A search for supersymmetric phenomena in final states with high jet multiplicity at the ATLAS detector

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Matthew N.K. Smith All rights reserved A search for supersymmetric phenomena in final states with high jet multiplicity at the ATLAS detector Matthew N.K. Smith

ABSTRACT

Proton-proton collisions at the Large Hadron Collider provide insight into fundamental dynamics at unprecedented energy scales. After the discovery of the Higgs boson by the ATLAS and CMS experiments completed the Standard Model picture of particle physics in 2012, the focus turned to investigation of new phenomena beyond the Standard Model. Variations on Supersymmetry, which has strong theoretical underpinnings and a wide potential particle phenomenology, garnered attention in particular. Preliminary results, however, yielded no new particle discoveries and set limits on the possible physical properties of supersymmetric models. This thesis describes a search for supersymmetric particles that could not have been detected by earlier efforts. The study probes collisions with a center of mass energy of 13 TeV detected by ATLAS from 2015 to 2016 that result in events with a large number of jets. This search is sensitive to decays of heavy particles via cascades, which result in many hadronic jets and some missing energy. Constraints on the properties of reclustered large-radius jets are used to improve the sensitivity. The main Standard Model backgrounds are removed using a template method that extrapolates background behavior from final states with fewer jets. No excess is observed over prediction, so limits are set on supersymmetric particle masses in the context of two different theoretical models. Gluino masses below 1500 and 1600 GeV, respectively, are excluded, a significant extension of the limits set by previous analyses.

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I understand what you're saying, and your comments are valuable, but I'm gonna ignore your advice.

-Roald Dahl, Fantastic Mr. Fox

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Introduction

If this all seems ambiguous, that's because it is; and if that troubles you, you'd hate it here; but if it gives you a feeling of relief, then you are in the right place and might consider staying.

—Neal Stephenson, Anathem

The third graders in the Nunaka Valley classroom of my home school district of Anchorage Alaska leaned eagerly forward at their desks, their faces raptly attentive. They were arrayed in a semi-circle facing the blackboard, which was adorned with the ornaments of Planet Week in science class. I had just finished explaining, in a few simple words, my work as a particle physics student at CERN (European Organization for Nuclear Research) outside Geneva, Switzerland. I had told them about the most fundamental building blocks of nature, about the primal forces that bind them, and about the engineering marvel constructed to explore them. I had explained the long history of collaboration between scientists the world over that had culminated in the discovery of the Higgs boson, the final piece in a puzzle whose construction has stretched over decades. I hinted at the mysteries still unsolved. Hands shot up and I fielded the expected questions: what's my favorite planet (Saturn); what's it like inside a black hole (very uncomfortable); do aliens exist because my mom said they might (you should listen to your mom); can I dunk a basketball (not reliably). Finally I called on one boy who took his time, screwing up his eyes for a moment, before asking: "I just don't get it. Why don't you just smash rocks together? I do it all the time—that would be way, way easier!"

We can chuckle at the naïveté of a young kid grappling with a complex scientific process. But honoring the question's intent forces us to explore some meaty ideas. We must discuss how we aim to keep breaking down matter until its most fundamental components are reached, smashing rocks into smaller rocks, on and on, even until those components are point-like in extension. Experimental and theoretical efforts have worked together to construct the Standard Model (SM) of particle physics, a marvel of structured and predictive science. Sometimes the experimental results are a surprise, as in the discovery of the τ lepton before any model had predicted its existence [1]. Other times the discovery is a long time coming, like the observation of the Higgs boson fifty years after it was predicted to be an integral part of the Standard Model [2, 3].

We must talk about electro-weak symmetry breaking and how an energy scale of about 1 tera-electronvolt (TeV), the energy scale at which the collisions at the Large Hadron Collider (LHC) at CERN take place, is essential to probe regions that have potential for new physics. After all, the ultimate goal of the experiments at CERN is to discover something never-before-seen. Supersymmetry (SUSY) stands out among potential new theories as an elegant extension to the Standard Model and could answer some of the remaining questions about mass hierarchy and dark matter.

We must dig into the speed, the bunch crossing arrangement, and pileup of the collisions; the magnets, silicon components, and chambers of the detector, the aesthetic simplicity (or lack thereof) in the underlying high-energy theory. The history of particle physics is one of a string of bigger, more powerful, more precise experiments dotting the globe. The machinery and ideas behind even the simplest detections are worthy of note.

In the end, though, the serious question from the earnest boy in the grade school

classroom in Anchorage, Alaska stands out in my memory because it reminds me of the almost visceral excitement of opening something up to see what's inside. That is what these years of study have been about. This thesis presents a search for SUSY using events at the LHC, recorded by the ATLAS (A Toroidal LHC ApparatuS) detector in collisions from 2012 through 2016. This search features events with many jets, large composite-jet mass, and missing transverse momentum, to probe an untouched SUSY parameter space. I will begin with the theory: Chapter 2 will introduce the Standard model, followed by Chapter 3 on jets and their construction and Chapter 4 on SUSY. Chapter 5 will discuss the LHC and the ATLAS detector. Chapter 6 will present the framework, results, and analysis of this search, and Chapter 7 will finish with conclusions and suggestions for further inquiry.

The Standard Model

If you want sense, you'll have to make it yourself.

-Norton Juster, The Phantom Tollbooth

Particle physics as we know it today is built upon the extraordinary successes of the Standard Model (SM). At its heart, the SM is based on the idea that symmetry is a basic and predictive property of nature. This concept, related to the idea of *naturalness*, will be revisited in the discussion of SUSY, in Chapter 4. Pieced together over the course of 50 years (though primarily in the '60s and '70s), the SM is a powerful set of interlocking theories that describe all fundamental particles and the fundamental interactions between them. Experiment has matched the SM with remarkable precision. Take, for example, the measurement of the electromagnetic coupling constant, α , which has a measured value recorded within one part in 10¹⁰ of the predicted theoretical value [4]. Indeed, measurements at the LHC have verified the predictions of the SM to such a degree as to make one wonder where new physics beyond the SM might be found. See Figure 2.1, which shows the match between theory and experiment in the measurement of SM cross-sections. The SM does have limits, however; most notably it lacks any treatment of gravity, but the scale at which particle experiments take place makes gravitational forces negligible.



Standard Model Total Production Cross Section Measurements Status: August 2016

Figure 2.1: A recent summary of Standard Model cross sections as measured by ATLAS. Theory and experiment agree closely across all channels.

As this thesis takes an experimental approach, in the following chapter I will first address the physical building blocks, that is, the particle composition, of the SM (2.1). Next I will motivate that particle composition by introducing the $SU(2)_C \otimes SU(2)_W \otimes$ $U(1)_Y$ symmetry group of the SM with a brief treatment of the Lagrangian, dividing it into its distinct components (2.2). Finally I will look toward physics beyond the SM with some examples of its shortcomings (2.3)

2.1 The Particle Composition of the Standard Model

The contents of the SM are fundamental, point-like, zero-extension particles, perhaps the logical conclusion of my favorite student's plan to smash smaller and smaller rocks. The particles are classified by their intrinsic angular momentum quantum number, or spin, which can take on integer or half-integer values (in units of \hbar). The latter, half-integer spin, are fermions, what we think of as matter. The former, integer spin, are bosons, which are carriers for the electromagnetic, weak, and strong forces (gravity is still excluded) and appear as particles as well.

The complete assortment of fundamental fermions is listed in Tables 2.1 and 2.2. Every fermion has an anti-fermion partner that is equivalent in mass but opposite in charge. Fundamental fermions are further divided between quarks and leptons.

Quarks may interact with any of the forces of the SM, as they are charged under both the strong force $SU(3)_C$ and the electroweak $SU(2)_W \otimes U(1)_Y$. They are divided into three generations; up/down, charm/strange, and top/bottom. Note how strongly tiered the quark masses are. The up and down quarks that make up protons and neutrons are only a few MeV, while the top quark is orders of magnitude larger at 173 GeV [5, 6], so heavy that it must decay before it can even hadronize and is thus never observed in a bound state. These masses are free parameters in the theory of the SM, which says nothing about the values they must take and does nothing to explain this striking hierarchy. In addition, single quarks are not found in nature—they must be confined to composite particles of 2 (mesons) or 3 (baryons) quarks.

Leptons may be either charged or neutral: charged leptons may only interact with the electromagnetic and weak forces, while neutral leptons, or neutrinos, only interact with the weak force. The SM predicts that neutrinos are massless, though experimental observation has revealed they do possess a non-zero mass [7]. The neutrino masses are so small, however, that they make negligible experimental impact at the LHC. Leptons are also divided into three generations; the electron, muon, and tau. The tau lepton has a much shorter lifetime and decays quickly to hadrons or other leptons and so is much more difficult to identify and study. For this reason leptonic analyses at the LHC often only consider the first two generations. The analysis presented in the thesis is a 0-lepton analysis, but uses control regions with a single lepton by this two-generation definition.

All elementary bosons of the SM can be found in Table 2.3. The first four listed are gauge bosons and force carriers; photons are the force carriers of the electromagnetic force, W^{\pm} and Z are the force carriers of the weak force, and gluons are the force carriers of the strong force. Higgs bosons, meanwhile, do not carry a force like the others, but rather give the vector bosons and charged fermions mass via the Higgs Mechanism. The Higgs was the final elementary particle of the SM to be discovered, at CERN in 2012 [2, 3].

Quark		Mass	Charge	Spin	Discovered in:
up	u	$2.3 { m MeV}$	$+\frac{2}{3}$	$\frac{1}{2}$	1968 [8, 9]
down	d	$4.8~{\rm MeV}$	$-\frac{1}{3}$	$\frac{1}{2}$	1968 [8, 9]
charm	c	$1.3~{\rm GeV}$	$+\frac{2}{3}$	$\frac{1}{2}$	1974 [10 , 11]
strange	s	$95 { m MeV}$	$-\frac{1}{3}$	$\frac{1}{2}$	1968 [8, 9]
top	t	$173 { m ~GeV}$	$+\frac{2}{3}$	$\frac{1}{2}$	1995 [5, 6]
bottom	b	$4.2 \mathrm{GeV}$	$-\frac{1}{3}$	$\frac{1}{2}$	1977 [12]

Table 2.1: The quark contents of the Standard Model and their properties, divided by generation.

Lepton		Mass	Charge	Spin	Discovered in:
electron	e	$0.51 { m MeV}$	-1	$\frac{1}{2}$	1896 [13]
e neutrino	ν_e	< 2 eV	0	$\frac{1}{2}$	1956 [14]
muon	μ	$106 { m MeV}$	-1	$\frac{1}{2}$	$1936\ [15,\ 16]$
μ neutrino	$ u_{\mu}$	$< 0.19~{\rm MeV}$	0	$\frac{1}{2}$	1962 [17]
tau	τ	$1.8 \mathrm{GeV}$	-1	$\frac{1}{2}$	1977 [1]
τ neutrino	$\nu_{ au}$	$<18~{\rm MeV}$	0	$\frac{1}{2}$	2000 [18]

Table 2.2: The lepton contents of the Standard Model and their properties, divided by generation.

Boson	Mass	Charge	Spin	Force	Discovered in:
photon γ	$< 10^{-18} {\rm ~eV}$	0	1	electromagnetic	1923 [1 9]
W^{\pm}	$80 { m GeV}$	± 1	1	weak	$1983 \ [20, \ 21]$
Z	$91~{\rm GeV}$	0	1	weak	1983 [22, 23]
gluon g	0	0	1	strong	1979 [<mark>24</mark>]
Higgs h	$125~{\rm GeV}$	0	0	—	$2012 \ [2, \ 3]$

Table 2.3: The boson contents of the Standard Model and their properties. The 0 gluon mass is not an experimental result, but a theoretical value. Experimental results constrain the gluon mass to below O(1) MeV [25].

2.2 The Dynamics of the Standard Model

The interactions of the pantheon of particles described in the previous section have a rich theoretical underpinning, beginning with the formulation of relativistic quantum mechanics in the early to mid 20th century. The fundamental concept was to describe particle behavior using the mathematics of field theory. Thus, to understand SM dynamics, we write down the SM Lagrangian in terms of interacting fields. In doing so it is important to revisit the idea of symmetry, which here surfaces through constraining the Lagrangian to be invariant under certain transformations. Imposing such invariance for each piece of the Lagrangian results in interacting gauge bosons, force carriers and motivators of SM dynamics. The purpose of performing a cursory outline of SM theory in this thesis is to prepare for and inform further discussion of Supersymmetry, which leans heavily not only on the particle structure but on the dynamics of the SM. As such, I will focus on a few key results, and gloss over the intermediate steps. For a more in-depth treatment, see [26, 27].

$$\mathcal{L}_{SM} = \mathcal{L}_{EW} + \mathcal{L}_{QCD} + \mathcal{L}_{Higgs} \tag{2.1}$$

2.2.1 Electroweak Interactions

To tackle the electroweak term in \mathcal{L}_{SM} , we address the $SU(2)_W \otimes U(1)_Y$ components of the SM symmetry and introduce the electroweak force. The formalism for the electroweak force was built up from the simpler quantum electrodynamics (QED) Lagrangian which details the interactions of charged particles through the exchange of photons. In QED a U(1) symmetry, symmetry of rotations, is imposed on the Lagrangian, resulting in the introduction of gauge fields. The gauge fields must be massless, spin-1 bosons, that is, they must be photons. Electroweak theory expands on the symmetry of QED by including SU(2), two-dimensional rotational symmetry, and an analogous process follows. It should be noted that the $U(1)_Y$ symmetry of the electroweak symmetry is not the same electromagnetic U(1) from before, but instead is the gauge group of the weak hypercharge. In addition, the mass eigenstates of the W and Z bosons arise from linear combinations of the gauge fields required by the new $SU(2)_W$ symmetry [28–30].

The Lagrangian of the electroweak component, including all gauge-invariant terms, is as follows:

$$\mathcal{L} = -\frac{1}{4} (W^a_{\mu\nu})^2 - \frac{1}{4} B^2_{\mu\nu} + (D_\mu H)^\dagger (D_\mu H) + m^2 H^\dagger H - \lambda (H^\dagger H)^2 \qquad (2.2)$$
$$B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu$$
$$D_\mu = \partial_\mu - ig W^a_\mu \tau^a - \frac{1}{2} ig' B_\mu$$

Examining the first two terms, W^a represents the gauge bosons from SU(2), B_{mu} is the boson from U(1), and H is a presciently labeled complex doublet with hypercharge 1/2. The covariant derivative D_{μ} is defined above, where g and g' are the couplings for SU(2) and U(1) respectively and τ^a is the ordinary generator for SU(2).

The remaining terms in the Lagrangian can be usefully grouped together as a potential:

$$V(H) = -m^2 |H|^2 + \lambda |H|^4$$
(2.3)

which comes to a minimum at $|\langle H \rangle| = \sqrt{\frac{2m^2}{\lambda}}$, and therefore the scalar field must have a vacuum expectation value (vev). This is crucial because the vev forces the ground state to spontaneously break the symmetry of the potential V(H). After simplifying by specifying the direction of the complex doublet H and using the proper choice of gauge to ignore the phase, the vev maybe written,

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0\\ v+h \end{pmatrix}$$
(2.4)

where $v = m/\sqrt{\lambda}$ and h is a real scalar field, identified as the Higgs boson. Through the process known as electroweak symmetry breaking, the Higgs component of the SM Lagrangian has already been identified [31–33]. Plugging in H, expanding the covariant derivative, and glossing over intermediate steps involving gauge boson mixing, yields the third term of the electroweak Lagrangian, $(D_{\mu}H)^{\dagger}(D_{\mu}H)$,

$$\mathcal{L}_{EW,Higgs} = \frac{1}{4}g^2(h^2 + 2vh + v^2)W^+_{\mu}W^{-\mu} + \frac{1}{8}(g^2 + g'^2)(h^2 + 2vh + v^2)Z_{\mu}Z^{\mu} - m^2h^2 - \lambda vh^3 - \frac{\lambda}{8}h^4$$
(2.5)

Even though the original Lagrangian contained only massless bosons, using this expression we can use the functional form of the Lagrangian $\mathcal{L} = \frac{1}{2}m_X X^2$ to read off the masses:

$$m_{\gamma} = 0$$

$$m_W = \frac{1}{2}vg$$

$$m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}v$$

$$m_h = \sqrt{2}|m| = v\sqrt{2\lambda}$$

The important takeaways here are twofold: First, we have established the electroweak dynamics of the SM. Second, in doing so we have broken the symmetry of the Higgs potential and not only given mass to the originally massless bosons, but introduced the final degree of freedom in h, the Higgs boson. The discovery of the Higgs boson in 2012 [2, 3] signified the acquisition of the final piece of the SM model puzzle.

2.2.2 Strong Interactions and QCD

Requiring gauge invariance leads to the generation of gauge bosons as carriers of the force of the theory. In the previous section, that meant photons, W and Z bosons, and finally the Higgs. But in the case of quantum chromodynamics (QCD), we will generate the gluon as force carrier of the strong force. Here imposing a local SU(3) symmetry group characterizes the interactions between quarks.

$$\mathcal{L}_{QCD} = \bar{\phi}(i\gamma^{\mu}D_{\mu} - m)\phi - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}$$
(2.6)

Here the covariant derivative is given:

$$D_{\mu} = \partial_{\mu} + g_s T_a G^a_{\mu}$$

where g_s is the strong coupling constant and T^a are the eight generators of $SU(3)_C$. The subscript 'c' denotes 'color', analogous to charge for the strong force, with values of red, blue, or green. Also,

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu$$

where f^{abc} are the structure constants for SU(3) that relate the generators via the commutation relation $[T_a, T_b] = i f_{abc} T_c$. G^a_μ are the gluon vector fields, analogous to the W, Z, and γ force carriers from electroweak interactions. These vector fields, however, are carriers of color charge as well, which means they themselves feel the strong force and are self-interacting, in stark contrast to QED.

2.3 Shortcomings

In this chapter I outlined the Standard Model of particle physics by first describing the composition of the particles, then building up some of the underlying mathematical framework motivating how they interact. While the study and verification of SM



Figure 2.2: An example of a second order Feynman diagram, for an interaction between a photon and a charged fermion (e.g., an electron). As long as momentum is conserved at each vertex, the intermediate momenta of k and k' are not constrained, and are free to diverge.

properties is a vital component of particle physics work, here I introduce the SM mostly to motivate the next steps beyond it.

Perhaps the most glaring omission from the SM, gravity, will not be addressed in these pages, nor will the addition of neutrino masses to the picture, but other significant shortcomings do exist that are targets for new physics research. The techniques of perturbation theory are used to calculate SM interactions via approximations accurate only to a given order in some small parameter. That is, expanding a term like $(1 + \sigma)^3$ and approximating to leading order in σ yields $1 + 3\sigma$, with a quadratic correction of $3\sigma^2$. But when applied to the SM, this perturbation theory process hits a snag in the calculation of higher-order corrections, because it requires the use of loop integrals. Loop integrals do not constrain the momenta of the intermediate particles (beyond conservation of momentum), as shown in Figure 2.2.

Because of this lack of constraint, higher-order terms may diverge at very high (ultra-violet) or very low (infra-red) momentum. This means that terms can grow very

large and must be canceled with another similarly enormous term to tie the theory to a predictive energy scale. In the case of the Higgs mass, quadratic divergences in the higher-order corrections mean that prior to this canceling process, the Higgs mass is at the Planck scale, or around 10^{19} GeV, while experimentally it sits comfortably at 125 GeV. Attempting to reconcile those values amounts to a highly unlikely 'finetuning'. This so-called *hierarchy problem* is a major unresolved issue in the SM, especially targeted by Supersymmetry, and will be addressed in Chapter 4 along with further motivations for physics beyond the SM.

Conclusions

This chapter outlined the theoretical framework that lies behind particle physics and introduced a pantheon of fundamental particles and forces. The mathematically symmetric structure of this framework appeals on its own, but the remarkable feature of the Standard Model is how well it matches experimental measurement. With that in mind, and looking ahead to the forthcoming Chapter 4 on Supersymmetry, any attempt to look for physics beyond the SM must take into account its predictive power. The goal moving forward is to reproduce the success of the SM, while simultaneously adding new theoretical structure to cope with its shortcomings. Achieving this goal will require delving into the theory behind particle detection.

Jets

And if these incidents now seem full of significance and all of a piece, it's probably because I'm looking at them in the light of what came later...

-Kazuo Ishiguro, Never Let Me Go

The essential mandate of a particle physics experiment is to collect the whole output from particle collisions, tally and measure the spray of outgoing particles, and trace backward to the intermediate states between that collision and that measurement. Crucially, detectors are not equipped to observe the partons immediately resulting from the hard-scatter. The original hadrons may be too short-lived to even reach the detector, or may be non-interacting particles like neutrinos, and pass through all of ATLAS without leaving a mark. These intermediate states hold the information vital to understanding fundamental particles and the interactions that govern them, but the experiment must perform some detective work to get to them.

To complicate matters even further, particles governed by the strong force–quarks and gluons–cannot be measured on their own because of the phenomenon of *confinement*. Color charge, described in the previous chapter, is hidden by confinement: Strongly interacting particles are never found alone and must form color-neutral bound states. Free quarks and gluons hadronize from QCD partons to create stable hadrons in the form of either mesons (two quarks) or baryons (three quarks). After hadronization, the newly formed color-neutral hadrons then may (or may not) go on to interact with the detector. Therefore the particles registered by the detector are not immediate remnants of the collision but are rather a chaotic mess-a parton shower-of fresh particles descended from the original particles. Studying quarks and gluons or other potential new strong interactions requires the introduction of additional structure to make order out of that mess. The fundamental organizing object is a *jet*.

The term jet refers to the collimated particle spray that originated with quarks and gluons, then underwent showering and hadronization (which will be discussed presently). The search for new physics presented in this thesis will make much use of jets as tools for organizing very complicated but potentially interesting events. With that direction in mind, this chapter will first build up the underlying behavior of partons in collisions, then move on to discuss the algorithms through which jets are constructed.

3.1 Connecting Collisions to Jets

Collisions at the LHC are not simple parton-parton interactions because the colliding particles are composites made up of quarks and gluons. On top of its influence on outgoing jets, confinement also plays an important role in the dynamics of the incoming colliding particles. A collision is never simply a proton-proton scattering, then, but rather a complex interaction between the partons that make up those protons. This means that the calculation of the cross-sections of possible outputs from the collisions cannot be limited to single set of particle inputs or a specific energy. Instead the calculation must average over all possible parton-parton interactions and energies. Thus when we say collisions at the LHC take place at a center of mass energy of $\sqrt{s} = 13$ TeV, we are quoting the upper bound on the energy, not necessarily the actual energy of the collision taking place.

In fact, the collision may involve more pieces than just the constituent two up quarks and one down quark composing the protons. The gluons binding together these hadrons may decay into virtual quark/anti-quark pairs and then reform again into gluons. The new virtual quarks are called *sea* partons, in contrast with the *valence* partons making up the proton. Virtual quark/anti-quark pairs flicker into and out of existence very quickly, but still register as important considerations in collision dynamics. So a seemingly simple proton-proton cross-section measurement must take into account the valence quarks, the sea quarks, and the gluons as potential participants in collisions.

3.1.1 Perturbative vs Non-perturbative QCD

Fortunately the QCD factorization theorem [34] states that the cross-section of the original hard-scatter process may be reconstructed by considering all of the component parton-parton cross-sections, weighting them, and combining them appropriately. The probability for a certain parton to interact with another parton at a certain fraction of the whole proton's energy is given by a *parton distribution function* (PDF). A sum over all possible parton interactions will yield the total cross-section between protons with momentum p_1 and p_2 :

$$\sigma(p_1, p_2) = \sum_{ij} \int dx_1 f_i(x_1, \mu^2) \int dx_2 f_j(x_2, \mu^2) \hat{\sigma}_{ij}(x_1 p_1, x_2 p_2, \mu^2, Q^2)$$
(3.1)

Here the component partons are colliding with fractions x_1 and x_2 of the total hadron momenta p_1 and p_2 . The matrix element cross-section $\hat{\sigma}_{ij}$ between two partons *i* and *j* depends on the momenta of those partons and the overall momentum scale Q^2 . The parton distribution functions f_i and f_j are summed over all possible parton interactions. They depend on the momentum fractions, and on the scale at which factorization takes place, μ^2 . This scale essentially divides the non-perturbative and perturbative regimes, separating the relatively long-distance physics of the hadron collision from the relatively short-distance physics of the constituent parton collisions.

It is worth examining the factorization scale μ^2 a bit more closely. Particle interactions can be well modeled by perturbation theory techniques, as described in Section 2.3, as long as the couplings are weak. For QED processes, perturbative methods work because the coupling constant increases with scale. Only energy regimes beyond an enormous ~ 10⁹⁰ GeV enter the non-perturbative region for QED. The QCD coupling α_S , on the other hand, *decreases* with scale, so that the non-perturbative region occurs at low energy instead. Indeed at energy scales much below a few GeV the coupling constant α_S grows unmanageably large, as can be seen in Figure 3.1. A perturbative description of QCD physics at this scale fails. This feature of QCD motivates the use of data-driven non-perturbative techniques for intra-hadron dynamics. The factorization scale, chosen so that the strong coupling is not too great, defines this non-perturbative region for which we must make use of PDFs.

Figure 3.2 shows an example set of PDFs, demonstrating the probability that a specific parton from the original protons will interact, for a given momentum fraction x and momentum scale Q^2 . At the lower momentum $Q^2 = 10 \ GeV^2$, the constituents of the proton dominate—the valence up and down quarks and the gluons that hold them together. But at higher momentum $Q^2 = 10^4 \ GeV^2$, sea charm and bottom quarks begin to register a higher probability, indicating a significant influence on the overall cross-section. PDFs are derived from the results of a host of experiments, and a number of different collaborations produce their own PDFs [36, 37]. Different assumptions and techniques used for fitting lead to slightly different experimental predictions and uncertainties among the various PDF sets.



Figure 3.1: Measurements of the strong coupling α_S as a function of energy scale Q [35]



Figure 3.2: A set of example PDFs, the MSTW from 2008, next-to-leading order (NLO). This plot shows the probability that a specific particle constituent of the proton will interact as a function of the momentum fraction x and the overall momentum scale Q^2 , to a one-sigma confidence level [36].

3.1.2 Parton Showering and Hadronization

The complex collision process described above is followed by the process of *parton* showering, through which the momentum carried by the original quarks produces a multitude of new particles. Parton showering is explained by the inverse relationship between energy and distance: Saying QCD coupling decreases with energy is tantamount to saying it increases with the separation between the interacting partons. Thus as the partons from a collision move apart, a sizable color potential is created. That potential causes quark/anti-quark pairs to spring into existence, splitting the original parton's momentum between them. The new partons are carried apart and again a color potential arises, producing yet more particles, and so on and so forth. Thus a single energetic parton produces a shower of other partons propagating in the same direction as the original.

Once the momentum of the parton shower has been exhausted and is no longer sufficient to produce a new quark/anti-quark pair, the resulting quarks will recombine once again into color-neutral hadrons, a process called *hadronization*. The resultant hadrons may then decay according to the SM branching ratios. In the end the energy deposited in the detector's calorimeter comes from these descendent hadrons, but still carries the history of that original parton. These final collimated energy deposits can be usefully constructed into jets, toward the purpose of cataloguing the final state particles and probing the original physics that produced them.

The final category of products from the collisions is the so-called *underlying event*. So far all partons discussed, and their resultant hadrons, originated from a single colliding parton pair. But other partons from the colliding hadrons are carried away from their hadron partners, yielding a color potential and producing their own parton showers. These partons may also experience lower-energy interactions, or may radiate energy. The underlying event is the umbrella term for all of these additional collision products, a separate story from the hard-scattering.



Figure 3.3: A recent example of a di-jet event measured by ATLAS

3.2 Jet Algorithms

On the surface, identifying the jets in an event would seem to be exceedingly simple. One can see, by eye, the spray of particles oriented in the same direction, governed by conservation of momentum. The task, then, is to sum up the 4-momenta of the particles in that group, registered as energy deposits in the detector's calorimeter. Figure 3.3, for example, shows two clear back-to-back jets; in principle jets are a very straightforward structure.

Complications quickly pile up, however. Suppose an event has six, or eight, or twelve jets, as in Figure 3.4. No longer is it so clear which particle ought to pertain to which jet. Even getting that far may be difficult, because a typical LHC event will produce many sources of energy, clouding the clarity of the calorimeter's energy deposits. Matching a signature in the detector to the proper particle can prove a challenge. Additional challenges arise on the theoretical side: Clearly a single particle ought to be considered a jet, but what happens when an outgoing particle radiates some energy, producing two adjacent particles, for example a quark radiating a gluon? Should that adjacent energy be absorbed into that same jet, or should it be



Figure 3.4: A recent example of a twelve-jet event measured by ATLAS

considered its own proper jet? From a practical perspective jet choices must share some consistent standard. To meet these challenges, a litany of jet algorithms have been suggested over decades of particle physics [38].

A jet algorithm defines the grouping process for three separate stages described in the previous section: the energy deposits in the detector, the hadron products from the parton shower, and the outgoing partons from the hard scatter. Each of these is collected into jets by the jet algorithm such that a roadmap exists tracing the path all the way from the collision to the detector and linking the kinematics of the collision output to the final state that has been detected. This procedure is called a
recombination scheme.

Over the years of particle physics experiments there has been significant disagreement over what constitutes a 'good' jet algorithm. Theorists tend to prefer that the algorithm be calculable, whereas experimentalists place the greatest value upon efficiency and simplicity. In 1990 a group of influential experimentalists and theorists at the Summer Study on High Energy Physics in Snomass laid down the first attempt to set standard criteria for jet algorithms [39, 40]:

- 1. Simple to implement in an experimental analysis
- 2. Simple to implement in the theoretical calculation
- 3. Defined at any order of perturbation theory
- 4. Yields finite cross section at any order of perturbation theory
- 5. Yields a cross section that is relatively insensitive to hadronization

While this agreement moved the ball forward in terms of achieving consensus, in practice no standardized algorithm was reached. The jet algorithms used by various experiments, meeting the above criteria to varying extents over the years fall into two broad categories: First, those based on "cones" of energy, which can be considered "top-down" algorithms. The features of QCD described in the previous section dictate that parton showering and subsequent hadronization will leave the energy flow of an event by-and-large intact. That is, the energy flows outward from the original parton in a cone shape. Second, algorithms based on sequential recombination, or "bottomup" algorithms. These build up the jet structure by repeatedly combining a particle with its nearest neighbor, according to a chosen distance criterion.

3.2.1 Cone Algorithms

The most basic version of a cone algorithm proceeds as follows [38]:

- 1. Select a seed particle, usually the highest-energy object.
- 2. Draw a cone of radius $R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ around the seed.
- 3. Combine all objects captured within the cone: this is the jet.
- 4. Select the next seed particle and repeat steps 1-3.
- 5. Resolve any ambiguities that arise between jets.

Beyond its simplicity and intuitiveness, the greatest strength of the cone algorithm is its speed. Constructing jets only requires computing the distance between the objects and the seed, so the complexity of the algorithm simply scales with the number of objects. Here objects can refer to the components of jets at any stage; the final state energy clusters detected by the experiment or the QCD partons from the collision. Here $\Delta \phi$ is the difference in azimuthal angle and $\Delta \eta^1$ is the difference in pseudorapidity (a spacial coordinate describing the angle of the particle relative to the beam axis).

Most cone algorithms in use today are "iterative cones" (IC). In these algorithms an extra step is added after step 3 above. Once the objects captured within the cone have been combined into the jet, the jet axis is redefined to be in the direction of the resultant sum of momenta. Steps 1 through 3 are repeated for the same jet, drawing a new cone around the redefined axis. Again the objects are collected into a jet, and again the jet axis is redefined. This process is repeated until the resulting cone is stable.

Iterative cone algorithms vary by how they cope with the problem of overlapping cones. One approach is the "progressive removal" technique [39], in which all components collected into a jet are removed from consideration as subsequent seed particles in step 4 above. A more prevalent technique, however, is the "split-merge"

 $^{{}^{1}\}Delta\eta = -\ln(\tan(\frac{\theta}{2}))$ where θ is the angle with the beam axis.

approach [38]. This method considers the fraction of the softer (lower-energy) cone's momentum that is carried by particles shared by the harder cone. If that fraction is above some parameter f, the cones are merged. If it's below f, the cones are split and shared particles are given to the closer jet.

Unfortunately, though cone algorithms succeed admirably in achieving item 1 of the Snomass criteria listed in the previous section, they struggle with the remaining four. These latter items treat the robustness of an algorithm: how reliable it is in theoretical calculation; how well it stands up to minor alterations in combined jet objects. These difficulties are better understood now than they were when those criteria were laid out, and can be more clearly defined using the terms *infrared* and *collinear* safety (together, IRC safety). Infrared safety requires that the result of a jet algorithm not change if an additional small radiation occurs, such as the emission of a low-energy gluon. Collinear safety requires that the result of a jet algorithm not change upon the splitting of a hard particle into two almost collinear softer particles. In each case the specific evolution of objects from the parton shower should not matter because the same energy with the same origin is propagating in the same direction. A robust algorithm will form safe jets that remain consistent under small fluctuations.

Cone algorithms are IRC unsafe. They fail infrared safety because a soft emission between two overlapping cones may fool the algorithm into merging the jets. They fail collinear safety because splitting one hard particle in two may cause the softer particles to be considered separately, so that one jet becomes two. In the language of the Snomass criteria, cone algorithms clearly fail item 5 as they may be sensitive to different parton showerings. Less obviously, they also fail items 2-4, which treat their performance in theoretical calculations (of cross sections, momentum spectra, etc.). In perturbative calculations the terms representing soft radiation and collinear splitting are divergent. Fortunately, each case produces terms that appear with opposite signs, thereby canceling the infinities. But if the divergent terms are allocated to separate objects by the jet algorithm, they can no longer cancel and the calculation breaks down. Reliable comparison of data and theory requires a different algorithmic approach.

3.2.2 Sequential Recombination Algorithms

The problems with cone algorithms are twofold: The forced selection of a seed at the beginning prevents collinear safety, and the split/merge process at the end makes the algorithm sensitive to small fluctuations in energy. Sequential recombination algorithms aim to address each of these by eliminating the seed entirely and focusing on the relationship between close-together pairs of particles. The structure of the algorithm is to define a distance parameter between these pairs, combine them if they are within some maximum distance apart, and iterate until no more combinations are possible.

The advantages of this approach are clear. No longer does a seed threshold force the jet algorithm to depend on a single particle's energy. Instead, the jets flow with the path of the energy through the event, free of strict association with one particle or another. In addition, the merging of objects has a clear end condition, avoiding the conflicts that arose from overlapping jet cones.

The origins of sequential recombination algorithms lie in e^+e^- experiments, where the leptonic nature of the collisions avoided the messiness of the underlying event and the high jet-multiplicity of hadronic experiments. The first example was the JADE algorithm [41, 42] which used the distance metric between a pair particles i, j:

$$y_{ij} = \frac{2E_i E_j (1 - \cos\theta_{ij})}{Q^2}$$
(3.2)

where E_i and E_j are the energies of the two particles and θ_{ij} is the angle between them. Q is the total energy of the event. The iterative process goes as follows [38]: First, find the closest-together particles with distance y_{min} . If $y_{min} < y_{cut}$, where the jet resolution cut y_{cut} is the algorithm's single parameter, then combine particles into a new single object and repeat. If $y_{min} > y_{cut}$, the process is over and all remaining objects are jets. The JADE algorithm is IRC safe because any soft radiation or collinear particles will be recombined early on in the clustering process.

Experiments with hadronic collisions complicate matters because the total energy is no longer a well-defined quantity. The momentum of the partons engaging the collision is unknown, and may be uneven. Thus only the transverse energy E_T is meaningful, as that quantity is invariant under boosts in the longitudinal direction, and it makes sense to choose a dimensionful distance parameter d_{ij} instead of the dimensionless y_{ij} . In addition, in hadronic collisions most of the particles continue down the beam pipe with zero transverse momentum, and particles close to the beam ought to be recombined with it and taken out of the picture.

For the purposes of the ATLAS experiment and the purposes of this thesis, the accepted jet algorithm is the anti- k_t algorithm [43]. It has distance metrics as follows:

$$d_{ij} = min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$$
(3.3)

$$\Delta R_{ij}^2 = \Delta \phi_{ij}^2 + \Delta y_{ij}^2 \tag{3.4}$$

$$d_{iB} = p_{Ti}^{-2} \tag{3.5}$$

where p_{Ti} is the transverse momentum of particle *i*. The first distance metric d_{ij} is the distance between particles *i* and *j*, while the second metric d_{iB} is the distance to the beam. *R* is the algorithm's size parameter, which replaces the earlier y_{cut} . This parameter has the same units as the angular distance ΔR , so it allows the resultant jets to be thought of loosely as cones with radius *R*.

The iterative process for the anti- k_t algorithm is identical to that of the JADE algorithm, except that now the minimum of both distance metrics is chosen. If d_{ij} is minimum, the particles i and j are combined and the process starts over as before.

If d_{iB} is minimum, particle *i* is considered a jet and removed from the list of input particles, and the minimizing process starts over. The iterations continue until there are no more particles.

The anti- k_t algorithm clusters objects that are close together, like the cone algorithms do, but in contrast it first combines low- p_T particles to nearby high- p_T particles before combining them with each other. The result is an intuitive conical jet, but without the failures that arise from seed particles and the merge/split process. Because it is IRC safe and performs well in reconstruction and calibration, the anti- k_T algorithm was adopted by experiments at the LHC. In implementing the algorithm, the goal is to create a jet that corresponds directly to the output from the original hard-scatter parton. In practice, however, energy from other partons may overlap with that defined jet, so a balancing act is required. For ATLAS the R parameter typically takes on values of R = 0.4 or R = 0.6, which are big enough to contain the breadth of a large parton shower, but small enough to avoid most contamination from the underlying event.

3.3 Conclusions

Jets are a powerful structure for tracing the path of particles from the original collision through to the deposition of energy in the detector. This chapter detailed the physics of that path, spelled out fundamental difficulties that must be overcome in the construction of a jet object, and introduced a progression of jet algorithms. The objective of jets, to probe QCD structures, will prove integral to the search for Supersymmetry, which predicts a whole new library of strong interactions.

Supersymmetry

A la realidad le gustan las simetrías y los leves anacronismos.

—Jorge Luis Borges, Ficciones

The Standard Model has had enormous success in uniting disparate theories into a coherent fundamental particle physics and predicting many experimentally-observed processes. The SM is not without its shortcomings and blindspots, however, some of which were touched upon at the end of chapter 2. Numerous extensions to the SM have been suggested over the years, and though none has emerged as a cure-all, Supersymmetry (SUSY) stands out from the rest. SUSY is an extension of the very symmetries of the SM that have proven such a strong tool for defining and explaining fundamental particle dynamics.

The following chapter will serve as an overview of SUSY, building up its motivation, outlining its particle structure, and introducing the concepts behind searches specific to the LHC [44, 45].

4.1 Motivations

With the goal of demonstrating its fallibility, Section 2.3 introduced some shortcomings of the SM, specifically those inherent in the use of perturbation techniques in calculations containing loop diagrams. Now I will revisit that treatment with an eye towards some major improvements SUSY has the potential to make over the SM. The subsequent outline of SUSY particles and interactions will address each of these motivating factors directly.

4.1.1 Fine-tuning and Naturalness

Perhaps the primary guiding directive in physics is towards simplicity. The strength of a theory lies in its ability to cohere a set of complex observations of physical phenomena into a simple pattern. In the case of the SM, this has meant recognizing the way an introduction of SU(3) color symmetry can transform the ocean of observed hadrons from a messy ad hoc chaos into an ordered model. Writing down the terms of the Lagrangian is a matter of examining the symmetries of the system; there are no random or accidental terms. A top-down model that uses a fundamental structure to make predictions is superior to a patchwork model that only aims to tie observations together. This underlying concept serves as a physicist's 'aesthetic' sense.

Re-examining the hierarchy problem from Section 2.3 with this aesthetic in mind clarifies the sense of wrongness in the Higgs mass corrections. To review, calculations in perturbation theory may contain loop terms that contain intermediate momenta that may diverge. Calculations of the Higgs mass parameter are hardly immune: Figure 4.1a shows the quantum correction from a loop with a fermion f. If the Higgs field H and the fermion f couple via a Lagrangian term like $-\lambda_f H \bar{f} f$, then this Feynman diagram describes a correction term

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \dots$$
(4.1)

where λ_f is the coupling with the fermion. All fundamental SM particles other than photons couple to the Higgs (which is how they gain their mass) with the exception of the gluon. The largest contribution comes from the top quark, in which case $\lambda_f \approx 0.94$



Figure 4.1: One-loop quantum corrections to the Higgs mass parameter m_H^2 , for (a) a fermion f and (b) a scalar particle S [44].

[44]. Here Λ_{UV} is the ultraviolet cutoff in momentum, specific to the theory. If the SM describes physics all the way up to the Planck scale, where a quantum gravitational picture must take over, a serious problem arises. If Λ_{UV} is of the same order of the Planck mass $M_P = 1.22 \times 10^{19}$ GeV, then it is some thirty orders of magnitude greater than the Higgs mass itself, which was measured in 2012 at 125 GeV [46]. This means that in order to hit that magical observed value the bare Higgs mass m_0 is forced to take on an exact value so that it precisely cancels with the correction Δm_H^2 with the remainder 125 GeV. The SM will only match observed results if the bare mass is defined to within one part in 10^{19} .

The ugliness of this correction lies in the way it contradicts the philosophy of simplicity. There is no underlying symmetry to motivate it. A theory is weak indeed if it must be fine-tuned after the fact to match experimental results; it is somehow unnatural to rely so on pure 'luck'. The concept of *naturalness*—the degree to which a model must be patch-fixed to obtain observed masses—is fundamental in judging the worth of supersymmetric models in solving this hierarchy problem.

4.1.2 Dark Matter

The next reason to explore physical descriptions beyond the standard model lies in its failure to address the phenomenon of dark matter. The term 'dark matter' refers to

excess mass in the universe the existence of which can be inferred from gravitational behaviors, but that emits no light whatsoever. The evidence comes primarily from observation of the motion of galaxies, which indicate that dark matter comprises some 85% of the mass of the universe [47]. The astrophysical case for dark matter, already decades old, is steadily increasing in strength: observations of galaxy mergers [48], the rotation of spiral galaxies [49], the cosmic microwave background [47], and much more are painting a clearer and clearer picture of the role of dark matter in the universe.

Every other piece of matter can be deconstructed into component particles so the natural next step, from a particle physics perspective, is to wonder how dark matter might appear as a particle. It emits no light so it must not interact with other matter beyond gravitation, and yet astronomical observation requires that it be ubiquitous. The natural SM candidate is the neutrino, which is suitably non-interacting and (though the SM does not predict so) has mass. But the neutrino mass is so small as to elude measurement, such that neutrinos do not interact gravitationally either and could not cluster to produce the dark matter distribution observed. Neutrinos (and other SM particles) won't suffice, and particle representation of dark matter must await further discoveries beyond the SM [50].

4.1.3 Unification

One final quirk of the SM lies in the different treatment it gives to the electroweak and strong components. Indeed, the unification of electromagnetism and the weak nuclear force into the electroweak model was itself a triumph, demonstrating that two previously linked but disparate forces are one and the same. As discussed in chapter 2, electroweak symmetry is broken by the Higgs mechanism, but the unity above that scale still prompts the question of whether a deeper symmetry might exist to combine all SM forces. The behavior of the SM coupling constants, shown



Figure 4.2: The dependence of the SM couplings α_i on energy scale [45].

in Figure 4.2, hints at this larger unification. Though the couplings never meet at the same point, they cross each other in a small enough region to evoke curiosity. Unification is not essential to the success of a model, but it certainly would follow the successful trend of the SM, to simplify, simplify, simplify.

4.2 The Particle Composition of SUSY

The underlying concept behind the particle composition of SUSY, at least outside of the Higgs sector, is to double the population, so that each established SM particle gains a supersymmetric partner, denoted with a tilde. Just as in the SM particles and anti-particles differ only by one quantum number–electric charge–SUSY only affects one quantum number–spin. Each spin-1/2 fermion, divided by helicity (righthanded or left-handed) is matched with a spin-0 bosonic superpartner (right or left respectively). Each gauge boson, which is a spin-1 vector boson prior to electroweak symmetry breaking, has a fermionic superpartner for each helicity state–a massless spin-1/2 fermion. (Note that in the SM neutrinos are only left-handed, and so only have a single superpartner). The nomenclature for labeling these new particles goes as follows: For quarks and leptons, an "s" (which stands for "scalar") is prepended to the name, creating squarks and sleptons. Tops become stops \tilde{t} and taus become staus $\tilde{\tau}$. A character with a tilde \tilde{x} represents that SM particle's supersymmetric partner. For bosons, "-ino" is appended to the name, creating higgsinos, gluinos, etc. The complete list of particles in the minimal supersymmetric extension to the Standard Model (MSSM), the simplest version of SUSY that will still address the hierarchy problem, is shown in Table 4.1.

The Higgs sector of the MSSM is more complex. The single Higgs h of the SM is replaced by two spin-0 chiral multiplets, one of which couples only to up-type fermions while the other couples only to down-type fermions. The old h becomes a linear superposition of the neutral scalar Higgs H_u^0 and H_d^0 . Through electroweak symmetry breaking the new H_u^0 and H_d^0 gain vacuum expectation values (vev) of v_u and v_d respectively, which must satisfy $v_u^2 + v_d^2 = v^2$ where v is the SM Higgs. This larger Higgs sector predicts not one, but five Higgs bosons: two CP-odd neutral scalars h^0 and H^0 , a CP-even neutral scalar A^0 , and two charged scalars H^{\pm} . The Higgs boson observed at the LHC would be the lighter h^0 .

Also via electroweak symmetry breaking, mixing occurs between the higgsinos and electroweak gauginos. Linear combinations of the four new neutral supersymmetric particles $(\tilde{H}_u^0, \tilde{H}_d^0, \tilde{W}^0, \text{ and } \tilde{B}^0)$ produce four neutral mass eigenstates, called *neutralinos* $\tilde{\chi}_i^0$ (where i = 1, 2, 3, 4 ranks the mass from lowest to highest). Likewise, linear combinations of the four new charged particles $(\tilde{H}_u^+, \tilde{H}_d^-, \tilde{W}^+, \text{ and } \tilde{W}^-)$ form four charged mass eigenstates, or *charginos* $\tilde{\chi}_i^{\pm}$ (i = 1, 2).

This new supersymmetric pantheon of particles is a mathematically elegant extension of the symmetries in the SM, and serves to address each of the concerns with the SM listed in the previous section. First, the MSSM is motivated by the hierarchy problem, so it solves it by design. Returning to the quadratic divergence from the loop correction to the Higgs mass shown in Figure 4.1 and Equation 4.1, it

Particle	Spin 0	Spin $1/2$	Spin 1
quark/squark	$(\tilde{u}_L \ \tilde{d}_L)$	$(u_L \ d_L)$	
	\tilde{u}_R, \tilde{d}_R	u_R, d_R	
	$(\tilde{c}_L \ \tilde{s}_L)$	$(c_L \ s_L)$	
	\tilde{c}_R, \tilde{s}_R	c_R, s_R	
	$(\tilde{t}_L \ \tilde{b}_L)$	$(t_L \ b_L)$	
	\tilde{t}_R, \tilde{b}_R	t_R, b_R	
leptons/sleptons	$(ilde{ u}_e ilde{e}_L)$	$(u_e e_L)$	
	\tilde{e}_R	e_R	
	$(ilde{ u}_{\mu} ilde{\mu}_L)$	$(u_{\mu} \ \mu_L)$	
	$ ilde{\mu}_R$	μ_R	
	$(ilde{ u}_{ au} ilde{ au}_L)$	$(u_{ au} au_L)$	
	$ ilde{ au}_R$	$ au_R$	
Higgs/higgsinos	$\left(H_u^+ \ H_u^0\right)$	$(\tilde{H}^+_u \ \tilde{H}^0_u)$	
	$\left(H^0_d \ H^d\right)$	$(\tilde{H}^0_d \ \tilde{H}^d)$	
gluons/gluinos		\tilde{g}	g
W bosons/winos		$\tilde{W}^{\pm}, \tilde{W}^0$	W^{\pm}, W^0
B bosons/binos		$ ilde{B}^0$	B^0

Table 4.1: The particle contents of the MSSM divided by spin, before electroweak symmetry breaking[44].

is evident that resolution of the dangerous terms in Δm_H^2 can only come about via systematically canceling the divergence. Consider Figure 4.1b, the diagram for loop corrections from a scalar particle that couples to the Higgs with a term $-\lambda_S |H|^2 |S|^2$ in the Lagrangian. This Feynman diagram yields the correction

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} [\Lambda_{UV}^2 - 2m_S^2 \ln(\Lambda_{UV}/m_S) + ...]$$
(4.2)

Comparing Equations 4.1 and 4.2 suggests that a new symmetry, adding new terms to the Lagrangian, could cancel out the divergence, provided the new contribution has the proper sign. Because the fermion loop and boson loop corrections to Δm_H^2 have opposite signs, solving the hierarchy problem means relating fermions to new bosons and bosons to new fermions-the precise structure of the MSSM. Adding two new scalars with $\lambda_S = |\lambda_f|^2$ neatly cancels the Λ_{UV} terms and eliminates the troublesome quadratic dependence on the UV scale. Additional restrictions on the theory may be added to further cancel higher-order terms in the corrections.

SUSY also provides a natural candidate for dark matter. A quantity called 'Rparity' is conserved under the transformations in the MSSM. R-parity is defined as $P_R = (-1)^{(B-L)+2s}$, where B and L are the baryon and lepton numbers and s is the spin. This takes on a value of +1 for SM particles (any particles without a tilde) and a value of -1 for supersymmetric particles. Conservation of R-parity is not a hard requirement for a SUSY model, but (most) models that break R-parity make statements about the lifetime of a proton that seem at odds with reality. In addition, requiring R-parity means that no supersymmetric particle can be produced on its own, nor can it decay solely to SM particles. Thus there must exist a lightest supersymmetric particle (LSP) that is stable. This LSP would only interact under the electroweak force, along with gravity, fulfilling the main dark matter criterion of non-interaction. The MSSM typically assumes the lightest neutralino $\tilde{\chi}_1^0$ to be the LSP and therefore the missing dark matter particle.



Figure 4.3: The dependence of the MSSM couplings α_i on energy scale [45]. Now the three couplings meet at around the $\mu = 10^{16}$ GeV scale.

Finally, revisiting the unification of the strong force with the electroweak, SUSY again possesses a tantalizing feature. As shown in Figure 4.3, SUSY changes the evolution of the coupling constants so that they meet at a mass scale of $\mu = 10^{16}$. This suggests that a larger symmetry group might be able to unify all three forces at high mass. While certainly not a necessity of the theory, and perhaps it is just a coincidence, the simplicity of this result adds significantly to the appeal of SUSY.

4.3 SUSY Breaking

Given the aesthetic purity of its symmetries and considering how it provides potential solutions to each of these outstanding physical problems, SUSY seems like a panacea. But it has one major downside; no supersymmetric particle has yet been observed. If SUSY were exact, if it existed in precisely the form described so far in this chapter, all sparticles would have masses that match their SM partners. They would appear everywhere in nature and would have been discovered hand-in-hand with the SM particles. Thus SUSY must be 'broken' in order to allow sparticles to have much higher masses such that they have eluded detection by lower-energy experiments. This SUSY breaking must be performed cautiously so that the quadratic divergence in the Higgs mass corrections is still cancelled. Otherwise the SM's hierarchy problem is simply replaced by a new SUSY one.

Writing down a complete SUSY Lagrangian amounts to following the same procedure as the SM, but with the new taxonomy of particles and their interactions. On top of that, however, the final piece of the MSSM Lagrangian comes in terms that introduce such a 'soft' breaking. Conserving R-parity and requiring gauge invariance yields the following additions in the most general case: [44]

$$\mathcal{L}_{soft}^{MSSM} = -\frac{1}{2} (M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{c.c.}) - (\tilde{\bar{u}} \mathbf{a}_u \tilde{Q} H_u - \tilde{\bar{d}} \mathbf{a}_d \tilde{Q} H_d - \tilde{\bar{e}} \mathbf{a}_e \tilde{L} H_d + \text{c.c.}) - \tilde{Q}^{\dagger} \mathbf{m}_{\mathbf{Q}}^2 \tilde{Q} - \tilde{L}^{\dagger} \mathbf{m}_{\mathbf{u}}^2 \tilde{\bar{u}}^{\dagger} - \tilde{\bar{d}} \mathbf{m}_{\mathbf{d}}^2 \tilde{\bar{d}}^{\dagger} - \tilde{\bar{e}} \mathbf{m}_{\mathbf{e}}^2 \tilde{\bar{e}}^{\dagger} - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_u H_d + \text{c.c.})$$

$$(4.3)$$

Here, bold characters represent 3×3 matrices across the families of fermions. In the first line, M_3 , M_2 , and M_1 are the gluino, wino, and bino mass terms. In the second line, $\mathbf{a_u}$, $\mathbf{a_d}$, and $\mathbf{a_e}$ are the scalar couplings.

All told, the MSSM adds a total of 105 new parameters (on top of the SM parameters) and there are many varying theories as to the precise mechanism of SUSY breaking. This thesis focuses on the search for SUSY from an experimental viewpoint, so it will not favor one specific SUSY model over another. Indeed the search will be designed to cast a large net—to be general to as many potential models as possible.

The experimental approach, with the goal of covering as much parameter space as possible, commonly uses the strategy of implementing *simplified models* in searches. The idea is to form a list of particles that appear in a specific observable signature. These particles are hypothesized to be at low mass, while the remaining sparticles are set at very high mass. The model may not be descriptive of reality, but it will shine light on a particular signature of interest.

Naturalness Revisited

The main motivation behind seeking a solution to the hierarchy problem, naturalness, can now be thought of as a rough judge of the effectiveness of a SUSY model. If a model avoids the fine-tuning of the SM Higgs mass only to fine-tune other parameters, it ought not to be considered effective. Naturalness is difficult to quantify and so is more of a guideline than a strict rule, but it governs the evolution of SUSY theory as results at the LHC continue to limit the parameter space available.

What requirements on SUSY parameters are unavoidable? The stop, which plays such a big role in canceling the primary contribution to the divergence Higgs mass correction from the top quark, must be light because the remaining correction is proportional to both the top and stop masses. The gluino couples strongly to the stop and so must also be light (about twice the stop mass) [51]. The higgsinos should not be much heavier than the Higgs, so the lightest neutralino $\tilde{\chi}_1^0$, which contains higgsino components from the mixing, will be light as well [45]. Beyond these criteria, SUSY models are free to tinker with parameters. This relative parameter freedom allows experimentalists to engage with a potential SUSY signature without committing to a specific SUSY breaking model.

4.4 SUSY and the LHC

SUSY could be detected indirectly because it adds terms to the calculation of loop corrections, so observing the branching ratios of decays from heavy particles could uncover deviation from the predicted SM values. The most convincing case for SUSY, however, would be direct detection. The LHC collides protons, and therefore quarks and gluons. This means that particles that couple most strongly to these quarks and gluons will have the greatest production in LHC collisions. The SUSY particles with the largest production cross-sections are squarks and gluinos.

Once the new SUSY particles have been (hypothetically) produced, they will tend to decay immediately thanks to the large mass gap between these particles and the LSP. For example, in the simplest of simplified models, the SUSY particle will decay to its SM partner and the LSP ($\tilde{g} \rightarrow g + \tilde{\chi}_1^0$). The colored particle (g) will hadronize and form a jet, while the LSP will pass right through the detector undetected because it is non-interacting. The LSP shows up as significant missing energy in the accounting of the collision. More complex models may introduce some intermediate SUSY particles, but their production will be small compared to the squark or gluino, thanks to the dependence of the cross-section on sparticle mass. Intermediate particles and their decays may favor signatures with more, softer, objects and without the high missing energy from the LSP.

Since the beginning of collisions at the LHC, the ATLAS experiment has conducted a comprehensive program of searches for SUSY [52–63]. To date, no significant excess above the predictions of the SM has been found. Each of these searches sets limits on the parameter space allowed for potential SUSY models. As the parameter space shrinks, the physically possible values of the squarks and gluinos are pushed to the fringes, and achieving naturalness becomes more and more difficult.

Figure 4.4 shows some example summaries of limits provided by SUSY searches at ATLAS. On the left is a simplified model of gluino pair production, in which the gluino decays promptly to four tops and two lightest neutralinos via two off-shell stops. Such gluinos are excluded up to 1900 GeV. The plot on the right combines stop searches from a number of different decay channels and assumed mass hierarchies and essentially excludes stops up to 850 GeV. The physical constraints on SUSY get tighter and tighter. This thesis presents a search that contributes to the limiting process.



(b)

Figure 4.4: Example summary limits on parameter space for (a) the Gtt simplified model of gluino production and (b) stop pair production from the ATLAS SUSY group [64].

4.5 Conclusions

SUSY presents an elegant extension to the SM, offering fixes to some important outstanding problems. The power of SUSY is undeniable; it addresses the hierarchy problem, potentially identifies dark matter, and perhaps even unifies disparate forces. Efforts to search for physics beyond the SM are well served to use SUSY as a conceptual guide. The analysis presented in this thesis will use simplified SUSY models to optimize the reach of the search as well as to analyze its results. But because it is a broken symmetry, SUSY still suffers limitations. Experimental results at the LHC are continually tightening those constraints.

The LHC and ATLAS

One moment it was a calculating machine, attempting dispassionately to keep up with the gouts of data. And then awash in those gouts, something metal twitched and a patter of valves sounded that had not been instructed by those numbers. A loop of data was self-generated by the analytical engine. The processor reflected on its creation in a hiss of high-pressure steam. One moment it was a calculating machine. The next, it thought.

-China Miéville, Perdido Street Station

A Toroidal LHC ApparatuS, or ATLAS, is one of four large-scale experiments in operation at the Large Hadron Collider (LHC), which is located at CERN (The European Organization for Nuclear Research) near Geneva, Switzerland. The following pages will introduce the LHC and its collision behavior, ATLAS and its detector makeup, and the process by which particles are reconstructed for later use in analysis.

5.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [66] is the largest and most powerful particle accelerator in the world. It occupies an underground ring 27 km in circumference spanning the border between France and Switzerland, running under the pastures and suburbs outside the city of Geneva at a depth between 175 m (near the Jura mountains) and 50 m (by Lake Geneva) [67]. The experiments located around the



Figure 5.1: An aerial view of Geneva and surroundings with the LHC ring superimposed. Courtesy of the ATLAS experiment [65].

ring along with the collider itself bring together 10,000 scientists and engineers from 113 countries, making the LHC perhaps the biggest large-scale collaborative scientific endeavor ever [67].

The ring occupied by the LHC once housed the Large Electron Positron (LEP) collider [68]. The excavation of the LEP tunnel was the largest civil engineering project in Europe's history until the excavation of the Channel Tunnel. The first beams circulated in 1989 and collisions ran for 11 years. LEP focussed on an in-depth study of electroweak interactions and proved, among many other things, that there exist exactly three generations of particles as outlined in chapter 2. Construction of the LHC began immediately upon the shutdown of LEP.

The purpose of the LHC, as an upgrade over LEP, is not only to produce higherenergy collisions at higher rates but to probe strong interactions as well, using pro-



Figure 5.2: Photo of the LHC tunnel and beam pipe. Courtesy of the ATLAS experiment [65].

tons.¹. Protons are extracted from hydrogen gas using a powerful electric field, then accelerated to 99.9999991% the speed of light via a chain of synchrotron accelerators, and finally injected into the LHC ring in the form of two beams circulating in opposing directions. The injection system is described in Figure 5.3. At various stages of the acceleration, protons are parsed into bunches by a process called radio-frequency (RF) acceleration. The protons traverse time-varied electric fields that accelerate the in-phase particles while decelerating the out-of-phase particles. The resultant beam is comprised of uniformly distributed bunches, and enters the LHC at a specific energy. In order to reach high energies, the beam first passes through the linear accelerator LINAC 2, followed by the Proton Synchrotron (SPS), all circular accelerators, before injection [69].

¹The LHC also accelerates and collides lead ions. Heavy ion collisions are of interest in the study of the early universe because the 'quark-gluon plasma' that results is a good imitation of the state of matter at the very incipient stage of the universe, before any hadronization occurred. These collisions are, however, unrelated to the scope of this thesis.



Figure 5.3: The injection system of the LHC and the placement of the four main LHC experiments around the ring [70].

The proton beams are guided through the beam pipe using superconducting electromagnets. Two types of magnets are required; one to maintain the beam's circulation energy and one to maintain the beam's focus. The former is provided by two sets of dipole magnets, one for each beam direction. The magnetic field deflecting the protons into the proper orbit comes from coils carrying current parallel to the beam pipe. The proton beam's extremely high energy requires a similarly extremely strong 8.33 Tesla magnetic field [71]. In order to achieve the current necessary to create such a strong field, the superconducting coils must be cooled to a temperature of 1.9 K using liquid helium. The second variety of magnets are quadrupoles placed along the straight sections of the ring to tighten the beam and prevent it from becoming diffuse. Additional focusing magnets are placed near each interaction point.

The LHC beam pipe is not a perfect circle, but rather is made up of eight curves and eight straight sections so that the proton beams may meet as close to head-on as possible [72]. Each straight piece could house a detector, but only four of the potential interaction points are occupied. ATLAS, the experiment used in this analysis, is located at Point 1 closest to the CERN facilities (See Figure 5.3). Continuing clockwise around the ring, ALICE (A Large Ion Collider Experiment), which focuses on studies of heavy ion collisions, is at Point 2. CMS, an all-purpose experiment like ATLAS, is at Point 5 and LHCb, which studies b-meson decays, is at Point 8.

The end properties of the colliding proton bunches differ between the two main periods of operation at the LHC. Run-1 began pp collisions at a center of mass energy of $\sqrt{s} = 7$ TeV from 2010-2011 and ended with $\sqrt{s} = 8$ TeV in 2012. Bunches were 5 ns long, contained ~ 10¹³ protons, and were spaced 50 ns apart [73]. Following Run-1, the LHC closed down for repairs and upgrades during the Long Shutdown 1 (LS1) from February 2013 to April 2015. In particular, the splice connections between the LHC dipole magnets were upgraded to permit beams with energy 6.5 TeV, nearing the design energy of 7 TeV [74]. The upgrade allows Run-2, from 2015-present, to collide $\sqrt{s} = 13$ TeV proton bunches spaced 25 ns apart [75].

Though the beams of protons are tightly compressed into bunches and meet at staggeringly high energy, the infinitesimal size of the proton means that crossing beams can simply pass through each other without any interaction. The rate at which events are produced, events being registered instances of proton-proton collision, is the collision's luminosity. Precisely, luminosity is the number of events per second per unit cross section, in cm²s⁻¹. Luminosity depends on the number of protons per bunch, the number of bunches per beam, the width and height of the beam, the revolution frequency, and the crossing angle at collision. The total number of events recorded in a certain period of time is given by the integrated luminosity $\int dtL$ and is typically given in units of inverse pico-barns, pb⁻¹ = 10³⁶ cm² [76].

Thus the total number of events with a certain signature is the product of the integrated luminosity and the cross section of that process. This means that processes with very small cross sections require very high integrated luminosity to register in the detectors. We need data, lots and lots of it. Figure 5.4 shows the cumulative



Figure 5.4: Cumulative luminosity versus day delivered to ATLAS during stable beams and for high energy p-p collisions [75].

integrated luminosity of the LHC pp collisions over time. The conditions of Run-2 have delivered much higher luminosity to the detectors, permitting them to probe new physics that was inaccessible in Run-1. The search presented in this thesis uses data from Run-2, up until August 2016, amounting to 18.2 ± 0.7 fm⁻¹ of $\sqrt{s} = 13$ TeV collisions.

High luminosity is crucial for producing the necessary bank of data needed for analysis of interesting processes at the LHC, but it comes with a downside. The higher the chance of a collision during a bunch crossing, the higher the chance there will be more than one interaction. The extra collisions contribute to *pileup*, which describes the chaotic condition of multiple interactions per crossing. Pileup is quantified by μ , the average number of collisions per bunch-crossing. As luminosity increases, so does μ , so that interesting events must be extracted from a background of other collisions. The pileup profiles for Run-2 to-date are presented in Figures 5.5 and 5.6. In analysis, steps must be taken to separate and discard pileup objects, e.g. to select only jets originating from the event and reject all jets originating in pileup.



Figure 5.5: The peak interactions per crossing, averaged over all colliding bunch pairs (a), and the peak luminosity per fill (b), in 2016 [75].



Figure 5.6: Mean number of interactions per crossing in 2015 and 2016, weighted by luminosity. [75].

5.2 The ATLAS Detector

The purpose of a particle detector is to produce a picture of the collision. The final outgoing particles are measured, their momentum and energy are determined, and they are used to reconstruct the event. By recombining the 4-momenta appropriately, the detector traces backward in time from the collision output, through the decay products, to the original particle of interest. For this detective work to even begin, the detector must accurately and precisely measure the particles emanating from the collision. Searches for new physics depend on the faithful representation of the output product.

In order to register an outgoing particle's trajectory, the detector measures its interaction with matter. Charged particles moving through matter will interact electromagnetically, leaving behind evidence of their passing that can be built into a record of their paths. As shown in Figure 5.7, different particles with different properties require different treatment in the detector. Electrons and photons have low (or zero) mass and interact easily with matter. By contrast, muons, which do not



Figure 5.7: A slice of the ATLAS detector demonstrating how outgoing particles from the collision interact with the various materials of the detector layers [65].

interact much, will survive passage through most matter, and neutrinos, which are virtually non-interacting, escape detection all together. Detection of muons must be treated as a special case, and neutrinos must be reconstructed by inferring their existence using conservation of momentum. To accommodate these various needs, particle detectors use a tiered system. First, the particles enter a tracking region, which traces the particles' paths from the collision deeper into the detector. Next, a series of calorimeters measures the energy and position of electrons, photons, taus, and hadrons. Finally, the passage of muons through the detector is tracked, and the muons are identified in the outermost region.

ATLAS [77] faces extraordinary challenges beyond those of a typical particle detector. The unprecedented center-of-mass energy of $\sqrt{s} = 13$ TeV at the LHC produces high particle multiplicity in all directions, so the detector must have fine granularity and comprehensive angular coverage. The tightly spaced 25 ns bunches create a rapid interaction rate of 40 MHz, requiring an advanced readout system to handle the massive influx of events. The new presence of pileup in collisions makes event reconstruction a challenge. Proximity of the detector to the LHC beam raises durability concerns from radiation.

Designed to meet this host of challenges, ATLAS looks like general purpose detectors of the past, but on a new scale (25 m tall and 44 m long). It is cylindrically symmetric about the beam pipe and consists of layers of subsystems; Figure 5.8 shows the tiered structure of the detector. Closest to the interaction point is the inner detector which primarily serves to reconstruct the trajectory of charged particles. It consists of the pixel detector, the semiconductor tracker (SCT), and the transition radiation tracker (TRT). A solenoid magnet surrounding the inner detector produces a 2 T axial magnetic field throughout, allowing precise measurement of particle momentum. Next are the electromagnetic and hadronic calorimeters (EMCAL, HCAL), which collect energy measurements of interacting objects. The calorimeters are made up of the liquid argon detectors (LAr) in the barrel and endcap and the plastic scintillator tiles (TileCal) in the barrel only. Outside this layer is another magnet system, this time toroidal, which provides a ~ 4 T magnetic field to bend particle trajectories. The final, farthest, tier is the muon system, for muon identification and momentum measurement, set among and beyond the toroidal magnets.

5.2.1 Coordinate definitions

The coordinate system used by ATLAS is right-handed, with the origin at the interaction point in the center of the detector. The beam pipe is the z-axis, pointing toward Geneva, the x-axis points to the center of the LHC ring, and the y-axis points up. Cylindrical coordinates are preferred in the transverse x-y plane; $r = \sqrt{x^2 + y^2}$ is the distance from the beam pipe, $\phi = \tan^{-1}(\frac{y}{x})$ is the azimuthal angle around it. The polar angle between an object and the beam is given by θ , which defines the pseudorapidity $\eta = -\ln[\tan(\frac{\theta}{2})]$ which is a more commonly-used quantity. 'Central' events have low η and 'forward' events have high η . The rapidity, in terms of



Figure 5.8: A schematic of the ATLAS detector, with people for scale [78].

momentum, is given $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$, which is equivalent to pseudorapidity in the zeromass limit. In this coordinate system the distance between two objects is defined $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$, which may look familiar from the earlier discussion of jet algorithms.

As discussed in chapter 3, though the momentum of the protons entering the collision is known, the precise momentum fraction of the constituent partons that actually do the colliding is not. This complicates any discussion of dynamics in the longitudinal direction. In general, quantities in the transverse plane, like the transverse momentum $\vec{p}_T = (p_x, p_y)$, are preferable because the total initial \vec{p}_T is zero. For example, the missing energy in collisions, an important quantity for any search for new particles, is most usefully given by E_T^{miss} which is defined as the negative vector sum $\Sigma \vec{p}_T$ over all recorded particles.

5.2.2 The Inner Detector

The inner detector of ATLAS, closest to the interaction point, provides the crucial link between the collision and the deposition of energy in the calorimeters. Its purpose is to reconstruct the trajectories taken by particles traversing the detector, known as their *tracks*. Tracks are very useful: Combined with knowledge of the magnetic field from the solenoid surrounding the inner detector, a particle's momentum can be measured precisely. Tracks also serve to identify the original hard-scatter vertex in an event, so that a clear distinction can be made between particles emanating from the vertex and particles emitted from displaced, softer, secondary vertices. To separate these tracks, the inner detector has very fine granularity, and the closer the detector layer is to the interaction point, the finer the granularity must be.

The structure of the inner detector is outlined in Figure 5.9. The innermost component is the pixel detector, followed by the SCT, and finally the TRT farthest from the beam crossing. Each detector has a cylindrical component centered on the beam pipe, the 'barrel', and two disk components perpendicular to the beam pipe at each end, the 'end-caps'. Prior to the start of Run-2 in 2015, an additional piece of the pixel detector was installed, called the Insertable B-Layer (IBL), to combat radiation damage from proximity to the beam and to provide additional granularity. All components of the inner detector must have some built-in redundancy so that they will be resilient to the inevitable loss of sensors due to prolonged exposure to radiation.

The pixel detector [80] stretches from ~ 50 to 150 mm from the interaction point and is made up of three barrel layers and two sets of three-layer end-cap disks. The layers are composed of 1,744 silicon sensors and each sensor has 46,080 readout channels, resulting in a total of approximately 80 million pixels of size 50 × 400 μ m or 50 × 600 μ m. The IBL [81] sits even closer to the beam, at r = 26 mm, and adds 286 sensors containing a total of 13 million pixels with even finer segmentation 50 ×



(b)

Figure 5.9: The structure of the ATLAS inner detector showing its component sensors. Figure (b) is missing the IBL, which was installed between Run-1 and Run-2 [79].

250 μ m. As a charged particle travels through the detector, it registers a hit in each layer. These position measurements, in the context of the solenoidal magnetic field, begin the process of building a particle track.

What constitutes a 'hit'? Each sensor is made of superconducting silicon, and when an energetic charged particle passes through, it pulls or pushes electrons, ionizing the atoms and producing electron-hole² pairs in the silicon. The more energetic the particle, the more charge is displaced. A bias voltage applied across the ends of the sensor induces an electric field that pulls the electrons and holes to the sensor's surface where the charge separation is amplified and recorded. In practice, a particle moving through the pixel detector will not register a hit in only one single pixel–rather it affects a group of adjacent pixels called a cluster. The magnitude of the signal in the various members of the cluster provides the position information necessary. In this way the charged particle's position can be measured with a precision of ~ 10 μ m in the transverse plane within the detector's range of $|\eta| < 2.5$.

The semiconductor tracker (SCT) [82], located just beyond the pixel detector between 275 and 560 mm from the interaction point, is comprised of four barrel layers and nine end-cap layers per side. The end-caps are staggered so that the SCT can maintain the coverage within $|\eta| < 2.5$ while ensuring particles pass through four layers. The SCT, like the pixel detector, also uses superconducting silicon sensors, and develops tracks in the same way. It has 4088 sensor modules organized into strips parallel to the beam in the barrel and radially outward in the end-caps. The barrel strips are uniform rectangles 80 μ m wide, ~ 12 cm long, and 285 μ m thick and the end-cap strips are trapezoids of similar dimensions. A second set of sensors is then stacked on top, but rotated by the small stereo-angle of 40 mrad. This allows measurements to a precision of 580 μ m in z for barrel and r for the endcap. All told, there are ~ 6.2 million channels in the SCT, providing particle position measurements

 $^{^{2}\}mathrm{A}$ hole is a region of negative charge in the silicon lattice due to the electron's removal.

in the *r*-phi plane precise up to 16 μ m.

The Transition Radiation Tracker (TRT) [83], furthest from the interaction point at $r \approx 550$ to 1080 mm, differs from the other components of the inner detector. It is made up of straw detectors-metal tubes 4 mm in diameter filled with xenon gas. A thin anode wire runs through the straw's center. The barrel has 52,544 straws of length 144 cm and the end-caps each have 122,880 straws of length 37 cm. This amounts to 420,000 readout channels. When a particle traverses the detector, it frees electrons in the gas which travel to the central wire, liberating more electrons in a cascade. The resultant electrons and positive ions travel to the anode and cathode ends respectively, where the time of their arrival is recorded. The drift time can be used to calculate an impact parameter for the charged particle, but not its precise position as before-the resolution is only 170 μ m.

In addition, polypropylene sheets between the straws mean that the dielectric constant varies. As a relativistic charged particle passes between materials of differing dielectric constant, it emits transition radiation, prompting the xenon gas to cascade higher-energy electrons. This process provides a tool for electron identification because the highly relativistic particles that are capable of producing this radiation are mainly electrons.

5.2.3 Calorimeters

The ATLAS calorimeters, located outside the inner detector and solenoid, are capable of measurement in a much wider, almost hermetic, cylinder about the interaction point-they cover a region in pseudorapidity up to $|\eta| < 4.9$ [77]. Rather than registering and recording a particle's passage through material, calorimeters force particles to deposit their energy into induced particle showers. Their purpose is to record the position and four-momentum of all electrons, photons, taus, and hadrons, while impeding passage so that only muons and neutrinos reach the muon spectrometer.



Figure 5.10: The composition and layout of the calorimeters in the ATLAS detector [84].

Calorimeters are crucial to any hadronic study because, in contrast to tracking detectors, they can measure neutral particles.

The complete ATLAS calorimeter system, shown in Figure 5.10, is divided up into the electromagnetic calorimeter (EMCal): the LAr electromagnetic barrel and the LAr electromagnetic end-cap (EMEC), and the hadronic calorimeter (HCal): the tile barrel, the extended barrel, the LAr hadronic end-cap (HEC), and the LAr forward calorimeter (FCal). All of these calorimeters can measure not only a particle's position, but the position and evolution of the shower particles resulting from its passage.

The calorimeters are designed to be sampling detectors, meaning that they alternate between material that passively absorbs the energy of the incoming particle and material that actively produces signals. The absorbent material should be dense to force interactions with the incoming particles, impeding their passage. As an added
benefit, the resultant cascade of subsidiary lower-energy particles is easier to measure. The layers of active material record the energy deposited by that cascade. As an energetic particle passes through the calorimeter its progress is repeatedly slowed and measured, until the particle and the shower carrying its momentum are stopped. Energy is lost with each repetition, so the calorimeter must be calibrated to correct the energy measured in the active layers to match that of the incoming particle. Calibration will always come at the cost of energy resolution, however, due to variations between the evolution of different showers.

The EMCal [77, 85] is again made up of a barrel and two end-caps. The barrel, located between 2.8 and 4 m from the beam, covers the region $|\eta| < 1.475$ while the end-caps, located between 33 and 210 cm from the beam, cover the region 1.375 < $|\eta| < 3.2$. The absorbing layers are made of lead and the active layers are made of liquid argon, with readout electrodes located halfway between the lead layers. Particles traveling through the liquid argon liberate electrons, creating positive ions. A strong voltage applied across the detector causes the free electrons to drift to one side, where the signal can be measured. The layers are arranged in like the bellows of an accordion (Fig. 5.11), end-to-end-to-end and so on, to ensure complete coverage in ϕ while minimizing the drift time between the particle interaction and its measurement. The position measurements of the LAr detectors are governed by readouts that come in the form of approximately square cells, or 'towers', in $\eta \times \phi$ space [86].

Beyond the EMCal is the HCal [77], which has both LAr and tile calorimeter components [88]. The tile barrel and extended barrel, spanning the $|\eta| < 1.7$ region, use iron plates as absorbing layers and plastic scintillator tiles as active layers. These detectors are composed of 64 module wedges stacked the length of the barrel, each with a size of $\Delta \phi \approx 0.1$. Though they use different materials, tile detectors function based on the same principles as the LAr detectors: Incoming particles interact with



Figure 5.11: The 'accordion' structure of the LAr electromagnetic barrel. Courtesy of the ATLAS experiment [65].



Figure 5.12: Schematic showing the structure and optical readout system of a wedge in the tile calorimeter [87].

the iron, losing energy and creating a shower of new particles. These new particles meet the scintillator where they excite the material, emitting light. The light is carried through fibers to photomultiplier tubes and read out as a signal containing position and momentum information (see Fig. 5.12) [87]. The HEC, covering $1.5 < |\eta| < 3.2$ and the FCal, covering $3.1 < |\eta| < 4.9$, are LAr calorimeters, but use copper plates instead of lead as absorbing material.

5.2.4 Muon System

The Muon Spectrometer (MS) is the furthest detector component of ATLAS from the interaction point. It covers the range $|\eta| < 2.7$ with a small gap around |eta| = 0for the cabling and cooling systems headed to the calorimeters. The purpose of the MS is to reconstruct the charged particles that make it all the way through the calorimeters which means that, in contrast to the other detector systems, it essentially only measures muons. Figure 5.13 shows the various components of the ATLAS muon system.

The largest component of the MS comes in the form of monitored drift tubes (MDTs). The 1088 MDTs in ATLAS operate in a similar fashion to the straws of the TRT, but on a bigger scale. The aluminum tubes, filled with a mixture of Argon gas and CO₂, are 30 mm in diameter and between 0.7 and 6.3 m in length. The toroidal magnets provide a strong field which bend the muons as they traverse the detector. The MDTs are arranged parallel to the magnetic field to maximize their coverage of the muon curvature. The result is a resolution of 35 μ m in the z direction [77].

More forward in the detector, but not yet at the end-cap, particle density increases to beyond the capabilities of the MDTs, which begin to be too sparse. Cathode Strip Chambers (CSCs), which have a faster response rate, are added in that region $(2.0 < |\eta| < 2.7)$ to supplement the MDTs. The 32 CSCs are multi-wire proportional chambers made up of two parallel metal sheets, divided up into cathode strips, with



Figure 5.13: Diagram of the ATLAS muon system, in the context of the whole detector [89].

anode wiring connecting them. Each chamber is filled, again, with Ar/CO_2 , and contains four parallel planes of wires, meaning four different position measurements for a particle traversing the chamber. The end resolution is 40 μ m in the r and 5 mm in ϕ [77].

The remaining subsystems of the MS, the Resistive-plate Chambers (RPCs) and the Thin-gap Chambers (TGCs), are used for triggering because of their rapid response time. *Triggering*, which will be discussed in the next section, refers to the selection of 'interesting' events from the sea of events containing no useful information. RPCs, in the barrel region, are parallel plates 2 mm apart that record hits using ionizing gas. They have a very course spatial resolution of 10 mm, but a much faster time resolution of 1 ns (drift times in the MDTs can near 500 ns). TGCs are to RPCs what CSCs are to MDTs; they have finer granularity for use in the more forward regions where particle multiplicity is high. TGCs are also multi-wire proportional chambers, have a response speed suitable for a trigger system, and can measure particles to within about 5 mm [77].

Though the MS is fully capable of measuring muons on its own, it is typically used in conjunction with the tracking results from the other ATLAS detectors. The magnetic field from the toroidal magnets bends muons in a direction perpendicular to the solenoid surrounding the inner detector, so the two measurements are essentially independent. Matching tracks from the inner detector to tracks from the MS improves the precision of muon selection.

5.3 Triggers

With the 25 ns bunch spacing of Run-2, collisions now occur at the LHC at a rate of 40 MHz, or 40 million times per second [77]. Multiplying that by the massive amount of information contained in each event (on the order of a megabyte) yields a potential output from the ATLAS detector far exceeding even the vast data storage available to the experiment. The solution is to implement a trigger system to decide when to store an event for further investigation and analysis, and when to discard it.

The ATLAS trigger system is tiered so that different studies and analyses can select the appropriate trigger menu. Level 1 (L1), the first trigger stage and the only trigger entirely implemented in hardware, looks for 'regions of interest' in the calorimeters and the MS. L1 already reduces the event rate to ~ 100 kHz and feeds the remaining events to the high level trigger (HLT). The HLT conducts a software-based reconstruction of the entire output of the detector, further cutting the rate to ~ 1 kHz [90].

The analysis presented in this thesis will use a multi-jet trigger, so I will briefly outline it here. At the L1 stage, jets are triggered on towers in the calorimeters. The signals in adjacent calorimeter cells are combined to form coarse-grained 0.1 × 0.1 towers in $\Delta \eta \times \Delta \phi$ space. A sliding window algorithm runs over these trigger towers, identifying regions of significant E_T . Then, the HLT stage constructs topological clusters from the complete output of the calorimeters. Low-energy jets are removed and pileup is subtracted. In the end, the multijet trigger requires six jets above $p_T = 45$ GeV. It is 90% efficient for a sixth jet with $p_T = 50$ GeV [90].

5.4 Data Quality

ATLAS is a massively complex experiment operating sealed underground, bombarded by high radiation. Pauses and gaps in the accumulation of usable data, planned and unplanned, are unavoidable and must be managed. Figure 5.14 shows the cumulative luminosity over time through 2015 and 2016. In total, of the 4.2 fb⁻¹ delivered in 2015 by the LHC, only 3.9 fb⁻¹ (93%) was recorded and only 3.2 fb⁻¹ (76%) was certified as 'good' for use in physics analysis. The data acquisition efficiency to date in 2016 is similarly 93% but the overall efficiency will be higher³ [75].

Some of the inefficiencies are built in: ATLAS misses recording data during the 'warm start' period, when the silicon detectors engage their high voltage power supplies, because they must wait to do so until a stable beam has been achieved by the LHC. Some inefficiency comes from recorded data being unusable, whether due to some non-operational subsystems (the IBL was turned off for two runs in 2015) or a large fraction of noisy channels. Minor inefficiencies from, e.g. channels in the inner detector disabled due to radiation, can be offset by strict object quality requirements. All told, ATLAS is an impressively efficient machine given the number of moving parts.

 $^{^{3}}$ The overall 2016 efficiency is not yet presented because detectors can often recover 'bad' data by administering corrections and reconstructing events offline.



Figure 5.14: The cumulative luminosity versus time delivered to ATLAS (green), recorded by ATLAS (yellow), and deemed good quality data (blue) in (a) 2015 and (b) 2016 (ongoing) [75].

5.5 Simulation

Accurate simulation of ATLAS events is not only a crucial step to demonstrating understanding of the processes underlying the collisions the detector measures, but also an important tool for studies seeking a benchmark for observations in data. Whether it is for calibrating a detector, measuring a Standard Model quantity, or searching for new physics, an ATLAS analysis will compare Monte Carlo (MC) simulations against the observed data.

The goal of a MC simulation is to generate reproduced events starting from the collision output partons and ending with the final state particles which would be received by the detector. This process begins with a calculation of the collision matrixelement (see section 3.1), with corrections, resulting in a set of outgoing partons. Because of the probabilistic nature of parton-parton interactions in pp collisions, the outputs can be simulated repeatedly to achieve a distribution matching that observed in real collisions. Next, often using a new simulation program, the matrix element generators are interfaced [91] with the parton decays, showering, and hadronization, which are modeled so that the end product of the MC program looks just like the input particles hitting the detector. Data from the detector and MC simulation form a symbiotic relationship: Data provides the template for evaluating the accuracy of MC. MC can then help calibrate later data readouts, or identify variations in data from the expected program.

A large library of MC models allows analyses to pick and choose from programs that best simulate data for each study's various important topologies. For example, POWHEG [92] tends to be used for simulating $t\bar{t}$ events. It is interfaced with a parton shower and hadronization model; either PYTHIA [93, 94], which orders input partons by p_T , or HERWIG [95], which uses an angular ordering scheme. Alpgen [96] is used for V+jet events, along with Sherpa [97], which is also used to reproduce diboson and multijet topologies. Madgraph [98] is used for multijet and γ +jet processes. The outputs from these event generators are lists of particle 4-momenta. These outputs are 'truth level' because they are not altered by the features and constraints of the ATLAS detector.

In order to match simulation to data, the MC output must be exported to a program that models the effect of the detector. GEANT4 [99] processes the truth level input in the context of a full simulation of ATLAS and its subsystems, including any limits in coverage, resolution, or the read-out system [100]. Multiple events are stacked to imitate the pileup distribution in data. In the end, the detector-level simulation output has undergone the exact same reconstruction process as real recorded data, and is identical in format. Offline studies can then treat simulation and data the same way.

5.6 Conclusion

Any effort to probe the physical processes such as those described in Chapter 2, 3, and 4 faces a daunting task and the ATLAS detector, a globally collaborative effort, has

risen to the challenge. ATLAS is a massively complex endeavor, with its multitude of subsystems, and the experiment itself is a feat of physics and engineering. The success of ATLAS lies in the studies it advances, be they measurements of known quantities or searches for new physics. The analysis presented here would be impossible without the support, infrastructure, and personnel of ATLAS.

Searching for SUSY in Multijet Events

He wanted to achieve something of surpassing beauty that would last. A creation that would mean that he...had been born, and lived a life, and had come to understand a portion of the nature of the world, of what ran through and beneath the deeds of women and men in their souls and in the beauty and the pain of their short living beneath the sun.

-Guy Gavriel Kay, Sailing to Sarantium

New physics at the TeV energy scale could emerge from collisions through a variety of processes. Theoretical models and predictions help build an informed judgment of the likelihood that a given search will yield fruit, so that experimental studies can focus their efforts where they will have the biggest impact. The ATLAS experiment divides up the potential new physics scenarios for maximum coverage. The value of each individual search depends upon its context within the whole, and the existence of the whole depends upon the thoroughness of each individual search.

As outlined in chapter 4, supersymmetry provides a structure for model creation. SUSY solves the hierarchy problem, offers a particle candidate for dark matter, and potentially hints at deeper unification of forces. If SUSY hopes to avoid the problems with fine-tuned mass parameters that plague the SM, the existence of new TeV-scale particles is very important. At minimum, naturalness suggests a light stop \tilde{t} , a light gluino \tilde{g} , and a light chargino $\tilde{\chi}_1^0$. SUSY searches seek out events with conditions amenable to the existence of one of these new particles. This chapter presents a search for new strongly interacting particles in final states with very high jet multiplicity and some missing energy, where the distribution of the jets is consistent with decays from heavy objects such that the jets can be reclustered into fewer high-mass jets. In the context of SUSY, this signature could come from pair-produced squarks or gluinos. These new strong particles then produce a decay to a heavy SM particle such as a top quark or a W, Z, or Higgs boson, or simply their own cascade decay chains, and either the cascade or the heavy SM particle decay will produce a large number of jets. The following sections will build up the models tested in this analysis, identify what the signature should look like in data, establish the SM background, and, finally, will evaluate the existence of new phenomena.

The data, amounting to a total integrated luminosity of 18.2 ± 0.7 fb⁻¹, was collected from April 2015 through 2016 from *pp* collisions with a center-of-mass energy of $\sqrt{s} = 13$ TeV.

6.1 Motivation

The larger ATLAS search for evidence of SUSY in collisions at the LHC has been ongoing since the beginning of 2010, when the proton beams first crossed at centerof-mass energy $\sqrt{s} = 7$ TeV. Run-1 saw many different SUSY searches implemented, covering a wide swath of potential values for SUSY parameters, but no deviations from the expected SM production was discovered. Instead, each search set limits on the possible values of the basic parameters, such as gluino mass. Every subsequent search that yields no new physics adds to the breadth of coverage of those limits in parameter space.

After the long shutdown (LS1), Run-2 began collisions at $\sqrt{s} = 13$ TeV in 2015, entering a new energy frontier. Higher energy corresponds to much higher heavy particle cross-sections, opening up a whole new region in SUSY parameter space. This meant that the strategy of the first studies was to aim for the lowest-hanging fruit; searches in events where the heavy particles decay to well-understood final states, using tried and tested techniques. The initial Run-2 analyses still found no SUSY, and set even tighter limits on the SUSY models viable in reality. Figure 6.1 shows the cumulative mass limits set by ATLAS at this stage.

The next cohort of searches, then, must target regions of parameter space untouched by the more typical analyses. With that in mind, this generation of searches can (1), take the time to optimize old analysis techniques, (2), use new or unorthodox techniques, or (3), investigate rare events that require very high integrated luminosity or are very clean channels. The study presented here, though it is still an early result, takes a combination of the second and third approaches. In contrast to many other searches for SUSY in hadronic channels at both ATLAS [52–62] and CMS [101–108], this search does not expect a large missing energy because of the high jet multiplicity requirement. Traditional hadronic searches need high missing energy to use as a trigger or to reject SM backgrounds, so they are insensitive to potentially interesting final states in which E_T^{miss} is low. Events with so many jets are rare, but the signal channel is comparatively clear and is uniquely sensitive to some SUSY processes.

This analysis represents the latest in a series of ATLAS analyses targeting a multijet+missing energy. The methods are inspired by Ref. [109], the first multijet analysis conducted in the lower energy conditions of Run-1, and Ref. [110], which added the selection based on large-radius jets. The first multijet study at $\sqrt{s} = 13$ TeV is Ref. [63], which solely presents the results of the b-tagged jet stream¹. In comparison to these previous analyses, the higher statistics now available from continued collisions provide better sensitivity, especially to particles with large mass. The selection on the sum of masses of large-radius reclustered jets (described in Section 6.6) im-

¹B-tagging means identifying and labeling jets from bottom quarks because they have different properties from other jets. This tag is useful for organizing selection criteria, for example.

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direct production \mathfrak{Z}^m gen. squarks	$ \begin{split} \tilde{b}_{1}(\tilde{t}_{1}, \tilde{b}_{1} \rightarrow b\tilde{t}_{1}^{0}) \\ \tilde{b}_{1}(\tilde{b}_{1}, \tilde{b}_{1} \rightarrow t\tilde{t}_{1}^{0}) \\ \tilde{b}_{1}(\tilde{b}_{1}, \tilde{b}_{1} \rightarrow t\tilde{t}_{1}^{0}) \\ \tilde{b}_{1}(\tilde{t}_{1}, \tilde{t}_{1} \rightarrow b\tilde{t}_{1}^{0}) \\ \tilde{t}_{1}(\tilde{t}_{1}, \tilde{t}_{1} \rightarrow b\tilde{t}_{1}^{0}) \\ \tilde{t}_{1}(\tilde{t}_{1}, \tilde{t}_{1} \rightarrow b\tilde{t}_{1}^{0}) \\ \tilde{t}_{1}(\tilde{t}_{1}, \tilde{t}_{2} \rightarrow \tilde{t} + Z) \\ \tilde{t}_{2}(\tilde{t}_{2}, \tilde{t}_{2} \rightarrow \tilde{t}_{1} + Z) \\ \tilde{t}_{2}(\tilde{t}_{2}, \tilde{t}_{2} \rightarrow \tilde{t}_{1} + K) \end{split} $	0 2 e, μ (SS) 1-2 e, μ 0 0-2 e, μ 0 2 e, μ (Z) 3 e, μ (Z) 1 e, μ (d)	2 b 0-3 b 1-2 b 1-2 b iotro-2 iotro-2 iotro-1 1 b 1 b 1 b 6 jets + 2 b	Yes Yes Yes 4. b Yes ag Yes Yes Yes	3.2 3.2 3.2 20.3 20.3 20.3 20.3 20.3 20.	Bi 325-540 GeV 840 GeV bi 7/17-170 GeV 325-540 GeV 840 GeV 3 7/17-170 GeV 200-500 GeV 79 3 7 90-198 GeV 200-500 GeV 79 3 7 90-198 GeV 200-510 GeV 79 3 7 90-245 GeV 205-715 GeV 79 3 7 90-198 GeV 205-715 GeV 79 3 7 90-198 GeV 205-715 GeV 79 3 7 90-198 GeV 205-715 GeV 79 3 7 90-245 GeV 205-715 GeV 79 3 7 90-245 GeV 150-600 GeV 79 7 7 90-245 GeV 320-610 GeV 70	5-785 GeV	m(r ²),>=100GeV m(r ²),==50GeV,m(r ²),=m(r ²),+=100GeV m(r ²),==2m(r),m(r ²),=55GeV m(r),==16eV m(r),==160eV m(r),==10GeV m(r),==20GeV m(r),==20GeV	ATLAS-CONF-2015-066 1602.09058 1209.2102, 407.0883 300516, ATLAS-CONF-2016-007 1403.5222 1403.5222 1506.08616 1506.08616
EW direct	$\begin{array}{c} \widetilde{A}_{1,k}\widetilde{A}_{1,k}\cdot\widetilde{L}^{-b}\widetilde{R}_{1}^{0}\\ \widetilde{X}_{1,k}^{+}\widetilde{X}_{1,k}\cdot\widetilde{L}^{+-b}_{1}(\mathbf{r})\\ \widetilde{X}_{1,k}^{+}\widetilde{A}_{1,k}\cdot\widetilde{L}^{+-b}_{1}(\mathbf{r})\\ \widetilde{X}_{1,k}^{+}\widetilde{A}_{1,k}\cdot\widetilde{L}^{-b}_{1}(\mathbf{r}), \widetilde{E}\widetilde{A}_{1}\cdot\widetilde{L}(\mathbf{r})\\ \widetilde{X}_{1,k}^{+}\widetilde{A}_{2,k}-W^{+}_{1}\widetilde{Y}_{1}^{-c}_{1}(\mathbf{r})\\ \widetilde{X}_{2,k}^{+}\widetilde{A}_{2,k}-W^{+}_{1}\widetilde{X}_{1}^{-c}_{1}(\mathbf{r})\\ \widetilde{X}_{2,k}^{+}\widetilde{X}_{2,k}^{b}\widetilde{R}_{1}\widetilde{R}_{1}, \widetilde{M}_{2}, \widetilde{M}_{2}-\widetilde{M}_{2}\widetilde{R}_{1}, \widetilde{M}_{2}, \widetilde{M}_{2}-\widetilde{M}_{2}\widetilde{R}_{2}, \widetilde{M}_{2}-\widetilde{M}_{2}, \widetilde{M}_{2}, \widetilde{M}_{2}, \widetilde{M}_{2}-\widetilde{M}_{2}, \widetilde{M}_{2}, \widetilde{M}_{$	2 ε,μ 2 ε,μ 2 τ 3 ε,μ 2 -3 ε,μ 2 -3 ε,μ 7 γ ε,μ - γ 1 ε,μ + γ	0 0 - 0-2 jets 0-2 b	Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	Z 90-335 GeV 140-475 GeV 140-475 GeV X 355 GeV 715 GeV X 140-475 GeV 635 GeV X 115-370 GeV 635 GeV	μ(<u>γ</u> ²),μ	$\begin{split} m(\tilde{r}_{1}^{0})=0 \ \text{GeV} \\ m(\tilde{r}_{1}^{0})=0 \ \text{GeV} (m(\tilde{r}_{1}^{0})+m(\tilde{r}_{1}^{0})) \\ m(\tilde{r}_{1}^{0})=0 \ \text{GeV} (m(\tilde{r}_{1}^{0})+m(\tilde{r}_{1}^{0})) \\ m(\tilde{r}_{1}^{0})=0 \ \text{GeV} (m(\tilde{r}_{2})+m(\tilde{r}_{1}^{0})) \\ m(\tilde{r}_{1}^{0})=m(\tilde{r}_{2}^{0}), \ m(\tilde{r}_{1}^{0})=0 \ \text{septons decoupled} \\ m(\tilde{r}_{1}^{0})=m(\tilde{r}_{2}^{0}), \ m(\tilde{r}_{1}^{0})=0, \ \text{septons decoupled} \\ m(\tilde{r}_{1}^{0})=m(\tilde{r}_{1}^{0}), \ m(\tilde{r}_{1}^{0})=0, \ \text{m}(\tilde{r}, \tilde{r})=0 \ \text{septons decoupled} \\ m(\tilde{r}_{1}^{0})=m(\tilde{r}_{2}^{0}), \ m(\tilde{r}_{1}^{0})=0, \ m(\tilde{r}, \tilde{r})=0 \ \text{septons decoupled} \end{split}$	1403.5294 1403.5294 1407.0350 1402.5294,1402.7029 1501.07110 1501.0710 1405.5086 1507.05493
sələitisq Long-lived	$\begin{split} \text{Direct} \vec{\chi}_{1}^{T} \vec{p}(\mathbf{d}, \text{long-lived} \vec{\chi}_{1}^{T} \\ \text{Direct} \vec{\chi}_{1}^{T} \vec{p}(\mathbf{d}, \text{long-lived} \vec{\chi}_{1}^{T} \\ \text{Stable, stopped } \vec{p} + \text{hadron} \\ \text{Metastable } \vec{q} + \text{hadron} \\ \text{Mass stable } \vec{r}, \vec{\chi}_{1}^{0} - \vec{\tau}(\vec{e}, \vec{p}) + \tau(\mathbf{c}, \vec{q}) \\ \text{Stable} \vec{r}, \vec{\chi}_{1}^{0} - \vec{\tau}(\vec{e}, \vec{p}) + \tau(\mathbf{c}, \vec{q}) \\ \text{GMSB, } \vec{x}_{1}^{1} - \vec{y}(\vec{c}, \vec{q}) + \tau(\mathbf{c}, \vec{q}) \\ \text{GMSB, } \vec{x}_{1}^{1} - \vec{y}(\vec{c}, \vec{q}) + \tau(\mathbf{c}, \vec{q}) \\ \text{GMSB, } \vec{y}_{1}^{1} - \vec{y}(\vec{c}, \vec{q}) \\ \text{Mass and } \vec{q} \\ \vec$	Disapp. trk dE/dx trk dE/dx trk μ 1-2 μ 2 γ displ. <i>ee/eµ/µ</i> displ. vtx + jets	1 jet 1-5 jets α	Yes Yes Yes ' ' ' Yes ' '	20.3 18.4 3.2 19.1 20.3 20.3 20.3 20.3	X X 270 GeV 495 GeV 850 GeV <td>/ 1.54 TeV 0 TeV 0 TeV</td> <td>m(ເຊົ້າ)-m(ເຊົ້າ)-160 MeV, rt(ເຊັ້າ)=0.2 ns m(ເຊົ້າ)-m(ເຊົ້າ)-160 MeV, rt(ເຊັ້າ) m(ເຊົ້າ)-160 MeV, rt(ເຊັ້າ) m(ເຊົ້າ)=100 GeV, r>100 GeV, r>100 GeV, r>100 GeV, r>100 ctangl to ctangl to ctangl </td> <td>1310.3875 1506.05532 1306.0554 70 uppeur 1411.6795 1409.5542 1409.5542 1504.05162 1504.05162</td>	/ 1.54 TeV 0 TeV 0 TeV	m(ເຊົ້າ)-m(ເຊົ້າ)-160 MeV, rt(ເຊັ້າ)=0.2 ns m(ເຊົ້າ)-m(ເຊົ້າ)-160 MeV, rt(ເຊັ້າ) m(ເຊົ້າ)-160 MeV, rt(ເຊັ້າ) m(ເຊົ້າ)=100 GeV, r>100 GeV, r>100 GeV, r>100 GeV, r>100 ctangl to ctangl to ctangl 	1310.3875 1506.05532 1306.0554 70 uppeur 1411.6795 1409.5542 1409.5542 1504.05162 1504.05162
Лан	$\begin{array}{l} \label{eq:linear_relation} LFV \ pp \rightarrow \widetilde{p}_{i} + X_{i} \ \widetilde{p}_{i} \rightarrow q \mu_{i} e_{i}/\mu r\\ \mathtt{Bilinear} \ RPV \ DSSM \\ \widetilde{\chi}_{i}^{\dagger} \widetilde{\chi}_{i}^{-1} \widetilde{\chi}_{i}^{\dagger} \rightarrow W_{i}^{0} \widetilde{\chi}_{i}^{0} \rightarrow eep_{\mu_{i}} ep_{\mu_{i}} \\ \widetilde{\chi}_{i}^{\dagger} \widetilde{\chi}_{i}^{-1} \widetilde{\chi}_{i}^{\dagger} \rightarrow W_{i}^{0} \widetilde{\chi}_{i}^{0} \rightarrow eep_{\mu_{i}} ep_{\mu_{i}} \\ \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} + W_{i} \widetilde{\mathfrak{g}}_{i} \rightarrow eep_{\mu_{i}} \\ \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_{i} \rightarrow \mathfrak{g} q \\ \widetilde{\mathfrak{g}}_{i} \widetilde{\mathfrak{g}}_$	$e_{\mu,e\tau,\mu\tau} \\ 2 e_{\mu} (SS) \\ 4 e_{\mu} \\ 3 e_{\mu} + \tau \\ 3 e_{\mu} + \tau \\ 0 \\ 0 \\ 2 e_{\mu} (SS) \\ 2 e_{\mu} \end{cases}$	- 0-3 b 6-7 jets 6-7 jets 6-7 jets 0-3 b 0-3 b 2 jets + 2 b	Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	Pr 760 GeV 8 $\overline{q}, \overline{g}$ 760 GeV 8 \overline{X}_1^+ 450 GeV 917 GeV 8 \overline{g} 930 GeV 980 GeV 8 \overline{g} 320 GeV 980 GeV	1.7TeV 1.45 TeV 1.45 TeV 6 eV V 0 TeV	$\begin{array}{l} \mathcal{X}_{11} = 0.11, \mathcal{A}_{1231/33} = 0.07 \\ \mathfrak{m}_{21} = \mathfrak{m}_{22} : cr_{12} : r < 1 \ \mathrm{mm} \\ \mathfrak{m}_{21} = 0.95 \ \mathrm{m}_{21} : r_{12} : r_{12} : r_{12} : r_{12} = 0 \\ \mathfrak{m}_{11} = 0.95 \ \mathrm{m}_{21} : r_{12} : r_{12} : r_{12} = 0 \\ \mathfrak{m}_{21} : r_{12} : r_$	1503.04430 1404.2500 1405.5508 1405.5086 1405.5086 1502.05686 1502.05686 1404.250 1601.07453 ATLAS-CONF-2015.015
Other *Onl stai	Scalar charm, č→c ⁰ y a selection of the available tes or phenomena is shown	o e mass limit	2 c S on new	Yes	20.3	3 7 510 GeV	- - -	m(t ⁰)<200GeV Mass scale [TeV]	1501.01325



proves sensitivity to heavy objects as well. The results of this update were published in an ATLAS conference note and presented at the SEARCH conference in August 2016 [111].

6.2 Signal models

Signal models are necessary both at the start of an analysis, to optimize the search for discovery, and at the end, to provide context and interpret the results. Early searches in Run-2, like this one, focus on discovery, so only a couple of optimal signal models are chosen for each analysis. Later studies aiming to set limits can afford to consider a wide range of models. Two classes of SUSY signal models are considered here. The first comes from the Run-1 multijet analysis [110], which was the most sensitive one for the '2-step' model, but was uncompetitive in others, so the 2-step is carried over to the current analysis and the others are not. The 2-step grid² involves the decay of the gluino in two steps; through a chargino, a heavier neutralino, and finally to the LSP. The second model, discussed in detail here, is a slice of the 'pMSSM' chosen based on the results of a scan of the parameter space.

6.2.1 2-step

The 2-step grid is a simplified model in which gluinos are pair-produced, then decay via a cascade:

²The term 'signal grid' refers to the practice of producing an array of potential values for one parameter of the model and matching it against an array for another parameter to create a search grid. Pairs of parameter values are signal 'points' on the grid. Each point on the grid is a model.



Figure 6.2: Feynman diagram of the 2-step decay process.

$$\tilde{g} \rightarrow q + \tilde{q}' + \tilde{\chi}_1^{\pm}$$
 $(q = u, d, s, c)$
 $\tilde{\chi}_1^{\pm} \rightarrow W^{\pm} + \tilde{\chi}_2^0$
 $\tilde{\chi}_2^0 \rightarrow Z + \tilde{\chi}_1^0$

The parameters of this process are the masses of the gluino, $m_{\tilde{g}}$, and the lightest neutralino, $m_{\tilde{\chi}_1^0}$. These lower masses constrain the masses of the intermediate particles, with $m_{\tilde{\chi}_1^\pm} = \frac{1}{2}(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$ and $m_{\tilde{\chi}_2^0} = \frac{1}{2}(m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})$. Figure 6.2 shows the Feynman diagram of this model. The 2-step model is characterized by very high jet multiplicity, from the decays of the quarks and W and Z bosons, and low lepton multiplicity. The limits on $m_{\tilde{g}}$ and $m_{\tilde{\chi}_1^0}$ are displayed in Figure 6.3. The summary of Run-1 SUSY analyses [112] found that this analysis outperformed all others—even the combination of the 1-lepton and 0-lepton lower jet multiplicity analyses—in a large section of the $m_{\tilde{g}}/m_{\tilde{\chi}_1^0}$ plane, motivating continued exploration of this region using these methods. Figure 6.4 shows the signal points on the 2-step grid that were chosen for this analysis, with the 2015 limits for reference.



Figure 6.3: (a), the Run-1 limits for the 2-step simplified model, including the most sensitive analyses in this region [112] and (b), the first Run-2 limits from the 2015 multijet search [63].



Figure 6.4: The distribution of the generated points in the 2-step grid with the expected and observed limits from the 2015 multijet analysis [63].

6.2.2 A slice of the pMSSM

The second model considered by this analysis is drawn from a two-dimensional subspace, or 'slice', of the 19-parameter phenomenological minimal supersymmetric extension to the Standard Model (pMSSM) [113]. Following Run-1, a large scan of the pMSSM was performed [114], revealing a class of models that were excluded by the Run-1 version of this analysis and not by any other analysis. Naturally, because they are difficult to search via other means, these are the most important areas of parameter space here. A representative sample of these interesting pMSSM points is shown in Figure 6.5.

These points are not random—there is a pattern that relates them. Each has a bino as the LSP near either the Higgs or the Z pole mass, light higgsinos, and a gluino around 1.2 TeV. Recognizing this allows the creations of a slice of pMSSM parameter space: Recalling the SUSY-breaking addition to the MSSM Lagrangian from Equation 4.3, the higgsino physical mass $(-\mu)$ and gluino physical mass (M_3) are varied and the LSP mass (M_1) is fixed at 60 GeV. The x- and y- axes in the signal grid become the higgsino and gluino masses, respectively. The remaining parameters in the pMSSM model, defined in Ref. [113], are not generally within the reach of



Figure 6.5: Particle spectra for a sample of potential SUSY models which are excluded by the multijet analysis and not excluded by any other analysis. Circled particles are the gluino, Higgsinos, and the bino LSP. Further examples are available in Appendix 7.

collider physics, and are set as follows:

$$m_A = M_2 = 3 \text{ TeV}, \quad A_\tau = 0, \quad \tan\beta = 10$$

$$A_t = A_b = m_{(e,\mu,\tau)L} = m_{(e,\mu,\tau)R} = m_{qL(1,2,3)} = m_{(u,c,t)R} = m_{(d,s,b)R} = 5$$
 Tev

which gives a Higgs mass around the true value of 125 GeV. It should be noted here that this model respects the constraints on new physics set by the invisible width of the Higgs [115] because the branching ratio to the LSP is very low.

Considering an example point on the signal grid, $(m(\tilde{g}), m(\tilde{\chi}_1^{\pm})) = (1200, 200)$ GeV, yields a decay chain with the following branching ratios:

$$\tilde{g} \to t + b + \tilde{\chi}_1^{\pm} \tag{44\%}$$

$$\tilde{g} \to t\bar{t} + \tilde{\chi}^0_{2,3} \tag{39\%}$$

$$\tilde{g} \to t\bar{t} + \tilde{\chi}_1^0$$
 (2%)

$$\tilde{g} \to b\bar{b} + \tilde{\chi}_1^0$$
 (1%)

$$\tilde{g} \to q\bar{q} + \tilde{\chi}_1^0 \tag{9\%}$$

$$\tilde{\chi}_1^{\pm} \to W + \tilde{\chi}_1^0 \tag{100\%}$$

$$\tilde{\chi}^0_{2,3} \to Z + \tilde{\chi}^0_1$$
(70%)

$$\tilde{\chi}_{2.3}^0 \to h + \tilde{\chi}_1^0 \tag{30\%}$$

The physical result of this decay is a large quantity of jets and a small E_T^{miss} from the neutralinos. In contrast to simplified models like the 2-step, models like this one do not fix the branching ratios, but rather allow them to vary as the masses of the sparticles change from point to point on the grid. In the regions of parameter space most relevant to this search, however, the branching fractions remain roughly constant.



Figure 6.6: The truth-level kinematic distributions a selection of pMSSM signal samples in comparison to a similar mass Gtt point. The dashed lines show Run-1 signal selections for the multijet analysis (top) and 2-6 jet analysis (centre and bottom).

To ensure that points like this one indeed do present a different analysis profile, truth-level samples were generated. Figure 6.6 compares the kinematic distributions of pMSSM signal points to a similar Gtt point typical of other hadronic searches. The trend toward low E_T^{miss} means that searches optimized for models like this Gtt point will miss regions accessible to the multijet analysis.

Using the truth-level grid and data from the 8 TeV collisions, the reach of various Run-1 analyses can be evaluated. As shown in Figure 6.7, different searches are



Figure 6.7: The limits from 8 TeV in the pMSSM plane. The various searches are complimentary.

sensitive to different parts of the plane. The lighter the higgsino mass, the less E_T^{miss} is present, and the 0-lepton and 3-b-jet searches get less and less effective. This is convincing evidence that the multijet analysis has a niche in parameter space where it is particularly sensitive and will detect a potential excess above the SM easily.

Signal events are simulated using the Monte Carlo generator Madgraph5, interfaced to Pythia8. The cross-section input is taken from a series of predictions for different choices of PDF, factorization, and renormalization, as described in Ref. [116].

6.3 Object definitions and Event Cleaning

This section will outline the key physical objects of the multijet search; how they are defined, how they are constructed from detector information, how their quality is ensured, and how they are used in this analysis.

6.3.1 Physical objects

Primary vertices

The points of origin of parton-parton interactions, vertices, are reconstructed from at least two particle tracks in the inner detector. The vertex with the largest sum of track transverse momentum $\Sigma |\vec{p}_T|^2$ is defined to be the primary vertex of the event.

Jets

Jets are reconstructed using the anti- k_t clustering algorithm from Chapter 3 with a jet radius parameter R = 0.4. The inputs to the algorithm are the position and energy of clusters of cells in the calorimeter. These clusters are formed by choosing cells registering uncommonly high energy, indicating the passage of a particle, and then combining neighboring cells. The jet momentum is constructed by treating each cluster of calorimeter cells as a 4-vector with zero mass and summing up those 4-vectors. The effect of pileup on jet energy is accounted for with a p_T -density correction applied on an event-by-event basis. All jets must satisfy $p_T > 20 \text{ GeV}^3$ and $|\eta| < 2.8$, and must pass overlap removal (described below).

Jets are also required to pass a 'jet cleaning', designed to remove non-collision jets originating from cosmic rays, detector noise, or beam background. Any event containing a jet that fails this cleaning is rejected. Jets produced in pileup interactions

³These requirements are known as a "cut". Stricter or gentler requirements are tighter or looser cuts.

are identified and removed by using a multivariate selection tool called the Jet Vertex Tagger [117] which develops a likelihood that a given jet originated at the primary vertex. Jets are not considered signal quality if they have $p_T < 50$ GeV, $|\eta| < 2.4$, and JVT < 0.59.

An algorithm that exploits the long lifetime, large mass, high decay multiplicity, and hard fragmentation of b-hadrons is used to identify to within some certainty the jets containing those b-hadrons, called b-jets [118]. These b-jets have been used in previous analyses to define signal regions, but here they are used only to divide control regions to target W+jets and $t\bar{t}$ and in overlap removal.

Leptons

Leptons (here referring only to electrons and muons) are used in this analysis to distinguish between signal regions and control regions. We distinguish between 'baseline' leptons, which are looser lepton candidates, and 'signal' leptons, which must pass a stricter selection. Baseline electrons must have $p_T > 10$ GeV and $|\eta| < 2.47$ and satisfy the "Loose" quality criterion from [119], which combines track properties from the inner detector with shower shape in the calorimeter to judge potential electron candidates. Baseline muons similarly must have $p_T > 10$ GeV and $|\eta| < 2.5$ and satisfy the "Medium" quality criterion from [120], which matches tracks from the inner detector with tracks from the muon spectrometer. Both electrons and muons must also pass overlap removal. If an event contains a baseline lepton, it is rejected in the signal region.

Signal leptons are used in the definition of the control regions. Signal electrons must satisfy the "Tight" quality criterion, rather than "Loose", and both electrons and muons must pass the "GradientLoose" isolation criteria [119, 120], which examines the lepton candidate's position with respect to nearby objects. Lastly, signal leptons must be associated to the primary vertex, with $|z_0\sin\theta| < 0.5$ mm and

 $d_0/\sigma(d_0) < 5(3)$ for electrons (muons), where z_0 and d_0 are the longitudinal and transverse impact parameters.

Taus are not used in this analysis, though a muon or electron resulting from tau decay and fulfilling the criteria above is treated the same way.

Photons

This analysis does not use photons for event selection, but they are important to the calculation of missing transverse energy described below. Photons are identified by requiring $p_T > 25$ GeV and $|\eta| < 2.37$, excluding $1.37 < |\eta| < 1.52$, and imposing the "Tight" criterion from [121], which again uses inner detector tracking information and calorimeter shower properties.

Missing transverse momentum

 E_T^{miss} is defined to be the negative vector sum of the momenta of physics objects, taken in a plane perpendicular to the axis of the beam. All of the objects above jets, leptons, and photons—participate in the reconstruction, along with a soft term [122] derived solely from tracks that are associated with the primary vertex but are not identified as any of these objects. The result is a 2-vector pointing opposite this sum of objects.

Large-R jets

Jets with a larger radius parameter R are produced by repeating the application of the anti- k_t clustering algorithm, but using the calibrated R = 0.4 jets as the algorithm's input. Jets must have $p_T > 20$ GeV and $|\eta| < 2.0$ and pass overlap removal to be used in the reclustering process. In the control regions, which contain leptons, the leptons are treated as jets in the reclustering and must pass the same requirements.

6.3.2 Overlap Removal

In order to avoid double counting of objects, overlap removal is applied to distinguish between them as follows:

- If an electron and a muon share an inner detector track, the electron is removed.
- If an electron and a jet are within $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.2$ of each other, the jet is removed, unless that jet is b-tagged with at least 85% efficiency in which case the electron is removed.
- If an electron is within $\Delta R < 0.2$ of a jet, the electron is removed.
- If a muon track is ghost-associated⁴ to a jet or is within $\Delta R < 0.2$ of a jet, the jet is removed
- If a muon is within $\Delta R < 0.4$ of a jet, the muon is removed.

This process ensures that jets, muons, and electrons are all considered separately.

6.3.3 Event Cleaning

The stochastic nature of the detector and the unpredictability of environmental factors mean that incoming data must be examined event-by-event for quality. For example, cosmic rays (muons) from the atmosphere or stray particles from the beam might reach the detector and happen to coincide with the timing of a collision, leading to events that should be rejected. Table 6.1 itemizes the event cleaning and data quality requirements for a good event.

⁴Ghost association is a technique by which the tracks are treated as infinitesimally soft particles by scaling down their p_T . The tracks are added as input to the jet algorithm, but because of their negligible p_T they make no impact on the reconstruction of calorimeter jets. Afterward, though, one can identify which tracks were clustered into which jets.

Requirement	Description
Good Runs List	Events must occur during time periods on a list of good runs (GRL) compiled by the experiment to en- sure data quality.
LAr, Tile, and SCT Errors	Reject events with known detector errors.
Jet Cleaning	As described in Section 6.3, any event that fails to pass jet cleaning cuts is vetoed.
Bad Muons	Poorly reconstructed muons can add a tail to E_T^{miss} distributions, so events with muons that have $> 20\%$ track momentum error are vetoed.
Good Vertex	Events lacking at least one primary vertex with at least two constituent tracks are vetoed.
Dead Tile	Among jets with $p_T > 50$ GeV and $ \eta < 2$, if the jet closest to the direction of the E_T^{miss} is within the dead tile region $(-0.1 < \eta < 1.0, 0.8 < \phi < 1.1)$, the event is vetoed.
Pileup jets	Events are rejected if there exists a jet with $50 < p_T < 70$ GeV, $ \eta < 2.0$, $JVT < 0.64$, and $\Delta \phi$ (jet, E_T^{miss}) > 2.2.

Table 6.1: Summary of the event cleaning and data quality requirements.

6.3.4 Key definitions

For clarity in the coming sections and plots, here are a few important variable definitions.

- H_T is the scalar sum of jet and lepton transverse momentum: $H_T = \Sigma p_T^{jet} + \Sigma p_T^{lep}$. Jets included in this quantity must pass the requirements outlined in the object definition and the leptons are signal leptons. Both must satisfy $p_T > 40$ GeV and $|\eta| < 2.8$.
- m_T , the transverse mass, is only defined for leptons: $m_T = \sqrt{2E_T^{\text{miss}} p_T^{lep}(1 - \cos\phi)}$ where $\phi = \phi(E_T^{\text{miss}}) - \phi(lepton)$.
- M_J^{Σ} is the sum of the masses of the large-*R* jets: $M_J^{\Sigma} = \sum_j m_j^{R=1.0}$. These composite jets must satisfy $p_T^{R=1.0} > 100$ GeV and $|\eta^{R=1.0}| < 1.5$.
- $E_T^{\text{miss}}/\sqrt{H_T}$ is a proxy for the E_T^{miss} significance. It is a crucial quantity in this analysis because the shape of $E_T^{\text{miss}}/\sqrt{H_T}$ is roughly invariant over changes in jet multiplicity. More details are forthcoming in the sections on event selection and multijet background.

6.4 Event Selection

The same distinct features of the multijet analysis that give it competitive sensitivity to some SUSY models—no leptons and a high jet multiplicity arranged into larger-R jets—provide the basis for selection of events and definition of signal regions. In comparison to the earlier Run-2 analysis [63] which focused on multiplicity of b-jets, this search introduces a 'fat-jet' stream using the properties of the large-radius jets described in Section 6.3.1. All events are recorded after the decision of the multijet trigger from Section 5.3 which requires at least six jets with $p_T > 45$ GeV and $|\eta| < 2.4$. Additional selections for each region tighten these jet requirements.

6.4.1 Signal Regions

The first step toward defining signal regions (SRs) is performing the lepton veto described in Section 6.3; any event containing a baseline lepton is rejected. Next, the number of jets with $p_T > 50$ GeV and $|\eta| < 2.0$ is counted and events with at least 8 jets are chosen. The number of jets provides the first division of signal regions into three regions containing ≥ 8 , ≥ 9 , and ≥ 10 jets. The signal regions are further subdivided by the sum of the fat-jet masses M_J^{Σ} , defined in Section 6.3.4, requiring $M_J^{\Sigma} > 340$ or $M_J^{\Sigma} > 500$ GeV. These regions are inclusive, such that the higher-multiplicity signal regions are subsets of the lower-multiplicity ones and the stricter M_J^{Σ} SRs are subsets of the loser ones.

The cross-section of QCD multijet production just from SM physics, called the 'multijet background' from now on, is very large, so much so that it dominates even at very large jet multiplicities. All of the models investigated in this search expect some amount of E_T^{miss} , either from the non-interacting LSP neutralino χ_1^0 or from $Z \to \nu \nu$ decay resulting in neutrinos. Thus it is sensible to cut on E_T^{miss} in search of signal events. Because of the multijet cross-sections, however, it is impossible to set an E_T^{miss} requirement that keeps signal events without also keeping a large multijet background. On top of this, multijet production is poorly modeled at high jet multiplicity so subtracting that remaining background is very challenging.

The solution to this conundrum, and the last selection variable, is $E_T^{\text{miss}}/\sqrt{H_T}$, the ratio of E_T^{miss} to the square root of the scalar sum of jet and lepton momenta. This value is closely related to the E_T^{miss} significance, $E_T^{\text{miss}}/\sigma(E_T^{\text{miss}})$, where $\sigma(E_T^{\text{miss}})$ is the uncertainty in the missing energy, because the dominant component of that uncertainty is jet mismeasurement. Most importantly, though, $E_T^{\text{miss}}/\sqrt{H_T}$ can be used to manage the multijet background with a data-driven approach because it is invariant over changes in jet multiplicity. This feature and its use in a template method will be covered further in Section 6.5.2. For now, we set a threshold of $E_T^{\text{miss}}/\sqrt{H_T} > 4 \text{ GeV}^{1/2}$ on all signal regions.

This threshold value balances sufficient signal acceptance with manageable multijet background. Lowering this cut leads to drastically increased background. Raising it increases the uncertainty on modeling of the non-QCD background and strains the statistics in the leptonic control regions. Perhaps most importantly, increasing the value takes away this search's advantage over other similar SUSY searches in exploring low- E_T^{miss} regions.

The choices of 340 and 500 GeV for the M_J^{Σ} divisions are based on a study of expected signal strength. The 340 GeV cut provides sensitivity to smaller mass splittings, but at twice the top mass it still avoids most SM backgrounds. The 500 GeV cut extends sensitivity to large mass splittings without cutting control region statistics too harshly. The exclusion contours for M_J^{Σ} thresholds of 340, 420, 500, and 580 GeV are shown in Figure 6.8. The plot demonstrates that the 500 GeV cut is important for reaching sensitivity to higher gluino mass, while the 340 GeV cut is needed to cover regions where the intermediate states are compressed. A 420 GeV cut would not add significance in either direction, while a 580 GeV cut sacrifices control region yield without substantially improving signal sensitivity.

Table 6.2 shows a summary of the signal regions used for this analysis. The shorthand for regions is read out as follows: SR - (N_{jets}) ij(jet p_T cut) - $(M_J^{\Sigma}$ cut) where 'i' means inclusive. For example, the signal region with at least 8 jets and a 340 GeV M_J^{Σ} cut is labeled SR-8ij50-MJ340.



Figure 6.8: Expected exclusion contours in the 2-step (left) and pMSSM (right) planes for signal region selections with $M_J^{\Sigma} > 340, 420, 500, 580$ GeV.

Signal region	8ij50	9ij50	10ij50
$R = 0.4$ jet $ \eta $		< 2	2.0 for all SRs
$R = 0.4$ jet p_T		> 50	GeV for all SRs
$N_{ m jet}$	≥ 8	≥ 9	≥ 10
M_J^{Σ}	> 340 GeV and $> 500 GeV$ for each case		
$E_T^{\rm miss}/\sqrt{H_T}$		$> 4 \mathrm{Ge}$	$eV^{1/2}$ for all SRs

Table 6.2: Signal region definitions.

6.4.2 Leptonic Control Regions

Leptonic control regions (CRs) are used to normalize backgrounds from non-QCD sources. To that end, two control regions are defined for each signal region, for a total of 12 regions. Each of these two control regions targets a major background; $W \rightarrow (\ell \nu) + \text{jets}$ by requiring zero b-jets, and leptonically-decaying $t\bar{t}$ by requiring ≥ 1 b-jets.

The control regions require exactly one lepton (electron or muon), using the definitions outlined in Section 6.3. To increase the yield, the control regions for a signal region with $N_{\rm jet}$ requires only $(N_{\rm jet}-1)$ jets, with the relaxed cut $E_T^{\rm miss}/\sqrt{H_T} > 3 \,{\rm GeV}^{1/2}$. The transverse mass (defined in Section 6.3.4) is limited to $m_T < 120$ GeV to eliminate contamination from other sources, like potential signals. Otherwise we want the events entering the control regions to resemble those entering the signal regions as much as possible. To that end, leptons in the control regions are treated as jets and included in quantities like H_T and $E_T^{\rm miss}/\sqrt{H_T}$, as long as they pass the same requirements jets must.

The summarized requirements on control regions are shown in Table 6.3. The control regions are labeled in the same way as the signal regions, with the addition of '0eb' for exactly zero b-jets or '1ib' for at least one b-jet; i.e. CR-7ej50-1ib-MJ340 is a region with exactly 7 jets, at least one of which is a b-jet, and a M_J^{Σ} cut at 340 GeV.

Control regions	
Trigger	Six jets with $p_T > 45$ GeV and $ \eta < 2.4$
Lepton p_T	$> 20 {\rm ~GeV}$
Lepton multiplicity	Exactly one, $\ell \in e, \mu$
m_T	$< 120 { m ~GeV}$
Jet p_T	$> 50 { m ~GeV}$
$\mathrm{Jet}\left \eta\right $	< 2.0
Number of jets including lepton	$N_{SR} - 1$
b-jet multiplicity	$= 0 \ (W) \ \mathrm{or} \ge 1 \ (t\bar{t})$
M_J^{Σ}	Same as SR
$E_T^{\rm miss}/\sqrt{H_T}$	$> 3 \text{ GeV}^{1/2}$

Table 6.3: Definitions of the control regions, which are used to normalized the main non-QCD backgrounds.

6.4.3 Multijet Template Regions

The multijet background is estimated using a template method, covered in detail in Section 6.5.2. The concept is to use the distribution of $E_T^{\text{miss}}/\sqrt{H_T}$ at a lower jet multiplicity as a representative template of the multijet background at higher jet multiplicity. 'Template regions' are defined by selecting exactly six jets and applying cuts in $E_T^{\text{miss}}/\sqrt{H_T}$. High $E_T^{\text{miss}}/\sqrt{H_T}$ template regions do the actual signal region background estimates and extraction. Low $E_T^{\text{miss}}/\sqrt{H_T}$ template regions are used for normalization. In addition, 'validation regions' that have only seven jets but are otherwise identical to the signal regions are used to validate the template background estimation and determine systematic uncertainties.

6.5 Standard Model Backgrounds

The new physics signature expected, based on the model predictions, is a large number of jets from the heavy particle decay cascade combined with missing energy from the non-interacting LSP. Extracting a signal requires identifying which Standard Model processes result in similar signatures and establishing their impact within the signal regions. If a significant number of events remain after the background events that leaked into the the signal regions are subtracted, we may have a discovery.

The dominant SM processes that produce background in the signal regions are multijet, $t\bar{t}$, and W+jets. The first source, the QCD multijet background, results in E_T^{miss} primarily via mismeasurement of jets. The second and the third are referred to as the leptonic background, from fully or semi-leptonic $t\bar{t}$ decays or W or Z bosons that decay leptonically in conjunction with jets. The E_T^{miss} comes from the neutrinos produced in these decays. The leptonic background contributes events to the zerolepton signal regions when no actual e or μ is produced ($Z \rightarrow \nu\nu$ or $W \rightarrow \tau\nu$ with a hadronically decaying τ), or when leptons are indeed produced but do not pass the acceptance criteria and are not identified.

Different techniques are used to estimate these two classes of background. As addressed in Section 6.4.1, events with such high jet multiplicity are not modeled well in simulation so the multijet background uses a completely data-driven template method. The leptonic backgrounds are simpler to simulate because comparatively lower order is required in QCD calculations to achieve accuracy. Thanks to this feature, the smaller backgrounds are determined solely by simulation and the larger ones are simulated and then normalized to data. The mulijet templates themselves require an estimation of the leptonic background so the leptonic methods will be addressed first.

6.5.1 Leptonic Background

The leptonic background is dealt with using the leptonic control regions described in Section 6.4.2 and summarized in Table 6.3. These regions are enriched in the primary sources of background, namely $t\bar{t}$ and W+jets, and designed to minimize contamination of the signal regions while maximizing the kinematic similarities to them. The $t\bar{t}$ and W+jets backgrounds are estimated using simulated events, then normalized to the data using a combined fit. The systematic uncertainties in the control and signal regions will cancel each other, assuming the kinematics are not too different.

Each of the two control regions associated with a signal region, characterized by bjet multiplicity, manages one of the two main backgrounds; $t\bar{t}$ events will tend to have b-jets while W+jets events will not. In order to improve the yield, all control regions require one fewer jet than their partner signal regions and have a looser $E_T^{\text{miss}}/\sqrt{H_T}$ requirement. To ensure potential signals do not contaminate the control regions, a maximum is set on transverse mass. Otherwise, though, the control region and signal region selections are identical (beyond, of course, the one-lepton selection). To further ensure that control region events look like signal region events, the selected electron or muon is treated as a jet for the purposes of jet counting, jet reclustering, and jet momentum calculations. The combination of these factors ensures that desired kinematic alignment.

Yields for further less-dominant backgrounds are calculated using exclusively simulation. Subdominant processes include Z+jets, vector boson pairs (WW, WZ, ZZ), $t\bar{t}$ production with a W, Z, or Higgs boson, and single-top production.

Figures 6.9 (number of jets), 6.10 (M_J^{Σ}) , and 6.11 $(E_T^{\text{miss}}/\sqrt{H_T})$ show the distributions of various kinetic variables for the six $E_T^{\text{miss}}/\sqrt{H_T} > 3 \text{GeV}^{1/2}$ control regions. Distributions for a more complete set of variables are available in Appendix 7. Good agreement is seen between data and simulation.

The leptonic background simulations are created using a variety of Monte Carlo generators, as shown in Table 6.4. A brief outline of each can be found in Section 5.5. In particular, top production is simulated using the POWHEG [92] or Madgraph [98] event generator integrated with PYTHIA [93, 94] for parton showering and hadronization.



Figure 6.9: The number of jets for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 340$ GeV.



Figure 6.10: The sum of large-R jet mass M_J^{Σ} for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 340$ GeV.


Figure 6.11: The distribution of $E_T^{\text{miss}}/\sqrt{H_T}$ for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 340$ GeV.

Boson (W, Z, diboson) production is simulated with Sherpa [97], which specializes in multijet topologies in comparison with other MC generators. All MC samples are reweighted so that their pileup distributions match the distribution observed in data. The detector response is processed using a full simulation of the ATLAS detector based on GEANT4 [99].

Background	Baseline Generator
$t\overline{t}$	POWHEG+PYTHIA6
W+jets	Sherpa2.2
Z+jets	Sherpa2.2
single top (Wt)	POWHEG+PYTHIA6
single top $(t-\text{chan})$	POWHEG +PYTHIA6
$t\bar{t}+X$	${\tt Madgraph}5{+}{\tt PYTHIA}8$
$t\bar{t}$ +H	$Madgraph_aMC@NLO+PYTHIA8$
diboson	Sherpa

Table 6.4: Generators used for the central values for each of the SM backgrounds. The 'X' in $t\bar{t}+X$ includes $t, t\bar{t}, W, Z$ and WW. See Section 5.5

6.5.2 Multijet Background

The data-driven template method for modeling the multijet background proceeds as follows: First, data is collected in a template region with exactly six jets (Section 6.4.3). Next, all of the SM leptonic backgrounds described in the previous section are subtracted. The assumption that $E_T^{\text{miss}}/\sqrt{H_T}$ is invariant across jet multiplicity allows the template distributions to be extrapolated to higher multiplicity. Finally, the multijet background is predicted at signal region jet multiplicity by normalizing the shape of the lower-multiplicity template. The low- $E_T^{\text{miss}}/\sqrt{H_T}$ (< 1.5 GeV^{1/2}) region is used for this process so that the signal region remains hidden.

The premise at the heart of the argument that $E_T^{\text{miss}}/\sqrt{H_T}$ is resistant to changes in the number of jets is that E_T^{miss} in the multijet background is due to jet mismeasurement. Unfortunately, this assumption is not precisely true at lower jet multiplicities, and a template build straight from the six-jet distribution would fail, as can be seen in Figure 6.12. The ratio of the higher multiplicity regions to the lowest is far from flat.

The issue is that E_T^{miss} (Section 6.3), contains by definition energy from tracks not associated with hard objects coming from the primary vertex. This definition is useful in many ways (it deals with pileup well), but there is intrinsic E_T^{miss} in any event from 'soft' tracks of neutral particles. This intrinsic E_T^{miss} is not related to jet mis-measurement in any way, so some kind of fix must be developed.

Previous analyses using a multijet selection [63, 109, 110] solved the problem by making templates in bins of H_T . This analysis, however, sets a cut on M_J^{Σ} , which is strongly correlated with H_T , as shown in Figure 6.13. Thus the analysis is always choosing high H_T , in effect skipping the need for the correction. The "closure" of the template, or the extent to which data matches simulation, should be restored simply by implementing the high M_J^{Σ} requirement. Evidence of this effect is seen in Figure 6.14: As the cut on M_J^{Σ} becomes tight, the templates start to overlap. That is, the templates for $M_J^{\Sigma} > 0$, > 100, and > 200 GeV are quite separated, but the templates for $M_J^{\Sigma} > 340$, > 420, and > 500 coincide to within error.

Figure 6.15 puts this principle to the test. On the left are the template shapes for various cuts on M_J^{Σ} , including no cut at all. On the right, the template method is applied and the multijet background is modeled. When the M_J^{Σ} cuts are applied the closure is much improved.

The results of the template method applied to the signal regions are shown in Figure 6.16. The distribution of $E_T^{\text{miss}}/\sqrt{H_T}$ for events with at least 8, 9, and 10 jets is displayed. The dashed lines are the predicted yields at representative points on the 2-step and pMSSM model grids, for which $(m(\tilde{g}), m(c\tilde{h}i_1^0)) = (1200, 400)$ GeV and $(m(\tilde{g}), m(c\tilde{h}i_1^{\pm})) = (1200, 400)$ GeV respectively. After accounting for



Figure 6.12: The distribution of $E_T^{\text{miss}}/\sqrt{H_T}$ at increasing jet multiplicities, prior to any cut on M_J^{Σ} . The ratios are far from steady, indicating that a template directly from the six-jet region would be ill-advised.



Figure 6.13: The correlation between M_J^{Σ} and H_T for data (left) and $t\bar{t}$ MC simulation (right).



Figure 6.14: Six-jet template shapes for various cuts on M_J^{Σ} . Templates with a tighter M_J^{Σ} cut overlap.

all of the various backgrounds described above, the events in the signal regions are well explained by SM processes. A small excess does seem to appear in the high- $E_T^{\text{miss}}/\sqrt{H_T}$ bins for the higher jet multiplicities but, as will be shown in Section 6.7, it turns out to be statistically insignificant when considered in the larger context because of deficits in other nearby bins.

6.6 Systematic Uncertainty

Systematic uncertainties in this study have a variety of sources. Any prediction, background or signal, using MC simulation is impacted by experimental systematics on the resolution and energy scale of the jets and leptons, and by uncertainty due to inefficiencies in the particle identification and reconstruction process. In addition, there are uncertainties on the estimates of the SM background from theoretical systematics on the simulated cross-sections. Finally, any variation in the shape of the



Figure 6.15: The six-jet template region (left) and the seven-jet template validation region (right) for various cuts on M_J^{Σ} . Application of a cut on M_J^{Σ} improves the template prediction of the multijet background.



Figure 6.16: Results of the template method in the six signal regions (without the $E_T^{\text{miss}}/\sqrt{H_T}$ cut) for greater than 8, 9 and 10 jets. Shown is the distribution of $E_T^{\text{miss}}/\sqrt{H_T}$ with leptonic backgrounds normalized to their post-fit values.

multijet template is treated as another systematic uncertainty.

6.6.1 Experimental Systematics

The dominant experimental uncertainties are on the scale [123, 124] and resolution [125, 126] of the energy and momentum measurements of jets. The jet energy scale systematic is estimated by varying a set of key nuisance parameters⁵ and observing the effect on jet energies. The jet energy resolution systematic is evaluated by smearing the jet energies by a gaussian and extracting the width, determined from the difference between the jet resolution measured in data and MC simulation.

Additional lower-impact sources of experimental uncertainty include the following: The ATLAS luminosity uncertainty [76] affects signal yields and any MC background predictions not normalized to data. All MC simulations come with a pileup uncertainty due to potential mis-modeling of the interactions overlapping the hard scatter event. Uncertainty in the lepton energy/resolution only impacts the signal region yield through background measurements using the one-lepton control regions.

6.6.2 Theoretical Systematics

Predictions of the leptonic backgrounds to the signal and control regions all carry their own theoretical systematics. These are estimated by comparing differences between the event yields of different MC generators, by varying the input parameters used to initialize the event within a single generator, and by comparing samples with differing amounts of extraneous radiation from sources outside the hard scatter.

The dominant leptonic backgrounds are treated separately: For $t\bar{t}$, the nominal POWHEG+PYTHIA6 simulation is compared with POWHEG+Herwig and POWHEG+PYTHIA8 to examine the parton shower modeling, and with Madgraph5_aMC@NLO for the

⁵Nuisance parameters are parameters that are tangential in some way to the measurement. The quantity of interest is treated as a Gaussian and the nuisance parameters are the width.

matrix element generation. The uncertainty is computed from the difference in yield. Comparison with samples which vary the amount of additional radiation (by e.g. adding a pair of partons to the matrix element calculation) produces the largest uncertainty, which can be greater than 70%. Uncertainties in W+jets production are quantified by varying the factorization, renormalization, resummation, and jet matching scales in the nominal Sherpa.

For the remaining simulated background systematics such comparisons are not feasible, whether because variations are unavailable, too statistically limited, or simply not worth the effort to calculate. Instead a fixed global uncertainty, chosen conservatively, is assigned to each background. The magnitudes are as follows: 50% on diboson production, 40% on Z+jets, 30% on $t\bar{t}+X$, and 30% on single top. Because each of these processes contributes minimally to the total leptonic background in the signal regions, they are greatly outweighed by the above $t\bar{t}$ systematics and the uncertainties inherent in the multijet template method.

6.6.3 Multijet Template Systematics

The uncertainties on the data-driven prediction of the multijet background are quantified using closure tests of the template method. The closure test works like this: First, the template is constructed in the appropriate 6-jet region and leptonic backgrounds are subtracted, as described in Section 6.5.2. Next, closure regions are defined; regions where little signal is expected. The template is applied to each closure region, the multijet background is modeled, and the amount by which the yield differs between the template prediction and data is the systematic uncertainty.

There are two categories of closure region. First, there are regions with jet multiplicity equal to that of the signal regions, but with $E_T^{\text{miss}}/\sqrt{H_T}$ below the signal region cutoff. There are three closure regions for each signal region: $E_T^{\text{miss}}/\sqrt{H_T} \in$ (1.5, 2.0), (2.0, 2.5), (2.5, 3.5) GeV^{1/2}. The second category contains the validation regions, which have exactly 7 jets and the same $E_T^{\text{miss}}/\sqrt{H_T}$ requirement as the signal regions.

The closure tests use the results of a background-only fit, described in Section 6.7. The fit output comes in the form of scale factors which are applied to the $t\bar{t}$ and W+jets components of the MC background and thus affect the template prediction.

The actual numerical systematic used for each signal region is taken to be the maximum deviation from data in any of the closure regions that have the same or lower jet multiplicity and the same M_J^{Σ} requirement. For example, the systematic uncertainty on the signal region SR-8ij50-MJ340, which has at least 8 jets and a cut at $M_J^{\Sigma} > 340$ GeV, is the largest deviation observed in the closure regions 8ij50-MJ340 (for all bins in $E_T^{\text{miss}}/\sqrt{H_T}$) and 7ej50-MJ340.

The complete list of uncertainties extracted from the closure tests is written in Table 6.5 and shown visually in Figure 6.17. Table 6.6 presents the final multijet template systematic, extracted from the maximum uncertainty registered each set of closure regions.

6.6.4 Template Flavor

The multijet template method described so far does not require any selection on b-jets. One might expect, however, that the jet flavor⁶ will have an impact on the $E_T^{\text{miss}}/\sqrt{H_T}$ distribution because b-jets are more likely be associated with true E_T^{miss} due to semi-leptonic decays of the b-hadrons. To explore this idea and to account for differences in flavor composition of events, a 'flavor template' was created, in contrast to the original 'nominal' template. The flavor template is comprised of a sum of two sub-templates; one based on a region requiring no b-jets and one based on a region requiring at least one, both otherwise identical in selection to the original template.

⁶'Flavor' refers to quark composition



Figure 6.17: The degree of closure (after performing the background fit) observed in each closure region. The prediction is given by the sum of the multijet template prediction and the leptonic background. The solid lines are the predicted numbers of events and the points are the observed numbers. The signal regions $(4.0, \infty)$ for 8ij50, 9ij50 and 10ij50 are also included but are not considered in the calculation of the systematic.

N jets	$E_T^{\rm miss}/\sqrt{H_T}$ range / GeV ^{1/2}	Prediction	Observation	% difference
=7	(1.5, 2.0)	25213.4	25414	-0.80
=7	(2.0, 2.5)	11886.8	11741	1.23
=7	(2.5, 3.5)	6150.3	6037	1.84
=7	$(4.0,\infty)$	1105.7	1021	7.66
≥ 8	(1.5, 2.0)	9984.5	10105	-1.21
≥ 8	(2.0, 2.5)	4716.8	4496	4.68
≥ 8	(2.5, 3.5)	2460.8	2280	7.35
≥ 9	(1.5, 2.0)	2333.3	2267	2.84
≥ 9	(2.0, 2.5)	1103.8	1052	4.69
≥ 9	(2.5, 3.5)	577.1	502	13.02
≥ 10	(1.5, 2.0)	453.9	443	2.41
≥ 10	(2.0, 2.5)	215.6	205	4.91
≥ 10	(2.5, 3.5)	112.7	99	12.13

⁽a) $M_J^{\Sigma} > 340 \text{ GeV}$

N jets	$E_T^{\rm miss}/\sqrt{H_T}$ range / GeV ^{1/2}	Prediction	Observation	% difference
= 7	(1.5, 2.0)	4075.4	4084	-0.21
= 7	(2.0, 2.5)	1799.9	1842	-2.34
=7	(2.5, 3.5)	984.5	948	3.71
=7	$(4.0,\infty)$	243.2	232	4.61
≥ 8	(1.5, 2.0)	2412.0	2460	-1.99
≥ 8	(2.0, 2.5)	1067.8	1064	0.36
≥ 8	(2.5, 3.5)	593.5	552	7.00
≥ 9	(1.5, 2.0)	752.7	735	2.35
≥ 9	(2.0, 2.5)	334.7	327	2.30
≥ 9	(2.5, 3.5)	186.1	156	16.16
≥ 10	(1.5, 2.0)	193.1	180	6.78
≥ 10	(2.0, 2.5)	86.3	87	-0.84
≥ 10	(2.5, 3.5)	48.1	46	4.33
(b) $M_I^{\Sigma} > 500 \text{ GeV}$				

Table 6.5: The degree of closure (after performing the background fit) observed in each closure region. The prediction is given by the sum of the multijet template prediction and the leptonic background.

Call the two templates F_b for the 'flavor-blind' original inclusive (0ib) template and F_s for the new 'flavor-split' (0eb + 1ib) template. Table 6.7 shows that in fact F_s predicts a larger uncertainty than F_b . This may be because F_s is overestimat-

Region	% difference
SR-7ej50-0ib-MJ340	7.66
SR-8ij50-0ib-MJ340	7.66
SR-9ij50-0ib-MJ340	13.02
SR-10ij50-0ib-MJ340	13.02

(a) $M_J^{\Sigma} > 340 \text{ GeV}$

Region	% difference
SR-7ej50-0ib-MJ500	4.61
SR-8ij50-0ib-MJ500	7.00
SR-9ij50-0ib-MJ500	16.16
SR-10ij50-0ib-MJ500	16.16
(b) $M_I^{\Sigma} > 500$	${ m GeV}$

Table 6.6: Final multijet template systematic uncertainties.

Region	Nominal Template	Flavor Template	Difference $(\%)$
VR 7ej50 MJ340	484.88 ± 17.50	511.95 ± 18.54	-5.58
SR 8j MJ340	190.80 ± 6.89	215.66 ± 7.92	-13.03
SR 9j MJ340	44.34 ± 1.60	52.91 ± 1.97	-19.31
$\mathrm{SR}\ 10\mathrm{j}\ \mathrm{MJ340}$	8.66 ± 0.31	11.03 ± 0.42	-27.38
VR 7ej50 MJ500	112.77 ± 9.79	119.01 ± 10.32	-5.54
SR 8j MJ500	65.48 ± 5.68	74.92 ± 6.58	-14.41
SR 9j MJ500	20.26 ± 1.76	24.15 ± 2.15	-19.21
SR 10j MJ500	5.23 ± 0.45	6.55 ± 0.59	-25.31

Table 6.7: The predicted multijet background as calculated by two methods. The 'nominal' template F_b , extracted from inclusive b-jet regions (0ib), and the 'flavor-split' template F_s which sums templates created with exactly 0 b-jets (0eb) and at least 1 b-jet (1ib). The percentage difference is calculated as (nominal-flavour)/nominal. Created using 12.1 pb⁻¹ of data.

ing the relative contribution of heavy flavor to the E_T^{miss} in comparison to jet mismeasurement. Using F_s actually pulls the prediction farther away from observation because, as can be seen in Table 6.5, F_b already overshoots the data slightly.

It is reasonable to expect that the differences in Table 6.7 come from overestimating the additional systematic uncertainty. To find a more realistic estimate, the templates are interpolated via a linear combination of F_b and F_s where the final template is given

$$\mathcal{T} = f \times F_b + (1 - f) \times F_s$$

where $f \in (0, 1)$ is a free parameter optimized separately in each signal region. The value of the optimal f is determined using the χ^2 distributions of the signal regions:

$$\chi^2 = \frac{(E - \mathcal{T})^2}{\sigma^2}$$

where E is the expected data in the region and σ^2 is the quadratic sum of the error on the data and the error on the template prediction. The value of f is chosen to minimize the χ^2 value, a process that is, unfortunately, not straightforward because the errors in \mathcal{T} depend on f. The flavor uncertainty for each closure region, shown in Table 6.8, is the difference in yield between the nominal (f = 1) template and \mathcal{T} . Just as before, the largest deviation is chosen as the flavor systematic in each signal region (Table 6.9).

6.7 Statistical Methods and Results

In order to ensure that the background predictions accurately represent the distributions seen in experimental results, fitting techniques are used to normalize the background profiles to measured data. Three such fits are employed in this analysis: First, for each signal region, a simultaneous fit is applied to the corresponding control regions and template region to extract the background estimate. The second and third fits take this background fit and extend it to include constraints on the signal using two configurations, one targeting a potential discovery of new physics and one aiming to set exclusion limits on SUSY parameters. These fits are carried out using the *HistFitter* package [127].

N jets	$E_T^{\rm miss}/\sqrt{H_T}$ range / GeV ^{1/2}	Prediction - Observation	% difference
= 7	(1.5, 2.0)	2.1	0.01
=7	(2.0, 2.5)	35.8	0.30
=7	(2.5, 3.5)	25.7	0.42
=7	$(4.0,\infty)$	5.4	0.49
≥ 8	(1.5, 2.0)	13.9	0.14
≥ 8	(2.0, 2.5)	8.2	0.17
≥ 8	(2.5, 3.5)	5.14	0.21
≥ 9	(1.5, 2.0)	14.7	0.63
≥ 9	(2.0, 2.5)	8.8	0.80
≥ 9	(2.5, 3.5)	2.9	0.50
≥ 10	(1.5, 2.0)	10.4	2.30
≥ 10	(2.0, 2.5)	7.2	3.34
≥ 10	(2.5, 3.5)	3.2	2.88
	(a) M_J^{Σ}	$> 340 { m ~GeV}$	
N jets	$E_T^{\rm miss}/\sqrt{H_T}$ range / GeV ^{1/2}	Prediction - Observation	% difference
= 7	(1.5, 2.0)	8.9	0.22
=7	(2.0, 2.5)	0	0
=7	(2.5, 3.5)	11.9	1.21
=7	$(4.0,\infty)$	9.0	3.72
≥ 8	(1.5, 2.0)	0	0
≥ 8	(2.0, 2.5)	22.9	2.14
≥ 8	(2.5, 3.5)	6.5	1.09
≥ 9	(1.5, 2.0)	11.8	1.57
≥ 9	(2.0, 2.5)	9.1	2.72
≥ 9	(2.5, 3.5)	2.3	1.20
≥ 10	(1.5, 2.0)	3.3	1.69
≥ 10	(2.0, 2.5)	0.7	0.81
≥ 10	(2.5, 3.5)	4.0	8.3

(b) $M_J^{\Sigma} > 500 \text{ GeV}$

Table 6.8: Template flavor systematics, optimized for each region via a linear combination of the flavor-blind 'nominal' template and the flavor-split template.

Region	% difference
SR-7ej50-0ib-MJ340	0.49
SR-8ij50-0ib-MJ340	0.21
SR-9ij50-0ib-MJ340	0.80
SR-10ij50-0ib-MJ340	3.34
(a) $M_J^{\Sigma} > 340$	${ m GeV}$
Region	% difference
SR-7ej50-0ib-MJ340	3.72
SR-8ij50-0ib-MJ340	2.14
SR-9ij50-0ib-MJ340	2.72
SR-10ij50-0ib-MJ340	8.3
(b) $M_J^{\Sigma} > 500$	GeV

Table 6.9: Summary of the maximal flavor systematics for each signal region.

6.7.1 Background Fit

The background-only fit serves to normalize the $t\bar{t}$ and W+jets background estimates from MC simulation in the control regions. The template regions also rely on this normalization, so for self-consistency the fit is conducted simultaneously on the two CRs and one TR corresponding to each SR. *HistFitter* builds a likelihood function from the product of Poisson probability functions, treating the various systematic uncertainties as nuisance parameters. The likelihood function [128] is:

$$\mathcal{P}(n_c, a_p | \mu_s, \alpha_p) = \prod_c \operatorname{Pois}(n_c | v_c) \times G(L_0 | \lambda, \Delta_L) \times \prod_p f_p(a_p | \alpha_p)$$
(6.1)

where the third term $f_p(a_p|\alpha_p)$ describes the way an auxiliary measurement a_p constrains the nuisance parameter (in this case the systematic uncertainty) α_p . The middle term $G(L_0|\lambda, \Delta_L)$ describes the available luminosity λ via a Gaussian probability distribution centered at the measured luminosity L_0 with uncertainty Δ_L . The luminosity at the time of writing was measured at 18.2 ± 0.7 fb⁻¹, derived using methods similar to Ref. [76]. If a channel c (in this case the signal or control region) expects to see v_c events, the observed events n_c form a Poisson distribution:

\mathbf{SR}	8ij-MJ340	9ij-MJ340	10ij-MJ340	8ij-MJ500	9ij-MJ500	10ij-MJ500
$\mu_{tar{t}}$	0.91 ± 0.05	0.87 ± 0.08	0.92 ± 0.15	0.79 ± 0.10	0.85 ± 0.14	0.83 ± 0.23
$\mu_{W+\mathrm{jets}}$	0.54 ± 0.15	0.54 ± 0.24	0.66 ± 0.51	0.48 ± 0.21	0.30 ± 0.30	0.16 ± 0.65

Table 6.10: Scale factors obtained from the background-only fit for each signal region

$$\operatorname{Pois}(n_c|v_c) = \frac{v_c^{n_c}}{n_c!} e^{-v_c}$$
(6.2)

Here, the total expected number of events v_c comes from summing over multiple backgrounds b:

$$v_c = \sum_b \lambda \eta_{b,c}(\alpha) y_{b,c} \mu_b \tag{6.3}$$

The yield $y_{b,c}$ is the number of events in channel c from background b per unit integrated luminosity expected before scaling. The normalization $\eta_{b,c}(\alpha)$ is the pre-factor governing the change in yield due to a systematic uncertainty α . That is, $\eta(0) = 1$ because no systematic is applied. At the other extreme, $\eta(1)$ and $\eta(-1)$ are given by the full uncertainty values above and below, as determined in Section 6.5.1. As the weighting of α varies, so does this normalization.

The scale factors for each background μ_b (for $b \in (t\bar{t}, W + \text{jets})$) are the object of the background fit. Backgrounds not included in the fit—the subdominant leptonic processes—are given scale factors of exactly 1. Running the fit amounts to minimizing the likelihood function \mathcal{P} and reading out μ_b , shown in Table 6.10. These are combined with the predictions from MC simulation and the multijet template to obtain the prediction of the total background in each signal region.

Tables 6.11, 6.12, and 6.13 are the end results of the background fit for each signal region and the corresponding control regions, comparing the predicted background count to the observed yield. As expected, the dominant sources of background are the multijet (for the SRs), $t\bar{t}$, and W+jets channels. Figure 6.18 shows the agreement of SM prediction and data in all control regions after the background fit.

Region	SR-8ij-MJ340	CR-7ej-0eb-MJ340	CR-7ej-1ib-MJ340
Observed events	424	173	604
Fitted bkg events	467.14 ± 39.74	172.76 ± 13.15	604.07 ± 24.62
Fitted ttH events	1.68 ± 0.50	0.71 ± 0.21	6.72 ± 2.01
Fitted ttX events	8.88 ± 2.65	3.10 ± 0.93	22.71 ± 6.78
Fitted diboson events	4.95 ± 2.46	17.04 ± 8.48	4.98 ± 2.48
Fitted st events	9.65 ± 4.27	6.73 ± 2.38	32.80 ± 11.18
Fitted Z events	9.49 ± 3.77	3.30 ± 1.31	1.16 ± 0.46
Fitted Wjets events	12.41 ± 5.15	61.10 ± 25.03	23.49 ± 9.92
Fitted ttbar events	107.99 ± 28.79	80.78 ± 18.63	512.21 ± 31.05
Fitted multijet events	312.10 ± 28.71	0.00 ± 0.00	0.00 ± 0.00
Region	SR-8ij-MJ500	CR-7ej-0eb-MJ500	CR-7ej-1ib-MJ500
Observed events	141	40	107
Fitted bkg events	153.28 ± 16.99	39.99 ± 6.32	107.07 ± 10.35
Fitted ttH events	0.42 ± 0.12	0.08 ± 0.02	0.94 ± 0.28
Fitted ttX events	3.14 ± 0.94	0.73 ± 0.22	5.27 ± 1.57
Fitted diboson events	1.27 ± 0.63	4.74 ± 2.37	2.09 ± 1.04
Fitted st events	3.48 ± 1.48	1.26 ± 0.70	7.98 ± 3.16
Fitted Z events	3.44 ± 1.37	0.74 ± 0.30	0.24 ± 0.09
Fitted Wjets events	4.95 ± 3.12	17.41 ± 10.48	4.60 ± 2.83
Fitted ttbar events	29.21 ± 15.74	15.04 ± 7.73	85.94 ± 11.79
Fitted multijet events	107.38 ± 8.69	0.00 ± 0.00	0.00 ± 0.00
Observed events Fitted bkg events Fitted ttH events Fitted ttX events Fitted diboson events Fitted diboson events Fitted st events Fitted Z events Fitted Wjets events Fitted ttbar events Fitted multijet events	$\begin{array}{c} 141\\ \hline 153.28 \pm 16.99\\ \hline 0.42 \pm 0.12\\ 3.14 \pm 0.94\\ 1.27 \pm 0.63\\ 3.48 \pm 1.48\\ 3.44 \pm 1.37\\ 4.95 \pm 3.12\\ 29.21 \pm 15.74\\ 107.38 \pm 8.69\\ \end{array}$	$\begin{array}{c} 40\\ \hline 39.99 \pm 6.32\\ \hline 0.08 \pm 0.02\\ 0.73 \pm 0.22\\ 4.74 \pm 2.37\\ 1.26 \pm 0.70\\ 0.74 \pm 0.30\\ 17.41 \pm 10.48\\ 15.04 \pm 7.73\\ 0.00 \pm 0.00\\ \end{array}$	$\begin{array}{c} 107\\ \hline 107.07 \pm 10.35\\ \hline 0.94 \pm 0.28\\ 5.27 \pm 1.57\\ 2.09 \pm 1.04\\ 7.98 \pm 3.16\\ 0.24 \pm 0.09\\ 4.60 \pm 2.83\\ 85.94 \pm 11.79\\ 0.00 \pm 0.00\\ \end{array}$

Table 6.11: Predicted yield in each background channel after applying the background-only fit for the 8-jet signal regions and corresponding control regions.

The signal region results are summarized in the conclusive table for this study, Table 6.14, which compares each fitted background yield to the observed data. This information is presented graphically in Figure 6.19. No signal region displays any significant excess over the SM expectations; all observed event counts are consistent with the predicted background. There is no SUSY to be found here.

6.7.2 Discovery Fit

Using only the background fit, no excess above the SM prediction was seen. A discovery fit serves to quantify what new physical processes are feasible or can be



Figure 6.18: Summary plot comparing the SM prediction to data for the control regions.



Figure 6.19: Summary plot comparing the SM prediction to data for the signal regions. No significant excess is observed

Region	SR-9ij-MJ340	CR-8ej-0eb-MJ340	CR-8ej-1ib-MJ340
Observed events	99	57	210
Fitted bkg events	110.33 ± 16.11	57.05 ± 7.55	209.94 ± 14.51
Fitted ttH events	0.46 ± 0.14	0.21 ± 0.06	2.61 ± 0.78
Fitted ttX events	2.95 ± 0.88	1.21 ± 0.36	10.25 ± 3.06
Fitted diboson events	0.50 ± 0.25	7.23 ± 3.60	2.22 ± 1.10
Fitted st events	1.35 ± 1.15	1.87 ± 0.72	11.40 ± 4.06
Fitted Z events	1.75 ± 0.69	1.15 ± 0.46	0.21 ± 0.08
Fitted Wjets events	$1.91^{+2.50}_{-1.91}$	19.45 ± 18.29	4.73 ± 4.60
Fitted ttbar events	28.67 ± 13.21	25.93 ± 15.99	178.53 ± 16.41
Fitted multijet events	72.75 ± 10.20	0.00 ± 0.00	0.00 ± 0.00
Region	SR-9ij-MJ500	CR-8ej-0eb-MJ500	CR-8ej-1ib-MJ500
Observed events	48	16	56
Fitted bkg events	47.89 ± 11.17	15.98 ± 3.42	55.92 ± 7.52
Fitted ttH events	0.14 ± 0.04	0.04 ± 0.01	0.49 ± 0.15
Fitted ttX events	1.33 ± 0.40	0.39 ± 0.12	3.10 ± 0.93
Fitted diboson events	0.07 ± 0.04	2.73 ± 1.38	1.65 ± 0.82
Fitted st events	$0.49^{+0.61}_{-0.49}$	0.66 ± 0.24	2.57 ± 1.43
Fitted Z events	0.69 ± 0.27	0.35 ± 0.14	0.04 ± 0.01
Fitted Wjets events	$0.65^{+1.22}_{-0.65}$	$4.57^{+5.47}_{-4.57}$	$1.07^{+1.39}_{-1.07}$
Fitted ttbar events	11.11 ± 10.04	7.24 ± 4.83	47.00 ± 8.18
Fitted multijet events	33.41 ± 5.57	0.00 ± 0.00	0.00 ± 0.00

Table 6.12: Predicted yield in each background channel after applying the background-only fit for the 9-jet signal regions and corresponding control regions.

ruled out, aiming to be as generic as possible. In this case, the lack of discovery makes it a misnomer, so 'model-independent exclusion fit' is perhaps a more suitable term.

Again each signal region is considered separately, and the same backgrounds and uncertainties from the background-only fit are used. On top of this, however, the fit conducts a scan of signal strengths to set an upper limit on the cross section of new physics allowed given the results observed in data. Control regions are assumed to be uncontaminated by signal. The outputs are the 95% confidence level (CL) upper limits on the visible cross section $\langle \epsilon \sigma \rangle_{\rm obs}^{95}$ and number of signal events $S_{\rm obs}^{95}$, shown in

Region	SR-10ij-MJ340	CR-9ej-0eb-MJ340	CR-9ej-1ib-MJ340
Observed events	22	15	64
Fitted bkg events	23.44 ± 6.06	14.99 ± 3.76	63.99 ± 8.01
Fitted ttH events	0.08 ± 0.02	0.04 ± 0.01	0.69 ± 0.21
Fitted ttX events	0.74 ± 0.22	0.32 ± 0.10	3.60 ± 1.08
Fitted diboson events	0.00 ± 0.00	1.85 ± 0.93	0.86 ± 0.43
Fitted st events	0.41 ± 0.30	0.27 ± 0.20	3.17 ± 1.07
Fitted Z events	0.26 ± 0.10	0.20 ± 0.08	0.03 ± 0.01
Fitted Wjets events	$0.65^{+0.66}_{-0.65}$	5.60 ± 5.49	$1.57^{+1.58}_{-1.57}$
Fitted ttbar events	7.21 ± 5.84	6.72 ± 3.81	54.07 ± 8.57
Fitted multijet events	14.09 ± 2.06	0.00 ± 0.00	0.00 ± 0.00
Region	SR-10ij-MJ500	CR-9ej-0eb-MJ500	CR-9ej-1ib-MJ500
Observed events	15	5	22
Fitted bkg events	12.52 ± 4.19	5.00 ± 2.08	22.01 ± 4.70
Fitted ttH events	0.01 ± 0.00	0.01 ± 0.00	0.16 ± 0.05
Fitted ttX events	0.47 ± 0.14	0.16 ± 0.05	1.40 ± 0.42
Fitted diboson events	0.00 ± 0.00	1.33 ± 0.68	0.81 ± 0.40
Fitted st events		014 0 10	1 5 4 1 0 50
	0.00 ± 0.00	0.14 ± 0.12	1.54 ± 0.52
Fitted Z events	$0.00 \pm 0.00 \\ 0.14 \pm 0.05$	$0.14 \pm 0.12 \\ 0.11 \pm 0.05$	1.54 ± 0.52 0.02 ± 0.01
Fitted Z events Fitted Wjets events	$0.00 \pm 0.00 \ 0.14 \pm 0.05 \ 0.09^{+0.56}_{-0.09}$	$0.14 \pm 0.12 \ 0.11 \pm 0.05 \ 0.61 ^{+3.89}_{-0.61}$	$1.54 \pm 0.52 \ 0.02 \pm 0.01 \ 0.17^{+1.09}_{-0.17}$
Fitted Z events Fitted Wjets events Fitted ttbar events	$0.00 \pm 0.00 \ 0.14 \pm 0.05 \ 0.09^{+0.56}_{-0.09} \ 3.24^{+4.03}_{-3.24}$	$0.14 \pm 0.12 \ 0.11 \pm 0.05 \ 0.61^{+3.89}_{-0.61} \ 2.63^{+3.39}_{-2.63}$	$\begin{array}{c} 1.54 \pm 0.52 \\ 0.02 \pm 0.01 \\ 0.17 \substack{+1.09 \\ -0.17} \\ 17.91 \pm 5.07 \end{array}$

Table 6.13: Predicted yield in each background channel after applying the background-only fit for the 10-jet signal regions and corresponding control regions.

Signal region	Fitted background			Observed events
Signal region	Multijet	Leptonic	Total	Observed events
SR-8j50-MJ340	312 ± 29	155 ± 30	467 ± 40	424
SR-9j50-MJ340	73 ± 10	38 ± 14	110 ± 16	99
SR-10j50-MJ340	14.1 ± 2.1	9.3 ± 5.9	23.4 ± 6.1	22
SR-8j50-MJ500	107.4 ± 8.7	46 ± 16	153 ± 17	141
SR-9j50-MJ500	33.4 ± 5.6	14 ± 10	48 ± 11	48
SR-10j50-MJ500	8.6 ± 1.6	4.0 ± 4.1	12.5 ± 4.2	15

Table 6.14: The expected post-fit SM background separated into multijet and leptonic contributions and the observed number of events from data. No significant excess is observed.

Signal Region	$\langle \epsilon \sigma \rangle_{\rm obs}^{95} [{\rm fb}]$	$S_{ m obs}^{95}$	$S_{ m exp}^{95}$
SR 8j50 MJ340	3.5	64	82^{+20}_{-20}
SR 9j50 MJ340	1.7	32	$35_{-4}^{+\bar{1}\bar{4}}$
SR 10j50 MJ340	1.1	19	19^{+1}_{-0}
SR 8j50 MJ500	1.9	34	41_{-8}^{+13}
SR 9j50 MJ500	1.6	29	27^{+8}_{-6}
SR 10j50 MJ500	0.83	15	12_{-2}^{+4}

Table 6.15: Left to right: 95% confidence level upper limits on the visible cross section $\langle \epsilon \sigma \rangle_{\rm obs}^{95}$ and on the true number of signal events $S_{\rm obs}^{95}$. Finally, $S_{\rm exp}^{95}$) is the 95% confidence level upper limit on the total number of signal events, given the expected number of background events.

Table 6.15.

6.7.3 Exclusion Fit

The final step of the analysis is to address the results in the context of the theoretical models that prompted the search in the first place. Because there was no new physics discovery, this amounts to setting exclusion limits on the parameters of each model. To accomplish this, the signal region is added to the background fit, creating a new scale factor μ_s and signal yield n_s . Each signal point on each grid becomes a new part of the sum v_c from Equation 6.3 with $\mu_s = 1$. Then the fit asks if that point can be excluded.

To make that judgment, the CL_s convention [129] is followed, which determines the exclusion power of the hypothesis by examining how consistent the data is with the background. The p-value⁷ assigned to the signal plus background case, p_1 , is normalized by the background-only p-value p_0 . For each signal point in each model, the significance $Z = \text{erf}^{-1}(1 - p_1)$ is determined, and the point is excluded at a 95% confidence level if Z > 1.64 [129].

 $^{^{7}}$ The p-value is the probability of obtaining a more extreme result than that observed. It is used to express the significance of a result

The resultant exclusion contours are shown in Figure 6.20. At each point, the signal region with the best expected limit is chosen—different signal regions contribute to different parts of the parameter space, with the looser signal regions tending to contribute more at low gluino mass whereas the tighter regions contributed most to setting the high gluon mass limit. For the 2-step model gluino masses are excluded below 1600 GeV, and for the pMSSM slice gluino masses are excluded below 1500 GeV, improving upon the 2015 multijet analysis' gluino mass limits of 1400 GeV for each model [63]. Both of these results significantly extend the limits set by all previous studies, contributing to the narrowing of available SUSY parameter space.



Figure 6.20: The 95% confidence level exclusion contours for the 2-step (top) and pMSSM (bottom) models. Everything below and to the left of the lines is excluded. The dotted red lines bracketing the observed exclusion represent the result of shifting the signal cross section by $\pm 1\sigma$. The yellow band bracketing the expected exclusion represents the $\pm 1\sigma$ variation of the expected limit. The shaded grey region shows the exclusion observed by the previous multijet analysis [63].

6.8 Summary

This chapter presented a search for supersymmetric particles in 18.2 fb^{-1} of 13 TeVproton-proton collisions produced at the LHC and collected by ATLAS. The events investigated featured many jets, with signal regions requiring $\geq 8, 9, \text{ and } 10 \text{ jets.}$ As a result, the search is distinct from many other similar SUSY searches, which require that events contain a large amount of missing energy to stand out from the background. To allow for relatively low thresholds on E_T^{miss} the QCD multijet background is determined using a data-driven template method that takes advantage of the invariance of $E_T^{\text{miss}}/\sqrt{H_T}$ over changes in jet multiplicity. The multiple background is characterized in events with fewer jets and then extrapolated to events with more jets. Other backgrounds are accounted for using simulation, with the largest contributors fitted to data. Results show no excess events over the Standard Model prediction, and are analyzed in the context of two SUSY models, the 2-step and a slice of the pMSSM. Limits are set on gluino production for each: the two-step model excludes gluino masses below 1600 GeV and the pMSSM-inspired model excludes gluino masses below 1500 GeV. The limit contours extend significantly beyond those of previous analyses, demonstrating the power of this search.

Conclusion

We looked at each other for the last time; nothing is as eloquent as nothing.

—David Mitchell, Cloud Atlas

Collisions at the LHC are exploring fundamental particle dynamics at neverbefore-reached energy scales. Years of data collection by ATLAS and other experiments at CERN have made available a veritable trove of information. The power of the Standard Model as a description of fundamental physics has been verified by the discovery of the Higgs boson and refined by the subsequent program of study that has measured particle properties and cross-sections to astounding precision. These successes have demonstrated the efficacy of direct detection methods—the youthful mind's desire to break things apart to see what lies inside.

Unfortunately investigations into potential new phenomena beyond the Standard Model have not yet yielded the anticipated bounty. This thesis presented a search for supersymmetric particles in final states with a large number of jets. The uniqueness of events with such high jet multiplicity allowed the analysis to reach regions of SUSY parameter space untouched by other searches, which tend to require large missing energy. Like the searches that came before it, however, this one found no significant deviation from the Standard Model predictions. The success of the combined SUSY program at ATLAS has come not in the discovery of a new particle pantheon, but in the comprehensive limits set across a wide range of theoretical models. The search presented here examined two different models, the 2-step and pMSSM slice, significantly extending previous constraints on gluino, neutralino, and chargino masses.

Null results can feel discouraging, but looking forward there are still many searches to be done and many places where SUSY might still be found. Collisions are ongoing at the LHC at the time of writing, and will continue until a long shutdown for upgrades begins in 2019. Further SUSY analyses will benefit from the library of limits set by their predecessors and simply from more data. As the quantity of data available for analysis increases, new searches for heavy particles with very small cross-sections become viable. The signal of the Higgs boson itself proved difficult to discern above all the noise, so perhaps the discovery of SUSY particles will require a similar bruteforce approach. Perhaps SUSY particles are not accessible to the LHC. Perhaps, despite its aesthetic appeal and solutions to several outstanding problems, SUSY just does not describe nature.

If I could return to the same classroom I visited in the introduction, after seeing a particle search through from start to finish, I would have a clear answer for the inquisitive rock-smasher. Picking apart the pieces of a particle collision is rewarding because it occurs at the frontier of knowledge, and because every result is a part of a much larger whole.

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Appendix A: The Particle Spectra of the pMSSM

Below are additional particle spectra for the phenomenological minimal supersymmetric extension to the Standard Model (pMSSM), as in Figure 6.5. The purpose of these spectra is to discern a pattern among potential pMSSM models in order to create a 'slice' of pMSSM that is useful for interpretation of the results of the search. These points are characterized by a LSP bino near the Higgs or the Z pole mass, light higgsinos, and a gluino around 1.2 TeV.







Figure 1: Particle spectra for a sample of potential SUSY models which are excluded by the multijet analysis and not excluded by any other analysis. Circled particles are the gluino, Higgsinos, and the bino LSP.

Appendix B: Control Region Variables

This appendix supplements the presentation of various kinetic variables for the six control regions in Section 6.5.1. The purpose of these plots is to compare the distribution of each variable in Monte Carlo simulation and in data to ensure that the control regions are suitably well-modeled for use in mitigating background. Good agreement is seen between data and simulation for each variable. The plots shown are as follows:

- Number of good jets, Figures 6.9 and 2
- M_J^{Σ} , Figures 6.10 and 3
- $E_T^{\text{miss}}/\sqrt{H_T}$, Figures 6.11 and 4
- Leading jet p_T , Figures 5 and 6
- Lepton p_T , Figures 7 and 8
- E_T^{miss} , Figures 9 and 10
- H_T , Figures 11 and 12



Figure 2: The number of jets for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 500$ GeV.



Figure 3: The sum of large-R jet mass M_J^{Σ} for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 500$ GeV.



Figure 4: The distribution of $E_T^{\text{miss}}/\sqrt{H_T}$ for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 500$ GeV.



Figure 5: The distribution of leading jet p_T for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 340$ GeV.



Figure 6: The distribution of leading jet p_T for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 500$ GeV.



Figure 7: The distribution of lepton p_T for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 340$ GeV.



Figure 8: The distribution of lepton p_T for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 500$ GeV.



Figure 9: The distribution of E_T^{miss} for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 340$ GeV.



Figure 10: The distribution of E_T^{miss} for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 500$ GeV.



Figure 11: The distribution of H_T for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 340$ GeV.



Figure 12: The distribution of H_T for the $t\bar{t}$ and W+jets control regions for 7 (top), 8 (center) and 9 (bottom), with $M_J^{\Sigma} > 500$ GeV.

Appendix C: Signal Region Reach

The signal regions are split by the number of jets and by the cut on M_J^{Σ} . The limit contours (Figure 6.20) are constructed by considering each point on the signal grid of each SUSY model and selecting the signal region that has the best-expected CLs value [129]. The CLs value is the adjusted confidence level, taking into account how well the data matches the only-background hypothesis. Figure 13 shows the bestexpected CLs value for each point in the 2-step and pMSSM grids. Once the proper region is selected, the exclusion fit is run on each signal point to form the complete exclusion contour.



Figure 13: The signal region yielding the best-expected CLs value for each point on the 2-step grid (top) and the pMSSM grid (bottom).