

ELECTRON IDENTIFICATION, ELECTRONICS UPGRADES, AND
ELECTROWEAK SUPERSYMMETRY AT ATLAS

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A DISSERTATION

in

Physics and Astronomy

Presented to the Faculties of The University of Pennsylvania
in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy
2019

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Acknowledgements

Physics is a collaborative field that builds upon collective knowledge that has been carved out over centuries. As a result, there are more people who deserve credit for making this thesis possible than I could possibly name or easily fit on just a few pages. I will try to highlight here a few people who have personally helped to make my time in graduate school both fun and fulfilling.

Thanks to Joe Kroll for taking me on as a student six years ago and mentoring me so closely over that time. I really appreciate everything that I have learned from you, your constant support of me and the rest of the students in the Penn group, and for all of the advice you’ve provided over the years—especially your ten tips to live forever. Thanks also to the rest of the Penn ATLAS faculty, namely Brig Williams, Evelyn Thomson, and Elliot Lipeles. Working in such a collaborative group has been one of my favorite things about being in the Penn ATLAS group, and I can’t imagine any better graduate school experience.

When I first joined Penn and started working on the electron likelihood, I learned a ton from Kurt Brendlinger and Sarah Heim. Thanks to both of you for the many hours that you spent teaching and mentoring me; my early years at Penn wouldn’t have been the same without the two of you. At Penn, I also owe a great deal of thanks to my other collaborators on the electron identification and efficiency measurements, namely Rob Fletcher, Lucas Flores, and Chris Lester. The rest of the e/γ group was also always supportive of me, even when I was an inexperienced young graduate student. Thanks to Christos Anastopoulos, Ludovica Aperio Bella, Moritz Backes, Eleonora Benhar Noccioli, Cristi Diaconu, Sandrine Laplace, Kristin Lohwasser, Gabi Pásztor, Philip Sommer, Kerstin Tackmann, Savannah Thais, Guillaume Unal, Manuella Vincter, and many others.

Thanks to Joana Machado Miguéns and Elodie Resseguie, my two constant collaborators in the world of electroweak SUSY searches. I’ll miss working with both of you, it was always really great! I was fortunate to later get to work on these searches with other Penn collaborators, namely Shion

Chen, Jeff Dandoy, and Ian Dyckes. Kurt Brendlinger and Keisuke Yoshihara also deserve thanks for sharing all of their extensive knowledge and expertise about fake leptons when I first started working on analysis. Even though we never overlapped as students at Penn, I learned a whole lot from Mike Hance, and I am really glad that he and Joana led the compressed electroweak analysis for its first result. There are countless other collaborators in the SUSY group who I am thankful for having worked with, including Sara Alderweireldt, Moritz Backes, Matthew Gignac, Julia Gonski, Ben Hooberman, Jesse Liu, Lorenzo Rossini, Sheena Schier, Jeff Shahinian, Iacopo Vivarelli, Sarah Williams, and Stefano Zambito.

Nearly everything I know about electronics is thanks to the Penn Instrumentation Group. Thanks to Paul Keener, Godwin Mayers, Mitch Newcomer, Adrian Nikolica, and Mike Reilly for all of the help. Thanks also to everyone who helped with the AMAC chip testing and irradiations, including Vani Ramabadran, Sicong Lu, Luis Gutierrez, Karol Krizka, Daniel Raimundo, Stefania Stucci, and Jim Kierstead.

There are many friends who haven't yet been mentioned that I should also thank, including Khilesh Mistry, Bijan Haney, Leigh Schaefer, Will DiClemente, Bill Balunas, Christian Herwig, Rachael Creager, Ben Rosser, Joe Mullin, James Heinlein, Eric Marzec, John Alison, Alex Tuna, and Kelvin Mei. It's been wonderful sharing offices with many of you, having fun in Geneva and at workshops around the globe, and solving the truly important problems in the world at lunch every day. I hope that our regular discussions about topics such as the connectivity of roads, Brewster's Millions / Operation Condor, and citrus classification (well, maybe all forms of classification) will come in handy someday. The city of Philadelphia should be considered an honorary friend as well. Thank you to Philadelphia for being the best place I've ever lived; I can't imagine a better home for the past six years.

There are many people who influenced me even before I got to Penn. I am indebted to Yuri Gershtein, Mohan Kalelkar, and Dave Maiullo, who were among the many people at Rutgers who initially set me on this course and instilled in me a sense of purpose in the pursuit of physics.

Thanks to my parents, Ron and Stephanie, for everything you taught me. I wouldn't be who I am without you. Thanks also to my brother Steven, my grandparents, my many aunts and uncles, and all of my cousins. I'm really lucky to have such a great family.

Finally, thanks to Kristen for being with me and supporting me every step of this journey—I'm so glad that I've had you by my side all this time, and I'm really excited to see what our future holds. I love you to the sun and back, forever.

ABSTRACT

ELECTRON IDENTIFICATION, ELECTRONICS UPGRADES, AND ELECTROWEAK SUPERSYMMETRY AT ATLAS

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I. Joseph Kroll

This thesis presents two searches for direct production of “electroweakinos”, the supersymmetric partner particles (“superpartners”) of the Standard Model photon, W , Z , and Higgs bosons. These searches were performed using 36 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ data collected by the ATLAS detector during Run 2 of the Large Hadron Collider (LHC). The first search focuses on a final state with three prompt leptons (electrons or muons) from on-shell W and Z bosons produced in decays of the electroweakinos. The second search focuses on compressed scenarios where the electroweakinos decay via off-shell W and Z bosons to pairs of leptons with small transverse momenta (p_T). This second search allowed for the first exclusions of directly produced compressed Higgsinos at the LHC. In describing these searches, particular emphasis is placed on the estimation of backgrounds which mimic prompt leptons. This thesis also details the ATLAS electron identification algorithm, which distinguishes prompt electrons from backgrounds using a likelihood-based method. Significant improvements have been made to this algorithm during Run 2 including reoptimization of the selection criteria for new detector conditions, extension of the algorithm to a wider range of electron p_T , and adaptation of the algorithm for the real-time selection of events. The corresponding measurements of the efficiencies for electron identification and other electron selection criteria are also described. Finally, readout electronics designed for upgrades to the ATLAS tracking system for use during the high-luminosity phase of the LHC are discussed. During this high-luminosity phase, an expected 3000 fb^{-1} of data will be delivered to ATLAS. It is therefore essential to ensure that ATLAS will be able to efficiently operate and collect data despite the significant radiation damage it will receive. The expected performance of one readout chip (“AMAC”) is demonstrated via functionality and irradiation tests of several prototypes, and good performance is observed.

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Preface

I started as a graduate student at Penn working on the ATLAS experiment in July 2013, and since that time I have focused on several “big picture” areas: electron identification and efficiency measurements, electronics for upgrades to the ATLAS tracking system, and searches for electroweak production of supersymmetric particles. This thesis describes all of these contributions in detail.

Electron Identification and Measuring Electron Identification Efficiency

Since I first joined ATLAS, I have worked to develop and improve the electron identification algorithms used by the entire experiment. This is important because many of the known fundamental particles, collectively referred to as members of the Standard Model of particle physics, can decay into electrons. Moreover, as most proposed extensions to the Standard Model introduce new particles which subsequently decay into Standard Model particles, the electron identification directly affects many searches for new physics at ATLAS, in addition to being essential for precision measurements of the Standard Model particles.

Electron identification is challenging because there are many background sources which can occasionally look similar to electrons when traveling through the ATLAS detector, and the production rates of these background sources, which we refer to as “fake electrons”, tend to be large. For example, the rate for production of W bosons which subsequently decay to electrons is on the order of one in a million events at the LHC, while the majority of the other events which we can see with the ATLAS detector involve “jets” of quarks and gluons which travel through the detector. While these jets typically leave quite different signatures in the detector compared with the signatures for electrons, the much larger production rates for jets means it is still possible for jets to mimic electrons. Processes containing fake electrons frequently serve as important backgrounds in analyses which use electrons for physics measurements and searches.

During the first LHC data collection period from 2011-2012, referred to as Run 1, several Penn graduate students worked to develop a set of selection criteria to efficiently select real, prompt electrons while rejecting fake electrons by relying on information from the many ATLAS subdetectors such as the charged particle tracking system and the energy deposited in the electromagnetic calorimeter. This was then followed by the development of a software tool which made use of a multivariate technique (the likelihood method) which could more efficiently use the information from the ATLAS detector, and improved the fake electron rejection power by a factor of two without significantly affecting the efficiency to select a prompt electron.

Starting in 2013, I took responsibility for maintaining and developing the likelihood-based electron identification algorithm, with the goal of having a well-performing electron identification for ATLAS which would be ready for the start of the second LHC data collection period (Run 2) in 2015. In particular, I wanted to ensure that the likelihood-based algorithm could be the default electron identification used by ATLAS physics analyses.

One of my most significant accomplishments has been to adapt and implement this method for use in the ATLAS software-based trigger system. This trigger system is used to select events in real-time, to determine which events should be saved for further analysis. This is necessary because the LHC delivers over one billion collisions per second, but there is only enough bandwidth and disk space to save around 1000 events per second. By using the likelihood method for electron identification at trigger level, fewer background events are written to disk than was the case in the past using less effective electron identification methods, and thus the limited bandwidth for the trigger system can be used more efficiently.

Many other improvements were necessary to the likelihood-based electron identification algorithm in the past few years. One such improvement was to adapt the algorithm to efficiently select electrons with transverse momenta as low as 4 GeV (where 1 GeV is roughly the mass of a proton) and up to several 1000s of GeV. In Run 1, the likelihood-based algorithm was only supported and efficient for electrons with transverse momenta between 7 GeV and several 100s of GeV, and extending this range to both smaller and higher momenta required careful study of the various signatures which an electron leaves in the ATLAS detector. Extending this momentum range which the electron identification algorithm was capable of covering has had a direct effect on searches for new physics at both low [1] and high energies [2,3], as these searches would not have been possible without these improvements.

When ATLAS first started collecting data again in 2015, I also became involved in the electron identification efficiency measurement. Precisely measuring the electron identification efficiency is

necessary for all ATLAS analyses which use electrons, and minimizing the systematic uncertainty associated with this efficiency measurement is important as it can otherwise significantly affect ATLAS analyses, particularly Standard Model measurements. This is performed using a “tag-and-probe” method, where the decay of the Z boson to two electrons is used to make unbiased measurements of electrons in the ATLAS data, followed by the removal of background events associated with fake electrons. I provided a common software framework for other ATLAS analyzers to use, so that anyone interested in using the tag-and-probe method to make measurements of electrons would be able to do so. To date, over 40 ATLAS analyzers have made use of this software as one of their primary ways of interfacing with the ATLAS data, and this has helped to prevent the need for people to “reinvent the wheel” with the software and instead allowed them to focus on the physics behind the electron efficiency measurements.

My work on preparing and commissioning the electron identification, as well as my work on the electron identification efficiency measurement, is documented in [4–6].

Electronics: the Autonomous Monitor and Control Chip

After contributing for several years to the detector performance through my work on the electron identification software, I wanted to expand my horizons and learn about detector hardware. In addition to faculty members, postdocs, and graduate students, the Penn High Energy Physics group also has a large number of engineers who comprise the Penn Instrumentation Group. Prior to Run 1, the Penn Instrumentation Group and many Penn students and postdocs developed the electronics for the Transition Radiation Tracker (TRT). This subdetector is part of the ATLAS “tracking system”, which measures the trajectory of charged particles. These charged particle measurements are essential for the reconstruction and identification of every particle which travels through the ATLAS detector, including for the electron identification which I previously worked on.

However, the existing ATLAS tracking system has sustained radiation damage which would start to become significant by the mid-to-late 2020s under the current LHC plans. Thus, the ATLAS collaboration will replace the TRT and the other subdetectors which are part of the existing tracking system in the mid-2020s. The replacement system, known as the Inner Tracker (ITk), will be used during ATLAS data collection from roughly 2025 through 2035, a period during which the LHC plans to deliver ten times more data than will be delivered to ATLAS up to that time. It is therefore essential that this detector will be tolerant to radiation damage.

Our group is responsible for designing and testing several application-specific integrated circuit

(ASIC) chips to be used by the ITk. In 2017, I began working on testing one of these ASICs, the Autonomous Monitor and Control Chip (AMAC). This chip is designed to provide power control for two other ASIC chips used in the ITk Strips subdetector, in addition to monitoring voltages, currents, and temperatures. Moreover, the AMAC provides the ability to flag when input monitored values such as voltage or temperature are either lower or higher than anticipated, in which case it may be dangerous for the system to continue operating.

A new iteration of the AMAC, referred to as AMACv2, was submitted for production in mid-November 2017. Before this submission, we wanted to check if a previous iteration of the chip, the AMACv1a, would continue to function after receiving a radiation dose as large as the dose expected during the LHC data collection period from 2025 through 2035. While the two versions are not identical, the concern was that if the AMACv1a malfunctioned due to these large radiation doses, then the AMACv2 might have similar vulnerabilities.

I worked with the Penn Instrumentation Group to improve the software and firmware used to perform tests of the AMACv1a and to measure various output quantities. We then brought our AMACv1a chip with its test and control system to Brookhaven National Lab's (BNL) cobalt-60 gamma-ray source, which is a source for high intensity photons with an energy of roughly 1 MeV. We collected data both before irradiation began and during the two months that the chip was being irradiated, and I analyzed the data and monitored the outputs during this time to be sure the chip was still giving sensible results. Ultimately, we exposed the AMACv1a to roughly 1.5 times the dose expected when the AMAC is installed in the ATLAS detector, and we found that the chip behaved as expected during this time. This meant there were no major issues which would require changes to the AMACv2 design.

In mid-2018, we received the AMACv2 chips, and I worked with collaborators at Penn and Lawrence Berkeley National Lab to test the functionality of the new version of the ASIC. This involved contributing to the design, software, and firmware for a brand new test and control system which could provide power to the AMACv2 and a means to control its inputs, as well as the ability to measure various output quantities. Since then, we have tested the basic functionality of the AMACv2 in addition to performing irradiation tests using gamma-rays at the BNL cobalt-60 source (to study total ionizing dose effects) as well as with 24 GeV protons at the CERN Proton Synchrotron (to study single event effects and bulk damage to the chip). These have been used to help determine changes for future versions of the chip, as well as to get an estimate of the AMAC's power consumption as a function of total ionizing dose.

Searching for Electroweak Supersymmetry

Finally, I have also been active in analysis of the ATLAS data to search for new physics. In these analyses, I have made extensive use of my expertise in electron identification.

Once the final missing piece in the Standard Model of particle physics, the Higgs boson, was discovered in 2012, there was an important new problem to be solved. The so-called “hierarchy problem” asks how it is possible for the Higgs boson to be a light particle despite quantum mechanical corrections to its mass which should force it to be heavier by many orders of magnitude. Supersymmetry (SUSY) is one proposed extension to the Standard Model which provides a solution to the hierarchy problem while simultaneously solving many other outstanding issues in particle physics. SUSY does so by introducing a new symmetry of nature which creates a supersymmetric partner particle for each Standard Model particle. These superpartners also contribute quantum mechanical corrections to the mass of the Higgs boson, but when the contributions from the Standard Model particles are positive, the corresponding contributions from the SUSY particles are negative (and vice versa), allowing these terms to cancel. Thus, SUSY is a very attractive theory as it provides a natural and simple solution to the hierarchy problem, and allows the Higgs boson to exist at the mass which has been measured by the ATLAS and CMS experiments.

However, searches for SUSY have already produced null results in many scenarios where the production of the superpartners should be common. Weakly produced scenarios (commonly referred to as “electroweak SUSY” scenarios), meanwhile, are much less constrained by existing searches. As ATLAS has collected a significant amount of data in recent years, there is motivation to use this existing data to search for rare production of SUSY particles—new physics could be hiding in data which ATLAS has already collected, just waiting to be discovered. Furthermore, there are well-motivated scenarios where the electroweak SUSY particles are naturally similar in mass (“compressed” scenarios), resulting in a small amount of energy which is available for the decay products. While well-motivated, such scenarios are difficult to probe as the particles which travel through the detector have small momentum, and can therefore be difficult to reconstruct and identify.

The searches I worked on made use of events with either two or three light leptons (electrons or muons) [1, 7]. In particular, the analysis which focused on events with two leptons attempted to probe the compressed SUSY scenarios, and relied on the very low transverse momentum electron identification which I had previously worked on. This analysis set limits on the direct production of Higgsinos, the superpartners of the Higgs boson, which was the first such result since the LEP experiments from over fifteen years ago.

As part of these searches for SUSY, I developed expertise in understanding and estimating fake lepton backgrounds, which are often difficult to estimate. While jets and other sources of fake leptons have large production rates, they typically look quite different from prompt leptons, and only occasionally mimic a prompt lepton. This makes it challenging to accurately measure the rates at which these particles are incorrectly identified as leptons in the ATLAS detector, and even small inaccuracies in understanding these rates can result in large uncertainties on the fake lepton estimates. This introduces an experimental challenge that must be addressed via techniques which use the ATLAS data in clever ways. These fake leptons were the dominant background source for the compressed SUSY search, in addition to being the primary source of uncertainty in the analysis. I used this knowledge to develop common software tools for others in the ATLAS collaboration to make use of for fake lepton estimation, along with contributing to a forthcoming ATLAS paper which will detail techniques commonly used for estimating fake lepton backgrounds.

While my work on fake lepton estimation was my most significant contribution to the SUSY searches I worked on, I also contributed to these searches in a broad variety of other ways. To highlight a few contributions, this includes development and maintenance of the software framework used for both of these searches, the production of the $\mathcal{O}(\text{GB})$ -sized inputs (“ntuples”) containing the relevant data and simulated events used for all of the studies and results in the compressed SUSY search, and studies of the working points used for leptons and b -jets. These analyses were performed using 2015–2016 data, but I also worked to ensure that the software framework for these searches will be equally successful for the upcoming papers using the full LHC Run 2 data (2015–2018).

SUSY is an extremely well-motivated extension to the Standard Model, and the LHC provides a unique opportunity to search for the particles predicted by the theory. If light SUSY particles exist and are weakly produced in the natural scenarios we are searching for, then we have the chance to make a discovery with the with the LHC Run 2 data collected by ATLAS and CMS. Furthermore, since ATLAS and CMS will be collecting data through the mid-2030s, we will eventually have a dataset many times larger than what has been collected so far, which will provide even more opportunities to discover and make measurements of the SUSY particles, or alternatively rule out many of the most promising variants of SUSY. Working on ATLAS with collaborators at Penn and elsewhere has made my time in graduate school extremely fulfilling, and I am excited to see the improvements and results that will come from ATLAS in the future.

Joseph P. Reichert

Philadelphia, March 2019

CHAPTER 1

Introduction

On July 4, 2012, the ATLAS and CMS experiments announced the discovery of a new particle whose properties were consistent with the Higgs boson [8,9], the final undiscovered particle in the Standard Model of particle physics. This marked an important milestone for the field of particle physics, as the Higgs boson had been predicted nearly 50 years earlier, and—incredibly—the long search for this particle was finally successful.

The Standard Model is a very successful theory, but there are many open questions in particle physics today, including the question of how the Higgs boson can have a relatively small mass despite quantum mechanical corrections that should naturally force its mass to be orders of magnitude heavier. Experimental particle physicists today want to solve this and other problems by discovering new physics beyond the Standard Model. The theoretical foundations for the Standard Model and one potential extension to it are discussed in Chapter 2.

Chapters 6 through 8 of this thesis describe two searches for supersymmetry, one of the most promising extensions to the Standard Model. Supersymmetry is capable of resolving many of these open questions, so if it is realized in nature, its discovery would be one of the most important scientific breakthroughs in history. The searches discussed in this thesis were designed to probe rare production of supersymmetric particles which subsequently decay to very distinctive final states containing light charged leptons, thus allowing for good discrimination between potential supersymmetric particles and the Standard Model backgrounds. A particular focus in this thesis regards the estimation of backgrounds which contain “fake” and “nonprompt” leptons. These serve as important backgrounds in searches for supersymmetry and other ATLAS analyses when the signatures deposited in the ATLAS detector by “prompt” leptons (such as those from direct decays of supersymmetric particles or the Higgs boson) are mimicked by these “reducible” background sources that

would not be present in a perfect, ideal detector.

The ATLAS detector was built to discover the Higgs boson and physics beyond the Standard Model by relying on the known signatures of several of the fundamental Standard Model particles. One of these particles is the electron; however, fake and nonprompt background sources can spoil the ATLAS electron identification capabilities, thus reducing the experiment’s ability to make discoveries and important Standard Model measurements in distinctive leptonic final states. As a result, one of the most important goals of the ATLAS experiment is to efficiently select prompt electrons while suppressing these backgrounds. A likelihood-based method is currently used as the default electron identification algorithm by all ATLAS analyses, and Chapter 4 of this thesis discusses the challenges that were associated with adopting it for a wide range of uses for the data collected by ATLAS in 2015–2018. Similarly, to ensure that the sensitivity of ATLAS physics analyses is not compromised due to mismodeling present in the simulated events typically used for the estimation of backgrounds resulting in prompt electrons, it is essential that the efficiencies of the electron identification algorithm and other electron selection algorithms are precisely known. These are measured by relying on the decay products of known resonances, as discussed in Chapter 5.

Finally, while the current ATLAS detector (described in Chapter 3) has been successfully operating since the Large Hadron Collider first started colliding protons nearly a decade ago, ATLAS will be unable to maintain its high performance forever into the future. Many components of the ATLAS detector have sustained radiation damage over the past decade, and will continue to do so until being replaced. The ATLAS Inner Detector, which is designed to track the trajectories of charged particles, will be replaced in the mid-2020s with the new Inner Tracker (ITk) subdetector. The various components of this subdetector are currently being designed and tested for resilience against radiation damage as well as high performance even in conditions where up to 200 proton–proton interactions occur simultaneously at the ATLAS interaction point. Chapter 9 focuses on the testing of several prototypes for one of the readout electronics chips which will be used in the ITk. These upgrades are critical for ATLAS, as they will allow ATLAS to collect good physics data into the future—data which might be used to discover and measure new particles associated with an undiscovered symmetry of nature.

CHAPTER 2

Theoretical Framework

2.1 Introduction to the Standard Model

The Standard Model (SM) of particle physics is a quantum field theory that describes all of the known elementary particles that comprise matter in the universe and three of the four fundamental forces which mediate interactions between them. This theory has been constructed over the course of the past century, and its predictions have been experimentally verified in a wide range of energy regimes during that time. The fundamental particles that are part of the Standard Model can be grouped into several categories, namely:

- **the charged leptons:** electron¹ [10], muon [12], and tau [13];
- **neutral leptons:** electron neutrino [14], muon neutrino [15], and tau neutrino [16];
- **up-type quarks:** up quark [17, 18], charm quark [19, 20], and top quark [21, 22];
- **down-type quarks:** down quark [17, 18], strange quark [17, 18, 23], and bottom quark [24];
- **gauge bosons:** photon [25], W boson [26, 27], Z boson [28, 29], and gluon [30–33];
- **scalar boson:** the Higgs boson [8, 9].

The citations next to each of these correspond to the experimental discoveries for the given particle, many of which subsequently resulted in a Nobel Prize awarded to the experimenters responsible for the discoveries or the theorists who predicted the new particles. Figure 2.1 graphically illustrates these Standard Model particles and provides a summary of information about the particle properties.

¹In this thesis, both electrons and positrons [11] (the antimatter counterpart of electrons) are typically referred to collectively as “electrons”.

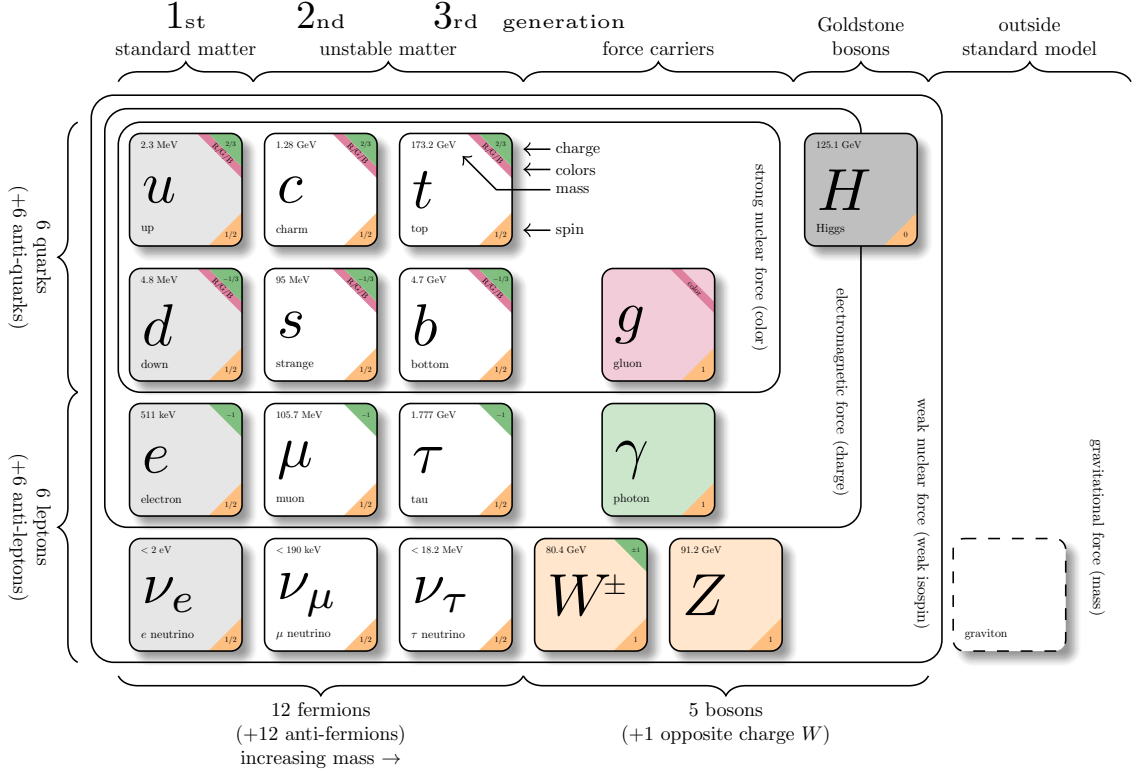


Figure 2.1: The elementary particles in the Standard Model, grouped according to the forces which mediate their interactions, their spin (fermions with half-integer spin and bosons with integer spin), and their generation (for the fermions). The electric charge, color charge, mass, and spin are also shown for each particle, when relevant [34].

The SM is invariant under a $SU(3)_C \times SU(2)_L \times U(1)_Y$ local gauge symmetry. The $SU(2)_L \times U(1)_Y$ component of this product group describes quantum electrodynamics (QED) and the weak nuclear force. QED [35] is the quantum field theory describing the electromagnetic force, which is mediated by photons and is responsible for interactions between electrically charged particles. The weak nuclear force, meanwhile, is mediated by the W and Z bosons. This force is responsible for nuclear decays as well as flavor-changing interactions among the quarks (i.e. interactions across the generations shown in Figure 2.1). The electromagnetic force and weak force are united at high energies, and are collectively referred to as the “electroweak” (EWK) interaction [36–39]. The other component of this product group, $SU(3)_C$, describes quantum chromodynamics (QCD), which is the non-Abelian gauge theory that governs interactions between quarks and gluons. Gluons are the force carriers of the strong force, which mediate interactions among quarks. Quarks are charged under a conserved quantity known as “color”, of which there are three possible values: red, green,

and blue. The strong force causes bound states of quarks to form, which are generically referred to as hadrons. Hadrons are always “colorless”, that is, either a combination of all three colors of quarks or a combination of a quark of a given color and its antimatter partner. Hadrons which are a bound state of three quarks are called baryons, while bound states of two quarks are called mesons. Some example baryons are protons and neutrons, while some example mesons are pions, kaons, and J/ψ [40–44].

The force carrying particles in the SM are spin-1 gauge bosons, while the matter particles are spin- $\frac{1}{2}$ fermions. The SM also includes one spin-0 particle, the Higgs boson. The Higgs boson is the particle responsible for the Higgs mechanism, which allows the fundamental particles to acquire mass and also allows for the breaking of the $SU(2)_L \times U(1)_Y$ electroweak gauge symmetry at low energies [42–48]. The Higgs boson was the final Standard Model particle which had not yet been observed until its discovery by the ATLAS and CMS experiments in 2012 [8, 9].

The SM has been extremely successful, and measurements of the vast majority of SM particles to date have agreed well with the theoretical predictions. The production cross-sections measured thus far by the ATLAS experiment alongside the predicted values can be found in Figure 2.2.

2.2 Introduction to Supersymmetry

Despite the successes of the Standard Model, it cannot be a complete theory of nature as there are many unsolved problems in particle physics which are not described by the Standard Model. First, the SM only explains the electroweak and strong interactions, but does not provide a quantum theory of gravity. The energy scale at which gravitational effects become important is the Planck scale:

$$M_{\text{Planck}} = \sqrt{\frac{\hbar c}{8\pi G}} \approx 2.4 \times 10^{18} \text{ GeV}, \quad (2.1)$$

where G is Newton’s gravitational constant, $\hbar$ is the reduced Planck constant, and c is the speed of light². However, the mass of the Higgs boson has loop-order quantum mechanical corrections associated with each particle that either directly or indirectly couples to the Higgs boson. For a fermion f with coupling λ_f , the correction to m_H^2 (for Higgs boson mass m_H) is:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{\text{UV}}^2 + \dots, \quad (2.2)$$

where Λ_{UV} is the ultraviolet momentum cutoff specifying the energy scale at which new physics becomes relevant and modifies the behavior of the theory at high energy. However, if the ultraviolet

²In this thesis and in many particle physics papers, units are typically used in which factors of $\hbar$ and c can be ignored.

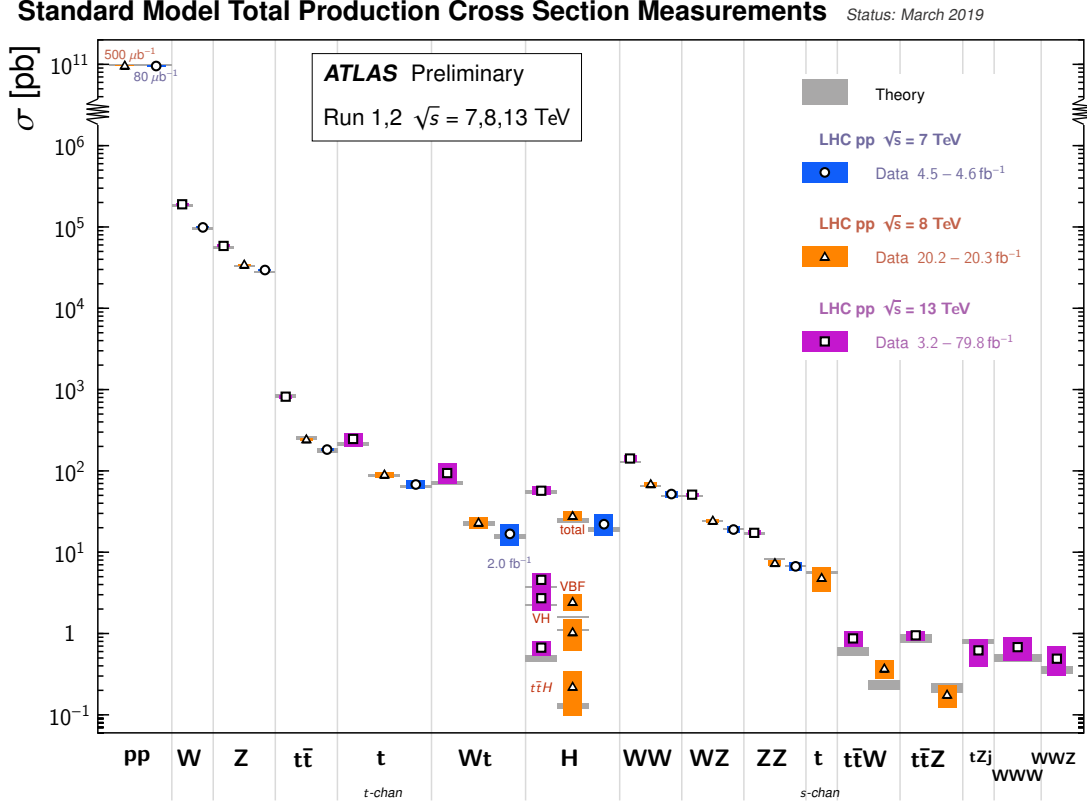


Figure 2.2: The production cross-sections of various Standard Model processes measured by the ATLAS experiment at $\sqrt{s} = 7, 8$, and 13 TeV, as of March 2019. The measurements are compared with theoretical predictions, and no major discrepancies have been observed to date [49].

cutoff is the Planck scale, then the correction to the Higgs mass is many orders of magnitude larger than the Higgs mass itself (roughly 125 GeV). This problem is referred to as the “hierarchy problem” [42, 50], and this appears to suggest that the corrections to the Higgs mass are fine-tuned to allow the corrections to cancel precisely. This, however, is not a particularly elegant or natural solution, which is why many particle physics theorists have attempted to study alternative models that could naturally avoid these large corrections and provide an explanation for the stability of the Higgs mass [50].

Another problem in the SM is the existence of dark matter, which is necessary to explain astrophysical observations. The only particles in the SM which interact weakly enough to contribute to the observed dark matter are the neutrinos; however, their masses are too small to account for the observations that suggest that dark matter comprises about 23% of the energy density of the

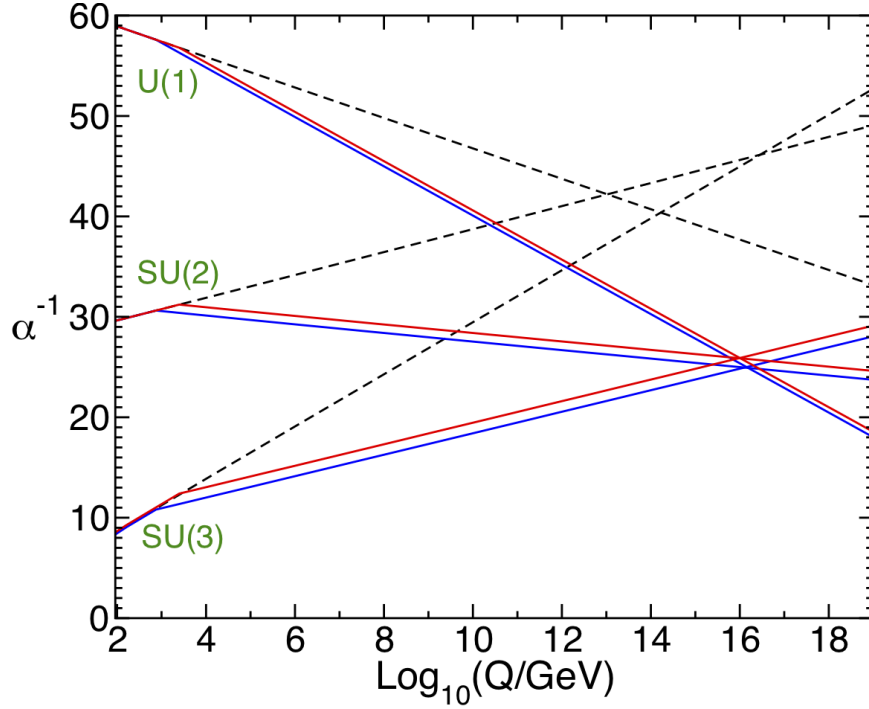


Figure 2.3: Unification of the gauge coupling constants, shown as a function of the energy. The y-axis shows the inverse of each SM gauge coupling. The dashed line represents the Standard Model, while the solid lines represent the Minimal Supersymmetric Standard Model with varied thresholds on the particle masses [50].

universe (compared with 5% for the Standard Model baryonic matter and 72% for dark energy). Instead, new weakly interacting particles must be introduced to explain this [42].

A third problem in the SM pertains to the unification of the forces. The coupling constants associated to each of the SM gauge interactions vary with energy in the SM, and it is expected that these would all converge to a single value in a Grand Unified Theory (GUT). Figure 2.3 shows that these do not converge in the Standard Model, but this unification is possible in extended models [50].

Supersymmetry (SUSY) attempts to resolve all of these issues, among others. SUSY predicts a new spacetime symmetry of nature which relates bosons to fermions. As a result, for each Standard Model particle, SUSY predicts a corresponding superpartner which differs by $\text{spin}-\frac{1}{2}$. These superpartners (“sparticles”) have names which add the prefix letter “s” to the names of the SM fermions and the suffix “-ino” to the names of the SM bosons. Some example SUSY particles are the selectron ($\tilde{e}$), the stop ($\tilde{t}$), and the bino ($\tilde{B}^0$, where the SM B^0 boson is mixed with the W^0 boson during electroweak symmetry breaking to form the photon and Z boson). As the Higgs mass

correction terms from Equation 2.2 differ by a minus sign for fermions and bosons, SUSY allows the contribution to the Higgs mass correction for each SM particle to cancel with its corresponding SUSY particle, assuming the SM and SUSY particles have the same mass. Of course, if the SUSY particles did have the same mass as the SM particles, they already would have been discovered. As a result, SUSY must be a broken symmetry, similar to the broken electroweak symmetry discussed in Section 2.1 [42, 50].

In addition to solving the hierarchy problem, many versions of SUSY (particularly those where R -parity is conserved) predict that the lightest supersymmetric particle, or “LSP”³, is stable. This naturally provides a dark matter candidate when the LSP is electrically neutral. Furthermore, the evolution of the gauge couplings with energy are dependent on the masses of the particles present in the given model. In addition to showing the running of the gauge couplings of the Standard Model, Figure 2.3 also shows how the couplings behave in example variants of SUSY—in both SUSY models shown, the gauge couplings unify at high energy due to the presence of the SUSY particles in the loop-order contributions to these couplings [50]. With all of these theoretical predictions, SUSY is an extremely promising theory of nature, and manages to resolve many open questions in particle physics.

2.2.1 The Electroweak Supersymmetry Sector

As the motivation for searches and description of analyses presented in Chapters 6 through 8 pertain to the EWK SUSY sector, this section describes the particle content in this sector of the Minimal Supersymmetric Standard Model (MSSM), which is the simplest variant of SUSY that is consistent with experimental observations.

In the MSSM, the EWK SUSY sector contains four neutralinos and two charginos. As with the EWK sector of the Standard Model, weak eigenstates mix to form the mass eigenstates. The weak eigenstates of the EWK SUSY sector include the bino ($\tilde{B}^0$), winos ($\tilde{W}^0, \tilde{W}^+, \tilde{W}^-$), and Higgsinos ($\tilde{H}_u^0, \tilde{H}_d^0, \tilde{H}_u^+, \tilde{H}_d^-$). These mix to form the mass eigenstates, which are referred to as neutralinos ($\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$) and charginos ($\tilde{\chi}_1^+, \tilde{\chi}_1^-, \tilde{\chi}_2^+, \tilde{\chi}_2^-$). Note that the subscripts shown for the neutralinos and charginos are ordered sequentially with smaller numbers always indicating smaller masses. The

³Similarly, the next-to-lightest supersymmetric particle is denoted “NLSP”.

mixing matrix for neutralinos [50] using $\psi^0 = (\tilde{B}^0, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$ as the gauge eigenstate basis is:

$$\mathbf{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}. \quad (2.3)$$

In this mixing matrix, M_1 , M_2 , and μ are the bino, wino, and Higgsino mass terms from the MSSM Lagrangian, respectively. m_Z is the mass of the Standard Model Z boson. s_W and c_W are shorthand for $\sin \theta_W$ and $\cos \theta_W$, where θ_W is the Standard Model weak mixing angle. Finally, s_β and c_β are shorthand for $\sin \beta$ and $\cos \beta$, where β is the angle from $\tan \beta = v_u/v_d$ (i.e. the ratio of vacuum expectation values for the up-type and down-type Higgs bosons). To obtain the mass eigenstates, one must diagonalize $\mathbf{M}_{\tilde{\chi}^0}$ using a unitary matrix $\mathbf{N}$, and then act on the gauge eigenstates with $\mathbf{N}$:

$$\tilde{\chi}_i^0 = \mathbf{N}_{ij} \psi_j^0. \quad (2.4)$$

This results in mass eigenvalues which can be determined from:

$$\mathbf{N}^* \mathbf{M}_{\tilde{\chi}^0} \mathbf{N}^{-1} = \begin{pmatrix} m_{\tilde{\chi}_1^0} & 0 & 0 & 0 \\ 0 & m_{\tilde{\chi}_2^0} & 0 & 0 \\ 0 & 0 & m_{\tilde{\chi}_3^0} & 0 \\ 0 & 0 & 0 & m_{\tilde{\chi}_4^0} \end{pmatrix}. \quad (2.5)$$

The corresponding mixing matrix for charginos in the $\psi^\pm = (\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$ gauge eigenstate basis is:

$$\mathbf{M}_{\tilde{\chi}_i^\pm} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix} \quad (2.6)$$

with

$$\mathbf{X} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix}, \quad (2.7)$$

where m_W is the mass of the Standard Model W boson. As with Equation 2.3, this can be used to obtain the mass eigenstates. Here, however, two unitary matrices $\mathbf{U}$ and $\mathbf{V}$ are used, one for the positively charged states and one for the negatively charged states:

$$\begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix} = \mathbf{V} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}, \quad \begin{pmatrix} \tilde{\chi}_1^- \\ \tilde{\chi}_2^- \end{pmatrix} = \mathbf{U} \begin{pmatrix} \tilde{W}^- \\ \tilde{H}_d^- \end{pmatrix}. \quad (2.8)$$

Then the mass eigenvalues can be computed via:

$$\mathbf{U}^* \mathbf{M}_{\tilde{\chi}^\pm} \mathbf{V}^{-1} = \begin{pmatrix} m_{\tilde{\chi}_1^\pm} & 0 \\ 0 & m_{\tilde{\chi}_2^\pm} \end{pmatrix}. \quad (2.9)$$

Chapter 6 contains additional information about electroweak SUSY and the general strategy for how the ATLAS detector is used to search for the production of supersymmetric particles, while Chapters 7 and 8 describe two of these searches.

CHAPTER 3

LHC and the ATLAS Detector

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [51, 52] is a superconducting particle accelerator and collider located at the European Organization for Nuclear Research (CERN) facility near Geneva, Switzerland. The LHC is installed in a 27 km circular tunnel that was initially used for the Large Electron–Positron Collider (LEP) [53]. While LEP collided electrons and positrons at a center-of-mass energy of up to $\sqrt{s} = 209$ GeV, the LHC is designed for proton–proton (pp) collisions with a maximum energy of $\sqrt{s} = 14$ TeV. These collisions occur at four interaction points along the LHC ring, where four independent experiments are located: ALICE [54], ATLAS [55], CMS [56], and LHCb [57]. ATLAS and CMS are designed as general-purpose detectors, while LHCb is designed primarily for studying b -hadrons and ALICE is designed primarily for studying heavy ion collisions. A diagram of the LHC ring, including these four experiments, can be found in Figure 3.1.

The protons used for pp collisions are obtained by ionizing hydrogen atoms. These protons are then accelerated in several stages, each of which increases the energy by an order of magnitude or more. The first stage is the Linac2 accelerator⁴, which accelerates protons to 50 MeV. This is followed by the Proton Synchrotron Booster (PSB), which accelerates the protons to 1.4 GeV. The protons are then injected into the Proton Synchrotron (PS), which further increases the energy of the proton beams to 25 GeV. These protons then enter the Super Proton Synchrotron, increasing the energy to 450 GeV. Finally, the protons are delivered to the LHC, where each beam is accelerated to an energy of up to 7 TeV; to do so, the LHC relies on superconducting 8 T magnets cooled using liquid helium to a temperature of 1.9 K. Note that the current nominal operation of the LHC accelerates

⁴Linac2 is currently being decommissioned, and will be replaced by the Linac4 accelerator, which is designed to accelerate negative hydrogen ions to 160 MeV before removing the two negatively charged electrons from each ion [59].

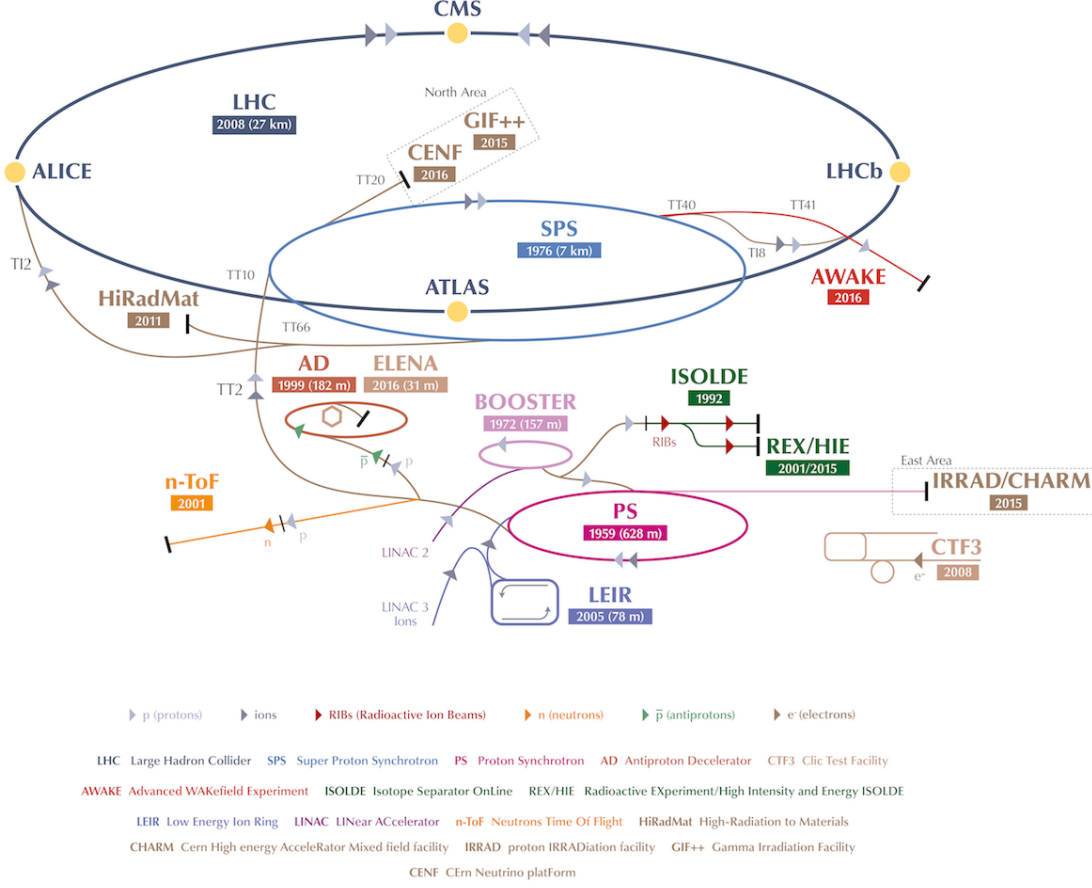


Figure 3.1: Diagram of the LHC and the CERN accelerator complex [58].

protons to an energy of 6.5 TeV per beam, resulting in a center-of-mass energy of $\sqrt{s} = 13$ TeV for pp collisions. Each instance of protons being delivered to the LHC is referred to as a “fill”; for each LHC fill, these beams can circulate for ten hours or more under stable operating conditions [52].

Proton beams in the LHC are composed of up to 2808 “bunches” of protons, with a separation of 25 ns between adjacent bunches. Each bunch contains roughly 10^{11} protons [52]. As a result, each bunch crossing results in many simultaneous pp collisions (collectively referred to as an “event”) at each of the interaction points along the LHC ring. This poses an experimental challenge for the detectors, as it becomes necessary to distinguish between activity in the detector due to one particular interaction from that of all of the other simultaneous interactions. The number of interactions per bunch crossing is referred to as the “pileup” (denoted μ), and Figure 3.2 shows that the average pileup in the 2015–2018 data collected by the ATLAS experiment was $\langle\mu\rangle = 33.7$ inelastic collisions per bunch crossing. Figures 3.3 and 3.4 show ATLAS event displays for events with 25 and 66

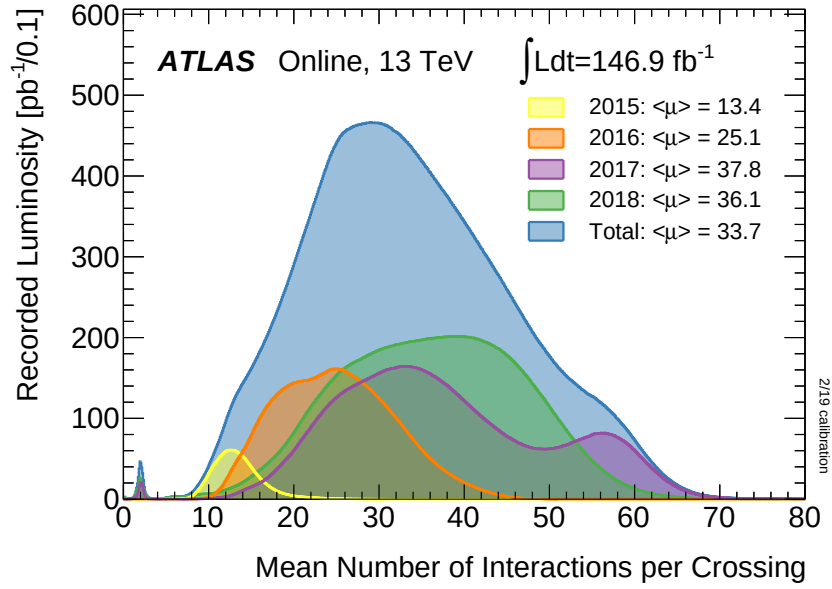


Figure 3.2: Average number of interactions per bunch crossing in the 2015–2018 data collected by the ATLAS experiment, weighted by the luminosity of the recorded events [60].

reconstructed vertices, respectively, to demonstrate what these high pileup collisions look like in the ATLAS detector.

If the LHC bunches were instead filled to allow for an average pileup of $\langle\mu\rangle = 1$ inelastic collision per bunch crossing, the resulting events observed by the various detectors would be significantly cleaner, and there would be no need to distinguish between simultaneous collisions. Unfortunately, pileup is a necessary evil: without it, collisions would be too infrequent to allow for the study of rare processes. There are two figures of merit used to specify the number of pp collisions delivered by the LHC. First is the instantaneous luminosity, which is the number of pp interactions per second. The LHC was designed to provide an instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (or equivalently, $10 \text{ nb}^{-1} \text{ s}^{-1}$). Figure 3.5 shows that the design has already been surpassed, with a peak instantaneous luminosity of $2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ delivered to ATLAS in 2018. The second measure of interest is the integrated luminosity, corresponding to the total number of pp collisions delivered by the LHC. Figure 3.6 shows that the total integrated luminosity delivered to ATLAS by the LHC in the “Run 1” data-taking period from 2011–2012 was 28 fb^{-1} , while the integrated luminosity delivered to ATLAS during “Run 2” from 2015–2018 was 156 fb^{-1} . To give a sense of scale, this corresponds to nearly 9 million Higgs bosons produced in collisions delivered to the ATLAS detector during 2015–2018 (based on the cross-sections shown in Figure 2.2). While this may sound like a large number,

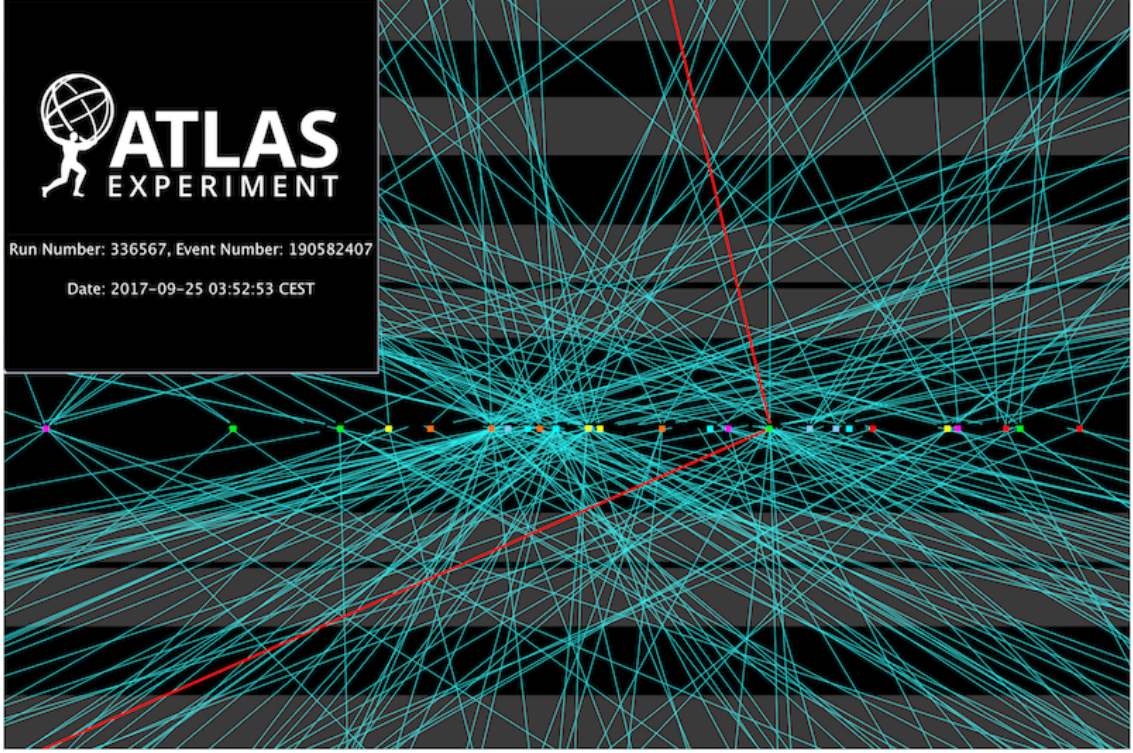


Figure 3.3: ATLAS event display for a $Z \rightarrow \mu\mu$ candidate event with 25 reconstructed vertices, recorded in September 2017. The two red lines represent the muons, which originate from a vertex shown as a green square. The other colored squares represent the 24 other reconstructed vertices, while the cyan lines represent tracks with $p_T > 500$ MeV [61].

only a fraction of these Higgs bosons are easily detected and measured, not to mention the large backgrounds present in many of the Higgs boson decay channels. This is a common challenge for Standard Model measurements and searches for new physics at the LHC, as will be apparent for the searches discussed in Chapters 7 and 8.

3.2 The ATLAS Detector

ATLAS [55] is a general-purpose particle detector which surrounds one of the LHC interaction points. The detector has a cylindrical geometry, with its center located along the LHC beam-pipe. ATLAS is roughly 80 feet tall, 145 feet in length, and weighs over 7000 tons. There are several categories of subdetectors which comprise this huge detector, including the Inner Detector tracking system for measuring the trajectories of charged particles, the Electromagnetic Calorimeter for identifying electrons/photons and measuring their energies, the Hadronic Calorimeters for measuring

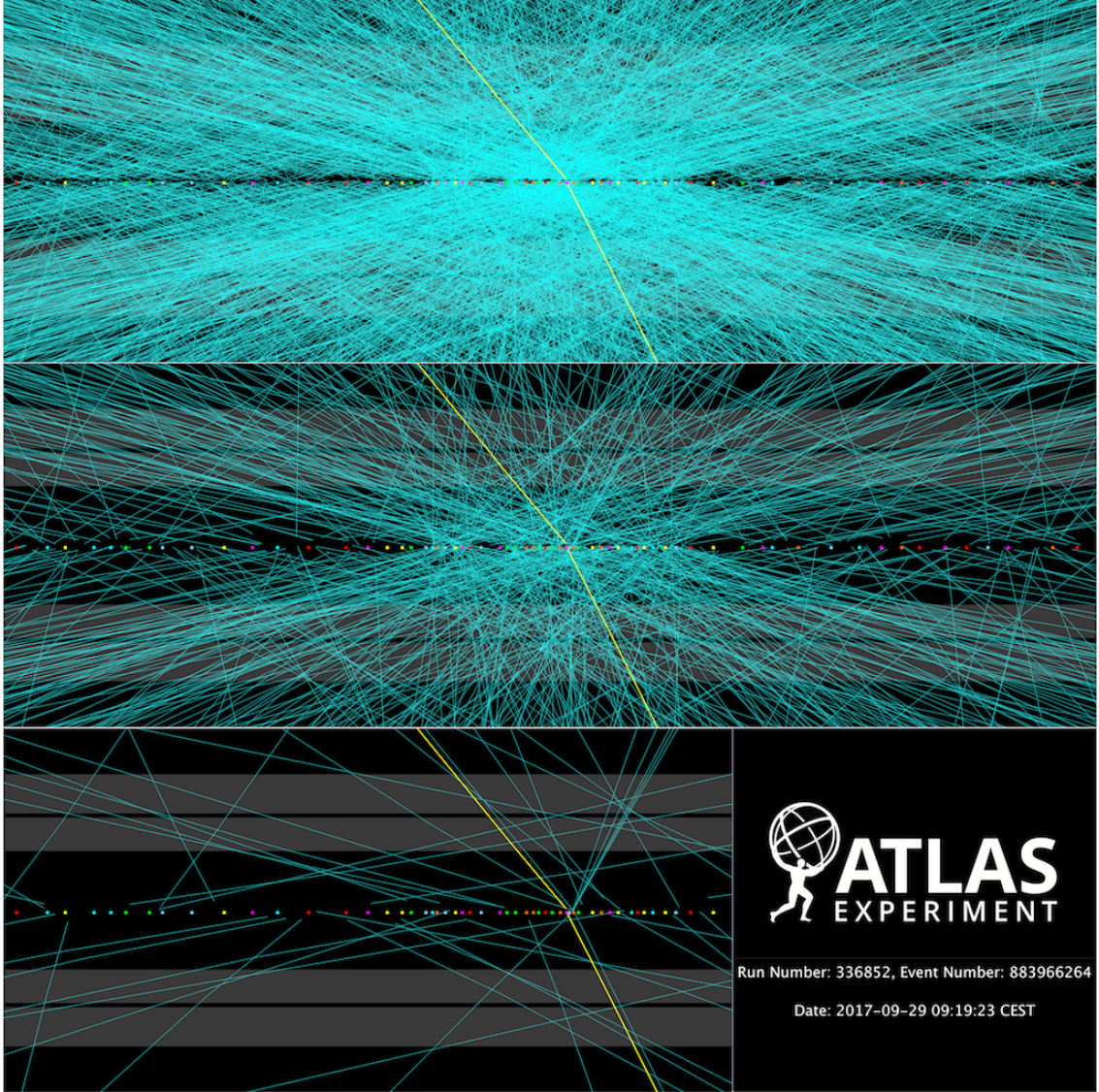


Figure 3.4: ATLAS event display for a $Z \rightarrow \mu\mu$ candidate event with 66 reconstructed vertices, recorded in September 2017. The two yellow lines represent the muons, which originate from a vertex shown as a pink square. The other colored squares represent the 65 other reconstructed vertices, while the cyan lines represent tracks with $p_T > 100$ MeV (top panel), $p_T > 1$ GeV (middle panel), and $p_T > 5$ GeV (bottom panel) [61].

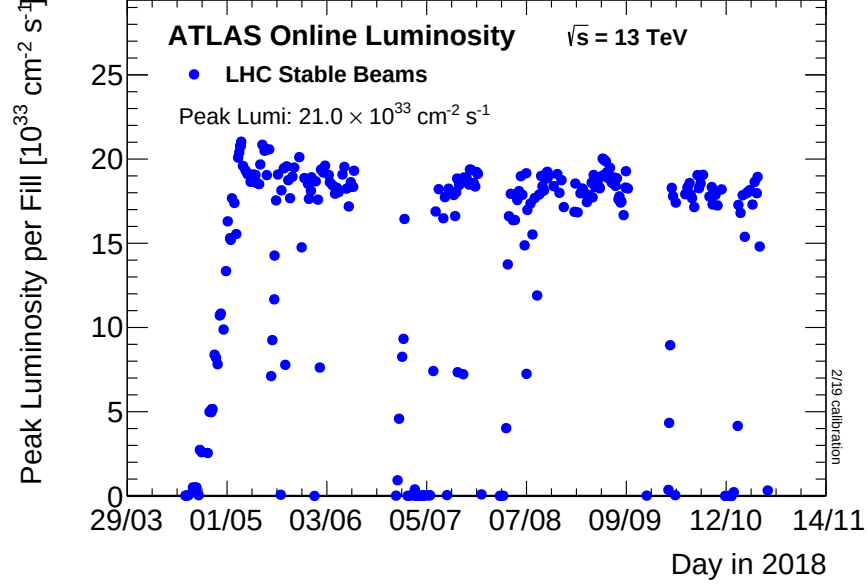


Figure 3.5: Peak instantaneous luminosity per LHC fill delivered to ATLAS in 2018, shown as a function of time. The largest instantaneous luminosity delivered to ATLAS in 2018 was $2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [60].

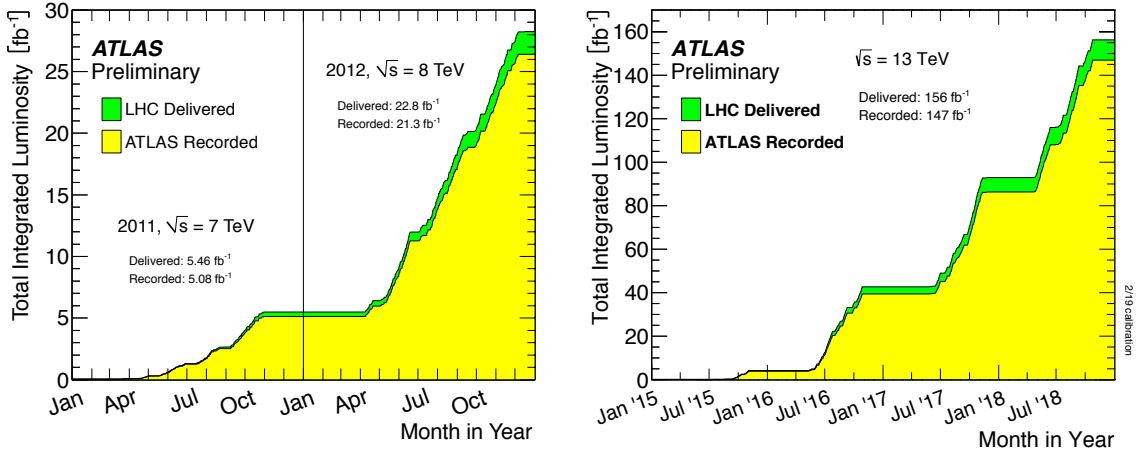


Figure 3.6: Total integrated luminosity delivered to and collected by ATLAS in Run 1 (left) and Run 2 (right). The green histogram denotes the total integrated luminosity delivered by the LHC, while the yellow histogram denotes the integrated luminosity that was collected by ATLAS. These two histograms differ due to inefficiencies in the data acquisition system as well as periods in which the detector is not fully functional (e.g. when the detector is initially turned on) [60].

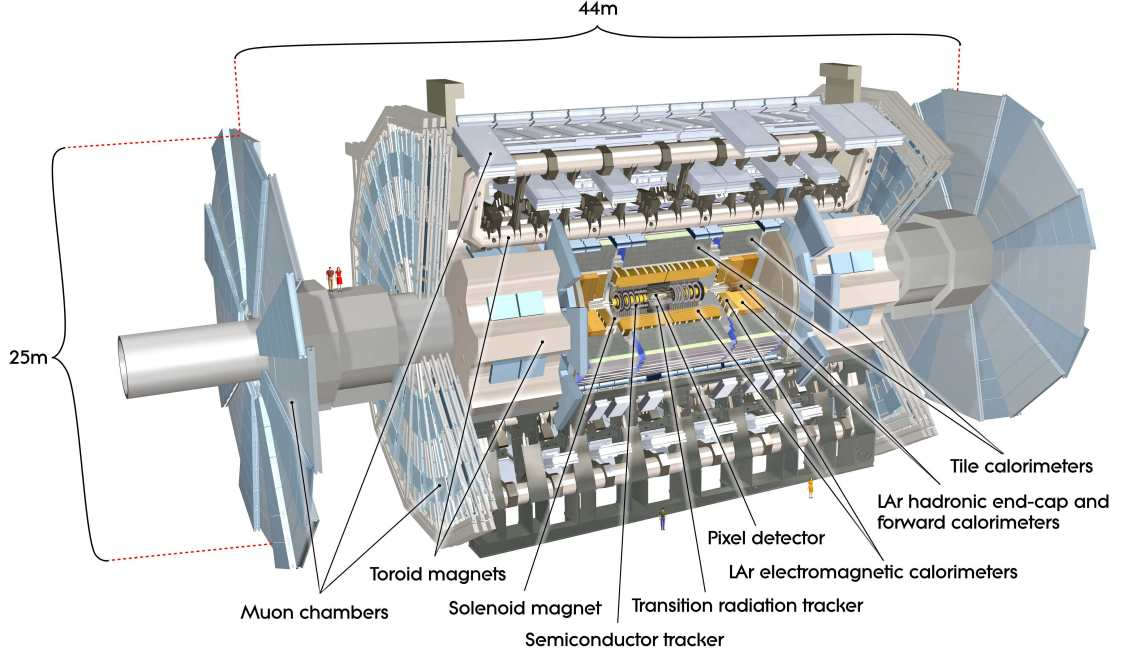


Figure 3.7: General cut-away view of the ATLAS detector, with arrows pointing to the many subdetectors that comprise ATLAS. Cartoon people are shown to provide a scale for the size of ATLAS, which is roughly 80 feet tall and 145 feet in length. The Inner Detector is the innermost subsystem, consisting of the Pixel Detector, the Semiconductor Tracker, and the Transition Radiation Tracker. This is surrounded by the Liquid Argon Electromagnetic Calorimeter, which is itself surrounded by the Hadronic Calorimeters (namely the Tile Calorimeter, the Liquid Argon Hadronic Endcap Calorimeter, and the Liquid Argon Forward Calorimeter). Finally, the Muon Spectrometer encompasses the outer layer of the ATLAS detector [55].

the energies of hadrons, and the Muon Spectrometer for identifying muons and measuring their trajectories. These subdetectors surround one another concentrically (in the order mentioned, with the Inner Detector as the innermost concentric layer), as can be seen in a cartoon of a cut-away view of the ATLAS detector in Figure 3.7.

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 along the beam-pipe. The x -axis points from the IP to the center of the LHC ring, and the y -axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse (x - y) plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Rapidity is defined by $y = \frac{1}{2} \ln[(E + p_z)/(E - p_z)]$, where E is the energy and p_z is the longitudinal component of the momentum along the beam direction. Angular distance is typically measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$,

though another angular distance $\Delta R_y \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$ is also frequently used when considering particles with non-negligible masses. The transverse momentum p_T and the transverse energy E_T are defined in the x - y plane. Note that charged particle tracking detectors measure particle momenta (and thus are quoted in terms of p or p_T) while calorimeters measure energy (and thus are quoted in terms of E or E_T); particles are usually referred to in terms of their p_T , though $p_T \approx E_T$ for sufficiently low mass particles in the relativistic conditions typically considered at the LHC.

3.2.1 The Inner Detector

The Inner Detector (ID) is a charged particle tracking detector, designed to measure the trajectory of electrically charged particles which travel through it. With the trajectory and the known 2 T magnetic field (generated by a large solenoid magnet) in which the Inner Detector is immersed, it is possible to determine the direction, momentum, and electric charge of these particles. These tracks are also used for vertexing, where information from multiple tracks are combined to determine a common origin; this is necessary for distinguishing interesting collisions from those associated to pileup collisions, as well as for identifying particles with short but nonzero lifetimes such as b -hadrons. The Inner Detector extends to $|\eta| < 2.5$, and is nearly symmetric in the ϕ direction.

The Inner Detector is composed of three subdetectors, listed in order of increasing radii: the Pixel Detector, the Semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT). These three tracking subdetectors each serve different purposes based on the granularity needed at different radii to allow for precision measurements of tracks along with the costs associated with the technology employed by the different subdetectors. A cartoon of the Inner Detector is shown in Figure 3.8, and a detailed schematic of its layout is shown in Figure 3.9.

3.2.1.1 Pixel Detector

The Pixel Detector is a high-granularity tracking detector which relies on silicon pixel sensors. When charged particles pass through these sensors, the silicon is ionized, thus resulting in an electrical signal which can be used to determine which sensors have “hits”. This subdetector consists of four cylindrical barrel layers in addition to three endcap disk layers on each side. Each pixel has a typical size ranging from $50 \mu\text{m} \times 250 \mu\text{m}$ for the innermost pixel barrel layer to $50 \mu\text{m} \times 400 \mu\text{m}$ for the three outer pixel barrel layers in the $\phi \times z$ plane [62, 64, 65]. The Pixel Detector has a total of 92 million readout channels [66].

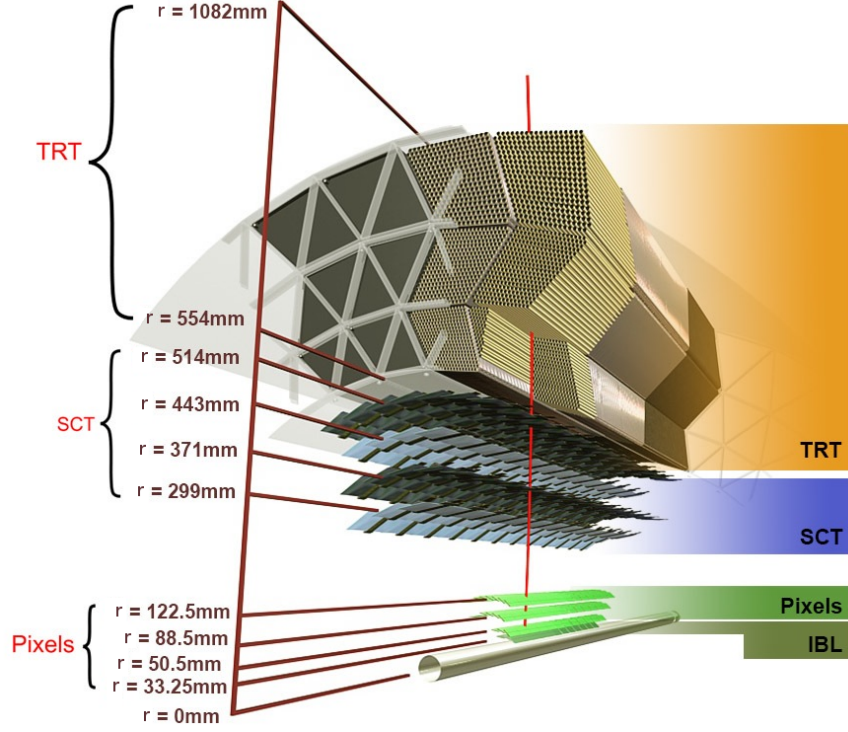


Figure 3.8: Cartoon of the barrel region of the Inner Detector [62].

The innermost pixel layer, also referred to as the Insertable B-Layer (IBL), was installed during the LHC shutdown period between late 2012 and early 2015, and was commissioned during the 2015 data-taking period at the start of Run 2. This additional pixel layer allowed the radius of the measurement point closest to the beam-pipe to be decreased from about 50 mm down to about 33 mm, which is beneficial for measuring vertex positions (particularly for b -hadrons) [64].

3.2.1.2 Semiconductor Tracker

The Semiconductor Tracker surrounds the Pixel Detector and employs a similar technology. The primary difference is that instead of using silicon pixel sensors, larger sensors referred to as silicon “strips” are used. These larger sensors are necessary due to the costs that would otherwise be associated with the use of highly granular pixels at the large radii (and subsequently large surface area) covered by the SCT. Each silicon strip in the SCT barrel has a typical size of $126 \text{ mm} \times 80 \text{ }\mu\text{m}$ [62]. The SCT consists of four cylindrical barrel layers in addition to nine endcap disk layers on each side. Each layer of the SCT has two sets of sensors at each position, offset by a stereo angle of 40 mrad. This allows these one-dimensional strip sensors to have resolution in two directions [55, 65].

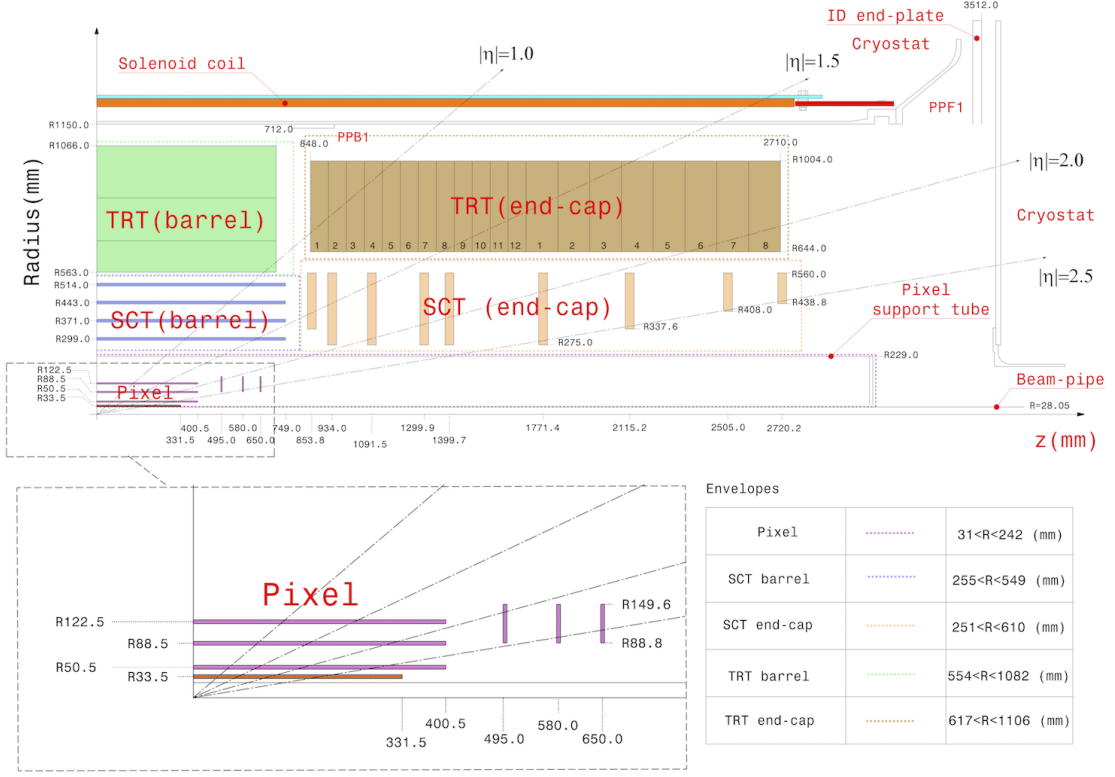


Figure 3.9: Schematic layout of the Inner Detector, shown only for $z > 0$ (note, however, that the Inner Detector is symmetric about the $z = 0$ axis). The top panel shows the entire Inner Detector, while the bottom panel shows a magnified view of the Pixel Detector [63].

The SCT has a total of 6.3 million readout channels [66].

3.2.1.3 Transition Radiation Tracker

The Transition Radiation Tracker surrounds the SCT, and is the outermost component of the Inner Detector. Rather than using silicon sensors, the TRT relies on drift tubes (“straws”) filled with a gas, typically a xenon-based mixture or an argon-based mixture. Each straw in the TRT barrel has a diameter of 4 mm and spans the full length of the barrel (144 cm long), with separate wires for readout in each half of the barrel (divided at roughly $\eta = 0$). As a result, the TRT barrel only provides measurements in the R - ϕ plane. Each track typically leaves around 30 hits in the TRT [65]. The TRT provides coverage for $|\eta| < 2.0$ and has a total of 350,000 channels [66].

In addition to tracking, the TRT is able to assist with particle identification. Charged particles which travel through the polyethylene fibers (in the barrel) and polypropylene foils (in the endcaps)

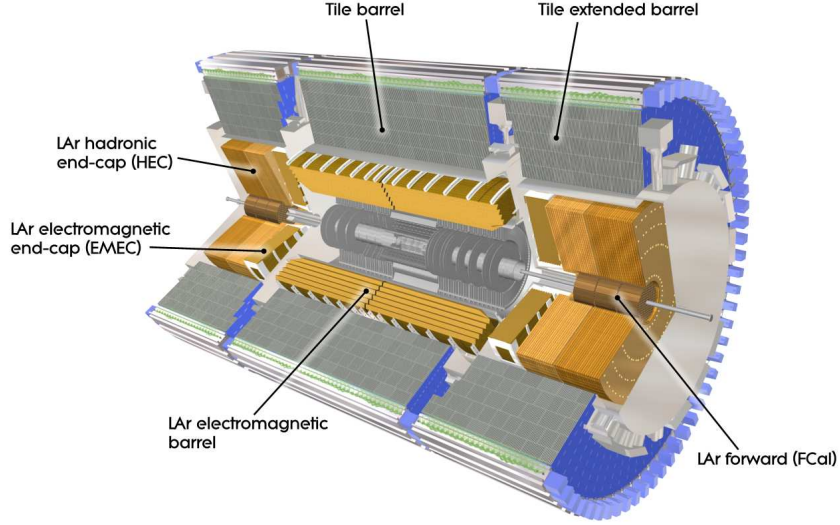


Figure 3.10: Cut-away view of the ATLAS calorimeter systems [55].

interleaved throughout the TRT emit transition radiation photons due to the dielectric constants of these materials. As the probability of transition radiation is determined by the Lorentz factor γ , electrons are far more likely than charged hadrons to emit transition radiation photons when passing through the TRT. These transition radiation photons typically have energies in the range 6–15 keV, allowing them to be absorbed by the xenon gas in the TRT straws. This results in a larger signal on the wire than the typical signals associated with particle tracking, thus providing a way to distinguish between electrons and hadrons [67]. Note, however, that the transition radiation photons cannot be absorbed by the argon gas that is present in some of the TRT straws, therefore these straws do not contribute to the electron identification capability of the TRT⁵.

3.2.2 The Calorimeters

ATLAS makes use of two types of sampling calorimeter systems for measuring the energies of electrons, photons, and hadrons. These two types of systems are the Liquid Argon (LAr) Calorimeter and the Tile Calorimeter, which both rely on absorber material to induce particle showers followed by active layers which perform the shower energy measurements. A cut-away view of the ATLAS calorimeter systems can be seen in Figure 3.10. The ATLAS calorimeter systems cover $|\eta| < 4.9$.

⁵The use of an argon-based mixture is due to leaks discovered in the TRT before the start of Run 2. Argon costs significantly less than xenon, so it was decided to replace the xenon in some regions of the TRT with argon, as these two gases provide similar tracking capabilities. This is discussed further in Section 4.6.

3.2.2.1 Electromagnetic Calorimeter

The LAr electromagnetic (EM) calorimeter consists of a barrel ($|\eta| < 1.475$) and one endcap on either side ($1.375 < |\eta| < 3.2$). To contain the electromagnetic showers, the EM calorimeter is designed to have a thickness of at least 22 radiation lengths (X_0) in the barrel and 24 radiation lengths in the endcaps [55]. Since an electron will lose all but $1/e$ of its energy due to bremsstrahlung for each radiation length, this ensures that only a small amount of EM energy will leak into the hadronic calorimeter. Lead plates, which have a radiation length of 0.56 cm [68], are used for the absorber material in the EM calorimeter. This allows the EM calorimeter barrel to only be about 50 cm thick while still being capable of stopping the majority of electrons and photons which pass through it [55].

For the active layer, the ATLAS EM calorimeter makes use of liquid argon, and readout of the energy sampled is performed by accordion-shaped kapton electrodes. This accordion geometry allows for complete symmetry about the ϕ direction, with no discontinuities or “cracks” between adjacent electrodes [55].

The EM calorimeter has four layers, as seen in Figure 3.11. First is a presampler layer (for $|\eta| < 1.8$), which is used to correct for energy lost by electrons and photons upstream of the calorimeter. This is followed by the first sampling layer, also referred to as the “strips” layer, which has a very fine granularity of $\Delta\eta \times \Delta\phi = 0.003125 \times 0.1$ in the barrel, allowing for discrimination between prompt photons and neutral pions (which predominantly decay to two collimated photons). Next is the second sampling layer, which has a depth of $16X_0$, and thus is where the majority of EM showering occurs. The granularity of this layer is $\Delta\eta \times \Delta\phi = 0.025 \times 0.0245$ ⁶. Finally, there is the third sampling layer, with a granularity of $\Delta\eta \times \Delta\phi = 0.05 \times 0.0245$ and a depth of $2X_0$. This third sampling layer is primarily used to estimate any remaining energy that was not sampled by the second layer; typically only a small fraction of the total energy for a given electron or photon will reach this layer [55].

3.2.2.2 Hadronic Calorimeter

The Tile Calorimeter consists of a barrel ($|\eta| < 1.0$) and one extended barrel on either side ($0.8 < |\eta| < 1.7$). Similar to the LAr EM calorimeter, it is important that the hadronic calorimeter is capable of containing the hadronic showers. This, of course, is more challenging as the typical interaction length (λ) in lead or iron for a pion is about 20 cm [68]; an interaction length is the

⁶To be precise, the granularity in ϕ is $2\pi/256$.

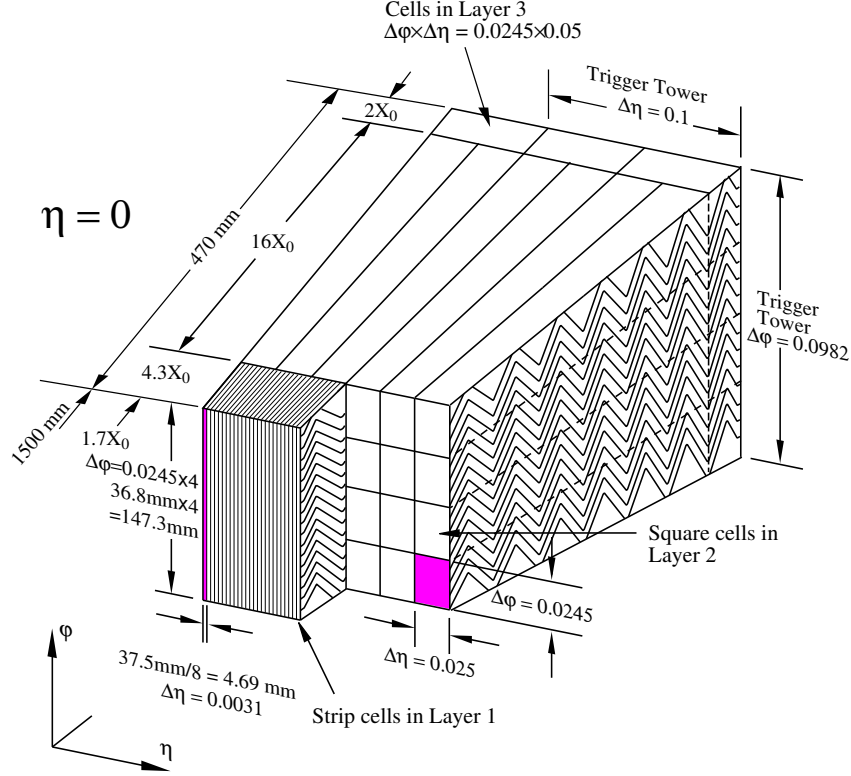


Figure 3.11: Cartoon of a segment of the EM calorimeter, demonstrating the granularity and radiation lengths associated to each of its four layers [55].

typical distance a relativistic hadron must travel before a nuclear interaction occurs. Steel is used as the absorber material in the Tile Calorimeter while scintillating tiles are used as the active material. The hadronic calorimeter has three layers, which have depths of 1.5, 4.1, and 1.8 interaction lengths in the first, second, and third barrel layers, respectively. The granularity of the Tile Calorimeter is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the first two layers and $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$ in the last layer [55].

In addition to the Tile Calorimeter, there is a LAr Hadronic Endcap Calorimeter (HEC) consisting of four layers per endcap which covers $1.5 < |\eta| < 3.2$. The HEC uses copper as the absorber material and liquid argon as the active material. The granularity of the HEC is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ for $1.5 < |\eta| < 2.5$ (the region aligned with the Inner Detector) and is $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ for $2.5 < |\eta| < 3.2$ [55].

Finally, there is a three layer LAr Forward Calorimeter which actually performs both electromagnetic and hadronic calorimetry for $3.1 < |\eta| < 4.9$. The first layer performs EM calorimetry using copper as the absorber material, while the other two layers perform hadronic calorimetry

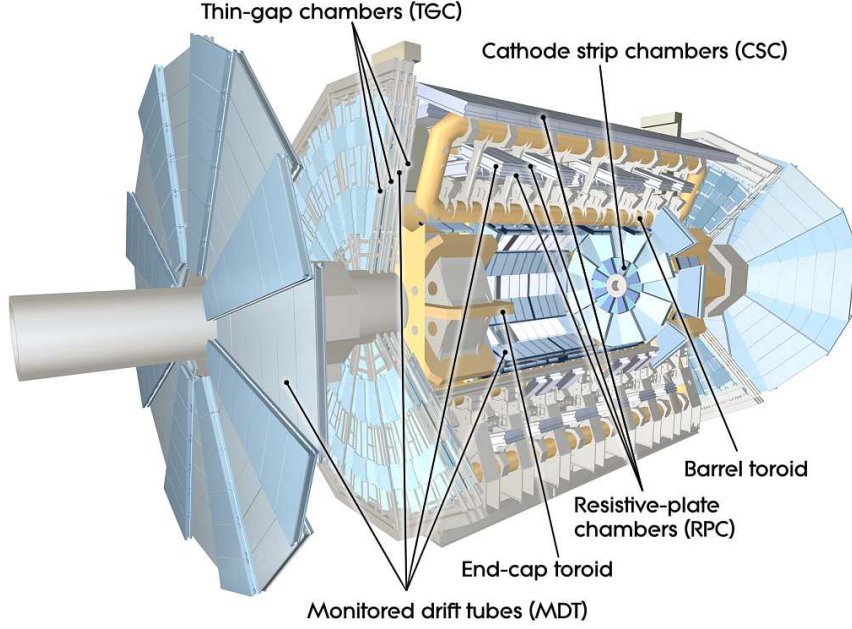


Figure 3.12: Cut-away view of the ATLAS Muon Spectrometer [55]. As the outermost subdetector of ATLAS, the MS spans 80 feet in height—and in fact, there are two elevator shafts which travel through the MS (though they are not shown in this cartoon) [69].

using tungsten as the absorber material. Liquid argon serves as the active material for all three layers [55].

3.2.3 The Muon Spectrometer

The Muon Spectrometer (MS) is the outermost subdetector of ATLAS, shown in Figure 3.12. This subdetector makes use of three superconducting air-core toroid magnets to generate a magnetic field which allows for measurements of the muon momenta. Muon trajectories are precisely measured using two different types of detectors, namely Monitored Drift Tubes (MDTs) in the region $|\eta| < 2.7$ (except for the innermost layer which only covers $|\eta| < 2.0$) and Cathode Strip Chambers (CSCs, which are multiwire proportional chambers with cathode strips) in the region $2.0 < |\eta| < 2.7$ [55].

Two additional types of detectors are also used by the Muon Spectrometer for trigger purposes and to provide a secondary measurement of the track coordinates. These are the Thin Gap Chambers (TGCs) in the region $|\eta| < 1.05$ and the Resistive Plate Chambers (RPCs) in the region $1.05 < |\eta| < 2.7$ (only 2.4 for trigger purposes) [55].

3.2.4 Particle Reconstruction and Identification Techniques

After particles travel through ATLAS, the only information which is retained is the set of raw signals from the various subdetectors. These signals, such as hits in the tracking detectors and energy deposition in calorimeter cells, are not particularly useful if analyzed individually on a channel-by-channel basis. However, they are powerful signatures when grouped together to determine which types of fundamental particles likely passed through the detector as well as the kinematics of these particles. This step, referred to as reconstruction, is performed by algorithms implemented in software.

Particle reconstruction occurs in several stages. First, trajectories of charged particles (tracks) and localized energy depositions (clusters) are reconstructed. The track reconstruction algorithm associates hits in the Inner Detector to individual particles by using pattern recognition and track fitting algorithms such as the Kalman Filter [70] and the ATLAS Global χ^2 Track Fitter [71]; more detail on ATLAS track reconstruction can be found in [55, 62]. Cluster reconstruction is performed using either a sliding-window cluster reconstruction algorithm or a topological cluster reconstruction algorithm, where the former builds clusters based on a fixed-size grouping of calorimeter cells which must exceed some energy threshold, while the latter builds clusters based on a variable-size grouping of calorimeter cells using contiguous energy depositions which exceed some noise threshold. These two cluster reconstruction algorithms are discussed in further detail in Sections 4.3 and 4.5, as well as in [6, 72].

Using these tracks and clusters, reconstruction of the underlying fundamental particles can proceed, and a very brief description of these particle reconstruction algorithms follows. Electron candidates are reconstructed as a sliding-window cluster in the EM calorimeter which is well-matched in $\Delta\eta \times \Delta\phi$ to an Inner Detector track [6]. Photon candidates are reconstructed as a sliding-window cluster in the EM calorimeter with either no associated track for (unconverted photon candidates) or at least one associated track which has properties that suggest that the object is more likely to be a photon conversion than an electron [73]. Muon candidates are reconstructed using several different algorithms; the algorithms relevant for the analyses discussed in Chapters 7 and 8 rely on candidates with tracks reconstructed in both the Muon Spectrometer and the Inner Detector (for “Combined Muons”) or candidates with tracks which are only reconstructed in the Muon Spectrometer but which are compatible with originating from the interaction point (for “Extrapolated Muons”) [69]. Quarks and gluons hadronize and travel through ATLAS as a spray of particles referred to as “jets”. These jets are reconstructed based on topological clusters in the hadronic calorimeter which are

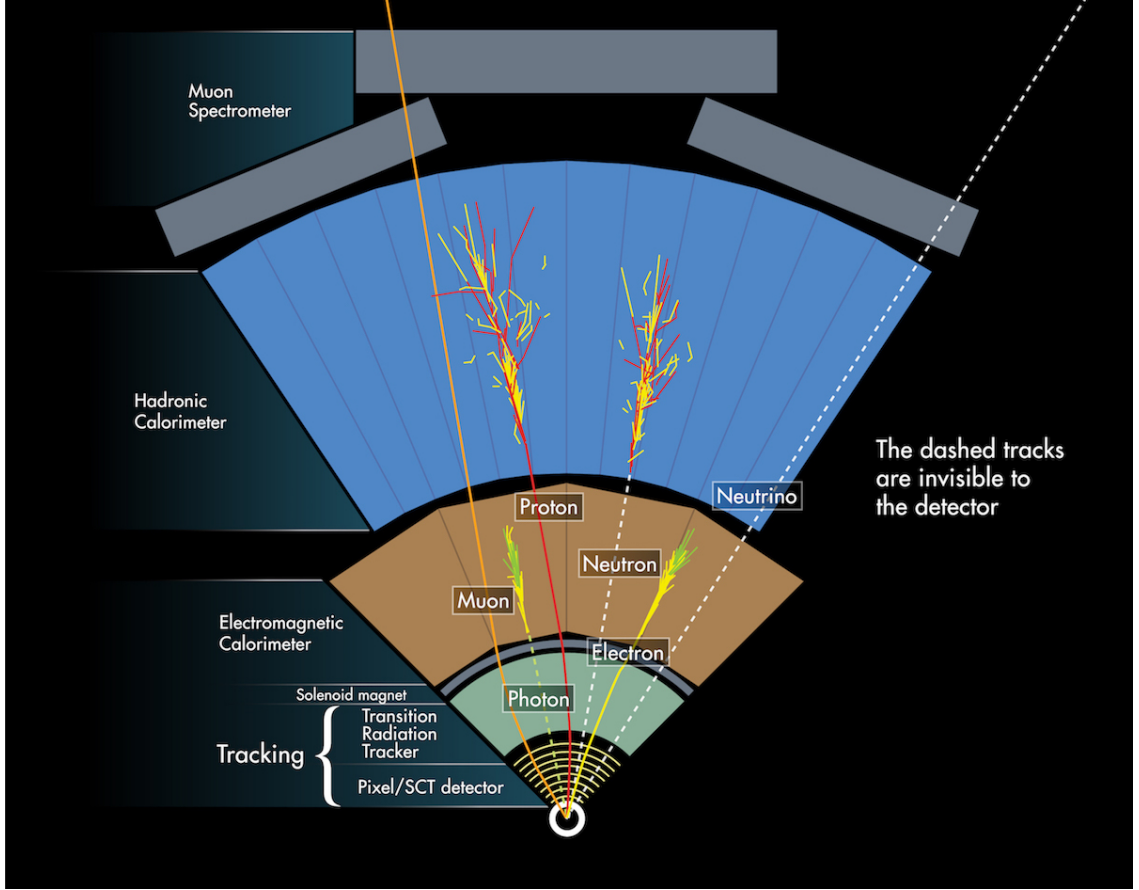


Figure 3.13: Cartoon demonstrating how different types of particles interact with the ATLAS detector [77].

used as input to the anti- k_t algorithm with radius parameter $R = 0.4$ [72, 74, 75] (at least for the analyses discussed in Chapters 7 and 8; other algorithms and radius parameters are also used for other purposes on ATLAS). Finally⁷, noninteracting particles such as neutrinos cannot be directly reconstructed. Instead, their presence can only be inferred by momentum imbalance due to the principle of momentum conservation. The missing transverse momentum $\mathbf{p}_T^{\text{miss}}$, whose magnitude is the missing transverse energy E_T^{miss} , is taken to be the transverse momentum vector with equal magnitude but opposite direction to the sum over all visible objects in the event. These visible objects include the reconstructed particles and a track-based “soft” term for hadrons which fall below the jet reconstruction p_T thresholds [76]. A cartoon demonstrating how the various types of particles interact with the ATLAS detector is shown in Figure 3.13.

⁷ATLAS also reconstructs other particles such as tau leptons, but these are outside the scope of this thesis.

Some reconstructed particles are then further selected by “identification” algorithms, designed to distinguish between the particles of interest and those which can leave similar signatures and mimic the given particle of interest. One example of this is electron identification, which is described in Section 4.4. Another example is b -tagging, where jets which are likely to contain b -hadrons (“ b -jets”) are selected based on requirements on the track transverse and longitudinal impact parameters (d_0 and z_0 ⁸), in addition to the presence of a secondary (displaced) vertex [78].

Isolation algorithms also exist for the light leptons to further distinguish against background objects such as hadrons; these are described for electrons in Section 4.5, though the same algorithms are also used for muons.

3.2.5 The ATLAS Trigger System

With a spacing of 25 ns between bunches, there are nearly 40 million bunch crossings each second. Due to limited computing resources, ATLAS is unable to record all of these collisions to disk—in fact, ATLAS can record fewer than 2000 events per second, which corresponds to less than one event saved for every 20,000 bunch crossings that occur. However, since most ATLAS measurements of Standard Model properties and searches for new physics pertain to rare processes (relative to the total pp cross-section), it is possible to use these limited resources to primarily record interesting events. This requires ATLAS to make decisions in real-time (“online”) about which events to record, which is a process known as “triggering”.

ATLAS uses a two-level trigger system, which makes use of a hardware-based Level 1 (L1) trigger followed by a software-based High Level Trigger (HLT). At L1, decisions are made within a maximum latency of $2.5\ \mu\text{s}$ based on either hits in the muon detector for muon signatures or localized energy deposition in the calorimeters for electromagnetic, hadronic, and $E_{\text{T}}^{\text{miss}}$ signatures. The L1 trigger input rate is the LHC collision rate of 40 MHz while its maximum event output rate is 100 kHz. The HLT then takes the 100 kHz events from the L1 trigger and selects events (“fires”) within a typical processing time of 200 ms using algorithms implemented in software (similar to those used by the final “offline” physics analyses) to allow for a peak output rate of about 1.5–2 kHz worth of events that are saved to disk [79–81]. This output rate decreases exponentially as a function of time over the course of a single pp fill, due to the decrease in instantaneous luminosity as pp collisions occur. Figure 3.14 shows the HLT output rate for a single fill from 2018, including a breakdown of

⁸ d_0 is defined as the distance of closest approach between the track and the primary vertex (chosen as the vertex with the largest $\sum p_{\text{T}}^2$ of associated tracks) in the transverse plane, while z_0 is the longitudinal distance between the vertex and the track position at which d_0 is defined.

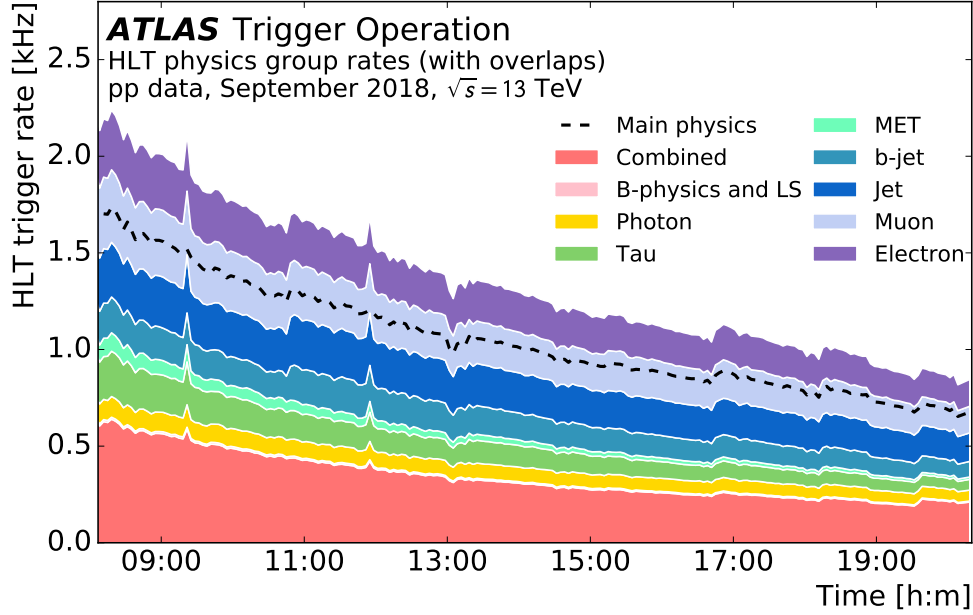


Figure 3.14: HLT rate as a function of time for a single fill from September 2018. The peak instantaneous luminosity for this fill was $2.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with an average of $\langle \mu \rangle = 56$ interactions per bunch crossing. The colored histograms represent the rate associated to each of the physics signatures shown in the legend, where “combined” refers to trigger algorithms which require multiple types of signatures (e.g. a trigger algorithm which requires both an electron and a muon). As a single event can satisfy multiple trigger algorithms, there is overlap between the different signatures shown in this plot; this overlap is accounted for in the rate of the “main physics” stream [82].

how the various HLT trigger signatures contribute to the total rate.

The ATLAS trigger menu, which is the collection of HLT signatures (“trigger chains”) enabled in a given data collection period, includes triggers which require either single objects (e.g. a single well-identified electron above a given p_T threshold) or multiple objects (e.g. two well-identified electrons above a given p_T threshold). While the majority of the HLT rate used by the trigger menu is dedicated to “primary” physics-dedicated triggers, which select every event that satisfies the given criteria, there are also “supporting” triggers used by ATLAS. These supporting triggers contribute to about 15% of the HLT rate and only fire for some fraction of the events that satisfy the given criteria. This fraction can be defined as $1/N$, where N is the “prescale” value of the trigger, i.e. if a given trigger has a prescale of 20, then only 5% of the events which satisfy the trigger-level selection criteria are actually saved. Supporting triggers are commonly used for detector performance measurements as well as for some background estimates in physics analyses [81].

CHAPTER 4

Electron Reconstruction, Identification, and Isolation

“The electron: may it never be of any use to anybody.”

— A toast to J. J. Thomson, discoverer of the electron,
by his colleagues at Cavendish Laboratory [83]

4.1 Introduction to the Electron Selection Algorithms

As the lightest charged lepton in the Standard Model, electrons are often a distinctive signature of decays of massive Standard Model particles produced at a particle collider. Several categories of “electrons” must be considered, namely:

- “Prompt” electrons from direct decay processes such as $W \rightarrow e\nu$ and $Z \rightarrow ee$.
- “Fake” electrons, which are typically hadronic jets improperly reconstructed and identified as an electron. Typically only a small fraction of hadrons fake an electron, but the cross-section for hadronic processes is often much larger than that of processes that decay to prompt electrons. At hadron colliders in particular, these cross-sections differ by several orders of magnitude, which means the suppression of these fake electrons is an important experimental challenge.
- “Nonprompt” electrons, which arise from photon conversions or semileptonic decays of heavy flavor hadrons. While these are real electrons, they only appear after some other particle travels through the detector for some time and then decays.

Example diagrams for prompt electron production and how the various background sources arise can be seen in Figure 4.1.

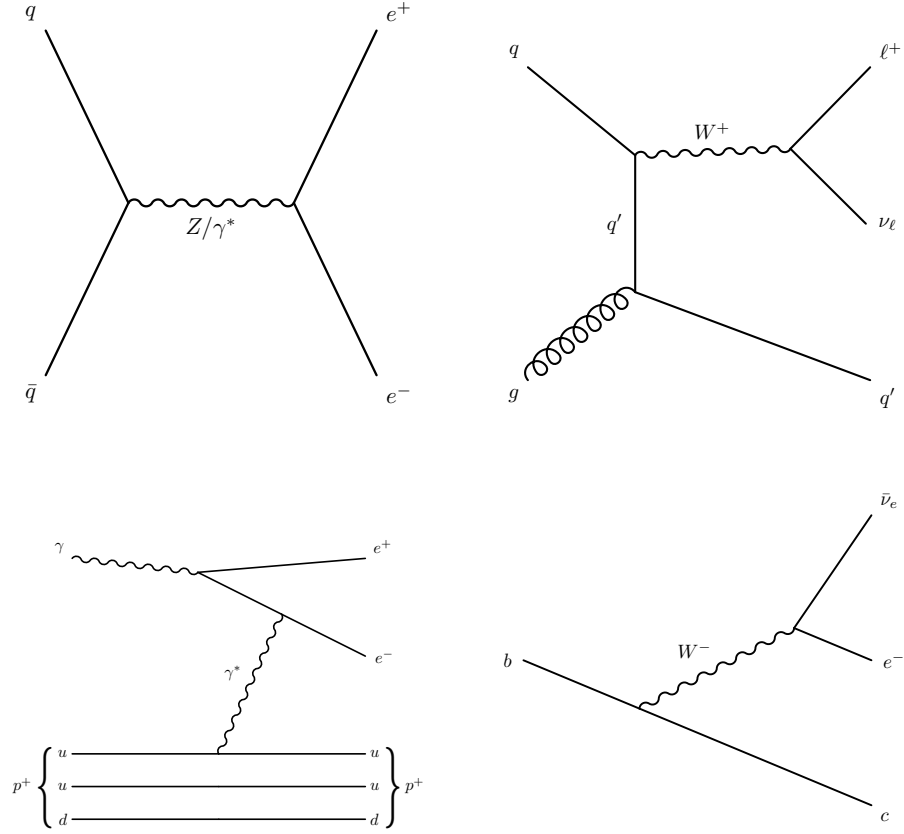


Figure 4.1: Example diagrams for prompt electron production and how the various background sources arise. Top left: prompt electrons produced via the $Z \rightarrow ee$ process, where the Z promptly decays to two electrons. Top right: W +jet process, where the final state quark can be misidentified as an electron. Bottom left: the photon conversion process, where a photon interacts with material in the detector (shown here as a proton) and subsequently converts into two electrons. Note that photons cannot convert in a vacuum due to momentum conservation, and thus the presence of detector material is necessary. Bottom right: semileptonic decay of a bottom quark to an electron, a neutrino, and a charm quark. Hadrons containing a b -quark typically have lifetimes of around 1 ps [68], allowing the b -quarks to travel some distance before decaying.

Reconstruction and identification of prompt electrons has been essential to the physics programs of many experiments over the past few decades. One prime example of this was the use of well-identified electrons for the discovery of both the W and Z bosons at the CERN Super Proton Synchrotron (SPS) in 1983 by the UA1 and UA2 experiments [26–29]. Similarly, without being able to efficiently reconstruct and select electrons and muons (collectively referred to as the “light” leptons), ATLAS would not have been able to discover the Higgs boson in the $H \rightarrow ZZ^{(*)}$ and $H \rightarrow WW^{(*)}$ channels in 2012 [8], among the many other ATLAS Standard Model measurements that would not have been possible. Since many potential signatures of new physics also have leptonic final states (including those searched for in Chapters 7 and 8), electrons are necessary for a large majority of analyses performed by ATLAS.

Electrons primarily interact with the ATLAS detector via the electromagnetic (EM) interaction, leaving charged-particle tracks in the Inner Detector and clusters of energy deposited in the EM calorimeter. Using these inputs, the reconstruction and selection of electrons for use in ATLAS physics analyses proceeds in several steps. After reconstructing the tracks and clusters, these objects must be associated to one another as part of the electron reconstruction step. This is then followed by the electron identification step, which is designed to distinguish prompt electrons from background sources based on information pertaining to the electron candidate tracks, clusters, and quantities which combine tracking and calorimeter information. Finally, as electrons tend to be well-isolated (with little activity surrounding the electron in $\Delta\eta$ and $\Delta\phi$), an isolation step is used to distinguish these electrons from backgrounds such as jets (which tend to be much more diffuse).

4.2 Collision Data and Simulated Event Samples

All data collected by the ATLAS detector undergo careful scrutiny to ensure the quality of the recorded information; data used for the studies in this chapter and in Chapter 5 are filtered by requiring that all detector subsystems needed in the analysis (calorimeters and tracking detectors) are operating nominally. After all data-quality requirements, 37.1 fb^{-1} of pp collision data from the 2015–2016 dataset are available for analysis. Some results shown are based on only a fraction of this total dataset (e.g. only 2015 data, only 2016 data, or only a portion of one of these datasets), and thus the integrated luminosity quoted for some results is less than 37.1 fb^{-1} .

Samples of simulated $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ decays as well as single electron samples are used to benchmark the expected prompt electron efficiencies and to define the electron identification criteria. The $Z \rightarrow ee$ Monte Carlo (MC) samples were generated with the POWHEG-Box v2 MC

program [84–88] interfaced to the PYTHIA v8.186 [89] parton shower model. The CT10 parton distribution function (PDF) set [90] was used in the event generation with the matrix element, and the AZNLO [91] set of generator-parameter values (tune) with the CTEQ6L1 [92] PDF set were used for the modeling of non-perturbative effects. The $J/\psi \rightarrow ee$ samples were generated with PYTHIA v8.186; the A14 set of tuned parameters [93] was used together with the CTEQ6L1 PDF set for both event generation and for the parton shower. The simulated single electron samples were produced with a flat distribution in η as well as in p_T in the region 3.5 GeV to 100 GeV, followed by a linear ramp down to 300 GeV, and then a flat distribution again to 3 TeV. For studies of electrons in simulated event samples, the reconstructed electron track is required to have hits in the Inner Detector which originate from the true electron during simulation.

Backgrounds that may mimic the signature of prompt electrons were simulated with two-to-two processes in the PYTHIA v8.186 event generator using the A14 set of tuned parameters and the NNPDF2.3LO PDF set [94]. These processes include multijet production, $qg \rightarrow q\gamma$, $q\bar{q} \rightarrow g\gamma$, W and Z production (as well as other electroweak processes), and top quark production. This sample of simulated background events is sometimes referred to as a “dijet” sample, as that is the process with the largest cross-section (though it clearly is not the only contributor). A filter was applied to the simulation to enrich the final sample in electron backgrounds. This filter retains events in which particles produced in the hard scatter (excluding muons and neutrinos) have a summed energy that exceeds 17 GeV in an area of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, which mimics the highly localized energy deposits that are characteristic of electrons. When using this background sample, prompt electrons from W and Z decays are excluded using generator-level simulation information.

Multiple overlaid pp collisions were simulated with the soft QCD processes of PYTHIA v8.186 using the MSTW2008LO PDF set [95]. The Monte Carlo events were reweighted so that the distribution of the average number of interactions per crossing $\langle\mu\rangle$ matches the one observed in the data. All simulated samples were processed with the GEANT-based simulation [96,97] of the ATLAS detector.

4.2.1 Selection of Prompt Electrons and Background Objects in Data

To obtain a relatively pure sample of prompt electrons in data, the “tag-and-probe” method is used. This method relies on the decay products of known resonances such as the Z , W , or J/ψ , and is used to select unbiased electron candidates (“probes”) by applying strict requirements on the other object in the decay (“tags”). $Z \rightarrow ee$ events are used for the electron identification optimization for electron $p_T > 15$ GeV, while $J/\psi \rightarrow ee$ events are used for electron $p_T < 15$ GeV. More details on

the triggers and selection criteria used to collect these events can be found in Sections 5.2 and 5.3.

To obtain a sample of objects which serve as backgrounds to electrons, prescaled single electron triggers are used. These triggers require a reconstructed electron candidate to pass a given p_T threshold (ranging from 5 GeV to 120 GeV in steps of 5–20 GeV), but do not apply any identification requirement at the HLT. Note that hadronic jets are frequently reconstructed as electrons due to the requirements imposed on the tracking and calorimetric quantities (as will be discussed in Section 4.3). Consequently, this sample primarily contains dijet events, as this is the process with the largest production cross-section at the LHC. However, this is a very inclusive selection, and includes other processes as well. To reduce potential contamination from electroweak processes containing prompt electrons, several requirements are imposed:

- If $E_T^{\text{miss}} > 25$ GeV, veto the event (to reduce contamination from $W \rightarrow e\nu$).
- If $m_T > 40$ GeV, veto the event (to reduce contamination from $W \rightarrow e\nu$). m_T is the transverse mass computed between the reconstructed electron and the $\mathbf{p}_T^{\text{miss}}$, and serves as a proxy for the W boson mass; see Equation 7.1 for more detail.
- If a second electron (which satisfies the Medium identification operating point and has $p_T > 4$ GeV) is present in the event and forms an invariant mass within $70 \text{ GeV} < m_{ee} < 110 \text{ GeV}$, veto the event (to reduce contamination from $Z \rightarrow ee$). Note that no electric charge requirements are imposed on these electrons, to suppress the (admittedly small) contamination from $Z \rightarrow ee$ electrons with an incorrect reconstructed charge.

This selection has been used to collect electron backgrounds for the optimization of the electron identification since the start of the 2017 data-taking period; before that, simulation was used to model these backgrounds.

4.3 Electron Reconstruction

The reconstruction of potential electron candidates in the precision region of the ATLAS detector ($|\eta| < 2.47$) makes extensive use of information from the Inner Detector tracking system and the high-granularity electromagnetic calorimeter. That is because there are three main signatures left behind by electrons as they pass through the ATLAS detector: localized clusters of energy deposited in the electromagnetic calorimeter, charged-particle tracks in the Inner Detector, and close matching in $\Delta\eta \times \Delta\phi$ between the tracks and the clusters. The electron reconstruction algorithms perform steps

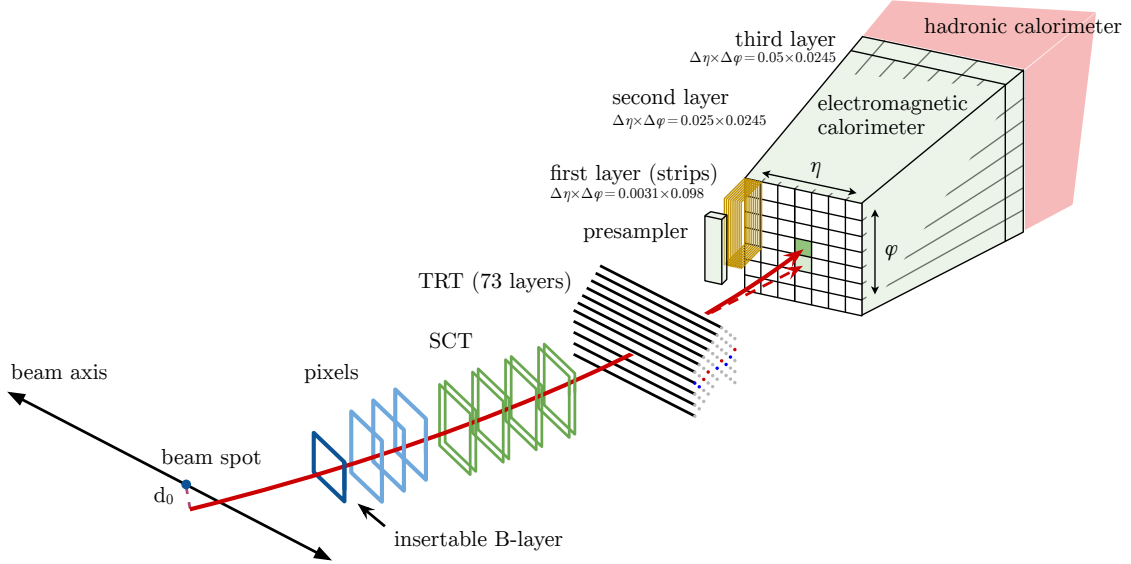


Figure 4.2: A schematic illustration of the path of an electron through the ATLAS detector, shown as the solid red trajectory. The electron first traverses the tracking system (pixel detectors, then silicon strip detectors, and lastly the TRT) and then enters the electromagnetic calorimeter. The dashed red trajectory indicates the path of a photon produced by the interaction of the electron with the material in the tracking system [6].

to look for each of these signatures, and proceeds in the order listed such that objects which have very different signatures from electrons can be vetoed as quickly as possible (to avoid wasting computing resources) while still being extremely efficient for prompt electrons. The electron reconstruction algorithm is greater than 99% efficient for prompt electrons with $p_T > 15$ GeV. Figure 4.2 provides a schematic illustration of the trajectory of an electron as it travels through the ATLAS detector. A full description of the electron reconstruction algorithm can be found in [6].

While electron reconstruction is greater than 99% efficient for $p_T > 15$ GeV electrons, this is not the case at low p_T . The electron reconstruction efficiency, as well as the efficiencies for the clustering, tracking, and track-to-cluster matching steps can be seen in Figure 4.3. Electron reconstruction inefficiencies arise at low p_T due to the first step of the reconstruction algorithm, namely the electromagnetic cluster reconstruction step. To start, “towers” of size $\Delta\eta \times \Delta\phi = 0.025 \times 0.0245$ (corresponding to the granularity of the second layer of the electromagnetic calorimeter) are constructed. The energy of each tower is the sum of the energy in the three layers of the calorimeter in addition to the presampler layer. A sliding-window algorithm is then used to look for adjacent groups of towers of size 3×5 (in $\eta \times \phi$) which have a total transverse energy greater than 2.5 GeV.

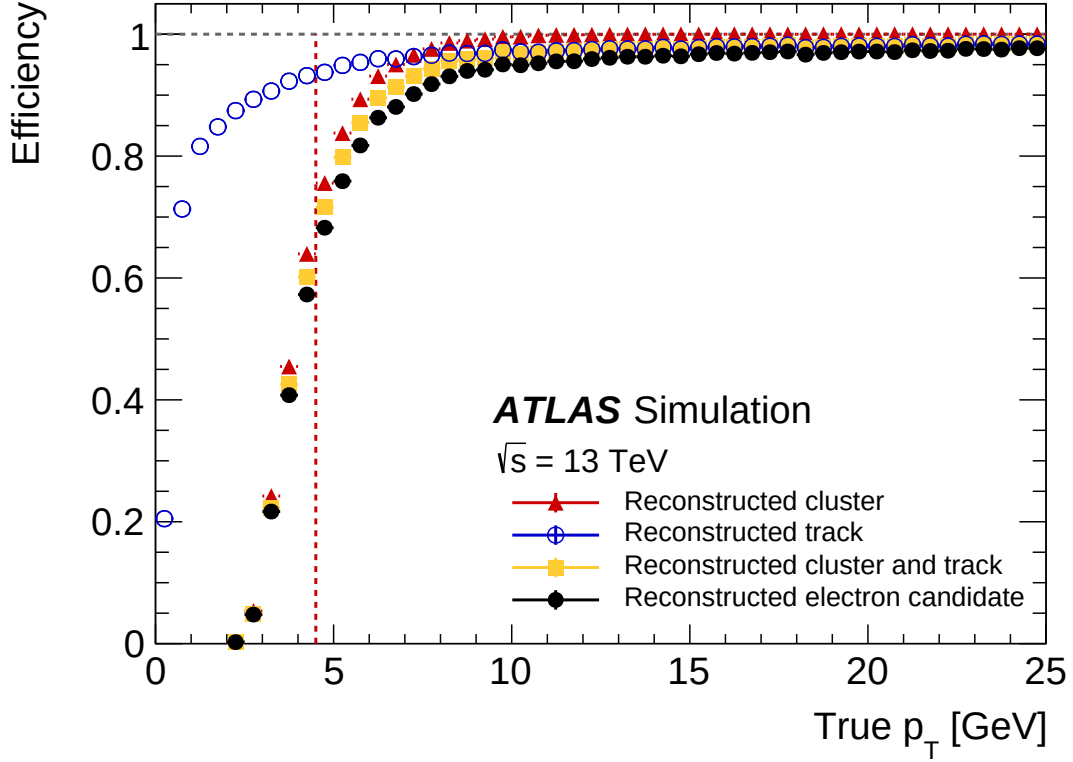


Figure 4.3: Electron cluster reconstruction, track reconstruction, and candidate reconstruction efficiency as a function of p_T . The red dashed line indicates the minimum electron p_T threshold currently supported by ATLAS for use in physics analyses [6].

This $\sum E_T > 2.5 \text{ GeV}$ threshold for reconstructing electromagnetic clusters is the problematic step, as it relies on raw, uncalibrated energies measured by the electromagnetic calorimeter, and the relative difference between the energy of a calibrated electron and that of an uncalibrated electron can be large at low p_T . As a result, the electromagnetic clusters of many low p_T electrons are not reconstructed, and thus the subsequent steps of the reconstruction algorithm do not occur. This inefficiency is particularly relevant for physics analyses which make use of soft leptons, as will be discussed in Chapter 8. To account for potential mismodeling of these inefficiencies in the simulation, additional reconstruction efficiency uncertainties at low p_T were determined using simulated samples with different material distributions; uncertainties of 2% in the barrel ($|\eta| < 1.37$) of the electromagnetic calorimeter and 5% in the endcaps ($1.37 < |\eta| < 2.47$) were found to be sufficient to cover potential mismodeling.

4.4 Electron Identification

The ATLAS electron reconstruction algorithms are very efficient for prompt electrons, as they are designed to accept the majority of objects which leave electron-like signatures. However, there are many backgrounds which can mimic an electron, and these backgrounds are frequently reconstructed as electron objects as well. Background sources for electrons include misidentified hadronic jets, electrons from photon conversions, and nonprompt electrons which result from the decay of heavy flavor hadrons. To suppress these backgrounds, electron identification (ID) algorithms are applied. Without these electron identification algorithms, ATLAS analyses would be challenged by significant background from sources of fake and nonprompt electrons—and even with strict electron identification requirements, such background sources can *still* be dominant in some cases. Thus, it is important for the electron identification algorithms to be efficient at rejecting background while still properly identifying prompt electrons as often as possible.

The discriminating quantities used for ATLAS electron identification are described in Table 4.1 and are based on signatures including Inner Detector track hits, the track transverse impact parameter, transition radiation in the TRT, calorimeter shower shapes, energy ratios, and track-to-cluster matching. These quantities are computed using information from the various ATLAS subdetectors, as illustrated in Figure 4.2.

4.4.1 The Electron Likelihood

The default ATLAS electron identification in Run 1 was initially a selection-criteria-based (or “cut-based”) identification; however, such an approach is inefficient for several reasons:

- Compared with multivariate analysis (MVA) techniques, a cut-based electron identification tends to have worse background rejection for a given signal efficiency.
- If a prompt electron satisfies all of the criteria for the cut-based identification except one, then it will still not be selected as an identified electron. MVA techniques tend to combine information from all of the discriminating quantities, and thus can still select such objects as identified electrons.
- Some discriminating quantities may have similar behavior for both signal and background, which prevents use of such quantities for identification purposes, as they cannot improve background rejection without also causing efficiency losses.

Table 4.1: Type and description of the quantities used in the electron identification. The columns labeled “Rejects” indicate whether a quantity has significant discrimination power between prompt electrons and light flavor (LF) jets, photon conversions (γ), or nonprompt electrons from the semileptonic decay of hadrons containing heavy flavor (HF) quarks (b -quarks or c -quarks). In the column labeled “Usage”, “LH” indicates that the pdf of this quantity is used in forming L_S and L_B (defined in Equation 4.1) while “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 0.025×0.0245 [6].

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 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 modeled by the simulation.	f_3	x			LH
Second layer of 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 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; often shown after transforming this variable using the same inverse sigmoid function used for the likelihood discriminant in Equation 4.3	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

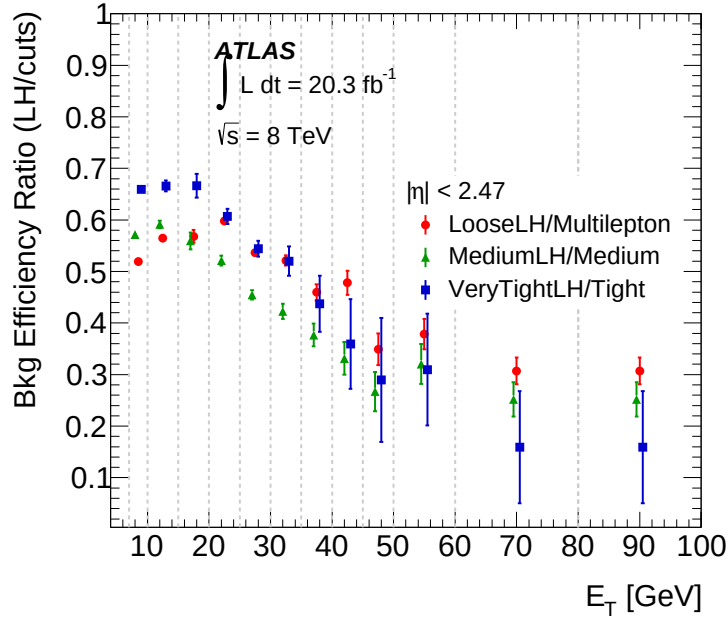


Figure 4.4: Ratios of background efficiencies between likelihood-based and cut-based electron identification operating points in Run 1, where each ratio is of operating points chosen to have roughly the same signal efficiency [98].

To improve upon the cut-based electron identification, several MVA techniques were studied. A likelihood-based (LH) electron identification was chosen for its discriminating power and its simplicity. The electron likelihood was first used by ATLAS analyses in Run 1 as an option for measurements and searches where the improved discriminating power could be beneficial. The ratios of background efficiencies for several cut-based and likelihood-based operating points from Run 1 are shown in Figure 4.4, which shows that for a given signal efficiency, the electron likelihood allowed for nearly a factor of two or better improvement in background rejection for $p_T > 25 \text{ GeV}$ [98]. As a result, the likelihood-based electron identification (also referred to as the “electron likelihood”) is the default for all ATLAS analyses in Run 2.

The electron likelihood is based on the products for signal (L_S) and for background (L_B) of n probability density functions (pdfs), P :

$$L_{S(B)}(\mathbf{x}) = \prod_{i=1}^n P_{S(B),i}(x_i), \quad (4.1)$$

where $\mathbf{x}$ is the vector of the various quantities specified in Table 4.1. $P_{S,i}(x_i)$ 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 nonprompt electrons from the decay of hadrons containing heavy flavor quarks. Correlations in the quantities selected for the likelihood are neglected.

For each electron candidate, a discriminant d_L is formed:

$$d_L = \frac{L_S}{L_S + L_B}. \quad (4.2)$$

The electron likelihood identification is based on this discriminant, which itself is based on the Neyman-Pearson lemma [99]. The discriminant d_L has a sharp peak at one for signal and at zero for 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 4.2:

$$d'_L = -\tau^{-1} \ln(d_L^{-1} - 1), \quad (4.3)$$

where the parameter τ is fixed to 15 [100]. As a consequence, the range of values of the transformed discriminant no longer varies between zero and one, and a sharp peak is no longer present. For each operating point, a value of the transformed discriminant is chosen: electron candidates with values of d'_L larger than this value are considered signal. Example distributions for the untransformed discriminant and the transformed discriminant are shown in Figure 4.5 for prompt electrons from Z boson decays and for background. This distribution illustrates the effective separation between signal and background when using the electron likelihood-based identification.

4.4.1.1 Electron Probability Density Functions

For analyses using only 2015–2016 data, the pdfs used in the electron likelihood were obtained from simulated $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ samples for signal electrons and simulation of generic two-to-two processes (primarily dijet events) for background objects, after applying data-driven corrections to the discriminating variables as described in Section 4.4.1.2. For analyses also using 2017 and 2018 data, the electron likelihood was updated to replace the simulated pdfs with data-driven pdfs based on the $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ tag-and-probe method for signal electrons, while the background pdfs are based primarily on dijet events collected using prescaled single electron triggers, both of which are described in Section 4.2.1.

After selecting the signal and background electron objects, finely binned histograms are used to create pdfs for each identification quantity from Table 4.1. As the distributions of the discriminating

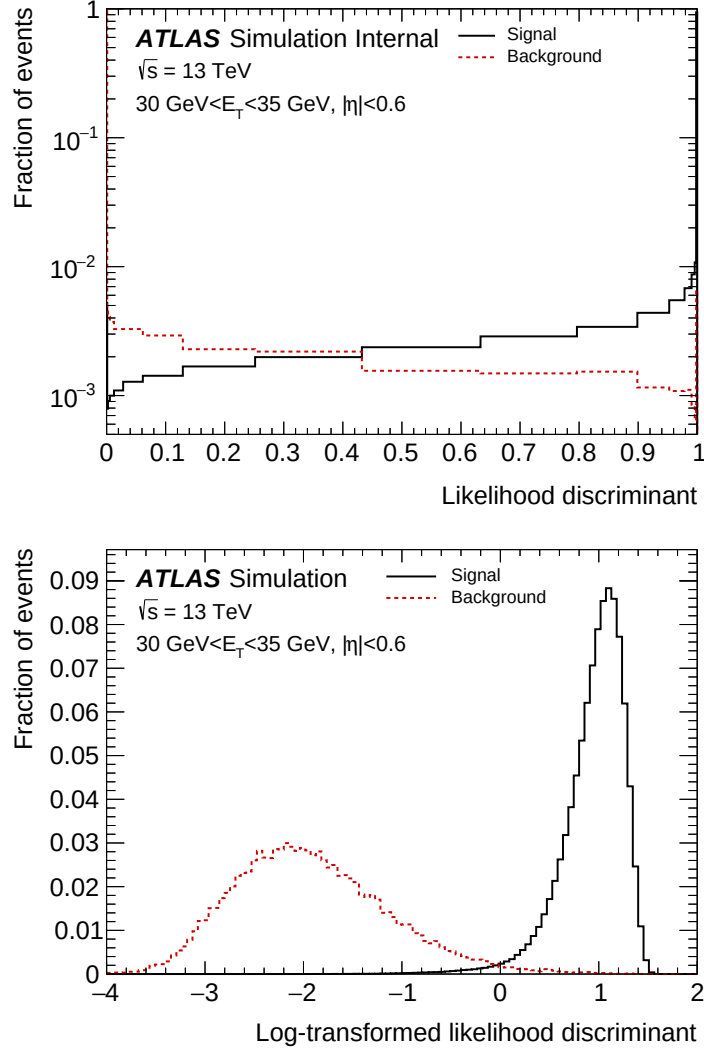


Figure 4.5: The untransformed likelihood-based identification discriminant d_L (top) and the transformed likelihood-based identification discriminant d'_L (bottom) for electron candidates with $30 \text{ GeV} < p_T < 35 \text{ GeV}$ and $|\eta| < 0.6$. The transformation is performed using the inverse sigmoid function shown in Equation 4.3. The black histogram is for prompt electrons in a $Z \rightarrow ee$ simulation sample while the red (dashed-line) histogram is for backgrounds in a generic two-to-two process simulation sample. The histograms are normalized to unit area. Note in the untransformed plot that greater than 90% of the entries are in the bin located at zero for background and at one for signal [6].

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 4.2: Boundaries in $|\eta|$ used to define the bins for the electron likelihood pdfs and likelihood discriminant requirements [6].

Bin boundaries in p_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 4.3: Boundaries in p_T used to define the bins for the electron likelihood pdfs and likelihood discriminant requirements. For $p_T < 15$ GeV, $J/\psi \rightarrow ee$ events are used for the signal electron pdfs, while $Z \rightarrow ee$ events are used for $p_T > 15$ GeV [6].

variables vary with both $|\eta|$ and p_T (primarily due to detector geometry, the large amount of material present in the detector at high $|\eta|$, and the behavior of high energy electrons compared with low energy electrons), separate pdfs are stored for each kinematic bin of interest. The kinematic bins used are shown in Tables 4.2 and 4.3. To avoid statistical fluctuations, the finely binned histograms are then smoothed using an adaptive kernel density estimator (KDE) implemented in the TMVA toolkit [100].

The signal and background pdfs for $20 \text{ GeV} < p_T < 30 \text{ GeV}$ and $0.60 < |\eta| < 0.80$, based on simulated events, are shown in Figures 4.6 through 4.8. Note that several quantities such as R_ϕ and f_1 demonstrate one of the reasons why the likelihood method is preferred over a cut-based selection: the signal distributions can have long tails which prevent the effective use of a cut-based criteria, whereas the likelihood can efficiently use these distributions as pdfs.

4.4.1.2 Data vs. Simulation Behavior

Imperfections in the detector modeling results in differences between some of the simulated quantities used in the electron identification when compared with those observed in data. These imperfections are largely due to mismodeling of the detector material, though mismodeling of other effects such as the alignment between the EM calorimeter and the Inner Detector, the magnetic field, and electronic crosstalk can also contribute. The differences between data and simulation typically appear as either a constant offset between the quantities (i.e. a shift of the distributions) or a difference in the widths of the distributions, quantified here as differences in the full-width at half-maximum (FWHM). In some cases, both shift and width differences are present for a single quantity. The quantities f_1 , f_3 , R_η , $w_{\eta 2}$, and R_ϕ have η -dependent offsets, while the quantities f_1 , f_3 , R_{had} , $\Delta\eta_1$, and $\Delta\phi_{\text{res}}$ have η -dependent differences in FWHM.

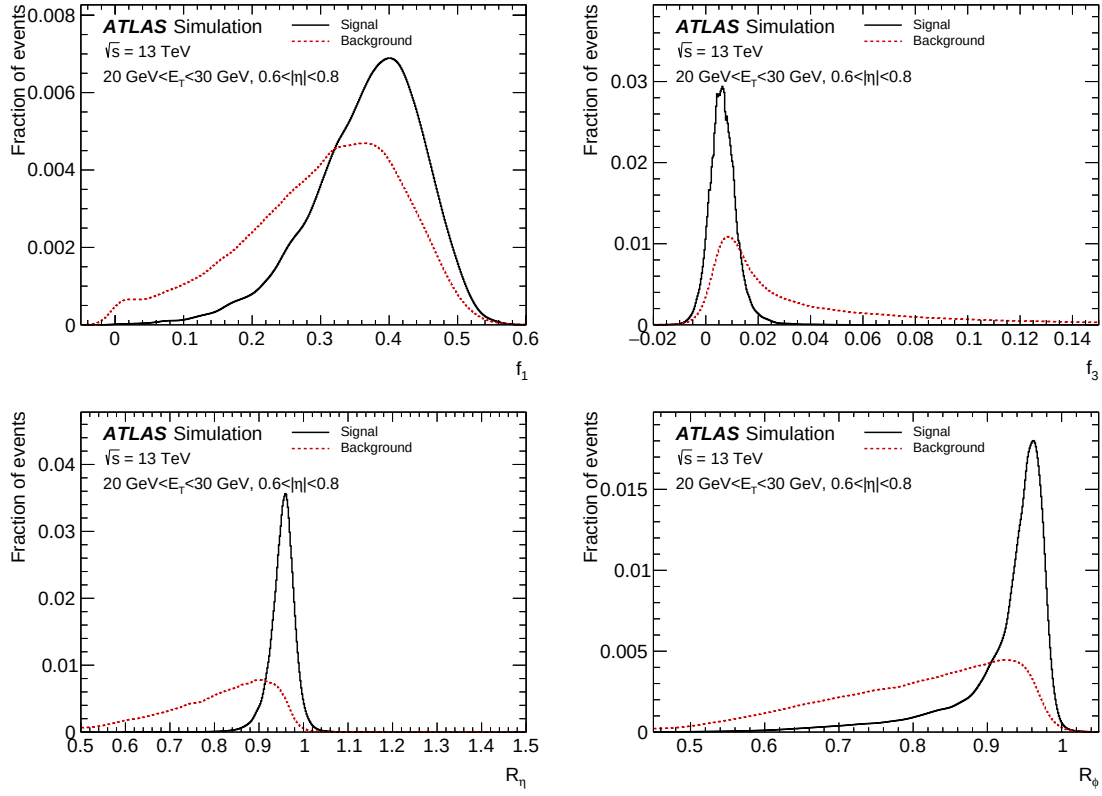


Figure 4.6: Distributions of the f_1 , f_3 , R_η , and R_ϕ variables used in the electron identification, shown for simulated signal electrons from $Z \rightarrow ee$ events (solid black line) and simulated background objects from a generic two-to-two process (dashed red line) with $20 \text{ GeV} < p_T < 30 \text{ GeV}$ and $0.60 < |\eta| < 0.80$. KDE smoothing has been applied to all of these distributions, as have the data-to-simulation corrections discussed in Section 4.4.1.2 [6].

To account for these differences when optimizing the electron likelihood using simulated events, shift and width corrections are applied to the discriminating variables. In the case of shift differences, the distribution in simulation is shifted by a fixed amount to make the distribution in simulation agree better with that in data. In the case of FWHM differences, the value in simulation is scaled by a multiplicative factor to modify the FWHM of the distribution. The optimal values of the shifts and width-scaling factors are determined by minimizing a χ^2 that compares the distributions in data with the distributions in simulation. Distributions of the variables used in the electron likelihood for data, simulation, and simulation after applying shift and width corrections are shown in Figures 4.9 through 4.11. These distributions are based on electrons collected via the tag-and-probe method with $Z \rightarrow ee$ events using 33.9 fb^{-1} of 2016 data [6].

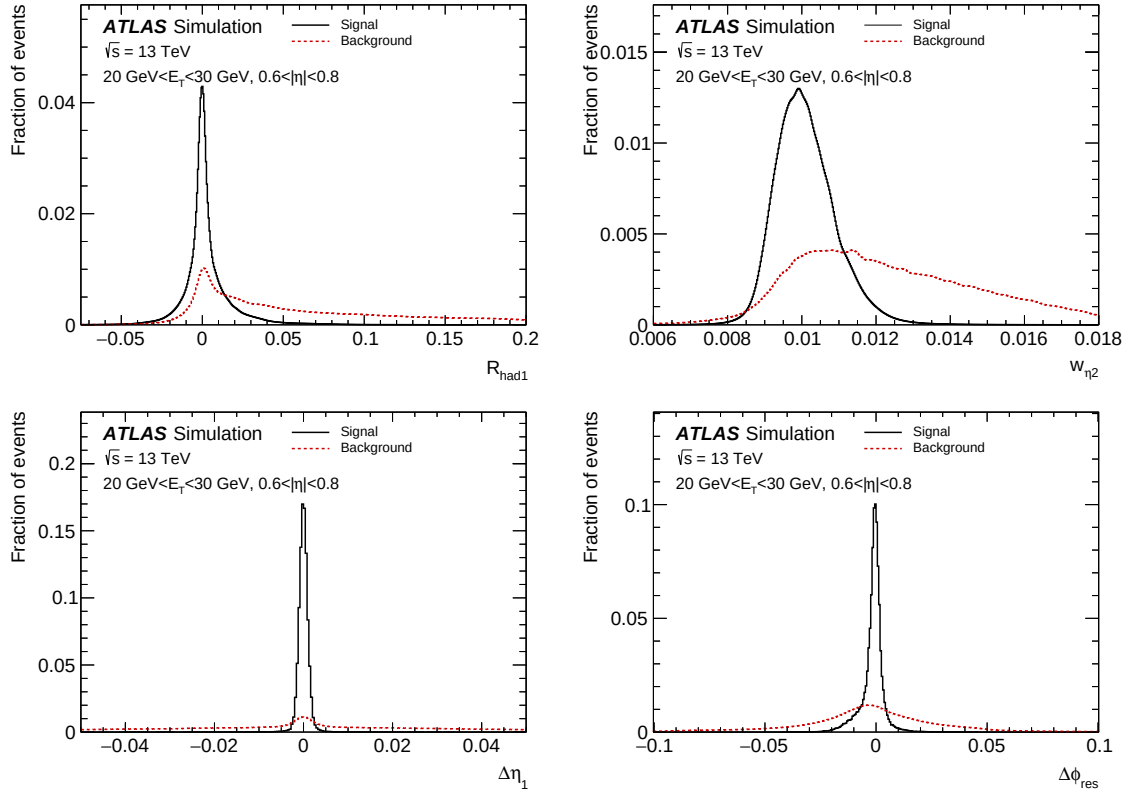


Figure 4.7: Distributions of the R_{had} , $w_{\eta 2}$, $\Delta\eta_1$, and $\Delta\phi_{\text{res}}$ variables used in the electron identification, shown for simulated signal electrons from $Z \rightarrow ee$ events (solid black line) and simulated background objects from a generic two-to-two process (dashed red line) with $20 \text{ GeV} < p_T < 30 \text{ GeV}$ and $0.60 < |\eta| < 0.80$. KDE smoothing has been applied to all of these distributions, as have the data-to-simulation corrections discussed in Section 4.4.1.2 [6].

4.4.2 Electron Identification Operating Points

As different ATLAS physics analyses desire different levels of electron signal efficiency and background rejection, several operating points are necessary. Four operating points are defined: VeryLoose, Loose, Medium, and Tight. Each corresponds to a more stringent requirement on the likelihood discriminant value than the one before it, and thus a larger background rejection (but correspondingly, a smaller signal efficiency). Simulated events, after applying the data-to-simulation shift and width corrections, are used to determine the discriminant requirement to be imposed for each operating point.

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

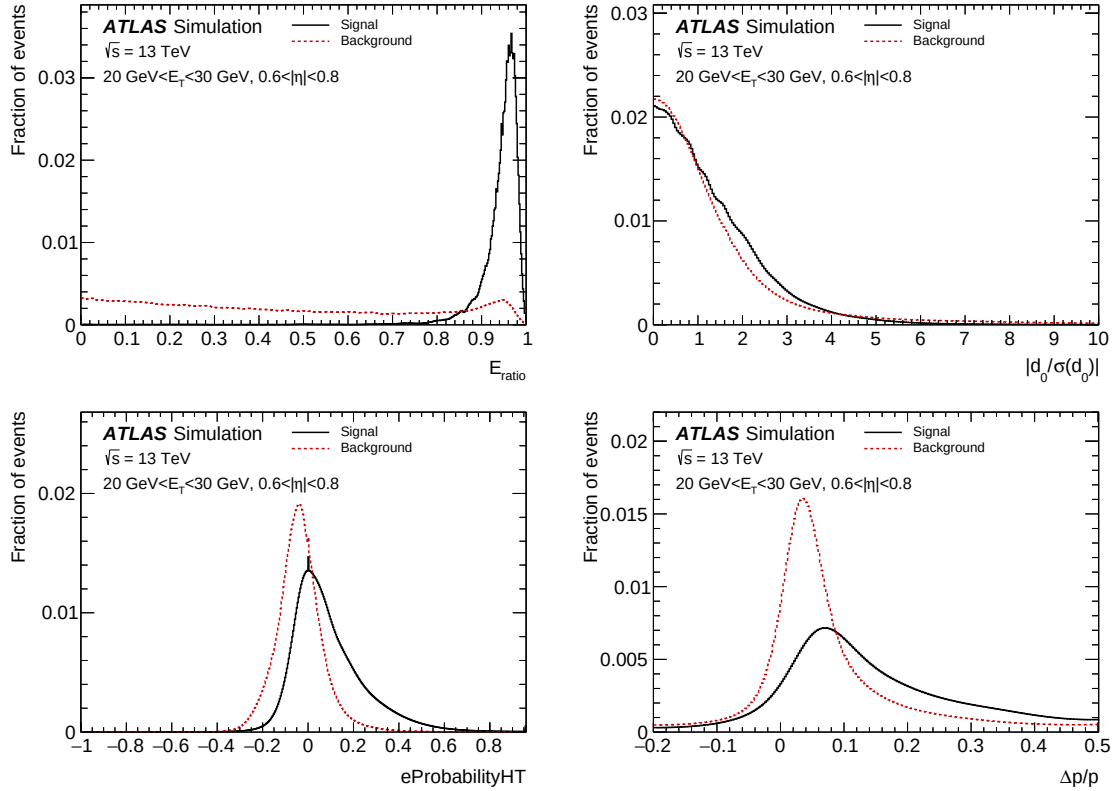


Figure 4.8: Distributions of the E_{ratio} , $|d_0/\sigma(d_0)|$, transformed eProbabilityHT, and $\Delta p/p$ variables used in the electron identification, shown for simulated signal electrons from $Z \rightarrow ee$ events (solid black line) and simulated background objects from a generic two-to-two process (dashed red line) with $20 \text{ GeV} < p_T < 30 \text{ GeV}$ and $0.60 < |\eta| < 0.80$. KDE smoothing has been applied to all of these distributions [6].

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.

Just as kinematic bins are necessary for the pdfs, these are needed for the discriminant requirements as well. The $|\eta|$ and p_T bins used for the likelihood discriminant requirements are shown in

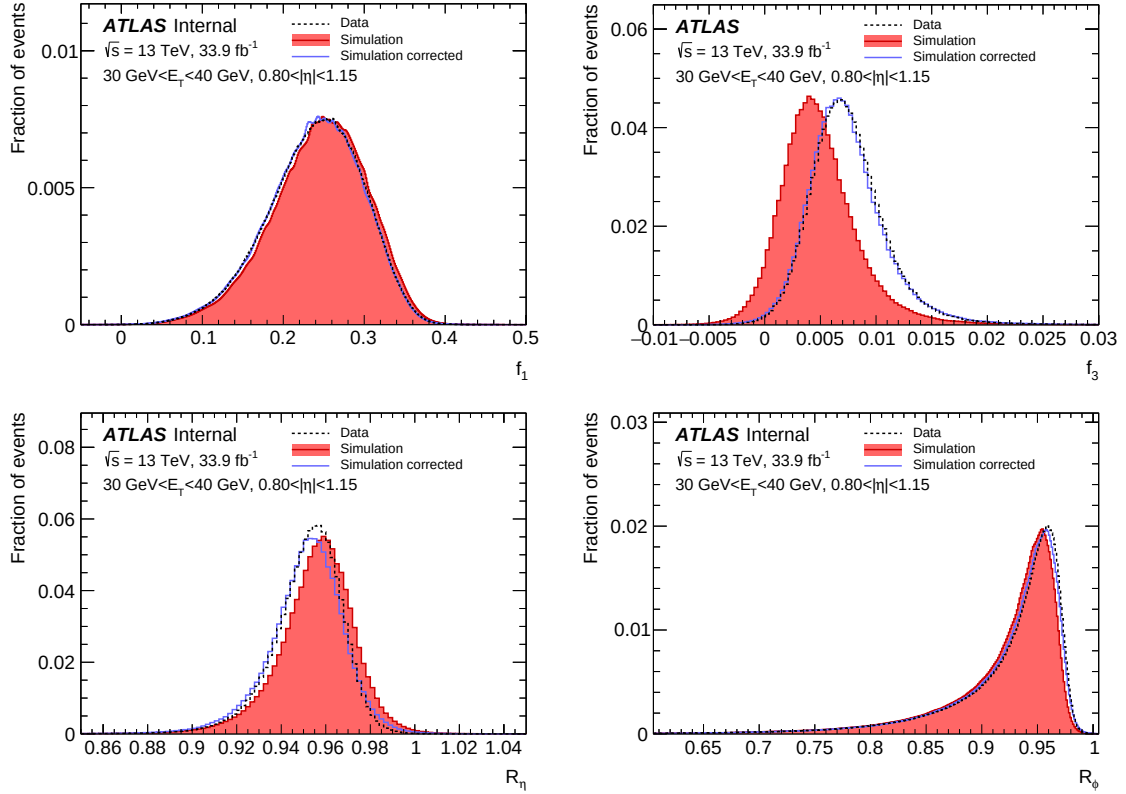


Figure 4.9: Distributions of the f_1 , f_3 , R_η , and R_ϕ variables used in the electron identification, measured using the $Z \rightarrow ee$ tag-and-probe method for probe electrons with $30 \text{ GeV} < p_T < 40 \text{ GeV}$ and $0.80 < |\eta| < 1.15$. To reduce the effect of background, these are shown only for VeryLoose probe electrons. KDE smoothing has been applied to all of these distributions. Data and simulation are overlaid, as are the “simulation corrected” distributions, which refers to the simulated distributions with shift or width corrections applied, as was done for the pdfs used by the electron likelihood for these particular variables [6].

Tables 4.2 and 4.3. Fewer p_T bins are used for the pdfs than for the discriminant requirements; this is to allow for a smoother increase of electron efficiency with p_T than would otherwise occur. As a general improvement to the electron likelihood with respect to Run 1, a “smoothing” procedure was implemented to interpolate the pdfs and discriminant cut values between the p_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 p_T when using p_T bins that are finer than that used for the identification optimization (which have a bin width of 5 GeV or larger for $p_T > 10 \text{ GeV}$). Figure 4.12 shows the impact of this procedure when using p_T bins of size 1 GeV; this procedure is now used by default for the electron identification operating points, as it avoids

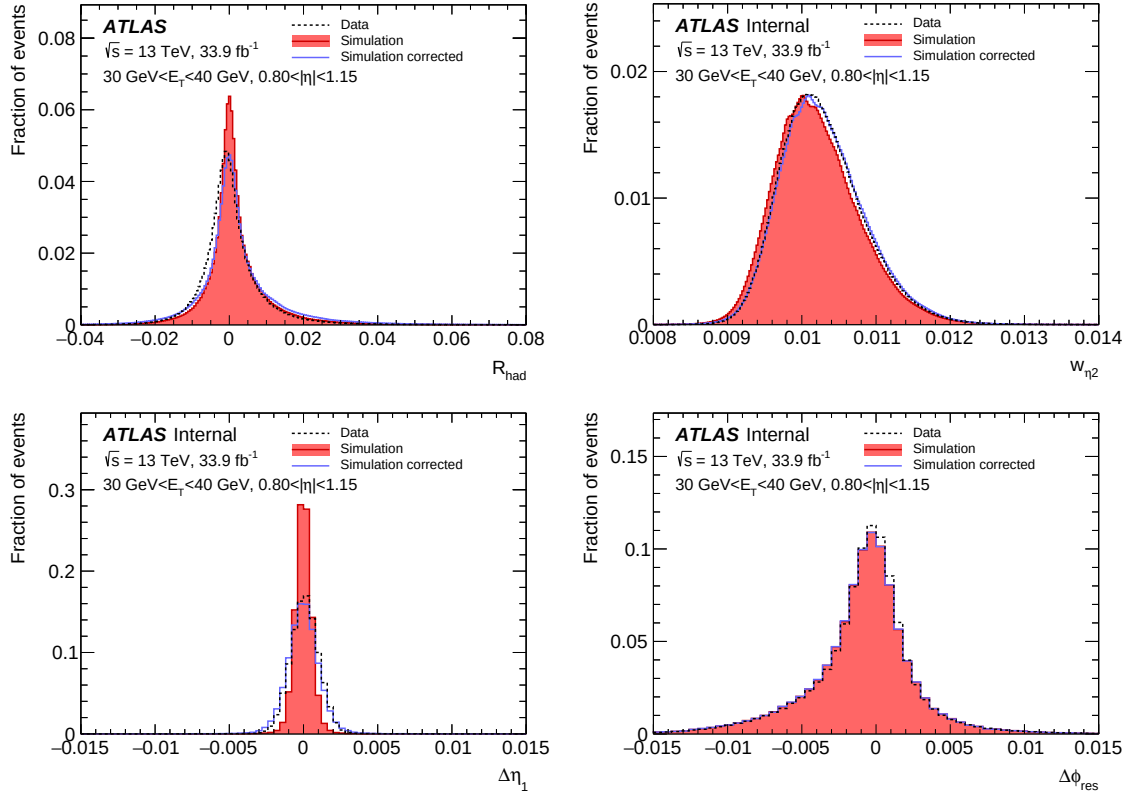


Figure 4.10: Distributions of the R_{had} , $w_{\eta 2}$, $\Delta\eta_1$, and $\Delta\phi_{\text{res}}$ variables used in the electron identification, measured using the $Z \rightarrow ee$ tag-and-probe method for probe electrons with $30 \text{ GeV} < p_T < 40 \text{ GeV}$ and $0.80 < |\eta| < 1.15$. To reduce the effect of background, these are shown only for VeryLoose probe electrons. KDE smoothing has been applied to all of these distributions. Data and simulation are overlaid, as are the “simulation corrected” distributions, which refers to the simulated distributions with shift or width corrections applied, as was done for the pdfs used by the electron likelihood for these particular variables [6].

large discontinuities at the bin edges defined by the operating points.

The efficiencies of these electron identification operating points in simulated $Z \rightarrow ee$, $J/\psi \rightarrow ee$, and dijet samples are shown in Figure 4.13. These operating points and their associated efficiencies in data are also discussed further in Chapter 5.

4.4.3 Mitigation of Pileup Dependence

Some of the powerful electron identification discriminating variables such as R_{had} tend to vary as a function of pileup—in the case of R_{had} , this is because pileup jets can deposit energy in the hadronic calorimeter near an electron, and cause the R_{had} distribution for prompt electrons to look

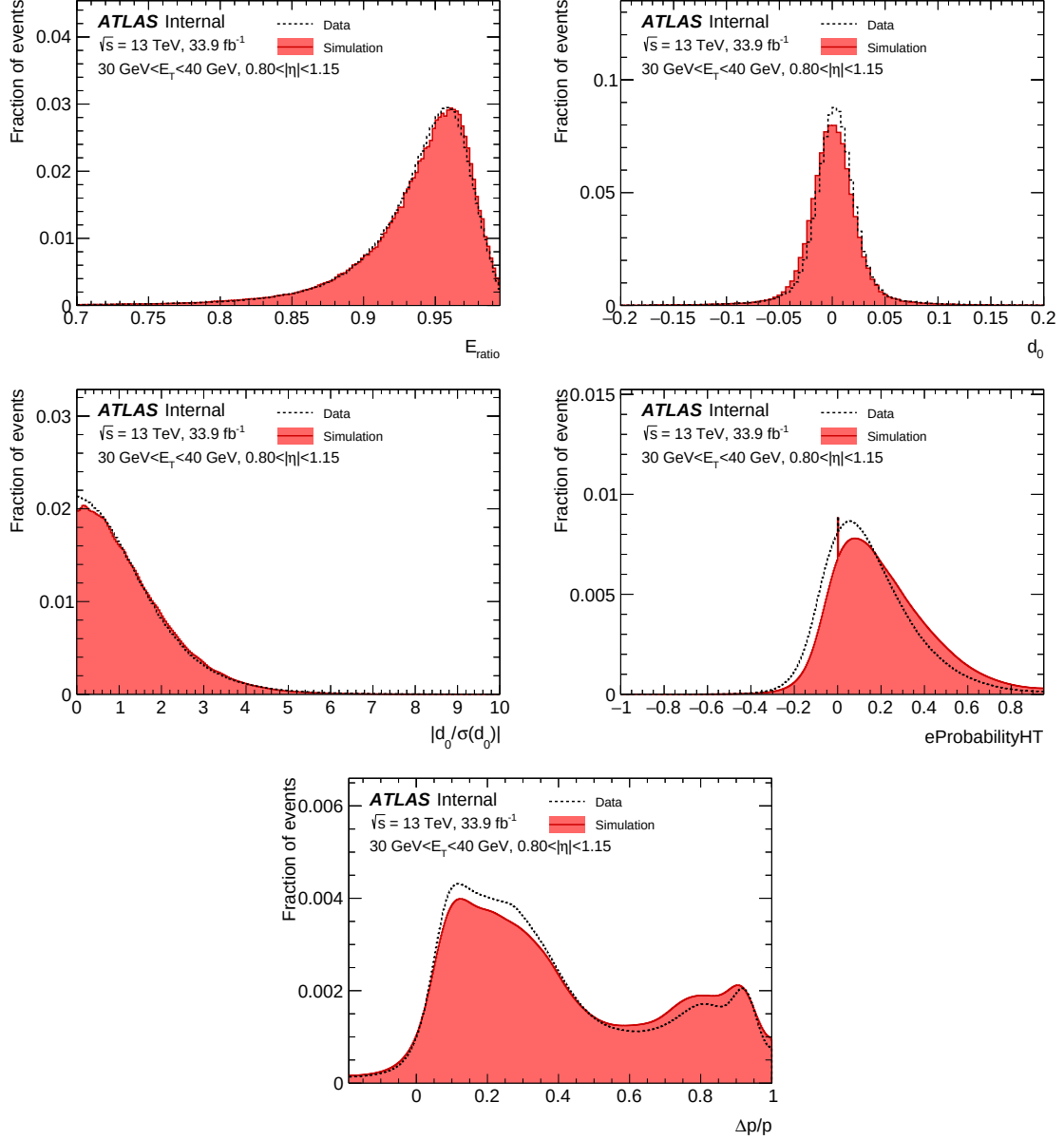


Figure 4.11: Distributions of the E_{ratio} , d_0 , $|d_0/\sigma(d_0)|$, transformed eProbabilityHT, and $\Delta p/p$ variables used in the electron identification, measured using the $Z \rightarrow ee$ tag-and-probe method for probe electrons with $30 \text{ GeV} < p_T < 40 \text{ GeV}$ and $0.80 < |\eta| < 1.15$. To reduce the effect of background, these are shown only for VeryLoose probe electrons. KDE smoothing has been applied to all of these distributions. Data and simulation are overlaid. None of the distributions shown in this figure used any shift or width corrections for the simulated pdfs [6].

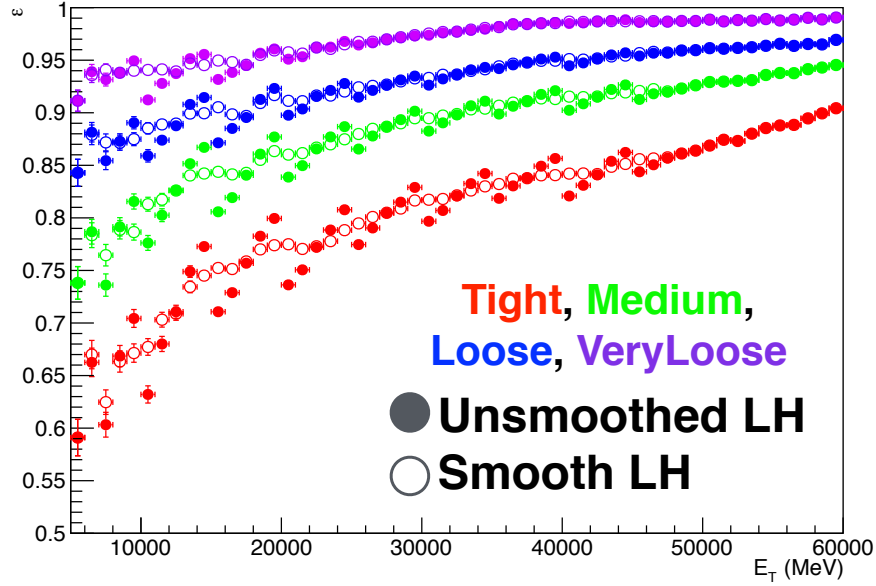


Figure 4.12: Efficiency of electron identification operating points determined using simulated $Z \rightarrow ee$ events, shown both before and after a smoothing procedure was applied to interpolate the pdfs and discriminant cut values between p_T bins. Clearly, the smoothed version has a much nicer behavior, and thus became the default.

more background-like at high pileup. In Run 1, good signal efficiency and background rejection as a function of pileup was ensured by linearly adjusting the discriminant cut values of the operating points (in each p_T and $|\eta|$ bin used) based on the number of reconstructed vertices (n_{vtx}) in the event:

$$d_L''(n_{\text{vtx}}) = d_L' - a \cdot n_{\text{vtx}}, \quad (4.4)$$

where d_L' comes from Equation 4.3 and a is a constant chosen for each kinematic bin to ensure that the signal efficiency at low and high n_{vtx} do not differ significantly, while still ensuring that background efficiency also does not dramatically increase with pileup. One drawback of this is that the pileup dependence of the various operating points differs, and thus the a value must also differ between the operating points. As a result, it is possible for the operating points to not be subsets of one another in some cases (i.e. Tight can select electrons that Medium does not). While the degree to which this happens was found to be for less than 0.05% of reconstructed electrons in Run 1, it was desired to force the operating points to be proper subsets of one another in Run 2, particularly for use in fake lepton background estimation by ATLAS analyses. To do so, the discriminant cut values were no longer changed as a function of n_{vtx} , but instead the discriminant value itself is transformed based on the n_{vtx} value for the given event. This allows the discriminant cut values to be kept fixed,

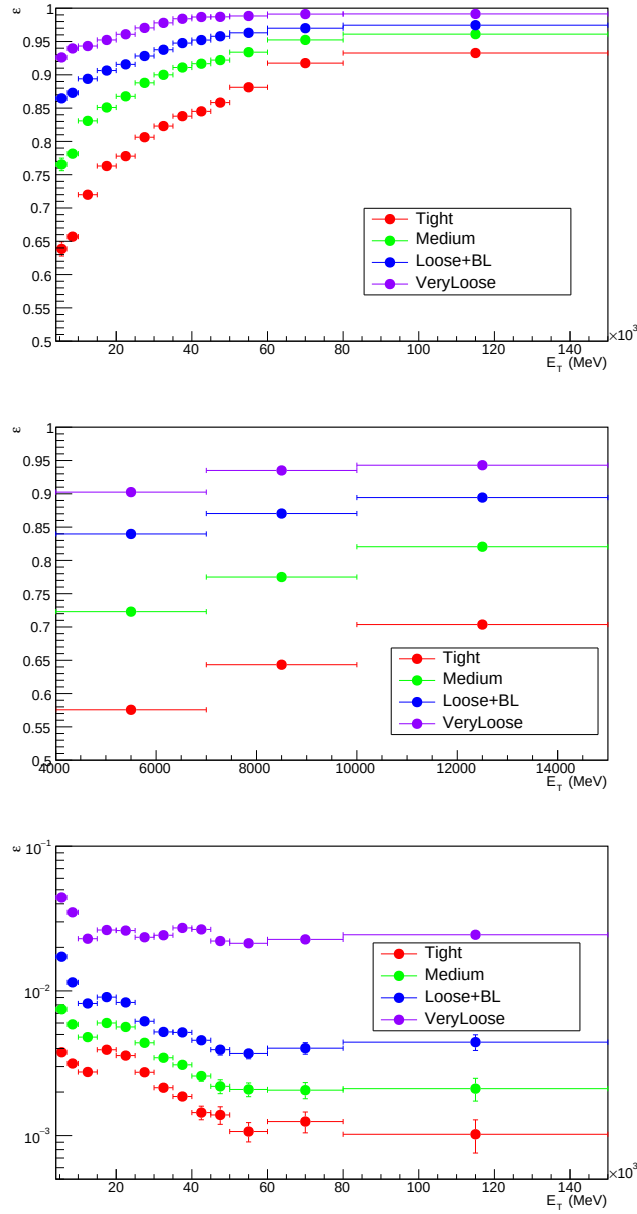


Figure 4.13: Electron identification operating point efficiencies as a function of p_T in simulated $Z \rightarrow ee$ (top), $J/\psi \rightarrow ee$ (middle), and dijet (bottom) samples. The $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ efficiency plots demonstrate the identification efficiency for prompt signal electrons (as measured with respect to all reconstructed electrons with a good-quality track), while the dijet efficiency plot demonstrates the identification efficiency for electron background processes. Note that the efficiencies for a given p_T bin need not agree perfectly between $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ because the topology of these processes can differ (e.g. different amounts of hadronic activity near the electron, boosted topologies with nearby electron pairs, etc.).

thus ensuring that the operating points (defined entirely by the discriminant cut value used and any additional rectangular cuts) can all be subsets of one another. The transformation used is designed to allow for a larger adjustment due to pileup of any discriminant values near the cut value used for the Tight operating point and no adjustment for those near the cut value used for the VeryLoose operating point. The transformation therefore takes the form:

$$d_L''(d_L', n_{\text{vtx}}) = \begin{cases} d_L', & d_L' \leq d_{\text{VeryLoose}} & \text{(I)} \\ d_{\text{VeryLoose}} + (d_L' - d_{\text{VeryLoose}}) \times \frac{d_{\text{Tight}} - d_{\text{VeryLoose}}}{d_{\text{Tight}}' - d_{\text{VeryLoose}}}, & d_{\text{VeryLoose}} < d_L' < d_{\text{Tight}}' & \text{(II)} \\ d_{\text{Tight}} + (d_L' - d_{\text{Tight}}') \times \frac{d_{\text{max}} - d_{\text{Tight}}}{d_{\text{max}} - d_{\text{Tight}}'}, & d_{\text{Tight}}' < d_L' < d_{\text{max}} & \text{(III)} \\ d_L', & d_L' > d_{\text{max}} & \text{(IV)} \end{cases} \quad (4.5)$$

where d_{max} is the maximum discriminant value for which a correction is applied (and $d_{\text{max}} = 2$ was chosen in Run 2), while d_{Tight}' is defined as:

$$d_{\text{Tight}}' = d_{\text{Tight}} - a_{\text{Tight}} \cdot \min(n_{\text{vtx}}, 50). \quad (4.6)$$

The $\min(n_{\text{vtx}}, 50)$ parameter is used here to ensure that the operating points do not have an increasingly large adjustment for $n_{\text{vtx}} > 50$; however, this may need to be revisited in Run 3 to ensure sufficient performance. d_{Tight} and a_{Tight} are chosen in the same manner as was done in Run 1, based on Equation 4.4. A sketch of the behavior of the operating points after applying this discriminant transform is shown in Figure 4.14. This procedure has been found to result in nearly the same performance as a function of pileup as that used in Run 1. Though this procedure is certainly more complicated than that used in Run 1, the benefit of being able to ensure that the operating points are subsets of one another makes it worthwhile, and thus this procedure has been used for all of the likelihood-based electron identification operating points developed in Run 2. A comparison of the efficiencies for the Tight operating point as a function of n_{vtx} both before and after applying the pileup-dependent likelihood discriminant transform is shown for both signal and background in Figure 4.15; without this correction, the background efficiency would exponentially increase with n_{vtx} .

4.4.4 Challenges and Performance at High p_T

Soon after Run 2 data-taking began in 2015, the Tight electron identification working point was found to be inefficient at high p_T . This was unexpected based on previous studies using an earlier software release from before the start of Run 2 (before the eProbabilityHT variable existed, and

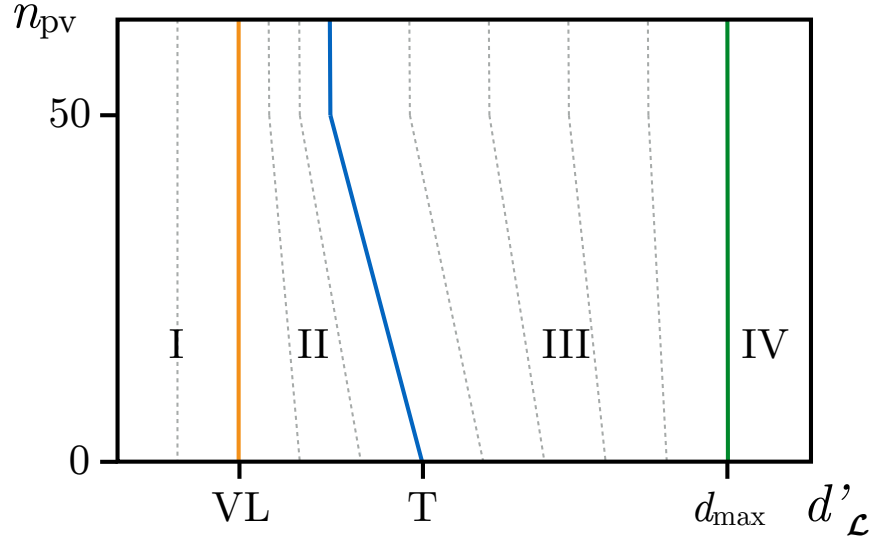


Figure 4.14: Sketch of the behavior of the electron identification operating points after applying the pileup-dependent discriminant transform from Equation 4.5. Lines of equal d'_L are shown as a function of d'_L and n_{vtx} (labeled here as n_{pv}), with the orange and blue lines highlighting the VeryLoose and Tight operating points, respectively. The green line highlights the discriminant value beyond which no additional correction is applied, d_{max} . The Roman numerals shown for each region correspond to those listed in Equation 4.5.

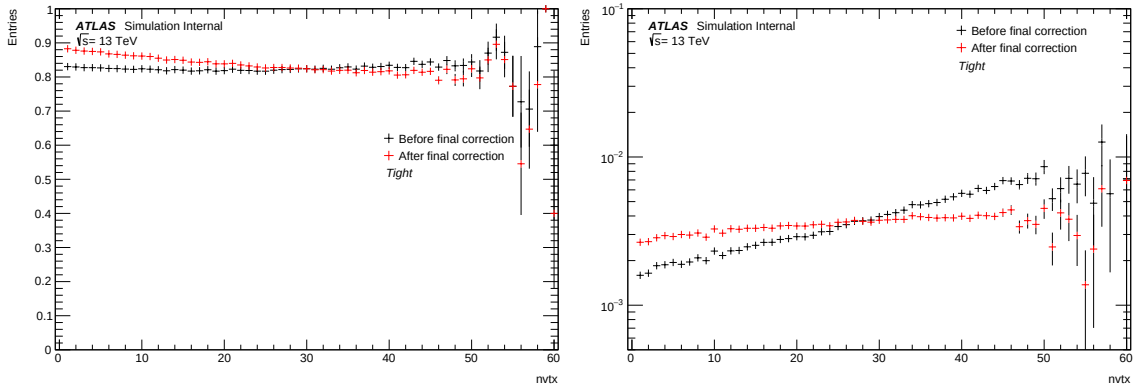


Figure 4.15: Tight efficiency as a function of n_{vtx} for signal electrons from $Z \rightarrow ee$ simulation (left) and background objects from dijet simulation (right), shown both before and after applying the pileup-dependent discriminant transform. While the signal efficiency is relatively flat as a function of n_{vtx} before any correction is applied, the background efficiency increases exponentially with n_{vtx} . After applying the transform, the signal efficiency has a slight linear decrease with increasing n_{vtx} , while the background efficiency only has a mild increase as a function of n_{vtx} .

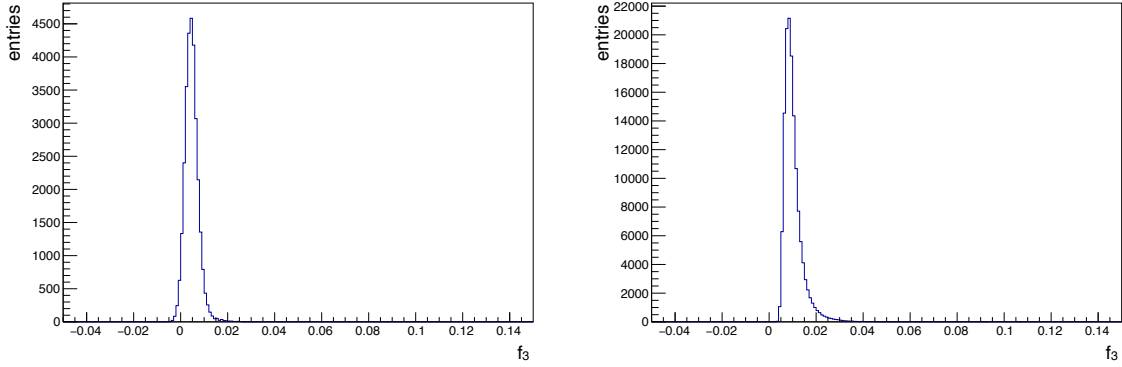


Figure 4.16: Example distributions of f_3 for prompt electrons from simulated Drell-Yan samples with $40 \text{ GeV} < p_T < 50 \text{ GeV}$ (left) and with $500 \text{ GeV} < p_T < 1000 \text{ GeV}$ (right). Both distributions are shown for electrons with $|\eta| < 0.6$. f_3 differs significantly at high p_T compared with the relatively low p_T region (near 40 GeV) which is used to define the likelihood pdfs, thus resulting in inefficiencies when included as part of the electron likelihood at high p_T .

using an older version of the electron reconstruction algorithm), and was worrisome as this could have a direct impact on searches for heavier versions of the W and Z (referred to as W' and Z') which decay to high p_T leptons. These searches benefit from the larger center-of-mass energy in Run 2 ($\sqrt{s} = 13 \text{ TeV}$) compared with that of Run 1 ($\sqrt{s} = 8 \text{ TeV}$, at least in 2012), so ATLAS planned to publish these searches as early as possible—but with an inefficient electron identification, the sensitivity of these searches would be compromised.

Prior studies had determined that the f_3 variable caused inefficiencies at high p_T , and thus it was previously decided to remove f_3 from the electron likelihood for $p_T > 100 \text{ GeV}$. This was well-motivated as f_3 is the fraction of energy deposited in the third layer of the electromagnetic calorimeter. As the electromagnetic calorimeter is roughly 25 radiation lengths long, most electrons deposit very little energy in this layer. However, at high p_T , electrons start to “punch through” to this layer and cause f_3 to deviate from zero; this causes the signal electrons to look more like the background objects. Distributions of f_3 for signal electrons in different p_T regimes (based on simulated high mass Drell-Yan samples [101]) can be seen in Figure 4.16. In the software release initially used for 2015 data, one can see in Figure 4.17 that while this variable was still problematic at high p_T , more had to be done to improve the high p_T efficiencies.

Studies were performed to look for additional culprits and determine a way to improve the high p_T electron identification efficiencies. These studies found that f_1 , R_{had} , and eProbabilityHT additionally behave different at high p_T than for electrons with $p_T < 100 \text{ GeV}$ (which is where the electron likelihood pdfs are derived); example distributions of these variables in different p_T regimes

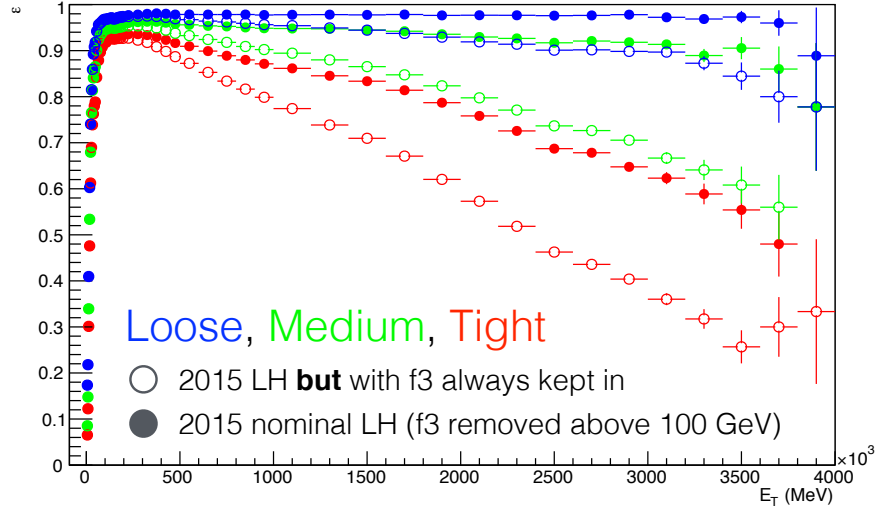


Figure 4.17: High p_T electron identification efficiencies with and without f_3 , determined using simulated Drell-Yan samples.

can be seen in Figure 4.18. Similar to f_3 , the distributions of f_1 and R_{had} differ for high p_T electrons as a smaller fraction of energy is deposited in the first layer of the electromagnetic calorimeter while more energy is deposited in the hadronic calorimeter. The eProbabilityHT variable, meanwhile, is modeled to linearly grow as $\log_{10}(\gamma)$ where γ is the relativistic Lorentz factor. As this may not be accurate at large values of γ , a large tail appears for eProbabilityHT.

However, these are some of the most important variables for discriminating prompt signal electrons from the various background sources, and thus it is not possible to simply remove these variables from the likelihood without significantly affecting background rejection. Several strategies were attempted, including:

- Use an analytic function to derive a “corrected” R_{had} variable as a function of p_T , to account for calorimeter punch-through effects. This caused background rejection to suffer.
- Remove the problematic variables at high p_T and introduce new discriminating variables that are not currently present in the electron likelihood. However, one of the most promising variables for this purpose is E/p , which could be mismodeled and have poor resolution in the simulation at high p_T , so a heavy reliance on the shape of this distribution would not be ideal.
- Add more bins to the electron likelihood, using simulated Drell-Yan and dijet samples to derive the pdfs at high electron p_T . This caused large discontinuities in electron identification efficiency at bin edges which could impact the searches. Moreover, it would be impossible

to measure the data-to-simulation correction factors for these high p_T bins, as the high p_T electron statistics available via the $Z \rightarrow ee$ tag-and-probe method tend to be small. Since each bin of the electron likelihood is independent, this would be problematic as it would be impossible to trust the simulation in the high p_T bins.

The solution that was ultimately settled on was to relax the likelihood discriminant selection for the Tight operating point to be identical to that of Medium at high p_T , and to introduce loose rectangular cuts on the E/p and w_{stot} variables for $p_T > 125$ GeV. This threshold was chosen based on the electron trigger used for the W' analysis in 2015 data, `HLT_e120_1hloose` (which requires trigger-level electrons with $p_T > 120$ GeV), to ensure that the data-driven fake lepton background estimation used by the analysis could still function without modifications. The performance of this reoptimized Tight identification working point can be seen in Figure 4.19 for both signal and background electrons, and the efficiency of this new working point is significantly higher than that of the initial Tight working point while still retaining a good background rejection.

To account for potential mismodeling in simulation at high electron p_T which cannot be determined due to a lack of statistics from $Z \rightarrow ee$ tag-and-probe data events, an additional systematic uncertainty was determined for electrons with $p_T > 125$ GeV. To do so, the data-driven shift and width corrections used for the optimization of the electron likelihood were applied to simulated Drell-Yan events containing high p_T electrons. Additionally, the $\Delta\eta_1$ variable is known to be mismodeled in simulation due to distortions in the calorimeter which are not typically simulated. To account for these, distortions of a similar magnitude were also injected into the simulated events. The electron identification efficiency in the Drell-Yan simulation was then compared before and after applying these corrections, and their ratio was used to assign an additional uncertainty. Figure 4.20 shows this for Tight, where a conservative 2.5% uncertainty was assigned, corresponding to the bin whose ratio has the largest deviation from 1. The same procedure was also performed for Medium and Loose, where an uncertainty of 2% was assigned.

In the subsequent software releases used by ATLAS to analyze 2015–2016 data as well as the full Run 2 data, studies of the high p_T behavior of the electron likelihood have been repeated, and the corresponding systematic uncertainties have been reevaluated. One small change which has been made is to adjust the p_T threshold used for the high p_T changes to Tight from 125 GeV up to 150 GeV. This was done to better align with the bin threshold typically used for the electron identification efficiency measurement. Similarly, while f_3 was previously removed from the electron likelihood for $p_T > 100$ GeV, this has since been adjusted to $p_T > 80$ GeV, to also align with the

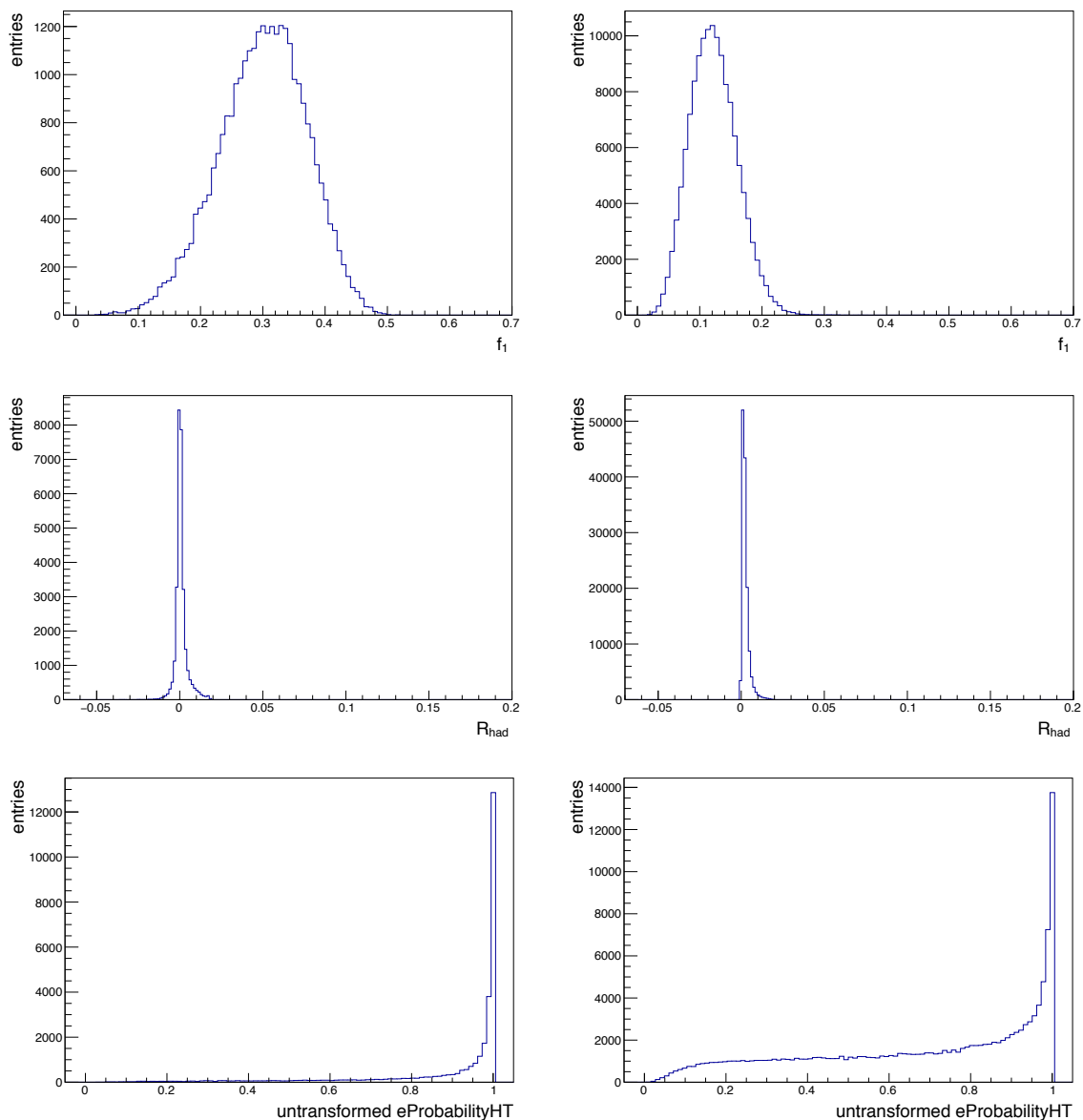


Figure 4.18: Example distributions of f_1 (top), R_{had} (middle), and untransformed eProbabilityHT (bottom) for prompt electrons from simulated Drell-Yan samples with $40 \text{ GeV} < p_T < 50 \text{ GeV}$ (left) and with $500 \text{ GeV} < p_T < 1000 \text{ GeV}$ (right). All distributions are shown for electrons with $|\eta| < 0.6$. These variables all differ significantly at high p_T , and are the source of inefficiencies for the Tight identification.

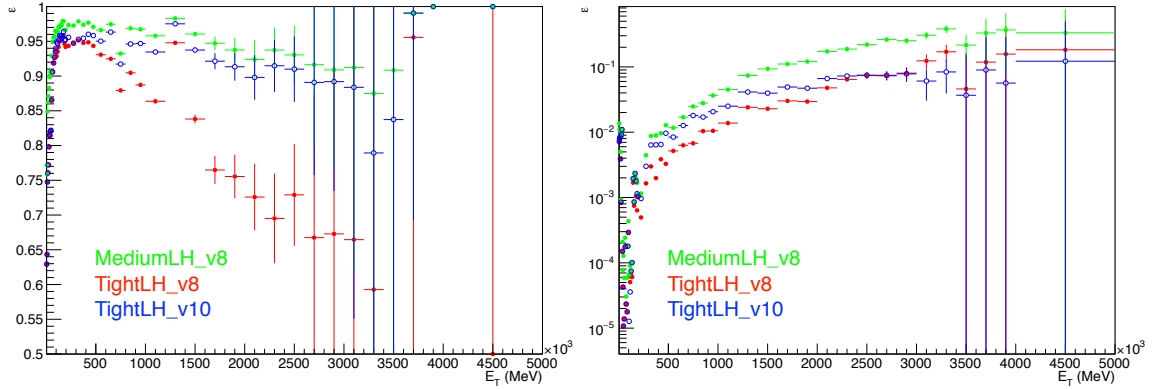


Figure 4.19: High p_T signal (left) and background (right) electron identification efficiencies determined using simulated Drell-Yan and dijet samples (respectively), shown both before and after improving the Tight operating point. The initial electron identification operating points used for 2015 data are labeled as “v8” in these plots, while the reoptimized Tight operating point is labeled as “v10”. Note that the points in the $700 \text{ GeV} < p_T < 800 \text{ GeV}$ and $1200 \text{ GeV} < p_T < 1400 \text{ GeV}$ bins for the signal efficiency plot appear to be outliers with respect to the general trend observed as a function of p_T ; these were determined to be due to single events with large weights, and therefore are not meaningful.

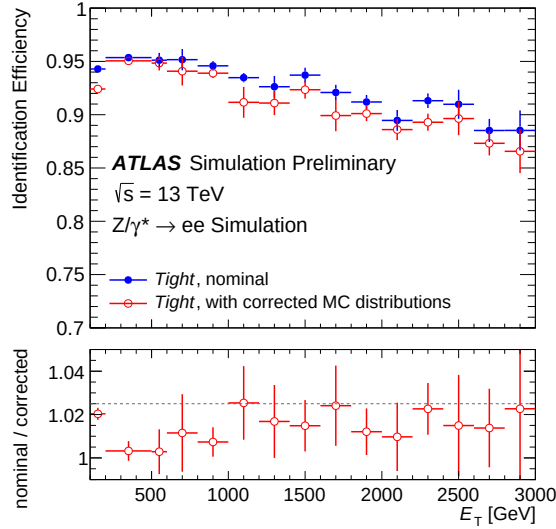


Figure 4.20: Electron identification efficiencies for high p_T electrons from simulated Drell-Yan events. The nominal, uncorrected simulation is compared with simulation after applying data-driven corrections to the identification variables. The ratio was used to determine the additional systematic uncertainty assigned for high p_T electrons [5].

binning used for the efficiency measurement. Other than these threshold changes, no additional treatment for high p_T electron identification has been introduced since the initial analysis of 2015 data, and the electron likelihood has been successfully used at high electron p_T by the W' and Z' analyses [2, 3].

4.4.5 Challenges and Performance at Low p_T

In Run 1, the electron identification algorithms were supported for electrons with $p_T > 7$ GeV. For Run 2, it was desired to push this threshold to lower p_T for the benefit of searches which rely on soft leptons, including the compressed electroweak SUSY search discussed in Chapter 8. Moreover, the electron identification pdfs in Run 1 used $Z \rightarrow ee$ tag-and-probe events for all p_T bins, despite the fact that there are relatively few $Z \rightarrow ee$ events with low p_T leptons (and in data, the purity of a $Z \rightarrow ee$ tag-and-probe selection at low p_T tends to suffer). To improve upon this, $J/\psi \rightarrow ee$ events were employed for the Run 2 pdfs for $4.5 \text{ GeV} < p_T < 15 \text{ GeV}$, and the likelihood discriminant cuts were chosen using $J/\psi \rightarrow ee$ events in this p_T range as well. Note that formally the identification operating points are functional from a technical standpoint starting with $p_T > 4$ GeV, but currently no efficiency measurement is performed until $p_T > 4.5$ GeV, and thus the electrons with $4 \text{ GeV} < p_T < 4.5 \text{ GeV}$ are not currently used by ATLAS.

The main difficulty at low p_T is the large amount of background present. As a result, the operating points at low p_T tend to have lower efficiency for prompt signal leptons as well as worse background rejection, as can be seen in Figure 4.13. Potential ways to improve the low p_T operating points are discussed in Section 4.6.

4.4.6 Electron Identification at the High Level Trigger

In 2012, the HLT used a cut-based selection for electrons, which was found to be inefficient when combined with the offline likelihood-based identification operating points. Moreover, as a likelihood-based electron identification can significantly improve background rejection with respect to a cut-based electron identification, use of the electron likelihood at trigger-level could allow for reduced HLT rates without losing efficiency due to either more stringent cut-based selection criteria or use of higher p_T thresholds by the electron trigger chains. Thus, a likelihood-based selection at the HLT was developed for Run 2, which is designed to be nearly identical to the offline identification operating points. The main differences are:

- Removal of the $\Delta p/p$ variable as it is currently only computed for tracks which have been processed through the Gaussian Sum Filter algorithm [102], which is currently too time intensive to use at the HLT.
- Use of trigger-level reconstructed quantities for the various discriminating variables, which can have different resolutions with respect to offline.
- Use of the number of interactions per crossing (μ) as the variable to determine how much to adjust the likelihood discriminant cut with increasing pileup, since n_{vtx} takes too long to calculate for every event containing a potential electron candidate.
- In 2015, d_0 and $|d_0/\sigma(d_0)|$ were included as pdfs in the primary likelihood-based electron trigger chains, but parallel chains were also defined with these variables removed from the electron likelihood to be used by e.g. analyses which rely on leptonically decaying τ leptons or searches for exotic particles with displaced decays. To avoid the need to duplicate these trigger chains again, the primary likelihood-based trigger chains starting in 2016 did not include d_0 and $|d_0/\sigma(d_0)|$ as input variables.

An additional set of likelihood-based identification criteria exist at the HLT which only rely on the calorimeter shower shapes (i.e. no tracking information is used). This is used as a very efficient preselection to quickly veto fake lepton events before processing events through the track reconstruction algorithms at the HLT, which take an order of magnitude longer to run than the cluster reconstruction algorithms. Events which fail this calorimeter-only identification do not need to undergo the tracking step, which helps to reduce the amount of computing resources needed. This “calo-only” electron likelihood step ran in parallel with the standard electron identification chains in 2015 before being used by default by all electron trigger chains in 2016. Starting in 2017, the calo-only electron likelihood step was replaced by the “ringer” algorithm, which is a fast neural network algorithm relying on the $\sum E_T$ of concentric rings of calorimeter cells surrounding the center of the reconstructed cluster. More information on the ringer algorithm will be detailed in a future publication describing the electron and photon triggers used by ATLAS in Run 2.

The distributions of the trigger-level discriminating variables used in the electron likelihood are overlaid with the offline-level distributions in Figures 4.21 through 4.24, based on data collected in 2016. The events are selected using the tag-and-probe method, with the trigger-level objects chosen to be electron candidates within $\Delta R < 0.07$ of a corresponding offline-quality probe electron. Many

of these distributions are quite similar between the trigger-level and offline; however, several key differences exist, all of which affect both signal electrons and the background electron candidates:

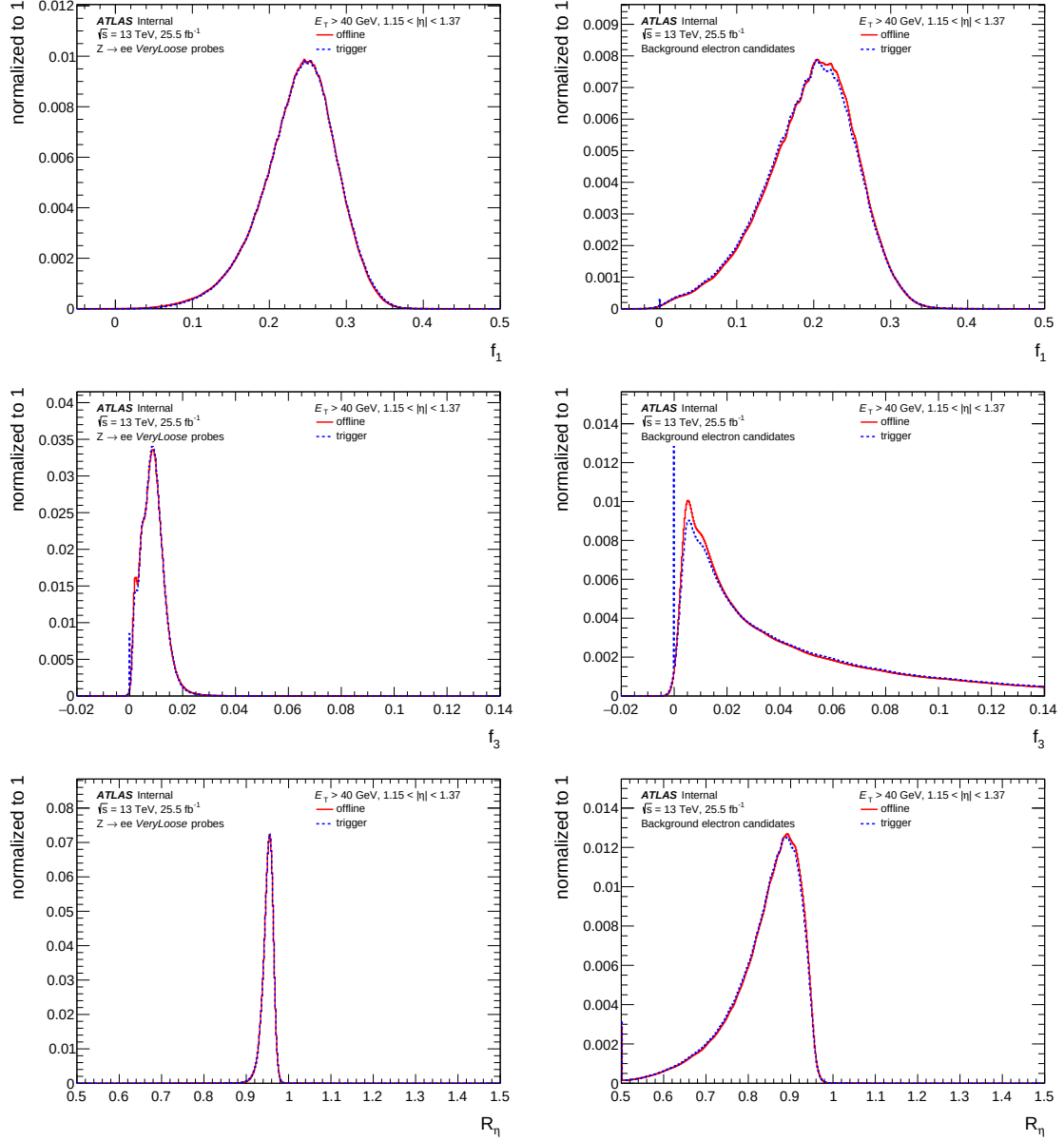
- f_3 has a contribution at zero at trigger-level which is not present offline. This may be due to zero energy measured in the third layer of the EM calorimeter, or use of an invalid cluster. The latter seems unlikely since this feature is much smaller in e.g. f_1 ; however, the precise source of this behavior for f_3 has not yet been investigated further.
- R_{had} has a visible shift to larger values at trigger-level compared to offline.
- eProbabilityHT has a visible shift to smaller values at trigger-level compared to offline (most prevalent for the background electron candidates).
- d_0 and $|d_0/\sigma(d_0)|$ tend to be wider at trigger-level than offline (especially for signal electrons), in part due to a neural network clustering algorithm which is used in the offline track reconstruction [62, 103], as well as improved knowledge of the beam-line position offline.

The efficiency of the likelihood-based electron identification at the HLT, as well as sources of inefficiency and background rates, are discussed in Section 5.7.

4.5 Electron Isolation

To suppress backgrounds which tend to leave more diffuse signatures in the Inner Detector and the EM calorimeter (as opposed to prompt electrons, which typically have very little activity surrounding them), isolation requirements are imposed. Isolation is performed by summing the transverse energy of clusters in the EM calorimeter or the transverse momenta of tracks in a cone of radius ΔR around the electron candidate object, excluding the candidate itself. Thus, the sum of calorimeter energy or track momenta in a given cone is expected to be small for prompt electrons and larger for the various types of background objects.

The ATLAS calorimeter-based isolation algorithm relies on reconstructed topological clusters built from cells in the EM calorimeter. This method is used rather than solely relying on the individual cells due to its ability to suppress contributions from pileup and the better agreement observed between data and simulation [72]. These topological clusters are seeded by cells with an EM energy that is at least four times larger than the expected noise for the given cell. The topological cluster is then expanded by iteratively adding any neighboring cells with an energy that is at least two times larger than the expected noise level. Once there are no additional cells which



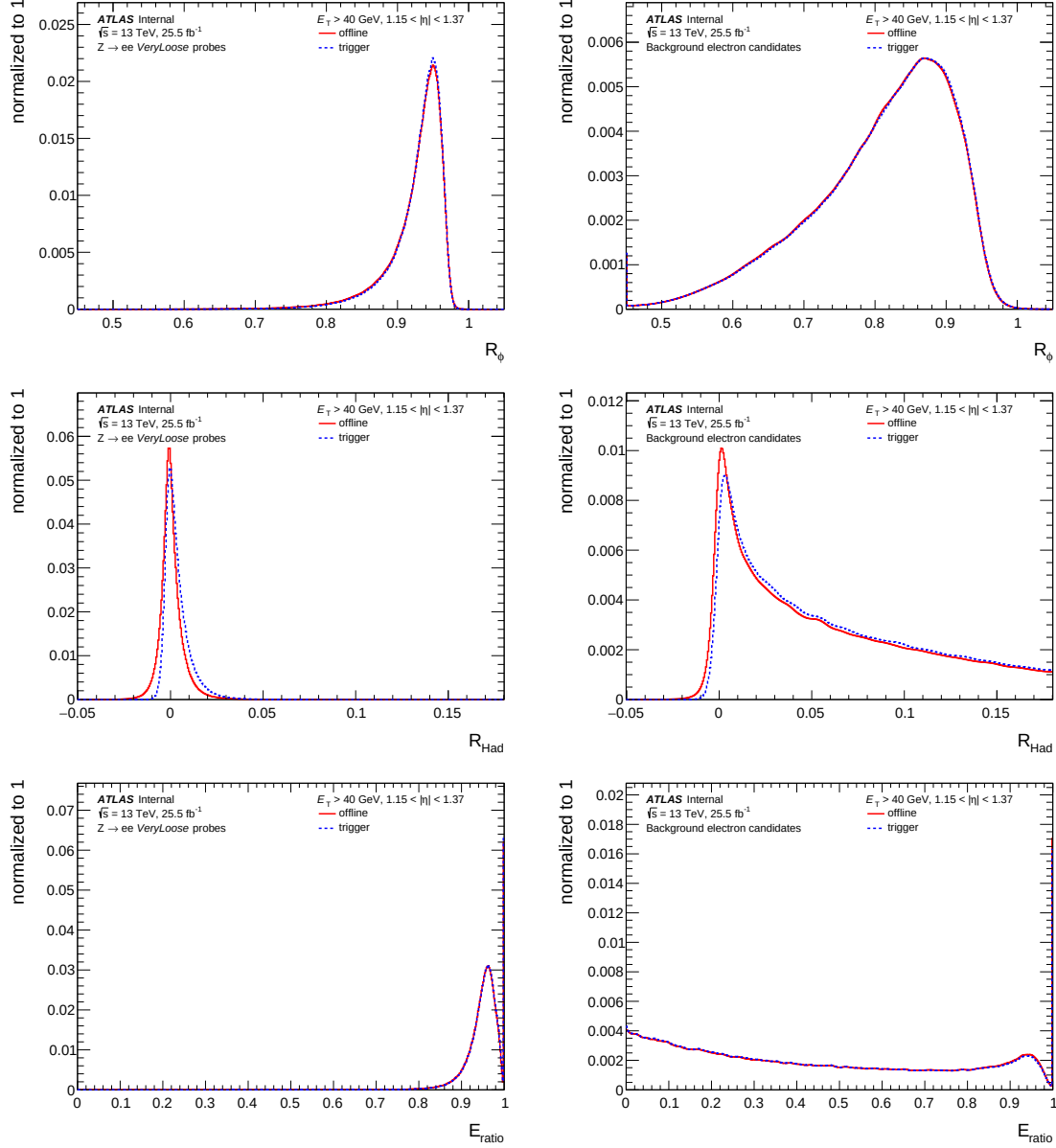


Figure 4.22: Distributions of the offline-quality and trigger-level variables R_ϕ (top), R_{had} (middle), and E_{ratio} (bottom), measured using VeryLoose probe electrons from $Z \rightarrow ee$ for signal (left) or electron candidates with a good-quality track for background (right), after KDE smoothing has been applied. These distributions are shown for 25.5 fb $^{-1}$ of 2016 data (selected using the procedures from Section 4.2.1), which corresponds to the dataset used for deriving the trigger-level pdfs used for the 2017 trigger. Only electron candidates with $p_T > 40$ GeV and $1.15 < |\eta| < 1.37$ are shown.

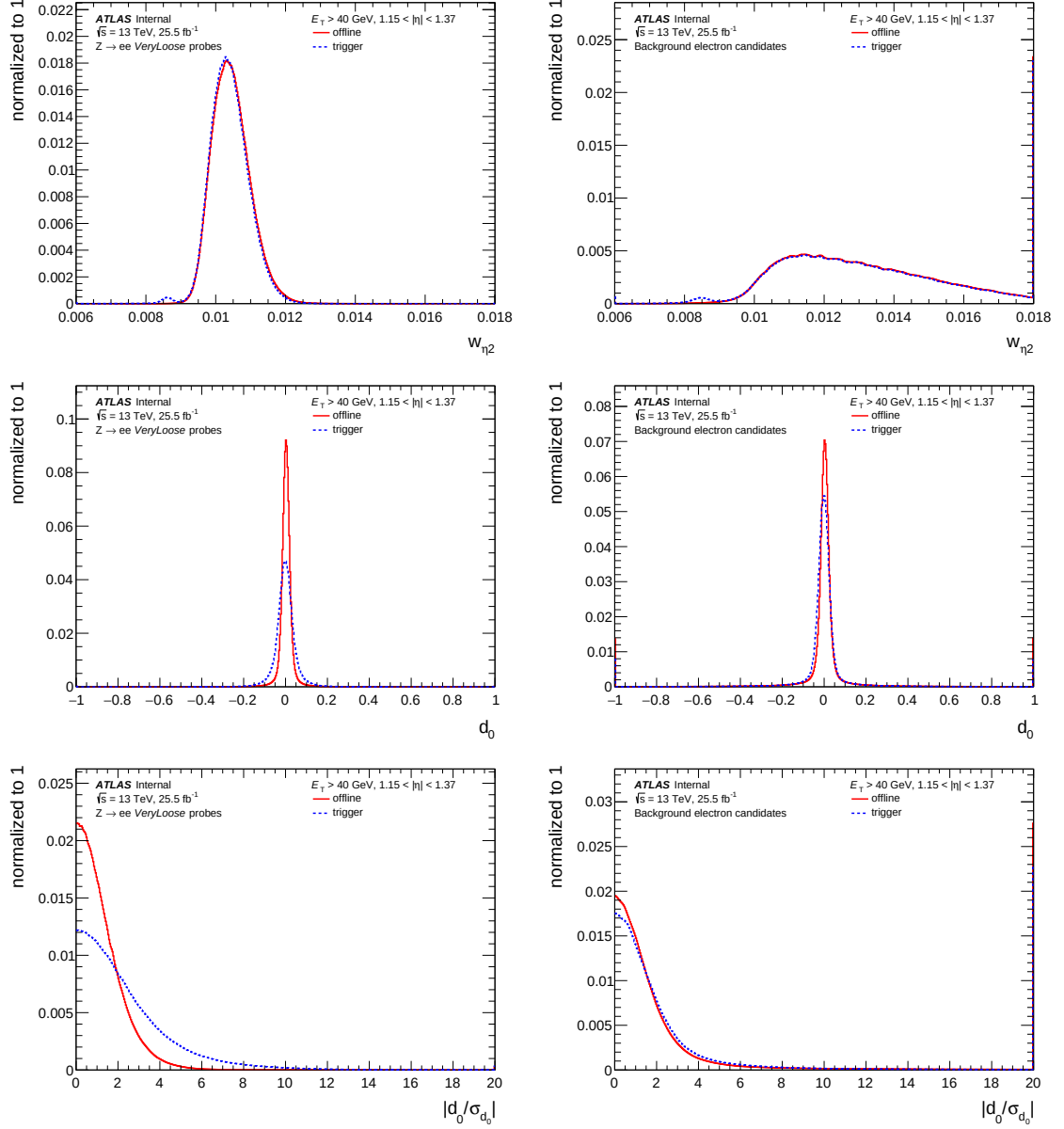


Figure 4.23: Distributions of the offline-quality and trigger-level variables $w_{\eta 2}$ (top), d_0 (middle), and $|d_0/\sigma_{d_0}|$ (bottom), measured using VeryLoose probe electrons from $Z \rightarrow ee$ for signal (left) or electron candidates with a good-quality track for background (right), after KDE smoothing has been applied. These distributions are shown for 25.5 fb $^{-1}$ of 2016 data (selected using the procedures from Section 4.2.1), which corresponds to the dataset used for deriving the trigger-level pdfs used for the 2017 trigger. Only electron candidates with $p_T > 40$ GeV and $1.15 < |\eta| < 1.37$ are shown.

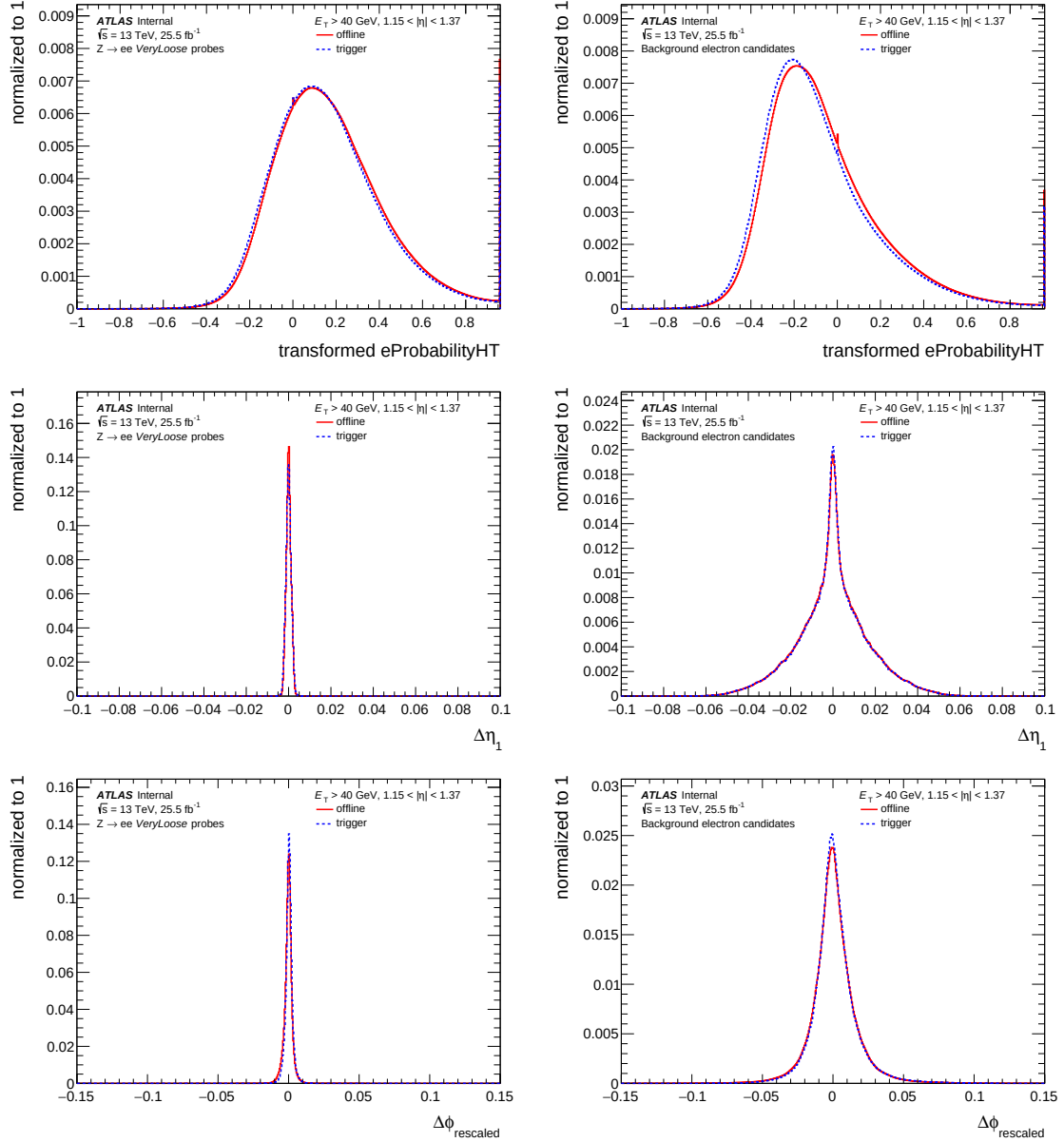


Figure 4.24: Distributions of the offline-quality and trigger-level variables transformed eProbabilityHT (top), $\Delta\eta_1$ (middle), and $\Delta\phi_{\text{res}}$ (bottom), measured using VeryLoose probe electrons from $Z \rightarrow ee$ for signal (left) or electron candidates with a good-quality track for background (right), after KDE smoothing has been applied. These distributions are shown for 25.5 fb $^{-1}$ of 2016 data (selected using the procedures from Section 4.2.1), which corresponds to the dataset used for deriving the trigger-level pdfs used for the 2017 trigger. Only electron candidates with $p_T > 40$ GeV and $1.15 < |\eta| < 1.37$ are shown.

satisfy this energy threshold, a final concentric shell of cells is added to the cluster. The energies of any positive-energy topological clusters whose centers fall within a given cone of size ΔR are then summed to obtain the raw isolation energy, $E_{T,\text{raw}}^{\text{isol}}$. As the electron candidate itself falls within this cone by construction, its energy must be subtracted from $E_{T,\text{raw}}^{\text{isol}}$. This electron energy, referred to as the core energy $E_{T,\text{core}}$, is computed as the total transverse energy deposited in a rectangle of 5×7 cells in $\Delta\eta \times \Delta\phi$ space (with total size $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$) around the center of the electron. In case of additional activity from the electron which falls outside of this rectangle, an additional leakage energy $E_{T,\text{leakage}}$ is assigned based on the average expected leakage energy as a function of electron E_T in a simulated single electron sample. Finally, contribution to the isolation cone due to pileup and the underlying event must also be estimated and removed based on the ambient energy density [104]. The total calorimeter-based isolation energy is then:

$$E_{T,\text{cone}}^{\text{isol}} = E_{T,\text{raw}}^{\text{isol}} - E_{T,\text{core}} - E_{T,\text{leakage}} - E_{T,\text{pileup}}. \quad (4.7)$$

Figure 4.25 schematically shows how the isolation energy is computed using the topological clusters, while Figure 4.26 shows how the various components affect the final corrected isolation energy $E_{T,\text{cone}}^{\text{isol}}$. Note that due to the granularity of the EM calorimeter, it is difficult to build an isolation cone with size much smaller than $\Delta R = 0.2$ [6].

The ATLAS track-based isolation algorithm, meanwhile, relies on tracks reconstructed in the Inner Detector with $p_T > 1$ GeV and $|\eta| < 2.5$. These tracks must satisfy the good-quality track requirement. An additional requirement is imposed on the longitudinal impact parameter z_0 , after correcting for the reconstructed position of the primary vertex and multiplying by the sine of the track polar angle⁹. This requirement of $|z_0 \sin \theta| < 3$ mm is used to select tracks which originate from the primary vertex under consideration, which reduces impact due to pileup. The track-based isolation then proceeds by summing the transverse momenta of tracks within a cone of size ΔR surrounding the electron candidate's track, excluding the candidate itself. As contributions from electrons which undergo bremsstrahlung should also be included as part of the candidate object, any tracks extrapolated to the second layer of the EM calorimeter which fall within a $\Delta\eta \times \Delta\phi = 0.05 \times 0.1$ window around the cluster position are also removed from the computation of the track-based isolation. The track-based isolation, after removing these contributions, is denoted as p_T^{isol} . Most ATLAS analyses currently use a variable-size cone for computing track-based isolation, which decreases in size as a function of p_T . This isolation variable is referred to as $p_{T,\text{var}}^{\text{isol}}$, and is

⁹ $|z_0 \sin \theta|$ is used instead of z_0 to avoid rejecting tracks with a large error at large values of $|\eta|$.

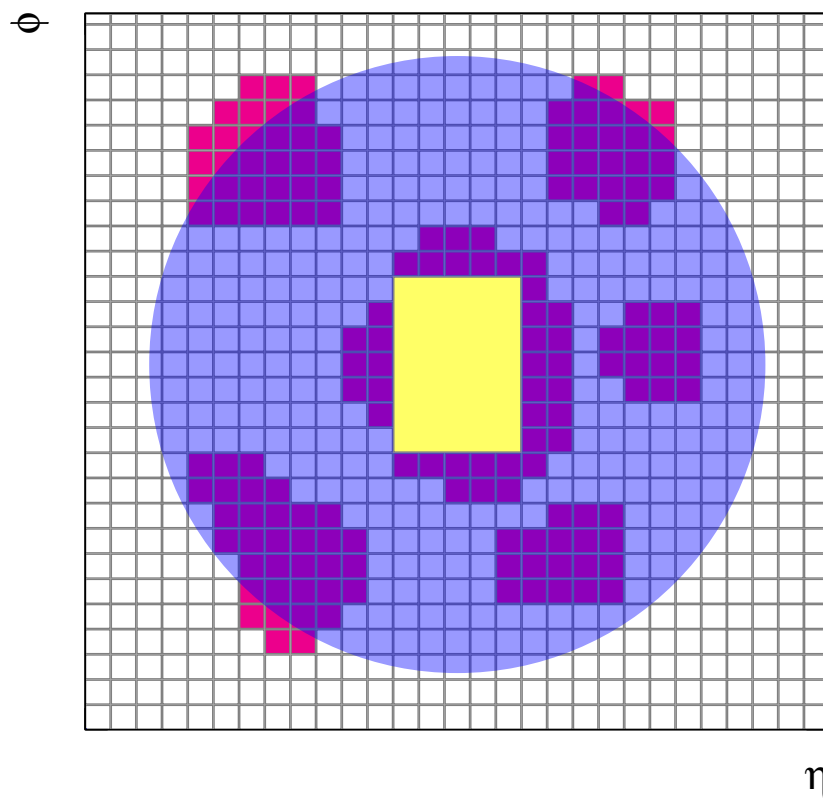


Figure 4.25: Schematic of the computation of calorimeter-based isolation energy. The grid represents the cells in the second layer of the EM calorimeter, shown in the η and ϕ directions. The candidate electron is located in the center of the purple circle, which represents the isolation cone of size ΔR . The topological clusters which fall within the cone are shown in red, the sum of which is the raw isolation energy $E_{T,\text{raw}}^{\text{isol}}$. The yellow rectangle represents the 5×7 cells (with total size $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$) used to estimate the electron core energy $E_{T,\text{core}}$ which must be subtracted from the total raw isolation energy. Any leakage of the electron energy outside of this yellow rectangle is estimated using the average expected value from simulation, and is denoted as $E_{T,\text{leakage}}$. Finally, contributions from pileup must also be subtracted, and is denoted as $E_{T,\text{pileup}}$ [6].

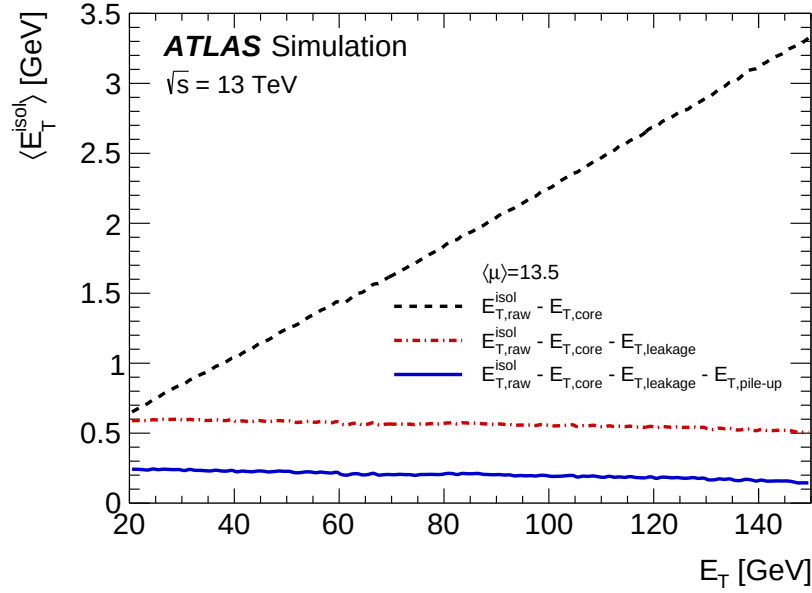


Figure 4.26: Effect of the various corrections to the calorimeter-based isolation energy, shown for a simulated single electron sample (with an average pileup of $\langle \mu \rangle = 13.5$) using an isolation cone of size $\Delta R = 0.2$ for electron candidates which satisfy the Tight identification. The black dashed line shows only the core correction, while the red dot-dashed line additionally adds the leakage correction. Without the leakage correction, the electron isolation energy would increase linearly with increasing E_T . Finally, the blue solid line shows the effect of the pileup-based correction to the isolation energy, which reduces the average isolation energy by more than a factor of two [6].

computed using a cone of size:

$$\Delta R(p_T) = \min \left(\frac{10 \text{ GeV}}{p_T [\text{GeV}]}, R_{\text{max}} \right), \quad (4.8)$$

where R_{max} is the maximum cone size [6].

The $E_{T,\text{cone}}^{\text{isol}}$ and $p_{T,\text{var}}^{\text{isol}}$ variables are then used to construct isolation operating points for use by ATLAS analyses. These operating points, which are optimized in bins of p_T and $|\eta|$, are chosen to either satisfy particular efficiency requirements (as measured with respect to Tight electrons, using electrons from simulated $Z \rightarrow ee$ events for $p_T > 15$ GeV and from simulated $J/\psi \rightarrow ee$ events for $p_T < 15$ GeV) or to satisfy fixed requirements on the isolation variables. Most of the electron isolation operating points use $\Delta R = 0.2$ and $R_{\text{max}} = 0.2$, though one operating point uses $R_{\text{max}} = 0.4$. A summary of the operating points used by ATLAS analyses is shown in Table 4.4 [6]. Note that the operating points used for muon isolation are nearly identical to those used for electron isolation, except that the muon isolation operating points use $\Delta R = 0.3$ and $R_{\text{max}} = 0.3$.

Operating point	$E_{T,\text{cone}}^{\text{isol}}$ ($\Delta R = 0.2$)	$p_{T,\text{var}}^{\text{isol}}$ ($R_{\text{max}} = 0.2$)	Total ϵ_{iso}
Loose (Track Only)	-	$\epsilon_{\text{iso}} = 99\%$	99%
Loose	$\epsilon_{\text{iso}} = 99\%$	$\epsilon_{\text{iso}} = 99\%$	98%
Gradient	$\epsilon_{\text{iso}} = 0.1143 \times p_T + 92.14\%$	$\epsilon_{\text{iso}} = 0.1143 \times p_T + 92.14\%$	90(99)% at 25(60) GeV
Gradient (Loose)	$\epsilon_{\text{iso}} = 0.057 \times p_T + 95.57\%$	$\epsilon_{\text{iso}} = 0.057 \times p_T + 95.57\%$	95(99)% at 25(60) GeV
Fix (Loose)	$E_{T,\text{cone}}^{\text{isol}}/p_T < 0.20$	$p_{T,\text{var}}^{\text{isol}}/p_T < 0.15$	-
Fix (Tight)	$E_{T,\text{cone}}^{\text{isol}}/p_T < 0.06$	$p_{T,\text{var}}^{\text{isol}}/p_T < 0.06$	-
Fix (Tight, Track Only)	-	$p_{T,\text{var}}^{\text{isol}}/p_T < 0.06$	-
Fix (Calo Only)	$E_{T,\text{cone}}^{\text{isol}} < 3.5 \text{ GeV}$	-	-
Fix (Track $R_{\text{max}} = 0.4$)	$E_{T,\text{cone}}^{\text{isol}}/p_T < 0.11$	$p_{T,\text{var}}^{\text{isol}}/p_T < 0.06$	-

Table 4.4: Definition of the electron isolation operating points and isolation efficiency ϵ_{iso} . For the ‘Gradient’ operating points, the units of p_T are GeV. All operating points use a cone size of $\Delta R = 0.2$ for calorimeter isolation and $R_{\text{max}} = 0.2$ for track isolation except for the final entry ‘Fix (Track)’ which uses $R_{\text{max}} = 0.4$. The values are obtained from simulated $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ samples using electrons which satisfy Tight identification requirements [6].

The efficiencies of the electron isolation operating points as measured in data are discussed in Section 5.6.

4.6 Future Improvements

Before the start of 2017 data-taking, the electron reconstruction algorithm was updated to rely on topological clusters rather than the clusters based on a sliding-window algorithm used in the past (and which were discussed in Section 4.3). This move to topological clusters was primarily implemented to improve the energy resolution of reconstructed electrons and photons, as it allows for recovery of soft photons from bremsstrahlung due to the ability of the topological clusters to reconstruct showers with energies as low as $\mathcal{O}(100 \text{ MeV})$ [105]. Figure 4.27 shows that the low p_T cluster reconstruction efficiency when using the topological clusters is significantly more efficient than when using the sliding-window clusters shown in Figure 4.3. However, the total electron reconstruction efficiency at low p_T still suffers. This happens because while the reconstruction of the topological clusters is now used as the first step of the electron reconstruction algorithm, the electron track refitting step performed by the the Gaussian Sum Filter (GSF) [102] algorithm is still seeded by the sliding-window clusters. This was only kept in place due to time constraints when the reconstruction algorithm was being updated, rather than for any particular physics reason. For the future, this can be changed to seed the GSF algorithm using the topological clusters, which could improve the electron reconstruction efficiency at $p_T = 4.5 \text{ GeV}$ from its current value of approximately 65% to potentially larger than 80%. This might also allow for a lower minimum p_T threshold for electrons supported by ATLAS (as the topological cluster reconstruction efficiency

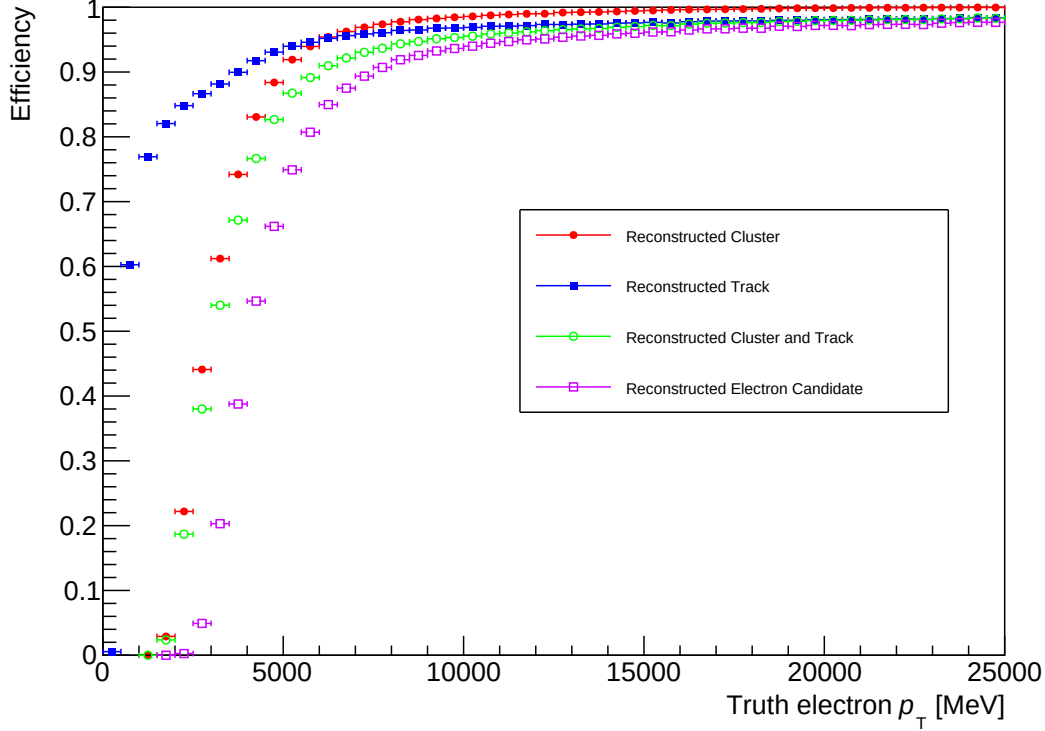


Figure 4.27: Electron cluster reconstruction, track reconstruction, and candidate reconstruction efficiency as a function of p_T , using topological clusters for the cluster efficiency step. The cluster efficiency shown here for the topological clusters is significantly larger than that of the sliding-window clusters shown in Figure 4.3. However, since the sliding-window clusters are still used to seed the GSF track refitting step, the total electron reconstruction efficiency at low p_T still suffers. If this is modified to use the topological clusters to seed the GSF tracking, the purple squares denoting the efficiency of the reconstructed electron candidates could be as large as that of the green circles denoting the efficiency for events to contain both a reconstructed cluster and a reconstructed track.

even at $p_T = 3.5$ GeV is about 75%), though this would additionally require work to improve the identification and isolation algorithms to efficiently suppress backgrounds at low p_T .

The use of topological clusters also provides potential new variables to study for electron identification, namely the topological cluster moments [72]. These have not yet been studied in depth for use in the standard central electron identification, but these are already used as the primary discriminating variables for forward electrons with $|\eta| > 2.5$. A few other variables not currently included in the electron likelihood, but which could potentially improve performance, are:

- $q \times d_0$: this variable would replace the standard d_0 by multiplying its value by the sign of the

reconstructed electron charge ($q = \pm 1$). Past studies have found that the d_0 distribution for prompt electrons tends to be offset from zero when only looking at electrons of either positive or negative charge. This offset is in opposite directions for positively and negatively charged electrons, and thus multiplying by the sign of the reconstructed electron charge makes these distributions nearly identical. This offset exists due to electrons which undergo bremsstrahlung, causing the electron tracks to bend more in the presence of the magnetic field, and thus the measured transverse impact parameter becomes larger than it would otherwise be. The use of $q \times d_0$ would therefore allow for a more distinctive distribution for prompt electrons, while backgrounds are expected to be more symmetric. Figure 4.28 shows this distribution for prompt electrons from $Z \rightarrow ee$ simulation for electrons which are reconstructed with either the correct or incorrect track and either the correct or incorrect electric charge.

- $\Delta(\text{curvature})/\sigma(\text{curvature})$: this variable may perform better at low p_T than $\Delta p/p$, as curvature is well-measured at low p_T and this variable would be sensitive to the amount of energy lost to bremsstrahlung, which is particularly important at low p_T . Curvature of a track is defined as $1/p_T$, and “ $\Delta(\text{curvature})$ ” here would be defined as the curvature difference between the perigee and the last measurement point (similar to $\Delta p/p$ in Table 4.1).
- $\Delta(\Delta\phi) = \Delta\phi_{\text{last measurement}} - \Delta\phi_{\text{first measurement}}$: this variable measures the change in the track-cluster matching between the first and last layers of the calorimeter (or if the calorimeter granularity is insufficient, it is possible to consider two other layers to compare between instead). This variable might be useful for rejecting photon conversions.

In addition to studying new variables to use in the electron likelihood, it may also be possible to use the discriminating variables in a more efficient manner. One way to do so would be to use modern machine learning techniques, which could provide significant discrimination between prompt electrons and backgrounds. These techniques should definitely be studied in the context of ATLAS electron identification since they are already commonplace in industry, and will likely become more widely used in particle physics experiments as time goes on. Of course, such techniques do introduce complexity, and any lack of understanding of the behavior of a given electron identification algorithm would only become more challenging when using a more complex technique. For instance, the challenges pertaining to efficient identification of high p_T electrons discussed in Section 4.4.4 took significant effort to fully understand and work towards improving, over the course of about six months. Had a more complicated identification algorithm been used than the likelihood method, it

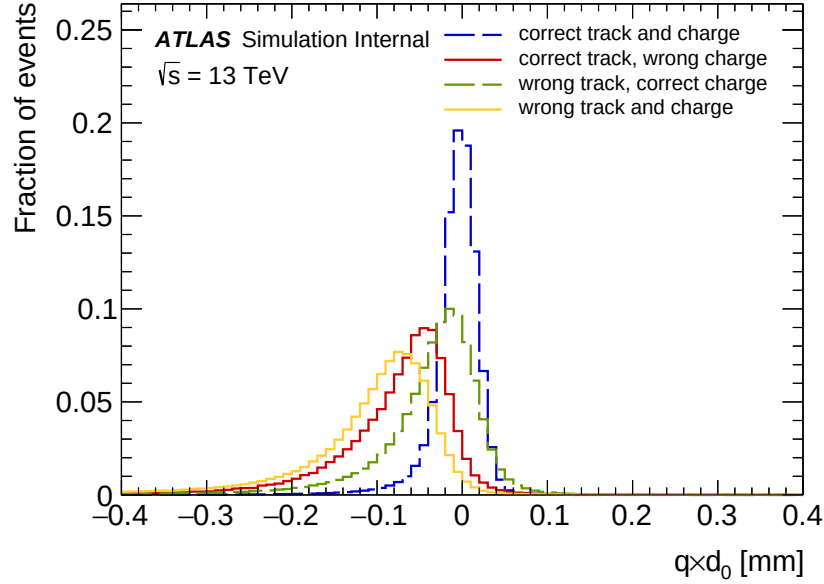


Figure 4.28: Distribution of $q \times d_0$ for prompt electrons from $Z \rightarrow ee$ simulation, shown for electrons reconstructed with either the correct or incorrect track and either the correct or incorrect electric charge. The incorrect track and incorrect charge can be chosen when bremsstrahlung occurs. Clearly, this distribution is not symmetric, and this asymmetry could be exploited for use in the electron identification [6].

seems likely that the underlying issues would have taken longer to understand and correct. Consequently, it is important to take significant care when studying potential new algorithms for use in electron identification.

One potential improvement which might not add significant complication would be to extend the likelihood method to consider a multiple background hypothesis. Currently, the background pdfs used in the electron likelihood are chosen in an inclusive manner using a sample dominated by light flavor hadrons. However, photon conversions and semileptonic decays of heavy flavor hadrons are important backgrounds for many ATLAS analyses, including the one discussed in Chapter 8. Thus, if it is possible to better discriminate against these nonprompt electrons, it could be beneficial. One downside does exist here: if one manages to improve rejection against heavy flavor hadrons and conversions, then the trade-off is that the rejection power against light flavor hadrons will likely suffer as a result. If this reduced rejection power against light flavor hadrons is only marginal or if light flavor hadrons are already a subdominant background for a given ATLAS analysis, then this could still be worthwhile to pursue. To mathematically extend the likelihood method to a multiple

background hypothesis, one can follow the procedure from Section 4.4.1 several times, i.e.: define a likelihood:

$$L_{S(B_j)}(\mathbf{x}) = \prod_{i=1}^n P_{S(B_j),i}(x_i) \quad (4.9)$$

for each background source j (using different pdfs for each background source, since the distributions of discriminating variables differ for each type of background), and then determine a discriminant for each background source:

$$d_{L,j} = \frac{L_S}{L_S + L_{B_j}}. \quad (4.10)$$

Then electrons which satisfy a requirement imposed for each discriminant value $d_{L,j}$ are selected, while those which fail this requirement for any of the background hypotheses would be vetoed. This approach was attempted in 2013, but was found to be unable to improve the total background rejection when studied using an inclusive sample dominated by light flavor hadrons. Unfortunately, it was not tested at the time in the context of an analysis where nonprompt electron backgrounds were dominant, and thus it is possible that this approach could have been successful if employed in such a scenario. It was also found to be difficult from a computational standpoint to optimize the discriminant cuts for several hypotheses simultaneously (while attempting to target a given signal efficiency for each kinematic bin of interest). However, this complication could be mitigated by determining the optimal discriminant cut value for a single background hypothesis and then making some assumption about the relative contributions for each background source. These assumptions could be based on the simulated background composition in a given analysis, and would allow for the optimal cut values for the $d_{L,j}$ discriminants for the other background sources to be directly computed based on the cut value determined for the single background case. Preliminary studies have been performed which suggest that rejection of heavy flavor hadrons could be improved by as much as a factor of ten, with a trade-off of worse rejection of light flavor hadrons by a factor of five [106].

Shortly before the start of Run 2, gas leaks were discovered in the TRT straws. The xenon gas in the TRT straws is responsible for the electron identification capabilities of the TRT, as the xenon is necessary to absorb the transition radiation photons emitted by electrons when passing through the TRT radiator sheets. However, as xenon is relatively expensive, it was decided to replace some of the xenon in the TRT with a significantly less expensive gas, argon. Argon allows the TRT to still function as a tracking detector, but is unable to absorb the transition radiation photons, and thus does not help with electron identification. Studies were performed at the start of Run 2 to ensure that the electron identification capabilities provided by the TRT would still be sufficient,

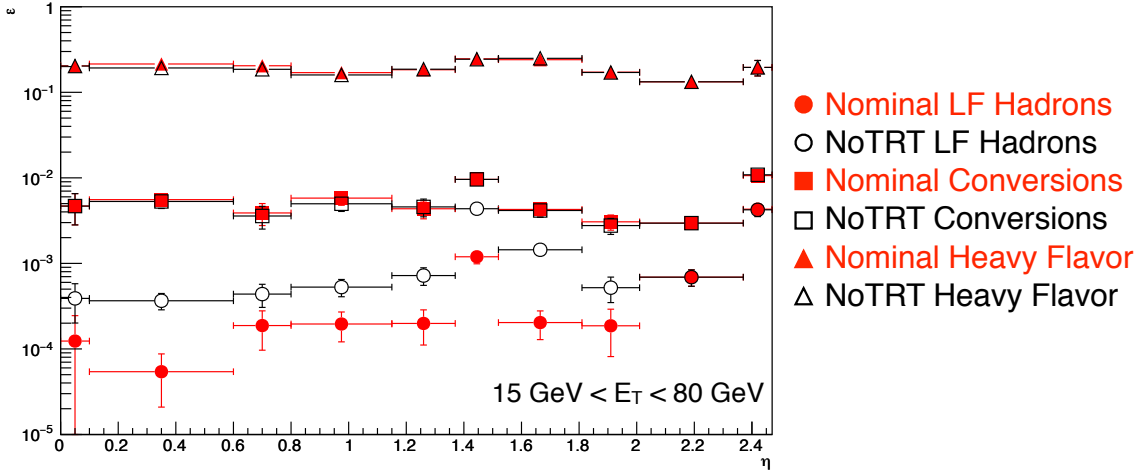


Figure 4.29: Simulated background efficiency as a function of $|\eta|$ for light flavor hadrons (circles), conversions (squares), and heavy flavor hadrons (triangles) using the nominal Tight likelihood-based identification (filled) and a variant chosen to provide the same signal efficiency but which uses no eProbabilityHT information (open). Only objects with $15 \text{ GeV} < p_T < 80 \text{ GeV}$ are considered. The eProbabilityHT variable, based on transition radiation in the TRT, is clearly an important discriminator against light flavor hadrons. In the $1.52 < |\eta| < 1.81$ bin for instance, the use of eProbabilityHT improves rejection of light flavor hadrons by a factor of 7. One interesting thing to note is that the efficiency for the heavy flavor hadrons is actually slightly larger for the nominal electron likelihood than for the one with no eProbabilityHT information—this is because transition radiation is a signature of real electrons, and the heavy flavor hadrons which satisfy the electron identification are typically those which decayed to a real electron.

given that many regions of the TRT still contained straws filled with xenon. Figure 4.29 shows the extreme case, where no TRT information would be usable for electron identification (i.e. if all of the xenon was replaced by argon, even though this was never likely to happen during Run 2). This study found that the use of the TRT-based variable eProbabilityHT allows for a huge improvement in rejection of light flavor hadrons compared to what would be possible without the TRT, with the $1.52 < |\eta| < 1.81$ bin demonstrating an improvement by a factor of 7. While this study was performed at the start of Run 2, it is extremely relevant for the future: the Run 3 version of the TRT is likely to no longer contain xenon gas in the barrel (and possibly none in the endcaps either, though it is still under consideration) due to the continued leaks and high cost of xenon. As a result, it is likely that rejection against light flavor hadrons will be affected in Run 3, and efforts should be made to study the potential impact this may have on ATLAS physics analyses.

CHAPTER 5

Electron Efficiency Measurements

5.1 General Methodology

Once electrons have been processed through the ATLAS reconstruction, identification, isolation, and trigger algorithms, it is necessary to understand the efficiencies associated to each of these selection criteria. As simulated samples are used for both signal and background estimation in the majority of ATLAS analyses, a poor understanding of the electron efficiencies would result in an improper estimate of signal or background processes which contain electrons in the final state. Thus, the electron efficiencies measured in data must be used to determine data-to-simulation efficiency correction factors to apply to the simulated electron candidates. These efficiency correction factors tend to be close to 1, but can differ from 1 due to the known mismodeling of the simulated tracking properties and calorimeter shower shapes.

The tag-and-probe method, previously discussed in Section 4.2.1, is commonly used for determining electron efficiencies in data. This method results in an unbiased sample of probe electrons, but this sample of probes is typically contaminated by some amount of background. To account for this, any residual background must be estimated and removed. To minimize the amount of background contamination, selection criteria on discriminating information such as the invariant mass of the parent resonance is often used, though one must be careful to not apply a selection criteria which could bias the electron efficiencies. These backgrounds, which arise from misidentified light hadrons, electrons from photon conversions, and nonisolated electrons from decays of heavy flavor hadrons, contribute the primary source of systematic uncertainty on the efficiency measurements.

Once a sample of background-subtracted probes has been obtained, one can apply the reconstruction, identification, isolation, or trigger algorithm of interest and measure its efficiency with

respect to another algorithm of interest (or with respect to all probes, when appropriate). The total efficiency ϵ_{total} is typically factorized as a product of different efficiency terms:

$$\epsilon_{\text{total}} = \epsilon_{\text{EMclus}} \times \epsilon_{\text{reco}} \times \epsilon_{\text{id}} \times \epsilon_{\text{iso}} \times \epsilon_{\text{trig}} = \left(\frac{N_{\text{cluster}}}{N_{\text{all}}} \right) \times \left(\frac{N_{\text{reco}}}{N_{\text{cluster}}} \right) \times \left(\frac{N_{\text{id}}}{N_{\text{reco}}} \right) \times \left(\frac{N_{\text{iso}}}{N_{\text{id}}} \right) \times \left(\frac{N_{\text{trig}}}{N_{\text{iso}}} \right). \quad (5.1)$$

The efficiency to reconstruct EM cluster candidates associated with all produced electrons, ϵ_{EMclus} , is given by the number of reconstructed EM clusters N_{cluster} divided by the number of produced electrons N_{all} . This efficiency is evaluated entirely from simulation. The reconstruction efficiency, ϵ_{reco} , is given by the number of reconstructed electron candidates N_{reco} divided by the number of EM cluster candidates N_{cluster} . The identification efficiency, ϵ_{id} , is given by the number of identified and reconstructed electron candidates N_{id} divided by N_{reco} . The isolation efficiency is calculated as the number of electron candidates satisfying the isolation, identification and reconstruction requirements N_{iso} divided by N_{id} . Finally, the trigger efficiency is calculated as the number of triggered (and isolated, identified, reconstructed) electron candidates N_{trig} divided by N_{iso} .

Note that in this thesis and in ATLAS publications describing electron efficiencies, when “identification efficiency” is referred to, it is this individual ϵ_{id} term which is typically meant, i.e. $\frac{N_{\text{id}}}{N_{\text{reco}}}$. Alternatively, one could imagine measuring each individual algorithm with respect to all probes; however, this is not what is typically done, as the level of background in N_{all} is much larger than after the subsequent algorithms have been applied.

Once efficiencies have been measured in both data and simulation, their ratio is taken to obtain the data-to-simulation correction factors. Uncertainties on the correction factors are then determined by varying the requirements on the selection criteria used to obtain the tag and the probe electron candidates as well as by varying the methodology used for the background estimation. The central value of the correction factor is chosen to be the average over all variations. The statistical uncertainty is computed assuming a binomial distribution for a given variation, using the approach described in [107]. Any statistical uncertainty on electron efficiency which is quoted also includes the statistical uncertainty associated to the background subtraction. The systematic uncertainty, meanwhile, is determined by taking the root-mean-square (RMS) of all of the variations.

Currently ATLAS only makes use of tag-and-probe measurements of $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ for electron efficiency measurements. In Run 1, additional tag-and-probe measurements using $W \rightarrow e\nu$ and $Z \rightarrow ee\gamma$ were also used to constrain the electron efficiency measurements and their uncertainties.

Bin boundaries in p_T [GeV]														
4.5	7	10	15	20	25	30	35	40	45	50	60	80	150	250

Table 5.1: p_T bins used for the electron efficiency measurements.

$Z \rightarrow ee$ events are used for the reconstruction and identification efficiency measurements for electron $p_T > 15$ GeV, below which there is too much background for an accurate measurement. For isolation and trigger efficiency measurements, meanwhile, $Z \rightarrow ee$ events are sufficient for electron $p_T > 4.5$ GeV, as these are measured with respect to (at least) identified electrons, which is a step that substantially reduces the amount of background present.

$J/\psi \rightarrow ee$ events are used for the identification efficiency measurement for electrons with $4.5 \text{ GeV} < p_T < 20 \text{ GeV}$. J/ψ candidates can be either be produced directly (“prompt” production) or via decays of heavy flavor hadrons (“nonprompt” production), the latter of which typically involves electrons which are surrounded by hadronic activity. Thus, only the prompt $J/\psi \rightarrow ee$ events are useful for tag-and-probe efficiency measurements, which creates the challenge of separating the prompt production from the nonprompt production. For electron $p_T > 20$ GeV, statistics of $J/\psi \rightarrow ee$ events tends to be poor, and is anyway dominated by boosted J/ψ particles which would be inappropriate to use since the tag and the probe electrons may have overlapping shower shapes, among other concerns. Due to the presence of the nonprompt J/ψ decays, the $J/\psi \rightarrow ee$ tag-and-probe measurement also cannot trivially be used for the isolation (and subsequently the trigger) efficiency measurement, since this could introduce biases. Finally, for the electron $p_T < 15$ GeV reconstruction efficiency, no measurement can be performed using $J/\psi \rightarrow ee$ events as the trigger used to collect this sample relies on one well-identified electron and a second reconstructed electron candidate. This trigger is already a prescaled trigger which only collects data during a fraction of the data collection period—if this requirement of the second reconstructed electron candidate were to be dropped, the purity of this trigger would be too poor to collect a large sample of $J/\psi \rightarrow ee$ events while still satisfying the ATLAS trigger rate requirements. Instead, the reconstruction efficiency for electron $p_T < 15$ GeV is taken purely from simulation, and is assigned conservative uncertainties based on studies of the material present in the ATLAS detector.

In the range $15 \text{ GeV} < p_T < 20 \text{ GeV}$ where the $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ identification efficiency measurements are both present, a combination is performed using a χ^2 procedure as described in [108]. The bins used for the efficiency measurements are listed in Tables 5.1 and 5.2; this granularity is necessary as the quantities used as input to the various electron selection algorithms vary with both p_T and η , and thus the efficiencies can vary with each.

Bin boundaries in η																				
Identification efficiency measurement for $p_T < 20$ GeV: only absolute η bins																				
0 0.1 0.8 1.37 1.52 2.01 2.47																				
All other measurements																				
-2.47	-2.37	-2.01	-1.81	-1.52	-1.37	-1.15	-0.8	-0.6	-0.1	0	0.1	0.6	0.8	1.15	1.37	1.52	1.81	2.01	2.37	2.47

Table 5.2: η bins used for the electron efficiency measurements.

The $Z \rightarrow ee$ tag-and-probe measurements do not have sufficient statistics to make meaningful measurements at high electron p_T . For the 2015–2016 dataset, the following was done to assign correction factors for the high p_T electrons:

- *reconstruction*: correction factors are measured up to $p_T = 150$ GeV and the same factors are applied for $p_T > 150$ GeV,
- *identification*: correction factors are measured up to $p_T = 250$ GeV and the same factors are applied for $p_T > 250$ GeV,
- *isolation*: correction factors are measured up to $p_T = 150$ GeV; beyond that the factors are assigned to be unity (with an inflated uncertainty applied).

Of course, the full Run 2 dataset collected from 2015–2018 may be able to improve upon this, as the statistics of this dataset is about a factor of four larger than the 2015–2016 dataset. This chapter primarily covers electron identification efficiencies as they pertain to the 2015–2016 dataset, but many details remain true in the 2015–2018 dataset, and this full dataset will be alluded to at times when relevant.

5.2 Electron Identification Efficiency Measurements using $Z \rightarrow ee$ Events

The $Z \rightarrow ee$ process serves as the primary source of unbiased electron candidates for the various electron efficiency measurements. To select these events, the unrescaled single electron triggers are employed, which require a well-identified electron satisfying a trigger-level p_T requirement; see Table 5.3 for details on these triggers. The events must contain two electron candidates with $|\eta| < 2.47$, with the tag electron located outside of the calorimeter transition region of $1.37 < |\eta| < 1.52$. To avoid any trigger bias the tag electron must have $p_T > 27$ GeV, be associated to the trigger-level object (with $\Delta R < 0.07$ between the trigger-level and offline electron objects), satisfy the Tight identification criteria, and be well-isolated. For the identification efficiency measurements, the probe electrons are required to have $p_T > 15$ GeV and must satisfy the good-quality track requirement of

2015	2016–2018
HLT_e24_lhmedium_L1EM20VH	HLT_e26_lhtight_nod0_ivarloose
HLT_e60_lhmedium	HLT_e60_lhmedium_nod0
HLT_e120_lhloose	HLT_e140_lhloose_nod0
	HLT_e300_etcut

Table 5.3: List of the primary lowest unprescaled single electron triggers used in 2015–2018. The number after “HLT_e” refers to the p_T threshold in GeV, while the letter “e” itself means a single electron candidate is required. “lhtight”, “lhmedium”, and “lhloose” refer to the trigger-level electron identification criteria which the electron candidate must satisfy. For 2016–2018, the primary electron triggers did not include any requirement on d_0 or $d_0/\sigma(d_0)$ in the likelihood-based electron identification algorithm, and thus “nod0” is included in the trigger names. “etcut” means the electron candidate must simply satisfy a given p_T threshold, and no further algorithm is applied. “ivarloose” is a loose trigger-level isolation requiring $p_T^{\text{varcone0.2}}/p_T < 0.1$. Finally, the “L1EM20VH” listed in the name of one of the 2015 triggers refers to the L1 seed; all of these triggers do require an L1 seed, but it is not always explicitly included in the trigger name.

at least seven total hits in the silicon detectors (i.e. combined between the pixel and SCT detectors) and at least one hit in the pixel detector. The tag-probe pairs used in the measurements described in this section all require the tag and the probe to have opposite-sign charge, except where explicitly mentioned otherwise. The signal events are nominally obtained from the tag-probe pairs with an invariant mass between 75 GeV and 105 GeV (chosen to primarily select events with m_{ee} near the Z mass peak).

For the electron identification efficiency measurements, two methods are used to distinguish between prompt electrons and the various background processes: the Z_{mass} method uses the dielectron invariant mass as the discriminating variable for background subtraction, while the Z_{iso} method uses the isolation distribution of the probe electrons. These two methods are treated as variations of the same measurement.

5.2.1 The Z_{mass} Method

In the Z_{mass} method, the identification efficiency is measured using the invariant mass spectrum of the tag-probe pairs to perform background estimation. The background is estimated using templates which are constructed using probes that fail identification and isolation criteria. These criteria are shown in Table 5.4, and require electrons to fail two or more cuts from a given cut-based identification working point in addition to failing isolation criteria. The inverted identification and isolation criteria chosen are similar to those used in Run 1 [98], which were carefully studied and selected to minimize signal contamination in the templates while properly describing the background in the full m_{ee}

	$p_T < 30$ GeV	$p_T > 30$ GeV
Variation 1	Fail two Multilepton cuts && $\frac{E_T^{\text{cone0.3}}}{p_T} > 0.02$ Normalize to high- m_{ee} tail (120-250 GeV)	Fail two Loose cuts && $\frac{E_T^{\text{cone0.4}}}{p_T} > 0.05$ Normalize to high- m_{ee} tail (120-250 GeV)
Variation 2	Fail two Multilepton cuts && $\frac{E_T^{\text{cone0.3}}}{p_T} > 0.02$ Normalize to Low- m_{ee} tail (60-70 GeV)	Fail two Loose cuts && $\frac{E_T^{\text{cone0.4}}}{p_T} > 0.20$ Normalize to high- m_{ee} tail (120-250 GeV)

Table 5.4: Templates and normalization regions used in different p_T ranges for the Z_{mass} method. When studied in Run 1, it was found that equivalent results could be obtained by either using two normalization regions or by using two template definitions (when studied in the region $30 \text{ GeV} < p_T < 45 \text{ GeV}$). Above 45 GeV a lack of statistics was observed for the low m_{ee} tail, so the low m_{ee} normalization is only used in the low p_T range. The Multilepton and Loose operating points in the table refer to cut-based operating points. Multilepton was optimized in Run 1 and is used for the templates without any modifications. Loose was optimized just prior to Run 2 before the commissioning of the LH-based identification. Multilepton applies cuts on more variables than Loose, and it has been found that inverting Multilepton cuts tends to describe the background better for $p_T < 30$ GeV than if this were to be replaced with an inversion of Loose cuts.

spectrum. The former is particularly important because simulation is used to subtract any residual signal contamination in the templates. As the simulation can be prone to mismodeling in the tails of the m_{ee} distribution, it is preferred to minimize this contamination as much as possible in order to reduce any reliance on the simulation for this measurement.

To be precise, the signal contamination is removed from the template distributions in data by first determining the distribution of simulated $Z \rightarrow ee$ events satisfying the template requirements, and then scaling this by the number of Tight data events near the Z boson mass peak divided by the corresponding number from the simulation, i.e. the factor:

$$\left. \frac{N_{\text{data}}^{\text{Tight}}}{N_{\text{MC}}^{\text{Tight}}} \right|_{\text{peak}}. \quad (5.2)$$

This scaled distribution of simulated events satisfying the template requirements is then subtracted from the template obtained in data, resulting in the “corrected template” that is subsequently used for the Z_{mass} method’s background subtraction. To demonstrate the necessity of minimizing signal contamination in the templates, Figure 5.1 shows the m_{ee} distribution when using a template which requires electrons that fail identification criteria while passing an isolation criteria (whereas the typical templates used require electrons to fail both identification and isolation requirements).

To enhance statistics for electrons with $p_T > 30$ GeV, template distributions from neighboring η bins are merged. This is necessary as the background distribution for electrons falls steeply with increasing p_T , and the statistical uncertainty in some of these bins would otherwise be large.

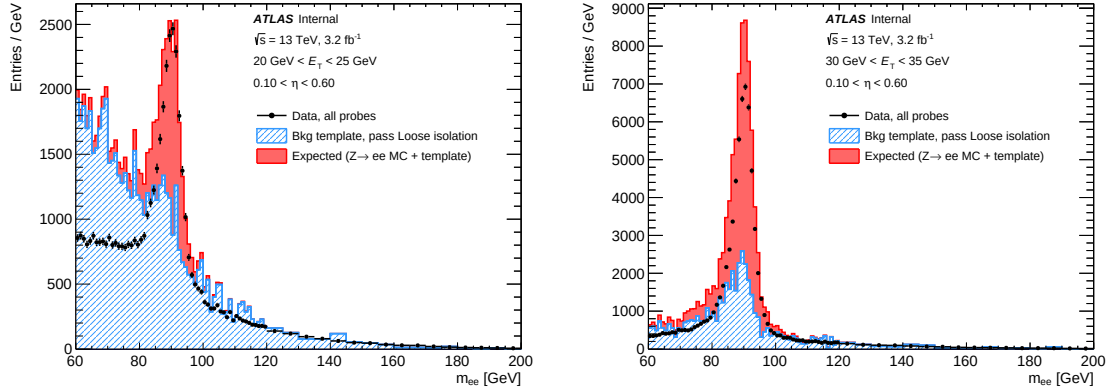


Figure 5.1: Example plots of the m_{ee} distribution for the Z_{mass} method when using a template criteria that requires electron objects which satisfy the “Loose” isolation working point, which is designed to be 99% efficient for prompt electrons. The left-hand plot is for the $20 \text{ GeV} < p_T < 25 \text{ GeV}$, $0.1 < \eta < 0.6$ bin at reconstruction-level, while the right-hand plot is at higher p_T , showing the $30 \text{ GeV} < p_T < 35 \text{ GeV}$, $0.1 < \eta < 0.6$ bin at reconstruction-level. In both example bins, the signal contamination is significant, as one can clearly see a peak in the background template distribution near the Z boson mass of 91.2 GeV. Moreover, the tails of these distributions are extremely poorly modeled, making this a very poor criteria to use for constructing a background template.

The denominator of the identification efficiency measurement consists of events which satisfy the good-quality track criteria, while the numerator of this efficiency measurement consists of the subset of those events which also satisfy the given identification operating point. By construction, the denominator contains significantly more background than the numerator (typically by several orders of magnitude), and thus presents a more significant challenge for the background estimation. However, the numerator is also nontrivial as it contains more signal contamination in the template and normalization regions which must be properly estimated. To handle these two distinct challenges, the numerator and the denominator use slightly different procedures for the normalization of the background estimate, though the same template distribution is used in both cases. These procedures are detailed in Sections 5.2.1.1 and 5.2.1.2. Example distributions showing the proper estimates of the numerator and denominator can be seen in Figures 5.2 and 5.3; the former is for an earlier ATLAS reconstruction release (20.1) and for 2015 data only, while the latter is for a more recent ATLAS reconstruction release (20.7) and for 2015–2016 data. The 2015–2016 dataset corresponds to ten times more data than 2015 alone, so the Z_{mass} method appears to be working well in both low and high statistics regimes, as well as across the two reconstruction releases mentioned.

Once the background-subtracted numerator and denominator distributions have been obtained,

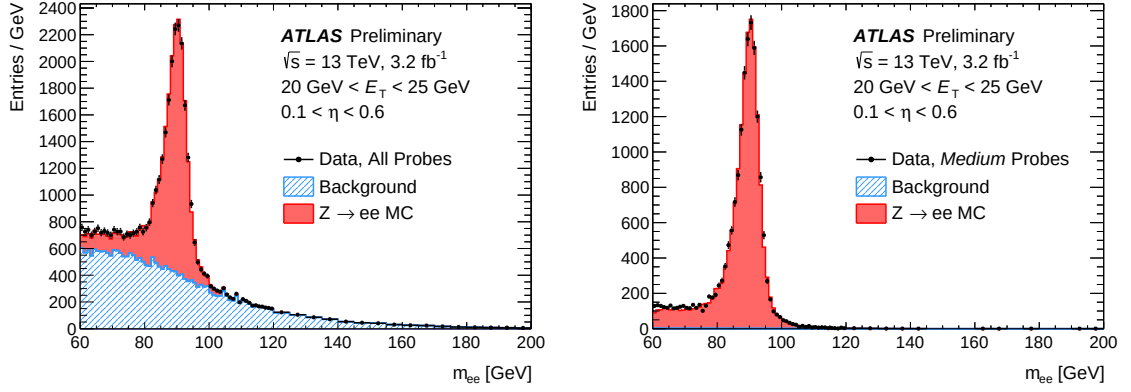


Figure 5.2: Illustration of the background estimation as a function of the invariant mass m_{ee} using the Z_{mass} method with the 2015 data. This is for the 20 GeV < p_T < 25 GeV, 0.1 < η < 0.6 bin, shown at reconstruction level (left) and for probes passing the Medium identification (right). The background estimation is performed by constructing templates using inverted isolation and identification criteria, which are then normalized as described in Sections 5.2.1.1 and 5.2.1.2 [5].

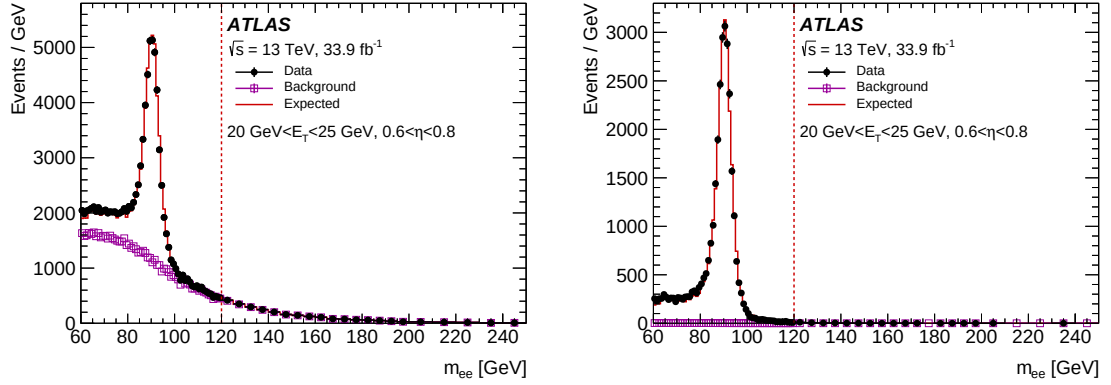


Figure 5.3: Illustration of the background estimation as a function of the invariant mass m_{ee} using the Z_{mass} method with the 2015–2016 data. This is for the 20 GeV < p_T < 25 GeV, 0.6 < η < 0.8 bin, shown at reconstruction level (left) and for probes passing the Tight identification (right). The background estimation is performed by constructing templates using inverted isolation and identification criteria, which are then normalized as described in Sections 5.2.1.1 and 5.2.1.2. The dashed red line indicates the minimum m_{ee} value for the invariant mass sideband of 120 GeV < p_T < 250 GeV used to perform the template normalization [6].

the number of events falling into a given m_{ee} region of interest are counted. To obtain the efficiency ϵ , the numerator count is then divided by the denominator count. Note that the distribution of data events before any background subtraction will sometimes be referred to as the “probe” distribution in this section, as it contains all probes.

5.2.1.1 The Z_{mass} Denominator

The denominator distribution is naturally contaminated with much more background than the numerator, and the measurement of this background is the main source of systematic error in the efficiency measurement.

To estimate this background, one must start with the corrected templates mentioned previously in Section 5.2.1 (determined by taking the data-driven template and subtracting off signal contamination estimated using $Z \rightarrow ee$ simulation rescaled to the Tight data events with m_{ee} near the Z mass). These corrected templates contain events which are enriched in background processes; they are being used to model and estimate the distribution of the background contributing to the total m_{ee} distribution, but the overall normalization of the template still needs to be determined. This is done by normalizing the background template to a background-dominated sideband (“tail”) of the total m_{ee} distribution (nominally $120 \text{ GeV} < p_T < 250 \text{ GeV}$). Of course, this normalization region can also contain some signal contamination, and this must also be removed before determining the normalization factor. Here, the simulation is poor in statistics, since relatively few $Z \rightarrow ee$ events fall into the tail of the m_{ee} distribution. This estimate of the signal contamination is instead achieved by measuring the number of events containing Tight probes in the sideband of interest, and dividing this by a rough estimate for the efficiency of the Tight working point (labeled as $\varepsilon_{\text{estimated}}^{\text{Tight}}$):

$$N_{\text{all prompt probes}} \Big|_{\text{tail}} = \frac{N_{\text{Tight}} \Big|_{\text{tail}}}{\varepsilon_{\text{estimated}}^{\text{Tight}}}. \quad (5.3)$$

Put differently, since the efficiency is the ratio of the number of Tight electrons to the total number of electrons, the estimate of the total number of electrons is simply the number of Tight electrons divided by the Tight efficiency. Note here that the number of Tight events is not corrected for any background contamination, but this is anyway small once the probes are required to pass Tight.

One might be concerned that this is a circular argument—this entire section is about computing the electron identification efficiency, so what is this “rough estimate for the efficiency” that is used as input to compute the actual efficiency? The answer is that the simpler procedure described in Section 5.2.1.2 is used to compute an approximate efficiency for the Tight working point, solely for use in this calculation of the denominator. For the final estimate of the Tight working point efficiency, one could repeat this procedure iteratively, using the latest estimate for the efficiency each time—however, past studies from Run 1 have found this to be unnecessary, as more than one iteration would yield negligible differences.

Putting all of these components together, the background estimate in the m_{ee} region of interest for computing the electron identification efficiency is:

$$N_{\text{data}}^{\text{denominator bkg}} \Big|_{\text{peak}} = \left(N_{\text{data}}^{\text{template}} - N_{\text{MC}}^{\text{template}} \frac{N_{\text{data}}^{\text{Tight}}}{N_{\text{MC}}^{\text{Tight}}} \right) \Big|_{\text{peak}} \times \frac{N_{\text{data}} - \frac{1}{\epsilon_{\text{estimated}}^{\text{Tight}}} N_{\text{data}}^{\text{Tight}}}{N_{\text{data}}^{\text{template}}} \Big|_{\text{tail}}. \quad (5.4)$$

5.2.1.2 The Z_{mass} Numerator

For the numerator, the corrected template is scaled using a simpler procedure. Since the opposite-sign events in the numerator have large signal contribution in the tails of the m_{ee} distribution, the same-sign events satisfying the identification working point are instead used for the template normalization. These same-sign events in the sideband are assumed to have negligible contribution from signal events, as the Standard Model has very few processes which result in a same-sign dilepton final state. This sample of same-sign tag-probe pairs is dominated by W +jets events with a jet which fakes an electron. As a simple approximation, the jet that is reconstructed as an electron is equally likely to take on either charge, making the same-sign sideband an excellent sample to normalize the background templates to. The numerator-level background estimate is then:

$$N_{\text{data}}^{\text{numerator bkg}} \Big|_{\text{peak}} = \left(N_{\text{data}}^{\text{template}} - N_{\text{MC}}^{\text{template}} \frac{N_{\text{data}}^{\text{Tight}}}{N_{\text{MC}}^{\text{Tight}}} \right) \Big|_{\text{peak}} \times \frac{N_{\text{data}}^{\text{numerator same-sign data}}}{N_{\text{data}}^{\text{template}}} \Big|_{\text{tail}}. \quad (5.5)$$

This is then used to compute the efficiency for each numerator criteria (i.e. identification working point) of interest.

Note that this simpler same-sign normalization would not be sufficient for the denominator as the denominator-level background is orders of magnitude larger. This procedure fails for the denominator in part because the assumption of charge symmetry for the W +jets events is only an approximation. In reality, the $W+c$ process and W boson events produced alongside a quark-initiated jet both tend to result in opposite-sign events more frequently when produced in the LHC's pp collisions. To demonstrate this, the denominator-level plot from Figure 5.2 is repeated using the numerator's normalization method, and is shown in Figure 5.4.

5.2.1.3 Calculation of Statistical Uncertainties

To calculate the statistical uncertainties, the procedure from [107] is used. This procedure begins by defining the number of events which pass the numerator requirement to be $N_{\text{num}} \pm \Delta N_{\text{num}}$ and those which fail the numerator to be $N_{\text{fail}} \pm \Delta N_{\text{fail}}$. Then the efficiency for the numerator criteria is

$$\epsilon = \frac{N_{\text{num}}}{N_{\text{num}} + N_{\text{fail}}}. \quad (5.6)$$

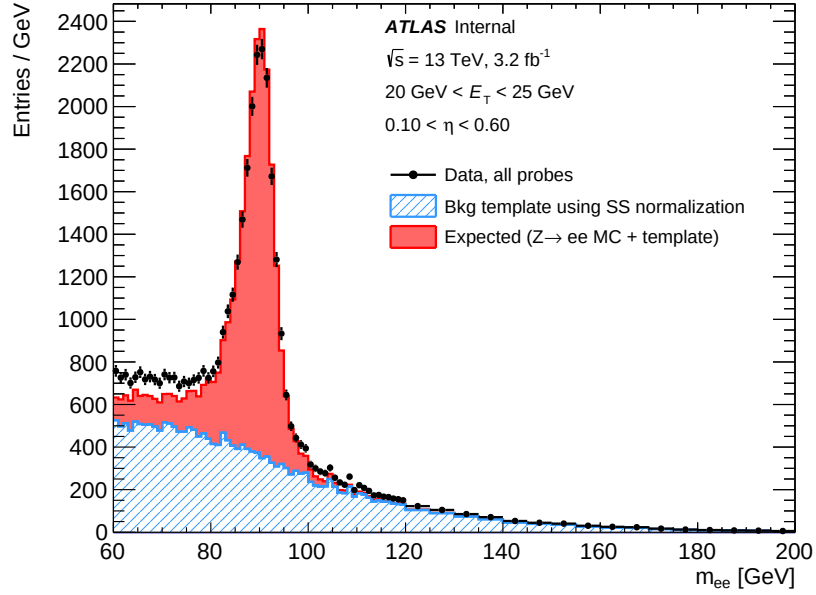


Figure 5.4: The denominator-level plot from Figure 5.2, but using the numerator method for the template normalization (scaling the template to the same-sign sideband). Clearly, the scaled template disagrees with the data in the low m_{ee} tail, whereas the method described in Section 5.2.1.1 resulting in the plot from Figure 5.2 estimates this properly.

With $N_{\text{den}} = N_{\text{num}} + N_{\text{fail}}$ and $(\Delta N_{\text{den}})^2 = (\Delta N_{\text{num}})^2 + (\Delta N_{\text{fail}})^2$, one can then compute the variance of this efficiency:

$$(\Delta \varepsilon)^2 = \left(\frac{\partial \varepsilon}{\partial N_{\text{num}}} \right)^2 (\Delta N_{\text{num}})^2 + \left(\frac{\partial \varepsilon}{\partial N_{\text{fail}}} \right)^2 (\Delta N_{\text{fail}})^2 \quad (5.7)$$

$$= \left(\frac{N_{\text{fail}}}{(N_{\text{num}} + N_{\text{fail}})^2} \right)^2 (\Delta N_{\text{num}})^2 + \left(\frac{-N_{\text{num}}}{(N_{\text{num}} + N_{\text{fail}})^2} \right)^2 (\Delta N_{\text{fail}})^2 \quad (5.8)$$

$$= \frac{N_{\text{fail}}^2 (\Delta N_{\text{num}})^2 + N_{\text{num}}^2 (\Delta N_{\text{fail}})^2}{(N_{\text{num}} + N_{\text{fail}})^4} \quad (5.9)$$

$$= \frac{(1 - \varepsilon)^2 (\Delta N_{\text{num}})^2 + \varepsilon^2 (\Delta N_{\text{fail}})^2}{(N_{\text{num}} + N_{\text{fail}})^2} \quad (5.10)$$

$$= \frac{(1 - 2\varepsilon)(\Delta N_{\text{num}})^2 + \varepsilon^2 ((\Delta N_{\text{num}})^2 + (\Delta N_{\text{fail}})^2)}{N_{\text{den}}^2} \quad (5.11)$$

$$= \frac{(1 - 2\varepsilon)(\Delta N_{\text{num}})^2 + \varepsilon^2 (\Delta N_{\text{den}})^2}{N_{\text{den}}^2}. \quad (5.12)$$

One can then take the square root to obtain the uncertainty:

$$\Delta \varepsilon = \frac{1}{N_{\text{den}}} \sqrt{(1 - 2\varepsilon)(\Delta N_{\text{num}})^2 + \varepsilon^2 (\Delta N_{\text{den}})^2}. \quad (5.13)$$

In the simulation, this is trivial to compute as no background contamination is present. The substitutions $\Delta N_{\text{num}}^{\text{MC}} = \sqrt{N_{\text{num}}^{\text{MC}}}$ and $\Delta N_{\text{den}}^{\text{MC}} = \sqrt{N_{\text{den}}^{\text{MC}}}$ can be made, resulting in a statistical uncertainty on the electron efficiency for the simulated events of:

$$\Delta \varepsilon^{\text{MC}} = \frac{1}{N_{\text{den}}^{\text{MC}}} \sqrt{(1 - 2\varepsilon^{\text{MC}})(\Delta N_{\text{num}}^{\text{MC}})^2 + (\varepsilon^{\text{MC}})^2(\Delta N_{\text{den}}^{\text{MC}})^2} \quad (5.14)$$

$$= \frac{1}{N_{\text{den}}^{\text{MC}}} \sqrt{(1 - 2\varepsilon^{\text{MC}})(N_{\text{num}}^{\text{MC}}) + (\varepsilon^{\text{MC}})^2(N_{\text{den}}^{\text{MC}})}. \quad (5.15)$$

In data, the background template method is used, so this is slightly more complicated. The terms ΔN_{den} and ΔN_{num} include contributions from:

- number of events in the peak of the data distribution,
- number of events in the tail of the data distribution,
- number of events in the peak of the template distribution,
- number of events in the tail of the template distribution.

Moreover, the template is constructed with respect to the good-quality track criteria, so the denominator and the template overlap. To properly measure the statistical uncertainty, these must be rewritten in terms of uncorrelated quantities. For the denominator, this is done by defining the following:

$$X_{\text{peak}} := N_{\text{data}}|_{\text{peak}} - N_{\text{data}}^{\text{template}}|_{\text{peak}} \quad (5.16)$$

$$X_{\text{tail}} := N_{\text{data}}|_{\text{tail}} - N_{\text{data}}^{\text{template}}|_{\text{tail}} \quad (5.17)$$

which are then used in the computation of $N_{\text{data}}^{\text{denominator}}|_{\text{peak}}$:

$$N_{\text{data}}^{\text{denominator}}|_{\text{peak}} = N_{\text{data}}|_{\text{peak}} - N_{\text{data}}^{\text{template}}|_{\text{peak}} \times \frac{N_{\text{data}}}{N_{\text{data}}^{\text{template}}}|_{\text{tail}} \quad (5.18)$$

$$= X_{\text{peak}} - N_{\text{data}}^{\text{template}}|_{\text{peak}} \times \frac{N_{\text{data}} - N_{\text{data}}^{\text{template}}}{N_{\text{data}}^{\text{template}}}|_{\text{tail}} \quad (5.19)$$

$$= X_{\text{peak}} - N_{\text{data}}^{\text{template}}|_{\text{peak}} \times \frac{X_{\text{tail}}}{N_{\text{data}}^{\text{template}}|_{\text{tail}}}. \quad (5.20)$$

Formally, there are missing terms from Equation 5.4 in the computation of $N_{\text{data}}^{\text{denominator}}$ here for use in the uncertainty calculation; however these terms all contribute negligibly to the statistical uncertainty as they are small relative to the others. Equation 5.20 uses fully uncorrelated variables

since the X terms explicitly do not include the template distributions. One can now perform standard error propagation for $N_{\text{data}}^{\text{denominator}}|_{\text{peak}}$, which gives:

$$\Delta N_{\text{data}}^{\text{denominator}}|_{\text{peak}} = \sqrt{N_{\text{data}}|_{\text{peak}} + \left(\frac{(X_{\text{tail}})(N_{\text{data}}^{\text{template}}|_{\text{peak}})}{N_{\text{data}}^{\text{template}}|_{\text{tail}}} \right)^2 \left(\frac{1}{N_{\text{data}}^{\text{template}}|_{\text{peak}}} + \frac{1}{N_{\text{data}}^{\text{template}}|_{\text{tail}}} + \frac{1}{X_{\text{tail}}} \right)}. \quad (5.21)$$

For the numerator, there is very small overlap between the template and the distribution of all probes passing the identification criteria, as the template explicitly inverts identification criteria. For the purpose of the uncertainty calculation, any residual overlap is assumed to be negligible and is ignored. In the same-sign region used to normalize the template, there actually is zero overlap, since the numerator distribution used for the efficiency calculation only considers opposite-sign probes. Given these constraints and assumptions, the propagation of uncertainties for the background-subtracted numerator based on Equation 5.5 can be calculated. This results in:

$$\Delta N_{\text{data}}^{\text{numerator}}|_{\text{peak}} = \sqrt{N_{\text{data}}|_{\text{peak}} + \left(N_{\text{data}}^{\text{numerator bkg}}|_{\text{peak}} \right)^2 \left(\frac{1}{N_{\text{data}}^{\text{template}}|_{\text{peak}}} + \frac{1}{N_{\text{data}}^{\text{template}}|_{\text{tail}}} + \frac{1}{N_{\text{numerator same-sign data}}|_{\text{tail}}} \right)}. \quad (5.22)$$

These can then be used in Equation 5.13 to compute the total statistical uncertainty on the efficiency.

5.2.1.4 Systematic Variations

Systematic uncertainties in the Z_{mass} method are assessed by performing several variations of the measurement:

- To assess the impact of allowing for more or less background into the measurement, the m_{ee} region of interest for measuring the numerator and denominator is varied between mass windows of [70 GeV, 110 GeV], [75 GeV, 105 GeV], and [80 GeV, 100 GeV].
- The tag selection criteria is varied between Tight, Medium with calorimeter isolation, and Tight with calorimeter isolation. The isolation used for this requires $E_{\text{T}}^{\text{cone0.4}} < 5$ GeV.
- The background template selection criteria and normalization region are varied, as described in Table 5.4.

After determining the efficiencies of a given operating point for all combinations of these variations, the mean and RMS are computed to determine the central value and systematic uncertainty, respectively. There are three mass window variations, three tag criteria variations, and two template

variations. This means there are a total of 18 variations in data and 9 variations in simulation, since the templates are only used to subtract background from the data.

Note that the use of a Medium tag with calorimeter isolation results in a selection which is actually looser than the trigger-level criteria for the single electron trigger. This has therefore been removed for the latest iteration of the efficiency measurement using the full Run 2 dataset, to avoid any trigger bias. The variation of tag identification and isolation criteria has always been found to contribute the least to the total uncertainty and may even be dropped in the future, so this is not thought to negatively impact the results in any way.

5.2.2 The Z_{iso} Method

Instead of relying on the m_{ee} distribution for estimating the background present in the $Z \rightarrow ee$ tag-and-probe sample, the Z_{iso} method relies on the distribution of the calorimetric isolation $E_{\text{T}}^{\text{cone0.3}}$ of the probe electrons. As prompt electrons from $Z \rightarrow ee$ tend to be well-isolated (resulting in small values of $E_{\text{T}}^{\text{cone0.3}}$), this variable provides good discrimination against background and provides relatively pure sideband regions for normalizing template distributions.

Similar to the Z_{mass} method, templates are constructed by inverting identification criteria. Note, of course, that since the probe isolation is used for the background estimation in this method, the templates cannot be built using inverted isolation criteria. Instead, the Loose cut-based identification as well as cuts on specific discriminating variables from Table 4.1 are inverted.

After constructing templates and accounting for signal contamination in a similar manner as the Z_{mass} method, the templates are normalized to the probe isolation sideband (nominally chosen to be $E_{\text{T}}^{\text{cone0.3}} > 12.5$ GeV). The signal can then be extracted by subtracting the background estimate from the sample of all probes. An illustration of this background estimation is shown in Figure 5.5. Several variations of this measurement are performed for the evaluation of systematic uncertainties:

- To assess the impact of allowing for more or less background into the measurement, the m_{ee} region of interest for measuring the numerator and denominator is varied between mass windows of [70 GeV, 110 GeV], [75 GeV, 105 GeV], and [80 GeV, 100 GeV].
- The definition of the probe isolation sideband region is varied between $E_{\text{T}}^{\text{cone0.3}} > 10$ GeV, $E_{\text{T}}^{\text{cone0.3}} > 12.5$ GeV, and $E_{\text{T}}^{\text{cone0.3}} > 15$ GeV.
- An isolation requirement with a larger cone size ($E_{\text{T}}^{\text{cone0.4}}$) is used to assess an uncertainty associated to the choice of isolation variable used in the measurement.

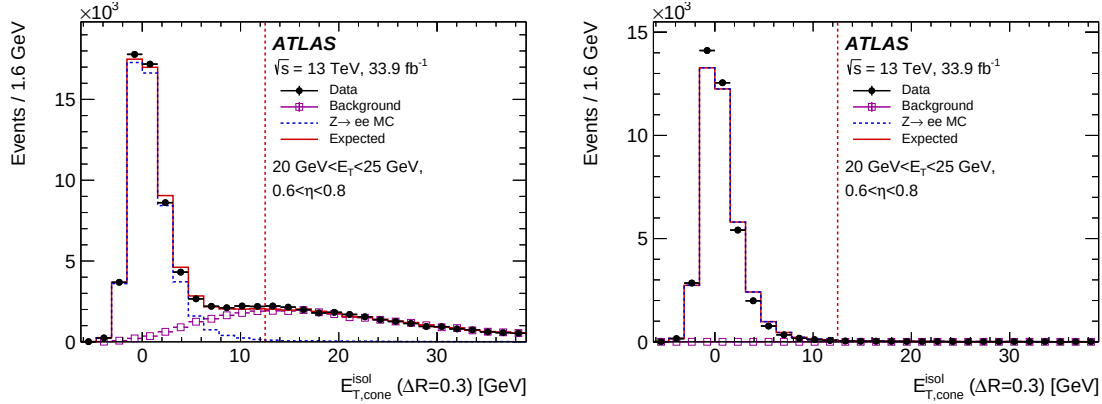


Figure 5.5: Illustration of the background estimation as a function of the probe isolation $E_T^{\text{cone}0.3}$, using the Z_{iso} method with the 2015–2016 data. This is for the $20 \text{ GeV} < p_T < 25 \text{ GeV}$, $0.6 < \eta < 0.8$ bin, shown at reconstruction level (left) and for probes passing the Tight identification (right). The background estimation is performed by constructing templates using inverted identification criteria, which are then normalized to the $E_T^{\text{cone}0.3} > 12.5 \text{ GeV}$ region (located to the right of the dashed red line).

- The tag selection criteria is varied between Tight and Tight with calorimeter isolation.

The statistical uncertainties are calculated using a similar procedure as Section 5.2.1.3.

5.3 Electron Identification Efficiency Measurements using $J/\psi \rightarrow ee$ Events

The $J/\psi \rightarrow ee$ process provides a source of probe electrons with $p_T > 4.5 \text{ GeV}$ for use in the electron identification efficiency measurement. Note that in Run 1 this was only performed for $p_T > 7 \text{ GeV}$ as the electron identification algorithms were not designed for lower p_T , and thus $4.5 \text{ GeV} < p_T < 7 \text{ GeV}$ electrons were not used by any ATLAS analyses. To select these events, dedicated prescaled dielectron triggers are used, which impose electron p_T requirements ranging from 4 GeV to 14 GeV, as described in Table 5.5. The events must contain two electron candidates with $|\eta| < 2.47$, where the tag electron must satisfy the Tight identification criteria while the probe electron must satisfy the good-quality track criteria. To further ensure that the tag electron is more likely to be a prompt electron rather a background object, the tag electron must be located outside of the calorimeter transition region of $1.37 < |\eta| < 1.52$. To avoid any trigger bias, the tag and the probe electrons must be associated to the trigger-level electron objects (with $\Delta R < 0.07$ between the trigger-level and offline electron objects), as well as each satisfying an offline p_T requirement.

2015	2016
HLT_e5_lhtight_e4_etcut_Jpsiee	HLT_e5_lhtight_nod0_e4_etcut_Jpsiee
HLT_e9_lhtight_e4_etcut_Jpsiee	HLT_e9_lhtight_nod0_e4_etcut_Jpsiee
HLT_e14_lhtight_e4_etcut_Jpsiee	HLT_e14_lhtight_nod0_e4_etcut_Jpsiee

Table 5.5: List of the dedicated $J/\psi \rightarrow ee$ triggers used in 2015 and 2016. The number after “_e” refers to the p_T threshold in GeV, while each instance of “_e” itself means an additional electron candidate is required. “lhtight” refers to the trigger-level electron identification criteria which the given electron candidate must satisfy. For 2016, the primary electron triggers did not include any requirement on d_0 or $d_0/\sigma(d_0)$ in the likelihood-based electron identification algorithm at trigger-level, and thus “nod0” is included in the trigger names. “etcut” means the given electron candidate must simply satisfy a given p_T threshold, and no further algorithm is applied. Finally, “Jpsiee” indicates that the trigger imposes an invariant mass requirement on the trigger-level dielectron pair of $1 \text{ GeV} < m_{ee} < 5 \text{ GeV}$. New triggers which additionally make use of m_{ee} requirements at L1 to allow for rate reduction were employed for 2017 and 2018; however, as this is not the primary focus of this thesis, the details are left for future publications.

To further reduce backgrounds and to enhance the purity of the $J/\psi \rightarrow ee$ events from prompt production, isolation criteria are applied to both the tag and the probe electrons (which is chosen to be very loose for the probe electrons, to avoid introducing bias into the measurement). Finally, to prevent the use of any dielectron pairs which might have overlapping shower shapes or other identification criteria which could interfere with one another, the tag and the probe electrons must be separated by $\Delta R > 0.15$. Except where specifically noted, the tag electron and probe electron are required to have opposite-sign charge [5].

Extracting the signal events in this measurement is challenging because there are several components to the m_{ee} spectrum in the $1.8 \text{ GeV} < m_{ee} < 4.6 \text{ GeV}$ range considered. The J/ψ events, $\psi(2S)$ events, and background events are fit using functions which model the behavior as a function of m_{ee} for each component. The J/ψ and $\psi(2S)$ events are modeled using a Crystal Ball function [109, 110] convolved with a Gaussian function, while the background is modeled using a second-order Chebyshev polynomial fit to same-sign events.

To primarily select events from promptly produced $J/\psi \rightarrow ee$ decays, the pseudo-proper time variable is exploited:

$$\tau = \frac{L_{xy} m_{\text{PDG}}^{J/\psi}}{p_T^{J/\psi}}, \quad (5.23)$$

where L_{xy} is the transverse distance between the J/ψ vertex and the primary vertex, $m_{\text{PDG}}^{J/\psi}$ is the nominal mass of the J/ψ meson (3.097 GeV), and $p_T^{J/\psi}$ is the reconstructed p_T of the dielectron pair. This variable is effective because the pseudo-proper time of nonprompt J/ψ events tends to be larger than that of prompt J/ψ events.

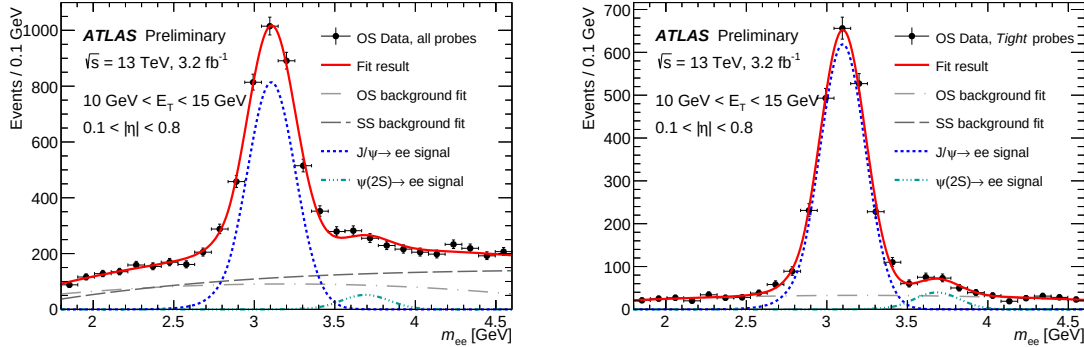


Figure 5.6: Illustration of the background estimation as a function of m_{ee} for the $J/\psi \rightarrow ee$ τ -cut method with the 2015 data. This is for the $10 \text{ GeV} < E_T < 15 \text{ GeV}$, $0.1 < |\eta| < 0.8$ bin, shown at reconstruction level (left) and for probes passing the Tight identification (right). Solid circles with error bars represent the opposite-sign (OS) pairs in data, the blue dashed line shows the fitted J/ψ signal, and the cyan dashed line shows the fitted $\psi(2S)$ signal. The background is estimated as the sum of the same-sign (SS) background and the residual OS background, both of which are shown as dashed gray lines.

Two methods of background estimation are used to extract events from prompt J/ψ production; the τ -cut method which applies a selection criteria of $-1 \text{ ps} < \tau < 0.2 \text{ ps}$ and the τ -fit method which fits the τ distribution in the range $-1 \text{ ps} < \tau < 3 \text{ ps}$. In the τ -cut method, any residual nonprompt J/ψ is estimated using simulation and past ATLAS measurements of $J/\psi \rightarrow \mu\mu$ [111]. In the τ -fit method, meanwhile, the τ distribution is fit using the sum of two Gaussians for the prompt component and the sum of two Gaussians convolved with an exponential decay function for the nonprompt component. The background estimation for these two methods is demonstrated in Figures 5.6 and 5.7, and the procedure used is documented in detail in [5, 6, 98].

Systematic uncertainties on the $J/\psi \rightarrow ee$ tag-and-probe measurement are determined by varying the isolation criteria used, the fitting procedure (including the signal and background shapes, the fit window, and the sideband definitions), as well as the m_{ee} window used for counting the number of signal events.

5.4 Combined Electron Identification Efficiencies

Note that combination of the data-to-simulation correction factors (also called “scale factors”) will primarily be discussed in this section, as these are the quantities of interest to ATLAS analyses. However, the procedures hold true for the efficiencies as well.

The Z_{mass} and Z_{iso} methods are statistically correlated, as are the J/ψ τ -cut and τ -fit methods.

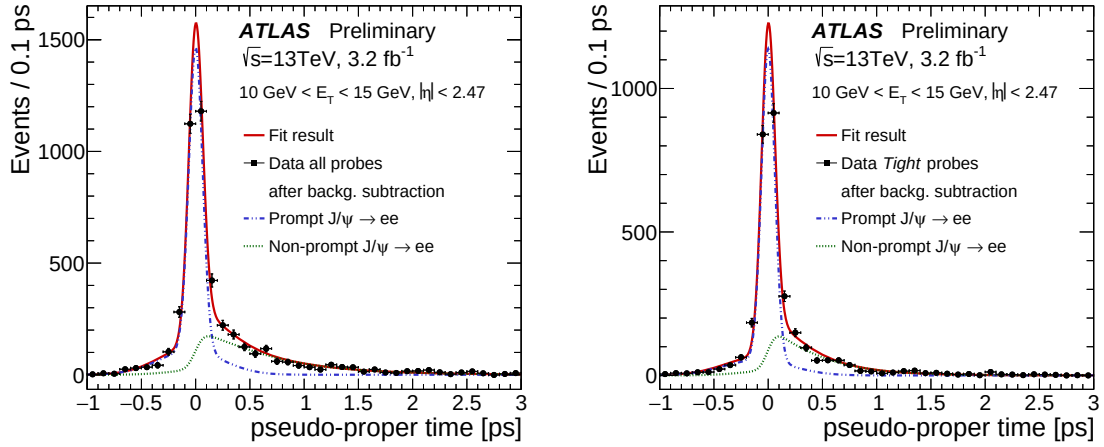


Figure 5.7: Illustration of the background estimation as a function of τ for the $J/\psi \rightarrow ee$ τ -fit method with the 2015 data. This is shown for probes with $10 \text{ GeV} < p_T < 15 \text{ GeV}$, and is inclusive in $|\eta|$. This is shown at reconstruction level (left) and for probes passing the Tight identification (right). Solid circles with error bars represent the OS data after performing background subtraction, while the prompt and nonprompt components of the J/ψ events are shown as dashed blue and green lines, respectively.

Systematic variations are also shared between the methods, and thus the methods are also systematically correlated. The two $Z \rightarrow ee$ methods are therefore simply treated as systematic variations of one another, as are the two $J/\psi \rightarrow ee$ methods.

To combine the efficiencies and their uncertainties, the central value and RMS are computed using all systematic variations for each measurement (i.e. take the central value and RMS from all $Z \rightarrow ee$ or all $J/\psi \rightarrow ee$ variations). To prevent a single method from dominating over the other for a given measurement, each variation is weighted according to the number of variations available for that particular method. As a result, Z_{mass} and Z_{iso} are given equal weight in the final combination, as are the J/ψ τ -cut and τ -fit methods. Example combined results, compared with those of the individual methods, are shown in Figures 5.8 and 5.9 for the Tight working point in 2015 data.

When these variations are not distributed in a Gaussian manner, it is possible for the systematic uncertainty to be too small to cover the envelope of variations. In such cases, the systematic uncertainty is inflated to ensure that 68% of all variations are covered.

In the $15 \text{ GeV} < p_T < 20 \text{ GeV}$ bin, the independent measurements of $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ events are both present. These are therefore combined using a χ^2 fit following the prescription from [5, 112]. The combined results are compared with the individual $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ results for this bin in Figure 5.10.

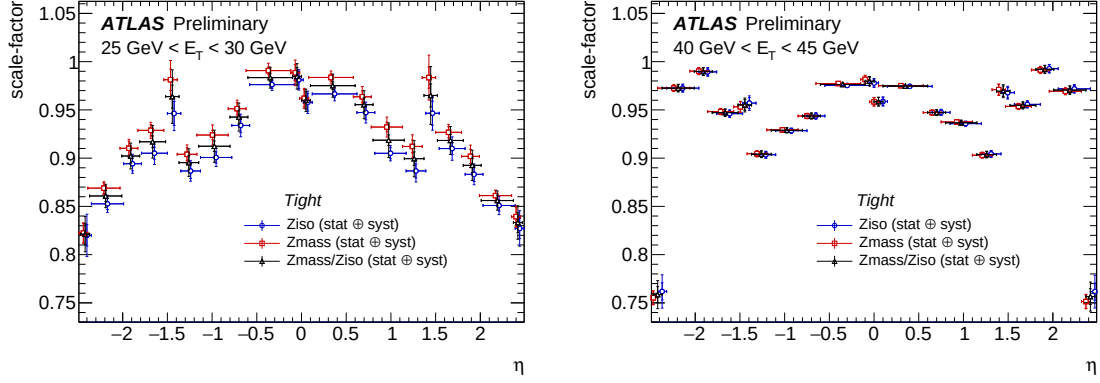


Figure 5.8: Data-to-simulation correction factors for Z_{mass} , Z_{iso} , and their combination for the Tight identification, shown for $25 \text{ GeV} < p_T < 30 \text{ GeV}$ (left) and $40 \text{ GeV} < p_T < 45 \text{ GeV}$ (right). The inner error bars show the statistical uncertainty, while the outer error bars show the total statistical plus systematic uncertainty. These were measured using 2015 data [5].

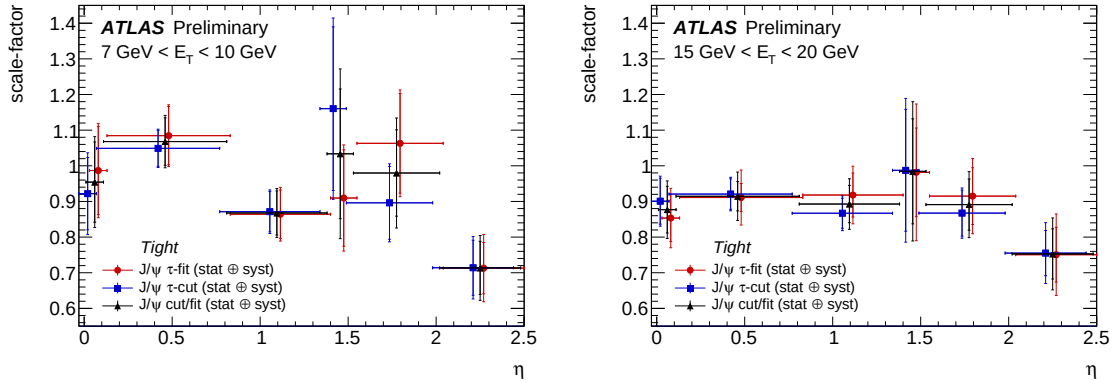


Figure 5.9: Data-to-simulation correction factors for J/ψ τ -cut, τ -fit, and their combination for the Tight identification, shown for $7 \text{ GeV} < p_T < 10 \text{ GeV}$ (left) and $15 \text{ GeV} < p_T < 20 \text{ GeV}$ (right). The inner error bars show the statistical uncertainty, while the outer error bars show the total statistical plus systematic uncertainty. These were measured using 2015 data [5].

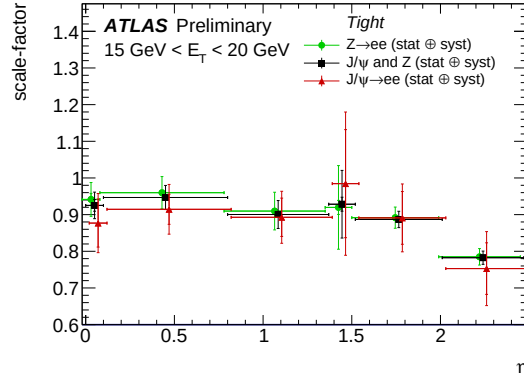


Figure 5.10: Data-to-simulation correction factors for $Z \rightarrow ee$, $J/\psi \rightarrow ee$, and their combination for the Tight identification, shown for the only region where these measurements overlap, $15 \text{ GeV} < p_T < 20 \text{ GeV}$. The inner error bars show the statistical uncertainty, while the outer error bars show the total statistical plus systematic uncertainty. These were measured using 2015 data [5].

The combined data efficiencies for 2015–2016 for the identification working points are shown in Figures 5.11 and 5.12. As mentioned in Section 4.4.2, the discriminant values used to define the identification working points were chosen using simulated events. The intended outcome was for the efficiencies to fall smoothly with decreasing electron p_T , to ensure that the background would be acceptable across the p_T range. Using the simulation out-of-the-box is known to be suboptimal, and thus the data-to-simulation offsets and widths described in Section 4.4.1.2 were used to account for mismodeling of the simulation. This method worked sufficiently at high p_T , but at low p_T were insufficient to fully correct the simulation, thus leading to operating points with larger efficiencies in data than intended at low p_T (and consequently, a worse background rejection). The figure also shows the corresponding rise in the data-to-simulation ratios at low p_T .

5.5 Electron Reconstruction Efficiencies

The electron reconstruction efficiency measurement proceeds similarly to the Z_{mass} method. The numerator for this efficiency measurement is all probes satisfying the good-quality track requirement, and thus the background estimation for this numerator is performed identically to the denominator of the Z_{mass} identification efficiency measurement. The denominator for the reconstruction efficiency measurement, however, is all reconstructed EM clusters. This denominator contains background from events containing probe clusters that have no associated good-quality track—for instance, $W(\rightarrow e\nu)+\gamma$ events could fall into this category when the prompt electron satisfies the tag criteria

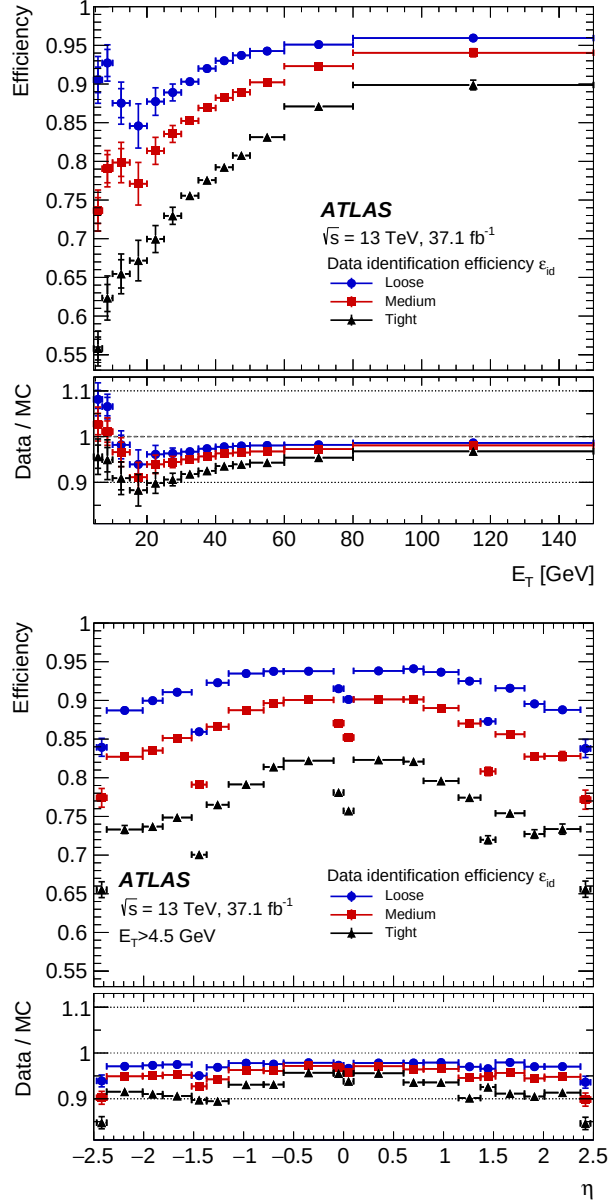


Figure 5.11: Electron identification efficiencies for 2015–2016 data measured using $Z \rightarrow ee$ events for the Loose (blue circle), Medium (red square), and Tight (black triangle) operating points are shown as a function of p_T (top) and η (bottom). The data efficiencies are obtained by applying the data-to-simulation correction factors (measured using $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ events) to the $Z \rightarrow ee$ simulation. The inner error bars show the statistical uncertainty, while the outer error bars show the total statistical plus systematic uncertainty; in some bins these are not visible because the uncertainty is small [6].

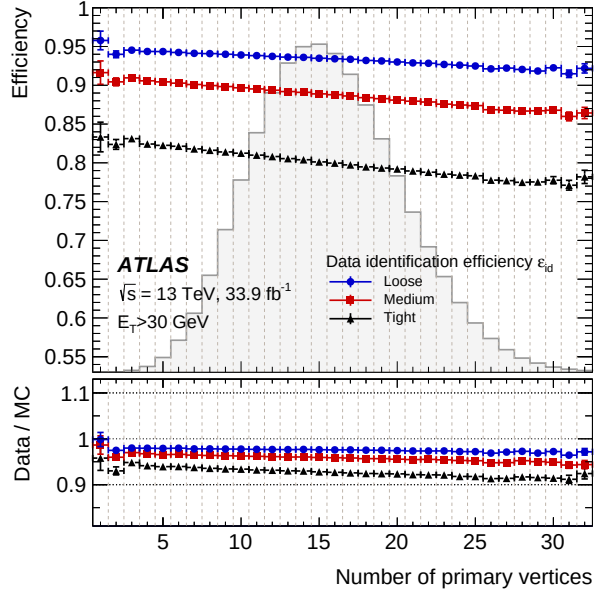


Figure 5.12: Electron identification efficiencies for 2016 data measured using $Z \rightarrow ee$ events for the Loose (blue circle), Medium (red square), and Tight (black triangle) operating points are shown as a function of n_{vtx} . The data efficiencies are obtained by applying the data-to-simulation correction factors (measured using $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ events) to the $Z \rightarrow ee$ simulation. The inner error bars show the statistical uncertainty, while the outer error bars show the total statistical plus systematic uncertainty; in some bins these are not visible because the uncertainty is small. The shaded histogram shows the distribution of the number of reconstructed primary vertices for the 2016 data [6].

and the photon satisfies the cluster reconstruction. This background is estimated using a polynomial fit to the sidebands of the m_{ee} distribution of all events containing a cluster-only probe. This background estimation is demonstrated in Figure 5.13, and the corresponding electron reconstruction efficiencies are shown in Figures 5.14 and 5.15.

5.6 Electron Isolation Efficiencies

The electron isolation efficiencies are measured using the Z_{mass} method in the same manner as the electron identification efficiencies described in Section 5.2.1. The primary difference, of course, is that the isolation efficiencies are measured with respect to the identification efficiencies, and thus the isolation criteria serves as the numerator of the efficiency calculation while the identification criteria serves as the denominator. Additionally, the isolation efficiencies are measured using probe electrons with $p_T > 4.5 \text{ GeV}$, which is possible due to the smaller background present in the sample

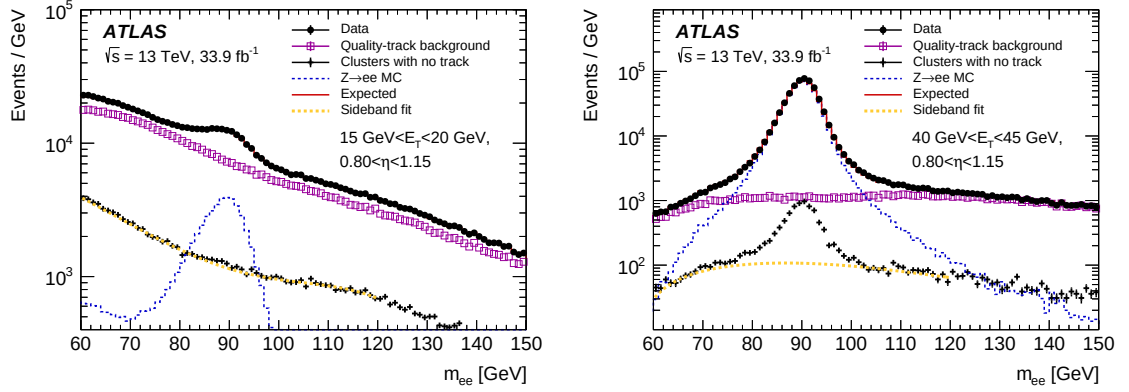


Figure 5.13: Illustration of the background estimation as a function of the invariant mass m_{ee} for the electron reconstruction efficiency measurement using the 2015–2016 data. This is for the $15 \text{ GeV} < p_T < 20 \text{ GeV}$, $0.80 < \eta < 1.15$ bin (left) and the $40 \text{ GeV} < p_T < 45 \text{ GeV}$, $0.80 < \eta < 1.15$ bin (right). Only the denominator of this efficiency measurement is shown as Figure 5.3 already shows the corresponding plot for probes which are reconstructed with a good-quality track [6].

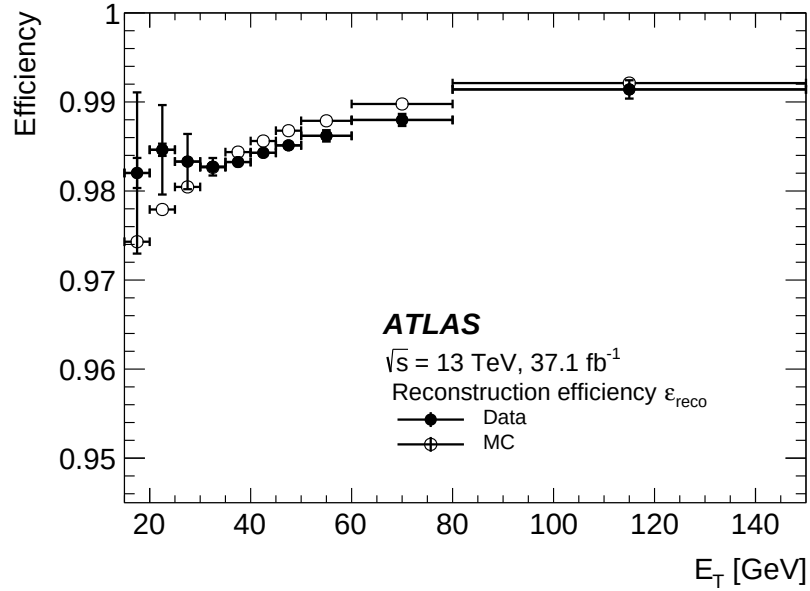


Figure 5.14: Electron reconstruction efficiency for 2015–2016 data measured using $Z \rightarrow ee$ events, shown as a function of p_T . The inner error bars show the statistical uncertainty, while the outer error bars show the total statistical plus systematic uncertainty; in some bins these are not visible because the uncertainty is small [6].

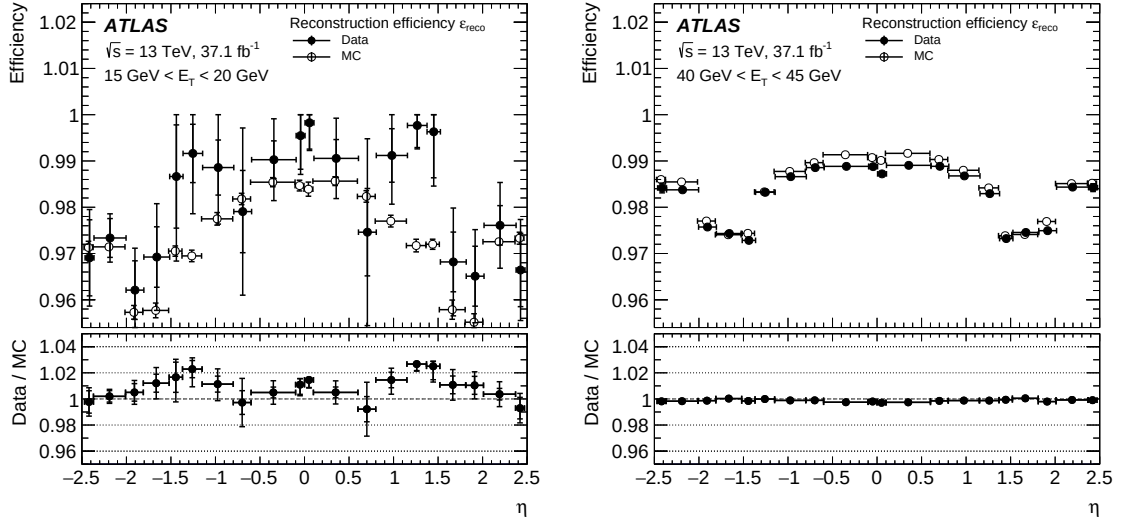


Figure 5.15: Electron reconstruction efficiency for 2015–2016 data measured using $Z \rightarrow ee$ events, shown as a function of η in the $15 \text{ GeV} < p_T < 20 \text{ GeV}$ bin (left) and in the $40 \text{ GeV} < p_T < 45 \text{ GeV}$ bin (right). The inner error bars show the statistical uncertainty, while the outer error bars show the total statistical plus systematic uncertainty; in some bins these are not visible because the uncertainty is small [6].

of identified electrons (compared with the sample of reconstructed electrons which serves as the denominator for the electron identification efficiency measurement). The template normalization procedure using same-sign events in the m_{ee} sideband from Section 5.2.1.2 is used for both the numerator and denominator of the isolation efficiency measurement. The efficiencies for the isolation working points, measured with respect to Tight identification, are shown in Figure 5.16.

5.7 Electron Trigger Efficiencies

The electron trigger efficiencies are also measured using the Z_{mass} method, in the same manner as the electron identification (Section 5.2.1) and isolation (Section 5.6) efficiencies. Since the electron trigger efficiencies are measured with respect to electrons which satisfy the reconstruction, identification, and isolation criteria, this measurement has a smaller level of background than any of the previous steps. Thus, it is possible to measure the electron trigger efficiencies using probe electrons with $p_T > 4.5 \text{ GeV}$.

As with the isolation efficiencies, the background estimation for both the numerator and denominator of the trigger efficiency measurement is performed with templates normalized using same-sign events in the m_{ee} sideband, as described in Section 5.2.1.2. An example trigger efficiency plot for

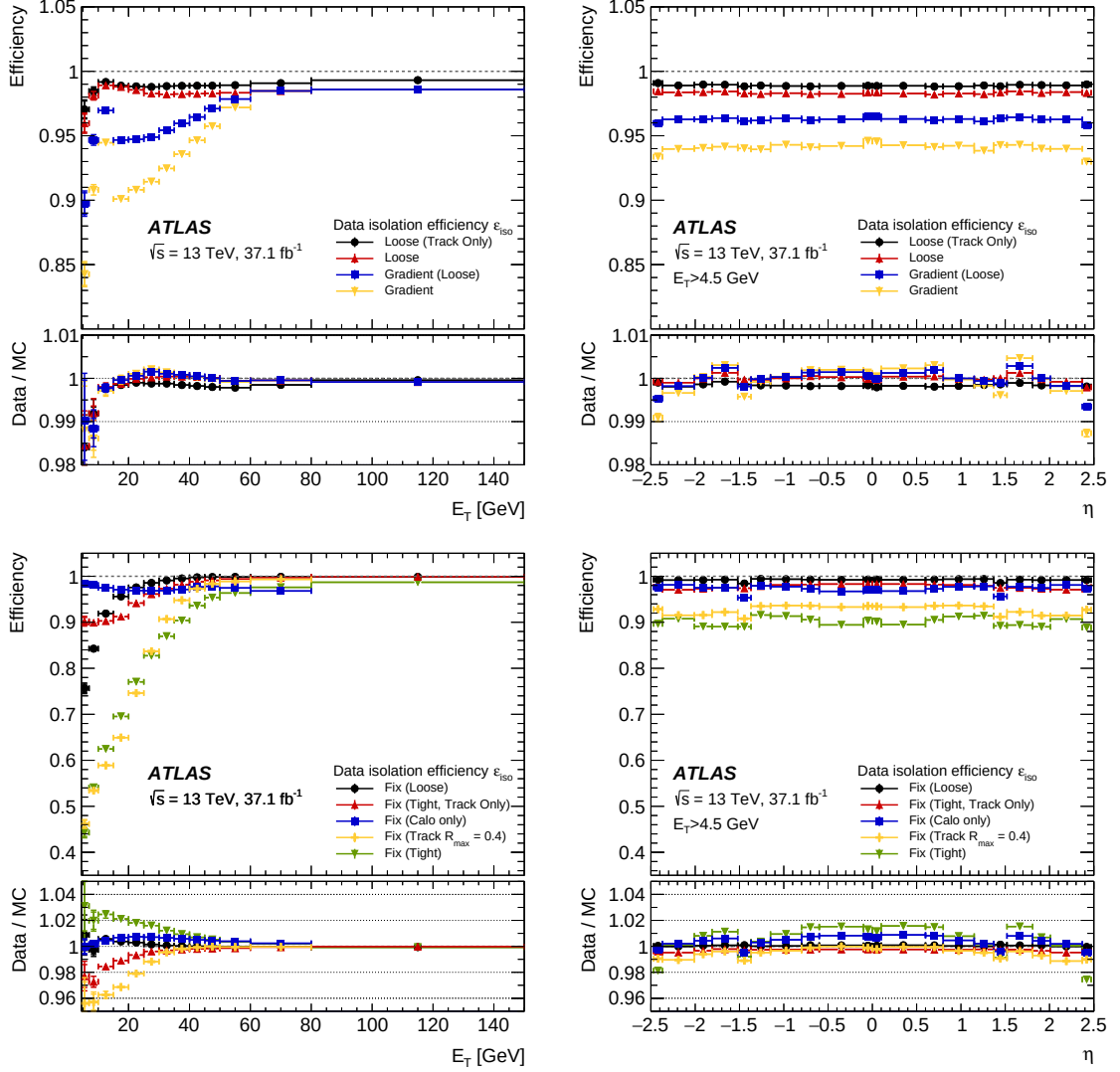


Figure 5.16: Efficiencies for electron isolation operating points measured with respect to Tight identification using the 2015–2016 data. These efficiencies were measured using $Z \rightarrow ee$ events, and are shown as a function of p_T (left) and η (right) for the efficiency-targeted (top) and fixed requirement (bottom) isolation working points, all of which are described in Table 4.4 [6].

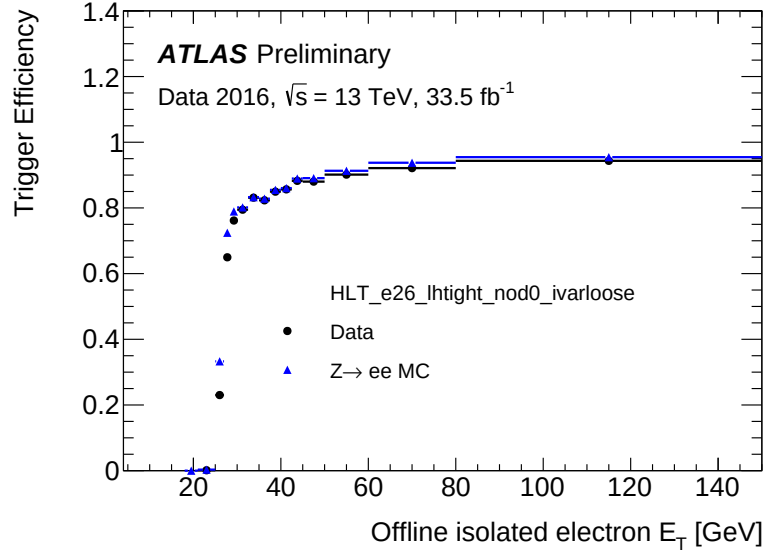


Figure 5.17: The efficiency of the `HLT_e26_lhtight_nod0_ivarloose` trigger in 2016 data is shown as a function of p_T . Note that the efficiency shown is measured with respect to only Tight identified electrons, with no offline isolation criteria applied. However, the HLT applies an isolation criteria of $p_T^{\text{varcone0.2}}/p_T < 0.1$ (as discussed in Table 5.3). As a result, the efficiency shown is slightly more pessimistic than what is used by most ATLAS analyses, which typically do require offline isolation. Regardless, the overall efficiency does not typically change significantly after isolation criteria is applied [113].

one of the single electron triggers, `HLT_e26_lhtight_nod0_ivarloose`, can be found in Figure 5.17. Ideally, the trigger efficiency measured with respect to offline identification (and isolation, when relevant) would reach 100% soon after the trigger-level p_T threshold, in which case nearly 100% of events selected at trigger-level would also be used offline. However, the `HLT_e26_lhtight_nod0_ivarloose` trigger efficiency with respect to Tight identification has an efficiency of about 80% at $p_T = 30$ GeV, and reaches 90% at $p_T = 50$ GeV. Some of these losses are due to the L1 trigger selection, as can be seen in Figure 5.18 which demonstrates the efficiency of the L1 trigger requirements used to seed the `HLT_e26_lhtight_nod0_ivarloose` trigger. At $p_T = 30$ GeV, the L1 selection is only about 80% efficient (and is therefore the primary cause of inefficiency at that p_T), while at $p_T = 50$ GeV it is nearly 99% efficient. Other losses are due to the selection performed at the HLT: Figure 5.19 shows the average inefficiency for `HLT_e26_lhtight_nod0_ivarloose` for electrons collected using a $Z \rightarrow ee$ tag-and-probe selection with typical average probe $p_T = 45$ GeV; the trigger-level likelihood-based electron identification contributes an inefficiency of about 6%, while the average inefficiency from all steps of the HLT is about 8.5% [113].

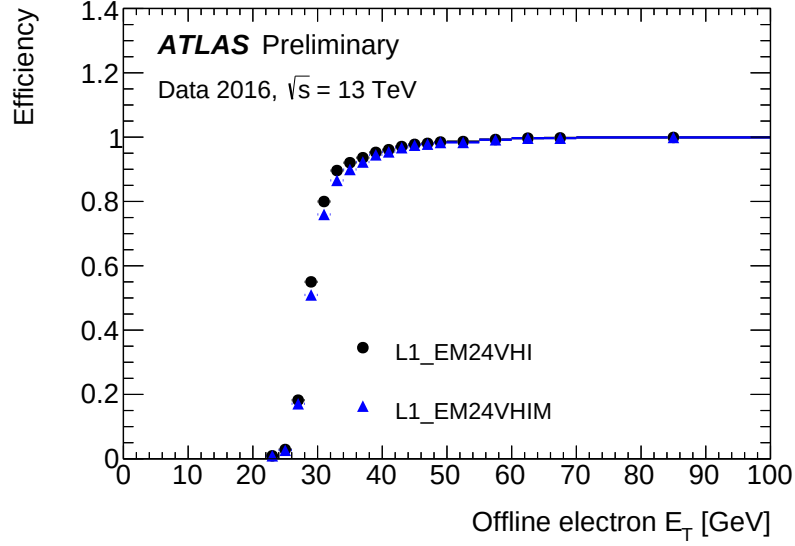


Figure 5.18: The efficiency of the L1_EM24VHI trigger in 2016 data is shown as a function of p_T , measured with respect to Tight identified electrons. While L1_EM24VHI was used to seed the `HLT_e26_lhtight_nod0_ivarloose` trigger in 2016, an additional trigger is also shown in the plot. This trigger, L1_EM24VHIM, adds a more strict isolation requirement in the L1 trigger for rate reduction purposes. This was implemented in case the trigger rates for L1_EM24VHI grew to be too large; however, L1_EM24VHI was ultimately unprescaled for all of Run 2, and thus the more strict L1 trigger was not needed [113].

One way to improve the efficiency would be to relax the trigger-level identification criteria. However, background rates would then rise. The `HLT_e26_lhtight_nod0_ivarloose` trigger collects data at a rate of nearly 90 Hz, while the total data collection rate of the ATLAS HLT is ~ 1500 Hz (as discussed in Section 3.2.5). By relaxing the electron identification criteria used at trigger-level, the p_T threshold for the lowest unprescaled single electron trigger would likely need to be increased to cope with the larger rates. The trigger rate for `HLT_e26_lhtight_nod0_ivarloose` as a function of p_T is shown in Figure 5.20. A few other options also exist for improving the trigger efficiency:

- Tighten the criteria used for the offline electron identification; this could result in tighter identification working points than desired by analyses, and would need to be performed carefully and with feedback from the ATLAS physics analysis groups.
- Improve the trigger-level reconstruction and identification to be more similar to that used offline. As mentioned in Section 4.4.6, the trigger-level electron identification uses fewer variables than offline (some of which are not used in order to allow the standard triggers to be

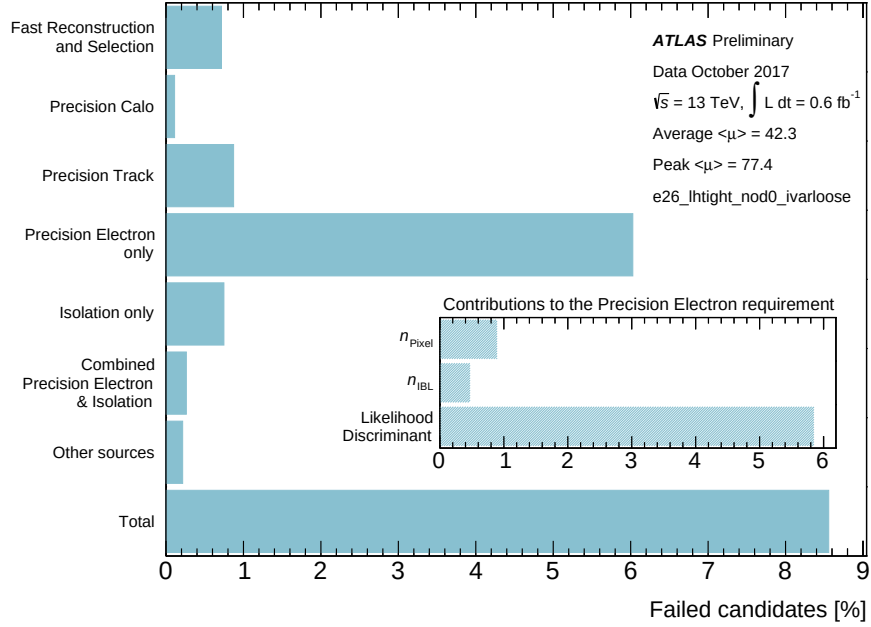


Figure 5.19: Inefficiency sources for the `HLT_e26_lhtight_nod0_ivarloose` trigger, measured with respect to Tight identification using 2017 data. Note that this is only measured in a few runs of 2017 data, and some detector conditions differ from the plots based on 2016 data shown in this section. In particular, the identification criteria used both offline and at trigger-level were reoptimized for 2017 data. The various inefficiency sources shown correspond to different steps of the HLT selection, which are described in detail in [113]. The step corresponding to the trigger-level identification criteria is categorized under “Precision Electron only”.

applicable to long-lived decays which the standard offline identification working points are not designed for, and some of which are too time intensive to currently compute at the HLT). If the resolution of the trigger-level discriminating variables were to be identical to that of the offline variables and the same quantities were used to define the identification working points both at the HLT and offline, then no inefficiencies would exist. Improvements to the resolution of the trigger-level distributions is already being attempted, e.g. by optimizing algorithms currently used offline for use in the HLT.

As unscaled triggers with higher p_T thresholds but less stringent requirements on trigger-level identification also exist, the logical OR of these triggers is usually used in ATLAS analyses. The efficiency for the combined set of single electron triggers used to collect data in 2016 is shown in Figure 5.21, and is about 5% larger than that of `HLT_e26_lhtight_nod0_ivarloose` by itself for $p_T > 60 \text{ GeV}$ (from Figure 5.17).

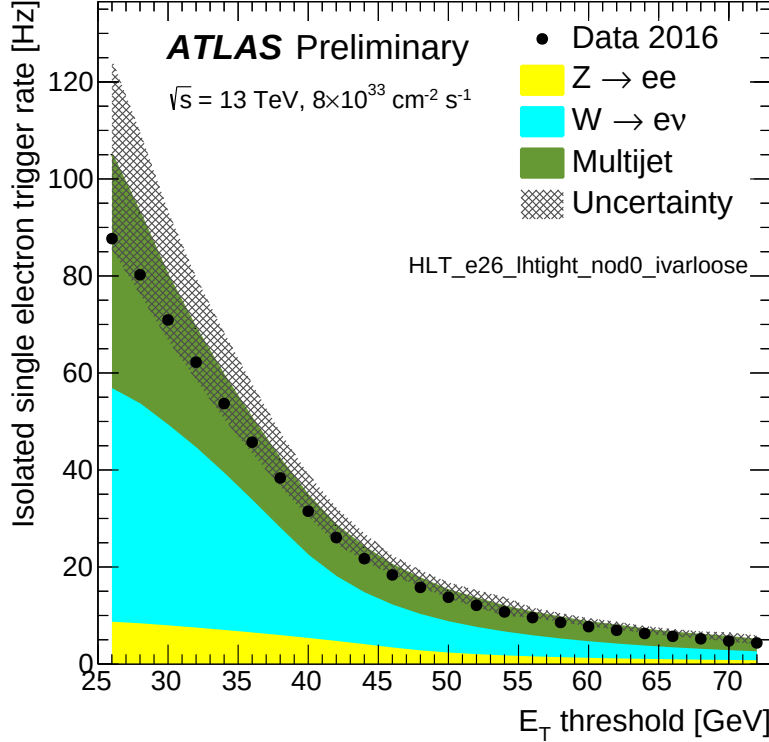


Figure 5.20: Trigger rate for HLT_e26_lhtight_nod0_ivarloose in 2016 data, shown as a function of p_T . The expected rates based on $Z \rightarrow ee$, $W \rightarrow e\nu$, and multijet simulation are shown along with the rates measured in data. The rate for this trigger decreases rapidly with p_T , from a rate of about 90 Hz at $p_T = 26 \text{ GeV}$ down to 70 Hz at $p_T = 30 \text{ GeV}$ and subsequently down to 30 Hz at $p_T = 40 \text{ GeV}$. However, both multijet production and $W \rightarrow e\nu$ contribute significantly at low p_T , and as a result it is typically desired to keep p_T thresholds as low as possible to avoid losing significant statistics of $W \rightarrow e\nu$ events [113].

5.8 Future Improvements

While the strategy used for electron efficiency measurements thus far in Run 2 has been fairly successful, there are areas to improve.

The background templates used for the Z_{mass} and Z_{iso} methods should be studied and reoptimized. These templates were last optimized at the end of Run 1, before changes to the reconstruction algorithm, identification algorithms, and detector conditions. In particular, Z_{mass} relies on inverting the Multilepton cut-based identification working point from Run 1. One of the rectangular cuts used by Multilepton is on the TRT-based variable F_{HT} , which was found to be less efficient after

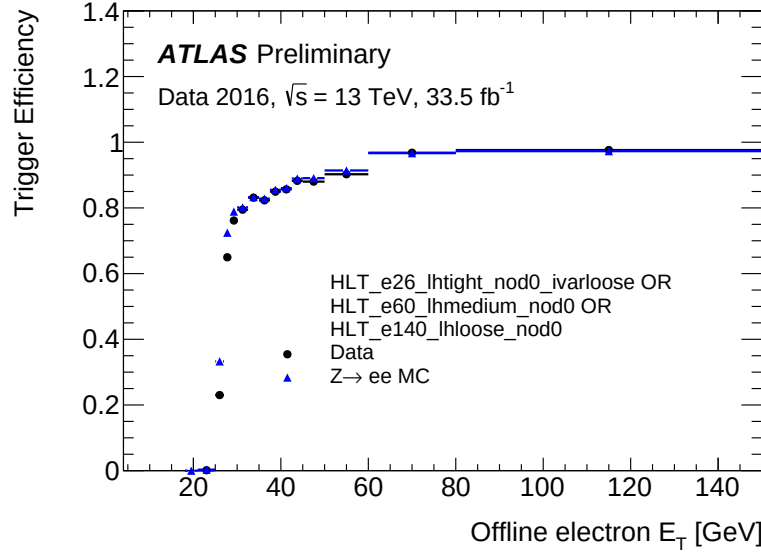


Figure 5.21: The efficiency of the logical OR of the `HLT_e26_lhtight_nod0_ivarloose`, `HLT_e60_lhmedium_nod0`, and `HLT_e140_lhloose_nod0` triggers in 2016 data is shown as a function of p_T . Note as with Figure 5.17 that the efficiency shown is measured with respect to only Tight identified electrons, while the `HLT_e26_lhtight_nod0_ivarloose` trigger applies an isolation criteria at the HLT. For $p_T > 60$ GeV, using the logical OR of the single electron triggers results in a data efficiency which is about 5% higher than using `HLT_e26_lhtight_nod0_ivarloose` by itself [113].

some of the xenon in the TRT was replaced by argon at the start of Run 2 (due to leaks discovered in the TRT). For all electron identification operating points developed since 2015, the `eProbabilityHT` variable has been used in place of F_{HT} , but `Multilepton` was never updated, and thus use of `Multilepton` for the Z_{mass} template is suboptimal. Moreover, as it is very likely that the entire TRT barrel (and possibly endcaps as well; this is still under discussion) will be filled with argon instead of xenon in Run 3, there will be no choice but to move away from templates based on the `Multilepton` operating point as it currently exists.

The reintroduction of tag-and-probe measurements using $W \rightarrow e\nu$ and $Z \rightarrow ee\gamma$ events could help by adding additional cross-checks on the existing measurements, as well as improving the statistical precision in the $10 \text{ GeV} < p_T < 20 \text{ GeV}$ range. $Z \rightarrow ee\gamma$ in particular can be a relatively simple method to implement for these purposes, and there is work in this direction already ongoing. This is less true for $W \rightarrow e\nu$ —work has proceeded in trying to implement this on ATLAS, but it tends to be more challenging due to the triggers needed to select $W \rightarrow e\nu$ events using a E_T^{miss} tag to obtain an unbiased sample of probe electrons, in addition to the complicated backgrounds present.

One of the primary goals of the electron efficiency measurements is to obtain data-to-simulation

efficiency correction factors which can be used to correct the simulated events used by ATLAS analyses; without these, all ATLAS analyses would have discrepancies of about 10% per Tight electron selected when comparing event yields in data with that of the simulation. However, instead of only correcting the efficiencies—a single number per electron—the underlying source of mismodeling could be corrected in all ATLAS analyses instead. That is, the shifts and widths to the shower shapes and tracking quantities discussed in Section 4.4.1.2 for the purposes of optimizing the electron identification operating points could additionally be used by analyses, rather than the current strategy of only using these shifts and widths for the identification optimization. In fact, this is exactly what ATLAS photon analyses already do, and correspondingly the photon data-to-simulation efficiency correction factors tend to be close to 1, as can be seen in Figure 5.22. However, doing the same for electrons on ATLAS would require detailed work to carefully measure these shifts and widths as a function of p_T and η , whereas any inaccuracies in these would currently have less of an impact. Ultimately, whether electron identification efficiencies are corrected or both the underlying variables and the efficiencies are corrected, the expected number of events for a given sample and analysis should be identical. However, it is possible that the latter strategy could allow for a reduction of the uncertainties on the electron efficiency measurements, which might make it worthwhile to pursue. An example of the efficiencies in data compared with that of simulation, both before and after applying the data-to-simulation shifts and widths, is shown in Figure 5.23.

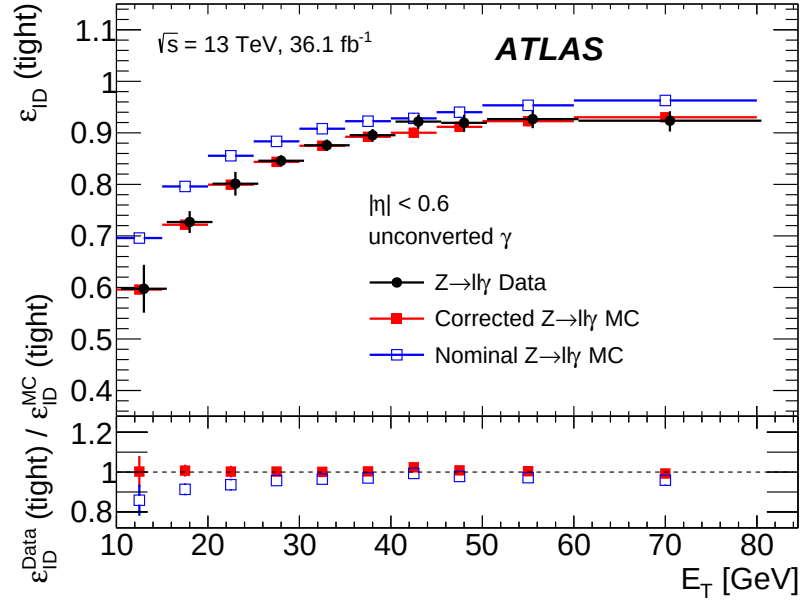


Figure 5.22: Photon identification efficiencies in data, simulation, and simulation after applying data-to-simulation shower shape corrections, measured using $Z \rightarrow \ell\ell\gamma$ events [73]. The data-to-simulation efficiency correction factors tend to be close to 1 after applying the shower shape corrections, as can be seen in the bottom panel.

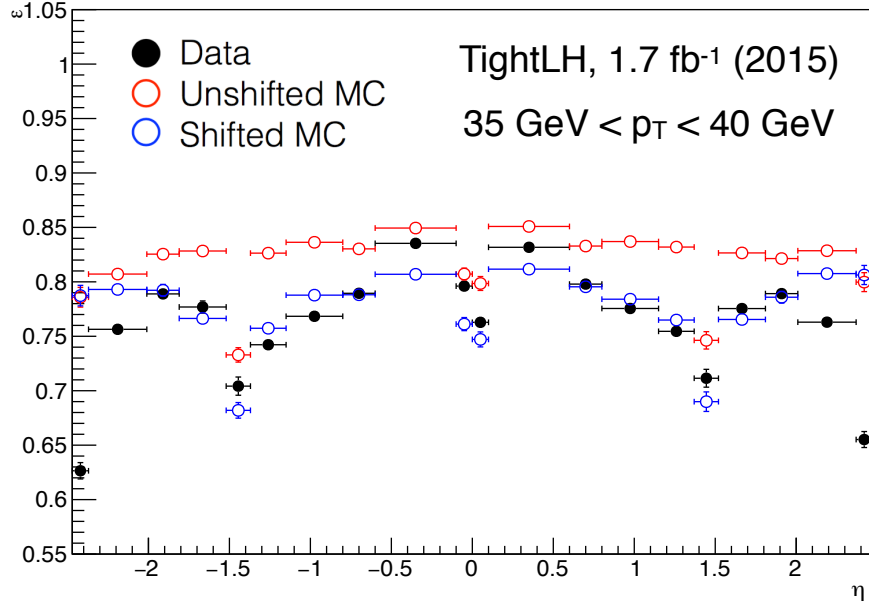


Figure 5.23: Example Z_{mass} -based electron identification efficiencies in data compared with that of simulation, both before and after applying the data-to-simulation shifts and widths. After applying the shifts and widths, a smaller data-to-simulation efficiency correction factor is necessary for most bins.

CHAPTER 6

Electroweak Production of Supersymmetric Particles

“Whether SUSY is there or not is neither Glashow’s nor Weinberg’s nor my choice. It’s a fact that only nature has decided. We are just there to pick up the response.”

— Carlo Rubbia [114]

6.1 Motivation to Search for Electroweak SUSY

As described in Section 2.2, SUSY predicts superpartners for each Standard Model state. This means that if SUSY is realized in nature, there are many new particles yet to be discovered. Since the supersymmetric particles are expected to have masses near the weak scale in order for SUSY to provide a solution to the hierarchy problem, one should expect many of the predicted sparticles to have masses which are sufficiently light to be produced at the LHC. Moreover, the predicted cross-sections for some of these sparticles are expected to be large at the LHC, as can be seen in Figure 6.1. However, while the strongly-produced gluinos ($\tilde{g}$) and squarks ($\tilde{q}$) have the largest production cross-sections at low masses, they also have some of the most stringent experimental limits at this time, as seen in Figures 6.2 through 6.4. Electroweak production of SUSY particles, meanwhile, tends to have much weaker limits due to the much smaller cross-sections of these sparticles. The ATLAS limits on the SUSY partners of the Standard Model electroweak bosons (electroweakinos) from Run 1 can be seen in Figure 6.5. This shows that by the start of Run 2, ATLAS had only placed limits on electroweakino NLSPs up to 425 GeV in scenarios with massless LSPs, and plenty of phase space was uncovered for scenarios with LSPs as light as 100 GeV. Note for all of the limit plots shown that simplified models are assumed, which are not always representative of real models of SUSY. Also note that in this thesis, R-parity conservation is always assumed (and thus the LSP is a stable

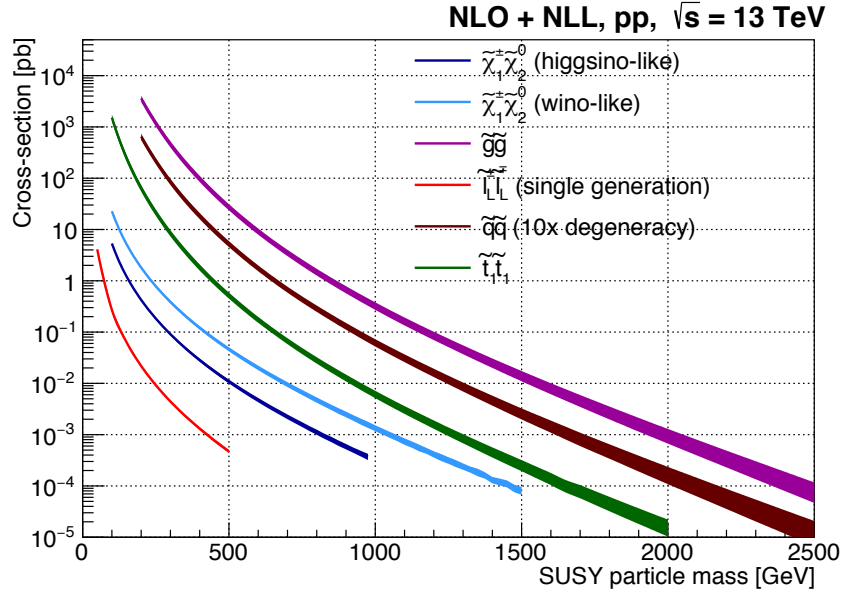


Figure 6.1: The predicted production cross-sections of various SUSY particles at $\sqrt{s} = 13$ TeV is shown as a function of the sparticle mass [115]. For reference, the cross-sections of the Standard Model processes (as measured by ATLAS, as well as the predicted values) can be found in Figure 2.2.

particle), though this need not be the case in general.

Additional motivation for searching for EWK SUSY comes from the various models which one can study. The neutralino and chargino mixing matrices, discussed in Section 2.2, can be examined in various regimes of M_1 , M_2 , and μ to study the potential SUSY scenarios and their physical implications on naturalness, dark matter, and other phenomena. The “wino-bino” and “Higgsino LSP” simplified models will be the primary focus, though Section 8.8 will discuss others as well.

In the wino-bino simplified model, $|M_1| < |M_2| \ll |\mu|$. This results in a bino-like $\tilde{\chi}_1^0$ LSP, while the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ NLSPs are wino-like. The Higgsino component is decoupled due to the large value of μ . This model is well motivated by dark matter coannihilation arguments [1, 117, 118] because the wino production cross-section is relatively large while the bino interaction cross-section is small, allowing these particles to satisfy dark matter relic density constraints. In such scenarios, the LSP serves as the dark matter candidate.

Using Equations 2.5 and 2.9, the neutralino and chargino masses can be computed in the limit

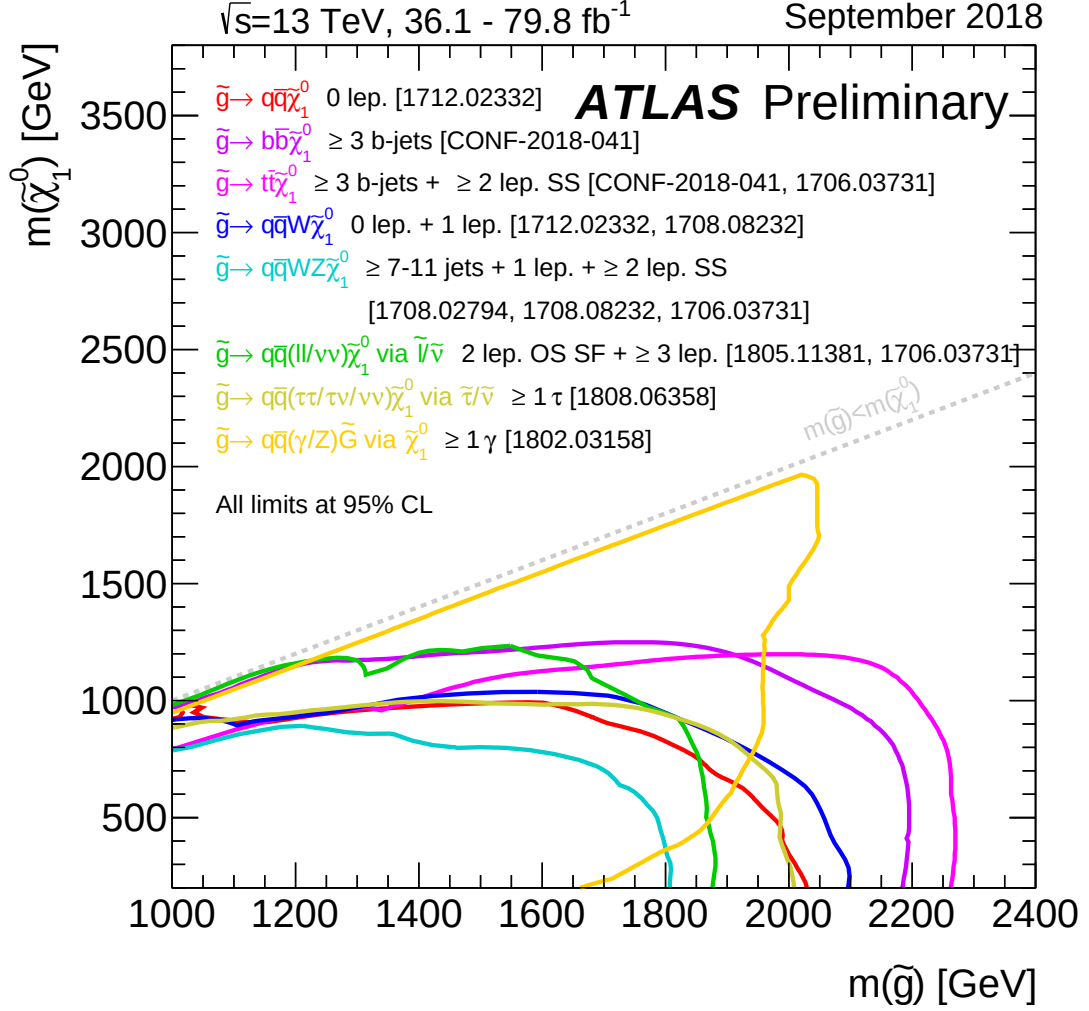


Figure 6.2: ATLAS exclusion limits on gluinos, shown at 95% confidence level based on 13 TeV data as of September 2018. These limits are shown as a function of the gluino mass on the x-axis and as a function of the LSP mass on the y-axis. The various limit curves displayed correspond to different decay modes searched for in dedicated analyses. Assumptions are made on the gluino branching ratios as well as the masses of intermediate states that may be present in the decay chains considered, and these assumptions can be found in the references shown in the plot [116]

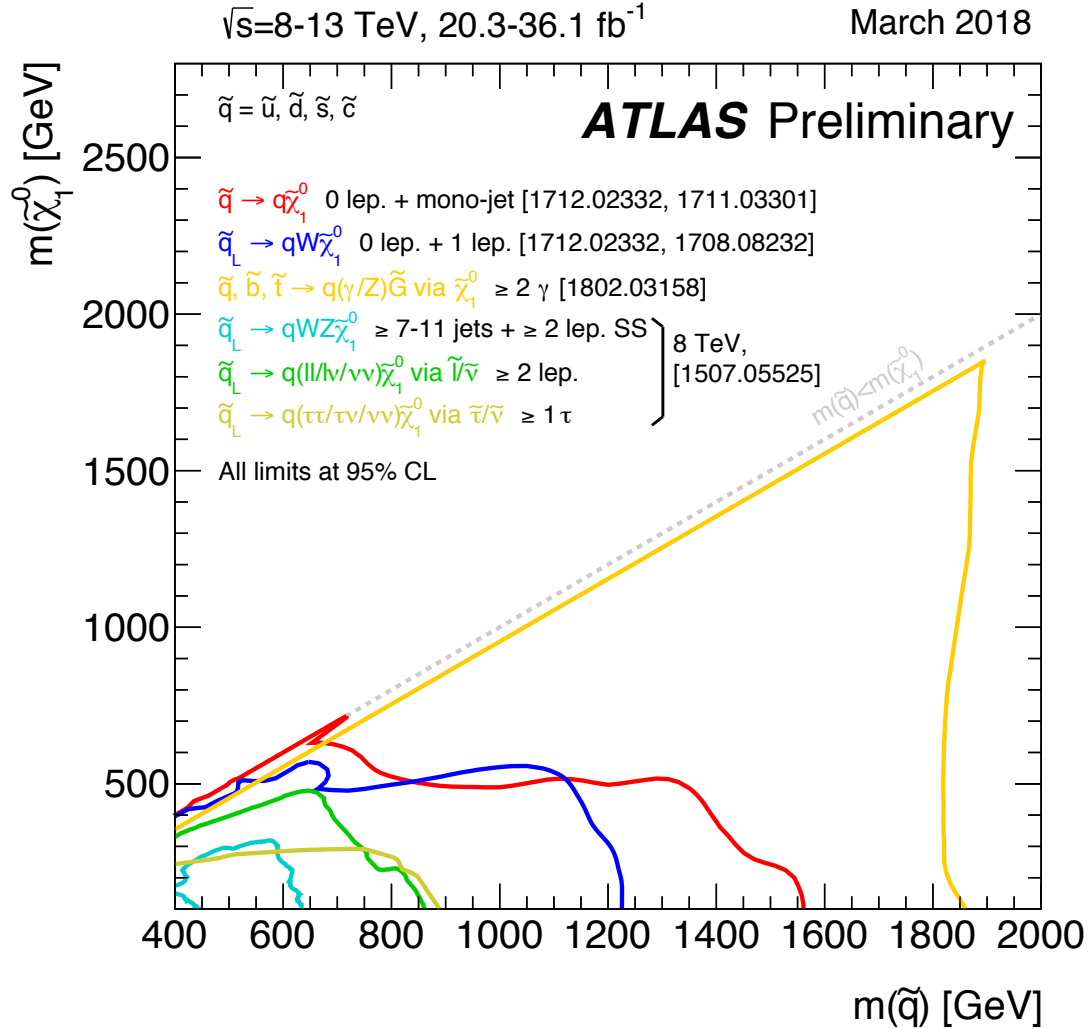


Figure 6.3: ATLAS exclusion limits on squarks, shown at 95% confidence level based on 8 TeV and 13 TeV data as of March 2018. These limits are shown as a function of the squark mass on the x-axis and as a function of the LSP mass on the y-axis. The various limit curves displayed correspond to different decay modes searched for in dedicated analyses. Assumptions are made on the squark branching ratios as well as the masses of intermediate states that may be present in the decay chains considered, and these assumptions can be found in the references shown in the plot [116]

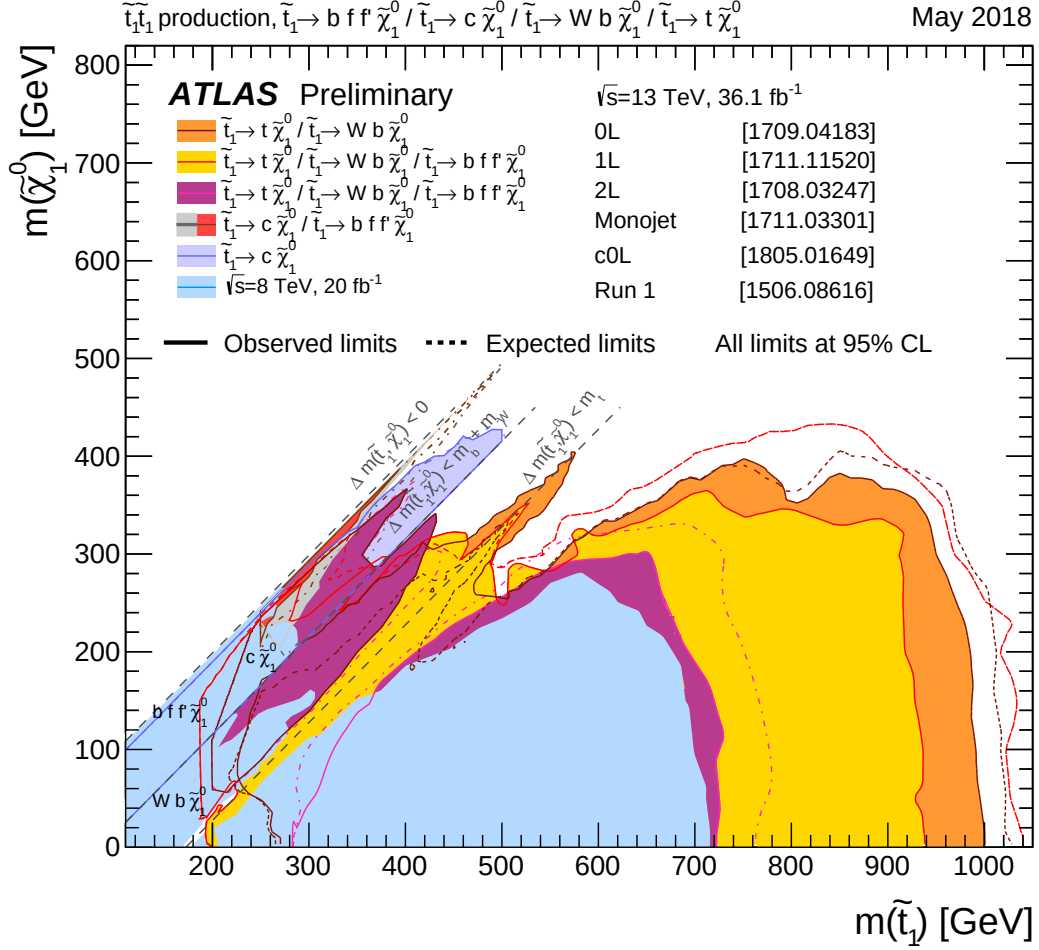


Figure 6.4: ATLAS exclusion limits on stops, shown at 95% confidence level based on 13 TeV data as of May 2018. These limits are shown as a function of the stop mass on the x-axis and as a function of the LSP mass on the y-axis. The various limit curves displayed correspond to different decay modes searched for in dedicated analyses. Assumptions are made on the stop branching ratios as well as the masses of intermediate states that may be present in the decay chains considered, and these assumptions can be found in the references shown in the plot [116]

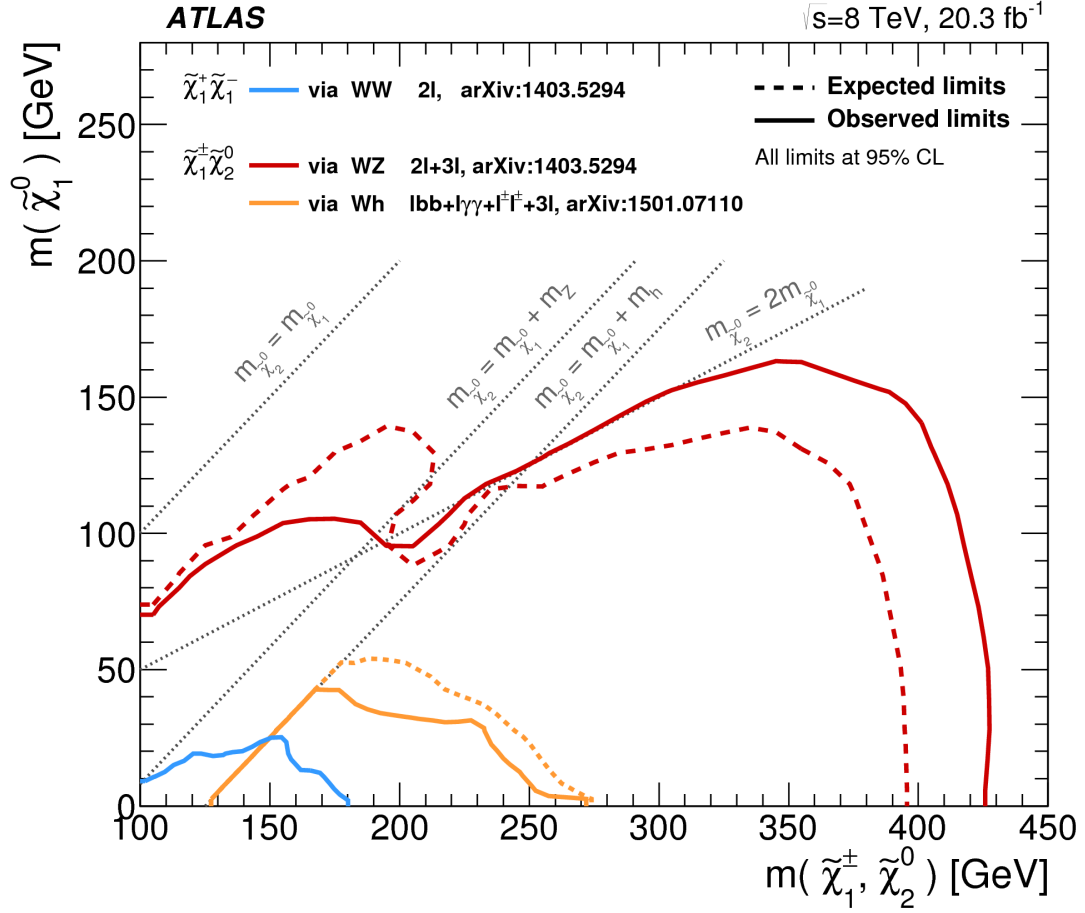


Figure 6.5: ATLAS exclusion limits on electroweakinos, shown at 95% confidence level based on 8 TeV data as of October 2015. These limits are shown as a function of the NLSP mass on the x-axis and as a function of the LSP mass on the y-axis. The $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are the NLSPs, and are assumed to be mass degenerate. These NLSPs are assumed to be pure wino states, and thus use the wino production cross-sections. The various limit curves displayed correspond to different decay modes searched for in dedicated analyses. Assumptions are made on the electroweakino branching ratios, and these assumptions can be found in the references shown in the plot [116]

of the wino-bino scenario to be:

$$\begin{aligned}
m_{\tilde{\chi}_1^0} &= M_1 - \frac{m_Z^2 s_W (M_1 + \mu \sin 2\beta)}{\mu^2 - M_1^2} + \dots \\
m_{\tilde{\chi}_2^0} &= M_2 - \frac{m_W^2 (M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} + \dots \\
m_{\tilde{\chi}_1^\pm} &= M_2 - \frac{m_W^2 (M_2 + \mu \sin 2\beta)}{\mu^2 - M_2^2} + \dots
\end{aligned} \tag{6.1}$$

One should notice that $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ here. While this need not be true in general, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are mass-degenerate in the wino-bino scenario [50], and are generated as such in any wino-bino simulation samples discussed in this thesis.

The Higgsino LSP simplified model is motivated by naturalness arguments. In this scenario, $|\mu| \ll |M_1|, |M_2|$. At tree-level in the MSSM, the Higgs mass is related to the Higgsino mass parameter μ by:

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2. \tag{6.2}$$

Thus at tree-level it is expected for μ to be at the weak scale to satisfy constraints from naturalness. In this scenario, the Higgsino mass is at the weak scale, while M_1 and M_2 are much larger (e.g. $\mathcal{O}(\text{TeV})$). In the limit of the Higgsino LSP scenario, Equations 2.5 and 2.9 can be examined in two separate scenarios for simplicity [119]:

1. Heavy bino: $|M_2| \ll |M_1|$
2. Heavy wino: $|M_1| \ll |M_2|$.

In the first case, the mass differences between the neutralinos and charginos are:

$$\begin{aligned}
m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} &\approx \frac{m_W^2 (1 \mp \sin 2\beta)}{2(M_2 + |\mu|)} \\
m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^\pm} &\approx \frac{m_W^2 (1 \pm \sin 2\beta)}{2(M_2 - |\mu|)} \\
m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} &\approx \frac{m_W^2 (\pm |\mu| \sin 2\beta + M_2)}{M_2^2 - |\mu|^2}
\end{aligned} \tag{6.3}$$

while in the second case the mass differences are:

$$\begin{aligned}
m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} &\approx \frac{m_W^2 \tan^2 \theta_W (1 \pm \sin 2\beta)}{2(M_1 - |\mu|)} \\
m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^\pm} &\approx \frac{m_W^2 \tan^2 \theta_W (1 \mp \sin 2\beta)}{2(M_1 + |\mu|)} \\
m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} &\approx \frac{m_W^2 \tan^2 \theta_W (\pm |\mu| \sin 2\beta + M_1)}{M_1^2 - |\mu|^2}.
\end{aligned} \tag{6.4}$$

As a result of these limiting cases, the mass difference between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ in the Higgsino LSP scenario is:

$$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx \begin{cases} \frac{m_W^2}{M_2}, & \text{for } |M_2| \ll |M_1|, \\ \frac{m_W^2 \tan^2 \theta_W}{M_1}, & \text{for } |M_1| \ll |M_2|, \end{cases} \quad (6.5)$$

where $\tan^2 \theta_W \approx 0.275$ [68]. Based on Equation 6.5, if one were to assume a value of 1 TeV for $\min(M_1, M_2)$ then the mass splitting between the two lightest neutralinos would be 1.8–6.5 GeV, and the mass splitting would be even smaller for larger values of $\min(M_1, M_2)$. These “compressed” mass spectra for $\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_2^0$ are generically true in the Higgsino LSP simplified model for these light electroweakino states dominated by the Higgsino component. Typical compressed mass spectra have mass splittings on the order 100s of MeV to tens of GeV, depending on the precise values of M_1 and M_2 . One can further examine Equations 6.3 and 6.4 to note that $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \approx 2(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})$; in other words, the $\tilde{\chi}_1^\pm$ mass is halfway between that of the $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ in the Higgsino LSP scenario. This convention for the relationship between the $\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_2^0$ masses is used in all simulation samples for the Higgsino LSP simplified model discussed in this thesis.

Searching for compressed spectra can be challenging as the final decay products tend to have small p_T , and thus are nontrivial to observe in the ATLAS detector; this will be discussed in further detail in Chapter 8. Furthermore, the cross-section for Higgsino production is roughly four times smaller than that of wino production, as seen in Figure 6.1, which makes searches for Higgsino production even more challenging.

6.2 Signatures of Electroweak SUSY Decays

To search for signatures of SUSY, “signal regions” (SRs) are constructed which select events which are characteristic of the signal model of interest while suppressing background events. These SRs are developed in a “blind” manner using only models for the signal and background events. Only after the backgrounds are well-understood in the SR are the regions “unblinded”, at which time the data is examined to see whether or not it agrees with the background model. The extent to which the data and background agree dictates how strong of limits are set on the signal model of interest. Naturally, if there is an excess of data events relative to the number of background events, the excess is then quantified to determine how significant the excess is, and whether or not it could point to signs of new physics.

In all of the EWK SUSY models considered in this thesis, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^0$ particles are directly produced, typically via an off-shell W or Z . The $\tilde{\chi}_1^0$ is stable due to R-parity conservation, while

$\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ decay via $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^\pm$. Other decays are also possible (including $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$), though some are suppressed by the masses of the particles involved (e.g. when $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are nondegenerate, $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^\pm W^\mp$ is allowed but very suppressed unless $\tilde{\chi}_2^0$ is much heavier than the decay products).

Fully hadronic final states are possible when the W or Z decay hadronically. However, light leptons (electrons and muons) tend to be a powerful signature in searches as there are far fewer potential background sources which contain leptons compared with those which contain jets. As a result, the focus in this thesis is on searches in the dilepton and trilepton final states.

Finally, thanks to the stable $\tilde{\chi}_1^0$ which does not interact with the detector, the signatures considered also contain E_T^{miss} , which further helps to distinguish signal from the Standard Model backgrounds. Of course, the final states considered always contain two LSPs—which will typically be produced back-to-back, thus canceling one another’s potential E_T^{miss} signature on average. In some signal regions an initial state radiation (ISR) jet is therefore required to provide something for the LSPs to recoil against, resulting in a large E_T^{miss} signature.

6.3 Background Estimation Strategy

Two categories of background processes exist: irreducible backgrounds and reducible backgrounds.

Irreducible backgrounds contain prompt leptons and real E_T^{miss} (from neutrinos which do not interact with the detector). These irreducible Standard Model backgrounds are typically estimated using simulated events. The simulation tends to describe prompt leptons and real E_T^{miss} well, and often have sufficient statistics for background estimation in analyses. These simulated events are corrected for object-level discrepancies with respect to the data (such as the electron efficiency correction factors described in Chapter 5). To further constrain individual background sources in case the simulation is inaccurate in a particular region of phase space relevant to a given analysis, dedicated “control regions” (CRs) are designed to normalize the simulation to the data. In order to be useful, these CRs are chosen to be disjoint from the SRs, must be enriched in the background process of interest, need to have reasonable statistics to avoid large statistical uncertainties on the normalization factors, require minimal signal contamination (from the model of interest as well as any other potential signal models), and must exhibit similar kinematic properties as the SRs. CRs can exist for several background sources in a given analysis; all of the CRs are then used to extract the data-to-simulation normalization factors using a simultaneous fit to the data. The background modeling after normalization is then validated in dedicated “validation regions” (VRs) which also

have similar kinematic properties to the SRs but are only used to validate the performance of the background modeling. ATLAS SUSY analyses typically use the `HistFitter` package [120] to perform the simultaneous likelihood fits to the CRs and SRs, as well as to perform the statistical interpretation of the results. Systematic uncertainties are treated as nuisance parameters in the likelihood fit.

Reducible backgrounds contain events which would not serve as backgrounds for a given analysis if the detector was perfect; ideally fake and nonprompt leptons would always be vetoed by the lepton selection algorithms, while detector mismeasurements that can affect the E_T^{miss} calculation would never occur. Of course, the detector is not perfect, and these reducible backgrounds serve as challenges which ATLAS analyses must overcome. Fake leptons in particular are discussed in detail in the following section.

6.4 Fake Lepton Backgrounds

Fake and nonprompt leptons frequently serve as challenging backgrounds to constrain in ATLAS analyses. “Fake” leptons arise when a hadron is incorrectly reconstructed and identified as an electron or muon. Relative to the number of hadrons produced, this tends to be a rare occurrence since the majority of hadrons passing through the ATLAS detector result in very different signatures compared to the signatures of leptons. However, the fact that the LHC is a high energy pp collider means the production rates of hadrons is many orders of magnitude larger than that of processes which result in leptonic final states, and thus these fake leptons can still serve as a significant source of background. Figure 6.6 shows example diagrams for two processes which can look nearly identical when a jet fakes a lepton.

Similarly, “nonprompt” leptons resulting from semileptonic decays of heavy flavor hadrons and photon conversions are typically suppressed by the lepton identification and isolation algorithms. Ideally, these processes are to be considered as b -jets and photons in ATLAS analyses—however, as these do ultimately decay to real leptons after traveling through the detector for some time, it is possible for such processes to be incorrectly labeled as electrons or muons.

Collectively, fake and nonprompt leptons are often simply referred to as fake leptons. While this nomenclature is not strictly correct for the reasons outlined above, it is often sufficient since fake and nonprompt leptons can be estimated simultaneously and serve as background sources for similar reasons.

Fake leptons tend to be poorly modeled in simulation, particularly because the composition of

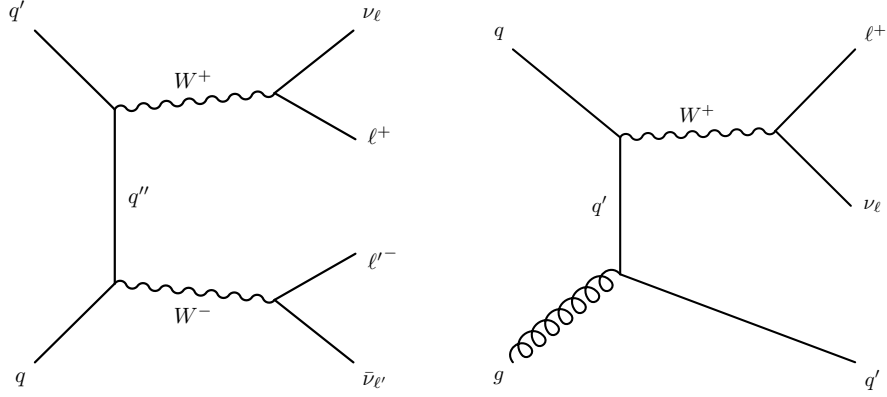


Figure 6.6: Diagrams for the WW (left) and W +jet (right) processes. When the jet in the W +jet is misidentified as a lepton, these two processes can be nearly indistinguishable.

the various sources of fake leptons is difficult to model properly. As a result, data-driven techniques are often used for estimating reducible backgrounds from fake leptons. However, the rarity at which fake leptons occur relative to the production rates of hadrons and other fake lepton sources means the misidentification rates are difficult to accurately measure, and thus these data-driven estimates can often have large uncertainties—though they are smaller than the uncertainties that would typically be necessary when using the poorly modeled simulation for the fake lepton estimates.

One commonly used technique for fake lepton estimation, the “fake factor” (FF) method, is described in Section 6.4.1.

6.4.1 The Fake Factor Method

As nomenclature, several categories of lepton identification are defined for use in the fake factor method:

- “baseline”, referring to a criteria which all other leptons considered must satisfy,
- “signal”, “ID”, or “tight”, which satisfy the signal lepton criteria used to select leptons in the analysis,
- “loose” or “anti-ID”, which satisfy a relaxed criteria enriched in fake leptons. The loose criteria is (typically) a subset of the baseline, but is **disjoint** from the tight criteria.

The labels N_T and N_L are used to refer to the total number of events with a tight or loose lepton, respectively. For events with more than one lepton, labels such as N_{TT} , N_{TL} , N_{LT} , and N_{LL} are used, where the labeling of the leptons is often ordered by decreasing p_T , but any criteria for the ordering is possible (and will be specified when appropriate). Meanwhile, the labels N^R and N^F are used to denote the total number of events with true prompt or fake leptons, respectively (where “R” denotes “real”), and similar for events with multiple leptons (e.g. N^{RR} , N^{RF} , N^{FR} , N^{FF} , etc.).

The efficiency, measured with respect to all prompt baseline leptons, for a prompt lepton to satisfy the tight or loose criteria is denoted ε^R or $\bar{\varepsilon}^R$ (respectively). The same notation is used for the fake leptons, where ε^F and $\bar{\varepsilon}^F$ denote the efficiencies for fake leptons to satisfy the tight or loose criteria (as measured with respect to all fake baseline leptons).

Note that the fake factor method sometimes refers to signal leptons as “numerator” leptons, and sometimes refers to anti-ID leptons as “denominator” leptons, and the notation is used interchangeably at times.

6.4.1.1 One Lepton Case

In the one lepton case, one can generically relate the number of prompt and fake leptons to the number of tight and loose leptons via the equation:

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \varepsilon^R & \varepsilon^F \\ \bar{\varepsilon}^R & \bar{\varepsilon}^F \end{pmatrix} \begin{pmatrix} N^R \\ N^F \end{pmatrix}. \quad (6.6)$$

Put differently, the number of tight leptons is equal to the number of tight prompt leptons plus the number of tight fake leptons, while the number of loose leptons is equal to the number of loose prompt leptons plus the number of loose fake leptons. Note that the number of prompt baseline leptons is *not* strictly equal to the number of prompt tight leptons plus the number of prompt loose leptons, as a third category also exists, namely the “missing” leptons which satisfy the baseline criteria but do not satisfy the loose or tight criteria. However, there is a “special case” which can be considered, where the loose criteria is chosen to be all of the baseline leptons which fail the tight criteria. In this special case, the number of prompt baseline leptons is equal to the number of prompt tight leptons plus the number of prompt loose leptons, and thus $\bar{\varepsilon}^R = (1 - \varepsilon^R)$ and $\bar{\varepsilon}^F = (1 - \varepsilon^F)$. In general, these equalities need not be true.

The goal of the fake factor method is to obtain the number of fake tight leptons, N_T^F . It is possible to reduce Equation 6.6 into a single analytic equation by multiplying both sides by the row

vector:

$$\begin{pmatrix} 1 & -\frac{\varepsilon^F}{\bar{\varepsilon}^F} \end{pmatrix}. \quad (6.7)$$

This results in:

$$N_T - \frac{\varepsilon^F}{\bar{\varepsilon}^F} N_L = \varepsilon^R N^R + \varepsilon^F N^F - \frac{\varepsilon^F}{\bar{\varepsilon}^F} \bar{\varepsilon}^R N^R - \frac{\varepsilon^F}{\bar{\varepsilon}^F} \bar{\varepsilon}^F N^F. \quad (6.8)$$

The fake factor is defined as $F = \frac{\varepsilon^F}{\bar{\varepsilon}^F}$. After making this substitution in the above equation and canceling terms, the result is:

$$N_T - F N_L = \varepsilon^R N^R - F \bar{\varepsilon}^R N^R. \quad (6.9)$$

Equivalently, the additional substitutions $\bar{\varepsilon}^R N^R = N_L^R$ and $\varepsilon^R N^R = N_T^R$ can be made, resulting in:

$$N_T^F = N_T - N_T^R = F(N_L - N_L^R), \quad (6.10)$$

where N_T^R represents the number of prompt tight leptons and N_L^R represents the number of prompt loose leptons. Thus the reducible background estimate for the number of tight fake leptons N_T^F in a given signal/validation/control region can be determined by computing the fake factor F , the number of loose leptons N_L for the given region (as measured in data), and the number of loose prompt leptons N_L^R in the given region (which must be estimated using simulation). This method relies on the fake factor $F = \frac{\varepsilon^F}{\bar{\varepsilon}^F}$, that is, the ratio of tight to loose leptons as measured in a separate region which is very pure in fake leptons. After measuring this ratio, the assumption is made that F in the fake factor measurement region is identical to what it would be if it could be measured in the signal/validation/control region; this motivates the use of a fake factor measurement region which is kinematically similar to the signal region, when possible. Systematic uncertainties on the fake lepton background prediction are designed to account for differences between these regions, particularly differences in the fake lepton background composition. Note that the region which is identical to the signal/validation/control region except for the presence of one or more anti-ID leptons in place of signal leptons is often referred to as the “anti-ID control region”.

While a fake factor measurement region that is 100% pure in fake leptons may not exist, an attempt is typically made to find a region which is still relatively pure in fake leptons. Example fake factor measurement regions include regions of phase space dominated by Z +jets/ Z + γ events (where the leptonic Z decay is used to tag the event while the jet or photon is used as the fake lepton candidate) or dijet events (typically collected using prescaled lepton triggers with loose lepton identification and possibly no isolation requirements at trigger-level); these two regions are discussed in further detail in Sections 7.5.1.1 and 8.5.1.1. Simulation is then used to remove contamination

in the fake factor measurement region due to prompt leptons. Thus in reality, the fake factor takes the form:

$$F = \frac{N_{\text{T, data}}(i) - N_{\text{T, prompt MC}}(i)}{N_{\text{L, data}}(i) - N_{\text{L, prompt MC}}(i)}, \quad (6.11)$$

where i refers to the i^{th} bin that the fake factor may be parameterized in. Binning the fake factor is typically necessary as the ratio of tight to loose leptons can vary significantly with lepton p_{T} . Other potential parameterizations such as $n_{b\text{-jets}}$ and lepton η are also used when needed; alternatively if statistics are too poor to parameterize the measured fake factors in several variables, the kinematic dependence of the fake factors can be used as a systematic uncertainty. Additionally, as the subtraction of prompt leptons during the fake factor measurement can be subject to inaccuracies due to imperfect simulation, an uncertainty is usually assigned to this too. This uncertainty on the prompt subtraction can be based on any known cross-section uncertainties for the primary processes which contaminate this region, known discrepancies between theory and experiment, or the normalization factors derived in particular kinematic regions relevant to the analysis.

6.4.1.2 Two Lepton Case

The relationship between prompt, fake, tight, and loose leptons in two lepton events is the equation:

$$\begin{pmatrix} N_{\text{TT}} \\ N_{\text{LT}} \\ N_{\text{TL}} \\ N_{\text{LL}} \end{pmatrix} = \begin{pmatrix} \varepsilon_1^{\text{R}} \varepsilon_2^{\text{R}} & \varepsilon_1^{\text{F}} \varepsilon_2^{\text{R}} & \varepsilon_1^{\text{R}} \varepsilon_2^{\text{F}} & \varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}} \\ \bar{\varepsilon}_1^{\text{R}} \varepsilon_2^{\text{R}} & \bar{\varepsilon}_1^{\text{F}} \varepsilon_2^{\text{R}} & \bar{\varepsilon}_1^{\text{R}} \varepsilon_2^{\text{F}} & \bar{\varepsilon}_1^{\text{F}} \varepsilon_2^{\text{F}} \\ \varepsilon_1^{\text{R}} \bar{\varepsilon}_2^{\text{R}} & \varepsilon_1^{\text{F}} \bar{\varepsilon}_2^{\text{R}} & \varepsilon_1^{\text{R}} \bar{\varepsilon}_2^{\text{F}} & \varepsilon_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}} \\ \bar{\varepsilon}_1^{\text{R}} \bar{\varepsilon}_2^{\text{R}} & \bar{\varepsilon}_1^{\text{F}} \bar{\varepsilon}_2^{\text{R}} & \bar{\varepsilon}_1^{\text{R}} \bar{\varepsilon}_2^{\text{F}} & \bar{\varepsilon}_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}} \end{pmatrix} \begin{pmatrix} N^{\text{RR}} \\ N^{\text{FR}} \\ N^{\text{RF}} \\ N^{\text{FF}} \end{pmatrix}. \quad (6.12)$$

As with the one lepton case, a row vector can be used to simplify this system of linear equations.

The row vector used is:

$$\left(1 \quad -\frac{\varepsilon_1^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}}} \quad -\frac{\varepsilon_2^{\text{F}}}{\bar{\varepsilon}_2^{\text{F}}} \quad \frac{\varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}}} \right). \quad (6.13)$$

For completeness, this will be worked out in full. However, the reader will note that all terms in the matrix will ultimately cancel except for the first column, which is why the chosen row vector is

so convenient:

$$N_{\text{TT}} - \frac{\varepsilon_1^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}}} N_{\text{LT}} - \frac{\varepsilon_2^{\text{F}}}{\bar{\varepsilon}_2^{\text{F}}} N_{\text{TL}} + \frac{\varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}}} N_{\text{LL}} = \quad (6.14)$$

$$\varepsilon_1^{\text{R}} \varepsilon_2^{\text{R}} N^{\text{RR}} + \varepsilon_1^{\text{F}} \varepsilon_2^{\text{R}} N^{\text{FR}} + \varepsilon_1^{\text{R}} \varepsilon_2^{\text{F}} N^{\text{RF}} + \varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}} N^{\text{FF}} \quad (6.15)$$

$$- \frac{\varepsilon_1^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}}} (\bar{\varepsilon}_1^{\text{R}} \varepsilon_2^{\text{R}} N^{\text{RR}} + \bar{\varepsilon}_1^{\text{F}} \varepsilon_2^{\text{R}} N^{\text{FR}} + \bar{\varepsilon}_1^{\text{R}} \varepsilon_2^{\text{F}} N^{\text{RF}} + \bar{\varepsilon}_1^{\text{F}} \varepsilon_2^{\text{F}} N^{\text{FF}}) \quad (6.16)$$

$$- \frac{\varepsilon_2^{\text{F}}}{\bar{\varepsilon}_2^{\text{F}}} (\varepsilon_1^{\text{R}} \bar{\varepsilon}_2^{\text{R}} N^{\text{RR}} + \varepsilon_1^{\text{F}} \bar{\varepsilon}_2^{\text{R}} N^{\text{FR}} + \varepsilon_1^{\text{R}} \bar{\varepsilon}_2^{\text{F}} N^{\text{RF}} + \varepsilon_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}} N^{\text{FF}}) \quad (6.17)$$

$$+ \frac{\varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}}} (\bar{\varepsilon}_1^{\text{R}} \bar{\varepsilon}_2^{\text{R}} N^{\text{RR}} + \bar{\varepsilon}_1^{\text{F}} \bar{\varepsilon}_2^{\text{R}} N^{\text{FR}} + \bar{\varepsilon}_1^{\text{R}} \bar{\varepsilon}_2^{\text{F}} N^{\text{RF}} + \bar{\varepsilon}_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}} N^{\text{FF}}). \quad (6.18)$$

This then simplifies to:

$$N_{\text{TT}} - \frac{\varepsilon_1^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}}} N_{\text{LT}} - \frac{\varepsilon_2^{\text{F}}}{\bar{\varepsilon}_2^{\text{F}}} N_{\text{TL}} + \frac{\varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}}} N_{\text{LL}} = \quad (6.19)$$

$$\varepsilon_1^{\text{R}} \varepsilon_2^{\text{R}} N^{\text{RR}} + \varepsilon_1^{\text{F}} \varepsilon_2^{\text{R}} N^{\text{FR}} + \varepsilon_1^{\text{R}} \varepsilon_2^{\text{F}} N^{\text{RF}} + \varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}} N^{\text{FF}} \quad (6.20)$$

$$- (F_1 \bar{\varepsilon}_1^{\text{R}} \varepsilon_2^{\text{R}} N^{\text{RR}} + \bar{\varepsilon}_1^{\text{F}} \varepsilon_2^{\text{R}} N^{\text{FR}} + F_1 \bar{\varepsilon}_1^{\text{R}} \varepsilon_2^{\text{F}} N^{\text{RF}} + \varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}} N^{\text{FF}}) \quad (6.21)$$

$$- (F_2 \varepsilon_1^{\text{R}} \bar{\varepsilon}_2^{\text{R}} N^{\text{RR}} + F_2 \varepsilon_1^{\text{F}} \bar{\varepsilon}_2^{\text{R}} N^{\text{FR}} + \varepsilon_1^{\text{R}} \bar{\varepsilon}_2^{\text{F}} N^{\text{RF}} + \varepsilon_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}} N^{\text{FF}}) \quad (6.22)$$

$$+ (F_1 F_2 \bar{\varepsilon}_1^{\text{R}} \bar{\varepsilon}_2^{\text{R}} N^{\text{RR}} + F_2 \varepsilon_1^{\text{F}} \bar{\varepsilon}_2^{\text{R}} N^{\text{FR}} + F_1 \bar{\varepsilon}_1^{\text{R}} \varepsilon_2^{\text{F}} N^{\text{RF}} + \varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}} N^{\text{FF}}). \quad (6.23)$$

By canceling terms, this becomes:

$$N_{\text{TT}} - \frac{\varepsilon_1^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}}} N_{\text{LT}} - \frac{\varepsilon_2^{\text{F}}}{\bar{\varepsilon}_2^{\text{F}}} N_{\text{TL}} + \frac{\varepsilon_1^{\text{F}} \varepsilon_2^{\text{F}}}{\bar{\varepsilon}_1^{\text{F}} \bar{\varepsilon}_2^{\text{F}}} N_{\text{LL}} = \quad (6.24)$$

$$\varepsilon_1^{\text{R}} \varepsilon_2^{\text{R}} N^{\text{RR}} - (F_1 \bar{\varepsilon}_1^{\text{R}} \varepsilon_2^{\text{R}} N^{\text{RR}}) - (F_2 \varepsilon_1^{\text{R}} \bar{\varepsilon}_2^{\text{R}} N^{\text{RR}}) + (F_1 F_2 \bar{\varepsilon}_1^{\text{R}} \bar{\varepsilon}_2^{\text{R}} N^{\text{RR}}). \quad (6.25)$$

Finally, rearranging this results in:

$$N_{\text{TT}} - N_{\text{TT}}^{\text{RR}} = F_1 (N_{\text{LT}} - N_{\text{LT}}^{\text{RR}}) + F_2 (N_{\text{TL}} - N_{\text{TL}}^{\text{RR}}) - F_1 F_2 (N_{\text{LL}} - N_{\text{LL}}^{\text{RR}}). \quad (6.26)$$

As the number of events containing at least one fake lepton is equal to $N_{\text{TT}} - N_{\text{TT}}^{\text{RR}}$, the above equation contains everything necessary to estimate the contribution from fake leptons in the two lepton final state. Similar to the one lepton final state, the measured quantities include the fake factors, the number of events with one or two anti-ID leptons for a given region (in data), and the number of events with prompt leptons in a given region (estimated using the simulation).

Observe here that this equation estimates the number of events with one fake lepton and with two fake leptons simultaneously; the contribution from events with two anti-ID leptons can be thought to pertain primarily to the events with two fake leptons, but it is also possible for events with just

one fake lepton to also have two anti-ID leptons. While the terms with multiple anti-ID leptons are sometimes ignored in ATLAS analyses (particularly because they are multiplied by two fake factors, and can become negligible when $F \ll 1$), this should not be done in general, as these terms are formally necessary and can impact the fake lepton background prediction. Also note that the events with two anti-ID leptons have a minus sign relative to those with just one anti-ID lepton. This can be thought of as a correction due to “double counting” of the events with two fake leptons, since events with two fakes contribute to both N_{LT} and N_{TL} . Of course, this does assume that the fake factor for the one fake lepton case is also applicable to the two fake lepton case, which may not always be true—for instance, if the processes containing two fake leptons primarily come from one background source (e.g. photon conversions) while the processes containing one fake lepton come from another background source (e.g. misidentified light flavor hadrons). In situations where this is an issue, more complex versions of the fake factor method must instead be used.

6.4.1.3 Three Lepton Case

Finally, there is the equation for three lepton final states:

$$\begin{pmatrix} N_{TTT} \\ N_{LTT} \\ N_{TLT} \\ N_{TTL} \\ N_{LLT} \\ N_{LTL} \\ N_{TLL} \\ N_{LLL} \end{pmatrix} = \begin{pmatrix} \epsilon_1^R \epsilon_2^R \epsilon_3^R & \epsilon_1^F \epsilon_2^R \epsilon_3^R & \epsilon_1^R \epsilon_2^F \epsilon_3^R & \epsilon_1^R \epsilon_2^R \epsilon_3^F & \epsilon_1^F \epsilon_2^F \epsilon_3^R & \epsilon_1^R \epsilon_2^R \epsilon_3^F & \epsilon_1^R \epsilon_2^F \epsilon_3^F & \epsilon_1^F \epsilon_2^F \epsilon_3^F \\ \bar{\epsilon}_1^R \epsilon_2^R \epsilon_3^R & \bar{\epsilon}_1^F \epsilon_2^R \epsilon_3^R & \bar{\epsilon}_1^R \epsilon_2^F \epsilon_3^R & \bar{\epsilon}_1^R \epsilon_2^R \epsilon_3^F & \bar{\epsilon}_1^F \epsilon_2^F \epsilon_3^R & \bar{\epsilon}_1^R \epsilon_2^R \epsilon_3^F & \bar{\epsilon}_1^R \epsilon_2^F \epsilon_3^F & \bar{\epsilon}_1^F \epsilon_2^F \epsilon_3^F \\ \epsilon_1^R \bar{\epsilon}_2^R \epsilon_3^R & \epsilon_1^F \bar{\epsilon}_2^R \epsilon_3^R & \epsilon_1^R \bar{\epsilon}_2^F \epsilon_3^R & \epsilon_1^R \bar{\epsilon}_2^R \epsilon_3^F & \epsilon_1^F \bar{\epsilon}_2^F \epsilon_3^R & \epsilon_1^R \bar{\epsilon}_2^R \epsilon_3^F & \epsilon_1^R \bar{\epsilon}_2^F \epsilon_3^F & \epsilon_1^F \bar{\epsilon}_2^F \epsilon_3^F \\ \epsilon_1^R \epsilon_2^R \bar{\epsilon}_3^R & \epsilon_1^F \epsilon_2^R \bar{\epsilon}_3^R & \epsilon_1^R \epsilon_2^F \bar{\epsilon}_3^R & \epsilon_1^R \epsilon_2^R \bar{\epsilon}_3^F & \epsilon_1^F \epsilon_2^F \bar{\epsilon}_3^R & \epsilon_1^R \epsilon_2^R \bar{\epsilon}_3^F & \epsilon_1^R \epsilon_2^F \bar{\epsilon}_3^F & \epsilon_1^F \epsilon_2^F \bar{\epsilon}_3^F \\ \bar{\epsilon}_1^R \epsilon_2^R \epsilon_3^R & \bar{\epsilon}_1^F \epsilon_2^R \epsilon_3^R & \bar{\epsilon}_1^R \epsilon_2^F \epsilon_3^R & \bar{\epsilon}_1^R \epsilon_2^R \epsilon_3^F & \bar{\epsilon}_1^F \epsilon_2^F \epsilon_3^R & \bar{\epsilon}_1^R \epsilon_2^R \epsilon_3^F & \bar{\epsilon}_1^R \epsilon_2^F \epsilon_3^F & \bar{\epsilon}_1^F \epsilon_2^F \epsilon_3^F \\ \bar{\epsilon}_1^R \epsilon_2^R \bar{\epsilon}_3^R & \bar{\epsilon}_1^F \epsilon_2^R \bar{\epsilon}_3^R & \bar{\epsilon}_1^R \epsilon_2^F \bar{\epsilon}_3^R & \bar{\epsilon}_1^R \epsilon_2^R \bar{\epsilon}_3^F & \bar{\epsilon}_1^F \epsilon_2^F \bar{\epsilon}_3^R & \bar{\epsilon}_1^R \epsilon_2^R \bar{\epsilon}_3^F & \bar{\epsilon}_1^R \epsilon_2^F \bar{\epsilon}_3^F & \bar{\epsilon}_1^F \epsilon_2^F \bar{\epsilon}_3^F \\ \epsilon_1^R \bar{\epsilon}_2^R \epsilon_3^R & \epsilon_1^F \bar{\epsilon}_2^R \epsilon_3^R & \epsilon_1^R \bar{\epsilon}_2^F \epsilon_3^R & \epsilon_1^R \bar{\epsilon}_2^R \epsilon_3^F & \epsilon_1^F \bar{\epsilon}_2^F \epsilon_3^R & \epsilon_1^R \bar{\epsilon}_2^R \epsilon_3^F & \epsilon_1^R \bar{\epsilon}_2^F \epsilon_3^F & \epsilon_1^F \bar{\epsilon}_2^F \epsilon_3^F \\ \bar{\epsilon}_1^R \epsilon_2^R \bar{\epsilon}_3^R & \bar{\epsilon}_1^F \epsilon_2^R \bar{\epsilon}_3^R & \bar{\epsilon}_1^R \epsilon_2^F \bar{\epsilon}_3^R & \bar{\epsilon}_1^R \epsilon_2^R \bar{\epsilon}_3^F & \bar{\epsilon}_1^F \epsilon_2^F \bar{\epsilon}_3^R & \bar{\epsilon}_1^R \epsilon_2^R \bar{\epsilon}_3^F & \bar{\epsilon}_1^R \epsilon_2^F \bar{\epsilon}_3^F & \bar{\epsilon}_1^F \epsilon_2^F \bar{\epsilon}_3^F \end{pmatrix} \begin{pmatrix} N^{RRR} \\ N^{FRR} \\ N^{RFR} \\ N^{RRF} \\ N^{FFR} \\ N^{FRF} \\ N^{RFF} \\ N^{FFF} \end{pmatrix}. \quad (6.27)$$

Here both sides are multiplied by the row vector:

$$\begin{pmatrix} 1 & -\frac{\epsilon_1^F}{\epsilon_1^R} & -\frac{\epsilon_2^F}{\epsilon_2^R} & -\frac{\epsilon_3^F}{\epsilon_3^R} & \frac{\epsilon_1^F \epsilon_2^F}{\epsilon_1^R \epsilon_2^R} & \frac{\epsilon_1^F \epsilon_3^F}{\epsilon_1^R \epsilon_3^R} & \frac{\epsilon_2^F \epsilon_3^F}{\epsilon_2^R \epsilon_3^R} & -\frac{\epsilon_1^F \epsilon_2^F \epsilon_3^F}{\epsilon_1^R \epsilon_2^R \epsilon_3^R} \end{pmatrix}. \quad (6.28)$$

As with the two lepton case, all entries in the matrix cancel except for those from the first column. This is left as a fun exercise to the reader (simply because the algebra is more tedious to type up than it is to write on paper!). Ultimately, this results in:

$$N_{TTT} - N_{TTT}^{RRR} = \quad (6.29)$$

$$F_1(N_{LTT} - N_{LTT}^{RRR}) + F_2(N_{TLT} - N_{TLT}^{RRR}) + F_3(N_{TTL} - N_{TTL}^{RRR}) \quad (6.30)$$

$$- F_1 F_2(N_{LLT} - N_{LLT}^{RRR}) - F_1 F_3(N_{LTL} - N_{LTL}^{RRR}) - F_2 F_3(N_{TLL} - N_{TLL}^{RRR}) \quad (6.31)$$

$$+ F_1 F_2 F_3(N_{LLL} - N_{LLL}^{RRR}), \quad (6.32)$$

which is the estimate for the number of three lepton events containing at least one fake lepton.

6.4.2 Anti-ID Criteria Available to Enrich in Particular Backgrounds

In the fake factor method, there is flexibility in the choice of anti-ID definitions used for the fake lepton estimation. In the simplest case, one can define the anti-ID leptons to be any lepton which passes the baseline criteria used by the analysis but fails the signal criteria. However, this might not be sufficient in some cases, if the composition of these anti-ID leptons differs significantly from the composition of the signal leptons. Of course, one caveat is that the composition is often studied using classification information from simulated events, but the whole point of using data-driven techniques for fake lepton estimation is that the simulation cannot be trusted to properly model the rates at which different sources of fake leptons are misidentified.

For both electrons and muons, a very efficient $|z_0 \sin \theta| < 0.5$ mm requirement (for longitudinal impact parameter z_0) is usually imposed for signal leptons for the purpose of suppressing fake leptons from pileup jets, in addition to ensuring that the leptons considered by the analysis originate from the primary vertex. Since many pileup jets can satisfy the baseline lepton criteria, particularly at low p_T , it is also often worthwhile to use this requirement for all baseline leptons considered in ATLAS analyses. Figure 6.7 demonstrates how essential this criteria can be for low p_T leptons. To avoid using events in a given anti-ID control region which are completely dominated by events containing fake leptons due to pileup jets, this $|z_0 \sin \theta| < 0.5$ mm requirement is a useful handle for aligning the anti-ID fake lepton background composition with that of the signal leptons. Furthermore, for baseline leptons this criteria is also useful to ensure that if the analysis vetoes on additional baseline leptons present in the event, the veto will not be as stringent as it otherwise would be (particularly since many pileup jets are expected to be present in the pp collisions at ATLAS).

For electrons, the VeryLoose and Loose identification operating points do not require a hit in the innermost pixel layer, as discussed in Section 4.4.2. As this innermost pixel hit is efficient at suppressing fake electrons from photon conversions, one can imagine using VeryLoose or Loose to enhance statistics of photon conversions as part of an anti-ID electron definition, when useful. Additionally, VeryLoose only requires one pixel hit, while all of the other operating points require at least two, which provides another option for adjusting the electron anti-ID definition to target fake electrons from photon conversions.

Finally, it is often a good idea to relax the “overlap removal” criteria for muons, which is needed to prevent “double counting” of objects which successfully meet the reconstruction criteria for multiple

types of objects. As overlap removal is often very efficient at suppressing fake muons from heavy flavor decays, relaxing this allows for enhanced statistics of fake muons. This can be factorized by either relaxing the overlap removal for both signal and anti-ID leptons in the fake factor measurement region (and *only* in this region) or by using the relaxed overlap removal requirement as part of the anti-ID definition in all regions considered. The former tends to be easier on a technical level in most cases, since the anti-ID definition will not be a subset of the baseline definition in the latter scenario (as the baseline leptons considered by ATLAS analyses must additionally satisfy overlap removal criteria).

6.4.3 The Matrix Method

One alternative to the fake factor method is called the “matrix method”. The matrix method proceeds by inverting the matrix from Equation 6.6 to determine the number of fake tight leptons.

$$\begin{pmatrix} N^R \\ N^F \end{pmatrix} = \frac{1}{\varepsilon^R \bar{\varepsilon}^F - \varepsilon^F \bar{\varepsilon}^R} \begin{pmatrix} \bar{\varepsilon}^F & -\varepsilon^F \\ -\bar{\varepsilon}^R & \varepsilon^R \end{pmatrix} \begin{pmatrix} N_T \\ N_L \end{pmatrix}. \quad (6.33)$$

As the number of fake tight leptons is $N_T^F = \varepsilon^F N^F$, the previous equations can be used to find:

$$N_T^F = \varepsilon^F N^F = \varepsilon^F \frac{1}{\varepsilon^R \bar{\varepsilon}^F - \varepsilon^F \bar{\varepsilon}^R} (-\bar{\varepsilon}^R N_T + \varepsilon^R N_L). \quad (6.34)$$

One in principle could measure the prompt and fake efficiencies for both the tight and loose leptons, but in practice the special case mentioned in Section 6.4.1.1 is typically used, so the loose efficiencies are $\bar{\varepsilon}^R = (1 - \varepsilon^R)$ and $\bar{\varepsilon}^F = (1 - \varepsilon^F)$, allowing for a simplification of these equations to:

$$\begin{pmatrix} N^R \\ N^F \end{pmatrix} = \frac{1}{\varepsilon^R - \varepsilon^F} \begin{pmatrix} 1 - \varepsilon^F & -\varepsilon^F \\ -(1 - \varepsilon^R) & \varepsilon^R \end{pmatrix} \begin{pmatrix} N_T \\ N_L \end{pmatrix} \quad (6.35)$$

and

$$N_T^F = \varepsilon^F N^F = \varepsilon^F \frac{1}{\varepsilon^R - \varepsilon^F} (-(1 - \varepsilon^R) N_T + \varepsilon^R N_L) \quad (6.36)$$

$$= \frac{\varepsilon^F}{\varepsilon^R - \varepsilon^F} (\varepsilon^R (N_T + N_L) - N_T). \quad (6.37)$$

Thus only the prompt and fake efficiencies for tight leptons need to be computed, in addition to the number of signal/validation/control region events with tight and loose leptons. Here, the assumption is made that the regions used for measuring the prompt and fake efficiencies result in the same efficiencies that one would measure in the signal region.

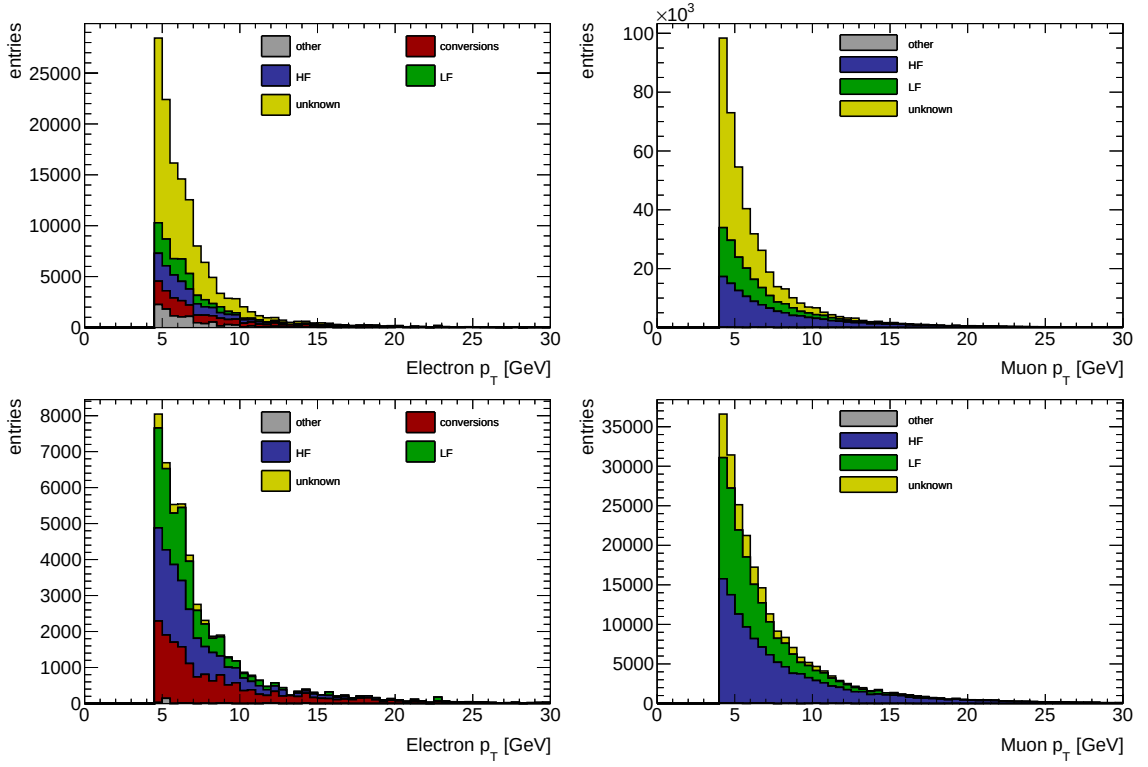


Figure 6.7: Fake electrons (left) and muons (right) from a simulated Z +jets/ Z + γ sample, shown for the various background types as a function of p_T . The fake leptons must pass the Medium identification (top) or the Medium identification in addition to satisfying the $|z_0 \sin \theta| < 0.5$ mm requirement (bottom). Before applying any requirement on $|z_0 \sin \theta|$, the “unknown” category is dominant at low lepton p_T ; this primarily consists of fake leptons due to overlaid pileup collisions, which are classified as unknown by the ATLAS software as the truth record for these overlaid events is not retained for the simulated samples used. For both electrons and muons, the $|z_0 \sin \theta| < 0.5$ mm requirement suppresses a large number of fake leptons due to pileup jets at low p_T , reducing this contribution by one to two orders of magnitude. Note that the overall number of fake muons in these plots is larger than that of fake electrons—this is only because the criteria used to prevent “double counting” of objects which are reconstructed as both muons and jets are relaxed in these particular plots, specifically to allow for enhanced statistics of fake muons.

The derivation of the fake factor method and the matrix method both start with the same definitions, so it is natural to wonder about the differences between these two methods. Some differences include:

- The fake factor method has significant flexibility in the choice of the loose lepton criteria, which can be helpful to provide a handle on the fake lepton composition among the loose leptons. The derivation for the matrix method, meanwhile, only works if the loose lepton criteria is chosen to be all baseline leptons which fail the tight lepton criteria. It is possible to choose a more complicated baseline criteria for these purposes in order to have similar handles on the fake lepton composition in the matrix method, but in practice few (if any) ATLAS analyses have ever done this with the matrix method.
- The fake factor method handles any subtraction of prompt leptons from the loose region in Equation 6.10 using simulation. In principle, this could be problematic if the simulation did not model the loose leptons well, but in practice this is typically used as a systematic uncertainty, and often found to be a small contributor.
- The matrix method relies on the number of events with tight leptons in the signal/validation/control region of interest. This means that before unblinding a signal region, the fake lepton estimate via the matrix method cannot be fully computed. A common approximation is to ignore the contribution from the tight leptons until after unblinding the signal region, at which point the proper estimate can be computed.
- The matrix method requires the analyzer to measure both prompt and fake efficiencies for the tight leptons used in the analysis, while the fake factor only requires the analyzer to measure the fake factors.

The analyses presented in this thesis rely on the fake factor method for estimating fake lepton backgrounds. However, the matrix method is an equally valid approach to fake lepton estimation, and presumably should give consistent results. Recent work in ATLAS has been performed to provide common software tools for computing these fake lepton estimates, which will allow analyzers to easily switch between these methods and verify if they are indeed consistent for their use cases (assuming identical fake factor and fake efficiency measurement regions), though it is possible that one method may still be easier to employ than the other for some analyses from a technical standpoint.

CHAPTER 7

Search for EWK SUSY in the Trilepton Final State

7.1 Motivation and Models Considered

The trilepton (“3 ℓ ”) EWK SUSY analysis focuses on a search for electroweak production of charginos and neutralinos which decay to a final state containing three leptons and large E_T^{miss} (due to the noninteracting LSPs in the decay). The diagram for the primary signal process of interest can be seen in Figure 7.1.

In the scenarios considered, the W and Z bosons in Figure 7.1 are both produced on-shell, which means the mass splitting between the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and the $\tilde{\chi}_1^0$ must be sufficiently large to allow for such decays to occur. As a result, the primary simplified model studied for this analysis is the wino-bino

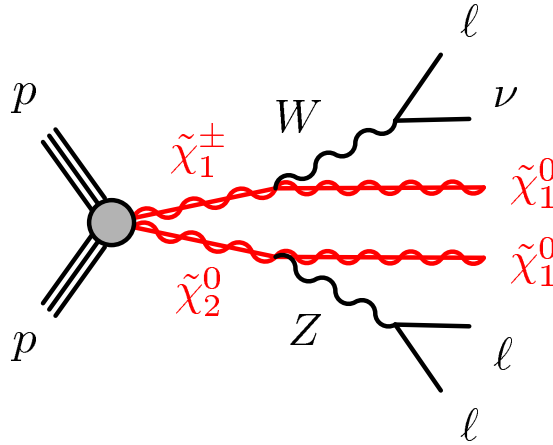


Figure 7.1: Diagram for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with decays via W and Z bosons to three leptons [7].

2015	2016
HLT_2e12_lhloose_L12EM10VH	HLT_2e17_lhvloose_nod0
HLT_mu18_mu8noL1	HLT_mu22_mu8noL1
HLT_e17_lhloose_mu14	HLT_e17_lhloose_nod0_mu14

Table 7.1: List of the primary lowest unscaled dilepton triggers used in 2015–2016. The strings “2e”, “e”, and “mu” indicate the number and flavor of leptons (electrons or muons) which are required to satisfy the p_T threshold; these p_T thresholds in GeV are listed after the aforementioned strings. For the electron triggers, “lhloose” and “lhvloose” refer to the trigger-level electron identification criteria which the electron candidate must satisfy. As mentioned in Table 5.3, “nod0” indicates that the electron triggers active in 2016 do not include requirements on the d_0 or $d_0/\sigma(d_0)$ variables. For the dimuon trigger, “mu8noL1” indicates that the 8 GeV muon required by the trigger does not need to satisfy any L1 requirements. Finally, “L12EM10VH” listed in the name of the dielectron trigger refers to the L1 seed (which requires two electrons at L1); all of these triggers do require an L1 seed, but it is not always explicitly included in the trigger name.

model discussed in Section 6.1.

7.2 Collision Data and Simulated Event Samples

This analysis relies on 36.1 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ data delivered by the LHC and recorded by ATLAS in 2015–2016 during stable data-taking periods. This integrated luminosity value is derived using a methodology similar to that detailed in [121], from a calibration of the luminosity scale using x – y beam-separation scans performed in August 2015 and May 2016. Events are collected using dilepton triggers which require either two electrons, two muons, or one electron plus one muon, as described in Table 7.1.

Various samples of Monte Carlo simulated events are used to model the SUSY signal and help in the estimation of the SM backgrounds. The samples include an ATLAS detector simulation [97], based on GEANT [96], or a fast simulation [97] that uses a parameterization of the calorimeter response [122] and GEANT for the other parts of the detector. The simulated events are reconstructed in the same manner as the data.

Diboson processes were simulated with the SHERPA v2.2.1 event generator [123, 124] and normalized using next-to-leading-order (NLO) cross-sections [125, 126]. The matrix elements containing all diagrams with four electroweak vertices with additional hard parton emissions were calculated with COMIX [127] and virtual QCD corrections were calculated with OPENLOOPS [128]. Matrix element calculations were merged with the SHERPA parton shower [129] using the ME+PS@NLO prescription [130]. The NNPDF3.0 NNLO parton distribution function set [131] was used in conjunction with dedicated parton shower tuning developed by the SHERPA authors. The fully leptonic channels

were calculated at NLO in the strong coupling constant with up to one additional parton for 4ℓ and $2\ell + 2\nu$, at NLO with no additional parton for $3\ell + \nu$, and at leading order (LO) with up to three additional partons. Processes with one of the bosons decaying hadronically and the other leptonically were calculated with up to one additional parton at NLO and up to three additional partons at LO.

Diboson processes with six electroweak vertices, such as same-sign W boson production in association with two jets, $W^\pm W^\pm jj$, and triboson processes were simulated as above with SHERPA v2.2.1 using the NNPDF3.0 PDF set. Diboson processes with six vertices were calculated at LO with up to one additional parton. Fully leptonic triboson processes (WWW , WWZ , WZZ and ZZZ) were calculated at LO with up to two additional partons and at NLO for the inclusive processes and normalized using NLO cross-sections.

Events containing Z bosons and associated jets (Z/γ^* +jets, also referred to as Z +jets in the following) were also produced using the SHERPA v2.2.1 generator with massive b/c -quarks to improve the treatment of the associated production of Z bosons with jets containing b - and c -hadrons [132]. Matrix elements were calculated with up to two additional partons at NLO and up to four additional partons at LO, using COMIX, OPENLOOPS, and SHERPA parton shower with ME+PS@NLO in a way similar to that described above. A global K -factor was used to normalize the Z +jets events to the next-to-next-to-leading-order (NNLO) QCD cross-sections [133].

For the production of $t\bar{t}$ and single top quarks in the Wt channel, the POWHEG-BOX v2 [88, 134] generator with the CT10 PDF set [90] was used, as discussed in [135]. The top quark mass was set at 172.5 GeV for all simulated samples involving top quark production. The $t\bar{t}$ events were normalized using the NNLO+next-to-next-to-leading-logarithm (NNLL) QCD [136] cross-section, while the cross-section for single top quark events was calculated at NLO+NNLL [137].

Samples of $t\bar{t}V$ (with $V = W$ and Z , including non-resonant Z/γ^* contributions) and $t\bar{t}WW$ production were generated at LO with MADGRAPH5_aMC@NLO v2.2.2 [138] interfaced to PYTHIA v8.186 [89] for parton showering, hadronization and the description of the underlying event, with up to two ($t\bar{t}W$), one ($t\bar{t}Z$) or no ($t\bar{t}WW$) extra partons included in the matrix element, as described in [139]. MADGRAPH was also used to simulate the tZ , $t\bar{t}t\bar{t}$ and $t\bar{t}t$ processes. A set of tuned parameters called the A14 tune [93] was used together with the NNPDF2.3 LO PDF set [94]. The $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}WW$ and $t\bar{t}t\bar{t}$ events were normalized using their NLO cross-section [139] while the generator cross-sections were used for tZ and $t\bar{t}t$.

Higgs boson production processes (including gluon–gluon fusion, associated VH production and vector boson fusion) were generated using POWHEG-BOX v2 [86] and PYTHIA v8.186 and normal-

ized using cross-sections calculated at NNLO with soft gluon emission effects added at NNLL accuracy [140], while $t\bar{t}H$ events were produced using MADGRAPH5_aMC@NLO 2.3.2 + Herwig++ [141] and normalized using the NLO cross-section [139]. All samples assume a Higgs boson mass of 125 GeV.

The SUSY signal processes were generated from LO matrix elements with up to two extra partons, using the MADGRAPH v2.2.3 generator interfaced to PYTHIA v8.186 with the A14 tune for the modeling of the SUSY decay chain, parton showering, hadronization and the description of the underlying event. Parton luminosities were provided by the NNPDF2.3 LO PDF set. Jet-parton matching was performed following the CKKW-L prescription [142], with a matching scale set to one quarter of the pair-produced superpartner mass. Signal cross-sections were calculated at NLO, with soft gluon emission effects added at next-to-leading-logarithm (NLL) accuracy [143–147]. The nominal cross-section and its uncertainty were taken from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales, as described in [115]. The cross-section for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production, each with a mass of 800 GeV, is 4.76 ± 0.56 fb.

In all simulated samples except those produced by SHERPA, the EVTGEN v1.2.0 program [148] was used to model the properties of b - and c -hadron decays. To simulate the effects of additional pp collisions per bunch crossing (pileup), additional interactions were generated using the soft QCD processes of PYTHIA v8.186 with the A2 tune [149] and the MSTW2008LO PDF set [95], and overlaid onto the simulated hard-scatter event. The simulated samples were reweighted so that the distribution of the number of pileup interactions matches the distribution in data [7].

7.3 Object Reconstruction

All events considered in the analysis must have a reconstructed primary vertex with at least two $p_T > 400$ MeV tracks associated to the vertex. To select the primary vertex in an event, the vertex with the largest $\sum p_T^2$ of the associated tracks is chosen.

As discussed in Section 6.4.1, “baseline” and “signal” object identification criteria are used in the analysis, where signal objects are a subset of the baseline objects. The signal objects are those which are used for the final analysis while the baseline objects are for use in data-driven estimates as well as for resolving overlap between different types of reconstructed objects.

Baseline electrons are chosen to be those which satisfy the Loose identification and which have $p_T > 10$ GeV with $|\eta| < 2.47$. Signal electrons are the subset of baseline electrons which also satisfy the Medium identification, the Gradient (Loose) isolation working point, have $|d_0/\sigma(d_0)| < 5$, and

Baseline Electrons	Baseline Muons
$p_T > 10 \text{ GeV}$	$p_T > 10 \text{ GeV}$
$ \eta < 2.47$	$ \eta < 2.4$
Pass Loose identification	Pass Medium identification
Signal Electrons	Signal Muons
$p_T > 10 \text{ GeV}$	$p_T > 10 \text{ GeV}$
$ \eta < 2.47$	$ \eta < 2.4$
Pass Medium identification	Pass Medium identification
Pass Gradient (Loose) isolation	Pass Gradient (Loose) isolation
$ d_0/\sigma(d_0) < 5$	$ d_0/\sigma(d_0) < 3$
$ z_0 \sin \theta < 0.5 \text{ mm}$	$ z_0 \sin \theta < 0.5 \text{ mm}$

Table 7.2: Baseline and signal lepton definitions used in the 3ℓ EWK SUSY analysis.

have $|z_0 \sin \theta| < 0.5 \text{ mm}$. Baseline muons are required to satisfy the Medium identification [69] with $p_T > 10 \text{ GeV}$ and $|\eta| < 2.7$, while signal muons must additionally satisfy the Gradient (Loose) isolation working point with $|d_0/\sigma(d_0)| < 3$ and $|z_0 \sin \theta| < 0.5 \text{ mm}$. These criteria are summarized in Table 7.2

Jets used in the analysis are reconstructed with the anti- k_t algorithm [74, 75] with radius parameter $R = 0.4$, using calorimeter topological clusters as input [72]. The energies of these jets are calibrated as described in [150], and the average expected energy contribution from pileup is subtracted according to the jet area [151]. Baseline jets are required to have $p_T > 20 \text{ GeV}$ with $|\eta| < 4.5$ while signal jets must have $|\eta| < 2.4$. To suppress jets originating from pileup collisions, all jets with $p_T < 60 \text{ GeV}$ and $|\eta| < 2.4$ are required to satisfy the Medium working point of the jet vertex tagger [151], which is used to determine if tracks associated to the jet are likely to have originated from the primary vertex. Any events containing a jet which fail basic quality criteria are rejected, as they may be due to detector noise or non-collision background [152].

b -jets in the analysis are the subset of signal jets identified using the MV2c10 b -tagging algorithm [153, 154]. MV2c10 is a multivariate boosted decision tree (BDT) algorithm which relies on track impact parameters and reconstructed secondary vertices to distinguish b -jets from charm quark jets, light quark jets, gluon jets, and hadronic τ leptons. The working point used in the analysis is designed to be 77% efficient for b -jets.

As leptons and jets can simultaneously satisfy multiple object reconstruction algorithms, an “overlap removal” procedure is necessary to resolve ambiguity and avoid double counting. This overlap removal uses baseline objects as input. The procedure used in this analysis proceeds as follows, in the order shown:

1. Electrons which share an Inner Detector track with a muon are removed, since these may be due to muons which emit bremsstrahlung radiation, followed by a photon conversion into electron pairs.
2. Electrons within $\Delta R = 0.2$ of b -tagged jets identified with the 85% efficient working point of the MV2c10 algorithm are removed since this is likely to be from a semileptonic b -hadron decay.
3. Electrons within $\Delta R = 0.2$ of non- b -tagged jets (also using the 85% efficient MV2c10 working point) are retained, while the jet is removed since this is likely to be due to an EM shower.
4. Electrons within $\Delta R = 0.4$ of any remaining jets are removed, as these are also frequently from semileptonic b -hadron and c -hadron decays.
5. When a jet is nearby in ΔR to a muon, if the muon p_T is greater than 70% of the total p_T of the tracks associated to the jet, the jet is removed if the muon is within $\Delta R = 0.2$ of the jet or if the muon is matched to a track associated to the jet. This step is skipped for jets with three or more associated tracks.
6. Muons within $\Delta R = 0.4$ of any remaining jets are removed, as these are also frequently from semileptonic b -hadron and c -hadron decays.

All signal electrons, muons, and b -tagged jets used in the analysis must be corrected in the simulation to match the reconstruction efficiencies in data [6, 69, 78].

Finally, the missing transverse momentum $\mathbf{p}_T^{\text{miss}}$ (with magnitude E_T^{miss}) is defined to be the negative vector sum of the transverse momenta of all of the objects in the event after overlap removal. An additional soft term is included in this vector sum to account for tracks which are associated with the primary vertex but not with any electron, muon, or jet objects. This is performed after calibrating the energies of the various objects, to ensure that the E_T^{miss} value is as accurate as possible [155].

7.4 Event Selection

To target events which can arise from the trilepton decay of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$, events are required to have exactly three leptons with $p_T > 20$ GeV each, as well as zero b -tagged jets with $p_T > 20$ GeV. To target events which could result from the $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$ decay chain, at least two of the leptons must form a “same-flavor opposite-sign” (SFOS) pair, which is indicative of leptonic Z

decays. When more than one SFOS pair is possible (i.e. all three leptons are the same flavor), there is ambiguity in which leptons may have come from the Z decay and which lepton may have come from the W decay. In this analysis, ambiguities are resolved using an algorithm to compute the minimum transverse mass $m_T^{\min}$. In general, a transverse mass m_T is computed as:

$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)} \quad (7.1)$$

for two arbitrary transverse momenta $\mathbf{p}_T$ and $\mathbf{q}_T$ (and their magnitudes p_T and q_T). For this search, the $m_T^{\min}$ algorithm is performed by iterating over all SFOS pairings, and computing a transverse mass using the $\mathbf{p}_T$ for the unpaired lepton and the $\mathbf{p}_T^{\text{miss}}$ as inputs. Whichever pairing results in the smallest transverse mass is then chosen; this means that when ambiguity is present, the lepton which results in the smallest transverse mass is the one assigned to the W , while the remaining leptons are assigned as the SFOS pair from the Z . This algorithm for assigning leptons to the Z and the W has been found to improve the analysis sensitivity to the signal models of interest relative to other potential assignments. When only one SFOS pair is present in the event, there is no ambiguity, and thus the SFOS leptons are assumed to be from the Z decay while the remaining unpaired lepton is assumed to be from the W decay. In such cases $m_T^{\min}$ is simply computed as the transverse mass using this lepton assigned to the W and the $\mathbf{p}_T^{\text{miss}}$ [7].

The $m_T^{\min}$ variable along with other kinematic variables including the invariant mass of the SFOS pair (referred to interchangeably as m_{SFOS} or $m_{\ell\ell}$), the p_T of the softest lepton ($p_T^{\ell_3}$), the vector sum of the p_T of the three leptons ($p_T^{\ell\ell\ell}$), E_T^{miss} , jet multiplicity ($n_{\text{non-}b\text{-tagged jets}}$, for the number of jets with $p_T > 20$ GeV that do not satisfy the b -tagging criteria), and the p_T of the leading jet (p_T^{jet1}) are all used to define the signal regions used in the analysis. The criteria used to define these signal regions are shown in Table 7.3.

Regions with “0J” in their name apply a jet veto, and thus only rely on the three leptons and E_T^{miss} in the final state. The minimum $m_T^{\min}$ requirement is chosen to be above the threshold for the W boson mass (approximately 80.4 GeV), to help minimize background from the WZ process. These three “0J” regions only differ in their E_T^{miss} requirement; by binning in this manner, the shape of the E_T^{miss} distribution can be exploited to improve the signal significance for a variety of signal models. Regions with “1J” in their name require at least one jet in the final state. Region SR3-WZ-1Ja in particular requires the leading jet to have relatively large p_T , thus providing an object for the LSPs to recoil against.

3ℓ signal region definitions							
Name	m_{SFOS} [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	$p_{\text{T}}^{\ell_3}$ [GeV]	$n_{\text{non-}b\text{-tagged jets}}$	$m_{\text{T}}^{\text{min}}$ [GeV]	$p_{\text{T}}^{\ell\ell}$ [GeV]	$p_{\text{T}}^{\text{jet1}}$ [GeV]
SR3-WZ-0Ja	81.2–101.2	60–120		0	> 110		
SR3-WZ-0Jb	81.2–101.2	120–170		0	> 110		
SR3-WZ-0Jc	81.2–101.2	> 170		0	> 110		
SR3-WZ-1Ja	81.2–101.2	120–200		≥ 1	> 110	< 120	> 70
SR3-WZ-1Jb	81.2–101.2	> 200		≥ 1	110–160		
SR3-WZ-1Jc	81.2–101.2	> 200	> 35	≥ 1	> 160		

Table 7.3: Summary of the signal regions used in the 3 ℓ EWK SUSY search. Note that the requirements listed are in addition to requiring three $p_{\text{T}} > 20$ GeV leptons in the event, zero b -tagged jets, and that the event had to be collected using one of the dilepton triggers [7].

7.5 Background Estimation

As discussed in Section 6.3, ATLAS analyses must estimate both irreducible and reducible backgrounds. The reducible backgrounds in the 3 ℓ search will be discussed in Section 7.5.1.

The primary contributor to the irreducible backgrounds is the Standard Model WZ process; the diagram for this process is shown in Figure 7.2. Simulation is used to determine the kinematic distributions for this background process, and these simulated events are normalized to the data in dedicated control regions. As the signal regions can be grouped into those which apply a jet veto and those which require at least one jet, the same grouping is used for the control regions (and thus two separate normalization factors are determined for WZ). The WZ control regions used are listed in Table 7.4. After normalizing the WZ background to the data, this background estimate is then tested in dedicated validation regions to ensure that the background estimate in the signal region can also be trusted. These validation regions are also listed in Table 7.4. Note that the validation regions require the invariant mass of the three leptons, $m_{\ell\ell\ell}$, to be at least 10 GeV away from the Z mass. This is done to eliminate impact from $Z \rightarrow \ell\ell$ events where one of the leptons radiates off a photon which then converts. Such events should be rare in the control and signal regions due to the large $E_{\text{T}}^{\text{miss}}$ requirements, but could be non-negligible in the lower $E_{\text{T}}^{\text{miss}}$ validation region. An example distribution of the $m_{\text{T}}^{\text{min}}$ variable in a WZ validation region is shown in Figure 7.3.

The remaining irreducible backgrounds in the analysis such as ZZ , $t\bar{t}V$, VVV , and Higgs tend to be small and are estimated purely with the simulation.

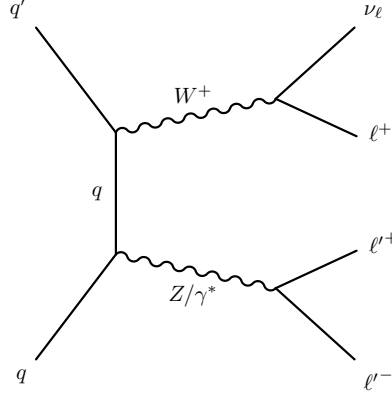


Figure 7.2: Diagram for the WZ background process, which is the primary irreducible background in the trilepton EWK SUSY search.

3ℓ control and validation region definitions					
Name	$m_{\ell\ell\ell}$ [GeV]	m_{SFOS} [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	$m_{\text{T}}^{\text{min}}$ [GeV]	$n_{\text{non-}b\text{-tagged jets}}$
CR3-WZ-0J	-	81.2–101.2	> 60	< 110	0
CR3-WZ-1J	-	81.2–101.2	> 120	< 110	≥ 1
VR3-Za-0J	$\notin [81.2, 101.2]$	81.2–101.2	40–60	-	0
VR3-Za-1J	$\notin [81.2, 101.2]$	81.2–101.2	40–60	-	≥ 1

Table 7.4: Summary of the control regions used in the 3 ℓ EWK SUSY search to target the WZ background. Note that the requirements listed are in addition to requiring three $p_{\text{T}} > 20$ GeV leptons in the event, zero b -tagged jets, and that the event had to be collected using one of the dilepton triggers [7].

7.5.1 3 ℓ Fake Lepton Backgrounds

As mentioned in Section 6.4, fake and nonprompt leptons (collectively referred to as “fake leptons” for simplicity) are typically due to light flavor jets that are improperly reconstructed and identified as a lepton, heavy flavor quarks that decay semileptonically, and photons that convert into a pair of leptons.

Fake leptons in the trilepton final state primarily arise from two types of processes:

1. Z +jets and Z + γ (collectively referred to as Z +jets/ Z + γ) are a background in the analysis when a Z decays to two prompt leptons while a jet or photon fakes an electron or muon. In final states requiring large $E_{\text{T}}^{\text{miss}}$, there must also be a mismeasurement of the $E_{\text{T}}^{\text{miss}}$ for

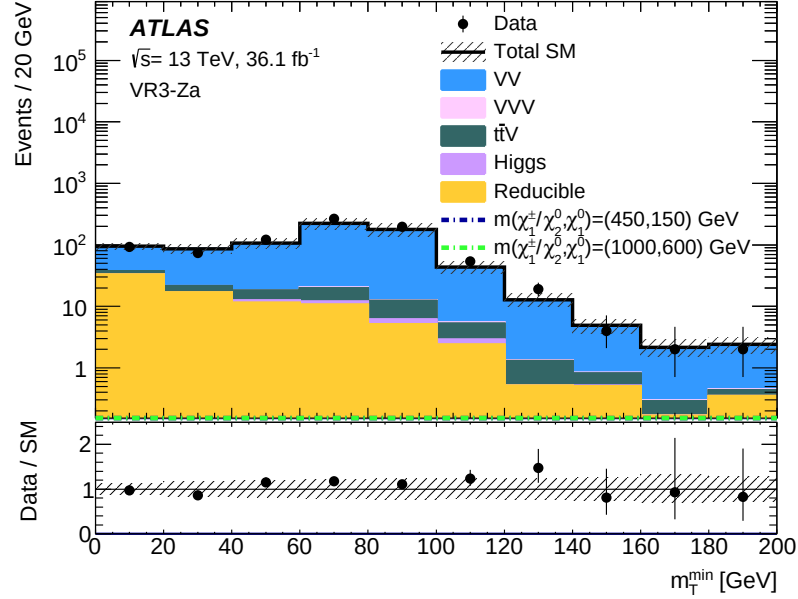


Figure 7.3: Distribution of the $m_T^{\min}$ variable in a validation region designed to verify the WZ background estimate. This validation region is similar to the VR3-Za-0J and VR3-Za-1J regions listed in Table 7.4, except that it requires $p_T^{\ell_3} > 30$ GeV and is inclusive in the multiplicity of both non- b -tagged jets and b -tagged jets. This validation region was designed for a slightly different signal region targeted at $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production decaying to three leptons via slepton-mediated decays (rather than W and Z decays), but nonetheless demonstrates the effectiveness of the WZ background estimation [7].

Z +jets/ Z + γ events to serve as a background, as leptonic Z +jets/ Z + γ decays result in a fully visible final state.

2. $t\bar{t}$, Wt , and WW (collectively referred to as “top-like” backgrounds) all have similar final states and can thus be treated simultaneously. The primary distinction between these are the number of b -jets in the final state. As $t\bar{t}$ has the largest cross-section, and as b -jets tend to result in fake leptons more frequently than light flavor jets or photon conversions due to their decay to prompt electrons and muons, $t\bar{t}$ is typically the dominant process contributing to the top-like fake lepton background.

Diagrams for these processes are shown in Figure 7.4.

Due to the known poor modeling of fake lepton composition in the simulation, data-driven techniques must be employed to estimate these backgrounds. For Z +jets/ Z + γ , the fake factor method from Section 6.4.1 is used, which relies on inverted lepton identification and isolation criteria to estimate the fake lepton background in data.

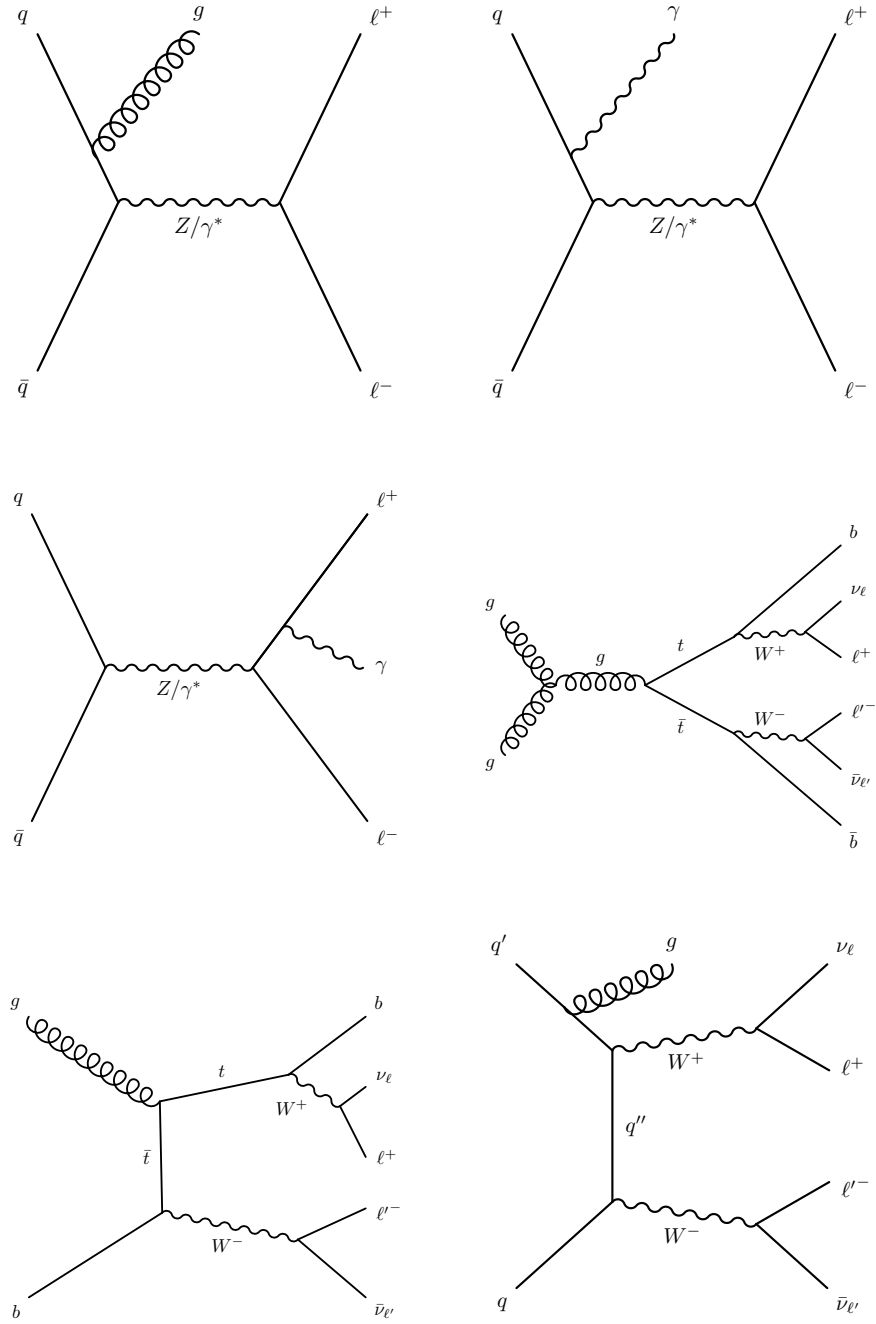


Figure 7.4: Diagrams for the fake lepton background processes in the trilepton EWK SUSY search, including Z +jet (top left), Z + γ with a photon from initial state radiation off of a quark (top right), Z + γ with a photon which radiates off of a final state lepton (middle left), $t\bar{t}$ (middle right), Wt (bottom left), and WW (bottom right).

Electrons	Muons
$p_T > 20 \text{ GeV}$	$p_T > 20 \text{ GeV}$
$ \eta < 2.47$	$ \eta < 2.4$
$ z_0 \sin \theta < 1.0 \text{ mm}$	$ z_0 \sin \theta < 1.0 \text{ mm}$
Pass VeryLoose identification	Pass Medium identification
	No overlap removal requirements
Fail Medium identification	$ d_0/\sigma(d_0) > 3$
OR $ d_0/\sigma(d_0) > 5$	OR fail Gradient (Loose) isolation
OR fail Gradient (Loose) isolation	

Table 7.5: Anti-ID electron and muon definitions used for the Z +jets/ Z + γ background estimation in the 3ℓ EWK SUSY analysis. Note that the $|z_0 \sin \theta| < 1.0 \text{ mm}$ requirement is primarily used to suppress anti-ID leptons from pileup interactions, while the relaxed muon overlap removal requirements are necessary to allow for sufficient statistics of anti-ID muons. These criteria can be compared with the baseline and signal lepton definitions for the analysis, listed in Table 7.2.

The top-like fakes, meanwhile, come predominantly from heavy flavor decays. This means that the composition is less of a concern, and thus a simpler approach can be used. A control region enriched in top-like events is used to determine data-to-simulation normalization factors which can be applied to the $t\bar{t}$, Wt , and WW simulated events. One could imagine trying to use the fake factor method to simultaneously treat Z +jets/ Z + γ and the top-like backgrounds, but this would also require the fake factors to be derived in a region containing the proper composition of both Z +jets/ Z + γ and top-like backgrounds, which is nontrivial. This would also result in larger statistical uncertainties, since the same number of data events would be used to estimate a larger total number of fake lepton background events, whereas the approach taken allows for simulation to be used for the top-like backgrounds.

7.5.1.1 Z +jets/ Z + γ Background Estimation

For background information on the fake factor method, see Section 6.4.1. The definitions of the anti-ID criteria used for electrons and muons in the trilepton analysis are described in Table 7.5.

As described previously, the fake factor F is the ratio of ID to anti-ID leptons as measured in a kinematic region in the data primarily consisting of fake leptons. In particular, the composition of the fake leptons in this region should ideally be as close as possible to the composition of fake leptons in the signal region to avoid large systematic uncertainties which would otherwise be necessary to account for e.g. estimating a background dominated by heavy flavor fake leptons by using events primarily consisting of light flavor fake leptons.

The fake factors used in the analysis are derived in a region dominated by Z +jets/ Z + γ events

	E_T^{miss}	m_T^{min}	SFOS pair	$ m_{\ell\ell} - m_Z $	$n_{b\text{-jets}}$
FF Region	$< 40 \text{ GeV}$	$< 30 \text{ GeV}$	required	$< 10 \text{ GeV}$	–
VRZjet	$< 40 \text{ GeV}$	$[30 \text{ GeV}, 50 \text{ GeV}]$	required	$< 10 \text{ GeV}$	–
SR-like region	$> 60 \text{ GeV}$	$> 60 \text{ GeV}$	required	$< 10 \text{ GeV}$	0

Table 7.6: Summary of regions used for the Z +jets/ Z + γ background estimate in the 3ℓ search. The FF region is used for measuring the fake factor in a Z +jets/ Z + γ enriched region. VRZjet is used to validate the Z +jets/ Z + γ background estimate. The SR-like region is only used with simulated events (as it has overlap with the signal regions), and is used to derive the simulation-based closure systematic uncertainty on the Z +jets/ Z + γ background estimate.

(referred to as the “fake factor measurement region” or “FF region”). This region requires events to have three baseline leptons with at least one SFOS pair of leptons. To suppress WZ and to be orthogonal with the analysis signal regions, further requirements of $E_T^{\text{miss}} < 40 \text{ GeV}$, $|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$, and $m_T^{\text{min}} < 30 \text{ GeV}$ are imposed. Events are required to pass one of the dilepton triggers from Table 7.1. Furthermore, the leptons paired with the Z boson are required to pass the signal lepton criteria, while the remaining lepton must satisfy either the ID or anti-ID criteria. The kinematic requirements for the FF region are summarized in Table 7.6.

As the 3ℓ analysis makes use of the m_T^{min} variable for assigning leptons to the W and Z bosons, the same is used for assigning leptons in the fake factor measurement. For bookkeeping, the trilepton events are labeled as $\ell_{(W \text{ or fake})} \ell_{Z_{\text{lead}}} \ell_{Z_{\text{sublead}}}$, where each lepton can either be tight or loose (labeled as T or L, respectively). Thus, a true WZ event with three tight leptons would be labeled TTT, while a true Z +jets/ Z + γ event where the fake lepton satisfies loose and the Z leptons satisfy tight would be labeled LTT. As the TLT and TTL configurations primarily occur for Z +jets/ Z + γ events where the Z leptons are mispaired, they can safely be ignored during the fake factor computation. Checks have been performed which showed that by including these extra events, the statistics of anti-ID events would increase by about 4%. Similarly, events with multiple fake leptons are negligible as long as F is sufficiently small. As a result, only the LTT and TTT events are necessary for computing F .

Although an attempt is made to reduce contribution from processes such as WZ in the fake factor measurement region, some contamination does occur. To ensure that only fake leptons are considered in the measurement of F , simulation is used to remove contamination from events containing prompt leptons. Moreover, as $t\bar{t}$ and the other top-like processes are estimated separately, these must also be subtracted from the ID and anti-ID events which fall into the fake factor measurement region. As will be discussed in Section 7.5.1.2, this subtraction is performed after applying the top-like data-

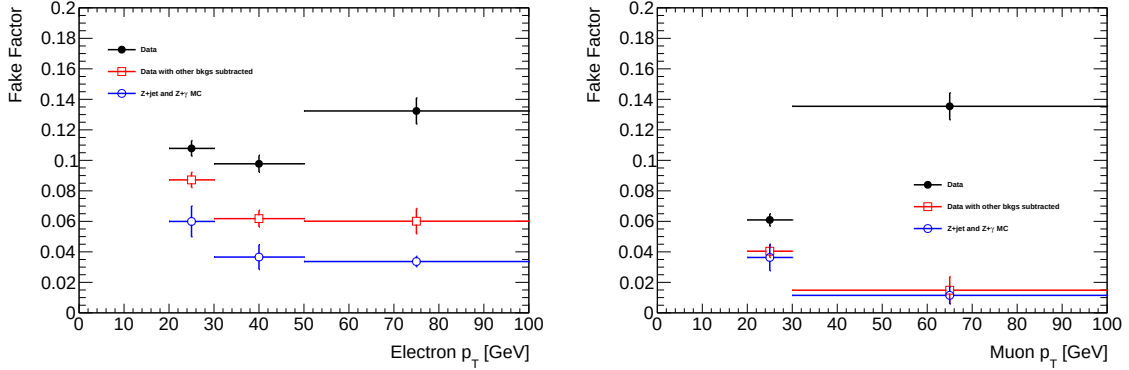


Figure 7.5: Z +jets/ Z + γ fake factors for electrons (left) and muons (right). The fake factors using uncorrected data are shown as black dots; these have significant contamination from WZ , the top-like backgrounds, and other processes. The fake factors used in the analysis are shown as red squares, and these are computed using the data after removing contributions due to these background processes (based on simulated events). These can be compared with the fake factors computed with Z +jets/ Z + γ simulation, which are shown as open blue circles. Perfect agreement between the corrected data fake factors and those obtained in the Z +jets/ Z + γ simulation is not guaranteed, since the inaccurate simulation of fake leptons is precisely why a data-driven approach is used. Note that the uncertainties shown are only statistical.

to-simulation normalization factors derived individually for the ID and anti-ID events. The fake factors measured for the analysis, both before subtracting these backgrounds and after removing their contamination, are shown in Figure 7.5.

These fake factors are applied in the signal, validation, and control regions to events which would fall into a given region except that at least one anti-ID lepton is present. These versions of each signal, validation, and control region are sometimes referred to as the “anti-ID control regions”; these are the regions where data events are collected which have the proper kinematic distributions to represent the fake lepton background, and where the fake factor weights are applied to effectively “promote” an anti-ID lepton to an ID lepton. As mentioned in Section 6.4.1, contamination in these anti-ID control regions is corrected using the simulation. While Section 6.4.1 describes the proper way to handle events with multiple anti-ID leptons, these events were ignored in this analysis as their impact was found to be negligible.

Several sources of uncertainty must be considered for the Z +jets/ Z + γ background estimate. First is the statistical uncertainty on the fake factor, which must be accounted for in the final Z +jets/ Z + γ uncertainty. Then there are two sources of systematic uncertainty, referred to as the diboson subtraction uncertainty and the simulation-based closure uncertainty.

As simulation is used to subtract the diboson contamination from the data in the FF region, the

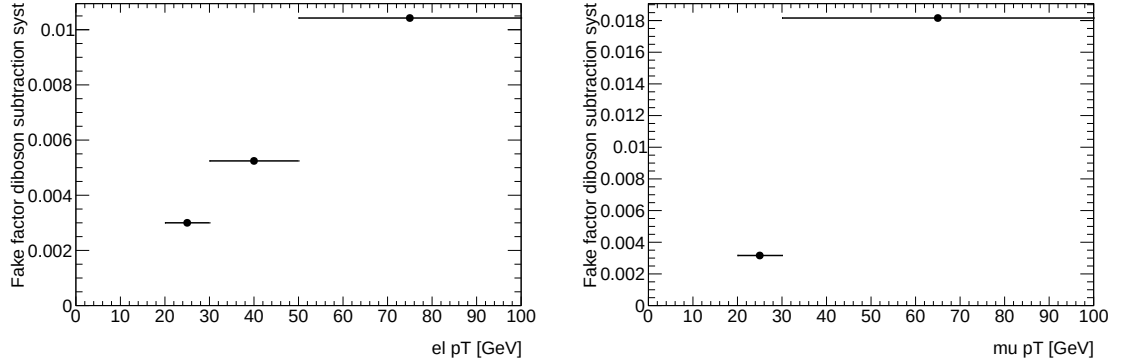


Figure 7.6: Evaluation of the diboson subtraction systematic uncertainty on the fake factor for electrons (left) and muons (right), shown as an absolute uncertainty on the fake factor central values. The difference between the nominal fake factor and the fake factor using a scaled diboson yield is taken as the uncertainty on the diboson subtraction.

uncertainty associated to this subtraction must be evaluated. To do so, the simulated WZ and ZZ yield is scaled up and down by 15%, and the fake factor is then recomputed. This 15% variation corresponds to the WZ cross-section discrepancy between experimental measurements and the NLO theory as of 2016 [156]. While this discrepancy was significantly reduced with the NNLO theoretical predictions, the simulation samples for WZ only account for NLO effects. The largest difference (i.e. either from varying the diboson subtraction up or down) with respect to the nominal fake factor is then used symmetrically as the diboson subtraction uncertainty on the fake factor. This is demonstrated in Figure 7.6.

The kinematic and composition differences between the FF region and the signal region must also be considered, to evaluate the extent of non-closure between the two. To do so, the simulated Z +jets/ Z + γ samples are used, and a simulation-based fake factor is computed in these two kinematic regions. The difference between these two simulation-based fake factors is used as the uncertainty on the MC closure. As multiple signal regions are used in the 3ℓ analysis, but the composition across the various signal regions should not vary much, an inclusive “SR-like” region is used. This region requires three leptons (which can be signal or anti-ID leptons), a b -jet veto, $|m_{\ell\ell} - m_Z| < 10$ GeV, $m_T^{\min} > 60$ GeV, and $E_T^{\text{miss}} > 60$ GeV. These kinematic selection criteria are summarized in Table 7.6. This selection would be inclusive across the six signal regions even with a more stringent criteria of $m_T^{\min} > 110$ GeV, but $m_T^{\min} > 60$ GeV is chosen to enhance the simulation statistics of this region. The evaluation of this uncertainty can be seen in Figure 7.7.

These systematic uncertainties are then added in quadrature to determine a total fake factor

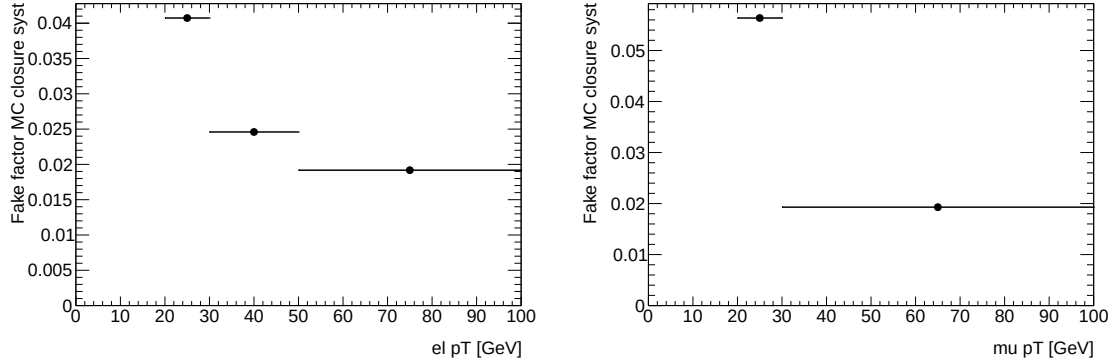


Figure 7.7: Evaluation of the Z +jets/ Z + γ simulation-based closure systematic uncertainty for electrons (left) and muons (right), shown as an absolute uncertainty on the fake factor central values. The difference between the simulation-based fake factor measured in the FF region and the corresponding simulation-based fake factor measured in the SR-like region is used to determine the uncertainty on the closure in the simulation. This is designed to address the kinematic and composition differences between the FF region and the SR-like region. This difference is then added in quadrature with the statistical uncertainties associated to these simulation-based fake factors, and this total is used as the simulation-based closure systematic uncertainty.

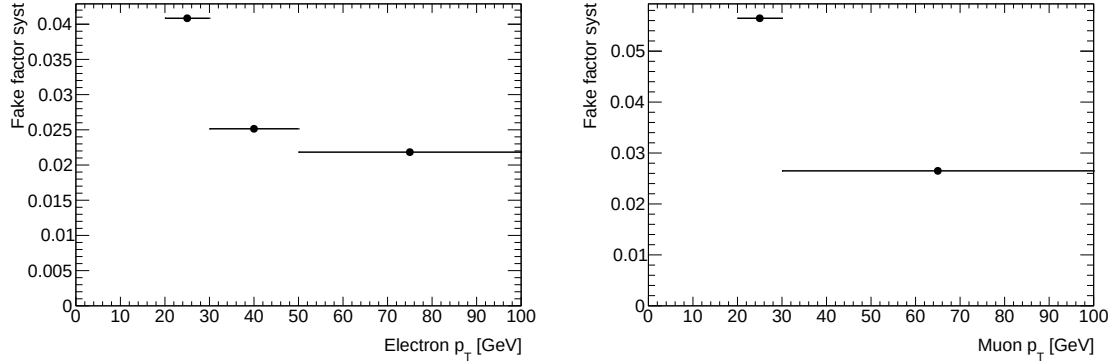


Figure 7.8: Total systematic uncertainty on the fake factor as a function of p_T for the fake electron (left) and fake muon (right) channels, shown as an absolute uncertainty on the fake factor central values. The closure uncertainty is typically dominant, but the diboson subtraction uncertainty is non-negligible at high p_T .

systematic uncertainty. These total uncertainties are shown in Figure 7.8

To validate the fake factor method, a Z +jets/ Z + γ validation region is constructed, referred to as VRZjet. As the FF region uses events with small values of both E_T^{miss} and m_T^{min} , VRZjet is chosen to be the region with $30 \text{ GeV} < m_T^{\text{min}} < 50 \text{ GeV}$ and $E_T^{\text{miss}} < 40 \text{ GeV}$. A depiction of VRZjet, the WZ control and validation regions defined in Table 7.4, and the FF region are shown in Figure 7.9. As with the signal regions, VRZjet also requires SFOS leptons with $|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$. To

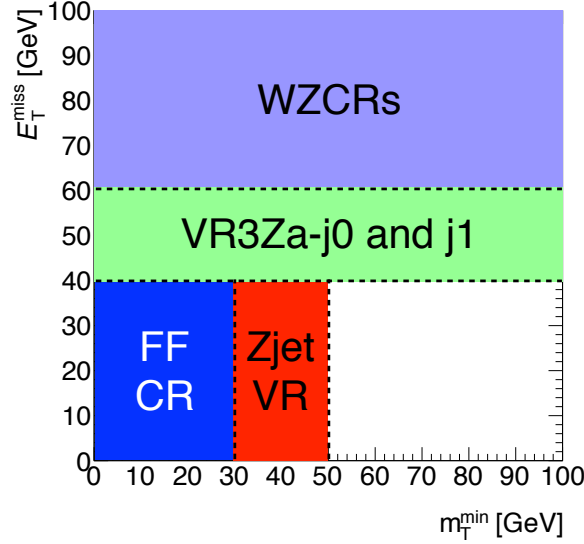


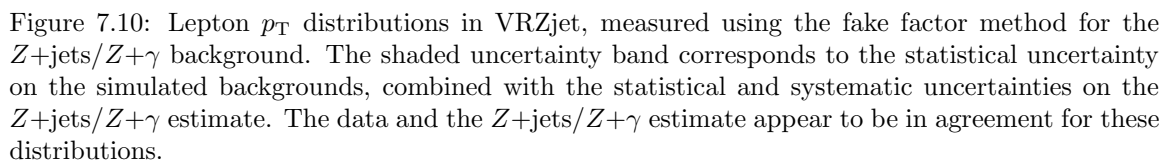
Figure 7.9: Cartoon demonstrating the $m_T^{\min}$ and E_T^{miss} selection used to obtain the FF region and VRZjet. The WZ control and validation regions are also displayed.

increase statistics, this validation region is inclusive in jet multiplicity, and no b -jet veto is imposed; these criteria are summarized in Table 7.6. The $Z+\text{jets}/Z+\gamma$ estimate in this validation region is then measured by looking at the LTT, TLT, and TTL events after subtracting the prompt (and top-like) simulated backgrounds from the data. These events are scaled by the fake factor weights, as described previously in this section. The sum of the $Z+\text{jets}/Z+\gamma$ estimate with the simulation-based backgrounds containing three signal leptons is then compared to the data for events with three signal leptons. The comparison between data and the background estimate for this validation region is shown in Figures 7.10 and 7.11, and good agreement is observed.

7.5.1.2 $t\bar{t}/Wt/WW$ Background Estimation

For top-like fakes ($t\bar{t}$, Wt , and WW), a control region is constructed using different-flavor opposite-sign (DFOS) trilepton events. In other words, events must be of the form $e^\pm e^\pm \mu^\mp$ or $\mu^\pm \mu^\pm e^\mp$, where the two same-flavor leptons must have the same-sign and the different-flavor lepton must have the opposite-sign. This is advantageous because it guarantees that one of the two same-flavor leptons is the fake lepton, and this criteria allows the control region to be very pure in events with top-like fakes.

In addition to the different-flavor opposite-sign requirement, events are required to pass one of the dilepton triggers from Table 7.1. These events must also have $E_T^{\text{miss}} > 60$ GeV and $m_T^{\min} > 60$ GeV,



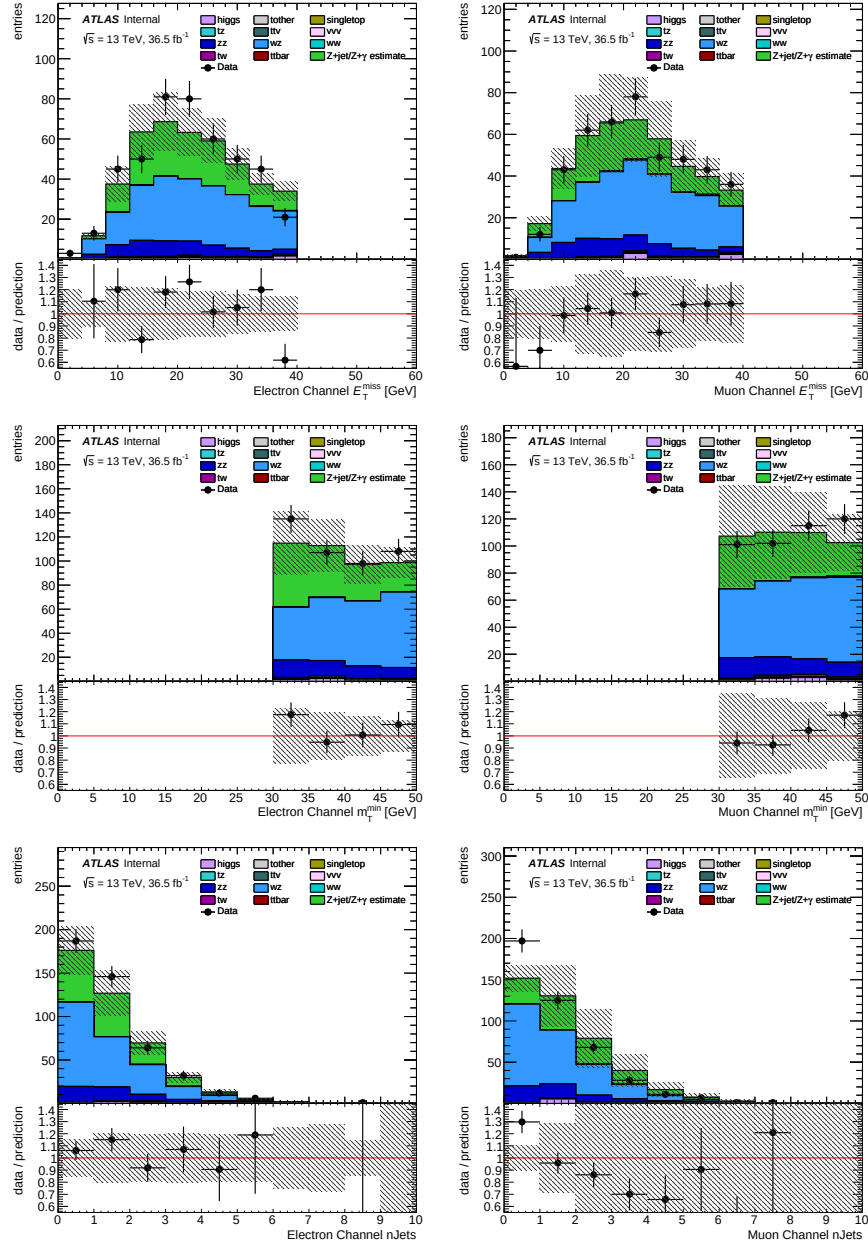


Figure 7.11: Various distributions in VRZjet for events where the third lepton is an electron (left) or muon (right), measured using the fake factor method for the Z +jets/ Z + γ background. The shaded uncertainty band corresponds to the statistical uncertainty on the simulated backgrounds, combined with the statistical and systematic uncertainties on the Z +jets/ Z + γ estimate. The data and the Z +jets/ Z + γ estimate appear to be in agreement for these distributions, though there is some tension in the $n_{\text{jet}} = 0$ bin of the muon channel's jet multiplicity distribution.

	$m_{\ell\ell\ell}$	$ m_{\ell\ell} - m_Z $	E_T^{miss}	m_T^{min}	SFOS pair	DFOS pair	$n_{b\text{-jets}}$
top-like CR	—	—	$> 60 \text{ GeV}$	$> 60 \text{ GeV}$	vetoed	required	—
VR3-offZb	$\not\in [81.2, 101.2]$	$\not\in [81.2, 101.2]$	$> 40 \text{ GeV}$	—	required	vetoed	> 0

Table 7.7: Summary of regions used for the top-like background estimate in the 3ℓ search. The top-like control region is used for measuring the top-like data-to-simulation normalization factors, which are then applied to simulated top-like events in the analysis signal, validation, and control regions. VR3-offZb is used to validate the top-like background estimate.

to allow for kinematic similarities between this control region and the signal regions; ideally more stringent requirements on E_T^{miss} and m_T^{min} would be imposed to allow for better alignment with the signal regions, but statistics would suffer. Also for increased statistics, no requirement is applied on the number of b -tagged jets in the event. The selection criteria for the top-like CR are summarized in Table 7.7.

This control region is used to determine data-to-simulation normalization factors to apply to the top-like background events in the signal, validation, and control regions used in the analysis. Normalization factors are determined separately for events likely containing fake electrons and those likely containing fake muons. In addition to being used to estimate top-like events containing three signal leptons, this estimate is also performed using events containing at least one anti-ID lepton (i.e. the LTT, TLT, and TTL events). This is necessary for use in the top-like background estimation which contaminates the $Z+\text{jets}/Z+\gamma$ estimate using the fake factor method.

For the top-like data-to-simulation normalization factors associated with the $Z+\text{jets}/Z+\gamma$ anti-ID control region, an electron normalization factor of 1.04 ± 0.09 is measured, along with a muon normalization factor of 1.05 ± 0.03 . For the events containing three signal leptons, data-to-simulation normalization factors were measured to be 0.99 ± 0.42 for electrons and 2.37 ± 0.89 for muons. The statistical uncertainty on these data-to-simulation normalization factors is propagated to the final estimate, and is used as the systematic uncertainty on the top-like background. While these large uncertainties are unfortunate, the top-like background tends to be a small contributor to the signal regions considered, and thus no action was deemed necessary to improve these for this iteration of the analysis. Future improvements are discussed in Section 7.8.

To validate the top-like fake background estimate, the region VR3-offZb is used. This validation region requires same-flavor opposite-sign events containing at least one b -jet. This region also requires $E_T^{\text{miss}} > 40 \text{ GeV}$ and for the $m_{\ell\ell\ell}$ and $m_{\ell\ell}$ to be at least 10 GeV away from the Z mass. The m_T^{min} algorithm is used to assign the leptons to the W and Z in the event, but no m_T^{min} requirement is applied. These selection criteria for VR3-offZb are summarized in Table 7.7. The kinematic

distributions in this region after applying the top-like data-to-simulation normalization factors are shown in Figures 7.12 and 7.13.

7.6 Results

Both experimental and theoretical systematic uncertainties must be considered when evaluating the backgrounds. The primary systematic uncertainties affecting the results include the jet energy scale and resolution, theoretical uncertainties associated with the modeling of the simulated events (e.g. the choice of renormalization, factorization, and merging scales used when simulating the events), the reweighting of the pileup profile in simulation to match that of data, the uncertainty of the theoretical cross-sections, the uncertainties associated with the WZ data-to-simulation normalization procedure, and the uncertainties on the reducible backgrounds. Further details on these uncertainties can be found in [7].

As mentioned in Section 6.3, the `HistFitter` package [120] is used for the statistical interpretation of the results. This is done using a profile likelihood method [157] with the systematic uncertainties treated as nuisance parameters in the likelihood. A background-only fit is performed where the control regions are fit to the data under the assumption of zero signal events; this fit allows for the extraction of the fit parameters, which in this analysis corresponds to the data-to-simulation normalization factors for the WZ background. The resulting unblinded signal region yields for the data as well as the final background estimate (after applying the normalization factors to the simulated events) are shown in Table 7.8. The E_T^{miss} distributions for each of these signal regions are shown in Figure 7.14.

No significant excesses above the Standard Model predictions are observed. As a result, exclusion limits are computed using the CL_s method [158]. Model-dependent limits are set on the simplified models by statistically combining the non-overlapping (“exclusive”) signal regions. The limits from the trilepton search were then overlaid with the limits from a dilepton search for the same wino-bino model, and the total exclusion limits (using the CL_s value from whichever channel had the better expected limit for each signal model point) on this simplified model are shown in Figure 7.15. This results in the exclusion of chargino and neutralino NLSP masses in the wino-bino model up to 580 GeV for massless LSPs, though there is plenty of room for lighter NLSPs provided the LSP is not massless. In addition to these model-dependent limits, generic model-independent limits are also determined, and are shown in Table 7.9.

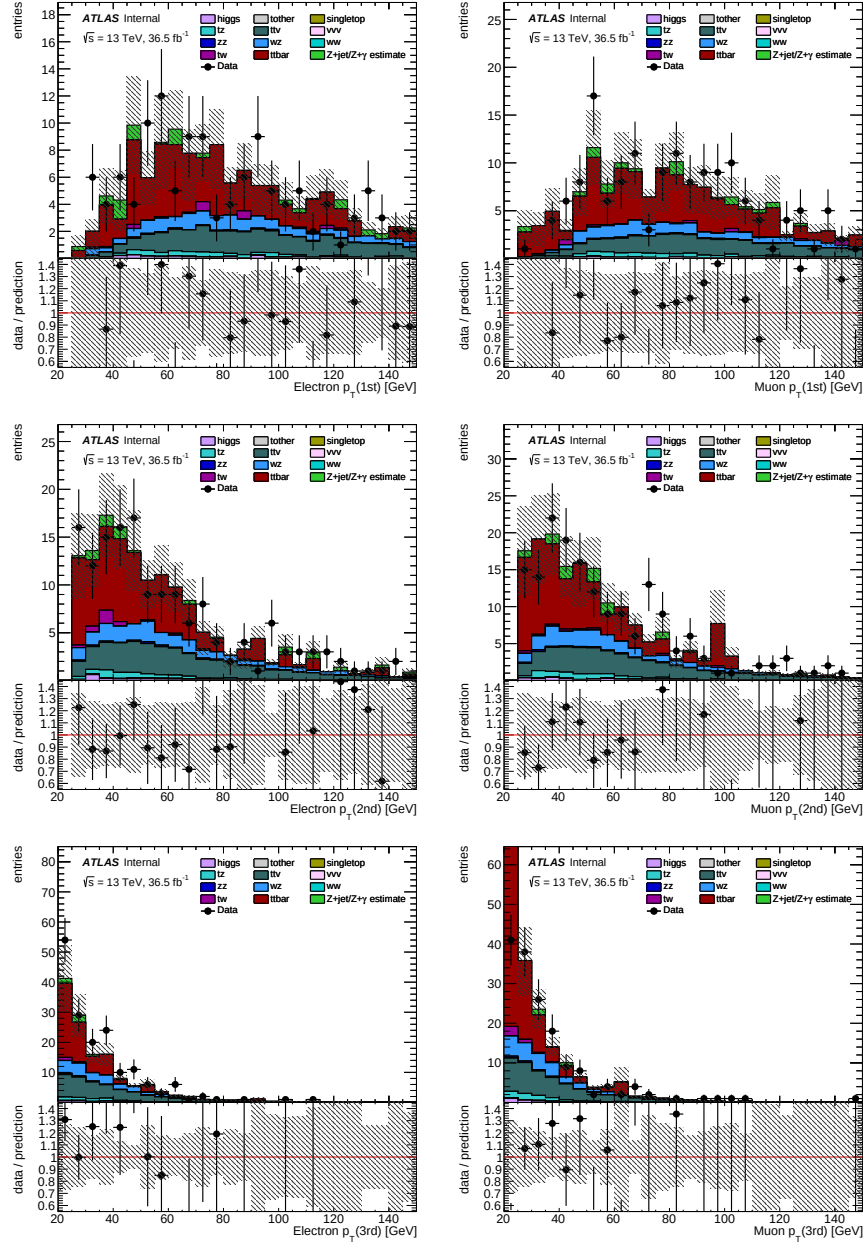
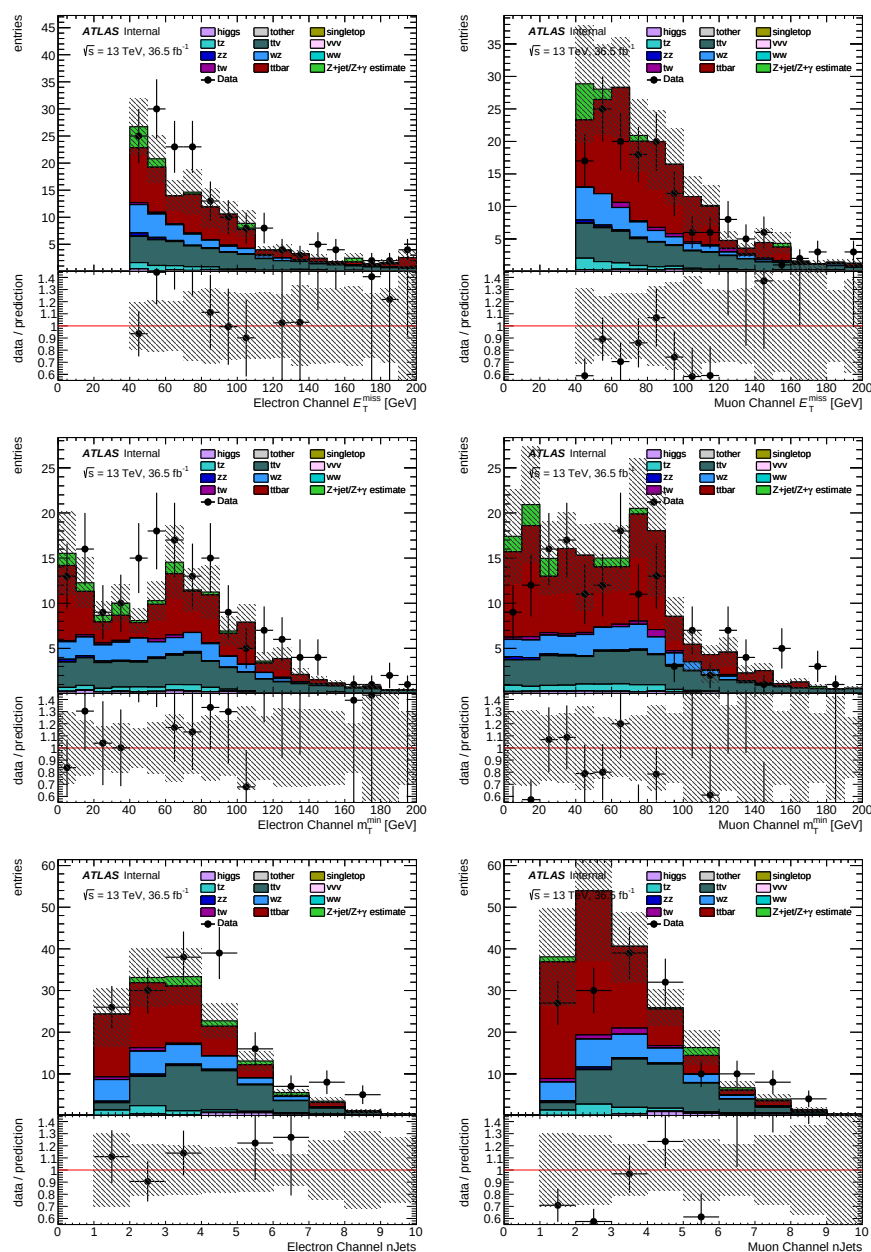


Figure 7.12: Lepton p_T distributions in VR3-offZb, measured using data-to-simulation normalization factors for the top-like backgrounds. The shaded uncertainty band corresponds to the statistical uncertainty on the simulated backgrounds, combined with the statistical and systematic uncertainties on the top-like background estimate. The data and the top-like estimate appear to generally be in agreement for these distributions, though there is a significant overestimate of the fake muons in the third lepton p_T distribution (which reaches roughly 75 entries in that discrepant bin, and has a data-to-MC ratio of 0.54).



SR3-	WZ-0Ja	WZ-0Jb	WZ-0Jc	WZ-1Ja	WZ-1Jb	WZ-1Jc
Observed	21	1	2	1	3	4
Total SM	21.7 ± 2.9	2.7 ± 0.5	1.56 ± 0.33	2.2 ± 0.5	1.82 ± 0.26	1.26 ± 0.34
WZ	19.5 ± 2.9	2.5 ± 0.5	1.33 ± 0.31	1.8 ± 0.5	1.49 ± 0.22	0.92 ± 0.28
ZZ	0.81 ± 0.23	0.06 ± 0.03	0.05 ± 0.01	0.05 ± 0.02	0.02 ± 0.01	—
VVV	0.31 ± 0.07	0.13 ± 0.04	0.13 ± 0.03	0.11 ± 0.02	0.12 ± 0.03	0.23 ± 0.05
$t\bar{t}V$	0.04 ± 0.02	0.01 ± 0.01	0.01 ± 0.01	0.14 ± 0.04	0.12 ± 0.02	0.08 ± 0.02
Higgs	—	—	—	0.01 ± 0.00	—	—
Reducible	1.1 ± 0.5	0.02 ± 0.01	0.04 ± 0.02	0.11 ± 0.06	0.07 ± 0.04	0.01 ± 0.00

Table 7.8: Observed and expected event yields in the signal regions of the 3ℓ search. All systematic and statistical uncertainties are included in the background-only fit used to estimate the Standard Model background prediction. The “reducible” category combines Z +jets/ Z + γ and the top-like backgrounds [7].

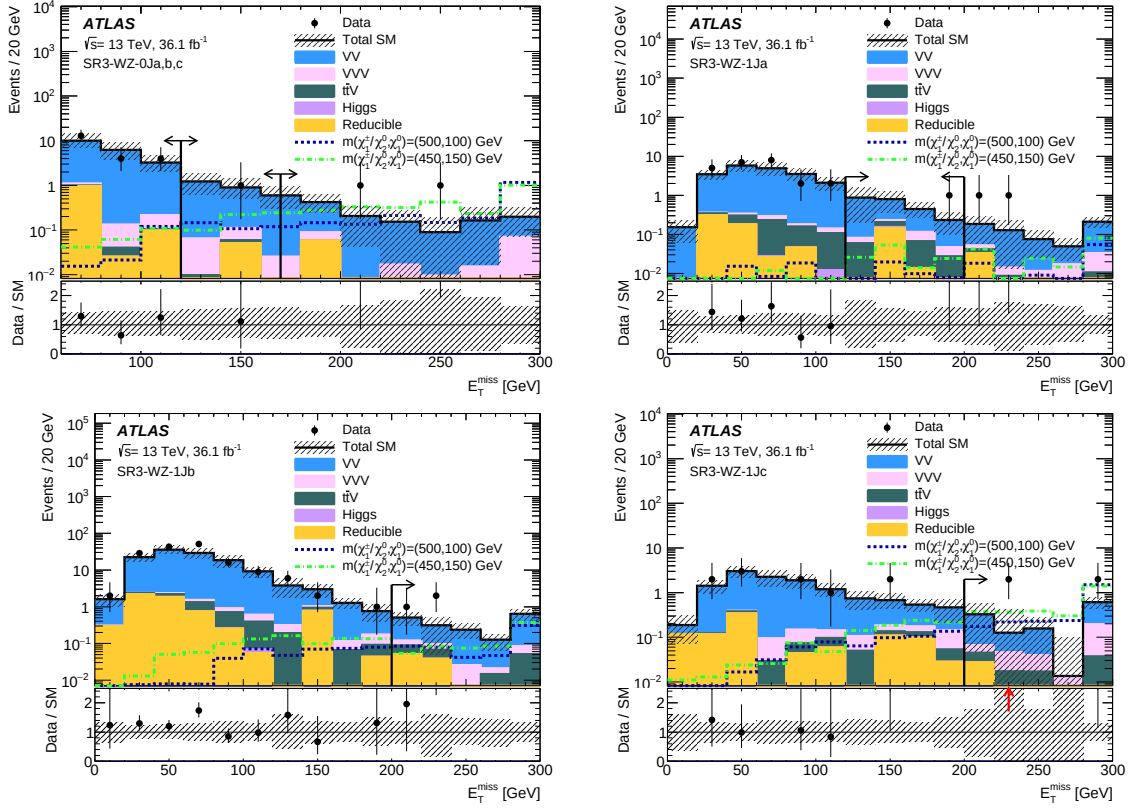


Figure 7.14: E_T^{miss} distributions in the 3ℓ signal regions. The upper-left plot shows SR3-WZ-0Ja,b,c, the upper-right plot shows SR3-WZ-1Ja, the bottom-left plot shows SR3-WZ-1Jb, and the bottom-right plot shows SR3-WZ-1Jc. The uncertainty bands shown include all of the systematic and statistical uncertainties. Simulated signal distributions are overlaid for comparison. The final bin in each histogram also contains the events in the overflow bin [7].

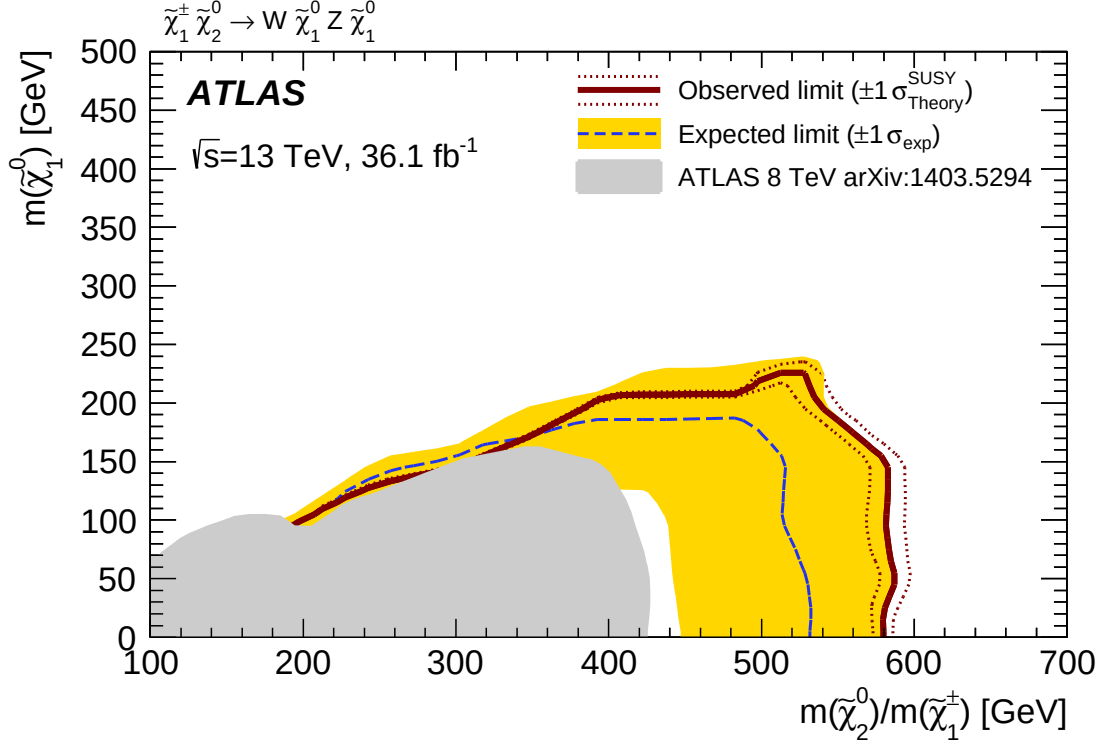


Figure 7.15: The observed (solid red line) and expected (dashed blue line) exclusion limits on the wino-bino simplified model are shown. These limits are for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with decays via W and Z bosons to the two and three lepton final states. The shaded yellow band indicates the $\pm 1\sigma$ variations to the expected limit based on the uncertainties on the Standard Model background expectations. The dotted red lines indicate the impact on the observed limit based on the change to the signal cross-section when varying its value by the theoretical uncertainty. All limits are computed at the 95% confidence level [7]. The observed limits on this simplified model as measured by ATLAS in Run 1 are also shown [159].

7.7 Related Searches

There are several ATLAS searches using the same 2015–2016 dataset which are closely related to the trilepton EWK SUSY search described, and which might be of interest to the reader.

First is the dilepton EWK SUSY search, which focuses on the same electroweakino production and subsequent decay to W and Z bosons as the trilepton search, but instead focuses on a final state containing two leptons and jets arising from the decays of the Standard Model bosons, plus E_T^{miss} from the noninteracting LSPs. A diagram of this process can be seen in Figure 7.16. This is the same analysis that was included in the exclusion limits shown in Figure 7.15. In fact, this analysis is so closely related to the trilepton search that both searches are documented in the same

Signal Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle_{\text{obs}}^{95}[\text{fb}]$	S_{obs}^{95}	S_{exp}^{95}	$p(s=0)$	Z
SR3-WZ-0Ja	21	21.7 ± 2.9	0.35	12.8	14_{-5}^{+3}	0.5	0
SR3-WZ-0Jb	1	2.7 ± 0.5	0.10	3.7	$4.6_{-0.9}^{+2.1}$	0.5	0
SR3-WZ-0Jc	2	1.6 ± 0.3	0.13	4.8	$4.1_{-0.7}^{+1.7}$	0.28	0.57
SR3-WZ-1Ja	1	2.2 ± 0.5	0.09	3.2	$4.5_{-1.3}^{+1.6}$	0.5	0
SR3-WZ-1Jb	3	1.8 ± 0.3	0.16	5.6	$4.3_{-0.9}^{+1.7}$	0.18	0.91
SR3-WZ-1Jc	4	1.3 ± 0.3	0.20	7.2	$4.2_{-0.4}^{+1.7}$	0.03	1.8

Table 7.9: Summary of yields and model-independent limits in the signal regions of the 3ℓ analysis. The observed (N_{obs}) and expected background (N_{exp}) yields in the signal regions are shown alongside the model-independent upper limits on the signal cross-section ($\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$) at the 95% confidence level. The observed (S_{obs}^{95}) and expected (S_{exp}^{95}) upper limits on the number of generic signal events—that is, any processes which could originate beyond the Standard Model—are also shown. The uncertainties on the expected yields and expected upper limits correspond to the total statistical plus systematic uncertainty on the background estimate. The last two columns show the p -value and the significance for the background-only hypothesis. In signal regions where the data yield is smaller than the expected value, the p -value is set to 0.5 and the significance is set to 0 [7].

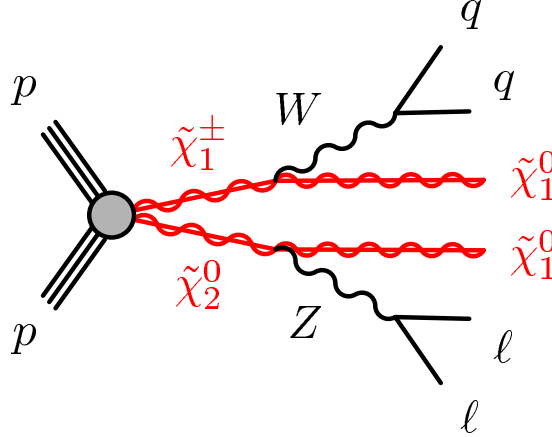


Figure 7.16: Diagram for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with decays via W and Z bosons to two leptons [7].

paper [7].

A second related analysis is the search for electroweakino production resulting in a trilepton final state via slepton-mediated decays. In such a scenario, the slepton is assumed to have a mass between that of the produced electroweakinos and the LSP, thus allowing for a decay chain involving sleptons, as seen in Figure 7.17. More assumptions are necessary in such a model, since the slepton generically does not need to have a mass which is between that of $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. The benefit of this model is that the sleptons always decay leptonically, as opposed to the W and Z which do so only a fraction of the time. As a result, higher electroweakino masses can be excluded for this

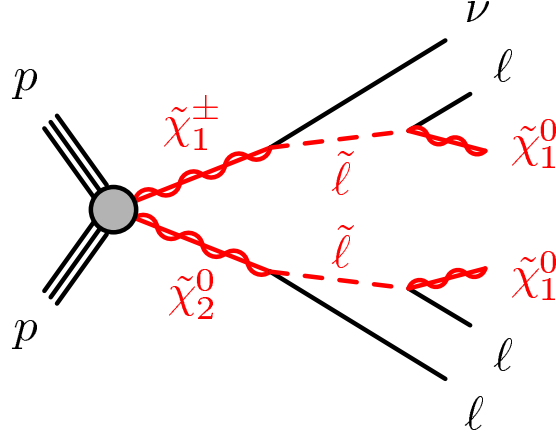


Figure 7.17: Diagram for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with decays via sleptons to three leptons [7].

model, though more assumptions are necessary. The exclusion limits on this scenario can be seen in Figure 7.18. This analysis was also documented in the same paper as the trilepton EWK SUSY analysis discussed in this chapter [7].

Another ATLAS trilepton EWK SUSY search focusing on the same wino-bino model and decays via W and Z bosons was also performed with the 2015–2016 data. This search used a different methodology for defining the analysis, namely the Recursive Jigsaw Reconstruction (RJR) technique [161–163]. This technique attempts to distinguish signal from background by recursively reconstructing the kinematics of intermediate particles in the process under consideration. This is done by exploiting the rest frames of these particles and making assumptions about any missing information due to noninteracting particles in the final state. This results in a complementary set of kinematic variables for use in the analysis, and ultimately a complementary phase space in which to search for new physics. The RJR-based trilepton analysis results are shown in Figure 7.19, where several excesses in data above the Standard Model expectation are observed in the signal regions used by the search. These excesses have significances of 2.1σ and 3.0σ in the SR3 ℓ _Low and SR3 ℓ _ISR regions, respectively. These excesses could be a hint of new physics, or may be statistical fluctuations. Analysis of the full ATLAS Run 2 dataset with roughly 140 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ data is currently underway, and should help to discriminate between these two possibilities.

Finally, ATLAS has performed a search for electroweakino production in scenarios where the NLSP and LSP are similar in mass, resulting in compressed final states. This is the focus of Chapter 8.

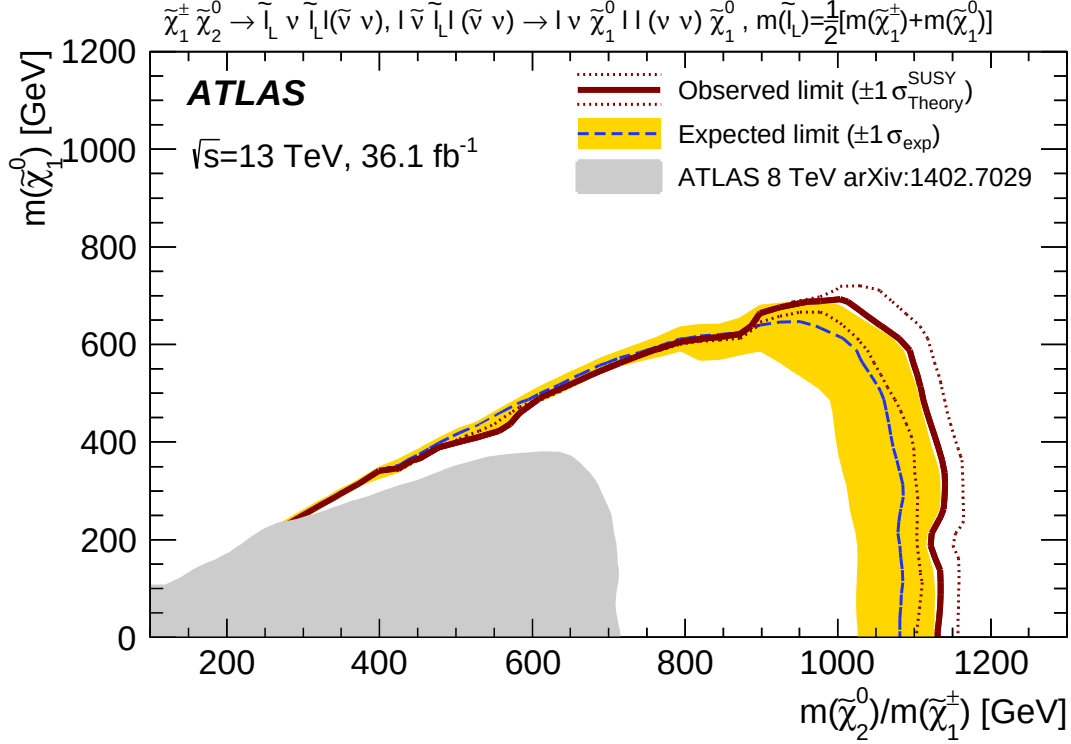


Figure 7.18: The observed (solid red line) and expected (dashed blue line) exclusion limits are shown for a simplified model of wino NLSP production followed by decays to bino LSPs via intermediate sleptons, in the three lepton final state. The shaded yellow band indicates the $\pm 1\sigma$ variations to the expected limit based on the uncertainties on the Standard Model background expectations. The dotted red lines indicate the impact on the observed limit based on the change to the signal cross-section when varying its value by the theoretical uncertainty. All limits are computed at the 95% confidence level [7]. The observed limits on this simplified model as measured by ATLAS in Run 1 are also shown [160].

7.8 Future Improvements and Searches

With the full Run 2 dataset, which is nearly four times larger than that of the 2015–2016 dataset, the conventional trilepton EWK SUSY search should be performed again. The large increase to the total integrated luminosity should improve the analysis sensitivity and allow ATLAS to either extend the exclusion limits to higher NLSP and LSP masses, or potentially find evidence for new physics if the masses of the new particles are within reach.

Another worthwhile direction for ATLAS to pursue is to perform a trilepton analysis targeting the region of Figure 6.5 with $m(\tilde{\chi}_1^0) \leq m(\tilde{\chi}_2^0) \leq m(\tilde{\chi}_1^0) + m_Z$. Although this region is difficult due to the off-shell Z boson present in the final state, this is an uncovered region of phase space for

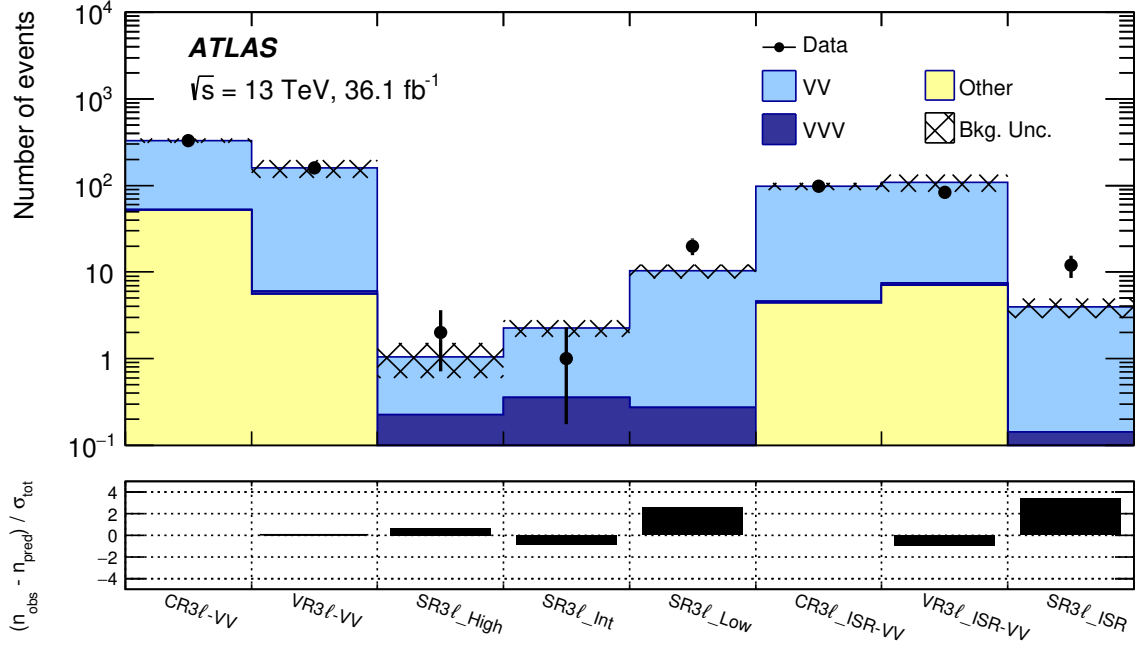


Figure 7.19: Summary of results from the RJR trilepton analysis. Excesses were observed in several signal regions, including a 2.1σ excess in $\text{SR}3\ell_{\text{Low}}$ and a 3.0σ excess in $\text{SR}3\ell_{\text{ISR}}$ [161].

ATLAS in Run 2. This is closely related to the compressed dilepton EWK SUSY search presented in Chapter 8, though it is likely that a trilepton analysis in this region would be more sensitive at larger mass splittings than the compressed dilepton analysis.

Finally, as mentioned in Section 7.7, the excess observed in the RJR trilepton analysis must be understood. To better understand the source of the excess, an “RJR mimic” trilepton analysis is currently underway, which attempts to target the same events as the RJR analysis but relies on more conventional kinematic variables than those used by the RJR technique. For example, rather than using the RJR variable p_{T}^{CM} , defined as the vector sum of the transverse momenta of the invisible system as computed in the center-of-mass frame, the RJR mimic approach simply uses $E_{\text{T}}^{\text{miss}}$; similar translations of the RJR variables are used throughout the RJR mimic analysis. As part of this RJR mimic analysis, the same approach for fake lepton estimation as discussed in Section 7.5.1 is used, though some improvements to the methodology are also included. These improvements are in part to simultaneously ensure that the same background estimate will also be useful for the off-shell trilepton analysis mentioned above, which will have to rely on lower p_{T} leptons in order to efficiently target the compressed region. For instance, the Z +jets/ Z + γ validation region from Table 7.6 is still used, but an additional requirement on the trilepton invariant mass $m_{\ell\ell\ell}$ is also imposed. This is done

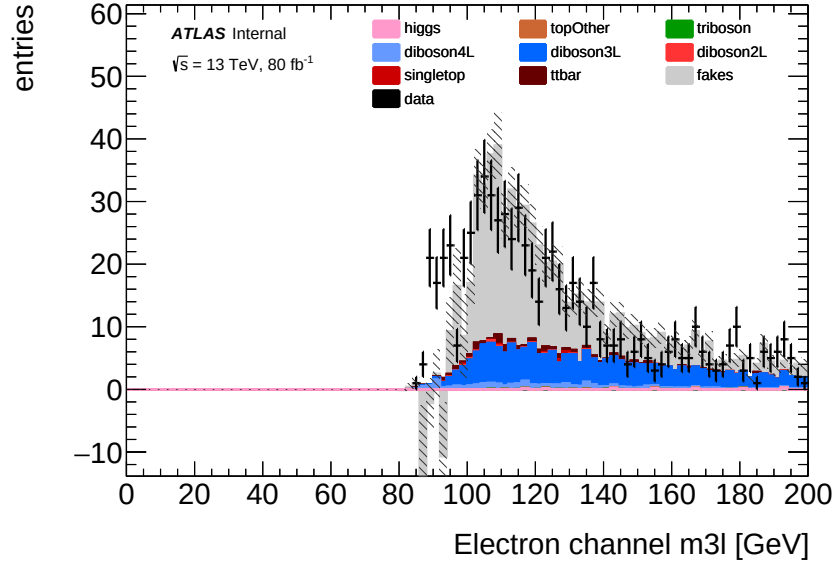


Figure 7.20: $m_{\ell\ell\ell}$ distribution in the Z +jets/ Z + γ validation region for events where an electron is the unpaired lepton (i.e. eee and $\mu\mu e$ events), studied using 80 fb^{-1} of 2015–2017 data as part of the RJR mimic trilepton analysis. As the $m_{\ell\ell\ell}$ distribution is not well-produced near m_Z , this region is vetoed in the RJR mimic analysis; this is likely due to $Z \rightarrow \ell\ell$ events where a photon radiates off of one of the leptons and then either converts to a pair of electrons or is improperly reconstructed as an electron. While the fake factor method would ideally estimate this background properly, it is nontrivial to do so: the fake lepton composition for $m_{\ell\ell\ell}$ near m_Z is likely to be dominated by photon conversions, while the composition in the rest of the distribution is likely to be more balanced between the potential sources of fake leptons. Additional work would be necessary to do anything more sophisticated to address this than to veto $m_{\ell\ell\ell}$ near m_Z .

to suppress backgrounds from $Z \rightarrow \ell\ell$ events where a photon radiates off of one of the leptons and then either converts to a pair of electrons or is improperly reconstructed as an electron, thus resulting in an $m_{\ell\ell\ell}$ value near m_Z ; Figure 7.20 shows that this region would be poorly modeled without this requirement, which also motivates the use of it throughout the RJR mimic analysis. This was particularly found to be necessary once the lepton p_T thresholds for this validation region were relaxed from $p_T > 20\text{ GeV}$ down to $p_T > 10\text{ GeV}$. Similarly, the top-like control region from Table 7.7 was found to benefit from a veto of the $|m_{\ell\ell} - m_Z| < 10\text{ GeV}$ region for the $e^\pm e^\pm \mu^\mp$ events; this is due to charge misidentification of electrons, and can be seen in Figure 7.21.

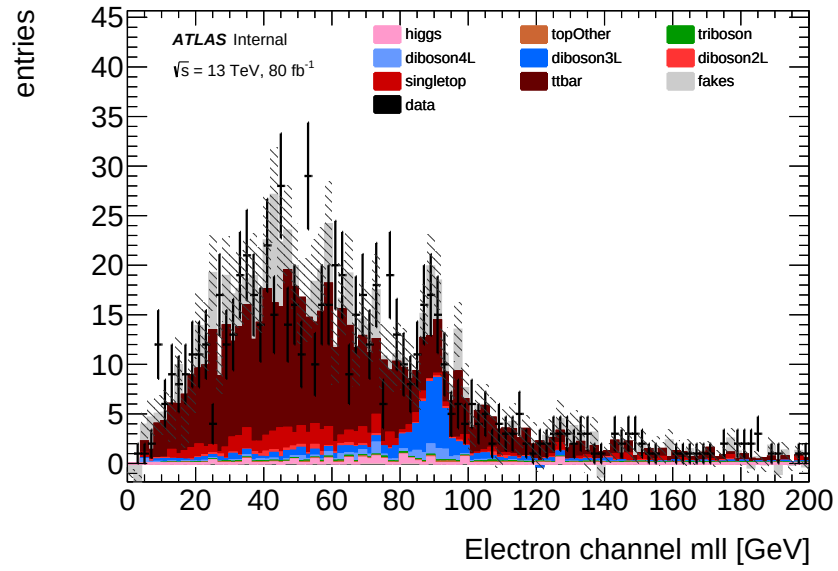


Figure 7.21: $m_{\ell\ell}$ distribution for same-sign leptons in the top-like control region for $e^{\pm}e^{\pm}\mu^{\mp}$ events, studied using 80 fb^{-1} of 2015–2017 data as part of the RJR mimic trilepton analysis. While the m_Z peak is well-modeled, it is better to simply veto this peak in order to increase the purity of events from top-like processes in this region.

CHAPTER 8

Search for Compressed EWK SUSY using Soft Leptons

8.1 Motivation and Models Considered

The compressed EWK SUSY analysis focuses on a search for electroweak production of SUSY particles in scenarios where the mass spectra for the SUSY states produced are compressed. The final states considered contain two soft (i.e. low p_T) same-flavor opposite-sign leptons as well as large E_T^{miss} . Two signal topologies are considered:

1. Pair production of electroweakinos (either $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ or $\tilde{\chi}_2^0 \tilde{\chi}_1^0$), resulting in soft same-flavor opposite-sign lepton pairs from off-shell Z^* decays.
2. Pair production of sleptons, where each slepton decays to a lepton and the $\tilde{\chi}_1^0$ LSP. The slepton mass is nearby in mass to the LSP, and thus the final state leptons for this scenario are also soft.

The electroweakino final state is the primary focus of this thesis; however, the search for the slepton final state is very similar and will also be covered, albeit with less attention at times. Diagrams for these two types of signal processes can be seen in Figure 8.1.

Several signal models discussed in Section 6.1 motivate this search. As mentioned, the Higgsino LSP simplified model is a well-motivated potential solution to naturalness, since this model results in a Higgsino mass near the weak scale, as required at tree level in the MSSM. This model automatically results in a compressed mass spectrum for the light electroweakinos, with mass splittings ranging from 100s of MeV to tens of GeV. The analysis was primarily designed to look for these light Higgsinos, since they naturally have this compressed mass spectrum. Another signal model

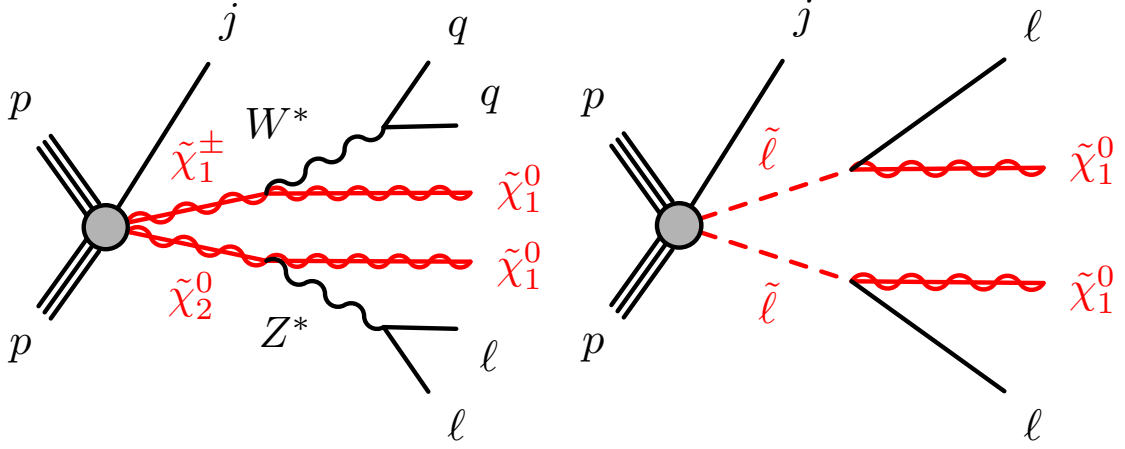


Figure 8.1: Diagrams of the signal processes considered in the compressed EWK search. Left: $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production followed by decays via $W^* \rightarrow qq$ and $Z^* \rightarrow \ell^+ \ell^-$. The jets from the W^* decay are not used in the search as they are typically too soft to be reconstructed. The search relies on a high p_T ISR jet to boost the system; this allows for a large E_T^{miss} signature from the noninteracting LSPs. Right: slepton pair production followed by decays to a lepton and the LSP. This scenario also relies on a high p_T ISR jet to boost the system in order to have a E_T^{miss} signature which can be used to discriminate against background [1].

considered is the wino-bino model, which is motivated by dark matter constraints. While the wino-bino model does not specifically require the electroweakinos to be compressed, the masses of these electroweakinos can take on a wide range of values, depending on the values of M_1 , M_2 , and the other parameters from Equation 6.1. The wino-bino model with a compressed electroweakino mass spectrum is just as motivated as the wino-bino model with a non-compressed mass spectrum, and thus it is worthwhile to search for this model in the compressed scenario. Finally, the slepton model is also motivated by dark matter constraints in scenarios where the slepton mass is near the weak scale while the LSP is a pure bino, and the mass splitting between the slepton and the LSP is small [1].

Prior to this search, the strongest limits on the compressed EWK SUSY models considered came from the Large Electron Positron (LEP) experiments in results published in the early 2000s [164–174]. The combined LEP limits on the Higgsino LSP simplified model are in Figure 8.2, shown as a function of the $\tilde{\chi}_1^\pm$ mass and the mass splitting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$.

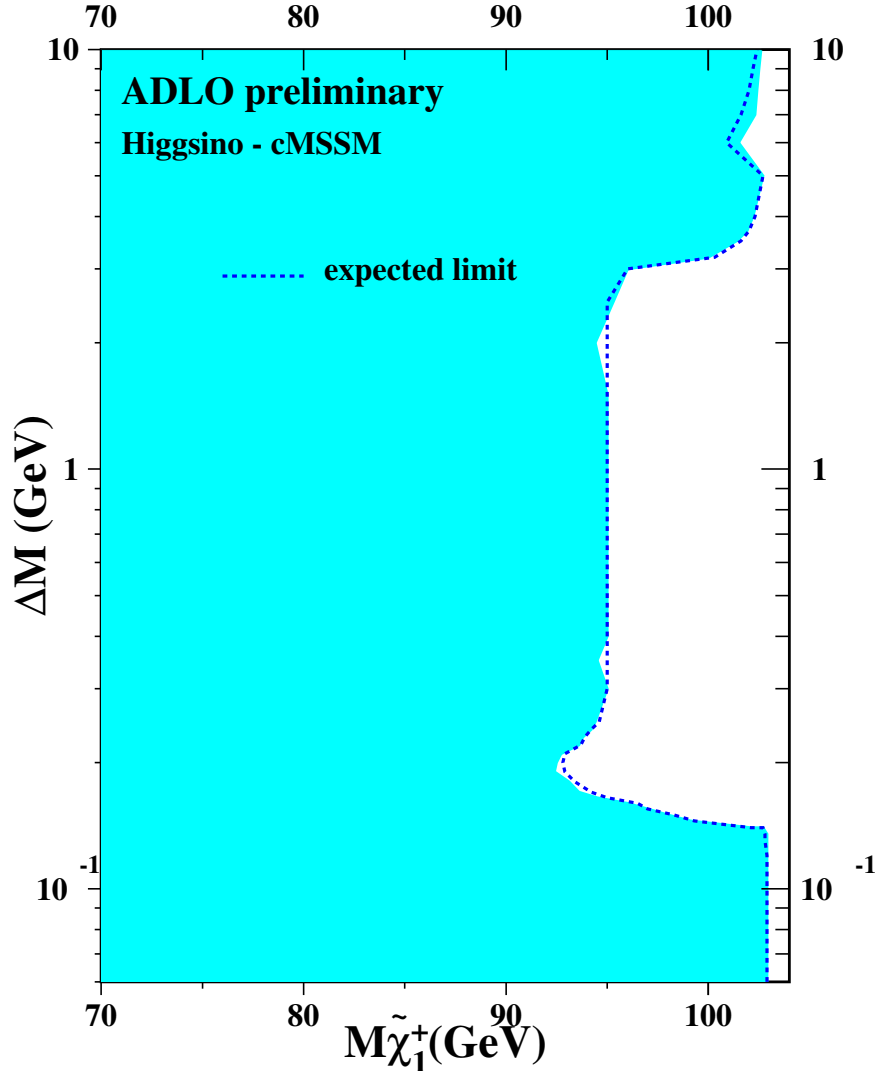


Figure 8.2: LEP limits on the Higgsino LSP simplified model, shown as a function of the $\tilde{\chi}_1^\pm$ mass and $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$. The dashed blue line shows the expected limit, while the shaded cyan region shows the observed limit. These results are the combined limits from the four LEP experiments (ALEPH, DELPHI, L3, and OPAL; collectively referred to as “ADLO”) [164].

2015	2016
HLT_xe70_mht	HLT_xe90_mht_L1XE50
	HLT_xe100_mht_L1XE50
	HLT_xe110_mht_L1XE50

Table 8.1: List of the primary lowest unprescaled E_T^{miss} triggers used in 2015–2016. The string “xe” indicates that the trigger imposes a E_T^{miss} requirement, and the number that follows the string indicates the p_T threshold in GeV. Note that in 2016 the p_T threshold for this trigger changed as a function of time (hence the three entries in the 2016 column which are all identical other than their p_T thresholds), to cope with the increased luminosity and consequently increased background rates. “mht” is a label for which trigger-level E_T^{miss} algorithm was used; this particular algorithm uses the negative vector sum of the jet momenta to compute the E_T^{miss} [175]. More recently, other algorithms have been employed which have been found to be more effective at keeping rates relatively low as a function of luminosity. All of the triggers in this table require $E_T^{\text{miss}} > 50$ GeV at L1.

8.2 Collision Data and Simulated Event Samples

This analysis relies on 36.1 fb^{-1} of $\sqrt{s} = 13$ TeV data delivered by the LHC and recorded by ATLAS in 2015–2016 during stable data-taking periods. This integrated luminosity value is derived using a methodology similar to that detailed in [121], and the relative uncertainty on the integrated luminosity is 2.1%. The average number of pp interactions per bunch crossing was 13.5 in 2015 and 25 in 2016. As the leptons used in the analysis are expected to typically be lower in p_T than the lepton trigger thresholds, the inclusive E_T^{miss} triggers are used to collect events. These triggers are described in Table 8.1.

Samples of Monte Carlo simulated events are used to model both the signal and specific processes of the SM background. For the SUSY signals, two sets of simplified models [176–178] are used to guide the design of the analysis: one based on direct production of Higgsino states (the Higgsino LSP model), and the other a model involving pair production of sleptons which decay to a pure bino LSP. For the interpretation of the results of the analysis, an additional scenario is considered: a simplified model assuming the production of wino-dominated electroweakinos decaying to a bino LSP (the wino-bino model). In all models considered, the produced electroweakinos or sleptons are assumed to decay promptly.

The Higgsino LSP simplified model includes the production of $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^+ \tilde{\chi}_1^-$. The $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ masses were varied, while the $\tilde{\chi}_1^\pm$ masses were set to $m(\tilde{\chi}_1^\pm) = \frac{1}{2}[m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0)]$. The mass splittings of pure Higgsino LSPs are generated by radiative corrections, and are of the order of hundreds of MeV [179], with larger mass splittings requiring some mixing with wino or bino states. However, in this simplified model, the calculated cross-sections assume electroweakino mixing

matrices corresponding to pure Higgsino $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ states for all mass combinations. The search for electroweakinos exploits a kinematic endpoint in the dilepton invariant mass distribution, where the lepton pair is produced in the decay chain $\tilde{\chi}_2^0 \rightarrow Z^* \tilde{\chi}_1^0, Z^* \rightarrow \ell^+ \ell^-$. Therefore, processes that include production of a $\tilde{\chi}_2^0$ neutralino are most relevant for this search, while $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production contributes little to the overall sensitivity. Example values of cross-sections for $m(\tilde{\chi}_2^0) = 110$ GeV and $m(\tilde{\chi}_1^0) = 100$ GeV are 4.3 ± 0.1 pb for $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ production and 2.73 ± 0.07 pb for $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ production. The branching ratios for $\tilde{\chi}_2^0 \rightarrow Z^* \tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \rightarrow W^* \tilde{\chi}_1^0$ were fixed to 100%. The $Z^* \rightarrow \ell^+ \ell^-$ branching ratios depend on the mass splittings and were computed using SUSY-HIT v1.5b [180], which accounts for finite b -quark and τ -lepton masses. At $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 60$ GeV, the branching ratios for $Z^* \rightarrow e^+ e^-$ and $Z^* \rightarrow \mu^+ \mu^-$ are approximately 3.5%, while in the compressed scenario at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 2$ GeV they increase to 5.1% and 4.9%, respectively, as the Z^* mass falls below the threshold needed to produce pairs of heavy quarks or τ -leptons. The branching ratios for $W^* \rightarrow e\nu$ and $W^* \rightarrow \mu\nu$ also depend on the mass splitting, and increases from 11% for large $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ to 20% for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) < 3$ GeV. Events were generated at leading order with MG5_aMC@NLO v2.4.2 [138] using the NNPDF2.3 LO PDF set [94] with up to two extra partons in the matrix element (ME). The electroweakinos were decayed using MADSPIN [181], and were required to produce at least two leptons (e, μ) in the final state, including those from decays of τ -leptons. The resulting events were interfaced with PYTHIA v8.186 [89] using the A14 set of tuned parameters (tune) [93] to model the parton shower (PS), hadronization, and underlying event. The ME-PS matching was performed using the CKKW-L scheme [142] with the merging scale set to 15 GeV.

The wino-bino simplified model considers $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ production, where the mass of the $\tilde{\chi}_2^0$ is assumed to be equal to that of the $\tilde{\chi}_1^\pm$. The generator configuration as well as the decay branching ratios are consistent with those for the Higgsino LSP samples. Pure wino production cross-sections are used for this model. An example value of the $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ production cross-section for $m(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm) = 110$ GeV is 16.0 ± 0.5 pb. The composition of the mass eigenstates differs between the wino-bino and Higgsino LSP models. This results in different invariant mass spectra of the two leptons originating from the virtual Z^* boson in the $\tilde{\chi}_2^0$ to $\tilde{\chi}_1^0$ decay. The different spectra are illustrated in Figure 8.3, where the leptonic decays modeled by MADSPIN are found to be in good agreement with theoretical predictions that depend on the relative sign of the $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ mass parameters [182], which differs between the Higgsino LSP and wino-bino models considered. Note, however, that the relative sign of the $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ mass parameters in a generic wino-bino model is actually a free parameter, and thus the $m_{\ell\ell}$ distribution shown for the Higgsino LSP model is also possible in the wino-bino scenario

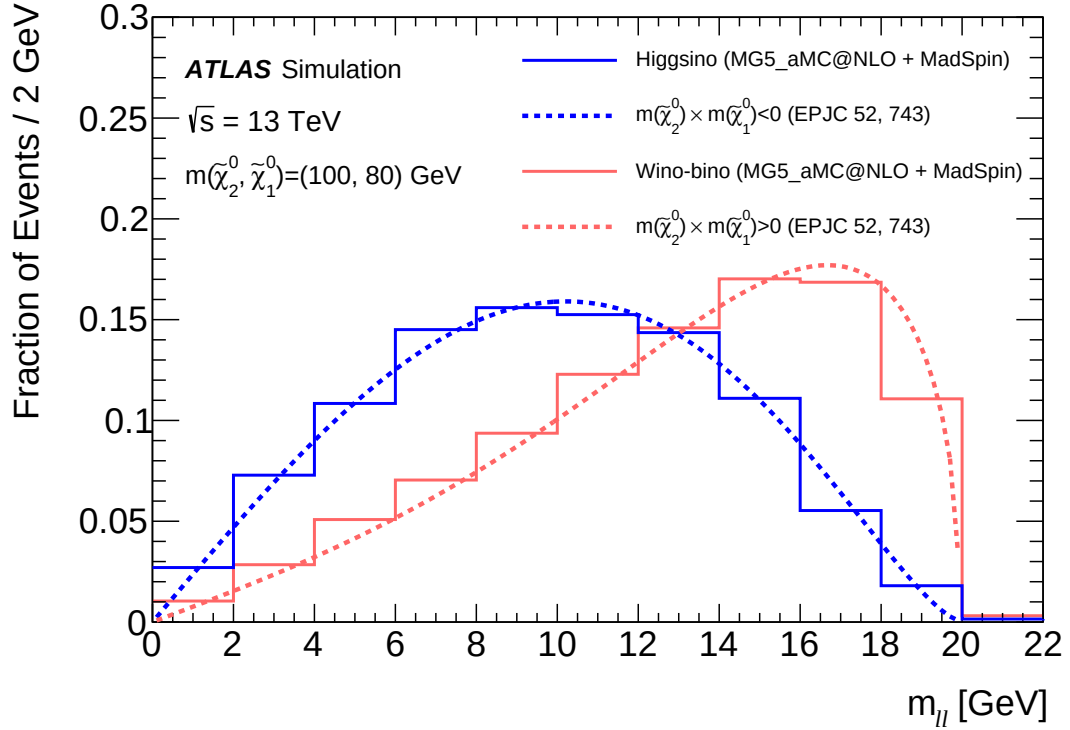


Figure 8.3: Dilepton invariant mass distribution for the Higgsino LSP (blue) and wino-bino (red) simplified models considered in the analysis. The endpoint of the $m_{\ell\ell}$ distribution is determined by the mass difference between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$. The distribution from the simulated events (solid line) is compared with the analytic calculation of the expected distribution (dashed line) based on [182]. The behavior of the mass splitting is determined by whether or not the product of the signed mass eigenvalues are positive or negative. In the Higgsino LSP model this product of signed mass eigenvalues is always negative, while either sign is possible for the wino-bino model. However, in these results the wino-bino model is always assumed to have a positive value for the product of the signed mass eigenvalues [1]. This is discussed further in Section 8.8.

(though this analysis does not consider a wino-bino model with the other $m_{\ell\ell}$ distribution).

The slepton simplified model considers direct pair production of the selectron $\tilde{e}_{L,R}$ and smuon $\tilde{\mu}_{L,R}$, where the subscripts L, R denote the left- or right-handed chirality of the partner electron or muon. The four sleptons are assumed to be mass degenerate, i.e. $m(\tilde{e}_L) = m(\tilde{e}_R) = m(\tilde{\mu}_L) = m(\tilde{\mu}_R)$. An example value of the slepton production cross-section for $m(\tilde{\ell}_{L,R}) = 110$ GeV is 0.55 ± 0.01 pb. The sleptons decay with a 100% branching ratio into the corresponding SM partner lepton and the $\tilde{\chi}_1^0$ neutralino. Events were generated at tree level using MG5_aMC@NLO v2.2.3 and the NNPDF2.3 LO PDF set with up to two additional partons in the matrix element, and interfaced with PYTHIA v8.186 using the CKKW-L prescription for ME-PS matching. The merging scale was set to one quarter of

the slepton mass.

Higgsino LSP, wino-bino, and slepton samples are scaled to signal cross-sections calculated at next-to-leading order (NLO) in the strong coupling, and at next-to-leading-logarithm (NLL) accuracy for soft-gluon resummation, using RESUMMINO v1.0.7 [183–185]. The nominal cross-section and its uncertainty are taken from an envelope of cross-section predictions using different parton distribution function sets and factorization and renormalization scales, as described in [115].

For the SM background processes, SHERPA versions 2.1.1, 2.2.1, and 2.2.2 [123] were used to generate $Z^{(*)}/\gamma^* + \text{jets}$, diboson, and triboson events. Depending on the process, matrix elements were calculated for up to two partons at NLO and up to four partons at LO using COMIX [127] and OPENLOOPS [128], and merged with the SHERPA parton shower [129] according to the ME+PS@NLO prescription [130]. The $Z^{(*)}/\gamma^* + \text{jets}$ and diboson samples provide coverage of dilepton invariant masses down to 0.5 GeV for $Z^{(*)}/\gamma^* \rightarrow e^+e^-/\mu^+\mu^-$, and 3.8 GeV for $Z^{(*)}/\gamma^* \rightarrow \tau^+\tau^-$. POWHEG-BOX v1 and v2 [86, 186, 187] interfaced to PYTHIA v6.428 with the PERUGIA2012 tune [188] were used to simulate $t\bar{t}$ and single top quark production at NLO in the matrix element. POWHEG-BOX v2 was also used with PYTHIA v8.186 to simulate Higgs boson production. MG5_aMC@NLO v2.2.2 with PYTHIA versions 6.428 or 8.186 and the ATLAS A14 tune was used to simulate production of a Higgs boson in association with a W or Z boson, as well as events containing $t\bar{t}$ and one or more electroweak bosons. These processes were generated at NLO in the matrix element except for $t\bar{t} + WW/t\bar{t}$, $t + t\bar{t}$, and $t + Z$, which were generated at LO. Table 8.2 summarizes the background sample generator configurations of the matrix element and parton shower programs, the PDF sets, and the cross-section calculations used for normalization. Further details about the generator settings used for the above described processes can also be found in [135, 139, 189, 190].

To simulate the effects of additional pp collisions, referred to as pileup, additional interactions were generated using the soft QCD processes of PYTHIA 8.186 with the A2 tune [149] and the MSTW2008LO PDF set [95], and were overlaid onto each simulated hard-scatter event. The simulated samples were reweighted to match the pileup distribution observed in the data.

All simulated samples underwent ATLAS detector simulation [97] based on GEANT [96]. The SUSY signal samples employed a fast simulation that parameterizes the response of the calorimeter [122]; the SM background samples used full GEANT simulation. EVTGEN v1.2.0 [148] was employed to model the decay of bottom and charm hadrons in all samples except those generated by SHERPA, which uses its internal modeling [1].

Table 8.2: Summary of simulated samples for Standard Model background processes. The PDF set refers to that used for the matrix element [1].

Process	Matrix element	Parton shower	PDF set	Cross-section
$Z^{(*)}/\gamma^* + \text{jets}$	SHERPA 2.2.1		NNPDF3.0 NNLO [131]	NNLO [133]
Diboson	SHERPA 2.1.1 / 2.2.1 / 2.2.2		NNPDF3.0 NNLO	Generator NLO
Triboson	SHERPA 2.2.1		NNPDF3.0 NNLO	Generator LO, NLO
$t\bar{t}$	POWHEG-Box v2	PYTHIA v6.428	NLO CT10 [90]	NNLO+NNLL [191–194]
t (s -channel)	POWHEG-Box v1	PYTHIA v6.428	NLO CT10	NNLO+NNLL [195]
t (t -channel)	POWHEG-Box v1	PYTHIA v6.428	NLO CT10f4	NNLO+NNLL [196, 197]
$t + W$	POWHEG-Box v1	PYTHIA v6.428	NLO CT10	NNLO+NNLL [137]
$h(\rightarrow \ell\ell, WW)$	POWHEG-Box v2	PYTHIA v8.186	NLO CTEQ6L1 [92]	NLO [198]
$h + W/Z$	MG5_aMC@NLO 2.2.2	PYTHIA v8.186	NNPDF2.3 LO	NLO [198]
$t\bar{t} + W/Z/\gamma^*$	MG5_aMC@NLO 2.3.3	PYTHIA v8.186	NNPDF3.0 LO	NLO [138]
$t\bar{t} + WW/t\bar{t}$	MG5_aMC@NLO 2.2.2	PYTHIA v8.186	NNPDF2.3 LO	NLO [138]
$t + Z$	MG5_aMC@NLO 2.2.1	PYTHIA v6.428	NNPDF2.3 LO	LO [138]
$t + WZ$	MG5_aMC@NLO 2.3.2	PYTHIA v8.186	NNPDF2.3 LO	NLO [138]
$t + t\bar{t}$	MG5_aMC@NLO 2.2.2	PYTHIA v8.186	NNPDF2.3 LO	LO [138]

8.3 Object Reconstruction

Many details of the object reconstruction for this analysis are identical to those described in Section 7.3 for the trilepton analysis. However, some differences do exist, particularly for the lepton identification, the b -tagging working point, and the overlap removal procedure. For completeness, the full event reconstruction procedure is listed here, including some repetition with respect to Section 7.3.

All events considered in the analysis must have a reconstructed primary vertex with at least two $p_T > 400$ MeV tracks associated to the vertex. To select the primary vertex in an event, the vertex with the largest $\sum p_T^2$ of the associated tracks is chosen.

Baseline electrons are chosen to be those which satisfy the VeryLoose identification and which have $p_T > 4.5$ GeV with $|\eta| < 2.47$ and $|z_0 \sin \theta| < 0.5$ mm. Signal electrons are the subset of baseline electrons which also satisfy the Tight identification, the Gradient (Loose) isolation working point, and have $|d_0/\sigma(d_0)| < 5$. Baseline and signal electron candidates which also satisfied the photon conversion reconstruction algorithms (referred to as “ambiguous” electrons) are discarded in order to suppress photon conversion backgrounds. Baseline muons are required to satisfy the Medium identification [69] with $p_T > 4$ GeV, $|\eta| < 2.5$, and $|z_0 \sin \theta| < 0.5$ mm. Signal muons must additionally satisfy the Fix (Tight, Track Only) isolation working point with $|d_0/\sigma(d_0)| < 3$. These criteria are summarized in Table 8.3. Signal processes with small dilepton invariant masses can often result in final state leptons which are nearby one another, and thus one lepton can fall within

Baseline Electrons	Baseline Muons
$p_T > 4.5$ GeV	$p_T > 4$ GeV
$ \eta < 2.47$	$ \eta < 2.5$
Pass VeryLoose identification	Pass Medium identification
$ z_0 \sin \theta < 0.5$ mm	$ z_0 \sin \theta < 0.5$ mm
Veto ambiguous electrons	
Signal Electrons	Signal Muons
$p_T > 4.5$ GeV	$p_T > 4$ GeV
$ \eta < 2.47$	$ \eta < 2.5$
Pass Tight identification	Pass Medium identification
Pass Gradient (Loose) isolation	Pass Fix (Tight, Track Only) isolation
$ d_0/\sigma(d_0) < 5$	$ d_0/\sigma(d_0) < 3$
$ z_0 \sin \theta < 0.5$ mm	$ z_0 \sin \theta < 0.5$ mm
Veto ambiguous electrons	

Table 8.3: Baseline and signal lepton definitions used in the compressed EWK SUSY search.

the isolation cone of the other lepton. Nominally, the isolation criteria would veto such objects; to improve signal acceptance, the contributions from these nearby leptons are excluded from the isolation calculation [1].

Jets used in the analysis are reconstructed with the anti- k_t algorithm [74, 75] with radius parameter $R = 0.4$, using calorimeter topological clusters as input [72]. The energies of these jets are calibrated as described in [150], and the average expected energy contribution from pileup is subtracted according to the jet area [151]. Baseline jets are required to have $p_T > 20$ GeV with $|\eta| < 4.5$ while signal jets must have $p_T > 30$ GeV and $|\eta| < 2.8$. To suppress jets originating from pileup collisions, all jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are required to satisfy the Medium working point of the jet vertex tagger [151], which is used to determine if tracks associated to the jet are likely to have originated from the primary vertex. Any events containing a jet which fail basic quality criteria are rejected, as they may be due to detector noise or non-collision background [152].

b -jets in the analysis are the subset of baseline jets with $|\eta| < 2.5$ which satisfy the 85% efficient working point of the the MV2c10 b -tagging algorithm [153, 154]. Note that while non- b -tagged signal jets use a requirement of $p_T > 30$ GeV, the b -jets only require $p_T > 20$ GeV (and b -jets are always considered to be signal objects). This p_T requirement as well as the 85% efficient working point are used to maximize rejection of $t\bar{t}$ in the signal region.

As leptons and jets can simultaneously satisfy multiple object reconstruction algorithms, an “overlap removal” procedure is necessary to resolve ambiguity and avoid double counting. This overlap removal uses baseline objects as input. The procedure used in this analysis proceeds as follows, in the order shown:

1. Electrons which share an Inner Detector track with a muon are removed, since these may be due to muons which emit bremsstrahlung radiation, followed by a photon conversion into electron pairs.
2. Electrons within $\Delta R_y = 0.2$ of non- b -tagged jets (using the 85% efficient MV2c10 working point) are retained, while the jet is removed since this is likely to be due to an EM shower.
3. Jets that are within $\Delta R_y = 0.4$ of a muon and which have fewer than three associated $p_T > 500$ MeV tracks are removed, to suppress impact from muon bremsstrahlung.
4. Electrons and muons within $\Delta R_y = 0.4$ of any remaining jets are removed, as these are also frequently from semileptonic b -hadron and c -hadron decays.

All signal electrons, muons, and b -tagged jets used in the analysis must be corrected in the simulation to match the reconstruction efficiencies in data [6, 69, 78].

Finally, the missing transverse momentum $\mathbf{p}_T^{\text{miss}}$ (with magnitude E_T^{miss}) is defined to be the negative vector sum of the transverse momenta of all of the objects in the event after overlap removal. An additional soft term is included in this vector sum to account for tracks which are associated with the primary vertex but not with any electron, muon, or jet objects. This is performed after calibrating the energies of the various objects, to ensure that the E_T^{miss} value is as accurate as possible [155].

8.3.1 Challenges Associated with Soft Leptons

The sensitivity of the analysis to compressed final states is very dependent on the ability to keep the lepton p_T thresholds used in the analysis as low as possible. As an example, if the mass splitting between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ is 10 GeV, then the average expected p_T for the leptons which result from the $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$ decay would be half of that mass difference, i.e. $p_T = 5$ GeV each (assuming the Z^* is produced at rest with $m_{\ell\ell} = 10$ GeV). However, 5 GeV is already below the lepton p_T thresholds supported by ATLAS in Run 1! Improving sensitivity to these compressed SUSY scenarios was one of the reasons that the supported lepton p_T thresholds for Run 2 were lowered to 4.5 GeV for electrons and 4 GeV for muons, after significant effort from many people on ATLAS who work on the electron and muon reconstruction algorithms, identification algorithms, isolation algorithms, and the efficiency measurements for each of these steps. This is one of the first ATLAS analyses to make use of leptons with these low p_T thresholds.

Some of the challenges for electron reconstruction have already been described in Section 4.3. As demonstrated by Figure 4.3, the electron cluster reconstruction step is inefficient at low p_T . This is because the EM clusters used to seed the rest of the reconstruction algorithm make use of uncalibrated objects with $\sum E_T > 2.5$ GeV, but the difference between calibrated and uncalibrated energy can be large at low p_T due to energy lost to material interactions. As a result, many low p_T electrons are missed by the electron reconstruction algorithm due to the uncalibrated cluster $\sum E_T$ threshold. Potential improvements to this for Run 3 and beyond are discussed in Section 4.6. Electron identification is also difficult at low p_T , particularly because of the considerable backgrounds which are present. Moreover, the electron identification algorithms have typically been optimized using input variables which were determined to be optimal primarily at higher p_T , and no dedicated studies aimed at improving the low p_T likelihood-based electron identification had been performed until Run 2.

Muon reconstruction and identification both tend to benefit from the smaller amount of background present. However, for $p_T = 4$ GeV muons, there are still many background objects which can fake a muon, including nonprompt muons from both heavy flavor decays and decays of light mesons. Another challenge is also present: the typical muon traveling through the ATLAS detector loses about 3 GeV of its energy before reaching the Muon Spectrometer. As some low p_T muons may be too soft to travel through and leave hits in all layers of the Muon Spectrometer, one potential improvement is to relax the muon identification requirements on the number of Muon Spectrometer hits; this was not done for the analysis presented here, but may be pursued in future versions of the search using the full Run 2 dataset.

The $|z_0 \sin \theta| < 0.5$ mm requirement discussed in Section 6.4.2 is essential for the analysis—without it, a significant number of fake leptons due to soft pileup jets would be present, and would reduce the analysis sensitivity.

The efficiencies (measured with respect to the true generated electrons and muons) to select signal electrons and muons in the analysis using the working points described in Section 8.3 are shown in Figure 8.4. Electrons with $p_T = 4.5$ GeV are 15-20% efficient, rise to be about 55% efficient at $p_T = 10$ GeV, and reach about 65% efficient for $20 \text{ GeV} < p_T < 30 \text{ GeV}$. Muons, meanwhile, are 40-60% efficient at $p_T = 4$ GeV, rise to an efficiency of about 75% at $p_T = 10$ GeV, and are about 80% efficient for $20 \text{ GeV} < p_T < 30 \text{ GeV}$ [1].

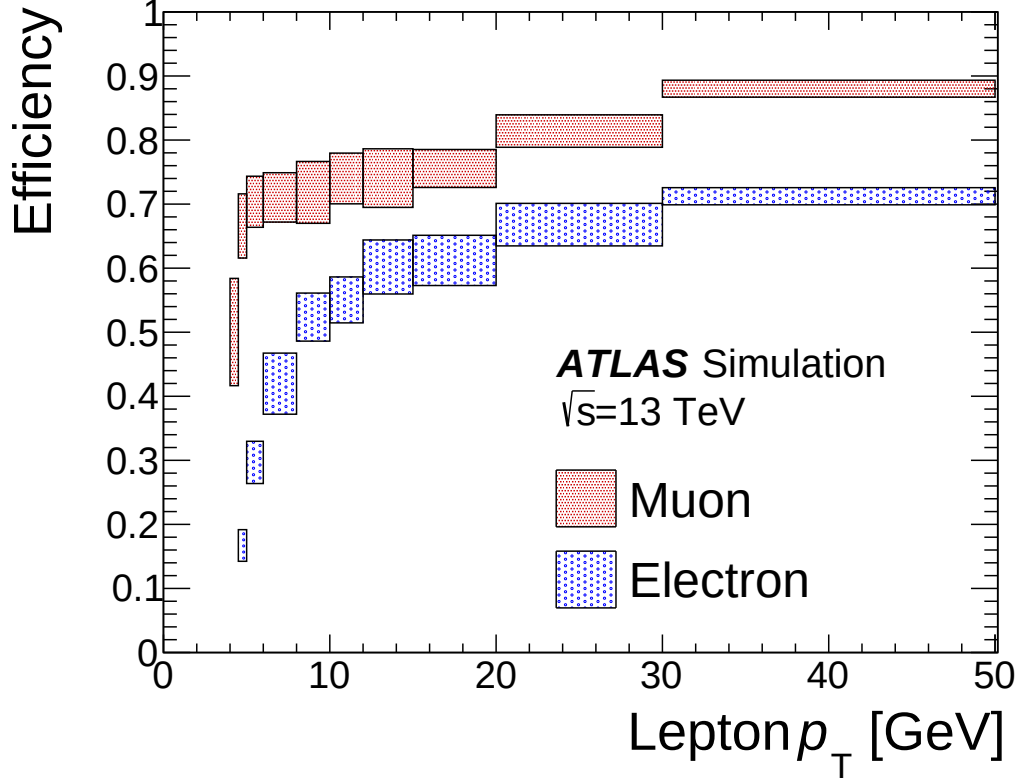


Figure 8.4: Signal lepton efficiencies as a function of lepton p_T for the electrons and muons used in the compressed EWK SUSY search, based on the working points described in Section 8.3. These efficiencies are measured with respect to the true generated electrons and muons. The samples used to determine the efficiencies are the simulated Higgsino LSP and slepton signal samples, where the objects are required to fall within the detector acceptance and the lepton p_T must be within a factor of 3 of $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$ for slepton samples and within a factor of 3 of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)/2$ for Higgsino LSP samples. The uncertainty bands shown demonstrate the range of efficiencies across the signal samples used for each p_T bin [1].

8.4 Event Selection

The trigger-level E_T^{miss} is computed using objects which are calibrated with potentially different energies than those used offline, so it is important to require a sufficiently large offline E_T^{miss} to ensure that the trigger is being used in an efficient manner. This motivates an analysis-level $E_T^{\text{miss}} > 200$ GeV requirement, as the E_T^{miss} triggers are greater than 95% efficient in this region. This strict E_T^{miss} requirement was also found to be effective at suppressing background from Drell-Yan production of light leptons ($Z^{(*)}/\gamma^* \rightarrow \ell^+\ell^-$, for $\ell = e$ or μ), and these are negligible backgrounds as a result. This was confirmed using simulated Drell-Yan events as well as with a data-driven cross-check [1].

As alluded to in Sections 6.2 and 8.1, the pair of $\tilde{\chi}_1^0$ LSPs in the processes considered will typically be produced roughly back-to-back. This means that in most $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ decays to soft leptons and LSPs, the resulting E_T^{miss} signature will be small, since the transverse momenta of the invisible LSPs would balance one another. Without this E_T^{miss} signature, there is nothing to distinguish the SUSY process from background, especially since the production cross-sections of these electroweakinos is small¹⁰. To have a large E_T^{miss} signature, the LSPs must travel in the same direction through the detector. One way for this to happen is if the event contains a high p_T ISR jet which can provide an object for the LSPs to recoil against. To exploit this signature, events are required to have a leading jet with $p_T > 100$ GeV and a large azimuthal separation from the $\mathbf{p}_T^{\text{miss}}$ (denoted $\Delta\phi(j_1, \mathbf{p}_T^{\text{miss}})$). To mitigate the impact of jet mismeasurements which could impact the E_T^{miss} , a requirement $\min(\Delta\phi(\text{any jet}, \mathbf{p}_T^{\text{miss}})) > 0.4$ is also imposed (i.e. all jets in the event must be separated from the $\mathbf{p}_T^{\text{miss}}$ by at least $\Delta\phi = 0.4$).

In the electroweakino case, the dilepton invariant mass is a powerful signature for discriminating against background. As seen in Figure 8.3, the $m_{\ell\ell}$ has a kinematic endpoint at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$. As the mass splitting between the neutralinos is unknown, the signal regions are binned in $m_{\ell\ell}$ to maximize sensitivity to potential signal events. These electroweakino signal regions also require the m_T (defined in Equation 7.1) computed using the leading lepton and the $\mathbf{p}_T^{\text{miss}}$ to be below the W mass; this is performed to suppress backgrounds from $t\bar{t}$, VV (i.e. the diboson processes WW , WZ , and ZZ), and W +jets. Unfortunately, such a requirement cannot be used effectively for the slepton final states as the $m_T^{\ell_1}$ for pair produced sleptons decaying to leptons and LSPs can frequently be large. As the electroweakinos and sleptons have different signatures which one can rely on, separate signal regions are determined for the two types of processes.

¹⁰Note that all of these statements are also true for the slepton final states.

In the slepton case, meanwhile, the m_{T2} variable can be used as a proxy for the slepton mass. m_{T2} , referred to as the “stransverse mass” [199, 200] is analogous to the transverse mass m_T , except that it is for pair produced particles which each decay to a visible and an invisible object. m_{T2} is defined as:

$$m_{T2}^{m_\chi}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{\text{miss}}) = \min_{\mathbf{q}_T} \left(\max \left[m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T, m_\chi), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T, m_\chi) \right] \right), \quad (8.1)$$

where m_χ is the mass of the invisible particles while the vector $\mathbf{q}_T$ and its magnitude q_T are chosen to minimize the larger of the two transverse masses defined by

$$m_T(\mathbf{p}_T, \mathbf{q}_T, m_\chi) = \sqrt{m_\ell^2 + m_\chi^2 + 2 \left(\sqrt{p_T^2 + m_\ell^2} \sqrt{q_T^2 + m_\chi^2} - \mathbf{p}_T \cdot \mathbf{q}_T \right)}. \quad (8.2)$$

Just as the electroweakino $m_{\ell\ell}$ has a kinematic endpoint at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$, $m_{T2}^{m_\chi}$ has a kinematic endpoint at the slepton mass. Of course, the LSP mass is a free parameter, so some assumption must be made for m_χ when calculating $m_{T2}^{m_\chi}$. For the purposes of this search, $m_\chi = 100$ GeV was chosen; however, it was found that this assumption did not significantly affect the analysis sensitivity for signal models with different LSP masses. The resulting m_{T2}^{100} variable is used to bin the slepton signal regions.

As can be seen in the diagrams from Figure 8.1, the final states of interest contain exactly two same-flavor opposite-sign leptons. However, other potential lepton pairings are still used in the analysis for control and validation regions, as discussed in Section 8.5. As mentioned previously, the compressed final states tend to result in soft leptons. As a result, the lepton p_T thresholds are chosen to be as small as possible. It was found that some background events due to fake leptons could be suppressed by requiring the leading lepton to have $p_T > 5$ GeV, but the subleading lepton is kept at its minimum supported threshold at this time (4.5 GeV for electrons and 4 GeV for muons).

The $Z \rightarrow \tau\tau$ +jets process can result in a similar signature as the signal model when the taus decay leptonically. To suppress this background, a variable referred to as $m_{\tau\tau}$ is used [119, 201, 202]. This variable uses the E_T^{miss} and the visible leptons in the event to reconstruct the kinematics of the tau leptons and to ultimately compute a proxy for the ditau invariant mass. This is nontrivial since each tau decays to a light lepton plus two neutrinos, resulting in four neutrinos in the final state which relate to the total E_T^{miss} in the event. $m_{\tau\tau}$ is taken to be the signed square root of $m_{\tau\tau}^2$, that is:

$$m_{\tau\tau} = \text{sign}(m_{\tau\tau}^2) \sqrt{|m_{\tau\tau}^2|} \quad (8.3)$$

where $m_{\tau\tau}^2$ is computed as

$$m_{\tau\tau}^2 \equiv 2p_{\ell_1} \cdot p_{\ell_2} (1 + \xi_1)(1 + \xi_2) \quad (8.4)$$

for lepton four-momenta p_{ℓ_1} and p_{ℓ_2} , with parameters ξ_1 and ξ_2 determined via the system of linear equations:

$$\mathbf{p}_T^{\text{miss}} = \xi_1 \mathbf{p}_T^{\ell_1} + \xi_2 \mathbf{p}_T^{\ell_2}. \quad (8.5)$$

This $m_{\tau\tau}$ variable can be used to successfully estimate the invariant mass of the ditau system when the tau leptons are boosted enough for the neutrinos from each leptonic tau decay to be collinear with the visible lepton momentum. Outside of this regime, the computed $m_{\tau\tau}$ variable can be far from the true ditau invariant mass, and can even be negative for real $Z \rightarrow \tau\tau$ +jets decays in cases where one of the leptons is back-to-back with respect to the $\mathbf{p}_T^{\text{miss}}$. Events are required to be outside of the range $0 \text{ GeV} < m_{\tau\tau} < 160 \text{ GeV}$, which is a selection criterion that allows for 87% of the $Z \rightarrow \tau\tau$ +jets background that falls into the electroweakino signal region to be rejected, with a loss of only 25% of signal events (for the $m(\tilde{\chi}_2^0) = 110 \text{ GeV}$, $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ sample tested).

As many background processes such as VV often have high p_T leptons, the scalar sum of the lepton transverse momenta ($H_T^{\text{lep}} = p_T^{\ell_1} + p_T^{\ell_2}$) is a useful discriminating variable. However, to be sensitive to a wide range of potential mass splittings, a simple requirement on H_T^{lep} may not be optimal. Moreover, an additional issue for backgrounds like VV is the potential for large E_T^{miss} which arises due to these high p_T leptons. Thus the ratio $E_T^{\text{miss}}/H_T^{\text{lep}}$ is used, as this quantity is small for many background events but typically large for the signal processes considered. To be optimal for a range of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ mass splittings (as well as $\tilde{\ell}$ and $\tilde{\chi}_1^0$ mass splittings), the requirement on this quantity is varied as a function of $m_{\ell\ell}$ or m_{T2}^{100} for the electroweakino and slepton signal regions, respectively. The requirements used are $E_T^{\text{miss}}/H_T^{\text{lep}} > \max[5, 15 - 2m_{\ell\ell}/(1 \text{ GeV})]$ for the electroweakino signal regions and $E_T^{\text{miss}}/H_T^{\text{lep}} > \max[3, 15 - 2\{m_{T2}^{100}/(1 \text{ GeV}) - 100\}]$ for the slepton signal regions. These criteria are motivated by Figure 8.5, which shows the amount of signal and background as a function of $E_T^{\text{miss}}/H_T^{\text{lep}}$ and either $m_{\ell\ell}$ or m_{T2}^{100} .

Finally, to avoid unnecessary impact from low mass resonances, the Z mass peak, photon conversions, and possible lepton misreconstruction effects, selected events must have $\Delta R_{\ell\ell} > 0.05$ and $1 \text{ GeV} < m_{\ell\ell} < 60 \text{ GeV}$ (excluding the J/ψ mass peak in the range $3.0 \text{ GeV} < m_{\ell\ell} < 3.2 \text{ GeV}$). In the electroweakino signal regions, the dilepton pair is additionally required to have $\Delta R_{\ell\ell} < 2.0$, since the leptons from the Z^* decay are not expected to have a large angular separation—note, however, that no such requirement is used for the slepton signal regions since the final state leptons arise from the decays of two independent sleptons.

The signal region event selection criteria are summarized in Table 8.4, with the binning strategy used for the signal regions summarized in Table 8.5.

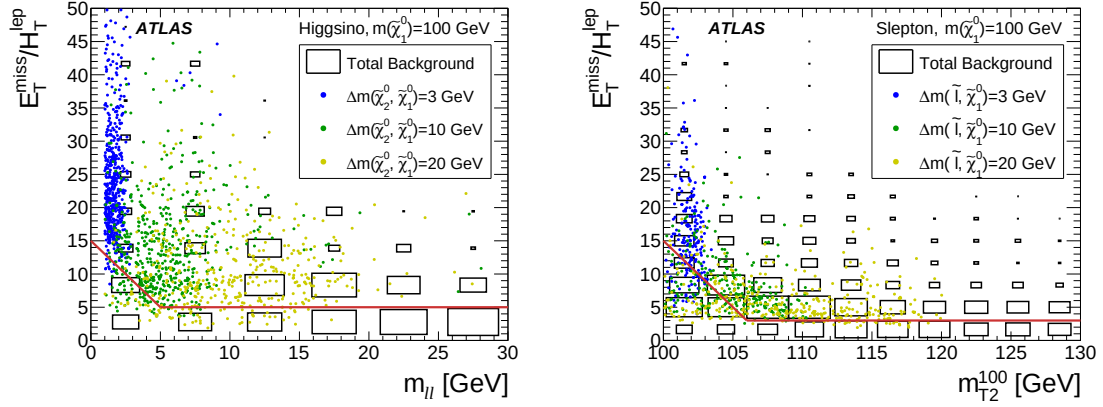


Figure 8.5: Distributions of $E_T^{\text{miss}}/H_T^{\text{lep}}$ as a function of $m_{\ell\ell}$ and m_{T2}^{100} for the electroweakino (left) and slepton (right) signal regions, after applying all of the other signal region requirements. The solid red line shows the requirement imposed on $E_T^{\text{miss}}/H_T^{\text{lep}}$ as a function of $m_{\ell\ell}$ and m_{T2}^{100} , where events below the line are rejected while those above the line are retained. Simulated signal events with the configurations listed in the legend are shown as circles, while the total background for each bin is represented by a square; larger squares indicate a larger amount of background [1].

Variable	Common requirement	
Number of signal leptons	= 2	
Lepton charge and flavor	e^+e^- or $\mu^+\mu^-$	
Leading lepton $p_T^{\ell_1}$	> 5 (5) GeV for electron (muon)	
Subleading lepton $p_T^{\ell_2}$	> 4.5 (4) GeV for electron (muon)	
$\Delta R_{\ell\ell}$	> 0.05	
$m_{\ell\ell}$	$\in [1, 60]$ GeV excluding $[3.0, 3.2]$ GeV	
E_T^{miss}	> 200 GeV	
Number of signal jets	≥ 1	
Leading jet p_T	> 100 GeV	
$\Delta\phi(j_1, \mathbf{p}_T^{\text{miss}})$	> 2.0	
$\min(\Delta\phi(\text{any jet}, \mathbf{p}_T^{\text{miss}}))$	> 0.4	
Number of b -tagged jets	= 0	
$m_{\tau\tau}$	< 0 or > 160 GeV	
	Electroweakino SRs	Slepton SRs
$\Delta R_{\ell\ell}$	< 2	—
$m_{T2}^{\ell_1}$	< 70 GeV	—
$E_T^{\text{miss}}/H_T^{\text{lep}}$	$> \max(5, 15 - 2 \frac{m_{\ell\ell}}{1 \text{ GeV}})$	$> \max(3, 15 - 2 (\frac{m_{T2}^{100}}{1 \text{ GeV}} - 100))$
Binned in	$m_{\ell\ell}$	m_{T2}^{100}

Table 8.4: Summary of the signal regions used in the compressed EWK SUSY search. The $m_{\ell\ell}$ and m_{T2}^{100} binning scheme used for the signal regions is defined in Table 8.5 [1].

Electroweakino SRs (bins shown in [GeV])								
Exclusive	$\text{SR}_{ee-m_{\ell\ell}}, \text{SR}_{\mu\mu-m_{\ell\ell}}$	[1, 3]	[3.2, 5]	[5, 10]	[10, 20]	[20, 30]	[30, 40]	[40, 60]
Inclusive	$\text{SR}_{\ell\ell-m_{\ell\ell}}$	[1, 3]	[1, 5]	[1, 10]	[1, 20]	[1, 30]	[1, 40]	[1, 60]
Slepton SRs (bins shown in [GeV])								
Exclusive	$\text{SR}_{ee-m_{\text{T}2}^{100}}, \text{SR}_{\mu\mu-m_{\text{T}2}^{100}}$	[100, 102]	[102, 105]	[105, 110]	[110, 120]	[120, 130]	[130, ∞]	
Inclusive	$\text{SR}_{\ell\ell-m_{\text{T}2}^{100}}$	[100, 102]	[100, 105]	[100, 110]	[100, 120]	[100, 130]	[100, ∞]	

Table 8.5: $m_{\ell\ell}$ and $m_{\text{T}2}^{100}$ bins used for the electroweakino and slepton signal regions, respectively. Each signal region is defined by the lepton flavor (ee , $\mu\mu$, or $\ell\ell$ for both). The inclusive bins are used to set model-independent limits while the exclusive bins are used to set limits on signal models [1].

8.5 Background Estimation

As described in Sections 6.3 and 7.5, both irreducible and reducible backgrounds must be estimated in ATLAS physics analyses. Fake leptons (due primarily to W +jets/ W + γ and semileptonic $t\bar{t}$ decays) are one of the dominant background sources in this analysis, and are discussed in Section 8.5.1.

The primary irreducible backgrounds in the analysis are dileptonic $t\bar{t}$, Wt , VV , and $Z \rightarrow \tau\tau$ +jets. Simulation is used to model these backgrounds, and two dedicated control regions are used in the analysis to normalize particular simulated processes to the data: one for $t\bar{t}/Wt$ and one for $Z \rightarrow \tau\tau$ +jets. It was not possible to find a high statistics control region that would be sufficiently pure in VV , so the diboson background is modeled only using simulation. Note that the simulated events in the two distinct control regions must be fit simultaneously to the data, as $t\bar{t}/Wt$ and $Z \rightarrow \tau\tau$ +jets events are present in both control regions. Diagrams for some of these processes are in Figure 8.6.

The control regions used in the compressed EWK SUSY search are chosen to be kinematically quite similar to the signal regions, and only invert or modify a few of the signal region event selection criteria. For $t\bar{t}$ and Wt , “CR-top” is used, which requires at least one b -tagged jet in the event. For $Z \rightarrow \tau\tau$ +jets, meanwhile, “CR-tau” is used, which relies on events with $60 \text{ GeV} < m_{\tau\tau} < 120 \text{ GeV}$. Both of these control regions allow for both same-flavor (ee and $\mu\mu$) and different-flavor ($e\mu$ and μe) events since $t\bar{t}$, Wt , and $Z \rightarrow \tau\tau$ +jets decay to different-flavor lepton pairs as often as they decay to same-flavor pairs. CR-top is 71% pure in $t\bar{t}/Wt$ and contains 1100 data events, while CR-tau is 83% pure in $Z \rightarrow \tau\tau$ +jets and contains 68 data events. These regions, including any additional selection criteria applied (e.g. to reduce signal contamination) are summarized in Table 8.6. Example distributions in CR-top and CR-tau are shown in Figure 8.7.

Validation regions are then used to verify that the background estimates behave as expected.

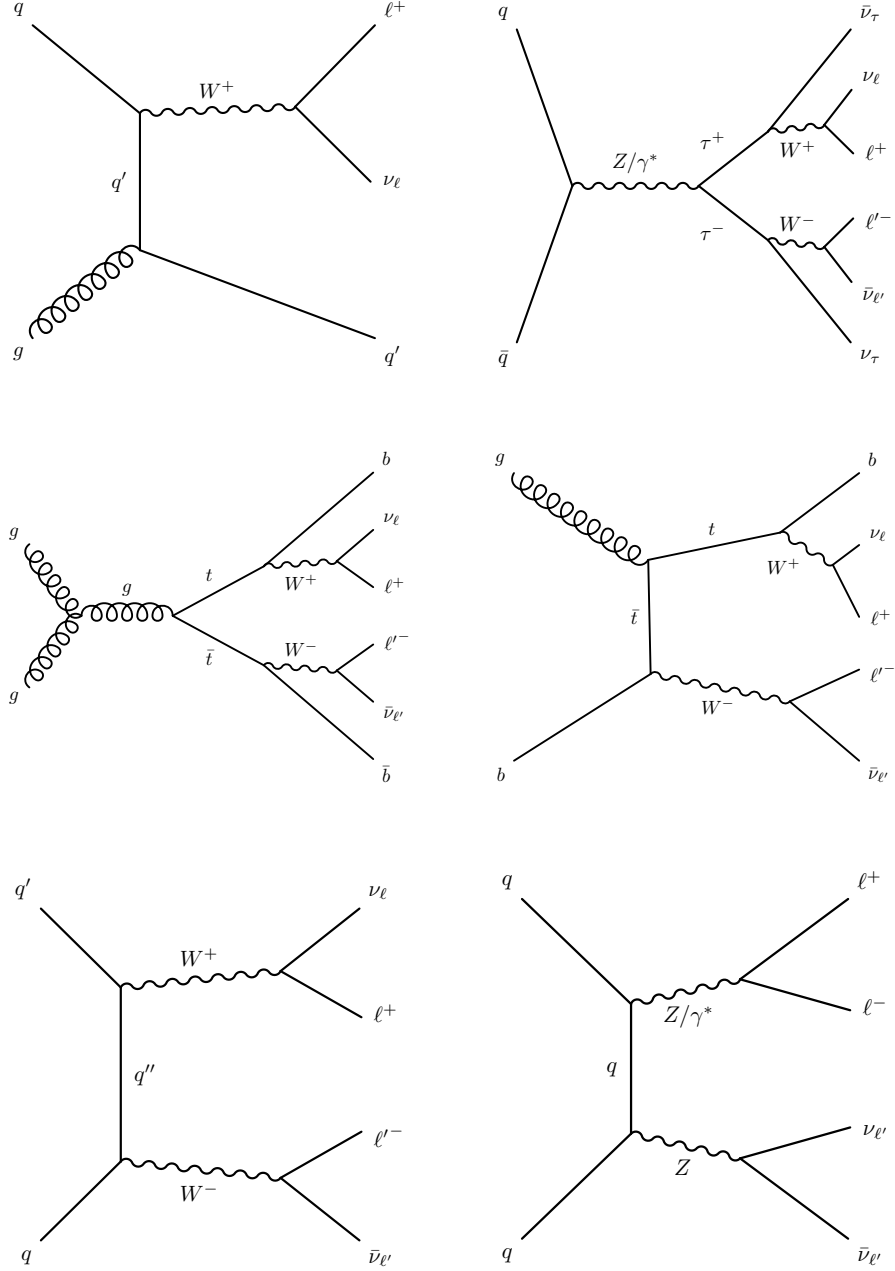


Figure 8.6: Diagrams for the background processes in the compressed EWK SUSY search, including W +jet (top left), $Z \rightarrow \tau\tau$ (top right), $t\bar{t}$ (middle left), Wt (middle right), WW (bottom left), and ZZ (bottom right). Note that W +jet is a reducible background in this analysis, as it only mimics the signal process when a jet fakes a lepton. Also note that the WW and ZZ processes interfere; as a result, they are typically grouped together and referred to as VV (diboson).

Region	Leptons	$E_T^{\text{miss}}/H_T^{\text{lep}}$	Additional requirements
CR-top	$e^\pm e^\mp, \mu^\pm \mu^\mp, e^\pm \mu^\mp, \mu^\pm e^\mp$	> 5	≥ 1 b -tagged jet(s)
CR-tau	$e^\pm e^\mp, \mu^\pm \mu^\mp, e^\pm \mu^\mp, \mu^\pm e^\mp$	$\in [4, 8]$	$m_{\tau\tau} \in [60, 120]$ GeV
VR-VV	$e^\pm e^\mp, \mu^\pm \mu^\mp, e^\pm \mu^\mp, \mu^\pm e^\mp$	< 3	
VR-SS	$e^\pm e^\pm, \mu^\pm \mu^\pm, e^\pm \mu^\pm, \mu^\pm e^\pm$	> 5	
VRDF- $m_{\ell\ell}$	$e^\pm \mu^\mp, \mu^\pm e^\mp$	$> \max\left(5, 15 - 2 \frac{m_{\ell\ell}}{1 \text{ GeV}}\right)$	$\Delta R_{\ell\ell} < 2, m_T^{\ell_1} < 70$ GeV
VRDF- m_{T2}^{100}	$e^\pm \mu^\mp, \mu^\pm e^\mp$	$> \max\left(3, 15 - 2 \left(\frac{m_{T2}^{100}}{1 \text{ GeV}} - 100\right)\right)$	

Table 8.6: Control and validation regions used in the compressed EWK SUSY search. Note that each pair of leptons in the “Leptons” column is listed with the leading lepton first. The common selection criteria in Table 8.4 are implied unless otherwise specified [1].

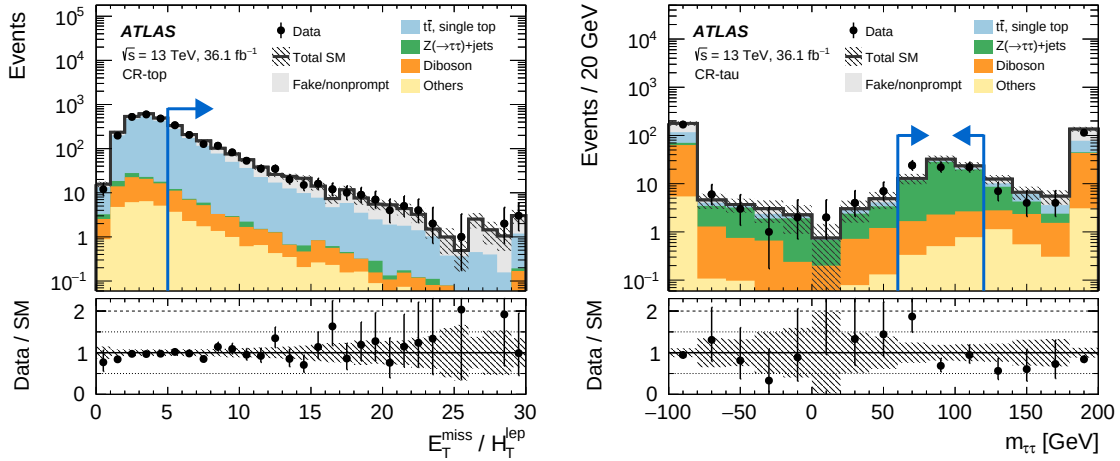


Figure 8.7: Example kinematic distributions of $E_T^{\text{miss}}/H_T^{\text{lep}}$ for CR-top (left) and $m_{\tau\tau}$ for CR-tau (right) after normalizing the $t\bar{t}/Wt$ and $Z \rightarrow \tau\tau + \text{jets}$ backgrounds to the data. Both plots are shown after applying all of the other requirements for the given control region, and the blue arrows indicate the control region requirement for the variable shown. The first and last bin include the underflow and overflow, respectively [1].

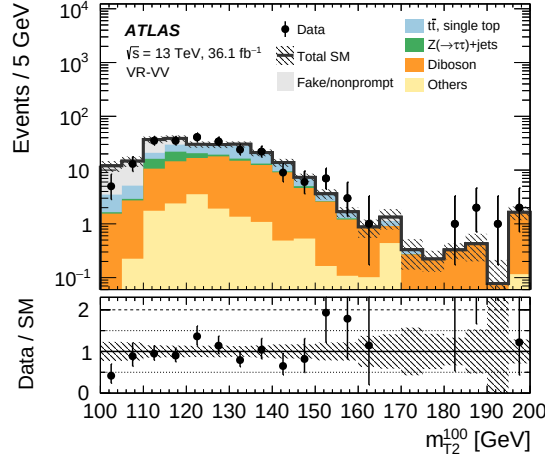


Figure 8.8: Example kinematic distribution of m_{T2}^{100} for VR-VV after normalizing the $t\bar{t}/Wt$ and $Z \rightarrow \tau\tau + \text{jets}$ backgrounds to the data. The first and last bin include the underflow and overflow, respectively [1].

To be sure that the simulated diboson events are sufficient for modeling the diboson background, “VR-VV” is used, which requires $E_T^{\text{miss}}/H_T^{\text{lep}} < 3.0$. As with the control regions, VR-VV also allows for both same-flavor and different-flavor lepton pairs. This region is 40% pure in VV events, with contributions of 25% from $t\bar{t}/Wt$, 20% from fake lepton backgrounds, and the remaining 15% from $Z \rightarrow \tau\tau + \text{jets}$ and other processes. A same-sign validation region, “VR-SS”, is used for the validation of the fake lepton background estimate as few Standard Model processes result in real same-sign dilepton pairs. VR-SS will be shown in Section 8.5.1.3. Finally, generic different-flavor validation regions are constructed which are chosen to be identical to the exclusive signal regions except that events containing different-flavor leptons are used. These validation regions are called “VRDF- $m_{\ell\ell}$ ” and “VRDF- m_{T2}^{100} ”, and will also be shown in Section 8.5.1.3 since these validation regions also tend to be dominated by fake lepton backgrounds. The validation regions are summarized in Table 8.6. An example distribution for VR-VV is shown in Figure 8.8, and a summary of the observed and expected number of events in the validation regions is shown in Figure 8.9.

8.5.1 Soft Fake Lepton Backgrounds

As previously mentioned in Sections 6.4 and 7.5.1, fake lepton backgrounds are due to misidentified light flavor hadrons, semileptonic decays of heavy flavor hadrons, and photon conversions to lepton pairs. The primary fake lepton background sources for the compressed EWK SUSY analysis are $W + \text{jets}/W + \gamma$ and semileptonic $t\bar{t}$ decays, and the data-driven fake factor method (described in

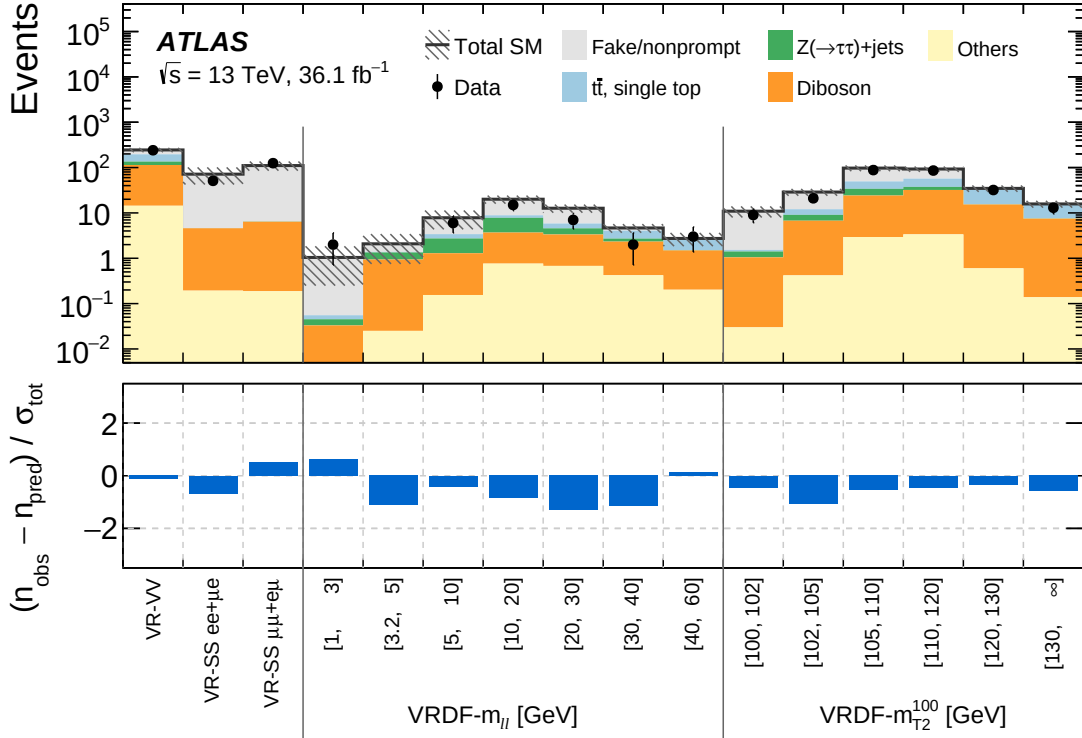


Figure 8.9: The observed and expected number of events in the validation regions are shown, along with the significance of any deviations. The background events are shown after normalizing the $t\bar{t}/Wt$ and $Z \rightarrow \tau\tau + \text{jets}$ backgrounds to the data. The uncertainties shown include both statistical and systematic uncertainties. The observed data in the validation regions tend to agree well with the Standard Model expectation; the largest deviation observed is roughly 1.5σ [1].

further detail in Sections 6.4.1 and 7.5.1.1) is used to estimate these backgrounds. The fake factors for this analysis were measured in a region dominated by dijet processes.

While the fake lepton backgrounds were relatively minor (compared with the WZ background) in the trilepton analysis discussed in Chapter 7, the fake lepton backgrounds are one of the most significant background sources in the compressed EWK SUSY analysis. Figure 8.10 shows the fake lepton background estimate as a function of subleading lepton p_T after applying the common signal region requirements from Table 8.4, without applying any of the specific electroweakino or slepton signal region requirements. At low subleading lepton p_T , fake leptons are clearly the dominant background—in the $p_T^{\ell_2} < 8$ GeV bin, the background due to fake leptons alone is a factor of 2.5 larger than all of the other backgrounds combined. As a result, it is critical for this background to be properly estimated and validated.

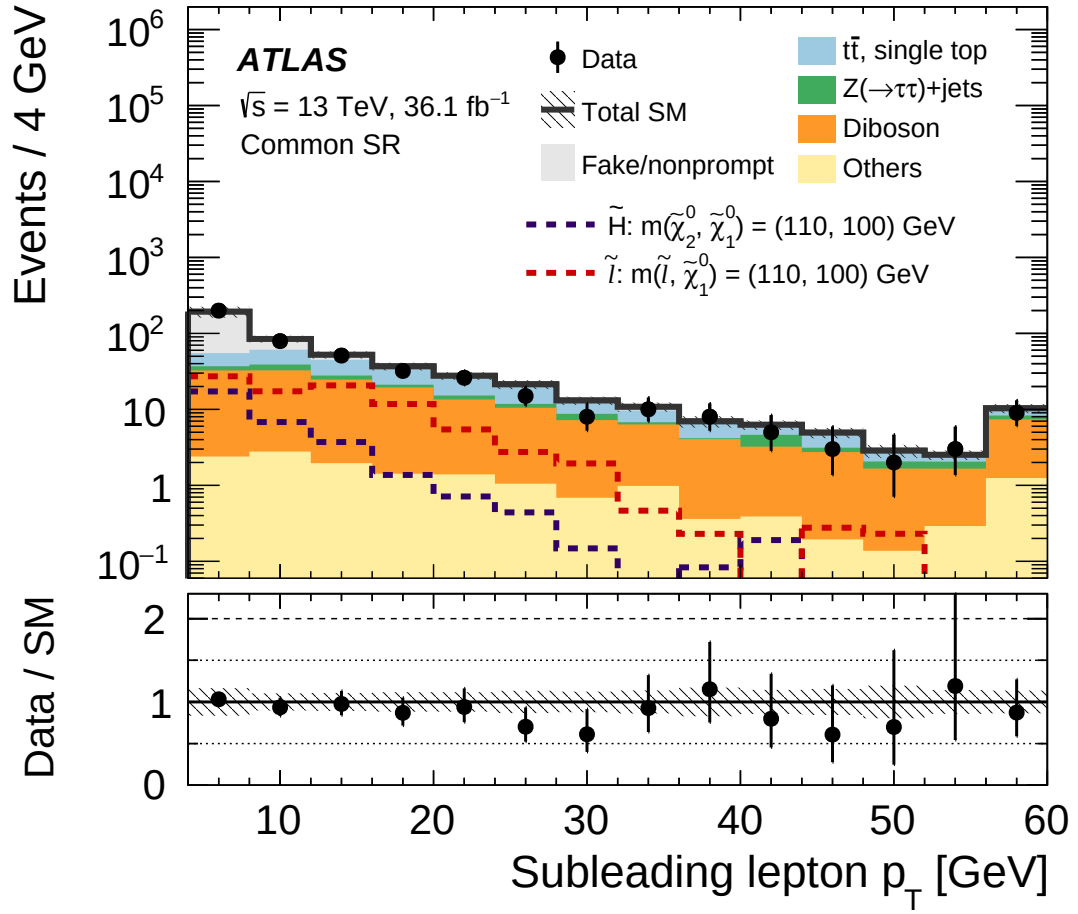


Figure 8.10: Subleading lepton p_T distribution after applying the common signal region requirements. Backgrounds due to fake leptons are the primary background source at low p_T [1].

8.5.1.1 Use of Dijet Events for Fake Lepton Background Estimation

The definitions of the anti-ID criteria used for electrons and muons in the compressed EWK SUSY analysis are described in Table 8.7. While the overlap removal requirements for the muons in the 3ℓ analysis were relaxed as part of the anti-ID criteria to enhance fake muon statistics (as described in Section 7.5.1.1), a different strategy was used in this analysis. Instead, overlap removal was relaxed for both ID and anti-ID muons in the fake factor measurement region; this achieves the same goal of enhancing statistics for measuring the muon fake factors, but has fewer technical challenges for implementation in the software framework used for the analysis.

The fake factors used in this analysis are derived in a fake factor measurement region (FF region)

Electrons	Muons
$p_T > 4.5 \text{ GeV}$	$p_T > 4 \text{ GeV}$
$ \eta < 2.47$	$ \eta < 2.5$
$ z_0 \sin \theta < 0.5 \text{ mm}$	$ z_0 \sin \theta < 0.5 \text{ mm}$
Pass LooseAndBLayer identification	Pass Medium identification
Veto ambiguous electrons	
Fail Tight identification	$ d_0/\sigma(d_0) > 3$
OR $ d_0/\sigma(d_0) > 5$	OR fail Fix (Tight, Track Only) isolation
OR fail Gradient (Loose) isolation	

Table 8.7: Anti-ID electron and muon definitions used for the fake lepton background estimation in the compressed EWK SUSY analysis. These criteria can be compared with the baseline and signal lepton definitions for the analysis, listed in Table 8.3. While baseline electrons in the analysis only need to satisfy the VeryLoose identification, the anti-ID electrons must satisfy the LooseAndBLayer identification. This identification criteria (discussed in Section 4.4.2) has a more strict requirement on the electron identification likelihood discriminant, as well as requiring an additional hit in the pixel detector and a hit in the innermost pixel layer. These criteria are very efficient at suppressing backgrounds due to photon conversions, so the use of LooseAndBLayer instead of VeryLoose is chosen to allow the background composition of the anti-ID electrons to be more similar to that of the signal electrons. Other potential anti-ID criteria were also studied in an attempt to bring the anti-ID fake lepton composition (in simulation) closer to that of the signal fake leptons; however, the other criteria attempted resulted in fewer anti-ID leptons available for the fake lepton estimate, and thus any potential improvement to the systematic uncertainty on the fake lepton composition would be counteracted by a larger statistical uncertainty.

dominated by dijet events. As the primary fake lepton background to estimate in the analysis is $W+\text{jets}/W+\gamma$ (with one prompt lepton and one fake lepton), one would ideally measure fake factors using $W+\text{jets}/W+\gamma$ events. However, a selection targeted at such events is typically contaminated by other processes, so the dijet process (with no prompt leptons and one fake lepton) is instead used to allow for a relatively pure selection of fake lepton events which can be used to measure fake factors. These events are selected using prescaled single lepton triggers, which impose lepton p_T requirements ranging from 4 GeV to 20 GeV, as described in Table 8.8. The selection criteria for this fake factor measurement region is fairly simple: the events are required to have a single ID or anti-ID lepton, must have $m_T(\mathbf{p}_T^\ell, \mathbf{p}_T^{\text{miss}}) < 40 \text{ GeV}$, and require a leading jet with $p_T > 100 \text{ GeV}$. The latter requirement is imposed to allow this region to be more similar to the signal region, while the m_T requirement is used to suppress $W+\text{jets}/W+\gamma$ and $t\bar{t}$ backgrounds containing prompt leptons. Both electron and muon fake factors are binned in p_T , while muon fake factors are additionally binned in b -jet multiplicity (either $n_{b\text{-jet}} = 0$ or $n_{b\text{-jet}} > 0$; this was done because the muon fake factors were found to have some dependence on $n_{b\text{-jet}}$).

While prompt lepton backgrounds from $W+\text{jets}/W+\gamma$, $Z+\text{jets}/Z+\gamma$, $t\bar{t}$, and single top processes

2015–2016
HLT_e5_lhvloose
HLT_e10_lhvloose_L1EM7
HLT_e15_lhvloose_L1EM13VH
HLT_e20_lhvloose
HLT_mu4
HLT_mu10
HLT_mu14
HLT_mu18

Table 8.8: List of the prescaled single lepton triggers used in 2015–2016 to collect dijet events. The strings “e” and “mu” indicate the flavor of the lepton which is required to satisfy the p_T threshold (in GeV) listed after these strings. For the electron triggers, “lhvloose” indicates the trigger-level electron identification criteria which the electron candidate must satisfy. “L1EM7” and “L1EM13VH” refer to the L1 electron requirements imposed; all of these triggers impose requirements at L1, but it is not always explicitly included in the trigger name.

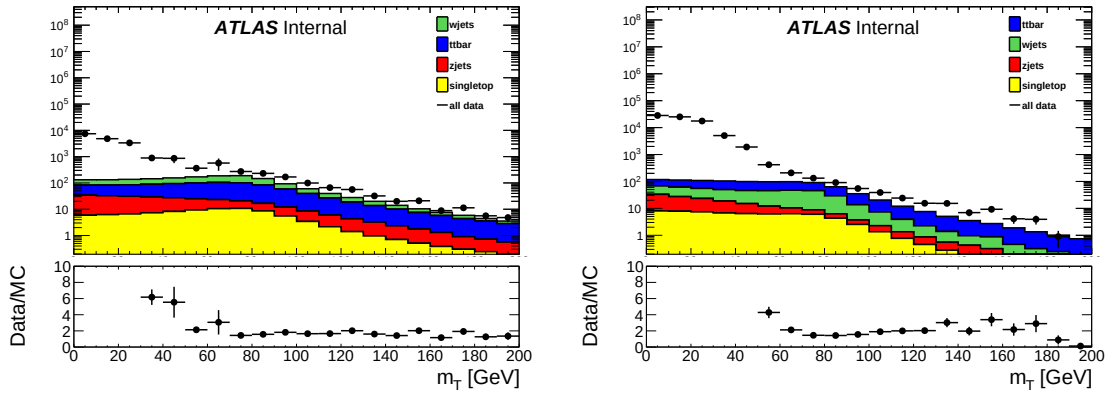


Figure 8.11: ID (left) and anti-ID (right) electron m_T distributions in the dijet fake factor measurement region. The fake factors are computed using the events with $m_T < 40$ GeV.

tend to be small, simulated events are nonetheless used to remove these contributions from the dijet fake factor measurement region. These events are normalized to the data in the $E_T^{\text{miss}} > 200$ GeV tail, where few dijet events are present. The precise normalization region is not particularly important since the background in the fake factor measurement region is several orders of magnitude smaller than the dijet events of interest, but another region with $m_T > 100$ GeV (which was used for the dijet-based fake factor measurement in [203]) is used as a systematic variation. The resulting m_T distributions of ID and anti-ID electrons and muons measured in this region are shown in Figures 8.11 through 8.13. The fake factors determined by taking the ratio of the ID distributions to the anti-ID distributions are shown as a function of p_T in Figures 8.14 and 8.15.

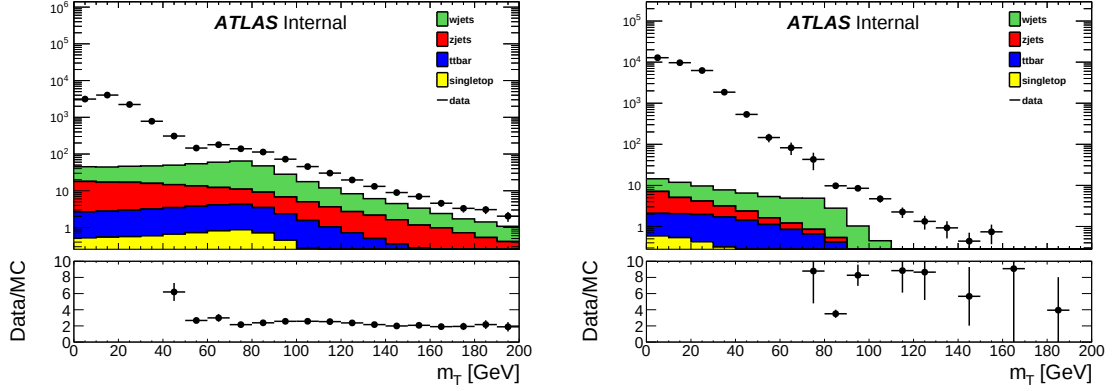


Figure 8.12: ID (left) and anti-ID (right) muon m_T distributions in the dijet fake factor measurement region with $n_{b\text{-jet}} = 0$. The fake factors are computed using the events with $m_T < 40$ GeV.

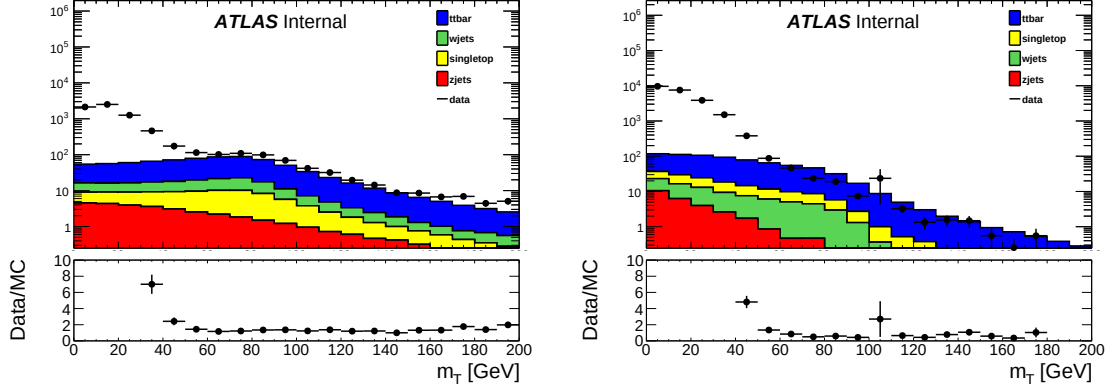


Figure 8.13: ID (left) and anti-ID (right) muon m_T distributions in the dijet fake factor measurement region with $n_{b\text{-jet}} > 0$. The fake factors are computed using the events with $m_T < 40$ GeV.

8.5.1.2 Evaluation of Fake Lepton Systematic Uncertainties

Several sources of uncertainty must be considered for the fake lepton background estimate. These include:

- **Statistical uncertainties on the fake factors.** These uncertainties can be large as the fake factors are measured using prescaled triggers, which only collect a small fraction of the dijet events produced at ATLAS. The total integrated luminosity collected by the logical OR of the prescaled triggers listed in Table 8.8 for 2015–2016 is about 165 pb^{-1} . The statistical uncertainties on the fake factors are those shown in Figures 8.14 and 8.15. Each p_T bin and lepton flavor shown is treated independently when evaluating this uncertainty, to ensure that

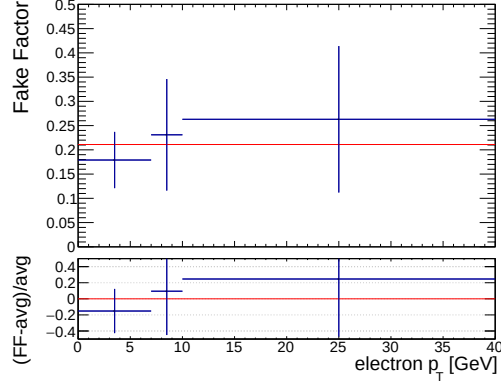


Figure 8.14: Electron fake factors as a function of p_T in the dijet fake factor measurement region. The red line indicates the average electron fake factor over all p_T . Uncertainties shown are statistical only.

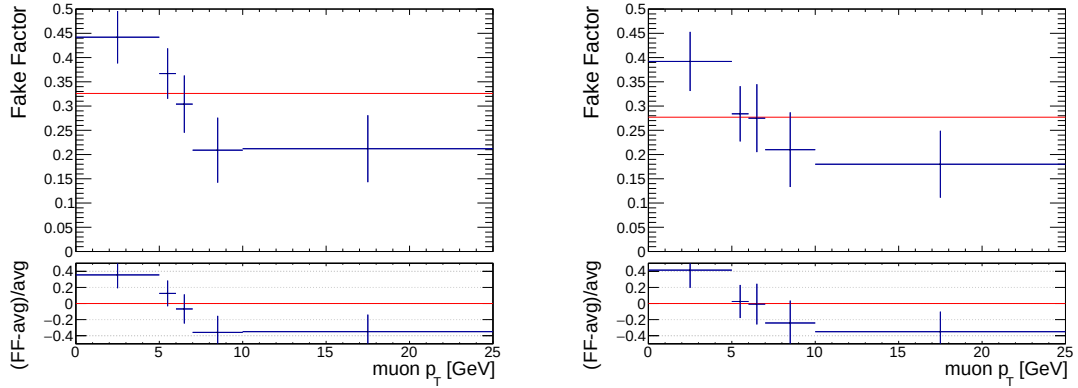


Figure 8.15: Muon fake factors as a function of p_T in the dijet fake factor measurement region for $n_{b\text{-jet}} = 0$ events (left) and $n_{b\text{-jet}} > 0$ events (right). The red line indicates the average muon fake factor over all p_T for the given b -jet multiplicity. Uncertainties shown are statistical only.

the uncertainty for leptons in different p_T or lepton flavor bins are treated as uncorrelated.

- **Subtraction of events containing prompt leptons in the fake factor measurement region.** While the fake factor measurement region is dominated by dijet events containing no prompt leptons, other processes do contribute to this region, as discussed in Section 8.5.1.1. Simulated events are used to estimate and remove the prompt lepton backgrounds from W +jets/ W + γ , Z +jets/ Z + γ , $t\bar{t}$, and single top processes in the dijet fake factor measurement region. Nominally these simulated events are normalized to the data in the $E_T^{\text{miss}} > 200$ GeV region, and the fake factors are computed in the $m_T < 40$ GeV region. Sys-

tematic variations include varying the $m_T < 40$ GeV requirement up and down by 10 GeV, varying the normalization region down to $E_T^{\text{miss}} < 175$ GeV, varying the normalization factor for the prompt component up and down by 20%, and using the $m_T > 100$ GeV region for the normalization instead of the E_T^{miss} -based normalization. The largest uncertainty that results from these systematic variations is a 19% uncertainty for muons with $p_T > 10$ GeV. The prompt subtraction uncertainty is less than 10% in all other bins.

- Kinematic dependence of the fake factors.** The fake factors are measured as a function of other variables to determine any kinematic dependence which may otherwise be uncovered by the fake factors and their uncertainties. Figures 8.16 through 8.18 show the fake factor distributions used to determine this uncertainty, which is done by considering the largest statistically-meaningful variation with respect to the average fake factor for the given lepton flavor. The variation of the fake factors as a function of $|\eta|$ is the primary contributor to this uncertainty, and an uncertainty of 25% is assigned for both electrons and muons.
- Non-closure in a validation region dominated by fake leptons.** Any remaining disagreement between the fake lepton estimate and the data in a fake-dominated region is used as an additional systematic uncertainty. This is designed to target any potential composition differences between the fake factor measurement region and the signal region, as well as between the signal leptons and the anti-ID leptons. The region used, VR-SS-loose, is identical to VR-SS from Table 8.6 but with no requirement on $E_T^{\text{miss}}/H_T^{\text{lep}}$, to allow for larger statistics. This region is therefore a superset of VR-SS. The RMS over the systematic variations from all other sources is compared with the data in VR-SS-loose as a function of the subleading lepton p_T (as this is the distribution most sensitive to the fake lepton composition). The difference, measured in quadrature, is then assigned as the closure systematic. This uncertainty is determined to be 38% for electrons with $p_T < 7$ GeV, 97% for muons with $7 \text{ GeV} < p_T < 10$ GeV, and 0% everywhere else. This 0% is assigned because the fake lepton estimate and the data agree within their uncertainties in VR-SS-loose for the other p_T bins considered. The relatively large value for the muons with $7 \text{ GeV} < p_T < 10$ GeV is due to an excess in VR-SS-loose which persists in the $\mu\mu$ and $e\mu$ channel, as well as in the tighter VR-SS. These checks, using fine-binned granularity in the subleading lepton p_T , can be seen in Figures 8.19 and 8.20. Regardless, the majority of fake muons are at lower p_T than this, so this does not have a significant effect on the final results. To validate this closure systematic, the subset region VR-SS is checked. Additionally, CR-top (where fake leptons are the second largest background) as

well as a same-sign version of CR-top (CR-top-SS) are checked to validate that this additional uncertainty is sufficient. Plots used to obtain and validate the closure systematic are shown in Figures 8.21 through 8.24.

8.5.1.3 Validation of Fake Lepton Backgrounds

Distributions in the regions used to validate the fake lepton background estimate (VR-SS, VRDF- $m_{\ell\ell}$, and VRDF- m_{T2}^{100}), including all statistical and systematic uncertainties, are shown in Figures 8.25 through 8.27. The background estimate agrees well with the data in these validation regions.

The fake lepton composition in simulation for ID and anti-ID leptons was studied in VR-SS and compared with that of the electroweakino signal region. These are shown in Figures 8.28 and 8.29, and the fake lepton composition tends to agree well between VR-SS and the signal region. While the ID and anti-ID fake lepton composition for electrons does have differences, the systematic uncertainties are designed to target this.

This comparison of simulated fake lepton composition could not easily be done for the dijet fake factor measurement region as the statistics of simulated dijet events which result in fake leptons tends to be poor. As the modeling of the fake lepton composition in simulated dijet events is also expected to be poor, this was not pursued. Nonetheless, as the fake lepton estimate models the data well in VR-SS, and the composition (at least in simulation) in VR-SS agrees well with that of the signal regions, it is expected that this estimate should properly model the fake lepton background in the signal region as well. As an additional check, however, an extra set of composition studies was performed based on whether leptons in data satisfied the anti-ID criteria due to the identification, isolation, or $d_0/\sigma(d_0)$ requirement (or some combination of these). The composition plots of anti-ID leptons from data in the dijet fake factor measurement region are shown in Figure 8.30 as a function of p_T . Additionally, data-driven composition plots of events with a leading signal lepton and an anti-ID subleading lepton in VR-SS, VR-SS-loose, and proxies for the signal region are shown in Figures 8.31 and 8.32. These demonstrate that in the dijet fake factor measurement region at low p_T , about 20% of anti-ID electrons are due to failing the isolation criteria, about 40% are due to failing the identification criteria, and 40% are due to failing both. Contributions due to the $d_0/\sigma(d_0)$ criteria are small. In VR-SS, VR-SS-loose, and the proxies for the signal region at low p_T , about 40% of anti-ID electrons are due to the isolation criteria, 40% are due to the identification criteria, and 20% are due to failing both. For muons, meanwhile, the anti-ID composition of the dijet fake

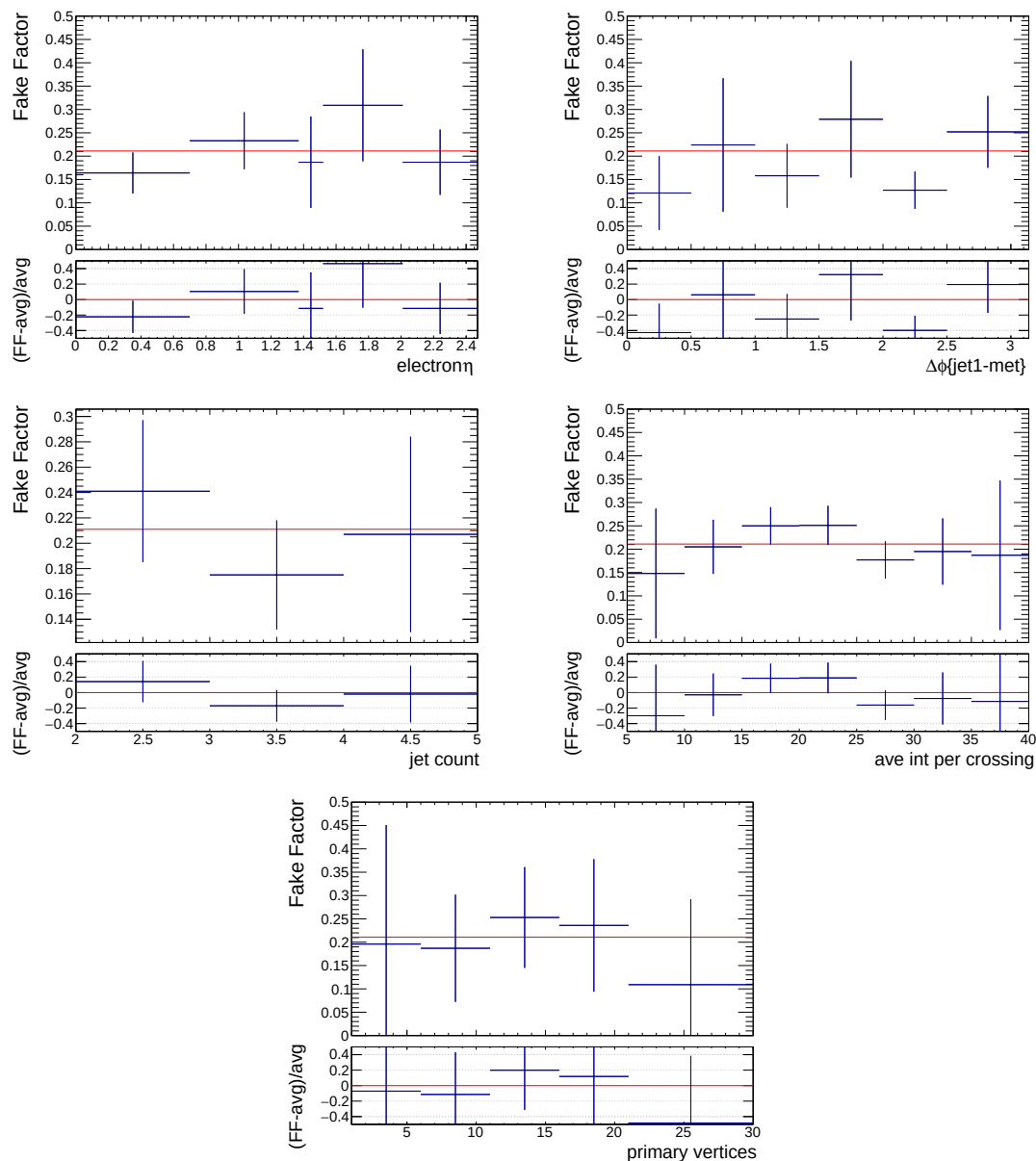


Figure 8.16: Kinematic distributions for the electron fake factors, including the fake factor as a function of $|\eta|$ (top left), $\Delta\phi(j_1, \mathbf{p}_T^{\text{miss}})$ (top right), jet multiplicity (middle left), the average number of interactions per crossing μ (middle right), and the number of reconstructed vertices (bottom). The largest statistically meaningful deviation from the average is seen for the distribution as a function of $|\eta|$, which is used to determine a kinematic dependence uncertainty of 25%.

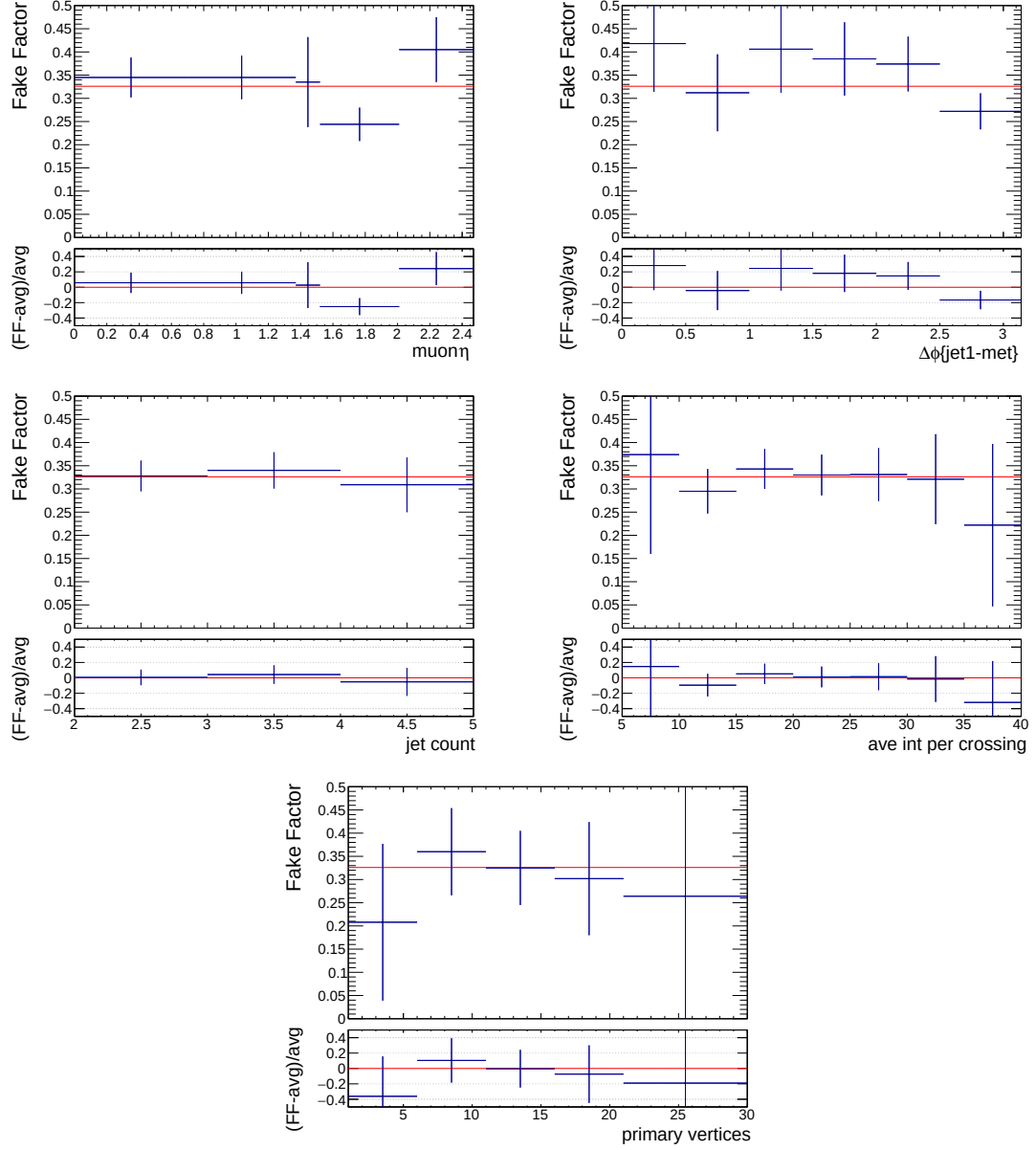


Figure 8.17: Kinematic distributions for the muon fake factors with $n_{b\text{-jet}} = 0$, including the fake factor as a function of $|\eta|$ (top left), $\Delta\phi(j_1, \mathbf{p}_T^{\text{miss}})$ (top right), jet multiplicity (middle left), the average number of interactions per crossing μ (middle right), and the number of reconstructed vertices (bottom). The largest statistically meaningful deviation from the average is seen for the distribution as a function of $|\eta|$, which is used to determine a kinematic dependence uncertainty of 25%.

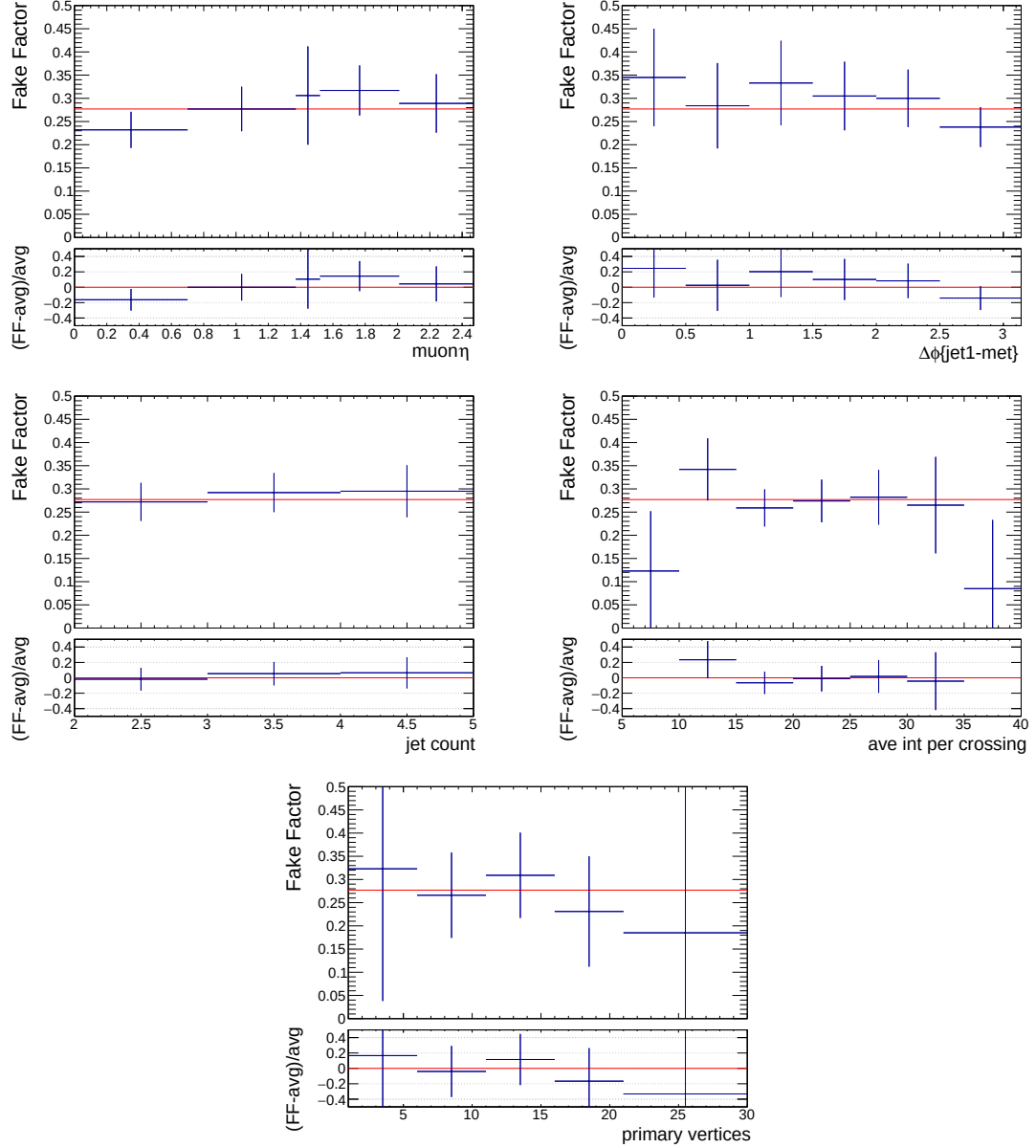


Figure 8.18: Kinematic distributions for the muon fake factors with $n_{b\text{-jet}} > 0$, including the fake factor as a function of $|\eta|$ (top left), $\Delta\phi(j_1, \mathbf{p}_T^{\text{miss}})$ (top right), jet multiplicity (middle left), the average number of interactions per crossing μ (middle right), and the number of reconstructed vertices (bottom). The largest statistically meaningful deviation from the average is seen for the distribution as a function of $|\eta|$, which is used to determine a kinematic dependence uncertainty of 25%.

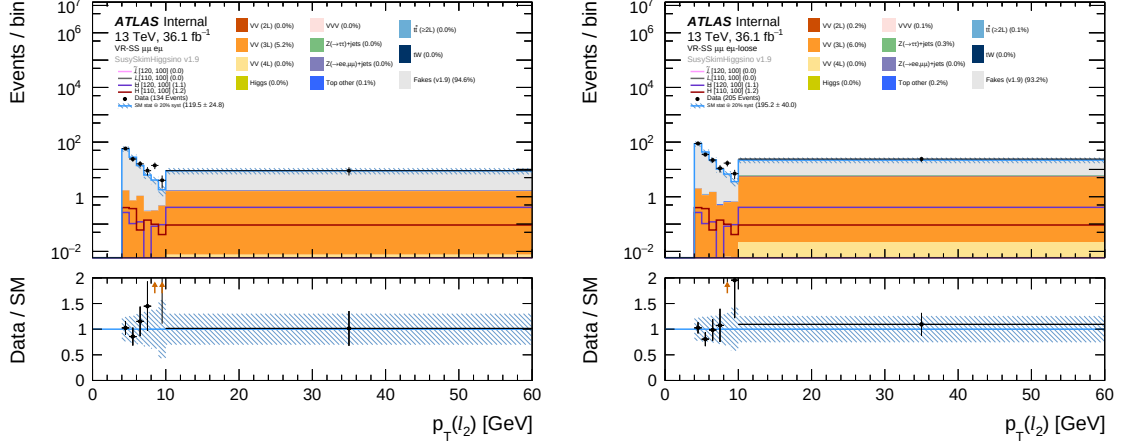


Figure 8.19: Data compared with the fake lepton estimate in VR-SS (left) and VR-SS-loose (right) for the $\mu\mu + e\mu$ channel. These plots use a fine p_T binning to demonstrate that the large closure systematic uncertainty derived is due to a localized excess in the $8 \text{ GeV} < p_T < 9 \text{ GeV}$ bin.

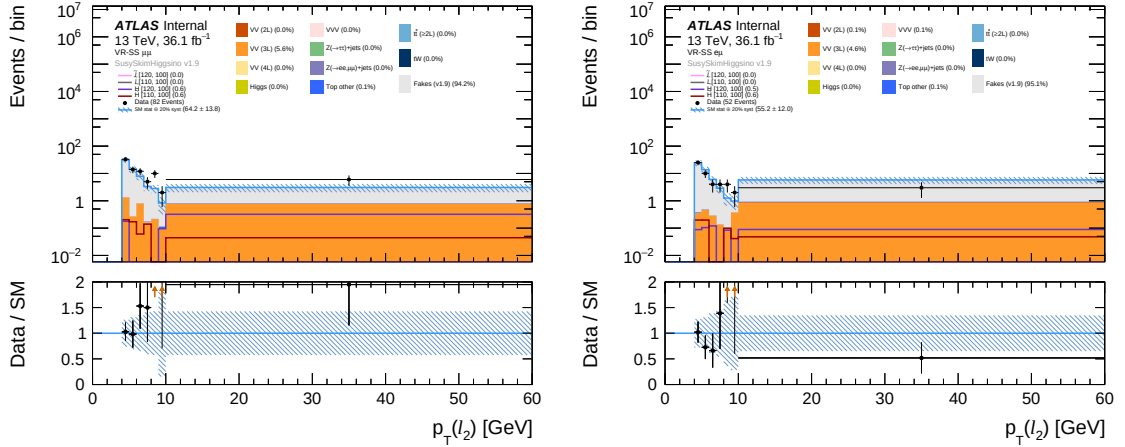


Figure 8.20: Data compared with the fake lepton estimate in VR-SS for the $\mu\mu$ channel (left) and the $e\mu$ channel (right). These plots demonstrate that the excess in the $8 \text{ GeV} < p_T < 9 \text{ GeV}$ bin persists in the individual flavor channels.

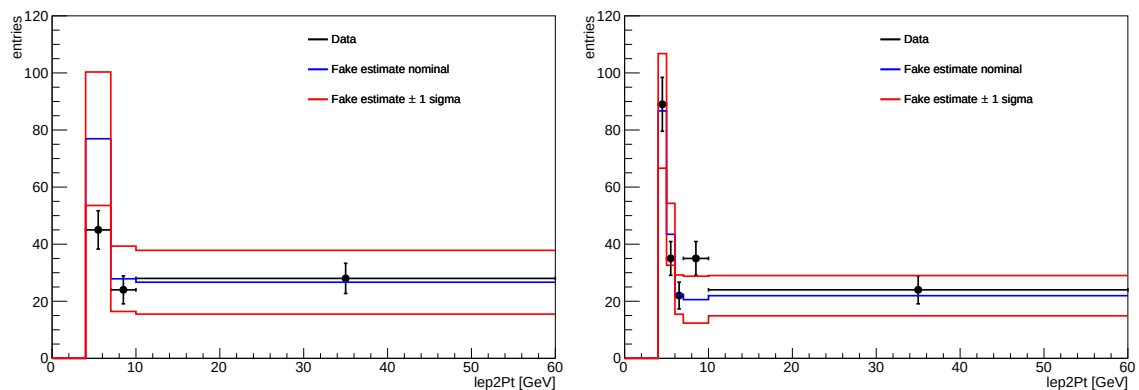


Figure 8.21: Data compared with the fake lepton estimate in VR-SS-loose for the $ee + \mu e$ channel (left) and the $\mu\mu + e\mu$ channel (right). This is used to calculate the closure systematic. Note that backgrounds from other sources are not removed here; thus the fake lepton estimate shown is in addition to any other background sources that contribute.

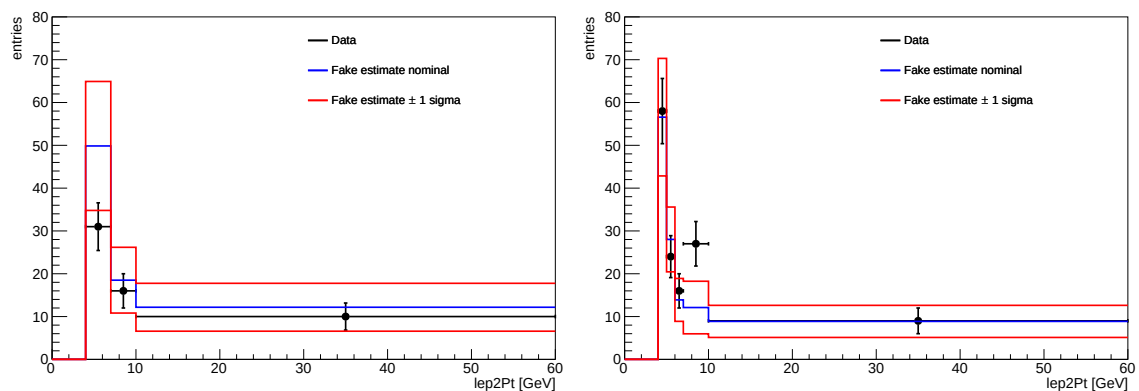


Figure 8.22: Data compared with the fake lepton estimate in VR-SS for the $ee + \mu e$ channel (left) and the $\mu\mu + e\mu$ channel (right). This is used to validate the closure systematic. Note that backgrounds from other sources are not removed here; thus the fake lepton estimate shown is in addition to any other background sources that contribute.

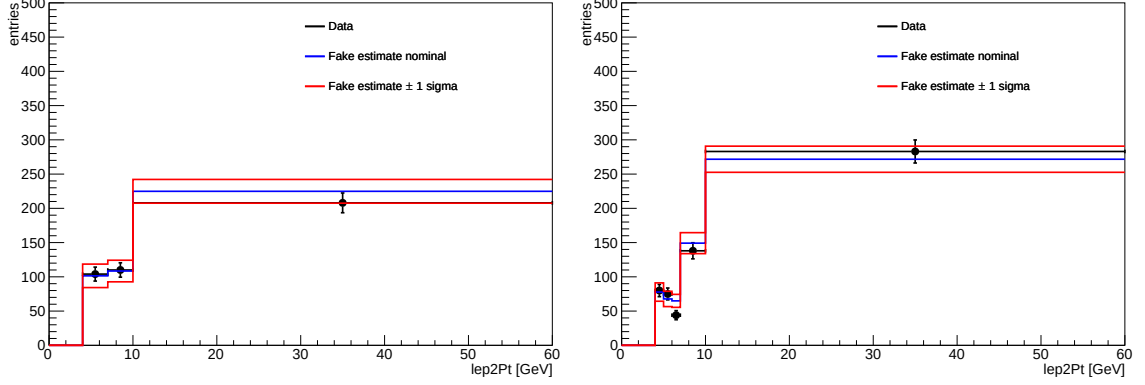


Figure 8.23: Data compared with the fake lepton estimate in CR-top for the $ee + \mu e$ channel (left) and the $\mu\mu + e\mu$ channel (right). This is used to validate the closure systematic. Note that backgrounds from other sources are not removed here; thus the fake lepton estimate shown is in addition to any other background sources that contribute.

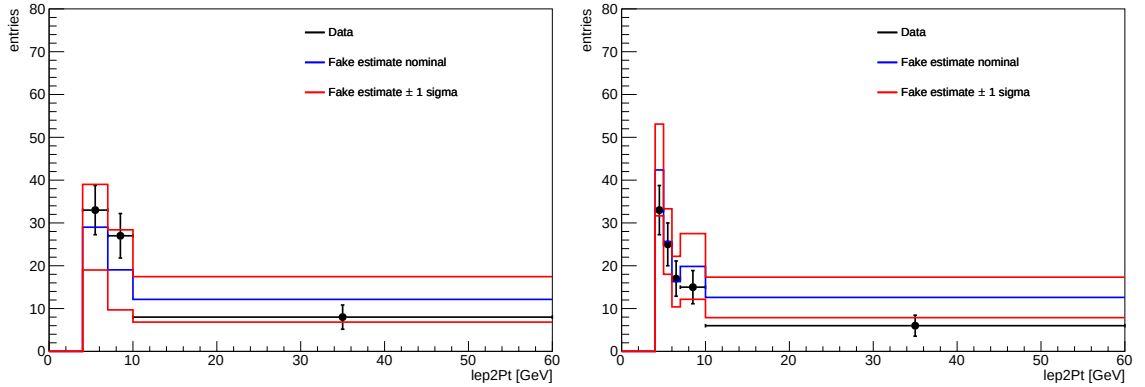


Figure 8.24: Data compared with the fake lepton estimate in CR-top-SS for the $ee + \mu e$ channel (left) and the $\mu\mu + e\mu$ channel (right). This is used to validate the closure systematic. Note that backgrounds from other sources are not removed here; thus the fake lepton estimate shown is in addition to any other background sources that contribute.

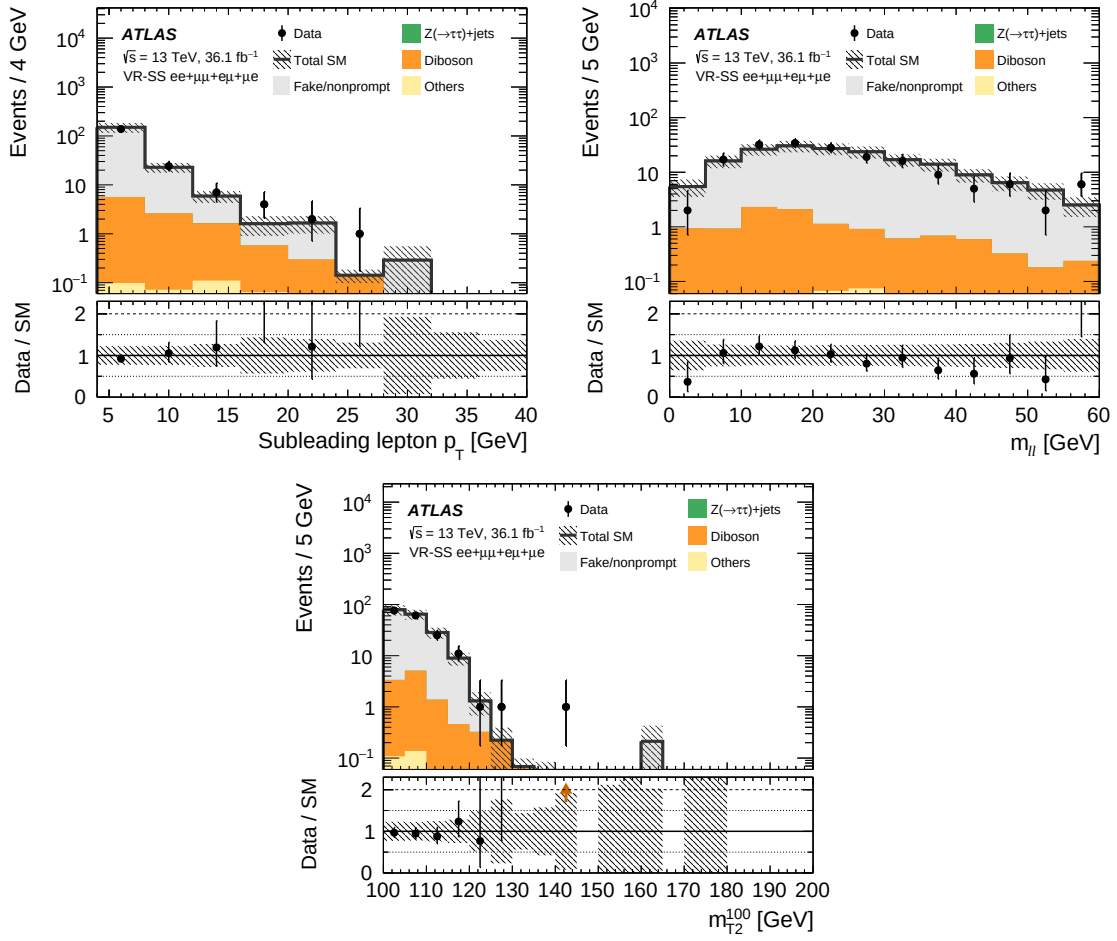


Figure 8.25: Distributions of $p_T^{\ell_2}$ (top left), $m_{\ell\ell}$ (top right), and m_{T2}^{100} (bottom) in VR-SS, shown for all lepton flavors [1].

factor measurement at low p_T is 50–60% due to the isolation criteria, 10–20% due to the $d_0/\sigma(d_0)$ criteria, and 20–40% due to leptons which fail both. This can be compared with the regions where the fake factors are applied, which tend to be 60–70% due to isolation, 20% due to $d_0/\sigma(d_0)$, and 10–20% due to both. Given the large uncertainties on the fake lepton estimate, the data-driven compositions in the dijet fake factor measurement region and the various regions where the fake factors are applied are within reasonable agreement.

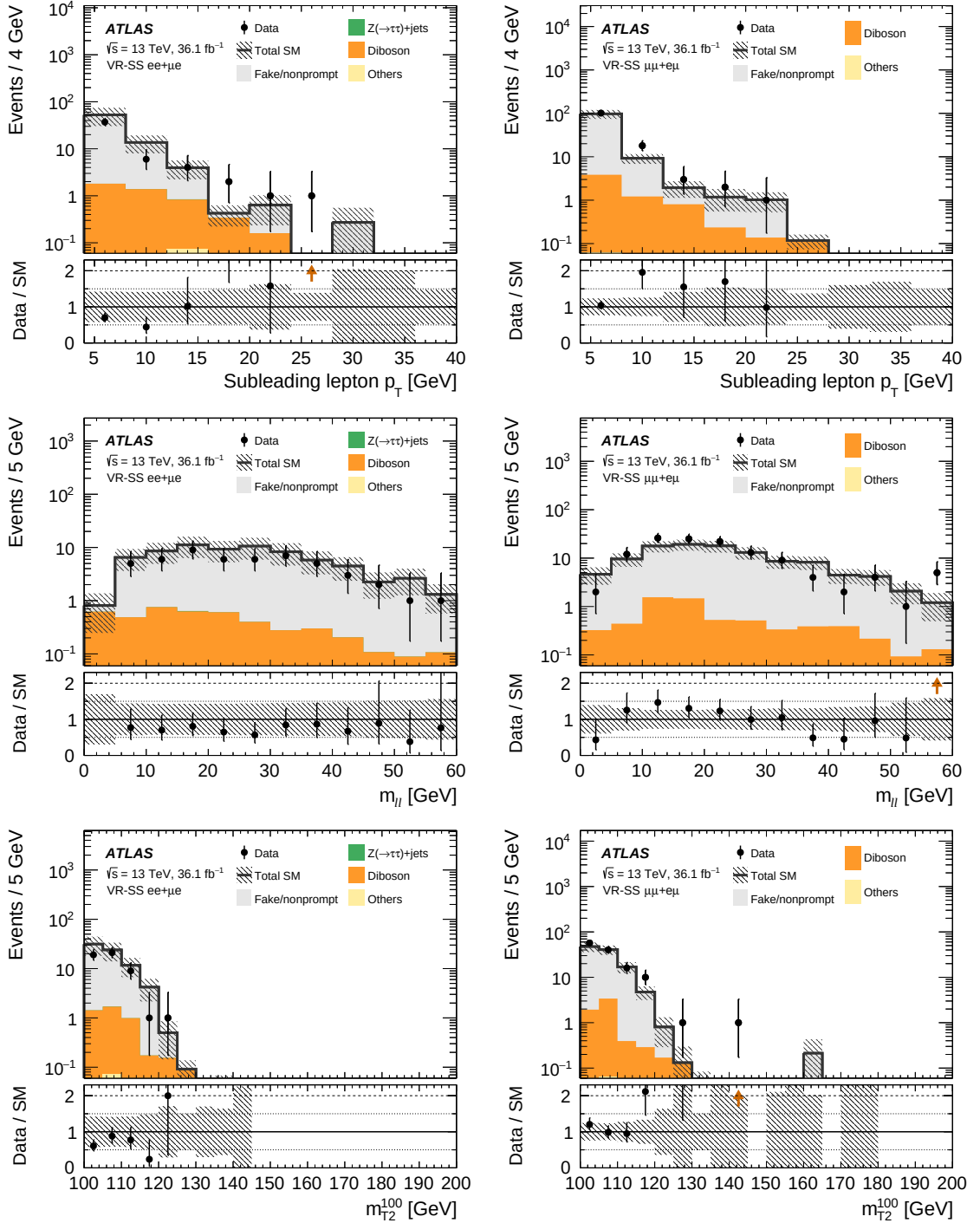


Figure 8.26: Distributions of $p_T^{\ell_2}$ (top), $m_{\ell\ell}$ (middle), and m_{T2}^{100} (bottom) in VR-SS, shown for $ee + \mu e$ events with a subleading electron (left) and for $\mu\mu + e\mu$ events with a subleading muon (right) [1].

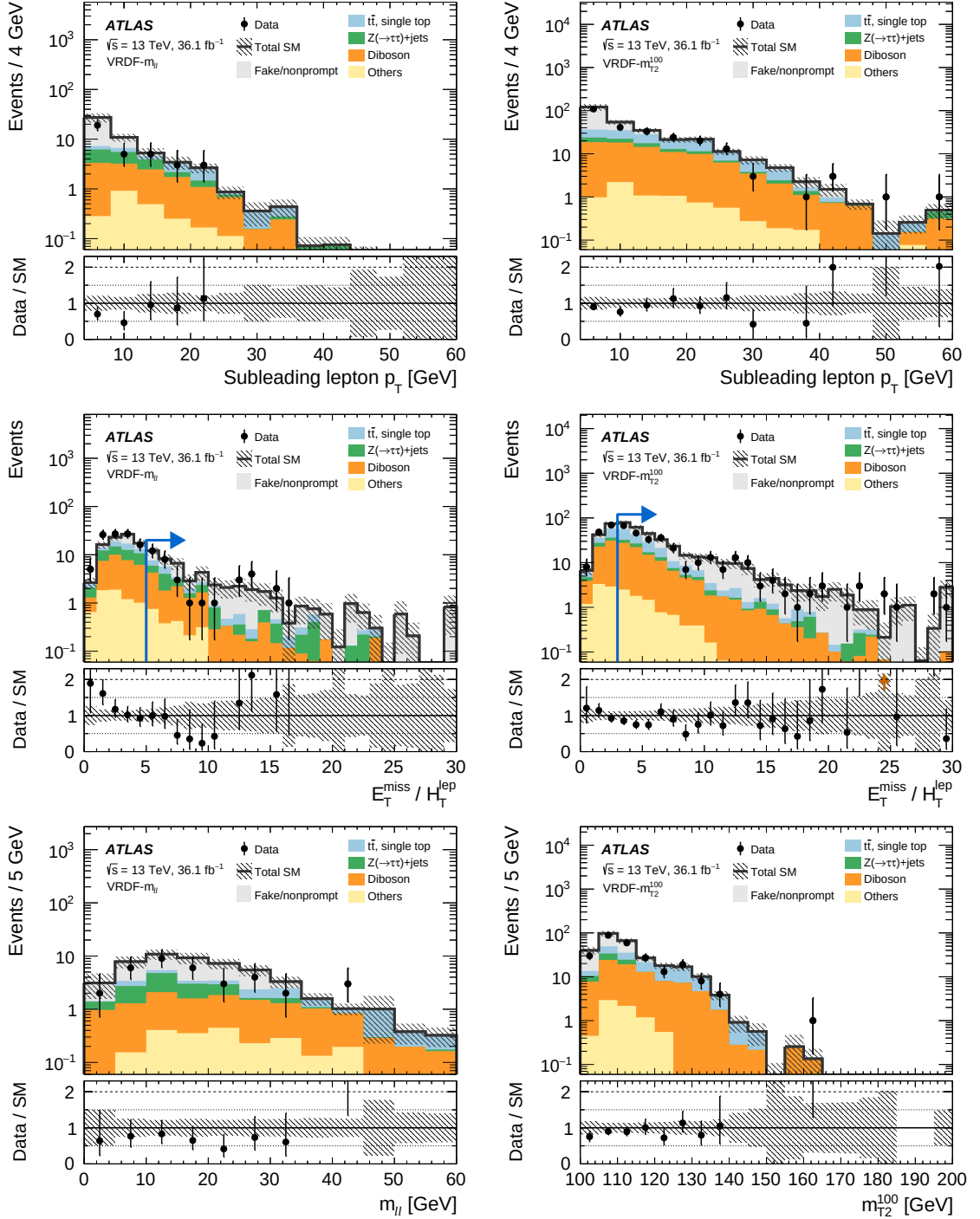


Figure 8.27: Distributions of $p_T^{\ell_2}$ (top), $E_T^{\text{miss}}/H_T^{\text{lep}}$ (middle), $m_{\ell\ell}$ (bottom left), and m_{T2}^{100} (bottom right) in VRDF- $m_{\ell\ell}$ (left) and VRDF- m_{T2}^{100} (right) [1].

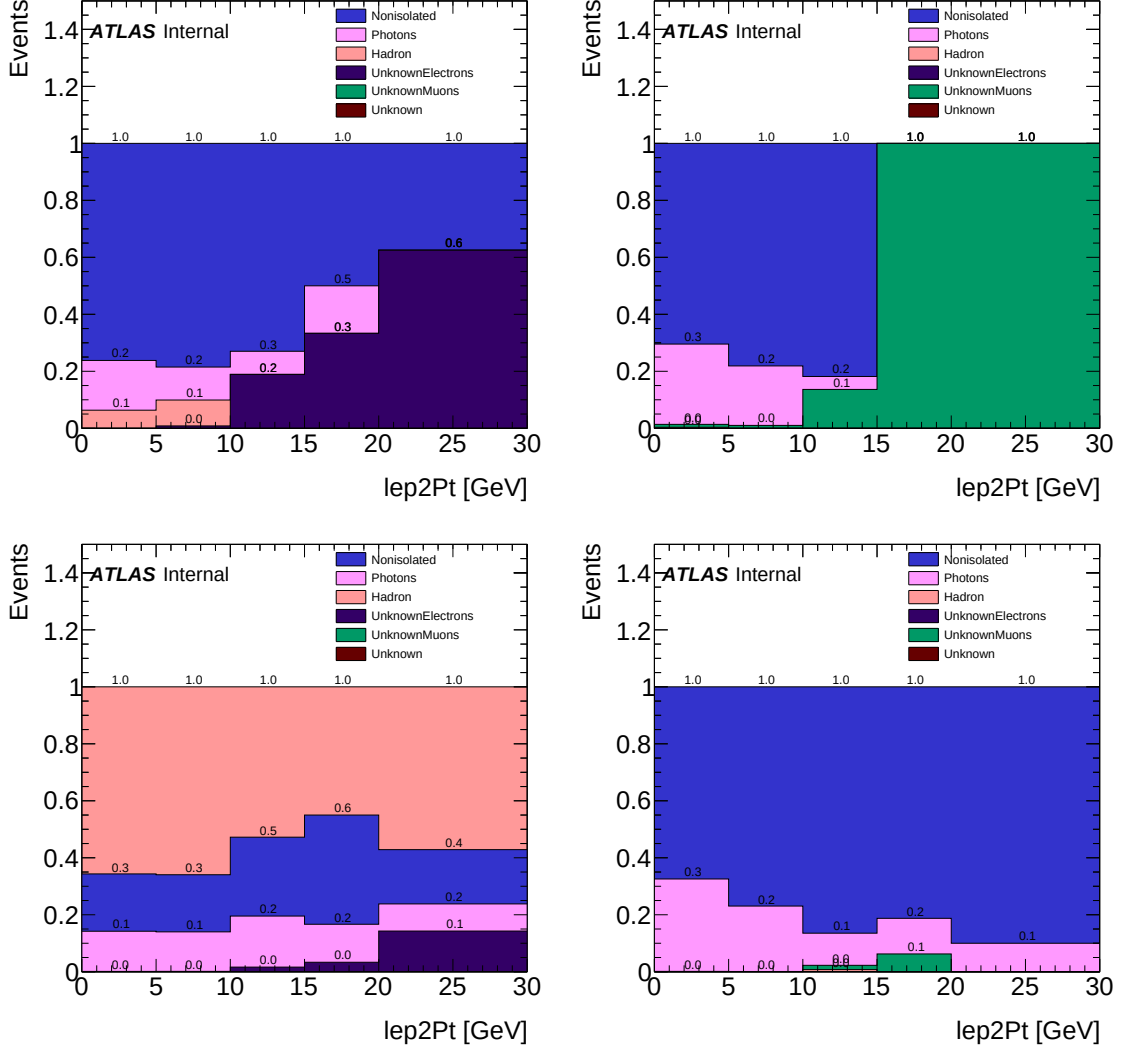


Figure 8.28: Simulated fake lepton composition as a function of $p_T^{\ell_2}$ in the inclusive electroweakino signal region for electrons (left) and muons (right) which satisfy the ID (top) and anti-ID (bottom) criteria. Fake electrons and muons satisfying the signal lepton criteria both tend to be due to “nonisolated” fakes from heavy flavor b -hadron and c -hadron decays.

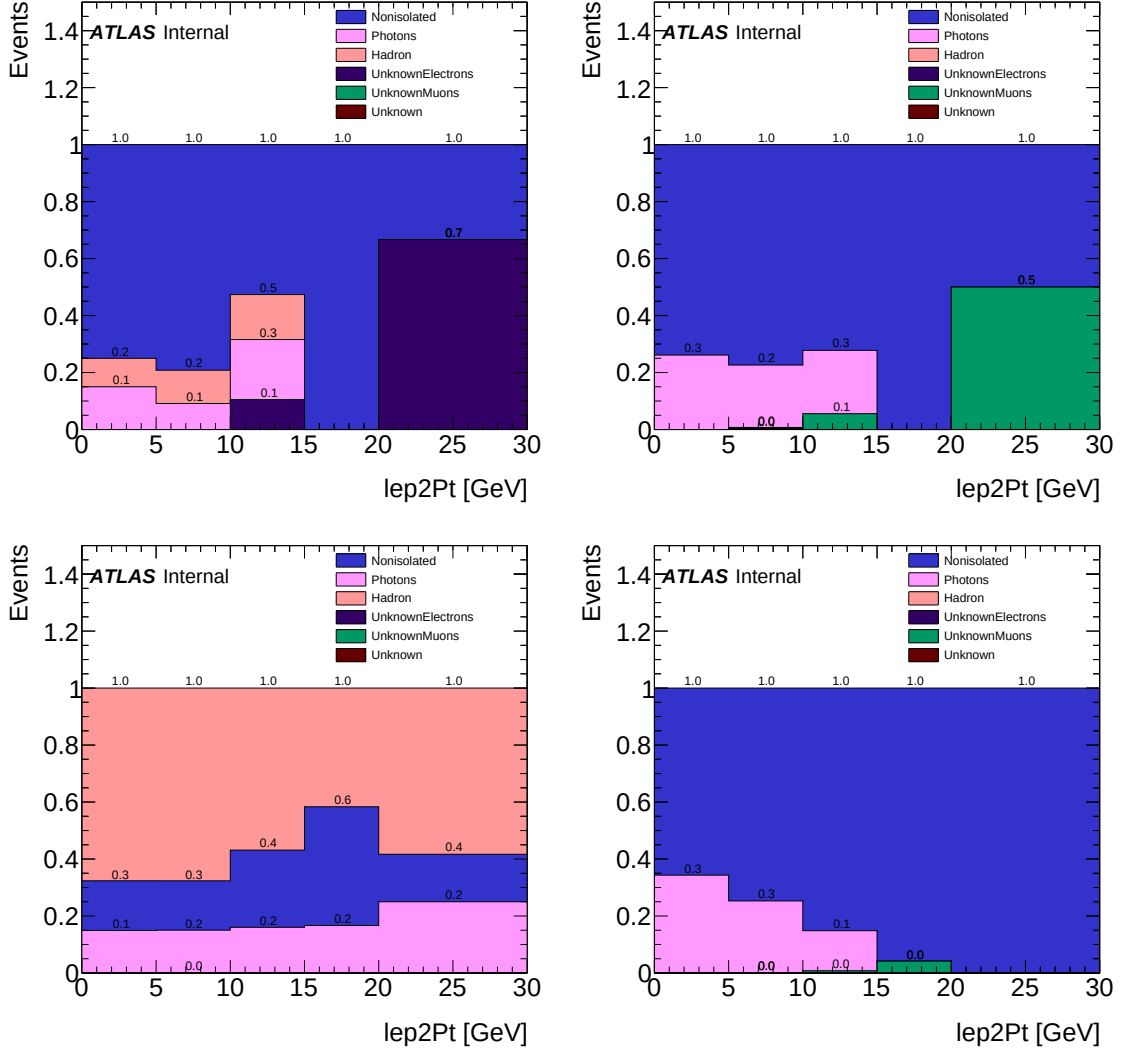


Figure 8.29: Simulated fake lepton composition as a function of $p_T^{\ell_2}$ in VR-SS for electrons (left) and muons (right) which satisfy the ID (top) and anti-ID (bottom) criteria. Fake electrons and muons satisfying the signal lepton criteria both tend to be due to “nonisolated” fakes from heavy flavor b -hadron and c -hadron decays. While the anti-ID electrons in VR-SS are predominantly misidentified light hadrons, the fact that this composition tends to agree well with that of the anti-ID electrons in the signal region (from Figure 8.28) means the good agreement between data and the fake lepton estimate observed in VR-SS should also be expected for the signal region. Differences between the ID and anti-ID fake lepton composition are handled by the fake lepton systematic uncertainties.

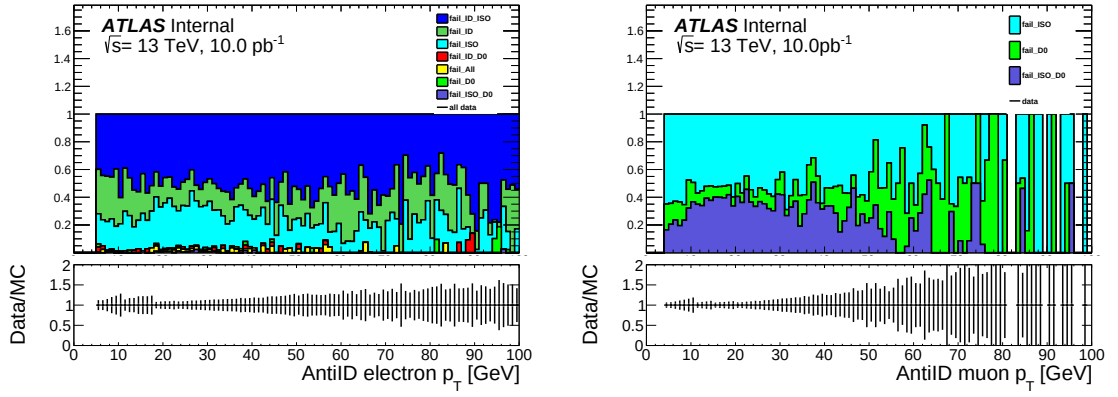


Figure 8.30: Data-driven composition in the dijet fake factor measurement region, for anti-ID electrons (left) and anti-ID muons in the $n_{b\text{-jet}} = 0$ case (right), shown as a function of lepton p_T . The bottom panel only illustrates the statistical precision as a function of p_T .

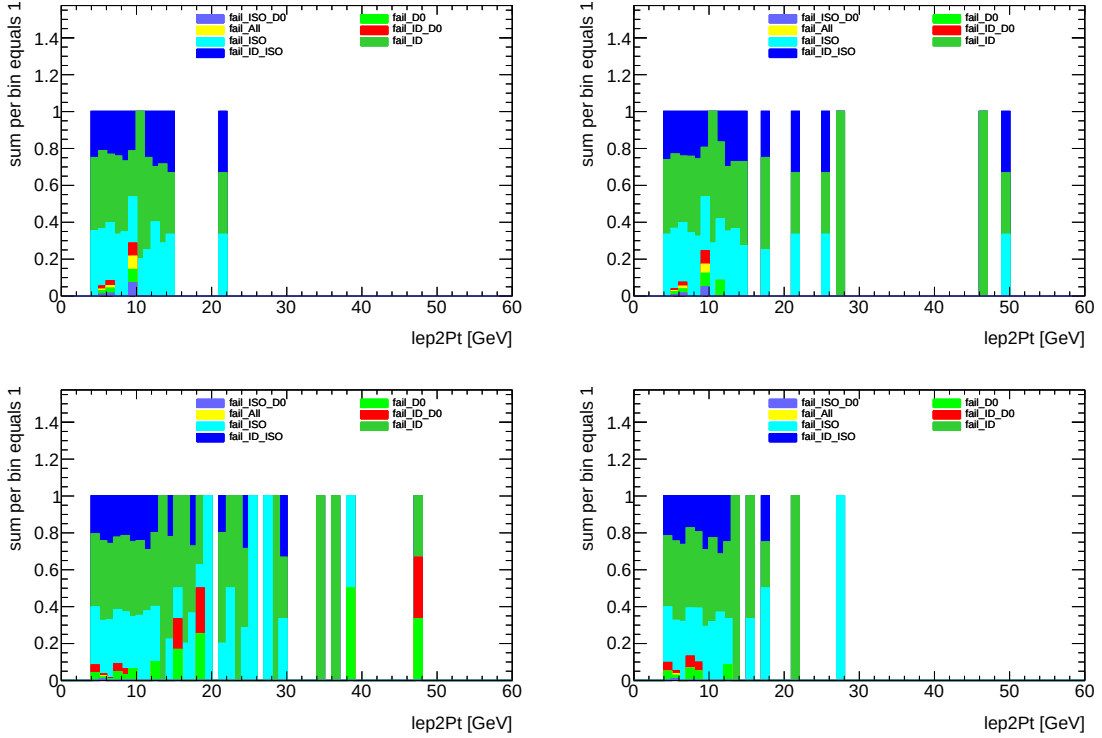


Figure 8.31: Data-driven composition of anti-ID electrons in VR-SS (top left), VR-SS-loose (top right), the common signal region from Table 8.4 (bottom left), and the common signal region with an additional $E_T^{\text{miss}}/H_T^{\text{lep}} > 5$ requirement (bottom right). These plots are shown as a function of $p_T^{\ell_2}$, and only ee events where the leading lepton is a signal lepton and the subleading lepton is an anti-ID lepton are used.

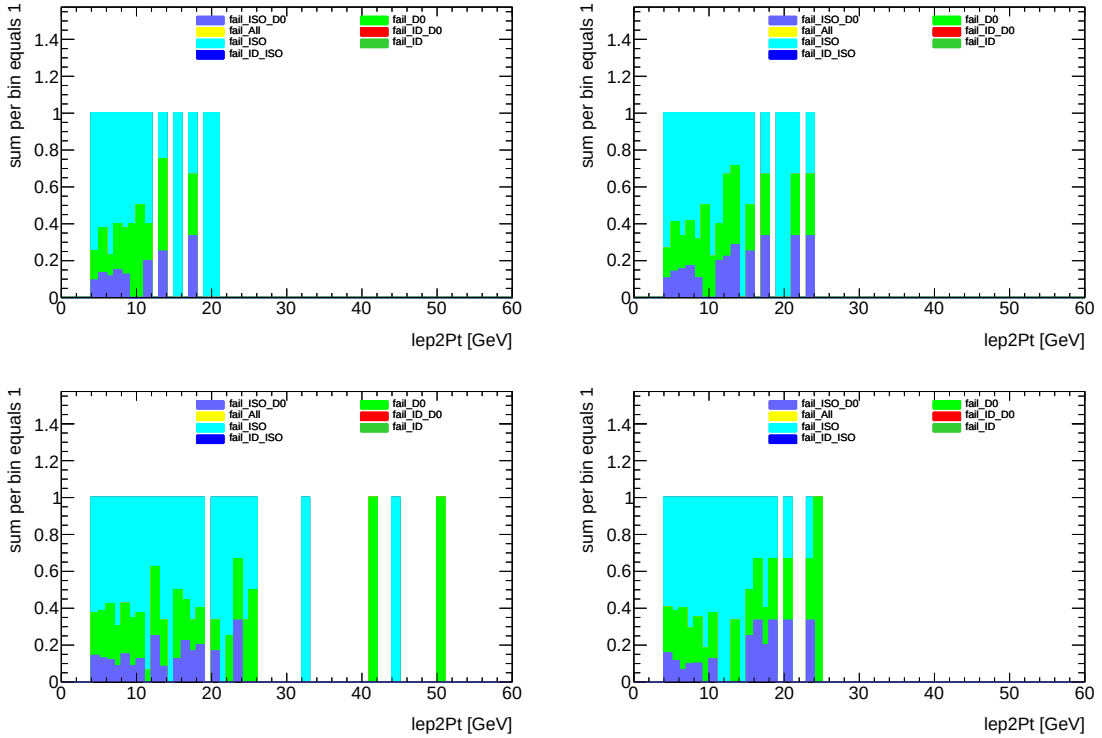


Figure 8.32: Data-driven composition of anti-ID muons in VR-SS (top left), VR-SS-loose (top right), the common signal region from Table 8.4 (bottom left), and the common signal region with an additional $E_T^{\text{miss}}/H_T^{\text{lep}} > 5$ requirement (bottom right). These plots are shown as a function of $p_T^{\ell_2}$, and only $\mu\mu$ events where the leading lepton is a signal lepton and the subleading lepton is an anti-ID lepton are used.

8.6 Results

Both experimental and theoretical systematic uncertainties are considered when evaluating the backgrounds. The largest source of systematic uncertainty affecting the results is the uncertainty on the fake lepton background estimate, described in Section 8.5.1.2. Other important systematic sources in this search include the jet energy scale and resolution, b -tagging uncertainties, the reweighting of the pileup profile in simulation to match that of data, the theoretical uncertainties associated with the modeling of the simulated events (e.g. the choice of renormalization, factorization, and merging scales used when simulating the events), and the uncertainties associated with the data-to-simulation normalization procedure used for $t\bar{t}/Wt$ and $Z \rightarrow \tau\tau$ +jets. Further details on these uncertainties can be found in [1], and Figure 8.33 shows the relative size of the various uncertainty sources for the exclusive bins of the electroweakino and slepton signal regions.

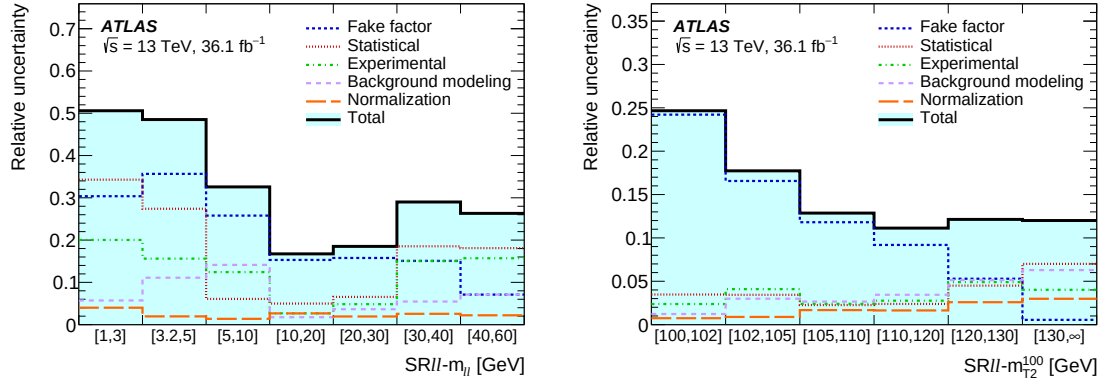


Figure 8.33: Breakdown of relative systematic uncertainties in the exclusive electroweakino (left) and slepton (right) signal regions. The experimental uncertainties shown include all detector systematics (e.g. jet energy resolution and scale, uncertainties on lepton identification and b -tagging, etc.) except for those due to the fake lepton background estimate [1].

As mentioned in Section 6.3 and 7.6, the `HistFitter` package [120] is used for the statistical interpretation of the results. This is done using a profile likelihood method [157] with the systematic uncertainties treated as nuisance parameters in the likelihood. A background-only fit is performed where the control regions are fit to the data under the assumption of zero signal events; this fit allows for the extraction of the fit parameters, which in this analysis corresponds to the data-to-simulation normalization factors for the $t\bar{t}/Wt$ and $Z \rightarrow \tau\tau$ +jets backgrounds. The normalization factors obtained from the background-only fit are $\mu_{\text{top}} = 1.02 \pm 0.09$ and $\mu_{\text{tau}} = 0.72 \pm 0.13$, where the uncertainties shown include the total statistical and systematic uncertainties.

The unblinded inclusive signal region distributions as a function of $m_{\ell\ell}$ and m_{T2}^{100} , after obtaining the final background estimate, are shown in Figure 8.34. Additional distributions of the various discriminating variables used in the analysis are shown for the common signal region in Figures 8.35 through 8.37.

No significant excesses above the Standard Model predictions are observed. Table 8.9 summarizes the number of observed and expected events in the inclusive signal regions, as well as the generic model-independent limits on new physics. Table 8.10, meanwhile, shows the exclusive signal region yields, including a breakdown of the primary background sources in each signal region. These exclusive signal regions are also summarized in Figure 8.38, which additionally quantifies the significance of any excesses or deficits observed in the data. As the exclusive signal regions allow the shape of the $m_{\ell\ell}$ and m_{T2}^{100} distributions to be exploited for maximal sensitivity to particular signal models, these are then used to determine the model-dependent exclusion limits on simplified models using

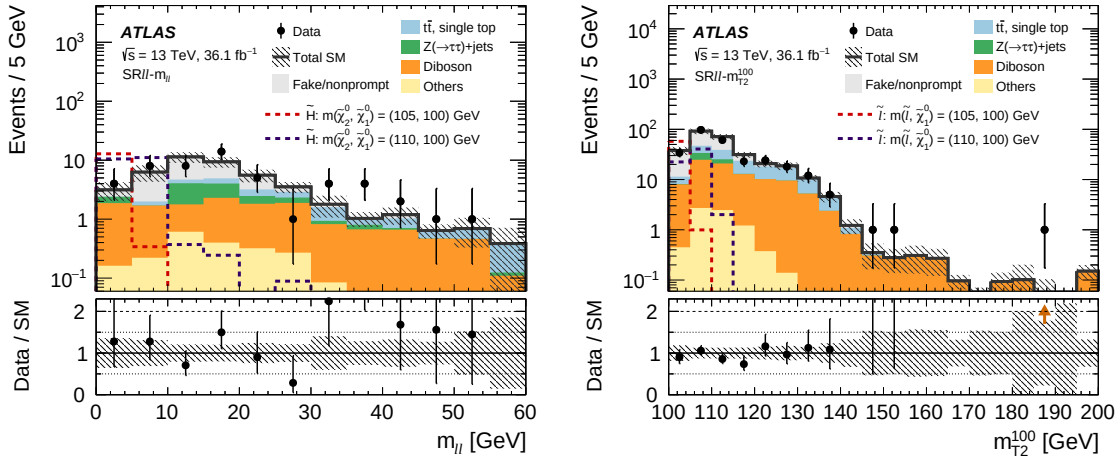


Figure 8.34: $m_{\ell\ell}$ and m_{T2}^{100} distributions in the inclusive electroweakino (left) and slepton (right) signal regions. Benchmark Higgsino LSP and slepton simulated signal samples are overlaid, where the masses of the sparticles are listed in the legends. Note that the $m_{\ell\ell}$ and m_{T2}^{100} distributions both have an endpoint corresponding to the mass splitting between the sparticles. A small fraction of events do have slightly larger $m_{\ell\ell}$ and m_{T2}^{100} values than expected; in both cases experimental effects such as energy calibration can contribute to this, while for the electroweakinos this can occur since $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ events are also generated (which do not decay to a Z^* , and thus do not have such an endpoint). The uncertainties shown include all statistical and systematic uncertainties. The last bin also includes the overflow [1].

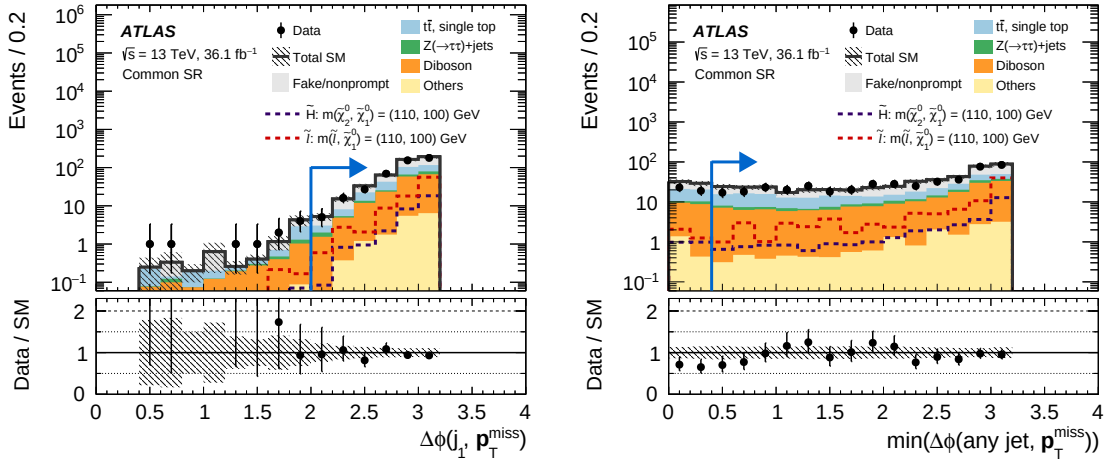


Figure 8.35: $\Delta\phi(j_1, \mathbf{p}_T^{\text{miss}})$ (left) and $\min(\Delta\phi(\text{any jet}, \mathbf{p}_T^{\text{miss}}))$ (right) distributions in the common signal region, with benchmark Higgsino LSP and slepton simulated signal samples overlaid. The masses of the sparticles are listed in the legends. The uncertainties shown include all statistical and systematic uncertainties. When present, the blue arrows indicate the location of the common signal region. When relevant, the first and last bin also include the underflow and overflow (respectively) [1].

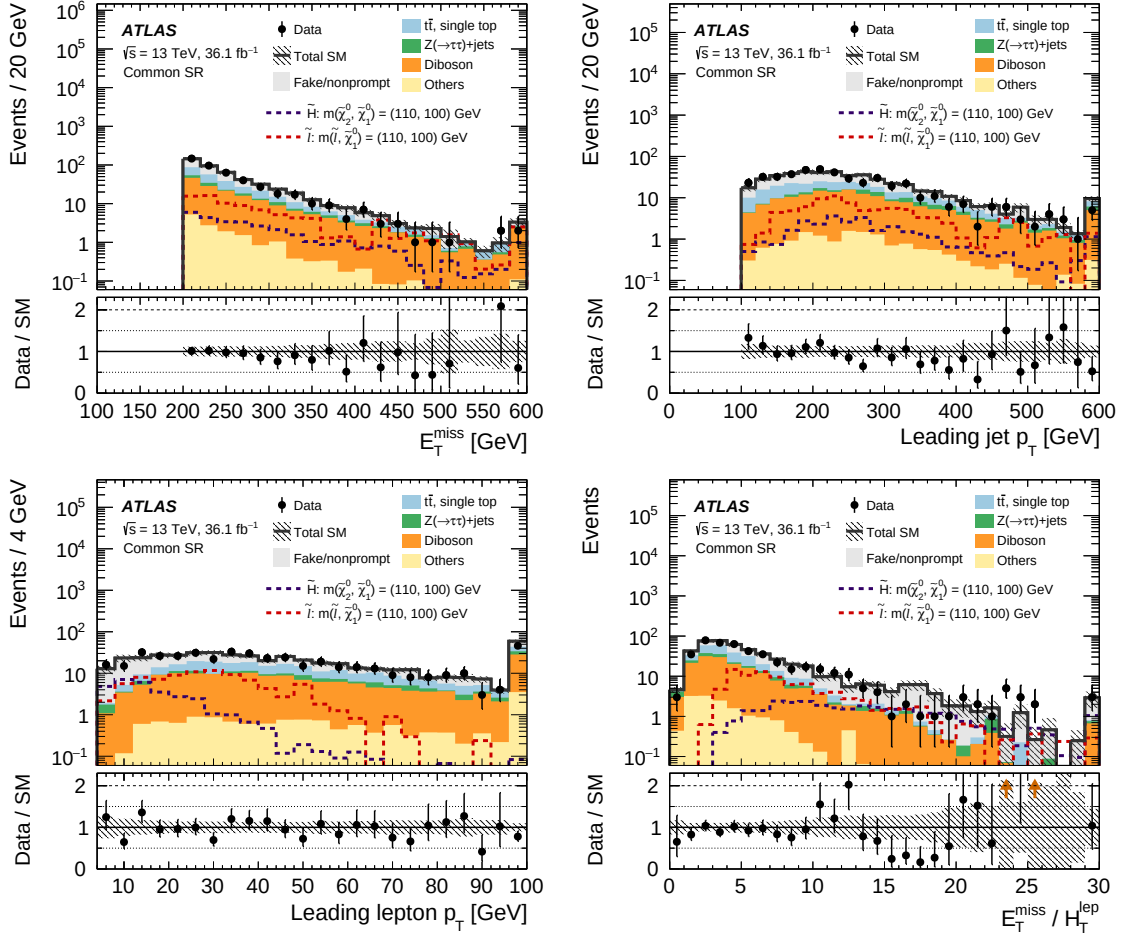


Figure 8.36: E_T^{miss} (top left), leading jet p_T (top right), leading lepton p_T (bottom left), and $E_T^{\text{miss}}/H_T^{\text{lep}}$ (bottom right) distributions in the common signal region, with benchmark Higgsino LSP and slepton simulated signal samples overlaid. The masses of the sparticles are listed in the legends. The uncertainties shown include all statistical and systematic uncertainties. When present, the blue arrows indicate the location of the common signal region. When relevant, the first and last bin also include the underflow and overflow (respectively) [1]. Note that the subleading lepton p_T distribution is already shown in Figure 8.10.

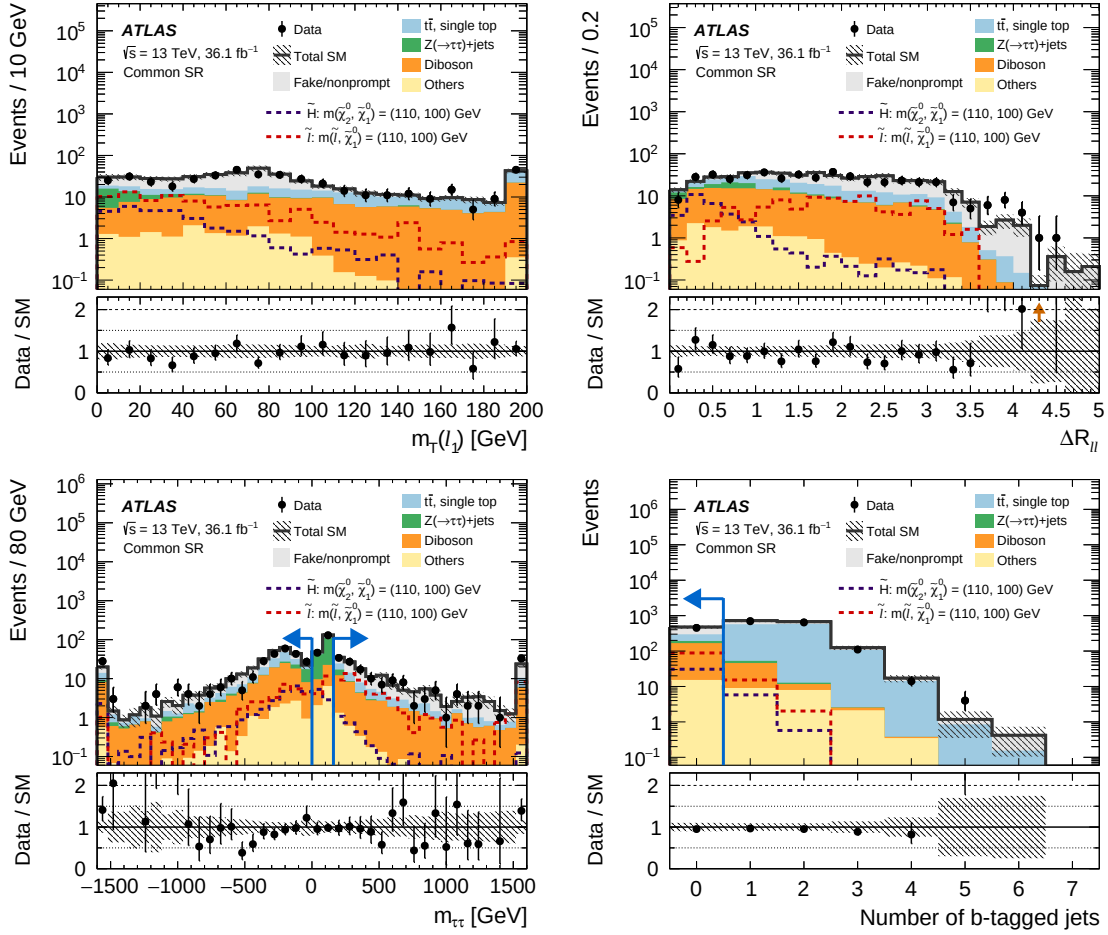


Figure 8.37: $m_T^{\ell_1}$ (top left), $\Delta R_{\ell\ell}$ (top right), $m_{\tau\tau}$ (bottom left), and $n_{b\text{-jet}}$ (bottom right) distributions in the common signal region, with benchmark Higgsino LSP and slepton simulated signal samples overlaid. The masses of the sparticles are listed in the legends. The uncertainties shown include all statistical and systematic uncertainties. When present, the blue arrows indicate the location of the common signal region. When relevant, the first and last bin also include the underflow and overflow (respectively) [1].

the CL_s method [158]. These model-dependent limits can be seen in the exclusion contours for the Higgsino, wino-bino, and slepton simplified models in Figures 8.39 through 8.41.

For the Higgsino LSP simplified model, $\tilde{\chi}_2^0$ sparticles are excluded up to masses of 145 GeV for $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ between 5 GeV and 10 GeV, and for mass splittings as small as $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \approx 2.5$ GeV for $m(\tilde{\chi}_2^0) \approx 100$ GeV. For the wino-bino model, which has larger production cross-sections, limits are set for $\tilde{\chi}_2^0$ with masses up to 175 GeV for $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \approx 10$ GeV, and for mass splittings as small as $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \approx 2$ GeV for $m(\tilde{\chi}_2^0) \approx 100$ GeV. For the slepton model, a fourfold degeneracy of the masses of the slepton states $\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\mu}_L$, and $\tilde{\mu}_R$ is assumed. These sleptons are excluded for masses up to 190 GeV for $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \approx 5$ GeV, and for mass splittings as small as $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \approx 1$ GeV for $m(\tilde{\ell}) \approx 70$ GeV. For mass splittings smaller than those excluded, sensitivity tends to be poor due to the low efficiency to reconstruct, identify, and isolate very soft leptons, thus resulting in a smaller acceptance to signals with small mass splittings. At larger mass splittings, meanwhile, the $m_{\ell\ell}$ and m_{T2}^{100} distributions for the signal samples start to become more similar to the distributions of the Standard Model backgrounds, thus reducing sensitivity [1].

8.7 Related Searches

The ATLAS compressed EWK SUSY search relying on events with soft leptons was successful for setting exclusion limits on the Higgsino LSP simplified model for neutralino mass splittings $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ as low as 2.5 GeV with the 2015–2016 dataset. However, the theoretical prediction for the mass splitting in a pure Higgsino LSP scenario is on the order of a few hundred MeV, which would be impossible to probe using the soft leptons that ATLAS is able to reconstruct. Moreover, with such small mass splittings, the lightest chargino is expected to be long-lived, with a lifetime of 0.05 ns in the pure Higgsino LSP case. To target this model, a search was performed for light charginos which leave hits in the pixel detector before decaying to a soft pion with $p_T \approx 300$ MeV and a noninteracting neutralino LSP. As the pion is too soft to reconstruct, the final state signature is a “disappearing” track containing hits in the pixel detector but none in the SCT, along with large E_T^{miss} [204]. Figure 8.42 shows the Higgsino LSP simplified model exclusion limits from this disappearing track analysis, overlaid with those from the soft dilepton search. This disappearing track search provides good complementarity for targeting this model, and provides ATLAS with two independent methods for searching for the Higgsino LSP simplified model.

As mentioned previously, the compressed EWK SUSY search presented in this chapter is very closely related to the trilepton search from Chapter 7. The current summary of ATLAS limits on the

Signal Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}	$p(s=0)$
SR ll - $m_{\ell\ell}$ [1, 3]	1	1.7 ± 0.9	0.10	3.8	$4.3^{+1.7}_{-0.7}$	0.50
SR ll - $m_{\ell\ell}$ [1, 5]	4	3.1 ± 1.2	0.18	6.6	$5.6^{+2.3}_{-1.0}$	0.32
SR ll - $m_{\ell\ell}$ [1, 10]	12	8.9 ± 2.5	0.34	12.3	$9.6^{+3.2}_{-1.9}$	0.21
SR ll - $m_{\ell\ell}$ [1, 20]	34	29 ± 6	0.61	22	17^{+7}_{-6}	0.25
SR ll - $m_{\ell\ell}$ [1, 30]	40	38 ± 6	0.59	21	20^{+9}_{-5}	0.38
SR ll - $m_{\ell\ell}$ [1, 40]	48	41 ± 7	0.72	26	20^{+8}_{-5}	0.20
SR ll - $m_{\ell\ell}$ [1, 60]	52	43 ± 7	0.80	29	24^{+5}_{-10}	0.18
SR ll - m_{T2}^{100} [100, 102]	8	12.4 ± 3.1	0.18	7	9^{+4}_{-2}	0.50
SR ll - m_{T2}^{100} [100, 105]	34	38 ± 7	0.49	18	23^{+7}_{-7}	0.50
SR ll - m_{T2}^{100} [100, 110]	131	129 ± 18	1.3	48	47^{+13}_{-15}	0.37
SR ll - m_{T2}^{100} [100, 120]	215	232 ± 29	1.4	52	62^{+21}_{-15}	0.50
SR ll - m_{T2}^{100} [100, 130]	257	271 ± 32	1.7	61	69^{+22}_{-17}	0.50
SR ll - m_{T2}^{100} [100, ∞]	277	289 ± 33	1.8	66	72^{+24}_{-17}	0.50

Table 8.9: Summary of event yields and model-independent limits in the inclusive signal regions. The signal region bins are shown in GeV. The observed (N_{obs}) and expected background (N_{exp}) yields in the signal regions are shown alongside the model-independent upper limits on the signal cross-section ($\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$) at the 95% confidence level. The observed (S_{obs}^{95}) and expected (S_{exp}^{95}) upper limits on the number of generic signal events—that is, any processes which could originate beyond the Standard Model—are also shown. The uncertainties on the expected yields and expected upper limits correspond to the total statistical plus systematic uncertainty on the background estimate. The last two columns show the p -value and the significance for the background-only hypothesis. In signal regions where the data yield is smaller than the expected value, the p -value is set to 0.5 and the significance is set to 0 [1].

wino-bino simplified model can be found in Figure 8.43, where the compressed search contributes primarily at small mass splittings while the trilepton search is one of the main contributors at large mass splittings.

The CMS experiment also performed a search for compressed EWK SUSY using events with two soft leptons and large $E_{\text{T}}^{\text{miss}}$ in the final state, which was also based on data collected in 2015–2016 [205]. The exclusion limits on the Higgsino LSP simplified model and the wino-bino simplified model obtained by CMS can be found in Figure 8.44. While ATLAS was sensitive to neutralino mass splittings $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ as low as 2.5 GeV, CMS only presented limits for mass splittings down to 7 GeV. This is likely due to the difficulty of generating the simulated background samples at small invariant masses; however, this could likely be improved for future versions of the analysis by CMS in the future. On the other hand, the CMS analysis excelled at larger mass splittings than the ATLAS analysis. The heaviest NLSPs that ATLAS expected to exclude have $m(\tilde{\chi}_2^0) = 155$ GeV at

$SRee-m_{\ell\ell}$	[1, 3]	[3.2, 5]	[5, 10]	[10, 20]	[20, 30]	[30, 40]	[40, 60]
Observed events	0	1	1	10	4	6	2
Fitted SM events	$0.01^{+0.11}_{-0.01}$	$0.6^{+0.7}_{-0.6}$	2.4 ± 1.0	8.3 ± 1.6	4.0 ± 1.0	2.4 ± 0.6	1.4 ± 0.5
Fake/nonprompt leptons	$0.00^{+0.08}_{-0.00}$	$0.02^{+0.12}_{-0.02}$	1.4 ± 0.9	4.0 ± 1.5	1.6 ± 0.9	0.7 ± 0.6	$0.02^{+0.11}_{-0.02}$
Diboson	$0.007^{+0.014}_{-0.007}$	$0.28^{+0.29}_{-0.28}$	0.51 ± 0.28	1.9 ± 0.6	1.36 ± 0.31	0.72 ± 0.22	0.80 ± 0.28
$Z \rightarrow \tau\tau$ +jets	$0.000^{+0.007}_{-0.000}$	$0.3^{+0.8}_{-0.3}$	$0.3^{+0.5}_{-0.3}$	1.7 ± 0.7	$0.25^{+0.26}_{-0.25}$	0.20 ± 0.18	$0.04^{+0.28}_{-0.04}$
$t\bar{t}$, single top	$0.00^{+0.08}_{-0.00}$	$0.02^{+0.12}_{-0.02}$	$0.11^{+0.14}_{-0.11}$	0.44 ± 0.29	0.63 ± 0.35	0.7 ± 0.4	0.6 ± 0.4
Others	$0.002^{+0.015}_{-0.002}$	$0.012^{+0.013}_{-0.012}$	0.12 ± 0.11	0.25 ± 0.16	0.21 ± 0.12	$0.05^{+0.06}_{-0.05}$	$0.0018^{+0.0033}_{-0.0018}$
$SR\mu\mu-m_{\ell\ell}$	[1, 3]	[3.2, 5]	[5, 10]	[10, 20]	[20, 30]	[30, 40]	[40, 60]
Observed events	1	2	7	12	2	2	2
Fitted SM events	1.1 ± 0.6	1.3 ± 0.6	4.9 ± 1.3	13.1 ± 2.2	4.2 ± 1.0	1.4 ± 0.6	1.6 ± 0.6
Fake/nonprompt leptons	$0.00^{+0.33}_{-0.00}$	$0.4^{+0.5}_{-0.4}$	3.0 ± 1.3	7.3 ± 2.1	$0.4^{+0.8}_{-0.4}$	$0.03^{+0.19}_{-0.03}$	$0.0^{+0.5}_{-0.0}$
Diboson	0.9 ± 0.5	0.7 ± 0.4	1.3 ± 0.6	1.4 ± 0.5	1.9 ± 0.4	0.9 ± 0.5	0.97 ± 0.28
$Z \rightarrow \tau\tau$ +jets	$0.18^{+0.25}_{-0.18}$	0.13 ± 0.12	$0.3^{+0.5}_{-0.3}$	2.4 ± 0.8	0.7 ± 0.4	$0.001^{+0.011}_{-0.001}$	$0.05^{+0.06}_{-0.05}$
$t\bar{t}$, single top	$0.01^{+0.10}_{-0.01}$	$0.02^{+0.12}_{-0.02}$	0.19 ± 0.13	1.4 ± 0.6	0.8 ± 0.4	0.37 ± 0.21	0.51 ± 0.33
Others	0.047 ± 0.030	$0.07^{+0.09}_{-0.07}$	0.13 ± 0.12	0.7 ± 0.5	0.35 ± 0.20	0.09 ± 0.07	0.020 ± 0.020
$SRee-m_{T2}^{100}$	[100, 102]	[102, 105]	[105, 110]	[110, 120]	[120, 130]	[130, ∞]	
Observed events	3	10	37	42	10	7	
Fitted SM events	3.5 ± 1.2	11.0 ± 2.0	33 ± 4	42 ± 4	15.7 ± 2.0	7.5 ± 1.1	
Fake/nonprompt leptons	2.9 ± 1.2	6.8 ± 2.0	13 ± 4	14 ± 4	1.9 ± 1.2	$0.01^{+0.10}_{-0.01}$	
Diboson	0.33 ± 0.12	2.3 ± 0.6	8.5 ± 1.6	12.7 ± 2.4	7.4 ± 1.4	4.3 ± 0.9	
$Z \rightarrow \tau\tau$ +jets	$0.13^{+0.23}_{-0.13}$	0.6 ± 0.4	4.1 ± 1.8	2.9 ± 1.0	$0.00^{+0.08}_{-0.00}$	$0.00^{+0.20}_{-0.00}$	
$t\bar{t}$, single top	0.08 ± 0.08	1.2 ± 0.5	6.5 ± 1.6	10.7 ± 2.4	6.3 ± 1.4	3.2 ± 0.9	
Others	$0.011^{+0.012}_{-0.011}$	0.17 ± 0.11	0.8 ± 0.4	1.3 ± 0.7	0.14 ± 0.09	0.06 ± 0.04	
$SR\mu\mu-m_{T2}^{100}$	[100, 102]	[102, 105]	[105, 110]	[110, 120]	[120, 130]	[130, ∞]	
Observed events	5	16	60	42	32	13	
Fitted SM events	6.8 ± 1.5	15.0 ± 2.1	57 ± 5	53 ± 4	24.9 ± 2.9	11.0 ± 1.4	
Fake/nonprompt leptons	5.1 ± 1.5	8.2 ± 2.1	26 ± 5	18 ± 4	1.2 ± 0.8	$0.02^{+0.17}_{-0.02}$	
Diboson	0.89 ± 0.22	4.1 ± 0.9	14.3 ± 2.2	18.0 ± 2.7	12.9 ± 2.2	5.9 ± 1.1	
$Z \rightarrow \tau\tau$ +jets	0.31 ± 0.23	$1.0^{+1.3}_{-1.0}$	6.6 ± 1.7	$1.6^{+1.8}_{-1.6}$	$0.03^{+0.25}_{-0.03}$	$0.02^{+0.24}_{-0.02}$	
$t\bar{t}$, single top	0.43 ± 0.22	1.4 ± 0.5	8.3 ± 2.2	12.4 ± 2.9	10.5 ± 2.6	5.0 ± 1.3	
Others	$0.020^{+0.024}_{-0.020}$	0.24 ± 0.15	1.8 ± 1.0	2.4 ± 1.3	0.35 ± 0.23	0.11 ± 0.07	

Table 8.10: Observed and expected event yields in the exclusive signal regions. The signal region bins are shown in GeV. Uncertainties shown for the background estimates are the total statistical plus systematic uncertainty [1].

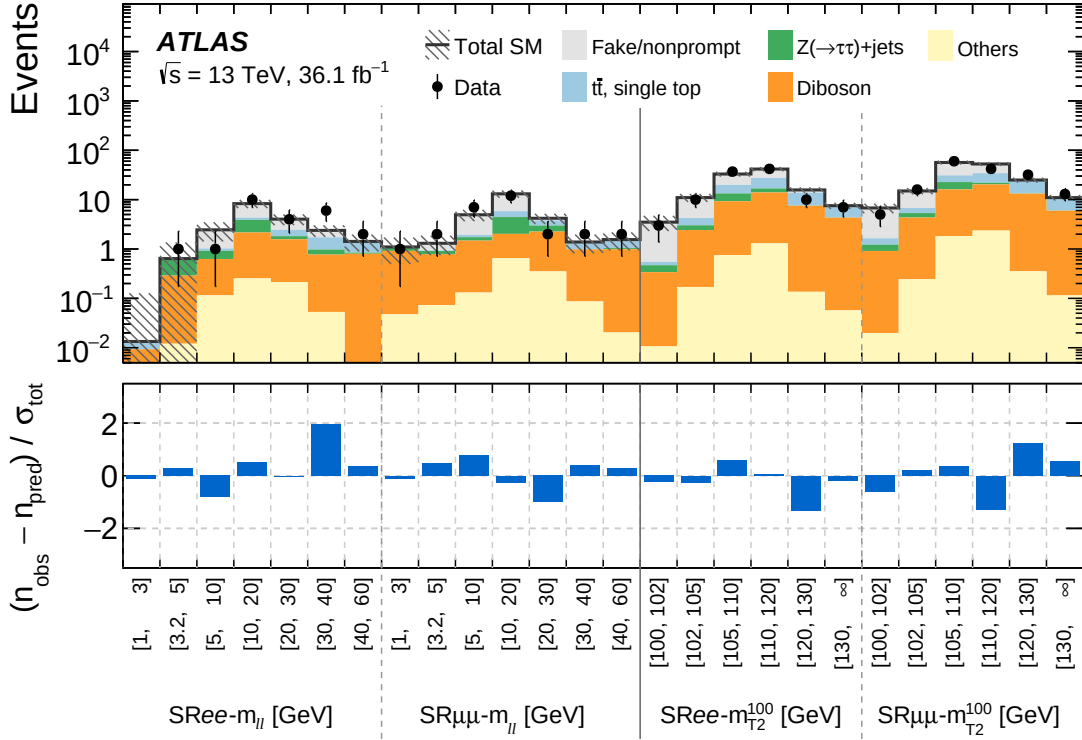


Figure 8.38: Observed and expected event yields in the exclusive signal regions. Uncertainties shown for the background estimates are the total statistical plus systematic uncertainty. The bottom panel of this figure shows the significance of any excesses or deficits observed in data, with respect to the Standard Model prediction [1].

$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 10$ GeV for the Higgsino LSP scenario and $m(\tilde{\chi}_2^0) = 190$ GeV at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 10$ GeV for the wino-bino scenario. For CMS, meanwhile, the expected exclusions are up to $m(\tilde{\chi}_2^0) = 150$ GeV at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 12.5$ GeV for the Higgsino LSP scenario and $m(\tilde{\chi}_2^0) = 200$ GeV at $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ in the range 15–20 GeV for the wino-bino scenario. These sensitivity differences are likely due to differences in the analysis optimization, which means ATLAS and CMS can learn from one another and make improvements for future versions of the analyses.

8.8 Future Improvements and Searches

The analysis presented in this chapter was the first attempt by ATLAS to search for direct production of compressed Higgsinos. There are several potential improvements to the analysis which should be considered in the future, in addition to other potential final states to study.

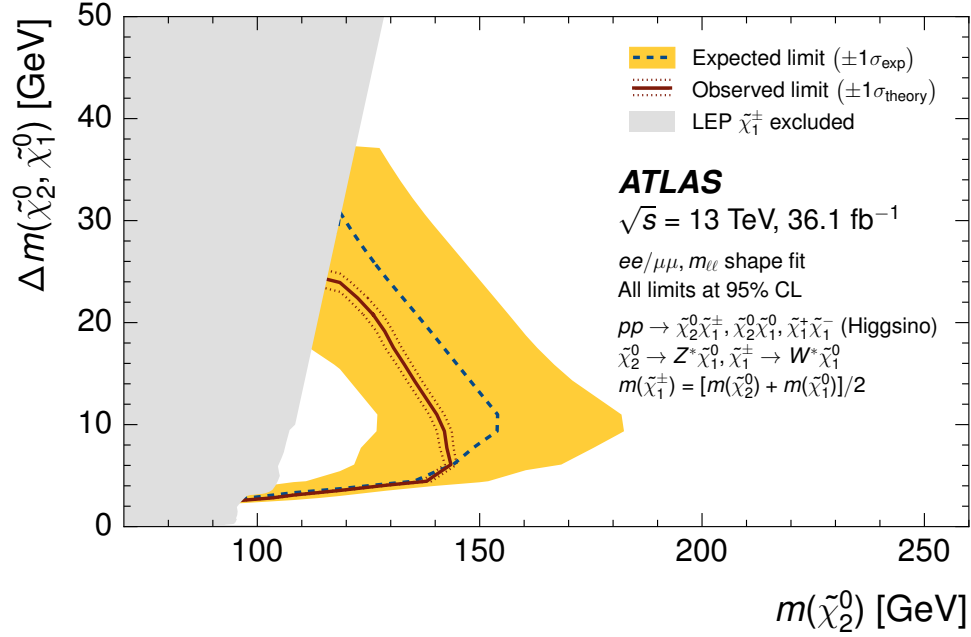


Figure 8.39: The observed (solid red line) and expected (dashed blue line) exclusion limits on the Higgsino LSP simplified model are shown as a function of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ and $m(\tilde{\chi}_2^0)$. The shaded yellow band indicates the $\pm 1\sigma$ variations to the expected limit based on the uncertainties on the Standard Model background expectations. The dotted red lines indicate the impact on the observed limit based on the change to the signal cross-section when varying its value by the theoretical uncertainty. The shaded gray region indicates the masses and mass splittings already excluded by LEP [164]. All limits are computed at the 95% confidence level. Exclusions on this model are computed using the electroweakino signal regions. In this model, the Higgsino production cross-sections are used, and the mass of the lightest chargino is set to be halfway between that of the two lightest neutralinos [1].

For interpreting the results, the Higgsino LSP and wino-bino simplified models considered are not the only models worth considering. As mentioned in Section 8.2 and in the caption of Figure 8.3, the product of the signed mass eigenvalues for the lightest neutralinos in the wino-bino simplified model can actually be either positive or negative, while that of the Higgsino LSP model is always negative. If one looks at the mixing matrix from Equation 2.3, this can be understood by diagonalizing the relevant subblocks pertaining to each scenario. In the Higgsino LSP case, diagonalization of the bottom right subblock results in eigenvalues for the lightest two neutralinos of $\pm\mu$. As μ can always be chosen to be real, the product of the two eigenvalues will necessarily be negative. In the wino-bino case, meanwhile, diagonalization of the top left subblock results in eigenvalues of M_1 and M_2 . However, it is generically only possible to choose a phase in which one of these two mass parameters must be real and positive, while the other must be real but has no constraint on its

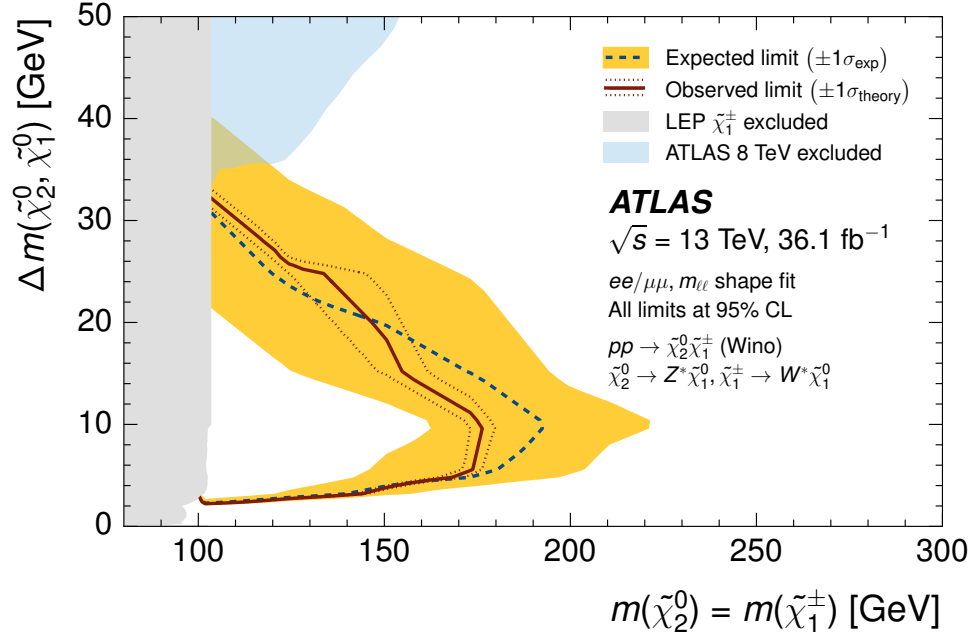


Figure 8.40: The observed (solid red line) and expected (dashed blue line) exclusion limits on the wino-bino simplified model are shown as a function of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ and $m(\tilde{\chi}_2^0)$. The shaded yellow band indicates the $\pm 1\sigma$ variations to the expected limit based on the uncertainties on the Standard Model background expectations. The dotted red lines indicate the impact on the observed limit based on the change to the signal cross-section when varying its value by the theoretical uncertainty. The shaded gray region indicates the masses and mass splittings already excluded by LEP [164]. The blue shaded region indicates the limits from the 2ℓ and 3ℓ electroweak SUSY searches by ATLAS in Run 1 [159, 160]. All limits are computed at the 95% confidence level. Exclusions on this model are computed using the electroweakino signal regions. In this model, the wino production cross-sections are used, and the mass of the lightest chargino is set to be equal to that of the second lightest neutralino [1].

sign [206]. Since there is a freedom allowing either M_1 or M_2 to be negative, the product of the eigenvalues associated to the lightest two neutralinos in the wino-bino case need not be positive, and thus either $m_{\ell\ell}$ distribution from Figure 8.3 is possible in this simplified model. Although this result only considered a wino-bino model where the product of eigenvalues is positive, the wino-bino simulated samples could be reweighted in the future to produce the alternative $m_{\ell\ell}$ distribution. These reweighted samples could then be used to set limits on this alternative wino-bino simplified model.

Another well-motivated model which ATLAS could consider studying closer involves either a mixed Higgsino-bino LSP or a mixed wino-bino LSP, i.e. $|\mu| \approx |M_1| \ll |M_2|$ or $|M_2| \approx |M_1| \ll |\mu|$ (respectively). In this model, referred to as the “well-tempered neutralino” model, the LSP

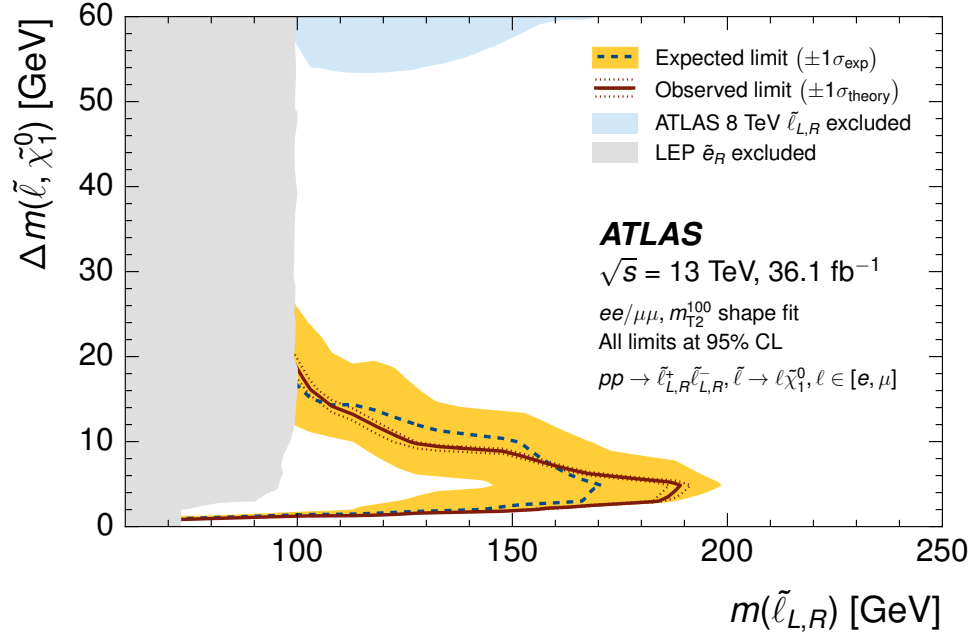


Figure 8.41: The observed (solid red line) and expected (dashed blue line) exclusion limits on the slepton simplified model are shown as a function of $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$ and $m(\tilde{\ell})$. The shaded yellow band indicates the $\pm 1\sigma$ variations to the expected limit based on the uncertainties on the Standard Model background expectations. The dotted red lines indicate the impact on the observed limit based on the change to the signal cross-section when varying its value by the theoretical uncertainty. The shaded gray region indicates the masses and mass splittings already excluded by LEP [165]. The blue shaded region indicates the limits on sleptons based on searches by ATLAS in Run 1 [159]. All limits are computed at the 95% confidence level. Exclusions on this model are computed using the slepton signal regions. In this model, the sleptons are assumed to be fourfold mass degenerate for left-handed and right-handed electrons and muons, i.e. $m(\tilde{e}_L) = m(\tilde{e}_R) = m(\tilde{\mu}_L) = m(\tilde{\mu}_R)$ [1].

composition can be tuned to match the observed dark matter relic density; the Higgsino-bino LSP case in particular can also keep μ near the weak scale to satisfy naturalness constraints [207]. An extension of this model, the “not-so-well-tempered neutralino” model, additionally allows for the possibility that several dark matter particles could contribute, and thus the LSP only needs to explain some fraction of the observed dark matter [208].

As for improvements to the search, there are several opportunities for ATLAS to explore. First is to make use of dedicated triggers which apply trigger-level selection criteria on several objects, including E_T^{miss} , jets, and soft leptons; some of these triggers have been active since 2016. This could allow for a reduction of the offline $E_T^{\text{miss}} > 200$ GeV requirement used in the analysis, and could help to improve the signal acceptance. Even without these dedicated triggers, it may be

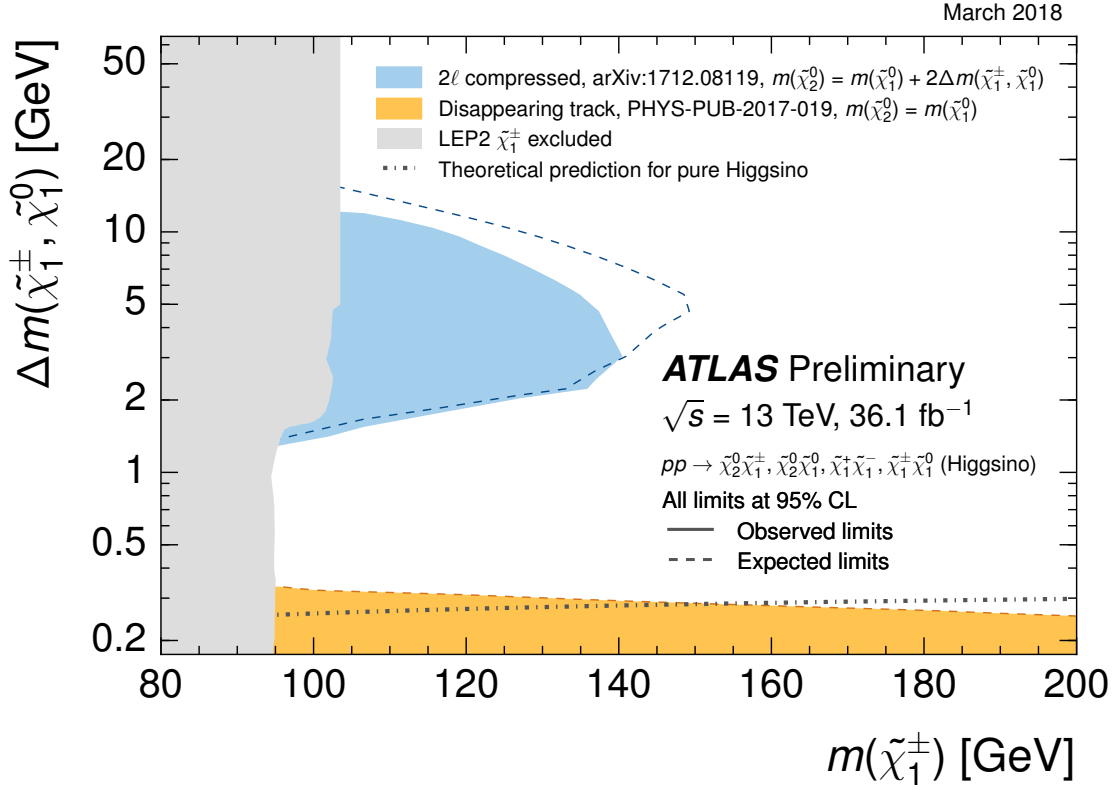


Figure 8.42: Summary of ATLAS limits on the Higgsino LSP simplified model, as of March 2018. These limits are shown at 95% confidence level as a function of the mass splitting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ and the $\tilde{\chi}_1^\pm$ mass, where the mass of the lightest chargino is assumed to be halfway between the masses of the two lightest neutralinos. The ATLAS limits on this model come from the search for events with two soft leptons (which has been the primary focus of this chapter) and from the disappearing track search [116].

possible to relax the offline E_T^{miss} requirement, as the inclusive E_T^{miss} trigger can be used even before it is fully efficient, though this must be done carefully (e.g. analysis-specific data-to-simulation efficiency correction factors may be necessary, as the simulation may not perfectly replicate the trigger efficiency observed in data).

In addition to the dilepton search pursued thus far, several other final states could be considered. As mentioned in Section 7.8, a tripleton search for compressed EWK SUSY is possible, and could be sensitive at larger mass splittings than those probed by the dilepton search. To push to lower mass splittings in spite of the low p_T lepton inefficiencies, one channel which could be considered is a variant on the dilepton search in which one of the leptons is not reconstructed. Since a single lepton final state would likely have far too much background, this single lepton could be paired with

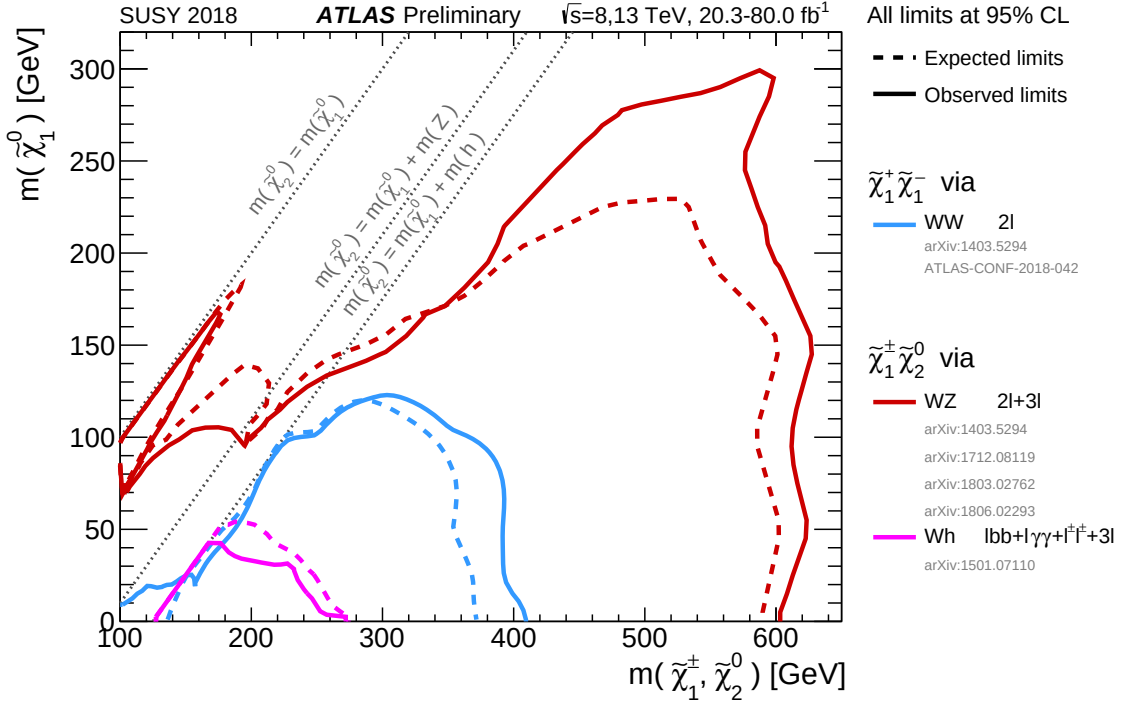


Figure 8.43: Summary of ATLAS limits on the wino-bino simplified model, as of July 2018. These limits are shown at 95% confidence level as a function of the $\tilde{\chi}_2^0$ mass (assumed to be mass degenerate with $\tilde{\chi}_1^\pm$) and the $\tilde{\chi}_1^0$ LSP mass. At small mass splittings, the search for events with two soft leptons (which has been the primary focus of this chapter) drives the sensitivity. At larger mass splittings, the search for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via on-shell W and Z decays to two or three leptons (which was the focus of Chapter 7) is the main contributor to the sensitivity [116].

a reconstructed track, the idea being that this track would have been reconstructed as a lepton in an ideal detector. Additional requirements could then be imposed on the track to distinguish the potential lepton from background objects. As in the dilepton search, this search would still benefit from the endpoint in the $m_{\ell\ell}$ distribution, which is a powerful discriminator against background. Of course, improvements to the soft lepton reconstruction, identification, and isolation algorithms (such as those discussed in Section 4.6) could improve the lepton selection efficiencies and background rejection, which would directly benefit searches for compressed EWK SUSY in all leptonic final states. On the topic of improvements to the lepton selection criteria, it is important to consider that when smaller mass splittings are probed, the NLSP lifetimes are correspondingly larger¹¹. As a result, it might become worthwhile in the future to study the impact of relaxing the requirements

¹¹The simulated electroweakino samples discussed in this thesis were all required to decay promptly, but in a more realistic model, this would not be the case.

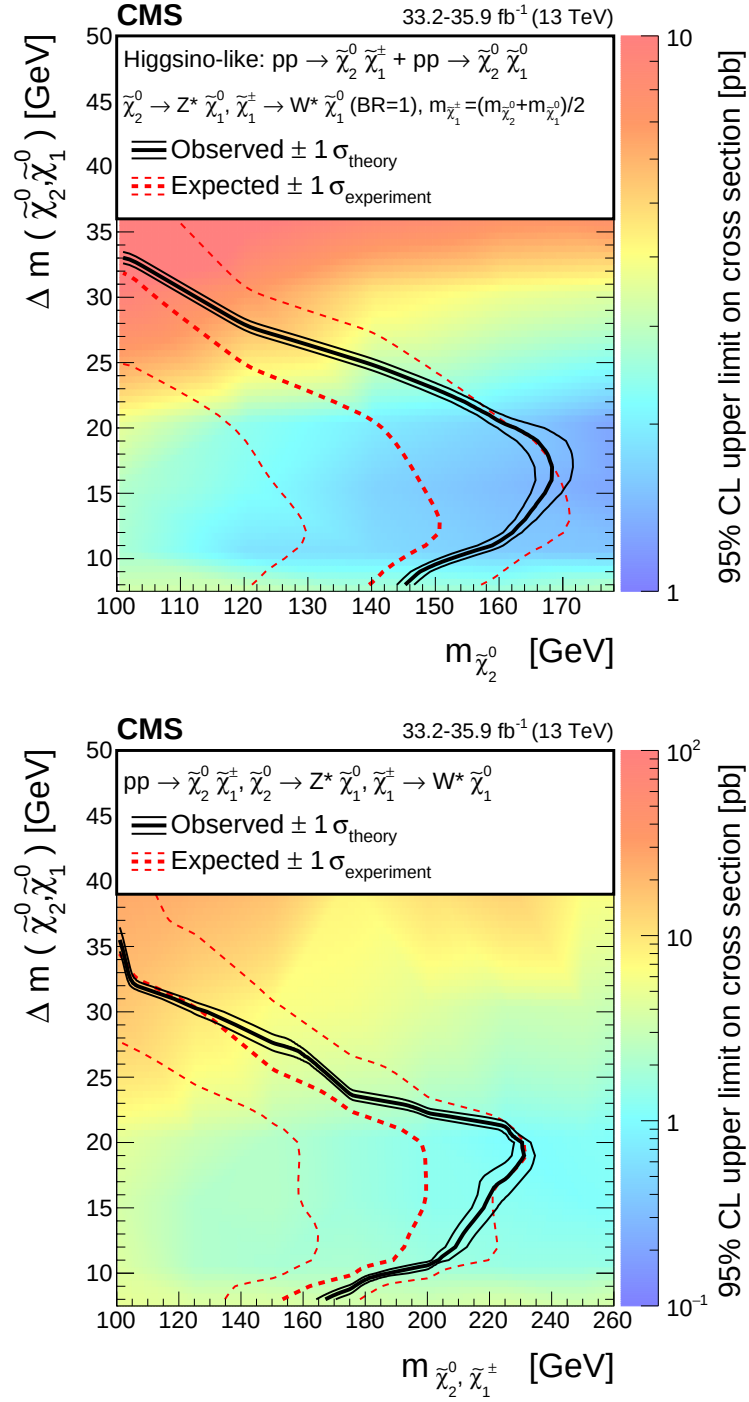


Figure 8.44: CMS limits on direct electroweakino production in the Higgsino LSP simplified model (top) and in the wino-bino simplified model (bottom) [205]. These can be compared with the corresponding ATLAS exclusion limits from Figures 8.39 and 8.40, respectively.

imposed on the lepton transverse impact parameter, as this could improve the sensitivity to these long-lived NLSPs.

Finally, one thing to keep in mind for the future is to ensure that sufficient statistics are collected for the background objects used to measure the lepton fake factors. In 2017 data, some of the ATLAS prescaled single electron triggers were accidentally disabled; fortunately other triggers with different electron p_T thresholds were still available. This was noticed before 2018 data collection, which made it possible for the set of triggers that had been removed from the 2017 trigger menu to be reinstated for 2018 data (with a larger rate to compensate for the lost statistics). Of course, an alternative way to avoid this issue would be to rely on a different physics process for computing the lepton fake factors. For instance, the fake factors measured using the Z +jets/ Z + γ process in Section 7.5.1.1 could be studied closely and compared with the dijet-based fake factors from Section 8.5.1.1. For the 2015–2016 analysis, these two sets of fake factors were initially studied and found to give different results in preliminary versions of the same-sign validation region, which is why the dijet-based fake factors were ultimately used. However, it is possible to change the Z +jets/ Z + γ event selection criteria in order to modify the event kinematics and consequently align the fake lepton composition with that of the dijet fake factor measurement region—or even better, with that of the signal region and the fake lepton validation region used in the analysis. Some example criteria might include a light jet veto, a b -jet veto, or a requirement on the invariant mass of the three reconstructed leptons ($m_{\ell\ell\ell}$).

CHAPTER 9

The Autonomous Monitor and Control Chip

“The beneficial uses of this electrical fluid in the creation, we are not yet well acquainted with, though doubtless such there are, and those very considerable.”

— Benjamin Franklin [209]

9.1 Motivation for Upgrades to the ATLAS Detector

The various components of the ATLAS detector were designed to perform for roughly ten years of operation, and are typically expected to remain functional for an integrated luminosity of 700 fb^{-1} [55]. As of 2019, ATLAS has received nearly 200 fb^{-1} , with an additional 300 fb^{-1} expected in Run 3 (which is scheduled to occur in 2021–2023).

By the mid-2030s, however, the High Luminosity LHC (“HL-LHC”) will deliver as much as 3000 fb^{-1} , which will certainly cause too much radiation damage for the current ATLAS detector to continue to function as intended. Moreover, at these high luminosities of $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and an average pileup of $\mu = 200$, the subdetectors of ATLAS would be less efficient than they currently are. For instance, the TRT occupancy would be nearly 100% and the SCT would have difficulty resolving nearby tracks [210]. Such inefficiencies would directly impact the usefulness of the HL-LHC dataset, which motivates upgrades and replacements for many of the ATLAS subdetectors. The current anticipated timeline for the HL-LHC is shown in Figure 9.1.

9.2 The Inner Tracker Detector

The existing Inner Detector will be replaced with a new subdetector called the Inner Tracker (ITk) in the mid-2020s, after the end of Run 3. The ITk, unlike the current Inner Detector, will use silicon

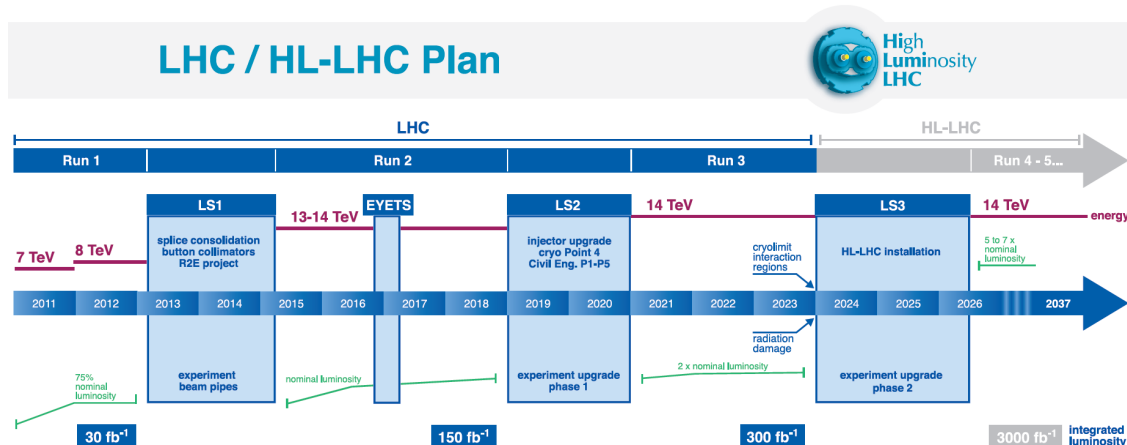


Figure 9.1: Anticipated HL-LHC timeline. Roughly 300 fb^{-1} is expected for Run 3 (2021–2023). Starting in 2023, the HL-LHC installation will begin, as will upgrades to the ATLAS detector. The HL-LHC is expected to deliver roughly 3000 fb^{-1} over the course of a decade, starting around the year 2026 [211].

sensors for tracking in all of its subdetectors. Additionally, while the current Inner Detector has three subdetectors—the Pixel Detector, the SCT, and the TRT—the ITk will only have two: the ITk Pixel and ITk Strips subdetectors. The proposed layout of the ITk is shown in Figure 9.2, and can be compared to the layout of the current Inner Detector shown in Figure 3.9.

The ITk will consist of approximately 5 billion pixel sensors and 18,000 silicon strip sensors (the latter corresponding to 60 million readout channels, as each silicon strip sensor has between 2000 and 6000 channels) with typical sizes of roughly $2500 \mu\text{m}^2$ and 100 cm^2 per sensor, respectively. In addition to the sensors, there are readout electronics which are necessary to ultimately convert information from the sensors into useful physics data. Together along with other essential components such as power boards, these sensors and readout electronics comprise electrical modules. These modules will be installed in the ITk in mechanical support structures called staves and petals. In addition to the electrical and mechanical components, cooling infrastructure will also be needed to ensure that the various components of the detector operate at their intended temperatures. All of these components are essential for the successful operation of the ITk [210, 212].

9.2.1 Readout Electronics for the ITk Strips

Application-specific integrated circuits (ASICs) will be used for the readout electronics in the ITk Strips detector. ASICs have been used frequently for readout systems in the HEP community for

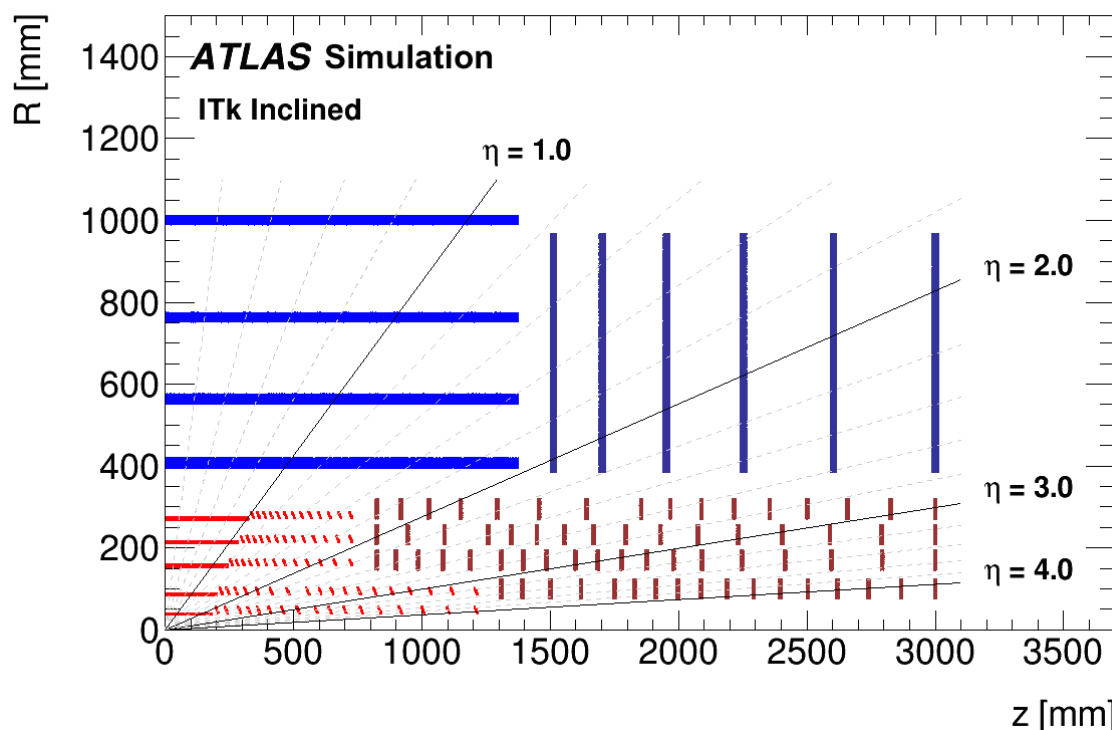


Figure 9.2: Schematic of the proposed layout of the ITk, with the ITk Pixel layers shown in red and the ITk Strips layers shown in blue [210].

many years, including in the existing ATLAS subdetectors. There are three ASICs which will be used in the ITk Strips:

- ATLAS Binary Chip (ABC): converts charge from silicon sensors to binary hit information.
- Hybrid Controller Chip (HCC): interface between ABCStar and the bus tape.
- Analog Monitor and Control Chip (AMAC): each AMAC measures analog environmental voltages, currents, and temperatures of an ITk Strips electrical module. The AMAC is a standalone chip that uses its internal ring oscillator to drive its data conversion logic and communications to the off-detector data acquisition system. The AMAC also provides interlock functionality for each of its monitored values, giving it power control (i.e. the ability to disable given outputs) in case of monitored values which are either below or above their intended range.

Several prototypes of each of these chips have been developed in the past few years; the most recent versions are referred to as the ABCStar, HCCStar, and AMACv2a.

The ITk Strips detector is comprised of nearly 18,000 modules. These modules each consist of the silicon strip sensors, a power board, and either one or two hybrids. The hybrids are connected to the power board, and each power board contains one AMAC. Each hybrid contains one HCCStar and 10–12 ABCStar chips. The ABCStars each receive signal charge information directly from the silicon sensor, and then proceed to amplify, shape, and discriminate these signals. This results in binary hit information which is transmitted to the HCCStar, which builds packets from the binary ABCStar information and transmits the packets to the bus tape (which itself is used to ultimately transmit data off-detector) [210]. A schematic of a module with these ASICs mounted is shown in Figure 9.3, and a cartoon of a module is shown in Figure 9.4.

9.2.2 Behavior of Irradiated ASICs

For historical context, the ATLAS IBL makes use of the FE-I4 chip (for “front-end integrated circuit, version four”) for its readout [64]. After installation of the IBL in 2015, it was observed that the FE-I4’s low-voltage (LV) current unexpectedly increased significantly during LHC operation. Figure 9.5 shows the LV current as a function of integrated luminosity, displayed as an average over all IBL module groups (where each module group contains four FE-I4 chips) [214]. This drastic increase in the module group LV current by up to nearly 1 A began already within the first fb^{-1} delivered to ATLAS in 2015, and did not reach a maximum until roughly 4 fb^{-1} was delivered (corresponding to a total ionizing dose, or “TID”, of about 1.1 Mrad). After reaching its maximum, the current subsequently decreased to within 10% of its initial value by the time an additional 0.5 fb^{-1} was delivered. This effect is often referred to as the “TID bump”.

The TID bump was found to be due to radiation damage to NMOS transistors which results in a leakage current [215]. Upon irradiation, positive charges are trapped and accumulate in the shallow trench isolation (STI) oxide. The purpose of the STI oxide in a transistor is to prevent leakage current; however, the positive charge accumulation results in an electric field which allows for leakage current to flow. With 80 million transistors in the FE-I4 chip, this transistor-level leakage current results in an increase to the overall current consumed by the chip. Over time, diffusion occurs and the positively charged holes in the STI oxide begin to move to the interface between the oxide and the silicon. This leads to trapping of electrons at the interface which compensates for the initial radiation damage as the overall charge imbalance in the transistor decreases. The transistor leakage current, and subsequently the overall current consumption for the ASIC, then decreases back to near its initial value.

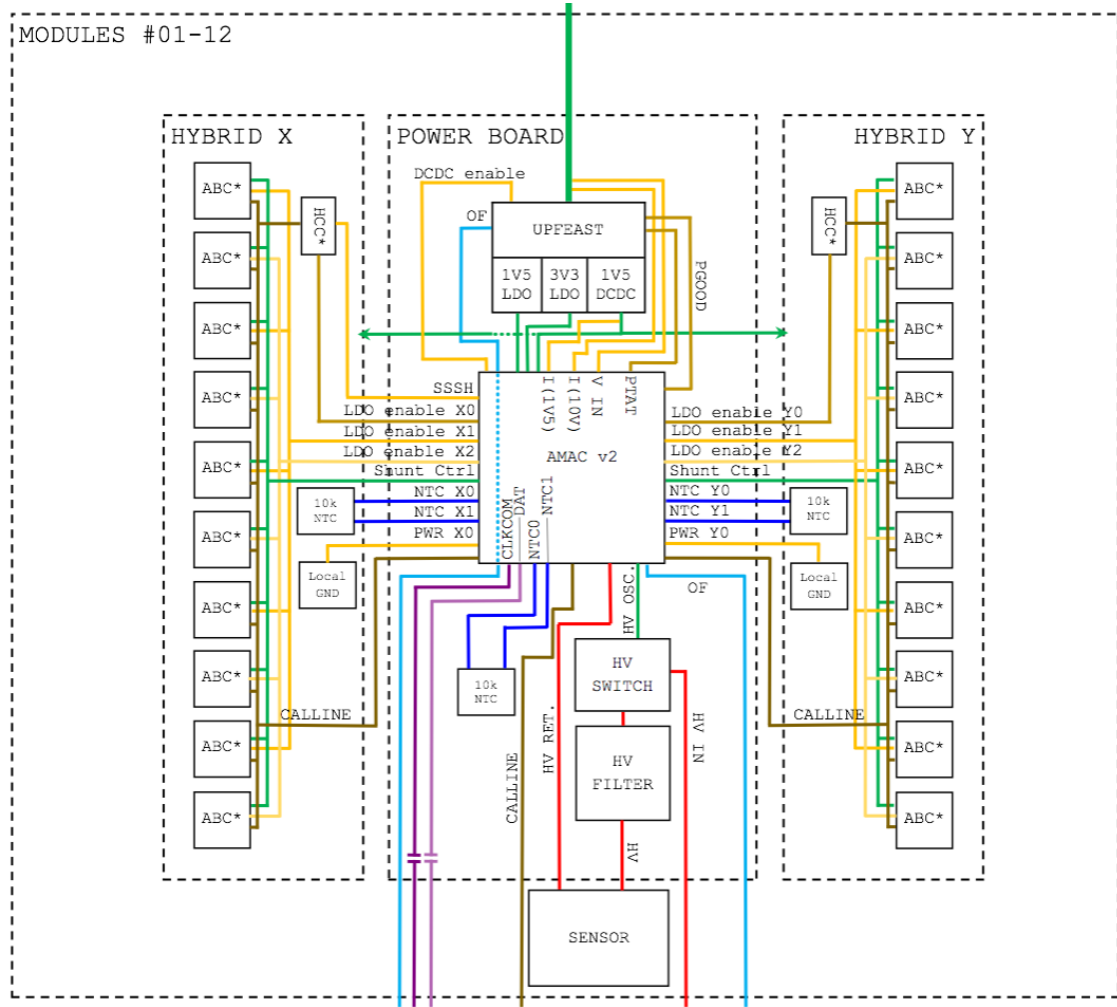


Figure 9.3: Schematic of an ITk Strips module including the three types of ASICs, the two hybrids, the power board, the silicon strip sensor, and the various other components comprising the module [213].

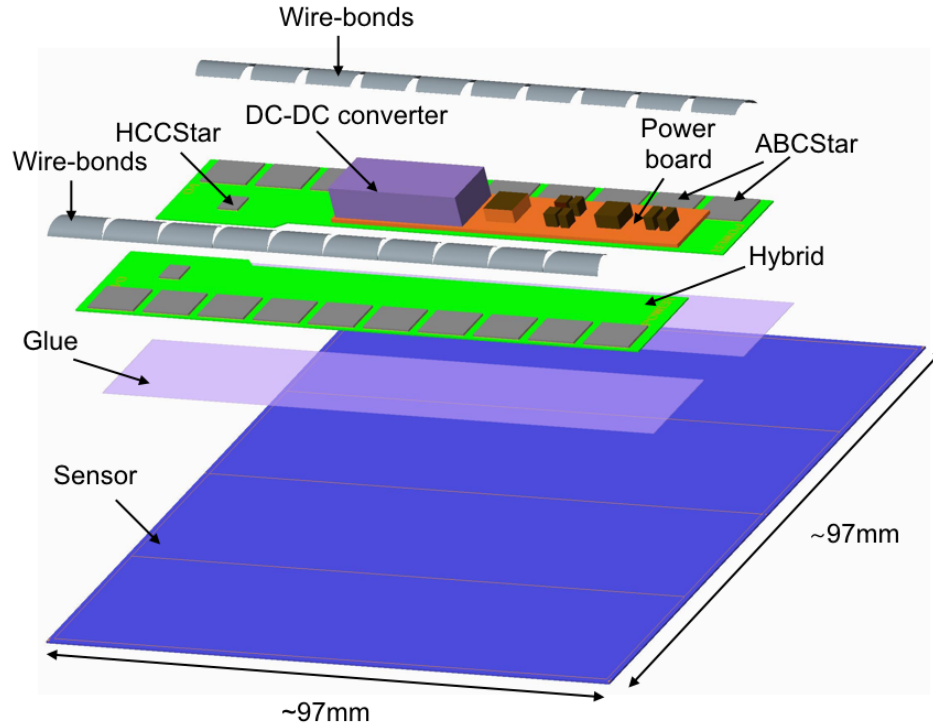


Figure 9.4: Cartoon of an ITk Strips module, depicting how the various components are connected [210].

Both the magnitude and duration of the TID bump are highly dependent on temperature, voltage, and dose rate. An example of the dependence on temperature and dose rate can be seen in Figure 9.6, which shows the current consumption for the ABC130 chip measured during various irradiation tests [210]. As a result of the impact of the TID bump on the IBL operations in 2015, ATLAS ASICs developed since the FE-I4 have been designed to be more tolerant to this effect as well as being tested extensively at a range of temperatures, dose rates, and TID. Most ATLAS ASICs irradiated to date have found the maximum value of the TID bump to occur within the first Mrad of irradiation.

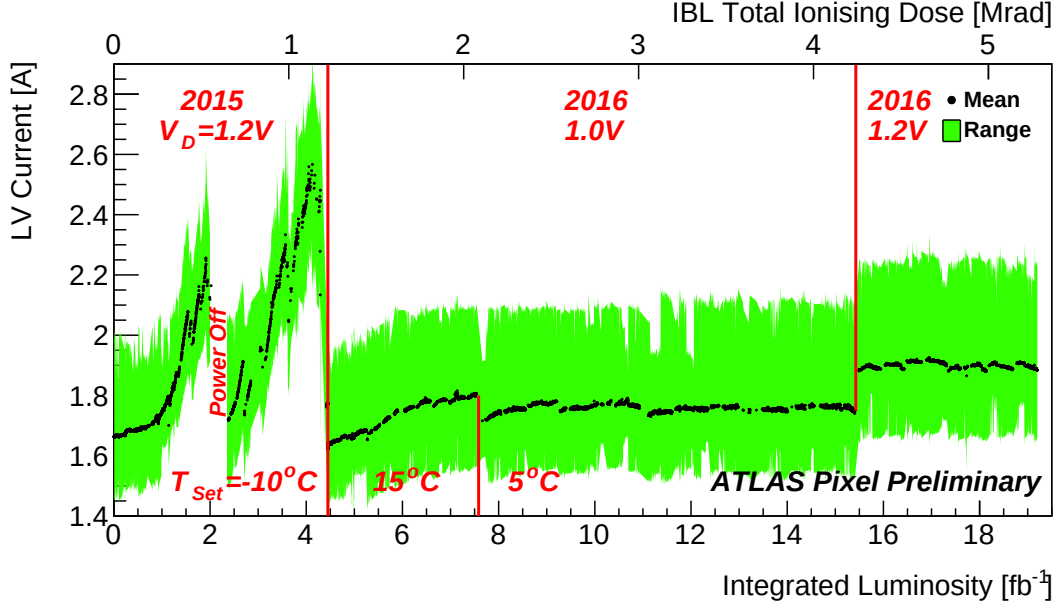


Figure 9.5: LV current as a function of integrated luminosity and TID, shown as an average over all IBL module groups. Each IBL module group contains four FE-I4 readout chips (i.e. one must divide the y-axis value by four to obtain the current consumption for a single chip). The LV current was found to increase by over 50% by the time 4 fb^{-1} was delivered, followed by a decrease to within 10% of its initial value. To mitigate this current increase for the 2016 data collection, the digital voltage V_D was reduced and the temperature of the module was increased; the digital voltage was later returned to its initial value of $V_D = 1.2 \text{ V}$ to reduce readout errors [214].

9.3 AMACv1a

When the ASICs for the ITk Strips were originally conceived, the HCC and ABC were the only ASICs deemed to be necessary. In such a scenario, monitoring of the HCC and ABC would have occurred at the hybrid-level via an analog monitor (AM) built into the HCC. However, the decision was later made to move this AM to a new chip, the AMAC, which would live on the power board and additionally provide control and interrupt functionality for the suite of ITk Strips ASICs.

The AMACv1 was the first iteration of the AMAC; this chip essentially just moved the AM block from the HCC to its own dedicated ASIC and added power control. Soon after, the AMACv1a was designed. This reused much of the top-level design of the AMACv1, but improved upon some issues observed in the initial prototype. These improvements included changes to the communication, as the AMACv1 required hysteresis inputs which made it difficult to initially communicate with the chip. The AMACv1a also added new features including a ring oscillator clock as well as introducing interlock functionality which monitors voltages, currents, and temperatures, and can take action in

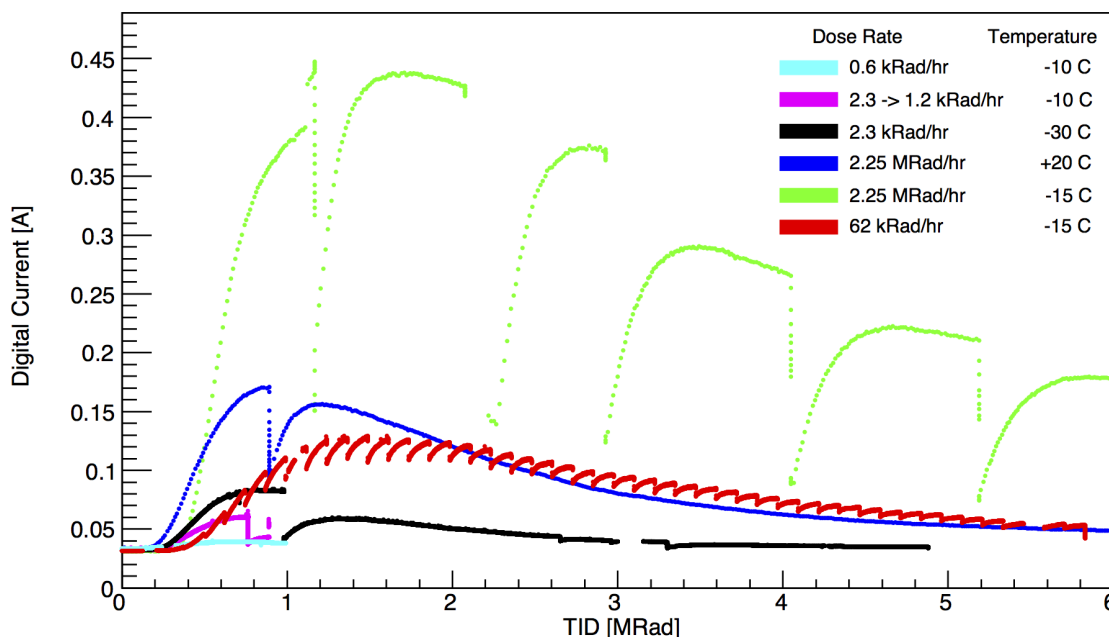


Figure 9.6: Current consumption as a function of TID for the ABC130 chip at various dose rates and temperatures [210].

case of unexpectedly high or low values (which could otherwise cause damage to the ASICs) [210].

The AMACv1a ring oscillator provides a clock with a nominal frequency of 40 MHz. This clock is divided by a factor of 48 for use in the AM (note that this clock division is by a factor of 40 in AMACv2 and newer prototypes). The AM functions by continuously performing a voltage ramp in steps (or “counts”) of 1 mV each. This reference voltage ramp is compared against each of the 14 channels monitored by the AM, and comparators are used to check when the ramp value is larger than the value of the given channel. Once this happens for two consecutive counts, the value is recorded to a register. The AM values are 10-bits each, i.e. the values monitored by the AM can be measured in a range from 0 to 1023 counts, where each count corresponds to roughly 1 mV (where the precise value can be different depending on the calibration of the AM). This allows the AM to perform measurements from roughly 0 V to 1 V; dividers are also in place for some channels to monitor voltages which would otherwise be above 1 V. Also note that while the AM monitors 14 channels, some of these channels are multiplexed, thus allowing for additional values which can be monitored by the AM. With the aforementioned clock rate and 1024 ramp steps, the AM sampling rate is 1 ms.

The AMACv1a has a total of 210 registers of 8-bits each, all of which are triplicated. This

provides protection against single event upsets (SEUs) and noise which could otherwise introduce inaccuracies in the values stored by the registers. By triplicating the registers, at least two of the three registers must show a change in order for it to be latched. These 210 registers are used for a variety of purposes including:

- to store the 10-bit AM channel values,
- control of AMAC settings such as the bandgap voltage reference, AM ramp gain, etc.,
- to enable interlocks, set their thresholds, and store flags indicating when the thresholds have been exceeded.

The bandgap voltage reference in particular has settings which can be used to adjust its voltage. This is because degradation of the bandgap voltage is expected as a function of radiation damage. Regular calibration of the bandgap will be needed for each AMAC chip installed in the ITk, to ensure that this bandgap voltage does not drift too far from its intended value of 600 mV.

The calibration of the AM is performed using an external digital-to-analog converter (DAC) voltage source. This DAC is directly connected to an AM channel dedicated for calibration, and a voltage ramp is performed using this DAC. The AM measurement (measured in AM counts) of the voltage set by the DAC is then compared with the expected value. By doing so, a conversion factor can be obtained for converting AM counts into voltages. For convenience, this is typically desired to be roughly 1 mV per count. If this is not the case, settings such as the bandgap control and AM ramp gain can be adjusted to tune the calibrated conversion factor to its desired value. However, this is purely done for convenience, and if this fine-tuning of the conversion factor results in e.g. a bandgap voltage reference which is outside of its desired range, then it may be preferred to use a less convenient conversion factor in the interest of keeping the AMAC voltages and other values closer to their intended operating values.

Finally, the AMACv1a chip makes use of the I²C serial protocol for reading and writing to the AMACv1a registers. I²C was chosen as it is a fairly simple and standard protocol. However, it is susceptible to noise and is not guaranteed to work across distances longer than a few meters. Figure 9.7 illustrates the issue of noisy measurements. To circumvent this, all measurements made using the AMACv1a test system were repeated ten times. These ten samplings were then combined using a trimmed average, where the lowest and highest value are removed and the remaining eight samplings were averaged. As multiple samplings would increase the time per measurement, this is not an ideal solution for the AMAC when installed in the ITk. Thus for future iterations of the

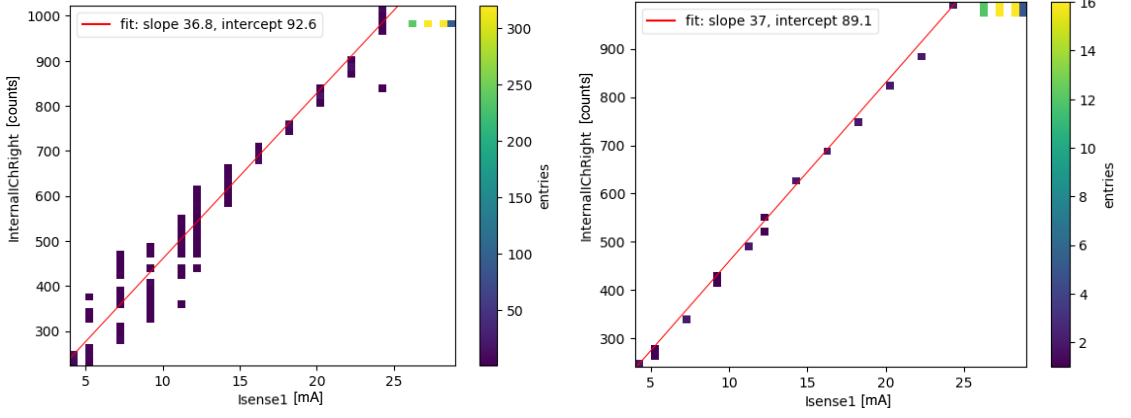


Figure 9.7: Left: Example ramp of current injected into the AMACv1a, where the x-axis is the externally measured current while the y-axis is the AMACv1a’s internal measurement of the current. These are expected to have a strong linear relationship. However, due to I²C noise, many measurements stray from the fit line. Right: Same as the left plot, except that each measurement is repeated ten times, and only the trimmed average over the central 80% of the samplings is plotted. The trimmed average agrees well with the fit, and thus this procedure is used for all subsequent AMACv1a measurements. Note that in both of these plots the z-axis is the number of entries; this can be large in cases where the measurements were repeated many times and overlaid.

chip including AMACv2, I²C was dropped in favor of a less noisy communications protocol (relying on a type of low-voltage differential signaling, or “LVDS-like” signaling; this is discussed in further detail in Section 9.4).

9.3.1 AMACv1a Irradiation using 1 MeV Photons at BNL

9.3.1.1 Facility and Setup

To study the effects of irradiation on the AMACv1a chip, the AMACv1a test system was brought to the Brookhaven National Lab (BNL) Co-60 gamma-ray facility. When Co-60 decays, it typically emits two photons with energies of roughly 1 MeV each, which allows for the study of effects due to ionizing radiation damage to the surface of the silicon chip. This facility was very convenient for these studies since it is within driving distance from the University of Pennsylvania, and the Co-60 source is capable of delivering doses of up to 35 krad per hour¹². At this dose rate, the AMACv1a was exposed to the maximum anticipated lifetime dose for the ITk Strips of 50 Mrad over the course of 58 days. Although TID effects are known to be both dose rate and temperature dependent,

¹²Note of course that this dose rate will decrease over time as Co-60 has a half-life of 5.27 years. For historical context, the source was installed in 1991, and was initially capable of dose rates greater than 1 Mrad per hour.

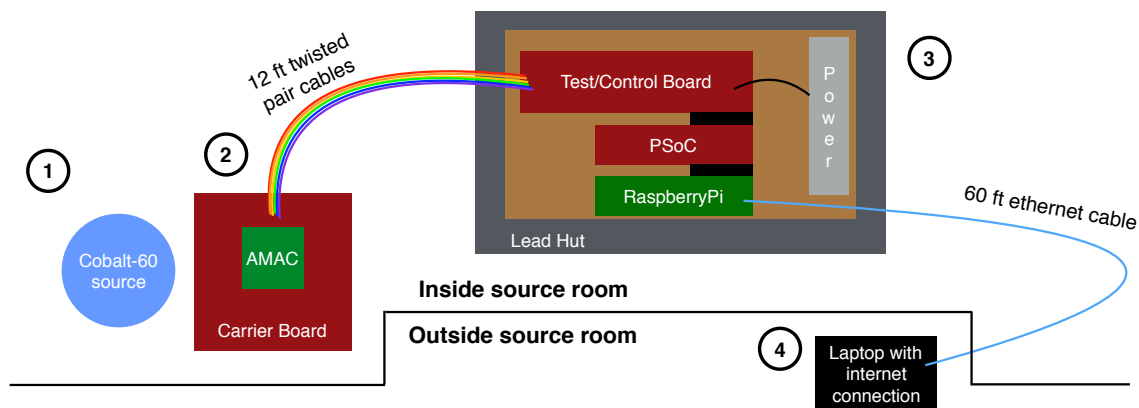


Figure 9.8: Diagram of the AMACv1a irradiation setup at BNL. Photographs of some of the components of the diagram are shown in Figures 9.9 through 9.11.

this irradiation was performed at a relatively large dose rate and at room temperature—thus the magnitude of any TID bump observed may not be applicable to what should be expected during installation in the ITk Strips detector. Ideally, this irradiation would have occurred at a lower dose rate and at cold temperature (e.g. -10°C , which is the anticipated operating temperature of the AMAC when installed in the ITk Strips); however, this irradiation was performed shortly before the submission of the AMACv2 design. A rapid study of the chip’s behavior under irradiation was therefore required to be sure no urgent changes to the AMACv2 design might be necessary.

The Co-60 source is located in the middle of a 14 foot $\times$ 14 foot room. This room is surrounded by a thick shield consisting of concrete blocks, to allow people to safely be adjacent to the room. The Co-60 source itself is surrounded by about one foot of lead, which allows the managers of the facility to safely enter the room to install test systems and other equipment.

To ensure irradiation of only the device under test (DUT), long cables are used to connect the DUT to any readout system (assuming any readout is performed). The readout system is enclosed in an ad hoc hut made of lead bricks located on the ground several feet away from the source. When necessary, the readout system can additionally be connected via a long ethernet cable to a laptop located outside of this room.

When an irradiation begins, the Co-60 source is raised from the ground (where the source is surrounded by the thick lead shield) to about four feet off of the ground (where no lead shielding is present). Naturally, there are many safety precautions to only allow for this when the room is properly secured, as well as mechanisms to immediately drop the source in case of an emergency.

A diagram of the AMACv1a irradiation setup at BNL can be seen in Figure 9.8.

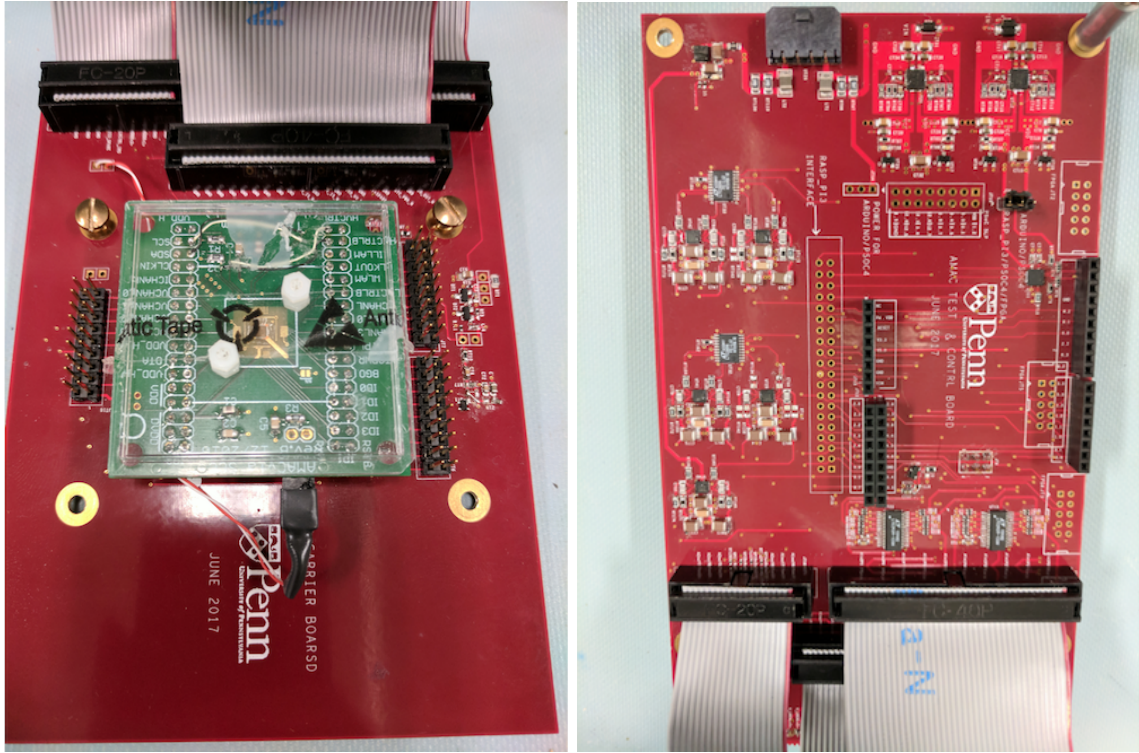


Figure 9.9: Left: The AMACv1a chip, located near the center of the picture, is mounted on the AMACv1a carrier board. The carrier board contains relatively simple components which are safe to be irradiated, and provides an interface between the AMACv1a chip and the long cables. Right: The AMACv1a test/control board, which supplies power to the AMACv1a, provides adjustable inputs, and transmits outputs from the carrier board via the long cables which connect them. Some of the signals sent from the carrier board to the active board include measurements of the carrier board voltages and currents via analog-to-digital converters, the carrier board temperature via a negative temperature coefficient (NTC) thermistor, and the digital values read from the AMAC registers using the I²C protocol.

9.3.1.2 Results

The maximum of the TID bump was observed within the first 0.3 Mrad of irradiation, which was less than ten hours after the AMACv1a was initially exposed to the source (at the dose rate of 35 krad per hour), as can be seen in the supply current plots shown in Figure 9.12. This then returned to its initial value by roughly 1.5 Mrad, about 48 hours later. This supply current was measured across a 1 Ω resistor located on the carrier board using an analog-to-digital converter (ADC), on a wire connected directly to the AMAC's power input. Additionally, an inverse TID bump was observed in the supply voltage as seen in Figure 9.13; this is simply a consequence of Ohm's law, since this voltage is measured on the side of the resistor closest to the AMAC.

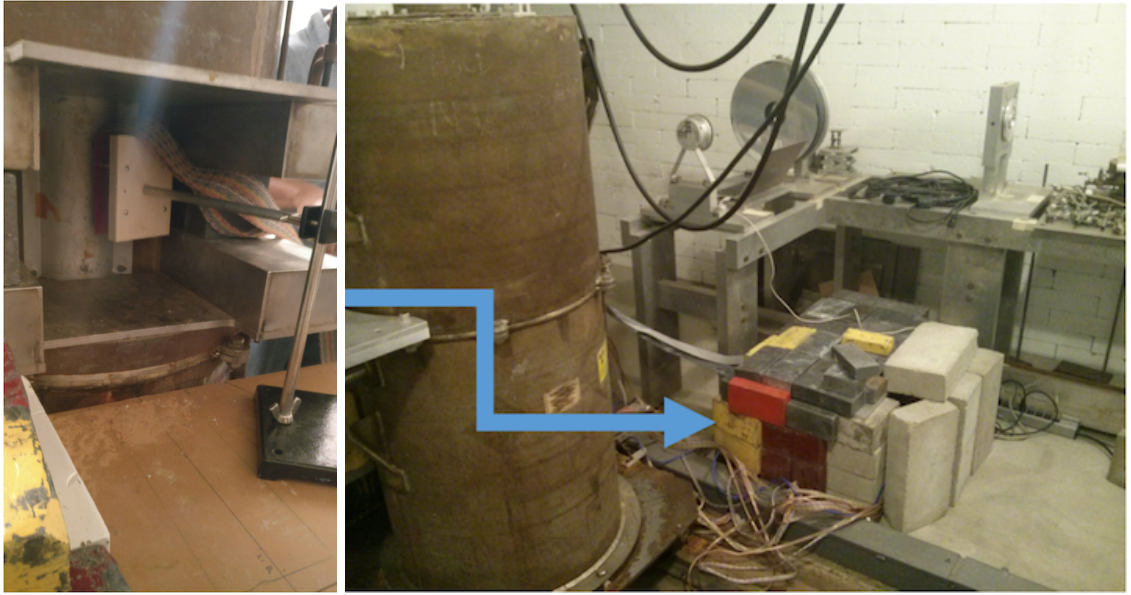


Figure 9.10: Left: Picture of the AMACv1a chip and carrier board directly in front of the thin metal shield of the Co-60 source. Right: The blue arrow indicates the path of the long cables from the AMACv1a carrier board to the lead hut. The carrier board is not shown in this picture, but it is located directly in front of the Co-60 source. The brown cylindrical structure on the left-hand side of this picture is the thick lead shield for the Co-60 source.

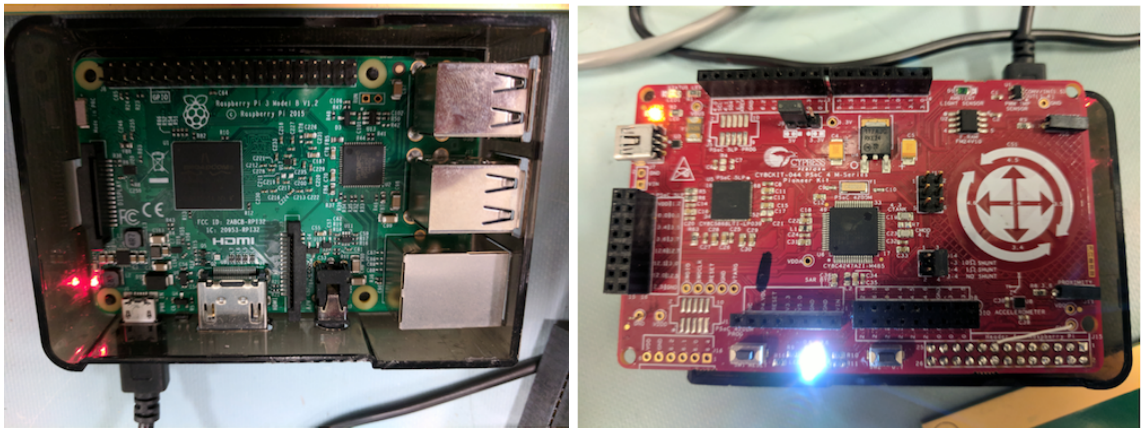


Figure 9.11: Left: Picture of the off-the-shelf Raspberry Pi single-board computer which was used to control the Python-based software for the AMACv1a test system. Right: Picture of the off-the-shelf Cypress Programmable System on Chip (PSoC) device. The PSoC was loaded with C-based firmware, and is the device responsible for communicating with the AMACv1a chip. The PSoC plugged into both the Raspberry Pi and the AMACv1a test/control board.

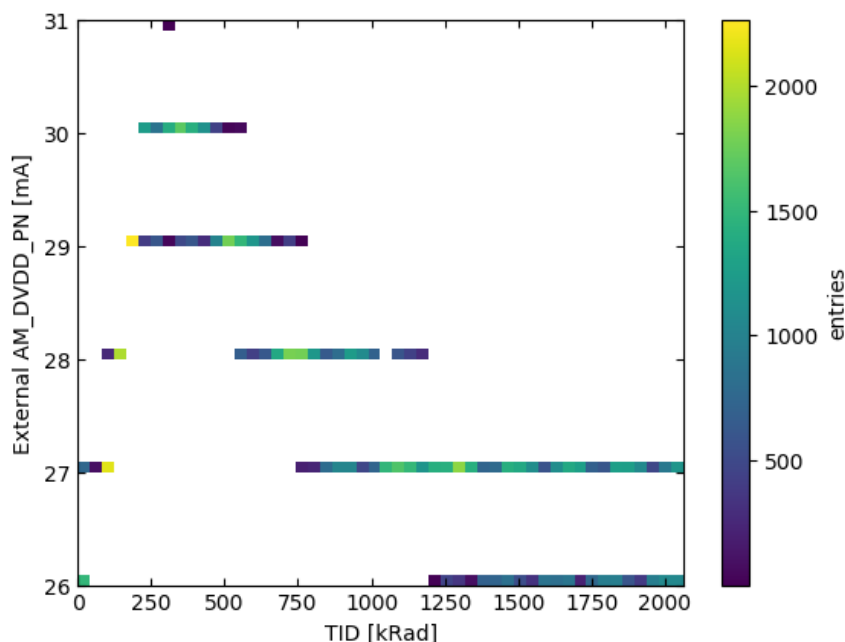


Figure 9.12: AMACv1a supply current TID bump from the BNL irradiation, shown as a function of TID. The current, referred to as “External AM_DVDD_PN” in the plot (as it is an external measurement of the AMAC’s digital DVDD input, measured differentially), increased by 20% before returning back to its initial value. This irradiation occurred at a dose rate of 35 krad per hour and a temperature of $21 \pm 2^\circ\text{C}$.

After irradiating the AMAC for the full 58 days (50 Mrad), the supply current decreased to 22 mA, which was 4 mA lower than its initial value of 26 mA. This long-term behavior can be seen in Figure 9.14. While a larger current consumption than intended has consequences for the total power consumption of the ITk Strips as well as the temperature, this smaller current consumption at high TID fortunately does not raise such concerns.

During the irradiation, both board measurements and AM channel measurements were regularly recorded to see if their values changed substantially with radiation damage. One example is shown in Figure 9.15, which displays both the external measurement and the AM’s internal measurement of the bandgap voltage reference. No significant issues were observed, though the internal measurement of the bandgap did appear to have much more noise after irradiation than the external measurement. The source of this noise was not ultimately understood, though it is possible that this could have been an artifact of the test setup (e.g. due to the long cables used or a similar issue related to the setup). Other AM channels did not exhibit the same level of noisiness as the internal bandgap; for instance, Figure 9.16 shows the behavior of the AM internal temperature measurement during

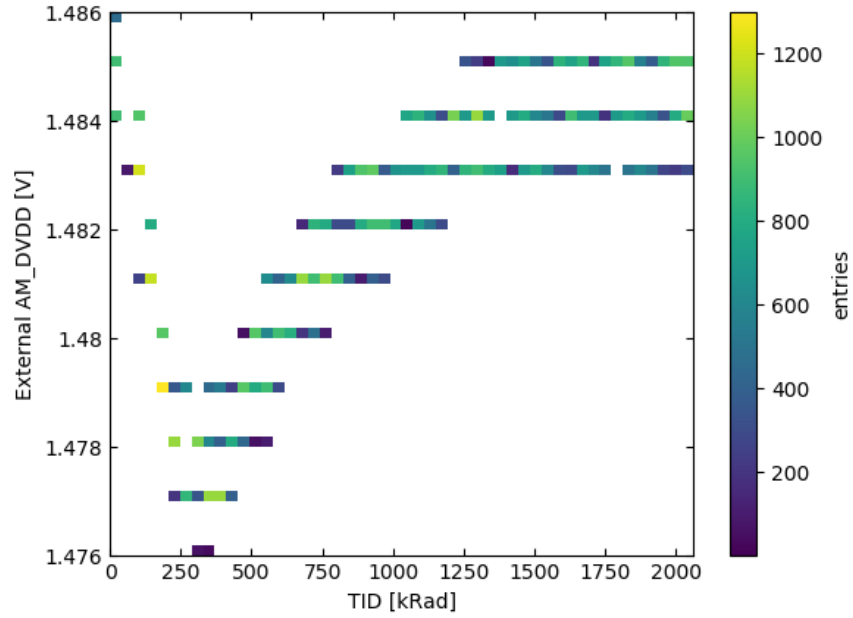


Figure 9.13: AMACv1a supply voltage inverse TID bump from the BNL irradiation, shown as a function of TID. This behavior was initially unexpected, but was later realized to be an artifact of how the voltage was measured, ultimately due to Ohm's law.

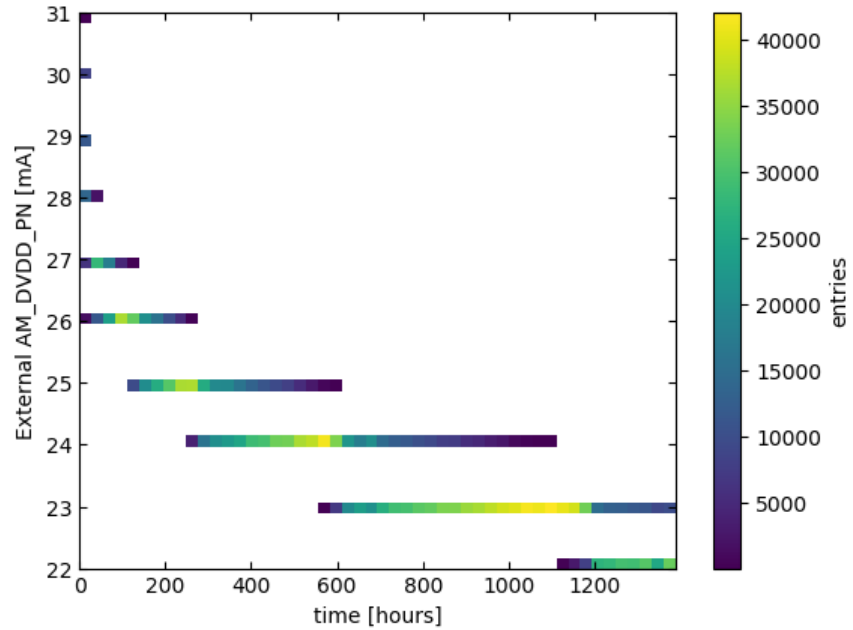


Figure 9.14: Long term behavior of AMACv1a supply current, shown as a function of time. After the initial TID bump, the AMAC current decreases to 15% lower than its initial value. To convert to TID, one can simply multiply by the dose rate of 35 krad per hour.

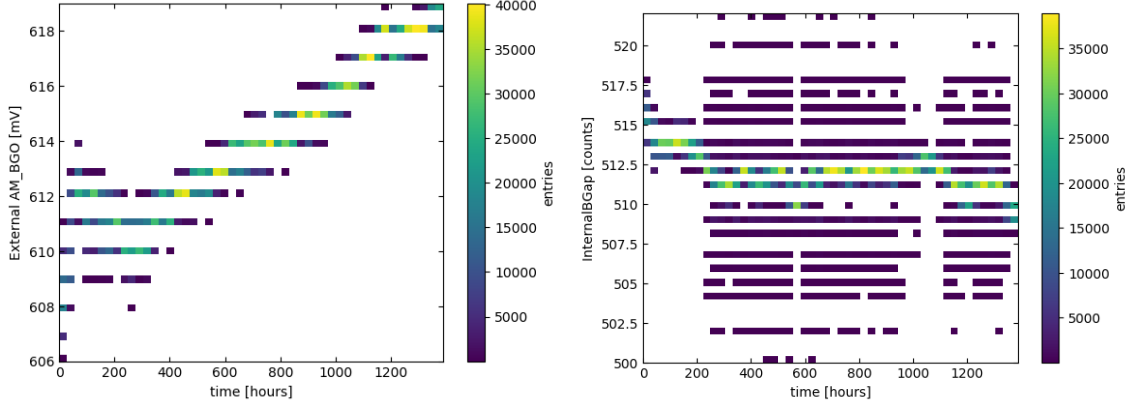


Figure 9.15: Left: AMACv1a external bandgap voltage reference measurement (via an external ADC). Right: AMACv1a internal bandgap voltage reference measurement (via the AM). After irradiation, the internal bandgap measurement was affected by noise while the external measurement was not.

the irradiation. This temperature monitor relies on a diode in the AMACv1a whose voltage output varies by about $1.8 \text{ mV}/^{\circ}\text{C}$.

The AMACv2 test/control board also contained a dedicated frequency counter for measuring the ring oscillator frequency. However, this measurement started to fail after a few days of irradiation, after another test setup was installed at the BNL Co-60 facility. Attempts were made to adjust wires in case of loose connections, at which point the measurement was successful again; however, it would subsequently fail again after some amount of irradiation. Fortunately, it is known that the ring oscillator itself was not failing, as the AM measurements would also be failing if that was the case. The issue was determined to likely be due to mechanical vibrations when the source was raised, particularly those related to the safety mechanisms. A plot of this frequency measurement can be seen in Figure 9.17.

9.4 AMACv2

As mentioned in Section 9.3, the use of I²C for the AMACv1a’s communication was suboptimal due to its susceptibility to noise and inability to communicate across long distances. For AMACv2, an LVDS-like signaling was instead used, which does not suffer from these problems. As this LVDS-like signaling is merely a way to transmit signals, an actual communications protocol also had to be implemented. An ad hoc serial protocol known as “Endeavour” was developed. Endeavour behaves similar to Morse code, and functions by transmitting long voltage-high signals to indicate a 1, short

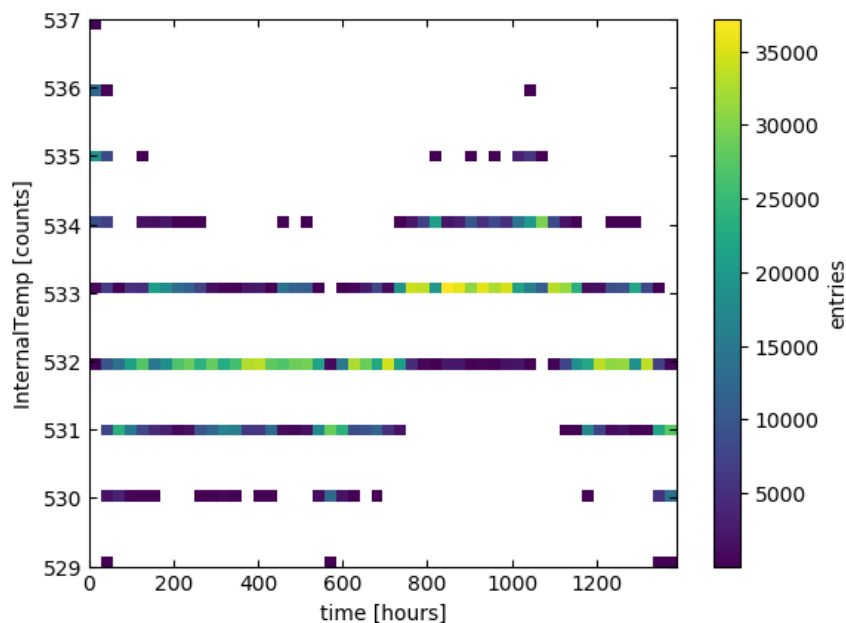


Figure 9.16: Right: AMACv1a internal temperature measurement (via the AM). This measurement varied by less than 10 counts during the entire irradiation, and did not exhibit any significant amount of noise.

voltage-high signals to indicate a 0, and voltage-low pulses when idle. The Endeavour protocol is dependent on the ring oscillator frequency, and can function properly at frequencies that are within nearly 50% of the nominal 40 MHz ring oscillator clock. The replacement of I²C was one of the major improvements of AMACv2.

The AMACv2 also introduced additional monitoring and control functionality. The AMACv2 has 16 AM channels which can be monitored, compared with the 14 present in AMACv1a. These 16 channels are listed in Table 9.1. To obtain more precise AM measurements at values near 0 V, an offset was introduced so that the AM channel range is roughly -25 mV to 1 V. As the ring oscillator frequency can vary from one chip to the next, a register setting which allows for this frequency to be adjusted was also included. Another improvement included in AMACv2 is the ability to switch the AMAC's power source from the linear regulator on the power board to the DC/DC supply, which may be necessary during the operation of the ITk Strips. Other improvements can be found in [216].

Despite the improvements and differences, much of the AMACv2 functions in a similar manner as the AMACv1a, and thus most of the descriptions of the ring oscillator, AM, registers, bandgap voltage reference, and calibration of the AM from Section 9.3 are all true for AMACv2 as well. One

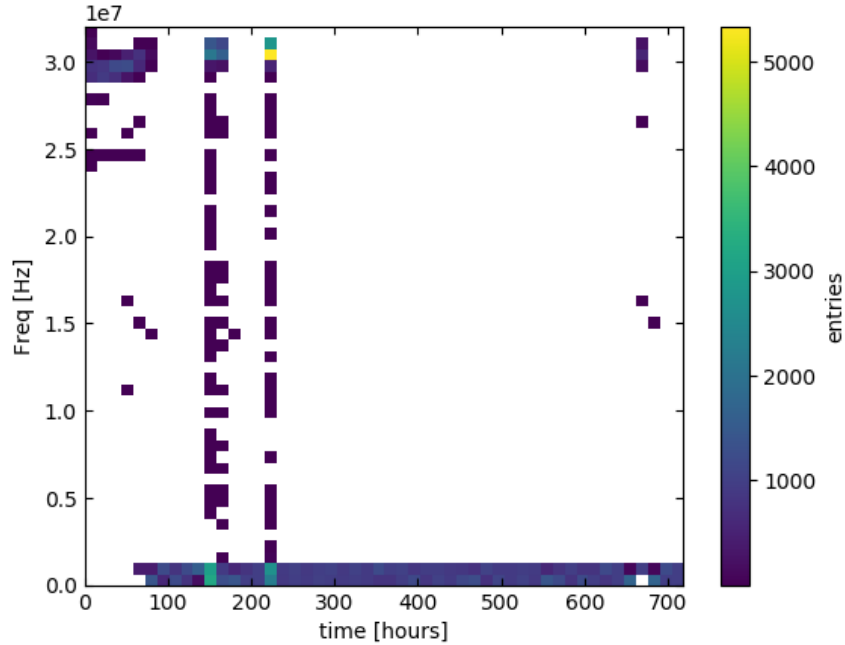


Figure 9.17: AMACv1a ring oscillator frequency measurement as a function of time. The measured frequency dropped to 0 MHz after another test setup was installed at the BNL Co-60 facility. Several pauses to the irradiation were made in the first 250 hours to attempt to fix a potential loose connection. This revived the frequency measurement, but only temporarily. Around 675 hours into the irradiation, the source was inactive for about 8 hours, during which time the frequency measurement was working again. Once the source was raised again, the measured value again went to 0 MHz.

small difference should be noted, which is that while AMACv1a had 210 registers of 8-bits each, the AMACv2 has 172 registers of 32-bits each. This allows for higher precision for many of the interlock thresholds, as well as more settings which can be configured for a given AMACv2 chip.

A photograph of the AMACv2 chip can be found in Figure 9.18.

9.4.1 AMACv2 Irradiation using 24 GeV Protons at CERN

9.4.1.1 Facility and Setup

For studying the effects of bulk damage to the AMACv2 chip and single event upsets (SEUs), the IRRAD facility [217] located at the CERN Proton Synchrotron (PS) was used. This facility makes use of the 24 GeV protons supplied by the PS which are delivered in spills which each last roughly 400 ms. Each spill can have up to 5×10^{11} protons, though the typical operating conditions during the AMACv2 irradiation was closer to 2.5×10^{11} protons per spill. With spills occurring once every

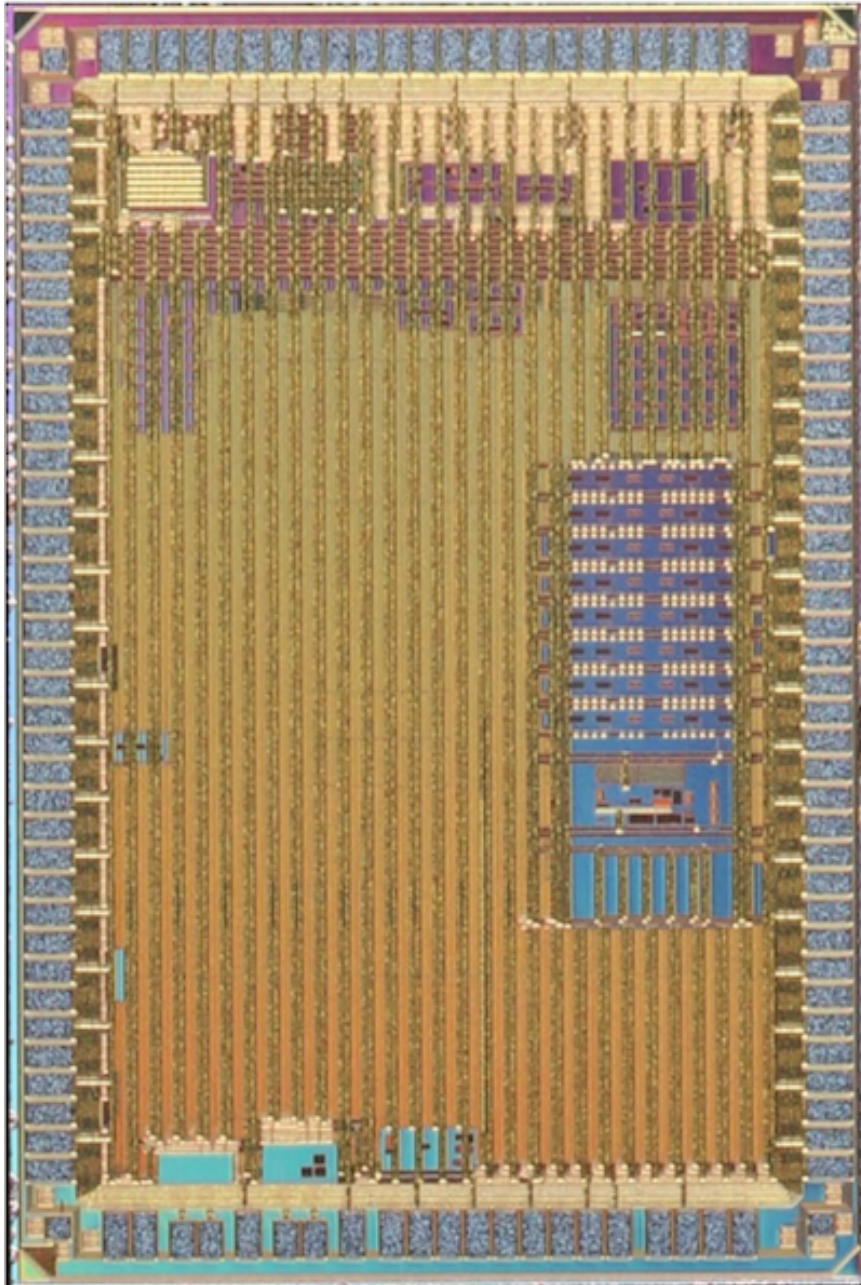


Figure 9.18: Photograph of the AMACv2 chip. This is a picture of the bare die, where the various features which can be seen (and which correspond to analog and digital components) are etched into the silicon.

Channel	Sub-Channel	Pad(s)	Description
0		VDCDC	DC/DC converter output, scaled by 1/2
1		VDDL	Linear regulator output, scaled by 1/2
2		DCDCin	Input voltage to DC/DC converter with a 1/15 divider
3	a	VDDREG	Diag: output of internal voltage regulator, scaled by 2/3
3	b	syst_BG_out	Diag: output of system bandgap
3	c	AM900BG	Diag: output of AM bandgap scaled to 900 mV and buffered
4	a	AM600BG	Diag: output of AM bandgap buffered
4	b	CAL	Calibration line from end-of-stave
4	c	AMintref	Diag: AM integrator reference
5	a	CALx	Output of hybrid X calibration DAC
5	b	CALy	Output of hybrid Y calibration DAC
5	c	Shuntx	Output of hybrid X shunt DAC
5	d	Shunty	Output of hybrid Y shunt DAC
5	e	DCDCadj	Output of DC/DC converter output adjust DAC (but wired to ground in AMACv2)
6		Die_temp	Die temperature, from diode
7		NTCxp,n	Hybrid X NTC temperature
8		NTCyp,n	Hybrid Y NTC temperature
9		NTCpbp,n	Power board NTC temperature
10		Hrefx	Hybrid X local ground
11		Hrefy	Hybrid Y local ground
12	a	Cur10Vp,n	DC/DC converter input current
12	b	Cur10V_TPLow	Input current measurement calibration test point low
12	c	Cur10V_TPHigh	Input current measurement calibration test point high
13	a	Cur1Vp,n	DC/DC converter output current
13	b	Cur1V_TPLow	Output current measurement calibration test point low
13	c	Cur1V_TPHigh	Output current measurement calibration test point high
14		HVret	Sensor HV bias return current
15		PTAT	DC/DC “Proportional To Absolute Temperature”

Table 9.1: Values available for the AMACv2’s AM to monitor. The measurements labeled “Diag” are diagnostic measurements of the AMAC itself [216].

10–30 seconds, this corresponded to about 1 Mrad per hour during the AMACv2 irradiation at IRRAD. Of course, 1 Mrad per hour is a much higher dose rate than the ITk Strips will experience, so these conditions are not realistic for studying the TID bump and similar TID-dependent effects, but they were nonetheless studied to get an upper limit on their behavior.

A diagram of the IRRAD facility and where the various components of the AMACv2 test system were located is shown in Figure 9.19. In case of occasional Endeavour communication errors during this high intensity irradiation, an automatic procedure was put in place to resend commands several times if a communication failure occurred. After several retries, several levels of resets (ranging from a reset of just the Endeavour block up to a hard reset of the AMAC itself) could occur. If communication errors persisted even after these resets, a power cycle of the test system would be initiated; fortunately, this condition was never reached during the irradiation.

While the low energy photons at the BNL facility used for the AMACv1a irradiation could be shielded by a relatively small amount of lead, this was not the case for the high energy protons used for the AMACv2 irradiation at IRRAD. The beam spray that results from the protons which

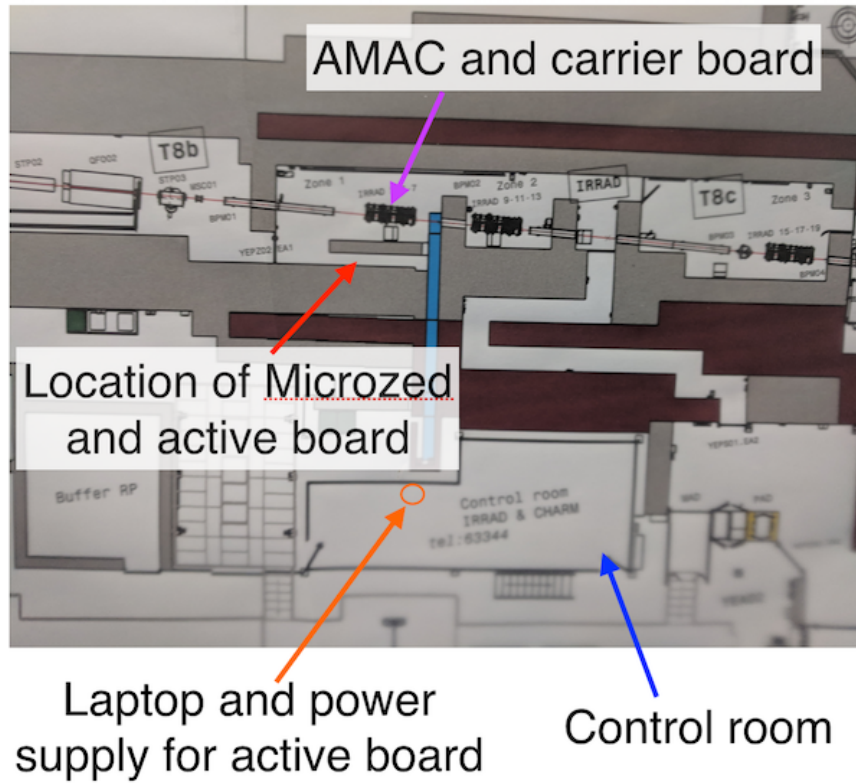


Figure 9.19: Layout of the AMACv2 irradiation setup at the IRRAD facility. Photographs of the AMACv2 test system consisting of the AMACv2 itself, the carrier board, the active board, and the Microzed FPGA board are shown in Figure 9.20.

interact with both air and any material placed in the beam-line (including the DUTs undergoing irradiation) can penetrate several meters of lead, as seen in Figure 9.21. As with the AMACv1a test system, long cables were used to connect the DUT to the readout system. The readout system was then placed behind a lead wall, but this wall was not sufficient to block all of the beam spray. As a result, the test system was found to have issues several times during the irradiation, forcing the SD card where the PetaLinux operating system lived to enter a read-only state at times. This could only be recovered from by manually power cycling the FPGA board, which caused gaps in the data collection. Roughly 40 hours after the start of the irradiation, an unrecoverable state was reached, and any remaining irradiation was done passively with no readout capability. The SD card was found to be corrupted when the system was removed at the end of the irradiation, which was likely caused by bitflips in the SD card's flash memory due to the beam spray.

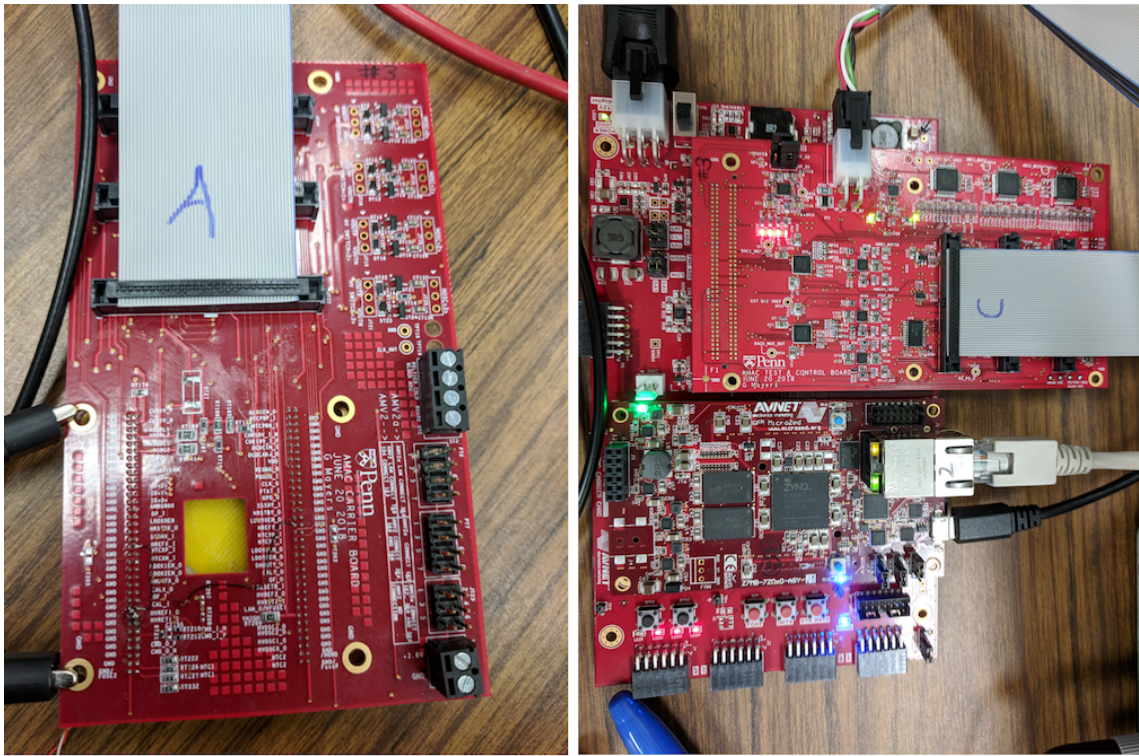


Figure 9.20: Left: The AMACv2 chip, located under the yellow plastic cover seen in the picture, is connected to the AMACv2 carrier board. The carrier board contains relatively simple components which are safe to be irradiated, and provides an interface between the AMACv2 chip and the long cables. Right: The AMACv2 test/control board (located on the top half of the picture), which supplies power to the AMACv2, provides adjustable inputs, and reads signals (such as ADC values, board temperature, and AMAC register values) from the carrier board via the long cables which connect them. This is connected to the FPGA Mezzanine Card (FMC) board which provides a connection between the test/control board and the FPGA, as well as a power source. The FMC board is then connected to the Microzed FPGA board (located on the bottom half of the picture), which contains the Zynq FPGA which was loaded with VHDL-based firmware used for communication with the AMACv2. The Microzed was connected via a long ethernet cable to a laptop located in the control room, and data was sent to this laptop every 5 minutes.

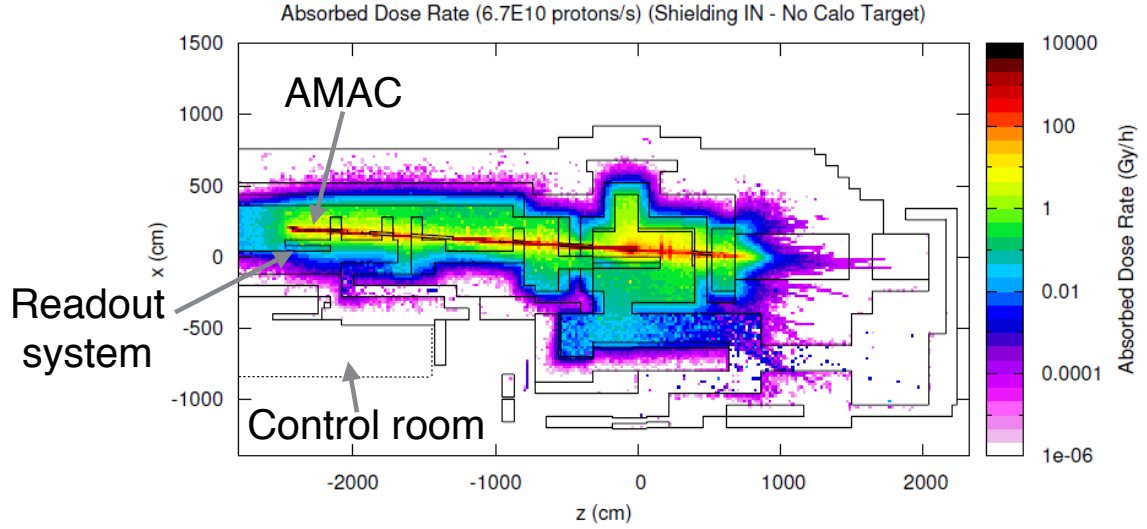


Figure 9.21: Simulated dose rate at various locations in the IRRAD facility caused by the remnant beam spray. The precise numbers are only accurate for a particular set of conditions at the IRRAD facility (which are detailed in [217]), but it is clear from this figure that the lead wall which was shielding the AMACv2 readout system could not block all high energy particles from reaching the readout system and its SD card.

9.4.1.2 Results

SEUs can occur when high energy particles ionize transistors in the AMAC. While the 1 MeV photons used during the BNL Co-60 irradiation of AMACv1a were relatively low energy particles which do not typically cause SEUs in the triplicated AMAC registers, the 24 GeV protons used during this irradiation of AMACv2 are energetic and diffuse enough to cause correlated bitflips in the triplicated AMAC registers. Note that for an SEU to have any impact, the same bits must be flipped in at least two of the three triplicated registers; this is specifically used for protection against potential SEUs. To study these SEUs, unused AMAC registers were filled with specific bits and regularly monitored to watch for bitflips. The observed AMACv2 SEU rate as a function of TID is shown in Figure 9.22, which shows a bitflip rate of 2% per Mrad. There were 69 registers of 32-bits each dedicated for this measurement—however, one should keep in mind that it was equally likely for bitflips to occur in any of the other ~ 100 registers which were already being used to control the AMAC. Any results obtained from this irradiation had to be carefully studied to decouple effects which appeared to due to be potential damage to the AMAC from those which were actually due to bitflips in registers which affected the AMAC’s output (e.g. by changing the gain of a voltage ramp or other similar register settings).

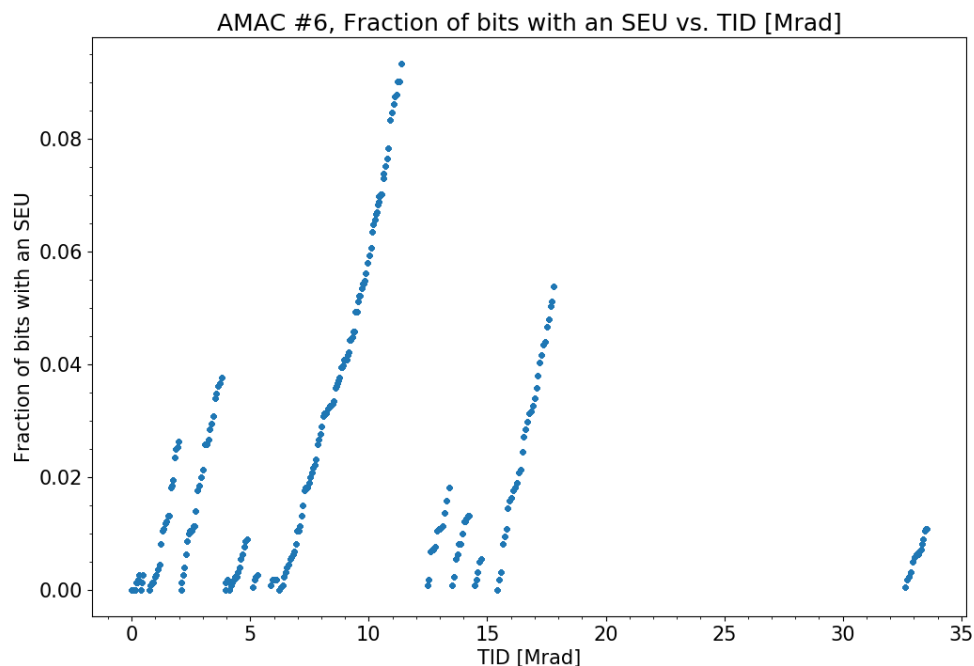


Figure 9.22: AMACv2 SEU rate at the IRRAD facility, shown as a function of TID. Note that gaps where the fraction of flipped bits drops to 0 are present for periods where the AMAC was reset. The slope of a given segment of this plot suggests that the bitflip rate is roughly 2% per Mrad.

With a bitflip rate of 2% per Mrad, it is important to contextualize whether or not this could be problematic once installed in the ITk Strips. One could reasonably expect a dose rate of about 1 Mrad per month during operation of the ITk Strips, which means 2% of all AMAC bits would flip each month. With roughly 18,000 AMAC chips total in the ITk, and 172 registers of 32-bits each, there are approximately 100 million AMAC bits available to flip. Thus, 2 million AMAC bitflips will occur each month during HL-LHC operations, which is about one bitflip every 1.3 seconds. As each AMAC can be recalibrated on a much faster timescale (on the order of milliseconds), this SEU rate should not cause any issues.

One example measurement made during the irradiation was of the AMAC's internal CALx channel. This is a calibration channel used to calibrate an internal DAC in the AMAC chip. Before any irradiation, this channel was found to increase linearly as a function of the internal DAC setting, as expected and as seen in Figure 9.23. Once the AMACv2 was placed in the proton beam, however, this linearity broke down at small voltages, as seen in Figure 9.24. Once the AMAC was subsequently

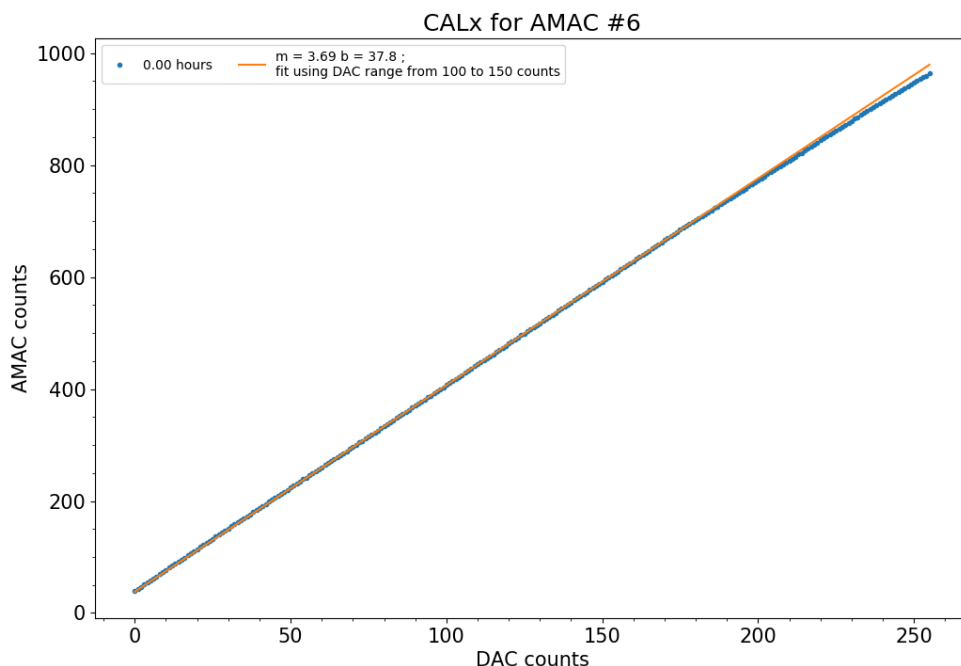


Figure 9.23: AMACv2 CALx measurement before irradiation at IRRAD. For this measurement, a DAC internal to the AMAC is used to set a voltage, and the corresponding AM channel is then read out. This tends to be quite linear; some small deviation is present at high DAC counts, but this is known to be due to when the current source for this internal DAC switches, and is not a concern.

removed from the beam, the linear behavior returned. Moreover, in the nonlinear case when the AMAC was in the beam, the y-intercept for the fit was a negative value. This suggests that this is an effect which will only occur during high intensity irradiations of this nature. The most likely explanation is that many positively charged protons were passing through the AMAC and stripping away electrons, which created a charge imbalance which the AMAC had to overcome. In the ITk Strips, the dose rate will be substantially smaller (by a factor of $\sim 10^3$), and thus it is unlikely that any such issue will occur. Note also that an external ADC measuring the voltage set by this internal DAC agreed well with the DAC, which means this was definitely an issue affecting the AM rather than some other artifact.

Similar behavior was observed for the AM CAL channel (as seen in Figure 9.25), which is the channel used for the AM calibration procedure to measure the conversion factor from AM counts to mV by setting a voltage using an external DAC which is then measured by the AM.

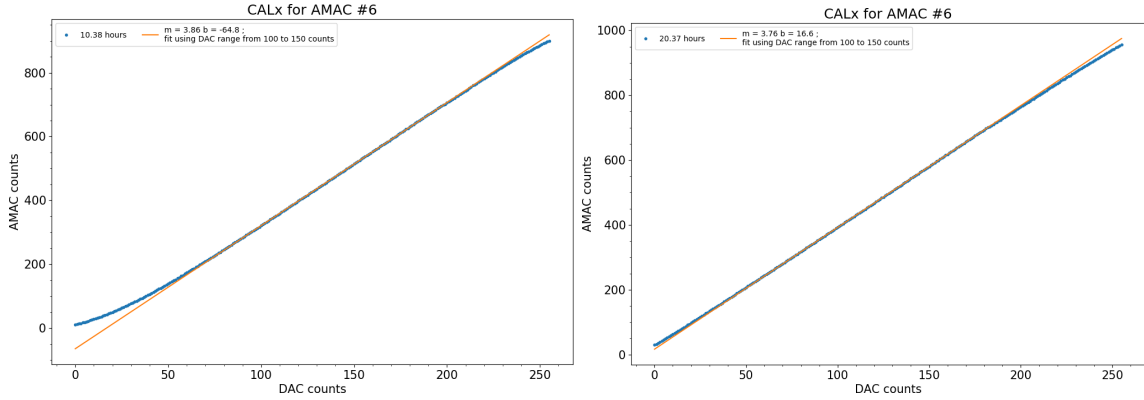


Figure 9.24: AMACv2 CALx measurement during irradiation at IRRAD. Left: Behavior when the AMACv2 was in the beam. The nonlinear behavior is believed to be due to the large number of protons passing through the AMAC and stripping away electrons. To support this hypothesis, note in particular the large negative offset to the fit intercept. Right: Behavior when the AMACv2 was removed from the beam. Any remnant nonlinearity at small DAC counts is thought to be due to remnant charge asymmetry as this measurement was made soon after removing the chip from the beam.

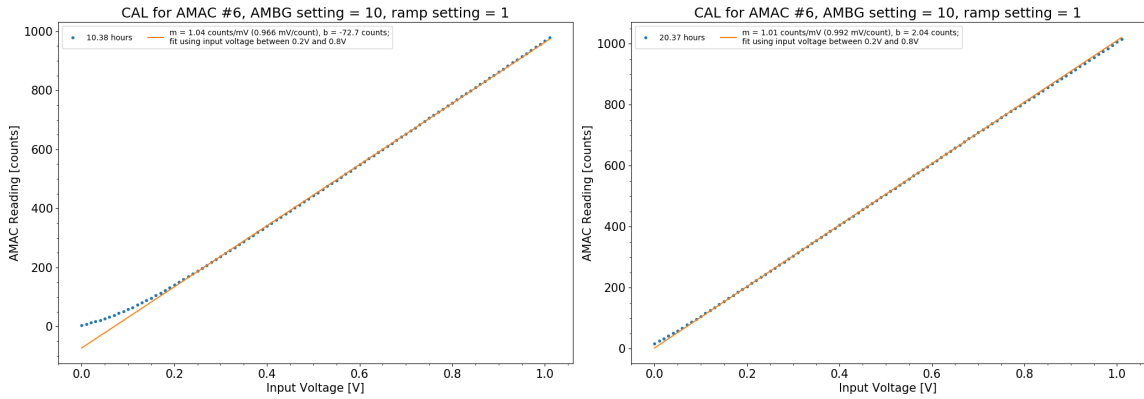


Figure 9.25: AMACv2 CAL measurement during irradiation at IRRAD. Left: Behavior when the AMACv2 was in the beam. Right: Behavior when the AMACv2 was removed from the beam. The nonlinear behavior when the AMACv2 is in the beam is likely due to the same effect as Figure 9.24, where the large number of protons passing through the AMAC create a large charge offset to overcome.

This measurement was also routinely made during the irradiation, to see if this conversion factor ever changed substantially. Of course, when installed in the ITk Strips detector, the chips can be routinely recalibrated if needed.

All of the AM channels were regularly read out. To check for stability of these measurements, Table 9.2 shows the values for each of the AM channels at various points during the irradiation.

All measurements appeared to be fairly stable across the range, never differing by more than 20%. Note that this is merely a snapshot to check for wild changes to any of the AM values, while smaller changes may not actually be meaningful—for instance, VDDL is the supply voltage, and is expected to change during the TID peak as described for the supply voltage in Section 9.3.1.2. Similarly, some channels depend on arbitrary external factors, and thus this table should only be taken with a grain of salt.

As mentioned previously, the operating conditions at IRRAD (where a dose rate of 1 Mrad per hour and room temperature were used) are not the same as those which the ITk Strips will experience (closer to 1 Mrad per month and a temperature of -10°C), but the TID bump was nonetheless studied to obtain an upper limit on its behavior. The maximum current consumption observed for the AMACv2 at IRRAD was 140 mA, as seen in Figure 9.26.

The ring oscillator frequency was regularly monitored during the irradiation to see if the frequency changed significantly with TID. At nearly 40 MHz, the frequency of the ring oscillator can be challenging to measure, and the comparator used to measure it can miss pulse edges on occasion. As a result, the test board also has “HV oscillators” present, which take the ring oscillator frequency and divide it by 400. This results in a frequency closer to 100 kHz, which is easier to measure. Plots of the ring oscillator and HV oscillator frequencies are shown in Figure 9.27. The HV oscillator frequency never changed by more than 3% during the irradiation. The ring oscillator for at least one particular setting showed a 9% drop toward the end of the portion of the irradiation during which active readout was functioning (which corresponded to roughly 33 Mrad). However, since the HV oscillator did not exhibit the same behavior, this is believed to be due to an issue solely with our ability to measure the ring oscillator. For instance, the pad voltage for this measurement may be smaller than it initially was, causing the comparator to miss more pulse edges than usual. However, since the pad used to measure the ring oscillator is only used for diagnostic purposes during chip testing, this should not be an issue that would affect operation in the ITk Strips.

To test the interlock functionality of the AMACv2, the external DAC for setting the PTAT channel was set to a mid-range value of about 500 mV. The relevant register settings were then enabled to fire an interlock if the PTAT value measured by the AM ever went about 740 counts. The DAC voltage was kept fixed, so a real interlock was never expected during the irradiation. The interlock flags were then checked every few minutes during the irradiation as part of the sequence of tests, and it was found that 40% of these checks found that an interlock had fired (at which point the relevant registers were reset to allow it to fire again in the future). Initially during this irradiation, the interlock block’s flag validation was disabled. The flag validation is designed to protect against

Channel (corrected for zero calibration)	Counts at 0 Mrad	Counts at 0.74 Mrad	Counts at 3.95 Mrad
VDCDC/2	717	709	710
VDDLRL/2	707	684	700
DCDCin	626	616	616
2/3 * VDDREG	826	803	811
syst_BG_out	655	634	641
AM900BG	975	977	973
AM600BG	656	650	652
CAL	0	0	0
AMintref	120	110	110
CALx	10	9	8
CALy	12	9	9
Shuntx	112	98	99
Shunty	115	100	101
DCDCadj (but wired to ground)	0	0	0
Die_temp	261	247	249
NTCxp,n	762	765	772
NTCyp,n	335	327	326
NTCpbp,n	390	383	383
Hrefx	0	0	0
Hrefy	0	0	0
Input Cur10Vp,n	409	339	359
Input calibration test point low	584	569	574
Input calibration test point high	635	615	618
Output Cur1Vp,n	532	473	523
Output calibration test point low	616	575	585
Output calibration test point high	629	587	597
HVret	319	350	353
PTAT	496	485	486
mV/counts at this TID:	0.999	0.998	0.992
AMAC in the beam?	no	no	no

Table 9.2: Table of AM channel values at various points during AMACv2 irradiation at IRRAD. The channel names correspond to those listed in Table 9.1. Note that in all of these measurements, the count with respect to zero is subtracted off. As this calibration for the offset is likely inaccurate when the AMAC was in the beam (based on the behavior seen in e.g. Figure 9.24), this table is only filled with values corresponding to times when the AMAC was out of the beam. Overall, the AM channel values appear to be fairly stable, though one should keep in mind that this table is only intended to look for large variations to any of the AM values, and that smaller changes may actually be expected due to external factors. Note that DCDCadj is mistakenly wired to ground in AMACv2, but will be fixed in the future.

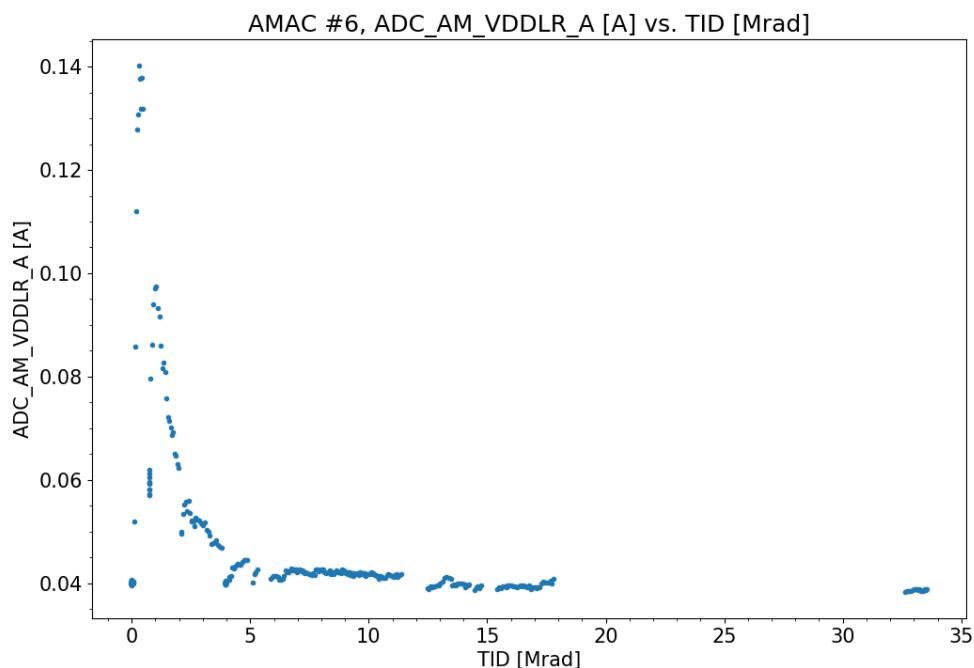


Figure 9.26: AMACv2 supply current TID bump measured during the IRRAD irradiation. Note as in Figure 9.22 that gaps in the data correspond to periods of time where the AMAC was reset and readout from the chip was not always functioning properly. Moreover, there are periods of time in this irradiation where the chip was removed from the beam, thus leading to instances where the current did not behave monotonically. The maximum current consumption observed was 140 mA, at a TID of ~ 0.3 Mrad. Note that the y-axis is labeled as “VDDLRL_A”, corresponding to the current measured for the the VDD input from the linear regulator.

noise by requiring agreement for 2, 3, or 4 AM ramp cycles before recording the value. After turning this on and requiring four latches, interlocks were found to occur about 20% of the time. This test led us to take a closer look at the implementation of the interlock block in the AMAC’s digital logic, and it was found that the latch mechanism for the interlocks was not properly protected against bitflips. Thus, a bitflip in a single flip-flop could cause the interlock to fire in AMACv2; luckily this can be improved for future versions of the chip.

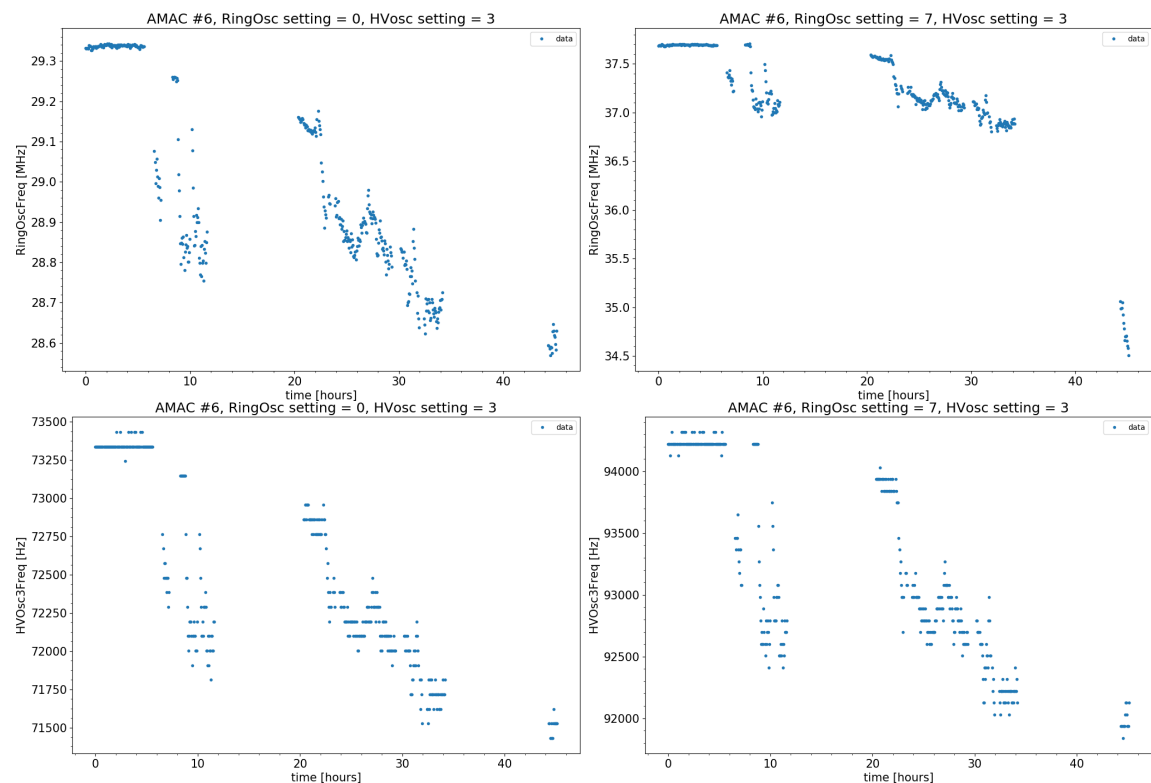


Figure 9.27: AMACv2 frequency measurements during the IRRAD irradiation. Note as in Figure 9.22 and other previous plots that gaps in the data correspond to periods of time where the AMAC was reset and readout from the chip was not always functioning properly. The left-hand plots use a register setting to adjust the ring oscillator to smaller frequencies, while the right-hand plots adjust this setting to use higher frequencies. The upper plots are of the ring oscillator measurement, while the bottom plots are of the HV oscillator measurement. The drop in the ring oscillator frequency in the upper right-hand plot appears to be larger than the relative drop seen in the other three plots; however, this is likely anomalous and purely due to our inability to measure this ring oscillator properly, since the HV oscillator and the true ring oscillator frequency should always precisely differ by a factor of 400. The time displayed on the x-axis is the time elapsed since the system was installed at the IRRAD facility, and the last data collected was at a TID of approximately 33 Mrad.

9.4.2 AMACv2 Irradiation using 1 MeV Photons at BNL

9.4.2.1 Facility and Setup

For studying the effects of ionizing radiation damage to the AMACv2, the same BNL Co-60 gamma-ray facility was used as for the AMACv1a. For details on the facility, see Section 9.3.1.1. While the AMACv1a irradiation was performed quickly to see if any urgent changes were needed for the AMACv2 design, there was less urgency for the AMACv2 irradiation at BNL. Due to the TID bump dependence on both temperature and dose rate, it was desired to use a more realistic temperature and dose rate, to provide a good proxy for how the AMAC will perform under the ITk operating conditions. Thus, a much lower dose rate of 0.6 krad per hour was initially used, and cooling was needed to lower the chip temperature to -10°C . As it would take nearly ten years to expose the AMACv2 to its anticipated lifetime dose of 50 Mrad at a rate of 0.6 krad per hour, this dose rate was only used to study the first 0.8 Mrad. The dose rate was subsequently increased to allow for study of the long-term behavior of the AMACv2, but this part of the irradiation is currently ongoing, and will not be discussed here.

The test system used was very similar to that which was used for the AMACv2 irradiation at the CERN IRRAD facility, and details on the test system can be found in Section 9.4.1.1. Minor changes to the testing system hardware and software were made, but nothing that changes the overall picture. However, additional equipment was necessary for the cooling. A peltier device capable of temperatures as low as -30°C was employed, and the AMACv2 carrier board was placed in an airtight coldbox made of foam. Moreover, to avoid condensation which could arise due to the low temperatures, nitrogen gas was flowed continuously to reduce the humidity in the coldbox. This system was also previously used during the irradiation of the HCC130 chip in 2016. Pictures of the AMACv2 cold box as well as the lead hut containing the AMACv2 test/control board, power supplies, and equipment used to control and power the peltier can be seen in Figure 9.28. To achieve the 0.6 krad per hour dose rate, the AMACv2 was placed roughly 30 inches from the thin metal shield surrounding the Co-60 source. A picture of the AMACv2 coldbox in front of the Co-60 source can be seen in Figure 9.29.

9.4.2.2 Results

The primary result from the BNL Co-60 irradiation of AMACv2 was the measurement of the TID bump, seen in Figure 9.30, using realistic temperature and dose rate conditions for the ITk Strips. The maximum supply current observed was 50 mA, corresponding to a 25% increase from its initial



Figure 9.28: Left: Coldbox surrounding the AMACv2 chip and carrier board. The pink foam was used to prevent leakage of the nitrogen gas, while the metal device on the left-hand side of the picture is the peltier and a fan necessary for the cooling. Plastic tubes can be seen on the right-hand side of the picture, which were used to provide the nitrogen flow (one tube for nitrogen coming into the coldbox, one for nitrogen leaving the coldbox). Various cables can be seen which were used for the carrier board to test/control board communication as well as to control the peltier and to monitor the temperature and humidity in the box. The humidity sensor is not radiation-hard, and thus was only used to measure the humidity before the irradiation began. Right: The inside of the lead hut used during the AMACv2 irradiation. Two wood boards containing various components were located in the hut. The bottom board was used for the temperature control and humidity monitoring, while the top board contained the AMACv2 test/control board as well as its power supplies.

value. This is not particularly large, but is useful for planning for the power consumption of the ITk Strips system.

The AM calibration procedure (using the CAL channel) and the internal DAC measurement (using the CALx channel) were repeated regularly during the irradiation. These are shown in Figure 9.31, which overlays all data collected for these measurements. All of the data from subsequent samplings lay directly on top of all of the previous points; clearly, the calibration did not change by any significant amount as a function of TID during this irradiation.

As was done for the IRRAD irradiation described in Section 9.4.1.2, the ring oscillator frequency was routinely measured. The largest changes observed here are no more than about 1%, as seen in Figure 9.32. Since Endeavour is intended to function well across a wide range of ring oscillator frequencies, changes of this size are perfectly acceptable.



Figure 9.29: The AMACv2 coldbox located in front of the Co-60 source.

As anticipated, no SEUs occurred during this irradiation. Similarly, no interlocks were fired either. Since the lack of SEUs means all of the AM channels and board measurements can be easily plotted, without having to carefully decouple SEU effects from TID effects, some examples of the bandgap voltage reference measurement are shown in Figure 9.33. The bandgap voltage changes by a few mV during the irradiation. Even extrapolating this out to much larger TID, this should be fine as the bandgap has a wide range of adjustability, precisely to compensate for radiation damage. The register settings which control this bandgap can be changed during the ITk Strips operation as needed.

9.5 Future Improvements and Studies

All of the results presented in this chapter were relevant for AMACv1a and AMACv2. However, a newer prototype called AMACv2a has now been fabricated and is currently undergoing functional testing. The AMACv2a is largely based on the AMACv2 design, but includes several improvements and fixes. One such improvement is a reduction of the time required to read an AM channel

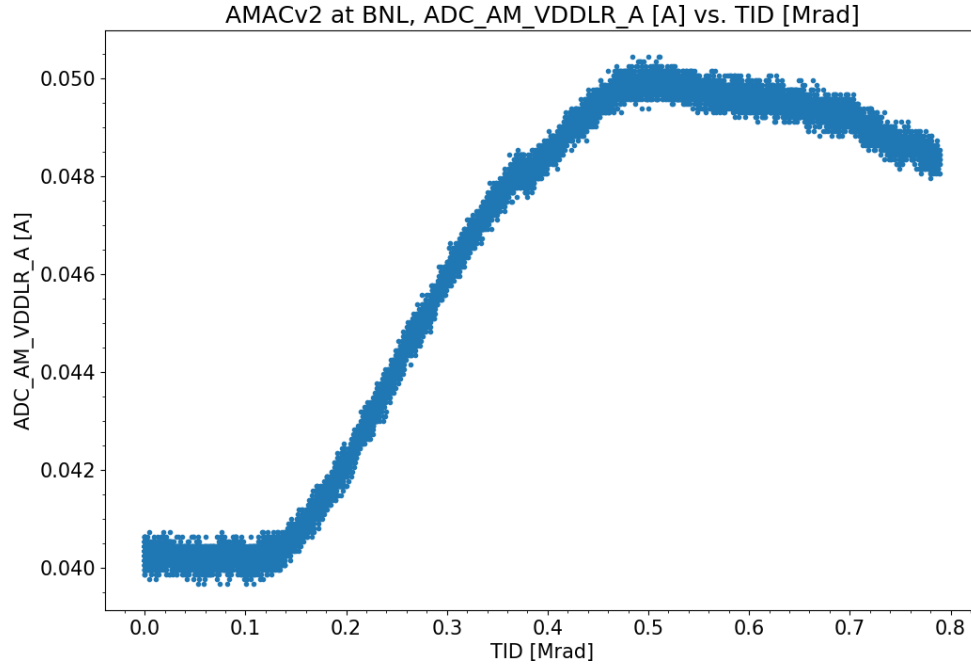


Figure 9.30: AMACv2 supply current TID bump measured during the BNL Co-60 irradiation. This irradiation was performed at a dose rate of 0.6 krad per hour and a temperature of -10°C . The peak value of the TID bump was 50 mA, corresponding to a 25% current increase. This maximal value occurred at a TID of roughly 0.5 Mrad.

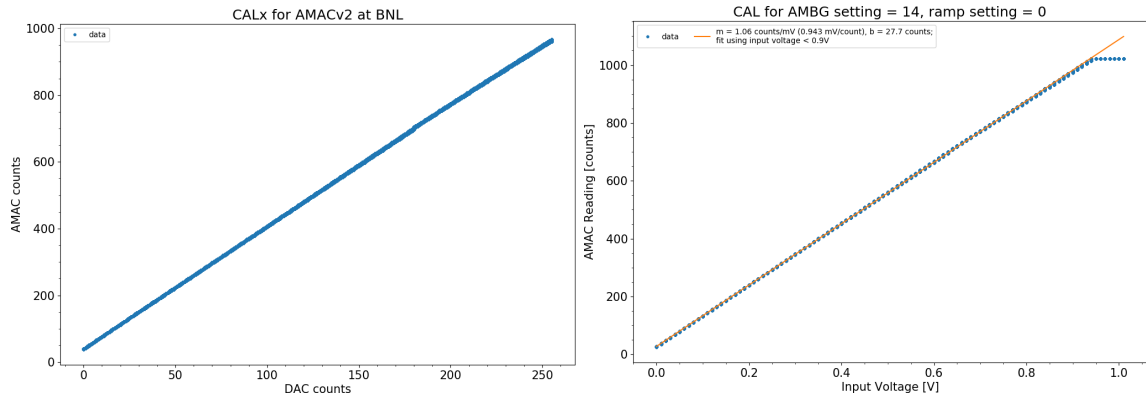


Figure 9.31: AMACv2 internal and external voltage ramps during irradiation at BNL. Left: AM CALx measurement shown as a function of the internal AMAC DAC value which sets the voltage for the CALx channel. Right: AM CAL measurement shown as a function of the voltage set by an external DAC. For both plots, over 10,000 measurements are overlaid spanning the data taken from 0 Mrad through 0.8 Mrad collected over the course of about two months. Clearly, both plots exhibit linearity and remain stable throughout the entire irradiation period.

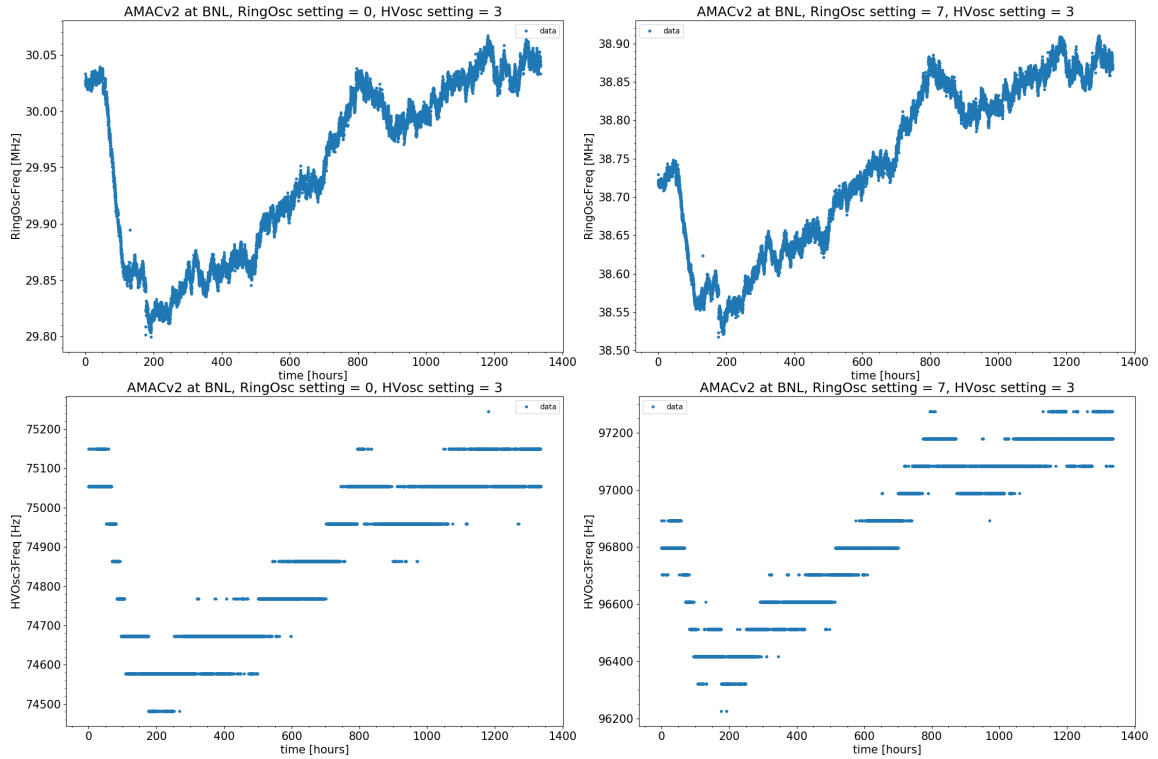


Figure 9.32: AMACv2 frequency measurements during the BNL Co-60 irradiation. The left-hand plots use a register setting to adjust the ring oscillator to smaller frequencies, while the right-hand plots adjust this setting to use higher frequencies. The upper plots are of the ring oscillator measurement, while the bottom plots are of the HV oscillator measurement. The ring oscillator and the HV oscillator plots tend to agree well, and the range of variation across the entire plot is roughly 1%.

from 1 ms down to 0.5 ms. At least one more prototype of the AMAC will be fabricated in the future, which will be able to include improvements such as SEU protection for the latch discussed in Section 9.4.1, along with any other improvements needed to address potential issues observed during the AMACv2a testing.

The AMACv2a will also undergo TID and SEU irradiation tests, similar to those the AMACv2 was subjected to. As the testing procedure for AMACv2 was not without its flaws, there are some potential areas for improvement to allow for fewer issues during the irradiations. As mentioned previously, the SD card used for the file system and output files during the proton irradiation at CERN became corrupted during the irradiation, likely due to damage in the flash memory due to bitflips caused by the beam spray. In the future, a network mounted file system could instead be used during irradiations. This would allow the operating system and output files to be physically

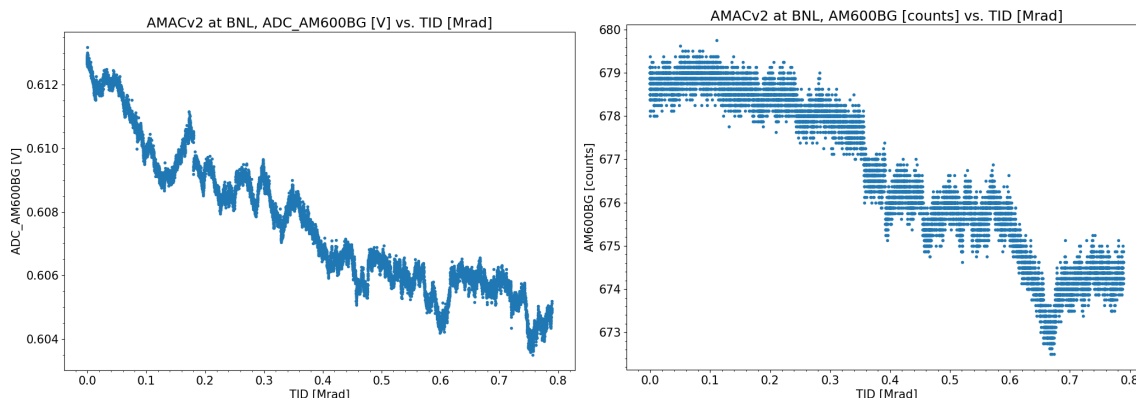


Figure 9.33: AMACv2 bandgap voltage reference measurements during the BNL Co-60 irradiation. The left-hand plot shows the external measurement of the bandgap, while the right-hand plot shows the corresponding internal measurement via the AM. These both tend to decrease with TID; however, since the bandgap is adjustable and the rate that these change with TID is small, there will be plenty of chances to recalibrate this during the ITk Strips operation.

located on an external laptop, which the Microzed could access via ethernet, thus removing any reliance on an SD card. Moreover, during the BNL irradiation of AMACv2, a potentially older SD card was accidentally used, and this SD card started to fail after several months. This was likely due to the limited number of lifetime writes to flash memory. This further motivates the use of a network mounted file system. After the proton irradiation at CERN, the commercial FMC board power supply was also found to be inoperable; as this was located near the test/control board and likely also damaged by the beam spray, it would be beneficial in the future to send this power (and any necessary power) over long cables as well. Finally, during the BNL irradiation, there was a brief time period where no new data was received due to an unplugged ethernet cable. To catch such issues sooner, automatic email notifications were added into the daily data analysis procedure. Ideally these notifications should be included from the very start of the irradiation, and could be expanded to monitor other issues (e.g. board temperature variations were also monitored in case the peltier failed).

All of the testing discussed was for single chips, but this obviously does not scale for the production testing of the nearly 18,000 chips needed for the ITk Strips. For this, wafer probing will be performed for the testing and calibration of all of the ITk Strips ASICs. After the wafers are probed and diced into the individual chips, the chips will be wirebonded to powerboards and hybrids. This will then be followed by module and stave assembly, ultimately leading to installation into the ITk Strips detector.

CHAPTER 10

Conclusion

This thesis presented two searches for electroweak production of supersymmetric particles using $\sqrt{s} = 13$ TeV data collected by the ATLAS experiment in 2015–2016. The first search focused on a trilepton final state and a benchmark wino-bino simplified model. This analysis contributed to exclusion limits on $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with decays mediated by gauge bosons for $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses up to 580 GeV, assuming a massless $\tilde{\chi}_1^0$ LSP. The second search focused on a dilepton final state containing soft leptons, allowing ATLAS to probe the compressed region where the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ are similar in mass. Significant understanding of soft leptons and fake lepton backgrounds were essential to the sensitivity of this compressed EWK SUSY search. For the particularly well-motivated Higgsino LSP simplified model, this search managed to exclude $\tilde{\chi}_2^0$ masses up to 145 GeV for $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ between 5 GeV and 10 GeV, as well as for mass splittings as small as $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \approx 2.5$ GeV for $m(\tilde{\chi}_2^0) \approx 100$ GeV. These exclusion limits, along with those from CMS [205] (which were published simultaneously), were the first limits on direct Higgsino production since the LEP experiments in the early 2000s.

In addition to these searches, this thesis described the likelihood-based electron identification algorithm used by all ATLAS analyses in Run 2. The optimization of this identification criteria has been critical for the performance of the ATLAS detector, both at trigger-level and analysis-level. The electron likelihood in Run 2 allowed for good discrimination between prompt electrons and background objects across a wide range of electron p_T , thus having a direct impact on many ATLAS Standard Model measurements and searches for new physics (including the searches discussed in this thesis). The procedure used for measuring electron selection efficiencies based on the tag-and-probe method was also discussed, with a particular focus on the electron identification efficiencies measured using $Z \rightarrow ee$ tag-and-probe events.

Finally, electronics for planned upgrades to the ATLAS tracking system were discussed. The prototypes of the AMAC chip have been found to largely function as intended, other than some small desired modifications which will be introduced for future prototypes. Several irradiation tests using 1 MeV photons as well as 24 GeV protons were performed, to ensure that the AMAC will continue to function properly even after being exposed to significant amounts of radiation. One particularly important result of these irradiations was the confirmation that the AMAC exhibits a dose-dependent current bump, resulting in a 25% current consumption increase within the first 1 Mrad of irradiation (under conditions similar to those expected for the ITk Strips subdetector), similar to many past ASICs which have been irradiated.

While it would have been nice if this thesis could have instead been titled “Electron Identification, Electronics Upgrades, and **Discovery** of Electroweak Supersymmetry at ATLAS”, not all hope is lost. ATLAS and CMS still have plenty of phase space left to cover, many potential searches which have not yet been attempted, and a large dataset which will be collected over the course of the next two decades. If SUSY or some other model of new physics is the correct theory of nature, the LHC experiments may have the exciting opportunity to make discoveries and measurements which could resolve some of the existing open questions in particle physics. Only time will tell.

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