include $\mu = 0$. This feature is considered undesirable since a physicist would not claim sensitivity to an arbitrarily small signal rate. The feature was the motivation for the modified frequentist method called CLs and the alternative approach called power constrained limits. To calculate the CLs upper limit, we define p'_μ as a ratio of p -values

$$p'_\mu = \frac{p_\mu}{1 - p_b} \quad (\text{B.6})$$

where p_b is the p -value derived from the same test statistic under the background-only hypothesis

$$p_b = 1 - \int_{\tilde{q}_{\mu, \text{obs}}}^{\infty} f(\tilde{q}_\mu|0, \hat{\boldsymbol{\theta}}(\mu = 0, \text{obs})) d\tilde{q}_\mu \quad (\text{B.7})$$

The CLs upper-limit on μ is denoted μ_{up} and obtained by solving for $p'_{\mu_{up}} = 5\%$. It is worth noting that while confidence intervals produced with the “CLs” method over cover, a value of μ is regarded as excluded at the 95% confidence level if $\mu < \mu_{up}$. The amount of over coverage is not immediately obvious; however, for small values of μ the coverage approaches 100% and for large values of μ the coverage is near the nominal 95% (due to $\langle p_b \rangle \approx 0$). For the purposes discovery one is interested in compatibility of the data with the background-only hypothesis. Statistically, a discovery corresponds to rejecting the background-only hypothesis. This compatibility is based on the following p-value

$$p_0 = \int_{\tilde{q}_{0,\text{obs}}}^{\infty} f(\tilde{q}_0|0, \hat{\boldsymbol{\theta}}(\mu=0, \text{obs})) d\tilde{q}_0 \quad (\text{B.8})$$

This p -value is also based on the background-only hypothesis, but the test statistic $\tilde{q}_0$ is suited for testing the background-only while the test statistic $\tilde{q}_\mu$ in Eq. 59 is suited for testing a hypothesis with signal. It is customary to convert the background-only p -value into the quantile (or “sigma”) of a unit Gaussian. This conversion is purely conventional and makes no assumption that the test statistic q_0 is Gaussian distributed. The conversion is defined as:

$$Z = \Phi^{-1}(1 - p_0) \quad (\text{B.9})$$

Where Φ^{-1} is the inverse of the cumulative distribution for a unit Gaussian. One says the significance of the result is $Z\sigma$ and the standard discovery convention is 5σ , corresponding to $p_0 = 2.87 \times 10^{-7}$. Most of this section was taken directly from [93].

APPENDIX C

Baseline Object Selection

C.0.1 Electron, Muon, and Jet Selection Summary Tables

Baseline electron	
Acceptance	$p_T > 10 \text{ GeV}$, $ \eta < 2.47$, crack veto
Impact parameter	$z_0 \sin(\theta) \leq 0.5 \text{ mm}$
Identification WP	LooseAndBLayerLLH
Object quality	BADCLUSELECTRON electron veto
Signal electron	
Acceptance	$p_T > 12 \text{ GeV}$
Impact parameter	$d_0/\sigma(d_0) < 5$
Identification WP	MediumLLH
Isolation WP	FCTight

Table C.1: Summary of electron selection criteria. Signal criteria are applied on top of baseline criteria after overlap removal.

Baseline muon	
Acceptance	$p_T > 10 \text{ GeV}, \eta < 2.7$
Impact parameter	$z_0 \sin(\theta) \leq 0.5 \text{ mm}$
Identification WP	Medium
Signal muon	
Acceptance	$p_T > 12 \text{ GeV}$
Impact parameter	$d_0/\sigma(d_0) < 3$
Identification WP	Medium
Isolation WP	FCTight_FixedRad
Object quality	Cosmic muon veto, bad muon event veto

Table C.2: Summary of muon selection criteria. Signal criteria are applied on top of baseline criteria after overlap removal.

Baseline jet	
Acceptance	$p_T > 20 \text{ GeV}$
Signal jet	
Acceptance	$ \eta < 2.8$
JVT	Medium ($p_T < 120 \text{ GeV}, \eta < 2.5$)
Object quality	LooseBad event veto
Signal b-jet	
Acceptance	$ \eta < 2.5$
b-tagger algorithm	MV2c10
b-tagging WP	Fixed 85%

Table C.3: Summary of jet selection criteria. Signal criteria are applied on top of baseline criteria after overlap removal.

C.0.2 Photon Selection

While photons are not used as signal objects in this analysis, they are used as input to the missing energy calculation. Photons have a minimum transverse momentum of 25 GeV and a maximum $|\eta|$ of 2.37, with a veto for photons that fall in the calorimeter crack region, corresponding to $|\eta|$ between 1.37 and 1.52. The **BADCLUSPHOTON** object quality criteria is required, as well as an author selection.

C.0.3 Missing energy

The missing transverse energy is calculated with the **Tight** working point, using all calibrated baseline objects in the event (electrons, muons, jets, and photons) as well as all tracks matched to the primary vertex not associated with these objects. Baseline jets are used only if they are tagged as originating from the hard scatter, using JVT. The E_T^{miss} significance is also calculated at this stage using Asg tools.

C.0.4 Overlap removal

Overlap removal is performed using the Asg tool and the standard recommendations therein, as outlined in <https://indico.cern.ch/event/631313/contributions/2683959/>, with the alteration that the b -jet overlap removal is p_T -dependent as described in the steps below. Technically, this is achieved by creating a standalone collection of jets which are only b -tagged in the desired p_T range. This collection of b -jets, rather than the standard collection used in the rest of the analysis, is then passed to the Asg tool. All objects that are rejected by overlap removal are removed from further overlap removal steps, and from future consideration in the analysis. Overlap removal follows the steps in the order outlined here:

- Electrons that share a track with another higher- p_T electron are rejected.
- Electrons that share a track with a non-calorimeter-tagged muon are rejected.
- Jets that are not b -tagged, or that are b -tagged with $p_T > 100$ GeV, and are within $\Delta R(e, \text{jet}) \leq 0.2$ of an electron are rejected.
- Electrons that are within $\Delta R(e, \text{jet}) \leq 0.4$ of a jet are rejected.
- Jets that are not b -tagged, or that are b -tagged with $p_T > 100$ GeV, and are ghost-matched to a muon (or within $\Delta R(\mu, \text{jet}) \leq 0.2$) and which satisfies $n_{\text{track}} < 3$ are rejected.
- Muons that are within $\Delta R(\mu, \text{jet}) \leq 0.4$ of a jet are rejected.

APPENDIX D

Event Displays

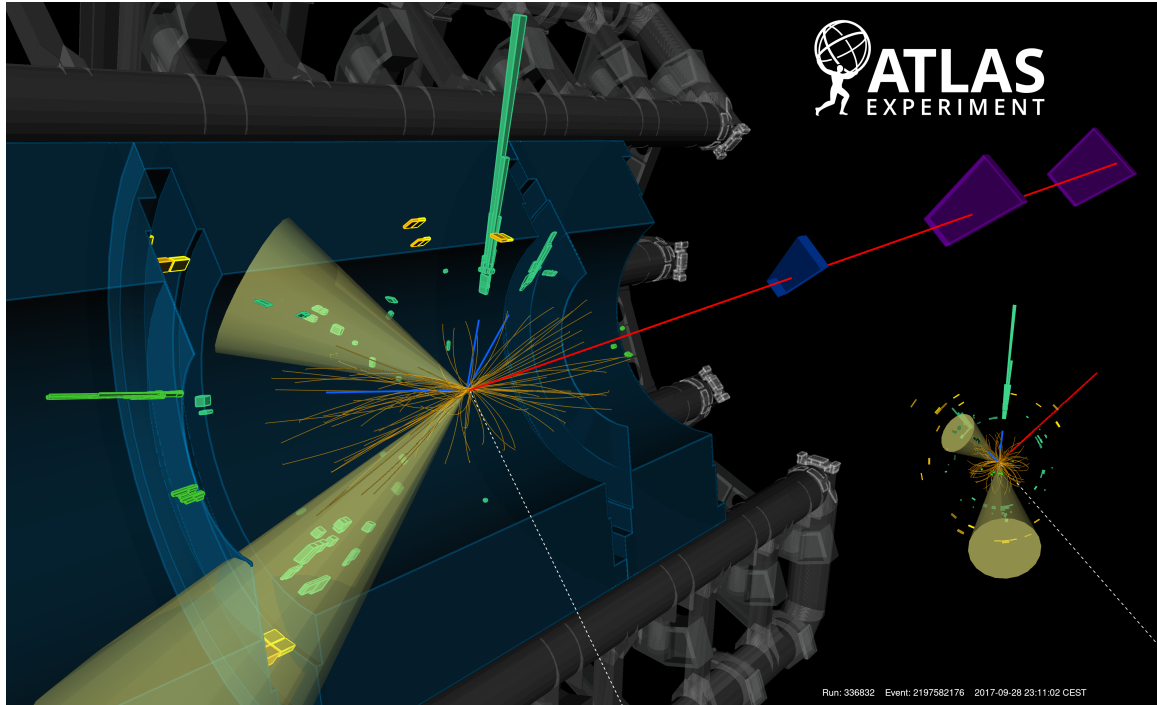


Figure D.1: The event display shows a data event recorded in September of 2017 which falls into the fully reconstructed signal region (SRFR). The event consists of three electrons (blue lines), one muon (red line) and two jets (yellow cones), neither of which are b -tagged. Two electrons with kinematic properties (p_T , η , ϕ) of (46.5 GeV, 1.14, 0.52) and (61.8 GeV, -2.14, 0.42) form an invariant mass of $m_{\ell\ell} = 93.2$ GeV, consistent with a Z boson. They are paired with a third electron (103.4 GeV, 0.09, 1.31), with $m_{Z\ell} = 365.8$ GeV. The first jet (77.9 GeV, -1.17, -2.00) and second jet (32.3 GeV, -0.76, 0.26) are used to reconstruct a second Z boson candidate of $m_{jj} = 94.7$ GeV. The jets are paired with the muon (44.7 GeV, 2.33, 2.04), with $m_{Z\ell} = 403.0$ GeV. The event has a missing transverse energy of $E_T^{\text{miss}} = 116.49$ GeV, which is represented as a dashed white line at $\phi = -2.40$ [51].

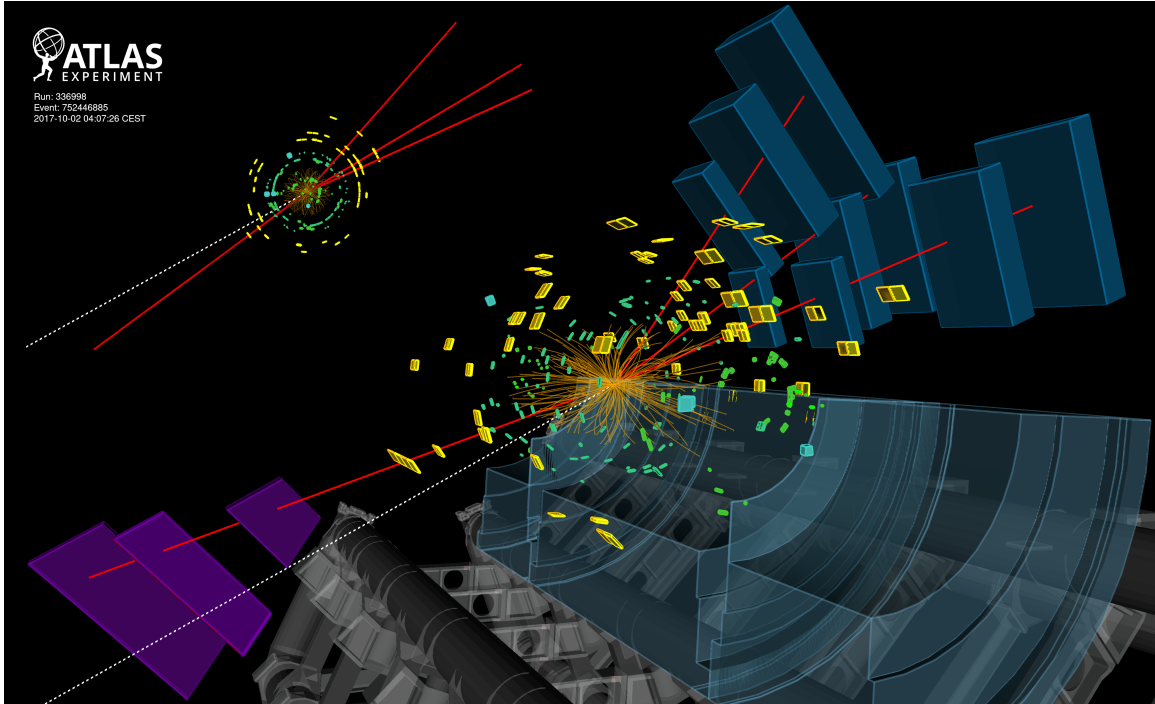


Figure D.2: The event display shows a data event recorded in October of 2017 which falls into the four lepton signal region (SR4 ℓ). This event consists of four muons (red lines). Two muons with kinematic properties (p_T , η , ϕ) of (179.0 GeV, -0.26, 0.53) and (292.9 GeV, 0.10, 0.43) form an invariant mass of $m_{\ell\ell} = 88.4$ GeV, consistent with a Z boson. They are paired with a third muon (206.8 GeV, -1.08, -2.50), with $m_{Z\ell} = 719.4$ GeV. There is a fourth muon (126.6 GeV, -0.29, 0.85) that is unpaired. The event has a missing transverse energy of $E_T^{\text{miss}} = 390.6$ GeV, which is represented as a dashed white line at $\phi = -2.66$. [51]

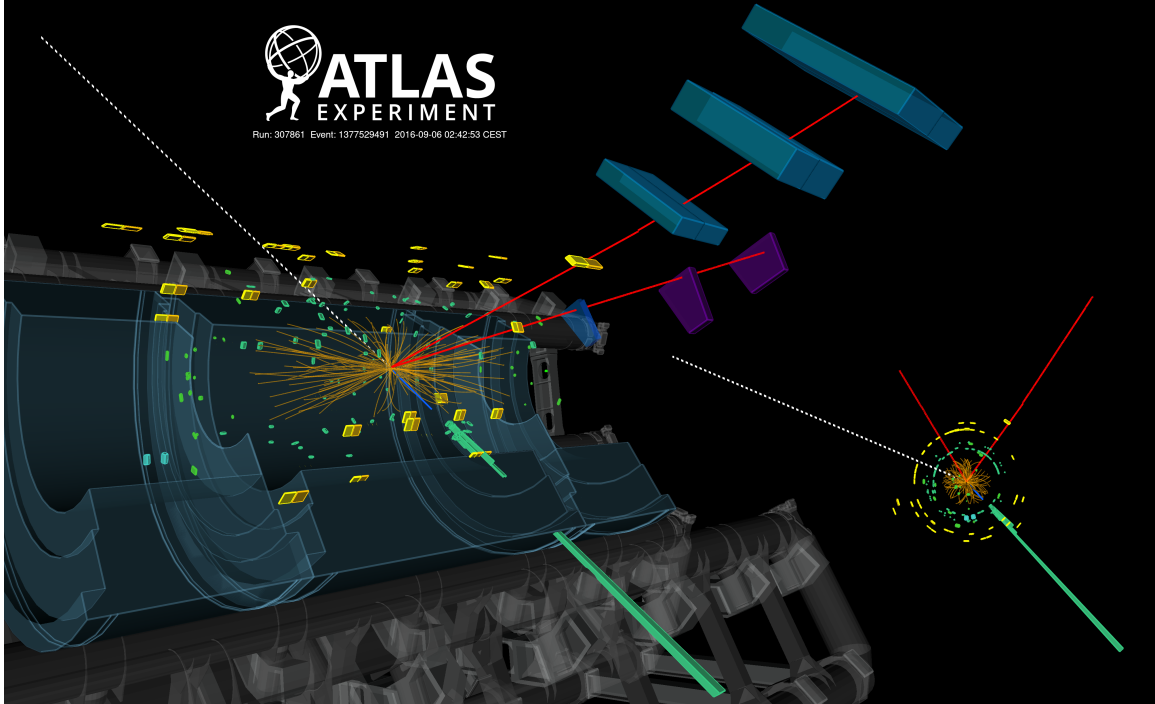


Figure D.3: The event display shows a data event recorded in September of 2016 which falls into the three lepton signal region (SR3 ℓ). This event consists of two muons (red lines) and one electron (blue line). The muons with kinematic properties (p_T , η , ϕ) of (217.0 GeV, -2.05, 1.87) and (14.4 GeV, -0.97, 0.74) form an invariant mass of $m_{\ell\ell} = 87.0$ GeV, consistent with a Z boson. The muons are paired with the electron (362.2 GeV, -0.53, -1.06), with $m_{Z\ell} = 742.7$ GeV. The event has a missing transverse energy of $E_T^{\text{miss}} = 172.5$ GeV, which is represented as a dashed white line at $\phi = 2.51$. [51]

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