

Search for the Supersymmetric Partner to the Top Quark using Recoils Against Strong Initial State Radiation

a dissertation presented
by
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to
The Department of Physics

in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy
in the subject of
Physics

Harvard University
Cambridge, Massachusetts
May 2017

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Abstract

The ATLAS experiment at Large Hadron Collider (LHC) searches for experimental evidence of many new beyond the standard model physics at the TeV scale. As we collect more data at the LHC we continue to extend our sensitivity to these new phenomenon, particularly probing increasingly more massive new particles. Despite this progress there are still regions of parameter space where constraints remain weak. One common cause of this lack of sensitivity is because the new particle has a very small mass splitting between it and its decay products. The particle then has little energy left over to give momenta to its decay products and the low momenta decay products are difficult to experimentally detect. These regions of small mass splitting are called compressed regions. We are able to gain sensitivity to these difficult regions by searching for new particles produced in conjunction with strong initial state radiation (ISR). The strong ISR boosts the new particle's decay products and gives them momentum.

This thesis covers the search for the supersymmetric partner to the top quark (stop) in the region when the stop and its decay products are nearly degenerate in

mass. No searches prior to 2016 was sensitive to this region. We were able to exclude stops up to a mass of 600 GeV in this region with 36.07 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ LHC proton-proton collision data. This data was collected by the ATLAS experiment during 2015 and 2016. As part of this analysis, this thesis introduces a new and more accurate technique for identifying whole ISR systems composed of multiple ISR jets. As the LHC provides more data and traditional search methods rule out parameter space at higher masses, it becomes equally important that we also gain sensitivity to the still unconstrained compressed regions at low masses. The methods demonstrated in this analysis are completely generalizable and can be used in many other BSM searches and precision SM model measurements of the ISR p_T spectrum.

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Acknowledgments

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Introduction

The Standard Model of Elementary Particles (SM) provides a concrete description of the interactions and dynamics of all known elementary particles with the exception of gravity. In the SM, matter is composed of three generation of fermions with spin 1/2 while interactions are governed by gauge symmetries and mediated by spin 1 gauge bosons.

The last piece of the SM, the Higgs boson, was discovered in 2012 at the Large Hadron Collider. The complex scalar Higgs field spontaneously break the electroweak (EW) symmetry by acquiring a vacuum expectation value (VEV). This process of electroweak symmetry breaking (EWSB) gives mass to the W and Z gauge bosons. The fermions also acquire their mass through Yukawa interactions between the Higgs and fermion fields.

Although the Brout-Englert-Higgs mechanism ensure that the SM theory will remain viable as a perturbative physical theory up to the Planck scale, current experimental evidence suggests that the SM is not a complete theory of nature. SM leaves several important fundamental questions unanswered. These open questions include but is not limited to the nature of Dark Matter (DM), the apparent matter/anti-matter asymmetry in the universe, the reason behind the SM mass spectrum, the potential unification of EW and strong interactions at high energy scales, the nature of neutrino mass and the hierarchy problem regarding the naturalness of the Higgs mass. The answers to these questions are at the frontier of physics research and form the major physics goals of many different physics experiments across multiple disciplines.

One proposed solution to many of these questions is the introduction of a new spacetime symmetry called supersymmetry. Supersymmetry imposes a new symmetry between fermions and bosons allowing one to transform into the other. In this way, the supersymmetric extension to the SM (SUSY) predicts the existence of a yet

undiscovered superpartner to every known SM particle. SUSY gives one possible solution to the hierarchy problem of the Higgs as large contributions to the Higgs potential are canceled out between SM particles and their superpartners. Some supersymmetric models also unify the strong and electroweak force at high energies, provides more cp violation to generate matter/antimatter asymmetry and produces plausible dark matter candidates. Plus when SUSY is imposed as a local symmetry, general relativity is automatically included offering a potential path to uniting general relativity with quantum mechanics.

All previous high energy experiments including the Tevatron and LEP have not detected the existence of superpartners leading us to believe that SUSY is a spontaneously broken symmetry. Many different SUSY symmetry breaking mechanism have been proposed but they all make the superpartners more massive then their SM counterparts.

A major goal of the Large Hadron Collider (LHC) experiment is to search for the predicted superpartners at an unprecedeted energy scale. If SUSY is the solution to the hierarchy problem and restores naturalness to the Higgs mechanism then the superpartner to the top quark (stop) is expected to be no heavier then a few TeV. The stop's mass is strongly constrained due to the large coupling between the SM top quark and the Higgs with $\lambda_t \sim 0.94$. As such, searches for the stop at the LHC is especially interesting because the stop's mass may be low enough to be directly produced at the energy scale of the LHC.

This thesis concerns the search for stops in an traditionally experimentally difficult region. One expected stop decay channel produces a the top quark along with the superpartner to a neutral electroweak boson, the neutralino ($\tilde{\chi}_1^0$). Traditional searches for SUSY often targets the experimental signatures of neutralinos as they are unique to SUSY. Experimentally this involves searching for events with large missing transverse energy (E_T^{miss}).

The traditional search strategy can effectively detect stops with large mass splittings between $m_{\tilde{t}}$ and $m_{\tilde{\chi}_1^0}$. However, when the stop mass is nearly degenerate to $m_t + m_{\text{ninoone}}$ the stop has just enough energy to produce the top and neutralino. The resulting stop decay produces gain little momenta from the stop decay. The low p_T neutralinos in turn generate very little E_T^{miss} . The only other observables in the event are the visible tops which are also produced in SM top/anti-top pair production. This inability to distinguish SM ttbar from stop signal greatly hampers the search sensitivity in this region. For example, SM ttbar can have a production cross-section anywhere from 50 to 300 times that of the stop in our region of interest.

The low decay product p_T problem is ubiquitous to all regions of phase space with small mass splittings. Many ATLAS searches in SUSY including charginos, Higgsinos, sbottom, sleptons, etc all have some region of phase space with a compressed mass spectra. In general, such regions of phase space are called compressed regions.

This thesis demonstrates a new method of searching for stops in the compressed

region by isolating events with strong initial state radiation (ISR). The ISR boosts the stops and gives additional momenta to the stop decay products. The correlation between ISR p_T and stop decay product p_T tend to be extremely strong in this region precisely because the stop decay products gain little momenta from the stop decays. Specifically there exists a strong correlation in both direction and magnitude between ISR p_T and E_T^{miss} in signal. The neutralinos will inherit a fraction of the original ISR p_T proportional to $m_{\tilde{\chi}_1^0}/m_{\tilde{t}}$ and E_T^{miss} and ISR systems should be back to back. This two-dimensional correlation allows us to separate signal from ttbar background and overcome the difference in production cross-section. We effectively converted the critical weakness of the region, decay products gaining little p_T from the stop decays, into a strength.

We also developed an accurate ISR identification system for this analysis. The algorithm works by first finding the axis of maximum back to back p_T call the thrust axis. The thrust axis should mimic the axis of back to back boost between the ISR and sparticle systems in events with strong ISR because the ISR and sparticle boost represents the single largest back to back kick in events with strong ISR. We then divide the event into two hemispheres according to the thrust axis. All objects in the same hemisphere as the E_T^{miss} are considered to have originated from a stop decay because we expect the neutralinos to travel in the same direction as the original stops. All objects in the hemisphere opposite the E_T^{miss} are considered to have originated from ISR. In this way, the thrust based algorithm is able to identify entire ISR

systems composed of multiple jets.

The ISR identification algorithm is completely general and can be used to identify ISR for SM processes as well as other BSM searches. The performance of the ISR identification algorithm is covered in detail in chapter 8. In summary, the algorithm can achieve a 9 percent uncertainty on the reconstructed ISR p_T in stop and ttbar events with at least 400 GeV of true ISR p_T . This uncertainty includes any detector uncertainty due to the reconstruction of jets, E_T^{miss} and other physics objects.

The ISR based search has allowed us to finally making a definitive statement on the existence of stops in a region with no previous exclusion sensitivity. Using the 36.07 fb^{-1} 2015 and 2016 $\sqrt{s} = 13 \text{ TeV}$ dataset, we were able to exclude stops in this compressed region with masses between 225 and 600 GeV to 95 percent confidence. We were able to achieve expected exclusion confidence limits of less than 5×10^{-4} for stop masses between 250 and 400 GeV.

The methods demonstrated in this thesis can be applied to other compressed region searches and searches involving ISR such as dark matter searches. The accurate ISR identification algorithm can also directly measure the amount of ISR produced in conjunction with SM particles. Potential applications includes measuring SM ttbar's ISR p_T spectrum.

The thesis is organized as follows. Chapter 1 presents an overview of the standard model and theoretical motivations for supersymmetry. Chapter 2 describes the experimental setup of the LHC accelerator and ATLAS detector. Chapter 3 and

chapter 4 details the reconstruction and calibration of physics objects at ATLAS the ATLAS trigger system.

The physics objects used in the analysis are defined in chapter 5. The Monte Carlo simulations of stop signal and SM background are described in Chapter 6.

Chapter 7 concerns the general strategy used in traditional SUSY searches and the general strategy of using ISR to separate signal from background in compressed region analyses. We present the new thrust based ISR identification algorithm in chapter 8. The algorithm is explained in context of a more general set of algorithms that uses exterminations to classify objects called recursive jigsaw reconstruction. The performance of the ISR identification algorithm is also demonstrated on both signal and background.

Chapter 9 - 11 describes the 2015 and 2016 LHC dataset that is used for this analysis and the kinematic selections used to define the signal region (SR). The chapters develop physical intuition on each signal region selection and explain how they reject different background.

The SM backgrounds in the SR are described in detail in chapter 12. This chapter covers the different methods used to estimate each background, going especially into detail on the dominate background: SM ttbar. A large portion is devoted to building intuition on the unique kinematic properties of each background. This physical intuition is used to explain the CR design and how the CRs are able to accurately estimate the background rate and minimize systematic uncertainties.

Chapter 13 describe each of the experimental and theoretical systematics associated with signal and background. Systematic uncertainty is divided into two categories; experimental uncertainties due to limitations on detector resolution and theoretical uncertainties on the Monte Carlo simulations.

Chapter 14 summarizes the statistical methods used to extract the signal strength. Finally chapter 15 and 16 show the results with 36.07 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ data and give an interpretation of the results on select signal models.

1

Theoretical Motivation

1.1 The Standard Model

The standard model (SM) describes our current understanding of the interactions of all known elementary particles. SM is composed of 3 parts; fermions with spin 1/2 that make up the visible matter in our universe; vector bosons with spin 1 that mediates the interactions between the fermions; and a scalar spin 0 Higgs boson that

gives mass to the massive fermions and the W and Z vector bosons. The fermions are organized in two groups, the quarks and leptons, with three families of increasing mass. The force mediators, the photon, W/Z boson, and gluon are respectively responsible for the electromagnetic, weak, and strong interactions. A diagram displaying the SM particles is shown in figure 1.1.

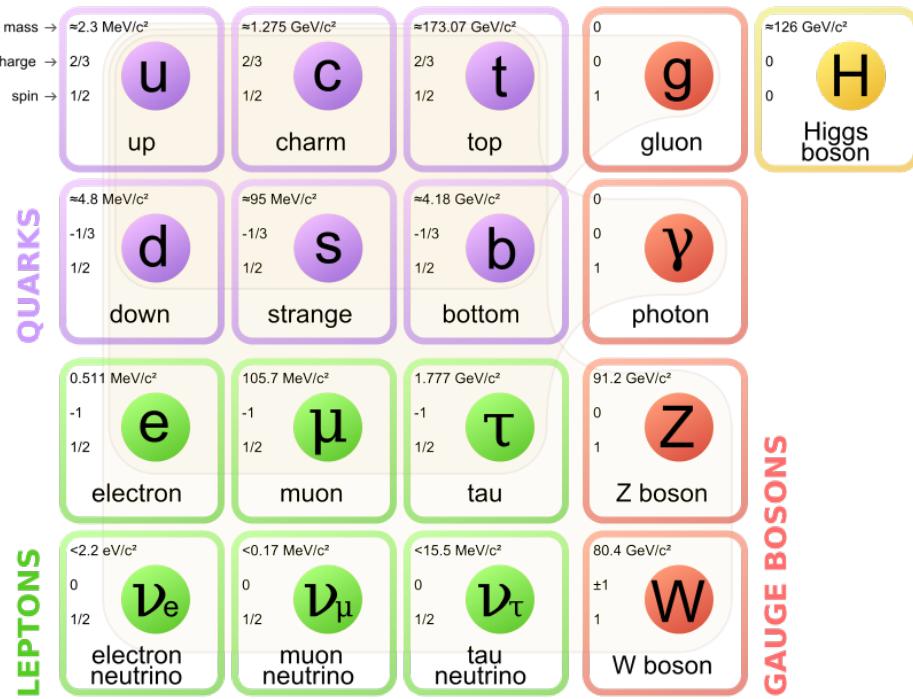


Figure 1.1: List of standard model elementary particles

Interactions in the SM are described by non-abelian Yang-Mills gauge theory with the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ where $SU(3)_C$ corresponds to the strong interaction and $SU(2)_L \times U(1)_Y$ corresponds to the electroweak interactions.

The quarks can interact via the strong interaction described by the $SU(3)_C$ sym-

metry. These quarks carry color charge in addition to their electromagnetic charges. The gluons mediate the strong interactions but unlike electrically neutral photons, gluons carry color charge. The self interaction of the gluon causes the coupling strength of the strong coupling constant α_s to diverge at low energies. This phenomena, called confinement, ensures that quarks are confined to be within composite color singlet states in the form of hadrons. At the same time, the running of α_s approaches zero at high energy; forming a phenomenon known as asymptotic freedom.

For energetic particles like those produced in proton-proton collisions at the LHC, colored partons will recursively radiate collinear gluons and quark/anti-quark pairs in a parton shower. These partons eventually form color-singlet hadrons once the energy scale is lower than IR-cutoff scale due to confinement. The result is a jet of color-neutral baryons and mesons localized in a narrow cone in the direction of the initial colored parton.

Both quarks and leptons also interact via the weak interaction. Specifically, the left handed component of the fermions form an $SU(2)_L$ doublet while the right handed handed components form an $SU(2)_L$ singlet. Therefore, only the left handed components of SM fermions carry weak charge and interact via the weak interaction.

The generators of the gauge groups correspond to the massless spin one vector bosons. The W^\pm and Z bosons acquire mass through spontaneous electroweak symmetry breaking using the Higgs mechanism. This is accomplished using an addi-

tional $SU(2)_L$ doublet of complex spin zero fields, the Higgs field. The Higgs has a nonzero vacuum expectation value (VEV) at the minimum of its quadratic potential shown in equation 1.1. When $\lambda > 0$ and $m_H^2 < 0$, $\langle H \rangle = \sqrt{-m_H^2/2\lambda}$.

$$V(H) = m_H^2|H|^2 + \lambda|H|^4 \quad (1.1)$$

This breaks the $SU(2)_L \times U(1)_Y$ electroweak symmetry and leaves only the $U(1)_{em}$ electromagnetism invariant. Meanwhile, the other gauge bosons from $SU(2)_L \times U(1)_Y$ gains a longitudinal degree of freedom from degrees of freedom associated with the Higgs doublet and thereby gaining mass. The photon, W^\pm and Z bosons are therefore linear combinations of the original $SU(2)_L$ and $U(1)_Y$ generators. The Higgs boson also gives fermions their mass through Yukawa couplings.

After symmetry breaking, only one neutral scalar component of the Higgs doublet is left. This is the massive Higgs boson observed in July 2012 at the LHC.

1.2 Introduction to Super-Symmetry

Theoretical calculations of the self interaction of the Higgs field give enormous quantum corrections to m_H^2 .⁴⁷ For example, the correction to m_H^2 from a loop containing a Dirac fermion f with mass m_f is given in equation 1.3. The Feynman diagram associated with the fermion loop is shown in figure ??

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \dots \quad (1.2)$$



Figure 1.2: One-Loop corrections due to a Dirac fermion f and a scalar \tilde{f} to the Higgs mass parameter m_H^2

λ_f is the Yukawa coupling between the fermion and the Higgs and Λ_{UV} is the ultraviolet cutoff used to regulate the loop integral. Λ_{UV} can be interpreted as around the energy scale of new physics. Since the scale of new physics maybe orders of magnitudes larger then the electroweak scale, the quadratic dependence of m_H^2 on Λ_{UV} makes the Higgs potential extremely sensitive to new physics. This sensitivity to high mass scales for the Higgs potential is referred to as the hierarchy problem.

Supersymmetry (SUSY) solves this problem by proposing that there exist a new space-time symmetry with respect to the transformation Q that turns fermions into bosons and bosons into fermions.

$$Q|Boson\rangle = |Fermion\rangle \quad Q|Fermion\rangle = |Boson\rangle \quad (1.3)$$

The supersymmetric Lagrangian is invariant under transformations of Q and Q^\dagger . In order for this to be satisfied, SUSY proposes the existence of a supersymmetric partner (superpartner) to every known SM particle. SM particles and their superpartners are related to each other by the Q transformation and differ from each other by spin 1/2. If SUSY was an exact symmetry then the SM particle and its superpartner must have the same mass. However, we have yet to discover even a single superpartner to the SM at collider experiments. Therefore, SUSY must be broken at low energies and the superpartners have significantly more mass than their SM counter parts.

Supersymmetry breaking can occur in many ways; the details of which are beyond the scope of this thesis. More details on SUSY symmetry breaking can be found in ⁴⁷. A brief summary of one example of supersymmetry break called Gauge-mediated supersymmetry breaking (GMSB) will be given here. In GMSB, some scalar fields in the SUSY Lagrangian gains a vacuum expectation value due to their potential energy shape. This symmetry breaking gives mass to some fermions and their superpartners called messengers. Both the scalars and the messengers are too heavy to be directly detectable and are not the SM superpartners.

Instead, the messengers contribute effective mass to the superpartners of SM particles via loop interactions. Gauge symmetry ensures that the loop correction to

the SM gauge bosons are zero to all orders of magnitudes, but the same protection is not afforded to their superpartners, the gauginos. These gauginos gain effective mass through one-loop diagrams involving virtual messenger particles. In a similar fashion, the scalar partners to SM fermions gain effective mass through two-loop diagrams involving virtual messengers and SM gauge bosons. In these way, GMSB leads to heavier superpartners relative to their SM counter parts.

In general, if a complex scalar particle \tilde{f} with mass $m_{\tilde{f}}$ exists and couples to the Higgs according to the term $-\lambda_s |H|^2 |\tilde{f}|^2$ then correction to the Higgs mass due to the loop diagram in figure 1.2 is given in equation 1.5.

$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2} [\Lambda_{UV}^2 - 2m_{\tilde{f}}^2 \ln \Lambda_{UV}/m_{\tilde{f}} + \dots] \quad (1.4)$$

This correction also contains a quadratically divergent term that has an opposite sign to equation 1.3. The two quadratic contributions to m_H^2 will cancel if $|\lambda_f|^2 = \lambda_s$ and we are left with only a term that is proportional to $\ln \Lambda_{UV}/m_{\tilde{f}}$. In fact, this cancellation of quadratically divergent term will occur not only for the one loop case, but for all orders of magnitude in perturbation theory if supersymmetry exists.

The term that remains after cancellation is proportional to equation ??.

$$\Delta m_H^2 \sim m_{\tilde{f}}^2 \left[\frac{\lambda_s}{16\pi^2} \ln \Lambda_{UV}/m_{\tilde{f}} \right] \quad (1.5)$$

Its important to note that while the correction is now not so strongly dependent

on Λ_{UV} because of the natural log, the correction term is also directly proportional to m_f^2 . This implies that the superpartners masses cannot be too large, otherwise the correction to m_H^2 is again too large. If we set Λ_{UV} to approximately the Planck scale M_P and $\lambda_s \sim 1$, we find that $m_{\tilde{f}}$ for the lightest supersymmetric particle should not be heavier than the TeV scale if we want to avoid any unphysical fine-tuning on the Higgs mass.⁴⁷

In particular, we know that the superpartner to the top quark has a coupling to the Higgs of order 1 due to $\lambda_S = |\lambda_f|^2 \sim 0.94^2$. This makes searches for the stop especially interesting as it is potentially within reach of the energy of the LHC.

1.2.1 R-Parity Conservation

Supersymmetry introduces many new interactions not found in the SM. Some of these interactions directly violate total lepton and baryon numbers. If such interactions exist then the half life of a proton may be only a tiny fraction of a second. However, proton decay experiments have shown that the proton half-life exceeds 10^{32} years. A new discrete symmetry, called R-parity, is introduced to remove these B and L violating terms from the supersymmetric Lagrangian.

The quantity P_R defined in equation 1.6 and must multiply to 1 for all interaction vertexes for R-parity to be conserved. P_R equals 1 for all SM particles and equals -1 for all superpartners.

$$P_R = (-1)^{3(B-L)+2s} \quad (1.6)$$

R-parity conservation has several important phenomenological consequences. In R-parity respecting SUSY, superpartners are always produced in pairs. Superpartners must always decay into other superpartners forming a long decay chain of SUSY particle to SUSY particle that ultimately end in the lightest supersymmetric particle (LSP) which is absolutely stable. If the LSP is electrically and color neutral, then it is an attractive dark matter candidate.

In this search, we assume R-parity is conversed and the LSP is a weakly interacting neutralino.

2

Experimental Apparatus

The study of standard model (SM) physics at the TeV scale and search for potentially new physics beyond the standard model (BSM) is the highlight of current physics programs at the Large Hadron Collider (LHC). The LHC is a circular superconducting hadron-hadron accelerator capable of accelerating and colliding both protons and lead ions. The LHC is built in the 27km LEP tunnels between 45 to 170m un-

derground near the city of Geneva. The entire LHC accelerator complex, shown in figure 2.1 is operated by the Organization for European Nuclear Research or CERN. More details on the LHC machine and the CERN accelerator complex can be found in³⁸.

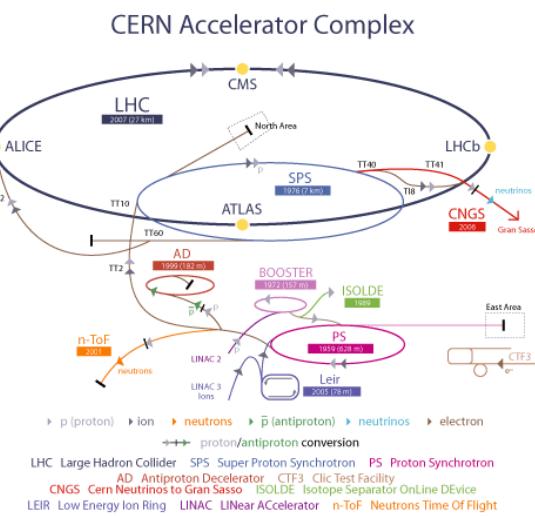


Figure 2.1: The Large Hadron Collider complex. (Figure taken from³⁸)

During 2015 to 2016, the LHC collided protons with a center of mass energy of $\sqrt{13}$ TeV. During 2016, the LHC has already surpassed its design peak instantaneous

luminosity by reach peak instantaneous luminosities of $1.34 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$.

The LHC uses four major particle detectors located at four interaction points at different locations in the ring to study the result of these collisions. Two of these, ATLAS and CMS are hermitic 4π general purpose detectors that study a wide variety of SM and BSM physics including SUSY. ATLAS and CMS are located at the opposite ends of the ring to ensure equal integrated luminosity and serve as validations to one another. The ALICE detector specializes in the collision of heavy ions and LHCb specializes in physics involving the bottom quark.

In addition to the 4 major particle detectors, three smaller experiments, TOTEM, MoEDAL and LHCf, study proton proton scattering cross sections, diffractive processes, and cosmic ray physics.

This analysis uses data collected by the ATLAS detector in 2015 and 2016. A summary of the ATLAS detector is given in section 2.1.

2.1 The ATLAS Detector

The ATLAS Detector is a general purpose detector designed to both search for new physics at the TeV scale and perform precision measurements of SM parameters.

The ATLAS detector is composed of several subdetector arranged in concentric cylinders surrounding the interaction point. The hermitic detector cover nearly the entire 4π solid angle around the interaction point. A cutaway view of the ATLAS de-

tector can be seen in figure 2.2. For more details on the ATLAS detector design and specifications see³⁵.

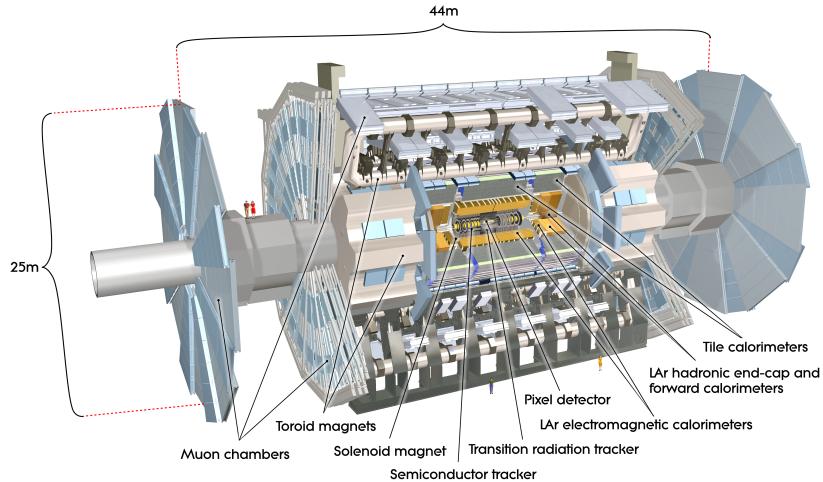


Figure 2.2: Cutaway view of the ATLAS detector with different sub-detector systems labeled. Figure taken from³⁵

Each subdetector system specializes in detecting a specific subset of particles which are expected to result from energetic particle collisions. The detector can be divided into the inner tracker, the electromagnetic calorimeter, the hadronic calorimeter and the muon spectrometer. The detector signatures left by different particles can be seen in figure 2.3.

Details on the reconstruction of physics objects can be found in chapter 3. A brief description of detector signatures will be given here in order to motivate the purpose of each subdetector system.

The inner tracker measures the position of charged particles as they fly through the detector. These position measurements are then connected to form a track

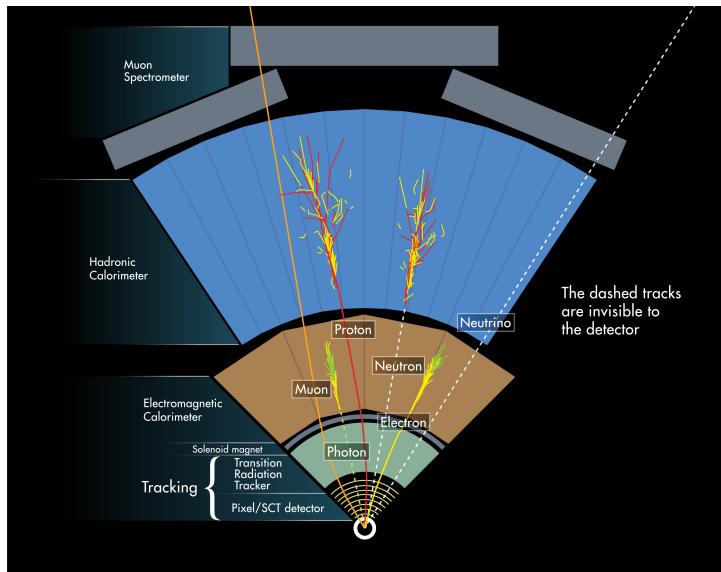


Figure 2.3: Artistic representation of different detector signatures left by particles in ATLAS.
Figure taken from⁴⁹

along the flight path of the charged particle. A central superconducting solenoid magnet provide a 2 Tesla axial magnetic field that bath the entire inner detector volume. The magnetic field bends charged particles thereby allowing for the measurement of momentum as a function of track curvature.

The calorimeters measure the energy of all charged and neutral particles that interact via the electromagnetic and strong force. The ATLAS calorimeter is a sampling calorimeter that alternates between absorber and active material layers. Electromagnetically charged particles such as the electron and photons interact with the dense absorber material mainly through bremsstrahlung, ionization and electron pair production. The newly emitted photons and electron will also pair produce or emit more photons until there is no more energy to continue the process. The result is a

cascade of EM particles called an EM particle shower. Hadronic particles that interact via the strong force will also form analogous hadronic showers.

The shower particles deposit energy in the active material layers within the calorimeter inducing a signal. We can measure the longitudinal and lateral shower shape and shower depth by combining information from the different layers. Showers from EM objects such as photons and electrons form denser narrow profiles while showers from strongly interacting particles form broad showers that penetrate deep into the hadronic calorimeter.

Muons are the only charged SM particle that are expected to be able to fully penetrate the calorimeter intact. Muons in turn leave a track in the muon spectrometer (MS). This track can be matched to the inner detector track forming a combined muon track that traverses the entire detector. A set of barrel and endcap superconducting toroid magnets provide magnetic field to the MS column and adding to the momentum measurement. Field strength vary depending on location but on average an integrated field of 2.5 Tm and 4 Tm are expected for muons traversing through the barrel and endcap.

A combination of these different detector signatures is used to identify and reconstruct the multitude of different particles produced in a particle collision. Electrons leave an electromagnetic shower in the calorimeter with an associated track. Unconverted photons leave an electromagnetic shower without an associated track. Hadrons fragment into jets and leave a hadronic shower in the calorimeter with per-

haps a number of associated ID tracks. Muons are reconstructed from a combined ID and MS track with limited energy deposited in the calorimeter. Taus either decay leptonically or semileptonically to an electron or muon or decays hadronically to pions and leave a narrow hadronic shower in the calorimeter with one or three associated tracks. Particles that interact via only the weak force i.e. neutrinos do not interact with the ATLAS detector. These weakly interacting particles escape the detector completely and their presence are inferred through the conservation of transverse momenta as E_T^{miss} .

The following subsections are dedicated to covering each subdetector in further detail.

2.1.1 Inner Detector

The inner detector consists of three independent sub-detectors. All 3 sub-detectors are immersed in a 2 T axial magnetic field produced by a solenoidal superconducting magnet. Two silicon semiconductor detectors; the Pixel detector and the Semiconductor Tracker (SCT) form the inner part of the tracking volume and the Transition Radiation Tracker (TRT) covers the outer part. The three independent sub-detectors represent the precise and robust pattern recognition system used to reconstruct charged particle tracks and measure charged particle momentum. The ID also provides precise impact parameter measurements and primary and secondary vertex reconstruction.

The layout of the inner detector can be seen in figure 2.4. A summary of the geometry and coverage of each ID subdetector is given in table ??.

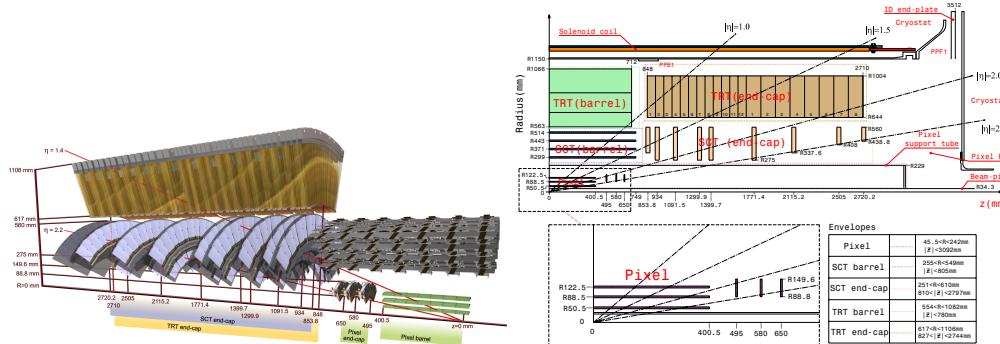


Figure 2.4: (a) Cutaway view of the ATLAS inner detector. (b) Radial View of the ATLAS inner detector (Figure Taken from ³⁵)

More detail on each sub-detector technology is given below.

Pixel Detector and the Insertable B-Layer

The Pixel detector consists of three layers of high resolution pixel sensors in the cylindrical barrel and three wheels of pixel sensors in the endcap. Another inner most layer of pixel sensors called the Insertable B-Layer (IBL) was added directly on top of the new beryllium beam pipe in the first long shutdown between 2012 and 2015. The new beam pipe decreases the amount of multiple scattering before the inner tracker.

The original 3 layer Pixel detector contain of 80.4 million readout channels spread over 1744 Pixel modules. Each module house a sensor tile with an area of 63.4×25.4 mm^2 . The sensors are composed of $250 \mu\text{m}$ thick n-type silicon wafer pixels with a

size of $50 \times 400\mu\text{m}^2$. The modules are read out by 16 front-end electronic chips with 2880 read out channel each.

The pixels have an intrinsic accuracy of $10\mu\text{m}$ in the bending ϕ direction and $115\mu\text{m}$ accuracy in the non-bending z direction in the barrel and ϕ direction in the end-cap.

Installed in 2014, the Insertable B-Layer (IBL) contributes another 12 million channels to the Pixel system in Run 2.^{41,31} Located directly on top of the beam pipe at 3.3 cm from the beam axis, the IBL is the new most inner layer of the Pixel detector (the previous innermost B-Layer was at 5 cm). A schematic representation of IBL stave relative to the beam pipe can be seen in figure 2.5.

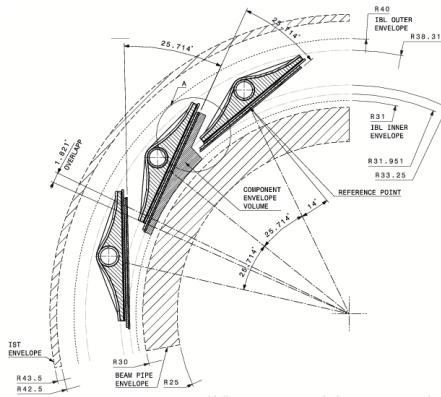


Figure 2.5: Schematic of the ATLAS Insertable B-Layer (IBL) (Figure Taken from⁴¹)

The IBL is composed of 14 staves tilted at 14° in ϕ . Each stave is equipped with 32 FE-I4 front-end chip bonded to silicon sensors. Each FE-I4 chip contain 26880 pixel cells with $50 \times 240\mu\text{m}$ pitch.

The IBL improves both the tracking lever arm and track spacial resolution. The combined gain translate to roughly a factor of 2 better impact parameter resolution and a factor of 4 b-tagging light jet rejection power.

Semiconductor Tracker

The SCT is composed of 4 coaxial layers of concentric cylinders in the barrel and 9 disks in each endcap and contributes at least 4 additional layers of high precision position measurements to tracks. The entire SCT consists of approximately 6.3 million readout channels spread over 4088 modules. A barrel module is equipped with $64.0 \times 63.6 \text{ mm}^2$ sensors orientated in the transverse plane. Barrel sensors are made of $285 \mu\text{m}$ thick silicon wafer and contain 768 strips, achieving a barrel strip-pitch of $80 \mu\text{m}$. The endcap modules contain sensors that are trapezoidal in shape with strip pitch that vary from $54 \mu\text{m}$ to $90 \mu\text{m}$.

The sensors are mounted on a back to back fashion at angle of 40 mrad relative to one another. This allows the measurement of non-bending direction along with improved spacial resolution in the bending ϕ direction. The intrinsic accuracy per SCT module, dictated by the strip pitch, is $17 \mu\text{m}$ in the bending ϕ direction and $580 \mu\text{m}$ in the non-bending direction.

Transition Radiation Tracker

The TRT is the outermost component of the ID and contribute approximately 351000 readout channels. Each channel corresponds to a 4 mm diameter polyimide straw drift tube with a $31\mu\text{m}$ gold plated tungsten anode wire, providing an intrinsic accuracy of $130\ \mu\text{m}$. The total channel number is low compared to the silicon detectors but the TRT is able to compensate for this by providing a long lever arm and high hit multiplicity.

In the barrel region, TRT straws are 144 cm long and arranged parallel to the beam axis in 73 layers. In the end-cap region, straws are 37 cm long and arranged in wheels with 160 radial layers. A typical barrel track will traverse 36 straws because the tubes are arranged a matrix with layers offset from one another.

The dielectric material used to interleave the straws induces transition radiation in traversing charged particles. The low energy transition radiation photons are absorbed by the Xenon-based gas mixture in the straws, thereby providing much larger signal amplitudes than minimum-ionizing charged particles. This can be used to distinguish electrons from pions based on the energy deposition.

In 2015 and 2016, approximately 1/3 to 2/3 of the TRT barrel and 1/7 of the TRT endcap are filled with an Argon gas mixture instead of Xenon due to leaks. This adversely affects electron identification efficiency by a few percent and is taken into account by a scale factor in simulation.

2.1.2 The Calorimeter

The ATLAS calorimeter provides near full solid angle coverage of the interaction point up to an η of 4.9. The calorimeter system is composed of two parts; the electromagnetic calorimeter (ECAL) and hadronic calorimeter (HCAL). Both ECAL and HCAL are sampling calorimeters with different absorber material depending on the detector region. The ECAL uses liquid argon (LAr) as the active material and HCAL uses both scintillating tiles and liquid argon (LAr) as active materials.

The cutaway view of the ATLAS calorimeter can be seen in figure 2.6 and a summary of the calorimeter geometry is given in table ??

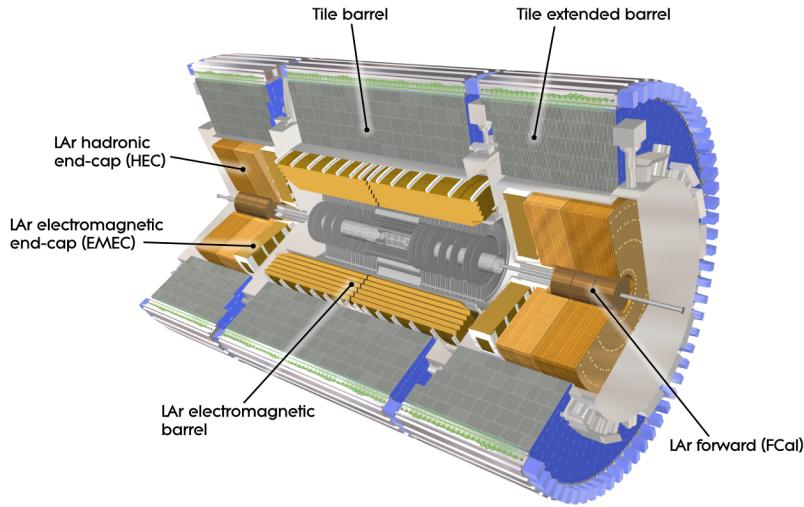


Figure 2.6: Layout of the ATLAS calorimeter. (Figure taken from³⁵)

The design EM resolution is $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.2\%$. The design hadronic energy resolution varies from $\sigma_E/E = (56.4 \pm 0.4)/\sqrt{E} \oplus (5.4 \pm 0.1)$ in the barrel region to

$\sigma_E/E = (94.2 \pm 1.6)/\sqrt{E} \oplus (7.5 \pm 0.4)$ in the forward regions.

Electromagnetic Calorimeter

The ATLAS ECAL is sampling calorimeter with lead absorber plates and LAr active material arranged in an accordion geometry. The ECAL provides coverage up to an η of 3.2 and the accordion design gives full crack-less coverage in ϕ .

The ECAL is split into a barrel and two endcap components with a transition region of $1.37 < |\eta| < 1.52$ in between. The barrel component is divided into two 3.2 m long half-barrel sections with an inner and outer radius of 2.8 m and 4 m respectively. The endcap is divided into two coaxial wheels each 63 cm thick with an outer wheel covering the $1.375 < |\eta| < 2.5$ region and an inner wheel covering the $2.5 < |\eta| < 3.2$ region.

The barrel ECAL is segmented longitudinally into 3 layers with an additional presampler layer in front of certain regions. The presampler is composed of a thin liquid-argon layer 11mm in depth and is designed to determine the energy loss from material upstream of the calorimeter. The first layer after the presampler has a depth of 4.3 radiation length (X_0) and a fine granularity with $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$. The high granularity allows for precision measurement of EM showers and can distinguish between the shower shape of electron/photons from those of $\pi^0 \rightarrow \gamma\gamma$ decays. The middle layer absorbs most of the energy in the EM shower and is made up of cells with $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ and a depth of $16X_0$. The back layer is designed

to collect the tails of the EM showers and to distinguish between EM and hadronic showers. The back layer has cell sizes of $\Delta\eta \times \Delta\phi = 0.05 \times 0.025$ and a depth of $2X_0$.

The endcap ECAL is also divided into three longitudinal layers that perform the functions as the layers in the barrel. The front layer has a depth of $4.4 X_0$ and varies in cell size from $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$ to $\Delta\eta \times \Delta\phi = 0.006 \times 0.1$. The middle layer has cells with the same size as the barrel at $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ and a similar depth. The back layer also has a $\Delta\eta \times \Delta\phi$ of 0.05×0.25 . A presampler also exists for the endcap with each presampler module consisting of two 2mm thick LAr layers.

The ATLAS ECAL segmentation can be seen in figure 2.7.

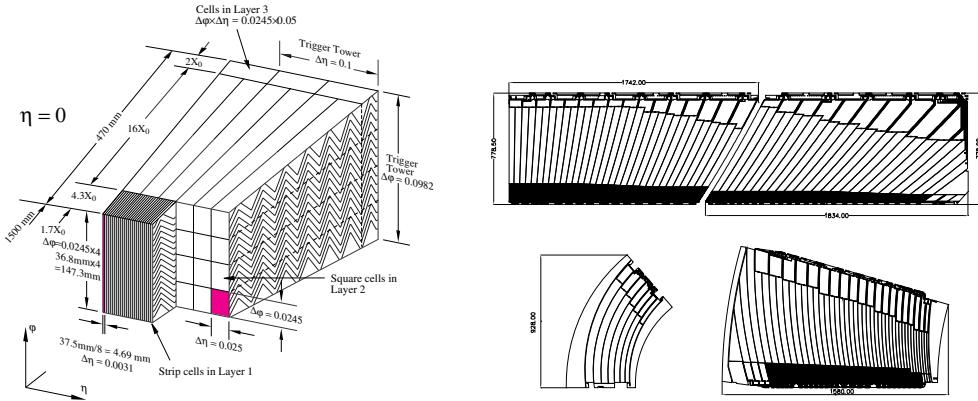


Figure 2.7: (a) The three layers of the EM module with the accordion geometry show. (b) Orientation of EM cells in the barrel and endcap relative to the IP. Cells are orientated to point back to the IP. (Figures taken from ³⁵)

The total thickness of the ECAL is at least $22X_0$ in the barrel and $24X_0$ in the endcap for electrons and photons and approximately 1.5 nuclear interaction length for hadronic objects.

Hadronic Calorimeter

The ATLAS HCAL is directly outside the ECAL and is responsible for containing and measuring the energy of hadronic showers. The HCAL consists of 3 separate detectors covering different η regions. The tile calorimeter covers the central region with $|\eta| < 1.7$. The LAr endcap calorimeter (HEC) covers the endcap region with $1.5 < |\eta| < 3.2$ and the LAr forward calorimeter (FCal) covers the forward region to upwards of $|\eta| < 4.9$.

The tile calorimeter is a sampling calorimeter using steel absorbers and scintillating tiles as active material. The two sides of each scintillating tile are read out by two separate photomultiplier tubes.

The barrel tile calorimeter covers an η range of $|\eta| < 1.0$ and two extended barrel tile calorimeter covers the $0.8 < |\eta| < 1.7$ region. Both barrel and extend barrel calorimeters are divided into 64 modules orientated along the ϕ direction. Each module covers a ϕ region of $\Delta\phi = 0.1$. The module is segmented in the radial direction into 3 longitudinal layers. The 3 layers have an approximate thickness of 1.5, 4.1 and 1.8 nuclear interaction lengths (λ) in the barrel and 1.5, 2.6, and 3.3 λ in the extended barrel.

A Schematic view of a tile calorimeter module can be seen in figure 2.8

The HEC uses LAr as the active material and copper as the absorber with copper plates interleaved between the LAr gaps. The HEC is located directly behind the

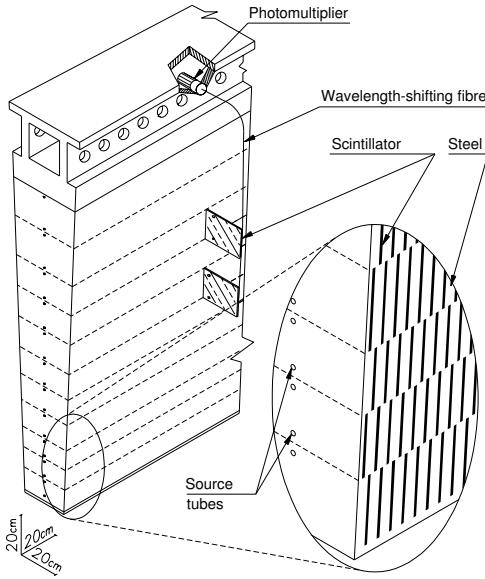


Figure 2.8: The tile calorimeter module with steel absorber, tile scintillators and photomultiplier readout. (Figures taken from³⁵)

ECAL endcap and share the ECAL cryostat. The HEC covers an η range of $1.5 < |\eta| < 3.2$ and overlaps slightly with the tile calorimeter and FCAL in order to minimize any drop in material density.

Geometrically the HEC consists of two independent wheels per endcap with each wheel subdivided into 32 wedge shaped ϕ modules. Each HEC module is composed of cells with a size of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ for the $|\eta| < 2.5$ region and $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ in higher eta regions. The HEC module is also segmented longitudinally into 2 layers making a total of 4 longitudinal layers in the 2 wheels. The combined depth of all 4 layers is approximately 10 interaction lengths.

The FCAL is an LAr sampling calorimeter that extends the η coverage of the HCAL

to 4.9. A compact design with very small LAr gaps is chosen for this high flux region. The FCal is segmented in the longitudinal direction with 3 distinct modules. The absorber material is copper for the first module and tungsten in the last two. The copper absorber is optimized for EM measurements while the tungsten is predominantly designed for hadronic interactions. The 3 modules combined achieves a depth of 10 nuclear interaction length.

2.1.3 The Muon Spectrometer

The muon spectrometer (MS) consists of three layers of precision tracking chambers to track the path of muons in the bending η direction. The precision tracking chambers mainly compose of Monitored Drift Tube (MDT) detectors but also some Cathode Strip Chambers (CSC) in the forward region. Complementing the precision trackers are fast trigger chambers, the Resistive Plate Chambers (RPC) in the barrel and the Thin Gap Chambers (TGC) in the endcap.

The MS is designed to be able to detect muon candidates with a wide range of momenta from 3 GeV to 3 TeV with standalone muon momentum resolution of $\sigma_{p_T}/p_T = 10\%$ at a p_T of 1 TeV. The configuration of the MS is shown in figure 2.9. The open design of the MS minimizes multiple scattering after the calorimeter and gives a large lever arm for high momentum resolution.

Eight air core superconducting toroid magnets in the barrel and eight additional magnets in the endcaps provide a 1.0 Tm to 7.5 Tm of bending power in the MS

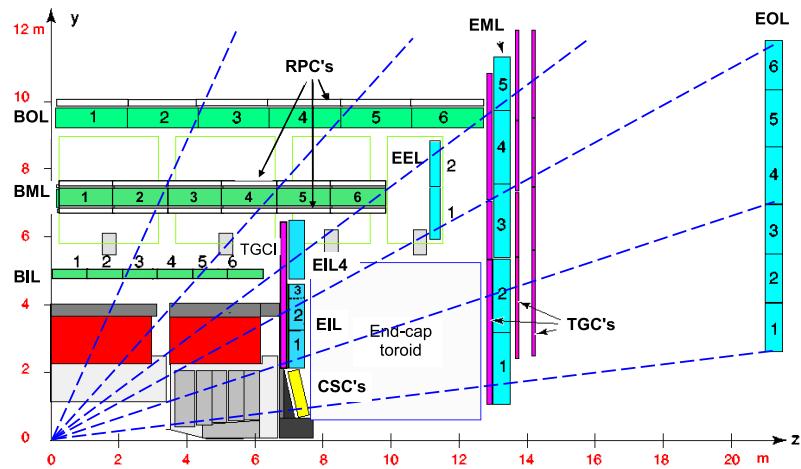


Figure 2.9: Cutaway view of the ATLAS Muon Spectrometer. (Figure taken from³⁵)

volume. The configuration of the magnets is shown in figure 2.10

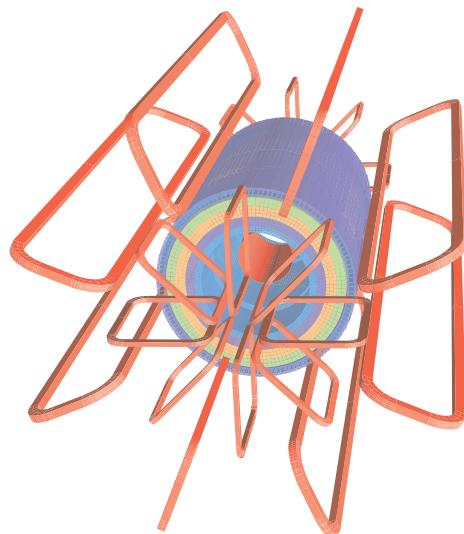


Figure 2.10: Geometry of the barrel and endcap toroid magnets. The cylinder represents the calorimeter. (Figure taken from³⁵)

The barrel magnets cover an $|\eta|$ range of 1.4 and the endcap magnets cover an $|\eta|$ range from 1.6 to 2.7. The area between $1.4 < |\eta| < 1.6$, called the transition region, has a mixed magnetic field from both the barrel and endcap. The endcap magnets are offset from the barrel magnets by 22.5 degrees in ϕ to allow a smoother magnetic field in the transition region.

Muon Precision Tracking

The ATLAS MS system consists of 3 stations of muon precision tracking chambers at approximately 5 m, 7.5 m and 10 m radii in the barrel and 7.4 m, 14 m and 21.5 m in z in the endcap. This provides precision tracking coverage up to an $|\eta| < 2.7$. Most precision tracking chambers use Monitored Drift Tube (MDT) technology with 3 to 8 layers of MDT tubes each. The only exception to this is the very high rate forward region with $2.0 < |\eta| < 2.7$ which uses CSC technology.

MDT tubes are 3cm diameter aluminum tubes filled with Ar/CO₂ gas mixture with a tungsten-rhenium anode wire. Each tube has an intrinsic resolution of 80 μm corresponding to a resolution of 35 μm per chamber and offer measurements in the bending η direction.

The CSCs are multiwire proportional chambers with one layer of anode wires in the bending plane and two layers of cathode strips. The position measurement is obtained by interpolating the signal on neighboring cathode strips. The strips are perpendicular to one another with 5.31mm (5.56mm) pitch in the bending plane and

12.5 mm (21.0 mm) in the non-bending plane for small (large) chambers. This result in a $60\mu\text{m}$ resolution per plane in the bending plane and about 5 mm resolution in the non-bending plane.

The structure of MDT tubes and CSC chambers can be seen in figure 2.12 and 2.12 .

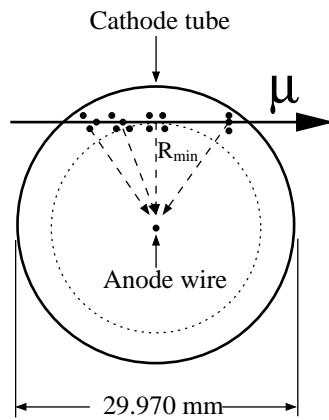


Figure 2.11: Schematic Representation of MDT tubes (Figures taken from³⁵)

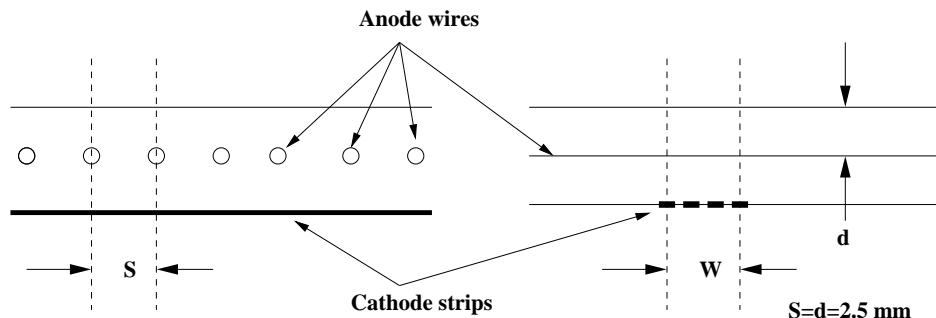


Figure 2.12: Schematic Representation of CSC chambers. (Figures taken from³⁵)

Muon Trigger Chambers

The ATLAS MS also features a system of fast trigger chambers consisting of three station of Resistive Plate Chambers (RPC) in the barrel and 4 stations of Thin Gap Chambers (TGC) in the endcap. The MS triggering system provides triggering coverage up to an η of 2.4. The RPCs are placed below and above the middle MDT station and outside the outer MDT barrel station. The TGC stations are arranged with one station in front of the inner endcap precision tracking wheel and 3 stations split in front and behind the middle endcap MDT wheel. The trigger searches for fast coincidences between the layers along the expected trajectory of a muon. Different maximum deviation from the straight infinite momentum path is allowed for triggers with different p_T thresholds.

In Run 2, muon triggers in the endcap also require coincidences in the inner-most layer of the TGC to reduce fake trigger rates due to particles interacting with beam shielding in the forward region.

A schematic of the muon trigger system is given in figure 2.13.

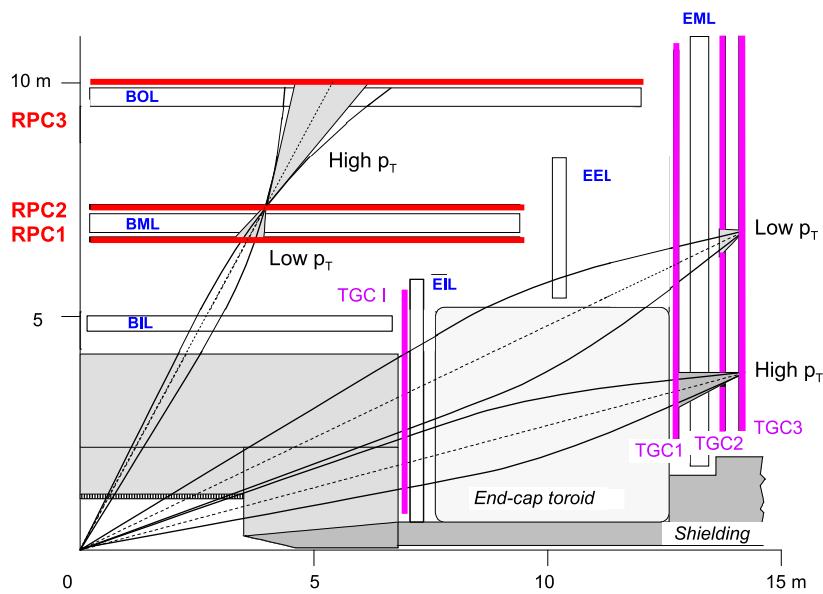


Figure 2.13: Schematic of the ATLAS muon trigger system. The coincidence windows for muons of different p_T is shown. (Figure taken from ³⁵)

3

Object Reconstruction at ATLAS

3.1 Inner Detector Track Reconstruction

Many reconstructed physics objects depend on tracking information in the inner detector (ID). ID tracks are combined with the EM calorimeter and Muon spectrometer information to identify and measure the momentum of electrons and muons. Hadronic jets use ID tracks to determine if the jet originated from a heavy flavored

hadron containing b-quarks or only light flavored hadrons. ID tracks are also crucial to identifying whether objects originate from the interesting hard scattering interaction or a less interesting pileup interaction.

Two types of inner detector tracks are reconstructed, primary tracks and secondary tracks. Primary tracks originate from the interaction point (IP) and are meant to reconstruct the trajectories of charged particles originating directly from the proton proton collisions. Secondary tracks target charged particles originating in the ID from secondary decays and interactions such as $\gamma \rightarrow e^+ e^-$ conversions.

Primary tracks are reconstructed in inside out fashion using the NEWT algorithm.³⁶ First, seed segments are created from three 3D space point measurements in silicon detectors. Each pixel cluster correspond to a single 3D space point. Two SCT clusters on the same layer must be combined to form a 3D space point because each SCT cluster only provide 2D position information.

The space point seeds can come from all pixel (PPP), all SCT (SSS) or two Pixel and one SCT (PPS) space points. PSS space points are rejected due to high fake rates.

Starting from the original seed, track reconstruction is performed layer by layer through the inner detector. Hits are added to the track one layer at a time from the inside out. Any ambiguities for shared hits are resolved using a strategy that penalizes less precise tracks. Merged clusters in the pixel are split using a set of trained neural networks.

In contrast secondary tracks are reconstructed from the outside in. Segments are reconstructed in the TRT and then extended inwards by adding silicon hits.

3.2 Vertex Reconstruction

On average around 25 proton-proton interactions occur in every beam crossing in Run 2. These p-p interactions are spread out in the Z coordinate due to the finite bunch length at the LHC. We are able to reconstruct the original interaction vertex (primary vertex) by tracing back charged particle tracks to the beam line. We are able to differentiate objects from the interesting hard scattering p-p interaction from other pileup interactions using reconstructed vertexes. A summary of the primary vertex reconstruction algorithm is given in this section.

A subset of reconstructed ID tracks are used to reconstruct the primary vertexes.

In Run 2 tracks must satisfy:

$$p_T > 400 \text{ MeV}$$

$$|\eta| < 2.5$$

number of silicon hits ≥ 9 if $|\eta| \leq 1.65$ or ≥ 11 if $|\eta| > 1.65$

IBL hits + B Layer hits ≥ 1

maximum 1 shared module (1 shared pixel hit or 2 shared SCT hit)

pixel holes = 0

SCT holes ≤ 1

A vertex seed is found by searching for the global maximum in the Z coordinate of reconstructed tracks. The vertex position is fitted using an algorithm that is robust to additional noise and outlier tracks called the adaptive vertex fitting algorithm^{14,39}.

Adaptive fitting determines the vertex position using a least squared fitting method, but gives the outlier tracks lower weights in the fit. The vertex position is repeatedly fitted until the fit position no longer changes. A new vertex center is found and new set of weights is calculated for each new fit. The weighting function also changes from fit to fit according to a predeterminate way; giving more weight to a smaller sub-set of tracks each iteration, ultimately approaching a step function.

This method of lowering the weight of outlier tracks in each fit and decreasing the weight in each iteration is called determinist annealing.³⁹ The procedure is analogous to repeatedly heating and cooling metal in a forge to make the metal's crystal lattice more regular. At each iteration, a more compact and regular set of tracks are selected eventually ending in a fix set of selected tracks.

After determining the vertex position, all tracks within 7σ of the vertex is considered to be associated with the vertex. A conservative 7σ acceptance is used to avoid one energetic vertex being split into two during reconstruction. Tracks incompatible with the vertex from a new vertex seed. This process is repeated until all tracks have been clustered into vertexes or no additional vertexes can be found. Each vertex must have at least two associated tracks.

The primary vertex with the highest total p_T summed over all associated tracks is identified as the vertex of the hard scattering interaction. All other primary vertexes are referred to as pileup vertexes.

3.3 Hadronic Jets

Energetic partons carrying color charge produced in the initial hard scattering will quickly fragment into multiple hadrons. The result is a shower of charged and neutral hadrons referred to as a parton shower. The parton shower leaves a roughly conical energy deposit in the electromagnetic and hadronic calorimeter and multiple associated tracks in the inner tracker. Some energy may even be deposited in the muon spectrometer if the initial hadron is energetic enough. This detector signature is referred to as a jet.

Identification and reconstruction of hadronic jets is very important for many different detector signatures including this analysis. Of key importance is the correct reconstruction of the initial parton energy. Also important is the rejection of jets resulting from pile-up interactions and identifying jets resulting from b-quarks. Jet reconstruction and energy calibration are described in sections 3.3.1 and 3.3.2. Jet vertex tagging and b-jet tagging are described in section 3.3.3 and ??.

3.3.1 Hadronic Jet Reconstruction

Hadronic jets are reconstructed by clustering energy deposits in the calorimeter.

First, all topologically connected calorimeter cells are clustered around a seed cell that passes the 4σ signal above noise threshold. These 3D clusters are referred to as topological clusters (topo-clusters).^{1,12} Neighboring cells around the cluster are added to the cluster if they pass a 2σ signal over noise threshold. This step is repeated until no neighboring cells pass the 2σ signal over noise threshold. At this stage, one last round of neighboring cells is added regardless of the amount of signal to noise ratio in those cells.

Topo-clusters are then grouped into jets according to the $\text{anti} - k_t$ algorithm. The $\text{anti} - k_t$ algorithm groups objects according to the distance measure d_{ij} defined in equation ?? with parameter $p = -1$. All objects within d_{ij} less than $d_{iB} = k_{Ti}^{2p}$ are grouped into a single jet.

$$d_{ij} = \min(k_{Ti}^{2p}, k_{Tj}^{2p}) \frac{(\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2)}{R^2} \quad (3.1)$$

The algorithm can best be explained by examining an example case. If a hard object 1 exists and is surrounded by only soft objects j then d_{1j} equals $k_{1j}^{2p}(\frac{\Delta R^2}{R^2})$ for all j where $\Delta R = \Delta\eta^2 + \Delta\phi^2$. d_{1j} will always be less than any d_{ij} if both i and j are both soft and have the same ΔR as 1 and j . Therefore, the $\text{anti} - k_t$ algorithm effectively

groups hard objects first before soft objects.

A perfectly conical jet of radius R will be formed if no other hard objects are found within a cone of $2R$. If two hard objects exist within $R < \Delta R_{1,2} < 2R$ of one another then two jets will be formed splitting the energy cells between them. If two hard objects exist within $\Delta R_{1,2} < R$ then they will both be grouped into a single jet.

The $\text{anti}-k_t$ algorithm is both infrared and collinear safe. Meaning the algorithm is insensitive to the radiation of additional soft particles and the collinear splitting of initial partons. Additional soft partons do not change the shape of the jets but the jet shape is flexible to accommodate the presence of other hard radiation.

ID Tracks are associated with jets according to a ghost association procedure.³⁰ Tracks with the same direction and location as real ID tracks but infinitesimally low p_T are allowed to be clustered by the $\text{anti}-k_t$ algorithm. If these tracks are assigned to the jet by the $\text{anti}-k_t$ algorithm then the real track is associated with the jet. In this way, we can determine which tracks are associated with the jet without disturbing the clustering of calorimeter energy. The same procedure of clustering infinitesimally low p_T objects is used to determine the jet area.

3.3.2 Jet Calibration and Systematics

Both the electromagnetic and hadronic calorimeters at ATLAS are sampling calorimeters. The energy deposited in the absorber material is effectively lost because the absorber do not actively record a signal. Therefore the energy measured using the

active material must be scaled up to compensate for this loss. For this reason and others including leakage of energy outside of the calorimeter edges and deposition of energy below the energy thresholds, reconstructed jets must be calibrated to determine the original hadron's energy.

A variety of MC based and data based methods are used to calibrate hadronic jets. Figure 3.1 shows the steps in jet calibration for Run 2.[?]

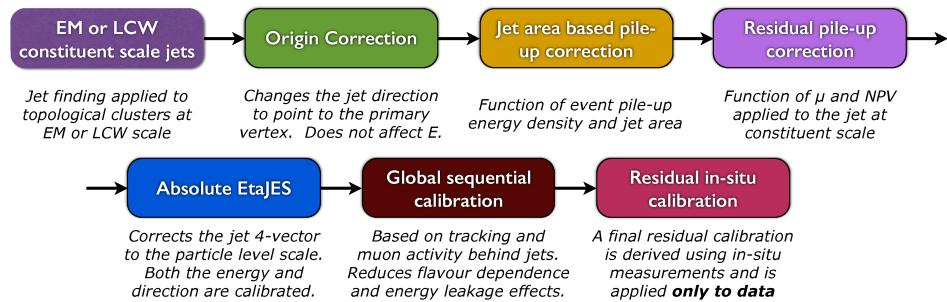


Figure 3.1: Flow chart of the steps involved in jet calibration. (Figure taken from[?])

First the individual topo-clusters in the jet are calibrated to the energy scale of EM showers using MC simulations.[?] It should be noted that this calibration is to EM showers correctly calibrates the energy in EM showers but underestimates the amount of energy lost in hadronic showers. Additional corrections are applied in the following steps to account for this difference.

A correction for energy deposited by pileup interactions are applied.² The correction is based on the measurement of average energy originating from pileup ρ multiplied by the measured jet area. The pileup energy density is defined in equa-

tion 3.2 and determined by measuring the median energy density of $R = 0.4$ k_t jets found in the central $|\eta| < 2.0$ part of the calorimeter. The k_t algorithm preferentially cluster soft objects first instead of hard objects and is more sensitive to soft pileup radiation and no p_T thresholds are applied to the reconstructed k_t jets as we are trying to measure soft objects.

$$\rho = \text{median}\left\{\frac{p_{T_i}^{k_t, \text{jet}}}{A_i^{k_t, \text{jet}}}\right\} \quad (3.2)$$

The area based pileup energy correction is subtracted along with two other residual corrections. The total pileup correction to jet p_T is given in equation ??.

$$p_T^{\text{corr}} = p_T - \rho \times A - \alpha \times (N_{PV} - 1) - \beta \times \langle \mu \rangle \quad (3.3)$$

It should be noted that the jet energy response still has a dependence on pileup after this area based correction has been applied. The sources of this dependence can be attributed to the incomplete cancelation of in-time and out-of-time pileup.¹⁰ For example, events with a low number of reconstructed vertexes (N_{PV}) in a run with high average number of interactions per bunch crossing ($\langle \mu \rangle$) may receive relatively large amounts of out-of-time pileup compared to in-time pileup. This effect is also parameterized by using the constants α and β in equation ??.

In the next step, the jet energy scale (JES) is applied. JES is a scale factor which relates the reconstructed jet energy with the true jet energy. JES is calibrated using

a number of MC and data driven methods. The JES is derived from an inclusive jet MC after pileup and origin corrections have been applied.

A residual difference between the energy responses of gluon and light quark jets remains after JES calibration.¹⁰ The difference can be as large as 8 percent and is due to a number of reasons including the factor of 2 difference in color charge between quarks and gluons. A global sequential correction scheme (GSC) is applied to account for this difference and correct for other detector based issues.⁹

GSC corrections uses information on the topology of energy deposits, associated inner detector tracks and activity in the muon spectrometer behind the jet. ID Tracking information is used to reduce the flavour dependence because gluon initiated jets tend to have a wider profile and more tracks. Muon spectrometer information is used to better estimate high energy jets which penetrate the full depth of the calorimeter. Information on the relative amount of calorimeter energy deposited in specific layers is used to improve the jet energy resolution.

Lastly, further corrections to the jet energy response are obtained by measuring the balance between jets and some reference objects directly in data.^{6,5} The reference object can be a photon, a Z boson or other jets. The p_T balance between jets and the reference objects are measured in data and compared to the MC. A residual correction is applied by the data over MC ratio based on equation ???. Systematic uncertainties on the jet energy responses including those on the jet energy scale and jet energy resolution are also derived using these data driven methods.

$$\frac{R_{data}}{R_{MC}} = \frac{\langle p_T^{jet} / p_T^{ref} \rangle_{data}}{\langle p_T^{jet} / p_T^{ref} \rangle_{MC}} \quad (3.4)$$

The jet p_T resolution for $|\eta| < 0.8$ and $0.8 < |\eta| < 1.2$ jets are shown in figure 3.2.⁵

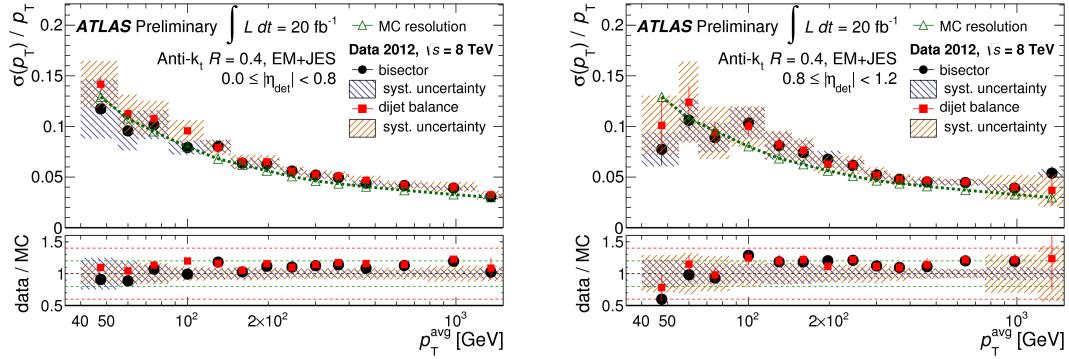


Figure 3.2: Jet p_T resolution for $|\eta| < 0.8$ and $0.8 < |\eta| < 1.2$ jets as a function of jet p_T in 8 TeV data. (Figure taken from⁵)

3.3.3 Pileup Jet Rejection and Jet Vertex Tagger

It is imperative to be able to distinguish between jets originating from the hard scattering interaction (hard scattering jets) and those originating from other pile-up interactions (pileup jets) in the high luminosity LHC environment. Pileup jets may originate from both the on average 25 additional p-p interactions in the same bunch crossing or from interactions in other beam crossings. We distinguish between the hard scattering jets from pileup jets using a multivariate discriminate known as the jet vertex tagger (JVT).⁴

The JVT discriminate is based on two variables corrJVF and R_{pT} defined in equations ?? and 3.6.

$$\text{corrJVF} = \frac{\sum_i p_T^{\text{trk}_i}(PV_0)}{\sum_i p_T^{\text{trk}_i}(PV_0) + \frac{\sum_{n \geq 1} \sum_i p_T^{\text{trk}_i}(PV_n)}{kn_{\text{trk}}^{\text{PU}}} \quad (3.5)}$$

$$R_{pT} = \frac{\sum_i p_T^{\text{trk}_i}(PV_0)}{p_T^{\text{jet}}} \quad (3.6)$$

The corrJVF variable roughly corresponds to the fraction of a jet's ID track p_T that originate from the hard scattering vertex. $\sum_i p_T^{\text{trk}_i}(PV_0)$ is the sum of all jet's associated track p_T that originate from the primary vertex PV_0 . The quantity $p_T^{\text{PU}} = \sum_{n \geq 1} \sum_i p_T^{\text{trk}_i}(PV_n)$ is the total amount of a jet's associated track p_T that originates from pile up interactions. p_T^{PU} is divided by $kn_{\text{trk}}^{\text{PU}}$ to correct for the fact that $\langle kn_{\text{trk}}^{\text{PU}} \rangle$ will increase linearly with the number of pileup vertexes $n_{\text{trk}}^{\text{PU}}$. This makes the variable corrJVF roughly independent to the number of reconstructed vertexes. The value k is set to an arbitrary 0.01 and the discriminating power of JVT was found to be independent of the choice of k .

R_{pT} is defined as the total track p_T of all associated tracks that originate from the primary vertex PV_0 divided by the fully calibrated jet p_T . It is important to note that the calibrated jet p_T includes pileup subtraction. R_{pT} peaks sharply at zero for pileup jets. On the other hand, R_{pT} corresponds to roughly the charged p_T fraction in hard scattering jets.

The JVT discriminate constructs a 2D likelihood based on these variables. The JVT discriminate determines the probability that a jet will be a hard scattering jet using the k-nearest neighbor (kNN) multivariate technique⁴⁰ trained on a $20 < p_T < 50$ GeV and $|\eta| < 2.4$ MC sample of hard scattering and pileup jets. The k-nearest neighbor (kNN) algorithm is robust relative to local fluctuations in sparsely populated regions.

For our analysis we require a jet vertex tagger value greater than 0.59. This corresponds to a 92 percent efficiency for jets originating from the hard scattering interaction and a 2 percent fake rate from pileup jets, if the jet has $|\eta| < 2.4$ and $p_T < 60$ GeV. The JVT efficiency as a function of jet p_T is shown in figure 3.3

3.3.4 Jet Quality and Jet Cleaning

Several variables are useful in discriminating between real hadronic jets and fake jets not coming from p-p interactions. The sources of fake jets include noise in the LAr and Tile calorimeters, beam induced backgrounds and cosmic raw showers. These variables can be divided into three broad categories: variables quantifying the EM and hadronic calorimeter energy ratio, ID track based variables and variables based on the pulse shape of the LAr calorimeters. Detailed descriptions of the variables used can be found in¹³ a brief summary will be given here.

Energy ratio variables can reject calorimeter noise and beam induced backgrounds and energy deposited from cosmic rays. Jets originating from beam induced back-

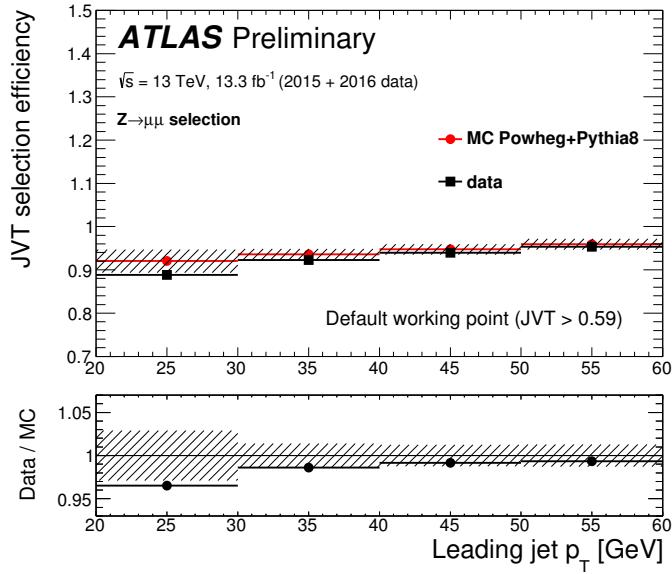


Figure 3.3: The distribution showing the jet vertex tagger efficiency as a function of jet p_T in 2015+2016 data. Only jets balanced against a $Z^- \rightarrow \mu\mu$ boson are accepted. Details can be found in⁴.

grounds tend to concentrate more energy in a few longitudinal layers compared to jets from p-p collisions. Multiple variables corresponding to the fraction of jets energy deposition in any one section along the expected direction of the shower relative to the total energy deposition are useful in discriminating against fake jets.

Energy ratio variables include:

f_{EM} : ratio of EM calorimeter energy to total jet energy

f_{HEC} : ratio of HEC calorimeter energy to total jet energy

f_{max} : maximum energy fraction in any single calorimeter layer

ID track based variables are useful because tracks can be matched to the primary vertexes in good jets. Fake jets have low fraction of tracks which can be matched to

primary vertexes.

list of track based variables include:

f_{ch} : ratio of the scalar sum of ID track p_T where ID track must originate from the primary vertex to jet p_T . approximately the fraction of jet energy carried by charged particles.

f_{ch}/f_{max} : ratio of f_{ch} and f_{max} , the maximum energy fraction in any single calorimeter layer

Pulse shape in the LAr should be consistent with those of a particle shower in good jets. A quality variable Q_{cell}^{LAr} measures the quadratic difference between expected and actual pulse shapes in each LAr cell. Quality variables based on the fraction of cells in a jet with poor quality and the average quality is found to provide discrimination power against LAr noise.

LAr pulse shape variables include:

$\langle Q \rangle$: weighted average of pulse quality of LAr cells (Q_{cell}^{LAr}) in a jet. Normalized to $0 < \langle Q \rangle < 1$.

f_Q^{LAr} : Fraction of energy in cells with poor quality pulse shapes in EM LAr Calorimeter

f_Q^{HEC} : Fraction of energy in cells with poor quality pulse shapes in hadronic endcap calorimeters (HEC) which also use LAr technology.

E_{neg} : total energy of all cells with negative energy

A jet satisfying any one of the following criteria is considered a BadLoose jet.

The presence of a BadLoose can result in poor E_T^{miss} reconstruction due to a noisy calorimeter or beam induced background. Therefore, if any baseline jet in the event

is found to be BadLoose then the entire event is rejected. This procedure is called jet cleaning.

A jet is considered a Loose jet if is not identified as a BadLoose jet. Loose jets are used as signal jets in most ATLAS physics analysis including this one.

$$f_{EM} > 0.5 \text{ and } |f_Q^{HEC}| > 0.5 \text{ and } \langle Q \rangle > 0.8$$

$$E_{neg} > 60 \text{ GeV}$$

$$f_{EM} > 0.95 \text{ and } f_Q^{Ar} > 0.8 \text{ and } \langle Q \rangle > 0.8 \text{ and } |\eta| < 2.8$$

$$f_{max} > 0.99 \text{ and } |\eta| < 2.0$$

$$f_{EM} < 0.05 \text{ and } f_{ch} < 0.05 \text{ and } |\eta| < 2$$

$$f_{EM} < 0.05 \text{ and } |\eta| \geq 2$$

3.3.5 Identifying Jets Originating from Heavy Flavor Hadrons

Hadrons containing b-quarks have long lifetimes, around 1.5 ps or a $c\tau$ of roughly 450 μm . The long flight distance allows us to reconstruct ID tracks with large impact parameters and perhaps reconstruct secondary vertexes.

Three separate algorithms have been setup to distinguish jets originating from b-hadrons (b-jets) from light hadrons and c-hadrons (c-jets). A brief description of each algorithm is given in this section. More details can be found in ¹⁷ and ⁸.

The first algorithm is based on track impact parameters for high quality tracks that are associated with jets. The discriminant is computed as a sum of the log like-

lihood ratio of each accepted track in the vertex or $\sum_i \ln(\frac{p_b}{p_{light}})$, where i sums over all accepted tracks in the jet and p_b is the PDF for a b-jet and p_{light} is the PDF for a light jet. The PDF uses transverse and longitudinal impact parameters d_0 and z_0 as observables and is derived from MC simulation.

The second algorithm seeks to reconstruct the secondary vertex associated with the b-hadron decay. This algorithm has the advantage that if a secondary vertex is consistent with the decays of long lived hadrons that do not contain b-jets such as K_s or Λ or photon conversions then the vertex maybe rejected. For example, secondary vertexes with a mass greater then 6 GeV are inconsistent with b decays and are rejected. Variables based on the secondary vertex location, energy, and mass can all be used to discriminate b-jets from light-jets and c-jets.

The third algorithm attempt to reconstruct the full b-hadron decay chain and is called the decay chain multi-vertex reconstruction algorithm. The algorithm uses a Kalman filter to determine the common line on which the primary vertex and the bottom/charm vertexes lie.

The output of the three algorithms are all combined into a multivariate discriminant called MV2. MV2 uses a boosted decision tree (BDT) algorithm⁴⁰ to gain better separation power between different jet flavors. This analysis uses the MV20c10 discriminant to tag b-jets. MV20c10 is selected as it gives the best balance between light jets and c-jet rejection for a given b-tagging efficiency.

The b-tagging efficiencies and mis-tag rates have been calibrated by the ATLAS

flavor tagging group. The distribution of the MV2c10 discriminate for light, charm and b-hadrons can be seen in figure 3.4. We make a selection at $\text{MV2c10} > 0.6459$ which corresponds to approximately 77% b-tagging efficiency with a factor of 134 reject rate for light jets.

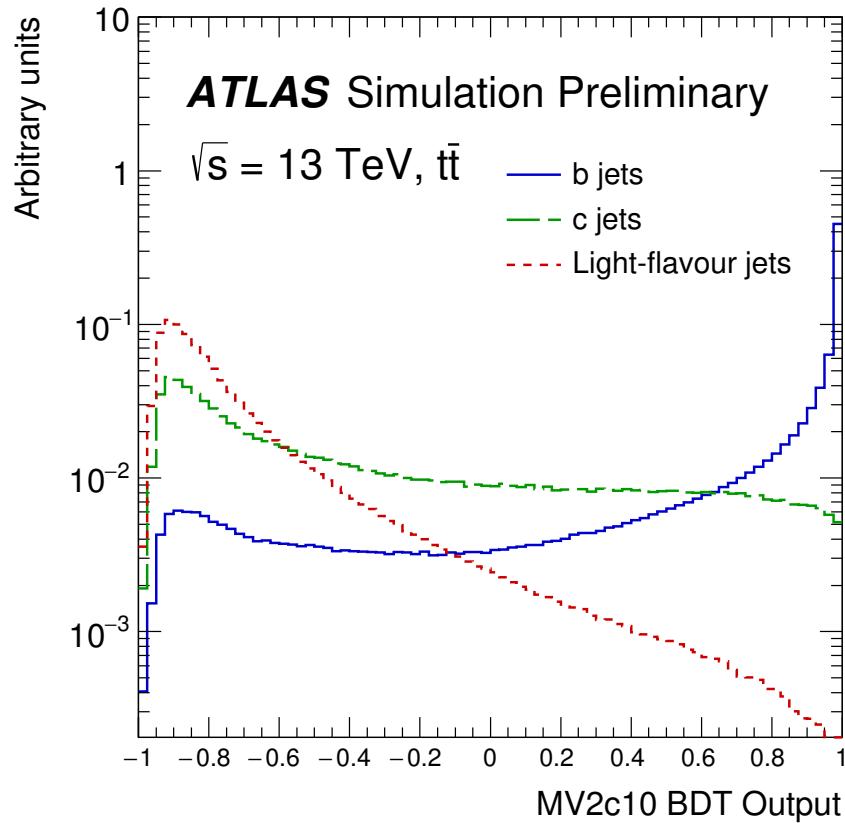


Figure 3.4: Distribution of the MV2c10 multivariate discriminate used for tagging b-jets.
Figure taken from¹⁷

3.4 Electron and Photons

3.4.1 Electron and Photon Reconstruction

Both electron and photon reconstruct start from clusters of energy deposits in the electromagnetic calorimeter. The EM calorimeter is first divided into a grid of towers each with the size of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. The energy from all longitudinal layers inside each tower is summed into the total tower energy.

The EM clusters are seeded by towers with energy above a certain threshold. A sliding-window algorithm groups energy towers near the seed into EM clusters.^{15,32} The window width is 3×7 towers in the barrel and 5×5 towers in the endcap. The reconstructed cluster therefore has a size of $\Delta\eta \times \Delta\phi = 0.075 \times 0.175$ in the barrel and 0.125×0.125 in the endcap. The same window size is used for electrons and photons to ensure better cancelation of systematics when using electrons to measure photon response.¹⁵ The window position is adjusted so that the reconstructed cluster energy is the local maximum. The different cluster sizes were optimized for the different energy distribution in the barrel and endcap calorimeters while minimizing pileup and noise contributions.¹⁵

Identified clusters are then matched to reconstructed ID tracks using the track and cluster position. ID tracks are required to have a minimum number of pixel and total silicon hits. Clusters are considered an electron candidate if a single well-

reconstructed ID track with an associated vertex is found. The cluster is considered an unconverted photon candidate if no tracks are found. The cluster is considered a converted photon candidates if two opposite signed collinear tracks which are consistent with electrons are present. The cluster is also considered a converted photon if a single track is present but the track lacks hits in the IBL of the pixel detector.

Furthermore, electron and photon candidates must satisfy a set of criteria. These variables include descriptions of the EM shower shapes, amount of hadronic activity behind the EM calorimeter and properties of associated tracks. More details on electron and photon identification are given in section 3.4.2 and ??.

A schematic of the electron reconstruction algorithm can be found in figure ??.

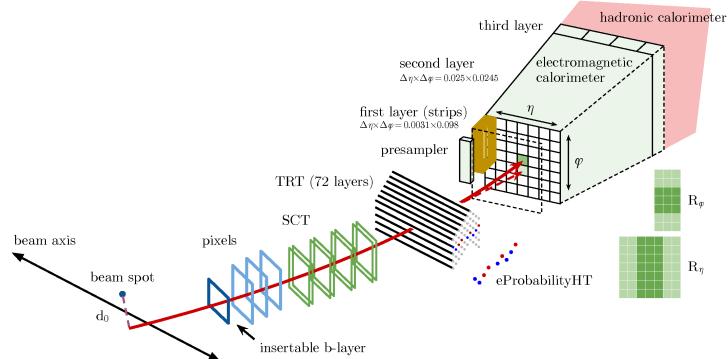


Figure 3.5: Schematic representation of the electron reconstruction algorithm. (Figure taken from¹⁶)

3.4.2 Electron Identification and Quality

Electron identification in Run 2 is based on a likelihood algorithm that depends on a list of kinematics variables including EM shower shape, EM vs hadronic activity ratio, activity in the TRT and properties of the associated track. The list of variables included in the likelihood can be found in¹⁶. A multivariate technique is used to ensure the PDF estimation is robust in low statistics regions in the high dimensional space.⁴⁰ Probability density functions (PDF) are formed for electrons and non-electron backgrounds for a set of discriminating variables used on MC. The probability of the candidate being an electron is calculated using the two PDFs.

Electron identification is split into categories *very loose*, *loose*, *medium*, and *tight*. Each operating point is a sub-set of another. For example, all tight electrons are also medium electrons and all medium electrons are also loose electrons. Because some shower shape distributions tend to broaden with the number of pileup collisions, the cut on the likelihood discriminant is loosened as a function of the number of vertices. This is done to preserve the identification efficient at high pileup and does not drastically increase the amount of background.¹⁶

The electron identification efficiency for the different electron qualities are shown in figure 3.7. 25 GeV tight electrons have an efficiency of 78 percent and fake rate of 0.3 percent. 25 GeV loose electrons have an efficiency of 90 percent and fake rate of 0.8. The efficiency increases with E_T while the fake rate decreases.¹⁶

3.4.3 Photon Identification and Quality

Photon identification is based on the shower shape and the amount of hadronic activity behind the EM cluster. The energy deposited in the cells in the first and second layer of the EM calorimeter are important for distinguishing the EM shower originating from photons and those originating the neutral mesons such as π_0 . A detailed list of the discriminating variables used can be found in ¹⁸.

The requirements differ for converted and unconverted photon candidates to account for differences in expected shower shapes. The requirements also differ according to pseudorapidity intervals to account for the varying amount of material upstream of the calorimeter. These requirements were optimized using a multivariate technique.⁴⁰

Two working points are included a loose and a tight selection. The loose ID exploits the variables only in the EM calorimeter and in the hadronic calorimeter layer and is typically used for the trigger and for background studies. The tight ID uses the full granularity of the EM calorimeter, including the fine segmentation of the first sampling layer, and tightens requirements on the variables used in the loose selection. The tight working point is the one generally recommended for physics analysis and photons used in this analysis are tight photons.

Distribution of photon identification efficiency for tight photons are shown in figure ??.

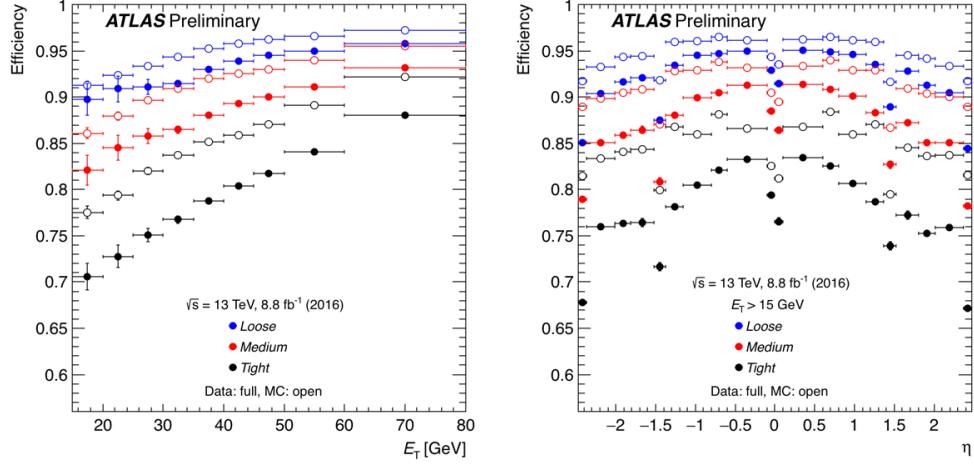


Figure 3.6: Electron identification efficiency in 2016 data as a function of E_T and η for different electron qualities. (Figure taken from ¹⁶)

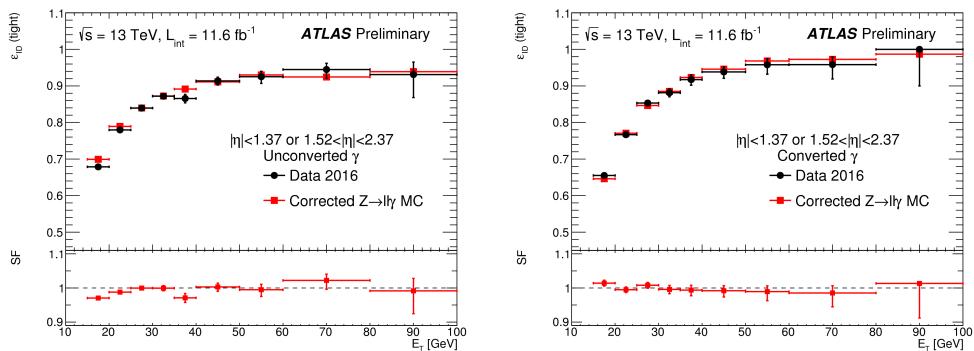


Figure 3.7: Photon identification efficiency in 2016 data as a function of E_T for converted and unconverted photons. (Figure taken from ¹⁵)

3.4.4 Electron and Photon Energy Calibration

Electron and photon energy must be calibrated because of the sampling nature of the EM calorimeter. At the same time, correctly estimating the amount of material upstream of the calorimeter is also important. Typically a 100 GeV electron will deposit between a few percent to 20 percent of its energy before it reaches the calorimeter.¹⁵ Plus roughly 5 percent of the electron energy may be deposited outside of the cluster. Electron and photon energy calibration account for all these effects to get an estimate of the true electron and photon energy. The calibration procedure follow the steps displayed in figure 3.8.

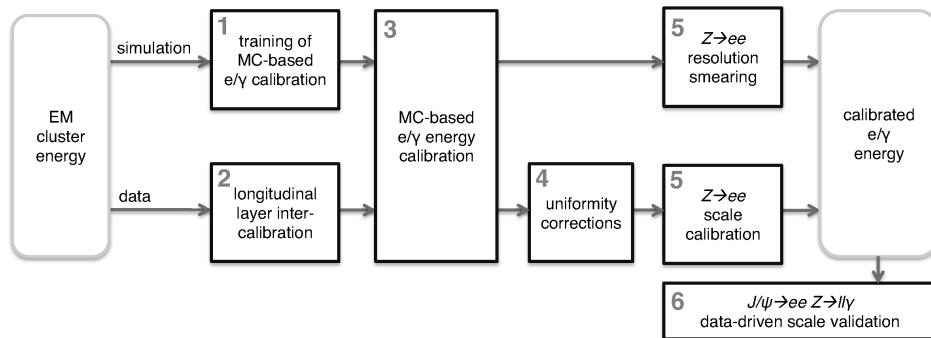


Figure 3.8: Flow chart of the steps involved in the calibration of the energy response of electrons and photons. (Figure taken from³²)

The EM clusters are first calibrated to the original electron or photon energy using a multivariate technique⁴⁰ based on MC simulations.^{15,32} The MC based calibration uses information on the EM cluster properties such as the longitudinal shower shape and information from any associated ID track. The response is different for

electrons, converted photons and unconverted photons.

The longitudinal layers of the EM calorimeter must be calibrated relative to one another. Specifically, the relative energy response of the presampler and the first and second layer must be validated using data. These cannot be done at the cluster level as clusters sum over all longitudinal layers. The intercalibration of the first and second layers of the EM calorimeter is performed with $Z \rightarrow \mu\mu$ decays. This is because muon energy deposits in the calorimeter are relatively insensitive to the amount of material upstream of the EM calorimeter. The presampler energy scale is calibrated as the ratio of data to MC in the presampler energy detected in electrons from W and Z s. This accounts for any mismodeling of the amount of material in front of the presampler.

A number of corrections are then applied to account for differences between simulation and data such as regions with non-optimal high voltage and geometrical effects. Finally a correction is applied to ensure that the $Z \rightarrow ee$ modeling in simulation agrees with data. The same scale factors derived for electrons from $Z \rightarrow ee$ are applied to photons and additional photon-specific systematic uncertainties are also applied.

Cross-checks of the electron and photon calibration is performed with $J/\psi \rightarrow ee$ and $Z \rightarrow ll\gamma$ events in data after all energy corrections are applied.

3.5 Muons

3.5.1 Muon Inner Detector and Muon Spectrometer Track Reconstruction

Muons are first reconstructed independently in the inner detector (ID) and muon spectrometer (MS). Later information from the ID, MS and calorimeter are combined to form different types of reconstructed muons. The type of reconstructed muon formed depend on the type of information available.³³

Muon tracks in the ID are reconstructed using the same algorithm for reconstructing all ID tracks summarized in section 3.1.

Muon tracks reconstructed in the MS start by forming segments in each individual muon chamber. A Hough transform is used to search for hits aligned in the bending η plane of the detector.⁴² The MDT segments are reconstructed by performing a straight line fit. The RPC or TGC hits are associated with the MDT segment and measure the coordinate in the non-bending ϕ plane. Segments in the CSC are constructed using a combinatorial search in η and ϕ planes. Segment reconstruction require that the segments are loosely compatible with a track originating from the collision point.

Muon spectrometer track candidates are built by fitting together the segments from different muon detector layers. The algorithm start from seed segments from the middle layer of the MS because the middle layer has more TGC and RPC hits

available. The algorithm searches for other segments in the other layers by matching their relative positions and direction. Segments are added to the track candidate if they satisfy a set of criteria based on hit multiplicity and fit quality. Afterwards seed segments from the middle layer have been exhausted, segments in the inner and outer layers are also used as seeds to search for their own tracks.

At least two matching segments are required to build a track, except in the barrel to endcap transition region. In the transition region, a single high quality segment with both MDT and trigger hits can be considered a track.

At this point, the same segment can be in several track candidates. Overlap removal is then performed to either assign the segment to a single track or allow the segment to be shared between two tracks. Tracks that share two segments in the inner and middle layer are allowed if there are no shared hits in the outermost layer. This preserves the high efficiency of reconstructing two close by muons which can result from the two-body-decays of low-mass particles.

Once the track candidate is identified, the hits associated with each track candidate are fitted using a global χ^2 fit. Hits with large χ^2 are removed and the track is refitted without the outlier hits. Additional hits consistent with the track trajectory can also be added to the track. Again the track is refitted if any new hits are added. A track candidate is accepted if the fitted χ^2 satisfies the selection criteria.

3.5.2 Muon Combined Reconstruction

Four different types of muons are reconstructed by combining information from the ID, MS, and calorimeters. The four different types of muons are defined below based on what subdetector information is used to reconstruct them.

Combined muons: Combine muons combine reconstructed ID and MS tracks by performing a global refit that uses all the hits from the ID and MS tracks. MS hits may be added or removed from the track to improve the fit quality. The matching between MS and ID tracks are done mostly in an outside-in fashion. The MS track is extrapolated inwards and matched to an ID track with the energy loss in the calorimeter taken into account. The inside-out matching approach where the ID track is extrapolated outwards is also used as a complementary method.

Segment tagged muons: An ID track is combined with a MS segment in the MDT or CSC to form a segment tagged muon. The ID track is extrapolated to the MS to find matching segments. Segment tagged muons add reconstruction efficiency to muons that are either so low p_T that they pass only a single layer of muon detector or are in MS regions with gaps in coverage.

Calorimeter tagged muons (Calo-tagged): Calo-tagged muons are built by combining an ID track with calorimeter energy deposits that are consistent with a minimum ionizing particle. Calo-tagged muons has the lowest purity rate of all reconstructed muons. However it recovers some efficiency in regions with none or low MS coverage such as the central $|\eta| < 0.1$ region. The $|\eta| < 0.1$ region is occupied by cabling and servicing to the calorimeter and ID and only has partial MS coverage. The calo-tagged muon identification algorithm is optimized for the $|\eta| < 0.1$ region and a momentum range of $15 < p_T < 100$ GeV.

Extrapolated muons: In extrapolated muons the muon trajectory is reconstructed using only the MS track and a loose requirement of compatibility with

the interaction point. Extrapolated muons are used mainly to extend acceptance passed ID coverage in the $2.5 < |\eta| < 2.7$ region.

3.5.3 Muon Quality

Reconstructed muons are flagged as loose, medium or tight in terms of quality. The quality selections identify prompt muons originating from the interaction point and reject backgrounds which mainly consist of muons originating from leptonic pion and kaon decays.

Pion and kaon decays in-flight can form a muon in the ID that then gets reconstructed as a track in the MS. The ID track of the muon will have a distinct kink topology. The resulting combined track will have both poor fit quality and poor matching between ID and MS track momenta. Therefore, combined muon use the following variables to distinguish between high and low quality muons:

q/p significance: q/p significance measures the compatibility of the ratio of charge and momentum (q/p) given by the ID and MS tracks. The quantity is normalized to the uncertainty on (q/p) from the two tracks.

ρ' : ρ' is the difference in p_T of the ID and MS tracks divided by the p_T of the combined track

fit χ^2 : The χ^2 of the fit to the combined track normalized to the degrees of freedom

Quality selections also set requirements on track hits to ensure a robust momentum measurement. Muon tracks have at least one Pixel hit and at least five SCT hits

with fewer than three Pixel or SCT holes. If the track is located between η of 0.1 and 1.9, we also require at least 10 percent of TRT hits originally assigned to the track are still included in the final fit.

Muon quality are split into four categories; Loose, Medium, Tight, and High- p_T . Loose, medium and tight muons are inclusive of one another. For example, all tight muons are also included in the looser categories. Medium muons represent a good balance between momentum resolution and reconstruction efficiency. Most analysis including this one uses medium muons to identify signal muons. We use signal muons in multiple one lepton control regions to estimate backgrounds. We use loose muons to veto on muons in the zero lepton signal and validation regions because of the higher muon reconstruction efficiency.

High- p_T muons sacrifices reconstruction efficiency for better momentum resolution in muons with $p_T > 100$ GeV and are used mainly for heavy resonances searches such as $W\ell$ and $Z\ell$. We do not use high- p_T muons and will not discuss their identification in detail. Detailed description of the loose, medium and tight muon categories are given below.

Medium muons: Medium muons are considered the default muons used in physics analysis at ATLAS. The identification algorithm is designed to minimize systematic uncertainties on momentum measurement and reconstruction efficiency. Only combined and extrapolated muons are accepted. Combined muons must have ≥ 3 hits in at least two separate layers. The only exception is in the central $|\eta| < 0.1$ region where tracks can have at least one MDT layer but no more than one MDT hole is allowed. Extrapolated muons must have at least three MDT/CSC layers and are allowed only in the forward

$2.5 < |\eta| < 2.7$ region which lies outside of ID coverage. q/p significance must be less than 7 in combined muons to ensure good agreement between ID and MS and reject decay-in-flight muons originating from hadrons.

Loose muons: Loose muons identification is designed to maximize reconstruction efficiency while still ensuring high quality tracks. All combined and extrapolated muons must satisfy the same requirements as the medium muons. On top of this calo-tagged and segment tagged muons are also allowed in the $|\eta| < 0.1$ region in order to increase efficiency. The majority of loose muons are still combined muons with approximately 97.5% of all loose muons being combined muons in the $|\eta| < 2.5$ region. The rest consist of 1.5% calo-tagged and 1% segment tagged muons.

Tight muons: Tight muons are optimized to maximizes muon purity but costs some reconstruction efficiency. Only combined muons with hits in at least two muon stations and satisfy the medium definition are accepted. The combined track fit's normalized χ^2 must also be less than 8. A two dimensional cut in ρ and q/p significance is also applied. The 2D cut is tighter for low p_T muons to have better background rejection in a regime where misidentification probability is higher.

3.5.4 Muon Reconstruction Efficiency and Momentum Calibration

Muon reconstruction efficiency and muon momenta calibrations are determined by studying narrow resonances decaying into muon pairs in data. A brief summary is given below and more details can be found in ³³.

Muon reconstruction efficiency is measured in data by using a tag and probe method using $J/\psi \rightarrow \mu\mu$ or $Z \rightarrow \mu\mu$ events. A well reconstructed muon (medium quality that fires the trigger) is considered the tag. Then a muon reconstructed us-

ing a different system to the one studied for example an bare ID track is considered the probe. We search to see if the probe is reconstructed as a muon. We can reject background processes by selecting for events who's tag and probe have an invariant mass and other kinematic features that are consistent with the narrow resonance .

The efficiency for medium and tight muons is a combination of two tag and probe measurements. First the probability of reconstructing a X muon is tested using a calo-tagged muon as the probe where X is a medium or tight muon. This essentially measure the probability of identifying a MS track of sufficient quality given an ID track+calo-tagged muon exists. Then the probability of an ID track of sufficient quality is measured using the MS track as a probe. The total efficiency is given by equation 3.7.

$$\epsilon(X) = \epsilon(X|ID) \cdot \epsilon(ID) = \epsilon(X|CT) \cdot \epsilon(ID|MS) \quad (3.7)$$

We assume that $\epsilon(ID) = \epsilon(ID|MS)$ or that the ID and MS track reconstruction occur independently of one another. We also assume that the X muon has the same probability of being reconstructed regardless of whether a calo-tagged muon was reconstructed or only an ID track was reconstructed or $\epsilon(X|ID) = \epsilon(X|CT)$.

Run 2 muon reconstruction efficiency for loose and mediums are shown in figure 3.9.

Muon momentum is calibrated to $J/\psi \rightarrow \mu\mu$ or $Z \rightarrow \mu\mu$ events in data. The p_T

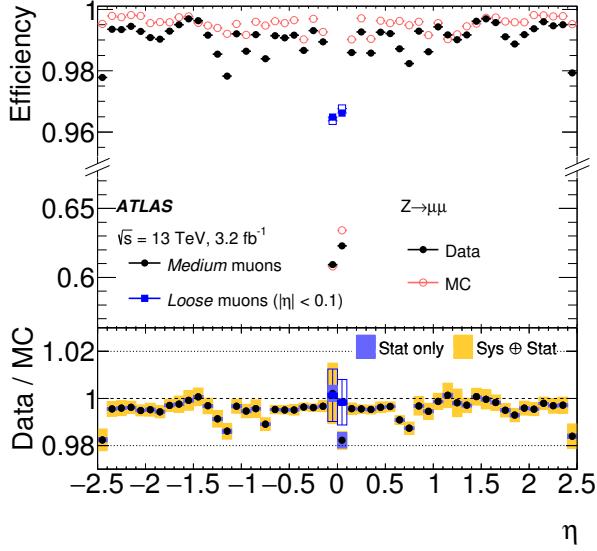


Figure 3.9: Distribution of muon reconstruction efficiency for loose and medium muons.³³ Loose and medium muons are identical except in the $|\eta| < 0.1$ region where loose muons also accept calo-tagged and segment tagged muons to recover efficiency.

of individual tracks are corrected to account for any inaccuracies in the detector description such as the magnetic field, dimensions of the detector and the amount of energy loss in the calorimeters. Correction parameters are extracted using a likelihood fit to data with templates derived from MC simulation. MS/ID alignment is also studied using special runs with no magnetic field. The correction parameters differ for different sections of η and ϕ regions because of the different amount of magnetic fields and independent alignment performed in each section.

On top of the total correction to the central value of the p_T , the momenta resolution is also estimated using data. The MC is smeared such that the reconstructed

di-muon mass peak agrees between data and MC. The muon momenta resolution is described according to equation 3.8

$$\frac{\sigma(p_T)}{p_T} = r_0/p_T \oplus r_1 \oplus r2 \cdot p_T \quad (3.8)$$

r_0/p_T accounts for fluctuations in the energy loss in the calorimeter material. r_1 describes multiple scattering, local disturbances in the magnetic field and displacement of hits. $r2 \cdot p_T$ describes the spacial resolution on the detector hits and any potential mis-alignment in the MS. Uncertainty on all 3 parameters r_0 , r_1 and r_2 are extracted using a likelihood fit to $J/\psi \rightarrow \mu\mu$ or $Z \rightarrow \mu\mu$ events in data.

The effect of muon momenta calibration on the MC simulation of $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ mass peaks can be seen in figure 3.10.

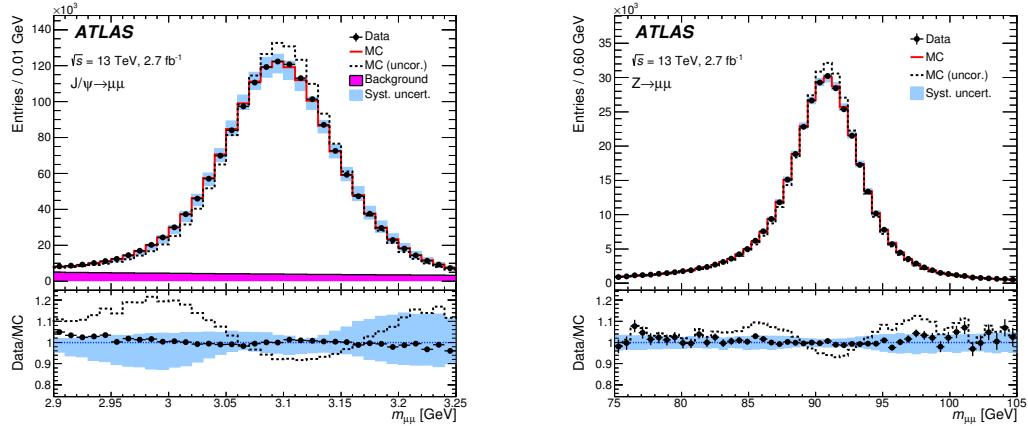


Figure 3.10: Dimuon invariant mass before and after muon momenta calibration in data and MC.³³

3.6 Missing Transverse Momentum

Stable or metastable particles which only interact via the weak force and gravity cannot be directly detected at ATLAS. In SM, these particles correspond to neutrinos. In BSM models, there maybe many other weakly interacting particles including WIMPs, gravitons, and a stable neutral SUSY LSP.

The presence of weakly interacting particles is inferred through conservation of transverse momentum. The total transverse momentum is zero in the initial colliding partons at the LHC. Therefore, any momentum imbalance in the transverse plane must be due to undetected particles in the final state.

3.6.1 E_T^{miss} Reconstruction

We reconstruct the E_T^{miss} according to equation 3.9. The first term is a negative vector sum of all hard fully calibrated objects and the second term represents the \vec{E}_t of all soft objects in the interaction.

$$E_T^{\text{miss}} = -\left(\sum_{\text{hard objects}} E_T + \sum_{\text{soft}} E_T\right) \quad (3.9)$$

Fully calibrated hard objects include muons, electrons, photons and jets that satisfy their respective baseline selections. Hadronic taus are not independently reconstructed and calibrated. Therefore, hadronic taus will most likely be reconstructed as

hadronic jets for our analysis. Baseline object definitions can be found in the physics object definitions in chapter 5 . An overlap removal algorithm have been applied to the baseline objects to remove any potential duplicate objects.

We use a track based method called Track Soft Term (TST)⁷ to reconstruct the contribution from soft objects. TST build the E_T^{miss} that is not associated with any hard objects by summing the p_T of ID tracks.

TST has the advantage of being relatively robust against pileup interactions because TST use ID tracks that are matched with the primary vertex. However TST cannot measure the contribution to E_T from neutral particles because neutral particles do not leave tracks in the ID. TST is the standard method of estimating E_T^{miss} at ATLAS in Run 2 due to the high pileup conditions.

Only tracks with $p_T > 400 \text{ MeV}$ are accepted and a number of track quality requirements are applied. The track quality requirement follows recommendations from the ATLAS tracking performance group and include a minimum of 7 silicon hits and a requirement on the track d_0 . Any tracks within a ΔR of 0.05 of any electron or photon cluster, the ID tracks of muons, and any ID tracks matched to jets are removed to avoid double counting. Further details on TST can be found in⁷.

E_T^{miss} reconstructed using this method is the standard E_T^{miss} used throughout all signal, control and validation regions in this analysis and is simply referred to as E_T^{miss} . This method of reconstructing E_T^{miss} is also referred to as TST E_T^{miss} to distinguish it from an alternative method of reconstructed E_T^{miss} called track E_T^{miss} described in

section 3.6.2.

3.6.2 Track E_T^{miss} Reconstruction

Track E_T^{miss} forms a complementary method of reconstructing E_T^{miss} . Track E_T^{miss} is reconstructed using a negative vector sum of all accepted ID tracks. ID tracks must pass the same requirements described in section 3.6.1 for the TST but no attempt is made at removing tracks that are associated with hard objects. The one exception to this is tracks associated with an electron. Because of the high number of interaction expected between an electron and the material in the ID, electron tracks are replaced with the electron calorimeter cluster instead.

Track E_T^{miss} is very robust against pileup conditions ATLAS has very good vertex resolution but neglects the presence of neutral particles. Track E_T^{miss} is also limited by η coverage of the ID which only extends to an $|\eta| < 2.5$. We use track E_T^{miss} as a cross check on the object based E_T^{miss} reconstruction described in 3.6.1. Both object based and track based E_T^{miss} must agree loosely in direction for our analysis.

3.6.3 E_T^{miss} Performance

E_T^{miss} performance maybe measured using a number of processes include $Z \rightarrow ll$, $W \rightarrow l\nu$ and $t\bar{t}$. $Z \rightarrow ll$ produced with additional jets is considered the gold standard. Very little intrinsic E_T^{miss} is produced in the $Z \rightarrow ll$ plus jets process. This presents a good opportunity to study the effect of the E_T^{miss} soft term calculation

since no hard invisible particles exist. The only variable intrinsic to E_T^{miss} reconstruction is the soft term. All other terms in E_T^{miss} reconstruction depend directly on the resolution of the respective reconstructed hard objects. $W \rightarrow l\nu$ is also used to study a topology with a high- p_T neutrino and therefore intrinsic E_T^{miss} and ttbar is used to study topologies with a large number of jets.

Results from $Z \rightarrow ll$ performance study⁷ will be summarized here. The $W \rightarrow l\nu$ E_T^{miss} and ttbar study will not be covered here but further detail can be found in⁷.

$Z \rightarrow \mu\mu$ events are selected by requiring exactly two same flavor, opposite signed muons with $p_T > 25$ GeV. The dilepton invariant mass must be within 25 GeV of the Z mass.

Distribution of the E_T^{miss} resolution in $Z \rightarrow \mu\mu$ events , defined as the root-mean-squared (RMS) of the E_T^{miss} distribution is shown in figure 3.11. The E_T^{miss} resolution degrades both with the total amount of E_T in the event and the number of reconstructed vertexes.

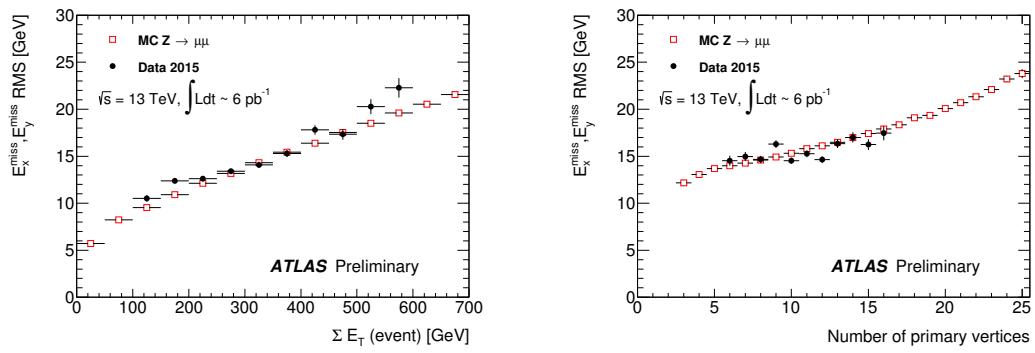


Figure 3.11: Distribution of the TST $E_{\text{T}}^{\text{miss}}$ resolution relative to the total E_{T} of reconstructed objects in $Z \rightarrow \mu\mu$ events and Distribution of the TST $E_{\text{T}}^{\text{miss}}$ resolution relative to the number of reconstructed vertexes in $Z \rightarrow \mu\mu$ events. $E_{\text{T}}^{\text{miss}}$ resolution degrades as E_{T} and pileup increases. (Figures taken from⁷)

4

Trigger

Due to the large volume of data produced at the LHC, an efficient and robust triggering system is essential in deciding which events are potentially interesting and recorded for later study. The ATLAS trigger system is divided into two levels in Run 2. The first-level trigger (Level1 or L1 trigger) is hardware based and uses a subset of detector information to quickly reduce the rate of accepted events from the initial

40 MHz to 100 kHz. Afterwards, the software based high-level trigger (HLT) further reduces the event rate to 1 kHz. Any events passing the HLT are recorded by ATLAS for further reconstruction and offline analysis.

Object reconstruct at the HLT is done only to the precision required by the executed trigger algorithms. The online reconstruction algorithms tend to be less precise than the offline reconstruction algorithms described in chapter 3 but are significantly faster.

A schematic showing the different ATLAS trigger components is given in figure 4.3. Only components relevant to the triggers used in this analysis will be discussed in detail. Further detail can be found in³⁴.

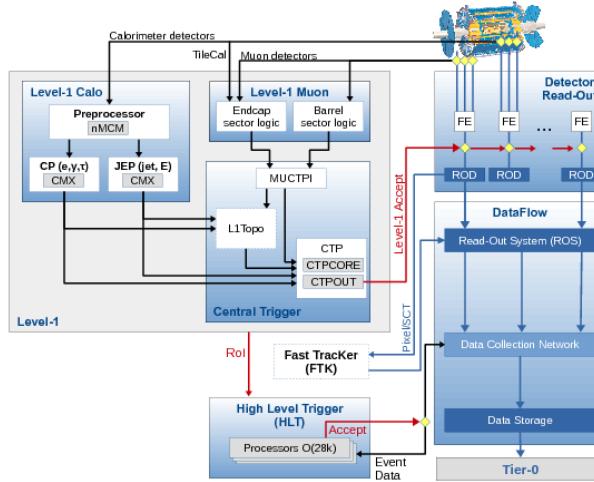


Figure 4.1: Schematic representation of the ATLAS trigger system and information flow.³⁴

We use the lowest un-prescaled E_T^{miss} trigger in this analysis. This corresponds to the HLT_xe70_mht_L1XE50 trigger in 2015, HLT_xe90_mht_L1XE50 for 2016 data taking period A-D3, HLT_xe100_mht_L1XE50 for the period D4-F1 and HLT_xe110_mht_L1XE50 for period F2 and onward. The HLT trigger thresholds increase multiple times in 2015 and 2016 to accommodate the increasing instantaneous luminosity but all the triggers used are evaluated using the same algorithm. All HLT triggers that we use are seeded by the L1_XE50 trigger.

A summary of the L1 and HLT E_T^{miss} triggers used in this analysis is given in section 4.1 to ??

4.1 Level 1 E_T^{miss} trigger

The L1 E_T^{miss} trigger is based on the vector sum of E_T in the calorimeter and is part of the L1Calo trigger system²¹ shown in figure 4.3. The process starts with trigger towers in the electromagnetic and hadronic calorimeters. Trigger towers are more coarse than those used in offline reconstruction: Most are 0.1×0.1 in $\Delta\eta \times \Delta\phi$. The trigger towers are calibrated at the electromagnetic energy scale (EM scale) which correctly reconstructs EM shower energy but underestimates hadronic showers.

These trigger towers are then built into jet elements composed of 2×2 EM trigger towers and combined with the 2×2 hadronic trigger towers directly behind the EM towers. The jet elements are then fed to the Jet/Energy-sum Processor (JEP).

The JEP calculates the global sums of E_t and E_T^{miss} by summing the E_x , E_y , and scalar E_t of all jet elements. If the total $E_T^{\text{miss}} = |\sqrt{E_x^2 + E_y^2}|$ is above a certain value the event passes the E_T^{miss} trigger and is passed to the HLT. The L1_XE50 E_T^{miss} trigger has a 50 GeV threshold.

4.2 HLT E_T^{miss} trigger

The reconstruction of E_T^{miss} for the HLT also begins with identifying topo-clusters in the calorimeters. Much like offline topo-clusters described in section 3.3.1. Seed cells with greater than 4σ signal over noise thresholds are first identified and neighboring cells with greater than 2σ thresholds are added. Neighboring cells with greater than 2σ are continually added until no neighboring cell pass the 2σ threshold. At this point, one final round of neighboring cells are added regardless of energy thresholds.

Jet reconstruction and calibration are also similar to offline jet reconstruction described in section 3.3.1. Jets are reconstructed using the $\text{anti}-k_t$ algorithm from topo-clusters. Jet calibration also follows the same basic offline procedure in section 3.3.2. However, HLT jet calibration and offline calibration procedures do differ in many ways including different pile-up corrections, track-based correction and certain in-situ corrections. Overall this leads to poorer jet resolutions at the HLT level. Some of these corrections were added in 2016 to further improve the agreement

between online and offline jet reconstruction. Details can be found in²⁰.

The E_T^{miss} is calculated directly by calculating the vector sum of the negative transverse momentum of all reconstructed jets. Only contributions from the calorimeter is taken into account in the E_T^{miss} calculation and muon tracks are not included. This method of calculating the E_T^{miss} from calibrated jets is referred to as missing H_T (MHT).

We apply a 70, 90, 100, or 110 GeV threshold to our HLT E_T^{miss} trigger depending on the data taking period. Trigger threshold increases over time because the instantaneous luminosity increases.

Trigger turn on curves as a function of offline E_T^{miss} can be seen in figure 4.2. The poorer online E_T^{miss} resolution leads to a more gradual turn on curve.

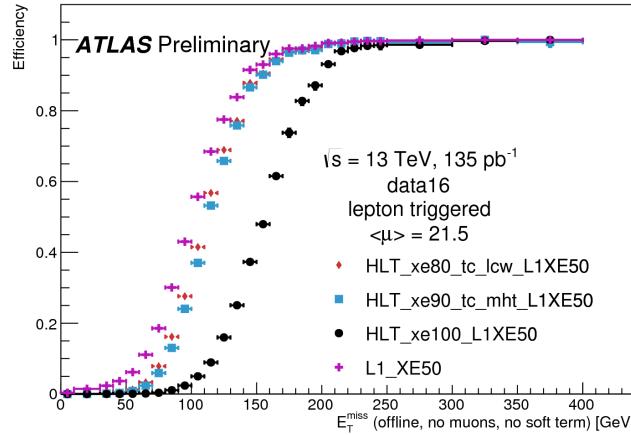


Figure 4.2: ATLAS trigger turn on curves for MHT E_T^{miss} triggers with several different thresholds. (Figure taken from²⁰)

4.3 Improvements to the E_T^{miss} Trigger in Run 2

A significant improvement to pileup mitigation was made to the L1Calo trigger system for Run 2.³⁴ The ATLAS Liquid Argon Calorimeter integrates its signal over a time window of 600 ns. This long time window corresponds to 24 bunch crossings. Hence, energy deposition from collisions occurring in neighboring bunches (referred to as out-of-time pileup) will be registered as signal. This results in a higher average signal amplitude (pedestal) in collisions at the beginning of a bunch train than those at the end of a bunch train.

The pedestal's dependence on bunch-crossing location was corrected offline but not at the trigger level in Run 1. However in Run 2, a dynamic bunch-by-bunch pedestal correction was implemented at the trigger level. This lead to a significant reduction in L1 E_T^{miss} trigger rate as shown in figure ??.

This improvement to the LAr energy calibration also improves the jet energy calibration at the HLT. This not only improves HLT E_T^{miss} trigger performance but also improves the performance of other HLT calorimeter triggers such as those on total E_T .²⁰

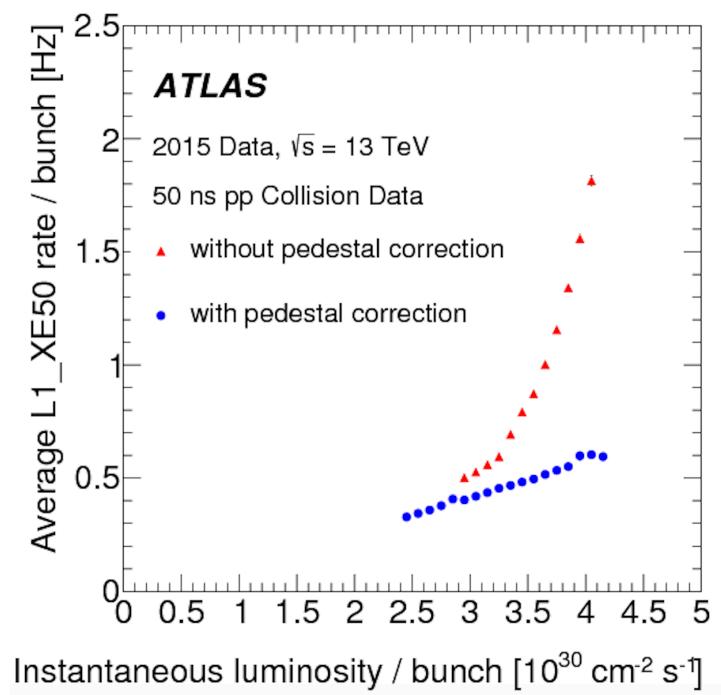


Figure 4.3: Improvement to the L1_XE50 rate with new dynamic pedestal correction for out-of-time pileup.³⁴

5

Physics Object Definitions

We require a certain set of quality cuts for all reconstructed physics objects used in this analysis. In general, we have a looser set of cuts on **baseline** objects and a tighter set of cuts on **signal** objects. The object selection is inclusive meaning that the tighter signal objects must also pass the looser baseline object selection.

Baseline objects are used to reconstruct the E_T^{miss} and to veto events. These appli-

cations benefit the most from having a higher reconstruction efficiency. The quality of lepton momenta resolution are less important when we veto since we are not performing any measurements on the lepton except tagging their presence. The same is true for the E_T^{miss} calculation where we want to perform the calculation on calibrated hard objects instead of relying on the soft term calculation.

In general, signal objects are used in the analysis in places where we need to ensure robust energy/momenta reconstruction or just the presence of well reconstructed objects.

For example signal electrons and muons are used in the 1 lepton control regions where the lepton momentum is used to calculate variables such as the transverse mass but baseline electrons and muons are used to veto events for the 0 lepton control region.

Signal jets are used in the 0 lepton signal and validation regions and 1 lepton control regions. Signal photons are used in the single photon control region used to estimate the ttV background.

Overlapping objects are resolved at the baseline level using the algorithm described in section 5.6. The E_T^{miss} is reconstructed using baseline objects that passed overlap removal according to the algorithm described in section 3.6.

All object definitions used follow the ATLAS performance group recommendations and SUSY group standards for MC15c samples (SUSYTools-00-08-54 and AnalysisBase-2.4.28). Details on each object is given below.

5.1 Electron Definition

Baseline electron candidates are selected using the `VeryLooseLH` quality definition. The energy clusters associated with the electron are required to have an $E_T = E_{cl}/cosh\eta > 7$ GeV and be within an η range of $|\eta_{cl}| < 2.47$. Electrons in the transition region between EM barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$) also called the crack region are accepted as long as they satisfy the `VeryLooseLH` criteria. Electron reconstruction and calibrated are summarized in section 3.4.

We use the gradient loose criteria for electron isolations. The isolation parameter changes depending on the lepton p_T in gradient isolation, ensuring a balance between efficiency and fake rate at all lepton p_T values.

Table ?? summarizes the baseline electron definition criteria.

Cut	Value
Acceptance	$p_T > 7$ GeV, $ \eta_{clust} < 2.47$
Quality	<code>VeryLooseLH</code>
Isolation	<code>Gradient Loose</code>
Overlap: e rejected if	$0.2 < \Delta R(e, jet) < 0.4$

Table 5.1: Baseline Electron selection criteria. The overlap removal is described in more detail in section 5.6.

Signal electrons require the tight likelihood `TightLH` quality requirement. The minimum p_T is also increased to 20 GeV. Table ?? summarizes the signal electron definition.

Cut	Value
Acceptance	$p_T > 20 \text{ GeV}, \eta_{\text{clust}} < 2.47$
Quality	TightLH
Isolation	Gradient Loose
Overlap: e rejected if	$0.2 < \Delta R(e, \text{jet}) < 0.4$

Table 5.2: Signal Electron selection criteria. The overlap removal is described in more detail in section 5.6.

5.2 Muon Definition

Baseline muon candidates must pass the Loose quality criteria. Baseline muons must also have a $p_T > 6 \text{ GeV}$ with $|\eta| < 2.7$. Electron reconstruction and calibrated are summarized in section 3.5.

We use the gradient loose criteria for muon isolations. The isolation parameter changes depending on the lepton p_T in gradient isolation, ensuring a balance between efficiency and fake rate at all lepton p_T values.

Baseline muon selections are summarized in table ??.

Cut	Value
Acceptance	$p_T > 6 \text{ GeV}, \eta < 2.7$
Quality	Loose
Isolation	Gradient Loose
Overlap: μ is rejected if	$\Delta R(\mu, \text{jet}) < 0.4$

Table 5.3: Selection criteria for baseline muons. The overlap removal is described in more detail in section 5.6.

Signal muon candidates must pass the Medium quality criteria. Signal muons must

have a $p_T > 20$ GeV, and be within $\eta < 2.7$. Signal muon selections are summarized in table ??.

Cut	Value
Acceptance	$p_T > 20$ GeV, $ \eta < 2.7$
Quality	Medium
Isolation	Gradient Loose
Overlap: μ is rejected if	$\Delta R(\mu, \text{jet}) < 0.4$

Table 5.4: Selection criteria for signal muons.

5.3 Jet Definitions

5.3.1 Calorimeter Jets

Jets are reconstructed from topological clusters using the $\text{anti}-k_t$ jet algorithm[?] with a distance parameter of $R = 0.4$. The jets are calibrated use the EM+JES calibration scheme and global sequential calibration is enabled. Area-based pileup corrections are also applied. More details on jet reconstruction and calibration can be found in section 3.3.

Baseline jets must have $p_T > 20$ GeV with no η requirement. A jet vertex tagger value greater than 0.59 is also required to reject pileup jets not originating from the hard scattering interaction for jets with $|\eta| < 2.4$ and $p_T < 60$ GeV. The 0.59 JVT working point corresponds to a 92% efficiency for jets originating from the hard scattering interaction and a 2% fake rate from pileup, if the jet has $|\eta| < 2.4$ and $p_T < 60$

GeV. Jets that pass this loose selection are considered when resolving overlapping objects and building E_T^{miss} .

After overlap removal, if any baseline jets are tagged as being BadLoose quality jets then the entire event is vetoed. This is because the presence of a bad quality jet probably also means poor E_T^{miss} reconstruction for the event. Details on jet quality can be found in section 3.3.4

Baseline jets are summarized in table ??.

Cut	Value
Acceptance	$p_T > 20 \text{ GeV}$, no η requirement
JVT	> 0.59 if $p_T < 60 \text{ GeV}$ and $ \eta < 2.4$ no requirement if $p_T > 60 \text{ GeV}$ or $ \eta > 2.4$
Quality	if any jet is BadLoose then veto whole event
Overlap	See section 5.6

Table 5.5: Selection criteria for baseline jets.

Signal jets are required to have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.8$ plus all selections applied to the baseline jets. Jet quality must satisfy the Loose criteria defined in section 3.3.4.

Signal jets are summarized in table ??.

5.3.2 b -tagged Jets

A subset of jets are identified as originating from a b -hadron using the MV2c10 b -tagging algorithm described in section 3.3.5. b -jet candidates must be within ID

Cut	Value
Acceptance	$p_T > 20 \text{ GeV}, \eta < 2.8$
JVT	> 0.59 if $p_T < 60 \text{ GeV}$ and $ \eta < 2.4$, no requirement if $p_T > 60 \text{ GeV}$ or $ \eta > 2.4$
Quality	Loose
Overlap	See section 5.6

Table 5.6: Selection criteria for signal jets.

coverage with $|\eta| < 2.5$. Any jet with $\text{MV2c10} > 0.6459$ is a b-tagged jet. The selection chosen corresponds to approximately 77% b-tagging efficiency with a factor of 134 reject rate for light jets and a factor of 6 rejection of c-jets.

5.4 Photon Definition

Baseline photons are used only for E_T^{miss} calculation. Baseline photons must have $p_T > 25 \text{ GeV}$ and $|\eta| < 2.37$ and pass the Tight quality selection. Photon reconstruction and calibrated are summarized in section 3.4.

The photon definition is summarized in table 5.7

Table 5.7: Baseline photon selection criteria.

Cut	Value
Acceptance	$p_T > 25 \text{ GeV}, \eta < 2.37$
Quality	Tight

Signal photons are used only in the $t\bar{t}\gamma$ control region to model the ttV background. Signal photons must pass the requirements in Table 5.8.

Table 5.8: Signal photon selection criteria.

Cut	Value
Acceptance	$p_T > 130 \text{ GeV}$, $ \eta < 2.37$
Quality	Tight
Isolation	FixCutLoose

5.5 E_T^{miss} Definitions

5.5.1 Calorimeter-based E_T^{miss}

The E_T^{miss} is calculated as the negative vector sum of all fully calibrated baseline object's E_t including baseline muons, electrons, photons and jets after overlap removal.

An extra term is added to the E_T^{miss} to account for energy in the event that is too soft to be associated with any selected objects. This soft term is calculated using inner detector tracks that are matched to the primary vertex and is relatively robust against pileup interactions. Details on the E_T^{miss} reconstruction can be found in section 3.6.

5.5.2 Track-based E_T^{miss}

A complementary method of determining the E_T^{miss} using only tracking information is used to discriminate against events with fake E_T^{miss} resulting from mis-reconstructed calorimeter jets. The track based E_T^{miss} or $E_T^{\text{miss,track}}$ is the negative vector sum of all

ID track p_T . $E_T^{\text{miss,track}}$ is very robust against pileup but does not include the contribution to E_T from neutral particles. None the less, a loose agreement in direction between $E_T^{\text{miss,track}}$ and calorimeter-based E_T^{miss} was found to be an effective discriminant against multijet QCD background. Details on $E_T^{\text{miss,track}}$ reconstruction can be found in section 3.6.2.

5.6 Resolving overlapping objects

Overlap removal between accepted physics objects must be performed in order to avoid double counting of objects such as the same calorimeter energy being assigned to a jet and an electron. The distance metric $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ is used to define overlapping objects. Objects too close in ΔR are considered overlapping and all except one object will be removed. The following guidelines are used for removing overlapping objects.

- If an electron and jet are located with $\Delta R < 0.2$ then the object is considered an electron and the jet is removed; unless the jet is b-tagged using the 85% working point in which case the jet is kept and the electron is removed.
- If a muon and jet are located with $\Delta R < 0.4$, then the object is considered a jet and the muon is removed; unless the jet has less than three tracks (with $p_T > 500$ MeV), in which case the jet is removed while the muon is kept.
- If an electron and jet are located with $0.2 \leq \Delta R < 0.4$, then the object is considered a jet and the electron is removed.

Overlap removal is performed on baseline objects before E_T^{miss} reconstruction.

6

Monte Carlo Simulation of Physics Processes at ATLAS

Simulated Monte Carlo (MC) samples are used to model the signal and background processes in this analysis. A summary of MC simulation parameters for stop signal and all SM backgrounds is given in table 6.1. Greater details on signal and back-

ground MC generation is covered in the following sections.

Process	Generator	fragm./hadron.
SUSY Signal	MadGraph5_aMC@NLO	Pythia 8
$t\bar{t}$	Powheg-Box v2	Pythia 6
Single top	Powheg-Box v2	Pythia 6
$W/Z+jets$	Sherpa 2.2.1	Sherpa
Diboson	Sherpa 2.2	Sherpa
$t\bar{t} + V$	MadGraph5_aMC@NLO	Pythia 8

Process	PDF set	UE Tune	Cross section order
SUSY Signal	NNPDF2.3	A14	LO
$t\bar{t}$	CT10	Perugia 2012	NLO
Single top	CT10	Perugia 2012	NLO
$W/Z+jets$	NNPDF3.0NNLO	Default	NLO
Diboson	CT10	Default	LO
$t\bar{t} + V$	NNPDF3.0NNLO	A14	NLO

Table 6.1: Overview of the nominal simulated samples.

6.1 Signal Monte Carlo Generation

For stop signal, the matrix element (ME) of the hard scattering interaction are calculated using MadGraph5_aMC@NLO to leading order accuracy (LO).²⁴ Up to two additional QCD partons are included in the ME calculation, making the total hard scattering process $pp \rightarrow t\bar{t} + j + j$.

The stop decays are treated differently depending on the mass splitting between the stop and its decay products. The different stop decays considered in this analysis are shown in the Feynman diagrams in figure 6.1.

If $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \geq m_t$, then the top can be produced on shell. PYTHIA 8⁵² performs

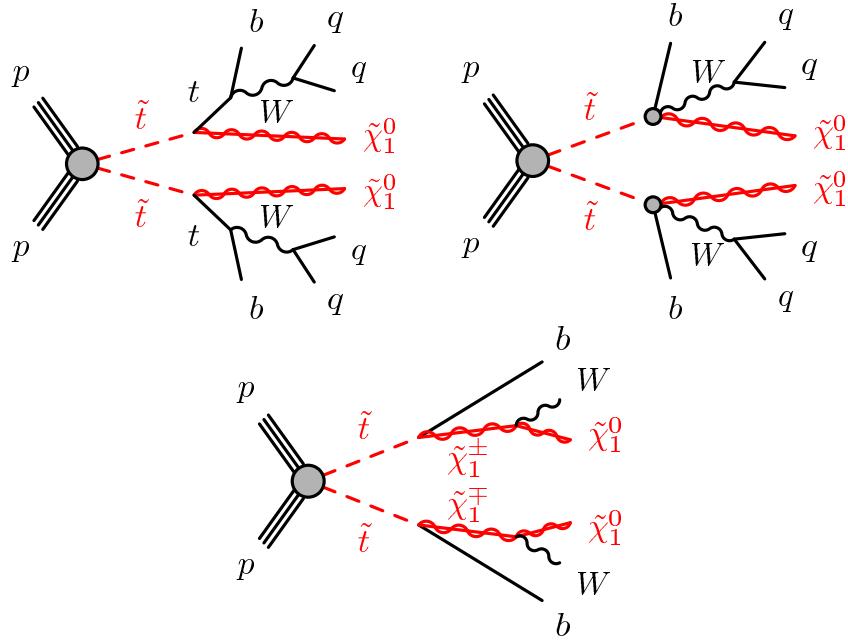


Figure 6.1: The decay topologies of the signal models considered in this analysis. The decay mode depends on the mass splitting between stop (\tilde{t}) and neutralino ($\tilde{\chi}_1^0$). If the mass splitting is larger than m_t , then a real top maybe produced in the 2 body decay $\tilde{t} \rightarrow t\tilde{\chi}_1^0$. If the mass splitting is too small then a stop may decay through a virtual top to $\tilde{t} \rightarrow bW\tilde{\chi}_1^0$. The stop decaying into b-quark plus chargino ($\tilde{\chi}_1^\pm$) channel is also considered in mixed decay interpretations.

the 2 body $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ decay and subsequent decays of the top. m_t is set to 172.5 GeV.

This process has the advantage of being computationally much faster when compared to decaying the stops as part of the ME calculation.

If $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} < m_t$, then the top must be produced off shell. PYTHIA 8 cannot perform the 3 body $\tilde{t} \rightarrow bW\tilde{\chi}_1^0$ decay or the 4 body $\tilde{t} \rightarrow bff\tilde{\chi}_1^0$ decay where the f stands for any fermions that can result from a W decay. Instead we use MadSpin²⁶ to perform the $\tilde{t} \rightarrow bW\tilde{\chi}_1^0$ or $\tilde{t} \rightarrow bff\tilde{\chi}_1^0$ decay. MadSpin can perform 3 body and

4 body decays with off shell virtual particles as long as the decay are ultimately a series of 2 body decays. Decaying the stop using MadSpin also is also much faster then calculating the decay within the ME.

After the ME calculation and stop decays, the parton shower (PS) and hadronization of jets are simulated using PYTHIA 8 with the EvtGen v1.2.0 program as afterburner. The matching between the matrix element and parton shower jets is performed with the CKKW-L prescription. The matching scale is set to 1/4 the mass of the stop..

The internal structure of the proton is modeled with the NNPDF3.0NNLO parton distribution function (PDF) set²⁷ with A14 set as the underlying event tuned parameters (UE tune)³. The A14 tune optimizes over 10 parameters that vary the amount of ISR, FSR and multiple parton interactions. The variations are reduced to a 5 variable subset that is found to cover experimental observables. Variable 1 mainly covers variation in the modeling of the underlying events. Variable 2 mainly covers variation in jet structure and variable 3a, 3b and 3c cover different variations of ISR and FSR production. All 5 variations are used to quantify the theoretical uncertainties associated with parton shower and multiple parton interactions and are added in quadrature.

Signal cross sections are calculated to next-to-leading order in the strong coupling constant with the resummation of soft gluon emission added to next-to-leading-logarithmic accuracy (NLO+NLL).²⁹ An envelope of cross section predictions is pro-

duced using different PDF sets and factorization and renormalization scales. The nominal cross section and the uncertainty are then taken from the median and 1σ fluctuations around the median within the envelope.

A 2D grid of signal samples is generated to cover the stop and neutralino mass phase space that we may be sensitive to. Stop masses between 200 and 700 GeV are generated separated in m_{stop} by 50 GeV. For each Stop mass, five different $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ are simulated: $\Delta m = m_t - 82.5$ GeV, $m_t - 52.5$ GeV, $m_t - 22.5$ GeV, $m_t - 7.5$ GeV, $m_t + 0.5$ GeV, $m_t + 15.5$ GeV, $m_t + 27.5$ GeV. An extra row of $m_{\tilde{t}} = 225$ GeV samples is also produced to clarify the 95% confidence limit at low stop masses.

6.2 SM Background Monte Carlo Generation

6.2.1 Standard Model $t\bar{t}$ Monte Carlo Generation

The nominal ttbar samples are generated using Powheg-Boxv.2.²² The matrix element calculation is computed to NLO accuracy and includes the $pp \rightarrow t\bar{t} + j$ process where the j represents an one additional emitted parton. The top quark mass is set to 172.5 GeV and the proton substructure is modeled by the NLO CT10 PDF set⁴⁵ for the hard scattering process. The hard scattering renormalization and factorization scales are set to the generator default of $\sqrt{(m_t)^2 + (p_{Tt})^2}$.

PYTHIA6 version 6.427 simulates the parton shower, hadronization and underlying event.⁵³ We use the Perugia 2012 tune⁵⁴ and the corresponding leading order

CTEQ6L1 PDF set⁵⁰ in PYTHIA6. The resummation damping factor or h_{damp} , used by Powheg to control the ME and PS matching and the amount of high- p_T ISR/FSR, is set to m_t .

ttbar cross-sections are calculated to NNLO accuracy in the strong coupling constant with the resummation of soft gluon emissions added to NNLL accuracy using the Top++v2.0 program.³⁷ Again an envelope of cross-sections is produced for different PDF sets including MSTW2008NNLO, CT10 NNLO and NNPDF2.3 NNLO. Variations in the renormalization and factorization scales, strong coupling constant, and top quark mass are also included in the envelope. The median of envelope is taken as the nominal ttbar cross-section and the 1σ variation in the envelope is taken as the ttbar cross-section uncertainty.

In addition to the total cross-section uncertainty, a number of ttbar samples are produced to study the variation in the shapes of ttbar kinematic distributions.

A radHi and radLo sample are produced to study the variation in the total amount of ISR/FST p_T . These samples are also produced using Powheg+PYTHIA6 but have different renormalization and factorization scales (x0.5 to radHi and x2 to radLo).

The radHi sample also increases the h_{damp} parameter from the nominal m_t to $2 \times m_t$.

We study the variation of the parton shower simulation using a Powheg+Herwig++ ttbar sample. The hard scattering ME calculation has not changed from the nominal. The PDF used for the ME calculation is still NLO CT10 and the calculation is still performed with Powheg-Boxv.2 with the $h_{damp} = m_t$. However the PS, fragmentation

and hadronization is now performed with Herwig++ with the CTEQ6L1 PDF set⁵⁰ with the UE-EE-5 parameter tune.[?]

Variation in the hard scattering ME calculation are studied by comparing the nominal to a sample generated with SHERPA[?]. The same CT10 PDF set is used for sherpa and the nominal sample.

Non overlapping samples that are filtered according to E_T^{miss} are generated to increase statistics at high E_T^{miss} where our analysis resides. These samples are then merged to form a continuous distribution in E_T^{miss} .

6.2.2 Standard Model Single Top Monte Carlo Generation

Like the nominal ttbar sample, the nominal single top samples are also simulated with Powheg-Boxv.2^{23,51} and interfaced to PYTHIA6 for hadronization and parton showering, with CT10 PDF set and using the Perugia 2012 set of tuned parameters.

Unlike the ttbar samples, single top samples are produced separately according to production channels. Three production channels exist including the s-channel, t-channel and the Wt channel. The largest contribution to our analysis comes from the Wt channel.

The NLO calculation of the $pp \rightarrow Wt$ includes contributions from $pp \rightarrow t\bar{t} \rightarrow t + b + W$. However $pp \rightarrow t\bar{t} \rightarrow t + b + W$ is already included in our simulation of ttbar and including it here would be double counting. We can subtract out the ttbar contribution at either the amplitude level (DR scheme) or at the matrix elements

level (DS scheme). Subtracting at the matrix element level also remove any potential interference between the single top $pp \rightarrow Wt$ and ttbar $pp \rightarrow t\bar{t} \rightarrow t + b + W$ processes. Subtracting at the amplitude level does not remove those interferences. Both schemes violates formal gauge invariance and there isn't a consensus on the correct procedure. The nominal single top sample is generated with the DR scheme and another sample is generated with the DS scheme. We compare the difference between the two samples to quantify the uncertainty due to the single top and ttbar interference.

RadHi and radLo samples are also produced for single top to study the variation in single top ISR and FSR emissions. These samples are also produced with Powheg+PYTHIA6 but have different renormalization and factorization scales (x0.5 to radHi and x2 to radLo). The radHi sample also increase the h_{damp} parameter from the nominal m_t to $2 \times m_t$.

We study the variation of the parton shower simulation using Powheg+Herwigg++ single top samples. The hard scattering ME calculation has not changed from the nominal. The PDF used for the ME calculation is still NLO CT10 and the calculation is still performed with Powheg-Boxv.2 with the $h_{damp} = m_t$. However the PS, fragmentation and hadronization is now performed with Herwigg++ with the CTEQ6L1 PDF set⁵⁰ with the UE-EE-5 parameter tune.

6.2.3 Standard Model $W + \text{jets}$ and $Z + \text{jets}$ Monte Carlo Generation

$W + \text{jets}$ and $Z + \text{jets}$ are generated with the SHERPAv2.2.1 program.⁷ The matrix element are calculated for the vector boson (V) plus 0,1, and/or 2 additional partons at NLO accuracy and 3, and/or 4 additional partons at LO accuracy.

The ME calculation is merged with SHERPA parton show according to the MEPS@NLO prescription. The proton substructure is modeled with the NNPDF3.0 NNLO PDF set and the PS tuning defined by SHERPA.

Systematic variations include a 7 point variation of the renormalization and factorization scales. The variations are used to quantify the theoretical uncertainty on our modeling of the $W + \text{jets}$ and $Z + \text{jets}$.

The $W + \text{jets}$ and $Z + \text{jets}$ samples are generated in multiple non-overlapping slices of vector boson p_T and b-jets and c-jets presence. The samples are then merged later to form a continuous distribution covering all phase space. This allows us to generate higher MC statistics in the high- p_T region with the presence of b and/or c-jets which is most relevant to our analysis.

6.2.4 Standard Model $t\bar{t} + V$ Monte Carlo Generation

$t\bar{t}+V$ where V is a W or Z boson samples are generated using MadGraph5_aMC@NLO with the NNPDF3.0NLO PDF set. The matrix element calculation is performed to NLO accuracy. The parton shower, fragmentation, and hadronization are simulated

using PYTHIA 8 with the underlying event tune A14. Variations in the hard scattering ME calculation are studied by generating another sample using SHERPA and comparing its results to the nominal sample. Variation in renormalization and factorization scales are also produced.

6.2.5 Standard Model $t\bar{t} + \gamma$ Monte Carlo Generation

$t\bar{t} + \gamma$ samples are generated using MadGraph5_aMC@NLO with the NNPDF3.0NLO PDF set. The matrix element calculation is performed to NLO accuracy. The parton shower, fragmentation, and hadronization are simulated using PYTHIA 8 with the underlying event tune A14. The sample only simulates events with a filter for high p_T photon . This sample is then merged with the nominal ttbar sample to form the $t\bar{t} + \gamma$ sample. The events with high p_T photons in the nominal ttbar samples are removed to avoid double counting.

6.2.6 Standard Model Diboson Monte Carlo Generation

dibosons samples are generated with SHERPAv2.2 using CT10 PDF set.

6.3 Detector Simulation

Two types of detector simulations are used. GEANT4⁷ is used to perform the detector simulation for all background samples including ttbar, $W + \text{jets}$, $Z + \text{jets}$,

single top, $t\bar{t} + V$, $t\bar{t} + \gamma$, and dibosons. For signal MC, a fast simulation framework is used in the interest of computing time. In fast simulation the majority of the detector are still simulated with GEANT4 with the exception of jets in the electromagnetic and hadronic calorimeter. Instead of simulating individual particle showers in the calorimeters, a predetermined parameterized description of the showers are used instead. The fast simulation framework was validated against full GEANT4 simulation for several selected signal samples and found to agree in observed kinematics.

Groups within ATLAS that measure the detector and reconstruction performance may recommend reweighing of different MC depending on better or worse than expected performance of different reconstruction algorithms. Corrections are applied through reweighing to correct for known differences between data and simulation for a number of factor including the lepton trigger, lepton reconstruction efficiencies, lepton momentum scale, lepton isolation, and b-tagging efficiency as recommended by ATLAS performance groups.

6.4 Pile-Up Simulation

Because the LHC is operating at such high instantaneous luminosities, there are around 25 proton-proton interactions per bunch crossing. Most of these interactions have low amounts of momentum transfer between the protons and are called minimum-bias interactions. In addition to the hard scattering interaction of inter-

est, all MC samples are produced with a varying number of simulated minimum-bias interactions. The distribution of additional overlaid minimum bias interactions is reweighed so that the distribution of additional interactions matches in data and MC.

7

General Analysis Strategy

7.1 General R-Parity Conserving SUSY Search Strategy

In R-parity conserving SUSY searches, the sought-after super-symmetric particles are produced in pairs. Each particle decays via a chain that ends in a stable, lightest super-symmetric particle (LSP). If the LSP is weakly interacting, it can not be directly detectable by the ATLAS detector and must be inferred from transverse momentum

conservation as E_T^{miss} . The rest of the products from the decay chain will be a series of SM particles.

All searches must distinguish between signal SUSY processes and background SM processes that mimic the signal detector signature. Traditional search methods often place a special emphasis on identifying the LSP as this is the one decay product that is unique to SUSY events. Practically this generally means searching for events with large amount of E_T^{miss} .

In regions with a large mass splitting between sparticle and LSP, the decay of the original sparticle generates large amounts of momentum for the LSP. Traditional searches therefore target the large amount of E_T^{miss} generated by the LSP as a method to separate signal from background.

Searches isolate signal by using this and other kinematic differences. Selections are made on sensitive variables forming a signal region (SR). The expected background rates in SR are predicted using a combination of MC and data driven techniques. One common technique involve making kinematically similar control regions (CR) and validation regions (VR). The CRs and VRs are designed to mimic the background kinematics in SR but are orthogonal to SR and are low expected signal rate. We directly measure the rate of background in kinematically similar CRs and use simulation to extrapolate between CR and SR. VRs form an independent cross check on these background predictions.

The data in SR is originally blinded to avoid any bias for or against discovery. We

unblind the SR only after we decide the background prediction in SR is well understood based on observations in CRs and VRs.

7.2 General Strategies in Compressed Regions

When the mass splitting between the original sparticle and its decay products becomes small, the sparticle has little energy to generate momenta in its decay products. The result is LSPs with low momenta. The traditional strategy of searching for events with large amount of E_T^{miss} therefore fails in this region of parameter space. This problem is ubiquitous to all regions with small mass splittings. We refer to all such regions as compressed regions.

In our analysis, the super-partner of the top, the stop is expected to decay into a neutralino and top. When the stop mass is close to that of the top mass plus the neutralino mass, both the top and neutralino gain very little momenta from the decay. The invisible neutralinos in turn generate very little missing transverse energy. This leaves only the visible tops which are mimicked by SM ttbar.

Traditional search methods depend on variables that are highly correlated with the total magnitude of E_T^{miss} such as m_{T2} and m_{eff} . Therefore traditional methods fail to separate stops from SM ttbar which has 50 to 300 times the production cross-section of stops in the region of interest. A High-Luminosity LHC study projects a 2σ exclusion limit up to a stop mass of 500 GeV with 300 fb^{-1} of data in this region.¹⁹

The projected p-value as a function of stop mass for 300 and 3000 fb^{-1} of data is given in figure 7.1

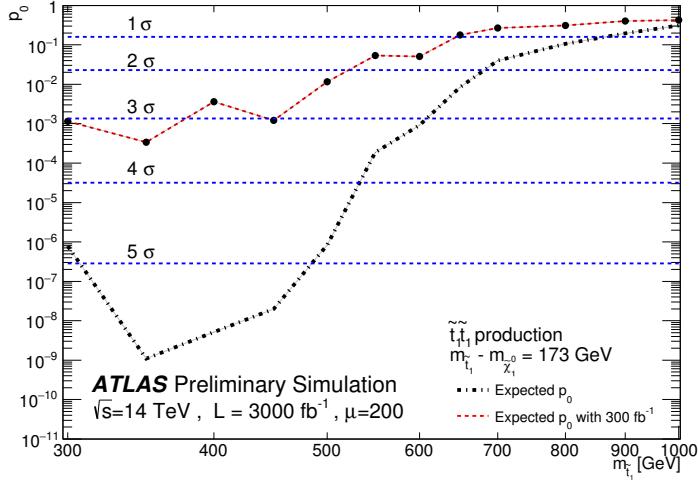


Figure 7.1: Projected HL-LHC sensitivity to the $\Delta m = m_t$ region with 300 and 3000 fb^{-1} of data. Sensitivity is quantified in terms of the p-value p_0 . 2 sigma exclusion is reached for stop masses below 500 GeV with 300 fb^{-1} . Figure taken from?

However, the soft decay products can gain additional momenta if the entire system is boosted by strong initial state radiation (ISR). The goal of the traditional searches have always been to identify the presence of the LSPs and use their presence to distinguish between signal and background. Instead of targeting events with large amount of E_T^{miss} , we use the correlations between the LSP momenta and any ISR jets to identify LSPs in compressed regions.^{46,25} Because LSPs gain little momenta from stop decays, the correlation between ISR and LSPs in compressed regions tend to be extremely strong. By targeting the correlations between ISR and E_T^{miss} instead of the total magnitude of E_T^{miss} , we effectively turn a weakness of the compressed

region into a strength.

The relationship between the decay products and ISR also has an additional benefit of being model independent. This correlation is dictated solely by relativistic kinematics rather than the underlying QFT of any particular model. The direction and magnitude of the momenta of the decay products are determined mostly by two things, how heavy the decay products are and how hard they are kicked by the ISR. For the $p\bar{p} \rightarrow \tilde{t}\bar{t} \rightarrow t\tilde{\chi}_1^0 \bar{t}\tilde{\chi}_1^0$ process, the relationship is given by equation 7.2. This ratio between the invisible decay products and the total ISR p_T is called R_{ISR} .

$$E_T^{\text{miss}} \equiv p_{\tilde{\chi}_1^0 \tilde{\chi}_1^0, T}^{\text{lab}} \sim \gamma_{\tilde{t}\bar{t}}^{\text{lab}} \beta_{\tilde{t}\bar{t}}^{\text{lab}} E_{\tilde{\chi}_1^0 \tilde{\chi}_1^0}^{\tilde{t}\bar{t}} \sim \frac{p_T^{\text{ISR}}}{m_{\tilde{t}\bar{t}}} 2\gamma_{\tilde{t}}^{\tilde{t}\bar{t}} m_{\tilde{\chi}} \sim p_T^{\text{ISR}} \frac{2\gamma_{\tilde{t}}^{\tilde{t}\bar{t}} m_{\tilde{\chi}}}{2\gamma_{\tilde{t}}^{\tilde{t}\bar{t}} m_{\tilde{t}}} \sim p_T^{\text{ISR}} \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{t}}} \implies (7.1)$$

$$R_{ISR} \equiv \frac{E_T^{\text{miss}}}{p_T^{\text{ISR}}} \sim \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{t}}}, \quad (7.2)$$

The ratio between E_T^{miss} and ISR p_T is proportional to the ratio between the mass of a single LSP and original sparticle. Its interesting to note that the back to back boost between the two original stops does not affect the correlation between the observable E_T^{miss} and ISR p_T . Although the LSP's can individually gain momenta from the back to back boost of the sparticles against one another, the back to back momenta will exactly cancel resulting in zero measurable E_T^{miss} .

The di-LSP system only gains p_T by inheriting it from the boost by the ISR system on the two sparticles. The fraction of the momenta that is inherited by the di-LSP

system is exactly $\frac{m_{LSP}}{m_{\text{sparticle}}}$ if the sparticle decay gives no additional momentum to the LSP.

Figure ?? shows the correlation between the R_{ISR} ratio in $pp \rightarrow \tilde{t}\bar{t} \rightarrow t\tilde{\chi}_1^0\bar{t}\tilde{\chi}_1^0$ simulation for two different stop masses (350 and 550 GeV) as predicted by equation 7.2. The Δm between stop and neutralino is 173 GeV or 550 MeV from the top mass in both cases. Both stop samples sharply peak at exactly $m_{\tilde{\chi}_1^0}/m_{\tilde{t}}$ with a gaussian width of approximately 4 percent. No detector resolution effects were included in the simulation and only the all hadronic decay channel was considered.

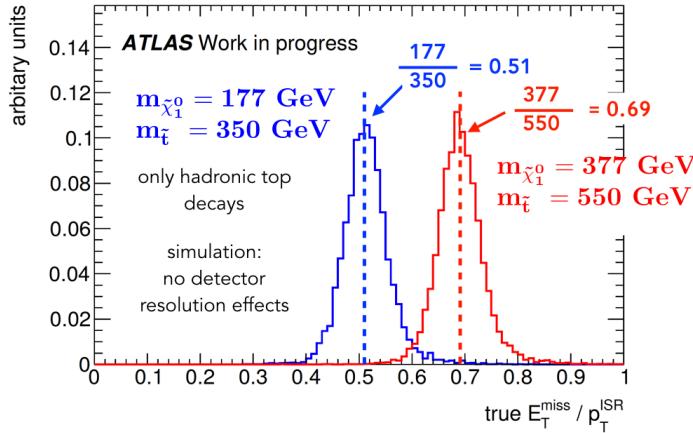


Figure 7.2: Correlation between the R_{ISR} ratio in simulation for two different stop masses. Both stop samples peak sharply at $m_{\tilde{\chi}_1^0}/m_{\tilde{t}}$ with only a gaussian width of 4 percent. Deviation from the preferred ratio is limited by the top width, as the top must be pulled off-shell to generate phase space. No detector resolution effects were included and only the all hadronic decay channel was considered.

The separation power of ISR and E_T^{miss} correlations are made even stronger considering the correlation is in 2 dimensions, in magnitude and direction. ISR and E_T^{miss}

are necessarily back to back in signal. In comparison, the neutrino gains significant momentum directly from the top decay in ttbar background and their correlation with ISR is not as absolute.

By constructing variables that capitalize on this correlation we are able to separate signal from SM backgrounds. At the same time, the increase in center-of-mass energy from 8 to 13 TeV can mean up to an order of magnitude increase in the production cross-section of signal plus strong ISR. The 13 TeV dataset presents a golden opportunity to search for many experimentally difficult physics processes that need a boost from strong ISR in order to be detected.

8

Recursive Jigsaw Reconstruction

8.1 Introduction to Recursive Jigsaw Algorithm on Events with E_T^{miss}

Every search involving missing energy has to contend with the fact that information about the invisible system is lost. The question of how to best fill the missing degree of freedom is a problem ubiquitous to all analysis that have E_T^{miss} especially when there exists multiple invisible particles in the event. The recursive jigsaw method

aims to compartmentalize the lost information and gain the most from what information that is available.

Traditional edge variables such as M_{T2} , shown in equation 8.1, extremize over all possible kinematic configurations of the two invisible particles \mathbf{p}_1 and \mathbf{p}_2 . These variables can form an edge corresponding to some kinematic limit. M_{T2} effectively extremizes over all possible configurations allowed by the missing degrees of freedom. However, optimizing over too large a phase space can unintentionally destroy useful information.

$$M_{T2}^2 \equiv \min_{\mathbf{p}_1 + \mathbf{p}_2 = \mathbf{E}_T^{miss}} \left[\max \{m_T^2(\mathbf{p}_{Tl-}, \mathbf{p}_1), m_T^2(\mathbf{p}_{Tl+}, \mathbf{p}_2)\} \right] \quad (8.1)$$

The recursive jigsaw reconstruction (RJR) method also uses maximizations and minimizations to pin down the missing degrees of freedom.^{43,44} However, these extremizations are restricted to be in a specific location of the decay tree.

For example, consider a simple particle decay chain where $a \rightarrow b c$ and then $c \rightarrow 1 2$. Recursive jigsaw would treat the situation differently if particle 1 was invisible compared to if particle b was invisible. To zeroth order, losing information about particle 1 affects only half the information on particle c which contains only half the information of particle a , but losing information on particle b directly affects half the information on particle a . Unlike traditional methods which extremizes over all possible configurations of the invisible particle. RJR compartmentalizes the lost

information and extracts the maximum amount of information from events with missing energy.

RJR separates the event according to a predefined "decay tree." The decay tree can be as detailed as needed be, either attempting to resolve every branch in the decay tree down to the level of the final state objects or forming aggregate states that have useful kinematics. Each node in the decay tree represents a particular intermediate state or final state. RJR will classify all accepted objects into the different nodes by extremizing certain metrics such as the state's mass and the state's energy. Specifics on the metrics used for each node are detailed in section 8.2. The extremizations set the unknown degree of freedoms in their respective center of mass frames. The result is then propagated back up the tree to the lab frame, creating a complete picture of the event with all ambiguities resolved.

For the compressed region, the most basic tree involves separating the event into sparticle and ISR systems and then further separating the sparticle system into visible and invisible parts. The decay tree is represented in figure. 8.1. Further detail can be added to the sparticle system such as resolving the stop decays. For this analysis, we found that attempting to reconstruct individual tops did not result in higher analysis sensitivity. The high multiplicity of hadronic jets makes reconstructing low pt tops very difficult in signal and gives little separation power because the dominant background is SM ttbar which also has real tops. Therefore, we avoid further resolving the sparticle node to the level of individual tops.

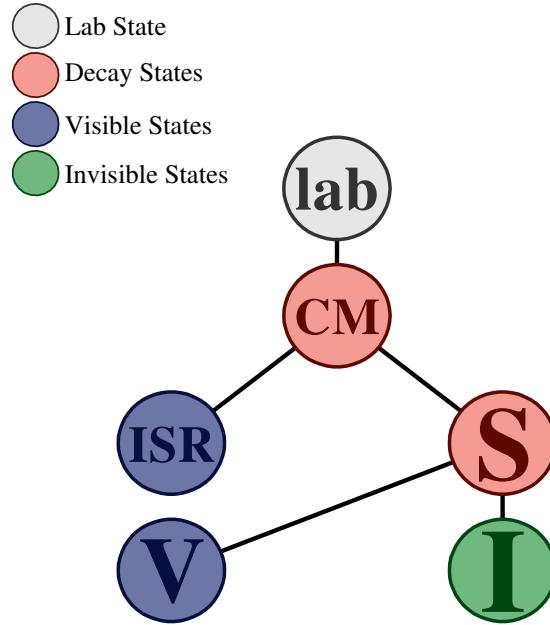


Figure 8.1: Decay Tree corresponding to ISR-assisted E_T^{miss} signal analysis strategy.

8.2 Recursive Jigsaw Method of Identifying Initial State Radiation

In order to separate the event into an initial state radiation (ISR) system and a particle system, we first boost to the transverse center of mass frame of all accepted objects. The transverse center of mass frame has the useful property that when the entire event is divided into two systems, these two systems must have equal and opposite transverse momenta. It's also important to note that the lab frame and the transverse center of mass frame only significantly differ in cases when an energetic object is not accepted. In other words, the two frames differ significantly only when the E_T^{miss} has a high probability of being miss reconstructed.

Once in the transverse center of mass frame, we find the thrust axis \vec{n} as defined in 8.2.

$$\vec{n} \equiv \max_i \vec{n} \sum_{\text{jets, } E_T^{\text{miss}}} |p_T^i \cdot \vec{n}| \quad (8.2)$$

The thrust axis \vec{n} represents the axis that maximizes the amount of back to back transverse momenta along it. If strong ISR is present, then the back to back recoil between ISR and stops should represent the single largest back to back kick in the event. Therefore, the thrust axis should approximate the direction of the back to back recoil between the stops and ISR in events with strong ISR.

We then divide the event into two hemispheres according to the thrust axis. The hemisphere containing the E_T^{miss} is identified as the sparticle hemisphere containing the decay products of the two stops. This is because we expect the sparticle hemisphere to contain the two neutralinos. The hemisphere opposite the direction of the E_T^{miss} is identified as the ISR hemisphere. All jets in the ISR hemisphere are considered to have originated from initial state radiation and all jets in the sparticle hemisphere are considered to have originated from one of the two stops.

The ISR identification algorithm can also be interpreted as an exclusive two jet clustering algorithm that seeks to simultaneously minimize the masses of both jets. This interpretation is a mathematically equivalent to the thrust axis interpretation. Since we are in the transverse center of mass frame, finding the thrust axis is the

same as simultaneous maximizing the p_T of the sparticle and ISR systems. The total E_T of the event, shown in equation 8.3, is constant. Maximizing the p_T of the sparticle and ISR systems is identical to minimizing the masses of the sparticle and ISR systems. At the same time, the jet axes are guaranteed to be arranged in a back to back fashion because we in the transverse center of mass frame. The jet axis is therefore identical to the thrust axis.

$$E_T = \sqrt{(m^{ISR})^2 + (p_T^{ISR})^2} + \sqrt{(m^{sparticle})^2 + (p_T^{sparticle})^2} \quad (8.3)$$

8.3 Performance of Initial State Radiation Identification Algorithm

We can check the performance of the thrust based initial state radiation (ISR) identification algorithm by plotting the ratio of reconstructed over true ISR p_T in signal simulation. Figure 8.2 shows the distribution of the ratio of reconstructed vs true ISR p_T for 350 GeV stop mass and 172 GeV neutralino mass signal sample. Only events with fully hadronic stop decays and at least 400 GeV of true ISR p_T are accepted for this plot. Detector resolution effects on jets and E_T^{miss} are included when calculating the reconstructed ISR p_T .

A simple and currently popular form of ISR identification is simply the equating the highest p_T jet with the ISR system. The highest p_T jet algorithm is represented by the red distribution in figure 8.2. The single jet algorithm loses 20 to 50 percent

$m_{\tilde{t}} = 350$, $m_{\tilde{\chi}_1^0} = 177$ Simulation, True ISR $p_T > 400$ GeV

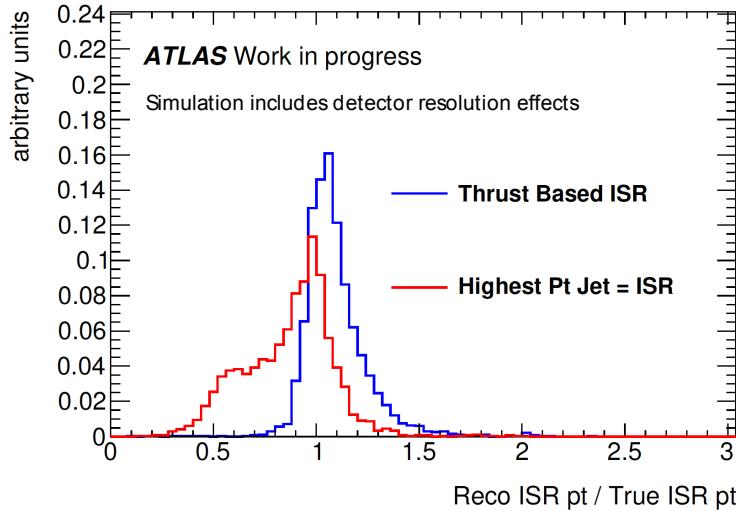


Figure 8.2: The distribution of the ratio of reconstructed vs true ISR p_T for the 350 GeV stop mass and 172 GeV neutralino mass signal sample. Only simulations with fully hadronic stop decays and at least 400 GeV of true ISR p_T are accepted. The red distribution is formed when the whole ISR system is equated to just the highest p_T jet. The blue distribution uses the thrust based ISR identification system.

of the ISR energy in about 40 percent of events. This is because the ISR system's energy is often split between multiple jets.

In comparison, the thrust based ISR identification system is able to capture the whole ISR system consisting of multiple jets. The fitted gaussian width of the blue peak is 9 percent and this uncertainty includes detector resolution effects. The gaussian mean is centered about 1.05. The reason for this is because a jet originating from a stop will occasionally go in the opposite direction as the E_T^{miss} and be misidentified as an ISR jet. The p_T of the misidentified sparticle jet tend to be small when compared to the total p_T of the ISR system. Hence, this misidentification shows

up as a 5 percent bias in the reconstructed ISR p_T . Optimization of the ISR identification algorithm shows that this small bias does not impact the sensitivity of the search.

The non-gaussian tail in the blue distribution that extends to a reconstructed over true ISR p_T ratio of 1.5 is due to energetic ISR jets that go in the same direction as the E_T^{miss} . In these cases, the ISR jets that are in the same direction as the E_T^{miss} are miss-reconstructed as having originated from a stop. Only the ISR jets going in an opposite direction to the E_T^{miss} are reconstructed as ISR jets. Therefore the reconstructed ISR system fail to partially cancel the p_T of the oppositely facing jets and the reconstructed ISR system has a larger p_T than the true ISR p_T . However, these cases are rare and the non-gaussian tail accounts for less than 15 percent of the events in blue distribution.

8.4 Kinematic Variables of Initial State Radiation and Sparticle Systems

Once we separated the event into two hemispheres according the thrust axis as described in section 8.2 we can construct a number of kinematic variables that captures different features of the two hemispheres. These variables are listed below.

$N_{\text{btag}}^{\text{s}}$: number of b-tagged jets associated with the sparticle hemisphere.

$N_{\text{jet}}^{\text{s}}$: number of jets associated with the sparticle hemisphere.

$p_{T,b}^{0,\text{s}}$: p_T of the leading b-tagged jet in the sparticle hemisphere.

$p_T^{\text{jet } 4, \text{ S}}$: p_T of the fourth highest p_T jet in the sparticle hemisphere.

M_T^S : transverse mass of the whole sparticle system and E_T^{miss} .

p_T^{ISR} : p_T of the ISR system

$\Delta\phi_{\text{ISR}, i}$: angular separation in ϕ of the ISR and the E_T^{miss} (evaluated in the transverse CM frame)

R_{ISR} : Ratio between E_T^{miss} and p_T^{ISR} (evaluated in transverse CM frame)

N_{jet}^S and N_{btag}^S quantify the jet multiplicity in the sparticle system. $p_{T,b}^{0,S}$, $p_T^{\text{jet } 4, \text{ S}}$, M_T^S and p_T^{ISR} quantify the amount of energy in the sparticle and ISR hemispheres.

Finally, $\Delta\phi_{\text{ISR}, i}$ and R_{ISR} describe the correlation between the ISR system and the E_T^{miss} in direction and magnitude. All of these variables will be used to separate signal from background in the signal region described in detail in section ??.

9

Collision Data Samples

9.1 Data Periods and Good Run List

This analysis uses the LHC proton-proton collision data at a centre-of-mass energy of $\sqrt{s}=13$ TeV that is collected by ATLAS in 2015 and 2016.

We select data where all relevant subdetector parts are running without defects and the quality of data is good. This is done by requiring the data pass a good run

list (GRL). The good run list is compiled from data that pass manual and automated checks on both detector hardware and the kinematics of reconstructed physics objects.

The GRLs used for the 2015 dataset is `data15_13TeV.periodAllYear_DetStatus-v79-repro20-02_DQDefects-00-02-02_PHYS_StandardGRL_All_Good_25ns.xml`.

The GRL for the 2016 data is `data16_13TeV.periodAllYear_DetStatus-v83-pro20-15_DQDefects-00-02-04_PHYS_StandardGRL_All_Good_25ns.xml`.

The dataset after GRL selection corresponds to a total integrated luminosity of $36.07 \pm 1.15 \text{ fb}^{-1}$. The total integrated luminosity as a function of time for 2015 and 2016 before the requirement of an GRL is shown in figure 9.1.

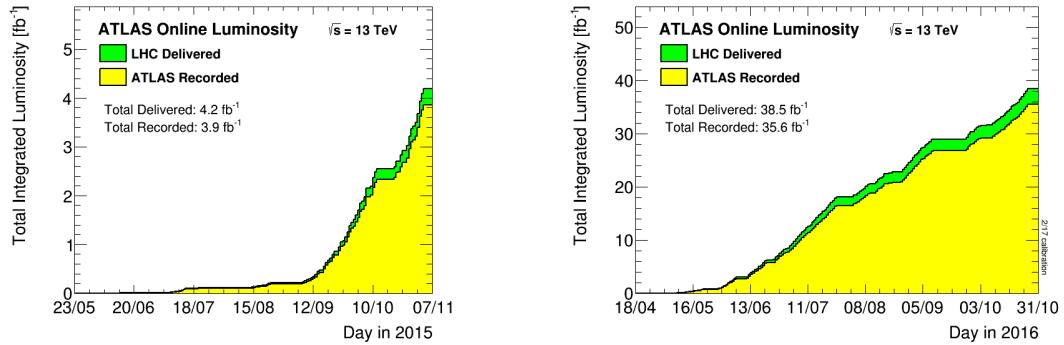


Figure 9.1: Distribution of the amount of data delivered by the LHC and recorded by ATLAS vs time in 2015 and 2016

Peak luminosity reached $1.38 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ in 2016. Taking data at this high rate means we expect multiple p-p interactions in every bunch crossing. The average number of interactions per bunch crossing, $\langle \mu \rangle$, is 13.7 in 2015 and 23.2 in 2016.

The distribution of the mean number of interactions per bunch crossing is given in figure 9.2.

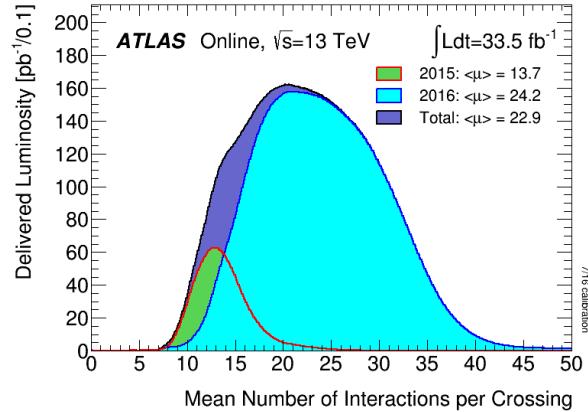


Figure 9.2: Distribution of the mean number of interactions per bunch crossing weighted by integrated luminosity for 2015 and 2016 ATLAS data taking.

In order to keep data flow to a manageable size, ATLAS only record events if a trigger is fired. The ATLAS trigger system is summarized in chapter 4. This analysis uses the lowest unprescaled E_T^{miss} trigger for each data taking period. This trigger is `HLT_xe70_tc_lcw` for all of 2015 data taking, `HLT_xe90_mht_L1XE50` for 2016 period A-D3, `HLT_xe100_mht_L1XE50` for 2016 period D4-F1, and `HLT_xe110_mht_L1XE50` for 2016 period F2 and onward.

10

Event Preselection

We first require that the event pass a few basic selections to ensure that the events do not have large amounts of calorimeter noise or non-collision backgrounds. These requirements are designed to reject events with poorly reconstructed jets or E_T^{miss} .

These basic selections are applied to all control regions (CR), validation regions (VR), and signal regions (SR). Together these basic selections are referred to as event

cleaning and jet cleaning.

A brief description of the preselection requirements is given below:

Cut 1 Data events must be in accepted according to the Good Runs List (GRL) described in chapter 9.1. This ensures all relevant subdetector of ATLAS are operating normally during data taking.

Cut 2 Remove events with noise bursts and possible incomplete events due to the TTC reset procedure from the data. Data events must have no error flags in the calorimeter and ID. The following error flags must be set to zero: larError == 0, tileError == 0, SCT error == 0, and coreFlags &0x4000 == 0.

Cut 4 Require that at least one reconstructed primary vertex must exist.

Cut 5 Events must not contain any BadLoose jets with $p_T > 20$ GeV (at any η range). Bad quality jets indicate the presence of calorimeter noise or non-collision backgrounds. Both can lead to poor E_T^{miss} reconstruction. Hence, the whole event is rejected. BadLoose jets are defined in jet quality selection in section 3.3.4.

Cut 6 The event must not contain any cosmic muons. Cosmic muons are identified as muons with large impact parameters ($|z_0| > 1$ mm and $|d_0| > 0.2$ mm). Only baseline muons after overlap removal are considered in cosmic muon identification.

Cut 7 The event must not contain any bad muons. This include any muons reconstructed from high energy jets punching through the calorimeter and depositing energy into the muon system, or from poorly reconstructed inner detector tracks that are incorrectly matched to muon spectrometer segments. These fake muons may result in misreconstructed E_T^{miss} so the whole event is rejected.

Details on all object definitions can be found in chapter 5.

On top of these basic requirements, additional preselection requirement are applied to each CR, VR and SR depending on the number of leptons required in the respective region.

10.1 Zero Lepton Pre-Selection

Any zero lepton region requires the selections given in table ??.

GRL, Event Cleaning and Jet Cleaning	
	E_T^{miss} Trigger
E_T^{miss}	$> 250 \text{ GeV}$
$N_{\text{baselinelept}}$	0
anti- k_t $R = 0.4$ signal jets	≥ 4 , $p_T > 80, 80, 40, 40 \text{ GeV}$
b -tagged signal jets	≥ 1
$ \Delta\phi(\text{jet}^{0,1}, E_T^{\text{miss}}) $	> 0.4
$E_T^{\text{miss,track}}$	$> 30 \text{ GeV}$
$ \Delta\phi(E_T^{\text{miss}}, E_T^{\text{miss,track}}) $	$< \pi/3$

Table 10.1: Zero lepton preselection criteria common to all zero lepton signal and validation regions.

All zero lepton regions trigger on E_T^{miss} using the lowest unprescaled E_T^{miss} trigger for that data period. An offline selection of $E_T^{\text{miss}} > 250$ GeV is required to ensure that all accepted events are on the trigger efficiency plateau. The trigger efficiency curve as a function of offline E_T^{miss} for select E_T^{miss} triggers can be seen in figure 4.2.

We require that the event contains exactly zero baseline leptons. We also require at least four signal jets with a minimum p_T of (80, 80, 40, 40) GeV in the event. At least one signal jet must be b-tagged at the 77 percent working point. These jet energy and multiplicity requirements are loose and will be superseded by more stringent selections in the SR, VRs and CRs.

For our analysis the primary reason that QCD multijet background is able to pass the SR selections is due to misreconstructed jets. QCD multijet produces little intrinsic E_T^{miss} . In order to pass the 250 GeV E_T^{miss} requirement, multijet background need additional fake E_T^{miss} from mis-measured jets. For example, an extremely energetic jet may punch through the calorimeter and be reconstructed with a small E_T . This lost E_T maybe reconstructed as E_T^{miss} .

The $|\Delta\phi(\text{jet}^{0,1}, E_T^{\text{miss}})| > 0.4$ requirement ensures that the E_T^{miss} is not collinear with the most energetic jets in the event. This provides strong rejection against fake E_T^{miss} resulting from a single misreconstructed energetic jet. Requirements on a loose agreement between E_T^{miss} and $E_T^{\text{miss,track}}$ also discriminate against E_T^{miss} resulting from misreconstructed jets and therefore QCD multijet.

10.2 One Lepton Pre-Selection

The one lepton preselection is similar to the zero lepton preselection except for several important requirements. The one lepton preselection is summarized in table ??.

GRL, Event Cleaning and Jet Cleaning	
E_T^{miss} Trigger	
E_T^{miss}	$> 250 \text{ GeV}$
$N_{\text{signallep}}$	1
N_{jets}	≥ 4
b -tagged signal jets	≥ 1
$ \Delta\phi(\text{jet}^{0,1}, E_T^{\text{miss}}) $	> 0.4

Table 10.2: One lepton pre-selection criteria common to all one lepton signal and validation regions.

First, the one lepton selections use signal leptons unlike the baseline leptons used in zero lepton regions. The one lepton regions use lepton momentum information and therefore require higher quality leptons.

Next, both signal leptons and signal jets are counted as “jets” in one lepton regions. This is because one lepton regions serve as CRs and VRs for this analysis and are designed to model the background in the SR. The biggest background contributions in SR come from backgrounds that decay through the hadronic tau channel. As such, we use the electron or muon in the one lepton CR and VR to model the hadronic tau in the zero lepton SR.

The $E_T^{\text{miss,track}} > 30 \text{ GeV}$ and $|\Delta\phi(E_T^{\text{miss}}, E_T^{\text{miss,track}})| < \pi/3$ requirements are re-

moved because the QCD multijet contribution to one lepton regions is negligible.

The $|\Delta\phi(\text{jet}^{0,1}, E_T^{\text{miss}})| > 0.4$ selection is kept because it provides a closer modeling of the phase space in SR.

11

Signal Region Definition

The kinematic selections in the signal region are designed to reject SM ttbar events, which comprise 70-90 percent of all background in SR. The same selections are also effective at rejecting sub-dominant backgrounds including W+jets, single top, Z+jets and QCD multijet backgrounds. This chapter first builds physical intuition on the dominant SM ttbar in section 11.1. A brief recap of the ISR reconstruction algo-

rithm is given in section ???. The SR kinematic selections are defined in section 11.2.

The section also goes into detail on the background rejection power of each SR selection. Lastly the SR yields and background composition are covered in section ?? and 11.4.

11.1 Physical Intuition on how Signal Region Selections Reject SM Background

The zero lepton SR is designed specifically to reject the dominant ttbar background.

The SR's design choice and signal and ttbar kinematics are summarized in this section. The SR's effect on sub-dominant backgrounds are also described near the end of the section. More detail on each SM background, including background estimation techniques, can be found in chapter 12.

95 percent of all ttbar which survive SR selection decay via the single hadronic tau and single lepton decay channels. SM ttbar that decays via the fully hadronic decay channel generates no little intrinsic E_T^{miss} and is negligible in SR. Therefore, understanding ttbar specifically require us to understand the single lepton decay channel where the leptonic top can decay via an electron, muon or tau.

It is important to note that a top decay cannot generate a neutrino with 250 GeV p_T if the top decays at rest. Therefore, the $E_T^{\text{miss}} > 250 \text{ GeV}$ requirement essentially forces the leptonic top to be boosted.

The leptonic top can only gain boost in one of two ways. Either the leptonic top

recoils against the hadronic top in a back-to-back fashion or both tops recoil against strong ISR. This break down of SM ttbar into two kinematically distinct populations is covered in more detail in section 12.2.

The thrust axis, the axis that maximizes the amount of back-to-back p_T along it, contains important information in both populations. In the top/anti-top population, the thrust axis aligns along the top/anti-top back-to-back boost. In the ttbar+strong ISR population, the thrust axis aligns along the ISR/ttbar back-to-back boost.

Figure 11.1 illustrates example events from the two distinct ttbar populations and the stop signal. We line up all three events according to their thrust axis and the hemisphere containing the E_T^{miss} displayed in the upper half.

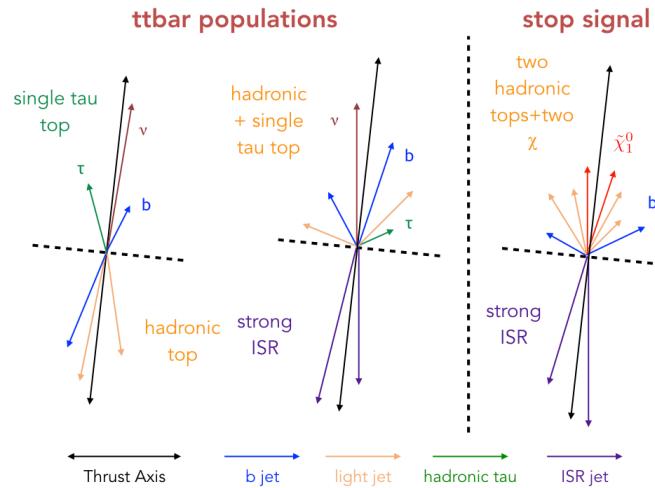


Figure 11.1: Basic depiction of the kinematics of the two ttbar populations and stop plus strong ISR events after 0 lepton pre-selection

We can immediately see that the signal has a significantly higher jet multiplicity

ity and total energy in the hemisphere with the E_T^{miss} than the top/anti-top back-to-back population in ttbar. Indeed, the signal has 6 jets originating from the two hadronic tops in the hemisphere with E_T^{miss} compared with only a single leptonic top in the top/anti-top back-to-back ttbar population. The ttbar plus strong ISR population looks more signal like as it has higher jet multiplicity and energy in the E_T^{miss} hemisphere. However, it still has less total energy than that of the signal.

By placing requirements on the jet multiplicity and total energy in the hemisphere with E_T^{miss} we are able to reject over 99 percent of ttbar events with less than 400 GeV of true ISR p_T . Acceptance of ttbar events increase with true ISR p_T but only asymptotically. Even at 1200 GeV of true ISR p_T , a ttbar event which already passed zero lepton preselection only has a 35 percent chance of passing the additional SR selection.

After pre-selection, 90 percent of all ttbar events belong to the top/anti-top back-to-back population. Boosting one top against the other top simply requires less center-of-mass energy than boosting both tops with additional strong ISR.

After SR selection, only approximately 10 percent of all ttbar events have true ISR p_T less than 400 GeV. A back-of-the-envelope calculation shows that ttbar events need around 600 GeV of ISR p_T in order to boost the neutrino past the 250 GeV E_T^{miss} selection if both tops started at rest. Such high ISR p_T is required because the neutrino must share the ISR p_T with the 5 other particles in the ttbar decay. This completely agrees with the true ISR p_T distribution in SR which peaks around 550-

600 GeV for ttbar background in SR. The ttbar true ISR p_T distribution in SR can be seen in figure 11.2.

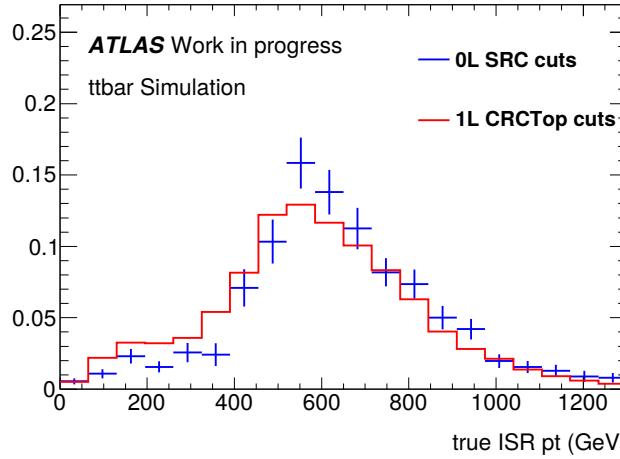


Figure 11.2: Distribution of true ISR p_T for ttbar that survive the signal selections

The analysis works by isolating ttbar with at least 550 GeV of ISR p_T . In comparison, a 400 GeV stop requires only 440 GeV of ISR p_T to pass the 250 GeV E_T^{miss} requirement. We effectively gain an order of magnitude in signal to background ratio (S/B) due to the lower required ISR p_T in signal.

At the same time, we gain another factor of 5 improvement in S/B simply by working in the zero lepton channel. In SR, the stops decay mainly via the all-hadronic decay channel with a 44 percent branching fraction. In comparison, 80 percent of ttbar background in SR decay via the hadronic tau channel with a branching fraction of approximately 10 percent.

The E_T^{miss} and ISR correlations in both direction and magnitude further improve

the S/B ratio by another factor of 5 to 10 depending on the stop mass. When combined, we are able to overcome the original 300 times difference in product cross section between the 400 GeV stop and SM ttbar.

As the stop mass increases, the required ISR p_T in signal decreases according to $m_t/m_{\tilde{\chi}_1^0}$, further increasing the accepted signal differential cross section, even if the signal production cross section is dropping. At the same time, the signal will peak at higher R_{ISR} ratios where background contributions are lower. In this way, the analysis is able to maintain sensitivity across a wide range of stop masses despite rapidly dropping signal production cross section at high stop masses.

After zero lepton preselection, the S/B ratio is 1.40 for a stop mass of 400 GeV. After signal region selection, the S/B ratio improves to approximately 2.1 for the same mass point. A quantitative breakdown of SR selection and yields is given in section 11.2 and 11.3.

At the same time, the same kinematic selections on jet multiplicity and total energy are also difficult for sub-dominant backgrounds such as $W+jets$, $Z+jets$, single top and QCD multijet to satisfy. It is in general difficult for these other processes to produce such high jet multiplicity and total energy in the same half of the event as the E_T^{miss} . Processes such as $W+jets$ and $Z+jets$ normally have the E_T^{miss} recoiling against other energetic jets. Therefore, energetic jets in these processes tend to lie in the hemisphere opposite the E_T^{miss} . Total sub-dominant background contributions to SR is around 10 to 30 percent depending on R_{ISR} region.

11.2 Signal Region Kinematic Selection

Kinematic Selections for Signal Region is defined in table 11.1.

The kinematic variables used are reconstructed using the recursive jigsaw method. A detailed description of this method and variable defined can be found in section 8.2. In short, the recursive jigsaw method separates the event into two hemispheres according to the thrust axis. The thrust axis, the axis that maximizes the amount of back-to-back p_T along it, should approximate the direction of ISR and sparticle back-to-back recoil in events with strong ISR. The hemisphere containing the E_T^{miss} is considered the sparticle hemisphere and the hemisphere opposite the E_T^{miss} is considered the ISR hemisphere. All jets in the sparticle hemisphere are considered to have originated from one of the stop decays. All jets in the ISR hemisphere are considered ISR jets. The performance of this ISR identification algorithm can be found in section 8.3.

We also construct variables that measure kinematic properties of both the ISR and sparticle hemispheres. These include N_{btag}^S and N_{jet}^S , which describe the jet multiplicity of the sparticle system. M_T^S , $p_T^{\text{jet } 4, S}$, and $p_{T,b}^{0,S}$ are all related to the total energy in the sparticle system. p_T^{ISR} corresponds to the total p_T of the ISR system. Finally R_{ISR} and $\Delta\phi_{\text{ISR}}$ quantify the correlation between the ISR system and E_T^{miss} in both direction and magnitude.

The selections on N_{jet}^S and $N_{\text{b-jet}}^S$ ensures that the hemisphere with E_T^{miss} has high

Table 11.1: Signal region definitions, in addition to the preselection requirements presented in Table ??.

Variable	SRC-1	SRC-2	SRC-3	SRC-4	SRC-5
$N_{\text{b-jet}}^S$			≥ 1		
N_{jet}^S			≥ 5		
p_T^{ISR}			$> 400 \text{ GeV}$		
$p_{T,b}^{0,S}$			$> 40 \text{ GeV}$		
$p_T^{4,S}$			$> 50 \text{ GeV}$		
m_S			$> 300 \text{ GeV}$		
$\Delta\phi_{\text{ISR}, E_T^{\text{miss}}}$			> 3.00		
R_{ISR}	0.30-0.40	0.40-0.50	0.50-0.60	0.60-0.70	0.70-0.80

amounts of jet multiplicity. These requirements are naturally satisfied in signal events because the two neutralinos go in the same direction as the six jets from the two stop decays. However, this requirement is more difficult to satisfy for the top/anti-top back-to-back ttbar population since these events contain only a single leptonic or hadronic tau top in the same hemisphere as the E_T^{miss} .

The ttbar plus strong ISR population is able to pass this selection as both the leptonic and hadronic tops are in the sparticle hemisphere. For this reason, the main background is comprised of these events after the sparticle jet multiplicity and the $p_T^{\text{ISR}} > 400 \text{ GeV}$ requirements. The S/B ratio is around 1.5 after these selections.

Next, we make a requirement on the total energy of the sparticle system. The total transverse mass of the sparticle system, m_S , must be greater than 300 GeV

and $p_T^{4,S}$, p_T of the 4th highest p_T jet in the sparticle system, must be greater than 50 GeV. $p_{T,b}^{0,S}$, the highest p_T b-jet in the sparticle system, must also be greater than 40 GeV.

In general, the signal with two fully hadronic tops has more energy in the sparticle hemisphere than ttbar. The top/anti-top back-to-back recoil population is nearly eliminated by these selections. Of the ttbar events that passed zero lepton preselection, less than 2 percent of ttbar events with true ISR p_T less than 400 GeV pass these additional requirements. Even for ttbar events with greater than 600 GeV of true ISR p_T , the selection efficiency remains at approximately 35 percent. S/B ratio improves to around 1.2 after these selections.

Lastly we make selections based on the correlations between the E_T^{miss} and ISR systems. $\Delta\phi_{\text{ISR}, E_T^{\text{miss}}} > 3.0$ ensures the E_T^{miss} and ISR systems are back-to-back. The ISR system and E_T^{miss} must be nearly back-to-back in signal because the neutralino gains momenta mainly from ISR. On the other hand, the neutrino in SM ttbar gains significant momentum from the top decay and its correlation with ISR is not as strong. This is also true for sub-dominant backgrounds including W+jet and single top.

The distribution of $\Delta\phi_{\text{ISR}, E_T^{\text{miss}}}$ with all previous selections on sparticle jet multiplicity and sparticle system energy applied is shown in figure 11.3.

The final R_{ISR} distribution after all signal selections is shown in figure 11.4. This R_{ISR} distribution is then separated into 5 bins from 0.3 to 0.8. The 5 SR bins are fitted simultaneously to extract the signal strength. We expect to receive very little

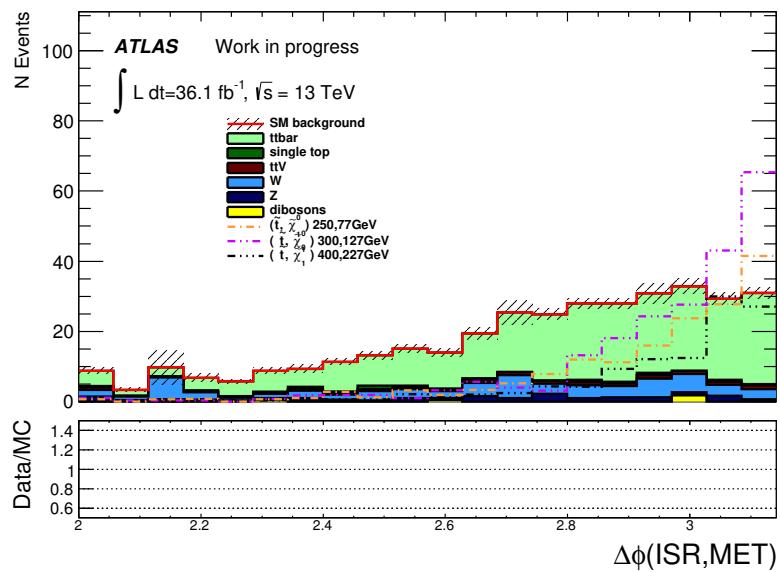


Figure 11.3: $\Delta\phi_{\text{ISR}, E_T^{\text{miss}}}$ distributions for the zero lepton preselection plus sparticle jet multiplicity, p_T^{ISR} , and sparticle total energy requirement with 36.07 fb^{-1} of data. The ratio between data and MC is shown in the bottom panel. The ratio between data and MC is shown in the bottom panel. The hatched area in both the top and lower panel represent the uncertainty due to MC statistics

signal events in R_{ISR} below 0.3 and the region is dominated by QCD background.

As such the R_{ISR} region below 0.3 is not included in the final SR fit.

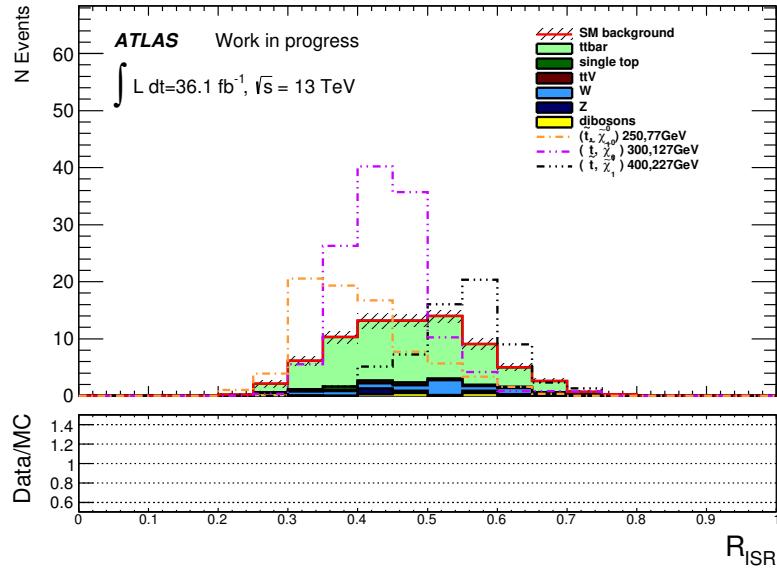


Figure 11.4: R_{ISR} distribution after signal region selection with 36.07 fb^{-1} of data. The ratio between data and MC is shown in the bottom panel. The hashed area in both the top and lower panel represent the uncertainty due to MC statistics

Stop samples with different stop and neutralino masses will peak in different locations in R_{ISR} with a S/B ratio of approximately 2:1 under the peak. The simultaneous fit to all five bins captures this peaking feature in R_{ISR} for any stop mass.

11.3 Signal Region Expected Yields and Kinematic Distributions

The expected yields in SR are given in table 11.2. All backgrounds have been normalized to CR defined in chapter 12. Signal yields for three example signal samples

with stop, neutralino masses of (300, 127 GeV), (400, 227 GeV), and (500, 327 GeV) are also shown for comparison. We achieved a 1 1 to 2 1 S/B ratio under the signal R_{ISR} peak in SR.

Distributions of kinematic variables in SR are shown in figure ??

11.4 Signal Region Background Composition

The dominant background in all signal region bins is SM ttbar. ttbar accounts for 85 percent of all backgrounds in the signal region. The next most prevalent background is W+jets which can reach up to 15 percent in high R_{ISR} bins. The breakdown of background composition is given in table ??

SRC1	
Z	0.46 ± 0.09
dibosons	0.39 ± 0.28
ttbar	18.19 ± 1.57
singleTop	1.44 ± 0.51
ttV	0.22 ± 0.10
W	0.64 ± 0.13
Total MC	21.34 ± 1.69
Data	20.00 ± 4.47
$(m_{\tilde{t}}, m_{\tilde{\chi}^0}) = (500, 327)$ GeV	0.11 ± 0.06 (-0.0 σ)
$(m_{\tilde{t}}, m_{\tilde{\chi}^0}) = (300, 127)$ GeV	30.68 ± 4.17 (5.5 σ)
$(m_{\tilde{t}}, m_{\tilde{\chi}^0}) = (400, 227)$ GeV	1.57 ± 0.45 (0.3 σ)

SRC2	
Z	0.90 ± 0.13
dibosons	0.21 ± 0.21
ttbar	31.20 ± 1.82
singleTop	1.02 ± 0.19
ttV	0.46 ± 0.19
W	1.53 ± 0.31
Total MC	35.30 ± 1.88
Data	22.00 ± 4.69
$(m_{\tilde{t}}, m_{\tilde{\chi}^0}) = (500, 327)$ GeV	1.42 ± 0.26 (0.2 σ)
$(m_{\tilde{t}}, m_{\tilde{\chi}^0}) = (300, 127)$ GeV	72.20 ± 7.29 (9.7 σ)
$(m_{\tilde{t}}, m_{\tilde{\chi}^0}) = (400, 227)$ GeV	10.81 ± 1.00 (1.7 σ)

SRC3	
Z	0.74 ± 0.15
dibosons	0.28 ± 0.28
ttbar	144 ± 1.07
singleTop	1.04 ± 0.41
ttV	0.44 ± 0.11
W	1.51 ± 0.37
Total MC	24.64 ± 1.25
Data	22.00 ± 4.69

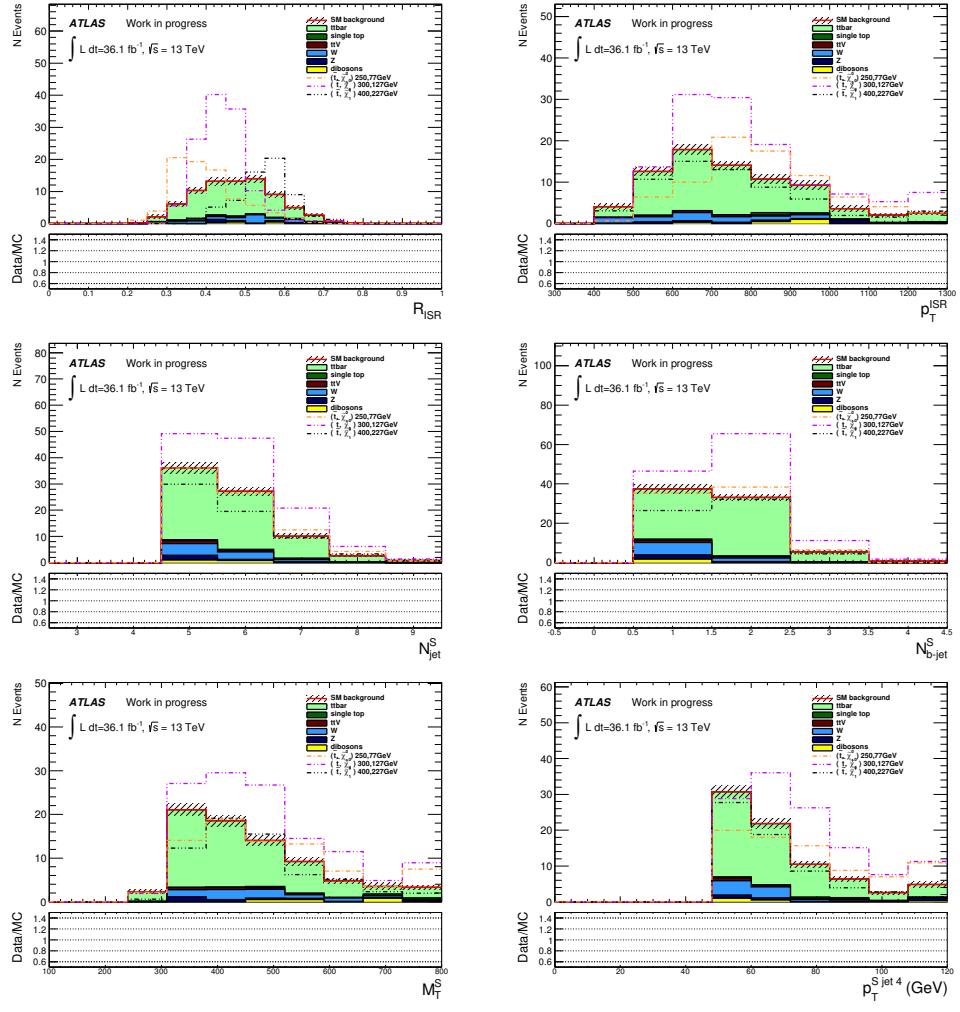


Figure 11.5: Distributions for signal region selection. The ratio between data and MC is shown in the bottom panel. The hashed area in both the top and lower panel represent the uncertainty due to MC statistics. QCD background estimation is not included.

R_{ISR} Range	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8
$t\bar{t}$						
$W+jets$						
$Z+jets$						
Single top						
QCD						
dibosons						

Table 11.3: Standard Model Background Composition in the Signal Region ??.

12

Standard Model Backgrounds

12.1 Common Background Estimation and Validation Techniques

We use both data and MC based background estimation technique for estimating background in the signal region. A common partially data driven technique directly measures the amount of background in kinematically similar control regions (CR) in data. Once we know the amount of background in the CR, we can then extrapolate

to the signal region using MC predictions.

We determined the background rate through a simultaneous fit to all SR and CRs when setting limits or calculating discovery significances. The background rate will be mainly constrained by the CRs because the CRs have significantly higher statistics than SR.

We also perform a background only fit to estimate the background rates. The background only fit extracts a normalization factor for each background by simultaneously fit all control regions. The normalization factors are then applied to the expected background rates in SR. The background only fit results may differ from the combined fit. However the two estimate should be similar as long as the CRs are well designed. A more detailed explanation of CR, SR and fitting procedures are covered in the statistical analysis chapter 14.

We use control regions to estimate the dominant ttbar background and subdominant W+jet, single top, and ttV backgrounds. Z+jets and diboson backgrounds are estimated using MC alone. Z+jets and dibosons contribute less than 5 percent of all backgrounds in the SR and we allow for an additional 100 percent theory uncertainty for these two samples. Finally QCD multijet background is estimated using the jet smearing method described in section 12.3.6. Details on the ttbar background is found in section 12.2. Details on the treatment of each sub dominate background can be found in section 12.3.

The scale factors for each background derived from the simultaneous fit to the CR

MC sample	Fitted scale factor
ttbar (SRA_TT)	1.147 ± 0.146
ttbar (SRA_TW)	1.150 ± 0.114
ttbar (SRA_T0)	0.856 ± 0.123
ttbar (SRB_TT)	1.219 ± 0.160
ttbar (SRB_TW)	1.009 ± 0.0697
ttbar (SRB_T0)	0.904 ± 0.0524
ttbar (SRC)	0.674 ± 0.0479
ttbar (SRD)	1.032 ± 0.110
ttbar (SRE)	1.041 ± 0.1083
W+jets	1.122 ± 0.155
Z+jets (SRA,B TT and TW)	1.213 ± 0.232
Z+jets (SRA,B T0)	1.115 ± 0.143
Z+jets (SRD)	1.081 ± 0.145
Z+jets (SRE)	1.233 ± 0.149
Single top	1.211 ± 0.389
ttbar γ	1.275 ± 0.184

Table 12.1: MC scale factors for SM backgrounds. Scale factors are derived by simultaneously fitting to all background CR using 36.07 fb^{-1} of data.

are given in table 12.1. ttbar background is scaled down by 0.707 because the MC over estimates the amount of ttbar that is produced with strong ISR.

12.2 Dominant Background: Standard Model $t\bar{t}$

The dominant background in this analysis is SM ttbar. After signal selection ttbar still accounts for 70-90 percent of the background depending on the R_{ISR} range. This section covers in detail the properties and treatment of SM ttbar in this analysis.

The section 12.2.1 demonstrates that there exists two kinematically distinct populations of SM ttbar, each with unique characteristics and observables. Section 12.2.2 describes how we are able to directly measure the amount of ttbar in SR using a one lepton CR.

12.2.1 Two Kinematically Distinct Populations of $t\bar{t}$

After the zero lepton preselection, 80 percent of ttbar events decay via the single hadronic tau channel. 15 percent of ttbar events decay via the single lepton channel where the lepton is an electron or a muon. The lepton is later lost because either it has too low p_T to be reconstructed, removed because they were too close to another jet or is mis-reconstructed as a jet. The rest of the five percent are due to di-leptonic decays. Fully hadronic ttbar is negligible after SR selections because they produce little intrinsic E_T^{miss} .

The $E_T^{\text{miss}} > 250 \text{ GeV}$ requirement in preselection selects ttbar with boosted leptonic tops. A top at rest simply do not have enough energy to produce a neutrino with 250 GeV of p_T . The leptonic top can gain boost mainly through one of two ways. Either the leptonic top recoils in a back to back fashion against the hadronic top or both tops can recoil against strong ISR.

In both situations the axis of maximum back to back p_T , the thrust axis, contains important information. In the case where the leptonic is recoiling against the hadronic top, the thrust axis lines up along the top/anti-top's axis of back to back recoil. In

the case where both tops are boosted by strong ISR, the thrust axis approximates the ttbar vs ISR recoil direction. An artistic representation of the role of the thrust axis in each ttbar population can be seen in figure 12.1.

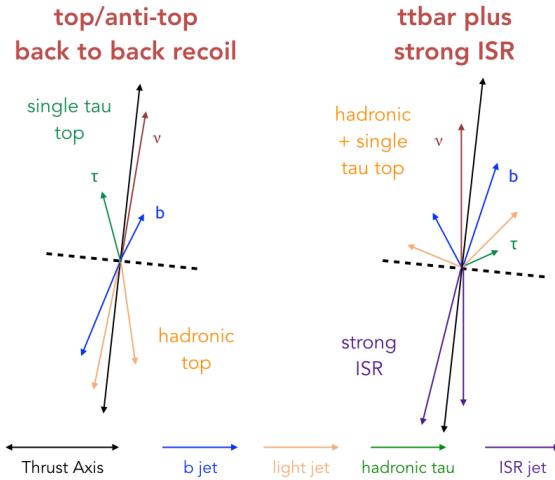


Figure 12.1: Depiction of the kinematics of the back to back ttbar population and the ttbar plus strong ISR population that exists after the zero lepton pre-selection. The two example event's thrust axis are aligned. The hemisphere containing E_T^{miss} has significantly higher jet multiplicities and total energy in ttbar plus strong ISR events.

The ttbar plus strong ISR population has on average much higher jet multiplicities and total energy in the hemisphere containing E_T^{miss} . Hence, we can use observable such as N_{jet}^S and M_T^S to distinguish ttbar plus strong ISR events from top/anti-top back to back recoil events.

12.2.2 Predicting the amount of $t\bar{t}$ in Signal Region using a One Lepton Control Region

Stop signal is expected to have a higher jet multiplicities and energy in the hemisphere containing E_T^{miss} than both ttbar populations. The stringent SR requirements on the jet multiplicities and total energy of the sparticle hemisphere effectively eliminate the top/anti-top back to back ttbar population and also rejects approximately 2/3 of ttbar plus strong ISR population. A detailed explanation of SR design and performance can be found in chapter 11.

The ttbar events that survives the SR selections are composed of almost exclusively ttbar that are also produced with strong ISR. Approximately 90 percent of the ttbar events in SR have an ISR pt of at least 400 GeV. A back of the envelope calculation shows that we need around 550-600 GeV of ISR p_T to boost the ttbar neutrino to above 250 GeV of p_T . The neutrino must share the ISR p_T with 5 other ttbar decay products and is not particularly efficient at absorbing ISR p_T . Figure 11.2 shows that the true ISR p_T distribution for ttbar in SR peaks at approximately 550 GeV. This demonstrates that the SR does indeed capture only ttbar with strong ISR p_T .

A direct consequence of selecting for only strong ISR ttbar is that the predicted ttbar background rates in SR is directly related to the amount of ISR/FSR in the MC. The next-to-leading order (NLO) Powheg+PYTHIA6 ttbar MC gives upwards of 30

percent uncertainty due to ISR/FSR systematic. The ISR/FSR theoretical uncertainty would completely dominate if we relied on MC to predict SR ttbar rates.

In order to decrease the ISR/FSR uncertainty, we directly measure the ttbar plus strong ISR rate in data using an one lepton ttbar CR (CRCTop). One lepton here refers only to electron and muons because they can be reconstructed with much greater purity then taus. The selections used to define the CRCTop is defined in table 12.2. All variables used are defined in section 8.4.

Table 12.2: One-lepton $t\bar{t}$ +ISR control region (CRCTop) definitions. The same E_T^{miss} triggers as mentioned in Table ?? are used.

Variable	1L 1b ttCR
1 Lepton Pre-Selection	
N_{lep}	1
$m_T(\ell, E_T^{\text{miss}})$	< 80 GeV
$\Delta R(b_{0,1}, \ell)_{\text{min}}$	< 2.0
N_{jet}^S	≥ 5
N_{btag}^S	≥ 1
$p_T^{4,S}$	> 40 GeV
p_T^{ISR}	≥ 400

CRCTop captures the same kinematic features as SR by targeting ttbar also produced with strong ISR p_T . The CR uses similar selections on the same kinematic variables as SR. The correlations on ISR and E_T^{miss} are removed to increase statistics and lower signal contamination. For example, $\Delta\phi_{\text{ISR}, i}$ specifies the direction of neutrino

relative to the direction of the ISR. A requirement of $\Delta\phi_{\text{ISR}, l} > 3.0$ essentially selects specific ttbar decay axis. Removing this cut opens up more phase space to ttbar decays but does not change the requirement on strong ISR p_T .

Figure 12.2 shows the true ISR p_T distribution for ttbar in SR and CR. Both distributions peak at roughly 550 GeV and have similar shapes. The one lepton CR essentially measures the amount of ttbar plus strong ISR directly in data. By normalizing ttbar background rates to the CR, we are able to limit the ISR/FSR uncertainty to below 10 percent for all R_{ISR} regions.

The close kinematic selection between CRCTop and SR also allow leads to cancellation of other systematics. For example, the 6 percent uncertainty on jet energy scale and jet energy resolution can be partially attributed to the CR and SR requiring jets of similar p_T . A more detailed discussion of systematics can be found in chapter 13

In the one lepton CRCTop, the lepton is included as a “jet” in the Jigsaw ISR algorithm and will be counted as a sparticle jet or an ISR jet depending on which hemisphere it falls. The lepton is meant to play the role of a hadronic tau jet in the zero lepton SR. This approximation is justified since roughly 80 percent of all ttbar events in SR decay via the hadronic tau channel.

Stop signal, especially those with $\Delta m \neq m_t$, tend to produce more E_T^{miss} because of the presence of neutralinos. A cut of $m_T(\ell, E_T^{\text{miss}}) < 80$ GeV is added to remove signal contamination. A $\Delta R(b_{0,1}, \ell)_{\text{min}} < 2.0$ cut is added to increase ttbar purity and

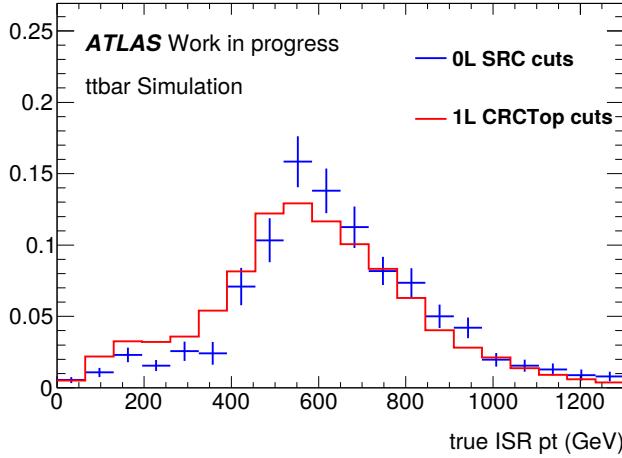


Figure 12.2: Distribution of true ISR pt for $t\bar{t}$ that survive the CR and SR selections. Both peak at roughly 550 GeV demonstrating that the one lepton CR and zero lepton SR captures the same population of $t\bar{t}$ plus strong ISR. Therefore, the one lepton CR essentially measures the amount of $t\bar{t}$ in SR directly from data with little extrapolation over ISR p_T .

ensure orthogonality to the W+jets control region.

The $p_T^{\text{jet } 4, S} > 50$ GeV cut is relaxed to $p_T^{\text{jet } 4, S} > 40$ GeV in order to increase statistics in the CR. The $p_T^{\text{jet } 4, S}$ cut specifies the p_T of the 4th jet in the sparticle system. The $p_T^{\text{jet } 4, S}$ cut can be correlated with ISR/FSR because there is a chance that the 4th most energetic jet in the sparticle system is from radiation and not from a top decay. However for this analysis it is more important to accurately gauge the amount of hard ISR of order hundred or more GeV that the $t\bar{t}$ system recoils against than amount of additional radiation in the same hemisphere as $t\bar{t}$. We found that loosening $p_T^{\text{jet } 4, S}$ cut to 40 GeV does not result in a large difference in the true ISR pt distribution in the CRCTop and SR.

CRCTop Signal Contamination

Signal contamination in CRCTop ranges from 1 percent at high stop masses to 12 percent at low stop masses for all mass points not already excluded by previous stop experiments. The largest signal contamination occurs at a stop mass of 225 to 250 GeV. Here, the signal contamination approaches 12 percent due to the large stop production cross-section. Lower stop masses result in higher signal contamination but our search does not have sensitivity to regions below 225 GeV.

The fact that CRCTop can attain such low signal contamination while selecting for ttbar background with such similar kinematic features as SR is impressive. The SR has a signal to background ratio of approximately 2 to 1 for stop masses between 250 GeV and 400 GeV. In comparison, CRCTop is able to achieve SR contamination of around 5 to 12 percent for the same signal points.

CRCTop is able to make up for this factor of 20-40 difference in S/B rate mainly due to two reasons. First CRCTop is a one lepton control region. Working in the one lepton region means both signal and ttbar background draw from the single muon and single electron decay channels. Signal and background therefore has similar decay fractions in CRCTop. The SR, on the other hand, mainly selects for signal with two tops that decay fully hadronically with roughly a 44 percent branching fraction. In comparison, the ttbar background in SR main decay via the single hadronic tau decay channel with only a 10 percent decay fraction. The CR therefore has a factor

of 5 decrease in S/B ratio compared to the SR based on branching fraction alone.

The SR also gains S/B by enforcing the correlations between the ISR system and E_T^{miss} . Removing the $\Delta\phi_{\text{ISR}, i} > 3.0$ requirements decreases S/B by another factor of 3. Including all regions of R_{ISR} in CRCTop and specifically targeting the R_{ISR} window under the signal peak decreases the S/B of 2 to 5 to the S/B depending on the stop mass and location of signal R_{ISR} peak. Removing the requirement on these correlations do no change the requirement on strong ttbar ISR p_T but opens up more phase space for ttbar to decay.

The two factors combine to make up the roughly factor of 30 decrease in S/B between SR and CRCTop; all the while preserving the agreement in true ttbar ISR p_T distribution shown in figure 12.2.

CRCTop Distributions

Distribution of important variables after normalization to 36.07 fb^{-1} of data are shown for CRCTop in figure 12.3. There seem to be no significant slope in the data over MC comparison in the CRCTop $p_T^{\text{jet } 4, \text{ S}}$ distribution. This is further evidence that the extrapolation from 40 to 50 GeV across $p_T^{\text{jet } 4, \text{ S}}$ is allowed.

There is a noticeable trend in the data over MC comparison in the CRCTop p_T^{ISR} distribution. The disagreement is not surprising given that a priori we have an 30 percent uncertainty due to the ISR/FSR uncertainty. This further demonstrate the need for a CR that directly measures the amount of ttbar with strong ISR pt in data.

The normalization scale factor for ttbar is 0.707 according to a background only fit on 36.07 fb^{-1} of data. This scale factor is quiet different from 1.0 which indicates that the ttbar MC alone does not well model the high ISR p_T phase space. Again, this difference is not unexpected given the 30 percent ISR/FSR uncertainty on ttbar MC.

12.2.3 Validating $t\bar{t}$ Predictions in Signal Region using a Zero Lepton Validation Region

We also define a zero lepton ttbar VR to validate the predicted background rates in SR. The ttbar VR (VRCTop) is kinematically similar to SR but has the $\Delta\phi_{\text{ISR}, i} < 3.0$ selection is inverted to ensure orthogonality and limit signal contamination. In ttbar events, $\Delta\phi_{\text{ISR}, i}$ specifies the direction of neutrino relative to the direction of the ISR. Inverting the $\Delta\phi_{\text{ISR}, i}$ selection only selects for ttbar with a different decay axis but does not change the requirements on strong ISR p_T . The $\Delta\phi_{\text{ISR}, i} < 3.0$ selection does effectively reject stop events because the neutralinos gain all their momenta from the ISR system in signal.

The requirement on M_T^S is reduced to 100 GeV (vs. 300 GeV in the SR) and an $N_{\text{jet}}^S \geq 4$ selection is applied (vs. $N_{\text{jet}}^S \geq 5$ in the SR) to enhance the yields of semi-leptonic $t\bar{t}$ events . A requirement of $M_T^{S,\text{Vis}}/M_T^S < 0.6$ is added to reduce signal contamination and reject QCD multijet background.

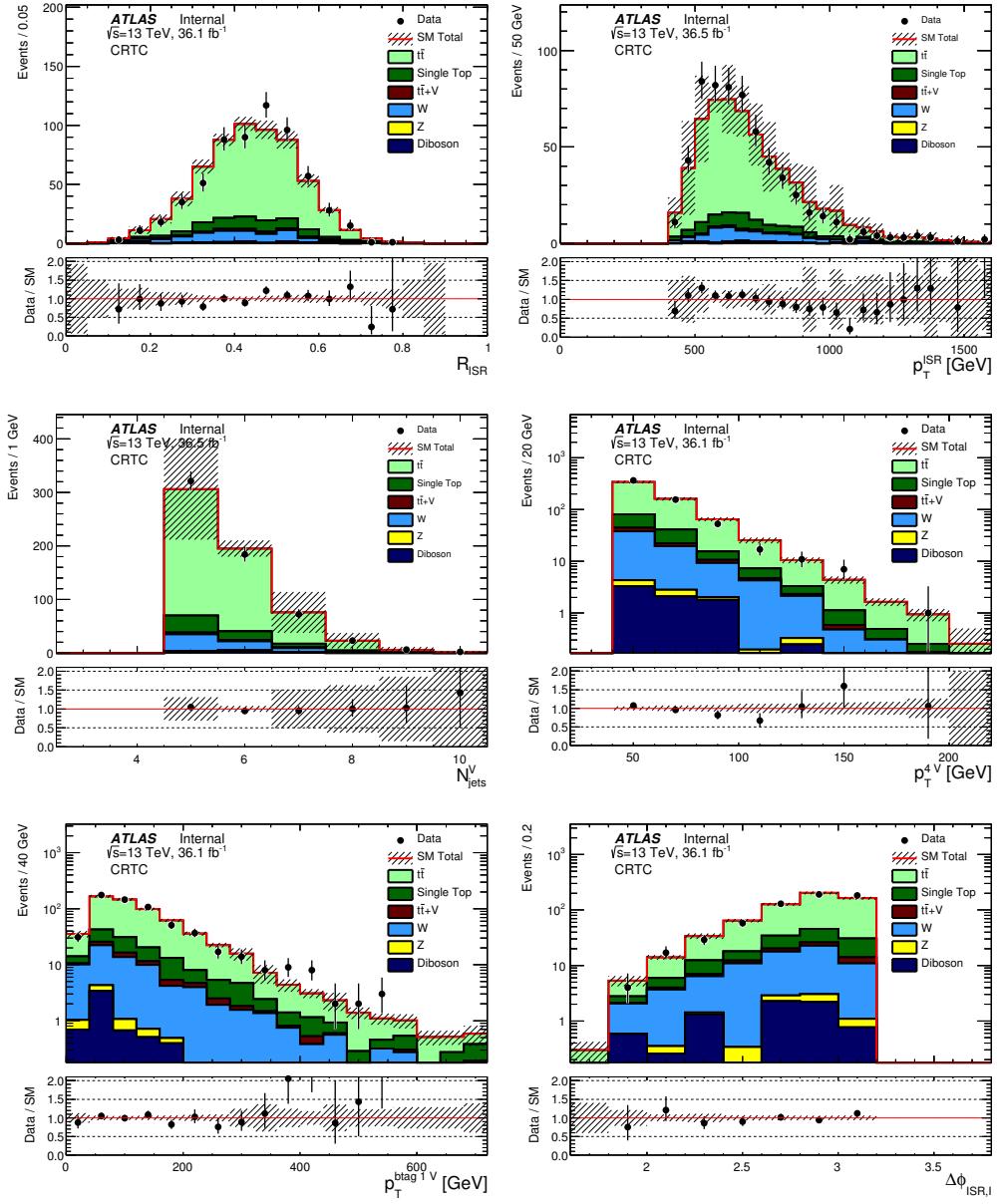


Figure 12.3: One lepton ttbar CR (CRCTop) distributions for 36.07 fb^{-1} of data. All backgrounds have already been normalized to CRs by performing a background only fit. The ratio between data and MC is shown in the bottom panel. The hashed area in both the top and lower panel represent the uncertainty due to MC statistics and detector systematic uncertainties.

Table 12.3: Zero-lepton $t\bar{t}$ +ISR validation region definitions, in addition to the SRC requirements listed in Table ??.

Variable	
N_{jet}^S	≥ 4
N_{btag}^S	≥ 1
$p_T^{\text{btag 1, S}}$	≥ 40
p_T^{ISR}	≥ 400
M_T^S	$> 100 \text{ GeV}$
$M_T^{S,\text{Vis}}/M_T^S$	< 0.6
$\Delta\phi_{\text{ISR, } I}$	< 3.00

Similar to CRCTop, the $p_T^{\text{jet 4, S}} > 50 \text{ GeV}$ selection is relaxed to $p_T^{\text{jet 4, S}} > 40 \text{ GeV}$ to increase VR statistics.

The distributions of the selection variables in VRCTop are shown in Fig. 12.4. The background rates have been normalized to CRs through the use of a background only fit to 36.07 fb^{-1} of data.

The predicted background rate in the VRCTop agrees with data to within 1σ . This demonstrates that CRCTop is an effective predictor of ttbar background rates in VR and SR. The R_{ISR} shape is well modeled as we see no distinct trends in the data vs MC ratio in R_{ISR} .

Similar to CRCTop, there is a noticeable trend in the data over MC comparison in the VRCTop p_T^{ISR} distribution. Again this is expected because the MC is a poor

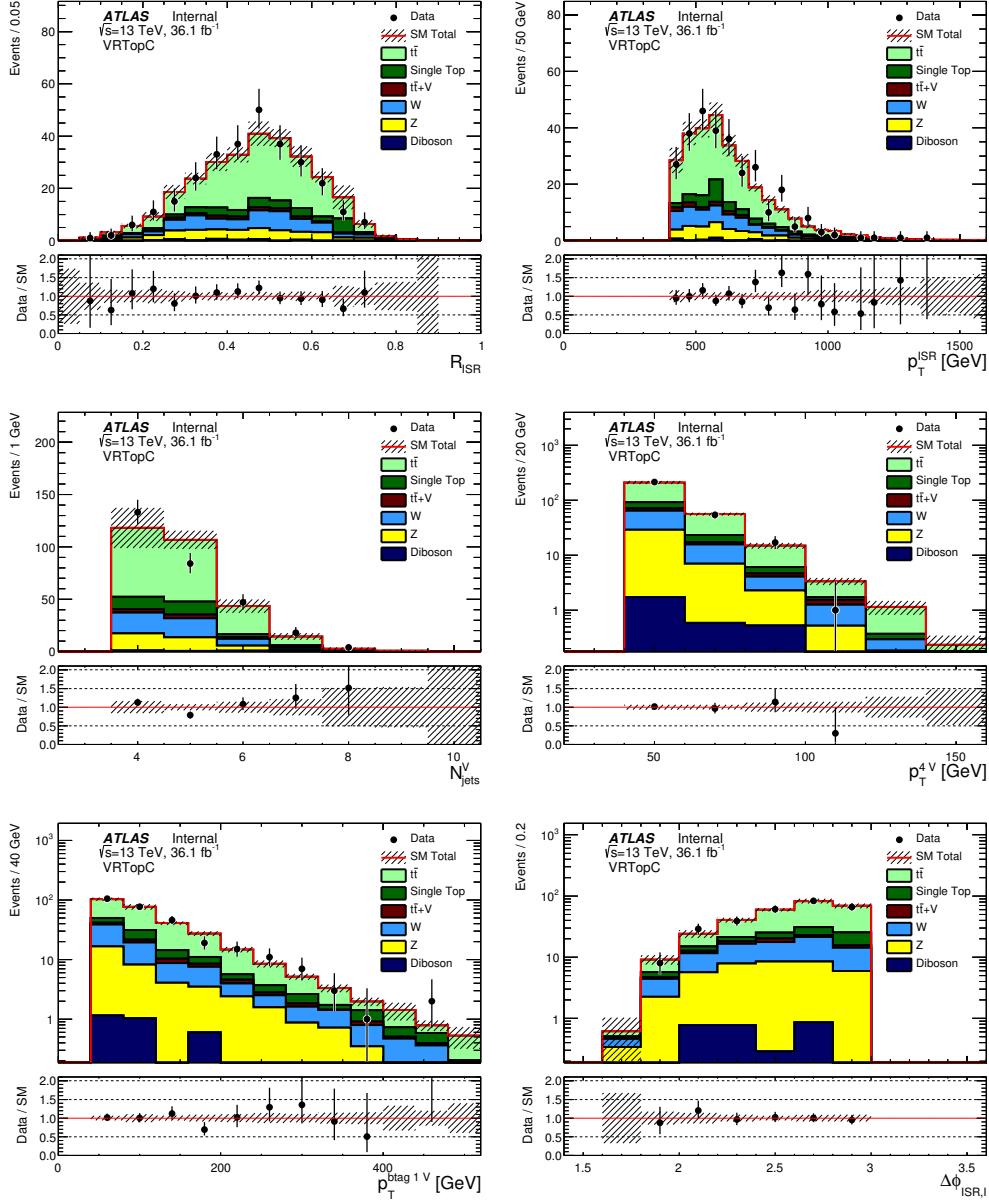


Figure 12.4: Distribution of select variables in the zero lepton $t\bar{t}$ validation region. The ratio between data and MC predictions are shown in the bottom panel. The background rates have been normalized to CRs through the use of a background only fit to 36.07 fb^{-1} of data. Experimental systematic uncertainties on background predictions are depicted as the hashed bands.

predictor of ISR p_T rates. The fact that data in VRCTop agrees with the predicted background rate proves that CRCTop can effectively measure the amount of ttbar with at least 400 GeV of ISR p_T .

12.3 Subdominant Backgrounds

12.3.1 Standard Model W+Jets

A W boson produced in conjunction with QCD jets (W +jets) consists our largest subdominate background. W +jets makes up 5 percent of the total background in the SR. However the distribution of W +jets is not uniform across R_{ISR} . W +jets can reach around 15 percent of all background in the SR bins with the largest R_{ISR} . This means the W +jets contribution mostly affects high stop mass samples because those signal samples peak at high R_{ISR} .

We estimate W +Jets using an one lepton control region defined in table 12.4.. The one lepton W +jet CR is designed to ensure high W +jet purity. All one lepton CRs are mutually exclusive including the ttbar, W +jets and single top CR.

The signal lepton is treated as a jet for the jet multiplicity and the jet p_T requirements. The mass requirement on the large R jet $m_{\text{jet}, R=1.2}^0 < 60 \text{ GeV}$ rejects events with reconstructed boosted tops. The $m_T(\ell, E_T^{\text{miss}})$ selection ensures that the transverse mass is consistent with those originating from a W boson.

Orthogonality between the W +jet CR and the single top CR is ensured by the re-

	CRW
Number of leptons	1
Number of jets (incl. lepton)	≥ 4
p_T of jets (incl. lepton)	(80,80,40,40) GeV
$\min \left \Delta\phi \left(\text{jet}^{0-1}, E_T^{\text{miss}} \right) \right $	> 0.4
E_T^{miss}	> 250 GeV
$m_T (\ell, E_T^{\text{miss}})$	($> 30, < 100$ GeV)
Number of b -jets	= 1
$m_{\text{jet}, R=1.2}^0$	< 60 GeV
$\Delta R(b_{0,1}, \ell)_{\text{min}}$	> 2.0

Table 12.4: Summary of the selection for the one lepton W +jets control region.

quirement on the number of b -jets. Orthogonality between ttbar CR and W +jet CR is ensured by the selection on $\Delta R(b_{0,1}, \ell)_{\text{min}}$, defined as the minimum ΔR between the two jets with the highest b-tag value and the selected lepton.

Distributions of select kinematic variables in the W + jets control region are shown in figure 12.5. The MC background has been normalized to data by performing a simultaneous fit to all CRs. The hashed bands on the total SM background correspond to the total experimental systematical uncertainty plus the MC statistical uncertainty. The yield in the W + jets CR is given in table 12.5.

Data and MC are compatible to within statistical uncertainty. No strong trends are observed in the data to MC ratios in any of the distributions.

CRW (60% purity)	
Z	1.99 ± 0.45
dibosons	9.85 ± 1.76
ttbar	128.42 ± 3.82
singleTop	51.14 ± 3.37
ttV	1.07 ± 0.16
W	288.12 ± 8.86
Total MC	480.58 ± 10.38
Data	531.00 ± 23.04
SF	1.17 ± 0.10

Table 12.5: Yields in the $W +$ jets CR with 36.07 fb^{-1} of data.

12.3.2 Standard Model Single Top

Standard Model single top consists of 3 to 7 percent of the background in any one R_{ISR} bin. In total, single top consist of 4 percent of the total background in SR. A one lepton single top control region is defined in table 12.6. The single top CR is orthogonal to both the one lepton W -jets control region and ttbar control region.

The signal lepton is treated as a jet for the jet multiplicity and the jet p_T requirement as well as for the top reconstruction. The $m_T(\ell, E_T^{\text{miss}})$ selection ensures that the transverse mass is consistent with a W decay. The $\Delta R(b, b) > 1.5$, the ΔR between the two b-jets with the highest b-tagging values, isolates single top events and rejects ttbar. This gives the single top CR a purity of $\sim 50\%$.

The mass requirement on the large R jet $m_{\text{jet},R=1.2}^0 > 120 \text{ GeV}$ searches for events with reconstructed boosted tops and ensures orthogonality with the $W +$ jets CR. The $\Delta R(b_{0,1}, \ell)_{\text{min}}$ selection ensures orthogonality with the ttbar CR.

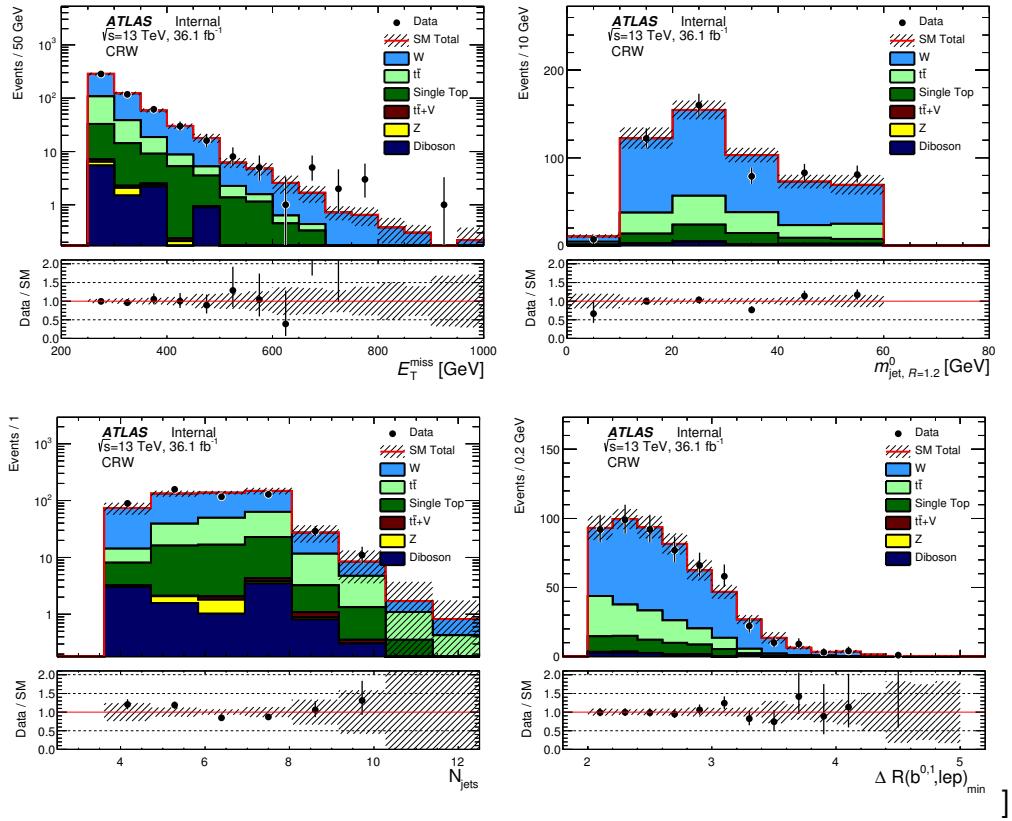


Figure 12.5: Postfit data/MC comparisons in the $W + \text{jets}$ CR. From left to right and top to bottom, the variables shown are E_T^{miss} , $m_T(\ell, E_T^{\text{miss}})$, $m_{\text{jet},R=1.2}^0$ and $\Delta R(b_{0,1}, \ell)_{\text{min}}$. The expected SM background has been normalized to data in the CR by performing a simultaneous fit to all background CRs. The hatched band on the total SM background correspond to the total experimental systematical uncertainty plus the MC statistical uncertainty.

Kinematic distributions in the single control region are shown in figure 12.6. The MC background has been normalized to data by performing a simultaneous fit to all CRs. The hashed bands on the total SM background correspond to the total experimental systematical uncertainty plus the MC statistical uncertainty. The yield in the single top CR is given in table 12.7.

Data and MC are compatible to within statistical uncertainty. No strong trends are

	CRST
Number of leptons	1
Number of jets (incl. lepton)	≥ 4
p_T of jets (incl. lepton)	(80,80,40,40) GeV
$\min \left \Delta\phi \left(\text{jet}^{0-1}, E_T^{\text{miss}} \right) \right $	> 0.4
E_T^{miss}	> 250 GeV
$m_T(\ell, E_T^{\text{miss}})$	$> 30, < 100$ GeV
Number of b -jets	≥ 2
$m_{\text{jet}, R=1.2}^0$	$v > 120$ GeV
$m_T^{b,\text{min}}$	> 200 GeV
$\Delta R(b_{0,1}, \ell)_{\text{min}}$	> 2.0
$\Delta R(b, b)$	> 1.5

Table 12.6: Selection for the one lepton, single top control region.

observed in the data to MC ratios in any of the distribution.

CRST (44% purity)	
Z	0.11 ± 0.05
dibosons	1.52 ± 0.54
ttbar	34.17 ± 2.10
singleTop	45.62 ± 1.41
ttV	2.42 ± 0.19
W	19.72 ± 1.69
Total MC	103.57 ± 3.10
Data	113.00 ± 10.63
SF	1.21 ± 0.29

Table 12.7: Yields in the CRST in 36.07 fb^{-1} of data.

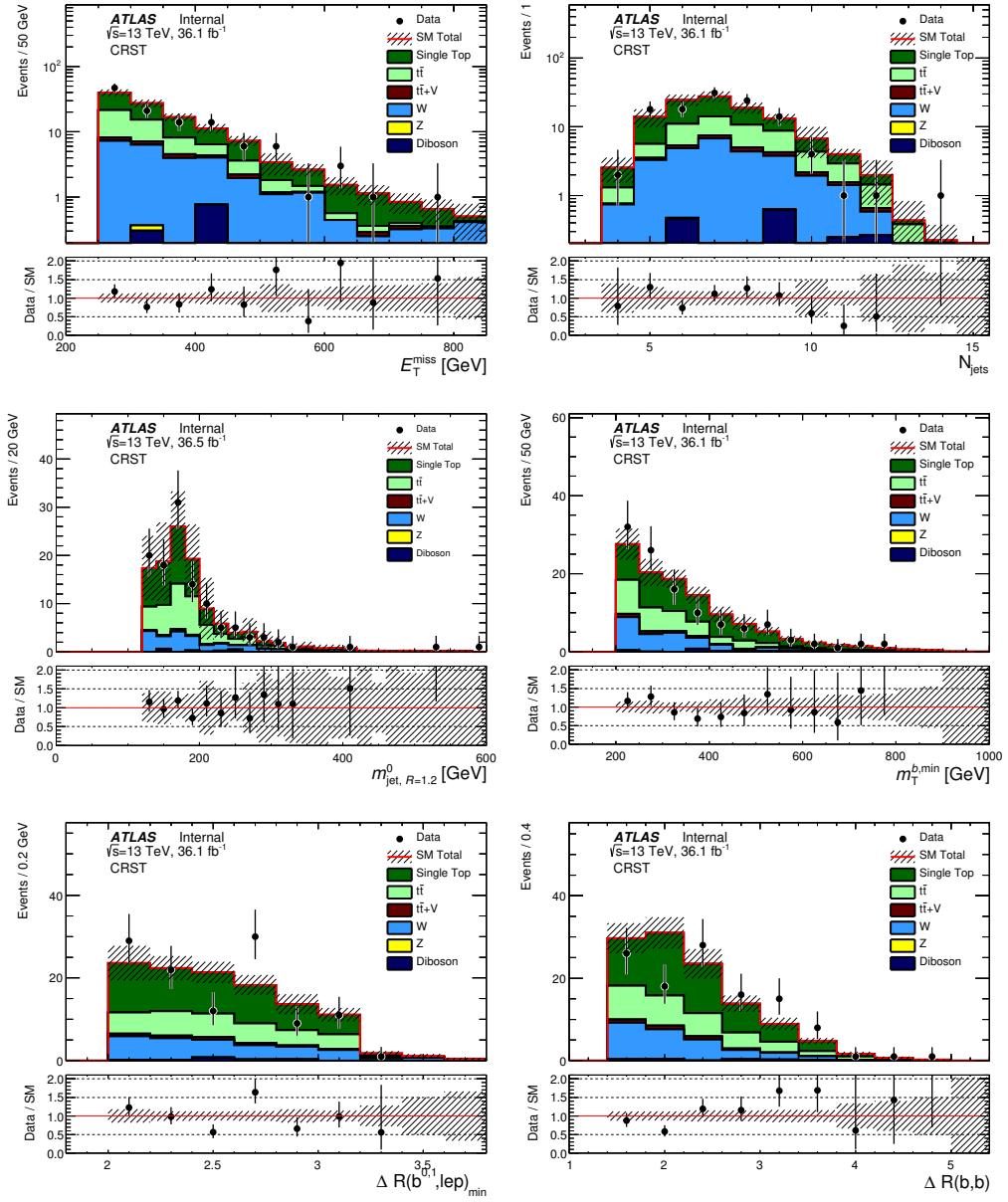


Figure 12.6: Single top control region distributions for 36.07 fb^{-1} of data after a simultaneous fit to all background CR. The ratio between data and MC is shown in the bottom panel. The hashed area on the expected SM background represent the uncertainty due to experimental systematics and MC statistics.

12.3.3 Standard Model $t\bar{t}+Z$

ttbar produced in conjunction with a Z boson consist of about one percent of the background in the SR. Although the background is essentially negligible we do estimate the amount of $t\bar{t} + Z$ using a $t\bar{t} + \gamma$ CR.

Using the charged leptonic Z boson decays to design a CR to estimate the $t\bar{t} + Z$ background would produce a CR with small systematic uncertainty. However, such CR tend to have low statistics because of the small branching fraction to electrons/muons compared to the branching fraction of neutrinos. A dilepton CR also contain a large contribution from SM ttbar and $Z + \text{jets}$.

We take another data driven approach by building a one-lepton CR for $t\bar{t} + \gamma$. $t\bar{t} + \gamma$ mimics $t\bar{t} + Z$ as the photon is in many ways like a lighter Z boson. The CR is designed to minimize theoretical uncertainties due to the extrapolation from the γ in CR to the Z in SR.

We require exactly one signal photon and one signal lepton. The lepton is not treated as a jet for the purpose of jet multiplicity and jet p_T requirements unlike in the other one lepton CRs. We also trigger on leptons instead of E_T^{miss} in this region. The lepton triggers used are defined in table 12.8.

We require a hight p_T photon with p_T greater than 150 GeV. The high p_T gamma ensures that we are in a region of phase space where the γp_T shape will mimic the heavier $Z p_T$. The true γp_T and the $Z p_T$ distributions is shown in figure 12.7 after se-

Table 12.8: Single Lepton triggers

Channel	Trigger
Data 2015	
Electron	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose
Muon	HLT_mu20_iloose_L1MU15 HLT_mu50
Data 2016	
Electron	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0
Muon	HLT_mu26_ivarmedium HLT_mu50

lecting for a boson p_T with greater than 150 GeV. We add a systematic uncertainty to account for the difference between the γ and $Z p_T$ spectrum.

The $t\bar{t} + \gamma$ control region is defined in table 12.9. The expected background and data yields in the $t\bar{t} + \gamma$ CR is given in table 12.10.

Kinematic distributions in the $t\bar{t} + \gamma$ control region are shown in figure 12.8. The MC background has been normalized to data by performing a simultaneous fit to all CRs. The hashed bands on the total SM background correspond to the total experimental systematical uncertainty plus the MC statistical uncertainty.

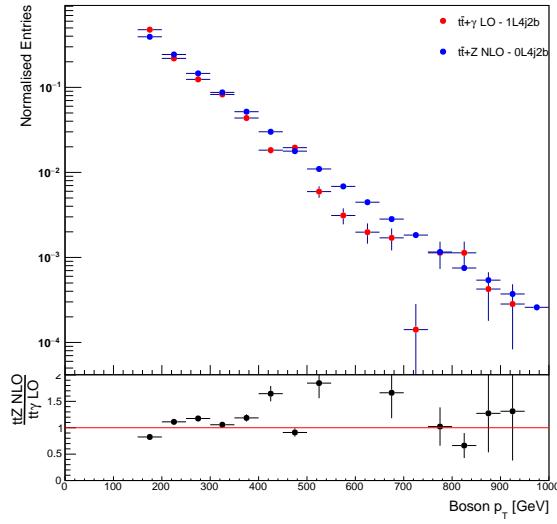


Figure 12.7: γ and Z p_T distributions with no detector resolution effects. A selection of $p_T > 150$ GeV has been applied.

Selection	Requirement
Event selection	Event cleaning
Trigger	1L Triggers
Leptons	= 1
Lepton p_T	28 GeV
Photons	exactly 1
jet multiplicity	≥ 4
Jet p_T	(80,80,40,40) GeV
b-jet multiplicity	≥ 2
γp_T	> 150 GeV

Table 12.9: Selection for the $t\bar{t} + \gamma$ one lepton CR. The one lepton triggers as described in Table 12.8

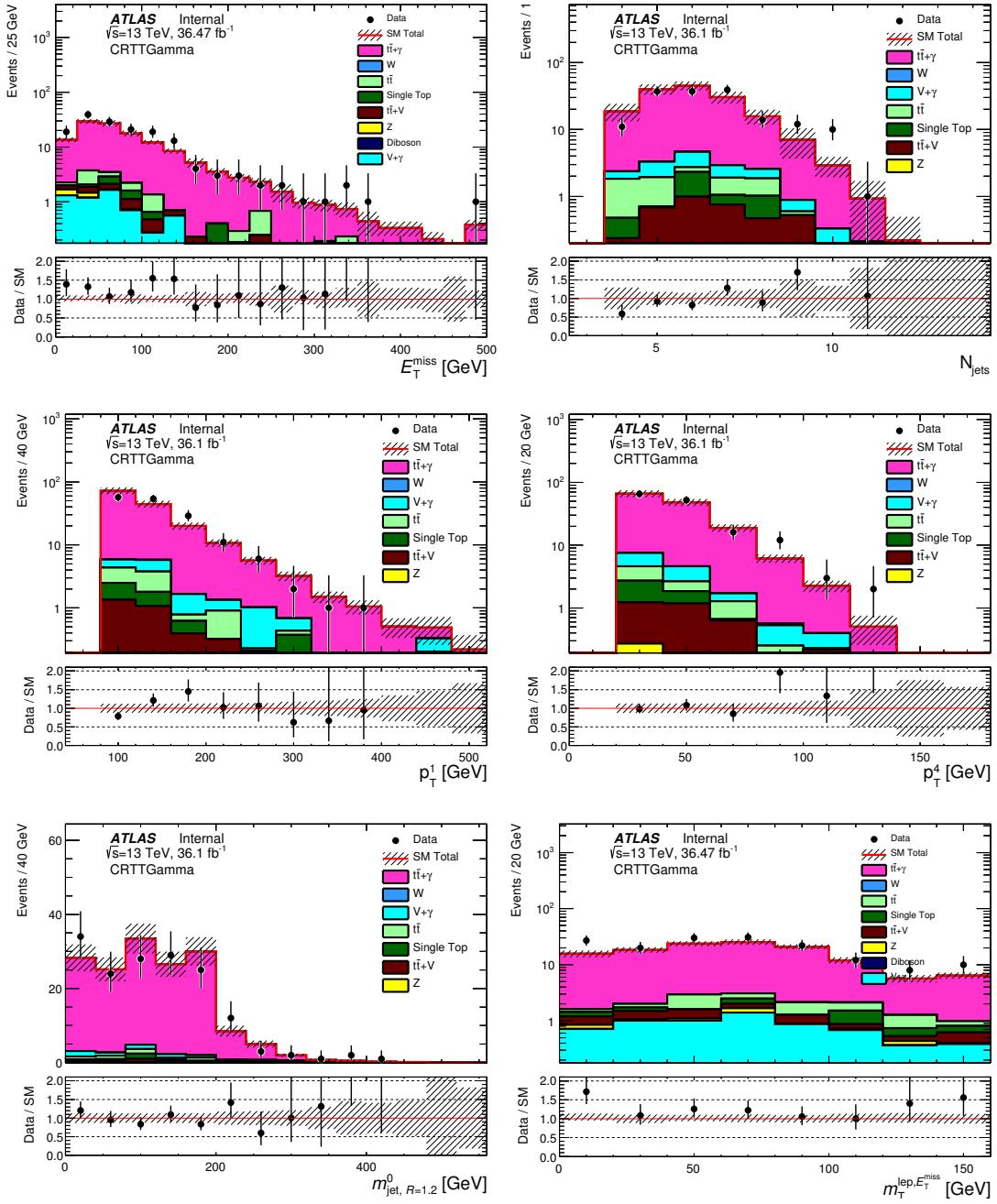


Figure 12.8: Distributions of select kinematic variables in the $t\bar{t} + \gamma$ CR. The hashed area in both the top and lower panel represents the uncertainty due to MC statistics.

Table 12.10: Background composition of $t\bar{t}\gamma$ CR.

CRTTGamma (87% purity)	
ttGamma	112.20 ± 1.49
VGamma	6.41 ± 0.70
Z	0.73 ± 0.21
dibosons	0.00 ± 0.00
ttbar	4.57 ± 1.23
singleTop	2.01 ± 0.81
ttV	2.42 ± 0.28
W	0.04 ± 0.02
Total MC	128.38 ± 2.23
Data	160.00 ± 12.65
SF	1.28 ± 0.12

12.3.4 Standard Model Z+Jets

Z+jets consist of 3 percent of all backgrounds in the SR. We use just the MC prediction for Z+jets because the rate of Z+jet is so low. We assign a 50 percent theory uncertainty to the Z+jets rate in the SR.

The ttbar validation region described in section 12.2.3 has a larger fraction of Z+jets event than those in the SR. The ttbar VR is kinematically similar to those of the SR with some loser cuts on jet multiplicity and ISR, E_T^{miss} correlations. The good agreement between data and MC in the ttbar VR is evidence that the Z+jets MC cannot be wrong by more than 50 percent.

12.3.5 Standard Model Diboson

Standard Model dibosons consist of approximately 1 percent of the background in the signal region. The diboson background consist of less than 2 percent of any single R_{ISR} bin in the SR. The background is negligible and we only use MC predictions for background estimation.

12.3.6 Standard Model QCD Multijet and all Hadronic $t\bar{t}$

Both QCD multijet and all hadronic $t\bar{t}$ creates little intrinsic E_T^{miss} . Instead misreconstructed jets can cause an imbalance in the total event E_t and generate fake E_T^{miss} . QCD contributions are only significant in the SR bins with low $R_{\text{ISR}} < 0.4$ and are estimated using the data driven jet smearing method.

The Jet Smearing Method

The jet smearing method first selects seed events from data with well reconstructed jets and little E_T^{miss} . Seed events are selected according to the criteria listed in table ???. We then repeatedly smear the seed events' jets with a predetermined jet energy response. The resulting pesudo-data events can have potentially large E_T^{miss} due to the smeared jets. A schematic demonstrating the jet smearing method is shown in figure 12.9.

The jet smearing methods have a number of inherent assumptions about the gen-

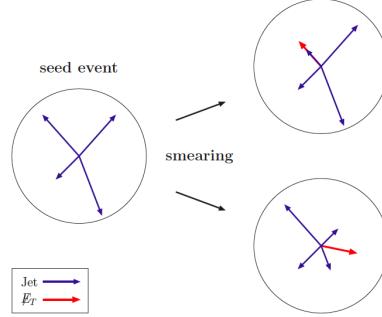


Figure 12.9: Schematic of the jet smearing method. A seed event with good jet energy measurements are repeatedly smeared with predetermined jet energy resolutions. The new E_T^{miss} is calculated as the difference between the seed event's and smeared event's jet momenta plus the original seed event's E_T^{miss} . (Figure taken from⁴⁸)

eration of E_T^{miss} in QCD multijet and all hadronic $t\bar{t}$ background. These assumptions include:

- The jet response captures all sources of jet p_T measurement fluctuations
- The E_T^{miss} in multijet events result predominately from mis-measured jets
- Jet response are independent on the presence of other jet and jet smearing can be applied on a jet-by-jet basis

These assumptions seem be well satisfied in the high E_T^{miss} , high jet multiplicity region of SR. We also validate QCD predictions in a QCD VR defined in section 12.3.6.

Other sources of E_T^{miss} not taken into account by the jet smearing method such as E_T^{miss} from pileup jets, mis-reconstructed soft term of the E_T^{miss} and object overlap removal are assumed to be negligible in the signal region.

The quantity $E_T^{\text{miss}} \text{sig.} = \frac{E_T^{\text{miss}} - 8 \text{ GeV}}{\sum E_T}$ measures the general significance of E_T^{miss} relative to total hadronic activity in an event. In general events with low $E_T^{\text{miss}} \text{sig.}$ have

Table 12.11: Seed event preselection

Cut
$n_{\text{prim.vertices}} > 0$
Jet trigger
Bad jet veto
Cosmic muon veto
Bad muon veto
Baseline lepton veto
≥ 4 jets
≥ 1 b-jets
$E_T^{\text{miss}} \text{sig.} < 0.3 + 0.1 \cdot n_{\text{n-bjets}}$

better reconstructed jets. However, the requirement on $E_T^{\text{miss}} \text{sig.}$ depends on the number of b-jets because b-quarks can emit significant portions of their energy in the form of neutrinos.

The jet response function include contributions from the following effects:

- Limited calorimeter granularity
- Hadronic energy falling outside of the jet radius or failed to be clustered correctly by jet reconstruction.
- Additional energy clustered into the jet that result from other sources.
- Energetic jet punching through the calorimeter.
- Dead material in the calorimeter.
- b-quark generating real E_T^{miss} through decay to neutrinos. B-tagged jets have a different jet response function than light quark jets to account for this difference.

QCD multijet Control Region and Validation Region

The pseudo-data resulting from the jet smearing processes is then normalized to data using the QCD control region defined in table 12.12. The QCD CR is designed to be similar to the SR except the $\min |\Delta\phi(\text{jet}^{0-1}, E_T^{\text{miss}})|$ is required to be between 0.05 to 0.1 instead of greater than 0.04. This region is dominated by QCD backgrounds with high E_T^{miss} due to a single mis-reconstructed energetic jet but with the same jet multiplicity and jet kinematics required in the SR.

Variable	CR
$\min \Delta\phi(\text{jet}^{0-1}, E_T^{\text{miss}}) $	[0.05,0.1]
$N_{\text{b-jet}}^S$	≥ 1
N_{jet}^S	≥ 5
$p_{T,b}^{0,S}$	$> 40 \text{ GeV}$
$\Delta\phi_{\text{ISR}, E_T^{\text{miss}}}$	> 2.00
p_T^{ISR}	$> 150 \text{ GeV}$
R_{ISR}	< 0.4
$p_T^{4,S}$	$> 50 \text{ GeV}$
b-tagged jets	≥ 1

Table 12.12: QCD CR definitions, in addition to the zero lepton preselection in Table ??.

Data vs QCD pseudo-data prediction for the p_T^{ISR} , $\Delta\phi_{\text{ISR}, i}$ and M_T^S variables for the QCD CR can be seen in figure 12.10. These variables are shown because they are extrapolated over from CR to SR.

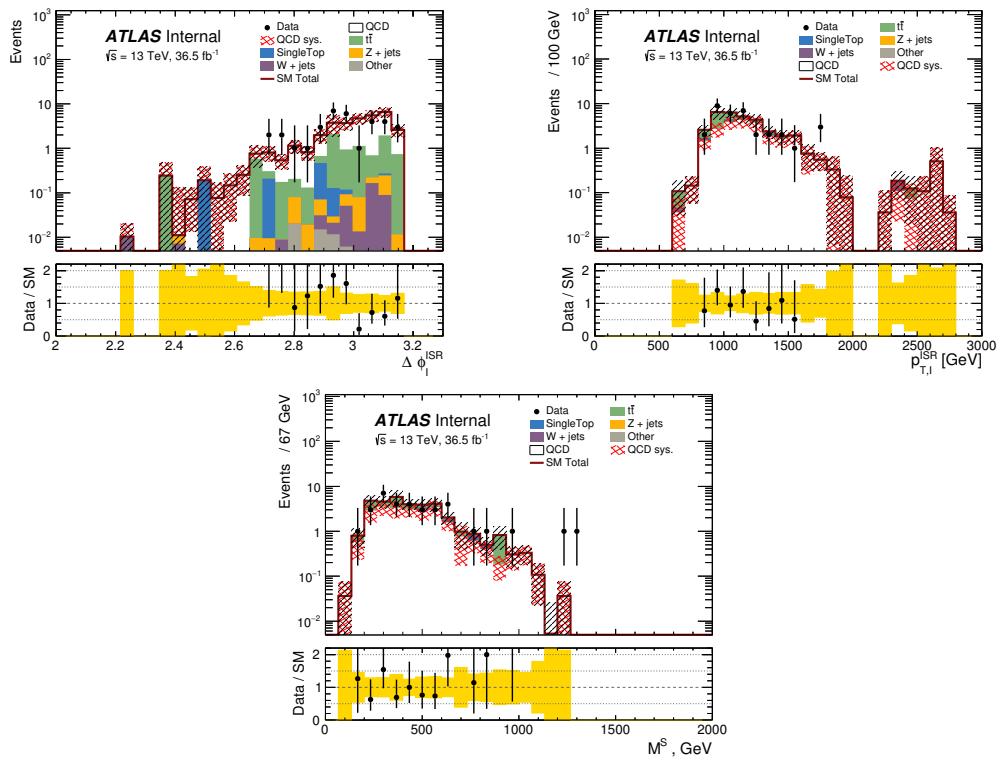


Figure 12.10: p_T^{ISR} , $\Delta\phi_{\text{ISR}, I}$ and M_T^S distributions in the QCD control regions.

The results of QCD multijet prediction using jet smearing after normalizing to the CR can be checked in the QCD VR defined in table 12.13. The QCD VR has the exact same kinematic selection as the SR except with a lower $\min |\Delta\phi(\text{jet}^{0-1}, E_T^{\text{miss}})|$ between 0.1 and 0.2. R_{ISR} is also required to be below 0.4 as we don't expect significant QCD contribution at higher R_{ISR} .

Table 12.13: QCD VR definitions, in addition to the 0 lepton preselection in Table ??.

Variable	VR
$\min \Delta\phi(\text{jet}^{0-1}, E_T^{\text{miss}}) $	[0.1,0.2]
$N_{\text{b-jet}}^S$	≥ 1
N_{jet}^S	≥ 5
$p_{T,b}^{0,S}$	$> 40 \text{ GeV}$
m_S	$> 300 \text{ GeV}$
$\Delta\phi_{\text{ISR}, E_T^{\text{miss}}}$	> 3.00
p_T^{ISR}	$> 400 \text{ GeV}$
R_{ISR}	< 0.4
$p_T^{4,S}$	$> 50 \text{ GeV}$
b-tagged jets	≥ 1

Data vs QCD pseudo-data prediction for the R_{ISR} and $\Delta\phi_{\text{ISR}, i}$ variables for the QCD VR can be seen in figure 12.10. A good agreement is found between data and pseudo-data predictions.

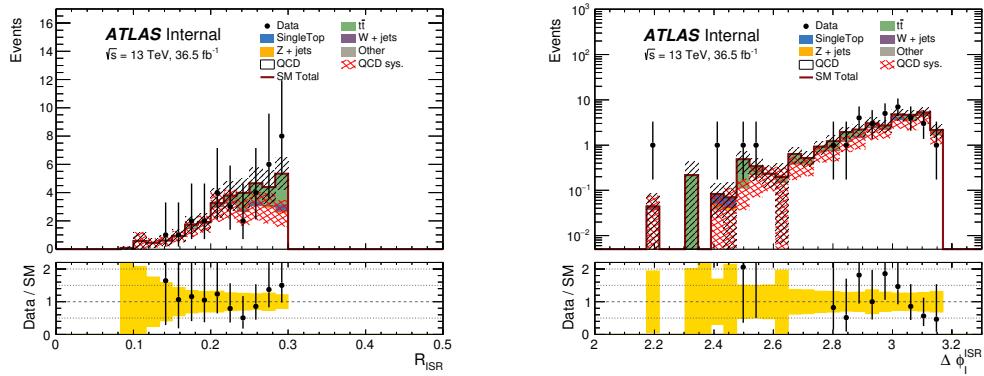


Figure 12.11: R_{ISR} and $\Delta\phi_{\text{ISR}, i}$ distributions in the QCD validation regions.

QCD prediction in the Signal Region

The predicted amount of QCD in the signal region is given by the amount of QCD pseudo-data that survive the signal region selection after normalization to the QCD CR. The systematic uncertainty on the SR QCD prediction is given by repeating the process with a tighter and looser set of seed event selections. An upward error correspond to seed events requiring $E_T^{\text{miss,sig.}} < 0.6 + 0.2 \cdot n_{\text{n-bjets}}$ and an lower error corresponds to seed events requiring $E_T^{\text{miss,sig.}} < 0.2 + 0.05 \cdot n_{\text{n-bjets}}$.

The expected QCD yield and uncertainty in the SR is given in table ??

SR R_{ISR} Region	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8
QCD expected yield	4.56 ± 2.38	1.58 ± 0.77	0.32 ± 0.17	0.04 ± 0.02	0.00 ± 0.00

Table 12.14: Expected yields of the QCD multijet backgrounds in SR.

13

Systematic Uncertainties

Systematic uncertainties can be categorized into two separate categories, experimental uncertainties and theoretical uncertainties. Experimental systematics result from uncertainties in physics object reconstruction, calibration and understanding the detectors. Theoretical systematics result from uncertainties in theoretical calculations. Experimental uncertainties such as jet energy resolution are assumed to

be 100 percent correlated across different background sources. On the other hand, theoretical uncertainties are assumed to be uncorrelated from one another.

In general systematic uncertainty are parameterized as independent nuisance parameters with gaussian constraints. The systematic on backgrounds are evaluated through a simultaneous fit to CR and SR. An estimate of the amount of systematic uncertainties on backgrounds in SR can be done by fitting the CR alone and extrapolating the result to the SR. If the background prediction fluctuate in the same way in the CR and SR the total systematic in SR would be partially canceled out in the transfer factor. This is why designing a CR that is kinematically similar to the SR is crucial to mitigating systematic uncertainties. More detail on CR design and systematics can be found in chapter 12.1 on background estimation and chapter 14 on statistics analysis.

The fit may compensate for a change in one systematic by varying several other systematics in order to get the best fit in CR. This can lead to correlations between systematics that are initially parameterized as independent nuisance parameters before the fit to CR. The correlation matrix between a reduced set of systematic variations and background scale factor after the simultaneous fit to all CRs are given in figure 13.1. The scale factor μ is the amount that the expected background MC must be scaled up/down by so that data and MC yields agree in the CR.

Total background systematics is around 20% in the SR. The dominate background systematic uncertainty in the region between $0.3 < R_{ISR} < 0.7$ is uncertainty on the

jet energy scale, uncertainty on the ttbar ISR/FSR, and uncertainty on the ttbar matrix element and parton shower calculation with each attributing roughly 10% to the total systematic uncertainty. The theoretical uncertainty on the amount of interference between SM ttbar and single top at NLO is also significant. The large systematic uncertainty in the R_{ISR} bin between 0.7 – 0.8 is completely due to MC statistics caused by the low expected yield. However the 0.7 – 0.8 R_{ISR} region is completely statistically dominated for the same reason, expecting only 0.7 background events.

The background uncertainty in each SR R_{ISR} region ordered by size of the systematic is given in table 13.1 and 13.2.

The post-fit pull is given in figure 13.2. No profiling of any systematics is observed.

A summary of the experimental and theoretical uncertainties relevant to this analysis is given in the sections below.

13.0.1 Experimental Uncertainties

Experimental systematics are estimated using a simultaneous fit of CR and the results extrapolated to the SR in a background only fit. Variations on background yield and kinematics are determined by different object performance groups using a number of simulation based and data driven in-situ techniques. A simultaneous fit to the CR gives the best fit value of the systematic parameter α and the systematic uncertainty associated with the background prediction in the SR.

Uncertainty of channel	SRC1	SRC2	SRC3
Total background expectation	20.56	27.54	18.86
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 4.53	± 5.25	± 4.34
Total background systematic	± 6.62 [32.18%]	± 4.89 [17.75%]	± 3.53 [18.72%]
alpha_ttbarGenPS	± 4.86 [23.6%]	± 1.91 [6.9%]	± 2.39 [12.7%]
alpha_RadLoHi	± 2.64 [12.8%]	± 2.19 [8.0%]	± 1.06 [5.6%]
alpha_JetSmearing	± 2.38 [11.6%]	± 0.77 [2.8%]	± 0.17 [0.91%]
alpha_theoSysSingleTop	± 1.66 [8.1%]	± 1.18 [4.3%]	± 1.21 [6.4%]
gamma_stat_SRC1_cuts_bin_0	± 1.29 [6.3%]	± 0.00 [0.00%]	± 0.00 [0.00%]
mu_ttbarC	± 0.91 [4.4%]	± 1.55 [5.6%]	± 1.03 [5.4%]
alpha_JER	± 0.81 [3.9%]	± 2.70 [9.8%]	± 1.14 [6.0%]
alpha_JET_GroupedNP_3	± 0.72 [3.5%]	± 0.03 [0.10%]	± 0.17 [0.89%]
mu_SingleTop	± 0.56 [2.7%]	± 0.40 [1.4%]	± 0.41 [2.2%]
alpha_MET_SoftTrk_ResoPerp	± 0.46 [2.3%]	± 0.56 [2.0%]	± 0.22 [1.2%]
alpha_cEff	± 0.43 [2.1%]	± 0.40 [1.5%]	± 0.11 [0.60%]
alpha_JET_GroupedNP_2	± 0.30 [1.5%]	± 0.78 [2.8%]	± 0.36 [1.9%]
alpha_JET_GroupedNP_1	± 0.27 [1.3%]	± 0.06 [0.23%]	± 0.04 [0.19%]
alpha_MET_SoftTrk_Scale	± 0.23 [1.1%]	± 0.29 [1.0%]	± 0.08 [0.45%]
alpha_theoSysDiboson	± 0.19 [0.94%]	± 0.10 [0.37%]	± 0.14 [0.76%]
alpha_CExtrap	± 0.16 [0.80%]	± 0.31 [1.1%]	± 0.19 [1.0%]
alpha_LightEff	± 0.15 [0.74%]	± 0.22 [0.80%]	± 0.04 [0.23%]
alpha_bEff	± 0.14 [0.70%]	± 0.00 [0.01%]	± 0.07 [0.36%]
alpha_JET_EtaNonClosure	± 0.11 [0.54%]	± 1.13 [4.1%]	± 0.01 [0.03%]
mu_Wjets	± 0.09 [0.45%]	± 0.22 [0.81%]	± 0.22 [1.2%]
alpha_theoSysW	± 0.09 [0.45%]	± 0.24 [0.88%]	± 0.23 [1.2%]
alpha_MET_SoftTrk_ResoPara	± 0.07 [0.35%]	± 0.19 [0.68%]	± 0.03 [0.15%]
mu_TtbarV	± 0.05 [0.22%]	± 0.09 [0.34%]	± 0.09 [0.47%]
alpha_PILEUP	± 0.02 [0.11%]	± 0.32 [1.2%]	± 0.12 [0.64%]
alpha_FTEtrap	± 0.02 [0.11%]	± 0.04 [0.13%]	± 0.03 [0.17%]
alpha_theoSysTTbarV	± 0.01 [0.07%]	± 0.03 [0.11%]	± 0.03 [0.15%]
alpha_JVT	± 0.01 [0.06%]	± 0.04 [0.13%]	± 0.04 [0.22%]
gamma_stat_SRC2_cuts_bin_0	± 0.00 [0.00%]	± 1.42 [5.1%]	± 0.00 [0.00%]
gamma_stat_SRC3_cuts_bin_0	± 0.00 [0.00%]	± 0.00 [0.00%]	± 0.96 [5.1%]

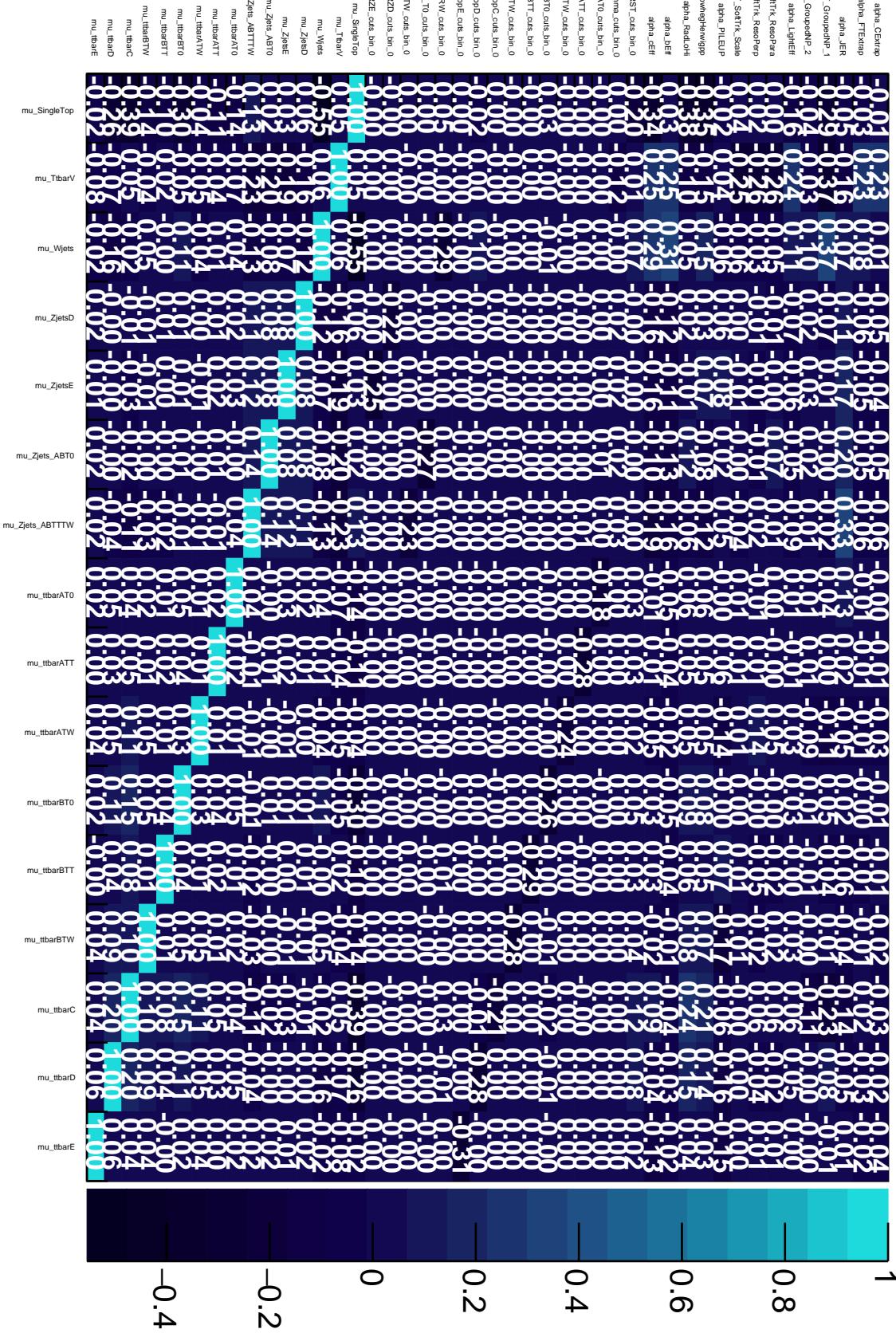
Table 13.1: Breakdown of the dominant systematic uncertainties on background estimates. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Uncertainty of channel	SRC4	SRC5
Total background expectation	7.69	0.90
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 2.77	± 0.95
Total background systematic	± 1.37 [17.77%]	± 0.71 [78.68%]
alpha_theoSysSingleTop	± 0.71 [9.3%]	± 0.00 [0.00%]
alpha_ttbarGenPS	± 0.68 [8.8%]	± 0.63 [69.1%]
gamma_stat_SRC4_cuts_bin_0	± 0.54 [7.0%]	± 0.00 [0.00%]
alpha_RadLoHi	± 0.46 [6.0%]	± 0.13 [14.8%]
alpha_JER	± 0.35 [4.6%]	± 0.09 [9.7%]
mu_ttbarC	± 0.35 [4.5%]	± 0.04 [4.9%]
mu_SingleTop	± 0.24 [3.1%]	± 0.00 [0.00%]
mu_Wjets	± 0.22 [2.9%]	± 0.02 [2.7%]
alpha_theoSysW	± 0.21 [2.7%]	± 0.02 [2.3%]
alpha_JET_GroupedNP_1	± 0.18 [2.3%]	± 0.04 [4.2%]
alpha_PILEUP	± 0.15 [2.0%]	± 0.13 [13.9%]
alpha_MET_SoftTrk_ResoPerp	± 0.14 [1.9%]	± 0.01 [1.6%]
alpha_MET_SoftTrk_ResoPara	± 0.13 [1.7%]	± 0.00 [0.12%]
alpha_LightEff	± 0.12 [1.6%]	± 0.02 [1.9%]
alpha_bEff	± 0.08 [1.0%]	± 0.01 [1.4%]
alpha_cEff	± 0.07 [0.93%]	± 0.03 [3.2%]
alpha_JET_EtaNonClosure	± 0.07 [0.87%]	± 0.11 [12.4%]
alpha_JET_GroupedNP_3	± 0.06 [0.72%]	± 0.02 [2.5%]
alpha_JVT	± 0.02 [0.29%]	± 0.00 [0.35%]
alpha_JetSmearing	± 0.02 [0.26%]	± 0.00 [0.15%]
alpha_CExtrap	± 0.02 [0.23%]	± 0.00 [0.22%]
mu_TtbarV	± 0.01 [0.17%]	± 0.01 [1.1%]
alpha_JET_GroupedNP_2	± 0.01 [0.15%]	± 0.09 [10.3%]
alpha_FTEtrap	± 0.01 [0.10%]	± 0.00 [0.17%]
alpha_MET_SoftTrk_Scale	± 0.01 [0.07%]	± 0.00 [0.11%]
gamma_stat_SRC5_cuts_bin_0	± 0.00 [0.00%]	± 0.21 [23.0%]

Table 13.2: Breakdown of the dominant systematic uncertainties on background estimates. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Reduced correlation matrix

Figure 13.1: Correlation matrix between select nuisance parameters.



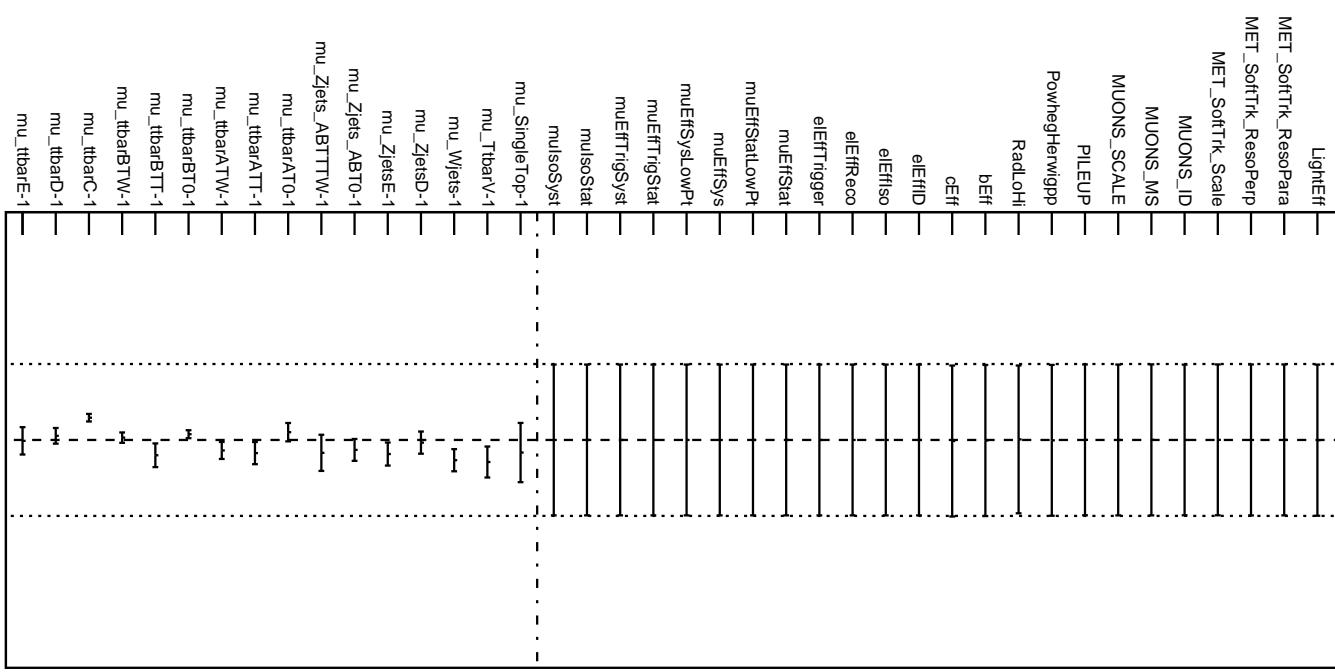


Figure 13.2: Post-fit pull plot for the background-only fit.

Uncertainties on the Jet Energy Scale (JES) and Jet Energy Resolution (JER)

The two main uncertainties affecting jet measurements are the uncertainties in JES and JER calibrations. The jet reconstruction and calibration process is described in section 3.3. Uncertainty in the calibration process leads to uncertainty in the calorimeter response to the true jet energy.

Uncertainties on the JES are derived from different in-situ techniques by the ATLAS Jet/ E_T^{miss} group. These techniques exploit the transverse momentum balance between a jet and a reference object such as a photon or a Z boson or between multiple jets in multijet events.^{5,6}. The uncertainty on JES depends on η and p_T of the jet. Uncertainties related to jet flavor composition and pile-up are also included.

The ttbar control region require similar jet multiplicity and jet energy as the SR. Therefore, much of the JES and JER uncertainties are canceled out in the transfer factor between the CR and SR. Even after the cancelations, the JES uncertainty contributes around a 10 percent uncertainty to background yields and is one the major systematic uncertainties in this analysis.

The fractional JES uncertainty as a function of η and p_T for 2016 data can be seen in figure 13.4.

Uncertainties on the JER are derived from dijet balance techniques.⁵ The fractional uncertainty on JER as a function of η and p_T can be seen in figure ??

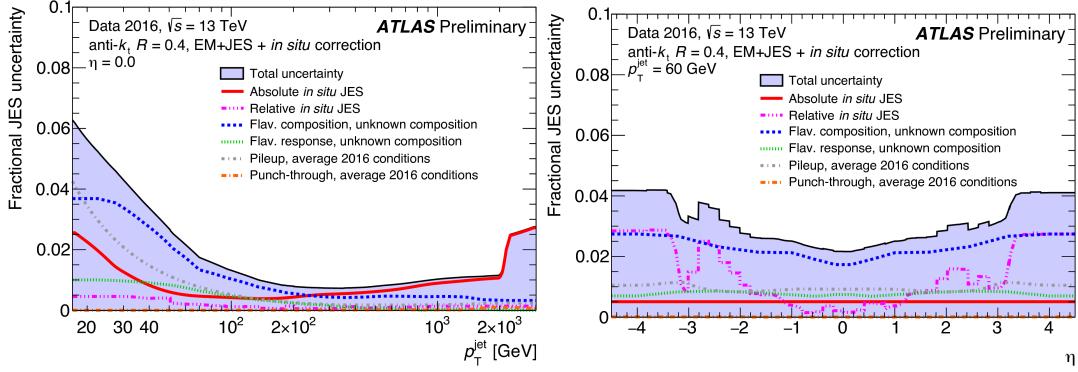


Figure 13.3: Fractional uncertainty on the jet energy scale (JES) vs jet η and jet p_T .

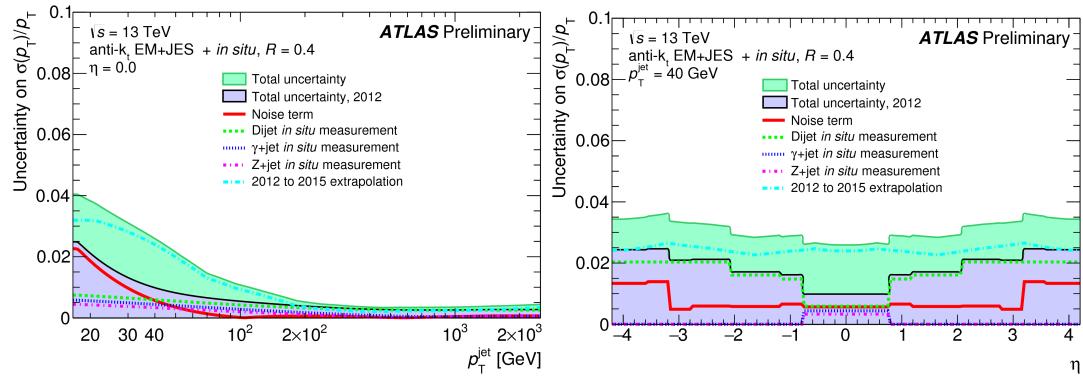


Figure 13.4: Fractional uncertainty on the jet energy resolution (JER) vs jet η and jet p_T .

Uncertainty on b -tagging

Uncertainties on b -tagging do not contribute a large systematic uncertainty to our analysis because we only require one b -tagged jet with a high p_T requirement of 40 GeV. At the same time, there is little extrapolation between background CRs and SR. The ttbar, $W+jets$ and QCD multijets all use CRs that also require one b -tagged jet. After fitting to CRs, b -tagging systematics amount to only 1-3 percent total uncertainty in SR.

The b -tagging uncertainty is derived by the ATLAS flavor-tagging working group. A separate set of weights are applied for each set of b -tagging variations. These include scale factors on b -tagging efficiencies and the rate of mis-tagging of c -jets and light-flavored jets.

Uncertainty on the E_T^{miss} Soft Term

The majority of the uncertainty on E_T^{miss} has already been accounted for by systematics on other reconstructed objects because the E_T^{miss} is built out of fully calibrated and reconstructed physics objects. However, there is one part of E_T^{miss} reconstruction that does not come from any hard physics object; the E_T^{miss} soft term. Therefore, uncertainty on the E_T^{miss} soft term forms an independent systematic uncertainty.

The uncertainty on the resolution and scale of the E_T^{miss} soft term is derived by the ATLAS Jet/ E_T^{miss} group using two in-situ methods using $Z \rightarrow \mu\mu$ events.¹¹ The

uncertainty on the E_T^{miss} track soft term (TST) vs the number of reconstructed primary vertexes in $t\bar{t}$ simulation is shown in figure 13.5.

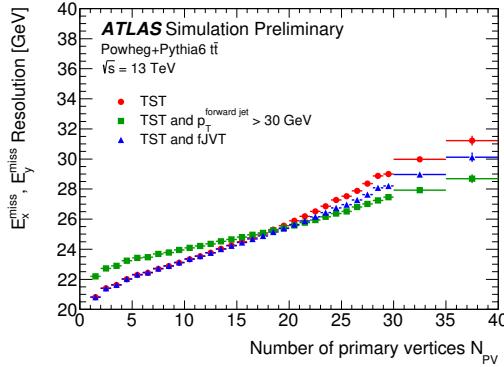


Figure 13.5: Uncertainty on the E_T^{miss} track soft term (TST) vs the number of reconstructed vertexes.

The E_T^{miss} soft term resolution and scale uncertainty contribute a 1–2% uncertainty on the total background yield. The small uncertainty result from the high required E_T^{miss} of at least 250 GeV and little to no extrapolation across E_T^{miss} between CR and SR for all major backgrounds.

Uncertainty on Lepton Reconstruction Efficiencies and Energy Scale

Uncertainty on lepton reconstruction and identification propagate to uncertainty on CR and SR yields. These uncertainties include uncertainties on e/ γ resolution, energy scale, and reconstruction efficiency and muon momentum and reconstruction efficiency. Lepton trigger scale factors are also taken into account for the $t\bar{t} + \gamma$ control region.

These uncertainties are derived by the ATLAS E/ γ and muon combined performance groups and result in sub 1% uncertainty on signal region yields.^{33,16}

Pileup

The uncertainty on the amount of pileup in 2015 and 2016 ATLAS data is estimated using a two sided variation in event weights. One set of weight simulate a lower rates of pile-up interactions and the other simulate a higher rate. Pile-up uncertainty contributes a 1-2% uncertainty on the total background yield in the SR.

13.0.2 Theoretical Uncertainties

Theoretical uncertainties quantify the uncertainty associated with MC generation including calculations on the matrix element, parton shower, and different scale parameters such as QCD renormalization, factorization scales and α_s etc. As the background is ultimately normalized to the CR, only difference comes from the transfer factor (defined in equation 13.1) will result in a different SR background yield.

$$T = \frac{N_{MC}^{SR}}{N_{MC}^{CR}} \quad (13.1)$$

We vary MC generation with respect to the default setting and determine the corresponding variation in the transfer factor according to equation 13.2. All theoretical uncertainties for different backgrounds are assumed to be independent of

one another.

$$\Delta_x = \frac{T_f^{\text{up}} - T_f^{\text{down}}}{T_f^{\text{up}} + T_f^{\text{down}}} \quad (13.2)$$

$t\bar{t}$ Theoretical Uncertainty

Theoretical uncertainties on ttbar production include uncertainties on the hard scattering matrix element (ME) calculation, uncertainties on the parton shower (PS), and uncertainty on the amount of ISR/FSR produced in association with ttbar.

The ttbar ISR/FSR uncertainty is estimated by using the radHi and radLo *PowHegPYTHIA* samples. These samples are produced with different renormalization and factorization scales compared to the nominal sample (x0.5 to radHi and x2 to radLo). The radHi sample also increase the h_{damp} parameter that help control the matching between PS and ME from the nominal m_{top} to $2 \times m_{\text{top}}$. In general, the radHi (radLo) sample generates a higher (lower) differential cross-section for ttbar that is produced in conjunction with strong ISR.

Uncertainties on the hard scattering and PS are calculated by comparing the nominal *PowHegPYTHIA* ttbar sample with *PowHegHERWIG ++* ttbar and *SHERPA 2.2.1* ttbar samples. The *PowHegHERWIG ++* sample do not vary the ME calculation with respect to the nominal sample but does perform a different set of PS calculation

with a distinct PS tune. The *SHERPA* 2.2.1 ttbar sample perform a different ME and PS calculation with a different PDF set and PS tune. More details on the different ttbar MC generation can be found in section 6.2.

We take an envelope of the *SHERPA* and *PowHeg**HERWIG++* variations as the combined ttbar hard scattering and PS uncertainty. This is because the *PowHeg**HERWIG++* and *SHERPA* samples both vary the PS and avoids double counting of the PS uncertainty. The total hard scattering plus PS uncertainty is defined as the maximum of equation 13.3 and 13.4.

$$\Delta_{\text{hard scatter}} = \frac{T_f^{\text{PowHeg}} - T_f^{\text{SHERPA}}}{T_f^{\text{SHERPA}}} \quad (13.3)$$

$$\Delta_{\text{PS}} = \frac{T_f^{\text{PYTHIA}} - T_f^{\text{HERWIG++}}}{T_f^{\text{PYTHIA}}} \quad (13.4)$$

The pre-fit $t\bar{t}$ yields in CR, VR and SR for the different ttbar samples and the ttbar theory uncertainty derived from transfer factor are given in table 13.3

	$t\bar{t}$ CR	SRC1	SRC2	SRC3	SRC4	SRC5	$t\bar{t}$ VR
ttbar	668 ± 9	16.7 ± 1.6	31.7 ± 2.1	21.7 ± 1.6	6.3 ± 0.8	0.60 ± 0.23	232 ± 5
ttbar (rad up)	872 ± 11	25.2 ± 2.3	39.5 ± 2.3	28.7 ± 2.1	8.6 ± 1.0	1.05 ± 0.33	293 ± 7
ttbar (rad down)	521 ± 9	10.1 ± 1.0	19.2 ± 1.6	15.8 ± 1.5	6.3 ± 1.2	0.7 ± 0.4	187 ± 5
ttbar (Powheg+H++)	621 ± 10	16.3 ± 1.8	27.8 ± 1.8	18.0 ± 1.5	6.5 ± 0.9	0.46 ± 0.18	206 ± 5
ttbar (Sherpa)	840 ± 40	30 ± 8	42 ± 9	22 ± 5	7.4 ± 3.2	< 0.01	297 ± 30
Transfer factors (in %)							
ISR/FSR		20	10	4	10	5	3.3
PS		5	6	11	11	20	4
hard scattering		40	5	19	10	100	2

Table 13.3: Expected yields for different ttbar samples and theory uncertainties based on transfer factor for the $t\bar{t}$ background for the SR, ttbar CR and VR.

$W + \text{jets}$ Theoretical Uncertainty

The *SHERPA* generator is used to estimate $W + \text{jets}$ theory uncertainties. Different scale variations and seven LHE3 variations are included to model the variations in *SHERPA* parton shower and ME calculations.

The theory uncertainty on $W + \text{jets}$ production obtained from transfer factors is given in table 13.4. Values are given as percent uncertainty on $W + \text{jets}$ yields in the SR.

Single Top Theoretical Uncertainty

Single top theoretical uncertainty include uncertainty on the PS, ISR/FSR, and the interference between ttbar and single top in the Wt channel. Single top uncertainties is evaluated on the Wt subprocess because the Wt subprocess dominates the single top background in signal region.

SR	uncertainty (%)
SRA-TT	9.5
SRA-TW	8.0
SRA-T0	6.1
SRB-TT	9.1
SRB-TW	7.9
SRB-T0	3.3
SRC1	11.4
SRC2	12.5
SRC3	11.8
SRC4	10.7
SRC5	9.5
SRC6	11.3
SRD-low	8.8
SRD-high	8.2
SRE	9.5
VRW	1.9

Table 13.4: Summary of the theory uncertainties (in percent) on W production obtained using variations on transfer factors.

The single top parton shower uncertainty is modeled by comparing the nominal *PowHegPYTHIA* sample with a *PowHegHERWIG ++* single top sample in a similar fashion to the $t\bar{t}$ PS uncertainty.

The single top ISR/FSR uncertainty is also modeled by comparing the radHi and radLo *PowHegPYTHIA* single top samples to the nominal *PowHegPYTHIA* samples analogous to the $t\bar{t}$ ISR/FSR uncertainty.

The single top interference uncertainty refer to the fact that at NLO the calculation of the $pp \rightarrow Wt$ process will include contributions from $pp \rightarrow t\bar{t} \rightarrow t + b + W$ which is already modeled in the SM ttbar MC. We can subtract out the ttbar contribution at either the level of amplitude (DR scheme) or at the level of matrix ele-

ments (DS scheme). Subtracting at the matrix element level also remove any potential interference between the single top $pp \rightarrow Wt$ and ttbar $pp \rightarrow t\bar{t} \rightarrow t + b + W$ processes. Subtracting at the amplitude level does not remove those interferences.

Both DR and DS schemes violates formal gauge invariance and there is no consensus on the correct procedure to treat the ttbar and single top interference. We quantify the interference uncertainty by taking the difference between the DR and DS schemes.

At the moment we take an 100% interference uncertainty because of the low MC statistics in DS scheme.

The pre-fit single top yields in SR, single top CR and VR for the different single top samples and the single top theory uncertainty derived from transfer factor is given in table 13.5.

	CRST	SRC1	SRC2	SRC3	SRC4	SRC5
st Wt (MET200)	41.7 ± 1.1	0.66 ± 0.14	1.14 ± 0.18	0.99 ± 0.17	0.39 ± 0.11	0.12 ± 0.08
st Wt (radHi, MET200)	50.4 ± 1.3	0.60 ± 0.14	1.26 ± 0.20	1.33 ± 0.21	0.57 ± 0.14	0.25 ± 0.10
st Wt (radLo, MET200)	34.9 ± 1.0	0.57 ± 0.13	0.77 ± 0.15	0.77 ± 0.15	0.37 ± 0.10	0.09 ± 0.06
st Wt (Powheg+H++, MET200)	39.2 ± 1.0	0.62 ± 0.13	0.84 ± 0.16	0.79 ± 0.15	0.38 ± 0.10	0.08 ± 0.06
st Wt (DS, MET200)	6.8 ± 0.4	0.12 ± 0.05	0.30 ± 0.09	0.23 ± 0.08	0.16 ± 0.06	0.020 ± 0.010
Transfer factors (in %)						
ISR/FSR		16 ± 17	6 ± 13	9 ± 13	3 ± 18	32 ± 32
PS		0 ± 30	22 ± 22	15 ± 24	0 ± 40	30 ± 70
Interference (DR vs DS)		10 ± 50	60 ± 50	40 ± 50	150 ± 110	0 ± 110

Table 13.5: Summary of the single-top theory uncertainties obtained in each of the signal regions. The uncertainties are symmetrized, and all numbers are given in percentages.

$t\bar{t} + W/Z$ Theoretical Uncertainty

$t\bar{t} + W/Z$ theoretical uncertainty include scale variations and NNPDF3.0 PDF variations. Plus an uncertainty on the difference between $t\bar{t}\gamma$ and $t\bar{t}Z$ vector boson p_T differential cross section is added for $t\bar{t} + W/Z$ due to the procedure of using $t\bar{t} + \gamma$ to estimate $t\bar{t} + W/Z$. SHERPA+OpenLoops is used to calculate $t\bar{t}\gamma$ and $t\bar{t}Z$ vector boson differential cross-section to NLO accuracy. The relative difference between SHERPA+OpenLoops and the nominal MadGraph5_aMC@NLO cross-sections is combined in quadrature with the scale and NNPDF3.0 PDF variations to give the total $t\bar{t} + W/Z$ theoretical uncertainty.

$t\bar{t} + W/Z$ theoretical uncertainty is given in table ?? . The systematic uncertainty maybe large for $t\bar{t} + W/Z$ production in the SR but $t\bar{t} + W/Z$ comprise about 1% of our expected background. Therefore, $t\bar{t} + W/Z$ do not contribute significantly to the total background uncertainty in the analysis.

Dibosons Theoretical Uncertainty

A 50% uncertainty is used for the dibosons estimate because the diboson yield is predicted using MC alone.

SR	uncertainty (%)
SRA-TT	15.1
SRA-TW	9.9
SRA-T0	13.7
SRB-TT	7.3
SRB-TW	5.7
SRB-T0	3.5
SRC1	95.5
SRC2	20.6
SRC3	21.4
SRC4	36.6
SRC5	30.9
SRD-low	12.3
SRD-high	15.1
SRE	55.0

Table 13.6: Summary of the theory uncertainties (in percent) on $t\bar{t}+W/Z$ production obtained on the transfer factor. The uncertainties are symmetries.

Z+jets Theoretical Uncertainty

A 50% uncertainty is used for the Z + jets estimate because the Z + jets yield is predicted using MC alone.

14

Statistical Analysis

14.1 Introduction to Log Likelihood Fitting

We check the consistency of data and expected SM background and extract information on any potential signal using log likelihood fitting. In log likelihood fitting, we select parameters that maximizes the total likelihood defined in equation 14.1.

$$\mathcal{L}(\vec{z}) = \prod_{i=1}^n P(x_i|\vec{z}) \quad (14.1)$$

x_i are data points and \vec{z} is a list of parameters. $P(x|\vec{z})$ is the fitted probability density function (PDF). The idea behind log-likelihood fitting is that the PDF $P(x|\vec{z})$ have the highest probability of producing the dataset x_i when the likelihood is maximized.

Maximizing the likelihood is equivalent to minimizing the negative log likelihood or NLL since logarithms are a monotonically increasing functions. Therefore, we can instead minimize the NLL M defined in equation 14.2

$$M(\vec{z}) = -\ln((\mathcal{L}(\vec{z})) = -\sum_{i=1}^n \ln(P(x_i|\vec{z})) \quad (14.2)$$

In collider physics we do not know the total number of observed events a priori. Instead, we have an expected value of events proportional to the cross-section times the luminosity. The actual number of measured events can vary according to a poisson distribution. We include the uncertainty on the number of observed events by multiplying a poisson distribution with expected rate λ to the likelihood; resulting in equation 14.3.

$$\mathcal{L}(\vec{z}) = \left\{ \frac{\exp^{-\lambda} \lambda^n}{n!} \right\} \prod_{i=1}^n P(x_i|\vec{z}) \quad (14.3)$$

For this particular analysis we perform a binned fit to the R_{ISR} distribution in the SR. Therefore the fitted PDF ($x_i|\vec{z}$) is not a full continuous function but a series of expected values in discrete bins. The binned $P(x|\vec{z})$ can be written as equation 14.4.

$$P_{b_i} = P(x_i|\vec{z}) = \int_{b_{i-1}}^{b_i} f(x|\vec{z}) \, dx \quad (14.4)$$

Where $f(x|\vec{z})$ is the continuous PDF and b_i and b_{i-1} are the bin edges for the i th bin. Assuming a poisson distribution of events in each bin, the extended likelihood and NLL becomes equation 14.5 and 14.6.

$$\mathcal{L}(N_{b_i}^{\text{data}}|\vec{z}) = \prod_{k=1}^{n_{\text{bins}}} \frac{(\lambda P_{b_i})^{N_{b_i}^{\text{data}}} e^{-\lambda P_{b_i}}}{N_{b_i}^{\text{data}}!} \quad (14.5)$$

$$M(\vec{z}) = -\ln(\mathcal{L}(\vec{z})) = -\sum_{i=1}^{n_{\text{bins}}} (N_{b_i}^{\text{data}} \ln(\lambda P_{b_i}) - \lambda P_{b_i} - \ln N_{b_i}^{\text{data}}!) \quad (14.6)$$

Where $N_{b_i}^{\text{data}}$ is the number of data in the i th bin, λ is the expected rate in the region, P_{b_i} is the probability of an event being in the i th bin if it is in the signal region and \vec{z} represent a list of fitted parameters such as the signal cross-section. Both λ and P_{b_i} can depend on the fitted parameters as the normalization and shape of the PDF can change with the fitted parameters.

We can also rewrite equation 14.5 and 14.6 as 14.7 and 14.8. In this interpretation, $\lambda P_{b_i} = N_{b_i}^{\text{MC}}$ is simply the expected number of events in a particular bin.

$$\mathcal{L}(N_{b_i}^{data} | \vec{z}) = \prod_{k=1}^{n_{bins}} \frac{(N_{b_i}^{MC})^{N_{b_i}^{data}} e^{-N_{b_i}^{MC}}}{N_{b_i}^{data}!} \quad (14.7)$$

$$M(\vec{z}) = -\ln((\mathcal{L}(\vec{z})) = -\sum_{i=1}^{n_{bins}} (N_{b_i}^{data} \ln(N_{b_i}^{MC}) - N_{b_i}^{MC} - \ln N_{b_i}^{data}!) \quad (14.8)$$

In this analysis we perform a simultaneous fit to multiple CR and SR to extract the best fit signal strength. We perform a simultaneous fit to multiple regions by maximizing the total NLL of all fitted regions. The total NLL is simply a sum of the individual NLL for each region.

14.2 Overview of Fitting to Control Regions and Signal Regions

In this analysis we use a SR to isolate signal from background. At the same time, we use multiple CRs that are kinematically similar to SR but have high background purity to estimate the background. The signal strength and expected background rate are both extracted through a simultaneous fit to all CRs and SR.

The amount of MC background in both the CR and SR will fluctuate with experimental and theoretical systematics before the fit. However after the fit the total amount of background will be normalized to the CR. If the MC yield for background fluctuate down for a given systematic then the normalization scale factor will increase. The increased normalization scale factor will compensate for any simulta-

neous drop in SR MC yield. This partial cancelation of fluctuations between CR and SR can lead to smaller systematic uncertainties. In effect, the CR reduces systematic uncertainty by directly measuring the amount of background in from data instead of relying solely on MC simulations.

The more kinematically similar the definition of the CR to the SR, the better the cancelation. Any extrapolation between CR and SR must be across well modeled variables. Otherwise large systematic uncertainties can arise or worse the background predictions in SR maybe wrong.

We can also check the result of our background predictions without unblinding the SR in validation regions. VRs receive the background normalization scale factors from the fit to CRs but do not participate in the fit. The VRs are designed to be kinematically similar to the SRs while keeping signal contaminations low. In this way, the VRs serves as a mid-point to check the extrapolation between CR and SR.

The relationship between CR, SR and VR is graphically depicted in figure 14.1.

In an excess were to exist in the SR, a simultaneous fit to all CR and SR is performed for to calculate the statistical significance of any potential excess (discovery fit). If no excess were found, then a simultaneous fit to all CR and SR is also performed quantify the maximum amount of signal cross-section that can be excluded (exclusion fit).

We also quantify the expected background rate and the systematic uncertainty in SR by performing a background only fit. In this case, only the CRs are fitted and

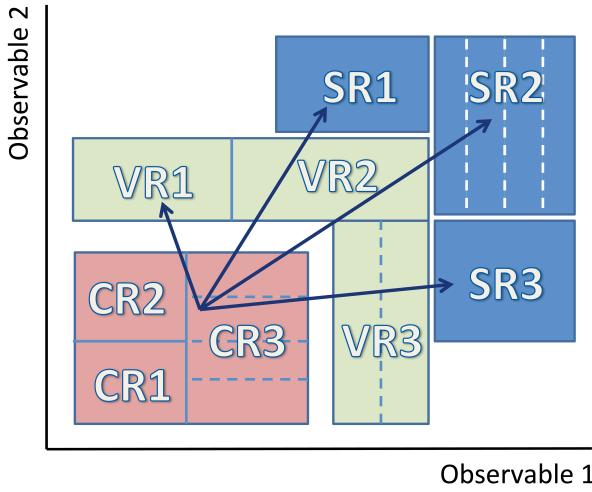


Figure 14.1: Basic diagram of data driven background estimation techniques. We define control regions (CR) that is dominated by background and have little signal. We can estimate the amount of background we expect in the signal region (SR) by measuring the amount of background in the CR and extrapolating to the SR using MC predictions.

the SR acts like another VR, receiving the fitted background normalization but not participating in the fit. The background only fit may give a different predicted background rate from the exclusion or discovery fit because the SR is not simultaneously fitted. However, the difference is expected to be small because the CRs are designed to have much greater constraining power on background rates than SR.

These three type of fits, the background only fit, the discovery fit and the exclusion fit are covered in more detail in sections 14.4 to 14.5. The parameterization of systematics as constrained nuisance parameters is covered in section 14.3.

We use the software package `HistFitter` (version `HistFitter-00-00-53`) to perform the statistical analysis.²⁸ At its core `HistFitter` is still performing log likeli-

hood fitting based on the principle introduced in section 14.1 but `HistFitter` provide many tools to easily manage and integrate multiple CR, VR, SR, signal samples, backgrounds, and systematics. `HistFitter` is built upon other statistical analysis software including `RooFit`.⁵⁵

14.3 Parameterization of Systematics as Gaussian Constraints

Systematics uncertainties are parameterized as fitted parameters called nuisance parameters. In general, the nuisance parameter α , is constrained to a particular value by a constraint function $C(\alpha)$. The constraint function $C(\alpha)$ is multiplied to the likelihood as shown in equation 14.9 and contributes to the total likelihood. The fitted PDF $P(x|\vec{z}, \alpha)$ can depend on a number of unconstrained fitted parameter \vec{z} and the constrained α .

$$\mathcal{L}(\vec{z}, \alpha) = \prod_{i=1}^n P(x_i|\vec{z}, \alpha) C(\alpha) \quad (14.9)$$

We pay a penalty on the total likelihood if the nuisance parameter α deviates from the value with maximum $C(\alpha)$. The fit finds the optimal point between changing the α so that the PDF best describes the data and the cost from the constraint function on α .

We use Gaussians as the constraint function for all systematics. The nominal value corresponds to $\alpha = 0$ and the plus and minus 1σ deviation corresponds to $\alpha = \pm 1$.

14.4 Background Only Fit and Background Estimation

The background rates are normalized to data through a simultaneous fit to CRs for the background only fit. The fitted background normalizations derived from the fit are then applied to the SR but the SR is not simultaneously fitted. No signal sample is included in the fit and any potential signal contamination in the CR is ignored. This fit has the advantage of being able to quantify the expected background rate and systematic uncertainties while the SR is blinded.

The background normalizations predicted in the background only fit may differ from the discovery and exclusion fits because the SR is simultaneously fitted in those fits. This difference should be small as long as the CRs have high background purity and significantly higher statistics than SR.

14.5 Exclusion Fit and Exclusion Limit Calculation

The exclusion fit is performed as a simultaneous fit to all CRs and all five SR R_{ISR} bins. The signal sample is included in both CR and SR and normalized to the fitted signal strength parameter.

The best fit signal strength is found when the negative log likelihood (NLL) is at a minimum after fitting to data. As the signal strength deviates from the best fit value, the NLL increases and we are more confident that the signal strength is not supported by data. We use the difference in NLL as our test statistic. The relationship

between the test statistic and statistical significance is approximated by a parabola in the asymptotic high statistics case.

We can calculate the NLL corresponding to the nominal signal strength of each signal model and compare it with the fitted minimum NLL. The difference in the two NLLs can be converted into the statistical significance using the parabolic relationship between the two. The statistical significance is quantified as the exclusion confidence limit (CL_s). If the CL_s is below 5 percent then the signal model has been excluded to 95 confidence.

We calculate the CL_s corresponding to a grid of signal models each with a different stop and neutralino mass. The CL_s are plotted in a 2D graph with the stop mass along the x-axis and the neutralino mass along the y-axis. These CL_s are then interpolated over to form a 2D contour plot. The contour corresponding to the 95 percent CL_s defines the parameter space excluded by the search.

We can also find the 95 percent confidence limit on the observed signal cross-section in each R_{ISR} bin. The observed signal cross-section is defined as the number of signal events predicted to exist in SR for any particular signal model and is equivalent to selection efficiency times the signal production cross-section. The limit on the observed cross-section is completely theory independent. It is simply a statement on the maximum additional BSM rate that can exist in SR without being ruled out to 95 percent confidence.

14.6 Discovery Fit and Discovery Significance Calculation

The discovery fit is also performed as a simultaneous fit to all CRs and SR. The signal sample is included only in the SR but not to the CR in the fit. Excluding the signal sample from the CR gives a more conservative estimate. If a signal is present in nature, the signal contamination would still contribute to the CR yield in data. The higher data yield will in turn increase background normalizations in CR. Hence, any potential signal contamination is considered essentially as additional background in CR.

Again, a well designed CR has little signal contamination so the difference between this approach and exclusion fit should be small. Our signal contamination is less than 12 percent for all relevant signal samples. The signal contamination drops to below 10 percent for all stop masses above 300 GeV.

We do not statically combine the 5 R_{ISR} bins for the discovery fit. The single R_{ISR} bin with the best significance is used to calculate the discovery significance. Again this is a conservative approach and gives us worse discovery significances but it makes the analysis less sensitive to potential shape uncertainties in signal.

We also use the difference in NLL as our test statistic for our discovery fit. The signal strength and background normalization that best fit the data is found at the minimum NLL. Then we calculate the NLL with a signal strength of zero. The difference between the zero signal strength NLL and the best fit NLL is our test statistic.

The relationship between the test statistic and statistical significance is given by a parabola in the asymptotic high statistics case.

The statistical significance of the zero signal strength fit is the p-value of the no signal hypothesis test. This p-value quantifies the discovery significance for the analysis. If the discovery significance is above 5 sigma then discovery can be claimed.

15

Results

Unblinded signal region distributions of the kinematic variables with the most discrimination power are shown in figure 15.1. The expected background yield have been normalized to all control regions using the background only fitting procedure described in section 14.4.

Signal region yields with 36.07 fb^{-1} of data can be seen in table 15.1 and 15.2.

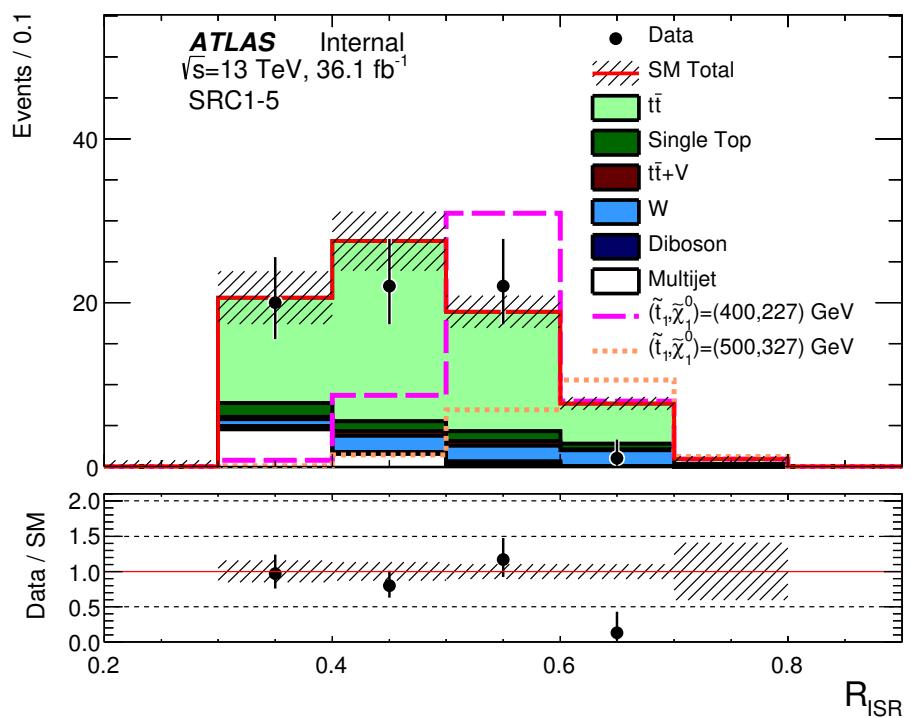


Figure 15.1: Unblinded R_{ISR} distributions for SRC1-5 for 36.07 fb^{-1} .

SRC yields	SRC1	SRC2	SRC3
Observed events	20	22	22
Fitted bkg events	20.56 ± 6.62	27.54 ± 4.89	18.86 ± 3.53
Fitted TTbar events	12.85 ± 5.87	22.05 ± 4.19	14.57 ± 3.23
Fitted Wjets events	0.81 ± 0.37	1.93 ± 0.48	1.91 ± 0.63
Fitted Zjets events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Fitted TtbarV events	0.29 ± 0.18	0.59 ± 0.38	0.56 ± 0.31
Fitted SingleTop events	$1.67^{+2.02}_{-1.67}$	$1.18^{+1.81}_{-1.18}$	$1.22^{+1.37}_{-1.22}$
Fitted Diboson events	0.39 ± 0.33	0.21 ± 0.11	0.29 ± 0.18
Fitted Multijets events	4.56 ± 2.38	1.58 ± 0.77	0.32 ± 0.17
MC exp. SM events	25.44 ± 8.64	35.98 ± 6.11	24.21 ± 4.34
MC exp. TTbar events	18.19 ± 8.07	31.20 ± 5.41	20.62 ± 4.14
MC exp. Wjets events	0.64 ± 0.29	1.53 ± 0.32	1.51 ± 0.44
MC exp. Zjets events	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
MC exp. TtbarV events	0.22 ± 0.14	0.46 ± 0.28	0.44 ± 0.23
MC exp. SingleTop events	$1.44^{+1.66}_{-1.44}$	$1.02^{+1.54}_{-1.02}$	$1.04^{+1.11}_{-1.04}$
MC exp. Diboson events	0.39 ± 0.33	0.21 ± 0.11	0.28 ± 0.18
MC exp. Multijets events	4.56 ± 2.38	1.58 ± 0.77	0.32 ± 0.17

Table 15.1: Region: SRC. Background-only fit results for an integrated luminosity of 36.07 fb⁻¹. The uncertainties are statistical and systematic.

No significant excess is observed in any region. An under fluctuation of background is observed in the R_{ISR} bin between 0.6 – 0.7 but is not statistically significant due to the low amount of expected events.

95 percent upper confidence limits on the observed cross-section ($\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$) and on the number of signal events (S_{obs}^{95}) in each R_{ISR} bin is shown in table 15.3. Observed limits are derived using the discovery fit procedure described in section 14.6. Discovery p-values are calculated using the asymptotic high statistics assumption.

SRC yields	SRC4	SRC5
Observed events	1	0
Fitted bkg events	7.69 ± 1.37	0.90 ± 0.71
Fitted TTbar events	4.92 ± 0.98	$0.63^{+0.69}_{-0.63}$
Fitted Wjets events	1.93 ± 0.45	0.21 ± 0.12
Fitted Zjets events	0.00 ± 0.00	0.00 ± 0.00
Fitted TtbarV events	0.08 ± 0.08	0.06 ± 0.03
Fitted SingleTop events	$0.72^{+0.77}_{-0.72}$	0.00 ± 0.00
Fitted Diboson events	0.00 ± 0.00	0.00 ± 0.00
Fitted Multijets events	0.04 ± 0.02	0.00 ± 0.00
MC exp. SM events	9.20 ± 1.60	1.11 ± 0.99
MC exp. TTbar events	6.95 ± 1.37	$0.89^{+0.97}_{-0.89}$
MC exp. Wjets events	1.53 ± 0.34	0.17 ± 0.09
MC exp. Zjets events	0.00 ± 0.00	0.00 ± 0.00
MC exp. TtbarV events	0.07 ± 0.06	0.05 ± 0.02
MC exp. SingleTop events	$0.62^{+0.64}_{-0.62}$	0.00 ± 0.00
MC exp. Diboson events	0.00 ± 0.00	0.00 ± 0.00
MC exp. Multijets events	0.04 ± 0.02	0.00 ± 0.00

Table 15.2: Region: SRC. Background-only fit results for an integrated luminosity of 36.07 fb $^{-1}$. The uncertainties are statistical and systematic.

Signal channel	$\langle\epsilon\sigma\rangle_{\text{obs}}^{95} [\text{fb}]$	S_{obs}^{95}	S_{exp}^{95}	CL_B	$p(s = 0) (Z)$
SRA_TT	0.31	11.2	$9.1^{+4.3}_{-2.5}$	0.69	0.29 (0.57)
SRA_TW	0.25	9.0	$9.2^{+3.6}_{-2.8}$	0.47	0.50 (0.00)
SRA_T0	0.40	14.6	$14.9^{+5.2}_{-4.3}$	0.46	0.50 (0.00)
SRB_TT	0.65	23.4	$24.0^{+7.8}_{-6.8}$	0.46	0.50 (0.00)
SRB_TW	0.73	26.2	$26.0^{+8.8}_{-6.6}$	0.52	0.48 (0.05)
SRB_T0	2.93	105.9	$90.8^{+24.3}_{-21.7}$	0.72	0.27 (0.61)
SRC1	0.44	16.0	$16.3^{+5.8}_{-4.2}$	0.47	0.50 (0.00)
SRC2	0.35	12.6	$15.5^{+5.9}_{-4.2}$	0.26	0.50 (0.00)
SRC3	0.44	15.8	$12.8^{+4.7}_{-2.7}$	0.69	0.30 (0.54)
SRC4	0.09	3.1	$6.5^{+3.3}_{-2.1}$	0.02	0.50 (0.00)
SRC5	0.06	2.2	$2.8^{+2.0}_{-1.1}$	0.32	0.49 (0.02)
SRD_low	0.57	20.7	$19.8^{+6.8}_{-4.9}$	0.57	0.43 (0.19)
SRD_high	0.32	11.6	$9.6^{+3.9}_{-2.4}$	0.71	0.27 (0.60)
SRE	0.14	5.0	$5.6^{+2.7}_{-1.7}$	0.40	0.50 (0.00)

Table 15.3: Left to right: 95% CL upper limits on the visible cross section ($\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$) and on the number of signal events (S_{obs}^{95}). The third column (S_{exp}^{95}) shows the 95% CL upper limit on the number of signal events, given the expected number (and $\pm 1\sigma$ excursions on the expectation) of background events. The last two columns indicate the CL_B value, i.e. the confidence level observed for the background-only hypothesis, and the discovery p -value ($p(s = 0)$).

16

Interpretation of Results

Since no significant excesses were observed in the signal region, the results are interpreted as exclusions on stop parameter space. The 95 percent confidence expected and observed exclusion limit is shown in figure 16.1. The exclusion CL_s are derived using the exclusion fit procedure described in section 14.5 where all 5 bins in R_{ISR} are simultaneously fitted and statistically combined. Previous 8 TeV stop ex-

clusion limits are shown in blue for comparison.

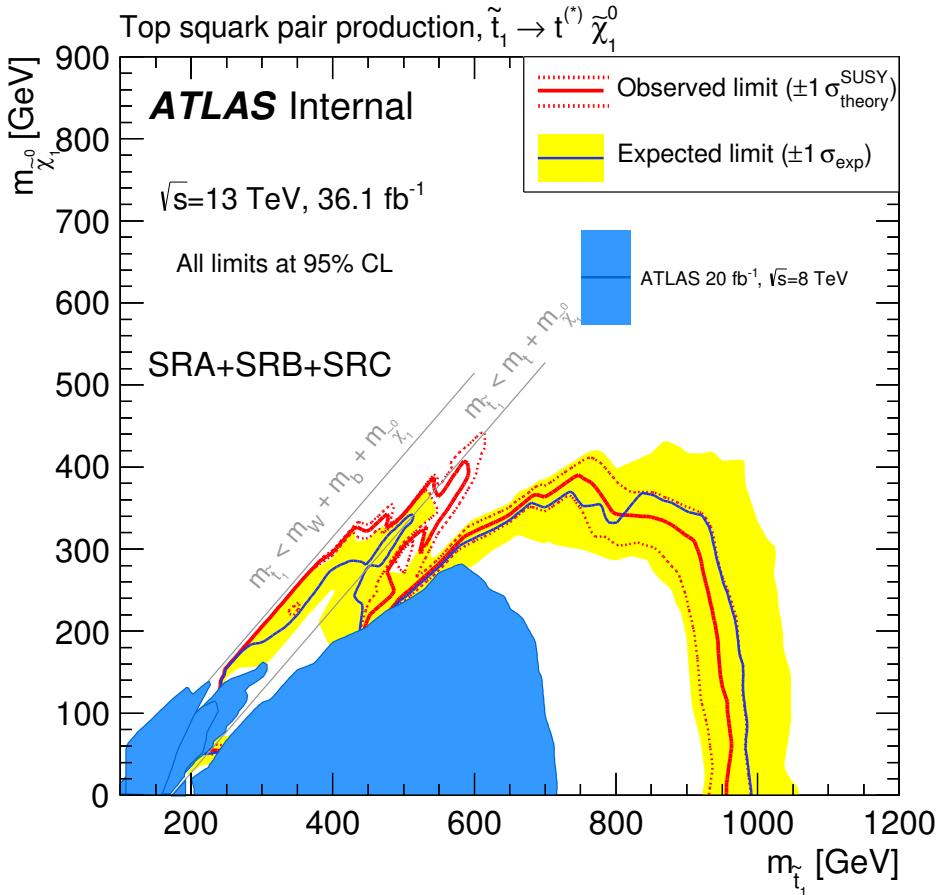


Figure 16.1: Results of the exclusion fits in the tN1 grid from a simultaneous fit to the compressed analysis SR

The compressed stop analysis fills in the 8 TeV gap in exclusion along the $\Delta m = m_t$ diagonal line. The analysis is able to exclude stops from 225 GeV to 600 GeV in this region with a CL_s below 5×10^{-4} for stop mass between 250 and 400 GeV. The analysis also extends the zero lepton sensitivity far into the 3 body decay region almost to the $\Delta m = m_W + m_b$ line.

Figure 16.2 shows the compressed stop analysis exclusion limit (SRC) combined with the bulk region 13 TeV stop 0 lepton analysis exclusion limit (SRA+SRB). The bulk stop 0 lepton analysis targets the high stop masses parameter space with large mass splitting between stop and neutralino masses. The stop decay gives a large amount of momenta to the resulting neutralinos in regions with large mass splittings. The bulk region analysis targets this kinematic feature and use large amount of E_T^{miss} to separate signal from background. Because of this, the bulk region analysis's strategy loses sensitivity as the Δm approaches m_t . A detail description of the bulk region stop 0 lepton analysis can be found in[?].

Figure 16.3 show how the exclusion limit on the stop/neutralino parameter space plane for different the branching fraction of $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b + \tilde{\chi}_1^\pm$. As the $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ branching fraction decreases, the $\tilde{t} \rightarrow b + \tilde{\chi}_1^\pm$ branching fraction increases. A new signal region SRD that directly targets the mixed decay channel is added to the analysis. Detailed documentation on the mixed decay analysis can also be found in[?]. Again the compressed analysis is responsible for the exclusion of all stop parameter space along the $\Delta m = m_t$ diagonal line when branching fraction to $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ is high.

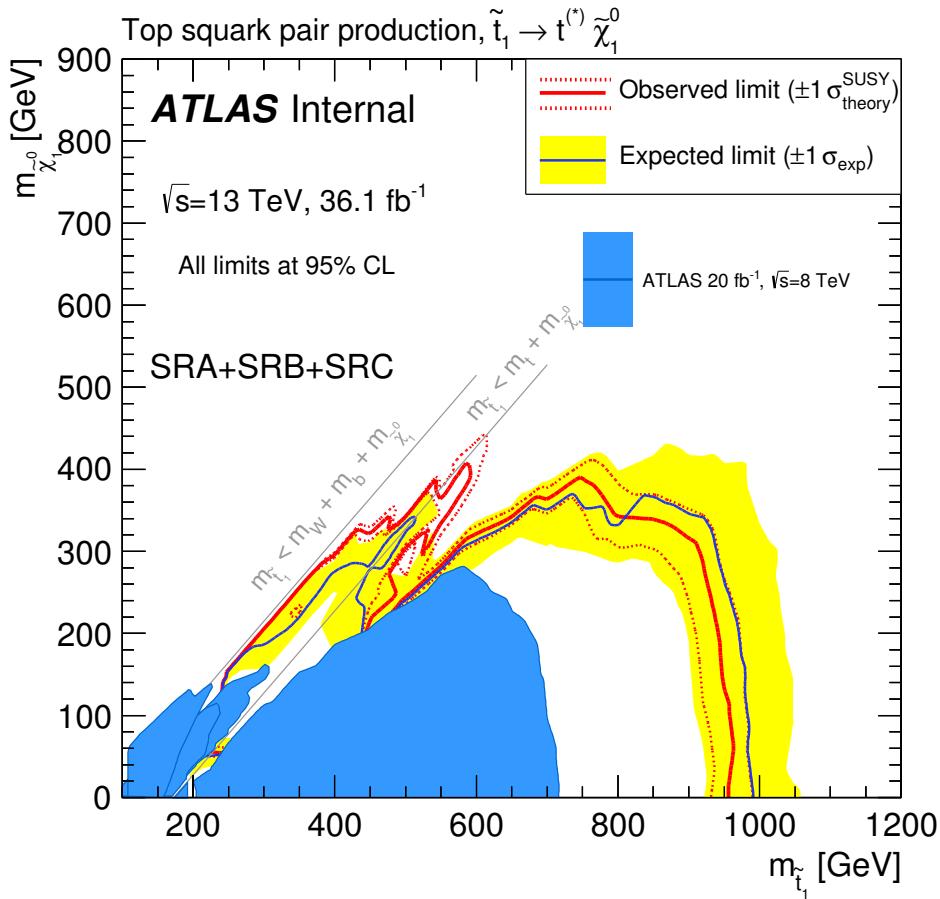


Figure 16.2: Results of the exclusion fits in the tN1 grid from the combination of the bulk region stop 0L analysis (SRA+SRB) and the compressed analysis (SRC). The bulk region analysis SRA targets high stop masses with large Δm and SRB targets high stop masses with medium amount of Δm . SRC is the compressed region analysis and adds sensitivity to the $\Delta m = m_t$ diagonal region where SRA and SRB lack sensitivity.

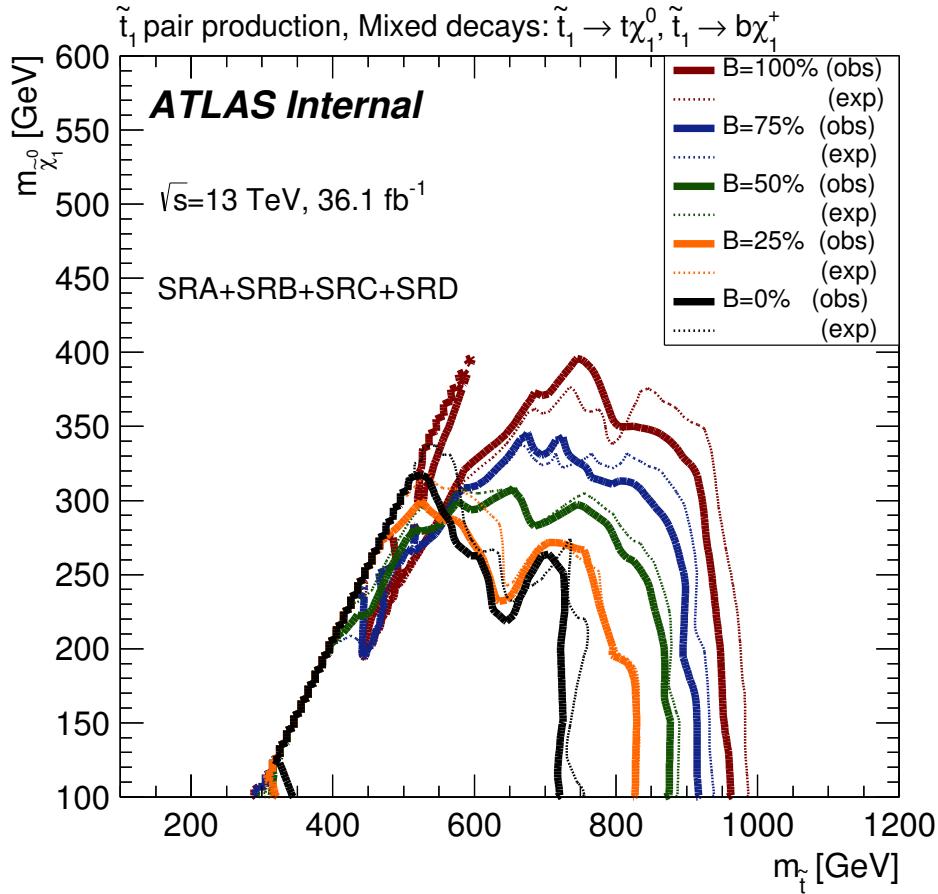


Figure 16.3: Results of the exclusion fits in the grid with two stop decay channels: $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$, with $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 1 \text{ GeV}$. The results are shown as a function of the branching ratio to $\tilde{t} \rightarrow t\tilde{\chi}_1^0$: 0%, 25%, 50%, 75% and 100%. The results are based on taking the signal region with the best expected CL_s , using SRA, SRB, SRC, and SRD. SRA and SRB target high stop masses in the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ decay channel at high stop masses and moderate to large Δm . SRC is the compressed region analysis that targets $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ with $\Delta m \sim m_t$. SRD targets a mix decay channel with branching fraction to both $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$. We can see that the compressed analysis SRC adds sensitivity to the $\Delta m = m_t$ line when the branching fraction is mainly to $\tilde{t} \rightarrow t\tilde{\chi}_1^0$.

17

Conclusion

We performed a search for the superpartner to the top quark using 36.07 fb^{-1} of 13 TeV LHC data collected by the ATLAS detector. The analysis was able to rule out stops between masses of 225 and 600 GeV if the $m_{\tilde{t}} - m_{\text{ninoone}} = m_t$ and the stop decayed with 100 percent branching ratio to $\tilde{t} \rightarrow \tilde{\chi}_1^0 + t$. No previous analysis was able to gain sensitivity to this experimentally difficult region of phase space. Tradi-

tional analysis strategy that focused on large amounts of E_T^{miss} failed due to low momenta imparted onto the neutralinos from the stop decays alone. The lack of E_T^{miss} made distinguishing between stops and the dominant SM ttbar background difficult. We demonstrated that by targeting events with strong initial state radiation and using the correlations between ISR and E_T^{miss} we are able to separate signal from ttbar and other SM background. Specifically the ratio between E_T^{miss} and ISR p_T called R_{ISR} was found to peak at $m_{\text{ninoone}}/m_{\tilde{t}}$ for signal. The spread of the peak is only 8 percent including detector resolution effects.

As part of this project, we developed a new and extremely accurate ISR identification algorithm. We were able to achieve 9 percent uncertainty on ISR p_T in both signal and ttbar background if the event contained at least 400 GeV of true ISR p_T . The uncertainty includes detector resolution effects and is derived using Monte Carlo simulation. The algorithm uses the axis of maximum back to back p_T called the thrust axis, to separate the event into an ISR hemisphere and a sparticle hemisphere.

In events with strong ISR, the back to back recoil between the particles produced in the hard scattering event and ISR should represent the single largest back to back kick in the event. Therefore, the axis of maximum back to back p_T , the thrust axis, will mimic the axis of the back to back recoil between the particles produced in the hard scattering interaction and the total ISR system. The method is completely generalizable for both new BSM particles and SM processes.

Using properties of both the sparticle and ISR hemispheres and the correlation between ISR and E_T^{miss} in signal we are able to achieve better than 2 to 1 signal to background for stop masses between 250 and 400 GeV. The background is 70-90 percent SM ttbar depending on the R_{ISR} region. The signal region specifically targets events with strong ISR in both signal and background and 90 percent of all ttbar which survives the signal region selection have > 400 GeV of true ISR p_T . Other background include $W+\text{jets}$, $Z+\text{jets}$, and single top at high R_{ISR} and QCD multijet at low R_{ISR} .

Total background systematics are between 15-25 percent in bins with appreciable expected background statistics. Of this only 10 percent is associated with the systematic uncertainty on ISR/FSR generation on ttbar. The ttbar control region which directly estimates the amount of ttbar plus strong ISR p_T and keeps ISR/FSR uncertainties in SR low. There is no extrapolation across ISR p_T between CR and SR and the distributions of true ISR p_T is nearly identical between SR and CR for SM ttbar. The uncertainty on ISR and partons showers are also small due to the fact that the ISR identification algorithm identifies entire ISR systems instead of individual jets. As such, the algorithm is insensitive to uncertainties associated with an ISR parton splitting into multiple jets during fragmentation and hadronization. The other largest systematic uncertainties include uncertainties on ttbar matrix element and parton shower calculations and theory uncertainty between the interference of SM single top and SM ttbar, each at about 5-10 percent.

This analysis serves also as a demonstration of the general strategy of using events with strong ISR to search for other BSM signatures with E_T^{miss} . The correlations between E_T^{miss} and ISR in compressed regions are dictated by special relativity alone. As long as decay products gain most of their momenta from ISR, the correlations will be strong regardless of the hard scattering particle.

The ISR identification algorithm is also completely generalizable. The thrust axis will mimic the back to back recoil between ISR and hard scattering particles so long as the ISR is strong enough to be the largest single back to back kick in the event. This gives potential application to other searches for SUSY including searches on Higgsinos, Charginos, and other ISR assisted searches such as the mono-jet/mono-photon searches for dark-matter. Even if the thrust based algorithm doesn't improve separation power between signal and background when compared to other ISR identification searches, using the thrust based algorithm can still significantly reduce ISR/FSR uncertainties. The thrust based ISR algorithm identifies entire ISR systems and is insensitive to uncertainties associated with a hard ISR parton splitting into multiple jets.

At the same time, the accurate ISR identification algorithm can also be used to measure SM ISR p_T spectrums. The thrust based algorithm is able to separate ttbar produced with around 550 GeV of ISR pt from ttbar with little ISR pt as demonstrated in the SM ttbar CR. Current ttbar ISR p_T differential cross-section measurements at ATLAS first attempt to reconstruct tops and identify all non-top jets as ISR jets.

Hadronic top reconstruction efficiency is extremely correlated with top p_T with a top reconstruction efficiency of only 30% at top $p_T = 200$ GeV. This means that ttbar ISR p_T measurements that require the reconstruction of tops are inherently biased towards events with high hadronic top p_T .

Because the ISR algorithm primarily uses the thrust axis and properties of the entire di-top system, we can avoid reconstructing individual tops but still identify a region with high purity of ttbar plus strong ISR. This gives a more independent measurement of the ttbar ISR p_T distribution and avoids any top reconstruction inefficiencies.

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