

A SEARCH FOR B - L R -PARITY-VIOLATING SCALAR TOP DECAYS WITH
THE ATLAS EXPERIMENT

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ABSTRACT

A SEARCH FOR B - L R -PARITY-VIOLATING SCALAR TOP DECAYS WITH THE ATLAS EXPERIMENT

J.G. Heinlein

Evelyn Thomson

This dissertation presents a search for stop pair production followed by decays to a charged lepton and a b quark, using the Full Run 2 dataset collected by ATLAS. This search is motivated by a supersymmetric model with an extra local symmetry $U(1)_{B-L}$, where the stop may be the lightest supersymmetric particle and can decay promptly via an R -parity violating coupling. The search identifies events with two high- p_T leptons (electrons or muons) and two high- p_T jets, one of which is b -tagged as initiated by a b -quark. In the absence of an excess, limits are placed on the stop mass for different values of the branching fractions for $\tilde{t} \rightarrow eb$, $\tilde{t} \rightarrow \mu b$, and $\tilde{t} \rightarrow \tau b$.

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Preface

Physics has been a passion of mine for as long as I can remember. From early high school in Mr Olstad's class, I knew I wanted to work for CERN one day. I would daydream about the future, where it was never a question that I would be a physicist, imagining the day I would move to Geneva and join the search for new physics. I committed to my studies to make this a reality, self-teaching for both of the AP physics tests my junior year of high school and taking intermediate college physics courses at Michigan State my senior year. In the fall of 2014, I began my undergraduate career at The University of Michigan with the goal of graduating in physics. Convinced that I needed to put the college credits earned in high school to use, I pushed myself to graduate in just three years with a dual major in physics and mathematics. While the process was difficult, I found respite in the film studies minor that I elected. When I got the acceptance email from Penn on Jan. 27, 2017, I immediately called my parents and told them: "I'm going to grad school. I'm going to be a doctor."

In the fall of 2017, I moved to Philadelphia to begin graduate school, following a summer of finishing my undergraduate thesis and remaining coursework with Michigan. At the end of my first year, I met with Evelyn Thomson and officially joined the ATLAS group. Once the paperwork was squared away, the first email I sent with my new CERN account was to John Olstad, reading:

Now, I find myself doing research for CERN and working on the LHC. This is a dream come true
and I am forever grateful for being able to spend time in your class.

and I exhaled for the first time in what seemed like an eternity; I had made it.

My first project with the Penn ATLAS group was to perform preliminary studies on improvements that could be made to the recently completed RPV stop search. During this time, I learned the ropes of performing analyses from fellow graduate student, Leigh Schaefer, and postdoc, Jeff Dandoy, who were working on a new search for RPV chargino decays. While there wasn't much for a fresh graduate student

to contribute to the chargino analysis, I was able to take extensive notes, ask numerous questions, and gain a deep understanding of the analysis process; I am immensely grateful for their patience.

In the latter half of my first year with the ATLAS group, I began work on my qualification task: a research task that services the collaboration as a whole in order to become an official ATLAS author. For this task, I assisted Ben Rosser in the testing of prototype ASICs for the High Luminosity LHC upgrade plan. Prior to this project, I had no real hardware experience and had plenty to learn. Ben and I were in charge of developing a suite of functionality tests to be performed in high radiation environments, much like the planned HL-LHC environment. This project provided me with my first opportunity to travel for work and see parts of the world I hadn't prior. In 2019, I traveled to Vancouver twice for proton irradiation of the HCCStar and to Louvain, Belgium for heavy ion testing. While these tests didn't exactly go as planned, as will become apparent in Ch. 4, I learned an immense amount about chip design, digital logic, and radiation testing.

At the end of 2019, following my qualification task, I returned to the RPV stop search as my primary focus. Due to the results of the HCCStar irradiation, many people were requisitioned to work on fixing the errors found. With the guidance of Evelyn and Jeff, I performed most of the analysis myself, which is exceptionally rare in such a large collaboration. This proved to be a particularly challenging task and required significant self-discipline to push for results. The bulk of my dissertation catalogues the work I performed on the B-L stop search, which has extended limits on stop pair production well beyond our expectations. I am incredibly proud of the work I was able to put into this analysis and the results we achieved.

Being a part of the ATLAS collaboration for the last 6 years has been a life-changing experience. I have traveled the world, contributed to cutting-edge physics analyses, and met the most wonderful people in the process. The Penn ATLAS group saved me from entirely burning out in my second year of graduate school. I was welcomed into the Penn ATLAS family with open arms and the memories I have made with the group will live with me forever. I will always cherish the care and guidance provided by my colleagues, the multi-hour lunches discussing the goofiest of classification problems, the HESTs, happy hours, and the multi-hour coffee breaks.

I present this dissertation to carry the torch of those who came before me and to add my chapter to the legacy of the LHC and the ATLAS experiment.

J.G. Heinlein

Philadelphia, December 2023

CHAPTER 1

Introduction

The field of elementary particle physics has been incredibly active for the last century. Beginning with the discovery of the electron in 1897 by J.J. Thomson, particle physics has led to a very clear picture of the building blocks of our universe. Throughout the 20th century, larger and larger high-energy particle accelerators were developed, leading to a rapid discovery an entire zoo of particles, without a complete theory to explain these observations. Developed in the latter half of the 20th century, the Standard Model succinctly classifies particles into two major categories based on spin: spin-1/2 fermions and integer spin bosons. In this framework, forces between the fermions are mediated by the spin-1 gauge bosons and particles acquire masses through their interactions with the Higgs field. Confirmation of the Standard Model was a major goal for particle physicists, culminating with the discovery of the scalar spin-0 boson in 2012. The Higgs boson was the final particle of the SM to be observed, thus closing this century-long chapter in particle physics research.

While the Standard Model has successfully guided the way until this point, there are many observations for which the SM does not contain an explanation. These observations lead to the prediction that the SM is part of a larger theory that we are yet to observe. Supersymmetry (SUSY) is a possible extension to the Standard Model which seeks to remedy many of the observations incompatible with the Standard Model by introducing a new symmetry between fermions and bosons, broken at an energy level above the TeV scale. Despite seeming like a clear prescription for Beyond the Standard Model (BSM) physics searches, SUSY is in fact an umbrella term for the classification of theories which introduce this boson-fermion symmetry, each of which provide unique phenomenology and unique signatures in experiment. Searches for supersymmetry are performed at the Large Hadron Collider in Geneva, Switzerland, which offers unprecedented access to TeV-scale physics. For this dissertation, I will discuss $B - L$ Minimal Supersymmetric Standard Model, which has a special connection to my institute of The University of Pennsylvania, being developed here

in-part by Professor Burt Ovrut.

This dissertation catalogues the search for $B-L$ scalar top pair production with R-Parity violating decays to a charged lepton and b-quark and is split into four main chapters. Chapter 2 presents the Standard Model of particle physics and the observations which lead us to believe there is more beyond it. The $B-L$ MSSM is presented as a potential extension to the Standard Model and the phenomenology of how the stop LSP would manifest in experiment. The LHC and the ATLAS detector, the experimental apparatuses utilized to perform the dedicated search for scalar tops, is described briefly in Chapter 3. The future upgrade to the LHC, the High Luminosity LHC (HL-LHC), and validation of its ASICs is discussed in Chapter 4. Finally, the dedicated search for resonances in the combined charged lepton + b-jet mass distribution from R-Parity violating stop decays is presented in Chapter 5, with a brief conclusion following in Chapter 6

CHAPTER 2

Theoretical Framework

2.1 Introduction to the Standard Model

The Standard Model of particle physics (SM) describes all known elementary particles which form the building blocks of the observable universe as well as three of the four fundamental forces (strong, electromagnetic, weak) [1–4]. Particles in the Standard Model are split into two main categories: Bosons (force carriers) and Fermions (matter particles). Bosons are integer-spin (0, +1, etc) particles with each associated to a specific interaction whereas the Fermions have half-integer spin (+1/2, etc). Particle interactions are governed by the Lagrangian of the underlying theory and are often represented in particle physics via Feynman diagrams which represent forces as the exchange of a boson. These diagrams are both convenient visual interpretations of the processes at hand as well as explicit mathematical treatments of the underlying physics. Each Feynman diagram is a representation of a given term in the Wick Expansion of perturbative S-matrices with the order of a given term corresponding to the number of interaction points (vertices) in the diagram. For the purpose of this dissertation, we will only discuss S-matrices which are perturbative and have Feynman representations, although some non-perturbative theories for physics beyond the Standard Model (BSM) exist. The observed particles are summarized in Fig. 2.1 with their associated mass, charge, and spin.

Bosons with spin 1 (given in red) are referred to as vector bosons. These bosons include the photon (responsible for carrying the electromagnetic force), the $W^\pm$ and Z bosons (mediating the weak force), and the gluon (responsible for the strong force). Notably, gravity is not currently understood within the Standard Model and is not associated to a SM vector boson. Gravity is instead currently characterized by Einstein's Theory of General Relativity (GR). While not discussed in this dissertation, there are many theories which seek to unify GR with the Standard Model by introducing the hypothetical particle the graviton. The final boson of the SM is a scalar particle called the Higgs Boson, which gives mass to all particles via interactions

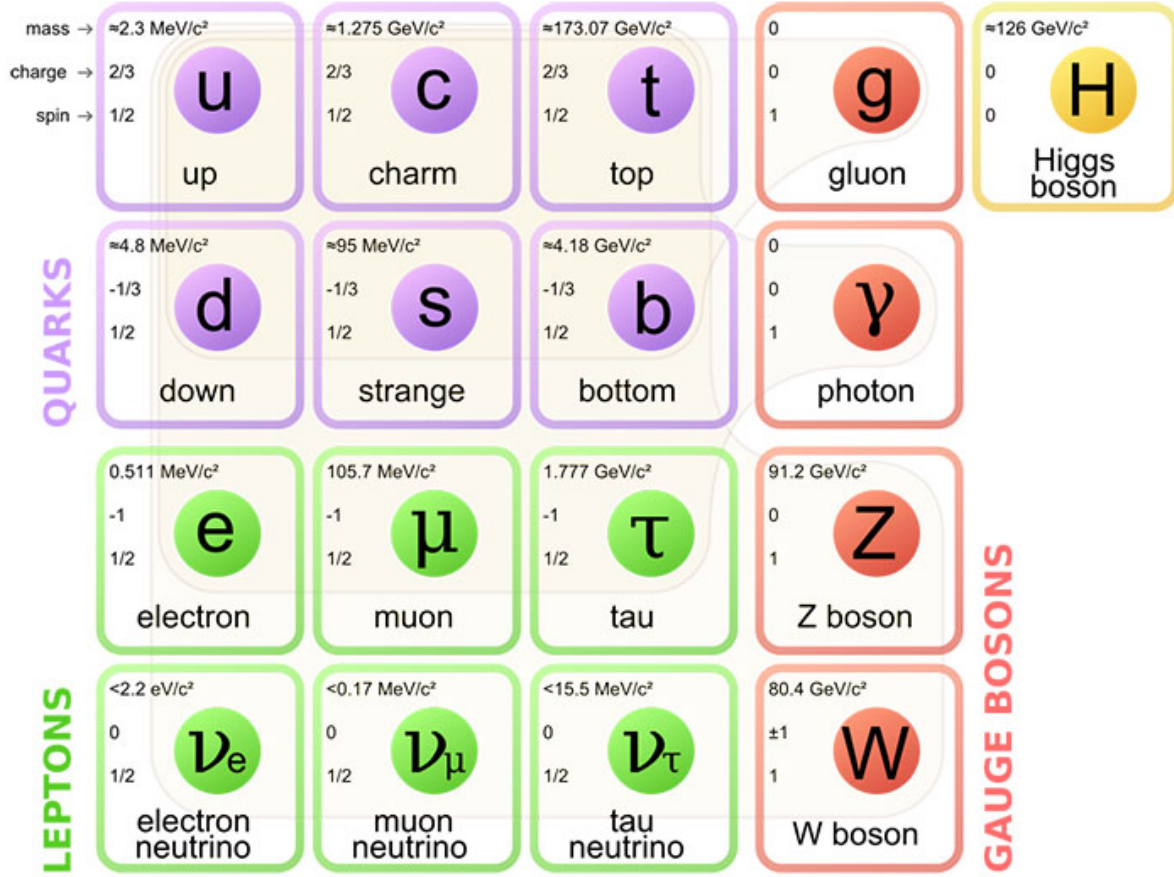


Figure 2.1: The fundamental particles of the Standard Model. The fermions are split into two categories: quarks in purple and leptons in green. The gauge bosons are given in red and Higgs boson in yellow. The mass, charge, and spin of each particle is given in the top left of each box. Fermions are organized by generation as well as charge [5].

with the Higgs field. The Higgs Boson and its interactions will be discussed further when we discuss the Higgs Mechanism in Sec. 2.1.2.

Fermions are classified into two categories based on their interaction with the strong force: Quarks which carry color charge and are sensitive to the strong force and Leptons which do not. Much like one would consider electric charge in terms of positive or negative, color charge is an inherent property of the quarks which may take on three potential values: red, green, or blue. It is important to remember that the designation of color is simply a representation of the three potential color charges and not a statement on the human-visible color of said particles. Due to color confinement (discussed more in depth in Sec. 2.1.1), quarks form color-neutral bound states of two or more quarks referred to as hadrons: mesons which are made of two quarks and baryons made of three quarks. Fermions are further organized into three generations by

mass (represented by columns in Fig. 2.1), with the first generation making up an overwhelming majority of the matter we see around us. An unknown particle or set of particles make up what is collectively referred to as Dark Matter (DM), which has currently only been observed via its gravitational effects on the universe.

2.1.1 The Standard Model Group Theory

The Standard Model is defined more precisely by a Lagrangian governed by the local gauge group [1, 2]:

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

The $SU(3)_C$ symmetry describes the interactions of the strong force. The eight generators of the group (G_μ^α for $\alpha = 1, 2, \dots, 8$) define the vector fields we call gluons. As previously described, these gluons interact only with color-charged particles, hence the C in $SU(3)_C$. Each gluon carries both a color and anti-color charge, allowing for the strong interactions of quarks and anti-quarks. Additionally, gluons are able to self-interact leading to the concept known as color confinement. When attempting to separate strongly-interacting particles, the self-interaction of gluons causes the binding force of quarks to scale linearly with spatial separation. Binding energy becomes so large in magnitude that it becomes more energetically favorable to rip new quark-antiquark pairs from the vacuum to form new bound state hadrons. The production of a (nearly) isolated quark/antiquark that does not join the bound state triggers a cascading effect of continually ripping new particles from the vacuum to create new hadrons until there is no longer enough energy to adequately separate quarks. This process is referred to as hadronization and is the basis for the frequently observed physics objects we refer to as jets.

The $SU(2) \times U(1)_Y$ symmetry provides the basis for both the Weak force and the Electromagnetic forces. At high energy, these forces are unified into what is referred to as the Electroweak (EWK) force. At high energy, the electroweak interaction is mediated by the massless vector fields of $SU(2)_L \times U(1)_Y$: W_μ^a (the 3 generators of $SU(2)_L$) and B_μ (the generator of the $U(1)_Y$ symmetry). Through the process known as the Higgs Mechanism (described in Sec. 2.1.2), an admixture of these vector fields form the physical $W^\pm$, Z^0 , and γ^0 bosons that we observe at our energy level.

2.1.2 The Higgs Mechanism

The Higgs Mechanism is the process in which the Weak bosons acquire a mass via the spontaneous symmetry breaking of the $SU(2) \times U(1)_Y$ electroweak symmetry [1–4]. As described prior, the generators of this symmetry, W_μ^a and B_μ , are not the physical bosons that exist after the symmetry breaking process. The Higgs Mechanism hypothesizes the existence of a charged, complex scalar doublet, ϕ , which is referred to

as the Higgs multiplet. The addition of the complex scalar field to the weak-sector Lagrangian yields the following result:

$$\mathcal{L}_{EWK} = -\frac{1}{4}(W_\mu^a)^2 - \frac{1}{4}(B_\mu)^2 + (D_\mu\phi)^\dagger(D_\mu\phi) + \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2 \quad (2.2)$$

where the covariant derivative D_μ acting on the Higgs field is given by:

$$D_\mu\phi = \frac{1}{2}[2\partial_\mu + (ig_W\sigma^a W_\mu^a + ig'B_\mu)]\phi \quad (2.3)$$

where g_W, g' are the relative coupling strengths for the $SU(2)$ and $U(1)$ gauge groups and σ^a are the Pauli matrices. As the energy of the universe cools beyond a critical temperature, the Higgs field, ϕ , acquires a non-zero vacuum expectation value (denoted as both vev or ν). The shape of this new Higgs potential is shown in Fig. 2.2. One can see that there is an infinite set of ground states accessible via rotation in the complex plane. By shifting into the unitary gauge, we can now express the Higgs Field in terms of the vev and a new physical scalar $h(x)$ with:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + h(x) \end{pmatrix} \quad (2.4)$$

Plugging this expression into Eq. (2.2) and diagonalizing the mass matrix, we can finally arrive at the physical $W^\pm$, Z^0 , and γ^0 as a linear combination of the previous massless gauge fields:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^{(1)} \mp iW_\mu^{(2)}) \quad (2.5)$$

$$Z_\mu^0 = \frac{1}{\sqrt{g_W^2 + (g')^2}}(g_W W_\mu^{(3)} - g' B_\mu) \quad (2.6)$$

$$A_\mu = \frac{1}{\sqrt{g_W^2 + (g')^2}}(g' W_\mu^{(3)} + g_W B_\mu) \quad (2.7)$$

with masses given by:

$$m_W = \frac{1}{2}g_W\nu \quad (2.8)$$

$$m_Z = \frac{1}{2}\nu\sqrt{g_W^2 + g'^2} \quad (2.9)$$

$$m_A = 0 \quad (2.10)$$

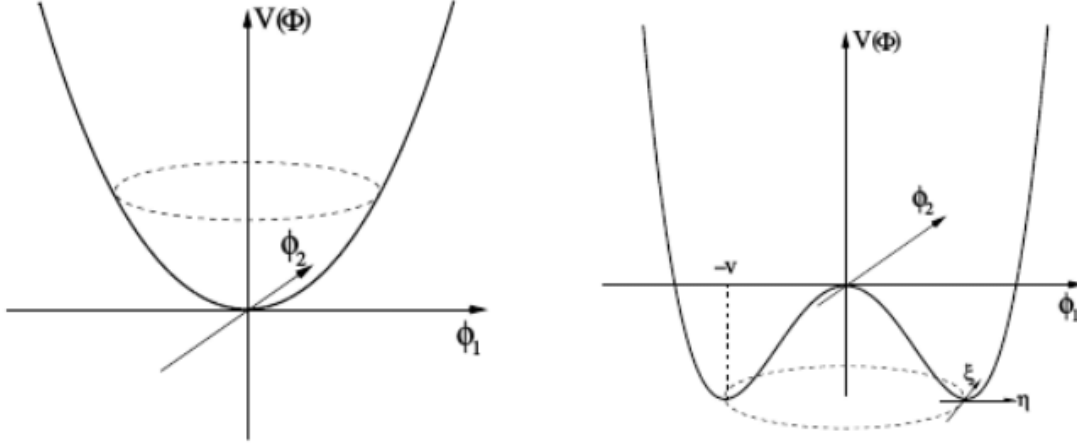


Figure 2.2: Diagrams of the Higgs potential before (left) and after (right) spontaneous electroweak symmetry breaking. After electroweak symmetry breaking, the field resembles the bottom of a wine bottle. The axes represent the real and imaginary components of the complex Higgs field. In the left diagram, the Higgs field has a vacuum expectation value of 0, while after EWK symmetry breaking it takes on a non-zero value of ν .

Once the dust has settled, we are now left with the scalar Higgs Boson, with mass $m_h = \nu\sqrt{2\lambda}$, measured to be 125 GeV in 2012 [6, 7]. Fig. 2.3 provides a nice diagram of how the weak fields mix to form observed physical fields after electroweak symmetry breaking. At the current time, it is not yet clear if this mechanism can be applied at higher energies to unify the electroweak force with the strong force in what is known as a Grand Unifying Theory (GUT).

2.1.3 The Standard Model Lagrangian

Once the Electroweak symmetry is broken, the Standard Model Lagrangian is given by:

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi) \quad (2.11)$$

This compact equation encodes the fundamental interactions of the Standard Model as we know them. The first term, $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$, describes the interactions of all gauge bosons with one another. This provides the framework for gluon-gluon interactions as well as interactions of the electroweak bosons. The second term, $i\bar{\psi}\not{D}\psi + h.c.$, encodes the interactions of fermions via the gauge bosons. The term $\not{D}$ is the covariant derivative, which contains information on the couplings of (anti)matter particles (denoted by ψ and $\bar{\psi}$) to one another. The third term, $\psi_i y_{ij} \psi_j \phi + h.c.$, describes the couplings of fermions to the Higgs field

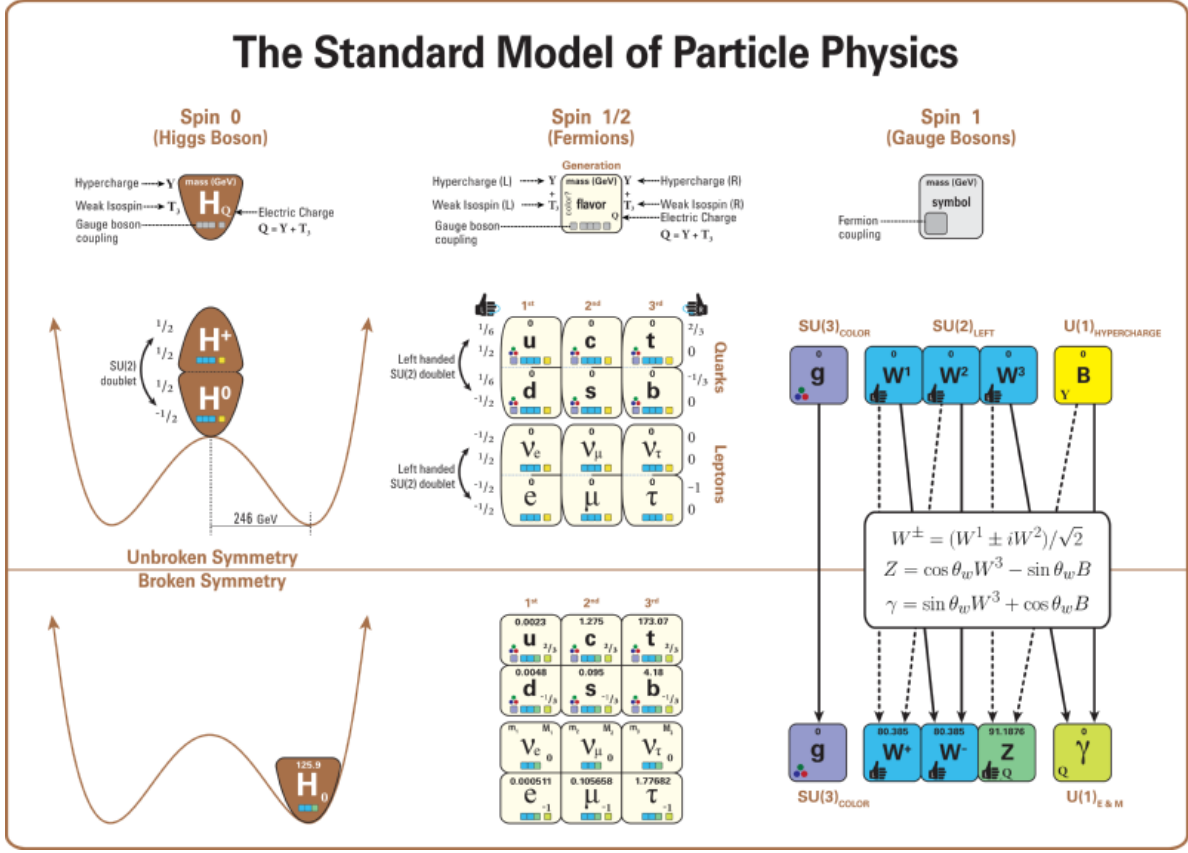


Figure 2.3: The field content of the Standard Model before and after EWK symmetry breaking. Before symmetry breaking, there are four massless gauge fields responsible for the unified electroweak force. After symmetry breaking, we are left with the massive $W^\pm$ and Z bosons and the massless photon (γ) [8]

which provides their mass. The Yukawa matrix y_{ij} encodes the coupling parameters of matter particles (ψ_i) to the scalar Higgs field ϕ , which have been determined experimentally. The fourth term, $|D_\mu \phi|^2$, denotes the interactions of the weak bosons with the Higgs field. As described previously, the photon does not obtain a mass during the Higgs mechanism while the $W^\pm$ and Z^0 both pick up mass terms via this interaction term. This term allows for the Higgs production mode known as Vector Boson Fusion (VBF). The final term of the Standard Model Lagrangian, $-V(\phi)$, collects all the remaining terms pertaining to the Higgs Potential. This describes both the shape of the potential as well as the self-interactions of the Higgs Boson. As described previously, the potential takes on a "wine bottle" shape which yields a continuous set of rotationally symmetric minima. In conjunction, these rules form one of the most successful theories for predicting the phenomena of particle physics, as seen in Fig. 2.4 where theoretical predictions from the standard model are compared to experimentally observed measurements for a variety of physics couplings

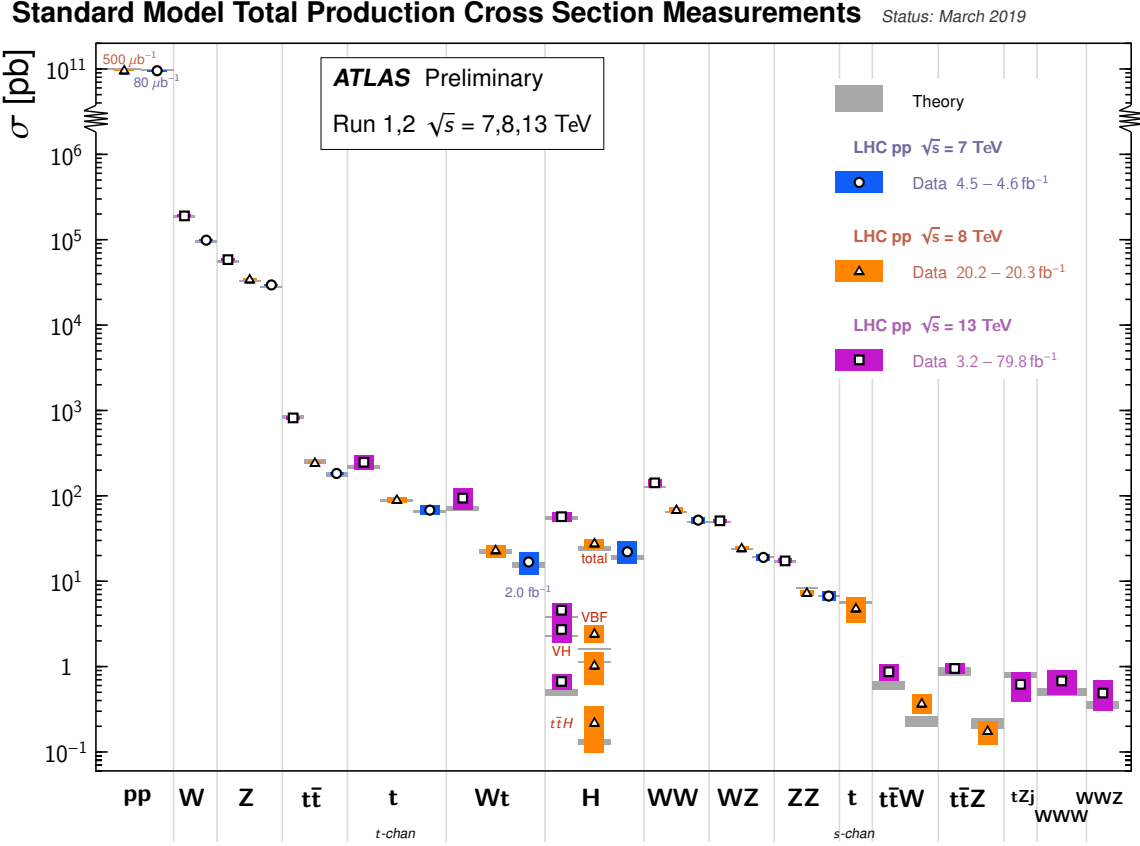


Figure 2.4: Predicted and observed values for various SM production cross-sections. Measured values are observed by the ATLAS experiment with $\sqrt{s} = 7, 8$, and 13 TeV pp collisions [9].

and processes. The full set of Feynman rules for the Standard Model can be found in Appendix A of Peskin and Schroeder's *An Introduction to Quantum Field Theory* [2].

2.1.4 Looking Beyond the Standard Model

While the Standard Model has proven to make exceptional predictions in the field of particle physics and been rigorously tested over the last few decades, there remain problems in physics which are not explained with the Standard Model. The first of these problems stems from the observation of the Higgs mass: when one attempts to write the loop diagrams which shift the Higgs from its bare mass (as seen in Fig. 2.5), it becomes clear that quadratic fermionic loops should yield an observed Higgs mass at the scale of the Planck constant. Yet, from the 2012 observation of the Higgs boson, we find the observed Higgs to have a mass of merely 125 GeV [6, 7]. This result either requires some immense fine-tuning well beyond reason or additional

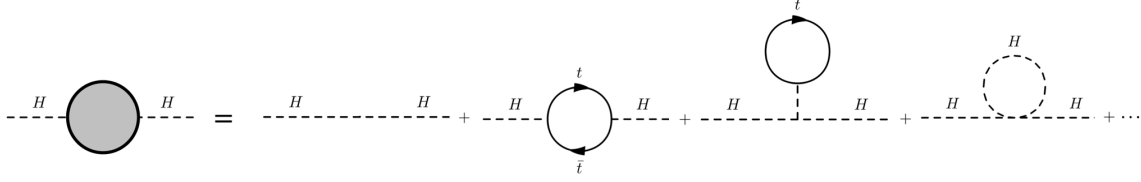


Figure 2.5: The measurable Higgs mass represented as a sum of loop corrections to the bare Higgs mass.

not-yet-observed interactions with the Higgs boson to provide a large cancellation of the quadratic terms. This problem is deemed "the hierarchy problem" and leads many to the belief the Higgs may be our looking glass into new physics [2].

The second major problem in the standard model arises from the acceleration of galaxies. As the universe expands, one might expect the gravitational attraction of massive bodies to steadily slow the expansion. However, when the Hubble Space Telescope observed distant supernovae, it was measured that the universe's expansion was accelerating. These observations form the basis of what we call "Dark Matter" and "Dark Energy." Current understanding fails to explain the nature and content of Dark Energy/Matter, but observations provide key insights to some of the properties of Dark Matter: it must be electrically neutral but has mass and interacts gravitationally. The only particles currently in the standard model which satisfy these conditions are the neutrinos, which have been ruled out due to their extremely light mass, leaving room for potential new Dark Matter particles.

The last open problem I will discuss is the previously mentioned lack of any gauge boson for the gravitational force. As we have shown, the standard model understands the concept of forces as the exchange of gauge bosons, such as the $W^\pm$ and the photon. While the other three major forces are understood through QFT, gravity remains described through the classical theory of general relativity. A "theory of everything" would seek to understand the quantization of gravity as a hypothetical graviton boson which would mediate the gravitational force at the Planck Scale (10^{18} GeV).

These open questions are not fully encompassing of the gaps left by the Standard Model, but summarize the primary motivations for the most popular extension to the Standard Model: Supersymmetry.

2.2 Introduction to Supersymmetry

There are many theories which extend the Standard Model in order to alleviate the gaps left by the Standard Model. Supersymmetry (SUSY) introduces a new fundamental symmetry between the fermions and bosons by assigning each SM fermion a spin-0 superpartner (dubbed squarks and sleptons) and a set of spin-1/2 superpartners (winos, binos, and higgsinos) to the SM bosons [10]. This process immediately doubles

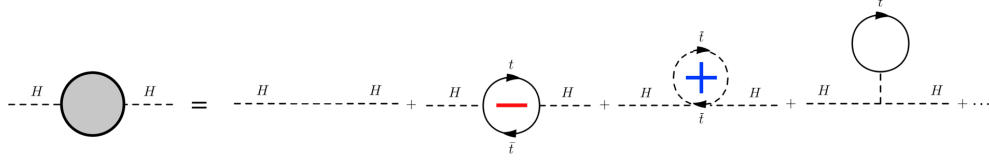


Figure 2.6: The measurable Higgs mass represented as loop corrections to the bare Higgs mass from both SM processes as well as SUSY interactions. The "+" and "-" signs illustrate the relative sign of each correction. The addition of SUSY loop corrections effectively cancels the large fermionic loop corrections from the SM.

the particle content compared to the bare SM, providing many dark matter candidates and avenues to search for new physics. To avoid the introduction of anomalies, SUSY necessitates the existence of two SM Higgs doublets where the observed SM Higgs is an admixture of the two neutral components of the doublets. The physical mass eigenstates of the superpartners to the electroweak bosons are an admixture of the aforementioned wino, bino, and higgsino superfields; the mass eigenstates are called Charginos and Neutralinos (classified by electric charge).

The introduction of superpartners to the fermions leads to a rather elegant cancellation if the masses of the sfermions are comparable to those of the fermions: the newly generated loop corrections to the Higgs boson mass come with a minus compared to their standard model counterparts. Adding these diagrams together now leaves the correction to the bare Higgs mass much smaller than the Planck scale (as seen in Fig. 2.6). The fine tuning now required to match the Higgs mass to observation is much more reasonable than the many orders of magnitude previously necessitated. In a scenario where SUSY is not spontaneously broken, the superpartners would be of identical mass to their SM partners, perfectly canceling the loop corrections. However, this symmetry must be broken as the SUSY particles would have been very apparent in the data of detectors at the energy frontier. The addition of numerous massive neutral particles creates opportunity for potential Weakly-Interacting Massive Particles (WIMPs) to explain the nature of dark matter. Finally, the gauging of SUSY incorporates the quantization of gravity due to the gravitino, the hypothetical graviton superpartner, acting as a mediator of the local SUSY transformation.

While SUSY is a large class of potential theories, the Minimal Supersymmetric Standard Model (MSSM) is often studied to minimize the number of particles added to the standard model and avoid the introduction of anomalies.

2.2.1 R-parity

Baryon number (B) and Lepton number (L) are considered "accidental symmetries" of the standard model [2]. That is, there is no inherent group symmetry associated to Baryon and Lepton number conservation but

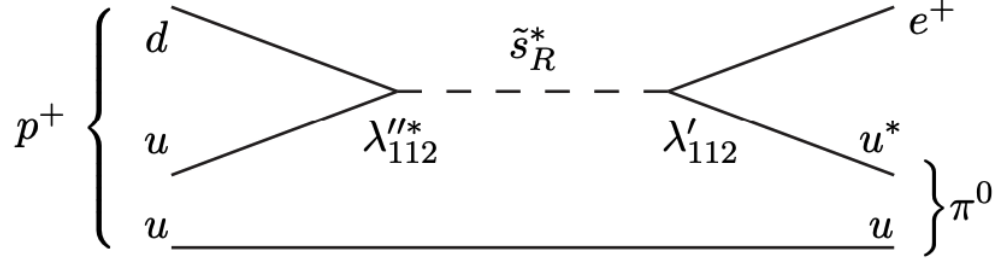


Figure 2.7: A hypothetical proton decay process to a positron and neutral pion via a scalar strange squark due to the addition of baryon- and lepton-violating terms from out-of-the-box SUSY.

instead these properties are conserved simply by the absence of B/L violating terms in the standard model Lagrangian. The most general superpotential one can add to the SM Lagrangian while obeying the MSSM gauge symmetries is given by [10]:

$$\begin{aligned}
 W_{MSSM} = & \bar{u}y_uQH_u - \bar{d}y_dQH_d - \bar{e}y_eLH_d + \mu H_uH_d \\
 & + \frac{1}{2}\lambda LL\bar{e} + \lambda' LQ\bar{d} + \mu' LH \\
 & + \frac{1}{2}\lambda''\bar{u}\bar{d}\bar{d}
 \end{aligned} \tag{2.12}$$

where the top line preserves Baryon and Lepton number, the second line of terms violate lepton number, and the final line violates baryon number. While the introduction of B/L violation may not initially seem like much of a problem, it introduces the possibility for proton decay to a neutral pion and positron via a down-type squark (shown in Fig. 2.7). The instability of protons is clearly a problem as our universe would be a giant soup of pions and positrons as opposed to the neatly structured atoms we see around us. Experiments such as Super-Kamiokande have set limits on the minimum proton lifetime well above the age of the universe at 6×10^{39} years [10]; thus, any proposed extensions to the Standard Model must keep the proton stable.

To mitigate this issue of proton decay, many SUSY models impose the conservation of a new multiplicative quantum number called R-parity [11], defined by:

$$R_P = (-1)^{3(B-L)+2s} \tag{2.13}$$

where B, L are baryon/lepton number respectively and s denotes spin. One may notice that this convention assigns all Standard Model particles $R_P = +1$ and all SUSY particles $R_P = -1$, hence R-parity occasionally referred to as "SUSY-ness." The addition of R-Parity conservation explicitly forbids the terms in Eq. (2.12) which violate lepton and baryon number. The removal of these terms resolves any issues of proton decay by

explicitly codifying baryon and lepton number as conserved quantities. The imposition of R-Parity Conservation (RPC) additionally ensures that the lightest supersymmetric particle (LSP) is stable by requiring an even number of SUSY particles at each vertex, thus preventing the decay of the LSP to purely SM particles. RPC models additionally provide a convenient candidate for the origin of dark matter by allowing for stable, color and electrically neutral particles which may exist at a relic density compatible with observation. For detector physics, RPC models with a stable LSP create a signature with high Missing Transverse Energy (MET) due to particles escaping the detector without interaction.

Despite the compelling arguments to implement R-Parity Conservation, its application is entirely ad hoc and perhaps excessively restrictive on new physics. One may notice from Figure 2.7 that we only need to suppress a single vertex of the hypothetical proton decay process to achieve results compatible with the proton lifetime. Thus, models which allow for some level of R-Parity Violation both question the assumptions made about the nature of new physics as well as provide unique experimental signatures at the Large Hadron Collider (LHC). R-Parity Violating (RPV) models allow the LSP to have both color and electric charge as well as fully decay to SM particles. Detector signatures for RPV models are thus able to have little to no MET when compared to RPC models. Since the detector LSP is no longer a dark matter candidate, many RPV models utilize the superpartner to the hypothetical graviton, the gravitino, as a dark matter candidate. The analysis presented in this dissertation searches for supersymmetric particles within a specific RPV model: The $B - L$ Model.

2.3 B-L SUSY Model

2.3.1 Theoretical Motivations

The B-L MSSM is a potential R-Parity Violating model which extends the SM by adding an additional $U(1)_{B-L}$ gauge symmetry to the SM group representation, yielding an overall gauge group of:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \quad (2.14)$$

The addition of the $U(1)_{B-L}$ gauge symmetry is the minimal supersymmetric extension to the SM possible which exactly specifies the additional discrete symmetry while preventing the decay of the proton. In this approach to SUSY, the difference of quantum numbers, B-L, is codified as an explicit symmetry of nature as opposed to individually conserving B and L. Both $B - L$ and R-Parity conservation are accidental symmetries of the standard model, however, the imposition of $B - L$ symmetry is much less strict than R-Parity conservation and allows a much wider array of potential SUSY search signals. The addition of

the $U(1)_{B-L}$ symmetry introduces a new massless gauge boson, the B' boson, along with its superpartner, the $\tilde{B}'$. Unfortunately, blindly adding the B-L symmetry introduces a new set of chiral anomalies due to the sum of $B - L$ not being equal to 0 for the right handed chiral states [12]. To remedy this and create a theory with a gauged $U(1)_{B-L}$ that is anomaly-free, the B-L theory introduces a set of three right handed neutrinos as well as their superpartners [13–18].

Similar to the Higgs mechanism, we expect the B-L symmetry to be broken above the electroweak scale due to the lack of evidence for a massless B' boson. The phenomenology of the model depends significantly on the scalar field which breaks the B-L symmetry: fields which carry even B-L charge, such as a Higgs singlet, result in the conservation of R-Parity while fields with odd B-L charge result in R-parity violation [13–20]. Through a scan of potential SUSY parameters, it was found that the symmetry most often was broken via a third generation right-handed sneutrino. Through the right-handed sneutrino acquiring a non-zero VEV, the B' boson is "eaten" and replaced by a massive Z' boson. With this choice of a sneutrino scalar field to break the B-L symmetry, Lepton Number conservation is broken, while Baryon Number is still conserved. This results in the preservation of the proton lifetime, as half the diagram has been effectively removed, while still allowing R-Parity Violation. For the purpose of particle accelerators, we assume the RPV couplings are highly suppressed compared to their RPC counterparts, resulting in the same pair production cross section with the key difference of the lightest supersymmetric particle needing not be stable and is allowed to decay to solely Standard Model particles.

Further motivating interest in this theory, a "top-down" approach has been studied extensively where theorists begin with a $SO(10)$ Grand Unified Theory (GUT) in an $E_8 \times E_8$ Heterotic M-theory. This symmetry is spontaneously broken by two Wilson lines, producing the exact gauge group of the B-L MSSM [17, 20–23]. This provides a unique argument for the existence of the $B - L$ theory as it is both intuitive from a "bottom-up" perspective as well as a "top-down."

2.3.2 Phenomenology of B-L Theory

To better focus experimental searches for the B-L MSSM, collaborating theorists performed a scan across the model's free parameters [24, 25]. The parameter space scan is performed by randomly selecting a set of potential values for the soft SUSY breaking parameters and renormalization group evolving them to the electroweak scale. Theories are then categorized by observable quantities, such as sparticle masses and branching ratios, to identify potential search signals for ATLAS analyses.

While the thought of scanning across such a wide parameter space may seem daunting, we are thankfully guided by prior experimental observation. A series of low energy requirements is enforced on generated

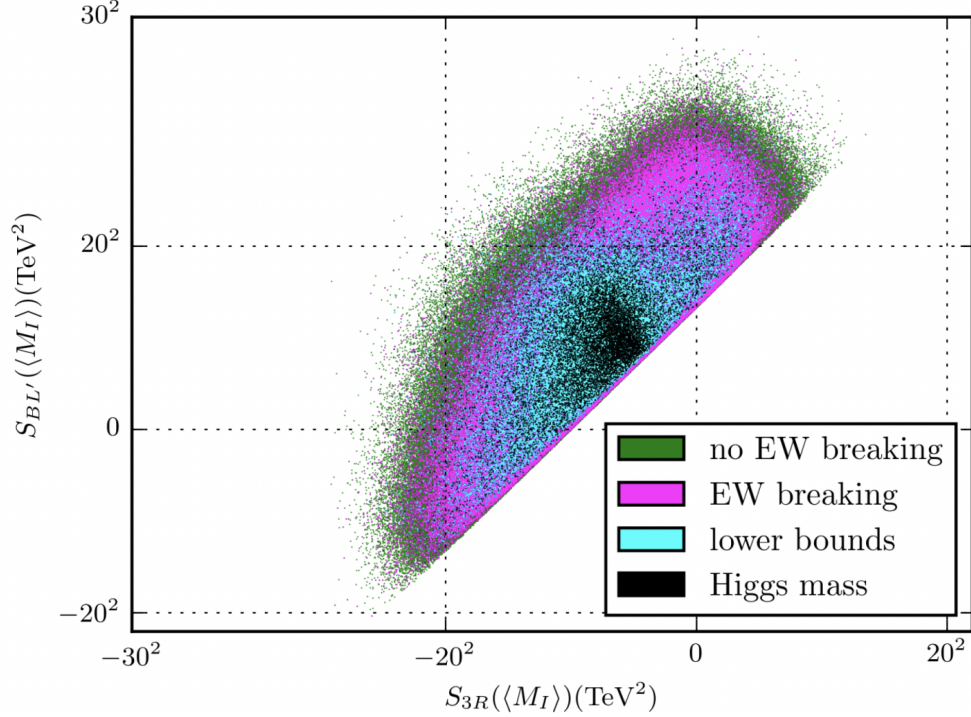


Figure 2.8: Results from $B - L$ parameter space scan and which experimental limits they satisfy [26]. Points are represented in the $S_{BL'}-S_{3R}$ hyperparameter space. Points in green do not provide a theory with EWK symmetry breaking. Points in magenta provide theories with EWK symmetry breaking but lack sparticle masses compatible with observed lower bounds. Cyan points represent theories with the presence of EWK symmetry breaking, sparticle masses compatible with observed lower bounds, but not a Higgs boson mass compatible with current observation. Black points represent theories which satisfy all experimental low-energy requirements.

points in order to be consistent with prior experimental results:

- The scale at which the B-L symmetry is broken must be sufficiently high in order to keep the hypothetical Z' boson above the existing ATLAS lower bound of 4.1 TeV
- The SM Higgs boson must be produced by the theory within three sigma of the 125 GeV measured by ATLAS
- sparticle masses must exceed the measured lower bounds at ATLAS
- Electroweak symmetry must be spontaneously broken and yield the observed $W^\pm$ and Z^0 masses

Parameter sets which satisfy the above conditions are designated as valid black points in Fig. 2.8 and split by the LSP of the theory in Fig. 2.9. One can see from Fig. 2.8 that while many combinations of parameters

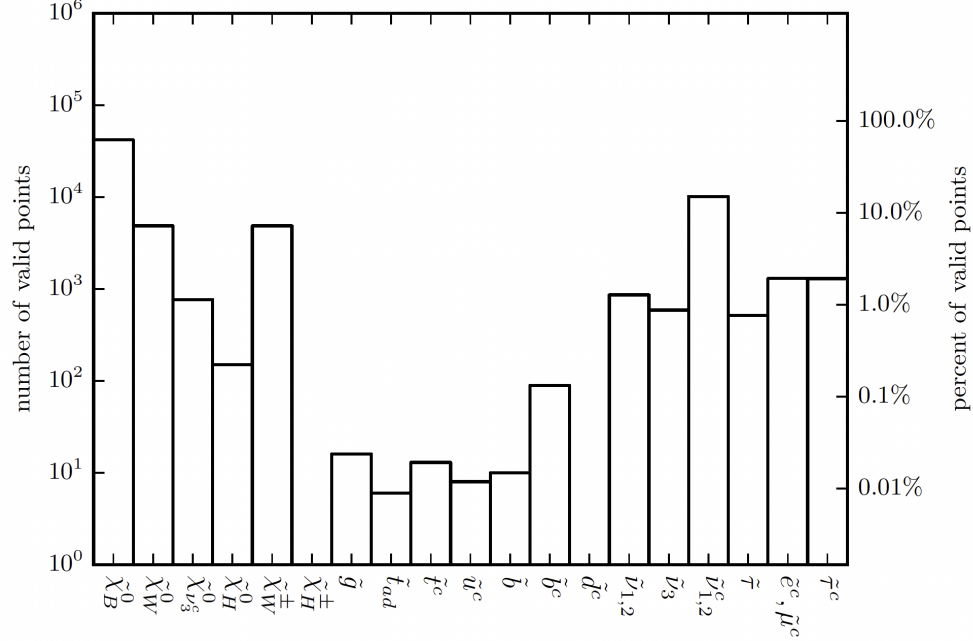


Figure 2.9: A histogram showing the frequency of theories in which the specified sparticle is the LSP for that point [26].

break the $U(1)_{B-L}$ symmetry, adding the progressively stringent requirements leaves only a small fraction of points as valid points. From here, searches at the LHC can be constructed based on: the likelihood of a given LSP, the theoretical production cross section at the LHC, and the signal identification capabilities for a given LSP and its decay products. For this dissertation, I have chosen a specific LSP, the supersymmetric partner to the top quark (the stop), as the target for a dedicated search with the ATLAS detector.

2.3.3 The stop LSP Phenomenology

The fraction of valid black points for each given LSP scenario can be seen in Fig. 2.9; the stop is denoted as $\tilde{t}^c$ and $\tilde{t}_{ad}$ for the (mostly) right-handed stop and an ad mixture of left- and right-handed stop chiral states, respectively. While the stop LSP scenarios represent less than one thousandth of valid points combined, the stop pair-production cross section dwarfs the EWKino sector (as seen in Fig. 2.10), primarily due to the added factors of the color sector [27]. This increased production cross section opens the door to probing stop masses at the multi-TeV scale, which will be demonstrated in Chapter 5.

Each option for the stop LSP yields distinct decay branching ratios with the right-handed¹ stop decaying

¹Here, we refer to the partner of the right-handed top as the right-handed stop and similar for the left-handed top/stop. However, due to the stop being a scalar particle, it has spin 0 and thus does not actually have chirality; this is simply a

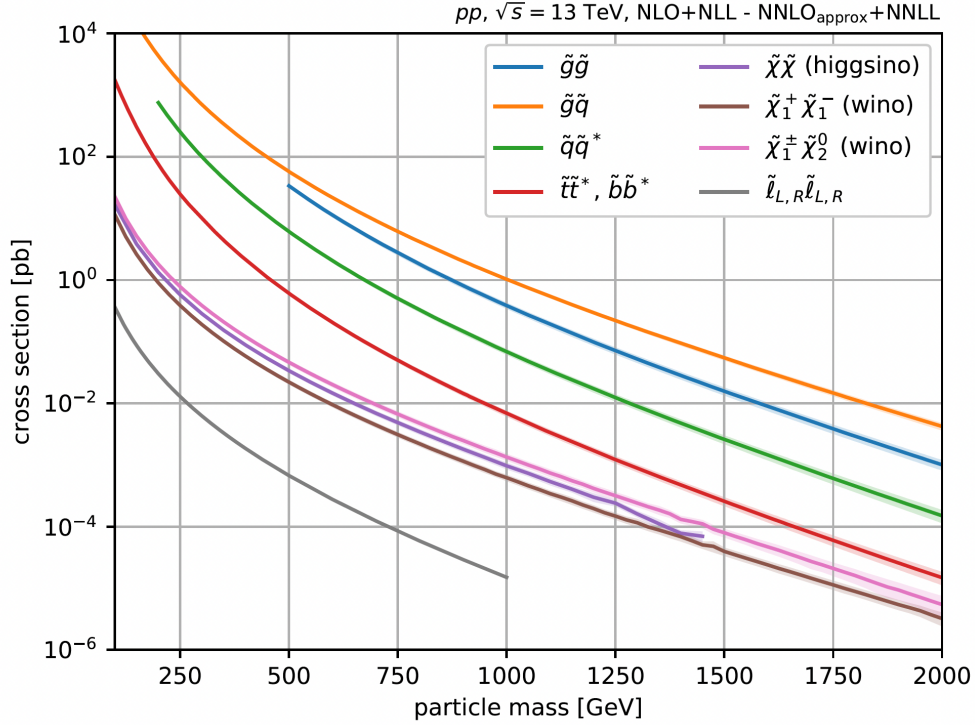


Figure 2.10: Theoretically-predicted cross-sections for various SUSY process at $\sqrt{s} = 13 \text{ TeV}$ [27]

predominantly to a top quark and neutrino, while the ad mixture stop decays almost entirely to a b-quark and a charged lepton. The chirality of the stop LSP additionally influences its decay length: the right handed stop has a longer lifetime of 1 mm or greater, while the ad mixture stop tends to have a much shorter lifetime closer to $1 \mu\text{m}$. These effects can be seen in Fig. 2.11, where stop LSP decay length and decay channel are plotted vs $\theta_{\tilde{t}}$, the "right-handedness" of the stop. From these distributions, one can see that most of the black points predict a stop LSP that is not purely right-handed, guiding my research to focus on the ad mixture stop LSP. Targeting the ad mixture stop is additionally convenient due to its preferred decays to a b-quark and charged lepton for reasons that will be made more clear in Sec. 5.1. For brevity, we will refer to the ad mixture stop as simply "stop" for the remainder of this thesis.

An unexpected result that can be found via the observation of a stop LSP is insight into the neutrino mass hierarchy. Briefly, this problem seeks to understand the mass ordering of the three neutrino mass eigenstates. Prior experimental results have yielded measurements of the magnitude of the mass splitting, but not the sign. This leads to the two potential scenarios shown in Fig. 2.12, where the "normal hierarchy" has the neutrino which is mostly electron-type as the lightest mass eigenstate and the smaller mass splitting

convention to note the scalar particles relationship to the chiral states of the SM top quarks.

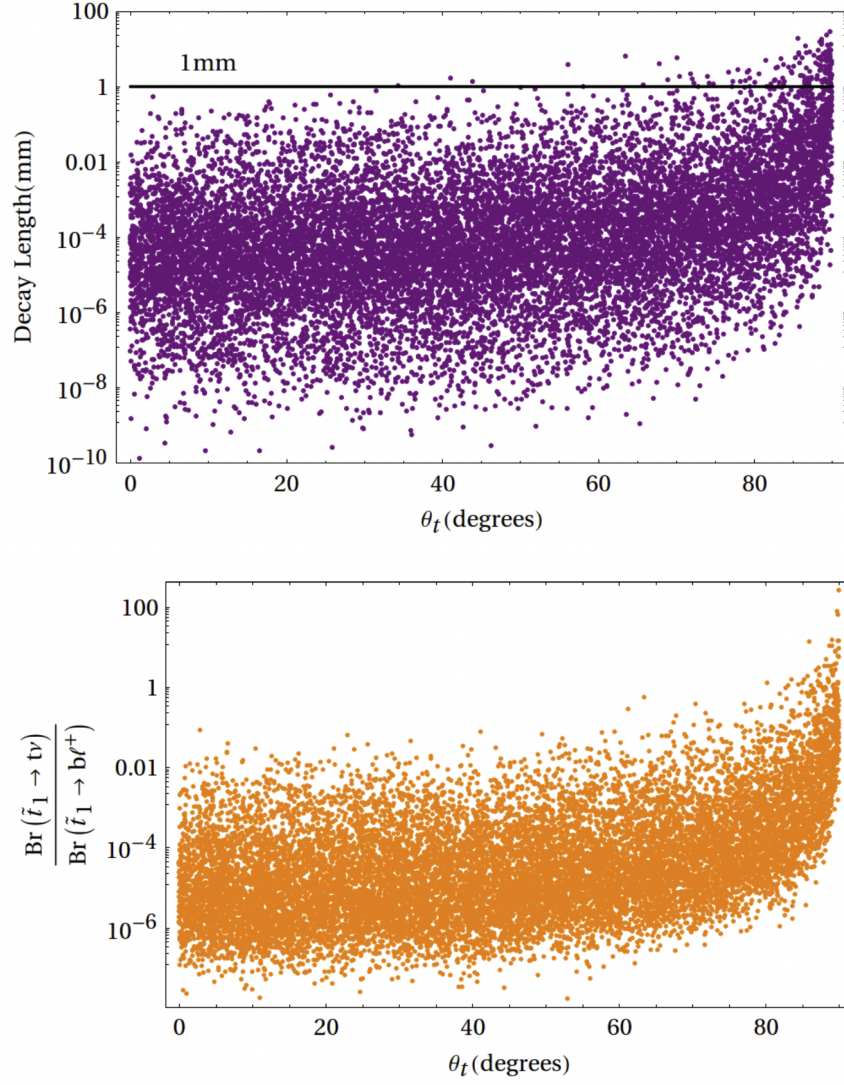


Figure 2.11: Top: distribution of predicted values for the stop decay length as a function of θ_t . Bottom: Ratio of $\text{BR}(\tilde{t} \rightarrow t\nu)$ to $\text{BR}(\tilde{t} \rightarrow b\ell)$ as a function of θ_t [25].

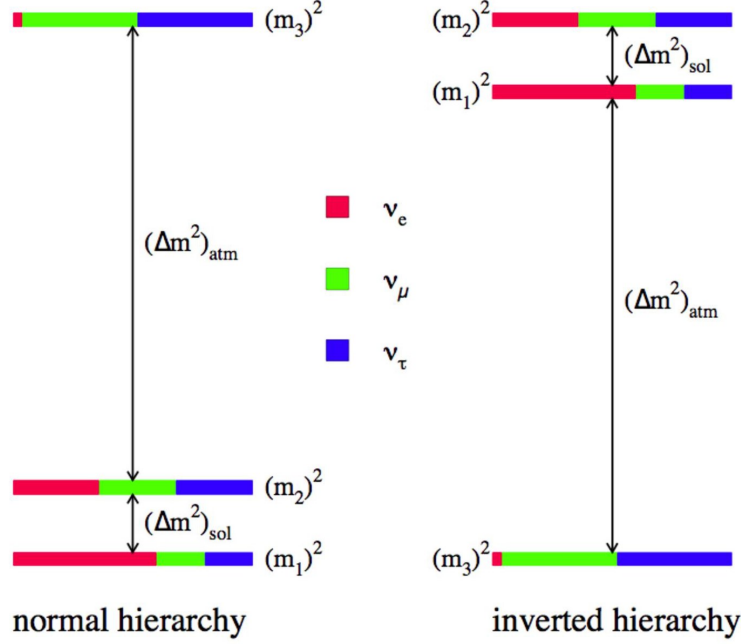


Figure 2.12: Diagram of the potential structures for the neutrino hierarchy. Left: Normal hierarchy where the small mass splitting is between the lowest two mass eigenstates. Right: Inverted hierarchy where the smaller mass splitting is between the higher mass eigenstates [28].

between the lightest two neutrinos and the larger splitting between the heavier two mass eigenstates. The "inverted hierarchy" flips this ordering, with the larger mass splitting between the lightest two neutrinos and the smaller splitting between the heavier. Due to the neutrino's involvement in the breaking of the $U(1)_{B-L}$, the branching fraction of the stop LSP is directly related to the neutrino hierarchy. One can see from Fig. 2.13 that the observation of a stop primarily decaying to a μ or τ would indicate the presence of a Normal neutrino hierarchy, while a preference for the electron decay channel would indicate an Inverted neutrino hierarchy. A lack of preference for a given decay channel, unfortunately, does not provide much insight into this problem as both hierarchy options are well represented in this phase space.

Over the course of my studies at the University of Pennsylvania, I have performed a dedicated search for the stop LSP scenario described above. The optimization and results of this analysis are described in immense detail in Chapter 5.

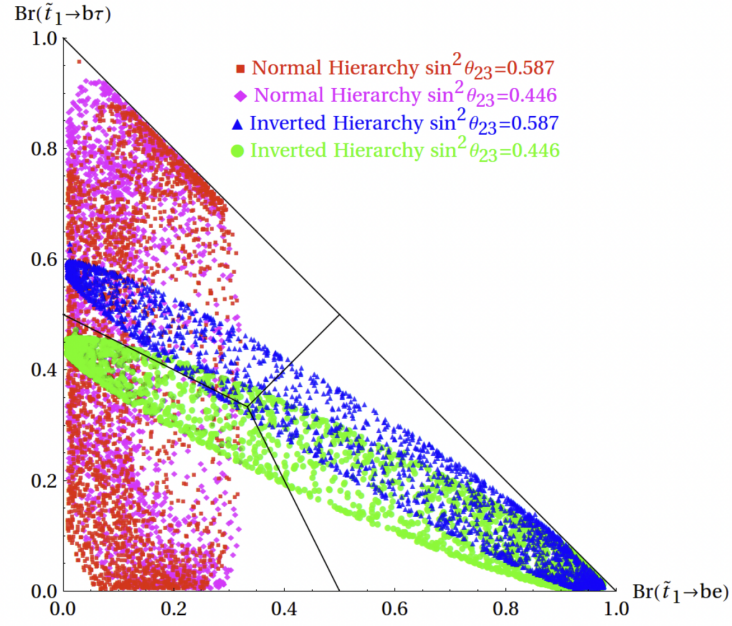


Figure 2.13: Distribution of stop branching fraction to each charged lepton. Points are divided based on the assumed neutrino hierarchy of the underlying theory as well as one of the neutrino mixing angles [24, 25].

CHAPTER 3

LHC and the ATLAS Detector

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [29] is a massive 27 km circular particle accelerator 170m below the Franco-Swiss border at the European Organization for Nuclear Research (CERN) campus outside of Geneva. Repurposing the tunnel built for the Large Electron-Positron Collider (LEP), the LHC is the highest center-of-mass energy hadron collider ever built. Unlike the electrons and positrons of LEP, the protons collided by the LHC are capable of achieving much higher energies in the same ring circumference due to their much higher mass suppressing bremsstrahlung (braking) radiation effects. There are four primary and independent experiments at four distinct interaction points along the LHC ring: ATLAS [30], CMS [31], LHCb [32], and ALICE [33]. ATLAS and CMS are two general purpose experiments designed for the discovery of the Higgs boson as well as searching for new physics beyond the standard model. By designing and operating two general purpose experiments, ATLAS and CMS are able to cross-check results and provide independent results without the need to construct a secondary accelerator facility of the LHC's scale. The LHCb experiment is designed to study the properties of b-hadrons and the ALICE experiment is designed to study the collisions of heavy ions. A diagram of the LHC ring, the accelerators which feed it, and the four primary experiments can be seen in Fig. 3.1. This dissertation will focus specifically on the ATLAS experiment in Sec. 3.2 as the dataset analyzed was produced from collisions within the ATLAS detector.

3.1.1 Acceleration

To collide protons, one must first create an isolated beam of protons; this is accomplished by ionizing hydrogen gas via the application of an electric field. The free protons are fed into the Linear Accelerator 2 (LINAC2), where they receive their first stage of acceleration bringing them to an energy of 50 MeV.

CERN's Accelerator Complex

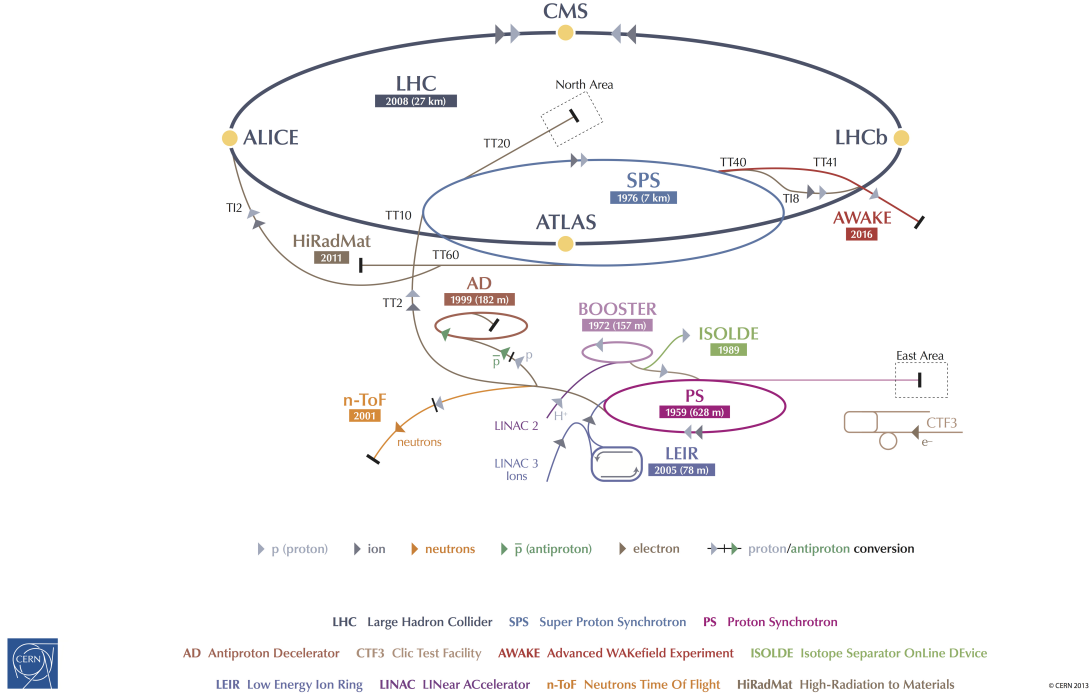


Figure 3.1: The LHC and the CERN accelerator complex [34]

The protons are then injected into a series of circular accelerators of increasing radius—the Booster, the Proton Synchrotron, and the Super Proton Synchrotron— which accelerate protons to energies of 1.4 GeV, 25 GeV, and 450 GeV respectively. From there, the protons are injected into the primary LHC where they receive their final acceleration to 6.5 TeV. By accelerating two distinct proton beams to 6.5 TeV, traveling in opposite directions around the primary LHC ring, the LHC is able to achieve a record-breaking center of mass energy of 13 TeV when colliding beams.

3.1.2 LHC Magnets

To achieve such high beam energies, the LHC relies on a complex series of magnets for focusing and directing protons beams on their path to collision sites. There are two main systems of superconducting magnets for directing proton beams: a series of 1232 dipole magnets for bending the trajectory of relativistic protons and 392 quadrupole magnets for focusing the proton beam as it travels the 27 km LHC ring. To maintain

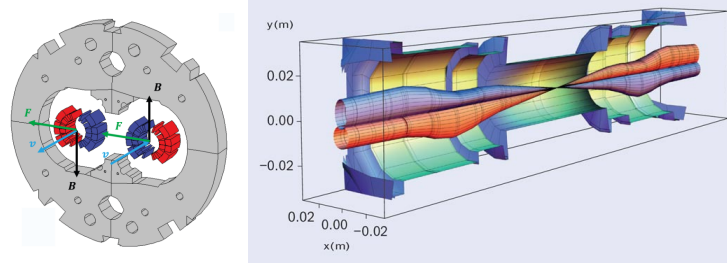


Figure 3.2: Left: Cross-sections of the LHC dipole magnets with polarity given in red and blue. Direction of B-field, particle velocity, and the resulting force are overlain [35]. Right: Beam envelopes near the interaction point 1 (the ATLAS detector). Beams are squeezed during the last 60 m on each side of the interaction point. The clockwise beam is shown in blue and the counter-clockwise given in red [36].

two beams of the same electric charge (+1 for protons) traveling in opposite directions, beams are separated into two distinct beampipes with their 8T local magnetic fields pointed in opposite directions. One can see from Fig. 3.2(a) that by flipping the direction of the B-field, same-sign beams traveling in opposite directions experience a magnetic force towards the center of the LHC ring. In the last 60 m as beams approach one of the four experimental interaction points, a series of three quadrupoles is used to focus the beams from their nominal transverse size to a beam spot of only $16 \mu\text{m}$. This series of magnets crosses the beams as shown in Fig. 3.2(b).

3.1.3 Bunch Structure and Pileup

Beams injected into the LHC ring are not individual, isolated protons but rather a series of small groupings of protons called "bunches." Each bunch is constructed from approximately 10^{11} protons in the Proton Synchrotron before being fed into the accelerator chain previously discussed. Bunches are injected with a steady time separation of 25 ns; the structure of these protons is designated a "bunch train." The nominal LHC filling scheme is given in Fig. 3.3. The nominal proton beam in the LHC consists of 2808 bunches per beam, or 3×10^{14} protons per beam.

Organizing protons in bunches provides both benefits and challenges to data analysis. For a given bunch crossing, there may be multiple proton-proton interactions; we refer to the non-unity number of interactions as "pileup." As pileup increases, the density of collisions per second increases, leading to increased complexity with identifying specific particle interactions. A series of event displays is given in Fig. 3.5 with each successive display adding stricter cuts on track transverse momentum, improving clarity. While introducing difficulties with particle identification, higher interactions per bunch crossing also allows the chance of observing much rarer physics processes previously unattainable without adequate statistics. For

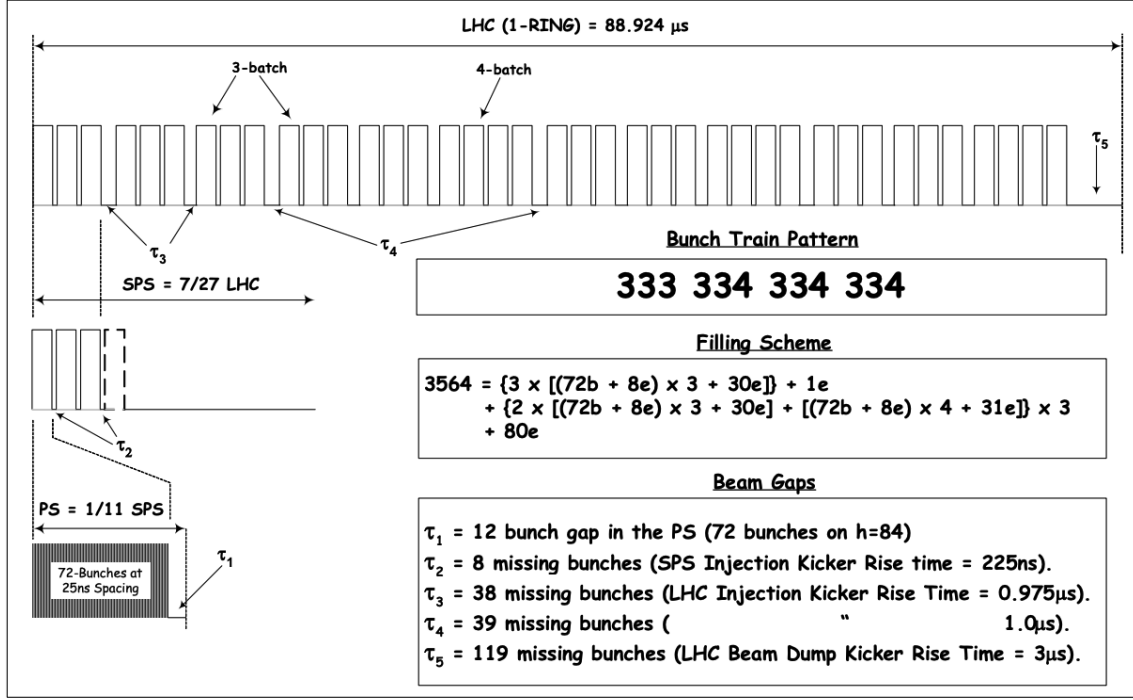


Figure 3.3: Diagram of the nominal bunch structure and filling scheme for the LHC with 25 ns spacing [37].

example, a hypothetical SUSY process might occur once per 100 million collisions on average. By increasing the rate of collisions, we decrease the time required to observe such a rare process. If we created a beam with one interaction per bunch crossing, we would get an extremely clear signal for analyzing, but the rate of data collection would be paltry. Naturally, one might suggest a continued increase in interactions per bunch crossing to reach extremely rare processes not yet observed, but this creates further technical challenges which will be described in further depth in Ch. 4. A histogram of recorded pileup, split by data collection year, is given in Fig. 3.4. For the Run 2 data collection period, ATLAS observed an average pileup of 33.7 interactions per bunch crossing.

3.1.4 Luminosity

Physicists define the concept of "Luminosity" to quantify the number of collisions observed by the LHC. Both instantaneous luminosity as well as integrated luminosity are used to understand the size of our dataset. Instantaneous luminosity measures the rate of data collection and is given in terms of either $\text{cm}^{-2}\text{s}^{-1}$ or inverse barns per second. A barn is a unit of area designed to describe the probability of a given collision or outcome (referred to as cross section). A barn is defined as 10^{-28}m^2 , roughly the cross-sectional area of

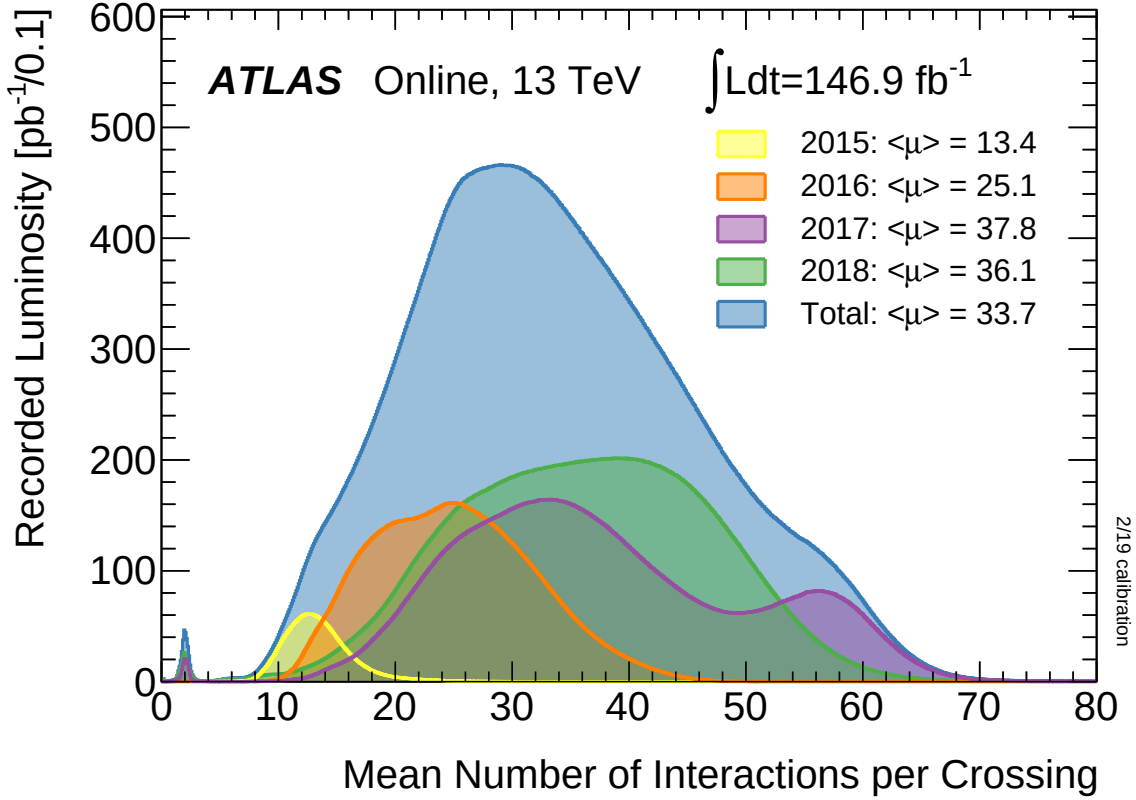


Figure 3.4: The luminosity-weighted pileup distributions split by data collection year. There was an observed pileup of 33.7 interactions per bunch crossing across the entire Run 2 data collection period [38].

a uranium nucleus. Further discussion of cross section and barns can be found in chapter 3.4 of Thomson's Modern Particle Physics [3]. We can observe the simple relationship of luminosity and cross section via the following equation:

$$N_i = \mathcal{L} * \sigma_i \quad (3.1)$$

where N_i is the expected number of events for a given process i , $\mathcal{L}$ is the integrated luminosity, and σ_i is the cross section of a given process. Instantaneous Luminosity is influenced by a number of beam-related factors and measured with:

$$\mathcal{L}_{inst} = \frac{N_1 N_2 f_{rev} \kappa \gamma}{4\pi \epsilon_n \beta^*} F \quad (3.2)$$

where N_1, N_2 are the number of protons for each bunch in the collisions, f_{rev} is the frequency of the beams (11.245 kHz), κ is the number of bunches per beam (2808), γ is the Lorentz Factor, ϵ_n is the emittance

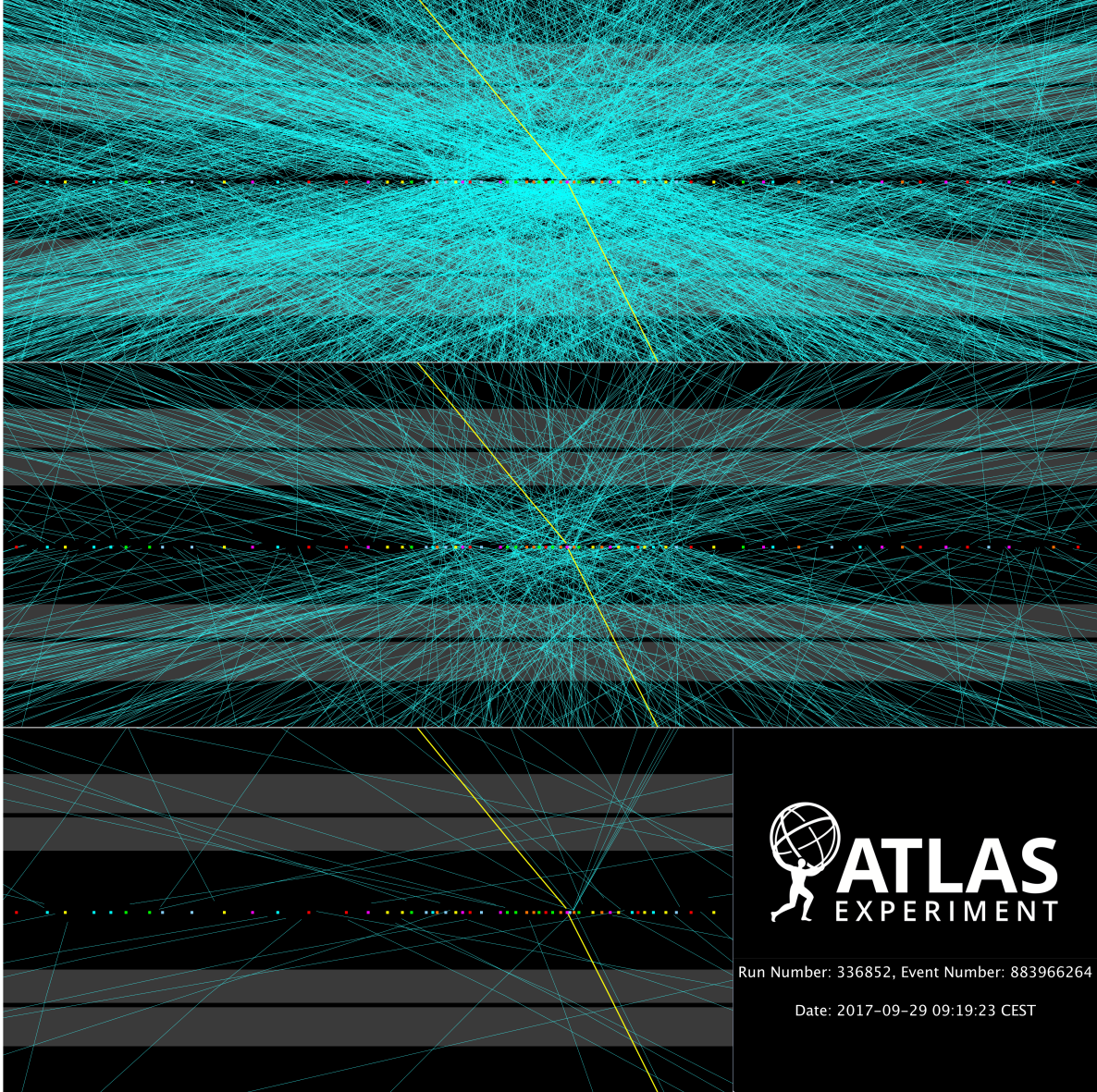


Figure 3.5: An event display for a candidate $Z \rightarrow \mu\mu$ event with an additional 65 reconstructed vertices from pileup pp collisions. The yellow lines represent reconstructed muons in the event while the cyan lines are additionally reconstructed tracks. Multi-colored dots represent the numerous reconstructed vertices. From top to bottom, an increasingly strict set of track p_T requirements are imposed: 100 MeV, 1 GeV, and 5 GeV [39].

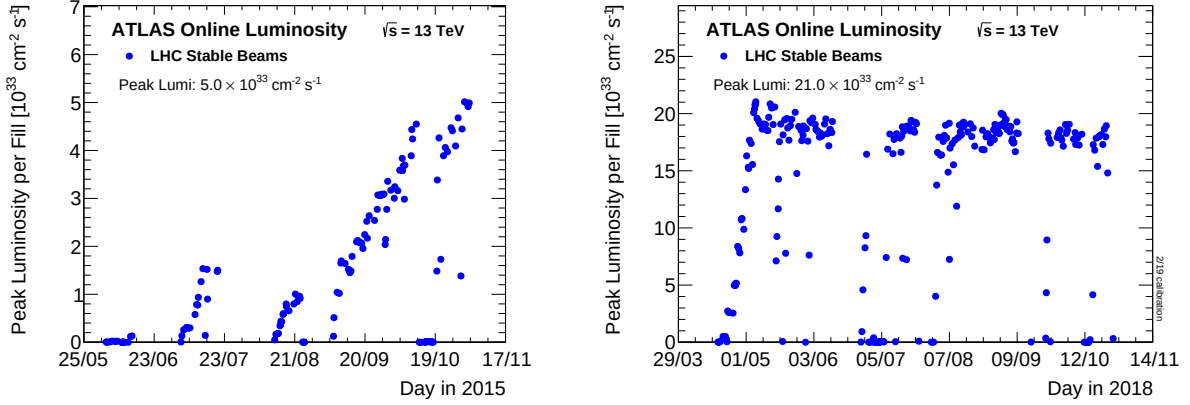


Figure 3.6: Peak instantaneous luminosity delivered to ATLAS during 2015 (left) and 2018 (right). A peak luminosity of $5.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ was recorded in 2015 and a peak luminosity of $21.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in 2018 [38].

of the beams, and β^* is the "squeeze" of the beams. The LHC was designed to produce an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for the ATLAS detector.

Integrated luminosity is exactly as the name implies: the integral of instantaneous luminosity over time:

$$\mathcal{L} = \int \mathcal{L}_{inst} dt \quad (3.3)$$

For the entirety of the Run 2 data collection period, the integrated luminosity of ATLAS data determined to be suitable for physics analysis was 140 fb^{-1} . Figures 3.6 and 3.7 show the peak instantaneous luminosity for select years as well as the recorded integrated luminosity for the data collection years. From the plots, one can see that the goals for peak luminosity were exceeded with a peak recorded luminosity of $2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

3.2 The ATLAS Detector

The ATLAS detector is a general-purpose particle detector located at one of the four main interaction points on the LHC ring (aptly named Point 1) [30]. The ATLAS detector is a massive 46 m long, 25 m wide, and 7000 metric tonnes in weight, making it the largest particle detector by volume in human history. The initial goal of the ATLAS detector was to discover and characterize the Higgs Boson, which was observed in July 2012.

ATLAS is comprised of numerous subdetectors, organized in layers, each designed for targeting distinct measurements for identifying particles. The Inner Detector lies closest to the interaction point and measures

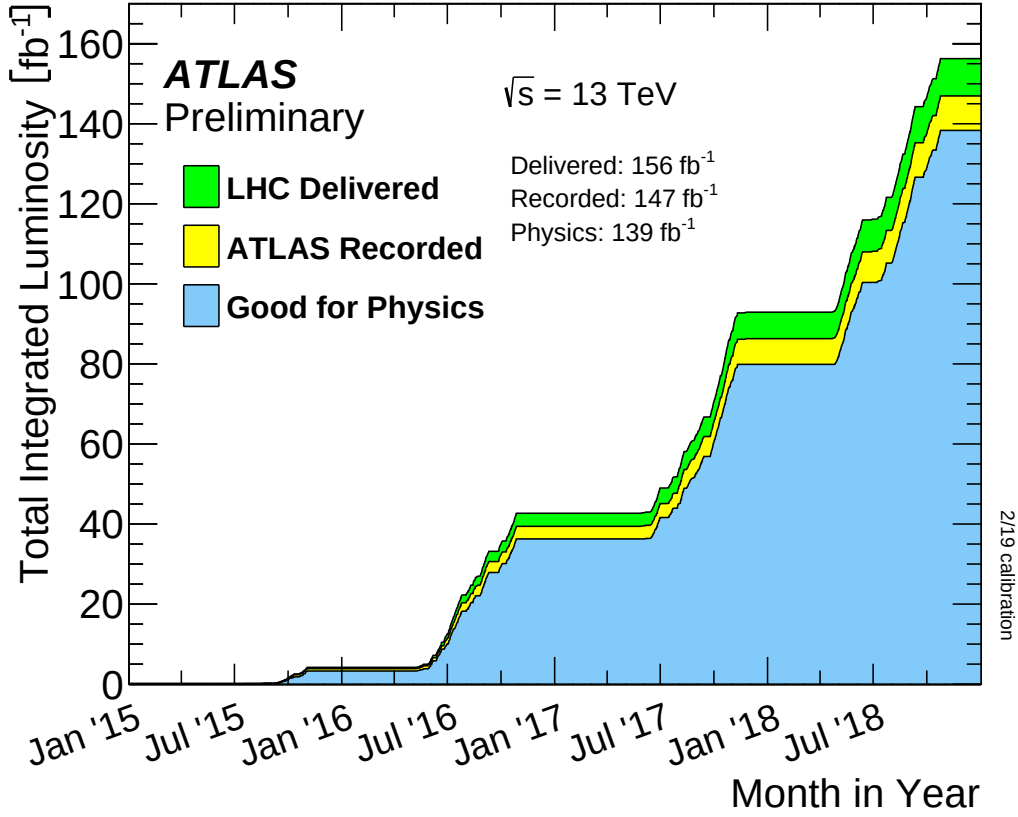


Figure 3.7: Integrated luminosity delivered across the Run 2 data collection period. The green area represents the total luminosity delivered by the LHC, the yellow is the total luminosity recorded by ATLAS, and the blue is the total luminosity determined to be suitable for physics analysis [38].

the trajectory and momentum of charged particles and is described in Sec. 3.2.2. The calorimeter system surrounds the Inner Detector and is used for measuring the energy of both electromagnetically interacting particles as well as strongly interacting particles; the calorimeters are discussed in Sec. 3.2.3. The Muon Spectrometer is the final, outer-most detector and is used for identifying and measuring the momentum of muons (described in Sec. 3.2.4). Together, these layers are able to perform snapshots of particle collisions, giving insight into fundamental laws they obey. A cut-away diagram of the ATLAS detector is given in Fig. 3.8.

3.2.1 Coordinates

The ATLAS Experiment utilizes a right-handed coordinate system where the origin is set to be the Interaction Point (IP) and Z-axis is defined to be the tangent to the beamline at the IP. Therefore, the X-Y plane gives

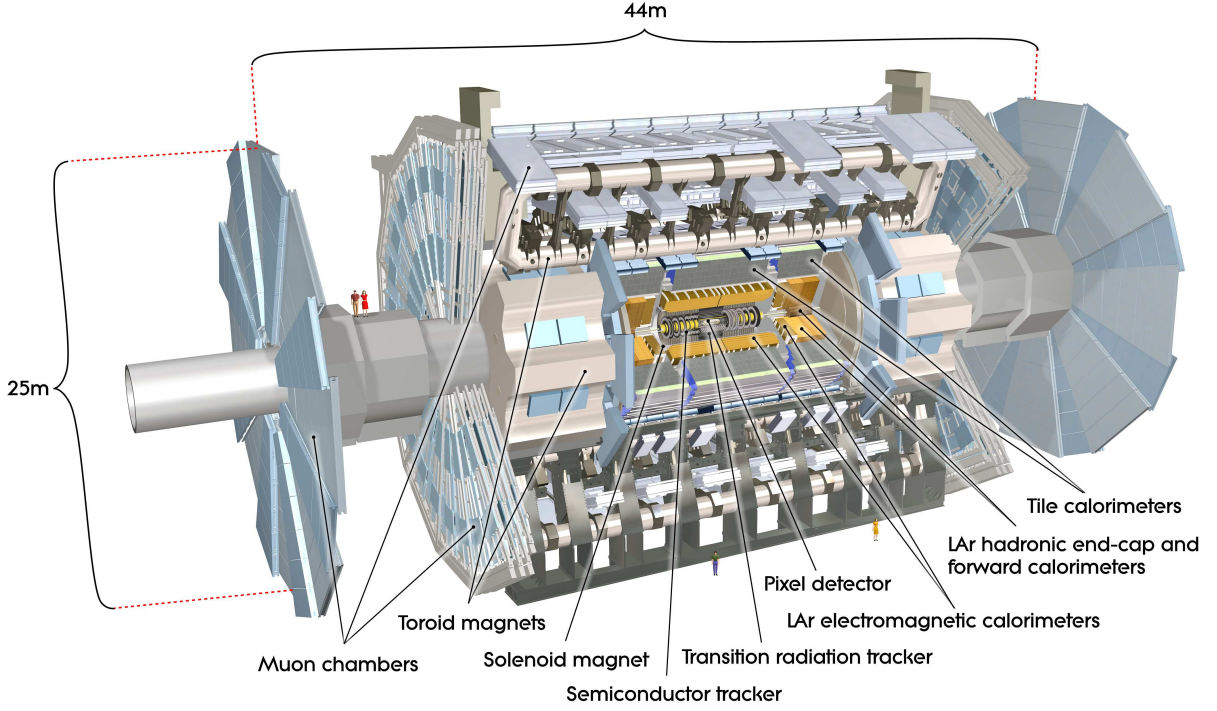


Figure 3.8: General cut-away view of the ATLAS detector [30].

a cross-sectional view of the accelerator. The X-axis is oriented to point from the IP to the center of the LHC ring while the Y-axis points upwards. The assignments of positive X and Y direction points the Z-axis towards Lake Geneva. Cylindrical Coordinates are employed where the azimuthal angle, ϕ , wraps the Z-axis while the polar angle, θ , describes the pitch of particles traveling from the IP. In this coordinate system, $\phi = 0$ points to the center of the detector and $\theta = 0$ points down the beamline in the positive Z-direction. Due to unknown boost of particles along the Z-axis, Rapidity (y) and Pseudorapidity (η) are typically employed instead of θ to preserve Lorentz Invariance of the chosen coordinate system. We define the rapidity of a given particle as $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ and the pseudorapidity as $\eta = -\ln(\tan \theta/2)$. These two definitions are equivalent when either a given particle is massless or the particle's energy is orders of magnitude larger than its mass (the massless limit), as is typically the case with the LHC. In this coordinate system, angular distance is defined as $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. The transverse momentum (p_T) is defined to be the component of a given particles momentum in the transverse (x-y plane) direction to the beams. Given that objects measured by the ATLAS detector are observed and characterized by their energy and trajectory, we often express information about an object in terms of its four-momentum. As demonstrated in Eq. (3.4),

the four-momentum of an object can be completely described using the measured η , ϕ , p_T , and Energy (E). This coordinate system preserves Lorentz Invariance.

$$\begin{aligned} p_x &= p_T \cos \phi \\ p_y &= p_T \sin \phi \\ p_z &= p_T \sinh \eta \end{aligned} \tag{3.4}$$

3.2.2 The Inner Detector

The Inner Detector (ID) is the closest detector to the Interaction Point and is designed to measure the trajectories of electrically charged particles passing through it. The inner detector is submerged in a massive 2T magnetic field provided by the large central solenoid. Through the measurement of trajectory of charged particles, we are capable of measuring the direction, momentum, and electric charge of charged particles emitted from the Interaction Point. In addition to measuring charged particles, the ID is capable of precision vertexing, allowing the ability to separate collisions of interest from pileup as well as identify displaced vertices for identifying jets initiated by b-quarks.

The ID consists of three main subdetectors (listed in order of closest to farthest from the IP): the Pixel Detector, the Semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT). A schematic of these detectors can be seen in Fig. 3.9. Detectors closest to the beamline require the finest granularity due to the higher density of particles per unit surface area. Due to limitations in both readout bandwidth and budget, subdetectors further from the interaction point have coarser granularity. For these reasons, the inner most layer of the ID is comprised of pixels, while the outermost layer (TRT) uses a coarser set of straws. A cross section of the Inner Detector can be seen in Fig. 3.10.

3.2.2.1 Pixel Detector

The innermost subdetector of the ID is the Pixel detector which uses silicon pixel sensors to provide fine granularity tracking of charged particles. The Pixel Detector is split into two main regions: the Barrel Region and the Endcap region. The barrel region of the pixel detector is cylindrically shaped and covers the beamline for the region of $|Z| \leq 400.5\text{mm}$. The barrel region is comprised of 4 layers between a distance of $R = 33\text{mm}$ to 149.6mm from the beamline. The inner-most layer of the barrel region is the Insertable B-Layer (IBL) and was implemented before the start of the Run 2 data collection period. The addition of the IBL improved the measurable radius from 50mm to 33mm from the IP, allowing for more precise measurements of heavy-flavor jets.

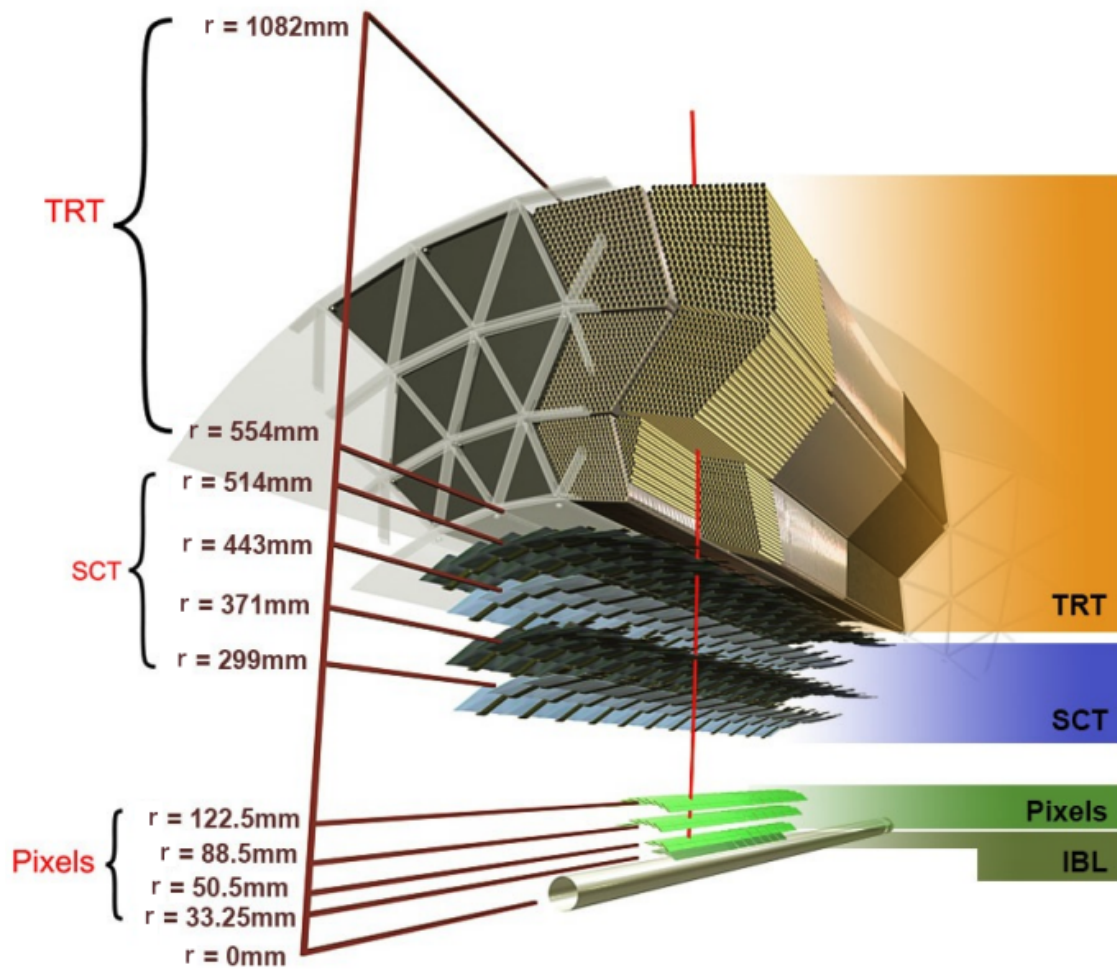


Figure 3.9: The Inner Detector barrel sub-systems [40]

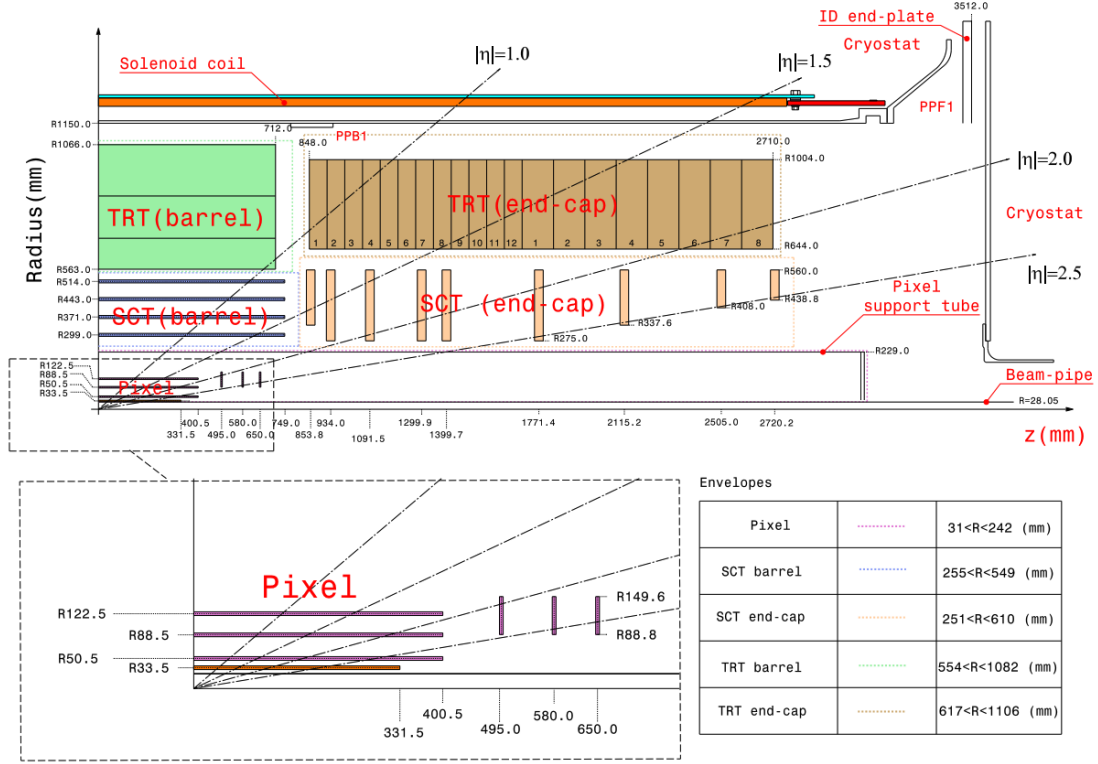


Figure 3.10: Schematic of the Inner Detector [41]

The endcap region is comprised of three disks on both ends of the barrel region with the beamline passing through the center of each disk normal to the surface. The rings of the barrel region are found at $|Z| = 495, 580, \text{ and } 650$ mm with an inner diameter of 88.8mm and an outer diameter of 149.6mm. In conjunction, these regions provide coverage up to $|\eta| \leq 2.5$. Each layer is comprised of multiple modules which are made up of both silicon pixel sensors and readout electronics.

Each layer of the pixel detector is divided into modules, which each contain silicon pixel sensors as well as readout electronics. As charged particles pass through a pixel sensor, they locally ionize the silicon, producing an electrical signal which can be interpreted by readout electronics. A signal from a given sensor is deemed a "hit," which can be sent off-detector via readout electronics to high accuracy particle tracking. The thickness of each pixel sensor is $250 \mu\text{m}$ while the surface dimensions of pixels in the IBL are 50 by $250 \mu\text{m}$ and 50 by $400 \mu\text{m}$ in the rest of the layers. In total, this subdetector contains a massive 92 million individual pixels.

3.2.2.2 Semiconductor Tracker

The semiconductor tracker (SCT) subdetector surrounds the pixel detector from a radius of $R = 275\text{mm}$ to $R = 560\text{mm}$. Given its placement at a larger distance from the IP, the SCT must cover a much larger overall surface area than the pixel detector. To avoid the ballooning costs and increased computational demands of covering a larger surface area with individual silicon pixels, the SCT is comprised of thin, longer, rectangular strip sensors. These sensors rely on the same underlying physics as the pixel detector, but cover a larger surface area per sensor. While this shift to strips gives a coarser granularity, we expect the density of incident particles on the sensors to be lower at higher distances from the interaction point.

Similar to the pixel detector, the SCT is divided into barrel and endcap regions. The barrel region of the SCT is comprised of four cylindrical layers, with the strip sensors oriented to provide finer granularity in the ϕ direction; that is, the longest side of the strip sensor is parallel to the Z-axis. Strips in the barrel region are $80\mu\text{m}$ by 63.96mm . Strip sensors in the nine endcap disks on each side are arranged radially like bike spokes and vary in size from 56.9 to $90.4\mu\text{m}$ wide by 54.4 to 65.1mm long. To improve spatial resolution in the barrel region, each layer of strips is comprised of two back-to-back strip sensors with a slight angular offset of 40 mrad . In total, the SCT has 15,912 sensors each comprised of 768 strips, leading to 6.4 million readout channels.

3.2.2.3 Transition Radiation Tracker

The outer-most subdetector of the Inner Detector is the Transition Radiation Tracker (TRT). The TRT is the only subdetector of the ID to not use silicon sensors for particle tracking. In lieu of silicon, the TRT utilizes a series of 352,256 drift tube straws of radius 2mm . The exterior of each straw is made of polyimide and filled with a xenon or argon based gas mixture (70% Ar/Xe, 27% CO_2 and 3% O_2). A tungsten wire runs through the center of each straw and is set as the ground reference point while the walls are held at a relative 1530 Volts. Charged particles passing through a straw ionize the gas mixture inside, causing freed electrons to drift towards the inner wire while ions drift towards the outer wall. In the strong electric field close to the wire, electrons rapidly gain sufficient energy to ionize more of the gas, resulting in an avalanche effect which amplifies the signal by a factor of 20,000. In the barrel region, the TRT covers a radius of $R = 563\text{ mm}$ to 1066 mm with the 54,544 straws oriented parallel to the beamline. Each straw is 144 cm length to cover the range $|Z| \leq 712\text{ mm}$. The 122,880 straws in each endcap region are oriented radially, like the strips in the end-cap SCT modules, for tracking particles within $|\eta| \leq 2.1$. The endcap TRT modules span from $|Z| \geq 848\text{mm}$ to $|Z| \leq 2710\text{mm}$.

In addition to tracking charged particles, the TRT aids in the identification of electrons. By placing

3 mm thick layers of polypropylene-polyethylene fiber between each straw, we can induce the production of transition radiation photons from particles changing media with different indices of refraction (n). The radiated photons can also travel through a straw and ionize the gas, creating a signal much larger than the particle it was radiated from. We can therefore separate hits in the TRT between whether they exceed a low threshold energy of about 300 eV or a high threshold energy of 6000-7000 eV. Hits which exceed the low threshold (LT) but not the high threshold (HT) are likely a particle passing through and this information can be used for reconstructing tracks. Hits which pass the high threshold are likely the result of transition radiation. The probability of producing transition radiation is proportional to the Lorentz factor (γ) of the incident particle. Due to the electron having a much lower mass than other commonly produced particles in ATLAS, such as pions, they are significantly more boosted and therefore more likely to produce transition radiation in the TRT. This higher probability can be exploited to improve the capability of identifying electrons.

3.2.3 The Calorimeters

ATLAS includes two types of calorimeter systems for measuring the energy of incident particles: the Liquid Argon (LAr) calorimeter for measuring electromagnetic showers and the Tile Calorimeter (TileCal) for measuring hadronic activity. In conjunction, these two calorimeters measure the energy of all SM particles except for muons and neutrinos, providing coverage for the region $|\eta| < 4.9$. Both calorimetry systems utilize alternating layers of absorber materials to induce particle showers and active layers for measuring shower energy. A diagram of the calorimeter system can be found in Fig. 3.11.

3.2.3.1 Liquid Argon Calorimeters

The Liquid Argon (LAr) calorimeter (also referred to as the Electromagnetic calorimeter, or ECal) is the inner of the two calorimeters and is used to measure the energy of particles interacting primarily via the electromagnetic force, such as electrons, positrons, and photons. The LAr calorimeter is made of layers of liquid argon (the active material) and lead (the absorbing material) arranged in an accordion-like geometry. This geometry ensures there is no path a particle can take and escape unchallenged through a "crack" in the absorbing material while preserves rotational symmetry in ϕ . Lead performs well as an absorbing layer due to the high electric charge of its nucleus, which causes electrons to slow down and emit bremsstrahlung radiation. The photons from this emission then create electron-positron pairs, which repeat the process, creating a "shower" of particles in the calorimeter.

Throughout the showering process, the charged particles ionize the liquid argon and energy is deposited

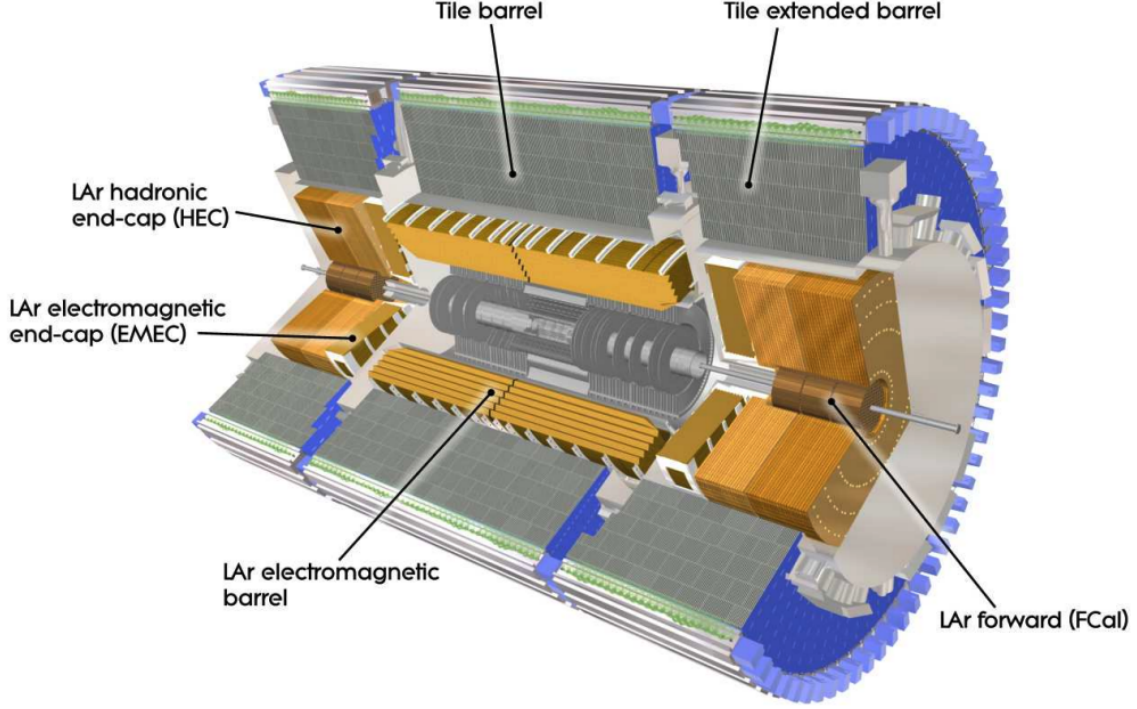


Figure 3.11: Cut-away view of the ATLAS calorimeters [30]

in the active LAr layers. The dimensions of the ECal are determined to best stop incident electrons, photons, and positrons in addition to fully contain and measure the energy of their associated showers. We define a radiation length (χ_0) to be the average distance in which an incident electron or photon's energy is reduced by a factor of $1/e$. A radiation length is unique to a given material and depends primarily on the material's atomic number: Z . In the case of lead, the radiation length is 0.56cm. To ensure the showers of the highest energy incident electrons are adequately captured in the ECal, the calorimeter has a depth of at least $22\chi_0$ in the barrel and a depth of at least $24\chi_0$ in the endcap layers.

3.2.3.2 Hadronic Calorimeters

The TileCal surrounds the ECal in the barrel region from $R = 2.28\text{m}$ to $R = 4.25\text{m}$, providing coverage for $|\eta| < 1.5$. While the ECal measures the showers of particles decaying electromagnetically, the Tile Calorimeter measures the energy of hadronic showers of particles interacting via the strong force. The

TileCal is comprised of three layers of depths 1.5, 4.1, and 1.8 hadronic interaction lengths sequentially. We define the hadronic interaction length (λ) as the expected distance a hadron must travel before a nuclear interaction occurs. Much like how we previously defined a radiation length, interaction length depends both on the absorbing material as well as the incident hadron. For pions in lead or iron, the interaction length is approximately 20cm (Much larger than the radiation length of electrons in the same material). Given the similar interaction length, but differing density and thus mechanical engineering cost of supporting the calorimeter, steel is chosen as the absorbing material in the hadronic calorimeters with plastic scintillating tiles as the active material. The first two of these layers provides granularity of $\Delta\eta x \Delta\phi = 0.1 \times 0.1$ with the outermost layer providing a granularity of $\Delta\eta x \Delta\phi = 0.2 \times 0.1$

There are two additional calorimeters which complement the TileCal: the Hadronic Endcap Calorimeter (HEC) and the Forward Calorimeter (FCal). The HEC covers the region of $1.5 < |\eta| \leq 3.4$ and utilizes copper as the absorbing material with liquid argon for the active layer. The first of the endcap wheels is aligned with the Inner Detector and provides a resolution of $\Delta\eta x \Delta\phi = 0.1 \times 0.1$ while the second wheel provides a coarser resolution of $\Delta\eta x \Delta\phi = 0.2 \times 0.2$. The Forward Calorimeter covers $3.1 < |\eta| < 4.9$ and consists of three layers, with the first utilized for EM calorimetry and the proceeding two for measuring hadronic activity. The first layer utilizes copper as the absorber with the outer two layers using tungsten. Liquid Argon is used as the active material for this entire calorimeter due to increased radiation hardness requirements in the forward direction. Both the HEC and the FCal provide a hadronic depth of 10λ , with a depth of $26.7\chi_0$ in the first layer of the FCal.

3.2.4 The Muon Spectrometer

The outermost layer of the ATLAS detector, the Muon Spectrometer (MS), is designed to measure the momenta of particles which were able to penetrate both of the previous calorimeters. Muons in particular are able to escape the calorimetry layers as their large mass ($200\times$ that of an electron) means they lose less energy via bremsstrahlung radiation, which scales inversely by a factor of mass squared. This decrease in braking radiation by a factor of $40,000\times$ when compared to electrons necessitates the construction of a dedicated muon subdetector. The Muon Spectrometer is the largest apparatus by volume, surrounding the entire ID and Calorimetry system and provides measurement capabilities within $|\eta| \leq 2.7$. Similar to prior subdetectors, the MS is split between a barrel region up to $|\eta| \leq 1.05$ and an endcap region from there covering up to $|\eta| \leq 2.7$. The muon spectrometer is immersed in a strong magnetic field (1T in the barrel and 0.5T in the endcap) provided by a system of toroidal magnets in the barrel and a large endcap toroid on each side of the Interaction Point. Muons passing through the toroidal B-field are deflected. In combination

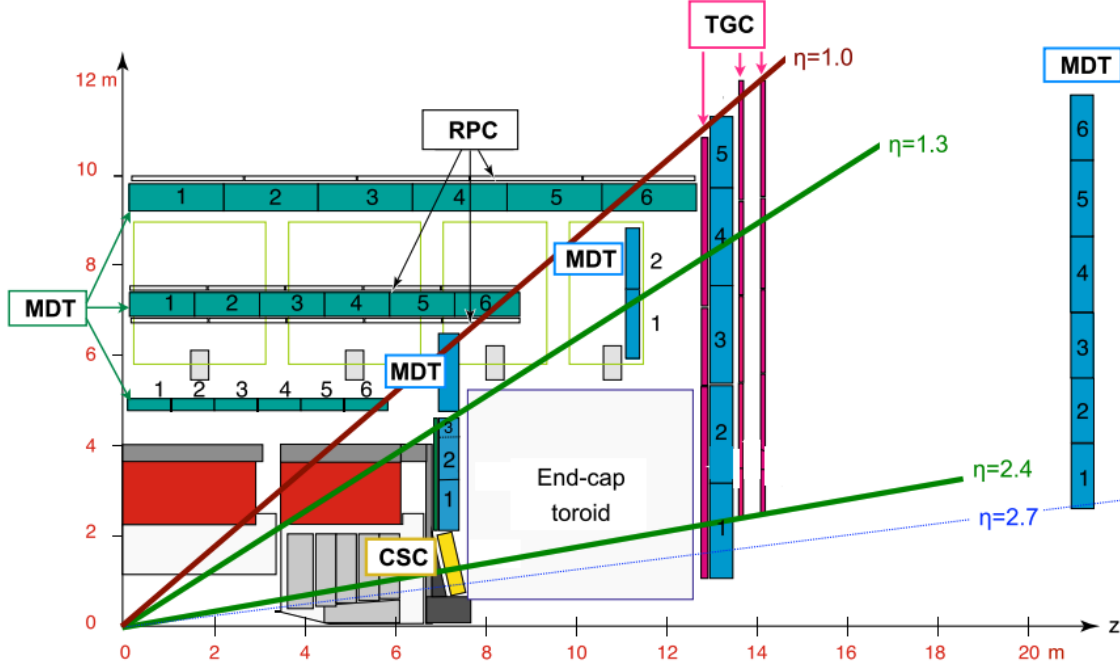


Figure 3.12: Schematic of the ATLAS muon system [30]

with the inner detector, the Muon Spectrometer allows the measurement of muon p_T within 3%.

The Muon Spectrometer uses two main detector technologies for measurements: Monitored Drift Tubes (MDTs) and Cathode Strip Chambers (CSCs). The MDTs work much like the previously discussed straws in the TRT: They are tubes filled with an ionizable gas (argon in this case) and contain a thin tungsten wire which runs through the center of the tube, kept at a high potential difference (3 kV) to the tube walls. The Cathode Strip Chambers work very similarly to straws, except they provide two-dimensional measurements. CSCs use a series of chambers with cathode strips placed perpendicular to a series of anode wires and filled with $\text{Ar-CO}_2\text{-CF}_4$ gas mixture. As a muon passes through one of the chambers, it ionizes the gas inside causing electrons to drift towards the anode wires while the ions drift towards the cathode strips. The combination of these two measurements allows precise spatial and timing measurements of muons.

In addition to the MDTs and CSCs, there are two detector technologies in the Muon Spectrometer system used for triggering: Resistive Plate Chamber (RPCs) and Thin Gap Chambers (TGCs). Resistive Plate Chambers cover the region $1.05 < |\mu| < 2.7$ with triggering capabilities up to $|\eta| < 2.4$. The RPCs are sheet capacitors with small 2mm gaps filled with $\text{C}_2\text{H}_2\text{F}_4$. As muons pass through and ionize the gas, the resulting freed electrons are read out on both sides of the detector. The TGCs work much like the CSCs, using a gold plated tungsten wires and $\text{CO}_2 - \text{C}_5\text{H}_{12}$ filling the chamber. The Thin Gap Chambers cover

the barrel region for $|\eta| < 1.05$ and provides high precision timing information up to 4ns. In conjunction with the MDTs and CSCs, these chambers can provide identification of bunch crossings and provide precise measurements of the coordinates not covered by the MDTs and CSCs.

3.3 The ATLAS Trigger System

There are many technical details that arise with in the acquisition and recording of data from particle collisions. As described prior, protons bunches are separated with a 25ns spacing, leading to a collision frequency of 40 MHz. To write a given event out to disk requires approximately 1.5 MB, leading to a hypothetical data transfer rate of 60 TB/s if we were to send all data off detector for physics analysis. The offline storage capability of CERN as well as bandwidth limitations constrain the rate and total number of collisions that are practically saved. A series of data filters, called Triggers, is used to take the 40 million events per second down to 2000. This corresponds to a bandwidth of 3 GB/s, down by a factor of 20,000. While this may seem alarming that ATLAS is throwing away over 99% of collisions, the primary goal of ATLAS is to search for extremely rare processes, allowing us to design triggers which target only the most interesting and rare observations.

ATLAS utilizes a two-level trigger system split based on when and where triggering occurs. Real-time triggering, referred to as "online" or "Level 1" triggers, is performed on-detector with a series of application specific integrated circuits (ASICs) in order to reduce the data bandwidth from 40 MHz to 100 kHz. The L1 triggers uses information from the calorimeter systems as well as the muon spectrometer in order to identify collisions with Regions of Interest (RoIs). Events which pass an online trigger are passed to a software-based "offline" set of triggers called high-level triggers (HLT). The HLT utilizes both the inner detector and the RoIs previously defined by the L1 triggers to make determinations on which events are worth accepting and writing to disk. The full set of triggers is referred to as the "trigger menu" and is carefully determined before each data collection period based on the physics needs of research within ATLAS.

3.4 Object reconstruction

Once information from individual subdetectors is stored, we look at the results in aggregate to piece together the physics process responsible for signature left in ATLAS. The process of taking hits in the trackers and energy deposits in the calorimeter to identify the particles responsible is dubbed "Reconstruction." The layers of the ATLAS detector are very intentionally designed such that common SM particles each leave unique, identifiable signatures in the detector. This can be seen from Fig. 3.14 which depicts the interactions of

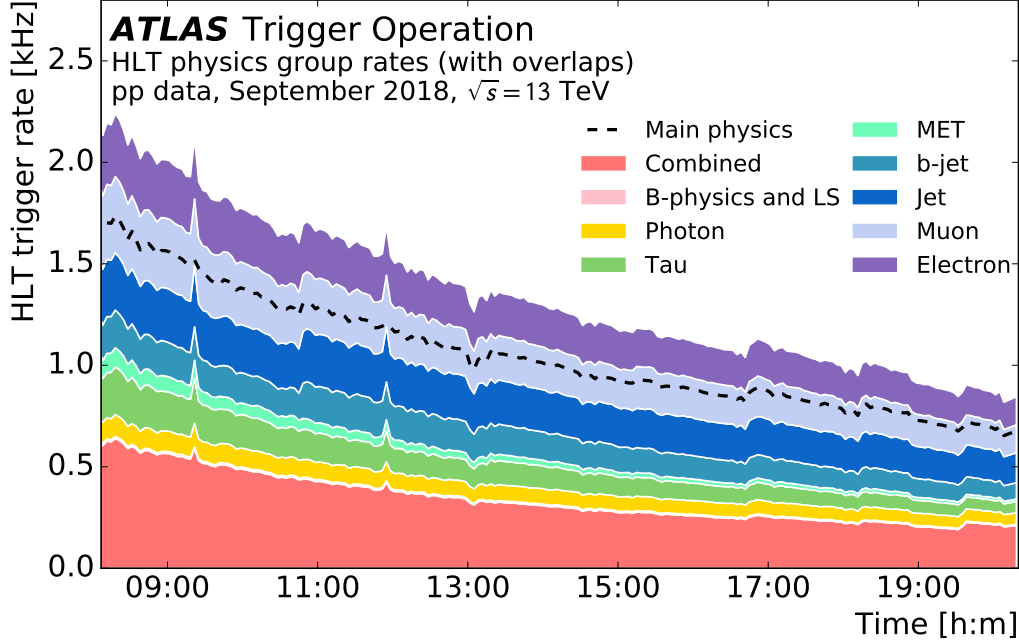


Figure 3.13: The HLT trigger rates for various targeted physics processes as a function of time. Each color represents the collection of both single-object and multi-object triggers. The "combined" trigger rate represents multi-object triggers with objects from two or more of the other specified groupings [42].

several particles as they pass through the ATLAS detector.

The EM Calorimeter, as previously described, is designed to fully stop incident electrons and photons while most other particles will "punch through" this layer. Therefore, by looking at showers fully contained within the ECal, one can reasonably identify those deposits as being left by an electron or a photon. Showers which can be matched to a track in the ID are then identifiable as electrons, as the photon does not leave ID tracks due to its lack of charge. Muons will leave tracks in the ID much like the electron, however, they will not be stopped by either of the calorimeters. With the aid of the Muon Spectrometer system, we can identify muons by matching tracks in the ID to tracks in the MS.

"Jets" of particles are created by hadronization of quarks due to color confinement, as described in Sec. 2.1.1. These jets are primarily constructed of hadrons and thus deposit large amounts of energy primarily into the HCal system, though neutral pions have an electromagnetic decay to two photons and leave energy in the ECal. It is often impossible to identify the initial color-sensitive particle responsible for the jet. However, b-quark initiated jets tend to have a displaced vertex (where the reconstructed tracks from the charged particles from the decay of the b-hadron appear to originate from a point displaced from the primary

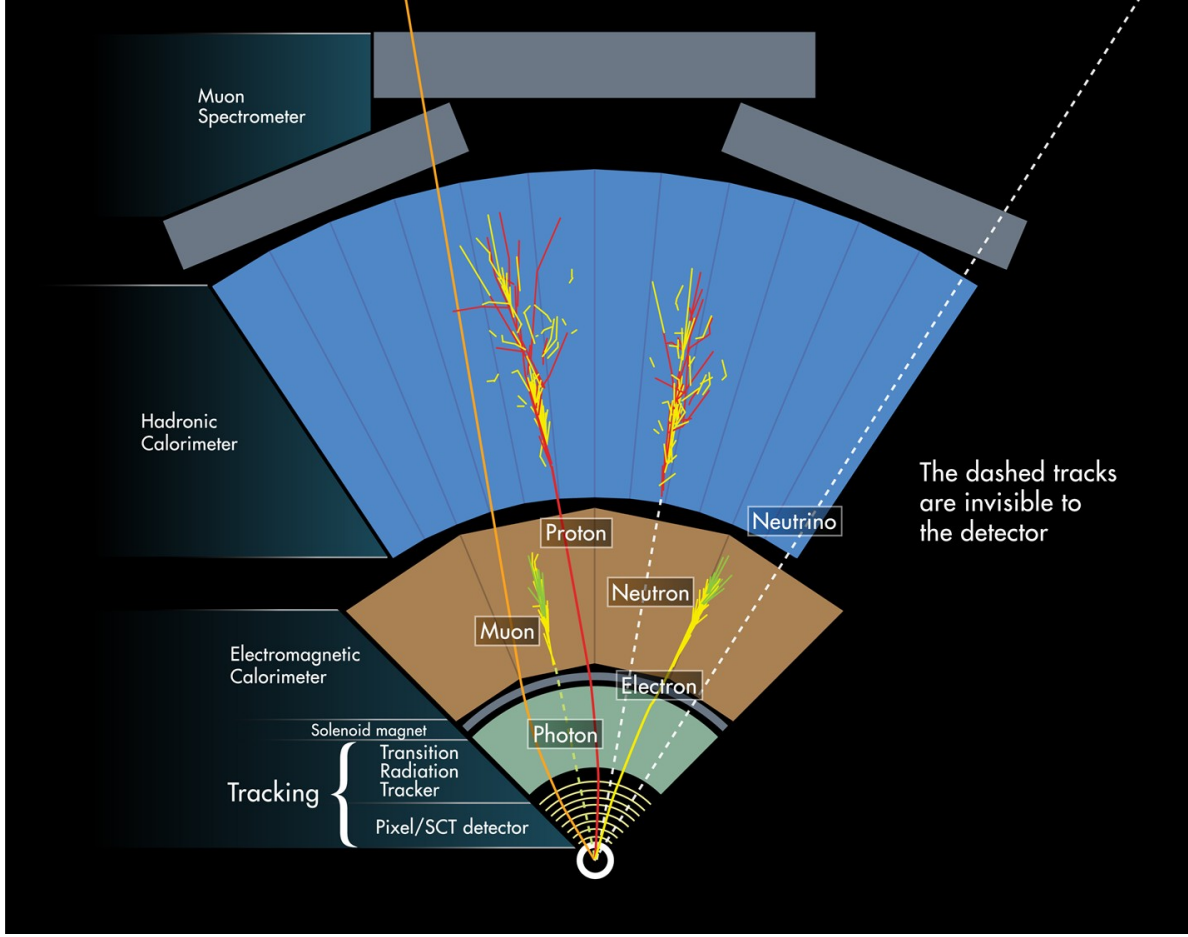


Figure 3.14: Schematic of the detector signatures left by various Standard Model particles in the ATLAS detector [43]

collision vertex) due to the lifetime of their associated b-hadrons (approx. 1 mm).

The final identification object, MET, isn't really an object, but is instead the lack thereof. Due to the beams being oriented in the z-direction, the initial transverse momentum is expected to be zero. The conservation of momentum therefore implies the final transverse momentum should be zero, necessitating that once all particles have been identified and measured, we should expect the vector sum of p_T to be zero. However, particles which do not interact with the detector, such as neutrinos or long-lived neutral BSM particles, will carry momentum out of the detector to never be directly measured. We summarize the contributions of these non-interacting particles with the variable E_T^{miss} , which is calculated as the additional p_T required to achieve balance, or $-\Sigma p_T$.

Once particles are identified in individual events, physics analyses are able to apply selection criteria on

the objects present to isolate potential signal events. Through extensive optimizations, these criteria become highly efficient for both identifying signal and rejecting background events. The goal is to find evidence of new fundamental particles of nature or make high-precision measurements of the SM. In the absence of evidence for new physics, limitations are set on the properties of new physics particles including particle mass, production rate, and decay mode. This general approach forms the basis for the B-L stop search and will be described in Chapter 5.

CHAPTER 4

The High-Luminosity LHC Upgrade

4.1 High Luminosity LHC Motivations

In the search for rare physics processes, two main factors define one's search capabilities: luminosity and center-of-mass energy. Center-of-mass energy dictates the production cross-section for each process and allows processes to shift from being off-shell to on-shell. Luminosity, as previously described, measures the quantity of data collected. These can be succinctly understood as defining the probability for a given process to occur and the number of dice rolls performed. The LHC was initially designed to run at a maximum center-of-mass energy of 14 TeV, of which it obtained a CoM energy of 13 TeV for the duration of Run 2 and 13.6 TeV for the start of Run 3. Over the course of Run 2, 140 fb^{-1} of data was collected and deemed suitable for analysis with an additional 300 fb^{-1} of data expected to be collected during Run 3. While the maximum CoM beam energy has been nearly attained, an increase in the collision rate will dramatically improve analyses by both increasing the number of hypothetical particles produced at ATLAS as well as decreasing observed statistical uncertainties on measurements.

The High Luminosity Large Hadron Collider (HL-LHC) is designed to increase the number of collisions per bunch crossing from $\langle\mu\rangle = 33.7$ to approximately $\langle\mu\rangle = 200$ [44]. This increase in collisions per crossing will lead to an overall increase in instantaneous luminosity from $2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and allow the collection of 300 fb^{-1} (the entirety of Run 3) in just the first year of data collection. The planned increase to instantaneous luminosity poses two primary hardware challenges to tackle: having fine granularity and fast readout capabilities to keep up with the increased information density as well as ensuring electronics are capable of accurately operating under high radiation doses. To facilitate these goals, the Inner Detector (described in Sec. 3.2.2) will be entirely replaced as part of the HL-LHC upgrade plan [45]. For this dissertation, I will focus on its replacement, the Inner Tracker (ITk), as it was the focus of my hardware-

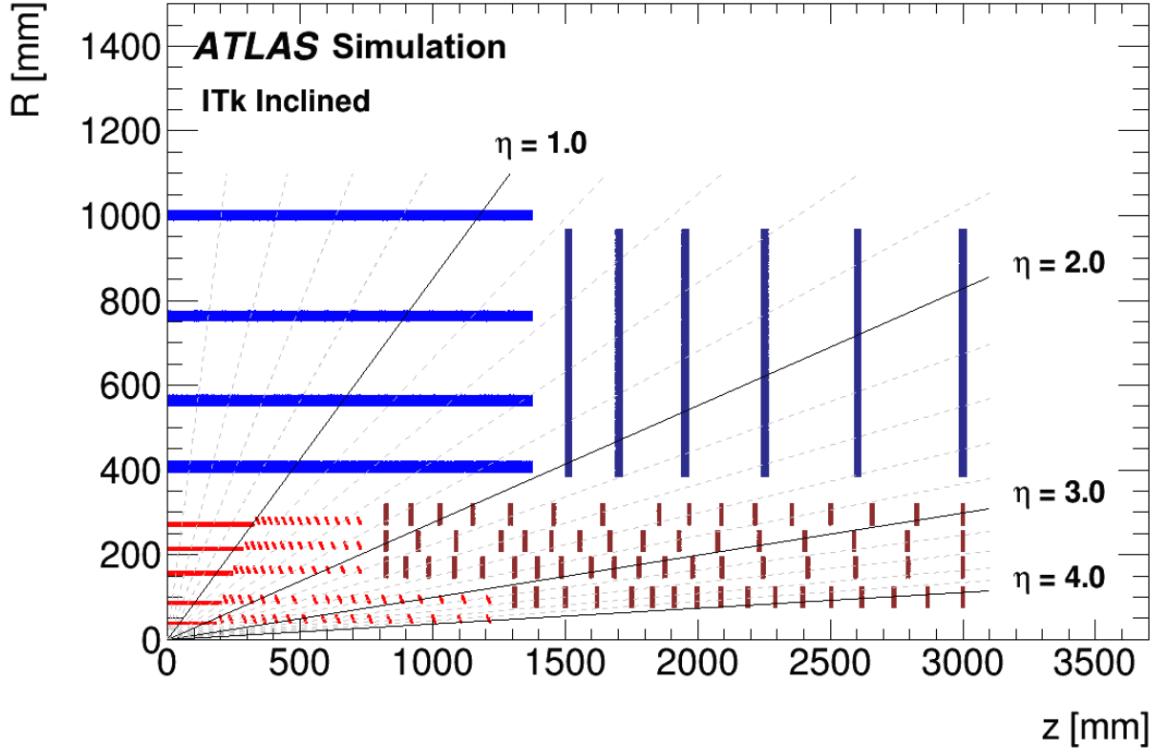


Figure 4.1: Schematic of the Inner Tracker [45]

related research.

4.2 The Inner Tracker

Given its proximity to the interaction point, the Inner Detector will be replaced by the Inner Tracker (ITk) following the Run 3 data collection period in order to meet the operating conditions of the HL-LHC. The ITk will be comprised of two silicon detectors: the Pixel detector and the Strips detector, which will each utilize an array of all-silicon sensors and extend the coverage of the ID from $|\eta| \leq 2.7$ to $|\eta| \leq 4.0$ [45]. Due to the predicted saturation of the TRT under the increased density of particles radiated from the IP, a replacement for TRT will be omitted with this upgrade. A schematic of the ITk can be found in Fig. 4.1, where it can be seen that the pixel layers begin at 45 mm from the IP and the strips at 40 cm.

As described previously, the replacement of the ID is necessitated by two main factors: the need for higher speed, finer granularity sensors and the need to withstand much higher radiation doses. The ID was initially designed to process approximately 23 interactions per bunch crossing, which as described prior has

already been exceeded during the Run 2 data collection period. In order to keep up with the approximately 10-fold increase in collisions per bunch crossing, the ID would be required to readout at a rate of nearly 1 MHz, over 10x the initial specifications. Due to the increase in both bandwidth requirements and granularity to distinguish the higher density of particles, a new detector must be developed.

The ID/ITk are the closest subdetector to the interaction point and thus are exposed to the highest doses of ionizing radiation. With an increase to collisions per bunch crossing comes a corresponding increase in particles radiated from the IP. It is projected that the ITk pixel detector will be exposed to approximately 1.7 Gigrads (GRads) and the ITk strips will be exposed to 50 Megarads (MRads). For reference, the current SCT is rated to withstand 10 MRads, of which it will have been exposed to approximately 5 MRads by the end of Run 3. Thus, the ID must be replaced in order to meet the radiation hardness requirements of the HL-LHC environment. The following sections will detail the design of the ITk strips sensors as well as the testing of its radiation hardness as these topics were the focus of my work.

4.2.1 ITk Strips Sensors

The geometry of the ITk strips sensors will be much like that of the SCT: four layers of staves covering the barrel region and six discs consisting of petal modules in the endcap region. A schematic of the ITk strips can be found in Fig. 4.2 with the petals and staves shown in Fig. 4.4. Each sensor is accompanied by a PCB called a hybrid (shown in Fig. 4.3), which holds the set of ASICs for powering and monitoring the strips modules. Application specific integrated circuits (ASICs) are a special kind of chip designed to perform a specific task efficiently and cannot be reprogrammed after fabrication. There are three primary ASICs on each hybrid module: the Atlas Binary Chip (ABCStar), the Autonomous Monitor and Control Chip (AMAC), and the Hybrid Controller Chip (HCCStar).

The AMAC, as the name suggests, is responsible for both monitoring and controlling the hybrid module. The AMAC measures useful quantities, such as temperature and overall power consumption, and is able to start up and reset the hybrid module as needed. The ABCStar connects to strip sensor channels, for which it digitizes and reports to the HCCStar. The HCCStar collects hit and clustering data from up to eleven ABCStars, serializes it, and transmits that information off-detector. During my time at UPenn, I worked on the HCCStar specifically and will describe its design in depth in the following section.

4.2.2 The HCCStar Design

The HCCStar is the ASIC responsible for issuing readout requests and serializing the hit data from its connected group of ABCStars. The serialized data is then transmitted to the end-of-substructure card to

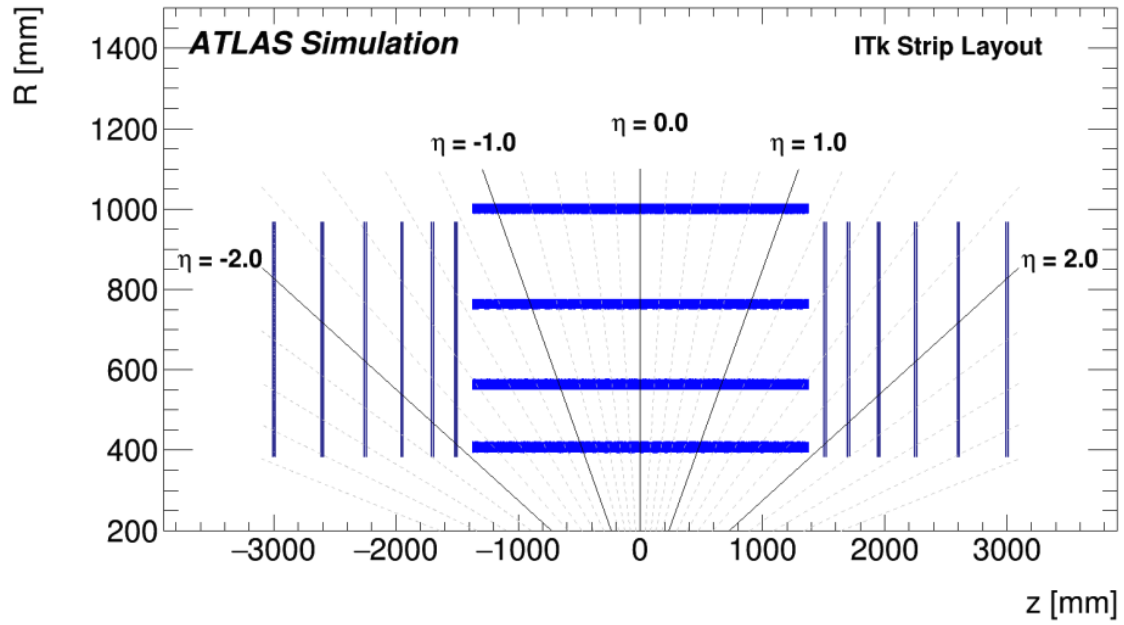


Figure 4.2: Schematic of the Inner Tracker Strips Detector [45]

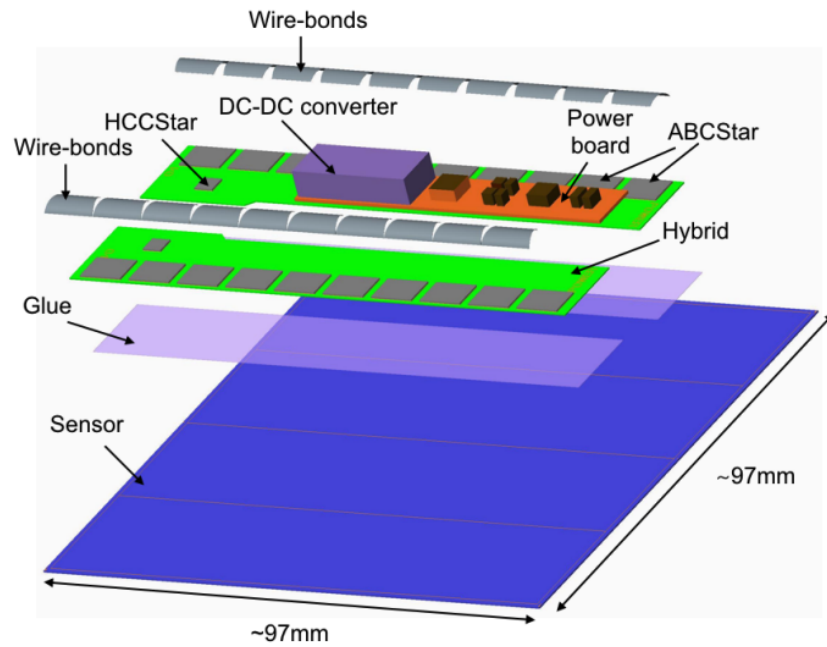


Figure 4.3: Schematic of the Inner Tracker Strips Hybrid Module [45]

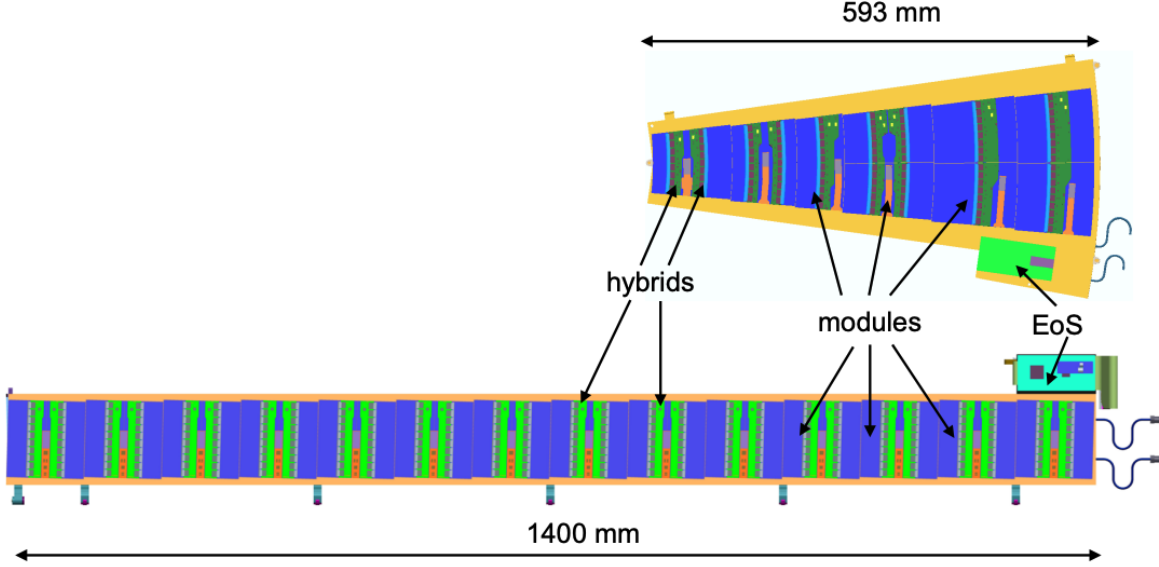


Figure 4.4: Schematic of the Inner Tracker Strips Petal and Stave Modules [45]

be sent off detector. A top-level block diagram of the HCCStar is given in Fig. 4.5, with each of the main components highlighted. The control path contains the primary logic protocol for the HCCStar along with the interface used to issue configuration and control commands to the ABCStar. The input channels are connected to each of the managed ABCStars and takes in the clustered hit data from each of the ABCStars. Hit data from each ABCStar is stored in the input channels until the packet builder is able to process it. Finally, the packet builder takes the physics data from each of the input channels and serializes it for transmission to the end-of-substructure card. This section of the HCCStar handles the error correction, synchronization of incoming packets, and the handling of register read and high priority request (HPR) packets. Given that the HCCStar is responsible for accurately serializing and sending the physics data from the ABCStars, which handle the direct sensor data, it is vital that the HCCStar operates quickly and accurately in the HL-LHC.

4.3 Irradiation Testing

As described previously, one of the main considerations when designing sensors for the HL-LHC is the ability to accurately perform in high radiation environments. Radiation effects can manifest in many ways, including physical degradation of circuitry, increased power consumption, and corruption or glitches in the digital logic. The second and third classes of effects will be discussed in depth.

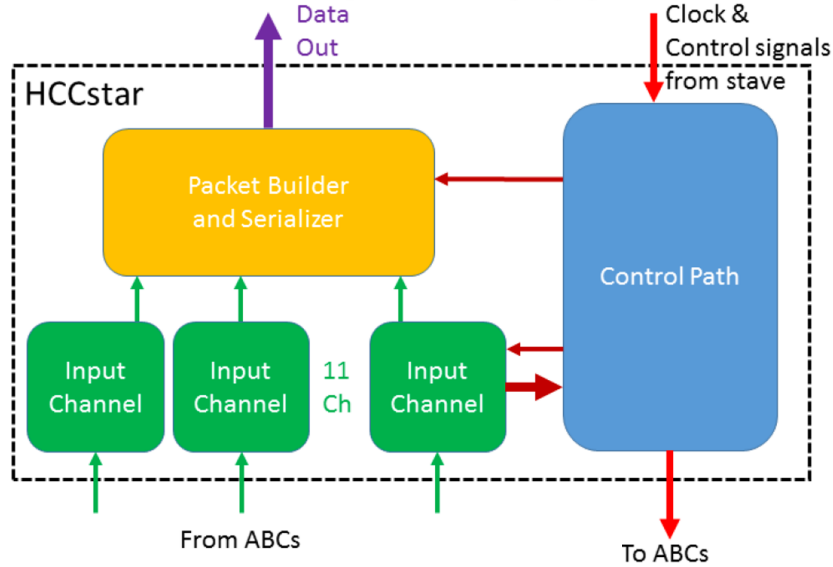


Figure 4.5: Block Diagram of the HCCStar ASIC

It is well documented that CMOS digital circuitry experience an increase in current draw at low Total Ionizing Dose (TID) followed by a drop back to near-nominal current draws [46–48]. This behavior is deemed the TID bump and must be characterized to ensure that ITk strips ASICs are able to properly function within specification throughout the duration of the HL-LHC data taking runs. One could imagine that a small increase in power draw across thousands of ASICs would add up in terms of both power draw and heat production.

To ensure nearby transistors do not leak current to one another, the technique of Shallow Trench Isolation (STI) is employed. As the ASICs are exposed to radiation, incident ionizing particles damage the individual transistors via the accumulation of positively-charged holes at the STI trenches. This accumulation leads to effectively lowering the threshold of the trenches and the leaking of current. As more and more modules are affected and more and more current leaks, the total current draw of the given ASIC increases over time. This effect eventually rebounds as further radiation occurs and the current draw lowers to near-nominal levels. It is expected that once this TID bump is passed, this effect will not be observed again and ASICs should operate as normal. It is important that ASICs are able to regulate this current shift in order to perform properly in high radiation environments. Observation of the TID bump from the first irradiation at TRIUMF is given in Fig. 4.8.

The other class of effects mentioned, where incident radiation can induce a state change in digital circuitry, is deemed Single Event Errors (SEEs) [49–51]. Single event effects can pose a major challenge to the operation

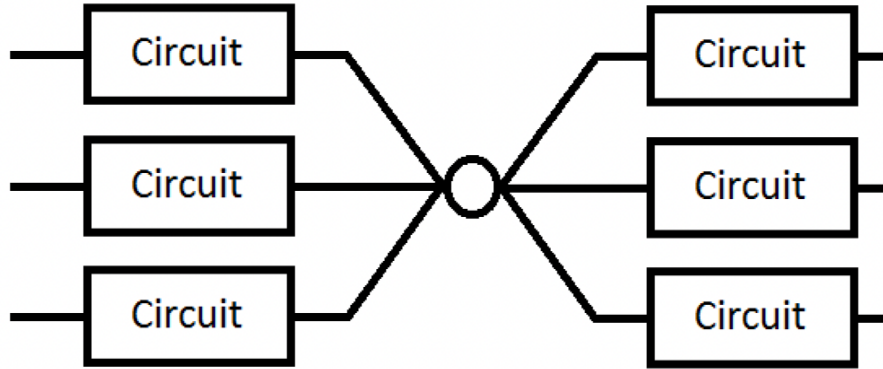


Figure 4.6: Schematic of the prototype HCCStar Voting Mechanism

of ASICs in high radiation environments as one can imagine that a digital logic bit flipping from a 0 to 1 can lead to a wide array of functionality errors, such as misreporting critical data, adjusting the configuration information of an ASIC (stored on chip), or corrupting memory addresses for accessing stored information. Given that the HCCStar is responsible for managing an array of ABCStars, it is vital that it can both synthesize, control, and report information from each ABCStar. In the absolute worst case scenario, a given HCCStar could necessitate a reset, which could take hundreds of milliseconds to execute and lead to the loss of data. If the chip is entirely unresponsive, it would have catastrophic effect as there is no possibility of repairing or replacing the front-end electronics during the HL-LHC data collection periods.

The prototype HCCStar I performed tests with implemented a series of error correcting measures in order mitigate the aforementioned effects. Each HCCStar contains a bandgap setting which enables the regulation of voltage throughout the TID bump and beyond as well as the implementation of digital logic triplication. Triplication of information allows for the correction of flipped bits by implementing a voter system and periodically checking the agreement of a given bit across three copies. By utilizing a majority voting mechanism, if one copy of information disagrees with the other two copies, it is corrected to create unanimous agreement. A schematic of the prototype HCCStar's triplication and voting mechanism is given in Fig. 4.6. Due to the nature of the voting system, only SEEs where a single copy of the information is altered can be corrected. The rarer scenario where two copies of the same information are flipped would lead to the voter correcting the only remaining correct value to agree with the two wrong values; this an uncorrectable SEE. The HCCStar was additionally designed with systems designed to monitor the rate of SEEs, namely, a read-only register which would detect when a majority voter corrected the value of a given triplicated bit. The thought is that by continually monitoring this register block, one could measure the SEE rate by counting the frequency of the SEE bit being flipped to 1 and reset the SEE status register via



Figure 4.7: Photos of the setup for the two rounds of proton irradiation. LEFT: the FPGA arrangement in a lead bunker placed out of the beamline. RIGHT: The arrangement of ITk Strips ASICs next to the proton beam pipe.

a fast command after each read cycle. To test the HCCStar’s capabilities in HL-LHC conditions, a series of irradiation tests are performed; these are described below.

4.3.1 Irradiation Testing Configuration and Results

Three types of irradiation testing were performed on the prototype HCCStar: gamma irradiation at Brookhaven National Lab (BNL), proton irradiation at TRIUMF, and heavy ion irradiation at UCLouvain. For gamma irradiation, the HCCStar is exposed to a cobalt-60 source, which produces 1 MeV gamma rays. Given the lower energy and fluence of incident particles, this testing is utilized to precisely measure the TID bump over the span of several months. During this time, current draw and regulated voltage are monitored while functionality testing is continuously performed on the HCCStar. Proton irradiation is performed by firing a concentrated beam of 480 MeV protons directly onto the HCCStar die to observe the rate of SEEs; this testing is performed over the span of a few days, with the HCCStar receiving constant exposure across 48 hours. The final testing, heavy ion irradiation, is performed by placing the HCCStar in a beam of heavy ions, which are swapped every few hours, in order to characterize the turn-on effect of SEEs as well as the saturated SEE rate with respect to linear energy transfer (LET).

For the two rounds of TRIUMF proton irradiation, the HCCStar is placed in the path of a high energy proton beam while connected to an FPGA. The FPGA is then connected via ethernet out of the testing area to the control room. To protect the FPGA from potentially damaging radiation, it is placed in a lead bunker at a safe distance from the beam (shown in Fig. 4.7). To control and monitor the HCCStar, a prototype version of the ITk strips data acquisition software (ITSDAQ) was utilized, which interfaced with a series of ROOT scripts designed to test the HCCStar’s functionality. During each read/write cycle, readout requests

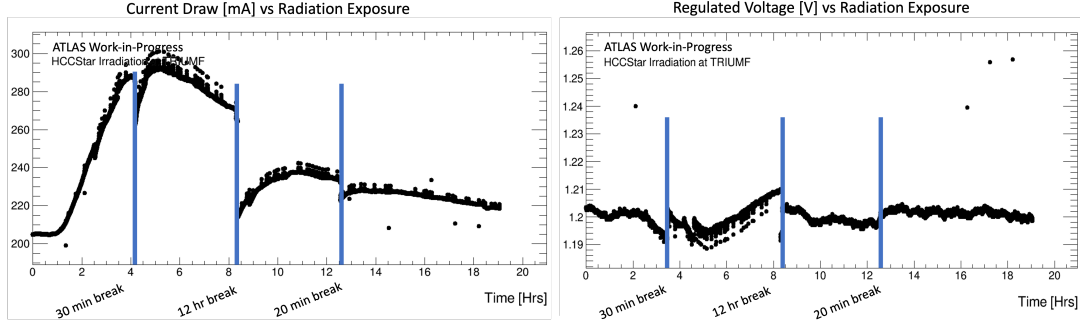


Figure 4.8: Plots of the current draw and regulated voltage of the HCCStar during proton irradiation. LEFT: Total current draw of the HCCStar. It can be seen that the HCCStar reaches a maximum current draw of 300 mA during the TID bump, over 50% greater than the nominal 200 mA. RIGHT: Regulated voltage of the HCCStar. Despite the increase in current draw, the HCCStar is able to regulate its voltage within 1% of its nominal 1.2 V.

were sent to the HCCStar via the control path and data packets were attempted to be passed through the HCCStar input channels. Following these requests, the SEE register was readout to measure the SEE rate as previously described and default values were reissued to the HCCStar. The tests were validated to work on a testbench in a radiation-free environment prior to irradiation testing.

Upon placing the HCCStar in the proton test beam, it became immediately apparent that the ASIC had severe radiation vulnerabilities. To begin, the SEE status register was consistently reporting that both an uncorrectable and a correctable SEE had occurred since the last read/write cycle, indicating that the SEE rate exceeded our polling rate. Physics packets would be routinely missed by the output monitor and frequently be returned with missing clusters of data or corrupted metadata. Finally, and perhaps the most surprisingly, the readout of HCCStar registers would frequently fail, either by returning empty packets or the contents of an entirely different register than requested. Given that these clearly indicated irradiation vulnerabilities, the scope of what testing could be performed on the prototype HCCStars needed to shift. The first round of irradiation was thus shifted to trying to diagnose the vulnerabilities observed and determine what data could be collected. This process was incredibly frantic and led to a massive overhaul of the previously designed ITSDAQ scripts by both myself and Ben Rosser at the eleventh hour.

With clear minds and a fresh approach, a second round of proton irradiation was performed at TRIUMF a few months later. For this run, physics mode tests were disabled and a new strategy to measure the SEE rate was performed. To ensure accurate measurement of register SEEs, each registers default value was changed such that it varied from all other register default values by at least 4 bits. This ensured that in the event a register readout differed from the expected default value, it was easily verifiable if the wrong

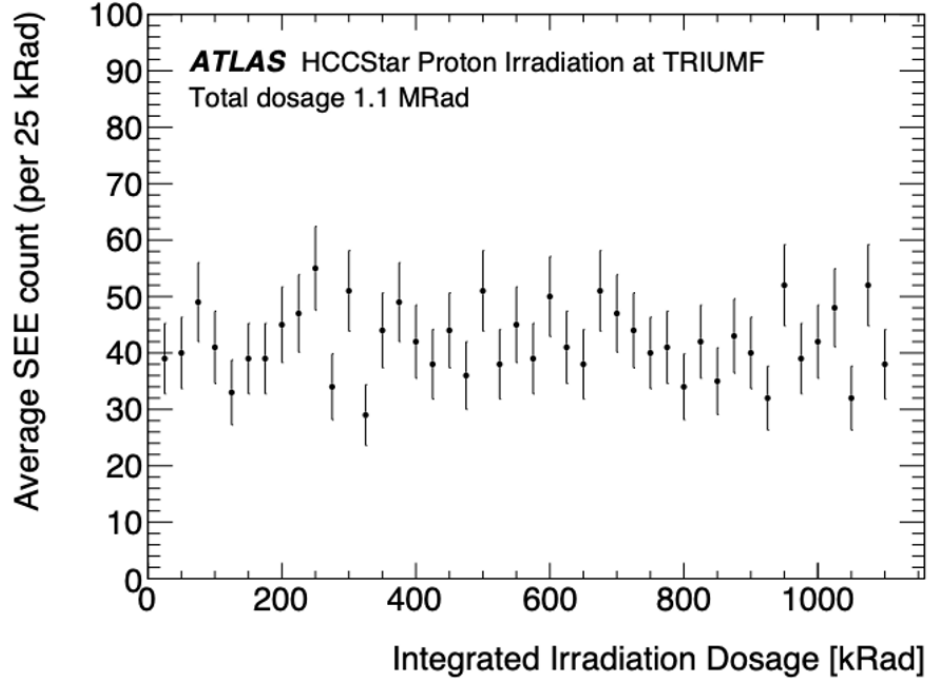


Figure 4.9: The average SEE rate observed during proton irradiation, binned per 25 kRad. Each bin is approximately the daily radiation dose the HCCStar will receive in the HL-LHC environment. It can be seen that the HCCStar is expected to observe approximately 40 correctable SEEs per day [52].

register was reported. Readouts where the wrong register value was reported were filtered from the results and not counted into the overall SEE rate. Thus, despite the HCCStar not functioning properly in a high radiation environment, a measurement of the SEE rate could still be made. This measurement was then used to extrapolate the SEE rate to the expected HL-LHC environment of $1 \frac{\text{kRad}}{\text{hr}}$. It can be seen from Fig. 4.9 that the HCCStar is expected to experience approximately 40 correctable SEEs each operating day.

Following proton irradiation tests, a series of heavy ion irradiations were performed at UCLouvain in Belgium. For these tests, the approach used in the second proton irradiation was used while varying the heavy ion beam incident on the HCCStar. Each heavy ion is expected to have a characteristic linear energy transfer (LET) when incident on silicon. From NASA studies, the SEE rate is expected to follow a Weibull distribution vs LET. This distribution is characterized by both a turn on energy, E_0 , which describes the minimum LET required to cause an SEE and the saturated cross-section, σ_0 , which describes the maximum observable SEE rate. The results of these studies are given in Fig. 4.11. For this testing, only a single chip was testable at a given time. Given that the HCCStar was already known to be non-functioning in the HL-LHC environment, priority was given to the other ITk strips ASICs present, namely the AMAC and ABCStar, leading to an increase in statistical uncertainties observed.

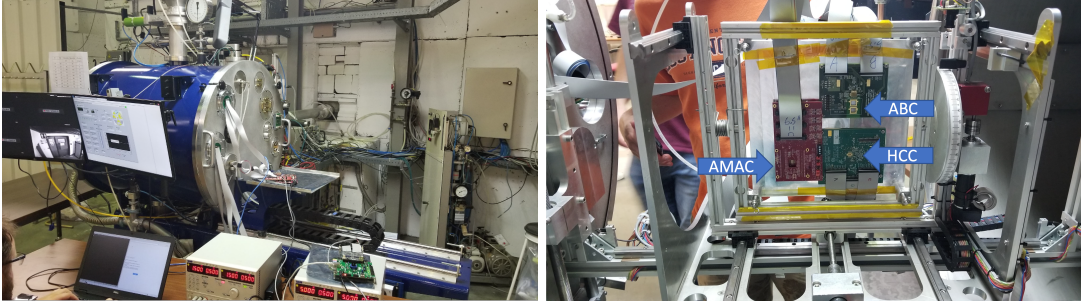


Figure 4.10: Photos of the setup for the heavy ion irradiation. LEFT: the vacuum tube which houses the ASICs during irradiation. RIGHT: The arrangement of ITk Strips ASICs in the vacuum chamber.

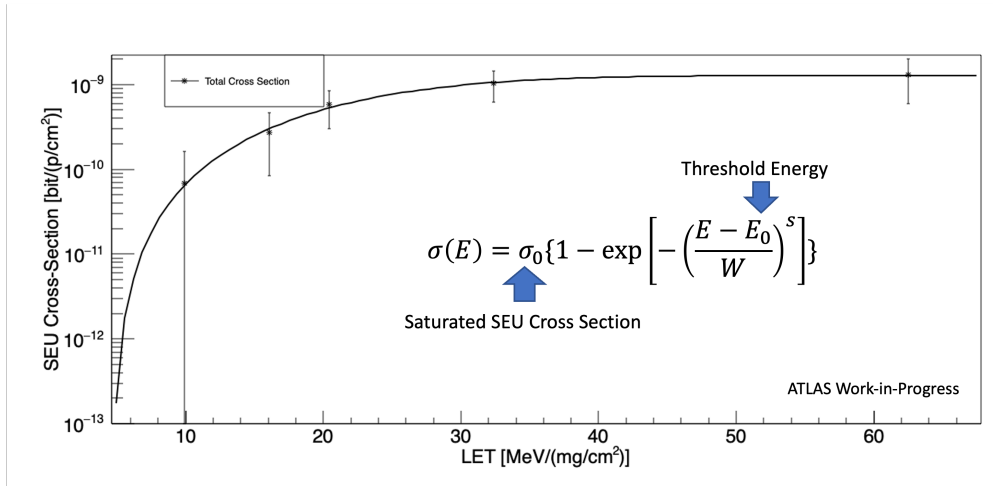


Figure 4.11: The uncorrectable SEU cross-section of the HCCStar vs Linear Energy Transfer (LET) during heavy ion irradiation. NOTE: uncertainty bars are massive due to the limited data collection period available to the HCCStar.

4.3.2 Improvements to the HCCStar

Following these irradiation tests, it was clear that the HCCStar design needed to be revisited if we hoped to have a functioning strips sensor for the ITk. Over the following years, an extensive redesign of the HCCStar was performed by the UPenn group. The main improvement implemented was the triplication of all vital flip-flops as well as the triplication of all voters and clocks. A schematic of this update to the voting systems is given in Fig. 4.12. The triplication of all necessary flip-flops ensures the protection of the control structures of the FIFO and prevents the pointers for the memory registers from being corrupted. The triplication of the voter system protects against the effects of single event transients (SETs), which can cause triple SEUs if they occur at the right time and space.

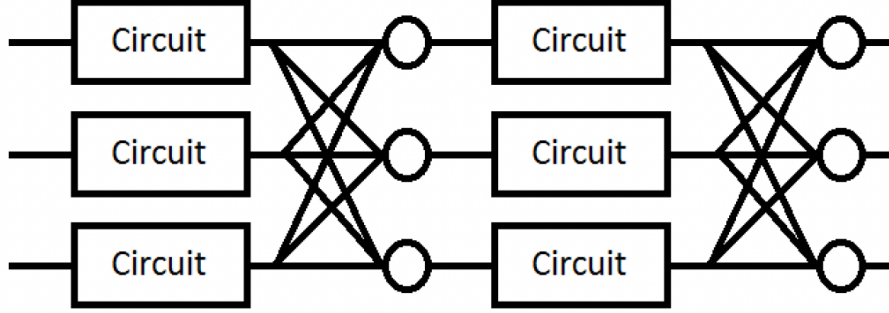


Figure 4.12: Schematic of the production HCCStar Voting Mechanism

To avoid the need for another redesign, extensive simulations of the new HCCStar were performed by Ben Rosser with cocotb. SEEs were then simulated at a rate much higher than expected in the HL-LHC environment. The results of these studies showed that the SEE rate was much better under control and that physics data should remain intact during high radiation. Thus, HCCStar v1 was fabricated and subjected to another round of irradiations. Heavy ion tests were performed again in February 2022 by Andie Wall, the results of which can be found in Fig. 4.13. From these studies, 0 uncorrectable SEEs were observed and thus the only result reported is the corrected SEE rate, which is observed to be nearly as low as the previous uncorrectable SEE rate with HCCStar v0. Another round of proton irradiation was also performed by Andie Wall, during which it was observed that the HCCStar should expect 180 correctable bit flips during the entire lifetime of the HL-LHC. With these improvements in place, readout electronics for the ITk strips detector are ready for production and the HL-LHC can become a reality.

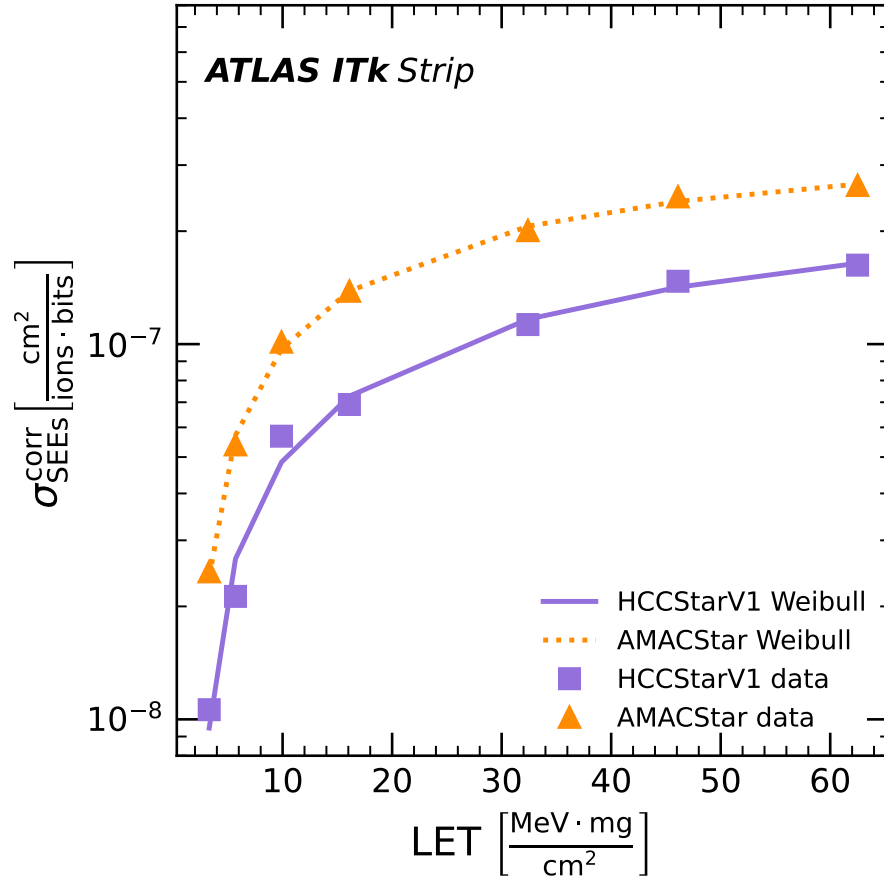


Figure 4.13: The correctable SEE rate for the HCCStar vs LET during the second round of heavy ion testing [53].

CHAPTER 5

B-L Stop Search

5.1 Analysis Overview

The stop LSP scenario is of particular interest to study. As motivated in Sec. 2.3.2, the theoretical production cross-section for $\tilde{t}\tilde{t}$ pair production is quite large, providing potential sensitivity in the multi-TeV range with sufficient data. In addition to the high cross-section, stop LSP decays to a b-quark and a charged lepton (shown in Fig. 5.1) provide an exceptionally clean analysis signal. A search for stop pair production, both decaying via the b-quark + charged lepton channel, creates a final detector state of two charged leptons and two b-jets. Leptons are well modeled in the ATLAS detector and provide clean tracks for precise measurement. Similarly, b-jets provide additional handles for identification by their formation of displaced vertices, which can be reconstructed by ATLAS. Additionally, this search contains no significant missing transverse energy (MET), unlike traditional RPC searches, due to the stops decaying to fully visible particles within the ATLAS detector. Thus, the final experimental signature of interest is events with two oppositely-charged leptons, two b-jets, and two resonances in the combined jet-lepton mass distribution at the same value. The search presented utilizes the Full 140 fb⁻¹ Run 2 dataset and has set world-leading limits on the pair production of R-parity-violating scalar tops.

Due to its connection to the neutrino hierarchy problem, it is of particular interest for this analysis to consider all possible lepton branching ratios for the stop LSP [24, 25]. As described previously, the stop LSP decaying primarily to electrons would be evidence for the normal neutrino hierarchy while lepton branching ratios to taus and muons would indicate an inverted hierarchy. Unfortunately, the tau lepton has an extremely short lifetime and routinely decays hadronically (approx 65% of the time). Thus, it is most convenient and straight forward for this analysis to only consider final states with electrons or muons. Limits on scenarios where the stop decays primarily to tau leptons are still able to be set through observation of

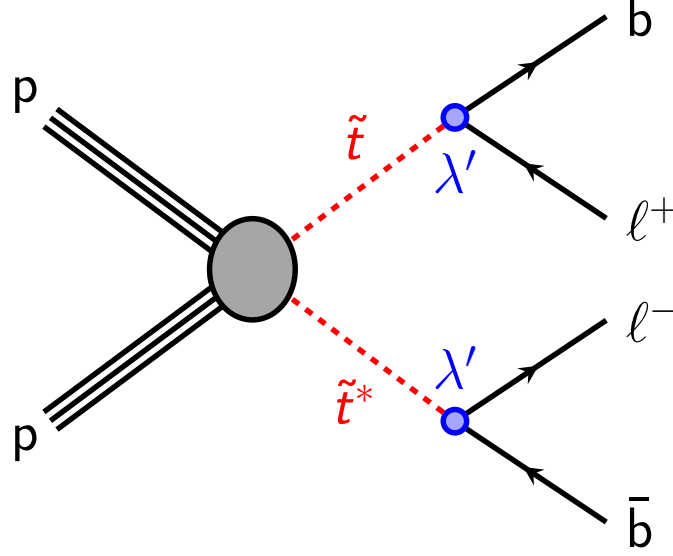


Figure 5.1: Feynman diagram for scalar top pair production, with stops decaying to a charged lepton and b -quark.

the other decay channels; however, these limits are expected to be weaker as the number of events for the observable decay channels will be more limited. With these considerations, the lepton final states studied by this analysis are: ee , $\mu\mu$, and $e\mu$.

A set of previous searches have looked for similar final states with both the ATLAS [54, 55] and CMS detectors [56]. These analyses include direct RPV stop searches in both the Run 1 and Early Run 2 datasets [57] as well as more general searches targeting pair production of first, second, and third generation leptoquarks. Unique to this analysis is the study of cross-generational final states ($e\mu$) along with a full scan of the lepton branching ratio plane, where the leptoquark studies targeted final states with same-generation leptons (ee , $\mu\mu$, $\tau\tau$). The early Run 2 RPV stop search has provided the strictest limits on the pair production rate of stops to date, excluding stop masses from 600 GeV up to 1500 GeV, depending on the hypothesized lepton branching ratio (results are summarized in Fig. 5.2). This analysis seeks to improve the results of the Early Run 2 analysis and push the observed excluded stop mass to nearly 2 TeV. With improvements to systematic uncertainty modeling, signal region design, and larger dataset, these goals are more than possible.

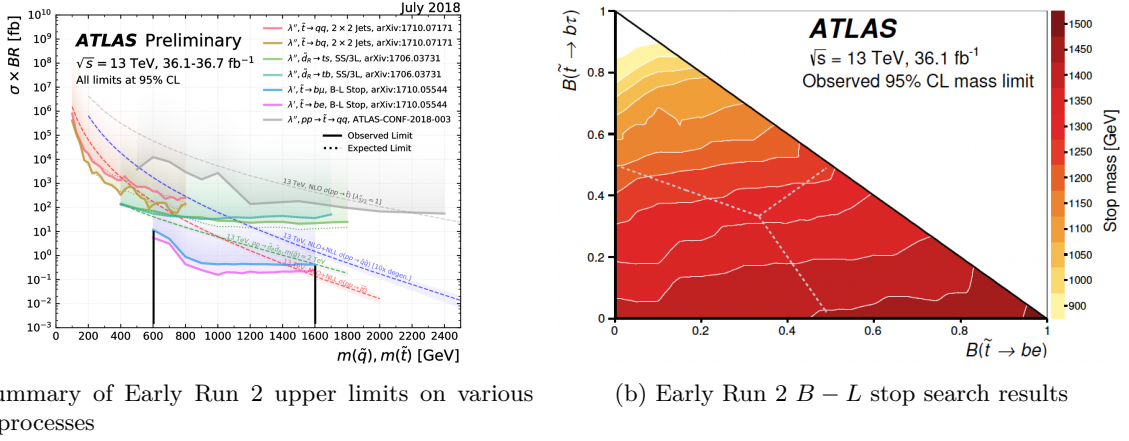


Figure 5.2: A summary of the Early Run 2 upper limits on SUSY production. Left: upper limits on the production rate of many SUSY processes. The cyan and magenta lines represent the previous upper limits on stop pair production decaying entirely to a b-quark and electron (magenta) or entirely to a b-quark and a muon (cyan). Previous exclusions were set where these lines cross the dotted red line. Right: the observed excluded stop mass across the lepton branching ratio plane from the Early Run 2 $B-L$ stop analysis.

5.1.1 Primary Backgrounds

The major SM background processes which this search is sensitive to are ones which produce two b-jets and two oppositely charged leptons. The first of these SM processes is dileptonic top quark pair production ($t\bar{t}$, colloquially: 'ttbar'), where each of the produced top quarks decay to a b-quark and W-boson. The W-bosons then decay leptonically to a charged/neutral lepton pair, leaving a detector signature of two b-quarks and 2 charged leptons as neutrinos are undetectable at ATLAS. The second major background is Wt channel single-top production, which as the name suggests, is the production of a single top quark and W-boson. As before, the top quark decays to a b-quark and W-boson and both W-bosons decay to charged/neutral lepton pairs. Another quark or gluon from Initial State Radiation or Final State Radiation can result in a jet containing a heavy-flavor quark that may be mis-identified as heavy-flavor initiated. The last major background is Drell-Yan ($Z/\gamma^* + \text{jets}$) processes. In this process, a photon or Z-boson is produced via quark-antiquark annihilation, which then decays leptonically to two charged leptons. For this process, both jets are picked up from ISR, without preference for being heavy-flavor initiated. The Feynman diagrams for each of these processes are given below in Fig. 5.3. Other processes, such as W+jets and diboson production, can also contribute a minor amount to the background estimate.

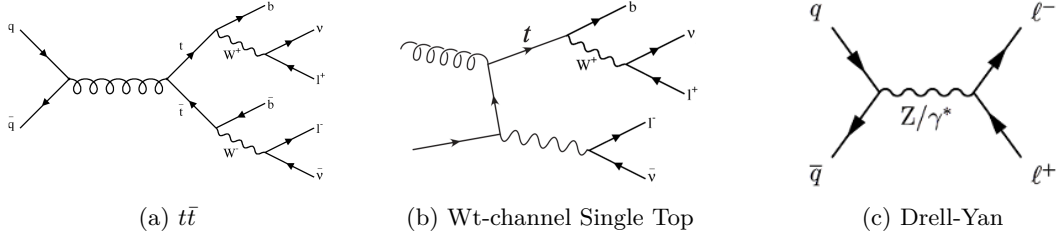


Figure 5.3: Feynman diagrams for the dominant background SM processes. Left: dileptonic $t\bar{t}$ where top quarks are pair produced and then decay to a b-quark and W-boson. Each W-boson then decays leptonically. Middle: Wt-channel for the Single top process. A top and W-boson are produced from quark-gluon interactions. The top decays to a b-quark and W-boson. Both W-bosons decay to a charged lepton and a neutrino. Right: the Drell-Yan process where quarks form a Z-boson which decays to two charged leptons.

5.1.2 Pairing Algorithm and Initial Background Rejection

Candidate signal events are required to have at minimum two leptons and two jets. If there are more than two leptons or two jets, the two leptons and two jets with the highest transverse momentum (p_T) are selected. The requirement of one b-tagged jet is then applied to these two highest p_T jets. The target signal signature is expected to have leptons with opposite charge in the final state, so the two leptons are required to have opposite charge. Events where the two highest leptons by p_T are not opposite charge are rejected.

Once events with two opposite-sign leptons and two jets are identified, a method must be determined to pair jets to leptons to properly reconstruct candidate stops. One extremely useful variable for reconstructing stops is the mass asymmetry (m_{bl}^{asym}). When processing events, there are two possible schemes for pairing the stop decay products: one which accurately reconstructs both stop masses and one which mispairs jets to leptons and yields two incorrect masses. Given that we do not know the hypothetical stop's mass, we are unable to compare the measured masses to a previously known value and instead must get more creative. Knowing that the two stop masses should produce two resonances at the same mass, choosing the pair which minimizes the asymmetry between the two candidate stop masses, $m_{b\ell}^0$ and $m_{b\ell}^1$, is efficient at correctly matching jets and leptons from the same stop decay.

$$m_{b\ell} \text{ asymmetry} = \frac{(m_{b\ell}^0 - m_{b\ell}^1)}{(m_{b\ell}^0 + m_{b\ell}^1)} \quad (5.1)$$

where $m_{b\ell}^0$ is chosen to be the higher of the two masses, setting $m_{b\ell}^{asym}$ to be strictly positive. A curious reader might wonder why the percent difference is chosen to define asymmetry as opposed to the simple difference of masses. Given that a large range of hypothetical stop masses is probed (600 GeV to 1900 GeV!), a simple difference would be biased towards selecting lower mass pairings over two high mass stops. Mass

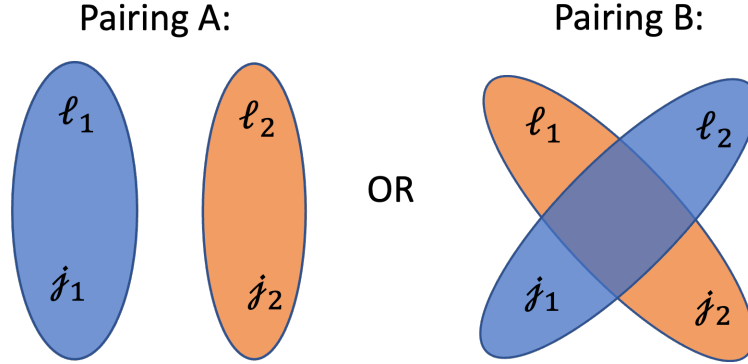


Figure 5.4: The two possible schemes for pairing signal jets to signal leptons. Left: the leading- p_T jet is paired to the leading- p_T lepton while the subleading- p_T jet is paired to the subleading- p_T lepton. Right: the leading- p_T jet is paired to the subleading- p_T lepton while the subleading- p_T jet is paired to the leading- p_T lepton.

asymmetry is not only a powerful tool for reconstructing stops, but also in rejecting background processes. Pair production processes, such as $t\bar{t}$ and stop pair production, are expected to have low m_{bl}^{asym} as there are two equal, resonant masses in each given event. Other backgrounds, such as Single top or Z+jets, are expected to create more random jet-lepton pairings, leading to a flat distribution in m_{bl}^{asym} . This effect can be seen in Fig. 5.5.

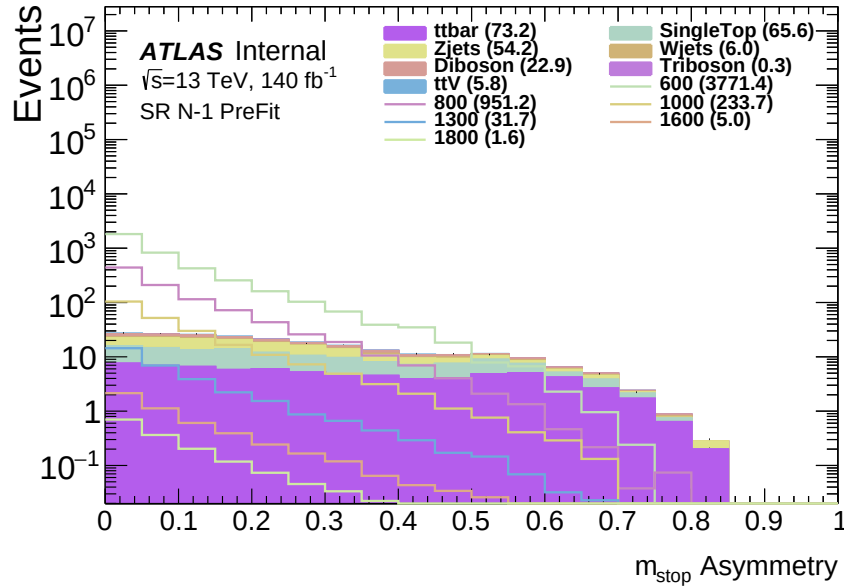


Figure 5.5: The N-1 distribution for the m_{bl} asymmetry (log-scaled). It is clear that the signal peaks at low m_{bl} asymmetry while other background processes are randomly distributed.

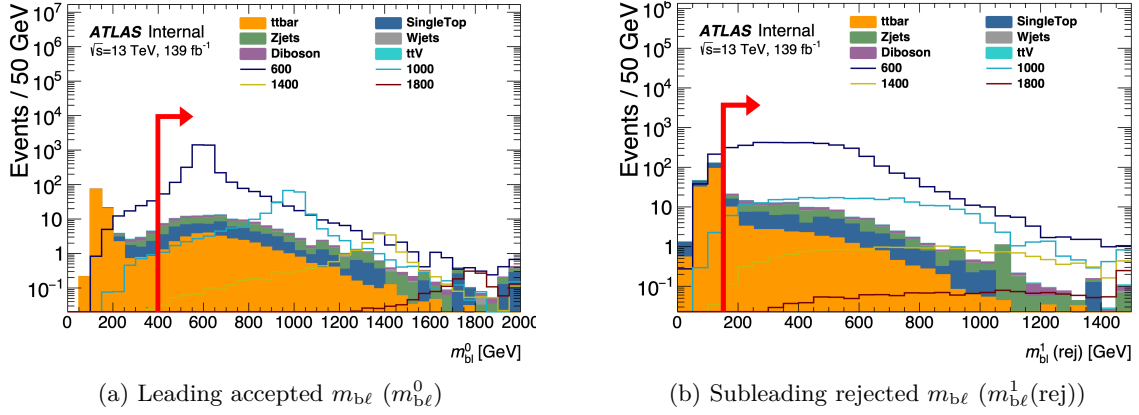


Figure 5.6: N-1 Distributions for the leading accepted m_{bl} (m_{bl}^0) and subleading rejected m_{bl} ($m_{bl}^1(\text{rej})$). Both of these cuts provide good rejection of the top-quark backgrounds

For backgrounds with standard model top quarks, the invariant mass of the bl pair has in principle a kinematic upper limit at the top quark mass. For the signal search regions, the leading bl mass of the chosen pairing is always required to be at least 200 GeV. This rejects events from the $t\bar{t}$ background where both top quarks in $t\bar{t}$ events are correctly reconstructed by the chosen pairing and both bl pairs have masses below the top quark mass with a small asymmetry. This requirement is also made in the control and validation regions in order to keep their composition similar to the signal regions. The effect of this selection can be seen in Fig. 5.6a.

To reduce the $t\bar{t}$ background where neither top quark is correctly reconstructed by the chosen pairing, the rejected combination is also considered. If one of the rejected bl pairs actually has the lepton and b jet from the same parent top quark, then that bl pair should have a mass below the top quark mass. Thus, a requirement on the rejected pairing is made as well, requiring that the lowest bl mass be above the top quark mass. The requirement is made at 150 GeV and it reduces markedly the Wt channel Single top process. This can be seen in Fig. 5.6b.

The Drell-Yan ($Z/\gamma^* + \text{jets}$) background is reduced by making a selection requirement on the invariant mass of the dilepton pair. Rather than a window around the Z boson mass, m_{ll} is required to be above 300 GeV to reduce this background in the signal search region, as seen in Fig. 5.7. For some of the control regions, this requirement is lowered to 200 GeV to improve statistics.

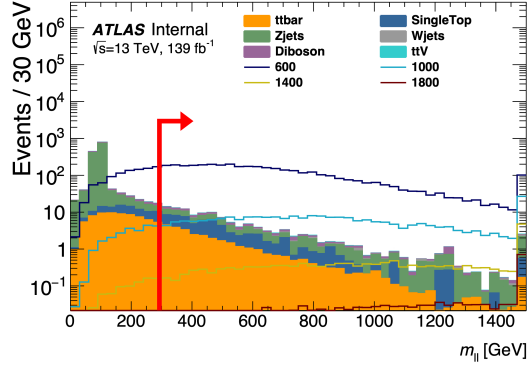


Figure 5.7: N-1 Distributions for m_{ll} . This cut provides strong rejection of the Z+jets background process.

5.2 Dataset and Monte Carlo Simulation

5.2.1 ATLAS Dataset

Run 2 of the LHC spanned 2015 to 2018, during which the ATLAS detector recorded approximately 145 fb^{-1} of data. Of this 145 fb^{-1} , 140 fb^{-1} was deemed suitable for physics analysis and recorded in the ATLAS Good Runs List (GRL) by the Data Preparation Group. To be added to the GRL, all subdetectors are required to be fully operational. For this analysis, the full 140 fb^{-1} Run 2 dataset was analyzed to maximize the available statistics to strengthen conclusions.

5.2.2 Monte Carlo Simulation

Standard Model background processes are studied through leveraging the immense power of Monte Carlo simulation. By studying the kinematic distributions of SM processes across billions of simulated collisions, physicists are able to form statistical models which can precisely identify hypothetical new physics. Once collisions are produced, the response of the ATLAS detector is simulated using an extremely detailed model in GEANT 4. In addition to modeling SM processes, stop pair production is simulated in order to better optimize analysis selections. The following sections detail the specifics of the Monte Carlo simulations employed by this analysis.

5.2.3 Monte Carlo Details

$t\bar{t}$ and Single top processes were produced [58] at NLO in QCD with the POWHEGBOX v2 generator [59] with the NNPDF3.0nlo PDF set. Calculated matrix elements are then interfaced with PYTHIA.230 using the A14 tune for parton shower modeling with the NNPDF2.31o PDF set. The inclusively produced $t\bar{t}$ cross-section

is then corrected to the NNLO in QCD theory prediction including the resummation of next-to-next-to-leading logarithmic (NNLL) soft-gluon terms calculated with TOP++2.0. Similarly, the Single top inclusive production is corrected to the NLO in QCD theory predicted cross-section with NNLL soft-gluon terms. To remove the interference effects of $t\bar{t}$, the Diagram Removal (DR) scheme is applied to Wt Single top production. Produced events are then filtered to create samples which only contain at least two charged leptons to speed up computation time.

Due to the majority of $t\bar{t}$ and Single top events being produced with significantly lower H_T than the targeted signal region, special H_T -sliced $t\bar{t}$ and Single top samples were utilized. These samples apply H_T requirements on produced events in order to boost available statistics at high H_T . This increase in available MC statistics dramatically improves modeling of systematic uncertainties as well as lowers observed statistical uncertainties in the Signal Regions, leading to improved signal sensitivity. Other than the additional H_T filter, the generation configuration is identical to the nominal samples.

Z+jets backgrounds are modeled using the SHERPA MC generator [60] with version 2.1 and default parton shower tune. These samples are calculated for events with up to two additional partons at NLO and up to four additional partons at LO in QCD. Cross-section measurements for Z+jets are then corrected to their NNLO theory predictions. The remaining, lesser backgrounds have their generation schemes summarized in Table 5.1.

Process	MC Generator	PS Modeling	Cross-section Order
$t\bar{t}$	POWHEGBOX v2	PYTHIA 8	NNLO+NNLL
Single Top (Wt)	POWHEGBOX v2	PYTHIA 8	NNLO+NNLL
W/Z +jets	SHERPA 2.2.1	SHERPA 2.2.1	NNLO
Diboson/Triboson	SHERPA 2.2.1	SHERPA 2.2.1	NLO
$t\bar{t} + V$	aMcAtNLO	PYTHIA 8	NLO

Table 5.1: Specific configurations used for the MC generation of each Standard Model background process.

Stop pair production is modeled using the MadGraph generator [61] with the CTEQ 6L1 and PYTHIA used for the PDF model. Stop-anti-stop pairs are produced for masses between 600 GeV and 1900 GeV in increments of 100 GeV from 600 GeV to 1000 GeV and increments of 50 GeV for the remaining range. Signal cross-sections are corrected to match the NLO+NNL theory prediction. Theory cross-sections and their associated uncertainties for each given stop mass are computed using an envelope procedure across the various PDF sets and choice of scale. Stop signal samples are produced with an equal branching ratio to all charged lepton flavors. For this analysis, final states with tau leptons are not considered.

5.2.4 Signal Sample Reweighting

To test the many potential stop branching ratios, signal events are reweighted according to their truth stop decay. This process avoids the need to generate distinct datasets for each of the extremely similar signal models. The desired stop branching fraction can be determined by weighting each event with the following approach:

$$\omega_{Signal} = 9 \prod_{i=e,\mu,\tau} \mathcal{B}_{target}(\tilde{t} \rightarrow b\ell_i)^{N_{\ell_i}} \quad (5.2)$$

where $\mathcal{B}_{target}(\tilde{t} \rightarrow b\ell_i)$ is the desired branching ratio to target charged lepton ℓ_i and N_{ℓ_i} is the number of target truth leptons ℓ_i directly produced from a stop decay. By utilizing this scheme, limits are able to be set across the lepton branching ratio plane in the absence of observed excess.

5.3 Object Selections

The physics objects used for this analysis (electrons, muons, and jets) are required to pass two sets of quality requirements, split into baseline and signal selections [62]. Baseline object selections are applied to create the input for both the calculation of MET as well as overlap removal. Signal selections are then applied to objects which pass the overlap removal procedure and apply a tighter set of criteria on candidate objects. Objects which pass both baseline and signal requirements are used for analysis, while objects which do not are discarded. While photons and MET are not used for this analysis, they are calibrated nonetheless to be used for internal optimization studies and potential analysis strategies.

Data events are required to fire one of the single lepton triggers (given in Table 5.2) and must be included in the ATLAS central "Good Runs List," which notates the luminosity blocks suitable for physics analysis. Data and MC events must also contain at least one reconstructed vertex associated to two or more tracks with $p_T > 500$ MeV. We identify the primary vertex of each event to be vertex with the greatest sum of square track p_T : Σp_T^2 .

The following sections detail the object selection criteria utilized by this analysis. Since baseline requirements do not deviate from the ATLAS standard recommendations, they are not detailed here.

5.3.1 Electrons

Signal electrons are defined as all baseline electrons which pass overlap removal and the following set of stringent kinematic and quality requirements, given in Table 5.3. The Tight Likelihood identification and Loose_VarRad isolation criteria are required for signal electrons [63]. Additionally, they are required to

Electron Triggers	Muon Triggers
2015	
HLT_e24_lhmedium_L1EM20VH	HLT_mu20_iloose_L1MU15
HLT_e60_lhmedium	HLT_mu26_ivarmedium
HLT_e120_lhloose	
2016-18	
HLT_e26_lhtight_nod0_ivarloose	HLT_mu50
HLT_e60_lhmedium_nod0	HLT_mu26_ivarmedium
HLT_e140_lhloose_nod0	

Table 5.2: Electron and muon triggers utilized for each year of data collection. Each trigger name specifies the object it fires on (e or mu) followed by the offline p_T threshold. Terms following the offline p_T are further selections of objects, such as lepton isolation or ID requirements.

have $p_T > 40$ GeV and small impact parameter. The high signal electron p_T can be used to reject some background processes and limit the presence of fake-ID electrons due to signal stops producing hard electrons (Figs. C.1c and C.1d).

Identification Quality	Tight
Isolation	Loose_VarRad
p_T	≥ 40 GeV
$ \eta $	≤ 2.47
$d_0/\sigma(d_0)$	≤ 5
$z_0 \sin(\theta)$	≤ 0.5 mm

Table 5.3: Summary of applied signal electron criteria. Signal requirements are applied on top of baseline requirements and after overlap removal has been performed.

5.3.2 Muons

The signal muon requirements after overlap removal are listed in Table 5.4. Signal Muons are required to have $p_T > 40$ GeV, be within $|\eta| < 2.7$, and have a small impact parameter. Similar to electrons, we use a high p_T threshold for muons to help reject backgrounds (Figs. C.1c and C.1d). An additional requirement is placed on the muon isolation at the **Loose_VarRad** working point [64]. A cosmic muon veto is applied, rejecting muons that are not consistent with the interaction point. Signal muons are required to pass the **isBadMuon** cleaning criteria, requiring the relative error on the combined q/p measurement to be smaller or equivalent to the individual measurements from the ID or ME track fits. If any muon fails the cleaning criteria, the event is rejected. The **HighPt** ID working point is used as recommended by the Muon Combined

Performance Working Group, since the stop signal samples primarily produces muons with $p_T > 300$ GeV as seen in Figs. C.1c and C.1d.

Identification Quality	HighPt
Isolation	Loose_VarRad
p_T	≥ 40 GeV
$ \eta $	≤ 2.7
$d_0/\sigma(d_0)$	≤ 3
$z_0 \sin(\theta)$	≤ 0.5 mm
Cleaning	isBadMuon

Table 5.4: Summary of applied signal muon criteria. Signal requirements are applied on top of baseline requirements and after overlap removal has been performed.

5.3.3 Jets

The jets used in this analysis are from the AntiKt4EMPFLOW collection [65, 66]. Baseline jets are required to have a $p_T > 20$ GeV, and $|\eta| < 4.5$. Jets are rejected if they are identified as pile-up by the track-based Jet Vertex Tagging (JVT) [67]. Jets with $p_T < 60$ GeV and $|\eta_{det}| < 2.4$ are checked for compatibility with the primary vertex at the 92% efficient **Tight** working point of the JVT.

Signal jet requirements are shown in Table 5.6. Signal jets are required to have a $p_T > 60$ GeV. As with leptons, we use a high p_T threshold for jets to help reject backgrounds and limit fakes. At least one of the two jets is required to be tagged as a b-quark initiated jet. The **Fixed** 85% efficiency working point is required using the **DL1r** b-tagging algorithm. The choice of this b-tagging Working Point (WP) is justified in Figs. C.1a and C.1b.

p_T	≥ 20 GeV
$ \eta $	≤ 4.5

Table 5.5: Summary of baseline jet criteria. Baseline requirements are applied to all jets before the overlap removal procedure.

p_T	≥ 60 GeV
$ \eta $	≤ 2.8
JVT	Tight
B-tagging	DL1r Fixed 85%

Table 5.6: Summary of applied signal jet criteria. Signal requirements are applied on top of baseline requirements and after overlap removal has been performed.

5.3.4 Overlap Removal

Overlap removal is performed on all baseline objects before signal object selections are performed with the following scheme:

1. Remove any calorimeter-tagged muon that shares an ID track with an electron.
2. Remove any electron that shares an ID track with a non-calorimeter-tagged muon.
3. Remove any jet within $\Delta R(e, \text{jet}) \leq 0.20$ of an electron. This jet is assumed to be a misreconstructed electron. If the jet is b-tagged, the electron is instead removed.
4. Remove any electron within $\Delta R(e, \text{jet}) \leq 0.40$ of a non-pile-up jet. This electron is assumed to be a constituent of the jet.
5. Remove any jet that is ghost-matched to a muon (or is within $\Delta R(\mu, \text{jet}) \leq 0.20$) and which satisfies either $n_{\text{track}} < 3$ or both $\frac{p_T^\mu}{p_{jet}^\mu} > 0.5$ and $\frac{p_T^\mu}{\sum_{\text{trk}} p_T} > 0.7$. If the jet is b-tagged, the muon is instead removed.
6. Remove any muon with $\Delta R(\mu, \text{jet}) \leq 0.40$ of a non-pileup jet.

5.4 Analysis Design

Events which pass the preselection requirements of two signal jets and two oppositely-charged leptons are considered for analysis. Preselection events are spit into orthogonal analysis regions, each defined by a distinct set of event requirements, called cuts. There are three categories of analysis regions used: Signal Regions (SRs), Control Regions (CRs), and Validation Regions (VRs). Signal regions are designed to have high signal purity with minimal background. In this case, the SR cuts are designed to select $\tilde{t}\bar{\tilde{t}}$ pair production events and reduce SM events. Throughout the analysis design and optimization process, data in the SRs is kept blinded to avoid biasing the search. Control Regions are created to isolate each of the major SM background processes (CR_{tt} for $t\bar{t}$, CR_{st} for Single top, and CR_Z for Z+jets) into high purity regions. The CRs are then used in the statistical process described in Sec. 5.8 to both normalize MC simulation to data and to form the basis for estimating background contributions in the SRs. The final region type, Validation Regions, are used to test the extrapolation from the CRs across each major analysis variable. During the design and validation process, the extrapolation from CR to VR is rigorously tested to ensure the accuracy of the background modelling. The inclusion of VRs allows testing of the background modeling and extrapolation while maintaining the blindedness of the SRs. A summary of the Region cuts is given

in Table 5.7. The following sections will discuss the design of each of the analysis regions, with detailed discussion on region optimization discussed in Sections 5.6 and 5.7.

Region	N_b	M_{bl}^0 acc [GeV]	M_{bl}^1 rej [GeV]	H_t [GeV]	M_{bl} asym	M_{ll} [GeV]	M_{bl}^0 rej [GeV]
SR	≥ 1	> 400	> 150	> 1000	< 0.2	> 300 GeV	–
CRtt	≥ 1	[180,500]	< 150	[500,800]	< 0.2	> 200 GeV	< 180
CRst	$= 2$	[180,500]	< 150	[400, 800]	< 0.2	> 200 GeV	> 180
CRZ	≥ 1	> 700	–	> 1000	< 0.2	[76.2,106.2]	–
VR M_{bl}^0 acc	≥ 1	> 500	< 150	[600,800]	< 0.2	> 300 GeV	–
VR M_{bl}^1 rej*	≥ 1	[200,500]	> 150	[600,800]	< 0.2	> 300 GeV	–
VR H_t	≥ 1	[200,500]	< 150	> 800	< 0.2	> 300 GeV	–
VRZ	$= 0$	[500,800]	> 150	> 1000	< 0.2	> 300 GeV	–

Table 5.7: Summary of the signal, control, and validation regions used for this analysis. All regions require at least two jets and two oppositely charged leptons. NOTE (*): VR M_{bl}^1 (rej) is split into two separate validation regions: VR M_{bl}^1 (rej)_SF and VR M_{bl}^1 (rej)_OF. Both of these regions have identical cuts besides flavor requirements. OF requires opposite flavor leptons ($e\mu$) while SF requires same flavor leptons (ee or $\mu\mu$).

5.4.1 Signal Region Design

As described previously, this analysis is searching for evidence of scalar top pair production with each stop decaying to a charged lepton and b-quark. Thus, events in the SRs are required to have at least two signal leptons of opposite charge and two signal jets. For two body decays within the ATLAS detector, one expects the decay products to each carry p_T equal to half the origin particle’s mass on average (the stop mass in this case). Thus, when probing stop mass ranging from 600 GeV to 1900 GeV, p_T distributions for jets and leptons are expected to peak between 300 GeV and 950 GeV. To avoid the influence of tracks misidentified as prompt light leptons (“fakes”), a minimum p_T requirement on signal leptons of 40 GeV is placed, while jets are required to have $p_T > 60$ GeV. While this requirement is higher than the ATLAS standard, it can be seen from Figs. C.1a and C.1d that it has little to no impact on signal efficiency. Signal jets are required to have at least one b-tagged jet in the two highest- p_T jets. This decision is primarily to boost signal efficiency at high stop mass, where there is little background.

To be included in the Signal Region, events must pass selections on the following kinematic observables:

- The $m_{b\ell}$ asymmetry (Eq. 5.1). With no invisible decay products, both $b\ell$ pairs should reconstruct the stop mass. The difference in $m_{b\ell}$ should therefore be small. SM backgrounds without two resonant decays (single top, Drell-Yan) will typically have larger values of $m_{b\ell}$ asymmetry. A requirement of $m_{b\ell}$ asymmetry ≤ 0.2 is applied for all SRs to reject backgrounds while keeping high efficiency for signal.

- The scalar sum of the p_T of the two leading leptons and the two leading jets (H_T). High-mass stops are expected to have decay products with large momentum and therefore signal events typically have higher H_T than SM processes, whose parent particles are typically light compared to stops. A requirement of $H_T \geq 1000$ GeV is applied for all SRs to reject backgrounds while keeping high signal efficiency for a signal with a stop mass value of 600 GeV.
- The dilepton invariant mass, $m_{\ell\ell}$. The background from $Z/\gamma^* + \text{jets}$ is reduced with a requirement of $m_{\ell\ell} > 300$ GeV for all SRs to reject backgrounds while keeping high efficiency for signal.
- The lowest invariant mass of the rejected $b\ell$ pairing ($m_{b\ell}^1(\text{rej})$). For SM top backgrounds, if the invariant mass is formed with the lepton and the jet from the same parent top quark in $t \rightarrow Wb \rightarrow \ell\nu b$ decays, then the invariant mass should be below the top quark mass. A requirement of $m_{b\ell}^1(\text{rej}) \geq 150$ GeV reduces the background from single top and $t\bar{t}$ where the rejected pairing makes the correct association between a lepton and a jet from a top quark decay.
- The highest invariant mass of the accepted $b\ell$ pairing ($m_{b\ell}^0$), also known as the mass of the leading $b\ell$ pair. A minimum requirement of $m_{b\ell}^0 \geq 180$ GeV is applied for all SRs, CRs and VRs. For the Signal Region, we require $m_{b\ell}^0 \geq 400$ GeV to reduce background and to explore possible stop masses of 600 GeV and above. Cutting on $m_{b\ell}^0$ reduces the background from single top and $t\bar{t}$ where the chosen pairing makes the correct association between a lepton and a jet from a top quark decay. In combination with the requirement on $m_{b\ell}^1(\text{rej})$, this largely eliminates $t\bar{t}$ events where the leading two leptons and jets are from the top quark decays.

N-1 plots for each of these kinematic observables are produced to demonstrate the cuts' power in separating background from signal. For these plots, all but one SR cut is applied, hence the term "N-1." The N-1 plots for the predicted SR yields are given in Appendix B.

Events passing the Signal Region cuts are then divided into bins in $m_{b\ell}$ (Table 5.8) as input for a variable-width, multi-bin shape fit (described further in Sec. 5.8). Due to the wide range of candidate stop masses probed, signal binning requires substantial optimizations to maximize limit setting capabilities. Many factors were considered in developing the final $m_{b\ell}$ bin widths, including: the effect of dominant theoretical systematics, the limited availability of Monte Carlo statistics, computation time for performing the full statistical treatment, and the expected limit setting potential on stop signal strength. These optimization studies are discussed extensively in Sec. 5.7.

To maximize exclusions on the stop production cross section, two distinct Signal Region strategies were used for each lepton branching ratio point probed: an inclusive set of 15 SR bins, agnostic to the lepton final

state and a set of 45 SR bins, which separates each bin by lepton flavor final state ($ee, e\mu, \mu\mu$) and treats each as orthogonal, independent SRs. The statistical methodology of how exclusion statements are generated from these configurations is described in depth in Sec. 5.8.4.

In addition to using these SR definitions for model-dependent results, a second set of regions were defined to produce model-independent results. These regions use the same baseline SR cuts as the regions, with the Orthogonal bins in $m_{b\ell}$ replaced by 15 nested bins in $m_{b\ell}$ each starting at the lower bin edges of the nominal SR definition; This adds a total of 15 more Signal Regions to consider.

Bin width [GeV]	$m_{b\ell}$ range [GeV]
50	[400, 900]
100	[900, 1200]
200	[1200, 1400]
Inclusive	(1400, ∞)

Table 5.8: The chosen binning for the shape fit of the $m_{b\ell}$ distribution.

5.4.2 Control Region Design

Two of the largest sources of background contamination in the Signal Region come from tops and Z+jets, with the top contribution divided into $t\bar{t}$ and single top production. Thus, three orthogonal control regions are defined to constrain the normalization of the $t\bar{t}$, single top and Z+jets MC distributions through a data-driven method and described in the following sections.

5.4.2.1 $t\bar{t}$ Control Region

The $t\bar{t}$ control region is chosen to maximize the background contribution from top pair production. The requirement on the number of leptons and jets is identical to the SR, with at least two opposite-charge leptons and two jets, at least one of which has to be b-tagged. The $b\ell$ pair mass asymmetry selection of $m_{b\ell}$ asymmetry < 0.2 from the SRs is also applied to the top CR to maintain similar kinematics.

In order to select $t\bar{t}$ events, the SR selection on the invariant mass of the subleading $b\ell$ pair rejected by the pairing algorithm is inverted to < 150 GeV; This ensures that we select $t\bar{t}$ events where the jets and leptons are mis-paired. The average H_T value, as defined in equation Eq. (5.3), needs to be lower in this region with respect to the SRs to remove contamination from signal events: a cut of $400 \leq H_T \leq 800$ GeV is applied. The value of $m_{\ell\ell}$ is loosened to < 150 GeV. It is expected that for $t\bar{t}$ production, both masses of the $b\ell$ pair rejected by the pairing algorithm are compatible with the top mass. Therefore, to discriminate

between Single top and $t\bar{t}$ events, a cut is made on the mass of the leading, rejected $b\ell$ pair of < 150 GeV. Finally, the leading $m_{b\ell}$ pair is required to be between 200 and 500 GeV

$$H_T = \sum_{i=1}^2 p_T^{\ell_i} + \sum_{j=1}^2 p_T^{b\text{-jet}_j} \quad (5.3)$$

5.4.2.2 Z+jets Control Region

The Z+jets control region (CRZ) places selections on the dilepton pair to isolate the leptons coming from a Z boson. It requires both leptons to have opposite charge and to be of the same flavor. Additionally, the di-lepton invariant mass must be consistent with mass of the Z boson ($|m_{ll} - m_Z| \leq 15$ GeV). Since the m_{ll} cut is very effective in removing signal contamination, it is possible to keep the average H_T and $m_{b\ell}$ of the CRZ events very close to the SR: requirements of $H_T \geq 1000$ GeV and $m_{b\ell} > 700$ GeV are placed. Finally, the $m_{b\ell}$ asymmetry is required to be less than 0.2.

5.4.2.3 Single Top Control Region

A Control Region for single top has been defined, in order to constrain this additional relevant component of the background. Due to the lower cross section compared to $t\bar{t}$ and Z , it is not as easy to select a region with a large single top purity. Due to difficulties with $t\bar{t}$ contamination in this region, the $t\bar{t}$ Control region was designed to have higher statistics in order to constrain the $t\bar{t}$ normalization factor. This allows for the single top background to be lower purity, in this case the purity for single top is about 30%, while still accurately modeling its presence in this Control Region. The strategy that was utilized to achieve this goal is described in detail in Sec. 5.6.

The main difference between the single top CR and CR $t\bar{t}$ is the cut on the leading $b\ell$ mass of the rejected pairing is inverted. While $t\bar{t}$ events are expected to have both $b\ell$ masses in the rejected pairing compatible with the top mass, only one is for Single Top backgrounds. This distinction allows for cutting the leading $b\ell$ mass in the rejected pairing above the top mass to separate $t\bar{t}$ events from the Single top CR. This region additionally requires both leading jets to be b-tagged, as this strengthens the discriminating power of the higher $m_{b\ell}^0$ rej requirement. While this requirement of two b-tags is non-intuitive, the combination of this requirement on N_{Tags} in combination with the cuts on the masses of the accepted and rejected pairings is found to reduce the $t\bar{t}$ background significantly more than the single top background. For $t\bar{t}$, requiring 2 b-tags improves the confidence that we have selected the correct jets from the top decay, leading to at least one of the potential jet-lepton pairing schemes to properly reconstruct both top quarks. The cuts on accepted $m_{b\ell} \geq 180$ GeV and $m_{b\ell}^0(rej) \geq 180$ GeV are now very effective at removing $t\bar{t}$ events.

5.4.3 Validation Region Design

A set of validation regions is defined to verify the quality of the extrapolations from the control regions to the signal regions. There must be sufficient agreement between data and the extrapolation in the validation region before the signal region is unblinded. The selection criteria for the validation regions is designed to lie between the control and signal regions.

The main extrapolations are from the $t\bar{t}$ and single top control regions to the signal region. In particular, there is a significant extrapolation on the invariant mass of the leading accepted $b\ell$ pair ($m_{b\ell}^0$), on the invariant mass of the subleading rejected $b\ell$ pair ($m_{b\ell}^1(\text{rej})$), and on the H_T . For this reason, three separate validation regions are defined by keeping all the $t\bar{t}$ control region cuts and inverting the selection on these three variables respectively. The upper bound on $m_{b\ell}^0(\text{rej})$ is also removed from the validation regions. Such region allows us to validate the major extrapolations from our control regions to our signal regions. For the VR which tests extrapolation over $m_{b\ell}^1(\text{rej})$, an additional requirement of the leptons being opposite flavor (from different lepton generations) is applied to remove Z+jets contamination.

The Z+jets CR applies similar selections as the SR, with the exception of the $m_{\ell\ell}$ cut that needs to be modified to select the Z peak. For this reason, a validation region (VRZ) is defined with exactly 0 b-tagged jets, to enhance the Z+jets background with respect to $t\bar{t}$ and single top. All the other SR cuts are applied, including $m_{\ell\ell} > 300$ GeV, with the only exception being the $m_{b\ell}$ of the leading accepted pair, for which a window of $[500, 800]$ GeV is used to reduce signal contamination. In addition to VRZ, a second VR is defined to test the Z+jets extrapolation over m_{ll} without extrapolating over N_b . This region takes the same cuts as $\text{VR}M_{bl}^1(\text{rej})$, adding the requirement of the signal leptons to be of the same generation; this region is denoted $\text{VR}M_{bl}^1(\text{rej})_SF$ or VRm1_SF .

5.5 Systematic Uncertainties

The methods for identifying events as well as simulating known processes is not a perfectly precise process; there is inherently inference and approximation (guided by prior results and calibrations) that must occur during analysis. The lack of perfect information leads us to introduce a wide array of systematic uncertainties that must be accounted for. Systematic Uncertainties (colloquially systematics) can originate from source such as limited computational power or statistics in MC generation, detector measurements and identification algorithms, and bounds on theoretical constants (such as α_S). These systematics are often sorted into three main categories: Experimental Uncertainties, Theoretical Uncertainties, and Statistical Uncertainties. It is important to account for each source of uncertainty as they can shift the expected yields in each of the analysis region, affecting limit setting capability. Each source of systematic uncertainty is treated as a

Nuisance Parameter (NP) and accounted for in the overall statistical model (described in further detail in Sec. 5.8.1). Systematics are computed for each analysis region separately and treated as correlated across regions unless otherwise specified.

The following sections describe the various sources of systematic uncertainty that have been accounted for by this analysis. A summary of these uncertainties for all Control Regions and Validation Regions can be found in Tables 5.9–5.11. The systematic uncertainties for the signal regions can be found in Appendix E. Systematics which do not exceed a relative uncertainty of 1% are pruned prior to the full statistical treatment to limit computational complexity.

5.5.1 Statistical Uncertainties

Statistical limitations in MC simulation are evaluated in each region by applying the standard Poisson uncertainty of $\sqrt{N}$. In addition to the standard statistical uncertainty application, finite MC statistics can also lead to poor modeling of select theoretical uncertainties; these effects are accounted for within the respective theoretical uncertainties and do not require independent nuisance parameters.

5.5.2 Experimental Systematics

Experimental uncertainties account for the limitations experienced when performing detector measurements. These uncertainties account for a wide range of sources, such as measurement of particle energy, efficiency in object reconstruction and identification, and detector response to energy deposits in calorimeters. The dominant sources of experimental uncertainty are relating to the measurement of jets and identification of b-quark initiated jets [68–70]. These sources are expected as jets do not form clean tracks like leptons and depend heavily on the clustering algorithms previously described. Due to the use of b-jets as an integral part of the search signature, the suite of uncertainties associated to b-jet identification efficiency is the largest observed experimental uncertainty. Experimental systematics are treated as Gaussian nuisance parameters which are correlated across regions.

In total, approximately 60 sources of experimental uncertainty are accounted for and applied to each SM background process independently. A summary of the full suite of experimental systematics accounted for is given below:

- **JES/JER:** Uncertainties on the jet energy scale (JES) and jet energy resolution (JER) can affect the event selection process. By taking in a jet’s measured p_T and η , observables of the jet can be systematically altered to better reflect their true values. Since this process can affect event selection, every event is processed an additional time for each possible up and down variation of each JES/JER

Uncertainty of channel	CRtt	CRst	CRZ
Total background expectation	3270.01	713.04	301.16
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 57.18	± 26.70	± 17.35
Total background systematic	± 57.20 [1.75%]	± 26.65 [3.74%]	± 17.35 [5.76%]
mu_ttbar	± 97.47 [3.0%]	± 11.61 [1.6%]	± 0.02 [0.01%]
alpha_theory_PDFaS_ttbar_region_CRtt	± 61.75 [1.9%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_scale_muRmuF_ttbar	± 25.62 [0.78%]	± 25.37 [3.6%]	± 0.25 [0.08%]
alpha_theory_rad_FSR_ttbar	± 21.23 [0.65%]	± 21.29 [3.0%]	± 0.08 [0.03%]
gamma_stat_region_CRtt_cuts_bin_0	± 12.29 [0.38%]	± 0.00 [0.00%]	± 0.00 [0.00%]
mu_SingleTop	± 11.51 [0.35%]	± 55.80 [7.8%]	± 0.07 [0.02%]
alpha_theory_rad_FSR_SingleTop	± 1.67 [0.05%]	± 0.00 [0.00%]	± 0.21 [0.07%]
alpha_theory_PDFaS_SingleTop_region_CRtt	± 1.24 [0.04%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_scale_muRmuF_SingleTop	± 1.18 [0.04%]	± 0.00 [0.00%]	± 0.09 [0.03%]
alpha_FT_EFF_B_systematics	± 0.98 [0.03%]	± 4.23 [0.59%]	± 0.00 [0.00%]
alpha_JET_JER_EffectiveNP_3_1up	± 0.93 [0.03%]	± 0.56 [0.08%]	± 2.47 [0.82%]
alpha_theory_scale_muF_SingleTop	± 0.82 [0.02%]	± 0.00 [0.00%]	± 0.05 [0.02%]
alpha_JET_Flavor_Response	± 0.61 [0.02%]	± 3.20 [0.45%]	± 0.27 [0.09%]
alpha_JET_JER_DataVsMC_1up	± 0.60 [0.02%]	± 0.07 [0.01%]	± 0.10 [0.03%]
alpha_theory_scale_muR_Zjets	± 0.48 [0.01%]	± 0.99 [0.14%]	± 0.00 [0.00%]
alpha_theory_scale_muRmuF_Zjets	± 0.47 [0.01%]	± 1.54 [0.22%]	± 0.00 [0.00%]
mu_Zjets	± 0.44 [0.01%]	± 1.04 [0.15%]	± 24.71 [8.2%]
alpha_JET_JER_EffectiveNP_1_1up	± 0.40 [0.01%]	± 0.74 [0.10%]	± 2.64 [0.88%]
alpha_JET_Flavor_Composition	± 0.37 [0.01%]	± 3.02 [0.42%]	± 0.19 [0.06%]
alpha_MUON_SAGITTA_RESBIAS	± 0.23 [0.01%]	± 0.13 [0.02%]	± 0.08 [0.03%]
alpha_JET_JER_EffectiveNP_2_1up	± 0.19 [0.01%]	± 0.60 [0.08%]	± 2.53 [0.84%]
alpha_JET_EtaIntercalibration_Modelling	± 0.18 [0.01%]	± 0.03 [0.00%]	± 0.04 [0.01%]
alpha_JET_JER_EffectiveNP_6_1up	± 0.18 [0.01%]	± 0.75 [0.10%]	± 0.18 [0.06%]
alpha_JET_Pileup_RhoTopology	± 0.18 [0.01%]	± 0.30 [0.04%]	± 0.00 [0.00%]
alpha_JET_JER_EffectiveNP_5_1up	± 0.17 [0.01%]	± 0.55 [0.08%]	± 0.15 [0.05%]
Lumi	± 0.16 [0.00%]	± 0.11 [0.02%]	± 0.20 [0.06%]
alpha_theory_PDFaS_Zjets_region_CRtt	± 0.15 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_FT_EFF_extrapolation	± 0.13 [0.00%]	± 0.31 [0.04%]	± 0.55 [0.18%]
alpha_theory_scale_muF_Zjets	± 0.10 [0.00%]	± 0.58 [0.08%]	± 0.00 [0.00%]
alpha_JET_EtaIntercalibration_NonClosure_2018data	± 0.10 [0.00%]	± 0.09 [0.01%]	± 0.01 [0.00%]
alpha_JET_EffectiveNP_Modelling3	± 0.09 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_JET_Pileup_OffsetMu	± 0.09 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_FT_EFF_Light_systematics	± 0.09 [0.00%]	± 11.89 [1.7%]	± 0.82 [0.27%]
alpha_JET_EffectiveNP_Modelling1	± 0.07 [0.00%]	± 0.16 [0.02%]	± 0.05 [0.01%]
alpha_JET_EffectiveNP_Mixed2	± 0.07 [0.00%]	± 0.00 [0.00%]	± 0.01 [0.00%]
alpha_theory_rad_ISR_SingleTop	± 0.07 [0.00%]	± 0.00 [0.00%]	± 0.15 [0.05%]
alpha_FT_EFF_C_systematics	± 0.06 [0.00%]	± 0.35 [0.05%]	± 0.28 [0.09%]
alpha_MUON_ID	± 0.06 [0.00%]	± 0.01 [0.00%]	± 0.00 [0.00%]
alpha_EG_SCALE_ALL	± 0.04 [0.00%]	± 0.06 [0.01%]	± 0.28 [0.09%]
alpha_JET_EffectiveNP_Mixed1	± 0.04 [0.00%]	± 0.11 [0.02%]	± 0.13 [0.04%]
alpha_MUON_MS	± 0.03 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_JET_JER_EffectiveNP_4_1up	± 0.03 [0.00%]	± 0.61 [0.09%]	± 0.18 [0.06%]
alpha_JET_Pileup_PtTerm	± 0.02 [0.00%]	± 0.15 [0.02%]	± 0.00 [0.00%]
alpha_EL_EFF_ID_TOTAL_INPCOR_PLUS_UNCOR	± 0.01 [0.00%]	± 0.00 [0.00%]	± 0.32 [0.10%]
alpha_EL_EFF_Reco_TOTAL_INPCOR_PLUS_UNCOR	± 0.01 [0.00%]	± 0.00 [0.00%]	± 0.25 [0.08%]
alpha_JET_JER_EffectiveNP_7restTerm_1up	± 0.01 [0.00%]	± 0.68 [0.10%]	± 2.44 [0.81%]
alpha_theory_PDFaS_Zjets_region_SR400_bin5a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_PDFaS_ttbar_region_CRZ	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.04 [0.01%]
alpha_theory_PDFaS_ttbar_region_CRst	± 0.00 [0.00%]	± 8.69 [1.2%]	± 0.00 [0.00%]
gamma_stat_region_CRZ_cuts_bin_0	± 0.00 [0.00%]	± 0.00 [0.00%]	± 3.95 [1.3%]
alpha_JET_Pileup_OffsetNPV	± 0.00 [0.00%]	± 0.26 [0.04%]	± 0.00 [0.00%]
alpha_theory_scale_muF_ttbar	± 0.00 [0.00%]	± 5.37 [0.75%]	± 0.09 [0.03%]
alpha_theory_scale_muR_ttbar	± 0.00 [0.00%]	± 18.92 [2.7%]	± 0.14 [0.05%]
alpha_theory_rad_ISR_ttbar	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.06 [0.02%]
alpha_theory_PDFaS_Zjets_region_CRst	± 0.00 [0.00%]	± 0.34 [0.05%]	± 0.00 [0.00%]
alpha_theory_PDFaS_Zjets_region_CRZ	± 0.00 [0.00%]	± 0.00 [0.00%]	± 16.20 [5.4%]
gamma_stat_region_CRst_cuts_bin_0	± 0.00 [0.00%]	± 7.93 [1.1%]	± 0.00 [0.00%]
alpha_theory_PDFaS_SingleTop_region_CRst	± 0.00 [0.00%]	± 6.93 [0.97%]	± 0.00 [0.00%]
alpha_JET_EffectiveNP_Statistical3	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.01 [0.00%]

Table 5.9: Breakdown of the dominant systematic uncertainties on background estimates in the CRs. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty.

Uncertainty of channel	VRm0	VRm1_OF	VRm1_SF
Total background expectation	348.34	68.44	117.56
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 18.66	± 8.27	± 10.84
Total background systematic	± 27.23 [7.82%]	± 6.13 [8.95%]	± 9.27 [7.89%]
alpha_theory_scale_muRmuF_ttbar	± 18.90 [5.4%]	± 3.19 [4.7%]	± 3.33 [2.8%]
alpha_theory_scale_muR_ttbar	± 10.50 [3.0%]	± 1.99 [2.9%]	± 2.28 [1.9%]
alpha_theory_rad_FSR_ttbar	± 10.16 [2.9%]	± 2.05 [3.0%]	± 1.80 [1.5%]
mu_ttbar	± 9.33 [2.7%]	± 1.04 [1.5%]	± 1.06 [0.90%]
alpha_theory_PDFaS_ttbar_region_VRm0	± 9.12 [2.6%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_scale_muF_ttbar	± 8.11 [2.3%]	± 1.07 [1.6%]	± 0.93 [0.79%]
mu_SingleTop	± 6.93 [2.0%]	± 4.54 [6.6%]	± 4.90 [4.2%]
alpha_JET_Flavor_Composition	± 2.11 [0.60%]	± 1.33 [1.9%]	± 0.83 [0.71%]
alpha_theory_scale_muRmuF_SingleTop	± 1.78 [0.51%]	± 1.18 [1.7%]	± 1.29 [1.1%]
alpha_theory_PDFaS_SingleTop_region_VRm0	± 1.44 [0.41%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_rad_FSR_SingleTop	± 1.18 [0.34%]	± 2.59 [3.8%]	± 3.29 [2.8%]
alpha_JET_JER_DataVsMC_lup	± 1.13 [0.32%]	± 0.65 [0.95%]	± 0.40 [0.34%]
alpha_theory_scale_muF_SingleTop	± 1.03 [0.30%]	± 0.40 [0.59%]	± 0.42 [0.36%]
alpha_JET_Pileup_OffsetNPV	± 0.85 [0.25%]	± 0.03 [0.05%]	± 0.52 [0.44%]
alpha_JET_Pileup_OffsetMu	± 0.83 [0.24%]	± 0.00 [0.00%]	± 0.27 [0.23%]
alpha_JET_EtaIntercalibration_Modelling	± 0.78 [0.22%]	± 0.37 [0.54%]	± 0.46 [0.39%]
alpha_theory_scale_muR_SingleTop	± 0.77 [0.22%]	± 0.80 [1.2%]	± 0.90 [0.76%]
alpha_JET_JER_EffectiveNP_7restTerm_lup	± 0.59 [0.17%]	± 0.03 [0.05%]	± 0.40 [0.34%]
alpha_FT_EFF_B_systematics	± 0.58 [0.17%]	± 0.00 [0.00%]	± 0.31 [0.27%]
alpha_JET_Pileup_RhoTopology	± 0.58 [0.17%]	± 0.45 [0.66%]	± 1.59 [1.4%]
alpha_theory_rad_ISR_SingleTop	± 0.52 [0.15%]	± 0.56 [0.82%]	± 0.00 [0.00%]
alpha_JET_Flavor_Response	± 0.49 [0.14%]	± 1.30 [1.9%]	± 1.00 [0.85%]
alpha_JET_EffectiveNP_Modelling1	± 0.39 [0.11%]	± 0.63 [0.92%]	± 1.34 [1.1%]
alpha_JET_EffectiveNP_Mixed1	± 0.28 [0.08%]	± 0.00 [0.00%]	± 0.01 [0.01%]
alpha_JET_EtaIntercalibration_NonClosure_negEta	± 0.24 [0.07%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_JET_Pileup_PtTerm	± 0.19 [0.05%]	± 0.04 [0.05%]	± 0.54 [0.46%]
alpha_MUON_SAGITTA_RESBIAS	± 0.19 [0.05%]	± 0.23 [0.33%]	± 0.63 [0.54%]
alpha_JET_EtaIntercalibration_NonClosure_2018data	± 0.18 [0.05%]	± 0.07 [0.10%]	± 0.44 [0.37%]
alpha_JET_JER_EffectiveNP_5_lup	± 0.18 [0.05%]	± 0.53 [0.78%]	± 0.20 [0.17%]
alpha_JET_JER_EffectiveNP_1_lup	± 0.16 [0.05%]	± 0.20 [0.29%]	± 0.19 [0.16%]
alpha_theory_scale_muRmuF_Zjets	± 0.15 [0.04%]	± 0.00 [0.00%]	± 3.59 [3.1%]
alpha_JET_JER_EffectiveNP_4_lup	± 0.14 [0.04%]	± 0.04 [0.06%]	± 0.17 [0.15%]
mu_Zjets	± 0.13 [0.04%]	± 0.01 [0.02%]	± 4.01 [3.4%]
alpha_JET_JER_EffectiveNP_6_lup	± 0.13 [0.04%]	± 0.06 [0.09%]	± 0.12 [0.10%]
alpha_JET_JER_EffectiveNP_2_lup	± 0.12 [0.03%]	± 0.90 [1.3%]	± 1.24 [1.1%]
alpha_theory_scale_muR_Zjets	± 0.11 [0.03%]	± 0.00 [0.01%]	± 2.67 [2.3%]
alpha_theory_scale_muF_Zjets	± 0.04 [0.01%]	± 0.00 [0.01%]	± 1.04 [0.89%]
alpha_EG_RESOLUTION_ALL	± 0.04 [0.01%]	± 0.27 [0.39%]	± 0.05 [0.04%]
alpha_FT_EFF_extrapolation	± 0.04 [0.01%]	± 0.00 [0.01%]	± 1.22 [1.0%]
Lumi	± 0.03 [0.01%]	± 0.08 [0.11%]	± 0.09 [0.08%]
alpha_JET_JER_EffectiveNP_3_lup	± 0.03 [0.01%]	± 0.13 [0.20%]	± 0.67 [0.57%]
alpha_JET_EffectiveNP_Statistical3	± 0.03 [0.01%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_JET_EffectiveNP_Statistical5	± 0.03 [0.01%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_JET_EtaIntercalibration_TotalStat	± 0.03 [0.01%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_FT_EFF_C_systematics	± 0.02 [0.01%]	± 0.09 [0.13%]	± 0.13 [0.11%]
alpha_EG_SCALE_ALL	± 0.02 [0.01%]	± 0.69 [1.0%]	± 0.99 [0.84%]
alpha_FT_EFF_Light_systematics	± 0.02 [0.01%]	± 0.73 [1.1%]	± 0.34 [0.29%]
alpha_MUON_MS	± 0.01 [0.00%]	± 0.24 [0.35%]	± 0.03 [0.02%]
alpha_JET_BJES_Response	± 0.01 [0.00%]	± 0.03 [0.05%]	± 0.32 [0.27%]
alpha_EL_EFF_ID_TOTAL_1NPCOR_PLUS_UNCOR	± 0.01 [0.00%]	± 0.01 [0.02%]	± 0.02 [0.02%]
alpha_MUON_SCALE	± 0.01 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_EL_EFF_Reco_TOTAL_1NPCOR_PLUS_UNCOR	± 0.00 [0.00%]	± 0.01 [0.01%]	± 0.02 [0.01%]
alpha_MUON_ID	± 0.00 [0.00%]	± 0.16 [0.24%]	± 0.01 [0.00%]
alpha_theory_PDFaS_ttbar_region_VRm1_SF	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.29 [0.25%]
alpha_theory_PDFaS_SingleTop_region_VRm1_OF	± 0.00 [0.00%]	± 0.27 [0.40%]	± 0.00 [0.00%]
alpha_theory_PDFaS_Zjets_region_VRm1_SF	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.43 [0.37%]
alpha_theory_rad_ISR_ttbar	± 0.00 [0.00%]	± 0.38 [0.56%]	± 0.47 [0.40%]
alpha_theory_PDFaS_ttbar_region_VRm1_OF	± 0.00 [0.00%]	± 0.28 [0.41%]	± 0.00 [0.00%]
alpha_theory_PDFaS_SingleTop_region_VRm1_SF	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.23 [0.20%]
alpha_JET_EtaIntercalibration_NonClosure_posEta	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.22 [0.19%]

Table 5.10: Breakdown of the dominant systematic uncertainties on background estimates in VRs. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty.

Uncertainty of channel	VRht	VRZ
Total background expectation	246.47	161.86
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 15.70	± 12.72
Total background systematic	± 12.82 [5.20%]	± 17.86 [11.03%]
mu_SingleTop	± 9.49 [3.9%]	± 1.45 [0.90%]
mu_ttbar	± 5.63 [2.3%]	± 1.45 [0.90%]
alpha_theory_scale_muRmuF_SingleTop	± 5.39 [2.2%]	± 1.34 [0.83%]
alpha_theory_scale_muRmuF_ttbar	± 5.24 [2.1%]	± 11.75 [7.3%]
alpha_theory_scale_muR_ttbar	± 4.94 [2.0%]	± 6.74 [4.2%]
alpha_theory_rad_FSR_SingleTop	± 4.32 [1.8%]	± 0.34 [0.21%]
alpha_theory_PDFaS_ttbar_region_VRht	± 4.00 [1.6%]	± 0.00 [0.00%]
alpha_theory_scale_muR_SingleTop	± 2.82 [1.1%]	± 0.77 [0.48%]
alpha_theory_rad_FSR_ttbar	± 2.76 [1.1%]	± 2.92 [1.8%]
alpha_theory_scale_muF_SingleTop	± 2.63 [1.1%]	± 0.59 [0.36%]
alpha_theory_rad_ISR_SingleTop	± 1.40 [0.57%]	± 0.22 [0.13%]
alpha_theory_PDFaS_SingleTop_region_VRht	± 1.36 [0.55%]	± 0.00 [0.00%]
alpha_JET_JER_EffectiveNP_6_lup	± 1.04 [0.42%]	± 0.24 [0.15%]
alpha_EG_SCALE_ALL	± 0.76 [0.31%]	± 0.10 [0.06%]
alpha_JET_JER_DataVsMC_lup	± 0.52 [0.21%]	± 0.33 [0.21%]
alpha_JET_Pileup_RhoTopology	± 0.45 [0.18%]	± 0.01 [0.01%]
alpha_JET_JER_EffectiveNP_2_lup	± 0.44 [0.18%]	± 0.67 [0.42%]
alpha_JET_JER_EffectiveNP_1_lup	± 0.41 [0.17%]	± 0.94 [0.58%]
alpha_JET_EtaIntercalibration_NonClosure_2018data	± 0.40 [0.16%]	± 0.43 [0.26%]
alpha_MUON_SAGITTA_DATASTAT	± 0.39 [0.16%]	± 0.00 [0.00%]
mu_Zjets	± 0.37 [0.15%]	± 6.04 [3.7%]
alpha_JET_Pileup_OffsetNPV	± 0.34 [0.14%]	± 0.10 [0.06%]
alpha_MUON_MS	± 0.33 [0.13%]	± 0.06 [0.04%]
alpha_MUON_ID	± 0.32 [0.13%]	± 0.00 [0.00%]
alpha_JET_JER_EffectiveNP_3_lup	± 0.32 [0.13%]	± 0.77 [0.47%]
alpha_JET_JER_EffectiveNP_5_lup	± 0.27 [0.11%]	± 0.35 [0.22%]
alpha_theory_scale_muR_Zjets	± 0.26 [0.10%]	± 3.04 [1.9%]
alpha_JET_JER_EffectiveNP_7restTerm_lup	± 0.25 [0.10%]	± 0.62 [0.38%]
alpha_JET_JER_EffectiveNP_4_lup	± 0.24 [0.10%]	± 0.27 [0.17%]
alpha_JET_EffectiveNP_Modelling1	± 0.24 [0.10%]	± 0.13 [0.08%]
alpha_theory_scale_muRmuF_Zjets	± 0.18 [0.07%]	± 2.84 [1.8%]
alpha_JET_BJES_Response	± 0.18 [0.07%]	± 0.13 [0.08%]
alpha_MUON_SAGITTA_RESBIAS	± 0.18 [0.07%]	± 0.99 [0.61%]
alpha_JET_Flavor_Response	± 0.11 [0.05%]	± 1.31 [0.81%]
alpha_FT_EFF_extrapolation	± 0.11 [0.04%]	± 2.43 [1.5%]
alpha_JET_EtaIntercalibration_Modelling	± 0.09 [0.03%]	± 0.18 [0.11%]
alpha_JET_Flavor_Composition	± 0.09 [0.03%]	± 0.98 [0.61%]
alpha_EL_EFF_ID_TOTAL_INPCOR_PLUS_UNCOR	± 0.07 [0.03%]	± 0.52 [0.32%]
alpha_theory_PDFaS_Zjets_region_VRht	± 0.07 [0.03%]	± 0.00 [0.00%]
alpha_theory_scale_muF_Zjets	± 0.07 [0.03%]	± 0.00 [0.00%]
alpha_FT_EFF_C_systematics	± 0.05 [0.02%]	± 0.70 [0.43%]
Lumi	± 0.05 [0.02%]	± 0.32 [0.20%]
alpha_JET_EffectiveNP_Mixed1	± 0.03 [0.01%]	± 0.57 [0.35%]
alpha_JET_Pileup_OffsetMu	± 0.03 [0.01%]	± 0.00 [0.00%]
alpha_JET_Pileup_PtTerm	± 0.03 [0.01%]	± 0.07 [0.04%]
alpha_EL_EFF_Reco_TOTAL_INPCOR_PLUS_UNCOR	± 0.03 [0.01%]	± 0.10 [0.06%]
alpha_MUON_SCALE	± 0.02 [0.01%]	± 0.00 [0.00%]
alpha_EG_RESOLUTION_ALL	± 0.02 [0.01%]	± 0.32 [0.20%]
alpha_FT_EFF_Light_systematics	± 0.01 [0.00%]	± 5.10 [3.2%]
alpha_theory_PDFaS_ttbar_region_VRZ	± 0.00 [0.00%]	± 1.85 [1.1%]
alpha_theory_PDFaS_SingleTop_region_VRZ	± 0.00 [0.00%]	± 0.42 [0.26%]
alpha_theory_scale_muF_ttbar	± 0.00 [0.00%]	± 4.50 [2.8%]
alpha_FT_EFF_B_systematics	± 0.00 [0.00%]	± 1.06 [0.65%]
alpha_JET_EffectiveNP_Modelling4	± 0.00 [0.00%]	± 0.46 [0.29%]
alpha_theory_rad_ISR_ttbar	± 0.00 [0.00%]	± 1.63 [1.0%]
alpha_theory_PDFaS_Zjets_region_VRZ	± 0.00 [0.00%]	± 2.39 [1.5%]
alpha_JET_EffectiveNP_Mixed2	± 0.00 [0.00%]	± 0.09 [0.05%]
alpha_JET_EffectiveNP_Modelling2	± 0.00 [0.00%]	± 0.48 [0.29%]
alpha_JET_EffectiveNP_Statistical6	± 0.00 [0.00%]	± 0.46 [0.29%]
alpha_JET_EffectiveNP_Statistical3	± 0.00 [0.00%]	± 0.45 [0.28%]
alpha_JET_EffectiveNP_Statistical1	± 0.00 [0.00%]	± 0.08 [0.05%]

Table 5.11: Breakdown of the dominant systematic uncertainties on background estimates in VRs. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty.

NP. Systematics are grouped into categories based on their correlation in order to reduce the required computation power.

- **B-tagging:** The efficiency of identifying b-quark initiated jets has been observed to vary between data and MC. To account for this disagreement, a scale factor is applied to each MC event to match the efficiency observed in data. An upward and downward uncertainty is applied to the efficiency scale factor for b, c, and light jets separately. This process does not affect the event selection process and thus is applied as a weight uncertainty on each MC event.
- **Jet Pileup:** These uncertainties are associated to the efficiency of identifying a jet as originating from pileup. These uncertainties are calculated by the Jet Vertex Tagger (JVT) and can affect whether or not a jet is considered for analysis. For this reason, pileup uncertainties require events to be reprocessed.
- **Lepton Energy Scale and Resolution:** This set accounts for the uncertainties on the calibration of electron/muon energy, momentum, and resolution measurements. As with the JES/JER uncertainties, these can affect the event selection process and require each event to be reprocessed an additional time for each up/down variation [64, 71].
- **Lepton Efficiency:** Similar to the b-tagging efficiency uncertainties, these account for the uncertainty on the scale factors applied to MC to match data yields for leptons. These account uncertainties on the SFs associated to reconstruction, identification, isolation, and trigger efficiency matching. These are applied at the event level as a weight uncertainty as the event selection is unaffected.
- **Luminosity:** A flat 0.83% uncertainty is applied to the measurement of integrated luminosity. It is derived following a methodology similar to that detailed in Ref. [72] and using the LUCID-2 detector for the baseline luminosity measurements, from calibration of the luminosity scale using the x-y beam-separation scans.

5.5.3 Theoretical Systematics

Theoretical uncertainties account for the mismodeling of event yield or shape in MC simulation. These uncertainties include, but are not limited to, shape uncertainties from the chosen renormalization/factorization scale (μ_R, μ_F), choice of strong coupling constant (α_S), and the chosen PDFs. Each of the above can affect the amount of observed Initial State Radiation (ISR) Final State Radiation (FSR) in each analysis region differently and must be computed separately for orthogonal regions. Additional theoretical uncertainties stem from the choice of Monte Carlo generator: different generators compute Matrix Elements (ME) differently

and also model the parton showering effects distinctly. The following sections describe the various sources of theoretical systematic uncertainty, with the largest contribution from the modelling of top backgrounds (described in depth in Sec. 5.5.3.2).

5.5.3.1 Cross-section Uncertainty

For all processes, there exists uncertainty on the production cross-section. Normalized backgrounds ($t\bar{t}$, Single Top, Z+jets) are expected to have these uncertainties cancel out in the fitting process. However, for minor backgrounds which are not normalized to data, such as W+jets, a conservative uncertainty is applied to the respective production cross-section during limit setting.

5.5.3.2 Top Systematics

A set of systematic uncertainties are evaluated separately for $t\bar{t}$ and single top. These systematic uncertainties played a major role in optimizing the Signal Region bin width, described in Sec. 5.7. Top systematics are calculated as uncertainties on the transfer factor from the relevant Control Region to the SR calculated in the following way for MC generator and parton shower Uncertainties:

$$\text{TF} = \frac{(\frac{\text{SR}}{\text{CR}})_{\text{shifted}} - (\frac{\text{SR}}{\text{CR}})_{\text{nominal}}}{(\frac{\text{SR}}{\text{CR}})_{\text{nominal}}} \quad (5.4)$$

And for ISR and FSR uncertainties using:

$$\text{TF} = \frac{(\frac{\text{SR}}{\text{CR}})_{\text{up}} - (\frac{\text{SR}}{\text{CR}})_{\text{down}}}{(\frac{\text{SR}}{\text{CR}})_{\text{up}} + (\frac{\text{SR}}{\text{CR}})_{\text{down}}} \quad (5.5)$$

The systematic uncertainties are calculated bin-by-bin with their relative uncertainties summarized in Figures 5.8–5.11. Due to statistics constraints from dividing the limited Monte Carlo events for a multi-bin fit, a loose version of the Signal Region which relaxes the Mbl asymmetry requirement from 0.2 to 0.4 was employed. Several systematic variations on the $t\bar{t}$ background are applied. These include:

- **MC generator:** Uncertainties associated with the generator were considered by comparing the Powheg+Herwig $t\bar{t}$ sample with the aMC@NLO+Herwig sample.
- **Parton Shower:** The uncertainty in the parton shower was evaluated by comparing Powheg+Herwig with the nominal Powheg+Pythia.

The systematic uncertainties applied to the single top background include:

- **MC generator:** The uncertainty associated with the different generators was accounted for by comparing the prediction from Powheg+Herwig with that from aMC@NLO+Herwig.

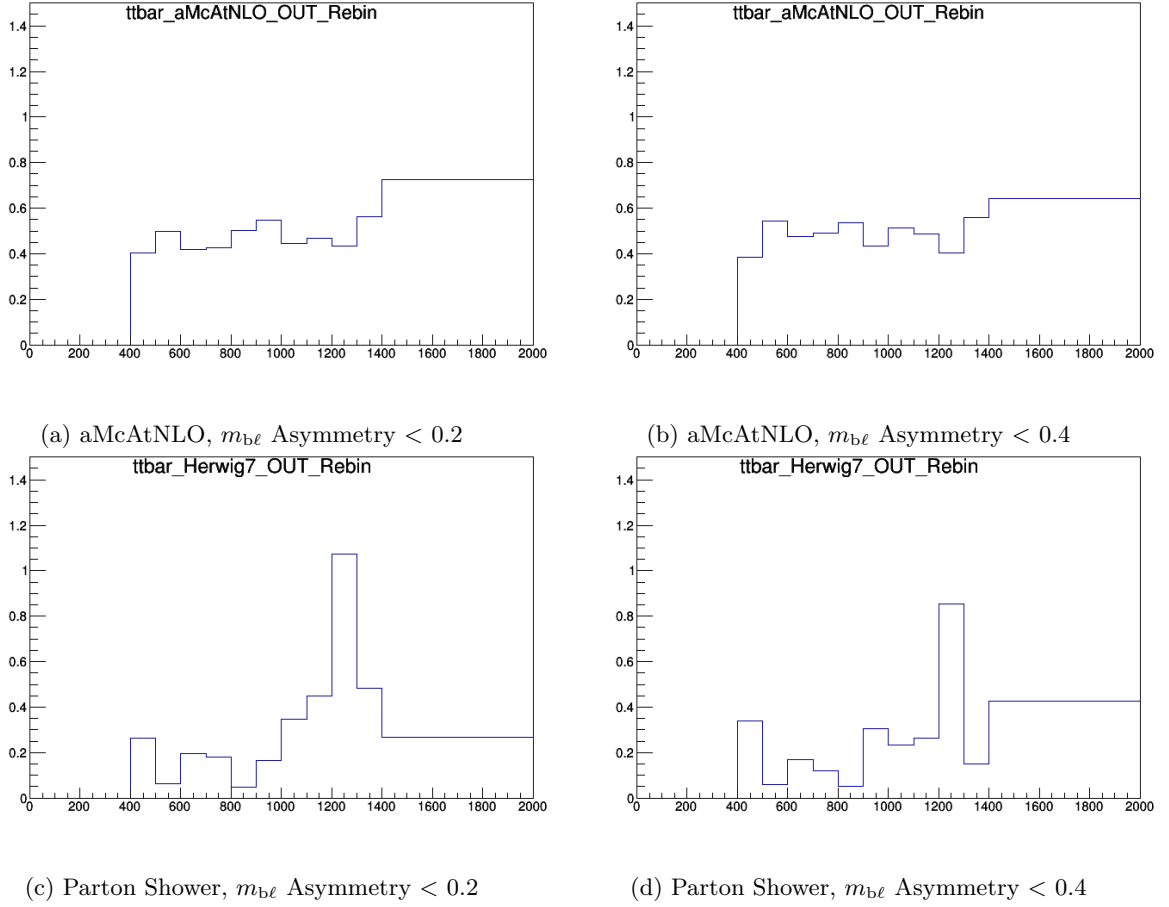


Figure 5.8: The theoretical uncertainties for the $t\bar{t}$ process with an SR bin width of 100 GeV. Uncertainties are given both with the nominal $m_{b\ell}$ Asymmetry cut of 0.2 as well as with a loosened cut of 0.4 to improve statistics.

- **Parton Shower:** The uncertainty associated with the parton showering was evaluated by comparing the prediction from Powheg+Pythia with that from Powheg+Herwig.
- **WWbb Interference:** The uncertainty associated with the interference effects between $t\bar{t}$, single top Wt and inclusive $WWbb$ production. This effect is further described in Sec. 5.5.3.3.

5.5.3.3 WWbb Interference Effects

For regions with significant contributions from Single Top Wt(b) and $t\bar{t}$, the interference effects of Leading Order (LO) $t\bar{t}$ with Next To Leading Order (NLO) Wt(b) must be considered. The nominal prescription for simulating Wt utilizes the Diagram Removal (DR) scheme for isolating Wt processes from $t\bar{t}$ bar. This

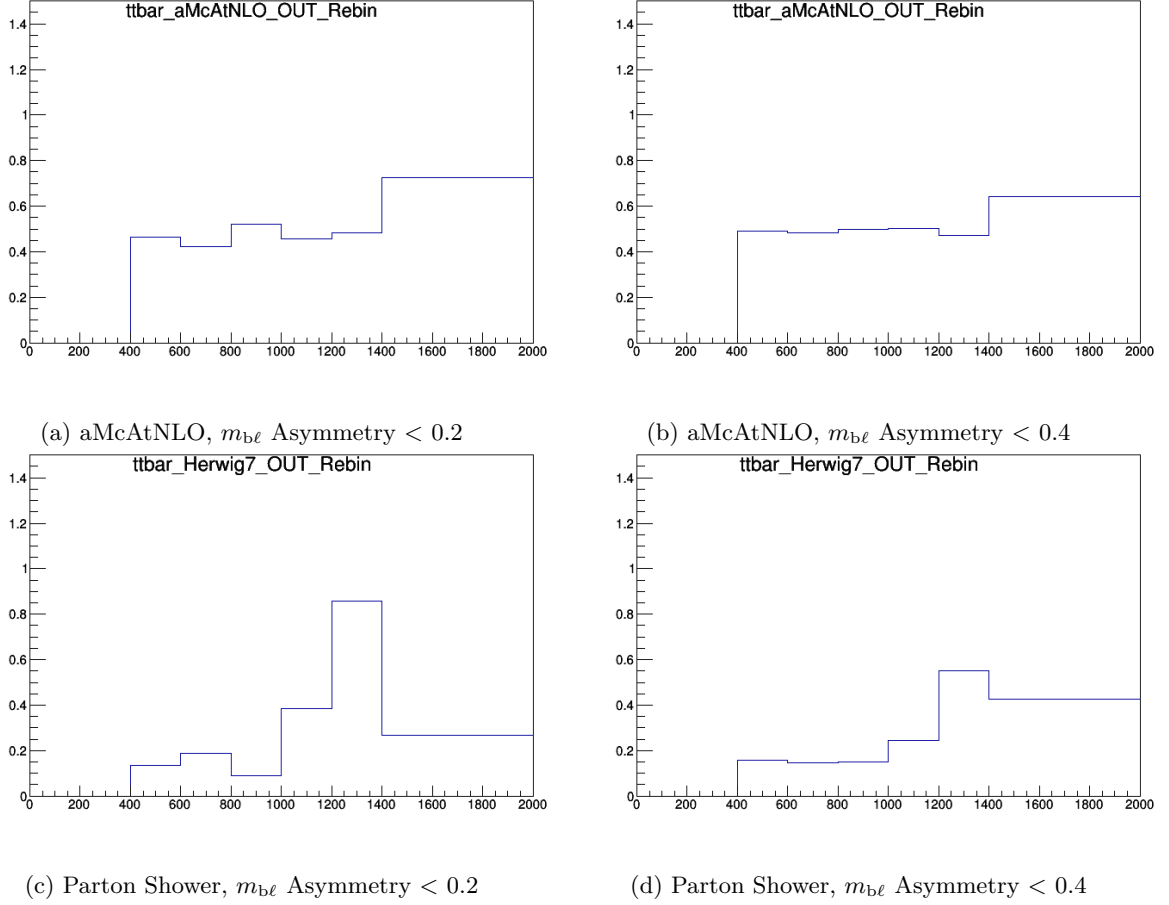


Figure 5.9: The theoretical uncertainties for the $t\bar{t}$ process with an SR bin width of 200 GeV. Uncertainties are given both with the nominal $m_{b\ell}$ Asymmetry cut of 0.2 as well as with a loosened cut of 0.4 to improve statistics.

only looks at the $|A^{tb}|^2$ portion of the $WWbb$ amplitude when calculating $Wt(b)$ production cross section, ignoring interference terms with $t\bar{t}$. The current ATLAS prescription is to use three Leading Order, Inclusive $WWbb$ samples generated using MG5_aMC@NLO split by the following scheme:

- **Double Resonant:** Requires the presence of two s-channel top quarks
- **Single Resonant:** Requires exactly one s-channel top quark and exactly 2 b-quarks in the final state at the Matrix Element (ME) level while vetoing the presence of two s-channel top quarks
- **Sum:** Requires at least one s-channel top quark and exactly 2-quarks in the final state at ME level

These samples are then compared to one another to calculate a relative uncertainty on the Single Top

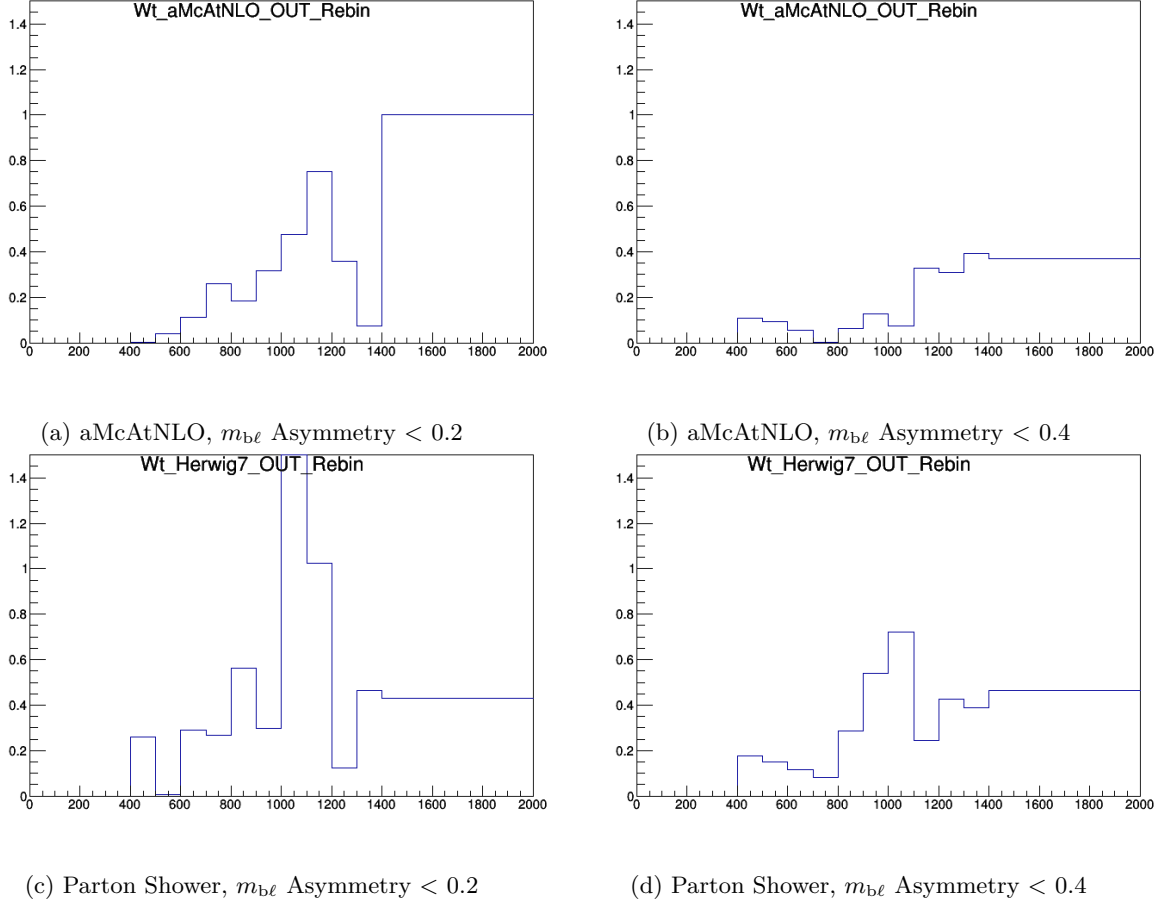


Figure 5.10: The theoretical uncertainties for the Wt process with an SR bin width of 100 GeV. Uncertainties are given both with the nominal $m_{b\ell}$ Asymmetry cut of 0.2 as well as with a loosened cut of 0.4 to improve statistics.

Wt(b) yields in each region with the following:

$$\text{Uncert}_{\text{WWbb}} = 1 - \frac{(\text{Sum} - \text{DoubleResonant})}{\text{SingleResonant}} \quad (5.6)$$

This is then applied as a Transfer Factor uncertainty in the Signal Region using the result as the shifted SR and CR yields. The bin-by-bin results are given in Figs. 5.12 and 5.13.

5.5.3.4 Internal Weight Systematics

Uncertainties on the renormalization and factorization (QCD) scales, α_s , and PDF error set were propagated to the samples as internal weights. Following PDF4LHC recommendations [73], a new background prediction

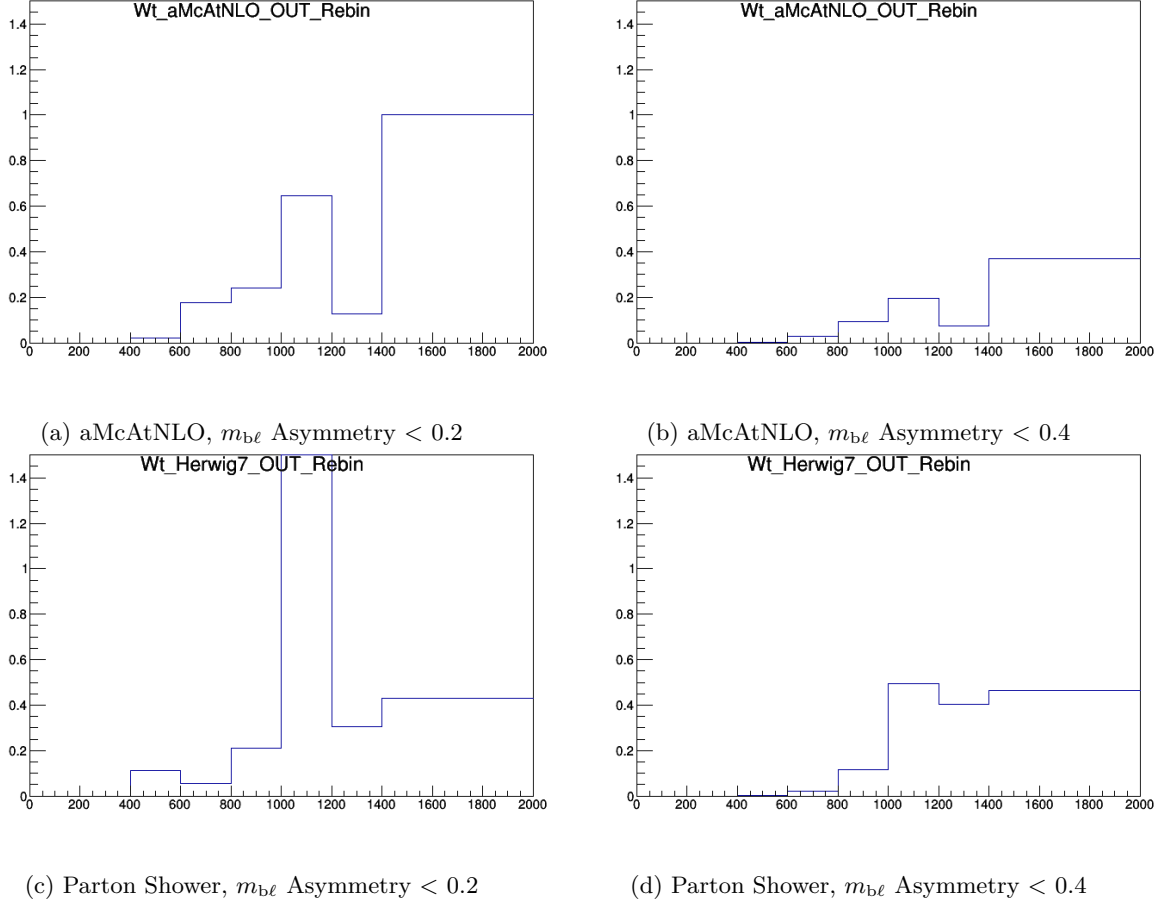


Figure 5.11: The theoretical uncertainties for the Wt process with an SR bin width of 200 GeV. Uncertainties are given both with the nominal $m_{b\ell}$ Asymmetry cut of 0.2 as well as with a loosened cut of 0.4 to improve statistics.

is derived in the $m_{b\ell}$ distribution of every SR for each of the variations. In each bin of the $m_{b\ell}$, the uncertainties are derived as follows.

- **QCD:** Six QCD scale NP variations change the scales (independently) by factors of 0.5 and 2, while avoiding opposite factors. Each QCD scale NP is propagated per-event to the final result, and is treated as correlated between regions (and therefore $m_{b\ell}$ bins), but is treated as uncorrelated between background categories. This uncertainty may therefore be constrained by the CR normalization procedure.
- α_S : Half the difference in event yield between the up and down variations, which each represent ± 0.001 shifts in α_S .

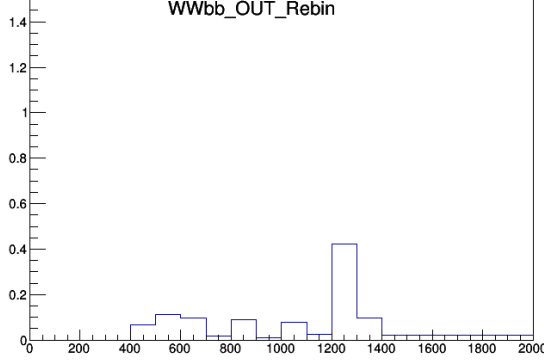
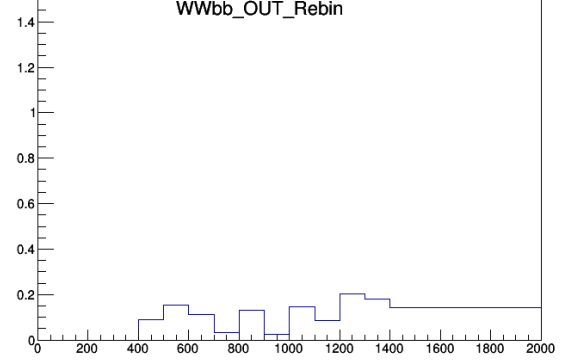
(a) WWbb Interference, $m_{b\ell}$ Asymmetry < 0.2 (b) WWbb Interference, $m_{b\ell}$ Asymmetry < 0.4

Figure 5.12: The bin-by-bin uncertainty on the WWbb interference effect, given in an SR bin width of 200 GeV. Uncertainties are given with both the nominal $m_{b\ell}$ Asymmetry cut of 0.2 as well as with a loosened cut of 0.4 to improve statistics.

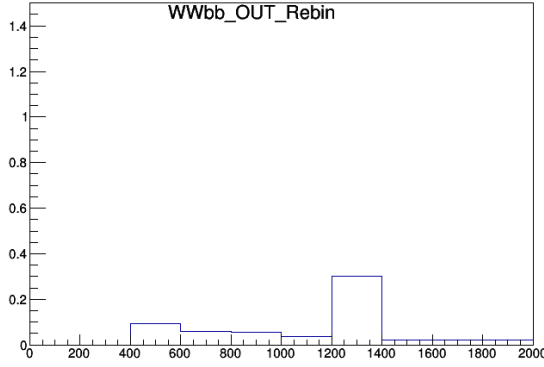
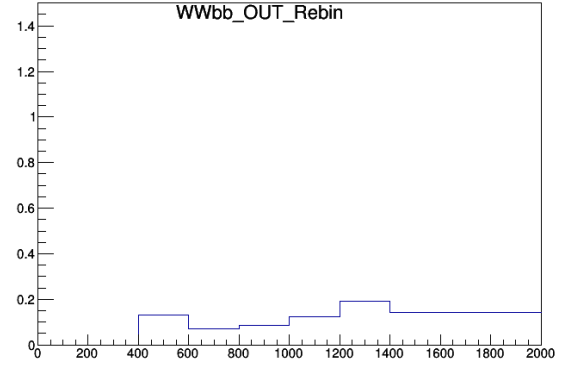
(a) WWbb Interference, $m_{b\ell}$ Asymmetry < 0.2 (b) WWbb Interference, $m_{b\ell}$ Asymmetry < 0.4

Figure 5.13: The bin-by-bin uncertainty on the WWbb interference effect, given in an SR bin width of 200 GeV. Uncertainties are given with both the nominal $m_{b\ell}$ Asymmetry cut of 0.2 as well as with a loosened cut of 0.4 to improve statistics.

- **PDF error set:** The standard deviation of the 100 PDF variations, treating positive and negative variations separately.

The α_S and PDF uncertainties are added in quadrature into a single envelope uncertainty. This combined PDF+ α_S envelope uncertainty is treated as uncorrelated between both regions and samples, and the uncertainties are not constrained by the CR normalization procedure. These uncertainties are derived for the major $t\bar{t}$, Single Top, and Z+jets backgrounds. The full bin-by-bin results are given in Appendix D.

5.5.3.5 Signal Theoretical Systematics

For SUSY signal theory uncertainties, TRUTH samples are generated with 100k events for 4 representative signal mass points (600 GeV, 1000 GeV, 1400 GeV, 1800 GeV) for each variation. Variation samples are then analyzed at TRUTH level and compared to Signal Region yields for the associated nominal sample.

The following uncertainties are considered for stop signal samples:

- **QCD scales** (scup and scdw)
- **Parton Shower merging scale** (qcup and qcdw)
- **Parton Shower tuning and ISR** (5 Variations: Var1, Var2, Var3a, Var3b, Var 3c)

For Parton Shower tuning and ISR, an envelope method is applied. Signal theory systematics are then symmetrized and added in quadrature inclusively across Signal Region bins. The combined signal theory uncertainty is then applied as a flat uncertainty to each SR bin. A summary of the signal theory uncertainties can be found in Fig. 5.14.

5.6 Control Region Optimizations

An careful study has been performed to define a Control Region for the single top background process. The Wt production mode with an ISR/FSR jet where the top decays to a b-quark and W boson and both W bosons decay leptonically (Shown in Fig. 5.15) is the primary way the single top background enters our signal regions. Unfortunately, the $t\bar{t}$ background has extremely similar event topology and is also produced at a significantly higher cross section. When developing a process pure control region for the single top process, we find high contamination of $t\bar{t}$ even with adding numerous cuts that should separate the two.

For the early Run 2 Analysis, Contranverse Mass (m_{CT}) was utilized to separate $t\bar{t}$ and single top in CRst. This variable was only used in events where 2 b-tags were present. For the Early Run 2 analysis, a 2 b-tag requirement was placed on CRst along with a cut on m_{CT} , while in the $t\bar{t}$ control region, the cut

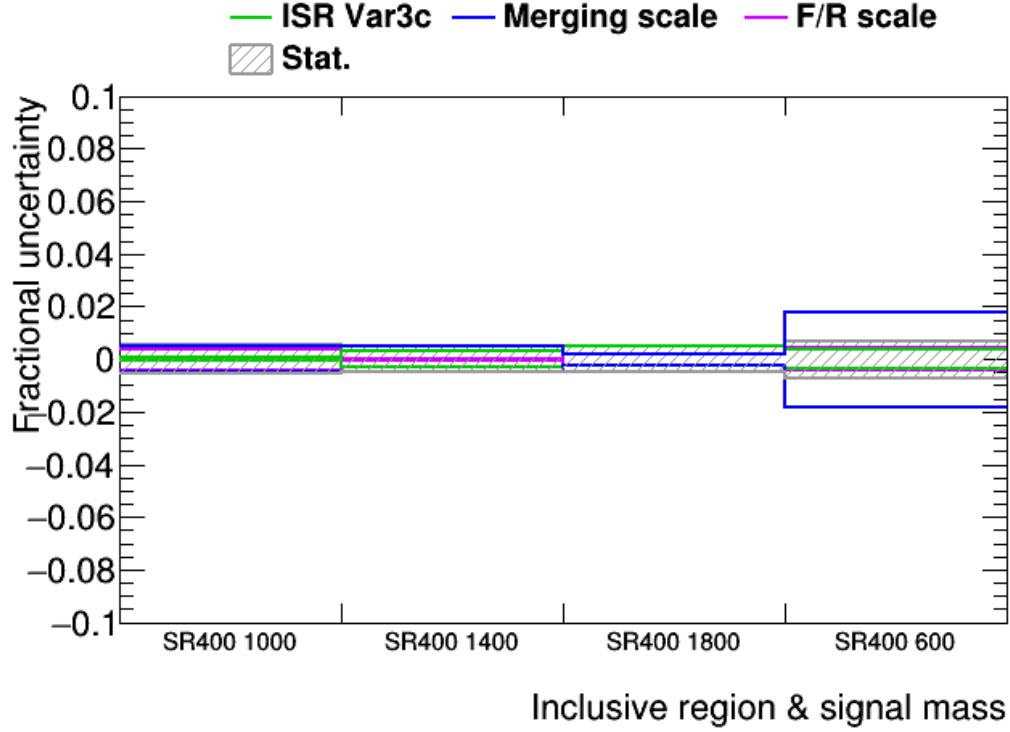


Figure 5.14: Summary of theoretical uncertainties on the accepted signal rate in the Signal Regions. Uncertainties are calculated for a set of representative signal masses (listed after SR400). Signal uncertainties are combined in quadrature applied to each signal sample as a flat uncertainty across all SR bins.

on m_{CT} was only applied for events with 2 b-tags. The list of cuts for the Early Run 2 Control Regions are listed below in Table 5.12. It was found that extrapolating from CRst to the SRs incurred a large theoretical uncertainty. The theoretical uncertainties from Early Run 2 for each SR are given in Table 5.13. These Signal Regions also utilized a loosened asymmetry cut to improve statistics at the time and the results listed are from the loosened region.

Region	N_b	$m_{b\ell}^0$ acc [GeV]	$m_{b\ell}^1$ rej [GeV]	H_T [GeV]	$m_{b\ell}$ asym	Z window	m_{CT} [GeV]
CRtt	≥ 1	[200,500]	< 150	[400,800]	< 0.2	$m_{\ell\ell} > 150$ GeV	$< 200^*$
CRst	$= 2$	[200,500]	< 150	< 800	< 0.2	$m_{\ell\ell} > 120$ GeV	> 200
Z CR	≥ 1	> 700	–	> 1000	< 0.2	[76.2,106.2]	–

Table 5.12: Summary of the Control Regions for the Early Run 2 analysis. All regions require at least two jets and two oppositely charged leptons. The * in the $t\bar{t}$ CR m_{CT} cut indicates that the upper cut is applied only in events with exactly 2 b-tagged jets, to make the region orthogonal to the single top CR.

For this analysis using the Full Run 2 analysis, I sought to develop new top Control Region cuts that would target minimizing the uncertainty from extrapolation to the Signal Region. The primary avenue was

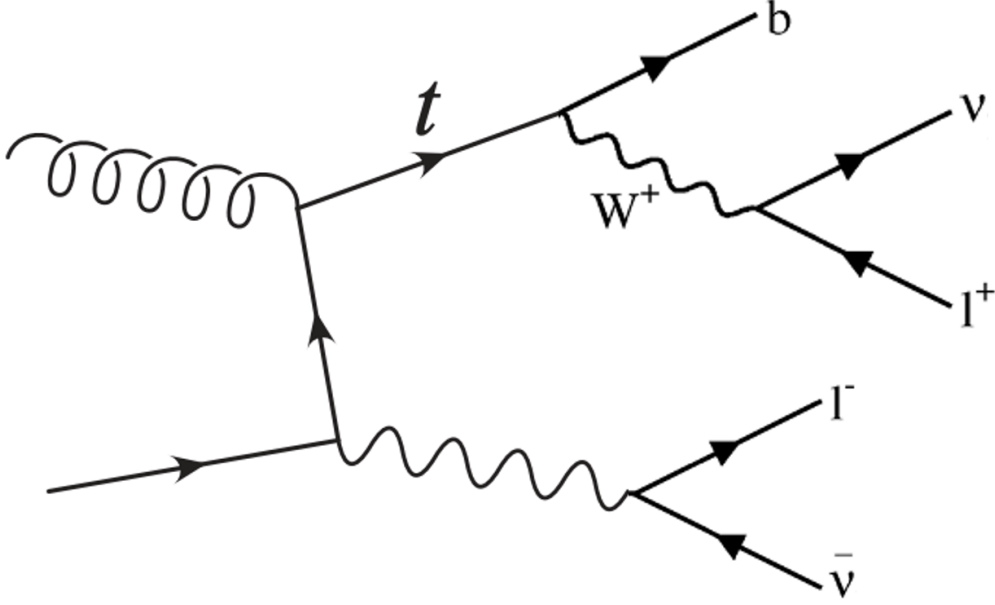


Figure 5.15: Feynman diagram for the Single top Wt-channel

Systematic	<i>SR800</i>	<i>SR1100</i>
$t\bar{t}$ (Parton Shower)	6%	13%
$t\bar{t}$ (aMCatNLO+H++)	120%	260%
Wt (Parton Shower)	47%	30%
Wt (aMCatNLO+H++)	10%	40%
WWbb Interference	63%	60%

Table 5.13: Summary of Theoretical Systematics from Early Run 2 RPV Stop Analysis in Each of the loosened SRs

through creating a list of cuts that are closer to the analysis variables used in the signal region to minimize the phase space extrapolated over. We found that using Contraverse Mass solely in the control regions along with a 2 b-tag requirement (while the SR requires 1) selected events too distinct from background events in the Signal Region to precisely model background expectation in the SRs. My goal was to re-evaluate these cuts and search for ways to achieve high Single Top purity in CRst while keeping the transfer factor uncertainty low.

The key difference between these processes is that $t\bar{t}$ events are pair produced, implying both low mass and low p_T asymmetry between candidate bl mass pairings whereas Single Top Wt processes need not be. From this knowledge, three variables were identified as potential avenues to distinguish Wt processes

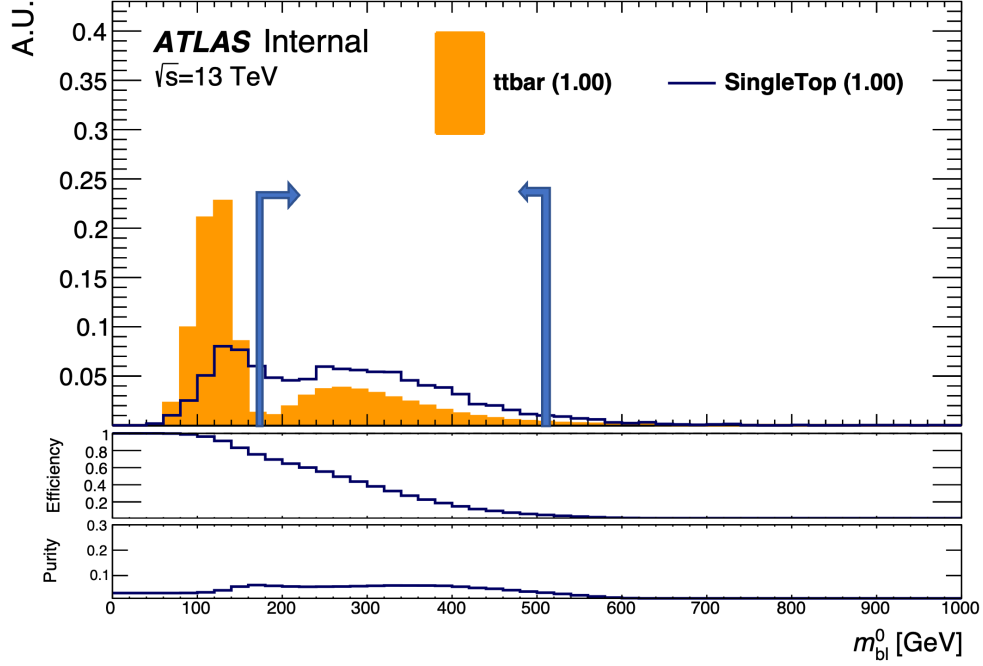


Figure 5.16: $m_{b\ell}^0$ distribution for $t\bar{t}$ and Wt processes after applying an $m_{b\ell}$ Asymmetry cut of < 0.2 . Blue arrows represent the proposed selection on $m_{b\ell}^0$ (180 - 500 GeV). Event yields are normalized to each sample's integrated sum of weights to better see differences in shape distributions.

from $t\bar{t}$ processes: $m_{b\ell}$ asymmetry, p_T asymmetry, and $m_{b\ell}^0(\text{rej})$. Through extensive studies, the following procedure was determined to best keep the Single top CR close in phase space to the SRs and reduce the overall systematic uncertainty observed from transferring from CRst to the SRs.

By selecting the jet-lepton pairing scheme which has the lowest $m_{b\ell}$ asymmetry as well as cutting $m_{b\ell}$ above the top mass for both top control regions, we are identifying top events where jets and leptons are incorrectly paired. This can be seen in Fig. 5.16, where only the mass asymmetry and $m_{b\ell}$ cuts are applied.

After these cuts are performed, it is insightful to look at the rejected, higher $m_{b\ell}$ asymmetry pairing; one should expect to see resonances in both $m_{b\ell}$ distributions for $t\bar{t}$, while only seeing a resonance in one of the $m_{b\ell}$ distributions for Single top. This behavior is forced by the previous cuts intentionally mispairing jets and leptons. By selecting the lower of the rejected mass pairings to be consistent with the top quark (performed in Fig. 5.17), we can now observe severe separation. Looking at the $m_{b\ell}^0(\text{rej})$ distribution in Fig. 5.18, we see that this final mass variable is consistent with the top mass for $t\bar{t}$ backgrounds, while being randomly distributed for Single Top.

This procedure is most effective when applying a 2 b-tag requirement, as the selection of 2 b-tags reinforces the assumption that the jets and leptons chosen for reconstruction are the direct decay products from the

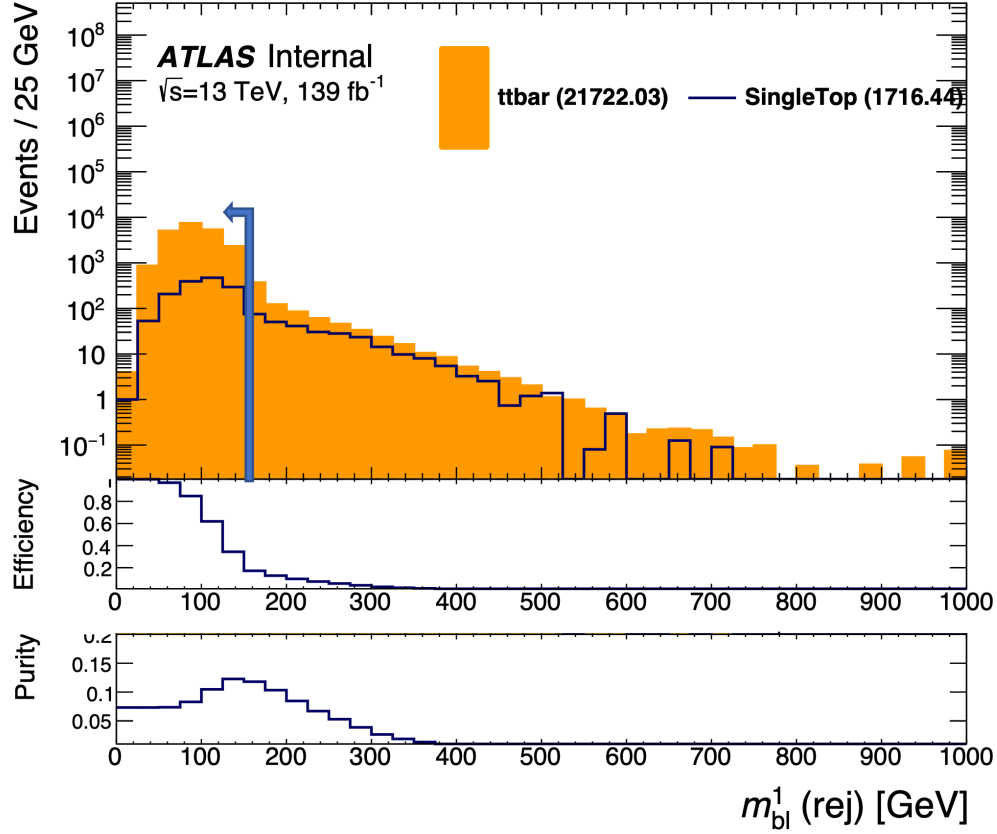


Figure 5.17: $m_{bl}^1(\text{rej})$ distribution for $t\bar{t}$ and Wt processes after applying selections on m_{bl} Asymmetry and m_{bl}^0 . The blue arrow represents the proposed selection on $m_{bl}^0(\text{rej})$ (< 150 GeV). Event yields are normalized to each sample's integrated sum of weights to better see differences in shape distributions.

aforementioned top processes. Without this requirement, one can see that the observed separation of Single top and $t\bar{t}$ is significantly weaker. This effect can be seen in Fig. 5.19.

While the final overall purity for this region is expected to be less than 50%, the $t\bar{t}$ control region is designed to have 10x higher statistics, which should precisely constrain the expected $t\bar{t}$ normalization factor. To ensure this effect, cuts on H_T and $m_{\ell\ell}$ were adjusted to increase expected $t\bar{t}$ events in CR $t\bar{t}$ to be roughly 4x larger than $t\bar{t}$ events in CR st . The cutflow of the $t\bar{t}$ background in the finalized CR st is given below in Table 5.14; one can see the final cut removes 95% of $t\bar{t}$ events, while retaining 80% of Single top events.

The much improved, observed systematic uncertainties for the top backgrounds are summarized in Figures 5.8–5.11.

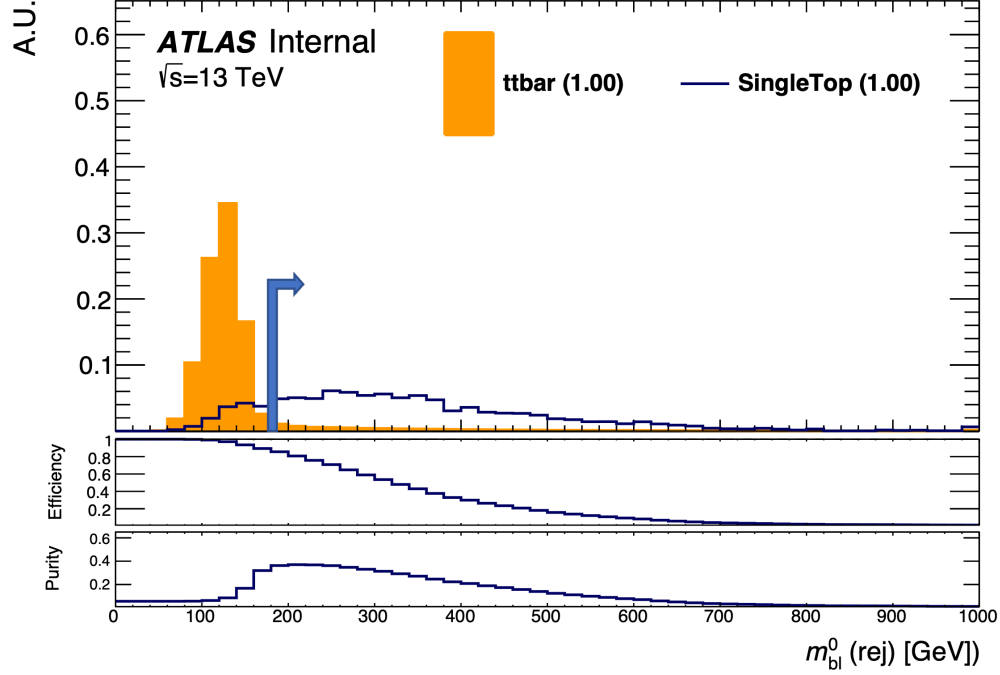


Figure 5.18: $m_{bl}^0(\text{rej})$ distribution for $t\bar{t}$ and Wt processes after applying CRst selections, minus a cut on $m_{bl}^0(\text{rej})$. The blue arrow represents the proposed selection on $m_{bl}^0(\text{rej})$ (> 180 GeV). Event yields are normalized to each sample's integrated sum of weights to better see differences in shape distributions.

	Ttbar	Single Top	Ttbar	Single Top
	≥ 1 Tag	≥ 1 Tag	2 Tag	2 Tag
Baseline	51832.15	2859.4	24120.22	768.94
Mbl0 Acc > 180	22974.47 (44%)	1836.31 (64%)	7978.36 (33%)	496.27 (64%)
Mbl1 Rej < 150	22116.07 (96%)	1500.79 (81%)	7917.82 (99%)	467.79 (94%)
Mbl0 Rej > 180	8966.39 (40%)	1228.82 (81%)	545.25 (7%)	376.96 (80%)

Figure 5.19: Comparison of cut efficiency for CRst with differing b-tagging selections (≥ 1 Tag vs. 2 Tag). It is clear that with the application of the 2-tag requirement that the given selections are more efficient for separating $t\bar{t}$ and Wt processes.

	Single Top	ttbar
all	11827805.65	15629625.85
init	1348659.24(0.11)	6761021.76(0.43)
Duplicates	1348411.64(1.00)	6749807.72(1.00)
JetCleaning	1342479.54(1.00)	6722005.99(1.00)
NPV	1342479.37(1.00)	6722005.99(1.00)
Trigger	1125016.98(0.84)	6040417.07(0.90)
JetSelectionBaseline	1113191.62(0.99)	6039634.83(1.00)
MuonSelectionBaseline	1113155.81(1.00)	6039517.08(1.00)
ElectronSelectionBaseline	1113155.81(1.00)	6039517.16(1.00)
PhotonSelectionBaseline	1113155.81(1.00)	6039517.16(1.00)
JetSelectionSignal	1113155.81(1.00)	6039517.16(1.00)
MuonSelectionSignal	1113155.81(1.00)	6039517.16(1.00)
ElectronSelectionSignal	1113155.81(1.00)	6039517.16(1.00)
HT_overlap	1109206.88(1.00)	5774929.88(0.96)
2_leptons	78513.11(0.07)	829475.47(0.14)
trig_match	78493.83(1.00)	829282.49(1.00)
OS_leptons	77823.15(0.99)	822496.57(0.99)
2_jets	14042.50(0.18)	299887.93(0.36)
2_btag	3248.96(0.23)	96448.72(0.32)
mass_asym	1842.02(0.57)	80571.57(0.84)
Ht	1724.96(0.94)	79754.02(0.99)
mll	521.55(0.30)	21721.46(0.27)
Z_select	521.55(1.00)	21721.46(1.00)
mbl2_wrong	399.86(0.77)	10692.17(0.49)
mbl1	337.20(0.84)	8448.35(0.79)
mbl1_wrong	264.80(0.79)	532.26(0.06)

Table 5.14: Cutflow yields for Single Top and $t\bar{t}$ backgrounds in Single Top Control Region. Yield relative to previous step shown in parentheses

5.7 Signal Region Optimizations

Signal regions are optimized to maximize sensitivity while minimizing background contamination. Orthogonal signal regions are defined by the larger mass of the b-jet lepton pair and must be constructed very carefully to maximize search potential. If bins are too large, too much background is allowed in the signal regions and sensitivity decreases. If bins are too small, the signal is divided into multiple bins and exclusion power is weakened. A variable-width, multi-bin fit allows a balance between these two constraints. This fit type increases sensitivity to high mass signals while maintaining sensitivity to low mass signals. The following criteria are considered when optimizing bin widths for the signal regions:

- The Reconstruction of the signal width.

- Available Background Statistics.
- Dominant Uncertainties.
- Expected Exclusions.

5.7.1 Reconstructed Signal Width

Fig. 5.20 shows reconstructed mass of jet lepton pairs. The red points correspond to electrons for both signal leptons and both jets b-tagged. The dark blue points correspond to samples with muons as both signal leptons. The green points represent samples with the electron as the higher mass lepton b-jet pair and the muon as the lower mass lepton b-jet pair. The turquoise points represent the higher mass lepton b-jet pair as the muon and the lower mass lepton b-jet pair as the electron. The dotted orange lines show the early run 2 orthogonal and overlapping signal regions for comparison with this analysis's inclusive signal region. Fig. 5.20 illustrates that signal samples with a muon as one of the lepton jet pairs as opposed to an electron corresponds with a larger width, in GeV, of a reconstructed signal sample. This effect can be attributed in large part to lepton energy resolution at the detector level. Electrons are detected by ATLAS with the electromagnetic calorimeter. Muons are detected by ATLAS with the muon spectrometer. The electromagnetic calorimeter detects a shower of particles where the number of particles in the shower is proportional to the electron's energy. The ID and the muon spectrometer measures p_T by reconstructing the sagitta, which is the deflection of the muon's path from a straight line due to the strong magnetic fields of the ATLAS magnets, and the size of the sagitta decreases with increasing p_T .

Eq. 5.7 illustrates that electron resolution improves with increased energy. Eq. 5.8 illustrates that muon resolution worsens with increased energy.

$$\frac{\sigma}{E} \propto \frac{10\%}{\sqrt{E}} \quad (5.7)$$

$$\frac{\sigma}{p_T} \propto 1 * 10^{-4} p_T \quad (5.8)$$

Jet energy is another important factor for signal sample resolution. The dependence on the relative jet energy uncertainty can be shown with Eq. 5.9. Here noise (N) is the contribution from the electronic noise in the calorimeter and scales as $1/p_T$. This term dominates for the low- p_T region below 30 GeV. The stochastic term (S) scales like $1/\sqrt{p_T}$. The constant term (C) represents fluctuations as a constant fraction of the jet p_T . The constant term dominates for the high p_T region, above 400 GeV. Comparing Eq. 5.9

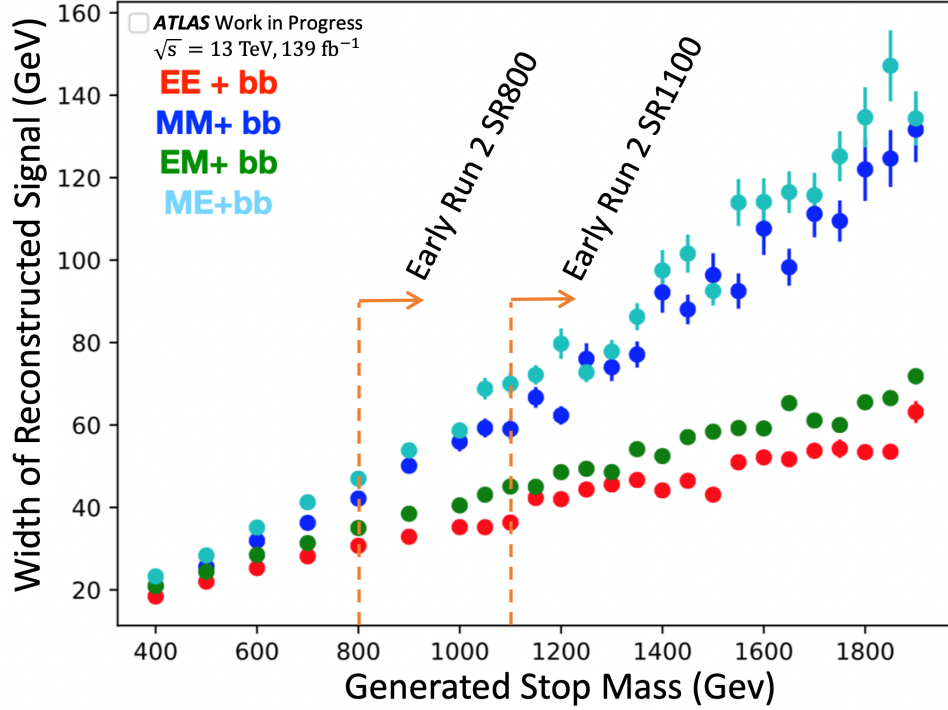


Figure 5.20: The width of the reconstructed mass of the higher mass b-jet and lepton pair is measured with respect to the mass of the candidate stop.

to Eq. 5.7 and Eq. 5.8, one can compute that the muon momentum resolution becomes dominant over jet resolution for momenta above 600 GeV. This corresponds to stop masses above 1200 GeV.

$$\frac{\sigma(p_T)}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C \quad (5.9)$$

5.7.2 Available Background Statistics

To determine the maximum value of $m_{b\ell}$ for a lower bound on an overflow bin, available background statistics were considered. When crafting the signal region, it was important to ensure that statistical uncertainties would not balloon at high values of $m_{b\ell}$. The unweighted MC yields were plotted to determine when insufficient statistics were available beyond a value of $m_{b\ell}$. Assuming the backgrounds follow a Poisson distribution, we can assign each background a relative statistical uncertainty of $\frac{1}{\sqrt{N}}$, where N is the number of background events above a given value of $m_{b\ell}^0$. It was decided that the upper limit for an acceptable statistical uncertainty was 33%; thus, we require that at least 10 raw MC events exist for each background in our overflow signal region. From this, I determined the maximum value of $m_{b\ell}$ to start an overflow bin

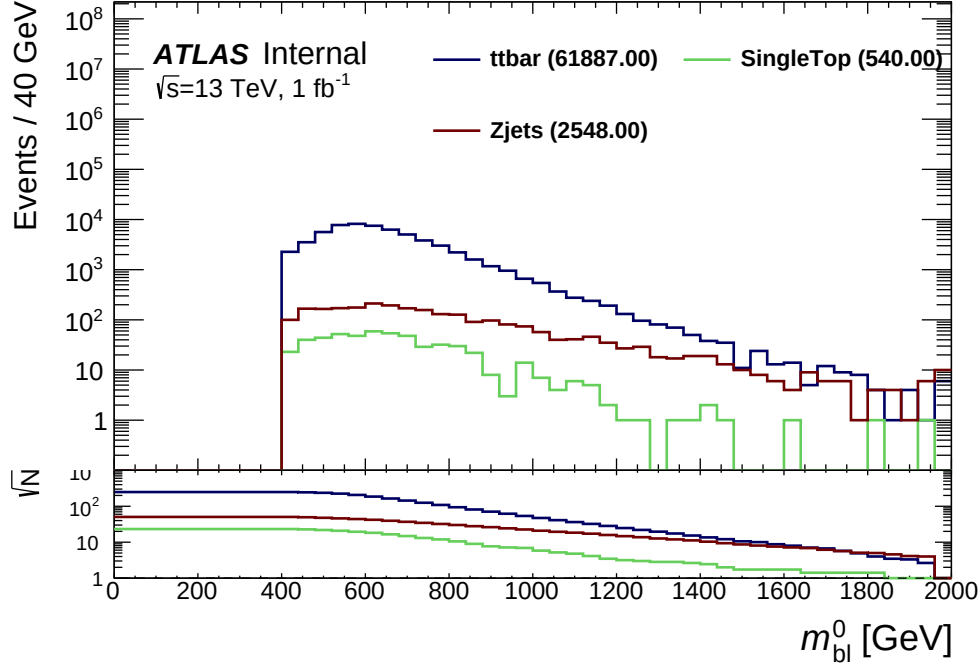


Figure 5.21: Raw Monte Carlo Yield for Primary Backgrounds vs m_{bl} . Bottom panel shows statistical uncertainty ($\sqrt{N}$) on each background if an overflow bin was set at that value of m_{bl}

was 1400 GeV. The results of this study are given in Fig. 5.21.

5.7.3 Dominant Uncertainties

A crucial aspect of determining the bin widths for our signal region was the consideration of dominant theoretical uncertainties. While one might typically optimize bin widths to maximize Z_n or a similar sensitivity metric, I also want to avoid the scenario of finalizing region definitions only to discover all sensitivity is lost due to large uncertainties. In the early Run 2 analysis, the dominant systematics were the theoretical uncertainties associated with modeling top backgrounds. While the control regions were re-optimized to minimize these effects prior, we wanted to ensure that those gains were not lost due to statistical limitations from slicing the Signal Region too finely when implementing a multi-bin fit.

The bin-by-bin systematic uncertainties were calculated for each of the top backgrounds using numerous candidate bin widths. Similar to the Early Run 2 analysis, a loosened SR was utilized where the cut on m_{bl} asymmetry was raised to 0.4 to improve statistics. We expect this loosening to not affect the results as m_{bl} asymmetry is seen to be relatively flat for top backgrounds in the Signal Region. The bin-by-bin systematics are plotted in Figures 5.8–5.11, comparing both the nominal and loosened SR schemes.

5.7.4 Expected Exclusions

The final and most critical aspect in determining the Signal Region binning is to look at the expected exclusions for a given mass point. For this study, I ran an exclusion fit in HistFitter over the entirety of the signal grid. The signal was generated with equal branching ratio to $e/\mu/\tau$. For the exclusion fits, the dominant sources of uncertainty were utilized; these uncertainties are: Theory Uncertainties described in Sec. 5.5.3.2 and Sec. 5.5.3.3, statistical uncertainties for all background and signal MC, and the uncertainty on the cross section of stop pair production. This fit was performed with either 25, 50, 150, or 200 GeV wide bins from $m_{b\ell} : [400 \text{ GeV}, 1400 \text{ GeV})$ with an overflow bin for $m_{b\ell} > 1400 \text{ GeV}$. The expected exclusion on the stop signal strength, μ_{SIG} , is plotted in Fig. 5.22. I additionally performed this fit using the original Signal Region binning from the Early Run 2 analysis ($m_{b\ell} > 800 \text{ GeV}$ and $m_{b\ell} > 1100 \text{ GeV}$) as a point of comparison. We see an improvement in the exclusion on stop signal strength for all mass points when switching from a nested SR scheme to a multi-bin fit in $m_{b\ell}$. The transition point between bin widths was determined by observing when the improvement on signal strength exclusion was found to be $< 10\%$ when swapping to finer binning (shown in Fig. 5.23). This yields the binning scheme shown in Table 5.15.

Bin width [GeV]	$m_{b\ell}$ range [GeV]
50	[400, 900]
100	[900, 1200]
200	[1200, 1400]
Inclusive	(1400, ∞)

Table 5.15: The chosen binning for the shape fit of the $m_{b\ell}$ distribution.

5.7.5 b -Jet Working Point Optimizations

The primary goal of this analysis is to push the boundaries of limits set on stop pair production cross section to higher values of $m_{b\ell}$; we expect very little background to be produced at high values of $m_{b\ell}$, thus our primary goal with selecting a b -jet working point is to boost signal acceptance as much as possible. To attain this, we implement the Fixed-85% Working Point for our b -tagging selections. This analysis would be interested in utilizing a hybrid or flat working point, which were not available at the time of optimizations. A comparison of various Working points is given below in Fig. 5.24. It can be seen that background at high mass is negligible and thus choosing a looser working point results in approximately a 50% gain in signal efficiency.

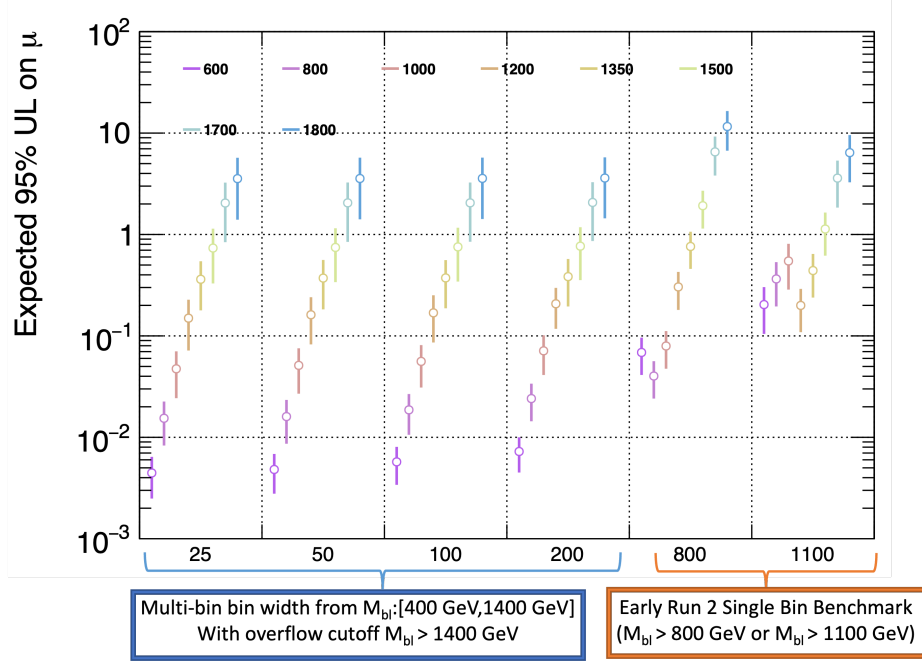


Figure 5.22: The expected exclusion on signal strength, μ , for selected signal mass points with various binning configurations. The first 4 bins utilize a multi-bin fit with an overflow bin beginning at $m_{b\ell} = 1400$ GeV. The bin width for the range 400 - 1400 GeV is given below each entry. The final 2 bins are designed to emulate the Early Run 2 analysis and use two nested SR bins which only apply a minimum $m_{b\ell}$ value of either 800 or 1100 GeV.

	Bin Width [GeV]				
	Run 2 Benchmark	200	100	50	25
600	0.0687*	0.0072 (848%)	0.0057 (27%)	0.0048 (19%)	0.0045 (8%)
800	0.0402*	0.0241 (67%)	0.0187 (29%)	0.016 (17%)	0.0154 (4%)
1000	0.0795*	0.0713 (12%)	0.0561 (27%)	0.0512 (10%)	0.0474 (8%)
1200	0.1998	0.2075 (-4%)	0.1688 (23%)	0.1616 (5%)	0.1496 (8%)
1300	0.3367	0.2954 (14%)	0.2922 (1%)	0.2782 (5%)	0.2608 (7%)
1400	0.638	0.5369 (19%)	0.5144 (4%)	0.5118 (1%)	0.5019 (2%)
1500	1.1319	0.7671 (48%)	0.7546 (2%)	0.7454 (1%)	0.735 (1%)

Figure 5.23: Comparison of expected exclusions on signal strength, given in table form. The relative improvement to expected exclusion on signal strength as finer bins are applied is given in parentheses. The dark line through the table represents the point when shrinking bin widths no longer improve expected exclusions by at least 10%.

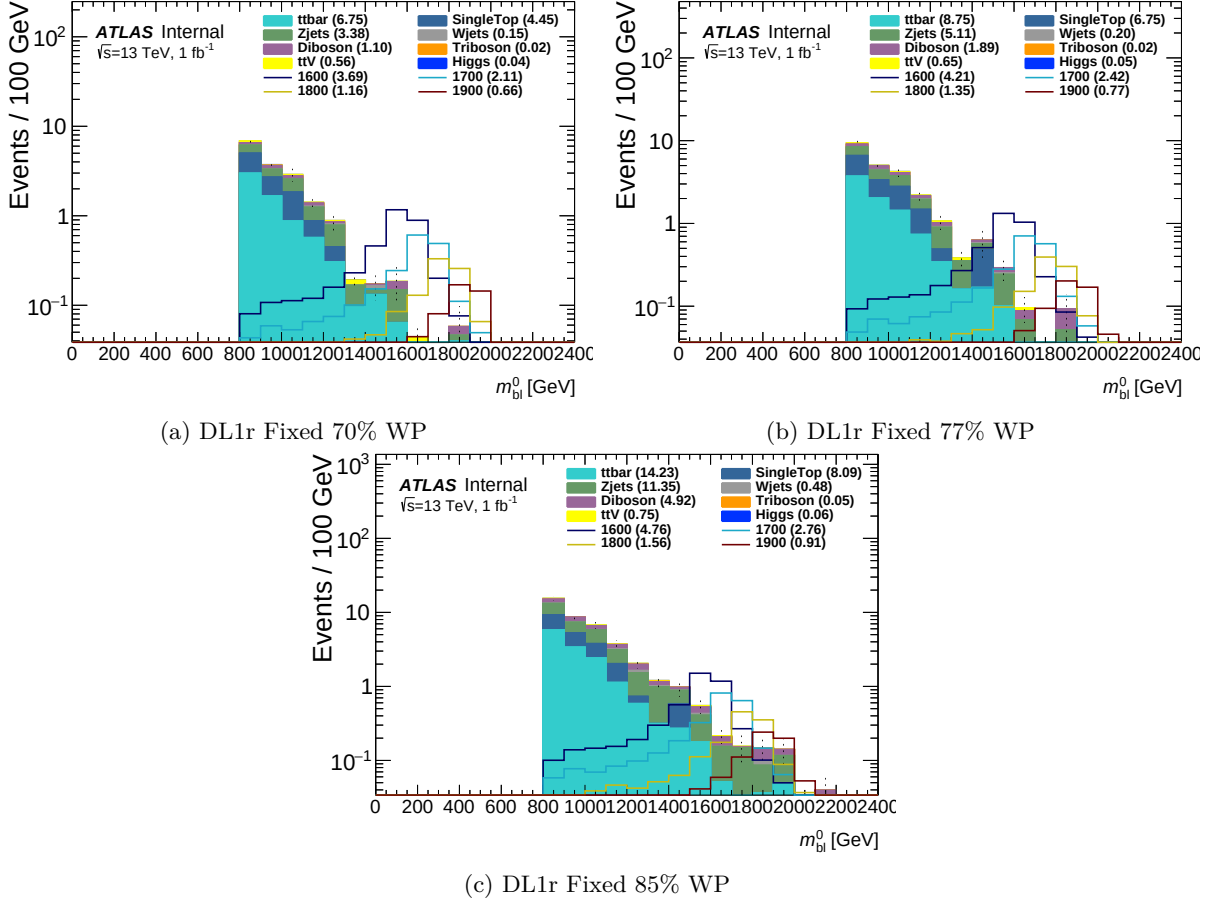


Figure 5.24: Comparison of signal efficiency with differing b-tag working points (WP). It can be seen that background yields are negligible and thus signal yield should be prioritized.

5.7.6 Signal Region Configuration Comparison

When studying the implementation of a flavor-aware fit, I looked at the relative improvement to the expected upper limit on signal strength, μ , for multiple SR designs. This study examined the efficacy of five different fit methods: A 15-bin, flavor-agnostic fit, a 15-bin fit in only the ee final state channel, a 15-bin fit in only the $\mu\mu$ final state channel, a 15-bin fit in the $e\mu$ channel, and a 45-bin flavor-aware fit across all channels. The results of these studies are shown in Fig. 5.25. It was observed that for the individual flavor channels (ee , $e\mu$, $\mu\mu$), the 45 bin performs a few % better in the corners of the lepton BR plane than just the 15-bin fit to the ee or $\mu\mu$ channels alone. When looking at the center of the BR plane, it is seen that the flavor-agnostic fit performs best, as all of the channels contain signal events and combining all flavor channels mitigates the effects of the limited MC statistics discussed prior. Therefore, to save analysis and computation time, I

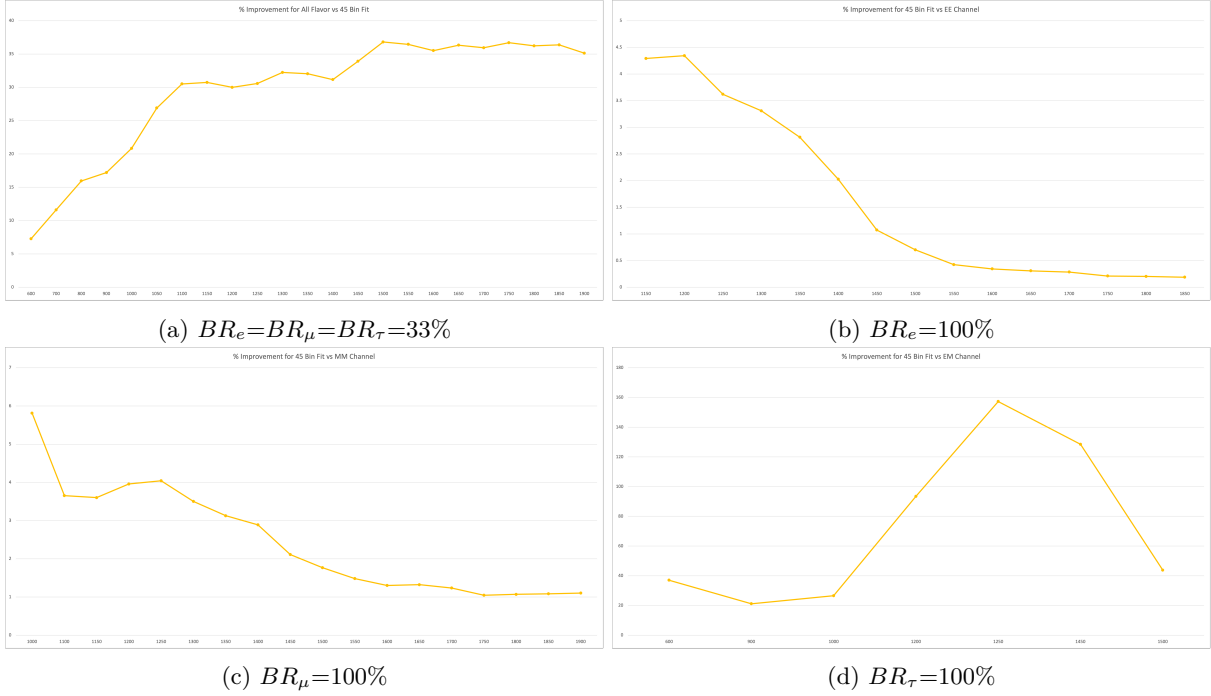


Figure 5.25: Comparison of expected exclusions on signal strength, μ , across different HistFitter configuration options. EM/MM/EE Channel refers to the configuration where the highest two leptons by p_T are the given flavor. "All Flavors" refers to the configuration where the fit is agnostic to lepton final state. "45 Bin Fit" refers to the configuration where HistFitter is provided with the flavor information in the signal region and performs a fit across 45 SR bins (15 bins for each lepton flavor final state). In all of the fits, the control regions are inclusive across lepton final state and produce the same normalization factors. This process is performed for 4 theoretical stop branching ratios, listed below each plot.

determined the best route would be to only perform the 45-bin flavor-aware fit and the 15-bin flavor-agnostic fit at each point in the lepton BR plane. To determine which result to report, the **expected** signal exclusion for two configurations is compared; the better of the two is then unblinded and reported as the observed limit.

5.8 Statistical Analysis

While complicated on the surface, this analysis boils down to effectively a counting experiment: we estimate the number events we expect in a given Signal Region, then count how many events we actually observe. From here, statistical statements can be made on the existence of new physics, given that we have accurately modeled the background standard model processes. From the Neyman-Pearson lemma, we know that the uniformly most powerful test between two simple hypotheses is the likelihood ratio test. Thus, by construct-

ing a statistical model for the analysis, we can compute the likelihood that the observed data is compatible with prediction. Given that the experiment is centered on a counting experiment, the Poisson distribution is best suited as the basis for the likelihood function. This statistical framework allows us to set upper limits on the production rate of both hypothetical scalar tops as well as generic beyond the standard model processes.

The follow sections describe the construction of the underlying statistical model as well as the various statistical tests performed. While complicated, the statistical inference is assisted by the use of the HistFitter software package, which is built on the RooFit, RooStats, and HistFactory extensions to ROOT. The HistFitter software package allows for simplified construction of the statistical model, fitting, and hypothesis testing.

5.8.1 Construction of the Likelihood Function

Given that an event is either observed in our region or not observed, the Poisson distribution is best suited as the basis of the statistical analysis. The conditional Poisson probability of observing N events with λ events expected is given by:

$$\mathcal{P}(N|\lambda) = \frac{e^{-\lambda}\lambda^N}{N!} \quad (5.10)$$

Were we to only use one Signal Region prediction with one observed value and no systematics to account for, this simple model would be sufficient. However, experiments of this scale are never that simple, and thus numerous process-pure control regions are created to better model the SM background processes. With the addition of further observation regions, the total probability can be constructed as the product of the conditional probabilities for each region, given compactly as:

$$\mathcal{P}(N|\boldsymbol{\lambda}) = \prod_{i \in Regs} \mathcal{P}(N_i|\lambda_i) \quad (5.11)$$

This total probability will form the basis for the likelihood function ($\mathcal{L}$), which will define our statistical model. Given that the goal is to make statistical statements on the production rate of scalar tops, it is best to parameterize the estimated number of events in a given region as

$$\lambda_i = \mathbf{b}_i(\boldsymbol{\theta}) + \mu_{Sig}s_i(\boldsymbol{\theta}) \quad (5.12)$$

Here, $s_i(\boldsymbol{\theta})$ denotes the expected signal contribution in a given region while $\mathbf{b}_i(\boldsymbol{\theta})$ denotes the set of expected background contributions, split by SM process, in a given region. The signal strength, μ_{Sig} , is the

parameter of interest for the model-dependent fit and is defined as the ratio of the tested stop production cross-section to the predicted theoretical cross-section ($\mu = \sigma/\sigma_{Theory}$). With this construction, $\mu=1$ would correspond to a signal hypothesis where stops are pair produced at the theoretically predicted cross-section, while $\mu=0$ corresponds to absence of stop production (the background-only hypothesis). μ_{sig} will become especially important in the limit setting procedure, described in Sec. 5.8.4.

In Eq. (5.12), the background and signal expectations are additionally dependent on a set of free "Nuisance Parameters" (denoted as θ). These nuisance parameters encompass the vast array systematic uncertainties described previously in Sec. 5.5 as well as the floating normalization factors for the primary backgrounds ($t\bar{t}$, Single Top, and Z+jets). Each nuisance parameter is assumed to be modeled by an independent Gaussian distribution, constructed such that $\theta_i=0$ corresponds to the central value of the systematic and the normalized to achieve a relative standard deviation of $\sigma_{\theta_i}=1$. Given that these nuisance parameters represent concepts such as normalization or relative uncertainties, it becomes clear how they are able to shift the predicted yields for both signal and background.

With the above definitions, we are able to construct a statistical model (our likelihood function) as the following:

$$\mathcal{L}(N|\mu_{Sig}, \theta) = \prod_{i \in SRs} \mathcal{P}(N_i|\lambda_i) \times \prod_{j \in CRs} \mathcal{P}(N_j|\lambda_j) \times \prod_{k \in NPs} G(0|\theta_k) \quad (5.13)$$

where "SRs" is the set of 15 (or 45) orthogonal Signal Region bins, "CRs" is the set of three Control Regions, and "NPs" is the set of Nuisance Parameters. $G(A|B)$ represents the conditional Gaussian distribution described above for each given nuisance parameter. Recall here that λ_i is parameterized by the signal strength along with separate background and signal estimates, each dependent on the set of NPs.

5.8.2 Limit Setting

With the construction of the likelihood function, we are equipped to make statements on the probability that a given signal hypothesis is consistent with the observed data. For this experiment, the background only hypothesis (where $\mu_{Sig} = 0$) is assigned as the null hypothesis and the signal+background hypothesis (where $\mu_{Sig}>0$) is the alternate hypothesis. To assess the confidence in rejecting the null hypothesis, we take a frequentist approach, where a "test statistic" is defined to facilitate a comparison between hypotheses.

The test statistic chosen for this analysis is the "profile likelihood ratio," denoted $q(\mu)$ and defined as:

$$q(\mu_{Sig}) = -2 \ln \frac{\mathcal{L}(\mu_{Sig}, \hat{\theta}(\mu_{Sig}))}{\mathcal{L}(\hat{\mu}_{Sig}, \hat{\theta})} \quad (5.14)$$

where μ_{Sig} is the tested signal strength, $\hat{\mu}_{Sig}$ and $\hat{\theta}$ are the signal strength and nuisance parameter values which maximize the likelihood function (defined in Eq. (5.13)), and $\hat{\theta}(\mu_{Sig})$ is the set of NP values which maximize the likelihood function for the tested μ_{Sig} . To calculate p-values from this test statistic, one must profile the probability distribution of $q(\mu_{Sig})$. This profiling is done through the MC generation of datasets with varying best-fit parameters, called "toys." Precision of modeling with toys depends on the number of toys generated, which can become quite computationally expensive dependent on the number of toys. Fortunately, with sufficient dataset sizes, one can approximate the profile likelihood ratio with the "asymptotic limit" approach. Here, the pdf of the profile likelihood ratio is assumed to be a non-central χ^2 distribution, from which one can calculate p-values with much less computation power. It must be noted though that one should compare results of using an asymptotic approximation to the utilization of toys for a few points in the tested phase space to validate this approximation.

From this point, three different statistical tests can be performed on the dataset: a Background-Only Fit, a Model-Dependent Fit, and a Model-Independent Discovery Fit. The configuration of these tests will be detailed in the following sections.

5.8.3 Background Only Fit

Before the data in the signal region is unblinded, it is necessary to validate that we can precisely model the data in CRs and VRs, where the signal contribution is expected to be negligible. This process is performed through a "background-only" fit, where the Control Regions are fit to extract the normalization factors (NFs) which produce the best data-MC agreement. With this information, one can predict the yields in the signal-absent validation regions and compare to the observed result to ensure proper background modelling and extrapolation across analysis variables.

In addition to the standard background-only fit, a series of additional fits were performed where either the VRs or the SRs are treated as additional constrain channels. This method ensures that during the model-dependent fits, where SRs will be simultaneously fit with CRs, a potential excess will not be normalized away by the choice of CRs, VRs, or SRs. That is, we want the likelihood fits to remain stable with the addition of new discovery channels. For this process, normalization factors are extracted and compared to the nominal background-only fit to ensure statistical compatibility. In addition, the nuisance parameters are profiled to observe any amount of overfitting or strong pulls. Finally, one can also produce "ranking plots" for profiling the nuisance parameters which pull the NFs the most.

5.8.4 Model-Dependent Fit

For model dependent fits, there are two primary metrics one is interested in: Expected upper limit on μ_{Sig} and observed upper limit on μ_{Sig} . These values express the alternate hypothesis with the maximum stop signal production rate that is compatible with the expected/observed data. It is standard within ATLAS to use the CL_S metric to measure confidence limit [74], given by:

$$CL_S = \frac{p_{s+b}}{1 - p_b} \quad (5.15)$$

where p_{s+b} is the p-value for the signal+background hypothesis and p_b is the p-value for the background-only hypothesis. For the purpose of this dissertation, we define the 95% confidence limit (CLs95) to be the signal strength (μ) such that $CL_s=0.05$. To extract the expected upper limit, the observed data in the SRs is replaced with the background expectation. This allows the quantification of a model's limit setting potential in the scenario where data and MC perfectly agree. For the scenario where an excess is observed, one expects to produce a weaker observed limit than expectation; in the case of a deficit, one may produce stronger limits than expected.

For this search, we consider the B-L RPV scenario where the stop is the LSP, as described previously. Given that both the mass and the lepton branching fraction are unknown, an independent exclusion fit is performed for each combination of the two. At each point, both the 15-bin, flavor-agnostic fit and the 45-bin, flavor-aware fit are performed. The fit which provides the best expected exclusion at each given point is then chosen to produce the reported observed exclusion on signal strength. As described prior, each signal region bin is treated as an independent Poisson distribution, each with its own predicted yields. The signal region mass binning is given again in Table 5.16.

Bin width [GeV]	$m_{b\ell}$ range [GeV]
50	[400, 900]
100	[900, 1200]
200	[1200, 1400]
Inclusive	(1400, ∞)

Table 5.16: The chosen binning for the fit of the $m_{b\ell}$ distribution.

5.8.5 Model-Independent Fit

One can make general statements on the production rate of new physics using a "discovery" fit. For this fit, the background-only hypothesis is tested against a generic, non-zero signal yield where the contributions

of the signal to the Control Regions is assumed zero. Given the lack of underlying signal model, the signal strength (μ) is simply the signal event yield in a given region. This test statistic allows us to set limits at the 95% CL on the visible cross-section ($\langle\epsilon\sigma_{\text{obs}}^{95}\rangle$) and the observed (S_{obs}^{95}) and expected (S_{exp}^{95}) number of events for new physics processes, independent of what that process may be. This fit considers one SR at a time, to avoid any assumption on relative signal contributions across SRs and $m_{b\ell}$ bins. This fit constructs each SR by taking the nominal SR cuts given in Table 5.7 and then adds a cut of $m_{b\ell} > X_i$, where X_i are the lower bin edges of the exclusion fit binning. The $m_{b\ell}$ requirement for the Discovery Regions is given in Table 5.17. Hence, this analysis has 15 discovery regions which are fit independently, corresponding to the 15 bins described in 5.16.

Discovery Region	$m_{b\ell}$ requirement
1	≥ 400 GeV
2	≥ 450 GeV
3	≥ 500 GeV
4	≥ 550 GeV
5	≥ 600 GeV
6	≥ 650 GeV
7	≥ 700 GeV
8	≥ 750 GeV
9	≥ 800 GeV
10	≥ 850 GeV
11	≥ 900 GeV
12	≥ 1000 GeV
13	≥ 1100 GeV
14	≥ 1200 GeV
15	≥ 1400 GeV

Table 5.17: The chosen $m_{b\ell}$ requirement for the model-independent Discovery Regions.

5.9 Results

To perform the statistical procedures described in Sec. 5.8, the **HistFitter** package, version 0.62.0, is utilized. **HistFitter** is a flexible statistical tool used by many ATLAS SUSY searches and allows for the simultaneous fit across signal and control regions [75]. For each process, a **ROOT** tree is created containing all the needed kinematic quantities, weights, and uncertainties which can be propagated directly to **HistFitter**.

Across fits, the Signal Region binning determined in Sec. 5.7 forms the basis for analysis regions. Each bin is treated as an independent Poisson distribution when determining the parameters which provide the best MC fit to data. The number of events passing each of the CR and SR selections is used to constrain

the normalization of the dominant background processes. Systematics described in Sec. 5.5 are treated as Gaussian nuisance parameters. Systematics are pruned at the SUSY recommended 1% level.

5.9.1 Background-Only Results

Following the procedure outlined in Sec. 5.8.3, the normalization factors for the $t\bar{t}$, Single Top, and Z-jets processes which provide the best Data/MC agreement are given in Table 5.18. As a reminder, the background-only procedure fits the major MC backgrounds simulations in the control regions to match the observed data. From here, one is able to extrapolate to the defined Validation Regions and verify the observed data shows no significant deviation from the MC prediction.

$\mu_{t\bar{t}}$	0.88 ± 0.027
μ_{Wt}	1.35 ± 0.24
μ_{Zjets}	0.88 ± 0.079

Table 5.18: Normalization factors obtained from the standard background-only fit (constrained only by CRs) using dominant theoretical systematics along with most detector systematics with 139.0 fb^{-1} , for each of the three main backgrounds.

The fitted background MC events and observed data events in each of the CRs and VRs is given in Fig. 5.26. These are broken down in more depth by each individual background process in Tables 5.19–5.21. No significant difference is observed between the MC predicted values and observed data in any of the VRs. The profile of NPs is given in Fig. 5.27, where it can be seen that none of the NPs are overfit or significantly pull the fit result in any given direction. In addition to the NP pulls, the correlation between NPs is given in Fig. 5.28; it is clear that the only correlations exist between systematic uncertainties and the normalization factors of dominant backgrounds, which is expected when fitting. Additionally, there is an anti-correlation between the $t\bar{t}$ normalization factor ($\mu_{t\bar{t}}$) and the Single Top NF (μ_{Wt}); this is due to the analysis strategy chosen, where the $t\bar{t}$ NF is largely constrained by CR_{tt} and the precision of that measurement influences one’s ability to extract an accurate Single Top NF.

To ensure potential excesses are not normalized away by the choice of CR/SR/VR, background-only fits are produced with either the VRs or SRs used as additional fitted control regions. Ranking plots are produced in order to determine which systematics primarily impact the normalization of dominant background processes. The following sections detail the configurations used along with their respective results. Additionally, these fits provide a measurement of the NFs and NP pulls when simultaneously fitting the SRs and CRs (the nominal exclusion fit procedure). These results, along with the diagnostics done in

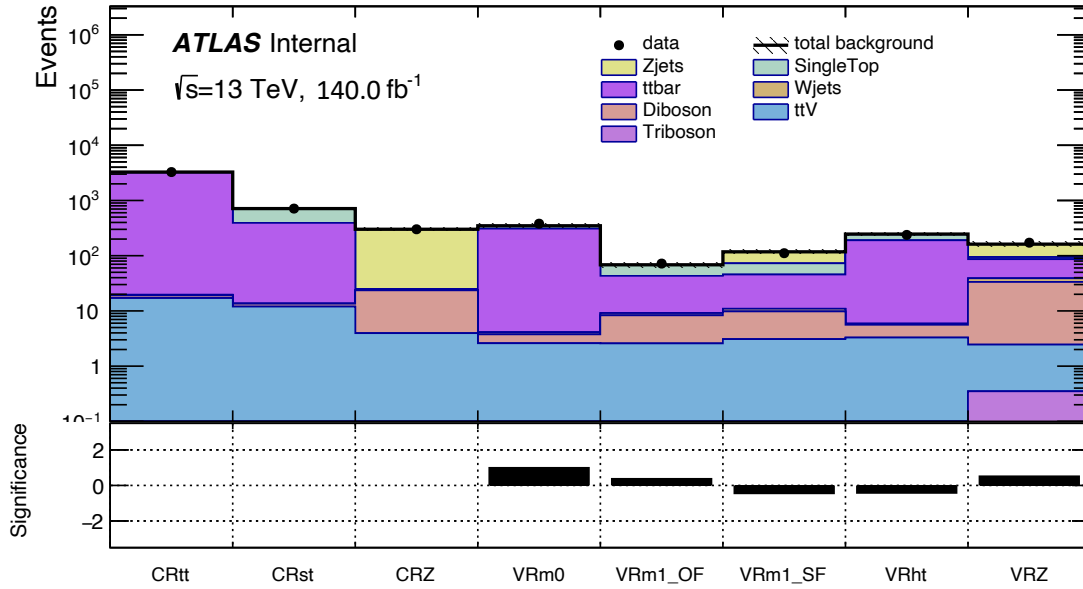


Figure 5.26: Post-Fit Yields for CRs and VRs with Pull Significance from the standard Background Only Fit. Control Regions agree perfectly by construction of the fit. No significant deviations are seen in the Validation Regions

<code>table.results.yields channel</code>	CRtt	CRst	CRZ
Observed events	3270	713	301
Fitted bkg events	3270.01 ± 57.20	713.04 ± 26.65	301.16 ± 17.35
Fitted ttbar events	3181.83 ± 59.96	379.00 ± 47.57	0.79 ± 0.34
Fitted SingleTop events	63.68 ± 11.95	308.82 ± 54.94	0.40 ± 0.30
Fitted Zjets events	4.87 ± 1.11	11.60 ± 3.11	276.35 ± 18.13
Fitted Wjets events	0.60 ± 0.20	$0.12^{+0.20}_{-0.12}$	0.08 ± 0.02
Fitted Diboson events	1.97 ± 0.12	1.53 ± 0.22	19.60 ± 5.11
Fitted Triboson events	0.02 ± 0.00	0.01 ± 0.00	0.02 ± 0.00
Fitted ttV events	17.05 ± 0.39	11.95 ± 0.37	3.92 ± 0.18
MC exp. SM events	3670.33 ± 81.01	683.86 ± 48.30	339.10 ± 19.77
MC exp. ttbar events	3598.04 ± 80.93	428.51 ± 47.68	0.90 ± 0.38
MC exp. SingleTop events	47.12 ± 2.33	228.53 ± 5.76	0.29 ± 0.22
MC exp. Zjets events	5.54 ± 1.20	13.21 ± 3.46	314.26 ± 18.99
MC exp. Wjets events	0.59 ± 0.20	$0.12^{+0.20}_{-0.12}$	0.08 ± 0.02
MC exp. Diboson events	1.97 ± 0.12	1.53 ± 0.22	19.62 ± 5.15
MC exp. Triboson events	0.02 ± 0.00	0.01 ± 0.00	0.02 ± 0.00
MC exp. ttV events	17.05 ± 0.39	11.95 ± 0.37	3.92 ± 0.19

Table 5.19: Expected and fitted results for the Control Regions for an integrated luminosity of 139.0 fb^{-1} . The results are obtained for the CRs using the background fit (see text for details). Nominal MC expectations (normalised to MC cross-sections) are given for comparison.

table.results.yields channel	VRm0	VRm1_OF	VRm1_SF
Observed events	380	72	111
Fitted bkg events	348.34 ± 27.23	68.44 ± 6.13	117.56 ± 9.27
Fitted ttbar events	304.42 ± 29.74	34.03 ± 5.08	34.61 ± 5.15
Fitted SingleTop events	38.33 ± 7.95	25.15 ± 5.54	27.12 ± 6.23
Fitted Zjets events	1.48 ± 0.41	0.13 ± 0.02	44.87 ± 6.57
Fitted Wjets events	$0.36^{+0.51}_{-0.36}$	0.83 ± 0.20	1.16 ± 0.68
Fitted Diboson events	1.16 ± 0.09	5.73 ± 0.29	6.70 ± 0.35
Fitted Triboson events	0.01 ± 0.00	0.04 ± 0.00	0.05 ± 0.01
Fitted ttV events	2.58 ± 0.44	2.53 ± 0.14	3.03 ± 0.14
MC exp. SM events	379.03 ± 30.76	66.47 ± 6.17	121.28 ± 8.82
MC exp. ttbar events	344.87 ± 30.67	38.58 ± 5.50	39.25 ± 5.58
MC exp. SingleTop events	28.37 ± 2.80	18.61 ± 2.42	20.08 ± 2.86
MC exp. Zjets events	1.68 ± 0.46	0.15 ± 0.01	51.02 ± 5.85
MC exp. Wjets events	$0.36^{+0.52}_{-0.36}$	0.83 ± 0.20	1.16 ± 0.69
MC exp. Diboson events	1.16 ± 0.09	5.73 ± 0.29	6.70 ± 0.36
MC exp. Triboson events	0.01 ± 0.00	0.04 ± 0.00	0.05 ± 0.01
MC exp. ttV events	2.58 ± 0.45	2.53 ± 0.14	3.03 ± 0.14

Table 5.20: Expected and fitted results for the Validation Regions for an integrated luminosity of 139.0 fb^{-1} . The results are obtained from the CRs using the background fit (see text for details). Nominal MC expectations (normalised to MC cross-sections) are given for comparison.

table.results.yields channel	VRht	VRZ
Observed events	238	172
Fitted bkg events	246.47 ± 12.82	161.86 ± 17.86
Fitted ttbar events	183.91 ± 10.95	47.34 ± 15.22
Fitted SingleTop events	52.52 ± 12.62	8.02 ± 2.49
Fitted Zjets events	4.14 ± 0.89	67.58 ± 9.36
Fitted Wjets events	0.29 ± 0.04	5.49 ± 0.89
Fitted Diboson events	2.31 ± 0.16	30.98 ± 1.01
Fitted Triboson events	$0.00^{+0.01}_{-0.00}$	0.35 ± 0.01
Fitted ttV events	3.28 ± 0.24	2.10 ± 0.11
MC exp. SM events	257.65 ± 11.73	175.48 ± 19.21
MC exp. ttbar events	208.18 ± 9.90	53.79 ± 16.97
MC exp. SingleTop events	38.87 ± 6.20	5.93 ± 1.48
MC exp. Zjets events	4.71 ± 0.87	76.85 ± 7.97
MC exp. Wjets events	0.29 ± 0.04	5.49 ± 0.90
MC exp. Diboson events	2.31 ± 0.16	30.97 ± 1.02
MC exp. Triboson events	$0.00^{+0.01}_{-0.00}$	0.35 ± 0.01
MC exp. ttV events	3.28 ± 0.24	2.10 ± 0.11

Table 5.21: Expected and fitted results for the Validation Regions for an integrated luminosity of 139.0 fb^{-1} . The results are obtained from the CRs using the background fit (see text for details). Nominal MC expectations (normalised to MC cross-sections) are given for comparison.

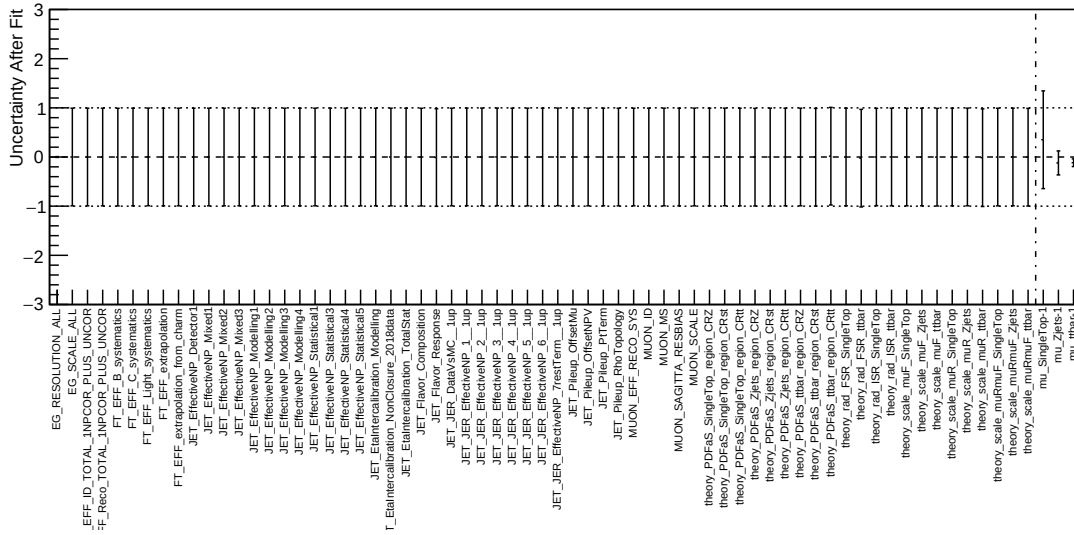


Figure 5.27: Profile of Nuisance Parameters used in standard Background Only Fit. No significant pulls or overfitting is observed.

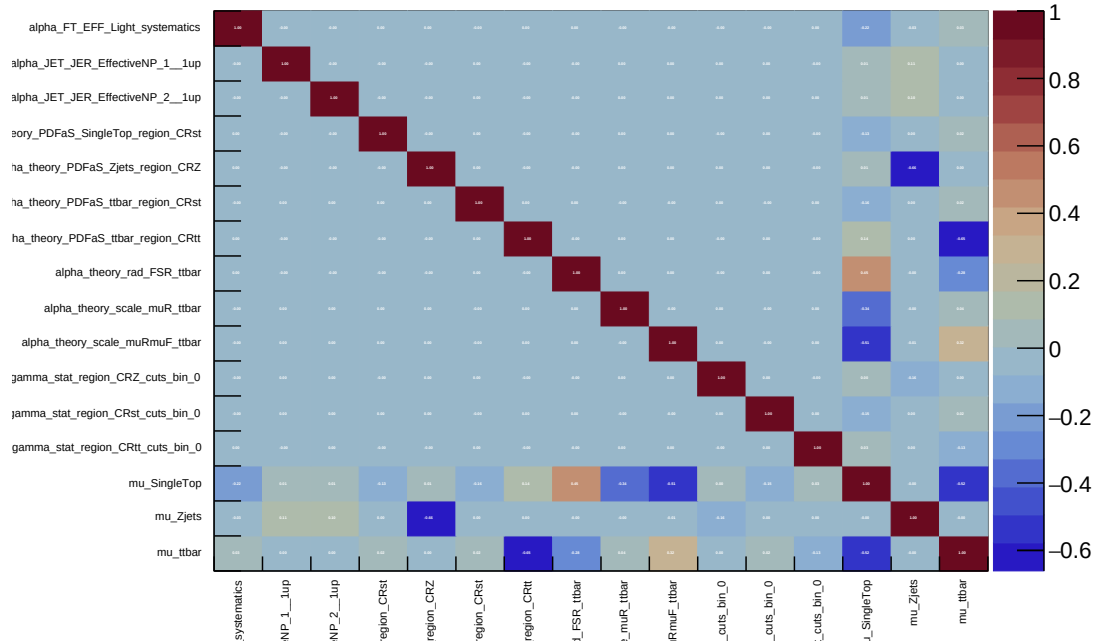
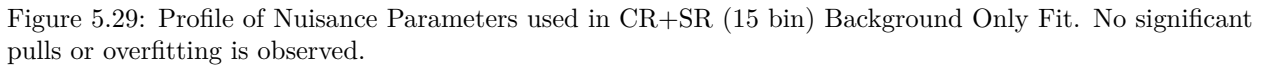


Figure 5.28: Reduced Correlation Matrix from Background Only Fit. There are no correlations between the systematic uncertainties. The only correlations are expected correlations between systematic uncertainties and the background normalization factors.



5.9.1.1 15 Bin SR in CR Background-only Fit

$\mu_{t\bar{t}}$	0.897 ± 0.023
μ_{Wt}	1.35 ± 0.23
μ_{Zjets}	0.89 ± 0.076

5.9.1.2 45 Bin SR in CR Background-only Fit

We perform a simultaneous fit of the 3 Control Regions (CRtt, CRst, CRZ) and the 45-bin Signal Region configuration. The resulting normalization factors are given in Table 5.23 and the profile of the nuisance

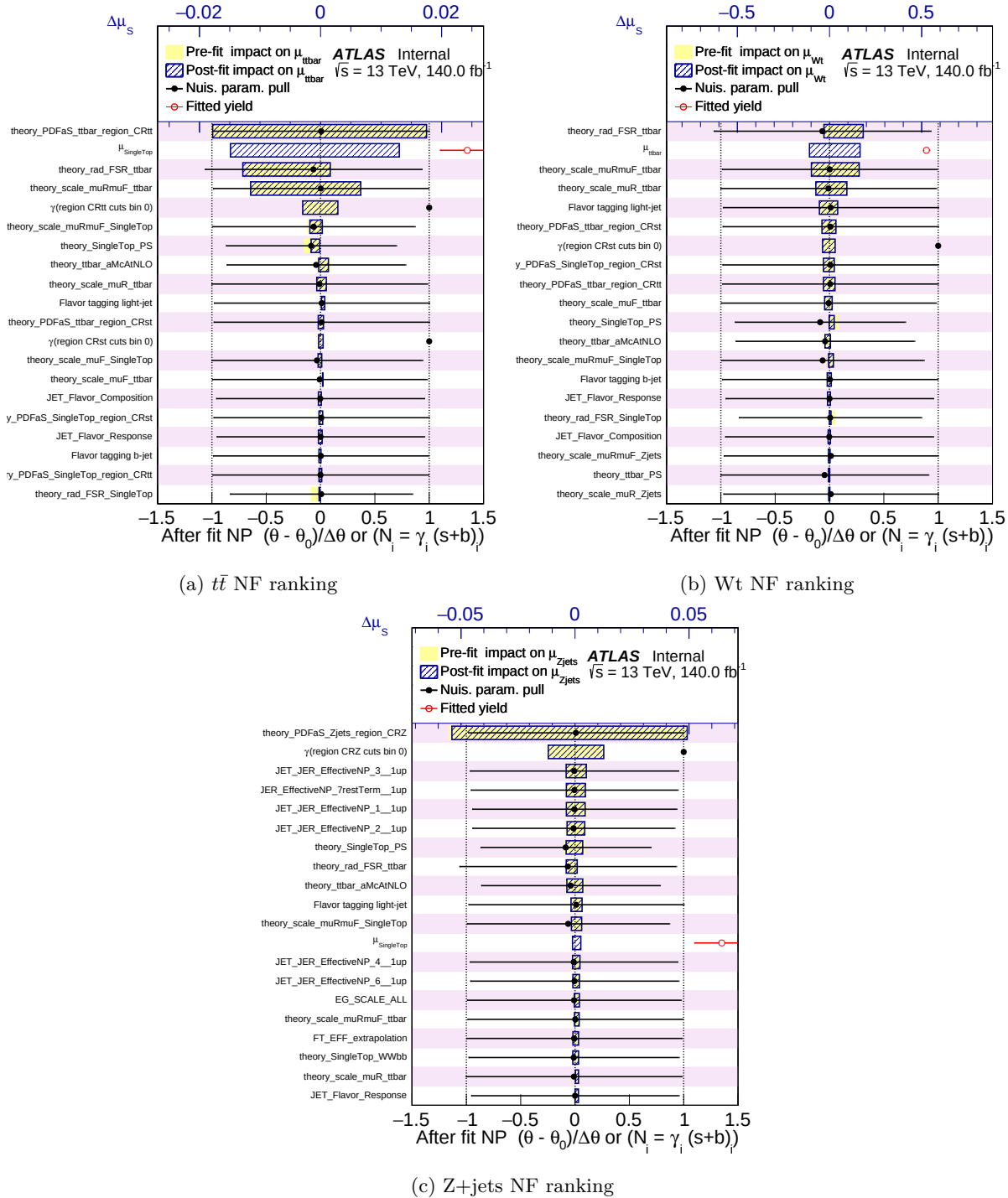


Figure 5.30: The "Ranking Plots" for the Normalization Factors of each dominant background process ($t\bar{t}$, Wt , Z -Jets) for the "overconstrained" fit where the 15 SR bins are considered constraint regions. These plots measure the pre and post fit impact of the various nuisance parameters on the given Normalization Factor: μ_{NF} . The 15 most-impactful nuisance parameters are displayed in each plot.

$\mu_{t\bar{t}}$	0.897 ± 0.025
μ_{Wt}	1.24 ± 0.21
μ_{Zjets}	0.88 ± 0.073

Table 5.24: Normalization factors obtained from the overconstrained background-only fit where the 3 Validation Regions are included as constraint regions. This fit uses dominant theoretical systematics along with most detector systematics for each of the three main backgrounds.

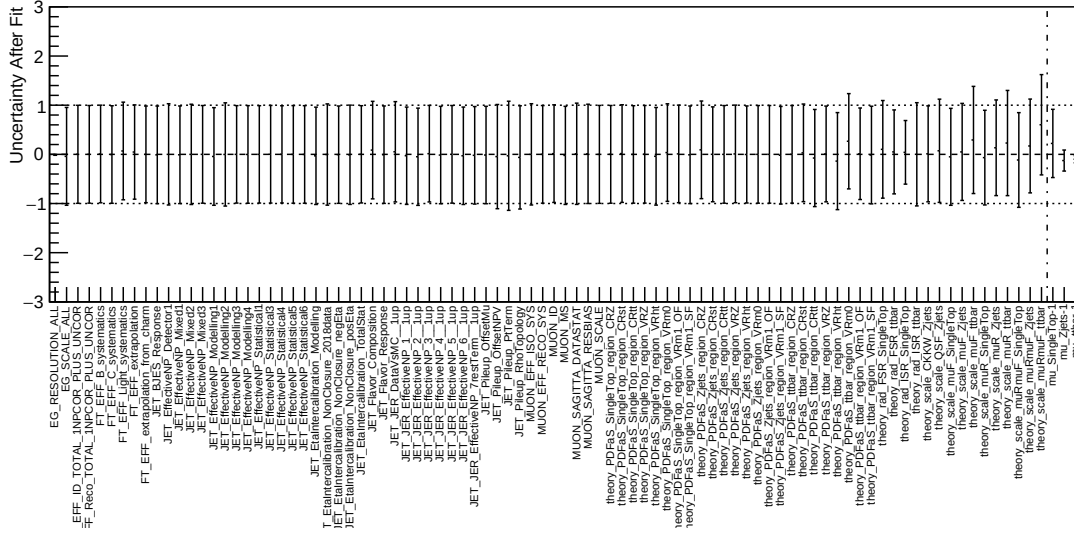


Figure 5.32: Profile of Nuisance Parameters used in CR+VR Background Only Fit. No significant pulls or overfitting is observed.

5.9.2 Model-Dependent Results

Post-fit yields are shown for the SRs in Fig. 5.34–Fig. 5.35. Yields for the 45 bin SR configuration is split across 3 plots (one for each lepton flavor channel). It can be seen that no signal region bin observes a significant excess and so limits must be set. Yields tables for the 15-bin SR configuration are given in Tables 5.25–5.28. The model-dependent exclusion limits on RPV stop pair production are derived using the profile log-likelihood ratio test at the 95% confidence level, as described in Sec. 5.8.4. Exclusion limits are calculated for several theoretical branching ratios of the $\tilde{t}$ to be , $b\mu$, and $b\tau$ by reweighting signal samples using truth decay information. For each signal hypothesis, a separate fit is performed to the CRs and SRs simultaneously to best match MC yields to data.

Exclusions are calculated across the lepton branching ratio plane with a grid spacing of 10% with the values between grid points interpolated using the RBF scheme in SciPy. This procedure is performed for each stop mass hypothesis and given as a series of contour plots in Figures 5.36–5.38.

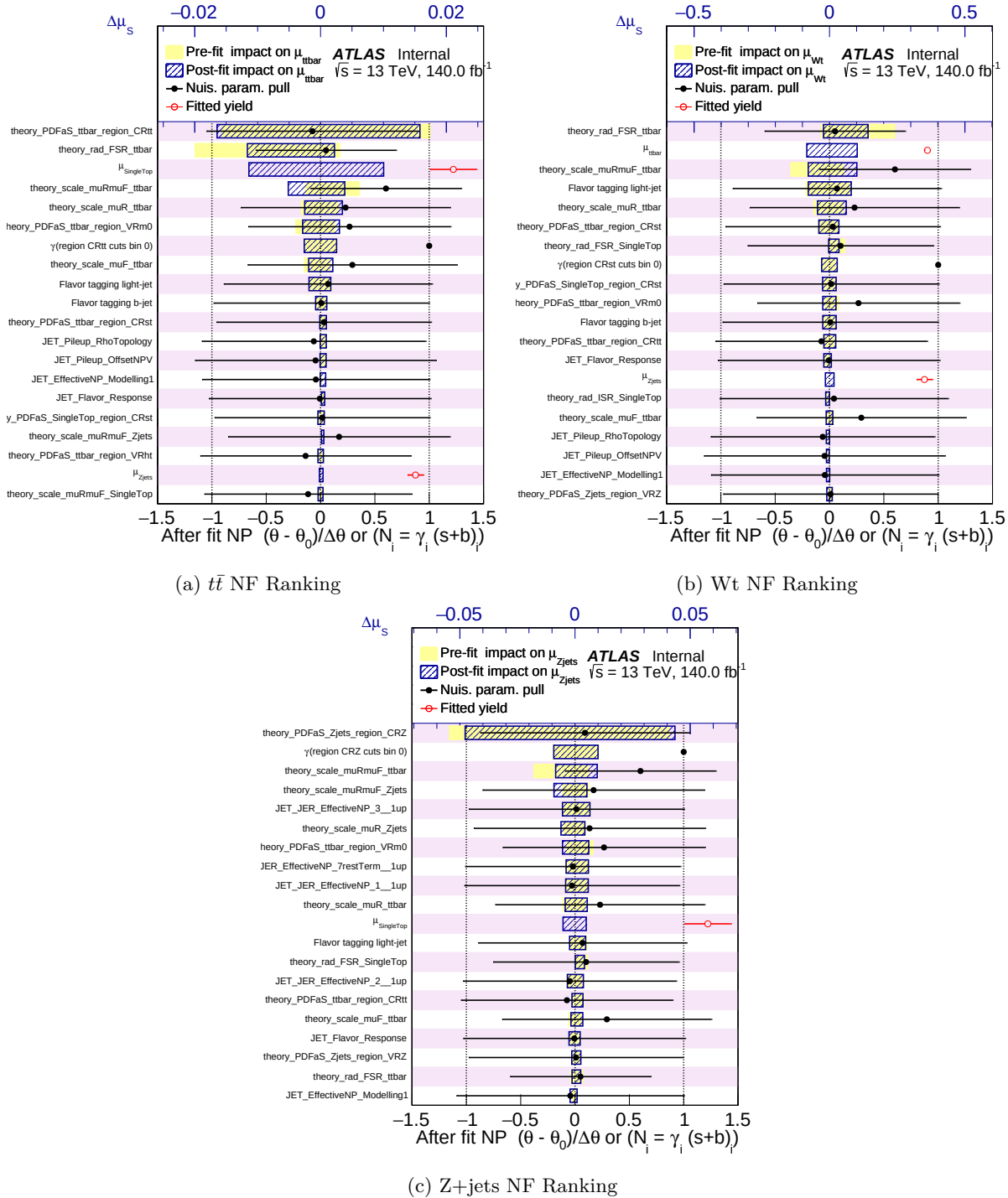


Figure 5.33: The "Ranking Plots" for the Normalization Factors of each dominant background process ($t\bar{t}$, Wt , Z -Jets) for the "overconstrained" fit where the validation regions are considered constraint regions. These plots measure the pre and post fit impact of the various nuisance parameters on the given Normalization Factor: μ_{NF} . The 15 most-impactful nuisance parameters are displayed in each plot.

table.results.yields channel	SR400_bin0a	SR400_bin1a	SR400_bin2a	SR400_bin3a
Observed events	4	6	6	7
Fitted bkg events	6.57 ± 1.70	8.94 ± 2.27	10.04 ± 2.88	10.74 ± 2.94
Fitted ttbar events	1.00 ± 0.74	1.74 ± 0.94	2.43 ± 1.54	2.88 ± 1.87
Fitted SingleTop events	2.52 ± 1.38	3.58 ± 1.93	3.37 ± 2.29	3.13 ± 2.26
Fitted Zjets events	1.87 ± 0.46	2.09 ± 0.40	2.71 ± 0.60	2.94 ± 0.66
Fitted Wjets events	0.15 ± 0.04	0.10 ± 0.06	0.08 ± 0.02	0.30 ± 0.14
Fitted Diboson events	0.79 ± 0.14	1.17 ± 0.23	1.21 ± 0.20	1.26 ± 0.19
Fitted Triboson events	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.00
Fitted ttV events	0.23 ± 0.04	0.25 ± 0.05	0.21 ± 0.05	0.23 ± 0.10
MC exp. SM events	6.30 ± 1.51	8.54 ± 1.95	9.87 ± 2.60	10.72 ± 2.81
MC exp. ttbar events	1.13 ± 0.83	1.98 ± 1.06	2.77 ± 1.75	3.27 ± 2.12
MC exp. SingleTop events	1.87 ± 0.97	2.65 ± 1.35	2.50 ± 1.64	2.32 ± 1.64
MC exp. Zjets events	2.12 ± 0.48	2.37 ± 0.40	3.09 ± 0.65	3.34 ± 0.69
MC exp. Wjets events	0.15 ± 0.04	0.10 ± 0.06	0.08 ± 0.02	0.30 ± 0.15
MC exp. Diboson events	0.79 ± 0.14	1.17 ± 0.23	1.21 ± 0.20	1.26 ± 0.19
MC exp. Triboson events	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.00	0.01 ± 0.00
MC exp. ttV events	0.23 ± 0.04	0.25 ± 0.05	0.21 ± 0.05	0.23 ± 0.10

Table 5.25: Expected and Observed results for the first 4 Signal Regions for an integrated luminosity of 140.0 fb^{-1} . The results are obtained from the SRs using the background fit (see text for details). Nominal MC expectations (normalised to MC cross-sections) are given for comparison.

table.results.yields channel	SR400_bin4a	SR400_bin5a	SR400_bin6a	SR400_bin7a
Observed events	10	6	10	8
Fitted bkg events	11.57 ± 2.73	11.93 ± 2.85	8.54 ± 2.25	7.98 ± 2.61
Fitted ttbar events	3.05 ± 1.80	2.63 ± 1.61	2.07 ± 1.30	1.85 ± 1.08
Fitted SingleTop events	3.54 ± 1.78	5.02 ± 2.33	3.30 ± 1.81	3.32 ± 2.15
Fitted Zjets events	3.16 ± 1.13	2.56 ± 0.44	1.91 ± 0.55	1.77 ± 0.56
Fitted Wjets events	$0.11^{+0.13}_{-0.11}$	0.23 ± 0.14	$0.11^{+0.15}_{-0.11}$	$0.05^{+0.14}_{-0.05}$
Fitted Diboson events	1.26 ± 0.14	1.10 ± 0.16	0.96 ± 0.16	0.77 ± 0.11
Fitted Triboson events	0.02 ± 0.00	0.02 ± 0.01	0.01 ± 0.01	0.01 ± 0.00
Fitted ttV events	0.43 ± 0.07	0.37 ± 0.06	0.17 ± 0.06	0.22 ± 0.06
MC exp. SM events	11.50 ± 2.73	11.34 ± 2.55	8.23 ± 2.11	7.60 ± 2.26
MC exp. ttbar events	3.47 ± 2.03	3.00 ± 1.83	2.35 ± 1.47	2.10 ± 1.22
MC exp. SingleTop events	2.62 ± 1.24	3.72 ± 1.60	2.45 ± 1.28	2.45 ± 1.52
MC exp. Zjets events	3.59 ± 1.21	2.92 ± 0.43	2.17 ± 0.59	2.01 ± 0.60
MC exp. Wjets events	$0.11^{+0.13}_{-0.11}$	0.23 ± 0.14	$0.11^{+0.15}_{-0.11}$	$0.05^{+0.14}_{-0.05}$
MC exp. Diboson events	1.26 ± 0.14	1.10 ± 0.16	0.96 ± 0.16	0.77 ± 0.11
MC exp. Triboson events	0.02 ± 0.00	0.02 ± 0.01	0.01 ± 0.01	0.01 ± 0.00
MC exp. ttV events	0.43 ± 0.07	0.37 ± 0.06	0.17 ± 0.06	0.22 ± 0.06

Table 5.26: Expected results for 4 of the Signal Regions for an integrated luminosity of 140.0 fb^{-1} . The results are obtained from the SRs using the background fit (see text for details). Nominal MC expectations (normalised to MC cross-sections) are given for comparison.

table.results.yields channel	SR400_bin8a	SR400_bin9a	SR400_bin10a	SR400_bin11a
Observed events	5	3	7	1
Fitted bkg events	7.24 ± 1.81	5.96 ± 2.07	7.82 ± 2.51	4.05 ± 1.36
Fitted ttbar events	1.52 ± 0.93	1.23 ± 0.87	1.70 ± 1.09	1.06 ± 0.73
Fitted SingleTop events	2.52 ± 1.44	2.42 ± 1.86	3.11 ± 2.25	$1.05^{+1.09}_{-1.05}$
Fitted Zjets events	1.76 ± 0.43	1.32 ± 0.33	1.56 ± 0.36	1.08 ± 0.20
Fitted Wjets events	0.32 ± 0.15	0.11 ± 0.02	0.21 ± 0.04	0.14 ± 0.03
Fitted Diboson events	0.95 ± 0.17	0.78 ± 0.23	1.07 ± 0.19	0.62 ± 0.10
Fitted Triboson events	0.01 ± 0.00	0.00 ± 0.00	$0.01^{+0.01}_{-0.01}$	$0.01^{+0.01}_{-0.01}$
Fitted ttV events	0.17 ± 0.04	0.10 ± 0.03	0.16 ± 0.03	0.10 ± 0.05
MC exp. SM events	7.04 ± 1.68	5.67 ± 1.77	7.45 ± 2.13	4.07 ± 1.25
MC exp. ttbar events	1.73 ± 1.05	1.40 ± 0.98	1.93 ± 1.23	1.20 ± 0.83
MC exp. SingleTop events	1.86 ± 1.02	1.79 ± 1.34	2.30 ± 1.61	$0.78^{+0.80}_{-0.78}$
MC exp. Zjets events	2.01 ± 0.48	1.50 ± 0.36	1.78 ± 0.36	1.23 ± 0.20
MC exp. Wjets events	0.32 ± 0.15	0.11 ± 0.02	0.21 ± 0.04	0.14 ± 0.03
MC exp. Diboson events	0.95 ± 0.17	0.78 ± 0.23	1.07 ± 0.19	0.62 ± 0.10
MC exp. Triboson events	0.01 ± 0.00	0.00 ± 0.00	$0.01^{+0.01}_{-0.01}$	$0.01^{+0.01}_{-0.01}$
MC exp. ttV events	0.17 ± 0.04	0.10 ± 0.03	0.16 ± 0.03	0.10 ± 0.05

Table 5.27: Expected results for 4 of the Signal Regions for an integrated luminosity of 140.0 fb^{-1} . The results are obtained from the SRs using the background fit (see text for details). Nominal MC expectations (normalised to MC cross-sections) are given for comparison.

table.results.yields channel	SR400_bin12a	SR400_bin13a	SR400_bin14a
Observed events	2	3	0
Fitted bkg events	3.82 ± 1.43	4.31 ± 1.52	2.17 ± 0.69
Fitted ttbar events	0.62 ± 0.45	0.43 ± 0.37	0.29 ± 0.26
Fitted SingleTop events	1.49 ± 1.01	1.67 ± 1.18	0.63 ± 0.59
Fitted Zjets events	1.09 ± 0.52	1.22 ± 0.36	0.73 ± 0.14
Fitted Wjets events	0.12 ± 0.04	0.50 ± 0.08	0.18 ± 0.04
Fitted Diboson events	0.42 ± 0.11	0.41 ± 0.08	0.31 ± 0.05
Fitted Triboson events	0.00 ± 0.00	0.01 ± 0.00	0.00 ± 0.00
Fitted ttV events	$0.08^{+0.08}_{-0.08}$	0.08 ± 0.02	0.03 ± 0.00
MC exp. SM events	3.67 ± 1.32	4.10 ± 1.29	2.14 ± 0.60
MC exp. ttbar events	0.71 ± 0.51	0.49 ± 0.42	0.32 ± 0.29
MC exp. SingleTop events	1.10 ± 0.73	1.23 ± 0.84	0.47 ± 0.43
MC exp. Zjets events	1.24 ± 0.60	1.39 ± 0.38	0.83 ± 0.15
MC exp. Wjets events	0.12 ± 0.04	0.50 ± 0.08	0.18 ± 0.04
MC exp. Diboson events	0.42 ± 0.11	0.41 ± 0.08	0.31 ± 0.05
MC exp. Triboson events	0.00 ± 0.00	0.01 ± 0.00	0.00 ± 0.00
MC exp. ttV events	$0.08^{+0.08}_{-0.08}$	0.08 ± 0.02	0.03 ± 0.00

Table 5.28: Expected results for the last 4 Signal Regions for an integrated luminosity of 140.0 fb^{-1} . The results are obtained from the SRs using the background fit (see text for details). Nominal MC expectations (normalised to MC cross-sections) are given for comparison.

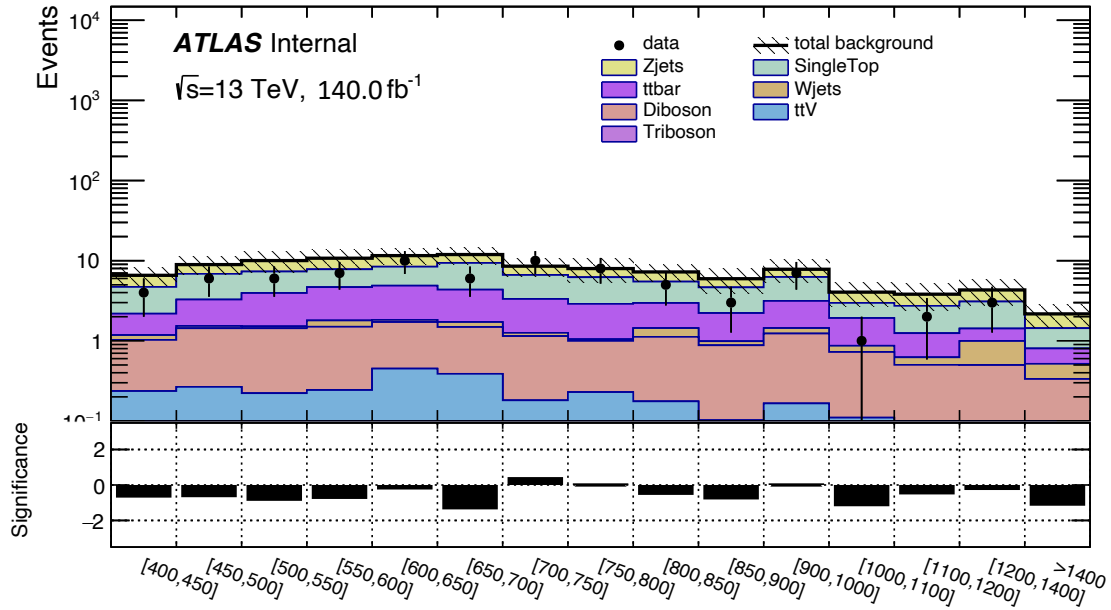


Figure 5.34: The observed Data and post-fit Monte Carlo expectation for SM processes in each Signal Region bin for the flavor-agnostic configuration. The bottom panel shows the significance of the difference between the expected yields and observed data.

The limit contours for selected theoretical stop masses are shown in Figures 5.36–5.38. Our weakest exclusions occur when $\text{BR}(\tilde{t} \rightarrow \tau)$ is high, which is expected. Due to slight downward fluctuations in the unblinded data, our exclusion strength performs slightly better than expected. Results of the model-dependent search are summarized in Fig. 5.39. For this plot, the highest excluded (CLs < 0.05) stop mass is determined for each grid point. We then interpolate the space between grid points using the RBF method described above. For the scenario where $\text{BR}(\tilde{t} \rightarrow e) = 100\%$, we exclude stop masses up to 1900 GeV. For $\text{BR}(\tilde{t} \rightarrow \mu) = 100\%$, we exclude stop masses up to 1800 GeV, and for $\text{BR}(\tilde{t} \rightarrow \tau) = 100\%$, we exclude stop masses up to 800 GeV.

5.9.3 Model-Independent Results

As described in Sec. 5.8.5, one can make general statements on the production rate of new physics. The discovery fit utilizes a nested SR scheme (given again in Table 5.17) in order to avoid assumptions on the nature of new physics and avoid the “look elsewhere” effect. The limits produced are conservative due to the assumption of a lack of signal events in the CRs: a real, observable signal present in both the SRs and CRs would lead to the effect being normalized away, weakening sensitivity in the SR.

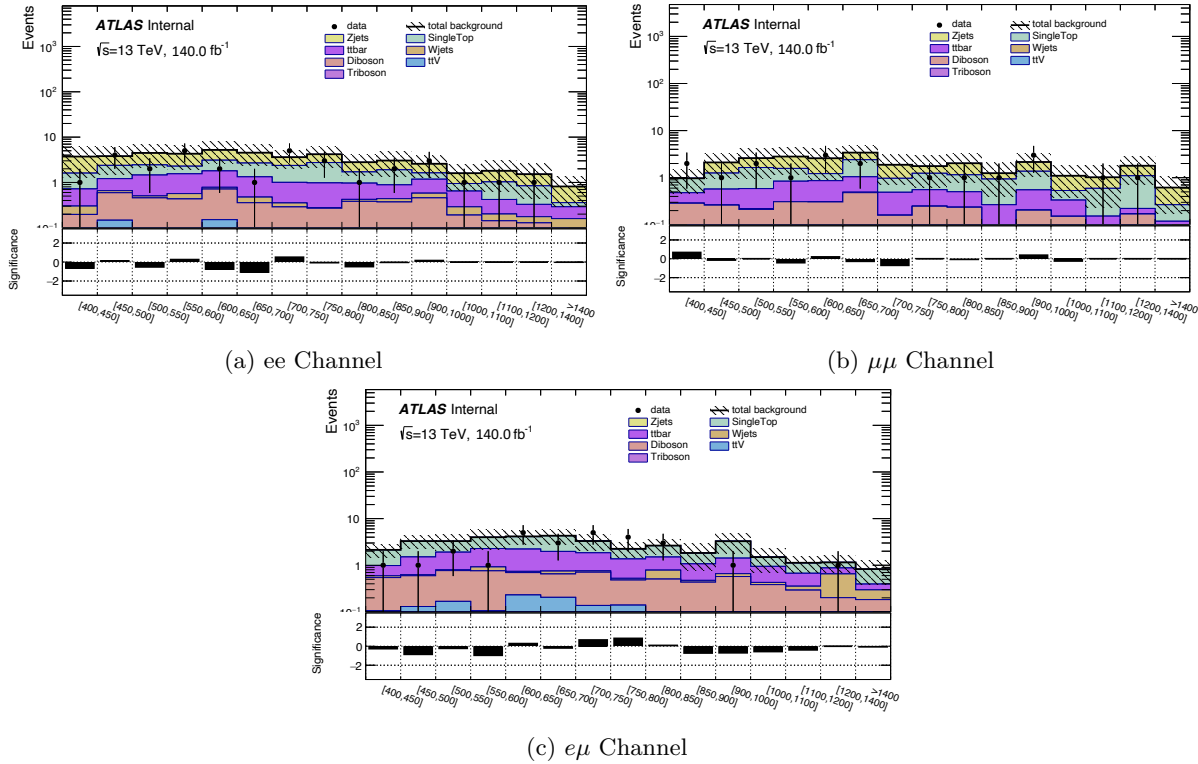


Figure 5.35: The observed Data and post-fit Monte Carlo expectation for SM processes in each Signal Region bin for the flavor-aware configuration. Each plot shows the yields for a single flavor channel of the 45 bin fit. The bottom panel of each shows the significance of the difference between the expected yields and observed data.

Results are reported with the following variables: N_{SMexp} , N_{obs} , $\langle\epsilon\sigma\rangle_{obs}^{95}$, S_{obs}^{95} , S_{exp}^{95} , CL_B , $p(s=0)$ (Z). The first two values, N_{SMexp} and N_{obs} , report the expected number of events in the listed SR along with the observed number of events. As can be seen, there are zero bins in which the observed number of events exceeds the expected. From here, S_{obs}^{95} and S_{exp}^{95} are calculated; these values represent the maximum number of signal events which could be produced and still be compatible with data at the 95% Confidence Level. S_{exp}^{95} is the expected upper limit on signal production in the scenario that N_{obs} exactly matches N_{SMexp} . $\langle\epsilon\sigma\rangle_{obs}^{95}$ translates the observed upper limit on signal production into the corresponding upper limit on production cross-section, based on the total recorded luminosity. CL_B denotes the confidence level observed for the background-only hypothesis, with no bins reporting incompatibility. The final value, $p(s=0)$, reports the discovery p -value under the background-only and its converted Z-score significance. All results are computed with an ensemble of 10,000 simulated pseudo-experiments (Toys) instead of the asymptotic approximation. Results are reported in their entirety in Table 5.29.

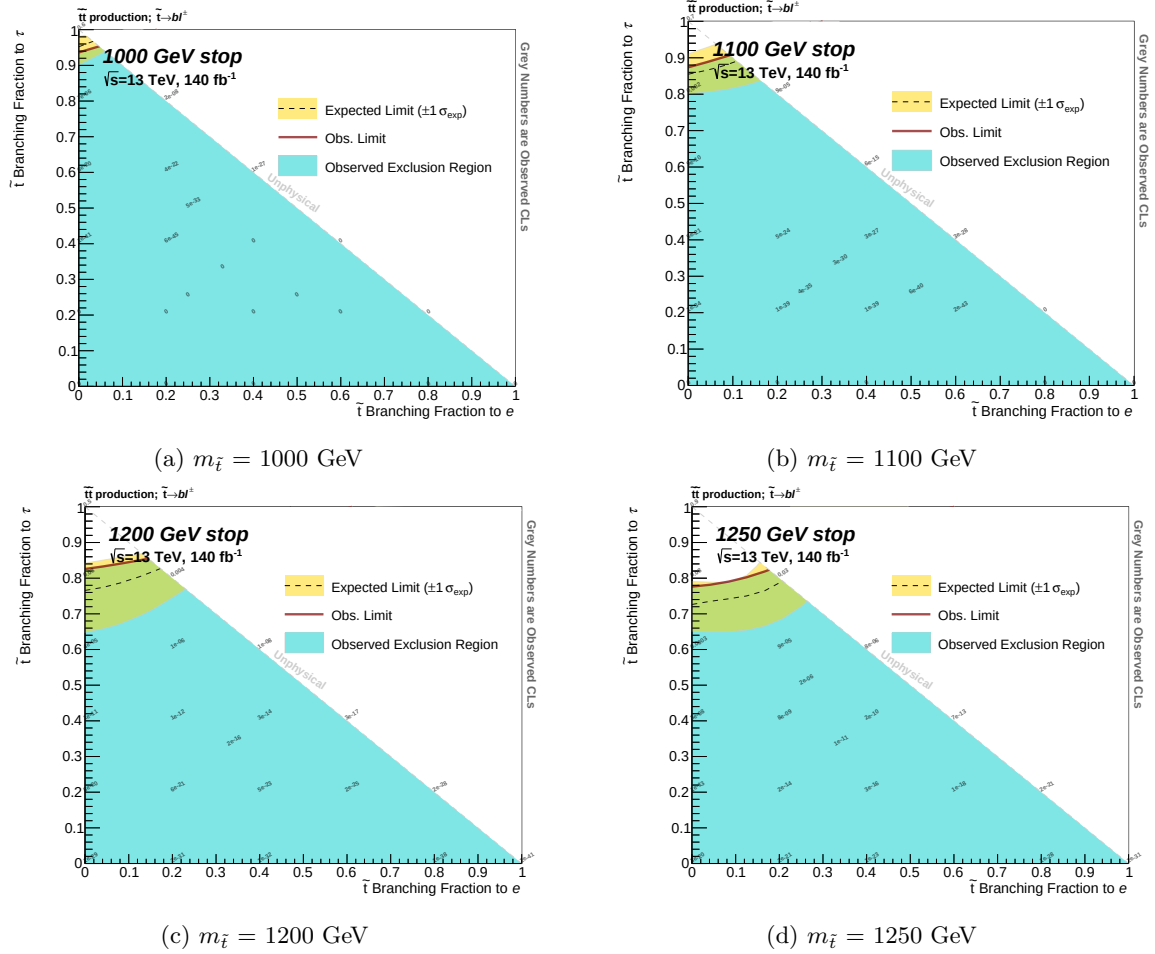


Figure 5.36: Limit contours for selected stop mass points (1000 GeV - 1250 GeV). The shaded blue region indicates BR points which are excluded. The dashed line indicates the expected exclusion strength of the search. The shaded yellow region indicates the $\pm 1\sigma$ bands for the expected exclusions. A contours are drawn utilizing the Full 140 fb^{-1} Run 2 dataset

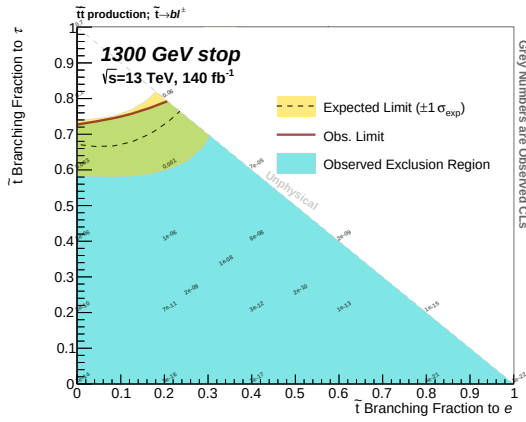
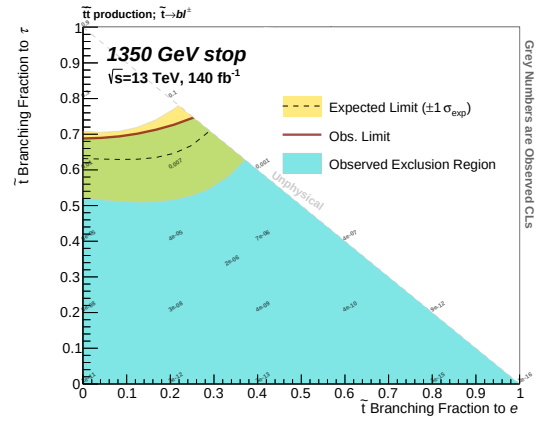
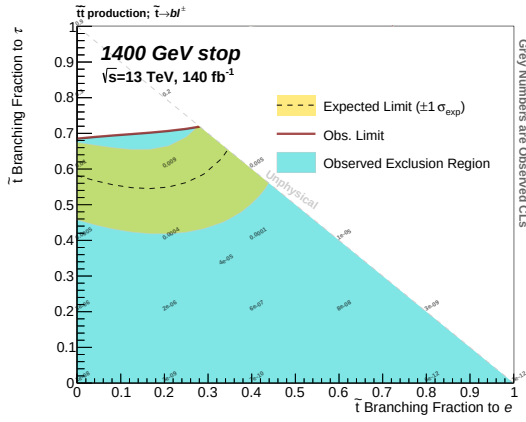
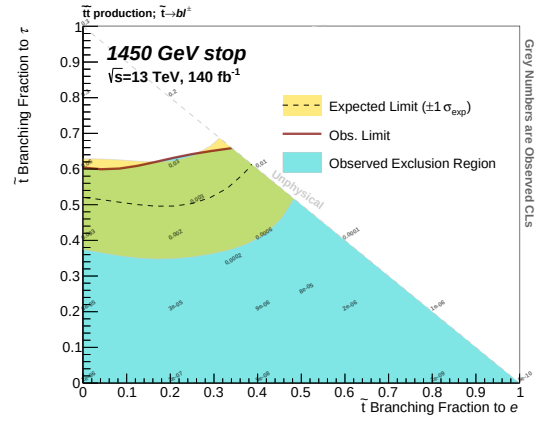
(a) $m_{\tilde{t}} = 1300$ GeV(b) $m_{\tilde{t}} = 1350$ GeV(c) $m_{\tilde{t}} = 1400$ GeV(d) $m_{\tilde{t}} = 1450$ GeV

Figure 5.37: Limit contours for selected stop mass points (1300 GeV - 1450 GeV). The shaded blue region indicates BR points which are excluded. The dashed line indicates the expected exclusion strength of the search. The shaded yellow region indicates the $\pm 1\sigma$ bands for the expected exclusions. A contours are drawn utilizing the Full 140 fb^{-1} Run 2 dataset

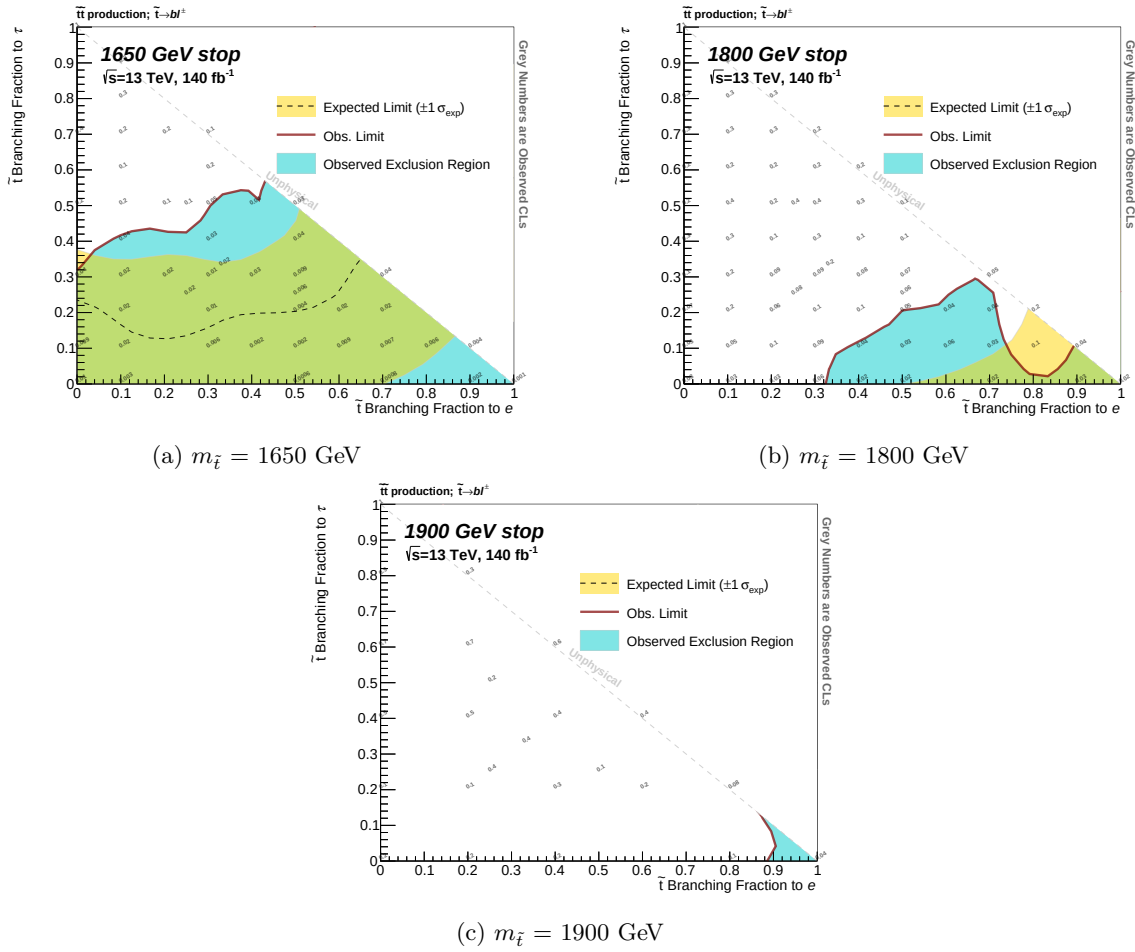


Figure 5.38: Limit contours for selected stop mass points (1650 GeV - 1900 GeV). The shaded blue region indicates BR points which are excluded. The dashed line indicates the expected exclusion strength of the search. The shaded yellow region indicates the $\pm 1\sigma$ bands for the expected exclusions. A contours are drawn utilizing the Full 140 fb^{-1} Run 2 dataset

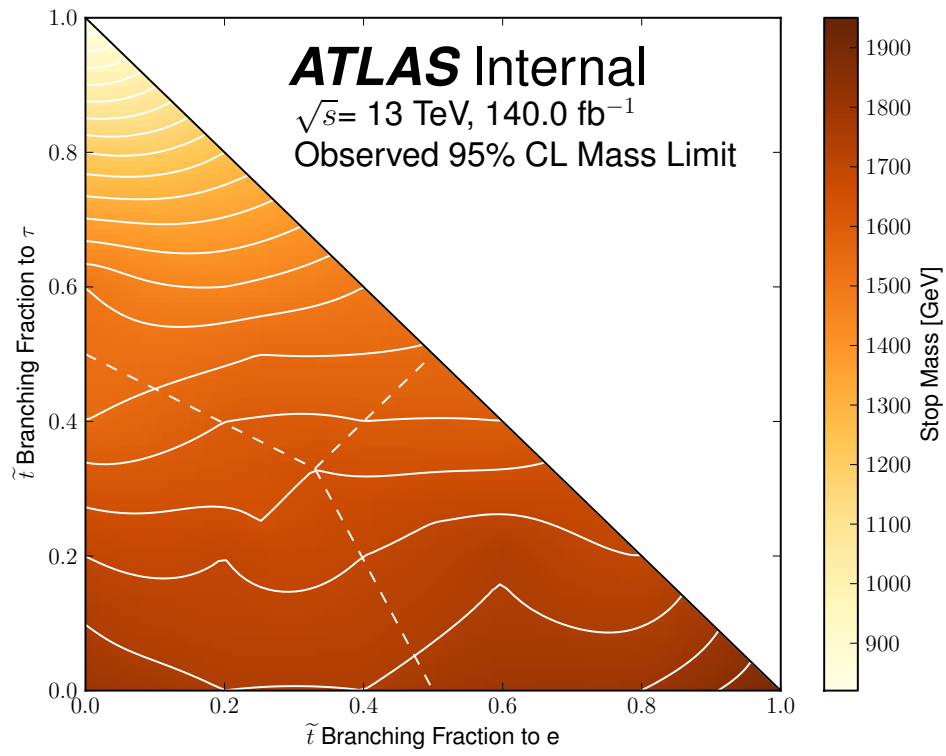


Figure 5.39: A summary of highest excluded stop mass across the lepton branching ratio plane.

Mass Range	N_{SMexp}	N_{obs}	$\langle\epsilon\sigma\rangle_{obs}^{95}[\text{fb}]$	S_{obs}^{95}	S_{exp}^{95}	CL_B	$p(s=0) (Z)$
≥ 400 GeV	84.03 ± 8.19	78	0.16	21.9	$32.1^{+10.6}_{-8.1}$	0.09	0.50 (0.00)
≥ 450 GeV	81.77 ± 7.63	74	0.13	18.6	$29.3^{+10.5}_{-7.7}$	0.06	0.50 (0.00)
≥ 500 GeV	72.71 ± 7.85	68	0.15	21.6	$30.0^{+10.0}_{-7.3}$	0.12	0.50 (0.00)
≥ 550 GeV	67.73 ± 7.30	62	0.13	18.3	$26.6^{+9.4}_{-6.9}$	0.11	0.50 (0.00)
≥ 600 GeV	59.94 ± 6.82	55	0.13	17.8	$25.2^{+8.9}_{-6.4}$	0.12	0.50 (0.00)
≥ 650 GeV	50.17 ± 5.92	45	0.11	15.2	$21.9^{+8.0}_{-5.7}$	0.11	0.50 (0.00)
≥ 700 GeV	43.43 ± 5.42	39	0.10	14.1	$19.7^{+7.3}_{-5.2}$	0.15	0.50 (0.00)
≥ 750 GeV	33.28 ± 4.63	29	0.08	11.9	$17.0^{+6.4}_{-4.5}$	0.12	0.50 (0.00)
≥ 800 GeV	26.62 ± 3.61	21	0.06	8.9	$14.3^{+5.7}_{-3.9}$	0.07	0.50 (0.00)
≥ 850 GeV	20.05 ± 3.17	16	0.06	8.3	$12.5^{+5.1}_{-3.4}$	0.10	0.50 (0.00)
≥ 900 GeV	16.85 ± 2.78	13	0.05	7.4	$11.2^{+4.7}_{-3.2}$	0.11	0.50 (0.00)
≥ 1000 GeV	9.89 ± 1.82	6	0.04	5.1	$8.4^{+3.8}_{-2.5}$	0.08	0.50 (0.00)
≥ 1100 GeV	8.46 ± 1.60	5	0.03	4.9	$7.8^{+3.6}_{-2.3}$	0.09	0.50 (0.00)
≥ 1200 GeV	5.34 ± 1.29	3	0.03	4.2	$6.4^{+3.2}_{-2.0}$	0.14	0.50 (0.00)
≥ 1400 GeV	1.83 ± 0.52	0	0.02	2.5	$4.2^{+2.4}_{-1.4}$	0.11	0.50 (0.00)

Table 5.29: Left to right: 95% CL upper limits on the visible cross section ($\langle\epsilon\sigma\rangle_{obs}^{95}$) and on the number of signal events (S_{obs}^{95}). The third column (S_{exp}^{95}) shows the 95% CL upper limit on the number of signal events, given the expected number (and $\pm 1\sigma$ excursions on the expectation) of background events. The last two columns indicate the CL_B value, i.e. the confidence level observed for the background-only hypothesis, and the discovery p -value ($p(s=0)$).

CHAPTER 6

Conclusion

This dissertation has presented a search for b-jet + charged lepton resonances from R-Parity violating decays of stops as well as validation of the HCCStar ASIC's radiation hardness. The theoretical framework of the Standard Model of particle physics as well as the $B - L$ MSSM as a hypothetical extension to the Standard Model was discussed in Chapter 2 to motivate the $B - L$ stop search. A background on the LHC as well as the ATLAS detector was given in Chapter 3 to better understand the goals and scope of the HL-LHC upgrade project.

Chapter 5 presented a search for scalar top squarks with direct R-Parity violating decays to a b-quark and a charged lepton using the Full Run 2 dataset. No significant excess was observed in this analysis and thus limits were subsequently set on the stop production cross-section. The strongest limits are set in the $\text{BR}(\tilde{t} \rightarrow e) = 100\%$ scenario, where we have excluded stop masses up to 1900 GeV. In the least advantageous scenarios, where $\text{BR}(\tilde{t} \rightarrow \tau)$ is high, limits are set at the 1 TeV scale. In addition to exclusions set on the $B - L$ RPV model, model-independent limits were set on the production cross-section of new physics processes resulting in two lepton-jet resonances with at least one of the jets being identified as b-quark initiated. These results set an upper limit on the production cross-section between 0.16 fb for $m_{b\ell} \geq 400$ GeV and 0.02 fb for $m_{b\ell} \geq 1400$ GeV.

While there has not been a direct measurement of new physics, the Run 3 data collection period has begun at the LHC, which seeks to triple the useable dataset for physics analysis. In addition, the HL-LHC will provide 10x the integrated luminosity previously collected, dramatically improving the ability to search for rare physics processes and perform further high-precision measurements of the Standard Model. While the lack of observation may seem grim to many, I find this to be an excellent opportunity to rethink the approach and assumptions behind physics analyses at the LHC. New discoveries may be hidden in our dataset or just around the corner, waiting for us to understand how to find them.

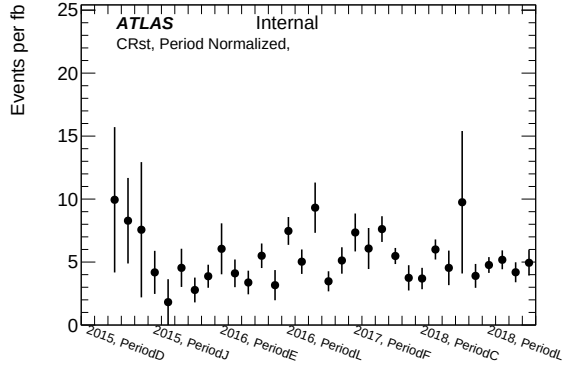
Appendices

APPENDIX A

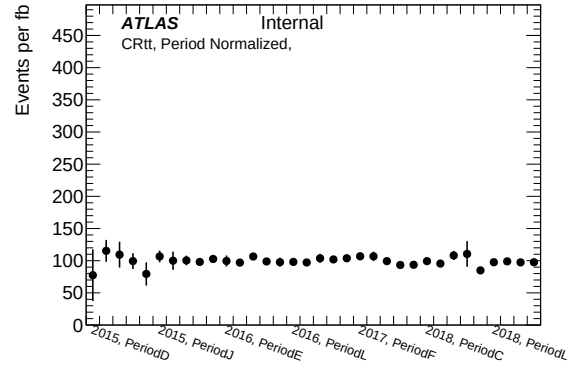
Diagnostics Plots

A.1 Period Normalized Data Distributions

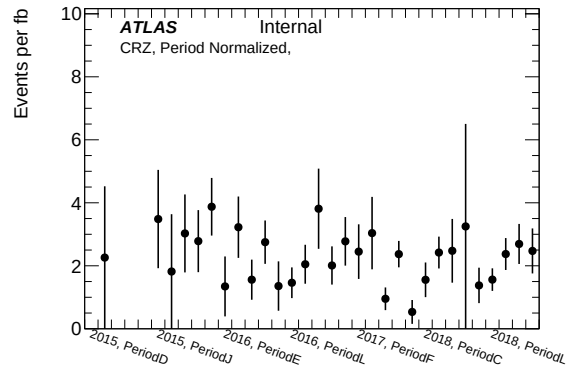
We plot the event yield per Data taking period, normalized to luminosity, to observe any potential period dependences.



(a) CRst

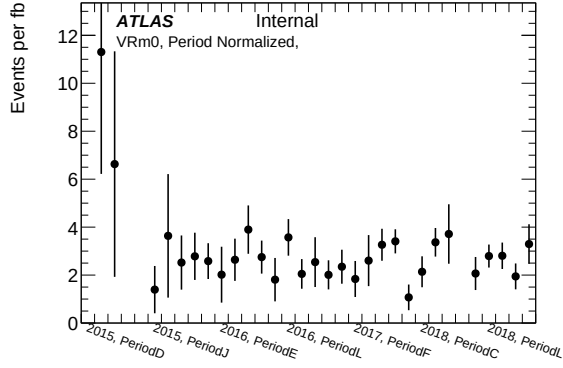


(b) CRtt

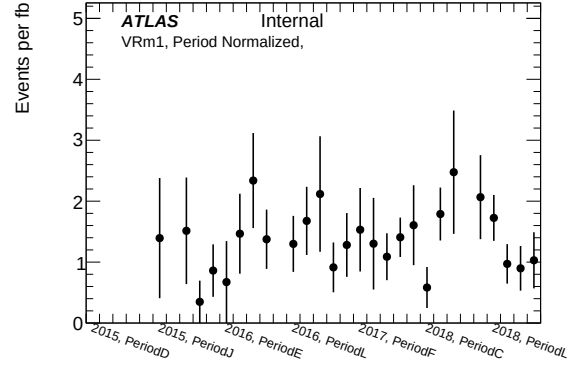


(c) CRZ

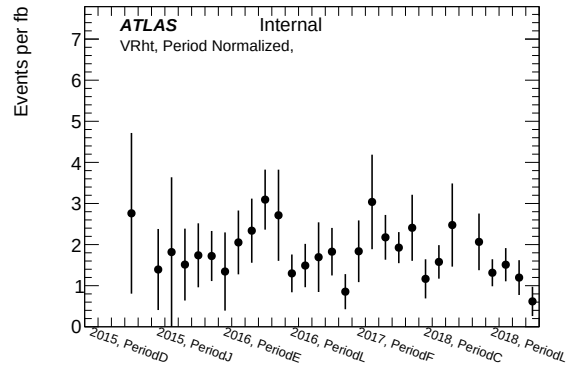
Figure A.1: Data yield per period, normalized to luminosity for all Control Regions. Uncertainties are purely statistical.



(a) VRm0



(b) VRm1

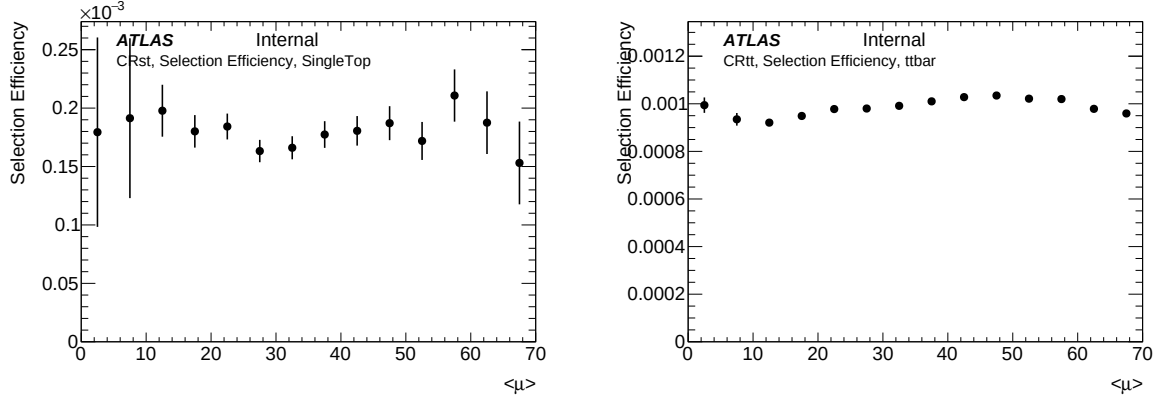


(c) VRht

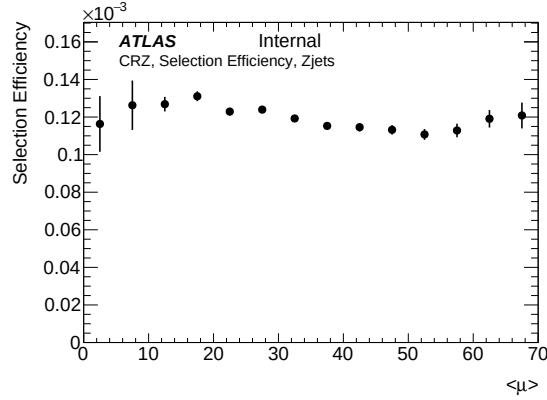
Figure A.2: Data yield per period, normalized to luminosity for all Validation Regions. Uncertainties are purely statistical.

A.2 Selection Efficiency vs Pileup

Selection efficiency for Signal and Background processes are plotted vs average pileup to observe potential dependences on pileup.

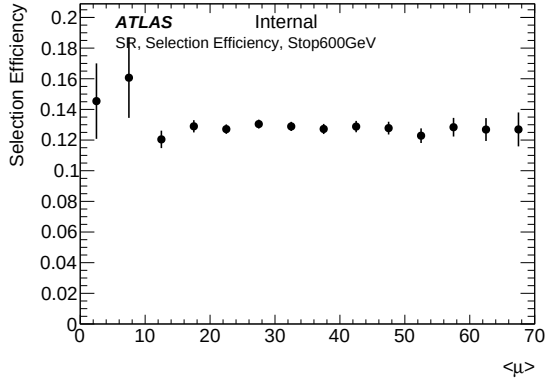


(a) Single Top Selection Efficiency vs avg pileup in CRst (b) $t\bar{t}$ Selection Efficiency vs avg pileup in CRtt

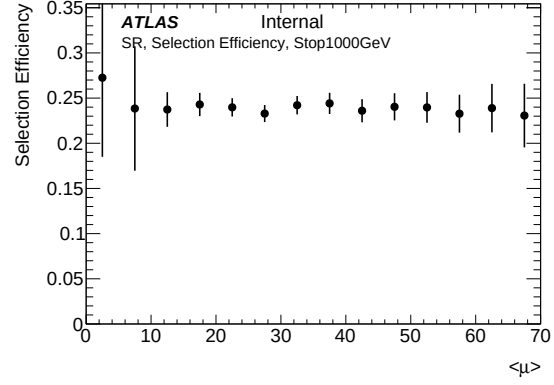


(c) Z+jets Selection Efficiency vs avg pileup in CRZ

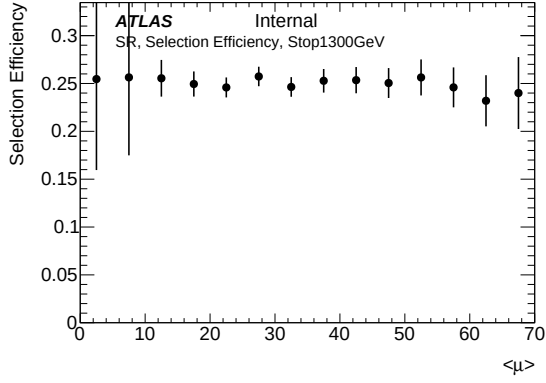
Figure A.3: Selection efficiency for dominant backgrounds in their associated Control Region vs Average pileup.



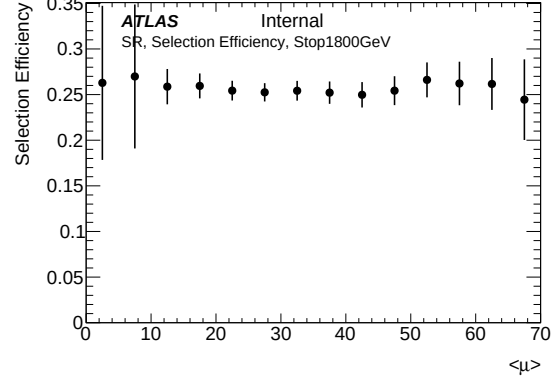
(a) 600 GeV Stop



(b) 1000 GeV Stop



(c) 1300 GeV Stop



(d) 1800 GeV Stop

Figure A.4: Selection efficiency for selected stop signal mass points in the Signal Region vs Average pileup.

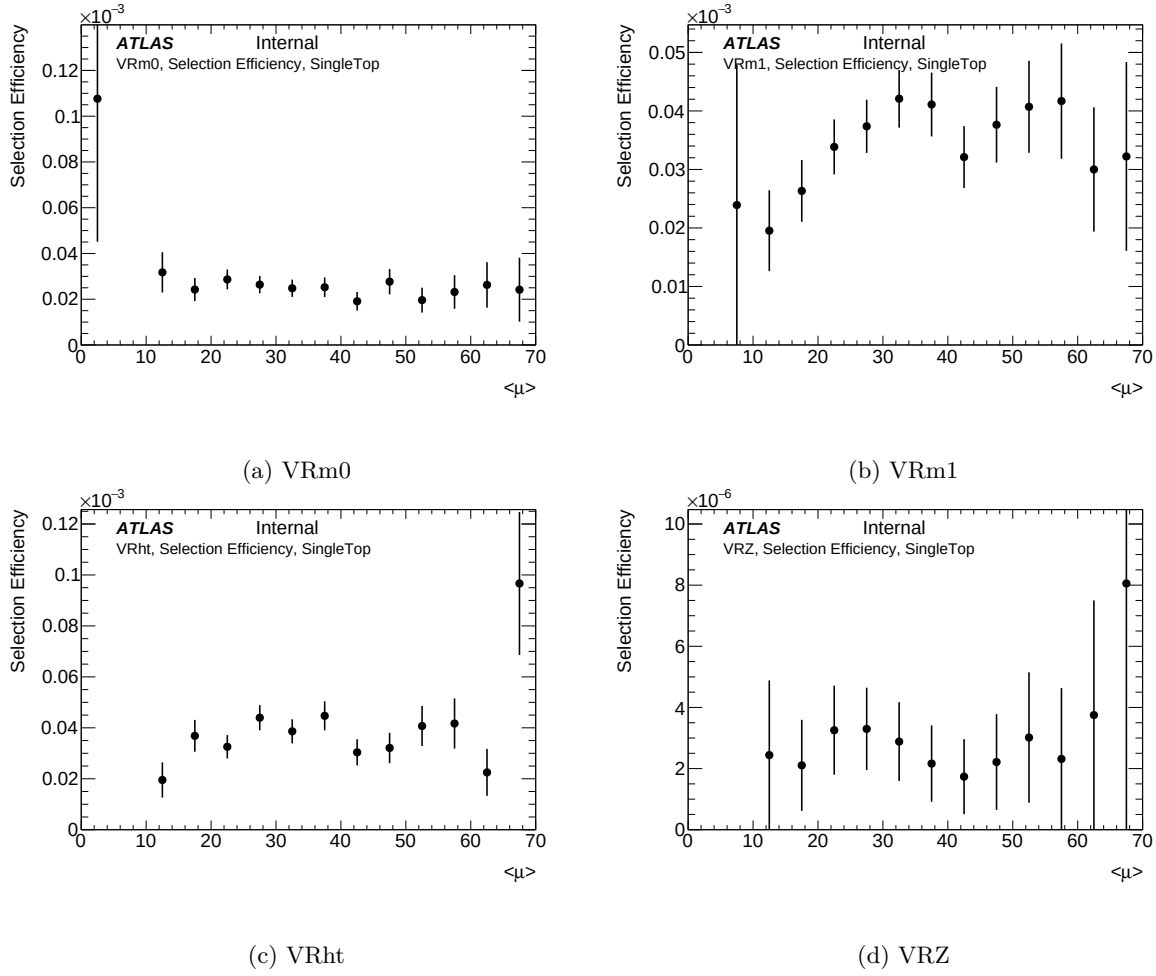
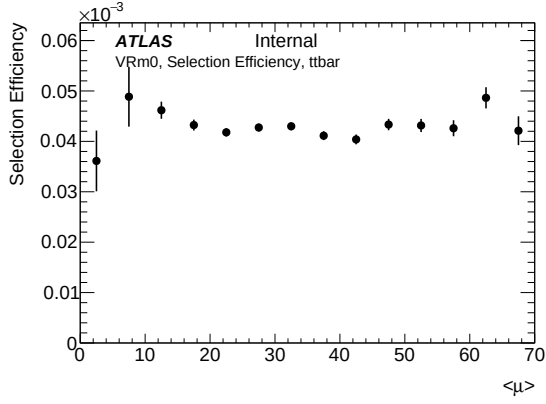
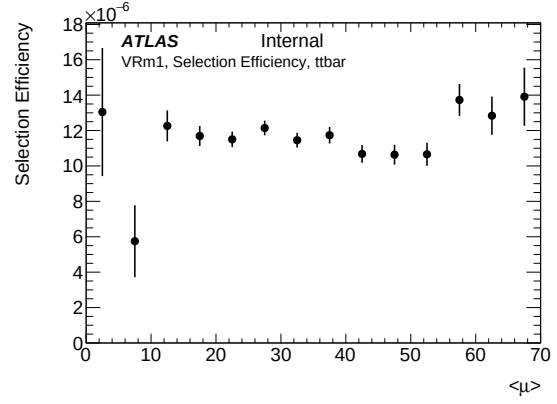


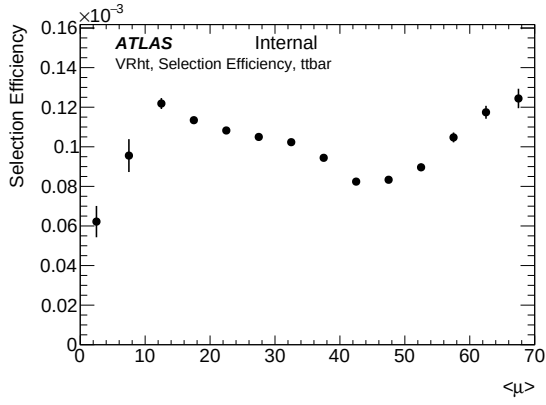
Figure A.5: Selection efficiency for Single Top processes in the Validation Regions vs Average pileup.



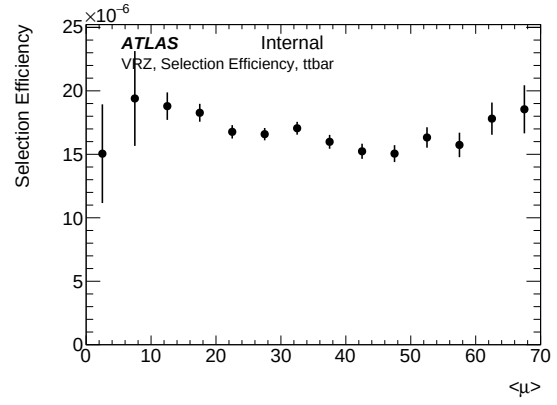
(a) VRm0



(b) VRm1



(c) VRht



(d) VRZ

Figure A.6: Selection efficiency for $t\bar{t}$ processes in the Validation Regions vs Average pileup.

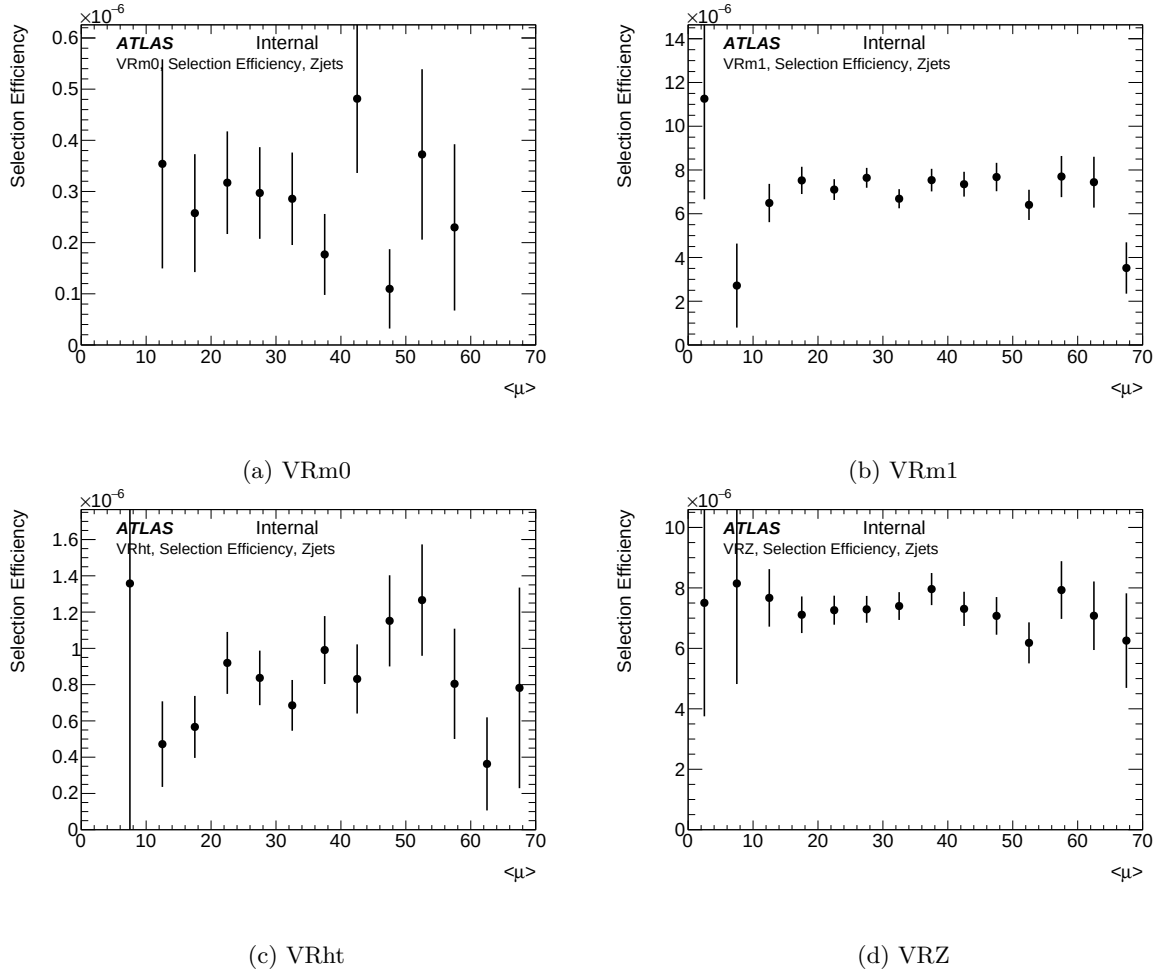
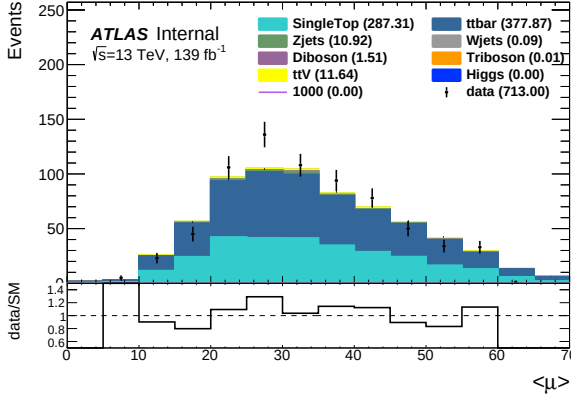


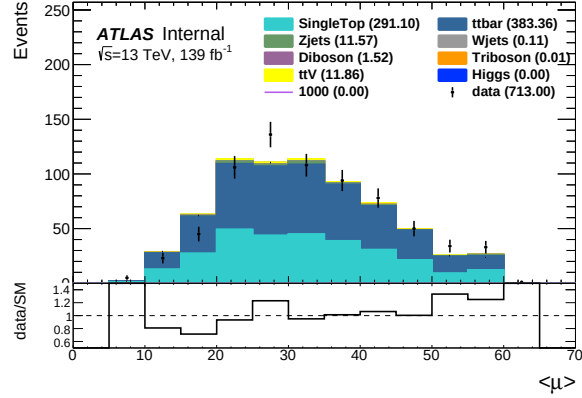
Figure A.7: Selection efficiency for Z+jets processes in the Validation Regions vs Average pileup.

A.3 Pileup Reweighting Verification

We plot Data vs Monte-Carlo comparisons for average pileup distributions in all analysis regions before and after pileup reweighting.

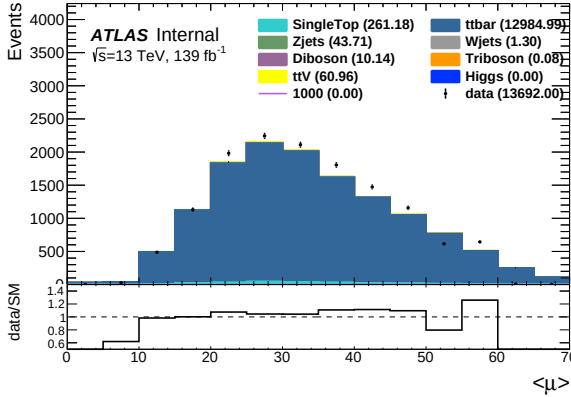


(a) CRst, Pre-PRW

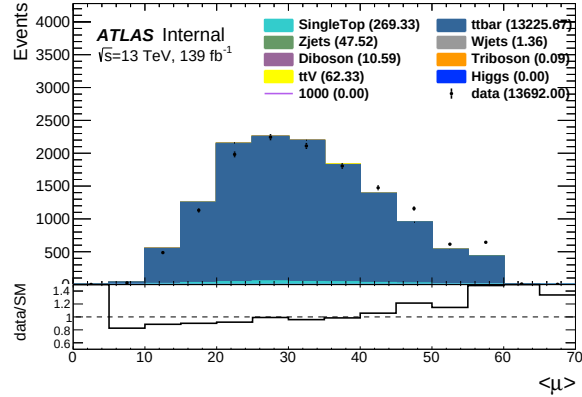


(b) CRst, Post-PRW

Figure A.8: Data/MC comparisons for average pileup in CRtt before and after pileup reweighting

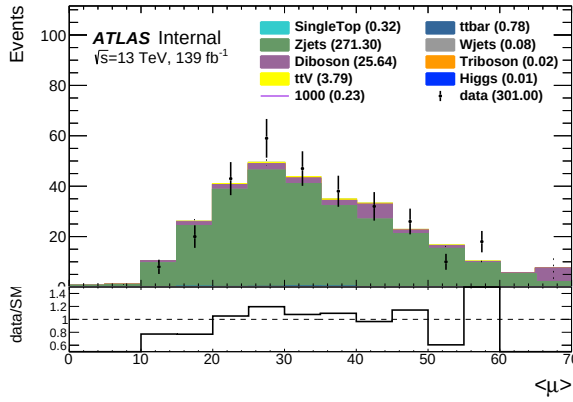


(a) CRtt, Pre-PRW

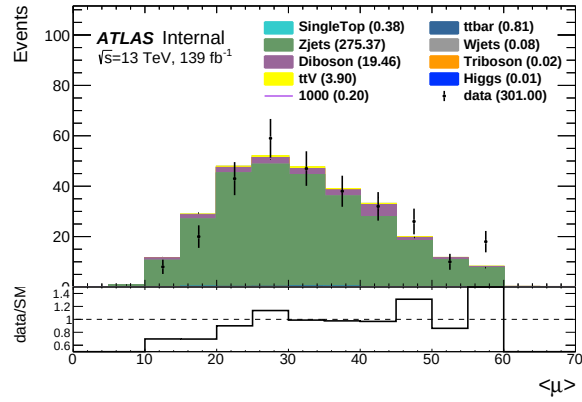


(b) CRtt, Post-PRW

Figure A.9: Data/MC comparisons for average pileup in CRtt before and after pileup reweighting

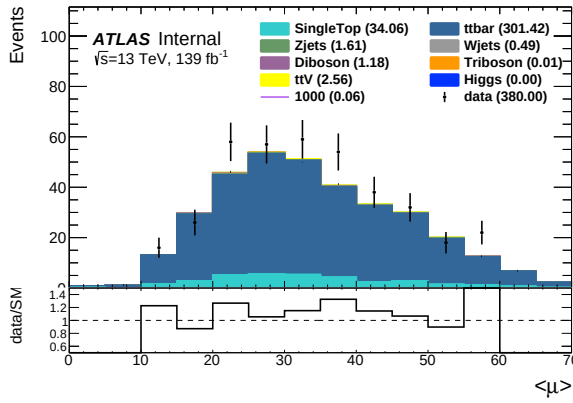


(a) CRZ, Pre-PRW

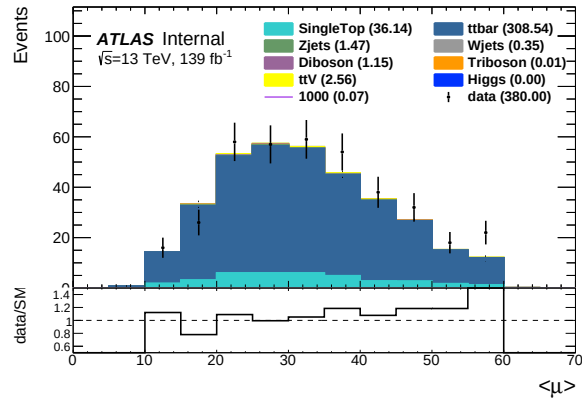


(b) CRZ, Post-PRW

Figure A.10: Data/MC comparisons for average pileup in CRZ before and after pileup reweighting

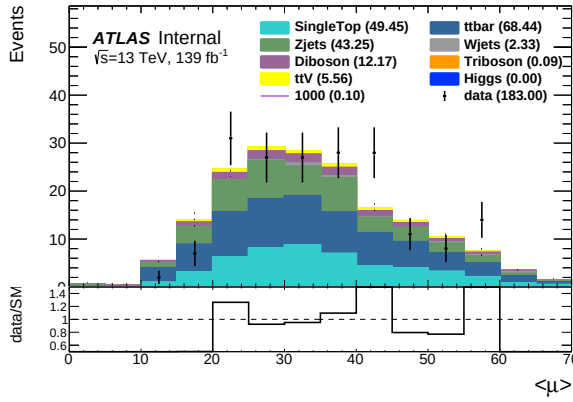


(a) VRm0, Pre-PRW

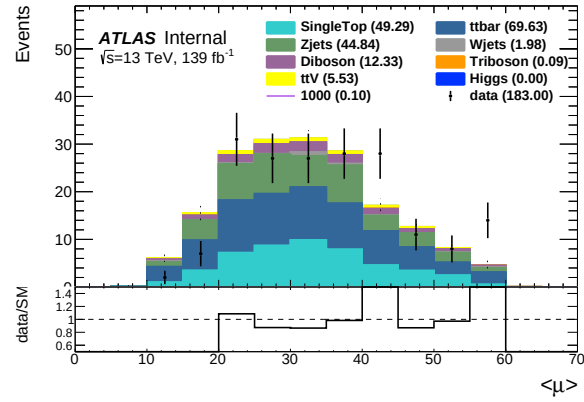


(b) VRm0, Post-PRW

Figure A.11: Data/MC comparisons for average pileup in VRm0 before and after pileup reweighting

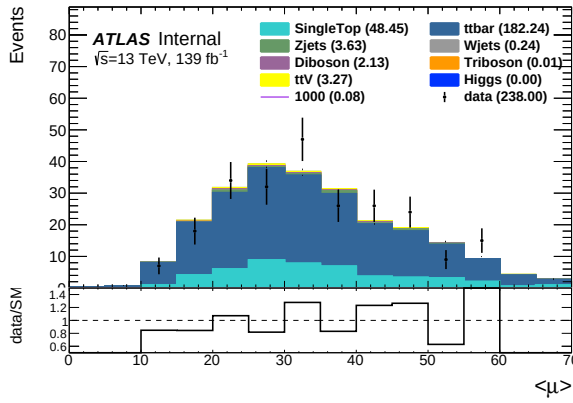


(a) VRm1, Pre-PRW

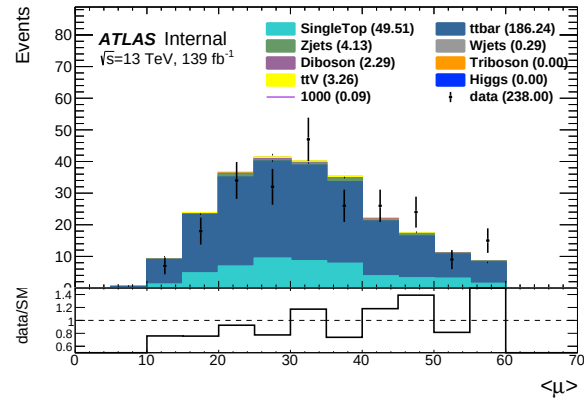


(b) VRm1, Post-PRW

Figure A.12: Data/MC comparisons for average pileup in VRm1 before and after pileup reweighting

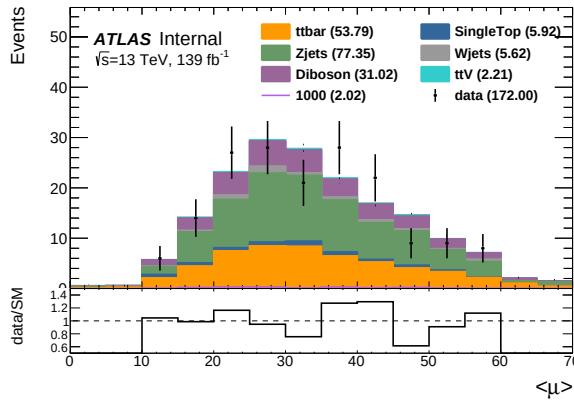


(a) VRht, Pre-PRW

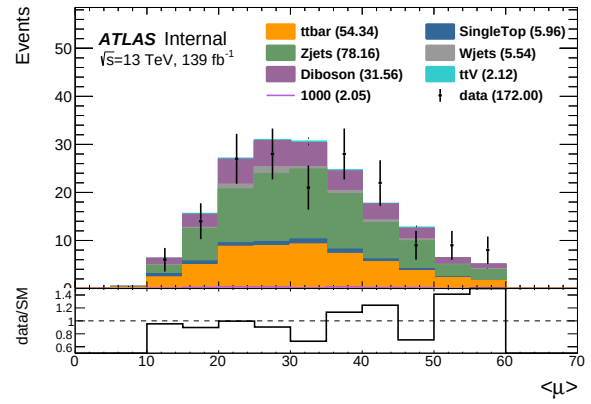


(b) VRht, Post-PRW

Figure A.13: Data/MC comparisons for average pileup in VRht before and after pileup reweighting



(a) VRZ, Pre-PRW



(b) VRZ, Post-PRW

Figure A.14: Data/MC comparisons for average pileup in VRZ before and after pileup reweighting

APPENDIX B

Signal Region N-1 Plots

Below are N-1 Plots for all of the primary analysis variables in the signal region.

Region	N_b	M_{bl}^0 acc [GeV]	M_{bl}^1 rej [GeV]	H_t [GeV]	M_{bl} asym	M_{ll} [GeV]	M_{bl}^0 rej [GeV]
SR	≥ 1	> 400	> 150	> 1000	< 0.2	> 300 GeV	-

Table B.1: Summary of signal region selections used for this analysis. All regions require at least two jets and two oppositely charged leptons.

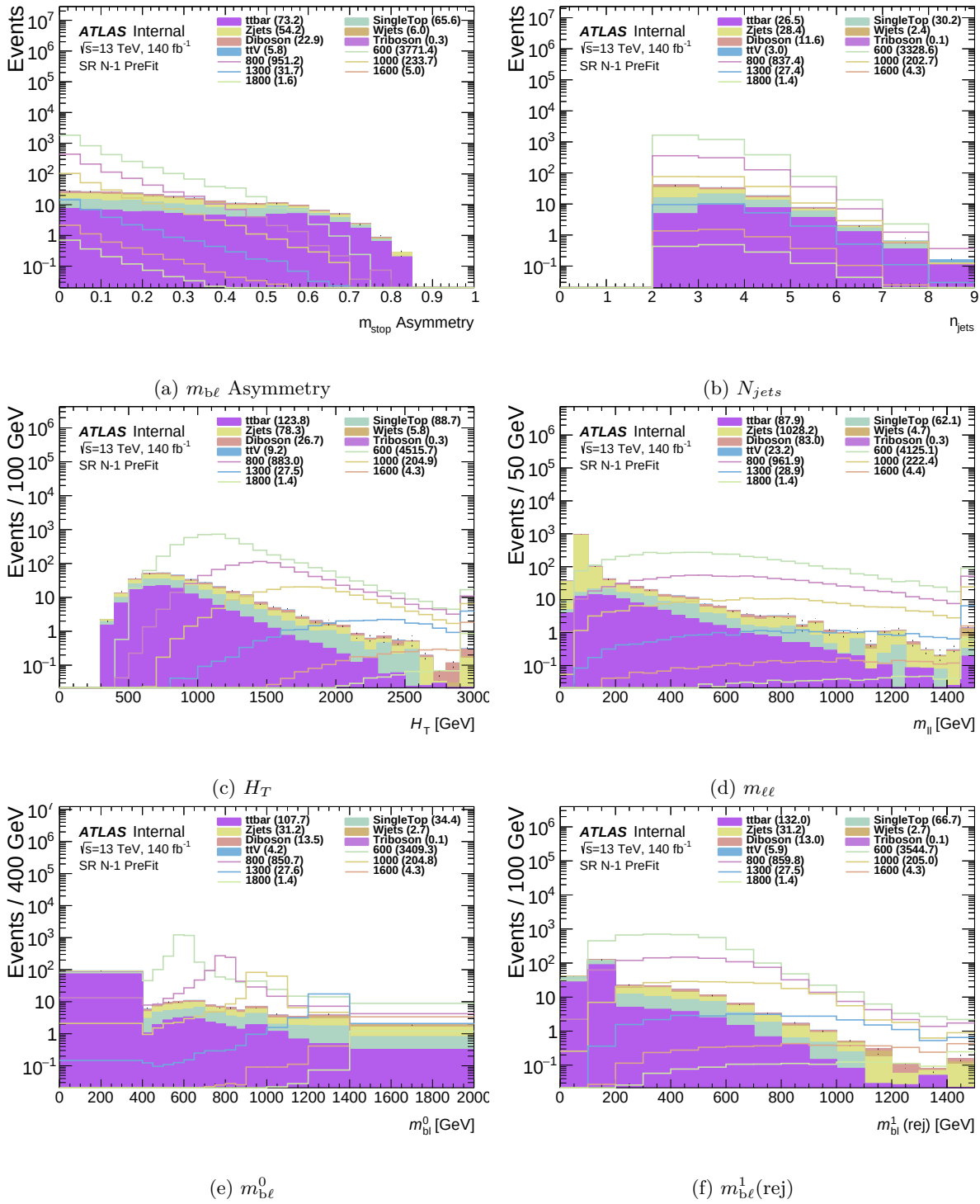


Figure B.1: N-1 plots for signal region. The Y axis for all plots is log scaled.

APPENDIX C

Signal Region Kinematics

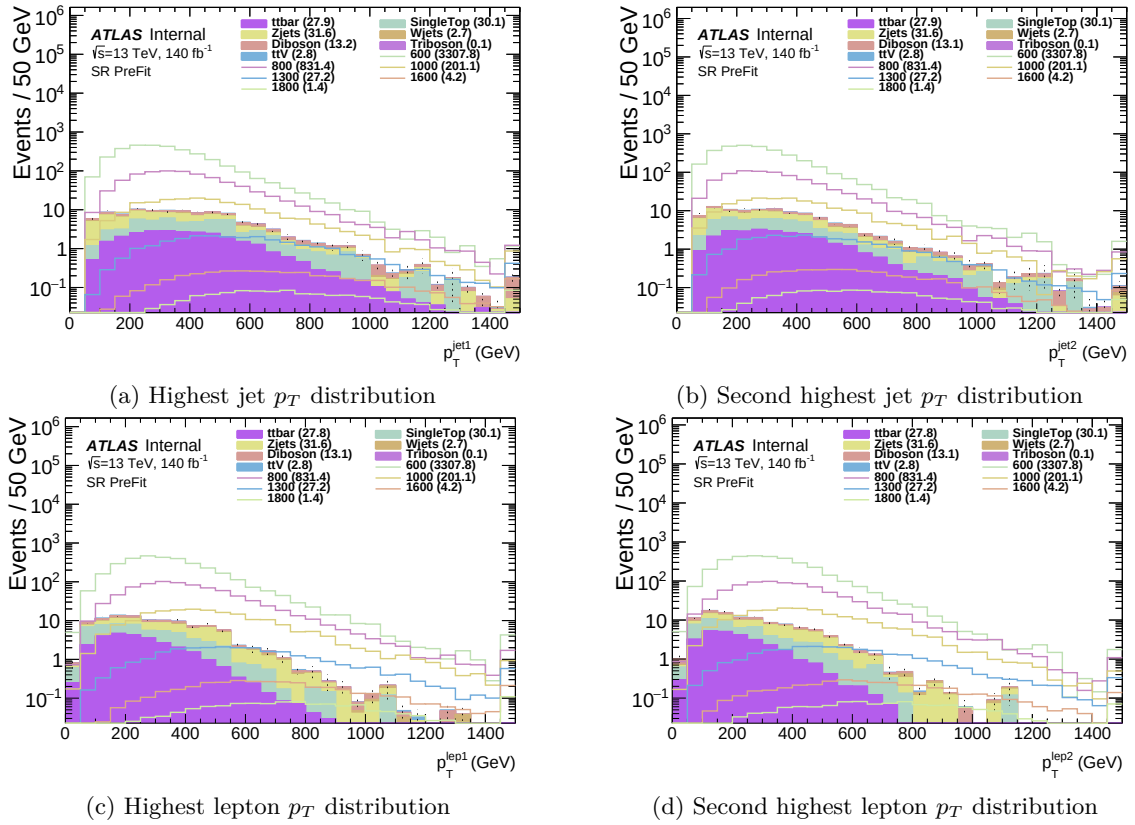
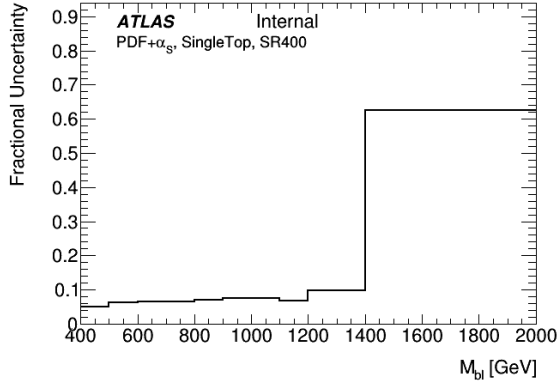
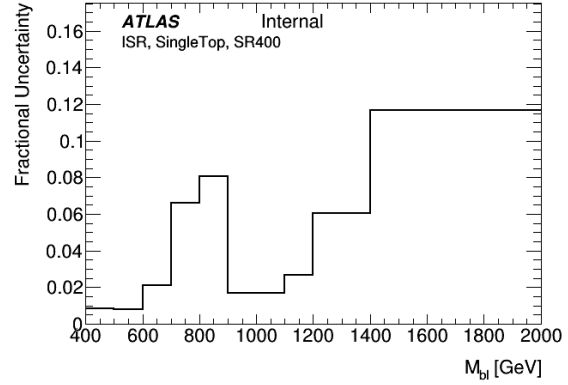


Figure C.1: p_T distributions for signal objects in the Signal Regions

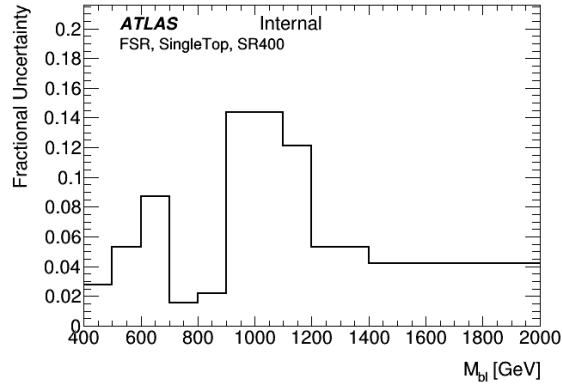
APPENDIX D

Bin-by-Bin Theory Systematics

The bin-by-bin theory systematics for the dominant backgrounds in the Signal Regions are given below.

(a) Single Top, PDF+ α_s Variation

(b) Single Top, ISR Variation



(c) Single Top, FSR Variation

Figure D.1: Systematic uncertainty on the Single Top processes in the Signal Regions. Results are reported bin-by-bin. NOTE: The largest bin in $m_{b\ell}$ is assumed to be a statistical effect and is set to the average of the previous bins for the statistical studies.

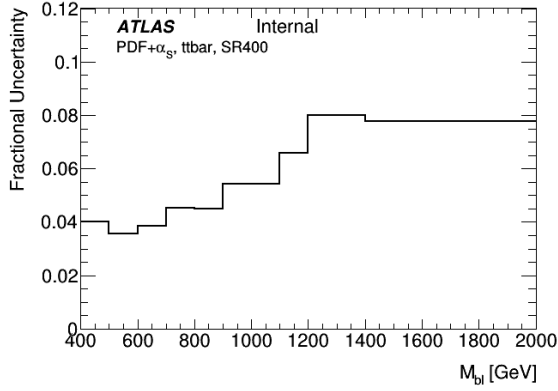
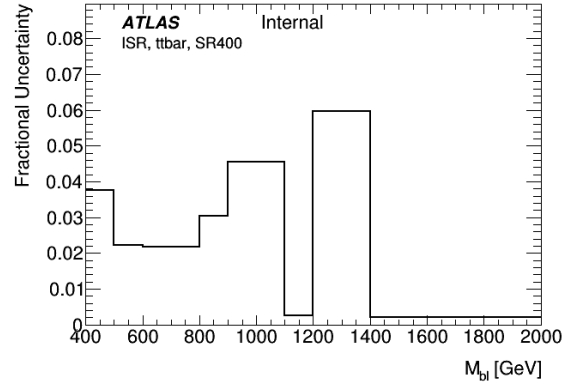
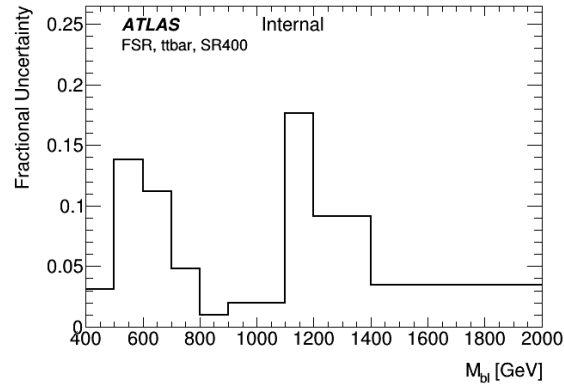
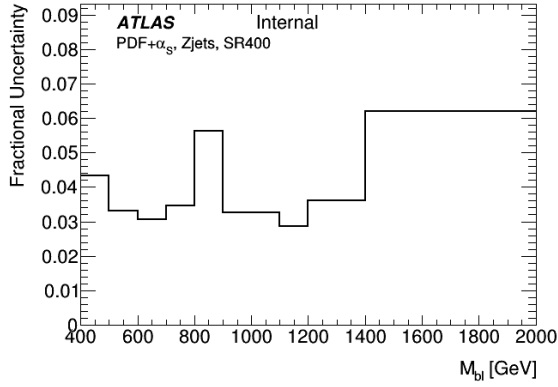
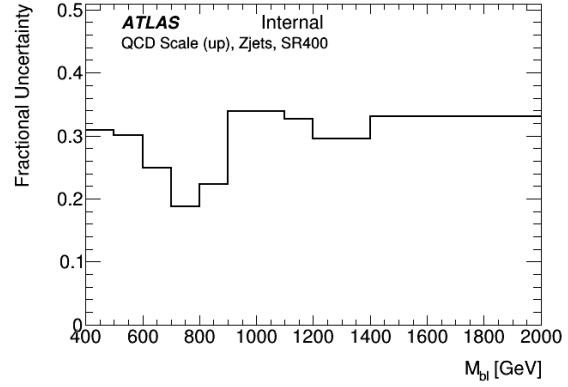
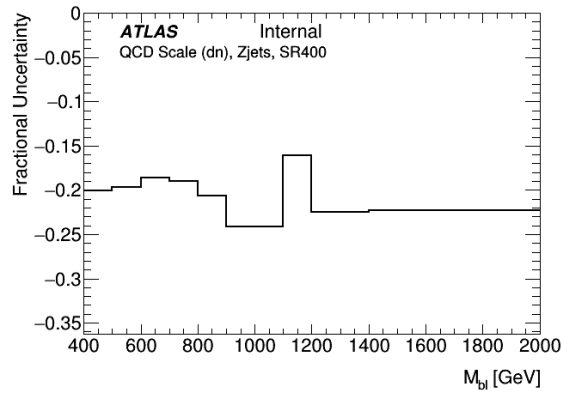
(a) $t\bar{t}$, PDF+ α_S Variation(b) $t\bar{t}$, ISR Variation(c) $t\bar{t}$, FSR Variation

Figure D.2: Systematic uncertainty on the $t\bar{t}$ processes in the Signal Regions. Results are reported bin-by-bin.

(a) Z+jets, PDF+ α_S Variation

(b) Z+jets, Scale Up Variation



(c) Z+jets, Scale Down Variation

Figure D.3: Systematic uncertainty on the Z+jets processes in the Signal Regions. Results are reported bin-by-bin.

APPENDIX E

Singal Region Systematics Tables

Below are the systematics tables for each of the Signal Region bins, broken down into each individual contribution. NOTE: Systematics are pruned at the 1% level.

Uncertainty of channel	SR400_bin0a	SR400_bin1a	SR400_bin2a	SR400_bin3a
Total background expectation	6.57	8.94	10.04	10.74
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 2.56	± 2.99	± 3.17	± 3.28
Total background systematic	± 1.70 [25.83%]	± 2.27 [25.38%]	± 2.88 [28.74%]	± 2.94 [27.37%]
gamma_stat_region_SR400_bin0a_cuts_bin_0	± 0.79 [12.1%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_rad_FSR_SingleTop	± 0.63 [9.6%]	± 1.15 [12.9%]	± 0.92 [9.2%]	± 1.68 [15.6%]
alpha_theory_SingleTop_aMcAtNLO	± 0.57 [8.7%]	± 0.10 [1.1%]	± 0.96 [9.5%]	± 0.29 [2.7%]
alpha_theory_scale_muRmuF_SingleTop	± 0.53 [8.0%]	± 0.62 [7.0%]	± 0.77 [7.7%]	± 0.48 [4.5%]
alpha_theory_ttbar_PS	± 0.52 [8.0%]	± 0.38 [4.2%]	± 0.38 [3.7%]	± 0.03 [0.31%]
mu_SingleTop	± 0.46 [6.9%]	± 0.65 [7.2%]	± 0.61 [6.1%]	± 0.57 [5.3%]
alpha_theory_ttbar_aMcAtNLO	± 0.40 [6.0%]	± 0.66 [7.4%]	± 1.24 [12.4%]	± 1.63 [15.2%]
alpha_theory_SingleTop_PS	± 0.38 [5.8%]	± 0.69 [7.7%]	± 1.01 [10.0%]	± 0.03 [0.32%]
alpha_theory_scale_muF_SingleTop	± 0.30 [4.5%]	± 0.33 [3.7%]	± 0.44 [4.4%]	± 0.26 [2.4%]
alpha_theory_scale_muR_SingleTop	± 0.23 [3.5%]	± 0.30 [3.3%]	± 0.34 [3.4%]	± 0.23 [2.1%]
alpha_theory_rad_ISR_SingleTop	± 0.23 [3.5%]	± 0.29 [3.2%]	± 0.23 [2.3%]	± 0.19 [1.8%]
alpha_theory_scale_muRmuF_ttbar	± 0.22 [3.3%]	± 0.36 [4.0%]	± 0.52 [5.2%]	± 0.63 [5.9%]
alpha_theory_SingleTop_WWbb	± 0.22 [3.3%]	± 0.33 [3.7%]	± 0.44 [4.4%]	± 0.55 [5.1%]
alpha_theory_scale_muRmuF_Zjets	± 0.21 [3.3%]	± 0.13 [1.5%]	± 0.16 [1.6%]	± 0.26 [2.4%]
alpha_JET_JER_EffectiveNP_5_lup	± 0.17 [2.6%]	± 0.26 [2.9%]	± 0.17 [1.7%]	± 0.32 [2.9%]
alpha_theory_scale_muR_Zjets	± 0.17 [2.6%]	± 0.09 [0.95%]	± 0.13 [1.3%]	± 0.27 [2.5%]
mu_Zjets	± 0.17 [2.5%]	± 0.19 [2.1%]	± 0.24 [2.4%]	± 0.26 [2.4%]
alpha_JET_JER_EffectiveNP_7restTerm_lup	± 0.17 [2.5%]	± 0.27 [3.0%]	± 0.22 [2.2%]	± 0.32 [3.0%]
alpha_MUON_SAGITTA_RESBIAS	± 0.16 [2.5%]	± 0.29 [3.3%]	± 0.62 [6.2%]	± 0.31 [2.9%]
alpha_JET_Flavor_Response	± 0.15 [2.2%]	± 0.13 [1.4%]	± 0.01 [0.13%]	± 0.44 [4.1%]
alpha_JET_JER_EffectiveNP_4_lup	± 0.14 [2.1%]	± 0.30 [3.4%]	± 0.27 [2.7%]	± 0.34 [3.1%]
alpha_JET_JER_EffectiveNP_6_lup	± 0.14 [2.1%]	± 0.16 [1.8%]	± 0.41 [4.1%]	± 0.24 [2.3%]
alpha_JET_Flavor_Composition	± 0.13 [2.0%]	± 0.09 [1.0%]	± 0.03 [0.31%]	± 0.42 [3.9%]
alpha_theory_scale_muR_ttbar	± 0.13 [2.0%]	± 0.21 [2.4%]	± 0.31 [3.1%]	± 0.38 [3.5%]
alpha_JET_JER_EffectiveNP_2_lup	± 0.13 [2.0%]	± 0.04 [0.49%]	± 0.27 [2.7%]	± 0.23 [2.2%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin0a	± 0.12 [1.9%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_JET_EffectiveNP_Mixed2	± 0.11 [1.6%]	± 0.02 [0.22%]	± 0.03 [0.27%]	± 0.00 [0.02%]
alpha_theory_rad_FSR_ttbar	± 0.10 [1.6%]	± 0.20 [2.2%]	± 0.42 [4.2%]	± 0.28 [2.6%]
alpha_EG_RESOLUTION_ALL	± 0.10 [1.5%]	± 0.02 [0.26%]	± 0.01 [0.11%]	± 0.02 [0.19%]
alpha_JET_Pileup_OffsetNPV	± 0.08 [1.3%]	± 0.03 [0.37%]	± 0.01 [0.14%]	± 0.03 [0.25%]
alpha_JET_EffectiveNP_Mixed1	± 0.08 [1.2%]	± 0.08 [0.84%]	± 0.03 [0.26%]	± 0.03 [0.26%]
alpha_theory_scale_muF_ttbar	± 0.08 [1.2%]	± 0.13 [1.4%]	± 0.19 [1.9%]	± 0.23 [2.1%]
alpha_JET_JER_EffectiveNP_3_lup	± 0.07 [1.0%]	± 0.13 [1.5%]	± 0.14 [1.4%]	± 0.21 [1.9%]
alpha_EG_SCALE_ALL	± 0.06 [0.95%]	± 0.08 [0.90%]	± 0.26 [2.6%]	± 0.00 [0.04%]
alpha_theory_PDFaS_Zjets_region_SR400_bin0a	± 0.06 [0.95%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_MUON_MS	± 0.06 [0.92%]	± 0.03 [0.32%]	± 0.15 [1.5%]	± 0.05 [0.44%]
alpha_FT_EFF_C_systematics	± 0.05 [0.75%]	± 0.02 [0.18%]	± 0.02 [0.21%]	± 0.01 [0.08%]
alpha_JET_JER_EffectiveNP_1_lup	± 0.05 [0.73%]	± 0.05 [0.56%]	± 0.15 [1.5%]	± 0.24 [2.2%]
alpha_theory_scale_muF_Zjets	± 0.05 [0.69%]	± 0.05 [0.52%]	± 0.04 [0.38%]	± 0.00 [0.00%]
alpha_theory_PDFaS_ttbar_region_SR400_bin0a	± 0.04 [0.66%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_rad_ISR_ttbar	± 0.04 [0.66%]	± 0.06 [0.66%]	± 0.07 [0.73%]	± 0.05 [0.49%]
alpha_JET_EffectiveNP_Modelling1	± 0.04 [0.66%]	± 0.08 [0.88%]	± 0.11 [1.0%]	± 0.25 [2.4%]
alpha_JET_JER_DataVsMC_lup	± 0.01 [0.21%]	± 0.08 [0.94%]	± 0.31 [3.1%]	± 0.12 [1.2%]
alpha_FT_EFF_Light_systematics	± 0.00 [0.04%]	± 0.13 [1.4%]	± 0.06 [0.63%]	± 0.14 [1.3%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin1a	± 0.00 [0.00%]	± 0.19 [2.1%]	± 0.00 [0.00%]	± 0.00 [0.00%]
gamma_stat_region_SR400_bin1a_cuts_bin_0	± 0.00 [0.00%]	± 1.02 [11.4%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_PDFaS_ttbar_region_SR400_bin3a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.10 [0.96%]
alpha_theory_PDFaS_Zjets_region_SR400_bin1a	± 0.00 [0.00%]	± 0.14 [1.5%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin3a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.19 [1.7%]
alpha_theory_PDFaS_Zjets_region_SR400_bin3a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.11 [1.1%]

Table E.1: Breakdown of the dominant systematic uncertainties on background estimates in the various signal regions. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Uncertainty of channel	SR400_bin4a	SR400_bin5a	SR400_bin6a	SR400_bin7a
Total background expectation	11.57	11.93	8.54	7.98
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 3.40	± 3.45	± 2.92	± 2.82
Total background systematic	± 2.73 [23.55%]	± 2.85 [23.90%]	± 2.25 [26.30%]	± 2.61 [32.74%]
alpha_theory_ttbar_aMcAtNLO	± 1.53 [13.2%]	± 1.18 [9.9%]	± 1.00 [11.7%]	± 0.92 [11.5%]
alpha_theory_SingleTop_aMcAtNLO	± 0.85 [7.3%]	± 0.39 [3.3%]	± 0.14 [1.6%]	± 0.16 [2.0%]
alpha_theory_scale_muRmuF_SingleTop	± 0.83 [7.2%]	± 1.05 [8.8%]	± 0.74 [8.7%]	± 0.58 [7.3%]
gamma_stat_region_SR400_bin4a_cuts_bin_0	± 0.76 [6.5%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_scale_muRmuF_ttbar	± 0.67 [5.7%]	± 0.55 [4.6%]	± 0.48 [5.7%]	± 0.41 [5.1%]
mu_SingleTop	± 0.64 [5.5%]	± 0.91 [7.6%]	± 0.60 [7.0%]	± 0.60 [7.5%]
alpha_theory_SingleTop_WWbb	± 0.57 [4.9%]	± 0.33 [2.8%]	± 0.00 [0.00%]	± 0.22 [2.7%]
alpha_theory_SingleTop_PS	± 0.49 [4.2%]	± 1.52 [12.7%]	± 0.71 [8.3%]	± 1.45 [18.2%]
alpha_theory_scale_muF_SingleTop	± 0.48 [4.1%]	± 0.60 [5.0%]	± 0.42 [4.9%]	± 0.31 [3.9%]
alpha_JET_JER_EffectiveNP_1_lup	± 0.47 [4.0%]	± 0.05 [0.39%]	± 0.27 [3.2%]	± 0.51 [6.4%]
alpha_JET_JER_EffectiveNP_5_lup	± 0.39 [3.4%]	± 0.06 [0.53%]	± 0.49 [5.7%]	± 0.38 [4.8%]
alpha_JET_JER_DataVsMC_lup	± 0.38 [3.3%]	± 0.01 [0.12%]	± 0.05 [0.56%]	± 0.15 [1.8%]
alpha_theory_scale_muR_ttbar	± 0.38 [3.3%]	± 0.32 [2.7%]	± 0.28 [3.3%]	± 0.24 [3.0%]
alpha_theory_scale_muR_SingleTop	± 0.36 [3.1%]	± 0.46 [3.8%]	± 0.33 [3.9%]	± 0.28 [3.5%]
alpha_JET_JER_EffectiveNP_2_lup	± 0.32 [2.8%]	± 0.21 [1.7%]	± 0.30 [3.6%]	± 0.79 [9.9%]
alpha_theory_rad_ISR_SingleTop	± 0.32 [2.7%]	± 0.14 [1.2%]	± 0.18 [2.1%]	± 0.30 [3.8%]
mu_Zjets	± 0.28 [2.4%]	± 0.23 [1.9%]	± 0.17 [2.0%]	± 0.16 [2.0%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin4a	± 0.27 [2.3%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_rad_FSR_ttbar	± 0.26 [2.3%]	± 0.36 [3.0%]	± 0.14 [1.7%]	± 0.05 [0.64%]
alpha_theory_scale_muF_ttbar	± 0.26 [2.2%]	± 0.21 [1.7%]	± 0.18 [2.1%]	± 0.15 [1.9%]
alpha_EG_SCALE_ALL	± 0.24 [2.1%]	± 0.12 [0.98%]	± 0.07 [0.81%]	± 0.10 [1.3%]
alpha_JET_JER_EffectiveNP_4_lup	± 0.24 [2.1%]	± 0.07 [0.60%]	± 0.45 [5.2%]	± 0.42 [5.2%]
alpha_JET_JER_EffectiveNP_7restTerm_lup	± 0.24 [2.1%]	± 0.03 [0.24%]	± 0.51 [6.0%]	± 0.47 [5.9%]
alpha_theory_scale_muRmuF_Zjets	± 0.24 [2.0%]	± 0.12 [1.0%]	± 0.27 [3.1%]	± 0.13 [1.7%]
alpha_theory_scale_muR_Zjets	± 0.23 [2.0%]	± 0.11 [0.93%]	± 0.24 [2.8%]	± 0.13 [1.7%]
alpha_theory_rad_FSR_SingleTop	± 0.23 [2.0%]	± 0.04 [0.35%]	± 0.01 [0.15%]	± 0.33 [4.1%]
alpha_theory_ttbar_PS	± 0.21 [1.8%]	± 0.72 [6.1%]	± 0.49 [5.7%]	± 0.00 [0.00%]
alpha_JET_Pileup_RhoTopology	± 0.21 [1.8%]	± 0.02 [0.14%]	± 0.05 [0.61%]	± 0.06 [0.73%]
alpha_JET_JER_EffectiveNP_3_lup	± 0.20 [1.7%]	± 0.27 [2.3%]	± 0.55 [6.4%]	± 0.51 [6.4%]
alpha_JET_Flavor_Composition	± 0.20 [1.7%]	± 0.18 [1.5%]	± 0.09 [1.1%]	± 0.03 [0.33%]
alpha_FT_EFF_Light_systematics	± 0.17 [1.5%]	± 0.11 [0.92%]	± 0.11 [1.2%]	± 0.08 [1.0%]
alpha_JET_JER_EffectiveNP_6_lup	± 0.17 [1.5%]	± 0.07 [0.60%]	± 0.43 [5.1%]	± 0.53 [6.6%]
alpha_JET_EffectiveNP_Modelling1	± 0.14 [1.2%]	± 0.04 [0.37%]	± 0.06 [0.68%]	± 0.00 [0.05%]
alpha_theory_PDFaS_ttbar_region_SR400_bin4a	± 0.12 [1.0%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_JET_Pileup_OffsetMu	± 0.12 [1.0%]	± 0.02 [0.15%]	± 0.01 [0.11%]	± 0.01 [0.08%]
alpha_JET_Pileup_OffsetNPV	± 0.11 [0.92%]	± 0.04 [0.36%]	± 0.06 [0.75%]	± 0.09 [1.1%]
alpha_theory_rad_ISR_ttbar	± 0.10 [0.85%]	± 0.04 [0.34%]	± 0.04 [0.42%]	± 0.05 [0.69%]
mu_ttbar	± 0.09 [0.81%]	± 0.08 [0.68%]	± 0.06 [0.74%]	± 0.06 [0.71%]
alpha_theory_PDFaS_Zjets_region_SR400_bin4a	± 0.09 [0.80%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_MUON_SAGITTA_RESBIAS	± 0.09 [0.79%]	± 0.05 [0.44%]	± 0.09 [1.0%]	± 0.21 [2.6%]
alpha_JET_EtaInterCalibration_NonClosure_2018data	± 0.08 [0.68%]	± 0.04 [0.35%]	± 0.10 [1.2%]	± 0.09 [1.1%]
alpha_JET_EtaInterCalibration_Modelling	± 0.06 [0.51%]	± 0.05 [0.40%]	± 0.12 [1.4%]	± 0.17 [2.1%]
alpha_EG_RESOLUTION_ALL	± 0.06 [0.48%]	± 0.14 [1.2%]	± 0.10 [1.1%]	± 0.00 [0.06%]
alpha_JET_Pileup_PtTerm	± 0.04 [0.32%]	± 0.01 [0.07%]	± 0.12 [1.5%]	± 0.08 [0.98%]
alpha_FT_EFF_extrapolation	± 0.02 [0.16%]	± 0.09 [0.73%]	± 0.09 [1.0%]	± 0.08 [0.97%]
alpha_MUON_MS	± 0.02 [0.14%]	± 0.03 [0.22%]	± 0.13 [1.5%]	± 0.15 [1.9%]
alpha_JET_Flavor_Response	± 0.00 [0.02%]	± 0.02 [0.15%]	± 0.32 [3.7%]	± 0.03 [0.31%]
gamma_stat_region_SR400_bin7a_cuts_bin_0	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.70 [8.7%]
gamma_stat_region_SR400_bin6a_cuts_bin_0	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.65 [7.7%]	± 0.00 [0.00%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin5a	± 0.00 [0.00%]	± 0.30 [2.5%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin7a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.20 [2.5%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin6a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.24 [2.8%]	± 0.00 [0.00%]
alpha_theory_PDFaS_Zjets_region_SR400_bin7a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.08 [0.99%]
alpha_theory_PDFaS_ttbar_region_SR400_bin6a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.09 [1.1%]	± 0.00 [0.00%]

Table E.2: Breakdown of the dominant systematic uncertainties on background estimates in the various signal regions. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Uncertainty of channel	SR400_bin8a	SR400_bin9a	SR400_bin10a	SR400_bin11a
Total background expectation	7.24	5.96	7.82	4.05
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 2.69	± 2.44	± 2.80	± 2.01
Total background systematic	± 1.81 [24.97%]	± 2.07 [34.82%]	± 2.51 [32.07%]	± 1.36 [33.49%]
alpha_theory_SingleTop_aMcAtNLO	± 0.89 [12.3%]	± 1.18 [19.8%]	± 0.39 [5.0%]	± 0.08 [1.9%]
alpha_theory_ttbar_aMcAtNLO	± 0.77 [10.6%]	± 0.71 [12.0%]	± 0.74 [9.4%]	± 0.54 [13.3%]
gamma_stat_region_SR400_bin8a_cuts_bin_0	± 0.60 [8.3%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_scale_muRmuF_SingleTop	± 0.51 [7.0%]	± 0.54 [9.0%]	± 0.73 [9.3%]	± 0.25 [6.1%]
alpha_theory_SingleTop_PS	± 0.50 [6.9%]	± 0.92 [15.4%]	± 1.68 [21.5%]	± 0.76 [18.7%]
mu_SingleTop	± 0.45 [6.3%]	± 0.44 [7.3%]	± 0.56 [7.2%]	± 0.19 [4.7%]
alpha_JET_JER_EffectiveNP_2_lup	± 0.43 [5.9%]	± 0.20 [3.3%]	± 0.01 [0.11%]	± 0.16 [4.1%]
alpha_theory_SingleTop_WWbb	± 0.41 [5.6%]	± 0.24 [4.1%]	± 0.07 [0.95%]	± 0.16 [3.8%]
alpha_theory_scale_muRmuF_ttbar	± 0.39 [5.3%]	± 0.36 [6.0%]	± 0.44 [5.7%]	± 0.29 [7.1%]
alpha_theory_scale_muF_SingleTop	± 0.29 [4.0%]	± 0.34 [5.6%]	± 0.46 [5.8%]	± 0.15 [3.7%]
alpha_JET_JER_EffectiveNP_6_lup	± 0.26 [3.5%]	± 0.06 [1.00%]	± 0.39 [5.0%]	± 0.22 [5.4%]
alpha_theory_scale_muR_SingleTop	± 0.22 [3.1%]	± 0.20 [3.4%]	± 0.27 [3.5%]	± 0.10 [2.4%]
alpha_theory_scale_muR_ttbar	± 0.22 [3.0%]	± 0.20 [3.3%]	± 0.24 [3.1%]	± 0.16 [3.9%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin8a	± 0.22 [3.0%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_MUON_MS	± 0.17 [2.3%]	± 0.01 [0.17%]	± 0.20 [2.6%]	± 0.03 [0.68%]
alpha_FT_EFF_Light_systematics	± 0.16 [2.2%]	± 0.14 [2.3%]	± 0.13 [1.7%]	± 0.09 [2.3%]
mu_Zjets	± 0.16 [2.2%]	± 0.12 [2.0%]	± 0.14 [1.8%]	± 0.10 [2.4%]
alpha_EG_RESOLUTION_ALL	± 0.16 [2.2%]	± 0.13 [2.2%]	± 0.01 [0.13%]	± 0.01 [0.13%]
alpha_theory_scale_muF_ttbar	± 0.15 [2.1%]	± 0.15 [2.4%]	± 0.18 [2.3%]	± 0.12 [2.9%]
alpha_JET_EtaIntercalibration_Modelling	± 0.15 [2.1%]	± 0.01 [0.14%]	± 0.04 [0.57%]	± 0.02 [0.55%]
alpha_JET_JER_EffectiveNP_3_lup	± 0.15 [2.0%]	± 0.03 [0.45%]	± 0.21 [2.6%]	± 0.14 [3.3%]
alpha_theory_rad_ISR_SingleTop	± 0.14 [2.0%]	± 0.57 [9.6%]	± 0.09 [1.2%]	± 0.18 [4.5%]
alpha_JET_Flavor_Response	± 0.14 [1.9%]	± 0.04 [0.64%]	± 0.08 [0.99%]	± 0.14 [3.5%]
alpha_theory_scale_muR_Zjets	± 0.12 [1.7%]	± 0.11 [1.8%]	± 0.03 [0.44%]	± 0.02 [0.59%]
alpha_JET_JER_EffectiveNP_7restTerm_lup	± 0.12 [1.7%]	± 0.00 [0.00%]	± 0.27 [3.5%]	± 0.19 [4.8%]
alpha_JET_Flavor_Composition	± 0.12 [1.7%]	± 0.07 [1.2%]	± 0.00 [0.01%]	± 0.13 [3.3%]
alpha_JET_JER_EffectiveNP_4_lup	± 0.12 [1.7%]	± 0.05 [0.86%]	± 0.33 [4.3%]	± 0.28 [7.0%]
alpha_theory_scale_muRmuF_Zjets	± 0.12 [1.6%]	± 0.10 [1.7%]	± 0.03 [0.42%]	± 0.02 [0.58%]
alpha_JET_Pileup_PtTerm	± 0.11 [1.5%]	± 0.01 [0.19%]	± 0.16 [2.0%]	± 0.09 [2.2%]
alpha_JET_EtaIntercalibration_NonClosure_2018data	± 0.10 [1.4%]	± 0.05 [0.86%]	± 0.14 [1.8%]	± 0.03 [0.82%]
alpha_theory_PDFaS_Zjets_region_SR400_bin8a	± 0.10 [1.3%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_JET_JER_DataVsMC_lup	± 0.09 [1.2%]	± 0.14 [2.4%]	± 0.17 [2.1%]	± 0.01 [0.19%]
alpha_JET_JER_EffectiveNP_5_lup	± 0.08 [1.1%]	± 0.11 [1.9%]	± 0.32 [4.1%]	± 0.15 [3.7%]
alpha_EG_SCALE_ALL	± 0.08 [1.1%]	± 0.22 [3.7%]	± 0.10 [1.3%]	± 0.06 [1.4%]
alpha_JET_EffectiveNP_Modelling1	± 0.07 [1.0%]	± 0.03 [0.48%]	± 0.12 [1.6%]	± 0.13 [3.2%]
alpha_theory_PDFaS_ttbar_region_SR400_bin8a	± 0.07 [0.99%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_ttbar_PS	± 0.06 [0.88%]	± 0.08 [1.3%]	± 0.52 [6.7%]	± 0.25 [6.1%]
alpha_FT_EFF_extrapolation	± 0.06 [0.86%]	± 0.09 [1.5%]	± 0.08 [1.1%]	± 0.03 [0.81%]
alpha_theory_rad_ISR_ttbar	± 0.05 [0.75%]	± 0.03 [0.56%]	± 0.06 [0.82%]	± 0.06 [1.6%]
alpha_theory_rad_FSR_SingleTop	± 0.05 [0.69%]	± 0.10 [1.7%]	± 0.50 [6.4%]	± 0.40 [9.8%]
alpha_MUON_SAGITTA_RESBIAS	± 0.05 [0.67%]	± 0.02 [0.41%]	± 0.14 [1.8%]	± 0.02 [0.49%]
mu_ttbar	± 0.05 [0.64%]	± 0.04 [0.63%]	± 0.05 [0.67%]	± 0.03 [0.80%]
alpha_JET_EffectiveNP_Mixed1	± 0.04 [0.53%]	± 0.11 [1.8%]	± 0.03 [0.43%]	± 0.11 [2.6%]
alpha_JET_EffectiveNP_Statistical1	± 0.01 [0.17%]	± 0.08 [1.3%]	± 0.00 [0.01%]	± 0.01 [0.22%]
alpha_JET_EffectiveNP_Modelling2	± 0.01 [0.15%]	± 0.08 [1.4%]	± 0.00 [0.04%]	± 0.08 [1.9%]
alpha_JET_JER_EffectiveNP_1_lup	± 0.01 [0.07%]	± 0.02 [0.37%]	± 0.15 [1.9%]	± 0.22 [5.5%]
alpha_MUON_SAGITTA_DATASTAT	± 0.00 [0.06%]	± 0.01 [0.23%]	± 0.01 [0.14%]	± 0.07 [1.8%]
alpha_JET_BJES_Response	± 0.00 [0.02%]	± 0.04 [0.75%]	± 0.01 [0.19%]	± 0.08 [1.9%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin9a	± 0.00 [0.00%]	± 0.17 [2.8%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin11a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.06 [1.5%]
gamma_stat_region_SR400_bin10a_cuts_bin_0	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.59 [7.6%]	± 0.00 [0.00%]
alpha_theory_PDFaS_ttbar_region_SR400_bin11a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.06 [1.5%]
alpha_theory_PDFaS_ttbar_region_SR400_bin10a	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.09 [1.2%]	± 0.00 [0.00%]
alpha_MUON_SCALE	± 0.00 [0.00%]	± 0.02 [0.30%]	± 0.02 [0.22%]	± 0.07 [1.7%]
alpha_theory_PDFaS_Zjets_region_SR400_bin9a	± 0.00 [0.00%]	± 0.08 [1.3%]	± 0.00 [0.00%]	± 0.00 [0.00%]
gamma_stat_region_SR400_bin9a_cuts_bin_0	± 0.00 [0.00%]	± 0.57 [9.6%]	± 0.00 [0.00%]	± 0.00 [0.00%]

Table E.3: Breakdown of the dominant systematic uncertainties on background estimates in the various signal regions. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Uncertainty of channel	SR400_bin12a	SR400_bin13a	SR400_bin14a
Total background expectation	3.82	4.31	2.17
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 1.95	± 2.08	± 1.47
Total background systematic	± 1.43 [37.56%]	± 1.52 [35.13%]	± 0.69 [31.84%]
alpha_JET_JER_EffectiveNP_1_lup	± 0.53 [13.9%]	± 0.46 [10.7%]	± 0.04 [1.8%]
alpha_theory_SingleTop_aMcAtNLO	± 0.49 [12.8%]	± 0.12 [2.8%]	± 0.23 [10.8%]
alpha_JET_JER_EffectiveNP_2_lup	± 0.46 [12.0%]	± 0.42 [9.8%]	± 0.05 [2.4%]
gamma_stat_region_SR400_bin12a_cuts_bin_0	± 0.46 [11.9%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_theory_scale_muRmuF_SingleTop	± 0.42 [11.0%]	± 0.44 [10.3%]	± 0.23 [10.6%]
alpha_JET_JER_EffectiveNP_7restTerm_lup	± 0.40 [10.4%]	± 0.33 [7.7%]	± 0.04 [1.7%]
alpha_theory_SingleTop_PS	± 0.37 [9.6%]	± 0.68 [15.7%]	± 0.29 [13.5%]
alpha_JET_JER_EffectiveNP_3_lup	± 0.34 [8.9%]	± 0.30 [6.9%]	± 0.03 [1.5%]
alpha_JET_JER_EffectiveNP_4_lup	± 0.31 [8.2%]	± 0.29 [6.7%]	± 0.03 [1.3%]
alpha_theory_ttbar_aMcAtNLO	± 0.30 [8.0%]	± 0.20 [4.7%]	± 0.18 [8.5%]
mu_SingleTop	± 0.27 [7.0%]	± 0.30 [7.0%]	± 0.11 [5.3%]
alpha_theory_scale_muF_SingleTop	± 0.26 [6.7%]	± 0.26 [6.1%]	± 0.16 [7.3%]
alpha_JET_JER_DataVsMC_lup	± 0.20 [5.2%]	± 0.05 [1.2%]	± 0.01 [0.45%]
alpha_theory_scale_muRmuF_ttbar	± 0.18 [4.8%]	± 0.13 [3.1%]	± 0.09 [4.4%]
alpha_JET_JER_EffectiveNP_6_lup	± 0.18 [4.7%]	± 0.15 [3.6%]	± 0.03 [1.4%]
alpha_theory_scale_muR_SingleTop	± 0.16 [4.3%]	± 0.18 [4.3%]	± 0.07 [3.2%]
alpha_theory_ttbar_PS	± 0.16 [4.3%]	± 0.24 [5.5%]	± 0.12 [5.6%]
alpha_MUON_SAGITTA_RESBIAS	± 0.14 [3.6%]	± 0.10 [2.4%]	± 0.02 [1.1%]
alpha_theory_SingleTop_WWbb	± 0.13 [3.4%]	± 0.32 [7.5%]	± 0.09 [4.2%]
alpha_theory_rad_FSR_SingleTop	± 0.11 [2.9%]	± 0.18 [4.1%]	± 0.04 [2.1%]
alpha_EG_RESOLUTION_ALL	± 0.11 [2.9%]	± 0.06 [1.4%]	± 0.01 [0.41%]
alpha_theory_rad_FSR_ttbar	± 0.11 [2.8%]	± 0.04 [0.84%]	± 0.01 [0.49%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin12a	± 0.10 [2.7%]	± 0.00 [0.00%]	± 0.00 [0.00%]
mu_Zjets	± 0.10 [2.5%]	± 0.11 [2.5%]	± 0.07 [3.0%]
alpha_theory_scale_muR_ttbar	± 0.10 [2.5%]	± 0.07 [1.6%]	± 0.05 [2.2%]
alpha_JET_EtaIntercalibration_Modelling	± 0.09 [2.4%]	± 0.06 [1.5%]	± 0.01 [0.28%]
alpha_FT_EFF_extrapolation	± 0.09 [2.3%]	± 0.08 [1.9%]	± 0.07 [3.1%]
alpha_theory_scale_muF_ttbar	± 0.08 [2.0%]	± 0.06 [1.4%]	± 0.04 [1.9%]
alpha_JET_Pileup_RhoTopology	± 0.08 [2.0%]	± 0.02 [0.46%]	± 0.01 [0.44%]
alpha_JET_Pileup_PtTerm	± 0.06 [1.7%]	± 0.05 [1.1%]	± 0.00 [0.00%]
alpha_FT_EFF_Light_systematics	± 0.06 [1.6%]	± 0.05 [1.2%]	± 0.06 [2.7%]
alpha_MUON_MS	± 0.05 [1.4%]	± 0.01 [0.25%]	± 0.01 [0.40%]
alpha_JET_Pileup_OffsetNPV	± 0.05 [1.2%]	± 0.05 [1.1%]	± 0.00 [0.00%]
alpha_JET_Flavor_Response	± 0.05 [1.2%]	± 0.07 [1.6%]	± 0.01 [0.27%]
alpha_theory_scale_muR_Zjets	± 0.04 [1.2%]	± 0.02 [0.39%]	± 0.01 [0.62%]
alpha_theory_rad_ISR_SingleTop	± 0.04 [1.1%]	± 0.10 [2.2%]	± 0.09 [4.2%]
alpha_theory_PDFaS_ttbar_region_SR400_bin12a	± 0.04 [1.1%]	± 0.00 [0.00%]	± 0.00 [0.00%]
alpha_JET_Pileup_OffsetMu	± 0.03 [0.78%]	± 0.04 [0.98%]	± 0.00 [0.00%]
alpha_JET_Flavor_Composition	± 0.02 [0.63%]	± 0.08 [1.8%]	± 0.01 [0.27%]
alpha_EG_SCALE_ALL	± 0.02 [0.41%]	± 0.06 [1.4%]	± 0.01 [0.57%]
gamma_stat_region_SR400_bin13a_cuts_bin_0	± 0.00 [0.00%]	± 0.62 [14.5%]	± 0.00 [0.00%]
alpha_theory_PDFaS_SingleTop_region_SR400_bin13a	± 0.00 [0.00%]	± 0.16 [3.8%]	± 0.00 [0.00%]

Table E.4: Breakdown of the dominant systematic uncertainties on background estimates in the various signal regions. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

APPENDIX F

Glossary

ABCStar Atlas Binary Chip. 44, 46, 48, 51

ALICE A Large Ion Collider Experiment. 21

AMAC Autonomous Monitor and Control Chip. 44, 51

ASIC Application Specific Integrated Circuits. 38, 44, 47–52, 120

ATLAS One of the general use particle accelerators at the Large Hadron Collider. Formerly stands for A Toroidal LHC ApparatuS. xiii, 14–16, 21, 23, 24, 27–29, 34–40, 42, 55–57, 61, 63, 67, 79, 90, 100, 101, 120

BNL Brookhaven National Lab. 49

BR Branching Ratio. 95, 96, 115–117

BSM Beyond the Standard Model. 3, 40

CERN European Organization for Nuclear Research. 21, 38

CL Confidence Limit. 101

CMOS Complementary Metal-Oxide-Semiconductor. 47

CMS Compact Muon Solenoid. 21, 56

CoM Center of Mass. 42

CR Control Region. x, xi, xiv, 66–71, 80, 81, 83–85, 87, 99, 101–103, 106, 108, 109, 113

CSCs Cathode Strip Chambers. 37, 38

DM Dark Matter. 5

DR Diagram Removal. 62, 78

ECal Electromagnetic Calorimeter. 34, 35, 39

EWK Electroweak. 5, 15

FCal Forward Calorimeter. 36

FIFO First-In-First-Out. 52

FPGA Field Programmable Gate Array. 49

FSR Final State Radiation. 76, 77, 83

GR General Relativity. 3

GRL Good Runs List. 61

GUT Grand Unifying Theory. 7, 14

HCCStar Hybrid Controller Chip. viii, xiv, 44, 46, 48–54, 120

HEC Hadronic Endcap Calorimeter. 36

HL-LHC High Luminosity Large Hadron Collider. 42–44, 46–49, 51, 53, 120

HLT High Level Trigger. xiii, 38, 39

IBL Insertable B-Layer. 30

ID Inner Detector. 30, 33, 36, 39, 43, 44, 64, 66

IP Interaction Point. 28–30, 33, 43, 44

ISR Initial State Radiation. 57, 76, 77, 83

ITk Inner Tracker. viii, 42–44, 47, 49, 51–53

JER Jet Energy Resolution. 72, 76

JES Jet Energy Scale. 72, 76

JVT Jet Vertex Tagging. 65, 76

LAr Liquid Argon. 34, 35

LEP Large Electron-Positron Collider. 21

LET Linear Energy Transfer. 49, 51

LHC Large Hadron Collider. xiii, 13, 16, 21–24, 27–29, 42, 61, 120

LHCb Large Hadron Collider, beauty. 21

LO Leading Order. 62, 78

LSP Lightest Supersymmetric Particle. vii, 13, 15–17, 19, 55

MC Monte Carlo. xiv, 63, 66, 69, 71, 72, 76, 77, 91, 93, 95, 99–102, 109

MDTs Monitored Drift Tubes. 37, 38

ME Matrix Element. 64, 76, 79

MET Missing Transverse Energy. 13, 40, 55, 63

MS Muon Spectrometer. 36, 39

MSSM Minimal Supersymmetric Standard Model. 11–14, 120

NF Normalization Factor. 99, 102, 107, 110

NLO Next-to-Leading Order. 61, 62, 78

NNLL Next-to-Next-to-Leading Logarithmic. 62

NNLO Next-to-Next-to-Leading Order. 62

NP Nuisance Parameter. 72, 76, 81, 98, 99, 102

PCB Printed Circuit Board. 44

PDF Parton Distribution Function. 61, 62, 76, 80, 83

QCD Quantum Chromodynamics. 61, 62, 80, 81

QFT Quantum Field Theory. 10

RBF Radial Basis Function. 109, 113

RoIs Regions of Interest. 38

RPC R-Parity Conserving. 13, 14, 55

RPCs Resistive Plate Chamber. 37

RPV R-Parity Violating. xiv, 13, 14, 56, 57, 100, 120

SCT Semiconductor Tracker. 30, 33, 44

SEEs Single Event Errors. 47–51, 53

SETs Single Event Transients. 52

SEUs Single Event Upsets. 52

SM Standard Model of particle physics. xiii, xiv, 3, 9–13, 15, 17, 34, 38, 41, 57, 58, 61, 66–68, 97

SR Signal Region. x, xi, 66–69, 71, 77, 80, 81, 83–85, 92–96, 98–102, 106–109, 113, 114

STI Shallow Trench Isolation. 47

SUSY Supersymmetry. xiii, 10–14, 17, 24, 57, 83, 101, 102

TGCs Thin Gap Chambers. 37

TID Total Ionizing Dose. 47–50

TileCal Tile Calorimeter. 34–36

TRIUMF TRI-University Meson Facility. 47, 49, 50

TRT Transition Radiation Tracker. 30, 33, 34, 37, 43

UCLouvain Université Catholique de Louvain. 49, 51

VBF Vector Boson Fusion. 8

VEV Vacuum Expectation Value. 14

VR Validation Region. xi, xiv, 66–68, 71, 99, 102, 103

WIMPs Weakly-Interacting Massive Particles. 11

WP Working Point. 65

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