Searches for New Physics in final states containing leptons, b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ at the ATLAS detector

UNIVERSITY OF LIVERPOOL

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by

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Abstract

This is my abstract.

Declaration

I hereby confirm this work is my own, except where other works are referenced. This work has not previously been submitted to any institute, including this one. This thesis does not exceed the relevant word count.

Matthew James Sullivan

Acknowledgements

During my eight years at the University of Liverpool, the people helping to make it such a memorable period of my life have become innumerable, and to thank each and every person would require an equally long period of time. For those not acknowledged by name I can only give my thanks for being involved in this part of my life. It has been a true privilege to call this city my home and be a part of the Department of Physics throughout.

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These acknowledgements would be incomplete without a mention to the circumstances within which a large portion of it was written. The COVID-19 pandemic has had a devastating impact on individuals and families the world-over, causing both physical and mental struggle. On a personal level, numerous thanks are owed for enabling me to submit this work in this turbulent time. Firstly, to UKRI, for their generous financial support, enabling me to continue my work during these challenging times. Secondly, thanks are owed to the NHS, both due to their handling of the national crisis and for their continued healthcare support during, undoubtedly, the most stressful period of my life. However, the period of national lockdown due to the coronavirus has also provided unforeseen opportunities for personal development, and I submit this work having gained far more than anticipated. Countless thanks are owed to Jess, for managing to keep my stress-levels under control, for

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Introduction

Since its inception the Standard Model (SM) of particle physics has withstood huge amounts of experimental scrutiny. The SM provides a mathematical framework in which to describe *all* non-gravitational interactions of the known fundamental particles. With the discovery of the Higgs boson, a cornerstone of the SM, by the ATLAS and CMS collaborations in 2012 [1, 2], the SM is considered complete.

While one cannot detract from the success of the SM's description of physics at the smallest scales, there are numerous open questions which have not yet been answered. The reconciliation of gravity with physics at the subatomic scale, the hierarchy problem, astrophysical evidence of dark matter, and the matter-antimatter asymmetry require explanations from physics Beyond the Standard Model (BSM). The experiments at the Large Hadron Collider (LHC) have a broad programme of direct and indirect searches for BSM physics. Aiding in this is the LHC itself, providing pp collisions at $\sqrt{s} = 13$ TeV at luminosities around $10^{34}\text{cm}^2\text{s}^{-1}$. The huge datasets collected by both ATLAS and CMS, afforded by the LHC and its excellent performance, provide an ideal environment for BSM searches.

The physics analyses presented in this Thesis target two BSM scenarios; searches for Supersymmetry (SUSY) and searches for Dark Matter (DM) production. In both scenarios, the SM Higgs sector is extended to include an additional Higgs doublet, hence these models being known as Two Higgs Doublet models (2HDM). SUSY extends the SM with an additional symmetry in which particles gain 'superpartners', particles which differ in spin by 1/2 from their SM counterpart. The superpartners to the SM gauge bosons and Higgs mix and form a rich particle spectrum containing charged and neutral states, known as charginos and neutralinos. The lightest supersymmetric particle (LSP), in this case the lightest neutralino, is a leading candidate for DM. A search for the weak production of SUSY particles, specifically a chargino-neutralino pair, decaying to the supersymmetric DM candidate is performed, through decays involving the SM Higgs and W boson. Aside from SUSY, by adding a pseudoscalar mediator, a, to a 2HDM model, DM can couple to the SM extended Higgs sector leading to a rich array of final states. The associated production of DM with a single top quark, a previously experimentally-uncovered final state, is studied in the context of the 2HDM+a model. In addition to DM coupling to the

SM through 2HDM+a scenarios,

Both BSM scenarios studied in this Thesis are experimentally-challenging, due to the low rate of new particle production when compared to irreducible SM processes. Advanced signal selection techniques using machine learning (ML) methods are studied, enabling the efficient selection of signal while substantially rejecting the SM background. The upcoming High-Luminosity upgrade of the LHC and ATLAS will provide the opportunity to probe many BSM scenarios to levels never before possible, with an expected dataset of 3000 fb^{-1} being collected by ATLAS by the end of operations. To prepare for the HL-LHC phase of operation, ATLAS will undergo a major upgrade of many detector components. The ATLAS inner tracker (ITk) will provide high-precision tracking in conditions where as many as 200 inelastic proton-proton collisions are expected in each bunch-crossing. The efficiency of the pixel modules of the ITk are studied after being irradiated to the expected HL-LHC dose. Combining ML methods with the huge High Luminosity (HL) ATLAS dataset, the sensitivity to SUSY at the High-Luminosity LHC (HL-LHC) is also studied.

Part I provides an overall introduction in the context of physics models and the experimental setup. First, a theoretical overview of the SM is given, motivates the need for BSM physics, and then gives an overview of SUSY and the 2HDM+a model of DM production. It also gives a brief description of the LHC along with an overview of the ATLAS detector. Finally, the datasets used in this thesis are discussed, along with discussion of the simulation methods and object defintions used in the subsequent Chapters.

Part II describes the core work of this Thesis, encompassing three analyses using pp data at $\sqrt{s} = 13$ TeV, presented in separate Chapters. Chapter 6 presents a search for electroweak SUSY using 36.1fb^{-1} data and subsequently 139fb^{-1}. Chapter 7 presents a search for DM production in association with a single top quark using 139fb^{-1} data.

Part III presents studies and work relevant for the HL-LHC phase. Chapter 8 illustrates the prospect for a search for the electroweak production of SUSY particles using 3000fb^{-1}data at $\sqrt{s} = 14$ TeV. Chapter B presents work done on the Inner Tracker (ITk) studying the performance of hybrid pixel modules for upcoming upgrade for the HL-LHC.

Part I

Theoretical overview and experimental apparatus

Chapter 1

The Standard Model and Beyond

This chapter presents an overview of the Standard Model (SM), along with the extensions to it which form the basis of the analyses in Chapters 6 and 7. The SM is currently our best description of nature but does not give a complete description of some fundamental physical phenomena, outlined in Section 1.2, which motivates searches for physics beyond the SM (BSM).

1.1 The Standard Model

The SM is the name given to the theory describing the fundamentals of particle interactions. Since its inception over half a century ago, it has withstood experimental scrutiny, each time providing a theoretical description of experimental data. The particle content of the SM was deemed complete in 2012, with the discovery of a particle consistent with the Higgs boson by the ATLAS [1] and CMS [2] collaborations.

The SM describes matter in terms of quarks and leptons and their interactions via three of the four fundamental forces through the exchange of force-carriers known as bosons. As alluded to at the beginning of this Chapter, the SM provides an incomplete description of physics at the smallest scales, which will be discussed later in this Chapter.

Overview

The SM particles are easily separable into two categories; fermions, which obey Fermi-Dirac statistics and have half-integer spin, and bosons, which obey Bose-Einstein statistics and have integer spin.

The fermions are further separable into two families, quarks and leptons, both of which have three generations. The quarks can be separated into 'up-type' and 'down-type', having electric charge $+\frac{2}{3}$ and $-\frac{1}{3}$, respectively. The 'up-type' quarks are the up (u), charm (c)

and top (t) quarks, while the 'down-type' quarks are the down (d), strange (s) and bottom (b). The leptons can be separated into charged leptons and neutral leptons (known as neutrinos), with the charged leptons having an electric charge of -1. The charged leptons are the electron (e), the muon (μ) and the tau (τ), with a corresponding electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ). The three generations of fermions are ordered in increasing mass, with the first generation containing the up and down quarks, the electron and its corresponding neutrino, the former three of which combine to make up everyday matter. In the SM neutrinos do not have mass, but experimental evidence of neutrino flavour oscillations [3] implies that neutrinos are in fact massive, although their mass hierarchy is not yet clear [4].

Composite particles can be formed from combinations of quarks when they undergo hadronisation. 'Hadrons' are defined as bound states of quarks, with mesons being formed from pairs of quarks and baryons being formed by three quarks. In recent years, more exotic bound states of quarks, such as tetra-quarks [5, 6] and penta-quarks [**?**, 7] have been observed by the LHCb collaboration. All quarks except the top quark undergo hadronisation after a period of time. The top quark, which has a much larger mass than the other quarks, has a lifetime around $\tau_t = 10^{-25}$ s and as such decays via the weak force before it can hadronisation. The first generation quarks, i.e. the up quark and down quark, can be combined to produce protons (uud) and neutrons (udd). Combining protons and neutrons with the first generation charged lepton, the electron, we give rise to nuclear physics and all physical matter in our universe.

The SM bosons are responsible for the interactions of the SM particles. Electromagnetic interactions are mediated by the massless photon (γ), and only occur between electrically-charged particles. Gluons (g), massless and electrically-neutral bosons, mediate the interactions between quarks, which carry the colour charge. The $W^\pm$ and Z^0 bosons mediate the weak interaction, which all SM fermions are subject to. Both the $W^\pm$ and Z^0 bosons are massive, and acquire their mass through the spontaneous breaking of the electroweak symmetry, as discussed later in this Chapter.

The particle content of the SM is summarised in Table 1.1.

Mathematical formulation of the SM

The SM is a quantum field theory (QFT) based upon the product of symmetry groups:

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \tag{1.1.1}$$

The $\mathrm{SU}(3)_C$ component describes strong interactions (QCD), the $\mathrm{SU}(2)_L$ component describes the electroweak sector and $\mathrm{U}(1)_Y$ describes electromagnetic interactions.

Name	Symbol	Charge (e)	Spin	Mass
Fermions - Generation-I				
Up-quark	u	$+2/3$	$1/2$	2.16 MeV
Down-quark	d	$-1/3$	$1/2$	4.67 MeV
Electron	e	-1	$1/2$	0.511 MeV
Electron-neutrino	ν_e	0	$1/2$	< 2 eV
Fermions - Generation-II				
Charm-quark	c	$+2/3$	$1/2$	1.27 GeV
Strange-quark	s	$-1/3$	$1/2$	93 MeV
Muon	μ	-1	$1/2$	105.66 MeV
Muon-neutrino	ν_μ	0	$1/2$	< 2 eV
Fermions - Generation-III				
Top-quark	t	$+2/3$	$1/2$	172.9 GeV
Bottom-quark	b	$-1/3$	$1/2$	4.18 GeV
Tau	τ	-1	$1/2$	1.78 GeV
Tau-neutrino	ν_τ	0	$1/2$	< 2 eV
Bosons				
W boson	$W^\pm$	± 1	1	80.4 GeV
Z boson	Z	0	1	91.2 GeV
Gluon	g	0	1	0
Photon	γ	0	1	0
Higgs boson	H	0	0	125.1 GeV

Table 1.1: A table describing the charge, mass and spin of the SM particles. Particle masses taken from [8].

In order to understand the mathematical formulation of the SM, the concepts of *groups* will be briefly discussed. A group is a set of mathematical objects, G, along with an operation, which obey the following 'axioms' [9]:

- *Closure*: For all $a, b \in G$, $a \cdot b \in G$
- *Associativity*: For all a, b and $c \in G$, $(a \cdot b) \cdot c = a \cdot (b \cdot c)$
- *Identity element*: An identity element, I, exists such that $I \cdot a = a \cdot I = a$
- *Inverse element*: An inverse element of a, a^{-1}, exists such that $a \cdot a^{-1} = a^{-1} \cdot a = I$

The commutation relations of the members of a group are important to know. As a

reminder, the commutator of two elements of a group, a, b is defined as:

$$[a, b] = (a \cdot b - b \cdot a) \tag{1.1.2}$$

Groups where the commutator of any two elements is always 0 are known as 'abelian', while groups where this does not hold are called 'non-abelian'. Abelian groups have n^2 generators of the underlying Lie algebra, while non-abelian groups have $n^2 - 1$ generators. While this seems conceptually-abstract, the number of generators of a group physically corresponds to the number of 'force-carriers' present in a theory governed by that group.

In equation 1.1.1, U(n) and SU(n) refer to unitary groups and special unitary groups, respectively. U(n) is the set of $n \times n$ unitary matrices ($U \cdot U^{-1} = I$), and SU(n) the subset of U(n) which have a determinant of 1. The individual symmetry groups will be discussed in more details in the following sections, starting with electromagnetic interactions and the U(1) group.

Quantum Electrodynamics

Electromagnetic interactions are described by Quantum Electrodynamics (QED). These interactions are unique in the SM, as they have infinite range. We will derive the Lagrangian describing QED, starting from the Dirac equation for free fermions:

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi \tag{1.1.3}$$

Due to the U(1) symmetry, QED is symmetric under *global* phase transformations of the form:

$$\psi(x) \to \psi'(x) = e^{i\alpha}\psi(x),\ \bar{\psi(x)} \to \bar{\psi}'(x) = e^{-i\alpha}\bar{\psi}(x) \tag{1.1.4}$$

Under *local* transformations, where $\alpha \to \alpha(x)$, the Lagrangian in Equation 1.1.3 is not gauge invariant:

$$i\bar{\psi}'\gamma^\mu \partial_\mu \psi' = i\bar{\psi}\gamma^\mu \partial_\mu \psi - \bar{\psi}\gamma^\mu \partial_\mu \alpha \psi \tag{1.1.5}$$

To resolve this, we define the covariant derivative:

$$D_\mu \equiv \partial_\mu + ieA_\mu \tag{1.1.6}$$

Note, with the introduction of the covariant derivative comes the introduction of the vector field, A_μ, which transforms as:

$$A_\mu \to A'_\mu = A_\mu - \frac{1}{e}\partial_\mu \alpha(x) \tag{1.1.7}$$

The result of a local transformation on the Dirac equation is now:

$$i\bar{\psi}'\gamma^\mu D'_\mu\psi' - m\bar{\psi}\psi = i\bar{\psi}\gamma^\mu\partial_\mu\psi - \bar{\psi}\gamma^\mu eA_\mu\psi - m\bar{\psi}\psi \tag{1.1.8}$$

Rearranging Equation 1.1.6 for ∂_μ and substituting in, we see local gauge invariance holds thanks to the introduction of the covariant derivative. Of particular interest is the term $\bar{\psi}\gamma^\mu eA_\mu\psi$, which couples the fermion fields to the vector field, which we associate to the photon, γ, with the coupling constant e corresponding to the electrical charge of the fermion. To complete the QED Lagrangian, one must add the electromagnetic Lagrangian to the Dirac Lagrangian. (For concision, we now adopt the Feynman 'slash' notation: $\not{\partial} = \gamma^\mu\partial_\mu$).

$$\mathcal{L}_{QED} = \mathcal{L}_{Dirac} + \mathcal{L}_{EM} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \tag{1.1.9}$$

As the interaction term, introduced by using the covariant derivative, couples fermions to the photon with a coupling e, QED interactions are only relevant for electrically-charged fermions. Figure 1.1 shows the QED interaction vertex.

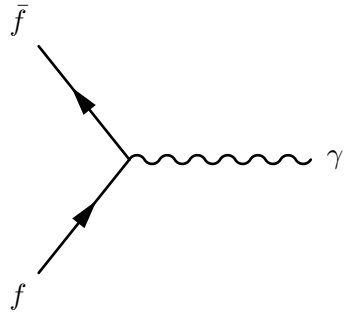


Figure 1.1: Feynman diagram showing the QED interaction vertex between a fermion and the photon.

Quantum Chromodynamics

Quantum Chromodynamics addresses the interactions between quarks and gluons. It is governed by the $\mathrm{SU}(3)_C$ symmetry hence having $N_C^2 - 1 = 8$ mediators. By virtue of the symmetry group being a *special* unitary group, the theory is non-abelian, resulting in gluons being able to self-interact. Similarly to QED, we begin from the Dirac Lagrangian and introduce a covariant derivative, in this case defined as:

$$\partial^\mu = D^\mu \equiv \partial^\mu\delta_{ij} - ig_s t^a_{ij}G^{a\mu} \tag{1.1.10}$$

where δ_{ij} is the Kroenecker delta (0 for $i \neq j$, 1 for $i = j$), g_s the strong coupling constant, $t^a = \frac{\lambda^a}{2}$ the generators of the $\mathrm{SU}(3)_C$ symmetry group with λ^a being the Gell-Mann matrices and G^a being the gluon gauge fields. Rewritting the Dirac equation from

Equation 1.1.3:

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}_j(i\gamma_\mu\partial^\mu - m\delta_{ij})\psi_i \tag{1.1.11}$$

In Equation 1.1.11, i and j index the quarks from 1 to 3 and a indexes the gluons from 1 to 8. Replacing the regular partial derivate in Equation 1.1.10 with the covariant derivative from Equation 1.1.11, we obtain:

$$\mathcal{L}_{QCD} = \bar{\psi}_j(i\gamma_\mu\partial^\mu\delta_{ij} - m\delta_{ij})\psi_i - g_s(\bar{\psi}_j\gamma_\mu t^a_{ij}\psi_i)G^{a\mu} \tag{1.1.12}$$

Adding in the kinetic term for the gluon fields and again using the Feynman slash notation, the full QCD Lagrangian is:

$$\mathcal{L}_{QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}G^{\mu\nu}_a G^a_{\mu\nu} \tag{1.1.13}$$

Equation 1.1.13 is helpful to understand the gluon self-interaction, with 3-gluon and 4-gluon interactions present in the expansion of the $G^a_{\mu\nu}G^{\mu\nu}_a$.

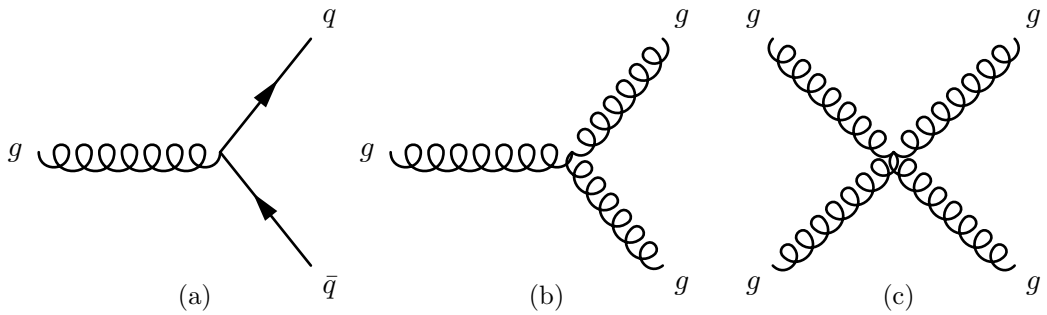


Figure 1.2: Feynman diagram showing the QCD quark-gluon interaction vertex (a), the triple gluon self-interaction (b) and the quartic gluon self-interaction (c).

The gauge coupling of QCD depends upon the momentum transfer of a process, Q^2, as follows:

$$g_s(Q^2) = \frac{4\pi}{\beta_0 \ln\left(\frac{Q^2}{\Lambda^2_{\text{QCD}}}\right)} \tag{1.1.14}$$

The Q^2 dependence of α_s means the coupling strength "runs" depending on the momentum transfer. At large Q^2, which corresponds to the high-energy or short-distance regime, quarks and gluons are treated as free particles. In this regime, perturbative QCD (pQCD) calculations can be used to make very accurate predictions. In pQCD, calculations proceed by performing a series expansion in α_s, where higher-order terms correspond to the contribution from Feynman diagrams with additional QCD vertices. Calculating the cross-section of a QCD process in this way can lead to ultraviolet (UV) divergences arising from loops in higher-order Feynman diagrams, which requires the introduction of the *renormalisation scale*, μ_R, to remove them. This means the evaluation of α_s is dependent upon

mu_R, which is typically set to the mass of the Z boson, m_Z, at which the strong coupling has a value of 0.118.

However, in the low-energy limit, where $Q^2 \to \Lambda^2_{\text{QCD}}$, where Λ^2_{QCD} is the energy at which quarks and gluons hadronise, known as the *hadronisation scale*, the strong coupling tends to infinity and hence perturbative calculations can no longer be used. This results in quarks being bound together into colour-neutral hadrons, a phenomena known as *colour confinement*. Colour confinement forbids the existence of a quark in isolation, instead forcing quarks to exist in colourless, bound states, known as hadrons. Due to the running coupling, when the separation of a quark-antiquark pair is increased, so does the energy of the strong interaction between them. With increasing separation, it eventually becomes energetically-favourable to produce another quark-antiquark pair. This quark-antiquark pair forms colourless, bound states with the initial quark-antiquark pair. An additional result of colour confinement is that the range of the strong force is extremely short, around 1fm.

Weak interaction and Electroweak unification

The third force described by the SM is the weak interaction, which describes interactions between the left-handed fermions and is described by The $\text{SU}(2)_L$ symmetry group. It is therefore expected that the weak interaction has 3 mediators (from $N^2 - 1$); W^1_μ, W^2_μ and W^3_μ. The weak interaction also introduces new quantum numbers known as weak isospin, T, as well as its third component T_3. With these quantum numbers, we can define weak isospin doublets, using the first generation leptons and quarks as examples:

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} ; \begin{pmatrix} u_L \\ d_L \end{pmatrix} \tag{1.1.15}$$

Both of the weak isospin doublets shown in Equation 1.1.15 have $T = \frac{1}{2}$, with the fermion in the 'upper' position having $T_3 = +\frac{1}{2}$ and the fermion in the 'lower' position having $T_3 = -\frac{1}{2}$.

An extremely important concept for understanding the weak interaction is chirality. Chirality is an intrinsic property of particles, and determines how they behave in the weak interaction. The subscript 'L' is present as only fermions with 'left-handed' chirality (anti-fermions with 'right-handed' chirality) interact via the weak interaction. 'Left-handed' fermions, and 'right-handed' anti-fermions have $T = \frac{1}{2}$ and hence form isospin doublets, whereas 'right-handed' fermions and 'left-handed' anti-fermions have $T = 0$ and hence are isospin singlets.

The introduction of weak isospin doublets enables a mechanism for quarks to change flavour through a charged-current interaction. For example, a 'down-type' quark can change into an 'up-type' quark through a transition of T_3. The Cabibbo-Kobayashi-Maskawa matrix, known as the CKM matrix, determines the probability of a quark, q, to transition to another flavour.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{1.1.16}$$

The CKM matrix is *almost* a diagonal matrix, with the on-diagonal elements being close to one, while the off-diagonal elements are small but non-zero. Therefore, the most probable quark flavour transitions are intra-generational, but inter-generation transitions are allowed.

It was shown by Glashow, Salam and Weinberg that the interaction can be unified with the electromagnetic interaction, with an overall symmetry group of $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$. We now introduce the weak hypercharge, $Y = 2(Q - T_3)$, where Q is the electric charge. At low energies, the electromagnetic and weak interactions independently explain physical phenomena, such as hyperfine splitting and β decay in nuclei. The unification of these two interactions into the electroweak interaction must therefore preserve the two separate interactions at low energy. However, above the 'unification energy', the two separate interactions are merged into a one. This new, unified interactions has four mediators; two massive, charged $W^{\pm}$ bosons, a massive, neutral Z and the massless, neutral γ from the U(1) symmetry in QED. The interaction vertices of the three massive electroweak gauge bosons are shown in Figure 1.3. Note, Figure 1.3b shows the interaction of only the negatively-charged W boson interacting with leptons.

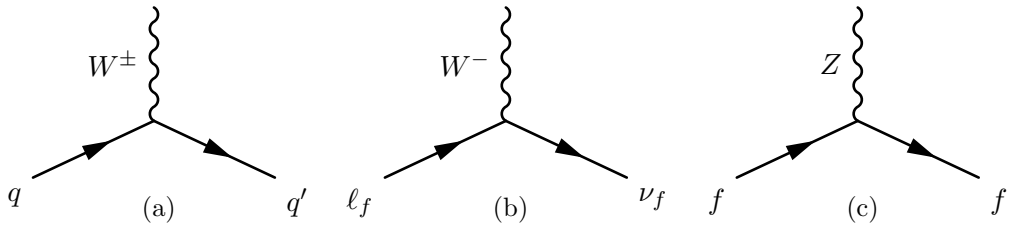


Figure 1.3: Feynman diagrams showing the massive electroweak gauge bosons interaction vertices. Note, as shown in (b), only the W^- couples to the lepton isospin doublet, whereas for the quark isospin doublets (a) both the $W^{\pm}$ are involved.

The $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry group is non-abelian, and thus the electroweak gauge bosons can self-interact. Similarly to gluons in QCD, there are triple and quartic self-

couplings; $W^{\pm}W^{\mp}Z/\gamma$, $W^{\pm}W^{\mp}Z/\gamma Z\gamma$ and $WWWW$.

As discussed previously, to ensure local gauge invariance of the SM electroweak Lagrangian, we define the covariant derivative:

$$\partial_\mu \rightarrow D_\mu \equiv \partial_\mu + \frac{i}{2}g\vec{\tau}\cdot\vec{W}_\mu + ig'\frac{Y}{2}B_\mu \tag{1.1.17}$$

where $\vec{W}_\mu$ and B_μ are the gauge fields, and g and g' are the couplings, of the $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$ symmetries, respectively. As the electroweak interaction only couples to 'left-handed' fermions, we can define projection operators, which project out the left- and right-handed components of a field:

$$P_L = \frac{1}{2}(1-\gamma^5); P_R = \frac{1}{2}(1+\gamma^5); \gamma^5 \equiv \begin{pmatrix} 0 & I_2 \\ I_2 & 0 \end{pmatrix} \tag{1.1.18}$$

We are then able to write the fermion field as $\psi = P_L\psi + P_R\psi = \psi_L + \psi_R$. The mass term in the Lagrangian, $m\bar{\psi}\psi$, now expands as:

$$m\bar{\psi}\psi = m\bar{\psi}_R\psi_L + m\bar{\psi}_L\psi_R \tag{1.1.19}$$

The left- and right-handed components of the fermion field, ψ, transform differently under the $\mathrm{SU}(2)_L\times\mathrm{U}(1)_Y$ symmetry and therefore the mass term in Equation 1.1.19 breaks local gauge symmetry. Therefore, we need to introduce a mechanism by which fermions, and also the electroweak gauge bosons, become massive.

The Higgs sector

The discovery of the $W^{\pm}$ bosons [10, 11] and Z boson [12, 13] in 1983 with masses around $m_W \sim 80$ GeV and $m_Z \sim 91$ GeV, in good agreement with electroweak predictions, proved the need for a mechanism through which the gauge bosons acquire mass. The Higgs mechanism, first proposed in the 1960's, provided such a mechanism by introducing an $\mathrm{SU}(2)_L$ doublet of complex, scalar fields:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \tag{1.1.20}$$

This doublet has isospin $T = \frac{1}{2}$ and hypercharge $Y = 1$. This field has a scalar potential defined as:

$$V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \tag{1.1.21}$$

The two terms in Equation 1.1.21 can be identified as a mass term for the scalar boson and a self-interaction term, respectively. Dependent upon the choices for μ^2 ($\lambda > 0$), the

potential can take on two shapes; parabolic for $\mu^2 > 0$ and a 'wine bottle' potential for $\mu^2 < 0$. For reasons discussed later, the Higgs potential has $\mu^2 < 0$, and the shape of this potential is shown in Figure 1.4.

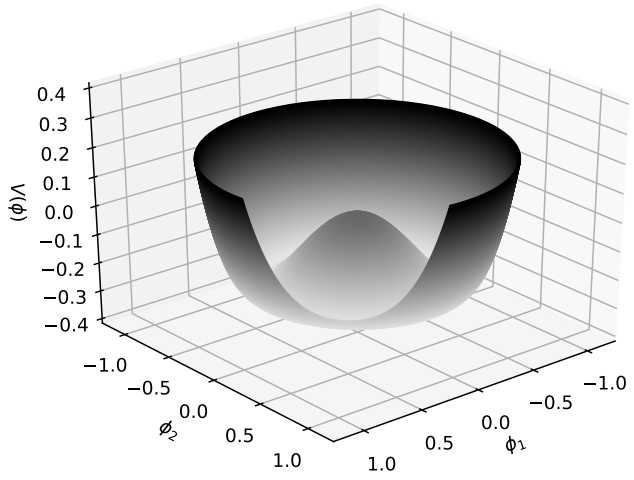


Figure 1.4: Schematic diagram showing the shape of the Higgs potential, known as the 'Mexican hat' potential.

The potential shown in Figure 1.4 evidently has a local minima at $\phi_1, \phi_2 = 0$. However, the global minima is at non-zero values of ϕ, and is given by:

$$\phi_{min} = \sqrt{-\frac{\mu^2}{2\lambda}} \tag{1.1.22}$$

We define $v^2 = \mu^2/\lambda$, where v is the vacuum expectation value (vev) of the the Higgs field. The vev of the Higgs field is therefore, non-zero, and is experimentally determined to be ≈ 246 GeV. It is convenient to choose the vevs of the ϕ_1, ϕ_2 and ϕ_4 to zero, while for ϕ_3 the vev is:

$$\langle 0|\phi_3|0\rangle^2 = v^2 = \frac{\mu^2}{\lambda} \tag{1.1.23}$$

The choice for the spontaneous symmetry breaking to be done with the field ϕ_3 is to allow the photon to remain massless. Expanding the Higgs field around the minima with $\phi_3 = h + v$, we eventually acquire a term for the Higgs mass of $m_H = \sqrt{-2\mu^2}$. Inserting

this field into 1.1.17, we obtain the mass terms for the electoweak gauge bosons:

$$\begin{aligned} m_W &= \frac{1}{2} g v \\ m_Z &= \frac{1}{2}\sqrt{g^2 + g'^2}\, v \\ m_\gamma &= 0 \end{aligned} \tag{1.1.24}$$

The Higgs Lagrangian contains couplings to not only the electroweak gauge bosons but also the SM fermions. The strength of the couplings to the fermions are given by y_f, known as *Yukawa couplings*. This coupling enables the fermions to acquire masses in a gauge-invariant way through the Higgs mechanism. The mass of a fermion, f, is given by:

$$m_f = y_f \frac{v}{\sqrt{2}} \, . \tag{1.1.25}$$

Fermion masses are experimentally-determined, hence determining the Yukawa coupling of the Higgs to that fermion. The interactions of the Higgs with the electoweak gauge bosons and SM fermions are shown in Figure 1.5. The Higgs decay branching ratios (BR) depends

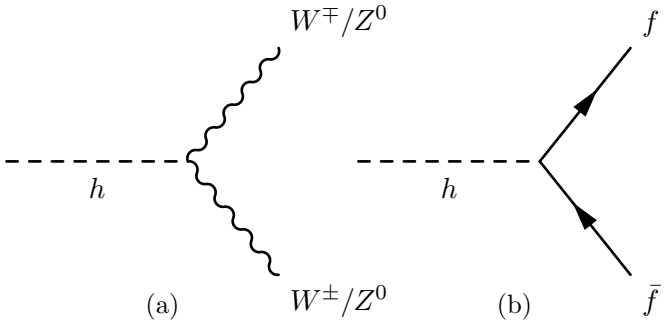


Figure 1.5: Feynman diagrams showing the Higgs interaction vertices with the electroweak gauge bosons (1.5a) and SM fermions (1.5b).

both upon the Higgs mass and the Yukawa coupling of the Higgs to the SM particles. Figure 1.6 shows the Higgs BRs for a SM Higgs boson with a mass in the range, 120-130 GeV. The largest Higgs BR is to a $b\bar{b}$-pair, which is important for the analyses detailed in Chapters 6 and 8.

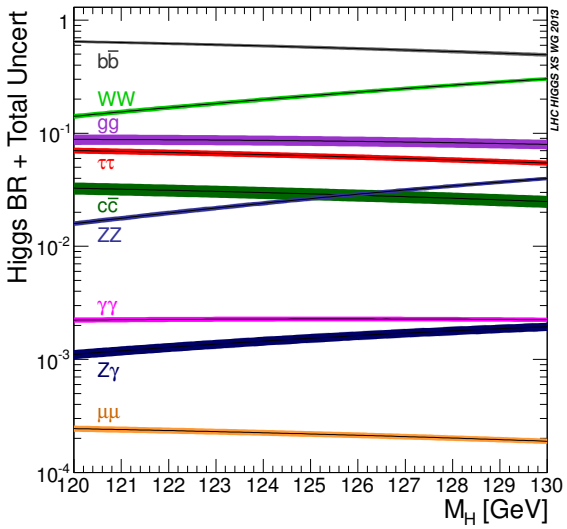


Figure 1.6: This plot shows the branching ratios of the SM Higgs decaying to SM particles in the mass range 120-130 GeV. **REF**

Open questions in the SM

The first of the open questions to be discussed is the hierarchy problem. While the SM does not account for gravitational interactions, it is impossible to have a complete description of nature, a so-called 'Grand Unified Theory' (GUT), without its inclusion. The hierarchy problem arises when considering a unified theoretical description of all four, fundamental forces. Gravity is expected to become the dominant interaction at the Planck scale, which has an equivalent mass of $O(10^{19})$ GeV. This is 17 orders of magnitude higher the electroweak scale and the Higgs mass, $O(10^2)$ GeV.

The Higgs mass consists of two terms; a 'bare' mass and the sum of the virtual corrections from particles coupling to the Higgs. We treat the Planck scale, Λ_P, as a cut-off value for the virtual contributions. Therefore, the physical Higgs mass can be written as:

$$m_H^2 = m_{H,\text{bare}}^2 + \delta m_H^2 = m_{H,\text{bare}}^2 - \frac{|g_f|^2}{8\pi^2}\Lambda_p^2 + \dots \tag{1.1.26}$$

Here, the neglected terms grows logarithmically in Λ_p. Assuming the SM is indeed valid upto the Planck scale, then the second term is $O(10^{19}\text{GeV})^2$, requiring an equally-large (to 1 part in over 10^{30} orders of magnitude) bare Higgs mass. The Anthropic Principle is sometimes invoked to justify this 'fine-tuning' [14], while extensions to the SM such as Supersymmetry (SUSY) provide elegant, mathematical solutions to the hierarchy problem.

Within the SM, neutrinos do not have mass, but experimental observation of neutrino oscillations implies that they do have mass, and that each neutrino flavour is a mixture of

the mass eigenstates. The SM includes only left-handed neutrinos, as described previously, while all other fermions are present in both left-handed and right-handed spinors. Neutrino mass may be explained by the presence of right-handed neutrinos which the SM does not include. Through the see-saw mechanism, right-handed neutrinos may also provide resolution to the unnaturally-small neutrino masses, orders of magnitude smaller than the other fermions. Alternatively, neutrinos may be Majorana fermions, particles which are their own antiparticle. The origin of neutrino masses and the question of why their mass is so small require explanation from BSM physics.

On larger scales, there are two troubling issues with the SM. Firstly, the SM predicts that at the Big Bang, the creation of the Universe, matter and antimatter should have been produced in equal quantity. If this were indeed true, the matter and antimatter should have all annihilated into photons ($f\bar{f} \rightarrow \gamma$), leaving a radiation dominated universe devoid of matter. However, at the present day, we can see this is not true. This matter-antimatter asymmetry is unexplained within the SM. The Sakharov conditions [15] enable the necessary excess of baryons over antibaryons, to be produced, known as baryogenesis. The conditions state that a process can result in a matter-antimatter asymmetry if it violates baryon-number conservation, charge symmetry (C) and charge-parity (CP) symmetry. BSM models such as SUSY and GUTs can provide additional particles which satisfy the Sakharov conditions, hence explaining the matter-antimatter asymmetry.

Observations of anomalous gravitational behaviour, such as in the rotational curves of galaxies, enable us to infer the existence of DM. Since we do not *visibly* observe DM, it is inferred that DM does not interact electromagnetically, therefore being electrically-neutral. It is also required for DM to be stable, as its effects are observed from the early universe in the cosmic microwave background (CMB), the residual radiation from the Big Bang, until now.

Recent measurements of the DM abundance estimate that $\Omega_{DM}h^2 = 0.1196 \pm 0.0031$, meaning that DM makes up as much as 26% of the universe. The only DM candidate within the SM are neutrinos as they are massive (inferred from neutrino mixing), neutral and stable. Therefore, neutrinos actually form part of the DM density. However, their contribution can be estimated as $\Omega_\nu h^2 \approx \frac{\sum_i m_i}{91\text{eV}} < 0.003$, a minor contribution to the total DM abundance.

1.2 Physics Beyond the Standard Model

There are countless proposed extensions to the SM, each which can provide solutions to some of the open questions. One such method is to postulate a DM candidate, and couple

it to the SM through some mediator. Section **??** describes one such model. Another way of generating New Physics is to extend the symmetries of the SM. One such extension is supersymmetry (SUSY), which is described in Section **??**.

Supersymmetry

SUSY introduces an additional symmetry to the SM in which SM fermions can become bosons and SM bosons can become fermions. An operator. Q, is introduced which enables transformations between bosonic and fermionic states, as follows:

$$\begin{aligned} Q\,|\text{boson}\rangle &= |\text{fermion}\rangle \\ Q\,|\text{fermion}\rangle &= |\text{boson}\rangle \ . \end{aligned} \tag{1.2.1}$$

The symmetry group of SUSY is of the form $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y \times \text{SUSY}$ such that when a SM particle undergoes a SUSY transformation, the SM quantum numbers are unchanged. Under this symmetry group, each of the SM particles gains a superpartner with spin differing by 1/2. The SM particles and their superpartners can be placed into either chiral multiplets or gauge multiplets.

The SM fermions and their bosonic, spin-0 superpartners form chiral multiplets. The superpartners to the SM fermions have an 's' prepended to their name, short for scalar. For example, the superpartner to the SM top quark is named the 'stop' quark. The SM bosons have 'ino' appended to their name, an example of this being the superpartners to the SM gluon being named gluinos. The SM vector bosons and their superpartners form gauge multiplets. In order to give masses to all of the particles, SUSY requires two Higgs doublets with weak isospin $Y = \pm 1/2$. This extended Higgs sector gives rise to four gauge eigenstates to the Higgs scalars: $\tilde{H}_u^+$, $\tilde{H}_u^0$, $\tilde{H}_d^0$ and $\tilde{H}_d^-$. These four eignenstates mix to form five mass eigenstates: h^0, H^0, A^0 and $H^\pm$. The SM Higgs boson discovered in 2012 is identified as the lightest CP-even SUSY Higgs, h^0, while the remaining mass eigenstates are much higher masses and are decoupled. A summary of the chiral supermultiplets and gauge supermultiplets are shown in Tables 1.2 and 1.3, respectively.

Names	Symbol	Spin-0	Spin-1/2	$SU(3)_C \times SU(2)_L \times U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L\ \tilde{d}_L)$	$(u_L\ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(3 generations)	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu}\ \tilde{e}_L)$	$(\nu\ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(3 generations)	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+\ H_u^0)$	$(\tilde{H}_u^+\ \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0\ H_d^-)$	$(\tilde{H}_d^0\ \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

Table 1.2: Chiral supermultiplets in the MSSM.

Names	Spin-1/2	Spin-1	$SU(3)_C \times SU(2)_L \times U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\tilde{W}^\pm\ \tilde{W}^0$	$W^\pm\ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Table 1.3: Gauge supermultiplets in the MSSM.

Mixing of mass eigenstates

The gauge eigenstates listed in Tables 1.2 and 1.3 are able to mix, resulting in mass eigenstates which are different from the gauge eigenstates. The gauge and mass eigenstates are presented in Table 1.4, showing the mixing between the gauge eigenstates.

Names	Spin	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	H_u^+, H_u^0, H_d^0, H_d^-	h^0, H^0, A^0, $H^\pm$
Charginos	1/2	$\tilde{W}^\pm$, $\tilde{H}_u^+$, $\tilde{H}_d^-$	$\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$
Neutralinos	1/2	$\tilde{H}_u^0$, $\tilde{H}_d^0$, $\tilde{W}^0$, $\tilde{B}^0$	$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$
Sleptons	0	$\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\nu}_e$	same
		$\tilde{\mu}_L$, $\tilde{\mu}_R$, $\tilde{\nu}_\mu$	same
		$\tilde{\tau}_L$, $\tilde{\tau}_R$, $\tilde{\nu}_\tau$	$\tilde{\tau}_1$, $\tilde{\tau}_2$, $\tilde{\nu}_\tau$
Squarks	0	$\tilde{u}_L$, $\tilde{u}_R$, $\tilde{d}_L$, $\tilde{d}_R$	same
		$\tilde{c}_L$, $\tilde{c}_R$, $\tilde{s}_L$, $\tilde{s}_R$	same
		$\tilde{t}_L$, $\tilde{t}_R$, $\tilde{b}_L$, $\tilde{b}_R$	$\tilde{t}_1$, $\tilde{t}_2$, $\tilde{b}_1$, $\tilde{b}_2$
Gluino	0	$\tilde{g}$	same

Table 1.4: Table showing the SUSY gauge and mass eigenstates.

As shown in Table 1.4, mixing occurs between the superpartners of the electroweak gauge bosons and Higgs bosons, the squarks and sleptons. For the squarks and sleptons, the

mixing of the SUSY gauge eigenstates is proportional to the mass of their SM counterparts, and as such is only relevant for the superpartners of the top and bottom quarks and the tau lepton. The L and R subscripts denote that there are superpartners for both the left-handed and right-handed fermions, and do not denote the handedness of the superpartners themselves. The winos, bino and Higgsinos can mix to form a rich spectrum of electroweak mass eigenstates. The bino, $\tilde{B}^0$, the neutral wino $\tilde{W}^0$ and the neutralino higgsinos $\tilde{H}_u^0$ and $\tilde{H}_d^0$ can mix to form four neutral mass eigenstates known as neutralinos. The charged winos, $\tilde{W}^\pm$ and the charged higgsinos $\tilde{H}_u^+$ and $\tilde{H}_d^-$ can mix to form two charged mass eigenstates known as charginos. The neutralinos, denoted by $\tilde{\chi}_i^0$, where $i = 1, 2, 3, 4$, while the charginos are denoted by $\tilde{\chi}_i^\pm$, where $i = 1, 2$. By convention, the charginos and neutralinos are labelled in ascending mass. The lightest neutralino, $\tilde{\chi}_1^0$, is generally the lightest supersymmetric particle (LSP). The production cross-section for squarks, sleptons, charginos and neutralinos is shown in Figure 1.7. In the R-parity conserving case, the LSP

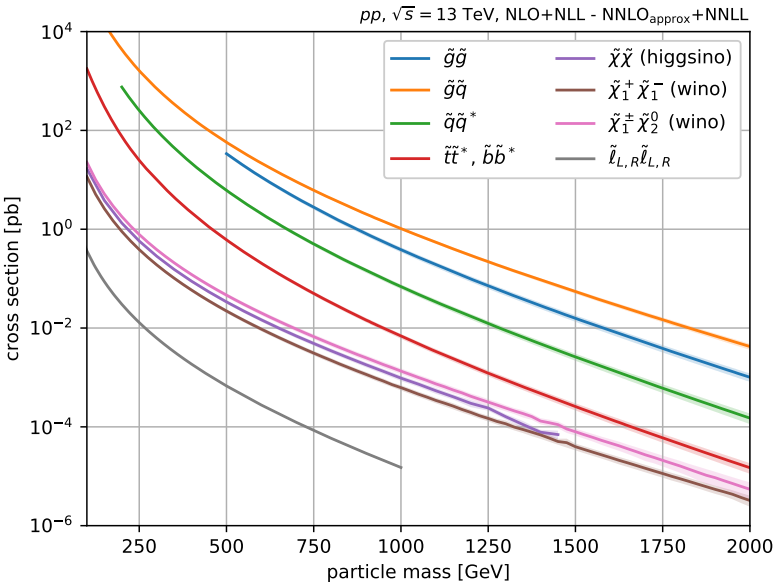


Figure 1.7: Figure showing the production cross-sections for pairs of SUSY particles at $\sqrt{s} = 13$ TeV.

is stable while the heavier charginos and neutralinos ($\tilde{\chi}_2^\pm$, $\tilde{\chi}_{3,4}^0$) can decay through a chain of decays until a final state containing LSPs and SM particles is reached. The two-body decay chains of charginos and neutralinos are shown in Figure 1.8, assuming that the diagrams containing H^0, A^0 and $H^\pm$ are disfavoured compared to diagrams with h^0 due to its lower mass, and that squarks are heavy and hence also disfavoured. In the case that the diagrams shown are kinematically-forbidden, decays can proceed via three-body decays involving SM fermions.

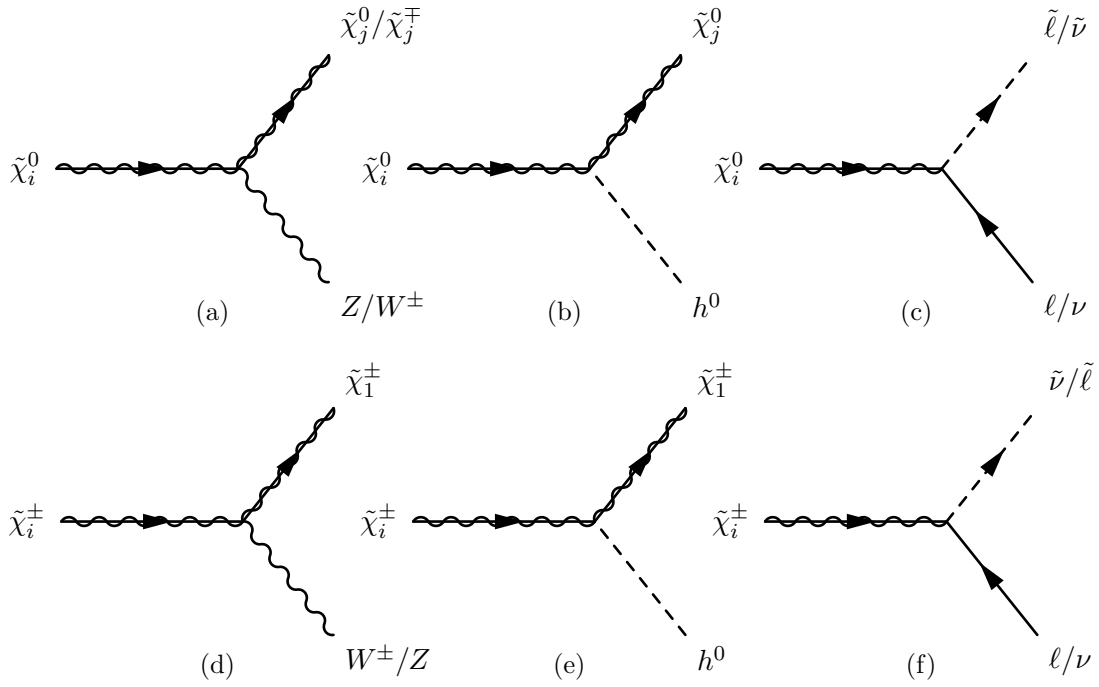


Figure 1.8: Diagrams showing the two-body decays of a given neutralino, $\tilde{\chi}_i^0$ (1.8a, 1.8b and 1.8c) and chargino, $\tilde{\chi}_i^\pm$ (1.8d, 1.8e and 1.8f).

Unification of fundamental interactions

As previously discussed, it was shown by Glashow, Salam and Weinberg that the electromagnetic and weak interactions unify above the electroweak scale, resulting in the combined electroweak interaction. It is postulated that above some grand unified theory (GUT) scale, the electromagnetic, weak and strong forces unify. However, in the SM, the evolution of the couplings of the three forces never converge. However, as described, SUSY introduces additional particles which alter the running of the coupling constants, allowing them to unify at the GUT scale. The running of the couplings are shown in Figure 1.9 for both the SM and SUSY.

Resolution to the hierarchy problem

As previously discussed, the squared-mass of the Higgs boson, m_H^2, is comprised of two components; a bare mass, $m_{H,\text{bare}}^2$, and the quantum corrections to the Higgs mass through fermion couplings, δm_H^2. The correction to the Higgs mass for a given fermion, f, is given by

$$\delta m_{H,f}^2 = \frac{|y_f|^2}{16\pi^2}\left[-2\Lambda_p^2 + 6m_f^2 \ln\left(\Lambda_p/m_f\right)\right] \ , \tag{1.2.2}$$

where, m_f is the mass of the fermion and y_f is the Yukawa coupling of that fermion to the Higgs boson. From Equation 1.2.2, it is evident that the top quark which has $y_f \approx 1$, yields

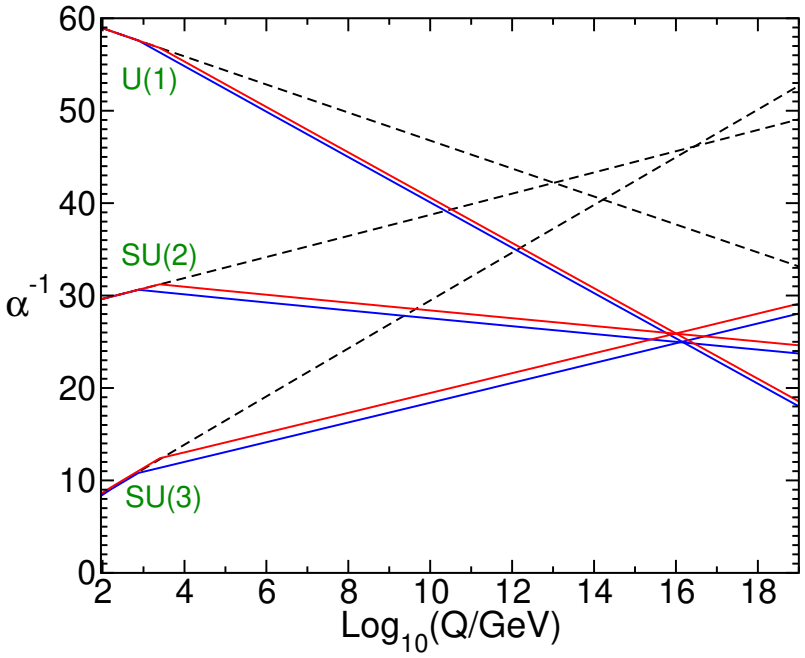


Figure 1.9: Diagram showing how the coupling constants evolve in SM-only (dashed) and SUSY (solid) scenarios. For the SUSY particles, the masses are varied from 750 GeV to 2.5 TeV.

the largest correction at around 30 orders of magnitude larger than the measured Higgs squared-mass, meaning there is either a high degree of 'fine-tuning' or there are additional quantum corrections from New Physics. SUSY introduces two scalars for each SM fermion (one for each of the left- and right-handed fields). The correction to the Higgs mass for a scalar, S is given by

$$\delta m_{H,f}^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_p^2 - 2m_S^2 \ln\left(\Lambda_p/m_S\right)\right] \ , \tag{1.2.3}$$

where m_S is the mass of the scalar and $\lambda_S = |y_f^2|$. Assuming that the scalars have the same masses as their SM counterparts, the quadratic component of the corrections to the Higgs mass exactly cancel. However, if the superpartners and their SM particles have identical masses, observations of SUSY particles would have been made long before the LHC. At the time of writing however, no observation of a SUSY particle has been made. In light of this, it can be inferred that SUSY must be a spontaneously broken symmetry, in a similar manner to the electroweak symmetry of the SM. The exact mechanism through which this occurs is not yet known. However, it is possible to break the SUSY symmetry 'by hand' by introducing additional terms in the Lagrangian, as follows:

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}} \ . \tag{1.2.4}$$

In Equation 1.2.4, $\mathcal{L}_{\text{SUSY}}$ contains all of the Yukawa and gauge interactions, while $\mathcal{L}_{\text{soft}}$ contains coupling parameters with positive mass and gauge parameters. The preservation of the unbroken SUSY is very important for the resolution of the hierarchy problem, as described in the following section.

R-parity

SUSY introduces an additional quantum number, known as R-parity, R_p. The R-parity is constructed using the spin (S), the baryon number (B) and lepton number (L) of the incoming and outgoing particles from an interaction vertex. The R-parity is defined as:

$$R_P = (-1)^{3(B-L)+2S} \, . \tag{1.2.5}$$

Using Equation 1.2.5, it can be seen that the SM particles all have $R_P = +1$, while the SUSY particles have $R_P = -1$. In SUSY models which conserve R-parity, processes which violate lepton and baryon number conservation are disallowed, which prevents the rapid decay of protons to leptons + mesons, a result which is consistent with experimental observation. The conservation of R-parity has three important consequences:

- The LSP is required to be stable. In models where the LSP is neutral and weakly-interacting with the SM, it becomes an excellent candidate for Dark Matter.
- Each SUSY particle must decay via a chain containing an odd number of LSPs, mostly just one.
- SUSY particles are pair-produced in pp collisions.

Extended Higgs sector and Dark Matter

In addition to producing DM through the decay of SUSY particles, models with extended Higgs sectors can provide a way in which DM can couple to the SM, through the addition of a mediator.

Chapter 2

The LHC and the ATLAS Experiment

The physics analyses detailed in the forthcoming chapters made use of data collected by the ATLAS detector, one of the four main experiments situated around the Large Hadron Collider (LHC) at the European Organisation for Nuclear Research (CERN). CERN is home to the the largest particle physics experiment to date, the LHC. Lying beneath the Franco-Swiss border at a depth of around 100m, it spans a cirumference of almost 27km. The LHC is a hadron-hadron collider, accelerating counter-circulating beams of protons (or heavy-ions for a short period every year) to provide collisions at four interactions points around the LHC; ATLAS, CMS, LHCb and ALICE. This thesis focuses entirely on proton-proton collisions recorded by the ATLAS experiment.

2.1 The LHC accelerator

The protons for the LHC beams are provided by a bottle of hydrogen gas. Protons are isolated by applying a strong electric field to hydrogen atoms, stripping away the electrons. These isolated protons are then transfered to a linear accelerator (LINAC2), where they undergo the initial acceleration to 50 MeV. Proton acceleration is achieved using Radio Frequency (RF) cavities. In the Proton Synchrotron (PS), the proton beam is divided into proton packets known as 'bunches', spaced by 25ns intervals, with each bunch containing around $\mathcal{O}(10^{11})$ protons. The 50 MeV proton bunches are further accelerated to an energy of 1.4 GeV by the Proton Synchrotron Booster (PSB) and subsequently to an energy of 25 GeV by the PS. The Super Proton Synchrotron (SPS) is the penultimate stage of acceleration, accelerating the 25 GeV proton bunches to an energy of 450 GeV. These proton bunches are injected into the LHC to produce two counter-circulating beams and are accelerated from 450 GeV to 6.5 TeV by RF cavities.

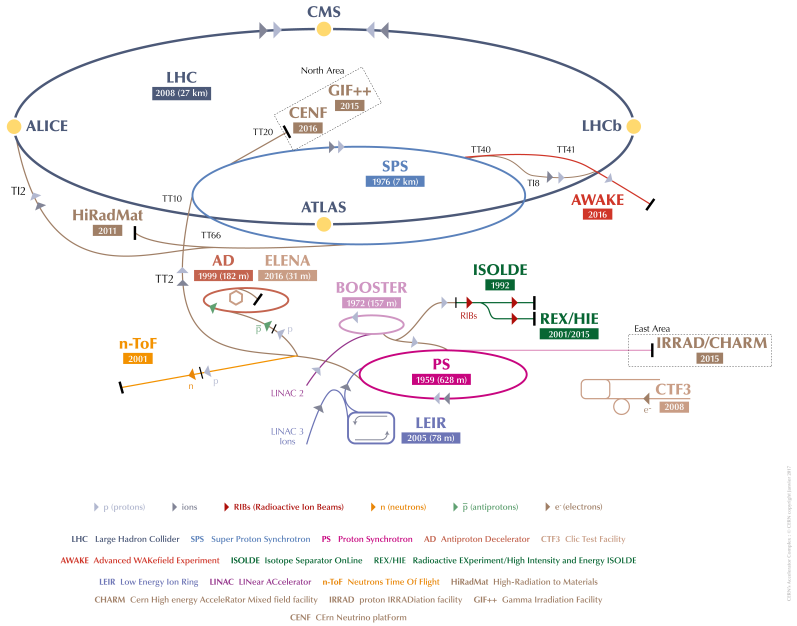


Figure 2.1: A diagram of the CERN accelerator complex. Of importance to the LHC accelerator are LINAC2, PSB, PS, SPS and LHC. [16]

2.2 Luminosity and pileup

The amount of data being delivered by LHC and recorded by its experiments is measured by the *luminosity*. The instantaneous luminosity, $\mathcal{L}$, of a beam is defined as the number of incident particles per square centimetre per second [$\mathrm{cm}^{-2}s^{-1}$]. For a circular collider, the expression for the instantaneous luminosity of two colliding beams is given by [17]:

$$\mathcal{L} = f\frac{N_p^2 n_b}{4\pi\sigma_x\sigma_y}F\ . \tag{2.2.1}$$

In Equation 2.2.1, N_p is the number of protons per bunch, n_b the number of bunches in each beam, f the frequency of bunch crossings (1/25ns = 40MHz), σ the size of the bunch at the interaction point (IP) and F a geometrical correction factor accounting for a non-zero crossing angle at the IP. The integrated luminosity (often shortened to 'luminosity'), is defined as the time-integral of the instantaneous luminosity: $L = \int \mathcal{L}dt$.

The luminosity is a measure of the total number of incident particles in a given area in a given time period and has units of an inverse area in square centimetres [cm^{-2}]. However, due to the huge number of incident particles every second, these units are rarely used; instead, integrated luminosity is often quoted in units of 'barns', where 1 barn (b) is defined as $10^{-24}\mathrm{cm}^2$. For a cross-section quoted in barns, the total number of expected

events, N_{exp}, in a dataset with integrated luminosity L and cross-section $\sigma_{pp\to X}$ is given by $N_{\text{exp}} = \sigma_{pp\to X} L$.

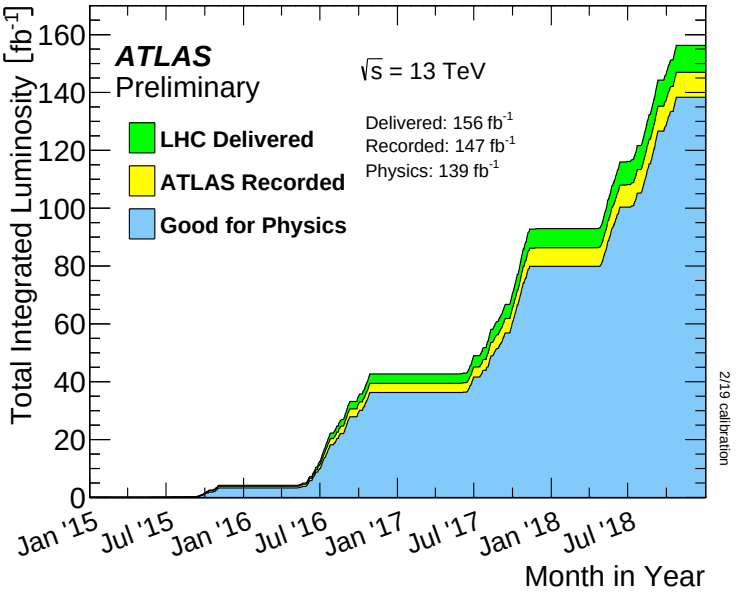


Figure 2.2: Plot showing the total integrated luminosity as a function of time during the Run-2 data-taking period. In total, the LHC delivered 156 fb^{-1} of data, with ATLAS recording 147 fb^{-1} and 139 fb^{-1} being established as suitable for physics analysis.

Due to the bunched beam structure and the intensity of the bunches, multiple inelastic proton-proton collisions are possible per bunch crossing. Pileup is an important effect in high energy physics experiments such as ATLAS, as large amounts of pileup degrade the reconstruction performance of an experiment. Pileup events can come from either the same bunch crossing, known as in-time pileup, or from the bunch crossing just before or after the bunch-crossing being considered, known as out-of-time pileup. The collision, or vertex, with at least two tracks and with the highest Σp_T^2 is usually defined as the primary vertex, or 'hard scatter', in an event. All other vertices, and the resultant final state particles, from the same bunch crossing are considered 'pileup' events. Figure 2.3 shows the pileup profile for each data-taking year for Run-2 of the LHC. The mean number of interactions per bunch-crossing is taken as the mean of the Poisson distribution of the number of interactions per bunch-crossing calculated for each bunch. It is calculated using the per-bunch luminosity, defined as:

$$\mu = \mathrm{L}_{\text{bunch}} \times \frac{\sigma_{\text{inel}}}{f_r} \,. \tag{2.2.2}$$

In Eq. 2.2.2, $\mathrm{L}_{\text{bunch}}$ is the per-bunch instantaneous luminosity, σ_{inel} is the inelastic cross-section (~ 80 mb for Run-2), and f_r is the bunch-crossing frequency.

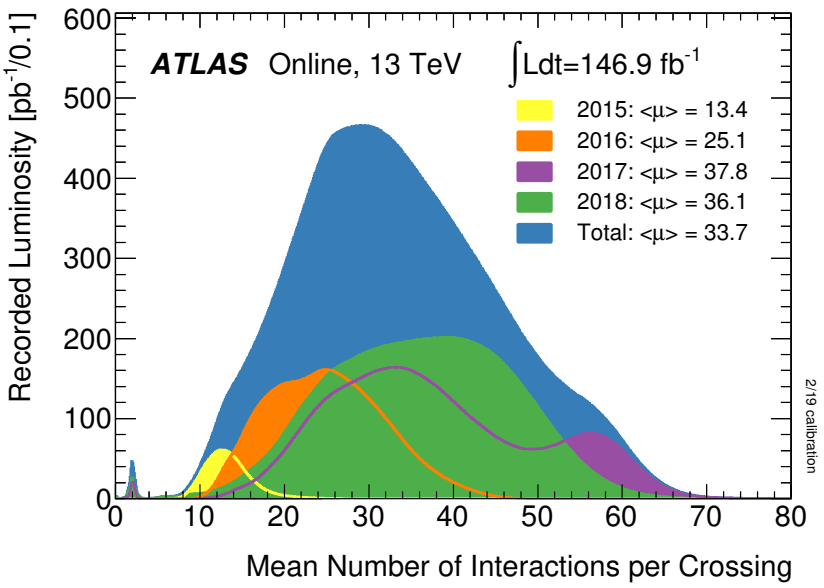


Figure 2.3: Mean number of proton-proton interactions per bunch crossing for Run-2 (2015-2018). The mean number of interactions per bunch-crossing is taken as the mean of the Poisson distribution of the number of interactions per bunch-crossing calculated for each bunch.

2.3 ATLAS overview

ATLAS, *A Toroidal LHC ApparatuS*, is one of the two general purpose detectors (GPDs) and is the largest of all of the LHC experiments, at 44m in length and 25m in width and weighing around 7000 tons. Figure 2.4 shows a schematic diagram of the ATLAS detector and its major subsystems. ATLAS is an almost hermetic detector, providing near-full 4π tracking and calorimetry through multiple detector subsystems. The ATLAS detector design was optimised for [18]:

- High-efficiency for charged particle reconstruction and identification.
- High-precision calorimetry, providing high-precision electron/photon identification and measurement along with accurate hadronic/$E_{\mathrm{T}}^{\mathrm{miss}}$ measurements.
- Precise muon momentum measurements using only the muon system, at even the highest luminosity.
- Ability to trigger on objects with low momentum.

ATLAS has four major subsystems; the Inner Detector (ID), the Electromagnetic Calorimeter (ECAL), the Hadronic Calorimeter (HCAL) and the Muon Spectrometer (MS), arranged in concentric layers about the beam pipe. ATLAS is designed to be symmetric in the forward-backward plane about the interaction point (IP), and when discussed

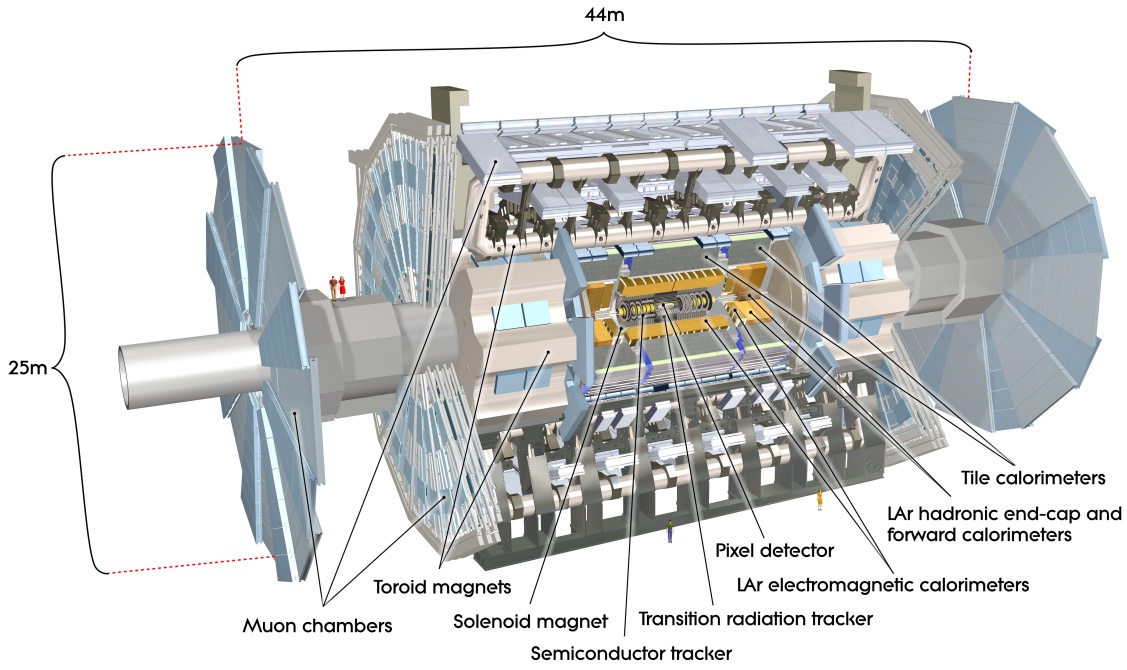


Figure 2.4: Cut-away diagram of the ATLAS detector. [19]

is often separated into three segments; the central region, the barrel region and the endcap region.

ATLAS uses a 'right-handed' coordinate system; the z-axis is defined in the beam direction, with the positive x-axis defined to point from the interaction point to the centre of the LHC and the positive y-axis being in the upwards direction. Side A of ATLAS, the side closer to Geneva Airport, is defined with positive z values, and Side C, closer to the Jura mountains, with negative z values.

The azimuthal angle, ϕ, and the polar angle, θ, are defined as the angle around the beam axis and the angle from the beam, respectively. From the polar angle, the pseudorapidity is defined as $\eta = -\ln\tan(\frac{\theta}{2})$. As the partons are highly boosted in the z-direction, and the partonic momentum fraction is not exactly known, object measurements are usually made in the plane perpendicular to the beam, the transverse plane, such as an object's transverse momentum, p_T or missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$.

2.4 Magnet system

When a charged particle of charge q moves with velocity v through a magnetic field of strength $|\vec{B}|$, the force on that particle is given by the Lorentz force,

$$\vec{F} = q\vec{v} \times \vec{B} \,, \tag{2.4.1}$$

where $\vec{v} \times \vec{B}$ denotes the cross-product of the velocity vector of the particle with the vector describing the magnetic field. Due to the presence of the a cross-product in the Lorentz force, the force experienced by the charged particle will be perpendicular to both the velocity vector and the magnetic field. The deflection of particle tracks by the magnet system enables the measurement of the momentum of an incident particle. The ATLAS magnet system is constructed from two superconducting magnet systems which enable this; a central solenoid (CS) which is surrounded by three toroid magnets. A diagram of the ATLAS magnet system is shown in Figure 2.5.

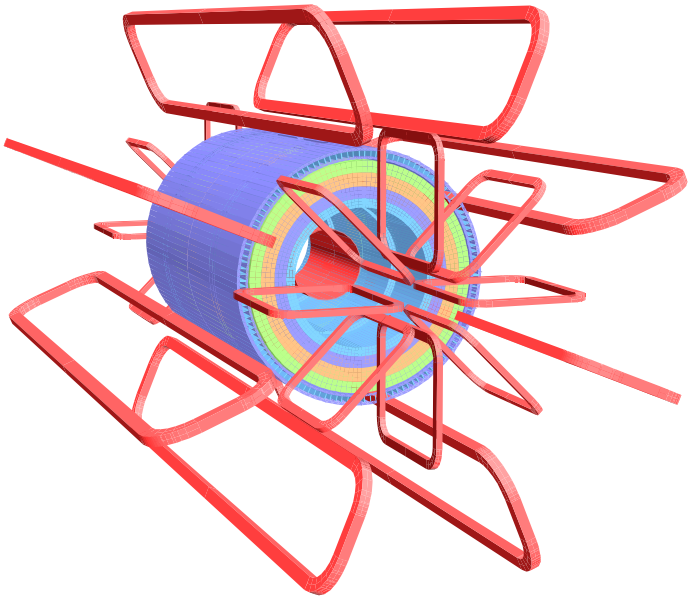


Figure 2.5: Diagram of the ATLAS magnet system, showing the barrel and end-cap toroids in red, while the CS is shown encased by calorimeter layers. [18]

The central solenoid (CS) provides a 2T magnetic field to the Inner Detector, peaking at around 2.6T at the magnet itself. The barrel toroid (BT) and endcap toroid (ECT) provides a magnetic field between 0.5-1 T for the muon spectrometer, peaking at 3.9T and 4.1T, respectively. Superconductivity of the magnet system is achieved using liquid helium cooled to around 4.5 K.

2.5 Inner Detector

The ATLAS Inner Detector (ID), shown in Fig. 2.6, is the innermost layer of the ATLAS detector. It is designed to provide high-precision tracking, vertex information, and for the identification of particles. The ID has 3 components; the Pixel detector, the Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT). The Pixel detector and SCT use silicon pixels and strips, respectively, while the latter uses straw detectors to provide tracking information. The ID is immersed in a 2T magnetic field provided by the CS, allowing precise momentum measurement through the measurement of track deflection. The Pixel and SCT detectors provide coverage in $|\eta| < 2.5$, while the TRT provides further tracking information up to $|\eta| < 2.0$.

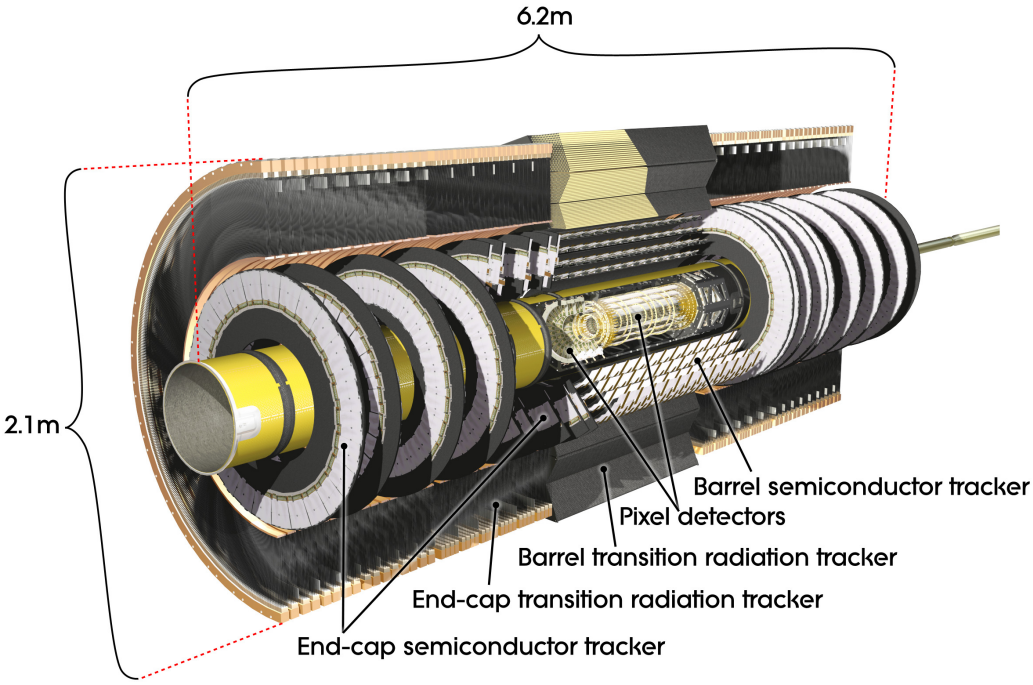


Figure 2.6: Cut-away diagram of the ATLAS Inner Detector. [19]

Pixel Detector

The Pixel Detector uses silicon semiconductor pixels to register particle hits from incident particles. Materials which exhibit semiconductive behaviour, such as silicon, have conductivity between that of an insulator and a conductor. The silicon pixels used in the Pixel Detector are constructed using a p-n junction. A p-n junction is the boundary between two silicon semiconductors which are doped to have excess of electrons (n-doped), or an excess of holes (p-doped). By applying a forward bias voltage to the pixel, the free electrons and holes can migrate across the junction through the depletion region. Conversely, when applying a reverse bias, the free electrons and holes are pulled away from the junction. When

Detector component	Modules	Pixel pitch [μm]	Resolution [μm]
Pixel Detector			
IBL	224	50 x 250	8 ($R-\phi$), 40 (z)
Barrel	1456	50 x 400	10 ($R-\phi$), 115 (z)
End-caps	288	50 x 400	10 ($R-\phi$), 115 (R)
SCT			
Barrel	2112	80	17 ($R-\phi$), 580 (z)
End-caps	1976	80	17 ($R-\phi$), 580 (R)

Table 2.1: Table giving a summary of the Pixel Detector and SCT module sizes and resolutions. [18, 20]

a sufficient reverse bias is applied, the pixel becomes fully depleted, meaning there is no current flow between the p-doped and n-doped side of the pixel. When a charged particle passes through a pixel, electrons and holes are liberated which drift to the electrodes of the pixel due to applied bias voltage, resulting in the collection of charge which is read out as a particle hit.

The Pixel Detector is the ID subsystem closest to the IP. It provides high-granularity, high-precision measurements of charged particles at radii as little as 3.3cm from the beam pipe. The system itself is constructed from three barrel modules at radii of $\sim$ 4cm, $\sim$ 10cm and $\sim$ 13cm, with five disks on either side at radii between 11cm and 20cm. The Pixel detector has 1744 silicon pixel sensors with a nominal pixel pitch of $50 \times 400\mu\text{m}^2$ and a thickness of 250μm. The barrel layers of the Pixel Detector contain 67 million readout channels, and the disks contain a further 13 million.

Since the initial detector design, a fourth layer has been added to the Pixel Detector, at a radius of $\sim$ 3cm. This layer is known as the 'Insertable B-Layer', or IBL. The IBL was developed and installed to improve the tracking and b-tagging performance of the ID in instantaneous luminosity conditions which exceeded the initial Pixel Detector design. The Pixel Detector's efficiency was expected to degrade due to the additional pileup produced by the higher-than-design instantaneous luminosity, but the inclusion of the IBL helped to combat this efficiency degradation while also providing an improvement to the impact parameter resolution. The pixel sensors used in the IBL have a pitch of $50 \times 250\mu\text{m}^2$. Table 2.1 summarises the semiconductor modules used in both the Pixel Detector and SCT.

Semiconductor Tracker

The SCT surrounds the Pixel detector, using detection techniques similar to that previously described for the Pixel detector. The SCT provides up to eight precision measurements

per track, aiding in high-precision measurement of charged particle momentum, as well as contributing to the measurement of the impact parameter and vertex position. The SCT is constructed from eight layers of silicon microstrip detectors, consisting of 4088 modules. The eight layers of barrel SCT modules have a total of 2112 microstrip modules with 80μm pitch, at radii between 30cm and 52cm. The SCT provides spatial resolution of 16μm in Rϕ and 580μm in z, allowing for tracks to be distinguished if they are separated by $\sim$ 200μm.

Transition Radiation Tracker

The TRT is the outermost layer of the ID, sitting at radii between 554mm $< r <$ 1106mm. The TRT is a straw-tube detector, utilising drift tube detectors to provide upto 36 additional measurements of each track. The drift tubes in the TRT are constructed from Kapton tubes, each of 4mm diamater, with a gold-plated tungsten wire in the centre of each drift tube with a diameter of 31 μm. The wire at the centre of each tube is at ground potential, while the wall of the tubes are at -1.5 kV. The tubes are filled with a mixture of xenon (70%), carbon dioxide (27%) and oxygen (3%). When a charged particle passes through a straw tube, electrons from the gas are liberated through ionisation processes. These electrons then drift toward the wire in the centre of the straw tube. The current flow created by the free electrons is registered as a particle hit. In total, the barrel TRT contains $\sim$ 50000 straws, while the end-caps contain 320000. Polymer fibres and foils fill the gaps between the straws in the barrel and endcap, respectively. The interface between the straws and the polymers used to fill the gaps can cause highly-relativistic particles to emit transition radiation. The probability of the emission of transition radiation depends upon the relativistic factor $\gamma = E/m$, and is hence strongest for lighter particles. Particle identification using transition radiation is performed to distinguish electrons from pions.

2.6 Calorimetry

The calorimeters in the ATLAS detector are designed to accurately measure the energy of incident particles. The calorimeter system can be separated into the Electromagnetic calorimeter (ECAL), the Hadronic calorimeter and the Forward Calorimeter (FCal) systems, all of which are sampling calorimeters. The ECAL is designed to measure the energies of incident electrons and photons, as well as any electromagnetically-interacting components of jets. The Hadronic Calorimeter is designed for measuring the energy of strongly-interacting objects, namely jets.

The ATLAS calorimeter systems use alternating layers of absorber material and active detector material. When a particle enters the absorber material of a calorimeter, a cascade of particle decays is initiated, known as a shower. Particles which interact via the EM interaction produce EM showers, in which photons pair-produce electrons and positrons,

both of which undergo Bremsstrahlung radiation of photons. Particles which interact via the strong force produce much more complex showers. Particle-nucleus interactions in the HCAL can produce additional hadrons, such as pions. Charged hadrons, will lose energy when traversing the absorber material through ionisation processes. In addition, neutral pions in their decay to two photons, $\pi^0 \to \gamma\gamma$, can induce an EM shower component.

The depth of the ATLAS calorimeters is optimised to contain EM showers within the ECAL and hadronic showers in the HCAL, hence minimising punch-through into the next detector layer. The radiation length, X_0, of a material is the mean length over which an electron will lose all but $1/e$ of its initial energy, while the interaction length of a material, λ, characterises the mean distance a hadron will travel through a material before undergoing a nuclear interaction. The depth of each calorimeter is optimised to fully contain their respective shower type.

The two calorimeter systems provide full coverage in ϕ and calorimetry in the range $|\eta| < 4.9$. Complete ϕ coverage is needed for precise reconstruction of $E_{\mathrm{T}}^{\mathrm{miss}}$, a principle component of searches using ATLAS. A diagram of the ATLAS calorimeter system is shown in Fig. 2.7.

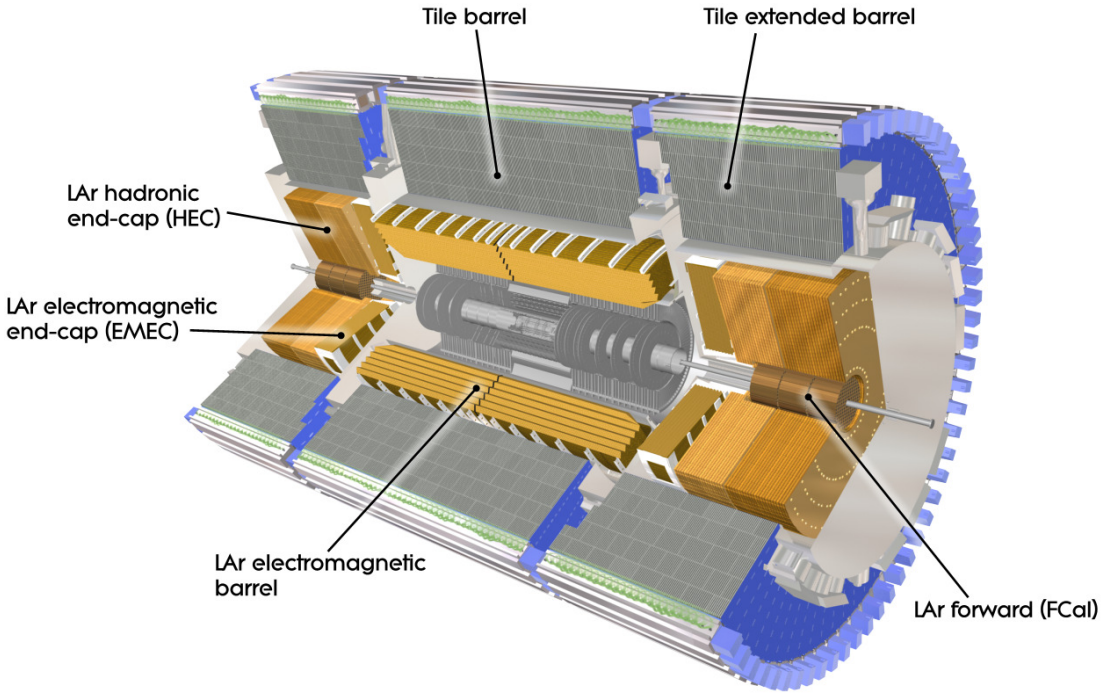


Figure 2.7: Cut-away diagram of the ATLAS Electromagnetic and Hadronic calorimeters. [19]

Electromagnetic Calorimeter

The ECAL is comprised of the barrel EM calorimeter which covers the pseudorapidity range $|\eta| < 1.475$ and the two end-cap EM calorimeters, each covering $1.375 < |\eta| < 3.2$. The ECAL is constructed using lead as the absorber material, while using liquid argon (LAr) as the active material. When a charged particle passes through the LAr, ionisation occurs, producing electrons. Using similar principles to the drift tubes described for the TRT, an electric field is applied, such that the ionisation electrons drift toward the electrodes. The thickness of the ECAL ranges from 22-38 radiation lengths to fully contain EM showers.

Hadronic Calorimeter

The Hadronic Calorimeter, as shown in Figure 2.7, can also be separated into several sub-systems; the scintilating-tile calorimeter (HCAL), the LAr hadronic endcap calorimeter (HEC) and the forward calorimeter (FCal).

The tile calorimeter covers the range $|\eta| < 1.7$ and sits adjacent to the the ECAL. It is separated into a central barrel and two extended barrels. Each of these barrels is comprised of 64 modules with a size of $\Delta\phi \sim 0.1$ made of steel plate absorbers and scintillating plastic tiles. When charged particles pass through these scintillating tiles, photons with UV wavelengths are produced from polystyrene. These photons are absorbed and re-emitted as visible-light photons by wavelength-shifting fluors. This light is collected by fibres and is transmitted to photomultiplier tubes (PMTs).

The HEC is similar in construction to the ECAL, using LAr as the active medium, but instead of using lead as an absorber, uses copper. The HEC provides coverage in the range $1.5 < |\eta| < 3.2$. The HEC is constructed with two sets of wheels, one per end-cap, HEC1 and HEC2, respectively. Each of the four HEC wheels (a front and back wheel per end-cap) is constructed from 32 identical wedge-shaped modules.

Forward Calorimeter

The FCal provides coverage over $3.1 < |\eta| < 4.9$. Each FCal is split into three components; FCal1 is an electromagnetic module, while FCal2 and FCal3 are hadronic modules. FCal1 uses copper as an absorber material, whereas FCal2 and FCal3 use tungsten. All FCal modules use LAr as the active component.

2.7 Muon System

The Muon Spectrometer (MS) is the outermost part of ATLAS. Muons pass through the entire ATLAS detector before decaying, with a flight distance of $c\tau \sim 700$m, and do not

undergo EM showering in the same way as electrons or photons. The main purpose of the MS is to detect charged particles escaping the calorimeter systems and measure their momentum within the $|\eta| < 2.7$ range, also providing triggering capabilities within $|\eta| < 2.4$.

The MS comprises four subsystems; Monitored Drift-Tube (MDT) chambers, Cathode Strip Chambers (CSCs), Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs). The 1150 MDTs cover the $|\eta| < 2.7$ range with a resolution of 35μm per chamber. At the innermost layer of the MS, the MDTs are replaced by CSCs in the range $2.0 < |\eta| < 2.7$ due to their higher rate capability. The CSCs have a z resolution of 40μm, and a ϕ resolution of 5mm.

The triggering capability of the MS is provided by the RPCs and TGCs in the barrel and endcaps, respectively. The RPCs have a spacial resolution in z (ϕ) of 10mm (10mm) and a temporal resolution of 1.5ns, while the TGCs have a spacial resolution in R (ϕ) of 2-6mm (3-7mm) and a temporal resolution of 4ns.

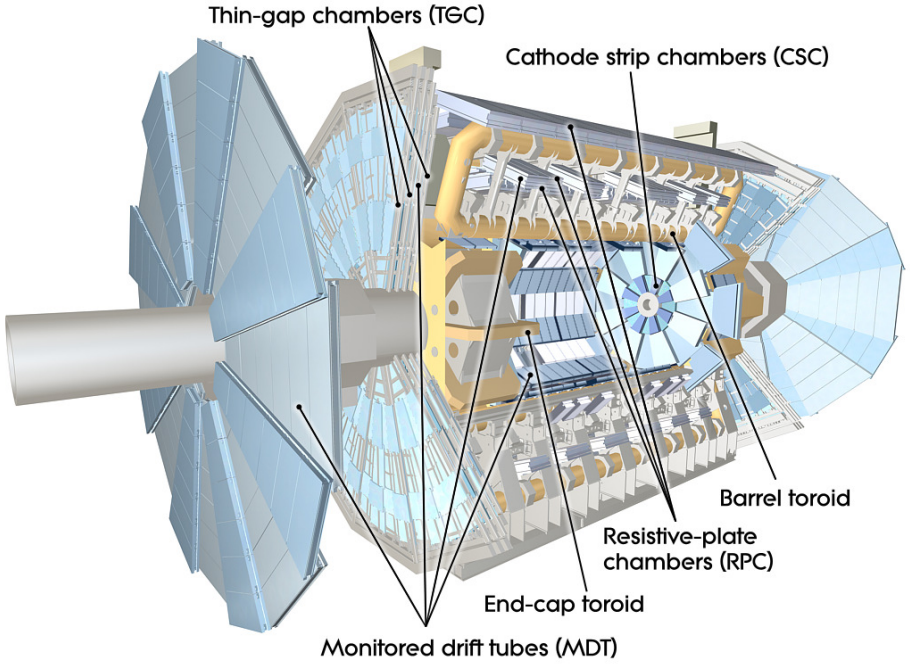


Figure 2.8: Cut-away diagram of the ATLAS Muon Spectrometer. [19]

2.8 ATLAS Trigger System

The temporal bunch-separation provided by LHC in Run-2 is 25ns, meaning the proton-proton bunch-crossing frequency is 40 MHz. However, saving all of these events to disk is not possible due to the huge bandwidth and storage required, with each event requir-

ing around 1.3MB of storage. Therefore, events which are deemed 'uninteresting' are not stored. To achieve this, ATLAS employs a trigger system, which makes rapid decisions on whether to save the event to disk.

The ATLAS trigger system consists of the Level-1 (L1) hardware trigger and the software-based High-Level trigger (HLT). The L1 trigger uses coarse detector information from the calorimeters and MS to identify muons, electrons, photons, jets and hadronically-decaying taus with high transverse momentum, or events containing large amounts of total transverse energy and $E_{\mathrm{T}}^{\mathrm{miss}}$. The L1 trigger uses a subset of the ATLAS subsystems; the RPC and TGC are used for muons, while the calorimeter subsystems are used for EM clusters, jets, tau leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$ and large total tranverse energy. The L1 trigger operates at a maximum of 100kHz, with each decision being made in less than 2.5μs. Regions-of-interest (RoIs) are identified by the L1 trigger; these are regions in η and ϕ containing potential physics objects. These RoIs are used as seeds in the HLT.

The software based HLT takes the full event information from the L1 RoI seeds and investigates the RoIs. The event reconstruction used in the HLT is then used to accept or reject the event. The HLT further reduces the event rate to around 1.5kHz. A functional diagram of the trigger and data acquisition system is shown in Figure 2.9.

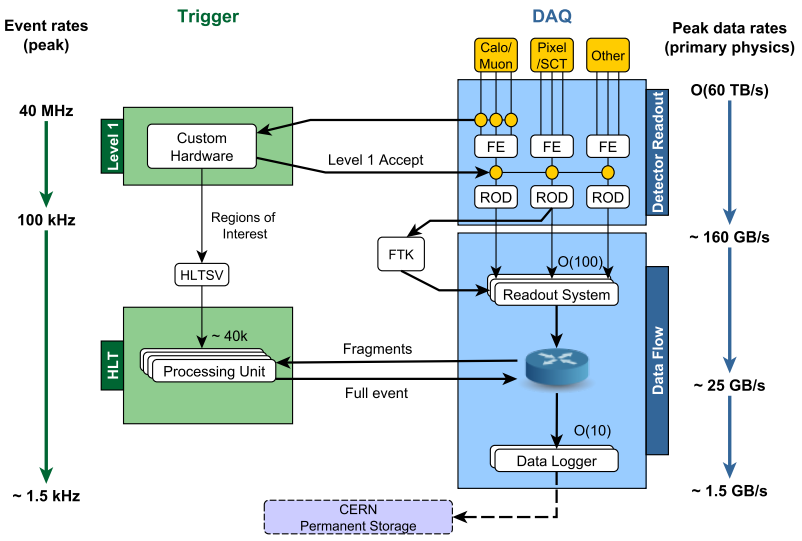


Figure 2.9: A functional diagram of the ATLAS trigger and data acquisition system (TDAQ). The diagram shows the flow of data from detector readout, through the L1 trigger, to the HLT and eventual disk storage. The steps following this are discussed in Chapter 4.

Chapter 3

Data and Monte Carlo samples

This Chapter discusses the datasets used in the physics analyses detailed in Chapter 6 and 7, discussing the running conditions during data-taking and the triggers used to collect the data. Along with the datasets, the procedure through which Monte Carlo (MC) samples are generated is discussed, along with a brief discussion of the generators used in the analyses in the subsequent Chapters. Finally, this Chapter discusses the complexities of simulating the single top Wt-channel process due to interference with the $t\bar{t}$ process, an effect which can generate uncertainties of $\mathcal{O}(100\%)$ on the predictions of the single top background. Studies are performed to quantify the impact of the interference in the analyses detailed in Chapters 6 and 7, where the single top process is one of the major SM backgrounds.

3.1 Datasets

The physics analyses discussed in Chapters 6 and 7 used data collected during the Run-2 data-taking period (2015-2018) in pp collisions at $\sqrt{s} = 13$ TeV, accumulating 139fb^{-1} ($\pm 1.7\%$) of collision data in total. The physics analysis described in Chapter 6 used a subset of this data, taken in 2015-2016, with a total integrated luminosity of 36.1fb^{-1} ($\pm 2.1\%$). The primary measurement of the luminosity is recorded by the LUCID detector [21], which sits 17m from the interaction point on both the A and C side of ATLAS and measures the visible number of interactions per bunch-crossing. In Run-2, proton bunches are separated by 25ns, compared to 50ns in Run-1. Each proton bunch contains $\mathcal{O}(10^{11})$ protons and as such each bunch-crossing can have multiple inelastic pp interactions. Each proton-proton collision which produces at least two tracks with $p_T > 0.4$ GeV is classed as an interaction point, being referred to as a collision vertex. The collision vertex in each bunch-crossing which has the highest $\sum p_T^2$ of tracks is identified as the Primary Vertex (PV). All other vertices are considered a background to the primary vertex, known as 'pileup', which is described in further detail in Chapter 2. Pileup at the LHC is one of the greatest challenges for accurate track reconstruction, and will continue to be so in the HL-LHC phase of operation. The pileup conditions for Run-2 are shown in Figure 2.3.

Triggers

As previously discussed, it is not possible to save all events to disk due to the huge bandwidth required to readout, partially-reconstruct and trigger on events in real-time. Events passing a L1 trigger are selected and processed with the HLT, and thus events are collected at a reduced rate of approximately 1.5kHz. This reduced event rate integrated over Run-2 still provides a huge dataset in which to search for evidence of New Physics. For the New Physics models considered in this Thesis, a common signature of the production of BSM particles is the presence of large amounts of $E_{\mathrm{T}}^{\mathrm{miss}}$ in an event, due to the presence of non-SM particles in the final state. The analyses described in Chapter 6 and 7 both used $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers to select events in data which may contain non-SM particles. Table 3.1 shows the list of triggers used in each data-taking year for the analysis detailed in Chapters 6 and 7.

Year	Triggers
2015	`HLT_xe70_mht`
2016	`HLT_xe90_mht_L1XE50`
	`HLT_xe100_mht_L1XE50`
	`HLT_xe110_mht_L1XE50`
2017	`HLT_xe90_pufit_L1XE50`
	`HLT_xe110_pufit_L1XE55`
2018	`HLT_xe110_pufit_xe70_L1XE50`
	`HLT_xe120_pufit_L1XE50`
	`HLT_xe110_pufit_xe65_L1XE50`
	`HLT_xe110_pufit_xe70_L1XE50`

Table 3.1: A table showing the list of $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers used in the analyses described in Chapter 6 and Chapter 7.

The names of the triggers listed in Table 3.1 hold information of the trigger thresholds and algorithms used. The inclusion of `L1XE50`, for example, indicates that the event must pass the L1 trigger threshold which is specified by `XE50`, representing a trigger threshold of 50 GeV. The `HLT` prefix indicates that an event must pass the HLT trigger where the trigger threshold is specified in the form `xe110`, where the 110 after `xe` indicates the HLT trigger threshold is 110 GeV. The HLT algorithm used to calculate the $E_{\mathrm{T}}^{\mathrm{miss}}$, which are described in detail in [21], are denoted by `mht` or `pufit` where the former calculates the $E_{\mathrm{T}}^{\mathrm{miss}}$ based on jets while the latter uses a pileup-suppression technique to estimate the $E_{\mathrm{T}}^{\mathrm{miss}}$. The cell-based algorithm. which uses the uncalibrated energy deposits in the calorimeter to estimate the $E_{\mathrm{T}}^{\mathrm{miss}}$, omits any additional designation from the trigger name. Where two separate `xe` thresholds are present in a name, the former refers to the threshold for the `pufit` algorithm, while the latter refers to the threshold for the cell-based algorithm.

Due to the evolving conditions throughout each year of data-taking, there are frequently multiple triggers listed per year. These are 'period-dependent' triggers, and as instantaneous luminosities grow and the pileup profile shifts to higher $\langle\mu\rangle$, as defined in Chapter 2, so too do the trigger thresholds. The efficiency of the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger is determined by,

$$\epsilon(\mathcal{S}_i) = \frac{N\left(\mathcal{S}_i|\text{trigger}\right)}{N\left(\mathcal{S}_i\right)} \,, \tag{3.1.1}$$

where $\mathcal{S}_i$ denotes some event selection criteria, the denominator is the number of events passing the selection $\mathcal{S}_i$ and the numerator is the subset of those events which also pass the trigger requirements. When performing searches for New Physics processes which have low rates compared to the SM backgrounds, a high-trigger efficiency is required to retain as many candidate signal events as possible. The efficiency of the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger in the years 2015-2018 is shown in Figure 3.1 as measured in $Z \to \mu\mu$ events.

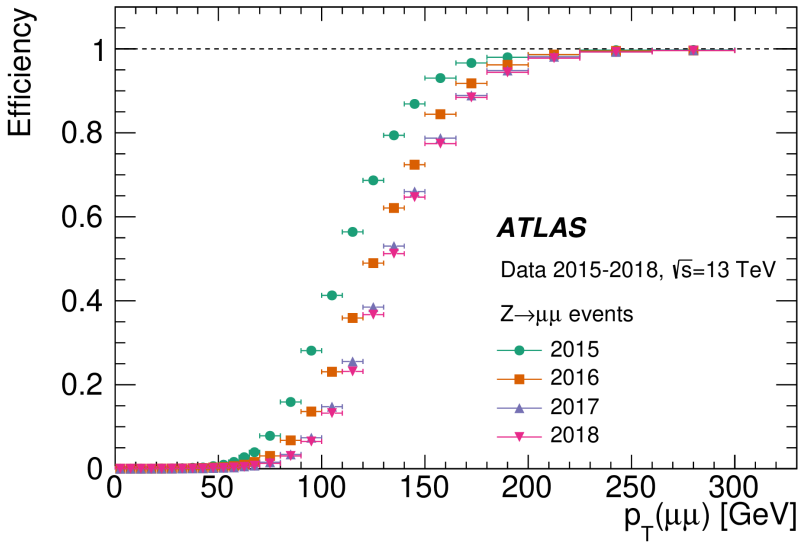


Figure 3.1: A plot showing the efficiency of the lowest unprescaled $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger from 2015-2018, known as the 'turn-on' curve.

In order to ensure the trigger accepts events in data and from all MC processes with equal efficiency, the analyses detailed in Chapters 6 and 7 require all events are on the trigger 'plateau', the region of constant efficiency, shown in the 'turn-on' curve in Figure 3.1 at values above 200 GeV.

3.2 Monte Carlo simulation

An accurate, precise simulation procedure is required in order to make meaningful comparisons between SM predictions and the data collected by ATLAS. This is known as Monte Carlo (MC) simulation. A generic MC simulation works by randomly sampling a process-specific distribution many times to obtain a sample of predictions for that process. In the context of this Thesis, MC simulation is used to produce simulated samples of SM and BSM processes, produced at the LHC and subsequently detected by ATLAS. This simulation process is known as *event generation*.

MC event generation

Typically, the procedure for simulating physical processes through MC simulation involves: *matrix element calculations (ME)*, *parton showering (PS)*, *hadronisation* and simulation of the *underlying event* (UE). This chain is represented in Figure 3.2.

The composite nature of protons is described by the parton model of hadrons, which describes the proton content as quarks and gluons collectively known as partons. In pp scattering events, the factorisation theorem enables the interaction of the protons to be *factorised* into terms describing the long-distance 'hard-scatter' interaction between two partons from the incoming protons and terms describing the short-distance distribution of the partons in the incident protons. The energy scale which separates the long-distance and short-distance phenomena is known as the factorisation scale, μ_F, and is introduced to remove low energy divergences from the cross-section calculation.

$$\sigma = \sum_{i,j} \overbrace{\int \mathrm{d}x_1 f_i\left(x_1, \mu^2\right) \int \mathrm{d}x_2 f_j\left(x_2, \mu^2\right)}^{\text{blah}} \underbrace{\sigma_{ij}\left(x_1, x_2, Q^2\right)}_{\text{blah}} \tag{3.2.1}$$

The incoming partons produce a PV, shown by the red circle and representing the ME calculation. The remaining partons from the incoming protons are also able to interact, producing multi-parton interactions (MPI), resulting in additional, softer particles. These softer interactions represent the UE and are shown by the additional blue partons and the purple oval. From the PV and the ME portion of the simulation, the PS is shown by the red cascade of partons being sequentially emitted. The light green ovals show the hadrons present after the PS and the subsequent green circles show the decay of these hadrons.

Each stage of the event generation procedure will be briefly discussed before summarising the MC simulations used to generate background samples used in the analyses detailed in Chapters 6 and 7. The details of the signal MC samples will be given in the relevant chapters.

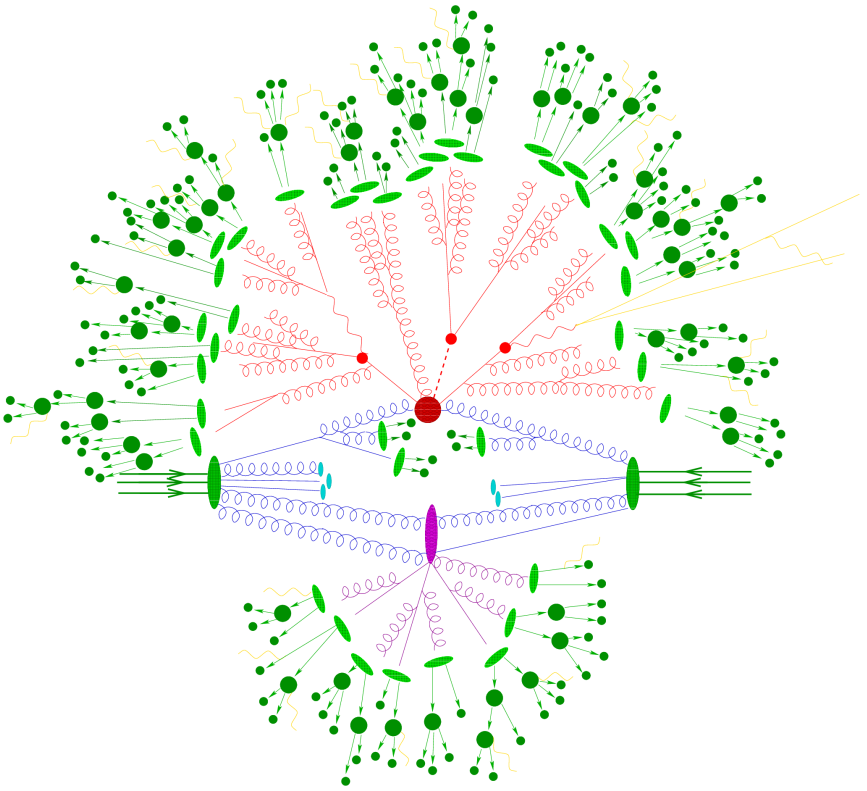


Figure 3.2: A representative diagram showing the MC simulation chain.

Hard scatter

The hard scatter calculation evaluates the process in which the incoming partons interact and undergo some transition into different final state particles, and is the highest-energy process evaluated during event generation. The hard scatter calculation is performed by evaluating the Feynman diagrams which represent the process of interest to yield the matrix element (ME). MEs can be calculated at different orders in QCD. LO MEs have two vertices, and hence the ME goes like $\mathcal{M} \propto g_s^2$, while the cross-section goes like $\sigma \propto |\mathcal{M}^2| \propto g_s^4$. Most processes relevant at the LHC are calculated at NLO, with $\mathcal{M} \propto g_s^3$. As an example, representative LO diagrams for $t\bar{t}$ are shown in Figure 3.3. The hard scatter

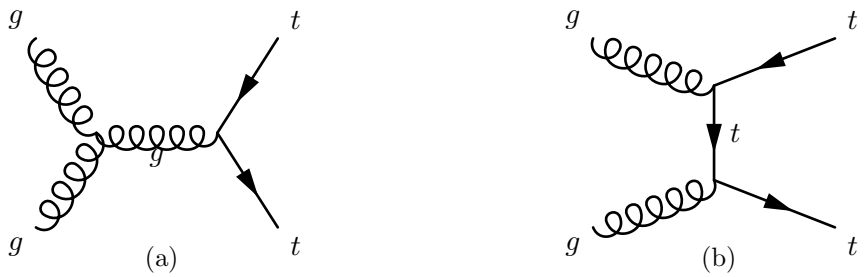


Figure 3.3: This figure shows LO Feynman diagrams for the $t\bar{t}$ process. These diagrams are also relevant for the discussion of $t\bar{t}$-Wt interference later in this Chapter.

calculation often results in unstable particles in the final state. The subsequent stages of the event generation process evolve these hard, unstable particles from the highest energy levels down to softer, stable particles.

Parton distribution functions

Due to the composite nature of protons, the collisions at the LHC are actually interactions of the partons within the proton; qq or gg, for example. Both the valence quarks (uud, for a proton) and sea quarks (virtual quark-antiquark pairs continually being created and annihilated inside the proton) contribute to the parton-parton collisions. Therefore, to accurately predict physical processes, the partons within the proton must be well-modelled, along with the fraction of the total proton momentum that each parton carries, known as the Bjorken x. Parton Distribution Functions (PDFs) predict the probabilty that a parton of a given type is present inside the proton with a given x, at a squared energy-scale Q^2. PDF sets are determined through fits to data, namely deep inelastic scattering (DIS) data, with data from ATLAS and CMS being included in the most recent global fits to data. [22]

PDFs can be calculated to differing orders in QCD, namely leading order (LO), next-to-leading order (NLO) and next-to-next-to-leading order (NNLO). The treatment of quark flavours is also a consideration when evaluating PDFs. The four-flavour scheme (4FS) and five-flavour scheme are the most common treatments of partons for PDFs. In the 4FS, b-quarks are treated as massive partons, unlike the other parton types, and the proton content is limited to gluons and the u, d, c and s quarks. In the 5FS, all partons are treated as massless and the proton can contain gluons and all quarks except the top quark. In both flavour-schemes, the b-quark is included in the final state.

Parton shower, Hadronisation and underlying event

The PS procedure evolves the hard scatter from an energy scale Q^2 down to the hadronisation scale Q_0^2, typically around the pion mass ($\sim$ 200 MeV), through sequential emissions of quarks and gluons, including soft and co-linear emissions. This procedure is repeated until all partons in the event reach the 'cut-off' point of the hadronisation scale, at around 1 GeV. This procedure takes the event from one with only a few final state particles to a complex final state with many quarks and gluons.

Considerations must be made when applying a PS algorithm to events with additional partons in the final state, such as MEs calculated at NLO. For example, an event with n-jets in the final state can be produced in two ways; by evolving an event, through soft/-colinear emission, produced at the ME-level with n partons in the final state, or by introducing an additional hard parton emission in the PS procedure to an $n-1$ parton event. The overlap between these two possibilities is treated using a matching/merging procedure.

The hadronisation procedure starts after the PS at the cut-off scale of around 1 GeV. This procedure combines the partons present after the PS into colour-neutral states, as required by QCD. There are two widely-used models of hadronisation; the Lund String model [23], and the cluster model [24]. The former treats quark-antiquark pairs as the ends of a string, with a potential energy between the quarks that is proportional to its length such that the $q\bar{q}$ pair are linearly-confined. As the distance between the $q\bar{q}$ pair increases, so too does the potential energy, until it is energetically-favourable for the string to break, forming an additional quark-antiquark pair. The cluster model uses the property of *preconfinement* in QCD, in which the partons in a shower cluster together into colourless groups. These colour-singlets follow an invariant mass distribution which is independent of the hard scatter process. Unstable hadrons are able to decay through allowed SM transitions until all particles in the final state are stable.

The underlying event refers to all partonic interactions other than the hard scatter. These interactions can arise from the partons from the incoming protons not involved in the hard scatter as well as from any additional partons radiated in the event. Additional jets can arise from the UE, although these are typically much softer than jets produced in the hard scatter.

Simulation of SM backgrounds

This section details the event generators used for simulating the SM background samples for the analyses described in the subsequent chapters. For the HL-LHC prospects study detailed in Chapter 8, the MC samples used were generated without being passed through the ATLAS detector simulation, but instead a parameterised detector simulation for the HL-LHC ATLAS detector. This is explained in more detail in Chapter 8 and Appendix A.

Top processes

The `POWHEG` event generator is used to simulate the hard scatter for both $t\bar{t}$ and single top (t, s and Wt-channels) processes, where the ME is evaluated at NLO accuracy in QCD. The ME generation is interfaced to `PYTHIA` for parton showering. The analysis detailed in Chapter 6 uses `PYTHIA6` for PS, while the analysis detailed in Chapter 7 uses a more recent version, `PYTHIA8`. The `CT10` PDF set is used and the samples are normalised to the next-to-next-to-leading order and next-to-next-to-leading logarithmic (NNLL) cross-sections. Simulating Wt-channel processes at NLO requires additional consideration due to interference with the $t\bar{t}$ process, which will be discussed later in this chapter.

The $t\bar{t}V$ ($V = W, Z$) and tWZ processes are simulated using the `aMC@NLO` generator to evaluate the ME at NLO accuracy, while tZ MEs are calculated by `MadGraph`. All setups

are interfaced to PYTHIA8 for PS and use the NNPDF2.3LO PDF set. $t\bar{t}V$ and tWZ backgrounds are normalised to NLO predictions, while the tZ background is normalised to LO.

The $t\bar{t}H$ process is also simulated using aMC@NLO for the ME calculation, but is interfaced to HERWIG for PS. The CTEQ6L1 PDF set is used and the background is normalised to the NLO prediction.

Vector boson process

V+jets ($V = W, Z$) processes are simulated using SHERPA2.2.1 with upto 2 jets at NLO accuracy and upto 4 jets at LO. The ME calculation is interfaced to the SHERPA PS algorithm. The NNPDFNNLO PDF set is used for generation, with the samples normalised to the NNLO prediction.

Diboson processes (VV with $V = W, Z$) are simulated using the SHERPA2.2.1 generator for the ME calculation, performed at NLO accuracy for upto 1 jet and LO for upto 3 jets. The NNPDFNNLO PDF set is used for the event generation, and the predictions are normalised to NLO predictions.

3.3 Simulating Wt-channel single top at NLO

In many search channels, the $t\bar{t}$ and single top backgrounds are among the most prominent backgrounds due to their relatively high cross-sections and complex, irreducible, multi-particle final states which can exactly mimic the final states of many New Physics processes. Making predictions of these SM processes at the highest precision possible therefore enables searches for New Physics to set the best possible statistical limits, but particular care must be taken to treat the interference of $t\bar{t}$ and Wt-channel single top correctly. Both the $t\bar{t}$ and single top backgrounds are simulated at NLO and normalised to NNLO cross-section calculations. At LO, Wt-channel single top will almost always have a final state containing WWb, distinct from the $WWbb$ final state in $t\bar{t}$ production, as seen by comparing Figure 3.3 and 3.4.

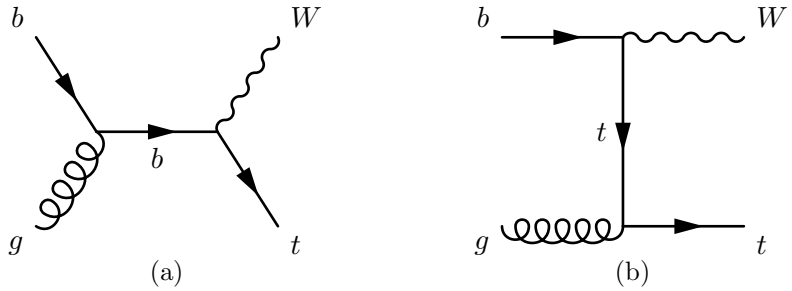


Figure 3.4: Feynman diagrams showing Wt-channel production at LO, where the final state is distinct from the $t\bar{t}$ process.

However, simulating Wt-channel single top at NLO introduces diagrams which have a $WWbb$ final state, meaning the $t\bar{t}$ and Wt processes can interfere. NLO diagrams for Wt-channel single top are shown in Figure 3.5. When considering the $WWbb$ final state, the

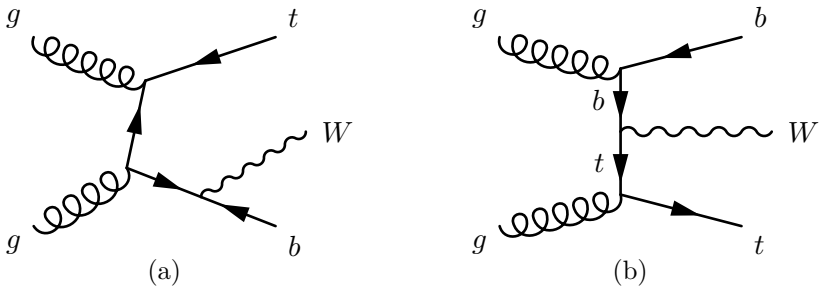


Figure 3.5: Feynman diagrams showing Wt-channel production at NLO. These diagrams interfere with the $t\bar{t}$ process due to their identical final state. The Wt diagrams at NLO can be separated into the number of resonant top quarks present. Figure 3.5b shows a 'single-resonance' diagram, while Figure 3.5a shows a 'double-resonance' diagram.

amplitude can be written as the sum of contributions from the $t\bar{t}$ and Wt process. As there is overlap between the two processes, diagrams with two resonant (on-shell) top quarks, known as 'double-resonance' diagrams are attributed to the $t\bar{t}$ process, while diagrams with a single resonant (on-shell) top quark are referred to as 'single-resonance' diagrams and are attributed to Wt production. The amplitude can be written as:

$$\mathcal{A}_{WWbb} = \mathcal{A}_{DR} + \mathcal{A}_{SR} \tag{3.3.1}$$

where DR and SR correspond to the double-resonant and single-resonant components, respectively. The production goes with the square of the amplitude, which is where the interference terms arise:

$$|\mathcal{A}_{WWbb}|^2 = |\mathcal{A}_{1R}|^2 + |\mathcal{A}_{2R}|^2 + 2\mathcal{R}e(\mathcal{A}^*_{1R}\mathcal{A}_{2R}) \tag{3.3.2}$$

The first term on the right side is the contribution from double-resonance diagrams, the second term from single-resonance diagrams and the last term from interference between the two sets of diagrams. All top-pair MC samples used in this Thesis are generated using only the diagrams which contribute to $\mathcal{A}_{2R}$, having exactly two resonant top quarks. The nominal choice for modelling the single top Wt-channel process uses only the diagrams which contribute to $\mathcal{A}_{1R}$, neglecting diagrams with two resonant top quarks and hence removing any interference from the cross-section. However, it is important to assess the size and impact of the interference, especially in the extreme regions of phase space often covered by searches for New Physics, as the interference becomes important in regions where $m_{Wb} \sim m_t$. Two schemes for assessing the impact of the $t\bar{t}$-Wt interference are

used in this Thesis and will be discussed in the following subsections.

Diagram removal vs. diagram subtraction

As previously mentioned, the nominal method of simulating the Wt-channel single top process is to remove all diagrams with two resonant top quarks; this method is known as the *diagram removal* (DR) scheme [25]. An alternate scheme of generation, known as *diagram subtraction* (DS) [25] is defined such that single- and double-resonance diagrams are included, and the contribution from the double resonance diagrams is subtracted at the cross-section level as follows:

$$d\sigma^{DS} = d\sigma^{WWbb} - d\sigma^{subt} \tag{3.3.3}$$

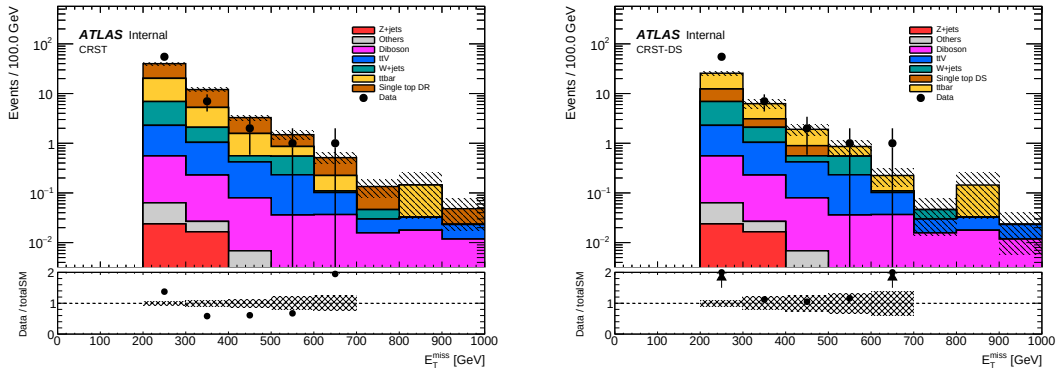
In Equation 3.3.3, the first term on the right is proportional to Equation 3.3.2. In the analysis detailed in Chapter 6, the differences between the DR and DS schemes for generating the Wt process were found to $\mathcal{O}(100\%)$ in *all* analysis regions due to poor MC statistics in the DS sample. The difference in the DR and DS prediction in the single top CR of this analysis (described in Table 3.3) is shown in Table 3.2. As seen in Table 3.2, the

Process	MC prediction
$t\bar{t}$	17.72 ± 1.85
Single top (DR)	28.54 ± 1.72
Single top (DS)	6.61 ± 1.9
W+jets	5.80 ± 1.32
$t\bar{t}V$	3.14 ± 0.27
Diboson	0.84 ± 0.26
Small backgrounds	0.10 ± 0.05
Total MC (DR)	56.1 ± 2.9
Total MC (DS)	34.2 ± 3.0
Data	64

Table 3.2: A table showing the estimated yields from MC of SM processes in CRST. The data-MC discrepancy is much larger with the DS Wt prediction and the region becomes dominated by top-pair production.

DR and DS schemes make drastically different predictions for the single top yield in this region. In the case of the DS prediction, the single top purity in this region is no longer dominant, becoming subdominant to top-pair production. The data-MC difference of the two predictions can be seen in Figure 3.6, showing the $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions in CRST with both the DR and DS Wt samples.

Due to the large differences in the DR and DS predictions observed, an alternate scheme for estimating the interference uncertainty was used, and is detailed in the next section.



(a) (b)

Figure 3.6: Plots showing the E_T^{miss} distribution in the single top CR of the analysis detailed in Chapter **??**. Figure 3.6a shows the data-MC comparison using the DR single top sample, while Figure 3.6b shows the same comparison using the DS single top sample.

In the analysis detailed in Chapter 7, studies were performed to find a kinematic region to use as a CR for the Wt background, a relatively minor but irreducible background to the signal. Using a similar method to those used to optimise the signal selection, as described in Section 5.3, a region where the single top background was dominant was found using a combination of an adapted random grid search and a genetic algorithm. The kinematic selections for this region are summarised in Table 3.3.

Variable	Selection
am_{T2}	> 220 GeV
m_W^{had}	< 60 GeV
m_T	$\in [40, 100]$ GeV
p_T^{b2}	> 50
$\Delta\phi(\ell, E_T^{miss})$	< 0.5

Table 3.3: This table shows the selections used, in addition to the preselection cuts listed in Table 7.2, for the single top CR study for the analysis detailed in Chapter 7.

The estimated yields and purity obtained using these selections are given in Table 3.4. The distributions of the subleading b-jet p_T and $\Delta\phi(\ell, E_T^{miss})$, used to define and isolate the Wt background, is shown in Figure 3.7 for both the DR and DS schemes. Due to the extreme differences in predictions between the DR and DS schemes, and the relatively small contribution of Wt in the SR, this CR was not used in the final analysis, detailed in Chapter 7.

Process	MC prediction
$t\bar{t}$	135.52 ± 1.87
Single top (DR)	253.39 ± 8.04
Single top (DS)	39.08 ± 3.2
W+jets	134.75 ± 4.35
$t\bar{t}V$	3.41 ± 0.25
Z+jets	0.83 ± 0.14
Diboson	7.66 ± 0.85
ttH	1.37 ± 0.1
tWZ	0.02 ± 0.03
Purity (DR)	47.2%
Purity (DS)	12.1%
Data	363

Table 3.4: This table shows the predicted background yields for all SM backgrounds considered, along with the purity of single top for both the DR and DS schemes, and finally the observed data in this region. As can be seen there is a huge discrepancy between the two Wt generation schemes, with the data being enveloped by the two predictions.

Coherent simulation of $WWbb$ final state

An alternative to the comparison of the DR and DS schemes was also used in the analysis detailed in Chapter 6. This approach uses three sets of complementary MC samples, 'singleres', 'doubleres' and 'sum', to simulate the $WWbb$ final state, generated at LO and at truth-level. The 'singleres' samples include diagrams with exactly one resonant top quark, corresponding to $\mathcal{A}_{1R}$, the 'doubleres' samples include diagrams with two resonant top quarks, corrsponding to $\mathcal{A}_{2R}$ and the 'sum' samples include all diagrams with at least one resonant top quark, corresponding to $\mathcal{A}_{WWbb}$. As these samples are generated at LO, these samples are used only as a comparison between themselves, and not the nominal DR prediction, generated at NLO. Figure 3.8 shows comparisons of the shape and normalisation of the m_T and m_{CT} distributions for the three samples at preselection level and in the single top CR.

Using the three sets of samples, it is possible to directly estimate the impact of the interference, by comparing the MC prediction for the Wt process with and without interference effects. The estimated yield for the Wt process with the interference effects, N_{MC}^{Wt+int}, is given by:

$$N_{MC}^{Wt+int} = N_{MC}^{sum} - N_{MC}^{doubleres} \tag{3.3.4}$$

This estimated yield can be directly compared with the prediction for the Wt process, N_{MC}^{Wt}. Table 3.5 shows a comparison of the nominal Wt DR prediction compared with the DS prediction, along with the predictions for the dedicated $WWbb$ samples, and finally

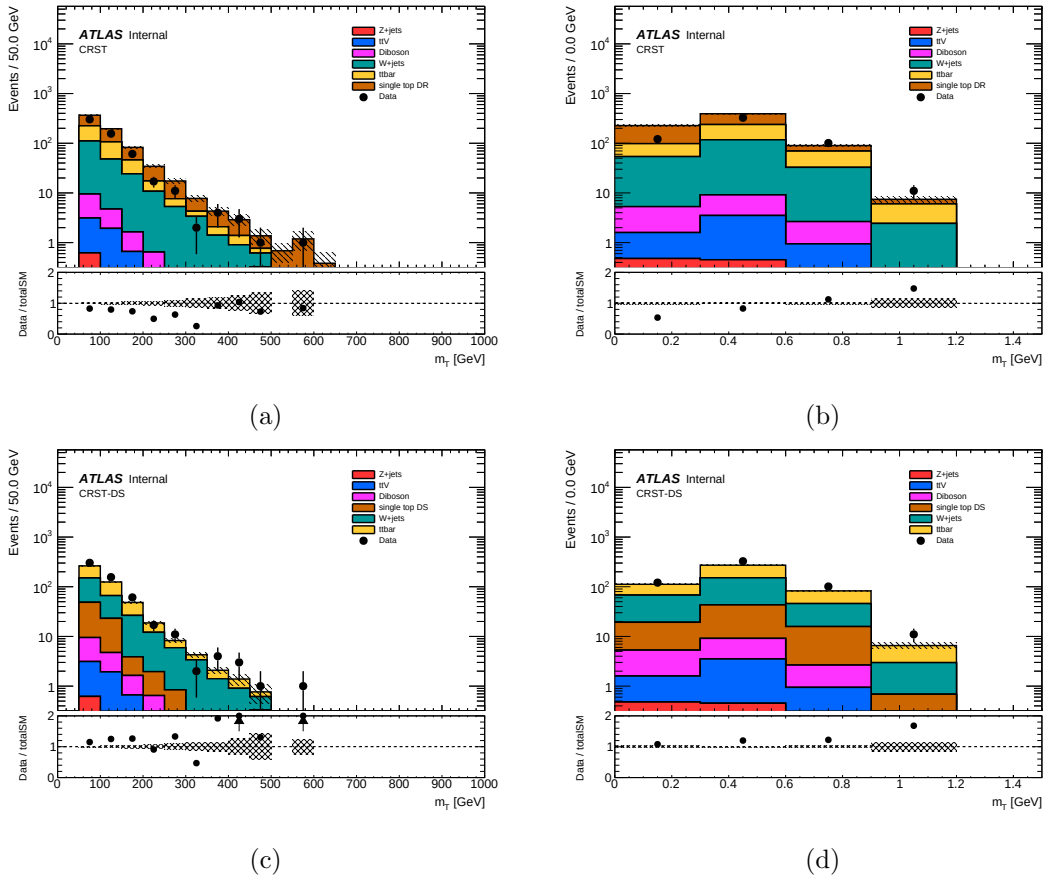


Figure 3.7: This figure compares the two key variables used to isolate the Wt background for the DR and DS schemes. Large differences are observed between the DR and DS schemes, with the observed data being enveloped by the two.

showing the predicted Wt yield including interference effects, calculated using Equation 3.3.4. It is

Region	TRLM	TRMM	TRHM	STCR
Single top (DR)	22.81 ± 3.12	19.67 ± 1.51	53.11 ± 2.51	28.54 ± 1.72
Single top (DS)	12.25 ± 2.17	13.22 ± 2.16	28.43 ± 2.97	6.61 ± 1.9
WWbb singleres	6.68 ± 0.05	8.62 ± 0.06	21.38 ± 0.1	23.44 ± 0.11
WWbb doubleres	23.28 ± 0.38	80.73 ± 0.48	598.7 ± 1.29	22.26 ± 0.3
WWbb sum	25.37 ± 0.4	84.94 ± 0.5	610.37 ± 1.34	29.97 ± 0.34
WWbb singleres + interference	2.09 ± 0.55	4.21 ± 0.69	11.67 ± 1.86	7.71 ± 0.45

Table 3.5: This table shows a comparison of the nominal DR Wt prediction with the DS prediction, and the predictions of the three sets of $WWbb$ samples. The value quoted for the $WWbb$ singleres + interference prediction is calculated using Equation 3.3.4. The DR and DS predictions both use samples reconstructed with the full ATLAS detector simulation, while the $WWbb$ samples are generated at truth-level.

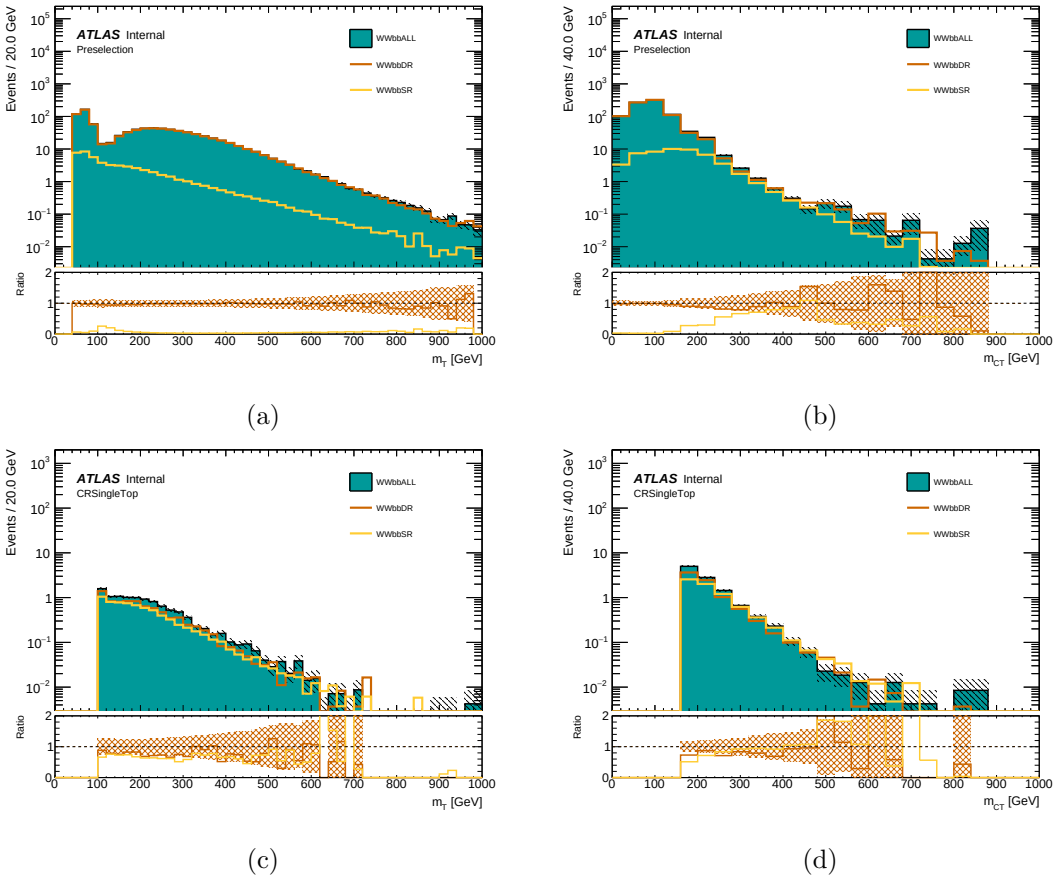


Figure 3.8: This figure shows the difference in shape and normalisation of for the $WWbb$ singleres, doubleres and sum samples. The ratio in the bottom panel shows the ratio of the singleres and doubleres to the sum, while the hatched error bar shows the sum in quadrature of the MC statistical uncertainty of the sum and doubleres sample. This error is equivalent to the statistical uncertainty on the estimate of the Wt singleres + interference.

The uncertainties derived using these samples are detailed in Section **??**.

Chapter 4

Object reconstruction

Particles produced in the pp collisions inside ATLAS can interact with the detector subsystems, as described in Chapter 2, with each type of particle leaving a unique signature. The combination of the tracking and calorimetry information enables the reconstruction of the underlying physics of an event. When combining this information, particles are referred to as physics 'objects', with the objects of interest to this Thesis being leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. This Chapter begins by giving an overview of the different signatures of each particle type, before summarising the reconstruction techniques for each object.

4.1 Reconstruction overview

The interaction of particles with the detector subsystems is determined by several factors. Firstly, charged particles create small electrial signals when passing through the tracking layers of the detector due to ionisation effects, whereas neutral particles pass through the tracking layers without leaving a signature. Secondly, the particle type will determine the type of particle shower that occurs when entering the calorimeters, with electrons and photons depositing almost all of their energy in the ECAL, and particles which interact via the strong interaction depositing energy in the HCAL. Finally, the presence of particles which do not interact with the detector subsystems, namely neutrinos and any massive, weakly-interacting new particles produced in the event, can be inferred from the total transverse momentum imbalance of the system, the $E_{\mathrm{T}}^{\mathrm{miss}}$. This is defined as the magnitude of the negative vector sum of all of the visible particles measured by ATLAS in an event. Figure 4.1 shows a representative diagram of the signatures of various particle types which are reconstructed within ATLAS.

By introducing loose requirements on the combination of the tracking and calorimetry information, 'baseline' objects are defined, placing requirements on the p_{T}, η and isolation of the object. Particle signatures in the same region of the detector can be reconstructed into multiple objects simultaneously, and thus to circumvent double counting a procedure

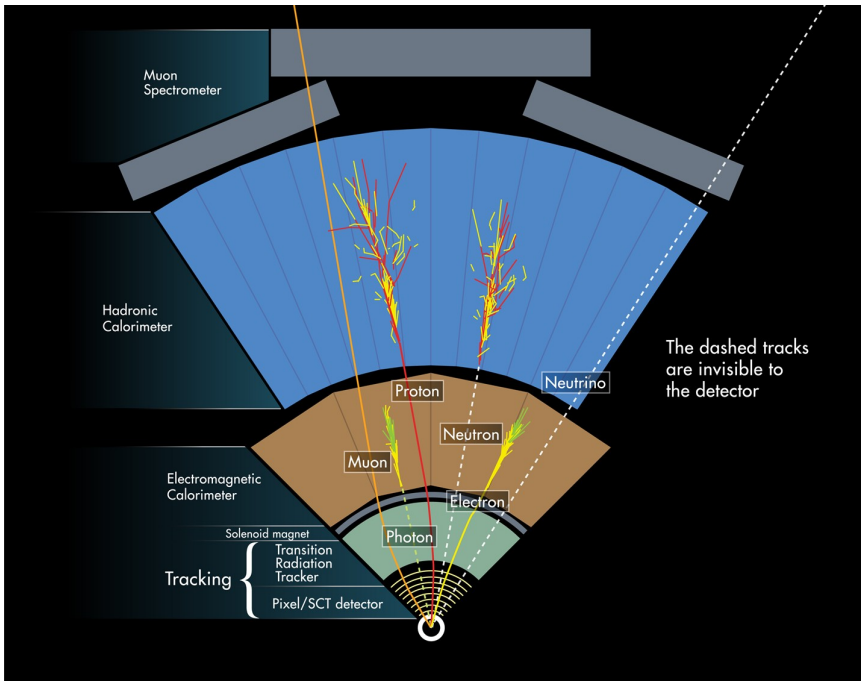


Figure 4.1: This diagram shows the various signatures left by different particles in the ATLAS detector. Solid lines represent a signature left in the corresponding detector subsystem, while dashed lines show the particle did not interact with that detector subsystem. [26]

is defined to remove overlap between objects, described later in this Chapter. Finally, a tighter set of requirements is placed upon the objects on a per-analysis basis, known as 'signal' requirements, which define the objects ultimately used in a specific analysis.

4.2 Leptons

The signals of interest in the analyses detailed in Chapters 6 and 7 have a single, charged lepton in the final state, which is required to be either an electron or muon. In both cases, this lepton originates from the decay of a W boson to $\ell\nu$. This Section will describe the reconstruction of electrons and muons, as well as briefly discussing the reconstruction of photons and tau leptons.

Electrons and photons

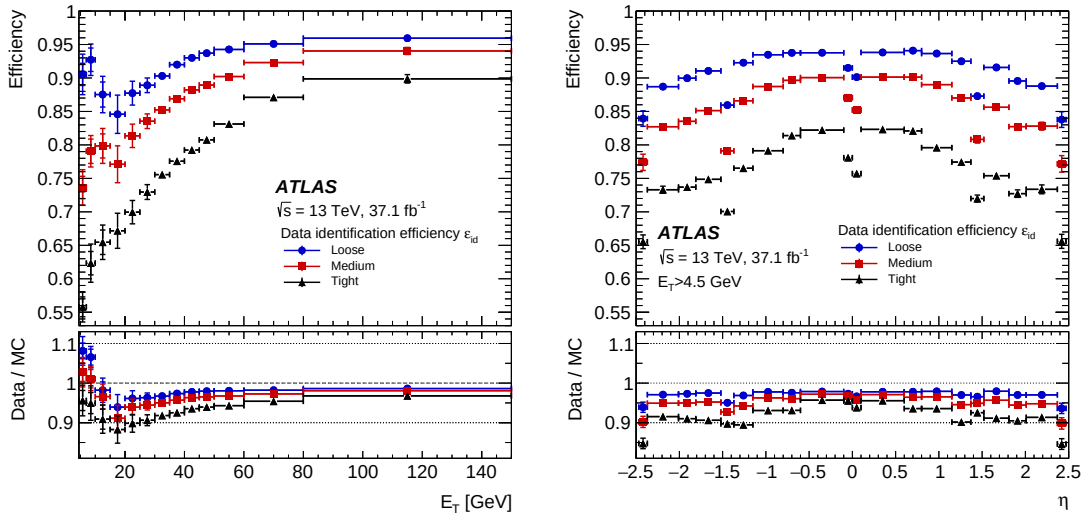
The reconstruction of electrons and photons use information from the ID and ECAL. While electrons interact with both subsystems, photons leave no hits in the ID, with their only signature being an EM shower in the ECAL. However, photons can undergo a conversion to an electron-positron pair when they interact with detector material, and hence the reconstruction of electrons and photons proceeds in the same way. Both electrons and photons are reconstructed within the range $|\eta| < 2.47$, such that full tracking coverage from the

pixel detector and SCT are available [27,28]. For the first step of electron/γ reconstruction, the ECAL is segmented into a 200×256 grid in η, ϕ. The energy deposited by an electron or photon at a given η, ϕ grid point is evaluated by summing the energy deposits in all layers of the ECAL, forming a 'tower'. A sliding-window of size 3×5 towers is scanned over the η, ϕ grid; any point of the grid where the summed E_{T} of all towers within the window exceeds 2.5 GeV is used as a seed for the clustering step. In order to identify the ECAL cluster as an electron or photon, the seed clusters are loosely matched to tracks in the ID. Tracks are extrapolated from the ID to the middle layer of the ECAL, with any track satisfying $\Delta\eta < 0.05$ and $-0.10 < \Delta\phi < 0.05$ considered as matched to the seed cluster. Seed clusters with at least one matched track are electron candidates while seed clusters with 0 matched tracks are photon candidates. Finally, the reconstructed energy of the candidate is determined by extending the window around the seed cluster to a size of 3×7 towers for $|\eta| < 1.37$ and 5×5 for $1.52 < |\eta| < 2.47$ and summing the energy deposits within the extended window.

Identification algorithms are applied to electron and photon candidates in order to quantify the quality of reconstruction and evaluate any potential misidentification. Photons radiated by electrons through Bremmstrahlung can produce electron-positron pairs, which subsequently interact with the detector material, providing a background to the prompt electron from the PV. Electron identification is performed in the region $|\eta| < 2.47$ using a likelihood discriminant, which takes as inputs tracking and calorimetry information, as well as quantities constructed from a combination of both tracking and calorimetry information. Photon identification is performed using selections on calorimeter quantities, such as quantities related to the shape of the EM shower in the ECAL, as described in [28].

In order to be applicable to a range of analyses, each with various electron selection efficiency and background rejection requirements, three working points are defined. The working points, Loose, Medium and Tight, have efficiencies of 93%, 88% and 80% for a prompt electron with $E_{\mathrm{T}} = 40$ GeV, respectively. The efficiencies of the three working points is shown as a function of electron E_{T} and η in Figure 4.2.

A characteristic signature of the prompt production of electrons is that there is relatively little activity surrounding the particle when compared to the semileptonic decay of heavy-flavour quarks, from misidentification or from photon conversion. The *isolation* of an electron can be exploited as a tool for rejecting such backgrounds. Two sets of isolation variables are defined, track-based and calorimeter-based, to evaluate how much activity surrounds an electron. Nine electron isolation working points are defined, to enable a balance of signal electron efficiency and background rejection to be achieved by analyses [27].



(a) (b)

Figure 4.2: Plots showing the electron identification efficiencies for the Loose, Medium and Tight working points, measured in $Z \to ee$ events [27], as a function of electron p_{T} (4.2a) and η (4.2b).

Muons

Muons are identified using inputs from the ID and MS, with additional information being provided by the calorimeters. The ID provides tracking information in the range $|\eta| < 2.5$, while the MS provides tracking information in the range $|\eta| < 2.7$. Muon reconstruction proceeds independently in the ID and MS; in the ID, tracks are built using information from the IBL, Pixel detector, SCT and TRT, in the same way as for all charged particles. Muon reconstruction in the MS proceeds by first searching for hit patterns in the individual MS cells, known as segments, and then fitting segments together from different layers to form track candidates. There are four types of reconstructed muon in ATLAS; *Combined (CB)*, *Segment-tagged (ST)*, *Calorimeter-tagged (CT)* and *Extrapolated (ME)* muons. Combined muons use hits in both the ID and MS detectors to build muon tracks, typically taking an 'outside-in' approach by starting reconstruction in the MS and matching the track candidate to a track in the ID.

Similarly to electrons, working points are defined for muon identification, enabling analyses to find an optimum balance of muon selection efficiency and background rejection. There are four muon ID working points defined; Loose, Medium, Tight and High-p_{T}, determining the quality of a muon reconstruction based upon the q/p significance and ρ' as well as the normalised χ^2 of the combined track fit. The q/p significance is defined as the absolute value of the difference between the measured charge-to-momentum ratio in the ID and MS, divided by the quadratic sum of the uncertainties on the measurements, while ρ' is defined

as the absolute value of the difference in the measured p_{T} in the ID and MS, divided by the p_{T} of the combined track [29]. The muon reconstruction efficiency as a function of the η is shown in Figure 4.3 for each of the muon identification working points. Muons originating

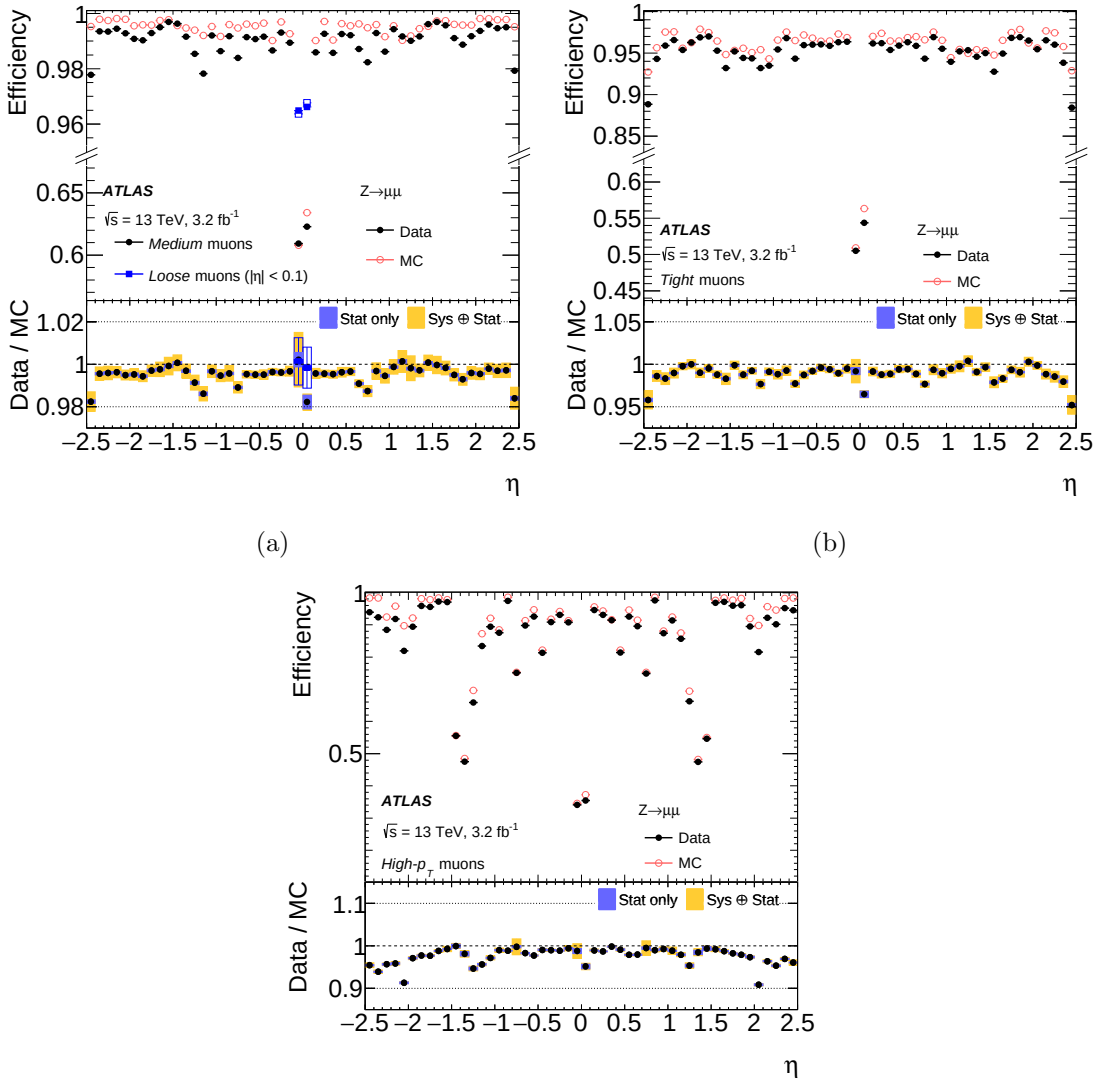
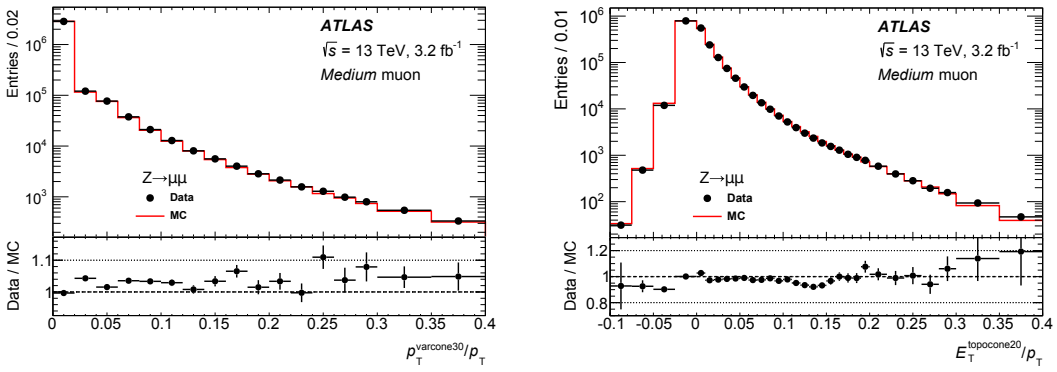


Figure 4.3: Plots showing the muon reconstruction efficiencies for the Loose and Medium (4.3a), Tight (4.3b) and High-p_{T} (4.3c) working points. All efficiencies are measured in $Z \to \mu\mu$ events.

from heavy particles such as the W boson are often well separated from any surrounding particles. Requiring that there is no surrounding activity from a muon, known as the isolation criteria, can be extremely useful for rejecting backgrounds such as QCD. Two muon isolation variables, one track-based and one calorimeter-based, are used to evaluate if a muon is isolated. The distributions of the track- and calorimeter-based isolation variables can be seen in Figure 4.4. Seven muon isolation working points are defined to enable



(a) (b)

Figure 4.4: Plots showing the distribution of the muon track-based (4.4a) and calorimeter-based (4.4b) for muons identified in $Z \to \mu\mu$ events with the Medium working point.

analyses to select an appropriate level of isolation for the signal under investiagation. The explicit definitions of the muon isolation working points is given in [29].

Taus

Taus, the heaviest of the charged leptons, can decay either leptonically ($\tau \to \ell\,\nu_\ell\,\nu_\tau$, $\ell = e, \mu$) or hadronically ($\tau \to$ hadrons ν_τ). The case with a leptonically-decaying tau, denoted by τ_{lep}, is simply reconstructed as either an electron or muon, with the neutrinos contributing to the real component of the $E_{\mathrm{T}}^{\mathrm{miss}}$. However, there is a dedicated reconstruction and identification flow for hadronically-decaying taus, denoted by τ_{had}. τ_{had} candidates are seeded from jets (the reconstruction of which is detailed later in this Chapter), which proceeds by matching tracks with $p_{\mathrm{T}} > 1$ GeV which lie within $\Delta R < 0.2$ of a seed jet to a collision vertex. Tau identification is then performed using a BDT, trained to reject QCD backgrounds, using tracking information and the calorimeter clustering information used to reconstruct jets.

4.3 Jets

When proton bunches cross inside ATLAS, the environment is extremely dense with quarks and gluons. Strong interactions between partons in the incoming bunches of protons can result in the ejection of quarks and gluons in the transverse plane. The outgoing quarks and gluons evolve through a sequence of hadronisation, gluon splittings and radiations, as described in Section **??** into a complex, highly-collimated collection of particles known as *jets*. The parton-dense environment of each bunch-crossing means pp collision events usually have numerous jets which can be from the hard scatter event, the proton remnants, or from pileup events. Jets provide an experimental tool for studying the strong interactions

of the hard scatter, and are extremely important in the analyses presented in Chapters 6 and 7, with both signal processes containing jets originating from the presence of b-quarks.

For the analyses detailed in Chapters 6 and 7, jet reconstruction begins by first clustering calorimeter cells which are topologically-connected in 3-dimensions, known as 'topoclusters' [30]. The requirement of cells being topologically-connected helps minimise the misidentification of jets due to electronic noise and pileup, and makes use of the high-granularity of the ATLAS calorimeters. Each calorimeter cell is expected to have a baseline level of noise, σ_{noise}, which is defined as:

$$\sigma_{\text{noise}} = \sqrt{\left(\sigma_{\text{noise}}^{\text{electronic}}\right)^2 + \left(\sigma_{\text{noise}}^{\text{pileup}}\right)^2} \tag{4.3.1}$$

The first step in reconstructing jets using topoclusters proceeds by finding calorimeter cells where the energy deposit is $E_{\text{cell}} > 4\sigma_{\text{noise}}$. All cells with $E_{\text{cell}} > 4\sigma_{\text{noise}}$ form the seed for 'proto-clusters', the seed for the following steps of the algorithm. The clustering algorithm then proceeds by finding all cells neigbouring a seed which satisfy $E_{\text{cell}} > 2\sigma_{\text{noise}}$. Finally, the clustering algorithm stops when no neighbouring cells satisfies $E_{\text{cell}} > 2\sigma_{\text{noise}}$ but satisfy $E_{\text{cell}} > 0$. In the context of this clustering algorithm, 'neighbouring cells' can be either adjacent cells in the same layer of the calorimeter, or cells in different calorimeter layers which have some overlap in η, ϕ space. Any protocluster containing more than one local maxima, a cell which has a greater energy deposition than its surrounding cells, are separated around their respective maxima so as not to bias the jet clustering algorithm.

All topoclusters are calibrated to an appropriate energy scale, either hadronic or EM, to account for the energy losses in reconstruction. The ATLAS calorimeters are non-compensating, meaning that an incoming electron, e, and hadron, h, both of energy E, will have a ratio of measured energy $E_e/E_h > 1$. A fraction of the energy of hadronic showers goes unmeasured as it is absorbed in the binding energy of nucleons which are released as the shower evolves in the HCAL [31]. To account for this, corrections are applied to signals identified as coming from a hadronic source. Corrections are also applied to estimate the true energy lost due to the noise-suppression requirements used for forming proto-clusters, as well as corrections for energy loss in any inactive detector material in the region near to the cluster.

Jet clustering algorithms

Jet reconstruction proceeds by clustering together the topoclusters described in the previous Section into jets which are determined to have originated from the same parton. Jet clustering algorithms can be separated into cone algorithms and sequential algorithms.

Cone algorithms The first jet clustering algorithm was developed in the 1970's and used in $e^+e^- \to q\bar{q} \to 2j$ events. Events were identified as containing two jets if at least 1-ϵ of the event's total energy was contained in two cones with opening half-angle δ. The choice of the parameters ϵ and δ is almost entirely arbitrary, and hence the algorithm can reconstruct vastly different final state jets and multiplicities depending entirely upon the parameter choice. In addition, in pp collisions the concept of total energy is obfuscated by the fact that the interacting protons contain partons with only a fraction of the total proton energy, with the residual energy either forming the underlying event or escaping down the beam pipe.

Most cone algorithms reconstruct jets through an iterative procedure, hence being known as iterative cones (IC). These algorithms proceed by first selecting a seed particle, i, and summing the momenta of all particles, j, satisfying the below condition:

$$\Delta R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} < R \, . \tag{4.3.2}$$

In the equation above, R represents the jet radius, which is the modern-day equivalent of the δ parameter discussed earlier. This process is repeated, each time taking the result of the previous iteration as the new seed, until the resulting jet cone is stable. This class of algorithms are not fully specified without specifying a definition for seed particles, and without defining a procedure for removing overlap between cones. Cone algorithms are also plagued by infrared and collinear (IRC) unsafety. An infrared-safe jet clustering algorithm will reconstruct the same set of final state jets regardless of additional soft emissions in an event, while a collinear-safe jet clustering algorithm will reconstruct the same set of final state jets if a parton of energy E is replaced by two collinear partons whose summed energy is equal to E. Most IC jet clustering algorithms use the hardest particle in an event as the seed which can violate collinear safety if the hardest particle in the event is replaced by two collinear particles. In this case, the hardest particle in the event may change, meaning the reconstructed final state jets may also change.

Sequential algorithms Sequential jet clustering algorithms work in a similar, iterative manner as for IC algorithms, except using a 'bottom-up' approach to the clustering. The first use of a sequential clustering algorithm was also in the context of electron-positron collisions. There are three widely-used sequential clustering algorithms today; the inclusive-k_t algorithm, the Cambridge/Aachen algorithm and the anti-k_t algorithm. All three of these algorithms can be specified by the following equations.

$$d_{ij} = \min\left(p_{\mathrm{T},i}^{2p}, p_{\mathrm{T},j}^{2p}\right) \frac{\Delta R_{ij}^2}{R^2} \tag{4.3.3}$$

$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \tag{4.3.4}$$

$$d_{iB} = p_{\mathrm{T},i}^{2p} \tag{4.3.5}$$

In Equation 4.3.3 and 4.3.5, $p_{\mathrm{T,i}}^{2p}$ and $p_{\mathrm{T,j}}^{2p}$ represent the transverse momentum of the ith and jth particle, respectively, raised to the power $2p$, where p is determined by the clustering algorithm being used. In the inclusive-k_t algorithm, the value of p is set to $+1$. This algorithm proceeds by iterating over all particles j within a radius R of i, calculating all d_{ij} and d_{iB} and finding the minimum. If $d_{ij} < d_{iB}$, the two particles are combined into a new particle and the algorithm proceeds from the start. If $d_{ij} > d_{iB}$, the particle i is determined to be a final-state jet and is removed from the list of particles, before the algorithm restarts from the beginning. Due to the construction of d_{ij} in the inclusive-k_t algorithm, an arbitrary number of particles can become final state jets, leading to extremely complex events. The anti-k_t algorithm follows the same procedure as for the inclusive-k_t algorithm, but provides resolution to this issue by setting $p = -1$ in Equation 4.3.5. Therefore, in the anti-k_t algorithm, jet clustering proceeds from hard seeds, and sequentially adds softer particles until the jet is stable and is classified as a final-state jet. In this thesis, the anti-k_t algorithm is used to clustering all jets, with the jet radius parameter R set equal to 0.4 in all analyses detailed in the subsequent Chapters.

Once jets are clustered, they must be calibrated to account for detector performance and resolution effects. The jet energy scale (JES) calibration is applied to account for the non-compensating behaviour of the ATLAS hadronic calorimeters, as described in Chapter 2. The JES calibration depends upon the jet p_{T} and η, as well as the pileup conditions and the flavour composition of the jet. These calibrations are derived by comparing data and MC samples in dijet, Z+jets and γ+jets p_{T} balance measurements. Jets arising from pileup events are suppressed using the Jet Vertex Tagger (JVT) discriminant [32]. The JVT uses information of the fraction of the transverse momentum of a given jet to originate from the PV to give a likelihood that a given jet is from the hard scatter event. By default, analyses require that the JVT value is > 0.59, with jets scoring less than this being rejected.

4.4 Flavour-tagging

For both measurements of SM processes and searches for BSM physics, identifying jets originating from heavy flavour (c, b) quarks is extremely important. b-quarks produced in the hard scatter hadronise and then travel a significant distance before decaying. The lifetime of b-hadrons is relatively long at around $1.5ps$ because of suppression in the CKM elements for V_{ub} and V_{cb}, meaning a b-hadron can travel several millimetres before decaying. The result of this is the presence of a second decay vertex distinct from the PV, with

tracks which have large impact parameters. The impact parameters of a track, d_0 and z_0, represent the transverse and longitudinal distance of closest approach to the PV, respectively. This distinctive signature enables jets originating from a b-quark to be 'tagged'.

The MV2c10 b-tagging algorithm is used to flavour-tag all b-jets in the analyses detailed in this Thesis. This algorithm utilises a Boosted Decision Tree (BDT) classifier which has 21 input variables, such as the jet p_{T} and η as described in [33]. The MV2c10 algorithm aims to distinguish b-jets from jets originating from a charm quark, named c-jets, jets originating from hadronic tau decays, named τ-jets and all other jets, originating from light-flavour quarks (u, d, s) and gluons, named 'light-jets'. The output of the MV2c10 BDT is shown in Figure 4.5, applied to a simulated set of $t\bar{t}$ events with dileptonic final states. The output of the MV2c10 algorithm, as shown in Figure 4.5 applied to a simulated

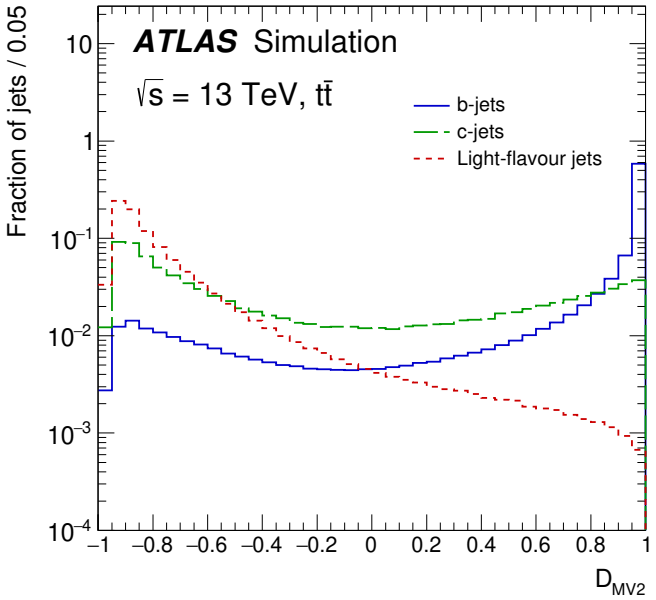
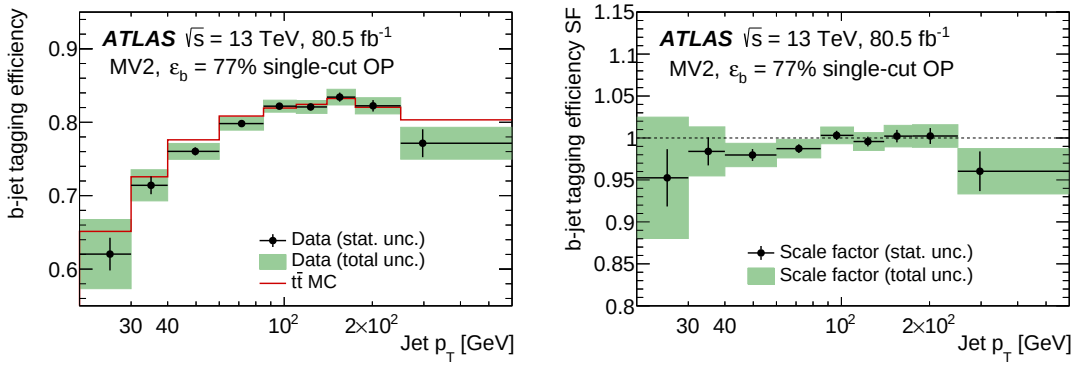


Figure 4.5: Figure showing the output of the BDT used by the MV2c10 algorithm to tag jets originating from b-quarks, using simulated $t\bar{t}$ events.

sample of dileptonic $t\bar{t}$ events, shows that the discriminant, D_{MV2}, peaks at values $\rightarrow 1$ for b-tagged jets (detailed further for any generic ML classifier in Chapter 5), while showing strong rejection of light-flavour jets. This discriminant is used by applying a lower-bound selection on the output of the BDT, such that any jet satisfying this requirement is tagged as a b-jet. Four b-tagging efficiency working points are defined, each corresponding to a different selection on the ouput of the BDT, providing an optimal balance of b-tagging efficiency, ϵ_b, and c/τ/light-jet rejection. The working point used in the analyses detailed in Chapters 6 and 7 is the $\epsilon_b = 77\%$ working point, corresponding to a selection on the BDT output > 0.64, which has a c-jet rejection of 4.9, a τ-jet rejection of 15 and a light-jet

rejection of 110. The jet rejection rate is defined as the inverse of the selection efficiency, $1/\epsilon_j$, where $j = c, \tau, \text{light}$. The efficiency of the MV2c10 b-tagging algorithm as a function of jet p_{T} is shown in Figure 4.6, along with the corresponding MC scale factors.



(a) (b)

Figure 4.6: Figure showing the efficiency of the MV2c10 b-tagging algorithm as a function of the jet p_{T} (4.6a) and the corresponding MC scale factors (4.6b) for the $\epsilon_b = 77\%$ working point.

4.5 $E_{\mathrm{T}}^{\mathrm{miss}}$

In searches for New Physics, it is expected that weakly-interacting BSM particles produced in pp collisions will escape direct detection. Therefore, in order to perform such searches, being able to reconstruct any momentum inbalance, indicating the presence of undetected particles, is crucial. The hermetic design of the ATLAS detector with near 4π solid angle coverage, as described in Chapter 2, enables the reconstruction of the momentum inbalance in each event, with the magnitude of this vector sum known as the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$.

While the presence of $E_{\mathrm{T}}^{\mathrm{miss}}$ is a signature of the production of weakly-interacting BSM particles, it is not a unique signature of New Physics. As previously mentioned and as shown in Figure 4.1, neutrinos pass through the entirety of the ATLAS detector without interacting, and as such any SM decay involving neutrinos can be an irreducible background to a BSM signal. Aside from real $E_{\mathrm{T}}^{\mathrm{miss}}$ from neutrinos, the accurate measurement of the $E_{\mathrm{T}}^{\mathrm{miss}}$ is complicated by detector imperfections; for example, physics objects being mismeasured, or particles passing through inactive detector material.

The $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated in x and y components, as shown in Equation 4.5.1, such that

the $E_{\mathrm{T}}^{\mathrm{miss}}$ vector is given by $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = (E_x^{\mathrm{miss}}, E_y^{\mathrm{miss}})$.

$$E_{x(y)}^{\mathrm{miss}} = -\sum_i p_{x(y),i}^{\mathrm{hard}} - \sum_i p_{x(y),i}^{\mathrm{soft}}. \tag{4.5.1}$$

The vectoral representation of $E_{\mathrm{T}}^{\mathrm{miss}}$ allows both the magnitude and direction in ϕ to be used in physics analyses. The magnitude and direction of the $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$ and ϕ^{miss}, are given by Equations 4.5.2 and 4.5.3, respectively.

$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + \left(E_y^{\mathrm{miss}}\right)^2} \tag{4.5.2}$$

$$\phi^{\mathrm{miss}} = \tan^{-1}\left(\frac{E_y^{\mathrm{miss}}}{E_x^{\mathrm{miss}}}\right) \tag{4.5.3}$$

The reconstructed $E_{\mathrm{T}}^{\mathrm{miss}}$ in ATLAS is constructed from two components; the 'hard-event' component, $E_{\mathrm{T}}^{\mathrm{miss,\,hard}}$, and the 'soft-signal' component, $E_{\mathrm{T}}^{\mathrm{miss,\,soft}}$. The former arises from the reconstruction of the analysis-level electrons, photons, muons, τ_{had}, and jets, while the latter arises from tracks and calorimeter deposits which are not associated with any of the final state objects. The analyses described in Chapters 6 and 7 use the Track Soft Term (TST) algorithm to calculate $E_{\mathrm{T}}^{\mathrm{miss,\,soft}}$, including all ID tracks associated with the PV but not associated with any final state object. Using only tracks associated with the PV, and excluded soft, neutral particle contributions, makes the soft $E_{\mathrm{T}}^{\mathrm{miss}}$ term robust against pileup effects.

4.6 Overlap removal

It is possible for multiple objects to be reconstructed from the same detector signatures, such as calorimeter deposits, such that there are overlapping reconstructed objects. It is therefore necessary to define a prescription through which to resolve this overlap. The overlap removal procedure is performed on loosely reconstructed, 'baseline' objects and proceeds as follows:

- If two electrons share a track in the ID, the lower p_{T} electron is rejected.
- If an electron shares an ID track with a muon, the electron is rejected.
- Any non b-tagged jets within $\Delta R = 0.2$ of an electron are rejected, or within $\Delta R = 0.2$ of a muon if the jet has < 3 tracks or if the muon and jet are ghost-associated.
- For the remaining jets, any electrons or muons satisfying $\Delta R < \min(0.4, 0.04 + 10\mathrm{GeV}/p_{\mathrm{T}})$ are rejected.

Objects remaining after the overlap removal procedure which pass the analysis-level reconstruction criteria form the final analysis objects.

4.7 Event cleaning

In order to ensure recorded data events entering analyses are of good quality, a set of event cleaning requirements are used. These requirements aim to remove any events which has noisy detector signals or which are poorly measured. These are summarised below.

Good Run List The Good Run List (GRL) is a record of all runs recorded by the ATLAS detector, which are deemed suitable for use in analyses. Typically, each run is broken down into 60s segments, known as *luminosity blocks*. Luminosity blocks in each run passing basic data quality requirements are included on the GRL. Events which were recorded in luminosity blocks or runs which are not included in the GRL are automatically rejected.

Trigger Each analysis has differing trigger requirements depending on the signal topology of interest. In this Thesis, the $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers, listed in Table 3.1 are used.

Primary Vertex All events must have a primary vertex (PV). As previously described, the PV is defined as the vertex having at least two tracks with the highest $\sum p_{\mathrm{T}}^2$. Events which do not have a vertex satisfying these requirements are rejected.

SCT, LAr and Tile calorimeter cleaning Noise bursts in the LAr calorimeter or Tile calorimeter trips can give incorrect measurements of the amount of electromagnetic or hadronic activity in an event, affecting the data quality. Events where such calorimeter activity was recorded are rejected. Events recorded during a reset of the SCT caused by a single particle upset (SEU) are also rejected. This occurs when there is a single particle upset (SEU) in a SCT module, which can cause the module to become extremely noisy until it is power-cycled.

Debug Stream Events which cause the ATLAS software-level trigger, the HLT, to crash or timeout form the input to the debug stream. These events are stored and reconstructed offline, where they are assigned to the debug stream. It is particularly important for analyses searching for New Physics to check events in the debug stream.

4.8 Object definitions summary

The working points and selections on acceptance used to define 'signal' objects in the analyses detailed in Chapters 6 and 7 are summarised in Table 4.1. The procedures through which objects are reconstructed have sets of associated systematic uncertainties which will be discussed in Chapter 5.

	SUSY $1\ell b\bar{b}$+$E_{\mathrm{T}}^{\mathrm{miss}}$		2HDM+a tW+$E_{\mathrm{T}}^{\mathrm{miss}}$
Dataset	36.1fb^{-1}	139fb^{-1}	139fb^{-1}
Electrons			
ID		TightLLH	
Isolation	Gradient (Loose)	FCLoose	FCLoose
		(FCHighPtCaloOnly for $p_{\mathrm{T}} > 200$ GeV)	
p_{T}	> 25 GeV	> 7 GeV	> 20 GeV
$\lvert\eta\rvert$		< 2.47	
Muons			
ID		Medium	
Isolation	Gradient (Loose)	FCLoose	FCLoose_FixedRad
p_{T}	> 25 GeV	> 6 GeV	> 20 GeV
$\lvert\eta\rvert$	< 2.7	< 2.5	< 2.5
Jets			
Algorithm		anti-k_t, R = 0.4	
p_{T}	> 25 GeV	> 30 GeV	> 30 GeV
$\lvert\eta\rvert$	< 2.8	< 2.8	< 2.5
b-jets			
Tagger		MV2c10	
p_{T}	> 25 GeV	> 20 GeV	> 20 GeV
$\lvert\eta\rvert$		< 2.5	
b-jet efficiency		FixedCutBEff, $\epsilon = 77\%$	

Table 4.1: A summary of the object definitions used in the analyses detailed in Chapters 6 and 7.

Chapter 5

Analysis methods

This Chapter aims to summarise the methods and tools used to perform the searches for New Physics described in the subsequent Chapters. Firstly, the general analysis strategy used in a search for New Physics is presented, with more relevant and specific detail given in Chapters 6 and 7. The key discriminatory variables used in this Thesis to select candidate signal events are described in Section 5.2. Section 5.3 of this Chapter describes some of the multivariate and machine learning (ML) methods used to select and optimise the acceptance of signal into the analyses, giving an overview of both conventional and more modern data selection techniques. Finally, Section 5.5 gives an overview of the statistical analysis performed and the methods used to draw statistical conclusions from the analyses detailed in the subsequent Chapters.

5.1 General search analysis strategy

Physics analyses targeting a BSM scenario generally define three classes of regions of phase space. *Signal regions* (SRs) are defined as regions of kinematic phase space which are enriched in the signal of interest. SRs can be defined by placing selections on kinematic and angular observables, such as the $E_{\mathrm{T}}^{\mathrm{miss}}$ or the angular difference between two jets $\Delta\phi(j_1, j_2)$, or through more abstract techniques such as placing a selection on some classifier trained to distinguish the signal of interest from the SM background. The latter will be discussed in Section 5.3.

Control regions (CRs) are defined as regions whose composition is dominated by a particular background process, such as $t\bar{t}$, while also having negligible signal contamination. Generally, SRs in searches are in an extreme part of kinematic phase space, far from where the SM background MC was validated, hence it is necessary to ensure reasonable agreement between data and the SM predictions for the background estimates in the CRs. A SM estimate is made for the controlled background in the corresponding CR by normalising the MC predictions to the observed data in that CR by fitting a floating normalisation

factor, typically denoted by μ_{process}. The background normalisation factor, μ_{process}, is both determined from and subsequently applied to all analysis regions included in the statistical analysis. This will be discussed further in Section 5.5.

Validation regions (VRs) are used as a method of ensuring the background estimation from the CR extrapolated to the SR is robust. Generally, this is achieved by defining VRs which differ from the SR definition by inverting only one SR selection. By defining multiple VRs, each with a different SR selection inverted, the extrapolation from CR to SR can be validated. However, VRs must also have low signal contamination, such that it is indeed the background estimate that is being validated.

A simplified diagram showing how CRs, VRs and SRs can be defined in terms of two observables is shown in Figure 5.1.

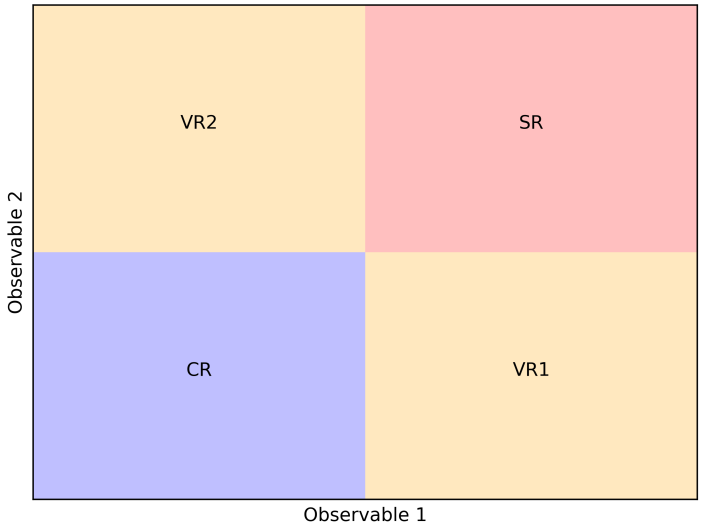


Figure 5.1: A simplified schematic diagram showing an example of a CR, VRs and an SR, all defined by placing orthogonal selections on two observables. The background estimation made in the CR is extrapolated and validated through VR1 and VR2 into the SR.

5.2 Discriminant variables

The analyses detailed in Chapters 6 and 7 have similar final states signatures including a single lepton, b-tagged jets and $E_{\text{T}}^{\text{miss}}$, and hence have very similar SM backgrounds to the respective signals. In particular, the presence of intermediate W bosons and $E_{\text{T}}^{\text{miss}}$ in the signal processes presented in Chapters **??** and 7 makes SM processes involving W bosons which decay leptonically an irreducible background to the signal. In addition, backgrounds

containing at least one top quark, where an intermediate W boson from $t \to Wb$ decays leptonically, are also irreducible due to the presence of a lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$ and b-tagged jets. In the analyses presented in Chapters 6 and 7, the $t\bar{t}$, Wt and W+jets processes are the largest, irreducible backgrounds to the signals of interest. This Section aims to summarise the variables used to reject these SM backgrounds while retaining the signal.

The first, and perhaps most obvious, variable used to discriminate between a BSM signal and the SM backgrounds is $E_{\mathrm{T}}^{\mathrm{miss}}$. The construction of the $E_{\mathrm{T}}^{\mathrm{miss}}$ is described in Chapter 4. Processes which contain BSM particles have real $E_{\mathrm{T}}^{\mathrm{miss}}$ if the BSM particles do not decay to visible particles, and hence could produce an excess of events in the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution. In such events, the amount of $E_{\mathrm{T}}^{\mathrm{miss}}$ is expected to be larger than the SM background, due to the presence of the additional BSM particles. However, real $E_{\mathrm{T}}^{\mathrm{miss}}$ from neutrinos in $W \to \ell\nu$ or $Z \to \nu\nu$ decays as well as $E_{\mathrm{T}}^{\mathrm{miss}}$ from misreconstructed jets can obscure a BSM signal. Therefore, a combination of applying selections on the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution with other kinematic selections is employed.

The transverse mass variable, m_{T}, can be used to reconstruct a single, massive particle undergoing a semi-invisible decay to one visible particle and one invisible particle. In this Thesis, the m_{T} variable is used to reconstruct W bosons, decaying to a charged lepton and a neutrino. In the case of an event with no BSM contributions, the only source of $E_{\mathrm{T}}^{\mathrm{miss}}$ is from the neutrino produced in the decay of the W boson and as such the m_{T} distribution has a kinematic endpoint around m_W. Detector effects smear the kinematic endpoint of the m_{T} distribution to around 100 GeV. The presence of $E_{\mathrm{T}}^{\mathrm{miss}}$ from BSM particles will produce a significantly different m_{T} distribution with a significantly longer tail compared to a SM-only case, and is therefore a powerful discriminant. The definition of m_{T} is given in Equation 5.2.1.

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}(\ell)E_{\mathrm{T}}^{\mathrm{miss}}\left(1 - \cos\Delta\phi(\mathbf{p}_{\mathrm{T}}(\ell), \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})\right)} \tag{5.2.1}$$

In Equation 5.2.1, $p_{\mathrm{T}}(\ell)$ is the transverse momentum of the lepton in the event while $\Delta\phi(\mathbf{p}_{\mathrm{T}}(\ell), \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$ specifies the azimuthal angle between the lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$. For the signal process of interest in the analysis detailed in Chapter 7, there are two intermediate W bosons, producing the single lepton final state as follows: $Wt \to W(Wb) \to (\ell\nu)(qq')b$. In addition to reconstructing the leptonically-decaying W boson using the m_T variable, the reconstruction of the hadronically-decaying W boson was achieved using an iterative reconstruction procedure, as described in [34]. The algorithm begins by clustering all of the $R = 0.4$ anti-k_t jets in an event into large, $R = 3.0$ jets. The radius of these large jets is then iteratively reduced until a radius which matches the p_{T} of the jet, defined by $R(p_{\mathrm{T}}) = 2 \times m_W/p_{\mathrm{T}}$, is reached. The mass of these 'reclustered' W boson candidates is denoted $m_{\mathrm{W}}^{\mathrm{had}}$.

The contransverse mass [35, 36], m_{CT}, is designed to reconstruct the masses of pair-produced particles which both decay in the same, semi-invisible manner. This is particularly useful for rejecting the $t\bar{t}$ process, where both legs decay into a W boson and a b-quark, followed by a subsequent decay of the W bosons. The m_{CT} is defined in Equation 5.2.2.

$$m_{\mathrm{CT}}^2 = \left(E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)\right)^2 - \left(\mathbf{p}_{\mathrm{T}}(v_1) - \mathbf{p}_{\mathrm{T}}(v_2)\right)^2 \tag{5.2.2}$$

The version of m_{CT} shown in Equation 5.2.2 violates Lorentz invariance under boosts of the laboratory centre-of-mass frame, and hence a modified, 'boost-corrected' version [36] is used in the analysis detailed in Chapter **??**. For this analysis, the visible particles v_1 and v_2 are identified as the two b-jets in the event, b_1 and b_2, in order to partially reconstruct the $t\bar{t}$ system. As described in [36], the m_{CT} distribution has a kinematic endpoint which can be calculated as shown in Equation 5.2.3.

$$m_{\mathrm{CT}}^{\mathrm{max}} = \frac{m_{heavy}^2 - m_{invisible}^2}{m_{heavy}} \tag{5.2.3}$$

Identifying $m_{heavy} = m_{top}$ and $m_{invisible} = m_W$ gives a kinematic endpoint around 135 GeV for $t\bar{t}$ production, which is the most dominant background in the analysis detailed in Chapter 6.

The stransverse mass variable, m_{T2} [37] is closely related to the transverse mass variable, m_{T}. It is again designed to reconstruct the mass of pair-produced particles, most relevantly here $t\bar{t}$, where each particle decays semi-invisibly. The m_{T2} is shown in Equation 5.2.4 for a two-lepton final state.

$$m_{\mathrm{T2}} = \min_{\mathbf{q}_{\mathrm{T}}} \left[\max\left(m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}(\ell_1), \mathbf{q}_{\mathrm{T}}), m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}(\ell_2), \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} - \mathbf{q}_{\mathrm{T}})\right)\right] \tag{5.2.4}$$

An asymmetric form of m_{T2} [38, 39], known as am_{T2}, is used in the analysis detailed in Chapter 7. When a pair of top quarks are produced and subsequently decay semi-leptonically, a selection applied to m_{T} above the W boson threshold will reject most events. However, for dileptonic $t\bar{t}$ where one lepton is not reconstructed, cuts applied on the m_{T} variable will not be enough to reject this process, as there is $E_{\mathrm{T}}^{\mathrm{miss}}$ from both legs due to the neutrinos. Selections on the am_{T2} variable can be applied in combination with selection on m_{T} to reject both semi- and dileptonic $t\bar{t}$ decays.

5.3 Selection optimisation methods

Searches for New Physics often involve signals which have cross-sections orders of magnitude lower than those of SM processes. It is therefore necessary to design analyses which

minimise the background contributions in the SRs, while also maintaining a high acceptance and selection efficiency for the signal of interest. Optimising SRs to satisfy these criteria is non-trivial, particularly when considering a large number of observables, and can often result in unreasonable computing times and loads.

Placing simple selections on the discriminating variables described previously does not give sensitivity to the signals of interest due to the huge irreducible SM backgrounds. In order to separate signals from the SM background, more sophisticated optimisation methods are used which take advantage of numerous discriminative variables in parallel. The methods used for region optimisation in this Thesis can be divided into two categories; 'grid-based' methods, and machine learning methods. Grid-based methods aim to find the optimum selection on each of the discriminative variables used in an analysis. For each variable, a set of proposed selections is defined. Each candidate region is defined as one combination of the proposed selections, with the full set of proposed regions forming a 'grid'. The total number of candidate regions is given by the product of the number of proposed selections for each variable, and hence rapidly grows as additional variables are added, or more proposed selections are tested. Therefore, for a grid with many candidate regions it is often impossible to test every region, and hence some grid-based algorithms aim to search the grid for an optimal solution without explicitly testing each candidate region. Machine learning (ML) classifiers do not explicitly optimise selections on individual discriminative variables and instead aim to classify events based upon the values of the variables. The inputs to ML classifiers are generally the discriminative variables of interest in an analysis. The classifier is trained to discriminate between the signal and the SM backgrounds by repeatedly being given events from each class and learning the differences between the distributions. ML classifiers make predictions on an event being signal-like or background-like, by outputting a number in the range $\in [-1, 1]$ or $\in [0, 1]$, depending on the classifier implementation, where predictions $\rightarrow 1$ represent a signal-like event. For ML classifiers, the SRs are defined by applying a lower bound selection to the distribution of the ML classifier predictions. The location of this selection is optimised by scanning over cuts and determining the optimal selection.

In order to determine the optimal solution in grid-based methods and determine the location of the optimal cut on the ML classifier output, the *significance* metric is defined. The definition of the significance metric used to assess the sensitivity of a region in this Thesis, denoted by Z and described in detail in [40], is shown in Equation 5.3.1.

$$Z = k\sqrt{2\left(n\ln\left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2}\right] - \frac{b^2}{\sigma^2}\ln\left[1+\frac{\sigma^2(n-b)}{b(b+\sigma^2)}\right]\right)} \tag{5.3.1}$$

In Equation 5.3.1, n is the number of observed events, b is the expected number of events, and σ is the uncertainty on the prediction b. The factor $k = 1$ for $n \geq b$, while $k = -1$ for $n < b$. The significance is typically evaluated for several benchmark signal models with specific parameter choices, targeting a particular region of the signal kinematic phase space. In this Thesis, the σ is estimated as being 30%, representing a conservative estimate of the dominant modelling and experimental systematics. A well-optimised SR will maximise the significance for the targeted signal phase space, while keeping SM background contributions to a minimum. However, in maximising the significance, it must be ensured that the SR is robust against statistical limitations arising from the MC. A SR which is underpopulated in MC events can give an unreasonably-high estimated significance, and as such it is typically required that there are at least 10 events in the MC for each major SM background, and also for the signal MC sample(s) used for region optimisation.

Details on the specific grid-based and ML methods used are given in the following subsections.

Grid-based methods

Grid-based optimisation methods define a grid of proposed regions, each defined by unique selections on each of the discriminative variables. For each variable, there are N_i test cuts, where i denotes the given variable, such that the total number of combinations of cuts, N, is given by $N = \prod_{i=1}^{M} N_i$. As N is given by a product, the number of combinations rapidly grows with grid granularity and the number of variables tested. In addition, these methods are often run on several benchmark signal models, each with different parameter choices. This ensures good sensitivity can be achieved across a wide range of the available kinematic phase space. Numerous grid-based methods were used in this Thesis, and will now be discussed.

Inclusive grid search

An 'inclusive' grid search finds the optimal combination of selections by calculating the significance for each benchmark signal model for *every* candidate region and returning the region with highest signficance for each signal. While this method is guaranteed to find the region with the highest significance for each benchmark signal model, the number of tests rapidly grows with increasing numbers of input variables or with a large number of proposed regions. The limiting factor of this method is the computational time required to find the optimal region through evaluating the significance for every combination. The subsequent grid-based methods evade this issue by randomly sampling points on the grid of candidate regions.

Random grid search

The random grid search (RGS) algorithm samples random points from the grid of candidate regions, evaluating the significance for each. To alleviate the computational requirements of the 'inclusive' grid search, the RGS algorithm typically samples a small portion of the grid, running for i iterations, calculating the significance at that point, and then removing that point from the grid. Due to the random nature of the RGS algorithm, it is never guaranteed that the algorithm will find an optimal solution without sampling the entire grid. Therefore, the RGS algorithm is run numerous times to ensure the highest significance combination it achieved can not be improved. Additionally, the RGS algorithm is run for several benchmark signal models, to ensure sensitivity across the kinematic phase space.

Adaptive random grid search

The RGS algorithm enables a large portion of a potential signal phase space to be probed without the computational expensive of studying the phase space grid at every point inclusively. However, the RGS method, by definition, randomly samples the grid of points with no 'awareness' of the significance. Hence, the RGS algorithm can sample a point with high significance, potentially close to the optimal solution, before randomly moving to a region of low significance. To circumvent this, a modified version of the RGS algorithm, known as the *adaptive* random grid search (ARGS), was developed. Instead of allowing the movement between any two points on the grid, the ARGS algorithm adapts the step size in a significance-aware way. Around regions of high significance, where $Z \geq 2$, the step size shrinks to allow a high-granularity study of the phase space around the point of interest. Once the significance falls below $Z = 2$, the step size grows again to allow bigger steps between grid points. Finally, once the significance drops below the activation threshold, $Z = 0.5$, the algorithm is free to move between any points on the grid, and is equivalent to the RGS algorithm.

Genetic algorithm

The genetic algorithm (GA) takes inspiration from the process of natural selection, in which the 'fittest' individuals survive the sequential evolution of the system. The GA starts by generating a 'population' of N combinations of cuts. The significance of each combination is calculated, with the lowest 50% of combinations discarded. The surviving 50% of combinations, known as the 'parents', are then copied, and undergo 'cross-over' and 'mutation', to produce 'offspring'. For the cross-over step, the offspring are ordered in terms of significance. In the cross-over step, adjacent offspring randomly switch values of cuts, while in the subsequent mutation step, random cut values are smeared using a Gaussian distribution. The significance of both the parents and the offspring are re-evaluated, and the process repeats, selecting the best-performing 50%. This process repeats

for a predefined number of iterations, $i = 100$, terminating early if the best significance found doesn't improve in 10 iterations.

Machine learning methods

Machine learning (ML) techniques are a wide and active area of research, and this section does not aim to review the state of ML research. Instead, it aims only to give an overview of the usage of ML in this context and describe the ML methods used in this Thesis, in particular the use of supervised learning ML *classifiers* to separate a signal from the SM background. Two types of classifier are relevant in this Thesis; Boosted Decision Trees (BDTs) and Deep Neural Networks (DNNs). Each will be described in their own section, along with details of their implementation.

ML models are, when first created, a completely general model described by a set of parameters, known as *hyperparameters*. The set of hyperparameters used are chosen to maximise the performance of the model, while allowing the model to be robust against unseen data. The ML models used in this Thesis, as previously mentioned, act as classifiers, predicting on an event-by-event basis which of a finite number of classes an event belongs to. This is particularly useful in searches, where one wishes to discriminate a signal from an often irreducible SM background. To give these models the ability to discriminate between the SM backgrounds and signal, they undergo *training*. The models are trained on MC, meaning the class of each event is known during the training phase, which is known as *supervised* learning. ML models can be susceptible to learning the input events and hence become unable to make meaningful predictions about unseen data, known as *overtraining*. In order to overcome this, the performance of the model is evaluated on a statistically-independent sample of events, known as the *validation* sample.

While the structure of each type of ML model is different, the inputs to and outputs of the models are the same. The inputs to the ML models used in this Thesis are physical observables, such as the amount of $E_{\mathrm{T}}^{\mathrm{miss}}$ or the transverse momentum of the objects in the event. The outputs of the ML models used are a number within in a fixed range. In the case of binary classification, where only two classes are defined, the output of the ML model is in the range $\in [-1, 1]$ for classifiers implemented in TMVA [41], and otherwise $\in [0, 1]$. For multiclass classification, where the number of classes $N_{\mathrm{class}} > 2$, the ML model outputs N_{class} values in the range $\in [0, 1]$, the sum of which are 1, where each value represents the prediction for a given class. In this case, events are assigned a class based upon which class score was highest.

Boosted Decision Trees

Boosted Decision Trees (BDTs) are constructed from an ensemble of decision trees, known as *weak classifiers*. Decision trees are constructed from nodes and leaves, with each node representing a test condition on one of the input variables, and each leaf representing a class label. Each individual decision tree has limited discrimination power when evaluated, and hence techniques such as *boosting* [42] are used to create an ensemble of weak classifiers with strong discrimination power. The boosting technique proceeds by iteratively creating trees and assigning each tree a corresponding weight, w_i, related to the classification accuracy of the tree.

During the training phase, the boosting procedure is used to minimise the differences between the prediction of the classifier, $F(\mathbf{x})$, given the inputs $\mathbf{x}$, and the true class of the input data, y_{truth}. The difference between the prediction of a classifier and the true class of an event is calculated using a *loss function*. The BDTs implemented in TMVA utilise the AdaBoost algorithm [43], while the BDTs implemented in XGBoost [44] use gradient boosting. During training, the AdaBoost algorithm proceeds by adjusting the weight of each decision tree in the ensemble to minimise an exponential loss function. However, the gradient boosting algorithm creates a new tree at each training iteration, fitted to the residual $y_{\text{truth}} - F(\mathbf{x})$, to minimise a logarithmic loss function.

The studies performed in Chapter 8 use BDTs implemented with TMVA. These BDTs use an inverse sigmoid transformation on the output of the form $y' = -\tau^{-1}\ln(y^{-1} - 1)$, where $\tau = 15$ [41]. The studies presented in Section 6.6 use BDTs implemented with XGBoost.

Neural Networks

Neural Networks (NNs) take inspiration from the structure of neural connections in the brain. A neural network is constructed from an input layer, an output layer and one or more hidden layers. A NN with 1 hidden layer is classed as a 'shallow' NN, while NNs with more than 1 hidden layer are classed as a 'deep' NN (DNN). Each layer in a NN is constructed from nodes, with the number of nodes in the input layer being determined by the number of input variables, and the number of nodes in the output layer being determined by the classification mode of the network. For binary classification, the NN will have a single node in the output layer, while for multiclass classification there will be N_{class} nodes, one for each class.

The connections between the nodes in the layers depends upon the structure of the NN. In this Thesis, the NNs used are 'fully-connected', meaning each node is connected to all of the nodes in the previous and next layer. These connections, known as *synapses*, each have

a corresponding weight w_i, where i represents the index of the input node in the previous layer. The input to a node in a layer is given by the weighted sum of the outputs of the nodes in the previous layer, as follows:

$$y = \sum_i w_i x_i + b \, . \tag{5.3.2}$$

In Equation 5.3.2, w_i represents the synaptic weight connecting the ith node in the previous layer to the given node, x_i is the output of the ith node in the previous layer and b is the bias. Each layer in a NN has a defined *activation function*, which acts upon the input to a node to produce an output value. The hidden layers in the NNs used in this Thesis use a Rectified Linear Unit (ReLU) activation, which is defined as $y(x) = \max(0, x)$. For the output layer, the sigmoid activation function is used for binary classification, while the softmax activation function is used for the multiclass case.

5.4 Estimating systematic uncertainties

There are two, broad classes of systematic uncertainties that need to be considered when performing an ATLAS analysis; *experimental* uncertainties, related to uncertainties in the reconstruction of the physics objects in an event, and *modelling* uncertainties, related to choices made in the MC simulation employed to aid in the estimate of the SM background or signal process.

Experimental uncertainties

Uncertainties arise in the simulation and reconstruction of the physics objects described in Chapter 4. Experimental uncertainties can affect both the normalisation and shape of distributions, meaning the number of reconstructed objects, e.g. leptons, passing region selections can vary. This Section briefly describes the experimental systematics evaluated in the analyses detailed in Chapters 6 and 7.

Luminosity The integrated luminosity of the dataset is determined using van Der Meer scans, first described in [45] and elaborated upon for ATLAS in [46]. The luminosity uncertainty affects the normalisation of MC predictions, and ultimately the model-dependent and model-independent limits of an analysis. For the analysis detailed in Chapter 6, which uses data collected in 2015-2016, the luminosity uncertainty is determined to be 2.1%, while for the analysis detailed in Chapter 7, using the full Run-2 dataset collected between 2015-2018, the luminosity uncertainty is determined to be 1.7%.

Jets As previously described in Section 4.3, the energy of reconstructed jets must be corrected to account for calorimeter non-compensation, detector acceptance and defects

and pileup. The JES calibration is derived using MC simulation and data [47], and the JES uncertainties arise from choices made when developing this calibration. The full JES uncertainty set totals around 100 nuisance parameters, while a reduced set of JES uncertainties totalling 7-8 parameters is also provided for analyses which are insensitive to small variations in the calibration [48].
The energy of jets cannot be measured exactly, despite the corrections to the jet energy from the JES calibration. The Jet Energy Resolution (JER) is defined as the width of the Gaussian distribution describing the measured jet energy at the calibrated jet energy scale. The JER is determined from both data and MC [49], with its uncertainty arising from choices made when determining the JER.

Flavour-tagging Uncertainties arise in the b-tagging calibration from experimental and modelling sources. The flavour-tagging efficiencies are derived from the comparison of dileptonic $t\bar{t}$ events, and as such choices made in the generation of the $t\bar{t}$ MC affect the measured efficiencies.

Leptons Uncertainties that arise in the reconstruction of leptons are related to the lepton energy resolution and scale calibrations, as well as the efficiencies corresponding to the reconstruction, identification and isolation. In this Thesis, lepton trigger efficiency uncertainties are neglected due to the use of the $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers in the analyses detailed in Chapters 6 and 7.

Missing transverse energy The uncertainties on the $E_{\mathrm{T}}^{\mathrm{miss}}$ are separated into uncertainties affecting the $E_T^{\mathrm{miss,\ hard}}$ and the $E_T^{\mathrm{miss,\ soft}}$ components, as described in Section 4.5. The uncertainties on the hard $E_{\mathrm{T}}^{\mathrm{miss}}$ term are derived by propagating the individual energy scale and resolution uncertainties on the physics objects in an event to the $E_{\mathrm{T}}^{\mathrm{miss}}$. The energy scale and resolution of the soft $E_{\mathrm{T}}^{\mathrm{miss}}$ term are evaluated using data and MC as described in [50].

Modelling uncertainties

Numerous sources of uncertainty arise in the modelling of SM backgrounds and signal. Typically, the dominant modelling systematics come from the specific choice of generator used to evaluate the ME and the choice of algorithm used to model the PS. In terms of specific modelling uncertainties, the interference between the $t\bar{t}$ and Wt processes is often large, as described in Section 3.3. Modelling systematics are evaluated by simulating the same physical process with two MC production configurations, taking the difference between the nominal and variation MC predictions as the 1σ uncertainty. This uncertainty is then applied in the statistical analysis as a 2-sided systematic affecting the normalisation and/or shape of the nominal distributions of the corresponding process. A general overview

of the sources of modelling uncertainty are described here, while specific information on the procedure used to evaluate the individual modelling uncertainties are given in Chapters **??** and 7.

Uncertainty calculation As previously mentioned, modelling uncertainties are calculated by comparing two MC predictions and taking the difference as the 1σ variation, which is known as a 2-point systematic. For backgrounds which are estimated using MC-only, the systematic in a given analysis region is calculated using the difference of the predictions of the two MC samples, as shown in Equation 5.4.1. The MC sample used as a variation can either be a statistically-independent sample, generated in a different configuration, or a weight-based variation of the nominal sample, where an alternate MC weight is applied to the nominal MC.

$$\alpha_{\text{syst}}^{\text{process}} = \pm \left| \frac{N(\text{MC})_{\text{variation}}^{\text{process}} - N(\text{MC})_{\text{nominal}}^{\text{process}}}{N(\text{MC})_{\text{nominal}}^{\text{process}}} \right| \tag{5.4.1}$$

For the analysis detailed in Chapter 6, the modelling uncertainties on the $t\bar{t}$, Wt and W+jets processes are estimated using transfer factors between the CR and SR/VR. The transfer factor between the CR and SR for a given process is shown in Equation 5.4.2.

$$\text{TF}_{\text{syst}}^{\text{process}} = \frac{N(\text{MC, SR})_{\text{syst}}^{\text{process}}}{N(\text{MC, CR})_{\text{syst}}^{\text{process}}} \tag{5.4.2}$$

The uncertainty in the SR is then given by the difference in transfer factors estimated using the nominal and variation MC samples, as shown in Equation 5.4.3.

$$\alpha_{\text{syst}}^{\text{process}} = \Delta\text{TF}_{\text{syst}}^{\text{process}} = \pm \left| \frac{\text{TF}_{\text{variation}}^{\text{process}} - \text{TF}_{\text{nominal}}^{\text{process}}}{\text{TF}_{\text{nominal}}^{\text{process}}} \right| \tag{5.4.3}$$

The transfer factor approach is not used in the analysis detailed in Chapter 7 as the SR bins each have a very different $E_{\text{T}}^{\text{miss}}$ spectrum, while the CRs are defined using a single $E_{\text{T}}^{\text{miss}}$ bin, and hence the extrapolation from the single-bin CRs to SR bins is difficult to validate. Therefore, modelling uncertainties in this analysis are evaluated using the prescription described in Equation 5.4.1.

PDF uncertainties The uncertainty due to the choice of the nominal PDF set was found to be $\mathcal{O}(1\%)$ on the dominant backgrounds, which is far less than the dominant systematics and statistical uncertainties. Hence, PDF uncertainties are neglected in this Thesis.

Generator uncertainties The choice of generator used to model the hard scatter is typically driven by the agreement between the MC predictions and data, with the generator which best reproduces the data across a range of phase space being deemed the nominal

choice. In order to ensure the estimate of the nominal generator is robust in the analysis phase space, the uncertainty on the calculation of the ME is evaluated by generating an MC sample which uses a different generator for the hard scatter, but is interfaced to the same PS algorithm. Variations of the generator uncertainty are not available for all processes; in this Thesis, the generator uncertainties are evaluated for the top-pair, single top and $t\bar{t}V$ processes.

Parton showering uncertainties Similarly to generator uncertainties, the nominal choice of PS algorithm is driven by the agreement between data and MC predictions. To estimate the impact of using a different PS algorithm, the nominal configuration is compared with a MC sample which is produced using the same generator for the hard scatter but using a different PS algorithm. Again, this is evaluated only for the top-pair, single top and $t\bar{t}V$ processes.

Scale uncertainties Numerous choices of scale are made when producing MC samples, such as the value of α_S, μ_R and μ_F. For the W/Z+jets, diboson and triboson backgrounds, the predictions of 7 variations of μ_R and μ_F are evaluated, with the values of μ_R and μ_F being evaluated at 0.5×, 1.0× and 2.0× the nominal values. The maximum downwards and upwards variation then define the asymmetric uncertainty on these scale choices. As mentioned in Section 3.2, there can be overlap between a LO with PS and NLO process, and hence matching and/or merging is used to remove the overlap. For the W/Z+jets backgrounds, the choice of scale used to perform such matching is varied from the nominal value of 20 GeV to 15 GeV and 30 GeV.

5.5 Statistical analysis

All statistical analyses performed in this Thesis were implemented in the HistFitter framework [51]. This framework requires an analysis structure similar to that shown in Figure 5.1. The use of CRs in the fit allows background process yields to be corrected to data, such that any mismodelling of data by the MC can be minimised in the SRs.

Fits using this framework utilise the background CRs to make estimates of the backgrounds in the SR by normalising the expected number of background events from the MC to data. Each background with a corresponding CR, known as a *normalised* background, acquire a normalisation factor, μ_p. This normalisation factor is derived by comparing the number of expected and observed events in a given CR for a given normalised background, enabling an extrapolation to the SR as shown in Equation 5.5.1.

$$N^{SR}_{\text{process}}(\text{Exp}) = \mu_p \cdot N^{SR}_{\text{process}}(\text{MC}) \tag{5.5.1}$$

In Equation 5.5.1, the number of expected events in a given region for a given process, $N^{SR}_{\text{process}}(\text{Exp})$, is calculated by multiplying the expected number of events for that process in that region from the MC, $N^{SR}_{\text{process}}(\text{MC})$, by the process-specific normalisation factor, μ_p, which is calculated automatically when performing the fit.

Fits are performed by constructing a likelihood function, L, depending upon the expected number of MC events in each CR and SR, the systematic uncertainties arising from statistical, experimental and theoretical sources on these backgrounds, and the observed number of events in each CR and SR. The likelihood function used by HistFitter is shown in Equation 5.5.2.

$$L(n, \theta^0|\mu_{\text{sig}}, b, \theta) = P(n_S|\lambda_S(\mu_{\text{sig}}, b, \theta)) \times \prod_{i \in CR} P(n_i|\lambda_i(\mu_{\text{sig}}, b, \theta)) \times C_{\text{syst}}(\theta^0, \theta) \quad (5.5.2)$$

The likelihood function is constructed around a product of Poisson distributions of observed (n_S, n_i) and expected (λ_S, λ_i) events in the SR and CRs, respectively. The Poisson expectations, λ_S and λ_i, depend upon the background prediction, b and the corresponding nuiscance parameters representing the systematic uncertainties, θ, as well as the signal strength parameter, μ_{sig}. The signal strength parameter can be set to 0 to remove signal being considered in the fit, or if considering signal can be set to 1 to include the nominal signal yield estimate for a signal under consideration. The systematics term, $C_{\text{syst}}(\theta^0, \theta)$, shown in Equation 5.5.3 is defined as a product of Gaussian constraints, θ_j, each representing a systematic variation, which are varied around $\theta^0_j = 0$ when maximising the likelihood function.

$$C_{\text{syst}}(\theta^0, \theta) = \prod_{j \in S} G(\theta^0_j - \theta_j) \quad (5.5.3)$$

In searches for New Physics, test statistics are used to quantify the agreement between the expected and observed yields in a given region. Of particular interest in this Thesis are the p-value and the CL_s. The p-value, given a hypothesis H_0, is interpreted as the probability that the alternate hypothesis, H_1, can provide a result at least as incompatible with H_0 as the observed result. The definition of the p-value is given in Equation 5.5.4.

$$p = \int_{t_{\text{obs}}}^{+\infty} g(t|H_0)dt \quad (5.5.4)$$

In Equation 5.5.4, $g(t|H_0)$ is the probability density of the test statistic, t, under the assumption of the hypothesis, H_0. In the event of a discrepancy between the expected and observed results, it is desirable to be able to quantify the size of a discrepancy, which is done using the significance, Z. This significance is defined such that a result which is Z standard deviations from the mean of a Gaussian distribution has an integral equal to the p-value.

The test statistic used for the purposes of setting limits on New Physics signals is the profile log likelihood ratio, shown in Equation 5.5.5.

$$t_{\mu_{\text{sig}}} = -2\log\left(\frac{L(\mu_{\text{sig}},\theta)}{L(\mu_{\text{sig}},\hat{\theta})}\right) \tag{5.5.5}$$

In Equation 5.5.5, L is the likelihood function defined in Equation 5.5.2, where the denominator has parameter choices such that the likelihood is maximised, while the numerator has parameter choices that maximise the likelihood for the specific signal hypothesis under test.

In the context of searches for New Physics, the p-value can be used to claim a discovery of New Physics, or exclude a given signal hypothesis. To claim the discovery of New Physics, one must reject the hypothesis that only the SM background contributes to the observed result to a level of $Z = 5\sigma$, corresponding to $p < 2.87 \times 10^{-7}$. The requirements to exclude a signal hypothesis are less stringent, requiring the rejection of the SM background plus BSM signal hypothesis with values of $p < 0.05$, corresponding to $Z = 1.64$. This exclusion limit correspondes to a 95% confidence limit.

One issue with using the p-value as the metric by which exclusion is performed is the case where the rates of the BSM process are small enough such that the SM-only and SM plus BSM signal distributions are very similar. In the case where an analysis has low sensivity to a particular signal hypothesis, or where there is a downwards fluctuation of data, the signal hypothesis can be rejected. To circumvent this, the CL_s method [52] was developed, where the CL_s is defined as shown in Equation 5.5.6.

$$\text{CL}_s = \frac{p_1}{1-p_0} = \frac{\int_{t_{\text{obs}}}^{+\infty} g(t|H_1)dt}{1-\int_0^{t_{\text{obs}}} g(t|H_0)dt} \tag{5.5.6}$$

In Equation 5.5.6, p_1 corresponds to the p-value that the alternate hypothesis, H_1, is at least as incompatible with H_0 as the observed result, while p_0 corresponds to the p-value that the observed result is compatible with the null hypothesis, H_0.

Background-only fit

The background-only fit is independent of any signal model assumptions, including only SM background MC in the fit. In this scenario, μ_{sig} is set equal to 0. This fit type includes only the CRs in the fit, and hence is not affected by the observed events in the SRs. The purpose of this fit is to estimate the background yields in the SRs and VRs in a signal-agnostic way, under the assumption that the CRs have negligible signal contamination. Additionally, the results of the background-only fit can be used to test the sensitivity of a

given analysis to a different signal than the one under study using the p-value hypothesis test previously described.

Model-dependent fit

The model-dependent fit regime includes background events and a specific signal model, fitting all processes together in both the CRs and SRs, including a signal strength parameter μ_{sig}. The signal is included in *all* regions, to allow any signal contamination in the CRs to be correctly accounted for when calculating the background normalisation factors, μ_p. The model-dependent fit is performed on every signal point generated, such that the entire phase space of signal parameters is probed.

Model-independent fit

The model-independent fit is used to set limits on any potential BSM process present in the SRs. This fit includes both the CRs and SRs, but does not include a signal model or allow signal contamination in the CRs. In this fit regime, the SRs are implemented as an inclusive, single-bin region. The result of this fit is used to set upper limits on the visible cross-section, σ_{vis}, of a generic BSM process.

Part II

Searches for New Physics in Run-2 ATLAS data

Chapter 6

Searches for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production

This Chapter presents an overview of searches for the pair-production of a chargino, $\tilde{\chi}_1^{\pm}$ and next-to-lightest neutralino, $\tilde{\chi}_2^0$, performed during the Run-2 period of data-taking. This Chapter focuses mainly on an analysis undertaken using data taken in 2015-2016, totalling 36.1fb^{-1}. Later in this Chapter, the results of an analysis using the full Run-2 dataset of 139fb^{-1} is presented, along with additional studies using machine learning to improve the sensitivity to the signal. Chapter 8 presents sensitivity studies for this signal at the High-Luminosity LHC, using a dataset of 3000fb^{-1} collected at $\sqrt{s} = 14$ TeV. The results of these analyses are interpreted in the context of a simplified SUSY model **INSERT REF**, in which the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ are unstable and each decay to the lightest neutralino, $\tilde{\chi}_1^0$, via a SM W boson and Higgs boson. The Higgs boson in this process, h, is the lightest CP-even Higgs from the extended SUSY Higgs sector, and is assumed to be a SM-like Higgs boson, with $m_{\mathrm{h}} = 125$ GeV and with the branching fraction of BR($h \to b\bar{b}$) = 58%. The final state of interest in this Chapter, and in Chapter 8, contains a single electron or muon from the decay of the W boson, two b-tagged jets from the decay of the Higgs boson, and $E_{\mathrm{T}}^{\mathrm{miss}}$ from the neutrino and the two $\tilde{\chi}_1^0$. The $h \to b\bar{b}$ decay is the most frequent decay of the Higgs boson, with a branching fraction of 58%, and therefore this channel is expected to have far higher signal yields than channels targeting other decay modes of h. A diagram of the signal process relevant for this Chapter is shown in Figure 6.1.

A search for this process was undertaken in Run 1 using 20.3fb^{-1} taken at $\sqrt{s} = 8$ TeV in this final state, as well as the dilepton, trilepton and diphoton final states. 95% confidence limits were set on this signal, excluding the process upto $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ masses of around 275 GeV for a massless $\tilde{\chi}_1^0$. The results for all four channels, as well as the statistical combination, are shown in Figure 6.2.

This Chapter first describes the simplified SUSY model used in both this Chapter and in Chapter **??**. The event selection used to describe candidate SUSY events is then described, followed by the background estimation strategy, before presenting the results of

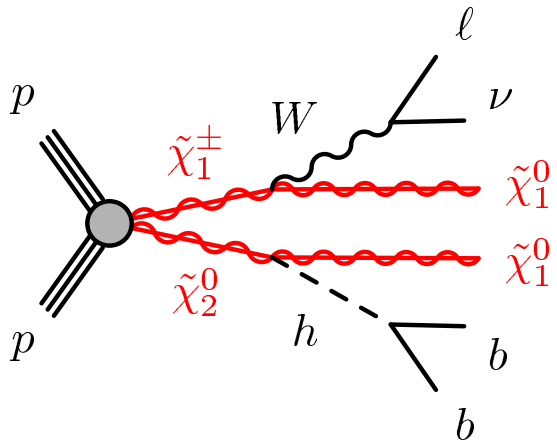


Figure 6.1: Diagram showing $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production, with the chargino and neutralino decaying via a SM W boson and a Higgs, respectively. The assumptions made in simplified SUSY model are summarised in Table 6.1.

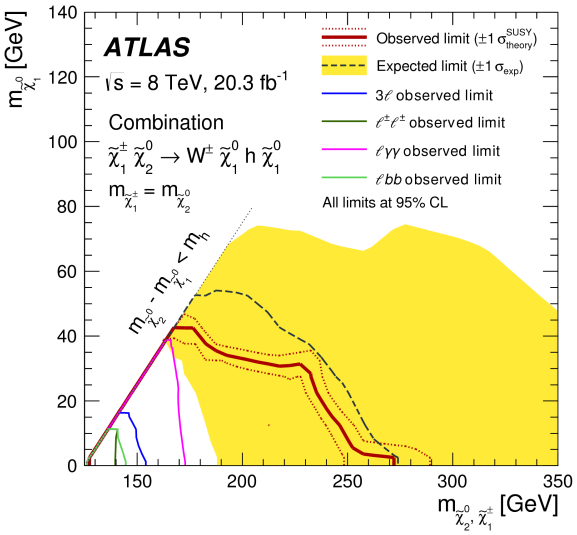


Figure 6.2: A plot showing the four exclusion limits obtained from searches for $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_2^0$ pair-production during the Run-1 data-taking period.

this analysis.

6.1 SUSY signal model

As discussed in Chapter 1, SUSY provides resolution to the hierarchy problem through the introduction of fermionic (bosonic) superpartners to the SM bosons (fermions). As of the time of writing, there has been no experimental observation of these superpartners and hence it is concluded SUSY is a broken symmetry, such that the superpartners have different masses to their SM partners. If the masses of the squarks and gluinos, the superpartners to the SM quarks and gluon, are much heavier than charginos and neutralinos, the

electroweak production of SUSY particles is expected to dominate at the LHC. The mass eigenstates of the charginos, $\tilde{\chi}_i^{\pm}$ where $i = 1, 2$, and neutralinos, $\tilde{\chi}_j^0$where $j = 1, 2, 3, 4$, are ordered from smallest to largest mass. In this Thesis, the lightest supersymmetric particle (LSP) correpsonds to the lightest neutralino, $\tilde{\chi}_1^0$, and is a DM candidate in the case where R-parity is conserved, meaning the LSP is stable and weakly-interacting.

SUSY models have an enormous parameter space with over 100 free parameters, such as the sparticle masses and couplings. Simplified models vastly reduce the number of free parameters, such that a single analysis can be sensitive to a large region of the SUSY model phase space. As previously mentioned, it is assumed the Higgs boson present in the decay of the $\tilde{\chi}_2^0$ is SM-like, such that it has a mass of $m_{\mathrm{h}} = 125$ GeV and $\mathrm{BR}(h \to b\bar{b}) = 0.58$. It is assumed that the branching ratios of the $\tilde{\chi}_1^{\pm} \to W\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ are both 100%. Therefore, the only free parameters of the simplified model used in both this Chapter and Chapter 8 are $\mathrm{m}(\tilde{\chi}_1^{\pm})$, $\mathrm{m}(\tilde{\chi}_2^0)$ and $\mathrm{m}(\tilde{\chi}_1^0)$. The further assumption that the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ are degenerate in mass reduces the number of free parameters to just two; $\mathrm{m}(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0)$ and $\mathrm{m}(\tilde{\chi}_1^0)$. The simplified model assumptions are listed again for reference in Table 6.1.

Model parameter	Assumption
$\mathrm{BR}(\tilde{\chi}_1^{\pm} \to W\tilde{\chi}_1^0)$	100%
$\mathrm{BR}(\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0)$	100%
$\mathrm{BR}(h \to b\bar{b})$	58%
m_{h}	125 GeV
Sparticle masses	$\mathrm{m}(\tilde{\chi}_1^{\pm}) = \mathrm{m}(\tilde{\chi}_2^0)$

Table 6.1: A table summarising the model parameter assumptions for the simplified SUSY model used in this Chapter and Chapter 8.

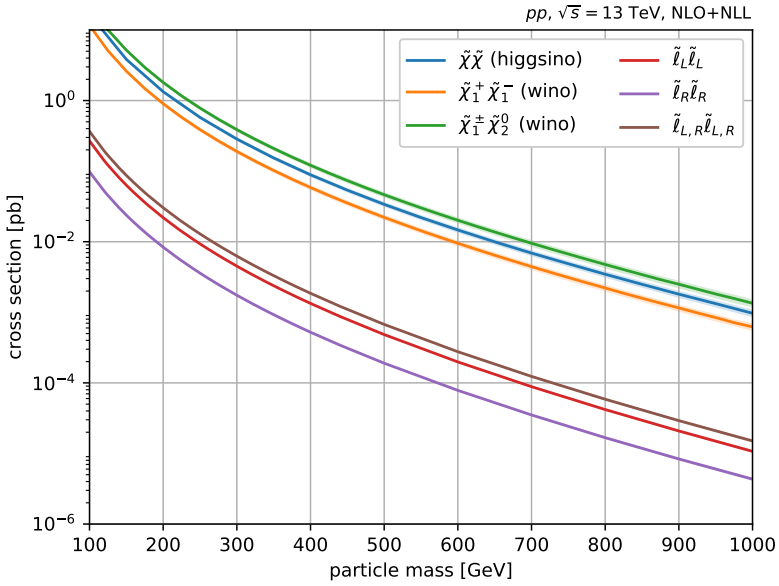


Figure 6.3

6.2 Event selection

Candidate events for this analyses are first selected using a set of loose, preliminary selections, known as 'preselection'. The preselection cuts, summarised in Table 6.2, target events with an event topology which matches that of the signal, in particular events with a single lepton, two b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. All events are required to have exactly 1 electron or muon passing the signal lepton requirements, with any extra baseline leptons being vetoed. Events are required to have either 2 or 3 jets with transverse momentum greater than 25 GeV, and exactly two jets being b-tagged using the MV2c10 algorithm. The b-tagged jets are also required to have transverse momentum greater than 25 GeV. Some data/MC discrepancies were seen at low m_{bb} and m_{T}, and hence lower bound requirements on these variables are placed. Finally, all events are required to pass one of the $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers detailed in Section 3.1.

6.3 Background estimation

The $t\bar{t}$, single top and W+jets backgrounds are the most dominant backgrounds in the three SR bins. Each of these major backgrounds have corresponding CRs defined in which to evaluate the process-specific normalisations, μ_{process}. The $t\bar{t}$ CR is defined with 3 m_{T} bins, matching the m_{T} ranges of the 3 SR bins, named CR($t\bar{t}$)-LM, CR($t\bar{t}$)-MM and CR($t\bar{t}$)-HM, respectively. The top-pair CRs invert the selection on the m_{CT} variable described in Chapter 5 to target the production of a pair of top quarks, while the selection on m_{bb} is inverted as the distribution is not expected to peak around the Higgs masses. A single-bin

Variable	Selection
N_ℓ^{baseline}	$= 1$
N_ℓ^{signal}	$= 1$
$p_{\text{T}}(\ell_1)$	> 27 GeV
N_{jet}	$= 2$ or 3
$p_{\text{T}}(\text{jet})$	> 25 GeV
$N_{b-\text{jet}}$	$= 2$
$p_{\text{T}}(b-\text{jet})$	> 25 GeV
m_{T}	> 40 GeV
m_{bb}	> 50 GeV

Table 6.2: A summary of the preliminary event selection used in the 36.1fb^{-1} search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production.

	SRLM	SRMM	SRHM
m_{bb}	$\in [105, 135]$ GeV		
m_{CT}	> 160 GeV		
$E_{\text{T}}^{\text{miss}}$	> 200 GeV		
m_{T}	$\in [100, 140]$ GeV	$\in [140, 200]$ GeV	> 200 GeV

Table 6.3: A summary of the signal region selections used in the 36.1fb^{-1} search for $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_2^0$ pair-production.

CR for the single top background, CR(t), and a single-bin CR for the W+jets background, CR(W), are also defined. The single-top CR is defined by requiring the m_{bb} is large to target the presence of b-quarks coming from the decay of a top quark and the initial state gluon splitting. Finally, the W+jets CR exploits the m_{T} variable, as described in Chapter 5, to target the decay of a single leptonic W boson, while rejecting the $t\bar{t}$ background. The full definitions of these regions are given in Table 6.4.

	Region				
Variable	CR($t\bar{t}$-LM)	CR($t\bar{t}$-MM)	CR($t\bar{t}$-HM)	CR(t)	CR(W)
m_{T} [GeV]	$\in [100, 140]$	$\in [140, 200]$	> 200	> 100	$\in [40, 100]$
m_{CT} [GeV]	< 160	< 160	< 160	> 160	> 160
m_{bb} [GeV]	$\notin [105, 135]$	$\notin [105, 135]$	$\notin [105, 135]$	> 195	< 80
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 200	> 200	> 200	> 200	> 200

Table 6.4

6 VRs are defined, 3 targeting m_{bb} values in a window around the Higgs peak, $m_{\text{bb}} \in [105, 135]$ GeV, with 3 further VRs targeting m_{bb} values in the sideband region. The

former VRs are referred to as 'on-peak' regions, denoted by $\mathrm{VR_{on}}$, while the latter are referred to as 'off-peak' regions and are denoted by $\mathrm{VR_{off}}$. Each set of VRs mirrors the SR binning in the m_{T} variable. The explicit VR definitions are given in Table 6.5.

	Region					
Variable	$\mathrm{VR_{on}}$(LM)	$\mathrm{VR_{on}}$(MM)	$\mathrm{VR_{on}}$(HM)	$\mathrm{VR_{off}}$(LM)	$\mathrm{VR_{off}}$(MM)	$\mathrm{VR_{off}}$(HM)
m_{T} [GeV]	$\in [100, 140]$	$\in [140, 200]$	> 200	$\in [100, 140]$	$\in [140, 200]$	> 200
m_{CT} [GeV]	< 160	< 160	< 160	> 160	> 160	> 160
m_{bb} [GeV]	$\in [105, 135]$	$\in [105, 135]$	$\in [105, 135]$	$< 95 \,\|\|\, \in [145, 195]$		
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 200	> 200	> 200	> 180	> 180	> 180

Table 6.5

6.4 Systematic uncertainties

Three sources of uncertainty are considered in this analysis; statistical uncertainties, arising from the finite statistics in both data and the MC, experimental systematics and modelling systematics. Section 5.4 describes the experimental systematics evaluated in this analysis. Modelling uncertainties are evaluated using the transfer factor prescription described in Section **REF**.

Source	Size (%)
	Modelling systematics
$t\bar{t}$ modelling	
Single top modelling	
	Experimental systematics
JES	
JER	
b-tagging	

Table 6.6: Table showing a summary of the dominant experimental and modelling uncertainties.

6.5 Results

Background-only fit results

The results of the background-only fit in the CRs, VRs and SRs for the $1\ell{+}b\bar{b}{+}E_{\mathrm{T}}^{\mathrm{miss}}$ channel are shown in Tables 6.7, **REF** and 6.8, respectively. As explained in Chapter 5.5, the

background-only fit configuration uses only the CRs to normalise the dominant backgrounds, in this case $t\bar{t}$, single top and W+jets. The $t\bar{t}$ background has 3 separate normalisation factors, one for each m_{T} bin, such that data/MC differences in each region can be corrected independently of each other. The results of the background-only fit are then extrapolated to the VRs and SRs, such that an estimate of the backgrounds in the SR can be derived without bias from any potential excesses in the SRs, or assumptions on the signal model itself. Excellent data/MC agreement is observed in the CRs and most of the VRs. In $\mathrm{VR_{on}}$-HM and SRMM, there are excesses between $1.5 - 2\sigma$.

The normalisation factors derived for the $t\bar{t}$, single top and W+jets backgrounds using the background-only fit configuration are given in Table 6.9. All values are compatible with unity, with the

Control regions	CR($t\bar{t}$)-LM	CR($t\bar{t}$)-MM	CR($t\bar{t}$)-HM	CR(W)	CR(t)
Observed events	192	359	1115	72	65
Fitted bkg events	192 ± 14	359 ± 19	1115 ± 34	72 ± 9	65 ± 8
$t\bar{t}$	147 ± 33	325 ± 32	1020 ± 90	15 ± 14	20^{+23}_{-20}
Single top	28 ± 25	22^{+24}_{-22}	60^{+70}_{-60}	4^{+6}_{-4}	33 ± 25
W+jets	16 ± 7	7.3 ± 2.7	25 ± 11	51 ± 17	8 ± 4
t$\bar{\mathrm{t}}$V	1.16 ± 0.20	2.8 ± 0.4	6.9 ± 1.1	0.079 ± 0.022	3.2 ± 0.6
Diboson	0.57 ± 0.24	0.92 ± 0.29	1.3 ± 0.4	2.1 ± 1.1	0.84 ± 0.28
Others	0.125 ± 0.032	0.20 ± 0.06	1.9 ± 0.5	0.24 ± 0.17	0.10 ± 0.04

Table 6.7

Signal regions	SRLM	SRMM	SRHM
Observed events	6	7	5
Fitted bkg events	5.7 ± 2.3	2.8 ± 1.0	4.6 ± 1.2
$t\bar{t}$	3.4 ± 2.9	1.4 ± 1.0	1.1 ± 0.6
Single top (Wt)	$1.4^{+1.4}_{-1.4}$	$0.8^{+0.9}_{-0.8}$	1.2 ± 1.1
W + jets	0.6 ± 0.4	0.20 ± 0.11	1.6 ± 0.6
t$\bar{t}$V	0.10 ± 0.04	0.32 ± 0.09	0.54 ± 0.14
Diboson	$0.12^{+0.15}_{-0.12}$	0.05 ± 0.03	0.08 ± 0.02
Others	0.10 ± 0.05	0.03 ± 0.01	0.04 ± 0.02

Table 6.8

1ℓ analysis	
$\mu(t\bar{t}\text{-LM})$	$\mathbf{1.02 \pm 0.14}$
$\mu(t\bar{t}\text{-MM})$	1.15 ± 0.13
$\mu(t\bar{t}\text{-HM})$	$0.89^{+0.21}_{-0.20}$
$\mu(W)$	1.40 ± 0.5
$\mu(t)$	$1.10^{+0.7}_{-1.1}$

Table 6.9

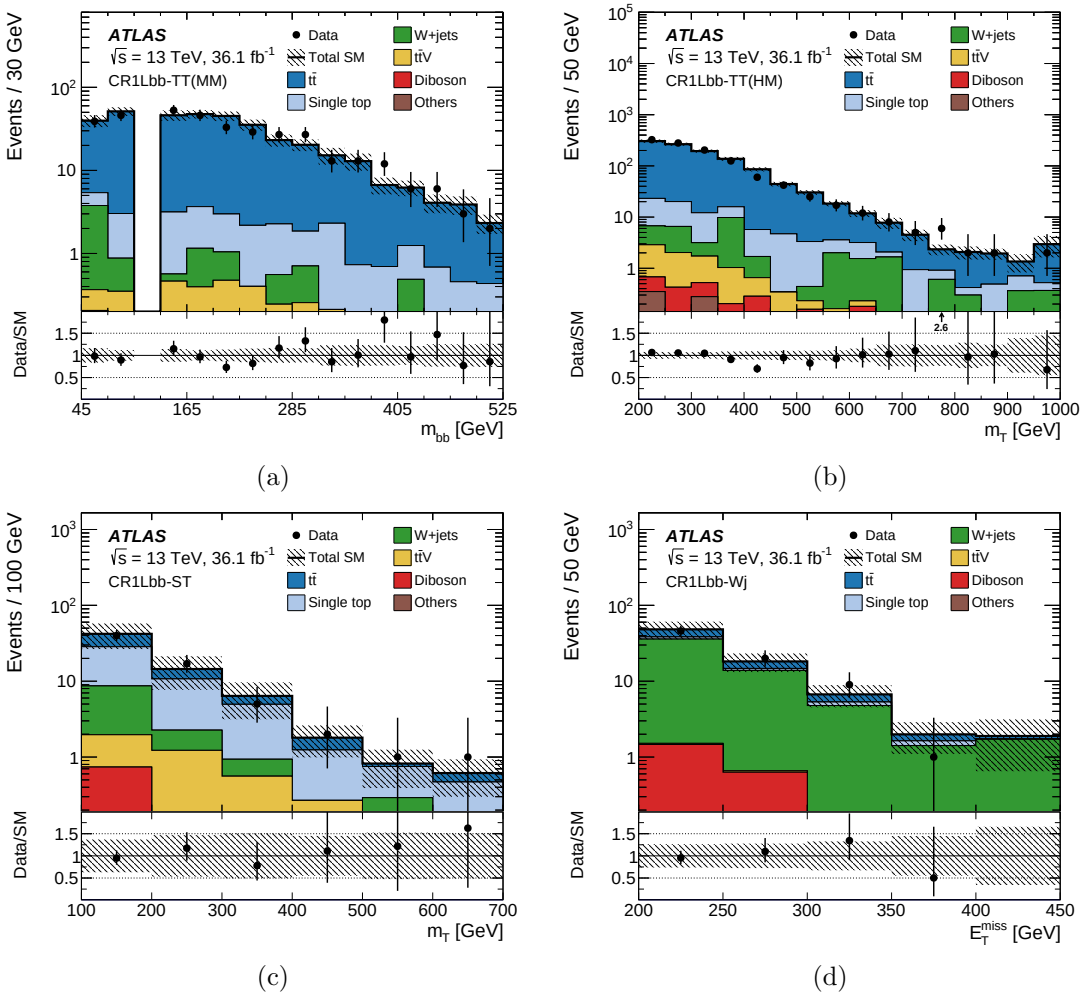

ATLAS
√s = 13 TeV, 36.1 fb-1
CR1Lbb-TT(MM)
CR1Lbb-TT(HM)
CR1Lbb-ST
CR1Lbb-Wj
Data
Total SM
tt̄
Single top
W+jets
tt̄V
Diboson
Others
Events / 30 GeV
Events / 50 GeV
Events / 100 GeV
Data/SM
m_bb [GeV]
m_T [GeV]
E_T^miss [GeV]
(a)
(b)
(c)
(d)

Figure 6.4

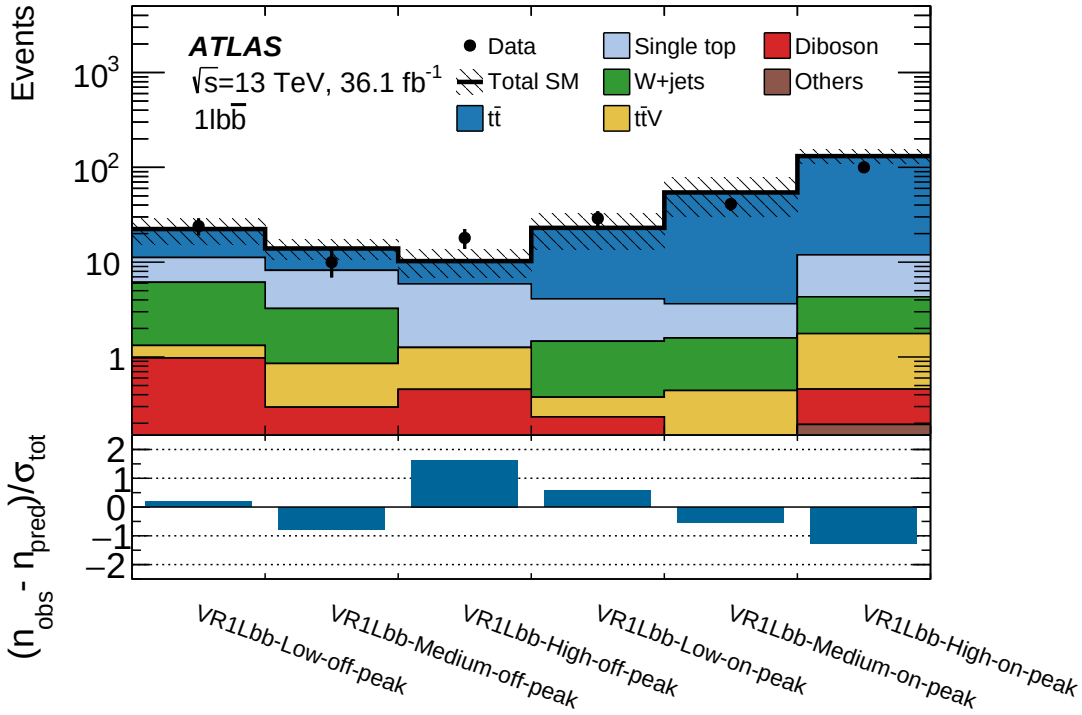

ATLAS
√s=13 TeV, 36.1 fb-1
1lbb
Data
Total SM
tt̄
Single top
W+jets
tt̄V
Diboson
Others
Events
(nobs - npred)/σtot
VR1Lbb-Low-off-peak
VR1Lbb-Medium-off-peak
VR1Lbb-High-off-peak
VR1Lbb-Low-on-peak
VR1Lbb-Medium-on-peak
VR1Lbb-High-on-peak

Figure 6.5

Model-dependent results

As shown in the background-only fit results presented previously, no significant excesses are observed in the SRs. In this case, model-dependent exclusion limits are set on $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production decaying via the Wh signature to the $1\ell + b\bar{b} + E_{\mathrm{T}}^{\mathrm{miss}}$ final state. As described in Section 5.5, the model-dependent fit configuration uses both the CRs and SRs to set 95% confidence limits on the presence of a given signal model. The model-dependent exclusion limits for the analysis using a dataset of 36.1fb^{-1} collected at $\sqrt{s} = 13$ TeV is shown in Figure 6.6, excluding $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ masses upto 550 GeV for a massless $\tilde{\chi}_1^0$.

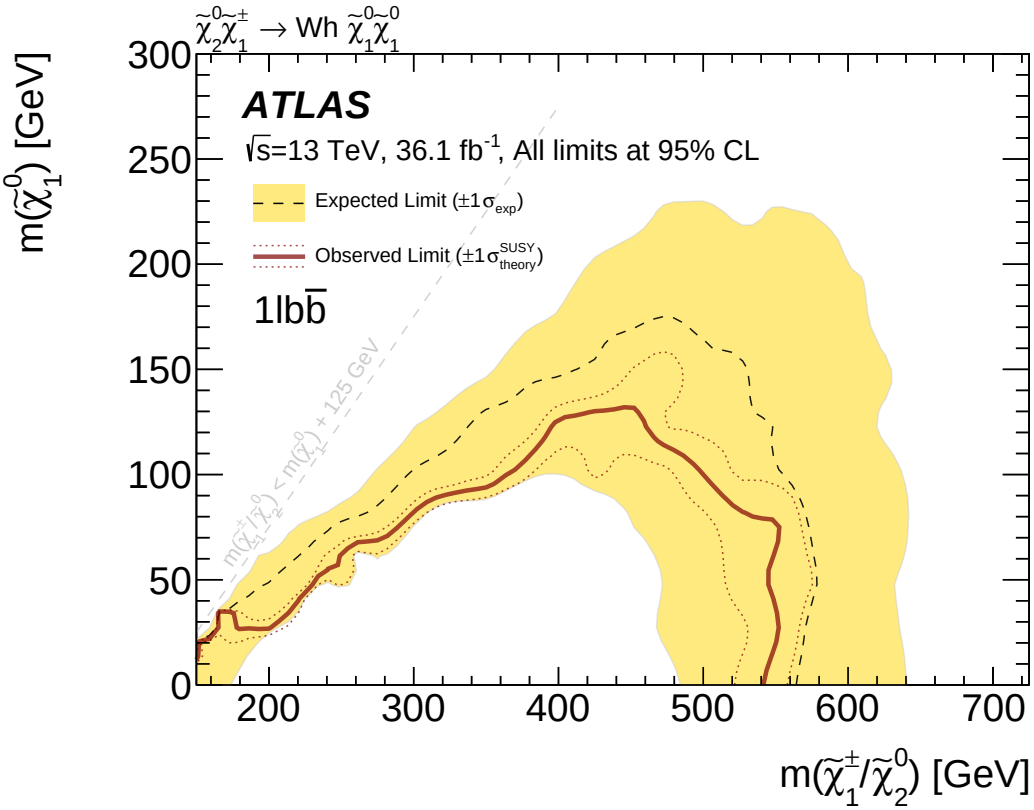


Figure 6.6

Model-independent limits

In addition to the model-dependent fit, 95% confidence limits are set on a generic BSM process using the model-independent fit strategy detailed in Section **??**. A visible cross-section, σ_{vis}, is derived which represents the product of the signal selection efficiency, ϵ, the detector acceptance, A and the production cross-section for the BSM process, σ_{BSM}. The model-independent limits on σ_{vis} derived using the SRs defined early are shown in Table 6.10, as well as limits on the expected and observed number of signal events.

	σ_{vis} [fb]	S_{obs}^{95}	S_{exp}^{95}	p_0-value
SRLM	0.23	8.3	$8.0^{+3.3}_{-2.2}$	0.46
SRMM	0.28	10.0	$5.6^{+2.9}_{-1.7}$	0.04
SRHM	0.18	6.4	$6.1^{+3.1}_{-1.9}$	0.44

Table 6.10: From left to right, the observed 95% CL upper limits on the visible cross-sections σ_{vis}, the observed (S_{obs}^{95}) and expected (S_{exp}^{95}) 95% CL upper limits on the number of signal events with $\pm 1\sigma$ excursions of the expectation, and the discovery p-value (p_0), truncated at 0.5.

6.6 Studies with 139fb^{-1}

ML studies

Reoptimised analysis results

Chapter 7

Search for Dark Matter produced in association with a Top Quark

This Chapter presents a search for the production of Dark Matter (DM) in association with a single top quark, also referred to as DMt, using the full Run-2 dataset collected by ATLAS of 139fb^{-1}. The results of the analysis are interpreted in the context of a simplified model of DM production, where the DM is coupled to an extended SM Higgs sector (2HDM) by a massive, spin-0, pseudoscalar mediator, a.

This Chapter focuses mainly on the $tW+E_{\mathrm{T}}^{\mathrm{miss}}$ signature with a single lepton final state. A complementary analysis of the two lepton final state was also performed, as documented in [53], and will not be detailed here. In addition to the $tW+E_{\mathrm{T}}^{\mathrm{miss}}$ signature, it was found that the sensitivity of these analyses to DM produced in association with a $t\bar{t}$ pair, referred to as DM$t\bar{t}$, was non-negligble. The overall sensitivity of this analysis to the DM$t+t\bar{t}$ signal was evaluted and is detailed in the fit results. Finally, in addition to the independent analyses of the single- and two-lepton final states, both channels were statistically-combined to increase the sensitivity to the DMt and DM$t + t\bar{t}$ signals.

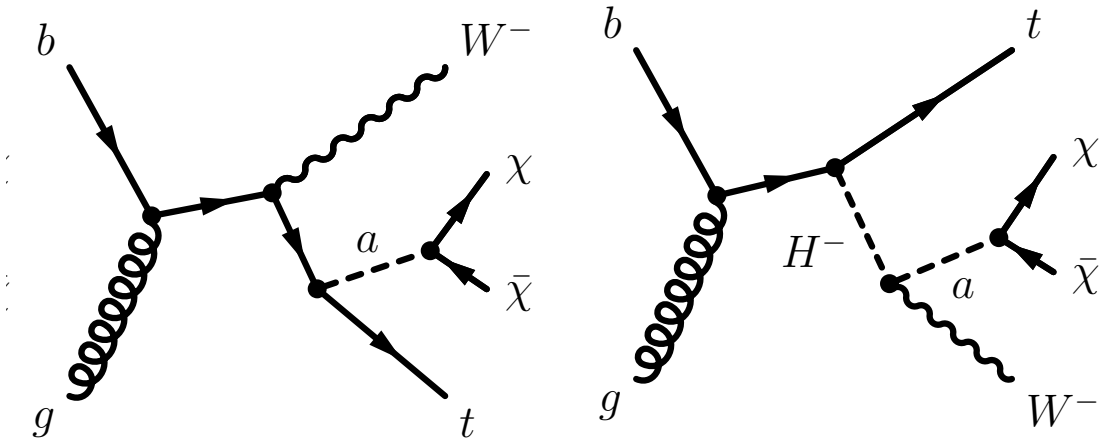
This Chapter begins with a description of the simplfied DM model used to interpret the results, focusing on the experimental signature of interest, the $tW+E_{\mathrm{T}}^{\mathrm{miss}}$ signature. The SR optimisation and selections, as well as the background estimation strategy are documented, before finally presenting the analysis results. Firstly, the background-only fit results in the CRs and SRs are presented, before presenting the model-dependent and model-independent results.

7.1 2HDM+a signal model

As described in Section **??**, there is a strong motivation for performing searches for the production of Dark Matter (DM) at the LHC. Many searches for DM production have already

been carried out using ATLAS data, with the results of the searches being interpreted in the context of the LHC DM simplfied models, as described in [54–56]. These models introduce a new, spin-0 pseudoscalar mediator which couples the SM to DM. However, such models have a limited phenomenology [57], and examples of these models violating gauge invariance and unitarity have also studied [58]. Therefore, while the DM simplified models serve as an excellent benchmark in searches for DM production, a more complete and theoretically-consistent description of DM production is needed.

The simplest extension to the LHC DM simplified models adds a second Higgs doublet to the SM (2HDM). This enables the mixing of the spin-0 mediator with the SM, while also not violating constraints set on the SM Higgs couplings. The particular model of interest in this thesis is the case of a 2HDM model, with an additional pseudoscalar mediator, a. For this model, the $tW+E_{\mathrm{T}}^{\mathrm{miss}}$ signature has not been previously studied, but has been shown to have promising potential in sensitivity studies [57]. The dominant Feynman diagrams for this signature are shown in Figure 7.1. The diagram shown in Figure 7.1a is present in the LHC DM simplified models, while the diagram shown in Figure 7.1b is only present in the 2HDM+a model. The latter diagram gives an approximate order-of-magnitude enhancement to the $pp \to tW\chi\chi$ cross-section through the on-shell production of the charged Higgs, H^-. The additional diagrams from the 2HDM+a model also interfere destructively with the diagrams from the LHC DM simplified model, restoring unitarity.



(a) (b)

Figure 7.1: Feynman diagram for dark matter production in the Wt channel, in the context of a 2HDM+a model. This chapter documents studies done in the single lepton channel, where one of the W bosons in the event decays leptonically.

In addition to the $tW+E_{\mathrm{T}}^{\mathrm{miss}}$ signature, the analysis described in the later sections of this Chapter is also sensitive to the $t\bar{t}+E_{\mathrm{T}}^{\mathrm{miss}}$ signature of associated DM production. A rescaling procedure is applied to the DM$t\bar{t}$ process, which is generated, using the DMSimp

framework [59], in the context of a simplified DM production model in which the pseudoscalar mediator a directly couples to the SM. The Feynman diagram for this process is shown in Figure 7.2. The predictions of this simplified model are rescaled to correctly model the prediction using the 2HDM+a model using the procedure described in [60], which also includes contributions from the heavy pseudoscalar A.

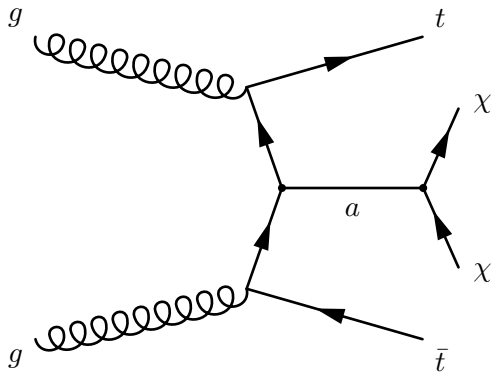


Figure 7.2: Diagram of DM produced in association with a $t\bar{t}$ pair, in the context of the 2HDM+a model under study in this Chapter. The sensitivity of the analysis described later in this Chapter to this signal is shown in Section 7.5.

The model under study in this Chapter is described in detail in [60], but an overview of the most prominent parameters and the choices assigned is given here. As previously described in Section **??**, models with a second Higgs doublet comprise five physical states; the CP-even scalars h and H, the CP-odd pseudoscalar A, and two charged Higgs bosons $H^{\pm}$. The coupling of the extended Higgs sector is of Type-II, such that one Higgs doublet couples to up-type fermions while the other couples to down-type fermions. The mixing in the extended Higgs sector is specified by three mixing angles, α, θ and β. α represents the mixing angle of the two CP-even states, θ represents the mixing of the CP-odd states, and $\tan\beta$ represents the ratio of the VEVS of the two Higgs doublets. The *alignment limit* is assumed, where $\cos(\beta-\alpha)=0$, such that h can be identified with the SM Higgs boson. To enhance the sensitivity to this model, it is assumed that there is maximal mixing between the Higgs sector and the mediator, A and a, and as such it is assumed that $\sin\theta = 1/\sqrt{2}$. As described in [60], it is assumed the masses of the CP-even neutral Higgs, the CP-odd Higgs and the charged Higgs states are degenerate, and the mass of the DM, m_{χ} is set equal to 10 GeV. Finally, the DM coupling to a is set equal to unity, $y_{\chi}=1$. Therefore, there are three free parameters; $\tan\beta$, $m_{H^{\pm}}$ and m_a. In order to set model-dependent limits on this process, two planes are defined to cover the largest possible region of the available model phase space. The first is a scan in the $m_a, m_{H^{\pm}}$ plane, assuming $\tan\beta=1$, while the second plane is a scan in the $m_{H^{\pm}}, \tan\beta$ plane, assuming $m_a = 250$ GeV. The cross-section dependence on $\tan\beta$ for the DMt and DM$t\bar{t}$ processes is shown in Figure 7.3, with $m_a = 250$ GeV and $m_{H^{\pm}} = 600$ GeV. As seen, the cross-section for the DM$t\bar{t}$ process has a $1/\tan^2\beta$ dependence, while the DMt has a more complex dependence on the value of

2071 $\tan\beta$. A summary of the model parameter choices is given in Table 7.1.

Fixed parameters	Assumption
$\sin\theta$	$= 1/\sqrt{2}$
$\cos(\beta - \alpha)$	$= 0$
m_h	$= 125$ GeV
m_H, m_A, $m_{H\pm}$	Degenerate
m_χ	$= 10$ GeV
y_χ	$= 1$

Table 7.1: A table summarising the model parameter assumptions for the simplified 2HDM+a model of DM production as described in [60].

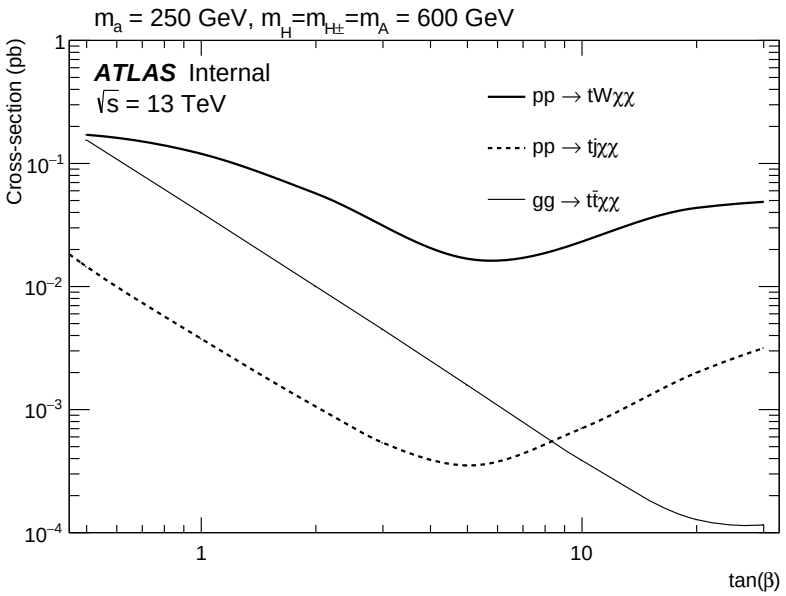


Figure 7.3: Diagram showing the production cross-section of DM produced in association with tW, t and $t\bar{t}$. The associated $t\bar{t}$ production cross-section is proportional to $1/\tan^2\beta$ as described in [61].

2072 7.2 Event selection

2073 The event selection for this analysis begins with a set of preliminary, loose selections, known
2074 as 'preselection'. The preselection cuts aim to select events matching the signal topology,
2075 while rejecting events with different topologies. All events are required to have exactly
2076 1 electron or muon in the final state, with any additional reconstructed leptons failing
2077 the 'signal' lepton requirements being rejected. At least three jets are required, to target
2078 events with at least one hadronically-decaying W boson, and at least one b-tagged jet is

required to select events with a top quark. To minimise the background contribution from $t\bar{t}$, events with a second b-tagged jet required it has a transverse momentum $p_{\mathrm{T}}(b_2) < 50$ GeV. The jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ must have an angular separation of at least 0.5 rad, to reject events which have mismeasured jets. All events are required to pass the event cleaning procedure described in Section 4.7, as well as passing one of the $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers as described in Section 3.1. In order to ensure a constant $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency, all events are required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV. The full preselection requirements for this analysis are defined in Table 7.2. The definitions for the objects used in this analysis are described in Chapter 4.

Variable	Selection
$N_{\ell}^{\mathrm{baseline}}$	$= 1$
$N_{\ell}^{\mathrm{signal}}$	$= 1$
$p_{\mathrm{T}}(\ell_1)$	> 30 GeV
N_{jet}	≥ 3
$p_{\mathrm{T}}(jet)$	> 30 GeV
$N_{b-\mathrm{jet}}$	≥ 1
$p_{\mathrm{T}}(b-\mathrm{jet})$	> 50 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 250 GeV
m_{T}	> 30 GeV
$\lvert\Delta\phi\rvert$	> 0.5 [rad]

Table 7.2: Preliminary selections used for the $tW+E_{\mathrm{T}}^{\mathrm{miss}}$ analysis. All events are also required to pass the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger, and the event cleaning requirements detailed in Section 4.7.The object definitions used are detailed in Chapter 4.

At the preselection-level, the dominant backgrounds, estimated from MC-only, are $t\bar{t}$ (67%), W+jets (18%) and single top production (11%), where the percentages in parenthesis represents the contribution of that process to the total background. Four key variables were identified which enabled rejection of the backgrounds while maintaining a reasonably high signal selection efficiency; $E_{\mathrm{T}}^{\mathrm{miss}}$, m_{T}, am_{T2} and $m_{\mathrm{W}}^{\mathrm{had}}$. These variables are defined in Section 5.2. The am_{T2}, $m_{\mathrm{T}}$and $m_{\mathrm{W}}^{\mathrm{had}}$variables formed the inputs to simultaneous adaptive random grid search and genetic algorithms, as described in Section 5.3. The SR selections are summarised in Table 7.3.

7.3 Background estimation

The major backgrounds in the E_T^{miss} bins of the SR vary, depending on bin, between $t\bar{t}$ and W+jets, with smaller contributions from Wt-channel single top production, $t\bar{t}+V$ and the diboson backgrounds. A single-bin CR for the $t\bar{t}$ background, CR($t\bar{t}$) and a 2-bin CR for the W+jets background, CR(W), are defined. For the W+jets background, the CR is

Variable	Selection
$p_{\mathrm{T}}(b_2)$	< 50 GeV
m_{T}	> 200 GeV
am_{T2}	> 220 GeV
$m_{\mathrm{W}}^{\mathrm{had}}$	> 60 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$ [binned]	$\in [250, 300]$ GeV
	$\in [300, 400]$ GeV
	$\in [400, 500]$ GeV
	$\in [500, 600]$ GeV
	> 600 GeV

Table 7.3: A table of the SR definitions, based on the

separated into 2 bins of lepton charge to exploit the charge asymmetry of $W^{\pm}$ production. The definitions of the CRs are given in Table 7.4.

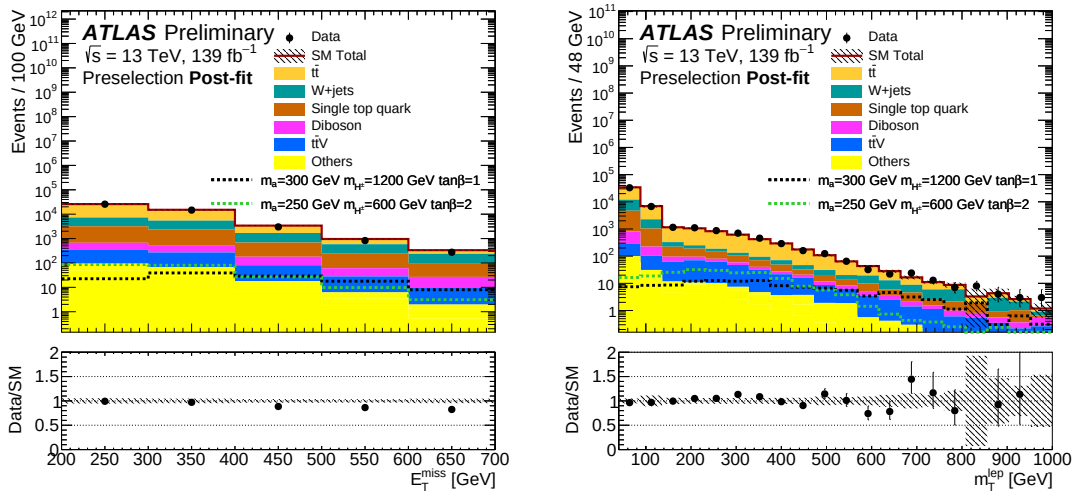
Region	CR($t\bar{t}$)	CR(W)
$N_{\ell}^{\mathrm{signal}}$	$= 1$	
p_{T}^{b1}	> 50	
p_{T}^{b2}	> 50	< 50
E_T^{miss}	> 250	
am_{T2}	< 220	> 220
m_T	> 200	$\in [40, 100]$
m_W	$-$	< 60

Table 7.4: Control region definitions for the tW+$E_{\mathrm{T}}^{\mathrm{miss}}$ analysis. The W+jets CR is split into two bins of lepton charge, such that the $W^{\pm}$ production charge asymmetry can be exploited.

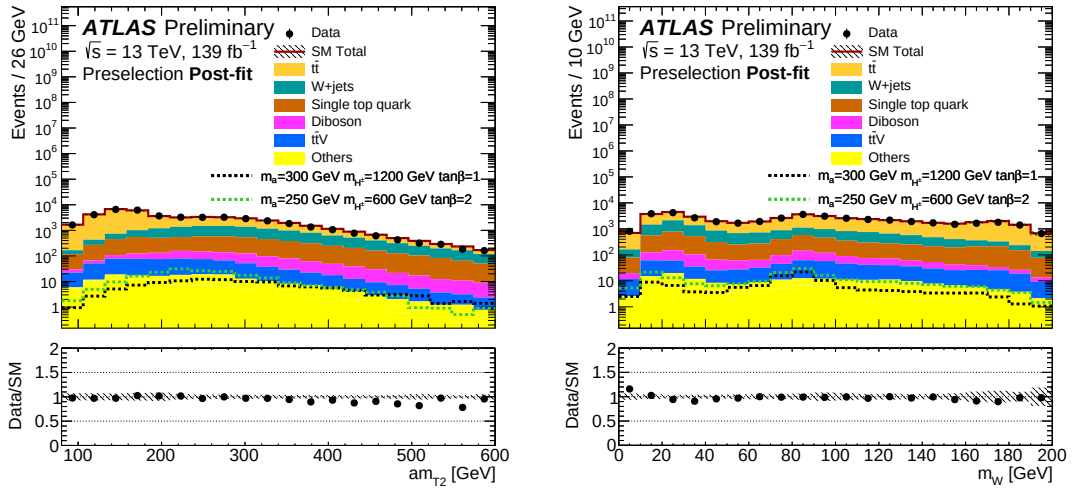
6 validation regions are defined which are in a region of kinematic phase space that is between the CRs and SRs. Two $t\bar{t}$ VRs are defined in order to validate the extrapolation of am_{T2} and m_W, while for the W+jets background, two VRs are defined to validate the extrapolation of m_T and m_W. Each of the W+jets VRs is split into two bins of lepton charge to mirror the CR definition. The VR definitions are explicitly defined in Table 7.5.

7.4 Systematic uncertainties

In addition to statistical uncertainties in the MC and on data, systematic uncertainties are evaluated on all MC background and signal samples, from both experimental and modelling sources. The experimental systematics considered are described in Section 5.4. The dominant experimental systematics in the SRs are from the JES, JER and b-tagging efficiency



(a) $E_{\mathrm{T}}^{\mathrm{miss}}$ (b) m_{T}



(c) am_{T2} (d) $m_{\mathrm{W}}^{\mathrm{had}}$

Figure 7.4: Post-fit plots of the key kinematic variables. The uncertainty band in the ratio plot contains only the MC statistical uncertainty and the experimental uncertainties.

systematics. The modelling uncertainties on the $t\bar{t}$ and single top backgrounds are the dominant modelling systematics in the SRs. The impact of the choice of the hard-scattering generator for the $t\bar{t}$ and single-top backgrounds is evaluated by comparing the `Powheg-Box` nominal prediction with `MadGraph5_aMC@NLO`, both interfaced to `Pythia8`. To assess the impact of the PS and hadronisation modelling, the nominal `Powheg+Pythia8`configuration is compared with the nominal hard-scatter generator configuration interfaced to `Herwig7`. As previously described in Section **??**, the uncertainty due to the modelling of the interference between the $t\bar{t}$ and Wt processes is evaluated by comparing the DR and DS schemes, with the derived uncertainty applied to the nominal Wt prediction. The uncertainty due to the choice of renormalisation and factorisation scales, as well as the ISR and FSR param-

Region	VR1($t\bar{t}$)	VR2($t\bar{t}$)	VR1(W)	VR2(W)
N_ℓ^{signal}		$= 1$		
p_{T}^{b2}		< 50		
E_T^{miss}		> 250		
am_{T2}	< 220	> 220	> 220	> 220
m_T	> 200	> 200	$\in [40, 100]$	> 100
m_W	–	< 60	> 60	< 60

Table 7.5: Validation region definitions for the $tW+E_{\text{T}}^{\text{miss}}$ analysis. The W+jets VRs, like the CR, are each split into two bins of lepton charge.

eters are varied using internal weights in the nominal sample. Table 7.6 gives an overview of the size of the dominant systematics in this analysis.

Source	Size (%)
	Modelling systematics
$t\bar{t}$ modelling	
Single top modelling	
	Experimental systematics
JES	
JER	
b-tagging	

Table 7.6: Table showing a summary of the dominant experimental and modelling uncertainties.

7.5 Results

Background-only fit results

The background-only fit results in the CRs, VRs and SR bins for the single lepton channel are shown in Tables 7.7, 7.8 and 7.9, respectively. In this configuration, only the CRs enter the fit, allowing an estimate of the backgrounds in the VRs and SRs without any signal assumptions. Generally, excellent data/MC agreement is observed in the CRs and VRs, while in the SRs there are $\sim 1\sigma$ excesses in bins 0 and 1 and an $\sim 1\sigma$ underfluctuation of data in bin 4.

The background normalisation factors for the $t\bar{t}$ and W+jets backgrounds, which are derived in the CRs, are shown in Table 7.10. These show excellent compatibility with the SM, agreeing with unity within 1σ.

Figures 7.5, 7.6 and 7.7 show the key kinematic variables for the CRs, VRs and SRs, respectively, including background normalisation factors from the background-only fit. Good modelling is seen in these variables.

Control regions	CR($t\bar{t}$)	CR(W^+)	CR(W^-)
Observed events	911	3143	1653
Fitted bkg events	907.41 ± 30.52	3135.45 ± 56.87	1665.08 ± 37.50
Fitted Top1L events	846.96 ± 34.11	748.75 ± 83.42	720.78 ± 86.33
Fitted SingleTop events	19.82 ± 11.53	276.59 ± 69.50	257.00 ± 70.15
Fitted Wjets events	3.18 ± 0.75	2005.00 ± 98.23	625.41 ± 42.11
Fitted Zjets events	$0.13^{+0.16}_{-0.13}$	6.63 ± 0.99	8.39 ± 1.29
Fitted Diboson events	0.87 ± 0.25	88.85 ± 15.55	46.05 ± 8.01
Fitted ttV events	31.01 ± 7.12	8.16 ± 2.69	5.96 ± 1.52
Fitted ttH events	4.37 ± 0.41	1.12 ± 0.17	1.17 ± 0.11
Fitted tWZ events	1.07 ± 0.29	0.36 ± 0.13	0.32 ± 0.11
MC exp. SM events	887.37 ± 88.05	3189.60 ± 85.25	1759.71 ± 97.50
MC exp. Top1L events	824.87 ± 86.06	801.90 ± 36.82	785.78 ± 51.79
MC exp. SingleTop events	21.98 ± 11.84	307.91 ± 73.54	292.39 ± 77.62
MC exp. Wjets events	3.06 ± 0.75	1973.56 ± 21.27	619.13 ± 17.57
MC exp. Zjets events	$0.14^{+0.17}_{-0.14}$	6.62 ± 0.99	8.46 ± 1.33
MC exp. Diboson events	0.88 ± 0.25	89.91 ± 15.87	46.48 ± 8.12
MC exp. ttV events	30.96 ± 7.19	8.19 ± 2.74	5.96 ± 1.53
MC exp. ttH events	4.40 ± 0.42	1.14 ± 0.17	1.18 ± 0.11
MC exp. tWZ events	1.07 ± 0.29	0.36 ± 0.13	0.33 ± 0.11

Table 7.7: Results of the background-only fit in the control regions for the single lepton channel of the search targeting the 2HDM+a tW+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature. This fit includes only the control regions used to normalise the $t\bar{t}$ and W+jets backgrounds.

Validation regions	VR1($t\bar{t}$)	VR2($t\bar{t}$)	VR1(W^+)	VR1(W^-)	VR2(W^+)	VR2(W^-)
Observed events	1389	482	6127	4479	651	464
Fitted bkg events	1394.19 ± 87.29	463.79 ± 33.54	6721.98 ± 451.82	5025.60 ± 440.57	613.26 ± 69.87	475.28 ± 49.85
Fitted Top1L events	1221.12 ± 70.15	282.62 ± 28.47	3644.44 ± 331.57	3570.86 ± 354.94	282.17 ± 40.09	285.73 ± 41.18
Fitted SingleTop events	$53.19^{+59.36}_{-53.19}$	56.98 ± 24.51	626.01 ± 280.23	612.94 ± 274.02	71.09 ± 36.09	73.39 ± 38.19
Fitted Wjets events	39.07 ± 8.23	68.62 ± 11.94	2245.29 ± 131.23	719.06 ± 48.51	203.16 ± 42.05	70.12 ± 12.03
Fitted Zjets events	3.97 ± 2.14	2.67 ± 0.46	7.66 ± 1.05	7.33 ± 1.00	3.56 ± 0.93	2.38 ± 0.39
Fitted Diboson events	15.29 ± 3.21	27.15 ± 5.48	160.21 ± 28.44	85.60 ± 15.61	34.51 ± 7.06	25.89 ± 5.81
Fitted ttV events	54.42 ± 12.05	22.54 ± 5.03	32.39 ± 2.79	23.86 ± 3.07	16.34 ± 3.79	15.27 ± 3.53
Fitted ttH events	3.57 ± 0.27	0.71 ± 0.04	4.48 ± 0.33	4.37 ± 0.43	0.69 ± 0.03	0.71 ± 0.05
Fitted tWZ events	3.56 ± 0.82	2.50 ± 0.62	1.51 ± 0.17	1.58 ± 0.22	1.72 ± 0.44	1.79 ± 0.46
MC exp. SM events	1372.55 ± 136.76	479.15 ± 31.63	6531.69 ± 623.89	4916.48 ± 572.80	646.06 ± 76.28	513.95 ± 55.99
MC exp. Top1L events	1196.25 ± 120.04	295.27 ± 11.81	3446.89 ± 545.33	3431.71 ± 495.53	307.24 ± 29.76	315.14 ± 29.76
MC exp. SingleTop events	$56.60^{+61.50}_{-56.60}$	60.42 ± 24.75	663.43 ± 286.28	650.26 ± 279.62	79.55 ± 36.91	82.83 ± 38.83
MC exp. Wjets events	38.71 ± 7.57	67.65 ± 10.70	2213.59 ± 60.05	710.50 ± 27.57	202.11 ± 38.29	69.50 ± 10.63
MC exp. Zjets events	3.90 ± 2.12	2.67 ± 0.47	7.73 ± 1.07	7.40 ± 1.03	3.53 ± 0.94	2.40 ± 0.40
MC exp. Diboson events	15.47 ± 3.26	27.35 ± 5.53	161.45 ± 28.79	86.62 ± 15.95	34.78 ± 7.11	26.22 ± 5.91
MC exp. ttV events	54.45 ± 12.19	22.57 ± 5.09	32.55 ± 2.84	23.97 ± 3.11	16.41 ± 3.85	15.34 ± 3.58
MC exp. ttH events	3.60 ± 0.28	0.72 ± 0.04	4.52 ± 0.34	4.42 ± 0.44	0.70 ± 0.03	0.72 ± 0.05
MC exp. tWZ events	3.58 ± 0.83	2.52 ± 0.63	1.52 ± 0.18	1.59 ± 0.23	1.73 ± 0.44	1.80 ± 0.46

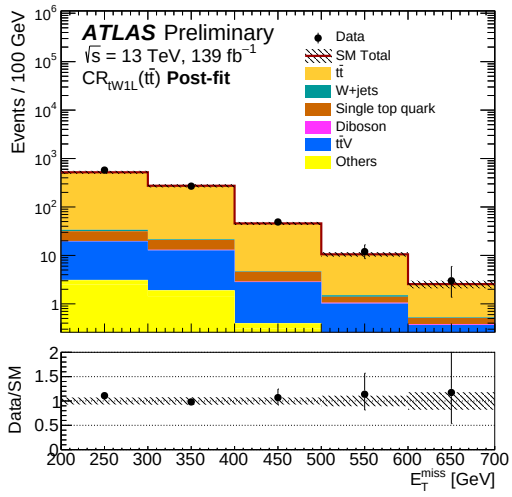
Table 7.8: Results of the background-only fit in the validation regions for the single lepton channel of the search targeting the 2HDM+a tW+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature. This fit includes only the control regions used to normalise the $t\bar{t}$ and W+jets backgrounds.

Signal regions	SR1LBin0	SR1LBin1	SR1LBin2	SR1LBin3	SR1LBin4
Observed events	182	191	60	24	12
Fitted bkg events	169.12 ± 13.98	171.28 ± 13.34	54.70 ± 6.05	20.16 ± 2.84	15.55 ± 2.79
Fitted Top1L events	101.34 ± 11.94	83.65 ± 11.53	20.07 ± 4.56	5.12 ± 1.70	2.31 ± 1.48
Fitted SingleTop events	16.28 ± 5.19	17.26 ± 5.22	5.42 ± 3.23	2.00 ± 1.77	$1.68^{+2.02}_{-1.68}$
Fitted Wjets events	27.77 ± 4.02	37.05 ± 4.34	14.24 ± 2.44	6.11 ± 0.97	5.87 ± 1.08
Fitted Zjets events	2.02 ± 0.91	1.10 ± 0.68	0.33 ± 0.09	0.15 ± 0.04	0.15 ± 0.02
Fitted Diboson events	7.20 ± 1.69	9.65 ± 2.00	4.59 ± 1.00	2.24 ± 0.47	2.59 ± 0.65
Fitted ttV events	12.28 ± 1.36	19.55 ± 3.51	8.71 ± 1.20	4.05 ± 0.72	2.53 ± 0.45
Fitted ttH events	0.56 ± 0.06	0.60 ± 0.06	0.17 ± 0.02	0.06 ± 0.02	0.03 ± 0.00
Fitted tWZ events	1.66 ± 0.21	2.42 ± 0.46	1.17 ± 0.15	0.42 ± 0.09	0.39 ± 0.09
MC exp. SM events	172.49 ± 16.86	174.00 ± 14.12	55.72 ± 6.71	20.60 ± 3.05	16.76 ± 3.15
MC exp. Top1L events	103.13 ± 12.92	85.61 ± 10.81	20.39 ± 4.67	5.28 ± 1.72	2.92 ± 1.51
MC exp. SingleTop events	17.86 ± 5.85	18.63 ± 5.36	6.02 ± 3.34	2.33 ± 1.85	2.35 ± 2.17
MC exp. Wjets events	27.59 ± 3.69	36.22 ± 4.24	14.21 ± 2.25	6.06 ± 0.87	5.75 ± 1.00
MC exp. Zjets events	2.08 ± 0.91	1.09 ± 0.67	0.33 ± 0.09	0.15 ± 0.04	0.15 ± 0.02
MC exp. Diboson events	7.30 ± 1.72	9.73 ± 2.01	4.64 ± 1.02	2.24 ± 0.47	2.62 ± 0.66
MC exp. ttV events	12.30 ± 1.38	19.67 ± 3.59	8.77 ± 1.22	4.06 ± 0.72	2.55 ± 0.46
MC exp. ttH events	0.56 ± 0.06	0.61 ± 0.06	0.18 ± 0.02	0.06 ± 0.02	0.03 ± 0.00
MC exp. tWZ events	1.67 ± 0.22	2.44 ± 0.46	1.18 ± 0.15	0.42 ± 0.10	0.39 ± 0.09

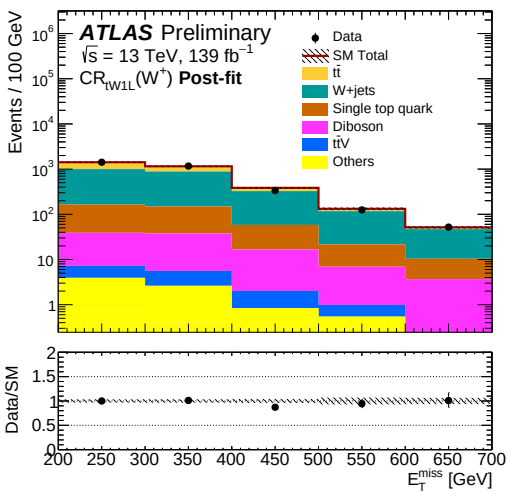
Table 7.9: Results of the background-only fit in the signal region for the single lepton channel of the search targeting the 2HDM+a tW+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature. This fit includes only the control regions used to normalise the $t\bar{t}$ and W+jets backgrounds.

1ℓ analysis	
$\mu(t\bar{t})$	0.96 ± 0.08
$\mu(\mathrm{W})$	1.01 ± 0.05
$1\ell + 2\ell$ combination	
$\mu(t\bar{t}\ 1\ell)$	0.96 ± 0.08
$\mu(t\bar{t}\ 2\ell)$	1.00 ± 0.03
$\mu(\mathrm{W})$	1.01 ± 0.05
$\mu(\mathrm{WZ})$	0.75 ± 0.26
$\mu(t\bar{t}Z)$	0.81 ± 0.16

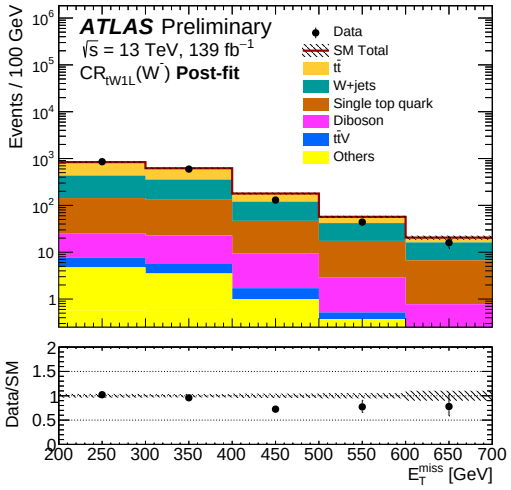
Table 7.10: Background normalisation factors the tW+$E_{\mathrm{T}}^{\mathrm{miss}}$ analysis



(a) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in CR($t\bar{t}$)

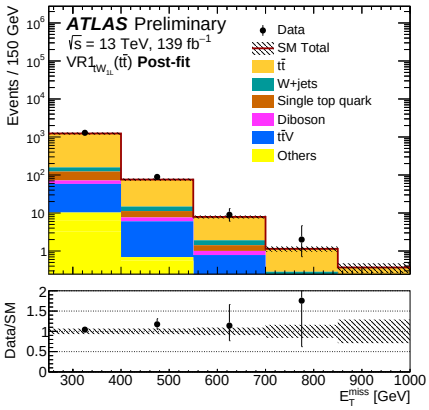


(b) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in CR(W^+)

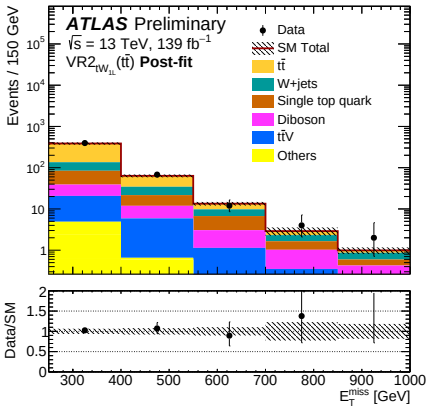


(c) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in CR(W^-)

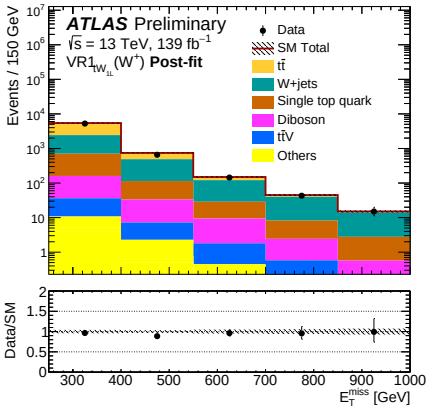
Figure 7.5: Post-fit distributions of the $E_{\mathrm{T}}^{\mathrm{miss}}$ variable in all CRs. Excellent data/MC agreement is observed. The uncertainty band on the ratio contains the MC statistical, experimental and modelling uncertainties.



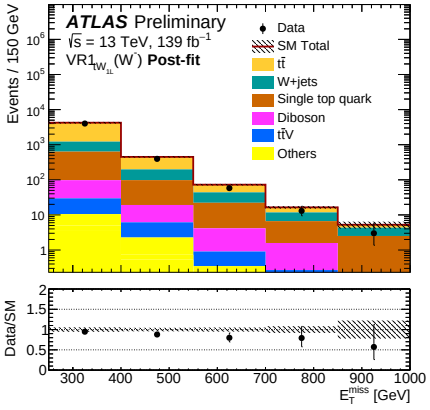
(a) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in VR1($t\bar{t}$)



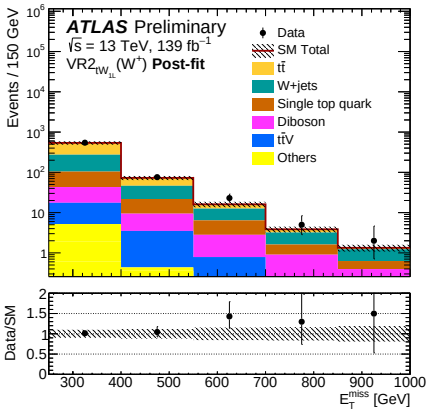
(b) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in VR2($t\bar{t}$)



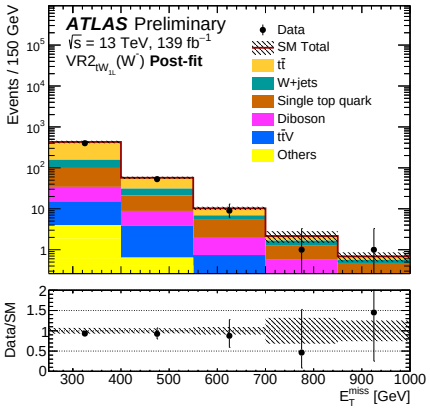
(c) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in VR1(W^+)



(d) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in VR1(W^-)

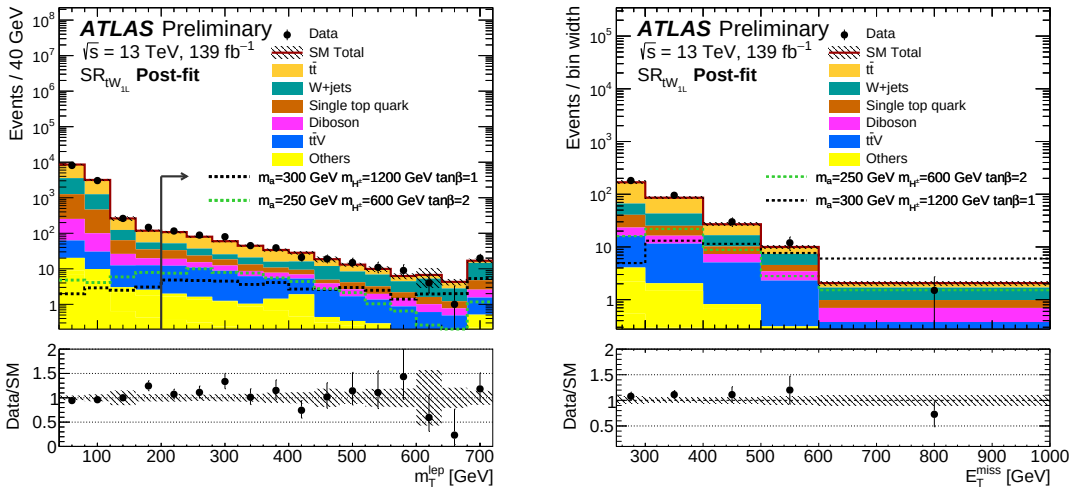


(e) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in VR2(W^+)

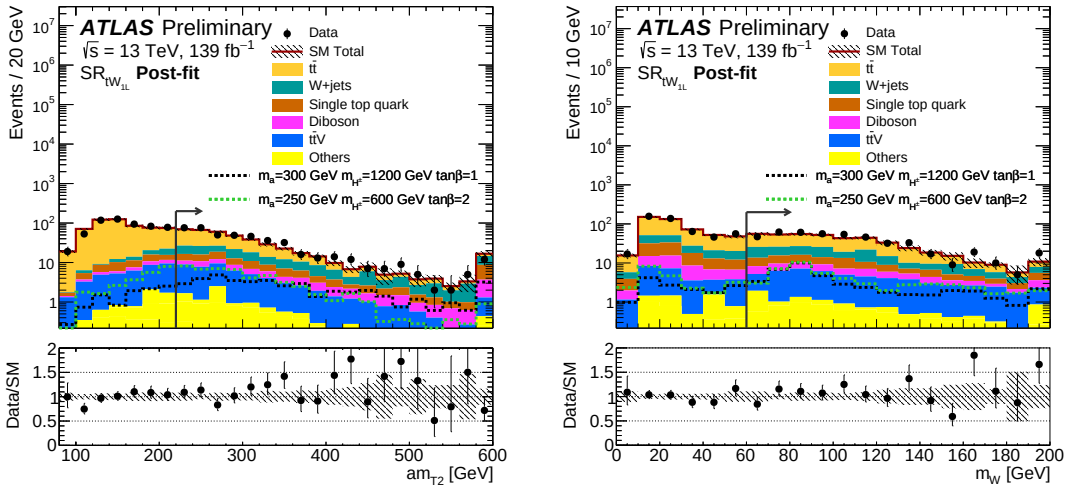


(f) $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in VR2(W^-)

Figure 7.6: Plots showing the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in all VRs. Good agreement between data and MC in all regions is observed. The uncertainy band on the ratio includes MC statistical, experimental and modelling uncertainties.



(a) m_{T} (b) $E_{\mathrm{T}}^{\mathrm{miss}}$



(c) am_{T2} (d) $m_{\mathrm{W}}^{\mathrm{had}}$

Figure 7.7: Plots showing the post-fit N-1 distributions of the key kinematic variables. In these plots, all selections are applied except those on the variable being plotted. All uncertainties are included in the error band on the ratio. No significant excess is observed in the SR bins.

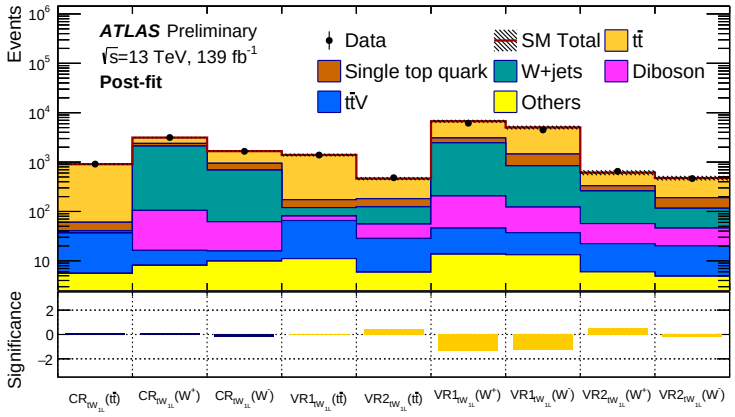
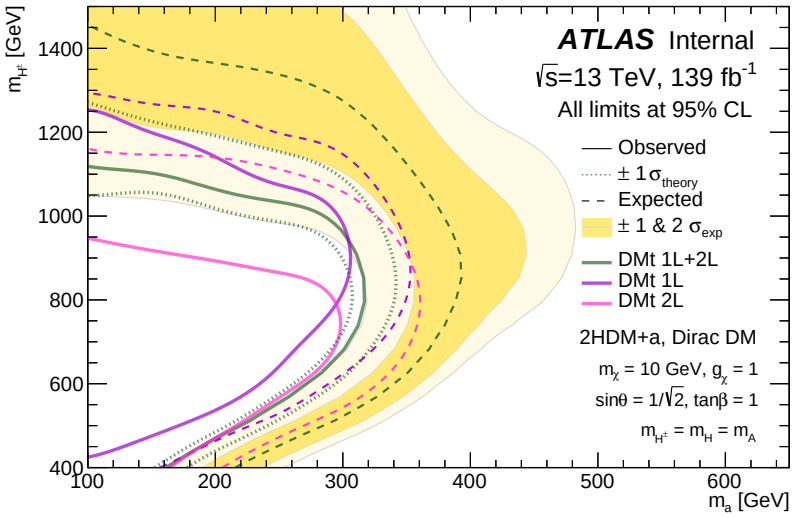


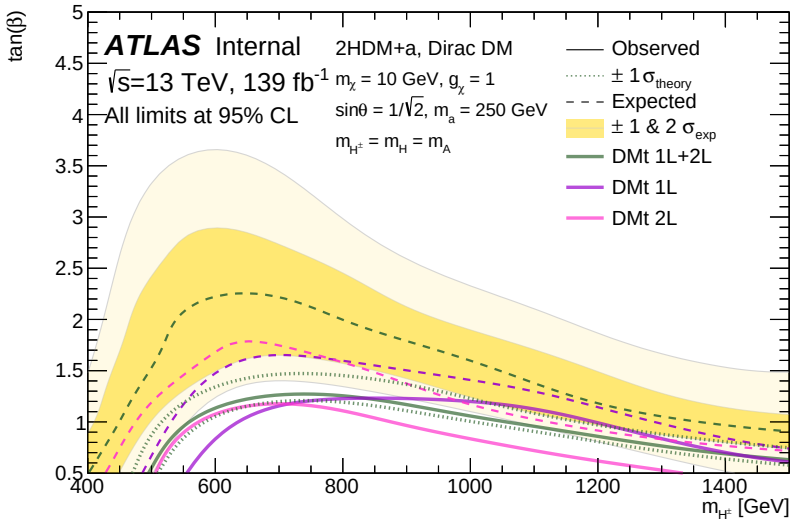
Figure 7.8: Summary plot showing the data/MC agreement in all control and validation regions for the single lepton channel of the search targeting the 2HDM+a tW+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature. The uncertainty used to calculate the significance of the data/MC difference includes the statistical component on the MC and the data, as well as the total systematic uncertainty on the background estimate.

Model-dependent limits

In the absence of a significant excess, limits are set on the 2HDM+a model at 95% confidence limits using the previously described prescription. Model-dependent limits are set on the DMt and the DM$t + t\bar{t}$ signatures, in both the $m_a - m_{H\pm}$ and $m_{H\pm} - \tan\beta$ planes. For the DMt signature, $H^{\pm}$ masses are excluded upto 1250 GeV for $m_a = 100$ GeV, while for the DM$t + t\bar{t}$ signature masses above 1400 GeV are excluded. The observed limit of the statistical combination of the 1ℓ and 2ℓ channels is not as sensitive as the dedicated 1ℓ channel due to the 2σ excess in the 2ℓ SR.

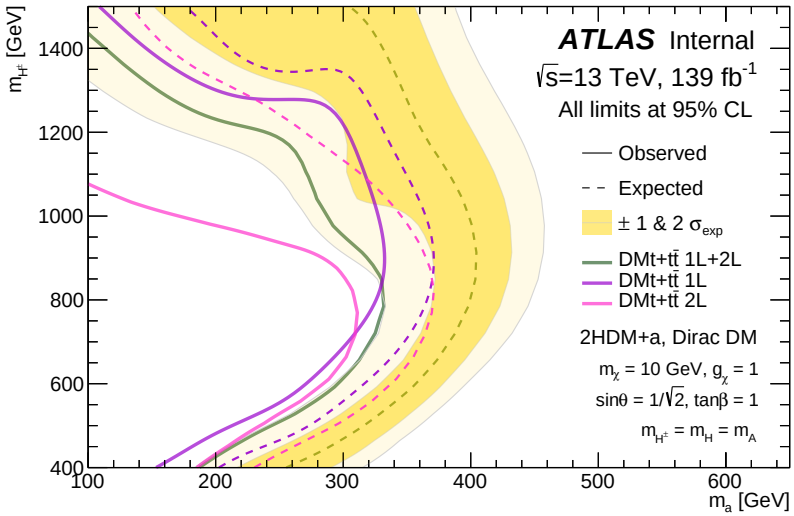


(a)

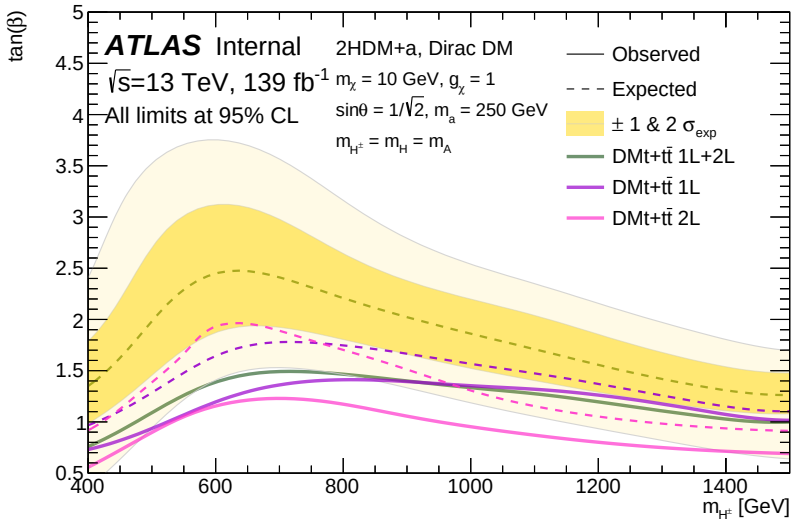


(b)

Figure 7.9: Plots showing the sensivitity to the 2HDM+a signal with the tW+$E_{\mathrm{T}}^{\mathrm{miss}}$ signature. Limits are shown in both the m_a-$m_{H^{\pm}}$ plane (a) and the $m_{H^{\pm}}$-tan(β) plane (b). Limits are shown for the analyses targeting the single lepton and di-lepton final states, along with the statistical combination of both channels.



(a)



(b)

Figure 7.10: Plots showing the sensivitity to the 2HDM+a signal for both tW and $t\bar{t}$ signatures. Limits are shown in both the m_a-$m_{H^\pm}$ plane (a) and the $m_{H^\pm}$-tan(β) plane (b). Limits are shown for the analyses targeting the single lepton and di-lepton final states, along with the statistical combination of both channels.

Model-independent limits

In addition to model-dependent limits being set on the 2HDM+a signal model, with both tW and $tW + t\bar{t}$ signatures, 95% CL limits are set on any generic BSM processes using the model-independent fit strategy described in Section 5.5. The limits are presented as limits on the *visible* cross-section, $\sigma_{\text{vis}} = \epsilon \cdot A \cdot \sigma_{BSM}$, where ϵ is the signal selection efficiency, A is the detector acceptance, and σ_{vis} is the production cross-section for a generic BSM process. To set limits on a generic BSM process, the SR definition from Table 7.3 are modified, such that the individual SR bins have no upper $E_{\text{T}}^{\text{miss}}$ limit and rather only a lower $E_{\text{T}}^{\text{miss}}$ threshold. The yields in these modified, 'inclusive' SR bins are shown in Table 7.11. The results of the model-independent fit are shown in Table 7.12, as 95% CL limits on the expected and observed number of signal events.

Inclusive signal regions					
$E_{\text{T}}^{\text{miss}}$ threshold [GeV]	> 250	> 300	> 400	> 500	> 600
Observed events	469	287	96	36	12
Fitted bkg events	431.47 ± 27.12	261.90 ± 20.10	90.65 ± 10.07	35.94 ± 5.22	15.54 ± 2.77
Fitted Top1L events	212.61 ± 25.01	111.14 ± 17.69	27.51 ± 7.36	7.44 ± 2.94	2.31 ± 1.48
Fitted SingleTop events	43.28 ± 14.49	26.66 ± 11.76	9.35 ± 6.53	3.92 ± 3.85	$1.68^{+2.02}_{-1.68}$
Fitted Wjets events	91.05 ± 7.64	63.29 ± 5.47	26.24 ± 2.82	11.99 ± 1.67	5.87 ± 1.08
Fitted Zjets events	3.76 ± 1.03	1.72 ± 0.69	0.62 ± 0.12	0.30 ± 0.05	0.15 ± 0.02
Fitted Diboson1L events	26.26 ± 5.49	19.06 ± 3.92	9.42 ± 1.97	4.83 ± 1.01	2.59 ± 0.65
Fitted ttV1L events	47.01 ± 2.76	34.75 ± 2.39	15.27 ± 1.17	6.57 ± 0.48	2.53 ± 0.33
Fitted ttH events	1.42 ± 0.09	0.87 ± 0.07	0.26 ± 0.02	0.09 ± 0.02	0.03 ± 0.00
Fitted tWZ events	6.07 ± 0.37	4.40 ± 0.31	1.99 ± 0.13	0.81 ± 0.08	0.39 ± 0.04
MC exp. SM events	439.58 ± 32.24	267.09 ± 22.29	93.09 ± 11.12	37.36 ± 5.64	16.76 ± 3.13
MC exp. Top1L events	217.33 ± 24.57	114.20 ± 16.85	28.59 ± 7.33	8.20 ± 2.91	2.92 ± 1.51
MC exp. SingleTop events	47.20 ± 15.05	29.34 ± 12.03	10.70 ± 6.75	4.69 ± 4.00	2.35 ± 2.17
MC exp. Wjets events	89.83 ± 6.17	62.24 ± 4.79	26.02 ± 2.29	11.81 ± 1.49	5.75 ± 1.00
MC exp. Zjets events	3.80 ± 1.04	1.72 ± 0.68	0.63 ± 0.12	0.30 ± 0.05	0.15 ± 0.02
MC exp. Diboson1L events	26.52 ± 5.55	19.23 ± 3.96	9.50 ± 1.99	4.86 ± 1.01	2.62 ± 0.66
MC exp. ttV1L events	47.36 ± 2.90	35.05 ± 2.50	15.38 ± 1.20	6.61 ± 0.49	2.55 ± 0.34
MC exp. ttH events	1.44 ± 0.09	0.88 ± 0.07	0.27 ± 0.02	0.09 ± 0.02	0.03 ± 0.00
MC exp. tWZ events	6.11 ± 0.38	4.44 ± 0.32	2.00 ± 0.13	0.82 ± 0.09	0.39 ± 0.04

Table 7.11: Table showing the expected and observed yields in the modified signal regions for the determination of the model-independent limits.

Region	$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$[fb]	S^{95}_{obs}	S^{95}_{exp}
SR1L ($E_{\text{T}}^{\text{miss}} > 250$ GeV)	0.72	100.6	$66.7^{+32.7}_{-16.4}$
SR1L ($E_{\text{T}}^{\text{miss}} > 300$ GeV)	0.51	70.8	$54.1^{+16.0}_{-15.9}$
SR1L ($E_{\text{T}}^{\text{miss}} > 400$ GeV)	0.24	32.9	$29.4^{+10.1}_{-6.4}$
SR1L ($E_{\text{T}}^{\text{miss}} > 500$ GeV)	0.14	18.9	$18.7^{+7.6}_{-4.9}$
SR1L ($E_{\text{T}}^{\text{miss}} > 600$ GeV)	0.08	10.6	$12.0^{+2.7}_{-3.6}$

Table 7.12: Table showing the model-independent limits derived for the five modified inclusive SRs. Visible cross-sections of BSM physics upto 0.72fb are excluded at 95% confidence limits, translating to an upper limit of around 100 events with a dataset of 139fb^{-1}.

Part III

High-Luminosity LHC studies

Chapter 8

Sensitivity to $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production at the HL-LHC

This chapter explores the potential sensivitivity of a search for chargino-neutralino pair-production using the ATLAS detector during the HL-LHC phase of operation. The HL-LHC is expected to begin operation in the latter half of the 2020's, bringing instantanenous luminosities around an order of magnitude higher than those currently at the LHC (7.5×10^{34}), along with an increase in centre-of-mass energy to $\sqrt{s} = 14$ TeV. It is expected that by the end of the HL-LHC phase, ATLAS will have taken 3000fb^{-1} of data, an expected ten-fold increase over the combination of Runs 2 and 3.

Along with the increased luminosity and collision energy delivered by the LHC, the ATLAS detector will be undergoing major upgrades in Long Shutdown 3 (LS3), providing an overhaul of many of the detector's subsystems. Of particular note is the new Inner Tracker (ITk), which will replace the current innermost tracking layers of the current ATLAS detector, vastly improving on the vertex resolution which will enable accurate track reconstruction in collisions with an average number of interactions per bunch-crossing, $\langle\mu\rangle$, of 200. Figure 8.1 shows a simulated $t\bar{t}$ event display from the ATLAS ITk in the expected pileup conditions at the HL-LHC.

With the increased centre-of-mass energy and the expected 3000fb^{-1} dataset, the physics analysis potential of the HL-LHC is unprecedented. Much of the HL-LHC physics program will be devoted to precision measurements of properties related to the Higgs boson and its relationship with the symmetry breaking mechanism of the electroweak sector of the SM. First sensitivity to the Higgs self-coupling is expected to be possible in the $HH \to b\bar{b}\gamma\gamma$ channel through both a conventional cut-and-count analysis [62] and a multivariate analysis [63]. This measurement will be used in combination with measurements in other final states, such as $b\bar{b}\tau\tau$ and $b\bar{b}b\bar{b}$ [64], further increasing sensitivity. It is also expected that measurements of the largest Higgs boson couplings to SM particles will be done with percent-level precision. Along with increased precision in measurements and

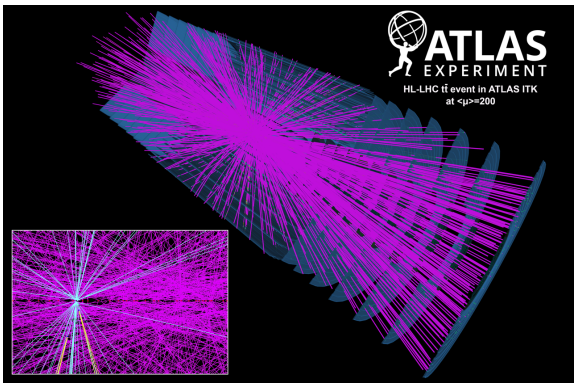


Figure 8.1: An event display of a simulated $t\bar{t}$ event in the ATLAS ITk at the HL-LHC, where there are an expected 200 interactions per bunch-crossing.

sensitivity to SM properties, the HL-LHC will also bring increased sensitivity to TeV-scale new physics. This chapter describes one such prospects analysis, forming part of a plethora of sensitivity studies [65].

The analysis described in this chapter targets the same signal model as in Chapter **??**, with a final state of a single electron/muon, two b-jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. The sensitivity is assessed in the context of current expected HL-LHC conditions. Due to the huge dataset expected to be collected at the HL-LHC, the sensitivity is expected to reach far beyond the Run-2 sensitivity, and as such, mass upto 1500 GeV are considered for the $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$.

8.1 MC simulation

Signal samples for this study are generated at leading-order in QCD, with upto two additional partons, using MadGraph5_aMC@NLO [66] for the matrix element (ME), while Pythia 8 [67] is used for the parton showering (PS), hadronisation and underlying event (UE). The A14 tune is used for Pythia 8 [68] while the NNPDF23LO PDF set [69] is used for generation. Partons are matched between the ME and PS using the CKKW-L [70] prescription, with the scale used for matching set to one quarter of the mass of the $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$. The cross-sections are evaluated at next-to-leading order in α_s and next-to-leading logarithmic precision for the resummation of soft gluon emissions. The nominal cross section is determined by evaluating the cross section predictions with different PDF sets, factorisation and renormalisation scales [71]. Similarly to the analyses previously described, numerous generator configurations were used to generate the MC background samples. These are summarised in Table 8.1.

All samples are generated at truth-level. A parameterised simulation of the detector response is applied to all truth-level MC samples. This will be described in more detail in the following section.

Process	Generator + fragmentation/hadronisation	Tune	PDF set	Cross-section order
W/Z+jets	Sherpa 2.2.1 [?]	Default	NNPDF30NNLO [?]	NNLO
$t\bar{t}$	Powheg-Box v2 + Pythia 8.186	A14	NNPDF23LO [?]	NNLO+NNLL
Single top	Powheg-Box v1 or v2 + Pythia 6.428 [?]	Perugia2012 [?]	CT10 [?]	NNLO+NNLL
Diboson (fully leptonic)	Sherpa 2.2.1	Default	NNPDF30NNLO	NLO
(semi leptonic)	Powheg-Box v1 + Pythia 8.186	AZNLO [?]	CTEQ6L1	NLO
Higgs	Powheg-Box v2 + Pythia 8.186	AZNLO	CTEQ6L1	NNLO+NNLL

Table 8.1: Summary table showing the ME and PS configurations used to generate the SM MC samples for this study.

8.2 Detector simulation

In order to make meaningful predictions of sensitivity, a simulation of the ATLAS detector at the HL-LHC was developed through a set of parameterised smearing functions. These functions, known as the UpgradePerformanceFunctions, simulate the detector response by smearing the kinematic and angular properties of the physics objects, as well as providing additional collision vertices to simulate the pileup conditions at the HL-LHC. The treatment of each object relevant to this chapter will be discussed separately. Some shorthand will now be introduced for the following sections. $R(m, n)$ represents a random number drawn from a uniform distribution in the range m to n. $G(\mu, \sigma)$ represents a number drawn from a Gaussian distribution with a mean, μ, and a standard deviation, σ.

Leptons

The steps taken in the reconstruction of charged leptons is highly dependent on the generation of lepton being considered, but there are some common steps. Lepton ID working points are assigned for all three generations of charged leptons, and the detector response to the E_T for electrons and taus and p_T for muons is simulated. The charge-flip probability (the probability that the reconstructed lepton has the opposite charge to its true value), $P(\ell^{\pm}_{truth} \rightarrow \ell^{\mp}_{reco})$, is explicitly parameterised for electrons and is also possible for muons. Finally, the misreconstruction of an electron as a photon is parameterised.

A parameterisation of the lepton ID efficiencies is used in order to choose which lepton ID working points the lepton has passed. For each lepton generation there are three ID efficiency parameterisations, one corresponding to each working point. These parameterisations can be seen in Figure A.1. For a given lepton, the three ID efficiencies corresponding to the ID working points are retrieved, and all which satisfy $R(0, 1) < \epsilon^i_{ID}$, with $i = 1, 2, 3$, are passed.

The p_T resolution for leptons is simulated differently for muons than for electrons and taus. For the former, the key quantity is the charge (in units of e) to transverse momentum ratio, $\frac{q}{p_T}$, while for electrons and taus it is the energy, E. For both quantities, the 'reconstructed' value is as follows:

$$\begin{aligned} E_{reco} &= E_{truth} + G(0, \Delta E) \\ \left(\frac{q}{p_T}\right)_{reco} &= \left(\frac{q}{p_T}\right)_{truth} + G\left(0, \Delta\left(\frac{q}{p_T}\right)\right) \end{aligned} \tag{8.2.1}$$

Here, ΔE and $\Delta\frac{q}{p_T}$ denote the resolutions on the respective quantity. The reconstructed muon transverse momentum is then given by $p_T^{reco} = \left|\left(\frac{q}{p_T}\right)_{reco}^{-1}\right|$, while for electrons and taus it is given by $p_T^{reco} = p_T^{truth} \times \frac{E_{reco}}{E_{truth}}$.

The charge-flip probability for electrons is parameterised in η and differs slightly for the three ID working points, as can be seen in Figure A.1. The charge-flip probability is determined by the tightest working point which is passed by the electron. A charge-flip occurs if the following condition is satisfied; $R(0,1) < P(e^{\pm}_{truth} \to e^{\mp}_{reco})$. For muons, particularly high-p_T or η muons, can undergo a charge flip when the $\frac{q}{p_T}$ is smeared.

Finally, electrons being misreconstructed as a photons is simulated through a parameterisation in η. For electrons with a $p_T > 20$ GeV, the probability of an electron being reconstructed as a photon is 2% for electrons with $|\eta\langle 1.37$ and is 5% for electrons with $|\eta\rangle 1.52$. An electron is misreconstructed as a photon if $R(0,1) < P(e \to \gamma)$.

Jets and flavour tagging

To simulate jet reconstruction, the first step of the detector simulation process is to smear the jet energy and p_T. The jet p_T is smeared by a multiplicative factor, $G\,(1, \Delta E)$, where ΔE represents the relative jet energy resolution determined from the parameterisation shown in Figure A.3a. The jet energy is smeared by multiplying the true jet energy by $\frac{p_T^{smeared}}{p_T^{truth}}$.

Jet flavour-tagging, in particular the tagging of jets originating from b-quarks, is of great importance to the study described in this chapter. The b-tagging working point used in this study has a b-tagging efficiency $\epsilon_b = 70\%$, which has much-improved light-jet rejection compared to the $\epsilon_b = 85\%$ working point. The flavour-tag efficiency, ϵ^b_{ftag}, is parameterised in jet p_T and η, and can be seen in Figure A.3b. Jets which have originated from a b-quark at truth-level are b-tagged if $R(0,1) < \epsilon^b_{ftag}$. The misreconstruction of jets as electrons, taus and photons is simulated by parameterising the so-called 'fake rate'. This is rate at

which an object is misreconstructed as another object.

$E_{\mathrm{T}}^{\mathbf{miss}}$

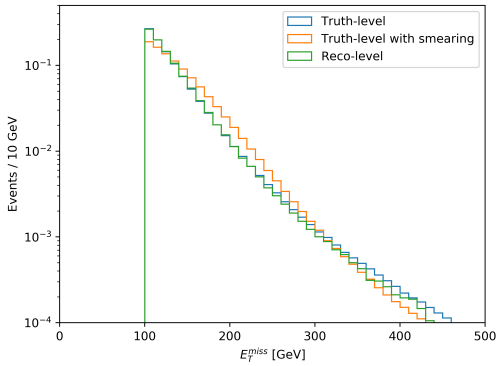
Smearing the $E_{\mathrm{T}}^{\mathrm{miss}}$ requires two steps. At truth-level, the missing transverse energy, $E_{T,truth}^{miss}$, is the sum of the transverse energies of all neutral particles in the event; in this study, only neutrinos and neutralinos contribute.

To account for mismeasurement due to pileup, $E_{T,truth}^{miss}$ is smeared by adding an additional term, $E_{T,pileup}^{miss}$, drawn randomly from the distribution shown in Figure A.4a. The $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution, ΔE_T, is then determined from the parameterisation shown in Figure A.4b, using the sum of the neutral particle and pileup $E_{\mathrm{T}}^{\mathrm{miss}}$ components as an input. The final $E_{\mathrm{T}}^{\mathrm{miss}}$ is then give as:

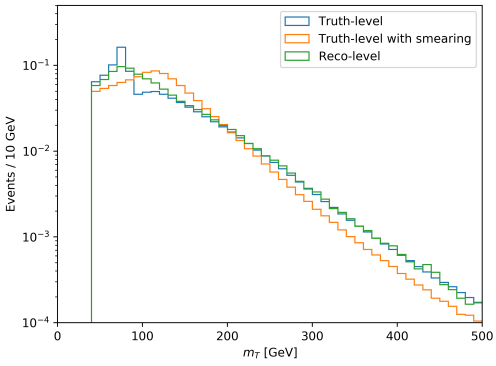
$$E_T = E_{T,truth}^{miss} + G(0, \Delta E_T) \tag{8.2.2}$$

Kinematic distribution comparison

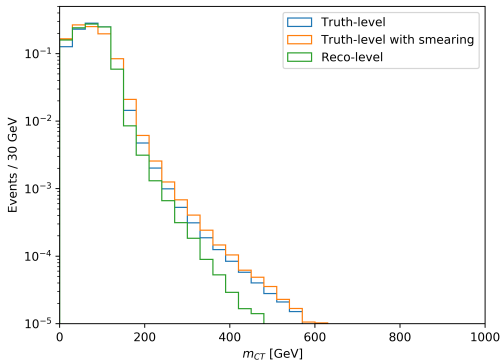
The effects of the detector simulation described in this section can be see in Figure 8.2. The 'truth-level' $t\bar{t}$ distribution includes no detector effects, the 'truth-level with smearing' $t\bar{t}$ distributions include the detector simulation described in this section, while the 'reco-level' sample is reconstructed using the full ATLAS detector simulation.



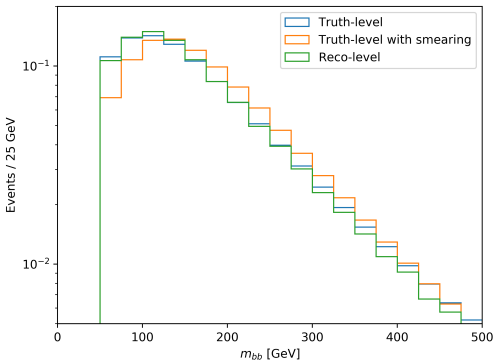
(a) $E_{\mathrm{T}}^{\mathrm{miss}}$



(b) m_{T}



(c) m_{CT}



(d) m_{bb}

Figure 8.2: The E_T^{miss}, m_T, m_{CT} and m_{bb} distributions at truth-level, truth-level with the detector smearing described in this section, and a fully reconstructed samples. All distributions are normalised to unity to compare only the shape of the distributions and not normalisations.

8.3 Event selection

The object definitions used to reconstruct the leptons and jets are summarised in Table 8.2 and Table 8.3, respectively.

	Electrons	Muons
p_{T}	25 GeV	25 GeV
$\lvert\eta\rvert$	< 2.47	< 2.7
ID	Tight	Medium

Table 8.2: A summary of the object definitions for leptons in the HL-LHC projection.

Similarly to the 36.1fb^{-1} analysis described in Chapter 6, a number of preliminary selections are applied to select events with the single lepton, two b-jet topology, as shown in Table 8.4.

	jets	b-jets
p_{T}	25 GeV	25 GeV
$\lvert\eta\rvert$	< 2.5	< 2.5
Jet radius (R)	0.4	0.4
b-tagging WP	-	70%

Table 8.3: A summary of the object definitions for jets in the HL-LHC projection.

Preselection	
Leptons ($p_T \geq 25$ GeV)	$1e$ or 1μ
Jets ($p_T \geq 25$ GeV)	2 or 3
b-jets ($p_T \geq 25$ GeV)	2
m_{T}	≥ 40 GeV
m_{bb}	≥ 50 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	≥ 200 GeV

Table 8.4: A summary of the preliminary selections used for for the HL-LHC projection.

The loose cuts on $m_{\mathrm{T}}$and $m_{\mathrm{bb}}$are employed to combat MC mismodelling seen in the analysis described in Chapter **??**, while the cut on $E_{\mathrm{T}}^{\mathrm{miss}}$ is used to both reduce the SM background and target events containing two $\tilde{\chi}_1^0$ in the final state.

Events passing the preliminary selections listed in Table 8.4 are used as inputs to Boosted Decision Tree (BDT) classifiers. The BDTs are implemented in Toolkit for Multivariate Data Analysis [41]. In this study, binary classification is performed such that the output of the BDT is a single value $\in [-1, 1]$. The key discriminatory variables which are given to the BDT classifiers as inputs are the $E_{\mathrm{T}}^{\mathrm{miss}}$, m_{T}, m_{CT}, m_{bb} and $\Delta R(\mathrm{b}_1, \mathrm{b}_2)$. Along with these, the transverse momentum of the lepton and the two b-jets are useful for background rejection. The distributions of $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{T}}$and $\Delta R(\mathrm{b}_1, \mathrm{b}_2)$for the signal are highly dependent upon the mass and the mass difference of the $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$and $\tilde{\chi}_1^0$, and as such having one classifier which performs equally well across the entire phase space is extremely difficult to achieve. To aid in this, three BDT classifiers are trained, targeting 'low', 'intermediate' and 'high' mass-splittings, ΔM = m($\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$) - m($\tilde{\chi}_1^0$). SR-Low targets $\Delta M < 300$ GeV, SR-Med targets $\Delta M \in [300, 600]$ GeV and SR-High targets $\Delta M > 600$ GeV. The signal grid, highlighted with the three targeted regions, is shown in Figure 8.3.

Due to the limited number of MC events in each individual signal sample, all signal samples in each mass-splitting regime ('low', 'intermediate' or 'high' ΔM) are summed together with an equal weight of 1. The sum of signals for each mass-splitting region provide a high-statistics signal sample on which to train the BDTs, with kinematic distributions representing a 'pseudo-average' of the individual signal samples. A benchmark

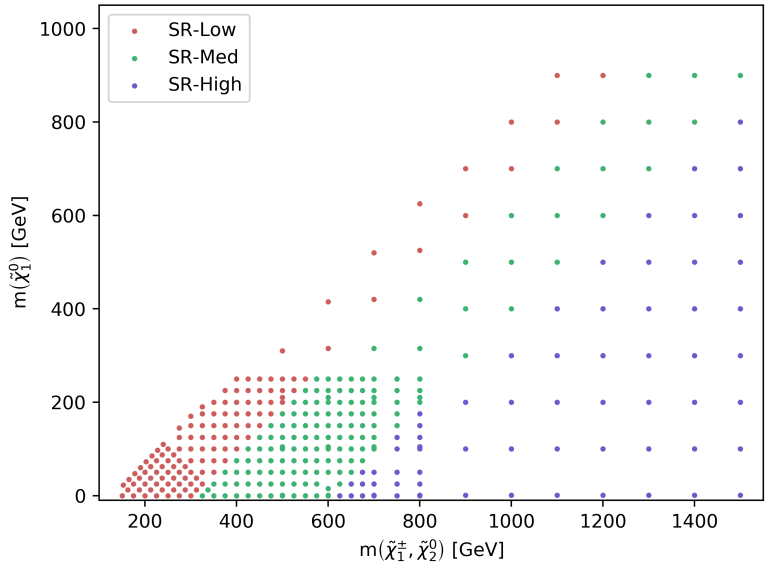
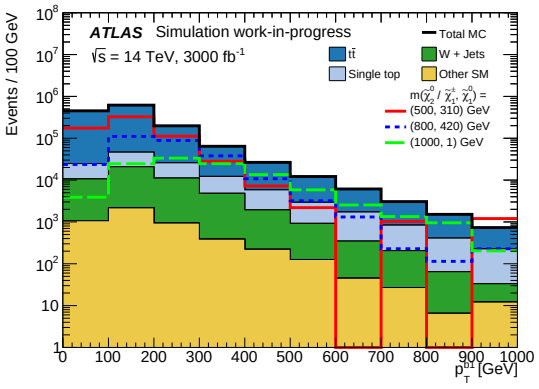
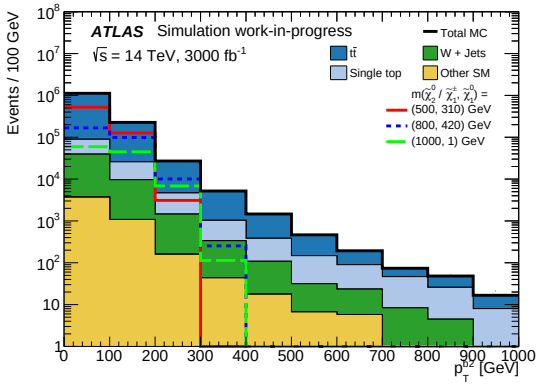


Figure 8.3: Plot showing the separation of the mass plane into the three defined categories.

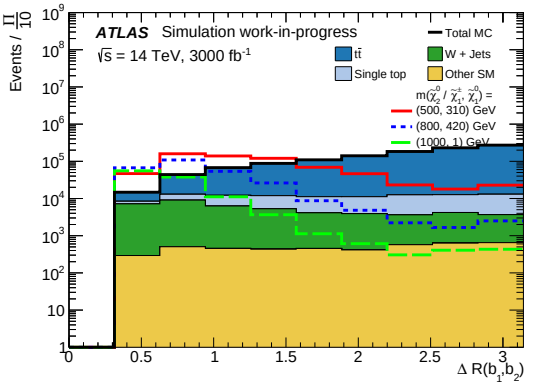
signal is chosen from each mass-splitting region for the purposes of comparing the kinematic distributions of signal and background, and for later deriving an optimal cut on the BDT output. The kinematic distributions forming inputs to the BDTs are shown, with benchmark signals overlaid, in Figure 8.4.



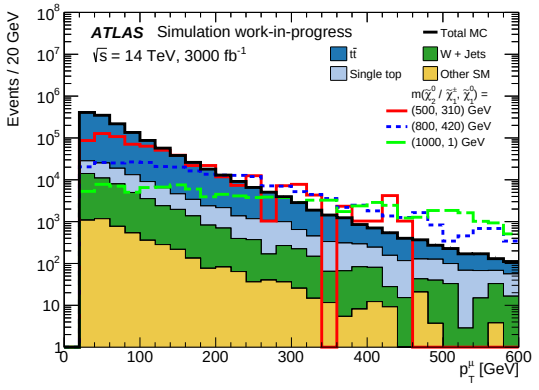
(a) p_T^{b1}



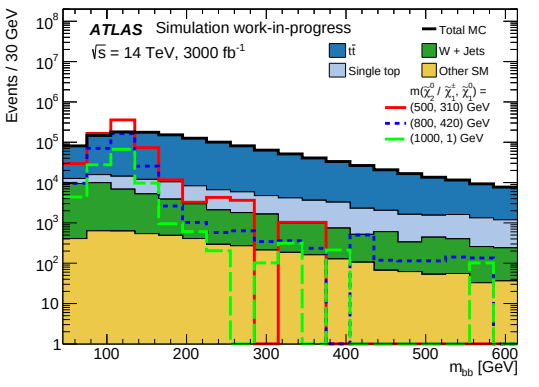
(b) p_T^{b2}



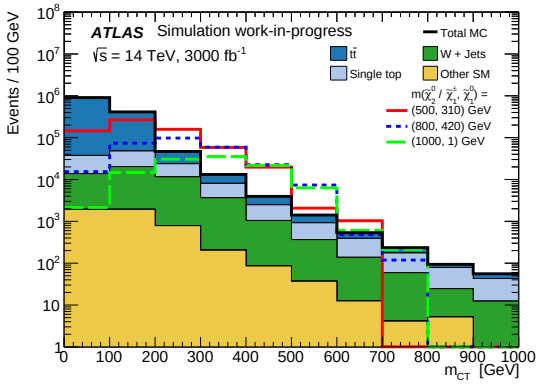
(c) $\Delta R(b1, b2)$



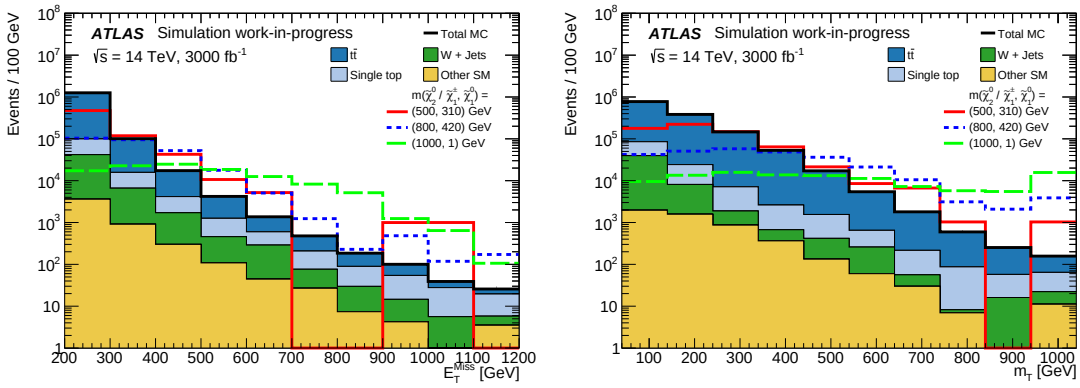
(d) $p_T^{\ell 1}$



(e) m_{bb}



(f) m_{CT}



(g) $E_{\mathrm{T}}^{\mathrm{miss}}$ (h) m_{T}

Figure 8.4: Kinematic and angular distributions for the BDT input variables at the preselection-level.

The estimate for signal and background yields in the SRs is obtained by placing a cut on the output of the BDTs. The optimal cut value is derived by scanning over the BDT output with an increasing lower bound, and calculating the binomial significance, Z_n, for that region's benchmark model and the SM background. The optimal cuts are shown in Table 8.5.

SR	Signal benchmark $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ [GeV]	BDT range
SR-M1	(500, 310)	> 0.25
SR-M2	(800, 420)	> 0.35
SR-M3	(1000, 1)	> 0.30

Table 8.5: Benchmark signal models and the corresponding optimised BDT output cut, derived by maximising the binomial significance, Z_n of the benchmark signal over the SM background.

The BDT output distributions for the SM backgrounds and the benchmark signal point for each region is shown in Figure 8.5. The arrows in these plots show the cut placed on the BDT output.

8.4 Systematic uncertainties

A joint strategy between the ATLAS and CMS collaborations was adopted for estimating systematic uncertaines for HL-LHC projection studies. For analyses with an existing Run-2 analysis, a prescription for extrapolating the current systematic uncertainties to 3000 fb^{-1} , where theoretical modelling uncertainties are expected to be half their current value. The extrapolation method for experimental uncertainties depend upon the system-

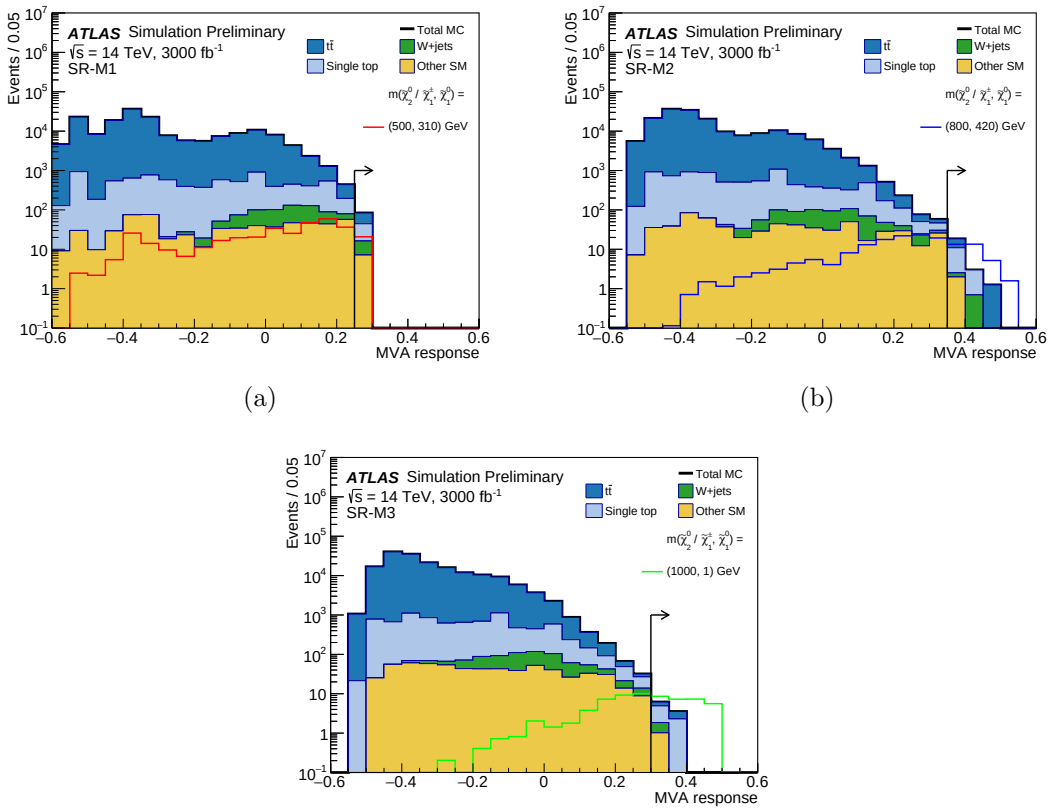


Figure 8.5: BDT outputs for HL-LHC projection. The arrow on each plot shows the cut placed on the BDT output, defining the SR.

atic under consideration and are provided as multiplicative factors which are applied to the Run-2 systematic uncertainties.

In this study, the systematics from the Run-2 analysis described in Chapter **??** are extrapolated from SR1Lbb-High, which is the signal region most kinematically similar to the regions presented in this analysis. The Run-4 extrapolated uncertainties are shown in Table 8.6.

SR1Lbb-High	
JET_JER_SINGLE_NP	10.30%
Wt-Interference	8.10%
ttbar-PS	6.40%
ttbar-Generator	5.50%
ttbar-Rad	5.00%
Wt-PS	4.50%
Wt-Rad	3.30%
JET_GroupedNP_2	2.90%
JET_GroupedNP_1	2.60%
MET_SoftTrk_Scale	2.00%
Wt-Generator	1.80%
EG_RESOLUTION_ALL	1.70%
JET_GroupedNP_3	1.10%
FT_EFF_B_systematics	0.98%
FT_EFF_C_systematics	0.97%
FT_EFF_Light_systematics	0.70%
MET_SoftTrk_ResoPara	0.45%
MET_SoftTrk_ResoPerp	0.42%
FT_EFF_extrapolation_from_charm	0.41%
EG_SCALE_ALL	0.36%
FT_EFF_extrapolation	0.18%
Pileup	0.17%
MUONS_ID	0.12%
JET_EtaIntercalibration_NonClosure	0.00%
EF_EFF	0.00%
MUONS_MS	0.00%
MUON_EFF_SYS	0.00%
Quadratic sum	18.13%

Table 8.6: A table showing the extrapolated systematic uncertainties based upon the Run-2 analysis.

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8.5 Results

The yields after the BDT cuts shown in Table 8.5 are shown below in Table 8.7. Entries denoted by '-' indicate there were no events of that particular process in the corresponding region. Figure 8.6 shows the 95% CL exclusion limit for this channel, as well as the 5σ

Processes	SR-M1	SR-M2	SR-M3
$t\bar{t}$	38.9 ± 8.4	8.7 ± 3.3	2.5 ± 1.8
single top	28.3 ± 4.8	10.7 ± 3.2	5.4 ± 2.5
W+jets	22.2 ± 5.4	3.0 ± 2.0	2.0 ± 1.8
ttV	5.1 ± 2.4	2.0 ± 1.4	1.0 ± 1.0
Diboson	2.0 ± 2.0	-	-
total background	96.5 ± 11.8	24.4± 5.2	10.9 ± 3.4
$m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (500, 300)$ GeV	20.7 ± 4.8	4.6 ± 2.3	1.0 ± 1.0
$m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (800, 420)$ GeV	44.3 ± 2.3	33.6 ± 2.0	21.2 ± 1.6
$m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1000, 1)$ GeV	32.2 ± 1.8	31.9 ± 1.8	28.9 ± 1.7

Table 8.7: Expected signal and background yields. The errors are statistical uncertainties. Entries marked − indicate a negligible background contribution.

discovery potential. The three signal regions are combined by taking the best expected sensitivity for each signal point. The systematics band, represented by the yellow area around the 95% CL exclusion line includes the extrapolated experimental and modelling systematics on the SM backgrounds, as well as the statistical uncertainty on all MC samples.

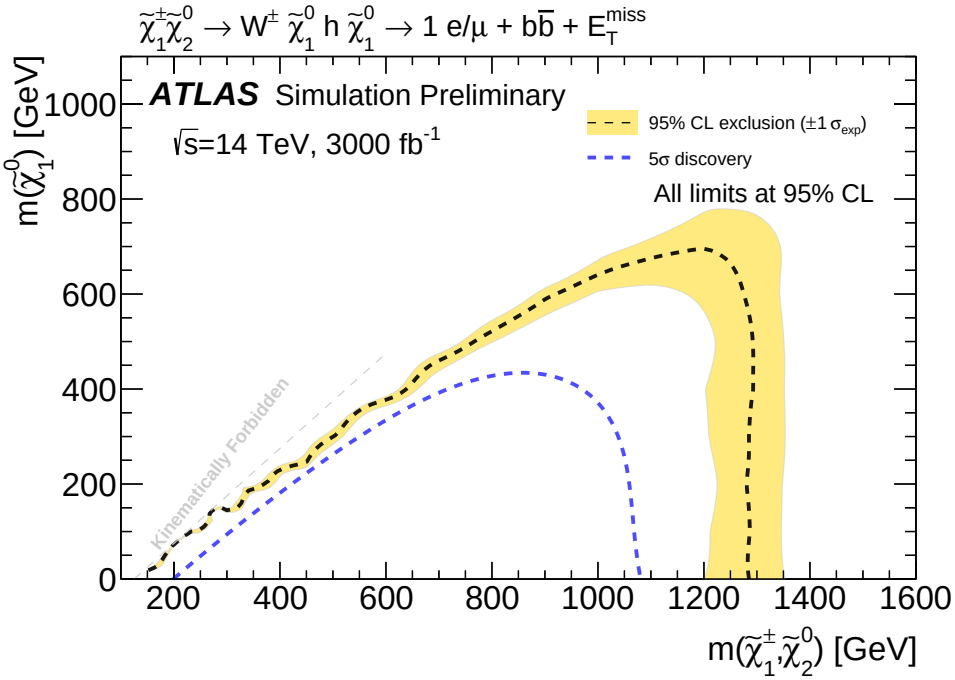


Figure 8.6: 95% CL exclusion limit and 5σ discovery limit for the analysis presented in this chapter.

As shown in Figure 8.6, it is expected that this channel can be excluded upto 1280 GeV, while there is discovery potential upto 1070 GeV. This far exceeds the exclusion limits at the end of Run-2, with results shown in Chapter 6 for both 36.1fb^{-1} and 139fb^{-1}. During this analysis, studies were performed using a both a conventional cut-based analysis and also using a deep neural network to perform binary classification of signal and background. These studies are included in Appendix A.

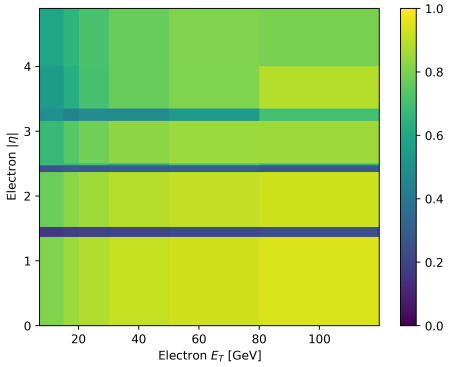
Appendix A

Sensitivity to $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production at the HL-LHC

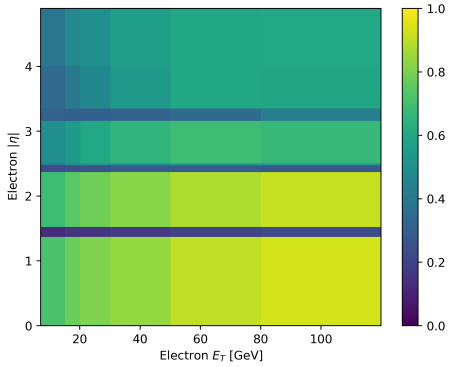
The first part of this appendix is dedicated to documenting the detector simulation parameterisations detailed in Chapter 8.

A.1 Detector simulation parameterisations

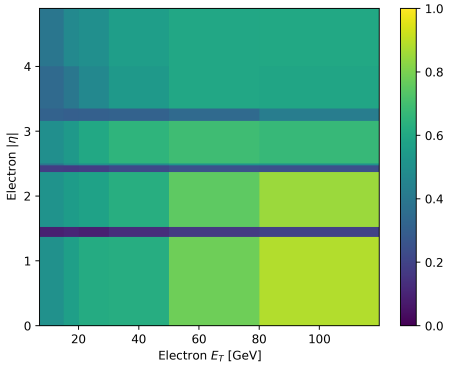
Electrons



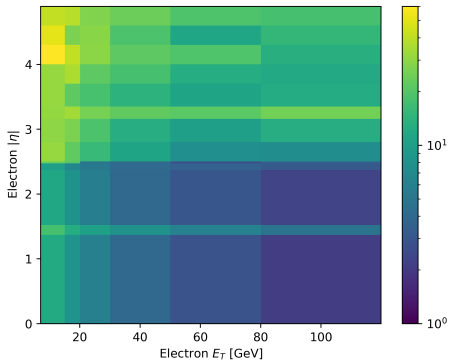
(a) ϵ_{rec} for 'loose' electron working point.



(b) ϵ_{rec} for 'medium' electron working point.



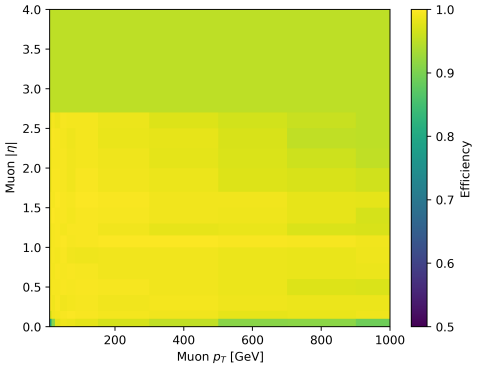
(c) ϵ_{rec} for 'tight' electron working point.



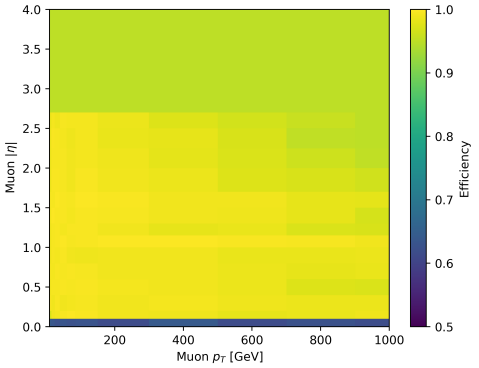
(d) Electron energy resolution (MeV).

Figure A.1: Electron ID efficiencies, energy resolution and charge-flip probability for the prospects study presented in Chapter 8. The

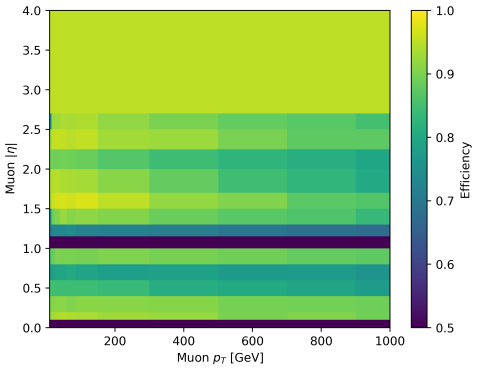
Muons



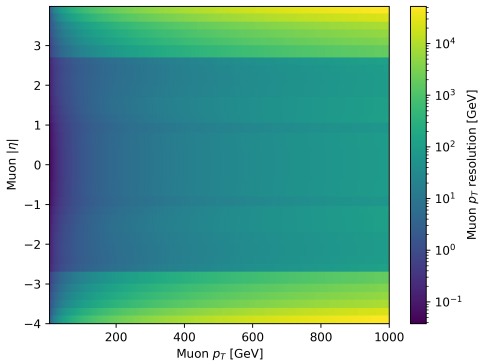
(a) ϵ_{rec} for 'loose' muon working point.



(b) ϵ_{rec} for 'tight' muon working point.



(c) ϵ_{rec} for 'high-p_T' muon working point.

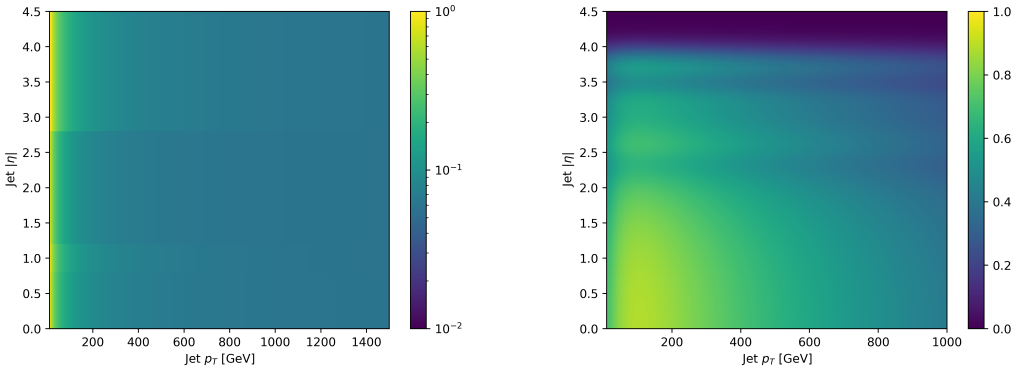


(d) Muon p_T resolution (MeV).

Figure A.2: Muon ID efficiencies and p_T resolution for the prospects study presented in Chapter 8. The

Taus

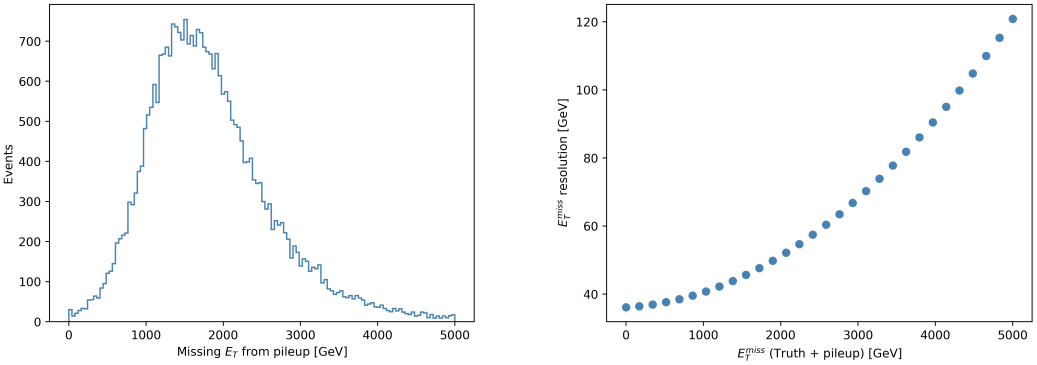
Jets



(a) (b)

Figure A.3: Parameterised relative jet energy resolution, shown in Figure A.3a, and parameterised b-tagging efficiency, shown in Figure A.3b, used in the HL-LHC detector simulation.

$E_{\mathrm{T}}^{\mathbf{miss}}$



(a) (b)

Figure A.4: Parameterised $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution from pileup, shown in Figure A.4a, and parameterised $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution, shown in Figure A.4b, used in the HL-LHC detector simulation.

A.2 Cut & count studies

A reoptimisation of the signal regions defined in Table 6.3 was performed to compare the potential sensitivity of the conventional analysis to the multivariate analysis described in Chapter 8. During the reoptimisation, the selections on the m_{bb} and m_{CT} variables are unchanged from Table 6.3. A scan over the lower bound of the m_T and E_T^{miss} variables was performed in steps of 10 GeV, with no upper bound. The lack of an upper bound on these variables means the regions are able to overlap, and therefore lose their orthogonality. However, as the final fit result takes the best expected sensitivity for each point, the orthogonality of signal regions is not required. The cuts maximising the binomial significance, Z_n, for the benchmark signal points shown in Table 8.5 are chosen for the three signal regions. These cuts are summarised in Table A.1. The sensitivity to each signal

	SRLM	SRMM	SRHM
m_{bb}	$\in [105, 135]$		
m_{CT}	> 160		
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 320	> 380	> 420
m_{T}	> 180	> 280	> 280

Table A.1: Reoptimised signal region selections for conventional analysis in order to compare sensitivity with the multivariate analysis described in Chapter 8. All cuts are in units of GeV.

point is assessed by calculating the binomial significance, Z_n, for each signal point in all three signal regions, and the combination of the regions takes the best expected significance for each point. The expected sensitivities can be seen in Figure A.5.

A.3 Deep learning studies

In addition to the the reoptimisation of the signal regions, described in the previous section, a study of the expected sensitivity using a DNN as a binary classifier was undertaken. A diagram of the DNN used in this study is shown in Figure A.6, and the model itself is implemented using Keras and Tensorflow. The inputs to the classifier are the same as described in Chapter 8for the BDT analysis, and the same procedure for separating the signal samples into three sets targetting different mass-splitting regimes is also the same. The DNN is trained on a GPU for a maximum of 10000 epochs, or until the accuracy of the classifier, evaluated using test data, has not improved in 2 epochs. To avoid overtraining, a dropout of 20% is used, such that upto 20% of the inputs to each layer can be ignored, at random, in each training epoch. Similarly to the BDT analysis described in Chapter 8, 3 classifiers are trained, one per mass-splitting region. The signal-background discrimination can be seen in Figure A.7.

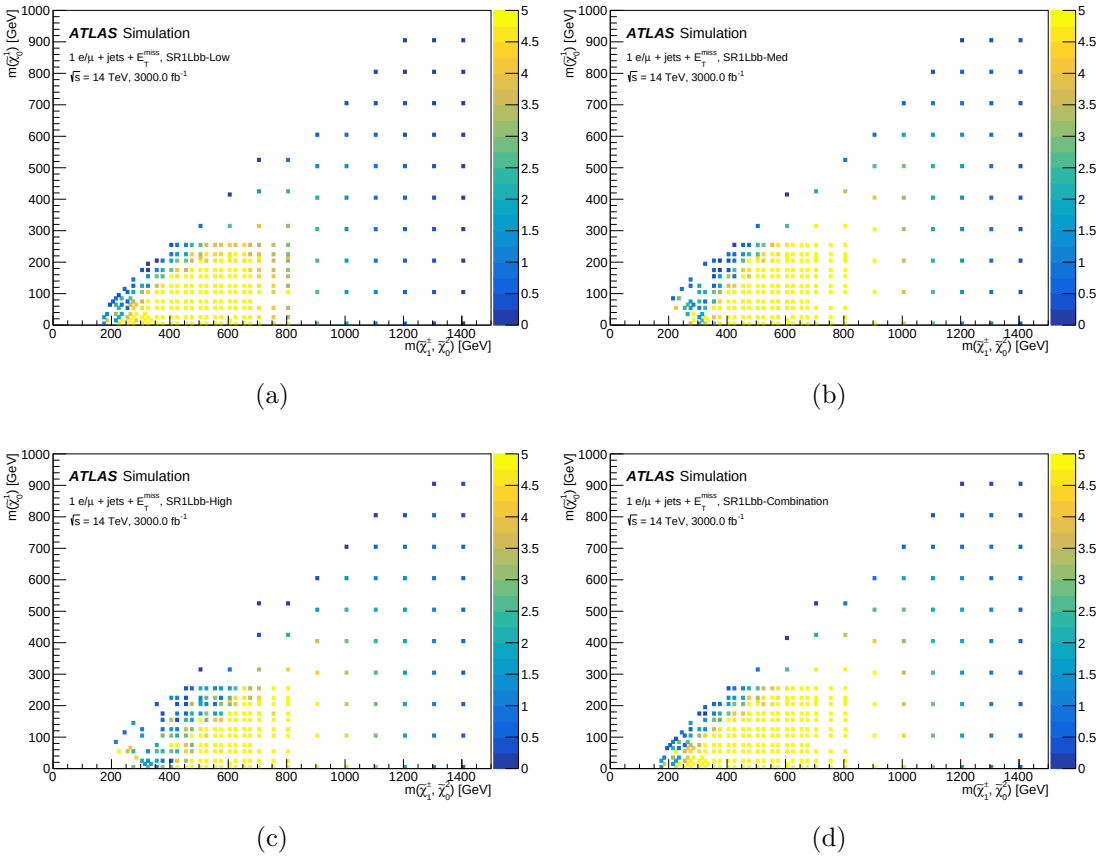


Figure A.5: Plots showing the binomial significance, Z_n, of each signal point in the reoptimised SRLM (A.5a), SRMM (A.5b), SRHM (A.5c), and the best expected combination (A.5d). All plots are produced assuming a total 15% background uncertainty.

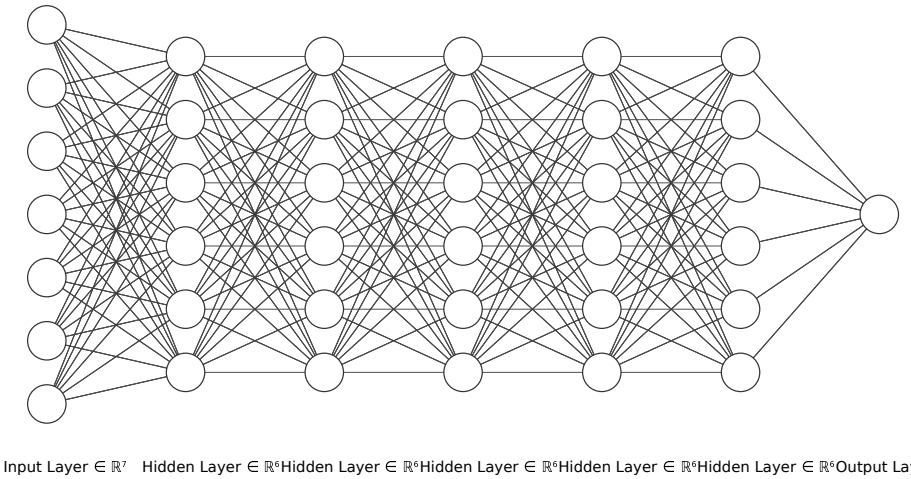
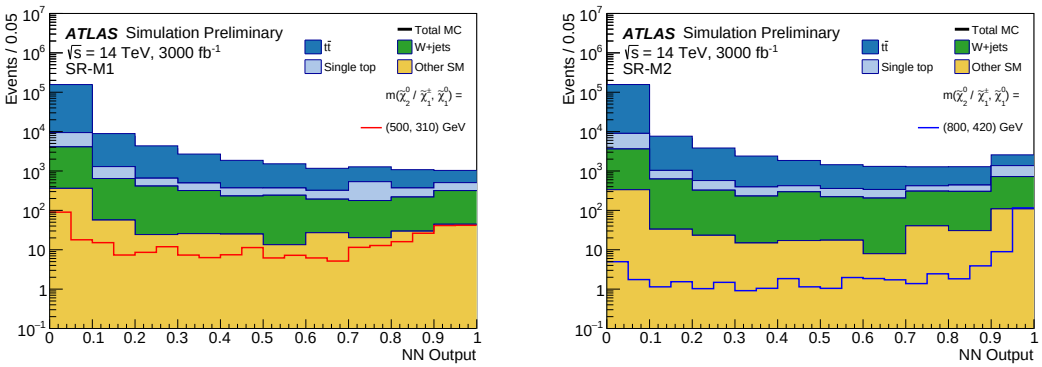
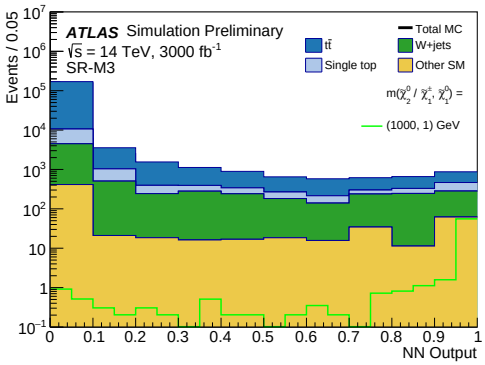


Figure A.6: A diagram showing the structure of the fully-connected Deep Neural Network tested as a binary classifier in the HL-LHC sensitivity study.



(a)

(b)



(c)

Figure A.7: Outputs for each of the DNN classifiers trained on the signal ensemble of each region and the dominant $t\bar{t}$ background.

The shape and range of the output of the DNN classifiers is due to the use of the sigmoid/softmax activiation on the output layer of the classifier, while TMVA performs a transformation of the form $y(x) = -\frac{1}{15}\left(\frac{1}{x} - 1\right)$ on the output of the classifier [41]. The DNN classifiers were not used in the final analysis as the sensitivity to the signal using a cut on the output of the DNN classifiers is much lower than for the BDT classifiers. While these studies were not performed due to time and resource constraints, it is expected that with larger MC statistics for the signal samples, fine-tuning of the DNN hyperparameters, and performing multi-class classification instead of binary classification, the DNN could achieve superior classification performance over the BDT classifiers.

A.4 Extending W+jets sample statistics

After applying all selections listed in Table 8.4 and the cuts on the BDT output listed in Table 8.5, the MC statistics in the W+jets sample was extremely low, such that the MC statistical uncertainty was $\sim 100\%$. For the final statistical analysis, a procedure was developed for extending the W+jets sample statistics in order to predict realistic yields and uncertainties. Using the detector simulation method described in Chapter 8, individual events in the nominal W+jets samples were smeared $N = 10$ times, to produce an extended sample with $\leq N$ times the input sample statistics. Due to the significant computing time of running this procedure, only B-filtered slices of the W+jets MC with $W \to e\nu/\mu\nu$ were used as the input for this procedure. A plot comparing the shape of the E_T^{miss} distribution for the nominal B-filtered samples with electrons, muons and taus and extended samples for B-filtered samples with electrons and muons is shown in Figure A.8.

The normalisation of the extended sample is corrected for the multiple smearing method by weighting each event by a factor $\frac{1}{N}$, and corrected for the missing $W \to \ell\nu$ slices by multiplying the expected yield of the extended sample by $N_{MC}^{nominal}/N_{MC}^{extended}$ evaluated at preselection level. The correction factor for the missing MC slices was found to be 1.21.

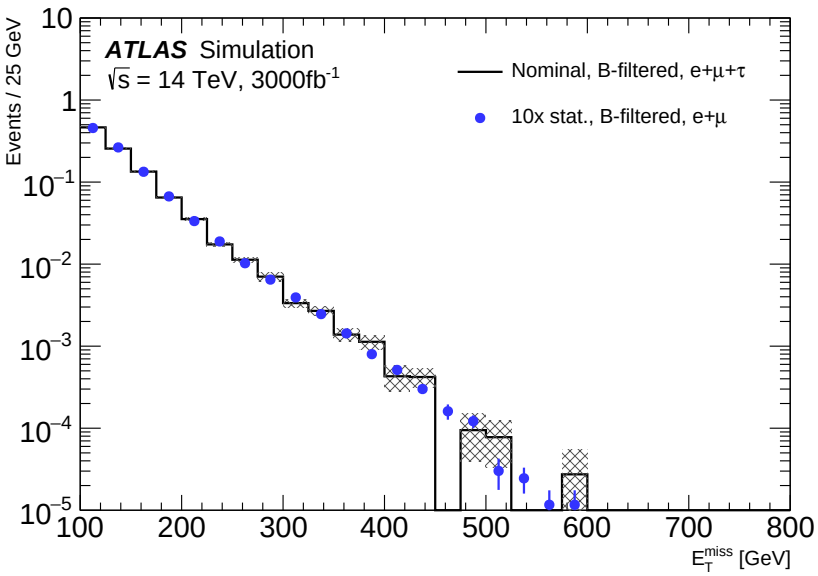


Figure A.8: A comparison of the E_T^{miss} distributions at preselection level for the nominal W+jets sample and the sample with extended MC statistics from the multiple event smearing method described in this section.

Appendix B

Testbeam studies of FE-I4 and RD53A performance at HL-LHC

The Run-2 period of data taking concluded in 2018, with ATLAS having recorded a dataset totalling 139 fb^{-1}, making way for the start of Long Shutdown 2 (LS2). With LS2 comes the start of preparations for the next phase of the scientific programme of the LHC and ATLAS, the High-Luminosity phase. The High-Luminosity LHC (HL-LHC) will begin running in the mid-2020s, bringing instantaneous luminosities around 5 times higher than in Run-2, reaching $7.5 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 14$ TeV. The total integrated luminosity to be recorded by ATLAS during this period is expected to total 3000-4000 fb^{-1}. Both the LHC and ATLAS will undergo numerous upgrades to prepare for the HL-LHC operations phase.

The first set of upgrades to the ATLAS detector, known as the Phase I upgrades, will take place in Long Shutdown 2 (LS2), between 2019-2021. The New Small Wheel (NSW) [72] will replace the current muon end-cap system, providing precision tracking and triggering capabilities. In addition, upgrades will be made to the electronics of the LAr calorimeter system, providing higher-granularity information to the L1 trigger [73].

Following the completion of Run-3 of LHC operations, both ATLAS and LHC will go into Long Shutdown 3 (LS3). During the High-Luminosity LHC (HL-LHC) phase, the instantaneous luminosity is estimated to result in an average of 200 inelastic *pp* collisions in each bunch-crossing, with bunch-crossings occuring every 25 ns. This instantaneous luminosity far exceeds the design of the ATLAS detector described in Chapter 2. The increase in luminosity will render the current ID of the ATLAS detector inoperable, and hence a new tracker will be installed, known as the ATLAS Inner Tracker (ITk). The ITk will be constructed using only silicon pixel and strip modules, as these technologies are suited for high-occupancy, high-radiation environments. This Appendix documents studies performed on the performance of pixel modules for the upcoming ATLAS Inner Tracker

(ITk) upgrade.

B.1 ATLAS ITk upgrade

B.2 Experimental setup

B.3

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$$\sqrt{s}$$

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of

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