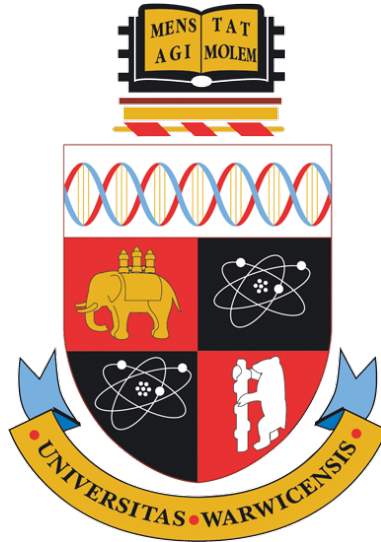




Progress towards the first measurement of the V_{cb} element of the CKM matrix in semi-leptonic $t\bar{t}$ decays

by

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Declarations

This work is submitted to the University of Warwick as part of my application for the degree of Doctor of Philosophy. It was produced by me and has not been submitted for any other degree applications.

As is usual in experimental particle physics this work was performed as part of an analysis team. This team consisted of myself, my supervisor and one other student at a time. Due to the small size of the analysis team I contributed to most aspects of the analysis. The following are parts of the analysis where the majority of the work was done by others:

- Preparation of the initial analysis concept and feasibility study [16].
- Selection of the basic event selection triggers and criteria
- Creation of the kinematic χ^2 quality metric
- Creation of the missing transverse energy correction
- Optimisation of the flavour tagging working point

The following are parts of the analysis where the majority of work was done by me:

- Studies to exclude fully-leptonic $t\bar{t}$ decays from event selection
- Studies to reduce gluon contamination
- Implementation of the analysis within the TRExFitter framework and all presented systematic error studies
- Inclusion of non- $t\bar{t}$ backgrounds and their uncertainties in the fit

- Studies to select the kinematic variable to fit to in order to separate semi-leptonic $t\bar{t}$ events from fully-leptonic $t\bar{t}$ events, non- $t\bar{t}$ backgrounds and heavy flavour $t\bar{t}$ backgrounds
- Implementation of selection criteria to separate $t\bar{t}$ simulated events into heavy flavour samples and the implementation of appropriate uncertainties on these in the fit
- Studies comparing simulated distributions with data in control regions
- Evaluation of the performance of alternative flavour-tagging working points

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Abstract

A method of measuring the $|V_{cb}|$ element of the CKM matrix for the first time in $t\bar{t}$ decays using the ATLAS detector at the Large Hadron Collider is presented. This method uses a binned template profile likelihood fit to measure the fraction of $t\bar{t}$ events where one top decays as $t \rightarrow Wb \rightarrow l\nu b$ and the other as $t \rightarrow Wb \rightarrow cbb$. The expected statistical and systematic uncertainties are evaluated for the Run 2 data-taking period corresponding to a centre-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ and an integrated luminosity of 139 fb^{-1} . Using an optimised flavour tagging working point not yet calibrated gave a fractional uncertainty of $\Delta|V_{cb}|/|V_{cb}| = 0.13(\text{stat.}) \oplus 0.13(\text{syst.}) = 0.19$, a different flavour tagging working point likely to be calibrated on a shorter timescale gave an uncertainty of $\Delta|V_{cb}|/|V_{cb}| = 0.16(\text{stat.}) \oplus 0.16(\text{syst.}) = 0.22$.

Chapter 1

Introduction

The Standard Model of particle physics is an incredibly successful model which describes the behaviour of the fundamental particles of the universe. However, it is known not to be a complete model and as such many different measurements are made to attempt to gain a deeper understanding of physics within the Standard Model and perhaps beyond. There are a large number of free parameters in the Standard Model which must be measured experimentally rather than being predicted by theory. Among these free parameters are parameters which define the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. This matrix relates the weak and mass eigenstates of quarks. The focus of this thesis is measuring the magnitude of V_{cb} , one of the elements of this matrix. Previous measurements of $|V_{cb}|$ have only ever been performed in B -meson decays where the W boson which decays to a charm and a bottom quark is off-shell. This thesis reports on work done to use the ATLAS detector at the Large Hadron Collider to perform the first measurement of $|V_{cb}|$ in $t\bar{t}$ decays, where the decaying W boson is on-shell. The majority of the work to complete this measurement has been completed and is presented here. The statistical uncertainty has been calculated and all systematic uncertainties have been included in the fit except for those due to flavour-tagging and a re-weighting process which must be applied to $t\bar{t}$ Monte Carlo samples. An estimate of the total expected uncertainty on the measurement is made and the steps to complete the measurement of $|V_{cb}|$ are laid out.

Chapter 2 of this thesis gives an overview of the Standard Model and the physics of the CKM matrix. Chapter 3 describes the Large Hadron Collider and the ATLAS detector. Chapter 4 describes the process of reconstructing physics objects followed by a description of the simulated Monte Carlo samples used in this thesis. The requirements for events to be selected for use in this analysis are set out and explained in Chapter 5. Chapter 6 describes the fitting method and the variables used in the fit, it also gives the result of a fit to simulated data accounting only for statistical error. The systematic uncertainties affecting the

analysis are detailed in Chapter 7. Chapter 8 presents some studies comparing kinematic distributions in data with those in simulation in some control regions. The implications of those results on the analysis are discussed. In Chapter 9 the total uncertainties in the measurement of $|V_{cb}|$ found for fits to simulated data are presented along with a discussion of these results and the steps required to run the fit on data. Steps which could be taken to reduce the uncertainties in future iterations of the analysis are also outlined. Finally, a brief summary of the results and the next steps are outlined in the conclusion in Chapter 10.

Chapter 2

Theoretical Background

2.1 The Standard Model of Particle Physics

2.1.1 Overview

The Standard Model (SM) of particle physics mathematically describes the fundamental particles that make up the universe and their interactions. The SM is a relativistic quantum field theory (QFT) where particles are excitations of the fundamental fields described by the theory.

Particles in the Standard Model have an intrinsic angular momentum called spin. Particles are split into two classes, based on their spin: fermions and bosons. Fermions are those with a half-integer spin while bosons are those with integer spin. The fundamental fermions consist of six quarks and six leptons. There are three generations of quarks with two quarks in each generation. One of these has a charge of $+\frac{2}{3}e$ and the other $-\frac{1}{3}e$. Their properties are summarised in Table 2.1. Leptons are also split into three generations with a charged lepton and corresponding neutrino in each generation. Table 2.2 summarises the properties of the leptons.

Particle	Charge/e	Mass
Up (u)	$+2/3$	2.16 MeV
Down (d)	$-1/3$	4.67 MeV
Charm (c)	$+2/3$	1.27 GeV
Strange (s)	$-1/3$	93 MeV
Top (t)	$+2/3$	172.8 GeV
Bottom (b)	$-1/3$	4.18 GeV

Table 2.1: Properties of the quarks. Masses are presented without uncertainties and taken from [1]. Masses use the modified minimal subtraction $\overline{\text{MS}}$ renormalisation scheme with $\mu = 2 \text{ GeV}$ for u, d, s quarks. The c and b quarks are renormalised at the $\overline{\text{MS}}$ mass. The top quark mass is measured from event kinematics [1].

The Standard Model describes three of the four fundamental forces, elec-

Particle	Charge/e	Mass
Electron (e)	-1	0.5110 MeV
Electron neutrino (ν_e)	0	< 1.1 eV
Muon (μ)	-1	105.7 MeV
Muon neutrino (ν_μ)	0	< 1.1 eV
Tau (τ)	-1	1.777 MeV
Tau neutrino (ν_τ)	0	< 1.1 eV

Table 2.2: Properties of leptons. Masses are presented without uncertainties and taken from [1]. Within the Standard Model neutrinos are massless.

tromagnetism, the weak force and the strong force. Gravity is not included. Forces in the Standard Model act through the exchange of spin-1 gauge bosons. The strength of the forces is determined by the coupling of the gauge bosons to the fermions. There is one more fundamental particle in the Standard Model, the Higgs boson. This is a spin-0 scalar particle. The Higgs boson is an excitation of the Higgs field which is responsible for giving all massive fundamental particles their mass. The properties of the bosons of the Standard Model are summarised in Table 2.3.

Particle	Force	Charge/e	Spin	Mass
Photon (γ)	Electromagnetism	0	1	0
Gluon (g)	Strong	0	1	0
W boson ($W^\pm$)	Weak	± 1	1	80.38 GeV
Z boson (Z)	Weak	0	1	91.19 GeV
Higgs boson (H)	-	0	0	125.3 GeV

Table 2.3: Properties of the fundamental bosons of the standard model. Masses are presented without uncertainties and taken from [1].

The Standard Model has been hugely successful, making predictions which have later been experimentally verified including the existence of the top quark [17, 18], the tau neutrino [19], and the Higgs boson [20, 21]. However, it does have limitations which make it clear that it is not a complete theory explaining all that we observe. To give a few examples: Gravity is not included in the model which it would have to be for a complete model. Astronomical observations show clearly that dark matter must exist but the Standard Model does not include any suitable candidates. Neutrinos in the Standard Model are massless, however, the observation of neutrino oscillations show that they do in fact have mass [22–24].

2.1.2 Quantum Electrodynamics

Quantum Electrodynamics (QED) is the quantum field theory that describes the interaction of particles via the electromagnetic force. The Lagrangian

density of QED is given by:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\gamma^\lambda D_\lambda - m)\psi. \quad (2.1)$$

The first term is the Lagrangian for Maxwell's equations in the absence of any electromagnetic sources. $F_{\mu\nu}$ is the field strength tensor defined as $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. A_μ is a massless spin 1 vector boson field corresponding to the photon. The second term is the Dirac Lagrangian which describes the motion of a free fermion. $\psi(x)$ are four-component spinors representing the fermions while $\bar{\psi}$ is the adjoint fermion spinor defined as $\bar{\psi} \equiv \psi^\dagger \gamma^0$. γ^λ are the gamma or Dirac matrices:

$$\begin{aligned} \gamma^0 &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, & \gamma^1 &= \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}, \\ \gamma^2 &= \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}, & \gamma^3 &= \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}. \end{aligned} \quad (2.2)$$

The Dirac matrices are constructed such that they obey the anti-commutation relation $\{\gamma^\mu, \gamma^\nu\} = 2\eta^{\mu\nu}$ where $\eta^{\mu\nu}$ is the Minkowski metric:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}. \quad (2.3)$$

Finally, the gauge covariant derivative $D_\lambda = \partial_\lambda - iqA_\lambda$.

The Lagrangian is constructed to be invariant under local $U(1)$ gauge transformations of the form $\psi(x) \rightarrow \psi'(x) = e^{iq\chi(x)}\psi(x)$. To achieve this A_μ must also transform as $A_\mu(x) \rightarrow A'_\mu(x) = A_\mu(x) - 1/q\partial_\mu\chi(x)$. The $-q\bar{\psi}\gamma^\lambda\psi A_\lambda$ term in the expanded Eq. 2.1 represents the interaction of the photon and fermion with strength governed by the charge q .

2.1.3 Quantum Chromodynamics

Quantum chromodynamics (QCD) describes the strong interactions between quarks and gluons. QCD is a non-Abelian gauge theory with $SU(3)$ symmetry.

Quarks and gluons have a property called colour charge or simply colour which is conserved within QCD. A quark's colour can be red, green or blue

while an anti-quark can be anti-red, anti-green or anti-blue. Colour confinement is the observation that coloured particles always form colour singlet states and never exist as free particles. In the case of quarks these are hadrons which are either mesons or baryons. Mesons consist of an equal number of quarks and anti-quarks, most commonly one of each. Baryons are made of an odd number of quarks, generally three quarks (with red, blue and green colour).

The QCD Lagrangian density is given by:

$$\mathcal{L}_{\text{QCD}} = \bar{\psi} (i\gamma_\mu D^\mu - m) \psi - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}, \quad (2.4)$$

where ψ is a colour triplet:

$$\psi = \begin{pmatrix} \psi_r \\ \psi_g \\ \psi_b \end{pmatrix} \quad (2.5)$$

and the covariant derivative D_μ and Gluon field strength tensor $G_{\mu\nu}^a$ are given by:

$$D_\mu = \partial_\mu + ig_s \frac{\lambda^a}{2} A_\mu^a, \quad (2.6)$$

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - g_s f^{abc} A_\mu^b A_\nu^c. \quad (2.7)$$

Here g_s is the strong force's coupling constant, f^{abc} are the structure constants of the group while λ^a are the 8 Gell-Mann matrices that generate the $SU(3)$ group [25] and obey the commutation relation:

$$\left[\frac{\lambda^a}{2}, \frac{\lambda^b}{2} \right] = i f^{abc} \frac{\lambda^c}{2}. \quad (2.8)$$

A_μ^a are the eight gluon fields. Since gluons carry colour themselves they are able to interact with other gluons: they are self-coupling.

2.1.4 Electroweak unification

In the Standard Model the weak interactions mediated by the Z and W bosons are unified with electromagnetism into a single electroweak model.

The left and right-handed chirality components of fermion fields are given by the projection operators P_L and P_R such that:

$$\psi_L = P_L \psi = \frac{1 - \gamma^5}{2} \psi, \quad (2.9)$$

$$\psi_R = P_R \psi = \frac{1 + \gamma^5}{2} \psi. \quad (2.10)$$

$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$ is the product of the four Dirac matrices. In the relativistic limit a particle's chirality corresponds to its helicity which is the projection of

its spin onto its direction of motion. A right-handed helicity corresponds to the spin being in the same direction as its motion.

The electroweak model requires local gauge-invariance under the $SU(2)_L \times U(1)_Y$ symmetry group. The L refers to the fact that the $SU(2)$ transformation only applies to the left-handed chirality components of particles (and right-handed chirality components of anti-particles).

The Y refers to the weak hypercharge. The theory has three vector gauge bosons (W^1, W^2, W^3) of weak isospin I and the B boson of weak hypercharge Y . The electric charge Q is related to the weak isospin and hypercharge of the particle by:

$$Q = I_3 + \frac{Y}{2} \quad (2.11)$$

where I_3 is the third component of the weak isospin.

Left-handed chirality fermions are paired as doublets with isospin $I = 1/2$ while right-handed chirality fermions are singlets with $I = 0$, as shown in Table 2.4. Since neutrinos only interact via the weak force; right-handed neutrinos do not interact via any force within the Standard Model and as such are not included in the table.

				I_3	Y
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	1/2	1/3
	u_R	c_R	t_R	-1/2	1/3
	d_R	s_R	b_R	0	4/3
				0	-2/3
Leptons	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	1/2	-1
	e^-	μ^-	τ^-	-1/2	-1
	e_R	μ_R	τ_R	0	-2

Table 2.4: Summary of the electroweak properties of fermions.

Field strength tensors for the W^i and B bosons are defined from the W^i and B fields as:

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g\epsilon^{ijk}W_\nu^jW_\mu^k, \quad (2.12)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu. \quad (2.13)$$

A covariant derivative is defined as:

$$D_\mu = \partial_\mu + i\frac{g}{2}\sigma^a W_\mu^a + i\frac{g'}{2}YB_\mu, \quad (2.14)$$

where σ^a are the Pauli matrices. Using these definitions and Feynman slash notation where $\not{a} = \gamma^\mu a_\mu$ the fermion part of the Lagrangian density of one generation of fermions is:

$$\mathcal{L}_{\text{fermion}} = i\bar{\psi}_L \not{D}\psi_L + i\bar{\psi}_Q \not{D}\psi_Q + i\bar{\psi}_{e_R} \not{D}\psi_{e_R} + i\bar{\psi}_{u_R} \not{D}\psi_{u_R} + i\bar{\psi}_{d_R} \not{D}\psi_{d_R}. \quad (2.15)$$

The first term corresponds to the left handed lepton doublet, the second the left handed quark doublet followed by the right-handed electron singlet and finally the right-handed up and down singlets.

During Electroweak symmetry breaking (EWSB) the $SU(2)_L \times U(1)_Y$ symmetry is broken giving the $U(1)$ symmetry of QED. In this process the W^i and B fields mix to give the A , $W^\pm$ and Z vector boson fields of the bosons we observe in nature. The $W^\pm$ gauge boson fields are a linear combination of W^1 and W^2 :

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2). \quad (2.16)$$

The A and Z fields come from the mixing of W^3 and B :

$$A_\mu = \cos \theta_W B_\mu + \sin \theta_W W_\mu^3, \quad (2.17)$$

$$Z_\mu = \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu. \quad (2.18)$$

θ_W is the weak mixing angle or Weinberg angle which is related to the couplings g and g' by:

$$\sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}, \quad \cos \theta_W = \frac{g}{\sqrt{g^2 + g'^2}}. \quad (2.19)$$

2.1.5 Higgs Boson

It is not possible to add mass terms for the W and Z bosons to the Lagrangian without breaking local gauge invariance. However, we know that the W and Z bosons do have mass and so a mechanism is required to give them mass. There is also a similar problem with fermion masses, where adding a mass term would couple the fields of left and right-handed fermions together and break the gauge symmetry. The solution to this is provided by the Higgs mechanism [26–29].

An $SU(2)$ doublet of complex scalar fields is introduced:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}. \quad (2.20)$$

An additional term is introduced to the Lagrangian:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mu^2 |\Phi|^2 + \lambda |\Phi|^4. \quad (2.21)$$

The last two terms are the negative of the potential of the Lagrangian with $\mu^2 > 0$. The potential is minimised when:

$$\Phi^\dagger \Phi = \frac{\mu^2}{2\lambda}. \quad (2.22)$$

It can be seen that this does not have a single solution, instead there are an infinite number of solutions in the complex plane with $|\Phi| = \mu/\sqrt{2\lambda}$. Because of gauge invariance we are able to take the solution to be:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad (2.23)$$

with the vacuum expectation value (VEV):

$$v = \sqrt{\frac{\mu^2}{\lambda}}. \quad (2.24)$$

The next step is to expand around the VEV:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \quad (2.25)$$

where $H(x)$ is a scalar field. This gives the Lagrangian:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = & \frac{1}{2} \partial_\mu H \partial^\mu H + \frac{1}{8} (v + H)^2 (g^2 |W_\mu^1 + iW_\mu^2|^2 + |gW_\mu^3 - g'B_\mu|^2) \\ & - \frac{\mu^2}{2} (v + H)^2 - \frac{\lambda}{4} (v + H)^4. \end{aligned} \quad (2.26)$$

Using eqs. (2.16) to (2.19) this becomes:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = & \frac{1}{2} \partial_\mu H \partial^\mu H + \frac{1}{4} (v + H)^2 (g^2 |W_\mu^+ W_\mu^-|^2 + \frac{g^2 + g'^2}{2} Z_\mu Z^\mu) \\ & - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4. \end{aligned} \quad (2.27)$$

The W and Z bosons have acquired mass terms with:

$$m_W = \frac{vg}{2}, \quad m_Z = \frac{v}{2} \sqrt{g^2 + g'^2}. \quad (2.28)$$

It can also be seen that the Higgs field has acquired a mass giving us the Higgs boson with mass:

$$m_H = \sqrt{2\lambda v^2}. \quad (2.29)$$

The Higgs Boson was experimentally discovered in 2012 [20, 21]. The current measured value of the Higgs mass is $m_H = 125.25 \pm 0.17$ [30].

2.2 The CKM Matrix

In Section 2.1.5 it was shown that the Higgs mechanism generates the masses of the gauge bosons but it also generates the masses of fermions. This is achieved by adding Yukawa terms to the Lagrangian. The quark terms are:

$$\mathcal{L}_Y = -Y_{ij}^d \overline{Q_{Li}^I} \Phi d_{Rj}^I - Y_{ij}^u \overline{Q_{Li}^I} \epsilon \Phi^* u_{Rj}^I + h.c. \quad (2.30)$$

$Y^{d/u}$ are 3×3 complex Yukawa matrices and the indices i and j are indices in generation space. As before Φ is the Higgs field and ϵ is the 2×2 anti-symmetric tensor acting in the space of weak isospin. Q_L^I are the three left-handed quark doublets while d_{Rj}^I and u_{Rj}^I are the three right-handed down and up-type quark singlets. Expanding around the VEV will give terms of the form:

$$\frac{v}{\sqrt{2}} Y_{ij}^q \overline{q_{Li}^q} q_{Rj}^q. \quad (2.31)$$

Here q represents either an up or down quark and the $v/\sqrt{2} Y_{ij}^q$ become the mass matrices of the quarks. The Yukawa matrices are not diagonal which shows that the mass eigenstates of quarks do not correspond to the weak eigenstates participating in the weak interaction. To get the mass terms of the physical quarks the Yukawa matrices must be diagonalised using unitary matrices $V_{qL/R}$:

$$Y^d \rightarrow V_{qL} Y^q V_{qR}^\dagger. \quad (2.32)$$

The corresponding basis shift is applied to the left-handed quark factors:

$$q_{iL} \rightarrow V_{qL} q_{iL}. \quad (2.33)$$

The coupling of the $W^\pm$ to the quarks then shifts as:

$$\frac{g}{\sqrt{2}} \overline{u_{iL}} \gamma^\mu W_\mu^+ d_{iL} \rightarrow \frac{g}{\sqrt{2}} \overline{u_L} \gamma^\mu W_\mu^+ V_{uL} V_{dL}^\dagger d_L, \quad (2.34)$$

where $V_{uL} V_{dL}^\dagger = V_{\text{CKM}}$ is the CKM (Cabbibo-Kobayashi-Maskawa) matrix [31] which we see relates the mass eigenstates of the quarks to their weak eigenstates:

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \quad (2.35)$$

The physical implication of the CKM matrix is that the W boson can decay to any charge-conserving quark anti-quark pair with the couplings of these decays specified by the matrix. Thus the probability of a decay of the form $W \rightarrow qq'$ will be proportional to the CKM matrix element $|V_{qq'}|^2$.

The CKM matrix is unitary by construction since it is the product of two basis-changing matrices. This strongly constrains the elements of the matrix. The matrix has 9 complex elements which corresponds to 18 degrees of freedom. The constraint provided by unitarity reduces this to 9 degrees of freedom: 3 moduli and 6 complex phases. The phases of the mass eigenstates are not fixed and as such 5 of the phases can be removed by redefinition of the quark phases. This one remaining phase is responsible for charge-parity (CP) violation in the quark sector.

The CKM matrix can be parameterised in terms of 3 mixing angles θ_{ij} and 1 CP violating phase δ . Using the notation $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$ this can be written:

$$V_{\text{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}. \quad (2.36)$$

An alternative parameterisation is the Wolfenstein parameterisation [32]. It is observed experimentally that $s_{13} \ll s_{23} \ll s_{12} \ll 1$, this hierarchy can be made explicit using powers of a parameter $\lambda = s_{12}$. The CKM matrix is then expressed in terms of the parameters λ, A, ρ and η defined through:

$$s_{23} = A\lambda^2, \quad s_{13}e^{i\delta} = A\lambda^3(\rho + i\eta) \quad (2.37)$$

meaning that the CKM matrix takes the form:

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \quad (2.38)$$

The current independently measured absolute values of the elements of the CKM matrix are [30]:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97373 \pm 0.00031 & 0.2243 \pm 0.0008 & (3.82 \pm 0.20) \times 10^{-3} \\ 0.221 \pm 0.004 & 0.975 \pm 0.006 & (40.8 \pm 1.4) \times 10^{-3} \\ (8.6 \pm 0.2) \times 10^{-3} & (41.5 \pm 0.9) \times 10^{-3} & 1.014 \pm 0.029 \end{pmatrix}. \quad (2.39)$$

These independent measurements of each element of the matrix can be combined

into a global fit which imposes unitarity on the matrix. This fit gives [30]:

$$|V_{\text{CKM}}|_{\text{GFit}} = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}. \quad (2.40)$$

2.3 Previous Measurements of $|V_{cb}|$

Previous measurements of $|V_{cb}|$ have used exclusive and inclusive semileptonic decays of B mesons to charmed final states [30]. Measurements using exclusive decays use B decays to specific states which include a charmed D or D^* meson, for instance $B^0 \rightarrow D^{*}(2010)^- \mu^+ \nu_\mu$ or $B^0 \rightarrow D^- \mu^+ \nu_\mu$. Inclusive measurements use the total semileptonic branching decay rate to states with a charmed hadron and a charged lepton.

Inclusive measurements are reliant on the Operator Product Expansion which is used in the Heavy Quark Expansion [30, 33, 34]. This gives the total decay rate of the B meson as being proportional to the product of $|V_{cb}|^2$ and a factor obtained from a systematic expansion in powers of Λ/m_b where Λ is a hadronic scale. Details of this expansion can be found in Chapter 76 of Ref. [30]. The average value obtained by these inclusive measurements is:

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \quad (\text{inclusive}). \quad (2.41)$$

Exclusive measurements use form factors which are calculated non-perturbatively which parameterise the effects of the strong interactions of the quarks in the mesons. Measurements either use the Caprini, Lellouch and Neubert (CLN) parameterisation [35] or the more general model by Boud, Grinstein and Lebed (BGL) [36]. The CLN parameterisation does not account for some higher order corrections which are now relevant and so the BGL expansion is now favoured [30]. The average of measurements using this expansion is:

$$|V_{cb}| = (39.4 \pm 0.8) \times 10^{-3} \quad (\text{exclusive}). \quad (2.42)$$

There is a 2.4σ tension between the inclusive and exclusive results [30] but if combined their average is:

$$|V_{cb}| = (40.8 \pm 1.4) \times 10^{-3}. \quad (2.43)$$

This tension corresponds to a p -value of approximately 1% [30] if assuming Gaussian errors. Since some of the uncertainties are theoretical and thus may not be Gaussian this may be an underestimate. Although interesting this is

not considered a very small probability within particle physics.

2.4 Semi-leptonic $t\bar{t}$ events

The leading order Feynman diagrams for $t\bar{t}$ production in proton-proton collisions are shown in Figure 2.2 with the quark anti-quark annihilation diagram only occurring due to the presence of sea anti-quarks. About 90% of $t\bar{t}$ production in 13 TeV collisions at the LHC is from gluon-gluon fusion [30]. The total cross-section of $t\bar{t}$ production can be estimated theoretically using the parton distribution functions of the protons and the cross-sections of the parton processes.

After production the top quarks then decay. Due to their large masses they can each decay to an on-shell W -boson and a quark, as such the top quark has a very short lifetime and decays before hadronisation can occur [30]. As can be seen by the values of $|V_{tb}|$ given in equations 2.39 and 2.40 in almost all cases the top quark will decay as $t \rightarrow W^+b$. In this work we refer to the b -quarks coming directly from the top decays as the “bachelor” bs .

The W boson can then either decay hadronically to quarks $W \rightarrow q\bar{q}'$ or leptonically $W \rightarrow l\nu_l$. Hadronic decays occur in $67.41 \pm 0.27\%$ of cases [30]. Semi-leptonic $t\bar{t}$ decays are those where one W decays hadronically and one leptonically as seen in Figure 2.2. The up-type quark in the hadronic W decay will either be an up quark or a charm quark. Except for negligible phase-space factors due to the masses of the quarks the probabilities of the W decaying to a final state with an up quark or a charm quark are equal. By definition $|V_{cb}|^2$ is then given by:

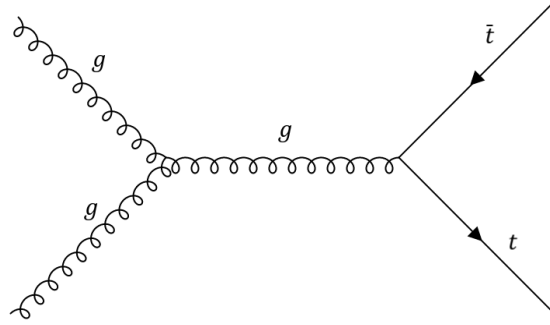
$$|V_{cb}|^2 = \frac{\Gamma(W \rightarrow cb)}{\Gamma(W \rightarrow cq)}, \quad (2.44)$$

where q is any of d, s, b .

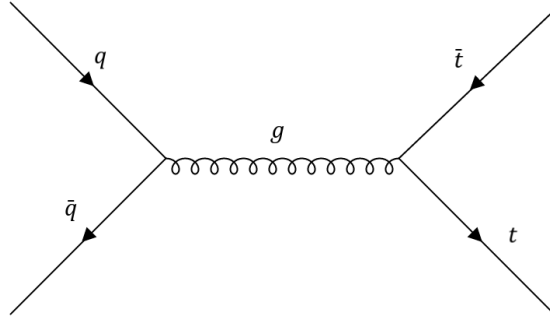
This analysis measures $|V_{cb}|$ directly by measuring how often $W \rightarrow cb$ occurs in semi-leptonic $t\bar{t}$ events. This was initially going to be achieved using a cut and count method suggested by Ref. [16] but moved to use the binned likelihood fit set out in Chapter 6. As outlined in Section 2.3, previous measurements have always been performed at the mass scale of the B meson. In contrast this measurement is at the W mass scale and avoids the theoretical complexities of extracting $|V_{cb}|$ in B meson decays where the W boson is off-shell. This measurement would be completely independent of previous measurements and should provide an independent test of the theoretical expansions involved in the extraction of $|V_{cb}|$ using B meson decays. When measured at the weak scale there is also the possibility that the measured value of $|V_{cb}|$ could be affected by new physics contributions [37].

Given this would be the first measurement of $|V_{cb}|$ at the weak scale any

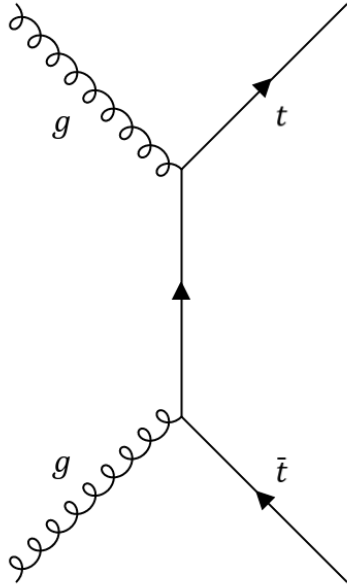
successful measurement would be significant without yet needing to achieve an uncertainty competitive with previous measurements. For this measurement to help resolve the tension between the value of $|V_{cb}|$ measured in exclusive and inclusive measurements would require an uncertainty close to the 2% seen in those measurements. The uncertainties presented in this thesis are significantly greater than this but nevertheless the main aim of this measurement is to demonstrate a new method with different sources of error. In the unexpected case that the measured value of $|V_{cb}|$ was significantly different to that measured previously the uncertainty would need to be of order the difference observed to be significant.



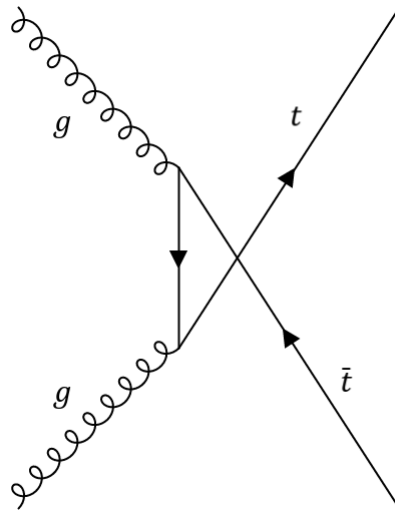
(a) Gluon fusion



(b) Quark anti-quark annihilation



(c) Gluon scattering



(d) Gluon scattering

Figure 2.1: Leading order Feynman diagrams of $t\bar{t}$ production in proton-proton collisions.

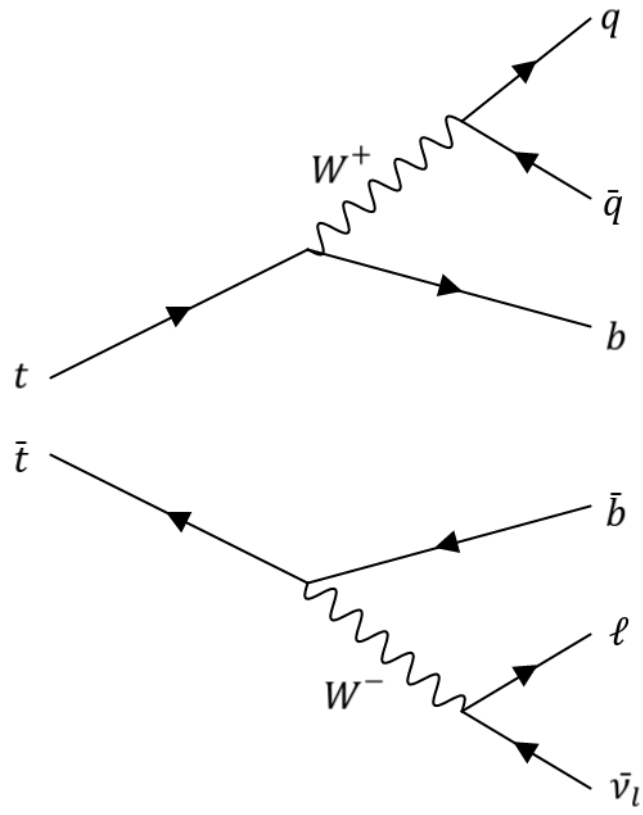


Figure 2.2: Feynman diagram of semi-leptonic decay of $t\bar{t}$ event.

Chapter 3

The LHC and the ATLAS Experiment

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [38] is a particle accelerator at the CERN laboratory on the border between France and Switzerland near Geneva. It is situated in a 26.7 km circumference underground tunnel formerly occupied by the Large Electron-Positron Collider (LEP). It is currently the largest and most powerful particle collider in the world. The tunnel consists of eight straight sections and eight arcs to form a ring. After injection bunches of 1.15×10^{11} protons are accelerated in opposite directions in two separate beam pipes. There are four interaction points where collisions between the two beams occur and detectors are built around these points: ATLAS, CMS, LHCb and ALICE.

Before being injected into the LHC ring the protons are accelerated using the CERN accelerator complex shown in Figure 3.1. During the Run 2 data-taking period used in the studies presented in this thesis the acceleration process was as follows: First, hydrogen atoms are stripped of their electrons and the resulting protons are accelerated by the LINAC 2 linear accelerator up to an energy of 50 MeV. The protons are then injected into the Proton Synchrotron Booster and accelerated to 1.4 GeV, the Proton Synchrotron increases their energy to 26 GeV before the Super Proton Synchrotron accelerates them to 450 GeV. The protons are then further accelerated within the LHC ring. The centre of mass energy of collisions during Run 2 was 13 TeV and so each beam was accelerated to 6.5 TeV.

The acceleration of the protons within the LHC is achieved using 16 radio-frequency (RF) cavities oscillating at a frequency of 400.8 MHz. The path and shape of the proton beams are controlled using superconducting NbTi magnets cooled to a temperature of 1.9 K using superfluid helium. There are 1232 main dipole magnets which steer the protons around the ring and are capable of

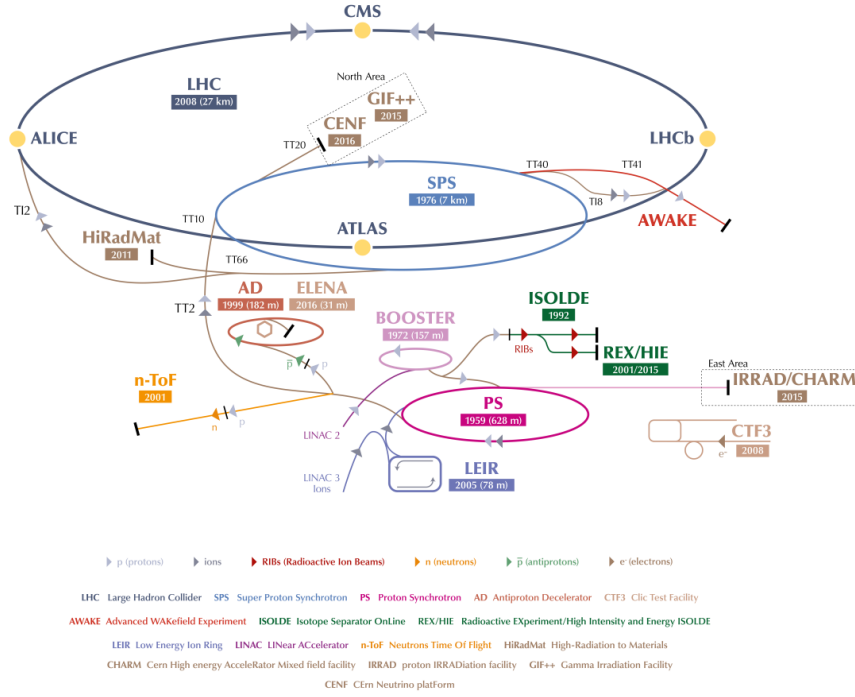


Figure 3.1: The CERN accelerator complex in 2016 [6].

generating fields of 8.3 T, however during Run 2 they produced fields of 7.7 T. 392 main quadrupoles focus the beam while sextupole, octupole and decapole magnets provide further corrections.

3.2 The ATLAS Detector

The ATLAS (A Toroidal LHC ApparatuS) detector [8] shown in Figure 3.2 is a general purpose particle physics detector. It is located at Point 1 of the LHC and is the largest of the LHC's detectors measuring 40 m long with a diameter of 25 m and a total weight of around 7000 tonnes. In order to cover the maximum solid angle possible around the interaction point the detector has a cylindrical shape and forward-backward symmetry.

At the centre of the detector is the barrel shaped Inner Detector (ID) designed to track charged particles. This is immersed in a 2 T magnetic field by the solenoid magnet that surrounds it. The next layer consists of electromagnetic calorimeters, followed by hadronic calorimeters. The outermost layer of the detector consists of muon spectrometers, here three air core toroid magnets provide a strong magnetic field.

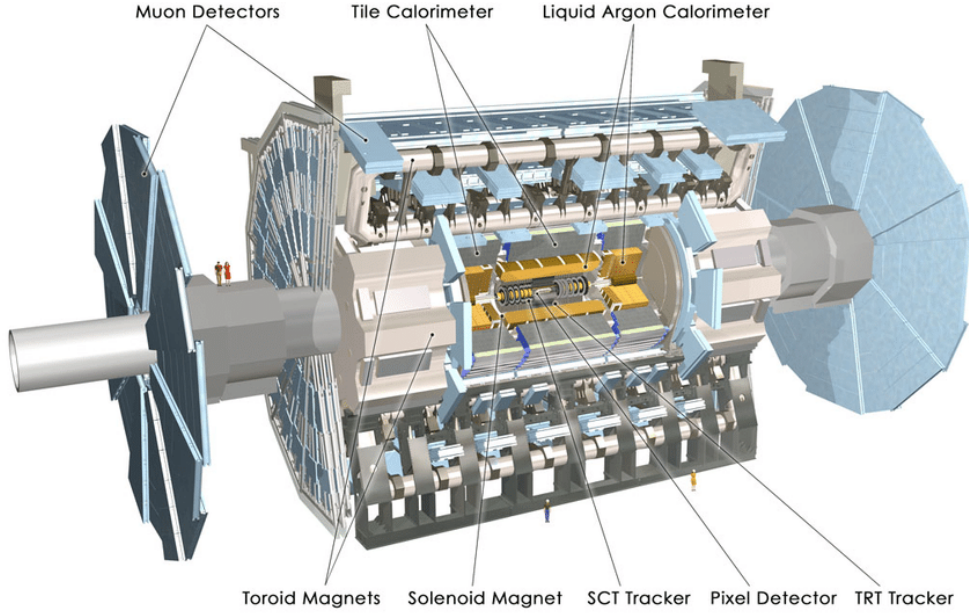


Figure 3.2: The ATLAS detector [7].

3.2.1 Coordinate System

ATLAS uses a right-handed Cartesian coordinate system (x, y, z) to describe the detector and particles measured within it. The centre of the coordinate system is taken to be the nominal interaction point. The z -axis is defined as being along the beam direction in an anti-clockwise direction. The positive x -axis is defined as pointing from the interaction point to the centre of the LHC ring while the y -axis is defined as pointing upwards.

Given the cylindrical symmetry of the detector and the fact that particles emanate from the centre of the detector it is often more helpful to use the azimuthal angle ϕ to describe the position in the x - y plane. This is defined as the angle relative to the x -axis in the x - y plane. The polar angle θ is the angle relative to the beam axis and from this the pseudorapidity $\eta = -\ln \tan(\theta/2)$ is defined. In the relativistic limit where the mass of an object can be ignored the pseudorapidity is equal to the rapidity defined as $y = 1/2 \ln[(E + P_z)/(E - p_z)]$.

The distance ΔR in the pseudorapidity-azimuthal angle space is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. Transverse quantities such as the transverse momentum p_T or transverse energy E_T are the components of those quantities projected onto the x - y plane.

3.2.2 Inner Detector

The ID is the section of the ATLAS detector closest to the beamline; Figure 3.3 shows a cut-away view with its sub-detector systems labelled. The ID is

designed to give precise tracking information for particles; it is immersed in a 2 T axial field from the solenoid magnet that surrounds it. This magnetic field allows the precise measurement of the transverse momentum of charged particles based on their radius of curvature.

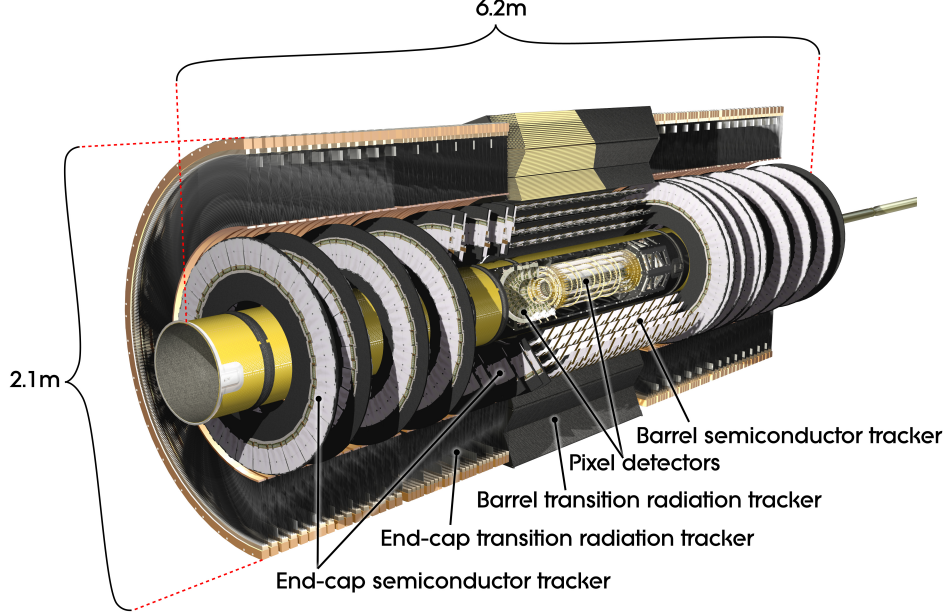


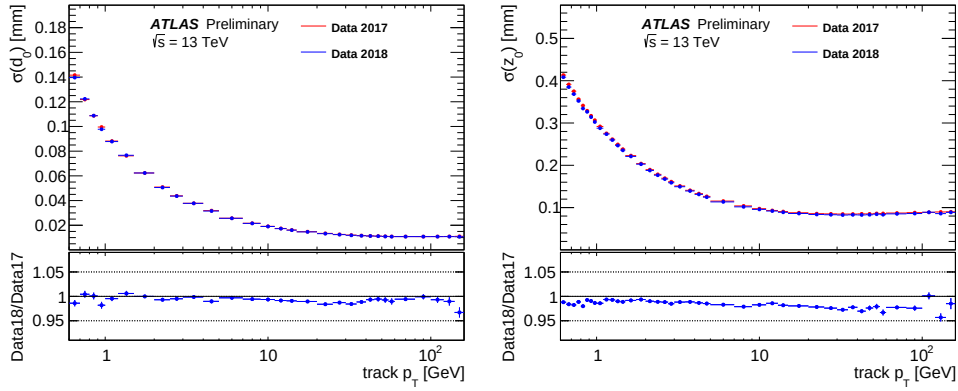
Figure 3.3: Cut-away view of the ATLAS inner detector [8].

The ID is composed of three sub-detectors. The innermost layer is the Pixel Detector, followed by the Semi-Conductor Tracker (SCT) made of silicon microstrips and finally the Transition Radiation Tracker (TRT) composed of gaseous straw tube elements. Figure 3.5 shows these layers and the path of a particle perpendicular to the beamline through the detector.

The precision tracking provided by the pixel and SCT cover the region of $|\eta| < 2.5$. Primary and secondary vertex measurements of charged tracks are made by the ID. The tracks of charged particles above a p_T threshold of 500 MeV are reconstructed with a minimum resolution of $\sigma_{p_T}/p_T = 0.05\%p_T \oplus 1\%$. The impact parameter resolution provided by this tracking is shown in Figure 3.4.

Pixel Detector

The Pixel Detector including the Insertable B-Layer (IBL) [39, 40] is the closest sub-detector to the beam pipe as seen in Figure 3.5. It is in the shape of a cylinder with a length of 1.4 m and a radius of 0.123 m. The Pixel detector offers the highest granularity among the sub-systems of the ID. The IBL is an additional layer of silicon pixel sensors added to the detector before Run 2 of the LHC. The IBL is positioned 33.25 mm from the beam axis and consists of pixels with dimensions of $50 \times 250 \mu\text{m}^2$ in the r - ϕ and z directions respectively.



(a) Longitudinal IP resolution

(b) Transverse IP resolution

Figure 3.4: Impact parameter resolution measured in dijet events in 2017/2018 [9]. The tracks were required to be associated with a jet with $p_T > 20$ GeV.

The IBL pixel modules are a combination of planar and 3D modules. Planar modules contain 53 760 pixel cells while 3D modules consist of 26 880 pixels. The IBL contains a total of 12 million pixels.

Following the IBL there are three more layers of modules in the barrel region. These are located at 50.5 mm, 88.5 mm and 122.5 mm from the beam axis. There are also three end-cap discs on both ends of the barrel. The planar pixel modules in these layers have larger pixels than those in the IBL with a nominal pixel size of $50 \times 400 \mu\text{m}^2$. Each module has 47 232 pixels but some are ganged giving a total of 46 080 readout channels. In total for the three layers there are 80.4 million readout channels. The intrinsic accuracy in the barrel layers is $10 \mu\text{m}$ in $r\text{-}\phi$ and $115 \mu\text{m}$ in z . In the end-cap discs the accuracy is $10 \mu\text{m}$ in $r\text{-}\phi$ and $115 \mu\text{m}$ in r .

Semiconductor Tracker

The Semiconductor Tracker provides further precision tracking of charged particles in the ID. It consists of four barrel layers and nine discs in the end-caps on each end of the barrel. These layers are made of microstrip modules with a mean strip pitch of $80 \mu\text{m}$; they have two sensor layers tilted at an angle of 40 mrad with respect to each other. The barrel layers are at 299 mm, 371 mm, 443 mm and 514 mm from the beam axis. The end-cap layers are between $839 < |z| < 2735 \text{ mm}$. There are a total of 6.3 million readout channels. Modules in the barrel have intrinsic accuracies of $17 \mu\text{m}$ in $r\text{-}\phi$ and $580 \mu\text{m}$ in z . Modules in the discs have intrinsic accuracies of $17 \mu\text{m}$ in $r\text{-}\phi$ and $580 \mu\text{m}$ in r . The SCT covers a pseudorapidity range of $|\eta| < 2.5$.

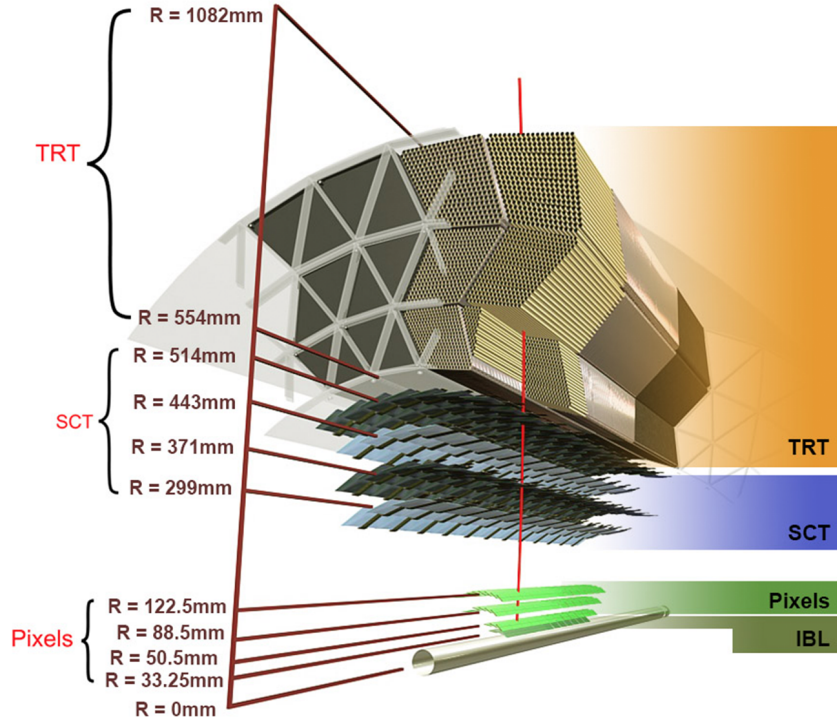


Figure 3.5: Sketch showing all layers of the ATLAS inner detector and their distance from the beam axis [10].

Transition Radiation Tracker

The TRT is the outermost section of the ID. It is made of polyimide drift (straw) tubes. These tubes have a 4 mm diameter and a 31 μm diameter tungsten wire plated with gold at their centre which acts as the anode. The straws are filled with a gas mixture of 70% Xe, 27% CO_2 and 3% O_2 . From 2012 onward some of the tubes were found to have developed leaks. Given the high cost of Xenon gas these tubes were instead filled with an Argon-based gas mixture [41]. The straws in the barrel were cut to 144 cm but their wires are divided into two halves at $\eta = 0$. They are aligned parallel with the beam-pipe. The straws in the end-caps were cut to 37 cm and are arranged radially in wheels. In total the TRT provides approximately 351 000 readout channels.

The straws in the barrel are interleaved with polypropylene fibres while the layers in the end-cap are interleaved with polypropylene foils. The purpose of these is to provide transition radiation for electron identification. When a charged particle passes through inhomogeneous material electromagnetic radiation is emitted, this is transition radiation [42]. The intensity of the radiation increases with the Lorentz factor $\gamma = E/m$ of the charged particle. As such a less massive particle will tend to radiate more than a more massive one allowing electrons to be differentiated from hadrons. The radiated photons are absorbed in the gas mixture and give much larger signal amplitudes than

those caused directly by the charged particles passing through the gas. This allows both the transition radiation and tracking signals to be obtained using separate low and high thresholds. The use of Argon in some of the straws does result in degraded electron identification performance.

The TRT can only provide r - ϕ information and has an intrinsic accuracy per straw of $130\,\mu\text{m}$. It is able to track particles with $|\eta| < 2.0$. The TRT provides a large number of hits, typically 36 per track. This large number of hits mean that despite having a lower precision per point compared to the other ID sub-detectors the TRT contributes significantly to the momentum measurement of particles.

3.2.3 Calorimeters

The sections of the ATLAS calorimeter system are shown in Figure 3.6. Closest to the ID is the liquid argon (LAr) electromagnetic calorimeter designed to measure the energy of particles which shower electromagnetically. The next layer consists of a variety of hadronic calorimeters designed to measure the energy of particles showering hadronically. The calorimeters provide full ϕ coverage in the $|\eta| < 4.9$ region. In the $|\eta| < 2.5$ region covered by the ID, the electromagnetic calorimeter offers fine granularity for precision measurements. All of the calorimeters consist of layers of material which measure energy deposits and passive material which interacts with the particles to create showers which are detected by the active layers. The interactions with the passive material are also important for containing particles in the correct calorimeter and preventing punch-through into the muon spectrometers.

Liquid Argon Electromagnetic Calorimeter

The EM calorimeter uses liquid argon for its active layers and lead plates as its absorber. The absorbers and kapton electrodes of the calorimeter are accordion-shaped allowing full coverage in ϕ without any cracks. A high voltage is applied between the electrodes collecting any charges produced by the interaction of particles with the liquid argon. The barrel section of the EM calorimeter covers the $|\eta| < 1.475$ region and has three layers for $|\eta| < 1.35$ and two layers for $1.35 < |\eta| < 1.475$. The barrel consists of two identical halves separated at $z = 0$ by a 4 mm gap. The two end-caps cover the region $1.375 < |\eta| < 3.2$ and has two layers in the $1.375 < |\eta| < 1.5$ region, three for $1.5 < |\eta| < 2.5$ and two for $2.5 < |\eta| < 3.2$. In addition to these layers there is a presampler LAr layer which is the innermost layer of the EM calorimeter in the region of $|\eta| < 1.8$, the purpose of this is to correct for energies lost by electrons or photons in the ID or solenoid prior to reaching the electromagnetic calorimeter.

Within the precision measurement region ($|\eta| < 2.5$) the first layer of the

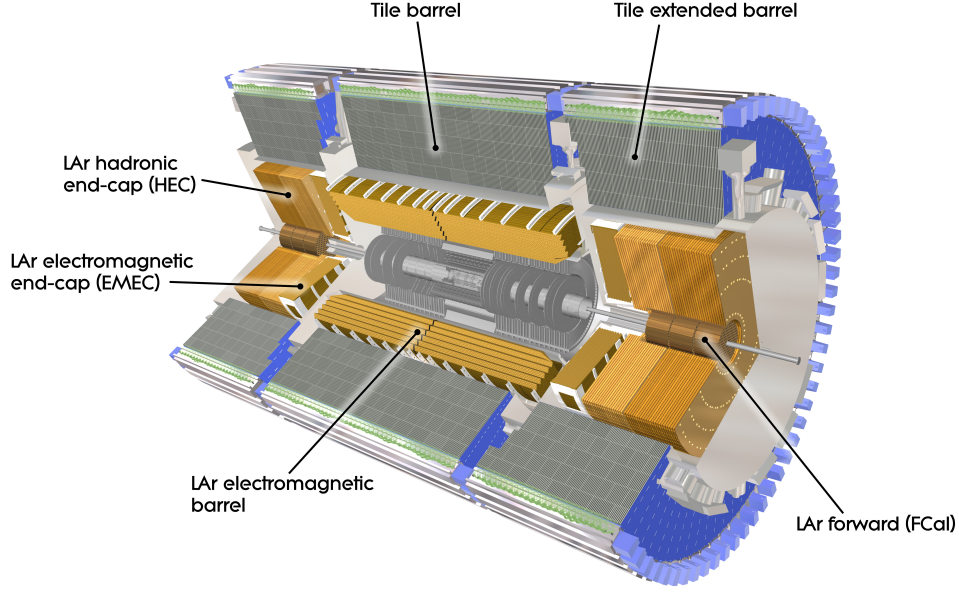


Figure 3.6: Cut-away diagram of the ATLAS calorimeter system [8].

calorimeter is finely segmented in η . The granularity varies with $|\eta|$, getting coarser for larger values. In the precision measurement region of the first layer this ranges from $0.025/8 \times 0.1$ in $\Delta\eta \times \Delta\phi$ for $|\eta| < 1.4$ to 0.025×0.1 for $2.4 < |\eta| < 2.5$. The fine granularity of the first layer allows for accurate position measurements. The second layer is less finely segmented and is the thickest layer absorbing the majority of the electromagnetic showers. The third layer is less finely segmented again and is used to estimate any leakage into the hadronic calorimeter. The electromagnetic calorimeter has a total thickness of more than 22 radiation lengths (X_0) in the barrel and greater than $24 X_0$ in the end-caps meaning that any leakage from EM showers should be minimal. The radiation length is defined as the mean distance over which a high energy electron loses all but $1/e$ of its energy by bremsstrahlung and $7/9$ of the mean free path for pair-production by a high energy photon [1].

The required resolution of the electromagnetic calorimeter when designing ATLAS was $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$. These requirements were met with the constant term varying between 0.5% and 0.7%.

Hadronic Calorimeters

ATLAS has three different hadronic calorimeters covering different η regions. These are the tile calorimeter, LAr hadronic end-cap and the LAr forward calorimeter. These are designed to have a performance of $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ in the barrel and end-cap and $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$ in the forward calorimeter.

Tile calorimeter: The tile calorimeter uses scintillating tiles as its active material and steel for its absorbing layers. Hadrons interact with the steel layers creating showers of particles, these particles interact with the tiles creating light which is detected by photomultiplier tubes. The main barrel covers the region $|\eta| < 1.0$ while two extended barrels cover the range $0.8 < |\eta| < 1.7$. The calorimeter is separated into three layers. In the barrel these are approximately 1.5, 4.1 and 1.8 interaction lengths (λ) thick while in the extended barrel these are approximately 1.5, 2.6 and 3.3λ thick. The first two layers have a granularity of 0.1×0.1 in $\Delta\eta \times \Delta\phi$ while the third has a granularity of 0.2×0.1 .

Liquid argon hadronic end-cap calorimeter: The hadronic end-cap calorimeters are located directly after the electromagnetic end-caps with which they share LAr cryostats. Unlike the electromagnetic calorimeter the hadronic calorimeter uses 25-50 mm copper plates for its absorbing layers, these are interleaved with 8.5 mm LAr gaps. Each hadronic end-cap is made of two independent wheels with 2 layers giving a total of 4 layers per end-cap. The end-caps cover the region $1.5 < |\eta| < 3.2$. For $|\eta| < 2.5$ they offer a granularity of 0.1×0.1 in $\Delta\eta \times \Delta\phi$, outside of this region the granularity is 0.2×0.2 .

Liquid argon forward calorimeter: The forward calorimeter covers the region of $3.1 < |\eta| < 4.9$. This forward region is not covered by any other detectors and as such the forward calorimeter is designed to measure electromagnetic as well as hadronic interactions. It consists of 3 modules in each end-cap, each module consists of a metal matrix with regularly spaced holes parallel to the beam axis. These holes are filled with the electrode structure consisting of concentric rods and tubes. The gap between the rod and the tube is filled with liquid argon. The small size of the gap avoids possible problems with ion buildup in the high flux forward region. The first module uses copper as its absorbing material and is optimised for electromagnetic measurements. The second and third modules are made of tungsten and are designed primarily to make hadronic energy measurements. The forward calorimeter is important for the measurement of the missing transverse energy in events and can also be used to reconstruct objects with lower precision than in the $|\eta| < 2.5$ range.

3.2.4 Muon Spectrometer

The muon spectrometer is the outermost of the main ATLAS sub-detectors. A diagram of its components is shown in Figure 3.7. The muon spectrometer is responsible for detecting muons in the region $|\eta| < 2.7$ and triggering on muons with $|\eta| < 2.4$. Only muons and neutrinos should penetrate far enough through the detector to reach the muon spectrometer and neutrinos will not

be detected.

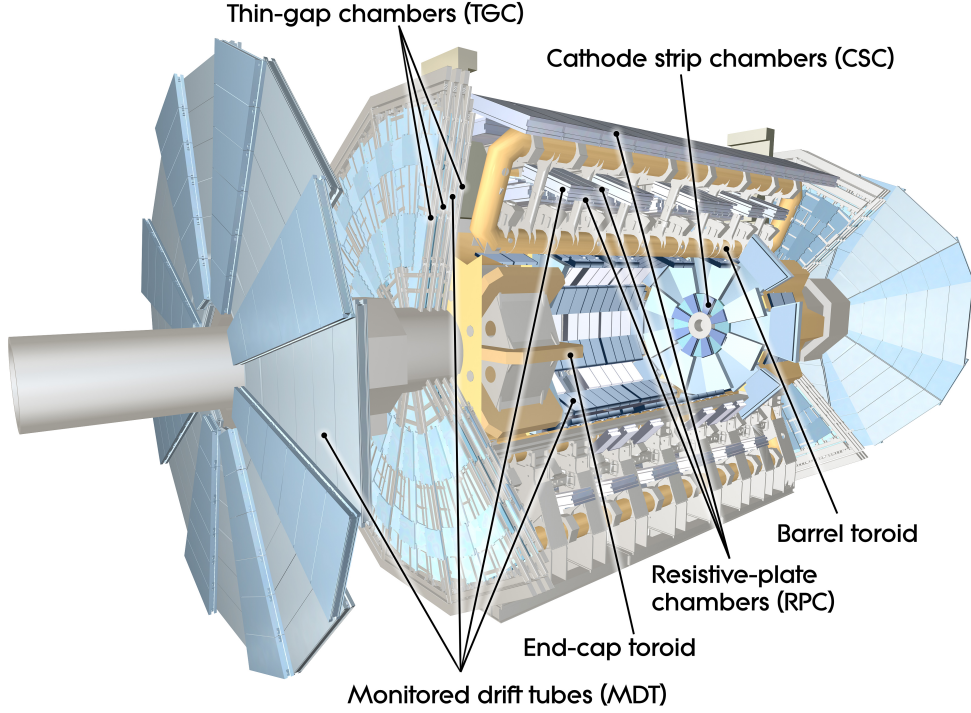


Figure 3.7: Cut-away diagram of the ATLAS muon system [8].

The magnetic deflection of muons is a key part of allowing the muon spectrometer to make precise measurements of muons' transverse momenta. This deflection is achieved by the three large superconducting air-core toroid magnets of the ATLAS detector. Each of these magnets consists of eight coils arranged radially and symmetrically around the beam pipe as shown in Figure 3.8. In the $|\eta| < 1.4$ region the magnetic bending is provided by the largest of these magnets: the large barrel toroid. For the $1.6 < |\eta| < 2.7$ region the magnetic bending is provided by one of the two smaller end-cap toroids, these end-cap toroids are rotated by 22.5° in ϕ relative to the barrel toroid. Between the two regions is the transition region $1.4 < |\eta| < 1.6$ where the deflection is caused by a combination of the two toroids.

There are gaps in the coverage of the muon system around $|\eta| = 0$ to allow for services to the solenoid magnet, the calorimeters and the inner detector. The size of this gap varies depending on the services required in each sector but the biggest gaps are 1-2 m. The angular range where a high momentum track is not recorded in all three muon layers is $|\eta| < 0.08$ for the large sectors. The muon chambers used can be split into two types: those used for precision tracking and those used for triggering.

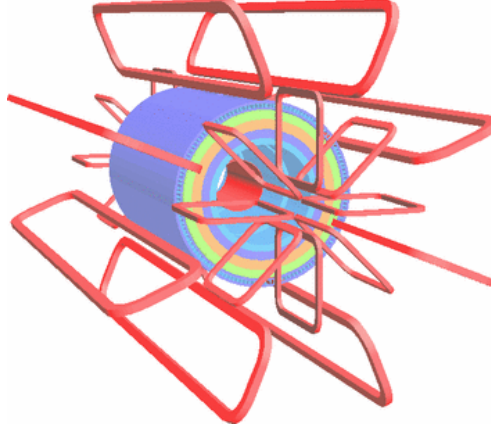


Figure 3.8: Geometry of ATLAS's magnet system [8].

Precision tracking

Precision tracking is provided by Monitored Drift Tubes (MDTs) and Cathode Strip Chambers (CSCs). Three layers of MDTs cover the $|\eta| < 2.7$ region, however the limit for safe operation of the MDTs is a counting rate of around 150 Hz/cm^3 which would be expected to be exceeded in the first layer of the $|\eta| > 2.0$ region. As such the innermost layer at $2 < |\eta| < 2.7$ is replaced with CSCs which have a higher granularity and are considered safe at counting rates up to 1000 Hz/cm^3 .

The MDT chambers consist of three to eight layers of pressurised drift tubes with a gas mixture of 93% Ar and 7% CO_2 at 3 bar. Electrons due to ionisation are collected by a gold-plated tungsten-rhenium wire in the centre of the tubes. In the barrel region the tubes are aligned with ϕ and in the end-caps they are mounted perpendicular to the beam-pipe. Each tube has an average resolution of $80 \mu\text{m}$ or $35 \mu\text{m}$ per chamber.

The CSCs are multi-wire proportional chambers made of cathode planes segmented into strips in orthogonal directions. This orthogonality allows for 2D position measurements. Each chamber contains four CSC planes and has a resolution of $40 \mu\text{m}$ in the bending plane and 5 mm in the transverse plane. The CSCs use a 80% Ar, 20% CO_2 gas mixture.

Triggering

The muon chambers responsible for triggering are Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCS). These chambers are capable of delivering information within a few tens of nanoseconds of a particle travelling through the detector. The triggering chambers measure the coordinates of the track in both the bending plane (η) and the non-bending plane (ϕ). Since the non-bending plane coordinate is not measured in the precision tracker this coordinate is then taken as the second coordinate of the measurement. The

RPCs cover the barrel region of $|\eta| < 1.06$ while the TGCs cover the end-cap region $1.05 < |\eta| < 2.4$.

There are three layers of RPCs, one either side of the middle MDF layer and one either above or below the third MDF depending on which sector of the detector it is in. The RPCs are gaseous parallel electrode-plate detectors using a gas mixture of 94.7% $\text{C}_2\text{H}_2\text{F}_4$, 5.0% $\text{Iso-C}_4\text{H}_{10}$ and 0.3% SF_6 . They use two parallel phenolic-melaminic plastic laminate plates kept 2 mm apart.

There are four layers of TGCs in the end-cap. The first layer is in front of the end-cap toroid and the innermost tracking layer. The second layer is in front of the second MDT wheel while the third and fourth are behind the second MDT wheel. TGCs are multi-wire proportional chambers with a shorter distance between the wires and the cathode than between the wires themselves. The TGCs use a gas mixture of 55% CO_2 and 45% $\text{n-C}_5\text{H}_{12}$.

3.2.5 Trigger System

When ATLAS is taking data bunch crossings occur at a rate of 40 MHz. During Run2 there were on average 33.7 pileup interactions as seen in Figure 3.9. It would be impossible to store the data from each of these collisions. As such the trigger and data acquisition (TDAQ) [8, 3] is used to only record relevant and useful events. The first step is the hardware based Level 1 (L1) trigger which reduces the event rate to 100 kHz. The second step is the software based High Level Trigger (HLT) which reduces the event rate to 1 kHz.

Level 1 Trigger

The L1 trigger uses custom-made electronics to implement the initial filtering of events. It searches for the signatures of high- p_T muons, electrons/photons, jets and τ -leptons decaying to jets. Events with a large missing transverse energy(MET) or a large total transverse energy are also selected. It does this using reduced granularity information from the calorimeters; trigger towers in all layers of the calorimeter have a granularity of 0.1×0.1 in $\Delta\phi \times \Delta\eta$. Muon information is provided by the previously mentioned RPCs and TGCs in the muon system. Detector regions where the L1 trigger has identified objects that pass its trigger thresholds are identified as Regions-of-Interest (RoIs) and these are passed on to the HLT.

High Level Trigger

The HLT is software based and uses commercially available hardware. Since the HLT is dealing with a much lower event rate than the L1 trigger it is able to perform a more complete reconstruction of each event. The HLT will either perform the reconstruction within the RoIs identified in the L1 trigger or over

the entire detector depending on the trigger needs. For most triggers an initial fast-pass reconstruction is performed which rejects the majority of events and then a slower precision reconstruction is used to make a final decision on those events passing the first stage.

3.2.6 Luminosity

The number of events of a process P that will occur is given by:

$$N_P = \sigma_P \int_0^T \mathcal{L} dt \quad (3.1)$$

Here σ_P is the cross-section of the process and $\mathcal{L}$ the instantaneous luminosity. Integrating the instantaneous luminosity over time gives the integrated luminosity L which will simply be referred to as the luminosity for the remainder of this work. As can be seen in 3.1 you need to know the luminosity to know how many events you expect. This is key for measuring a cross-section or for understanding how many events you expect from background processes you are not measuring but need to be accounted for.

ATLAS has multiple detectors that can measure the luminosity. The LUCID-2 [43] detector was used as the main online and offline luminometer for Run 2. LUCID-2 is one of the smaller forward detectors at ATLAS, it surrounds the beam-pipe in each of the forward arms at approximately ± 17 m from the interaction point. It consists of 16 photomultiplier tubes (PMTs) with quartz windows in each arm; the quartz windows act as a Cherenkov medium allowing the detection of particles from inelastic p - p scattering at small angles. The PMTs are also coated with ^{207}Bi which decays by electron capture and gamma emission giving precise energy peaks that act as a calibration signal for the gain stability of the PMTs. From the raw hit counts the visible interaction rate per bunch crossing is calculated which is proportional to the instantaneous luminosity. The relation between the interaction rate and the instantaneous luminosity was calibrated using dedicated low-luminosity van der Meer scans.

The instantaneous luminosity measurements of LUCID-2 were complemented by measurements from the ATLAS beam conditions monitor diamond detectors and from offline measurements of the multiplicity of reconstructed charged particle tracks [44]. Measurements of the luminosity over a series of bunches is also provided by measurement of the liquid argon gap currents in the LAr calorimeters and photomultiplier currents in the tile calorimeter.

3.3 Run 2 Data-Taking

The work presented in this thesis uses data collected during Run 2 of the LHC's operation. Run 2 occurred from 2015 to 2018 during which the centre of mass energy of collisions was $\sqrt{s} = 13$ TeV. The total integrated luminosity at ATLAS during Run 2 after data-quality selections was 139 fb^{-1} with an uncertainty of 1.7% [44]. The luminosity is broken down by year in Figure 3.10 and pile-up in Figure 3.9. The instantaneous luminosity generally increased over the course of Run 2 and as seen in Figure 3.9 this meant that the pileup profile changed significantly too. These differences are accounted for in simulated data by applying year-by-year corrections to the simulated data based on the pileup profile.

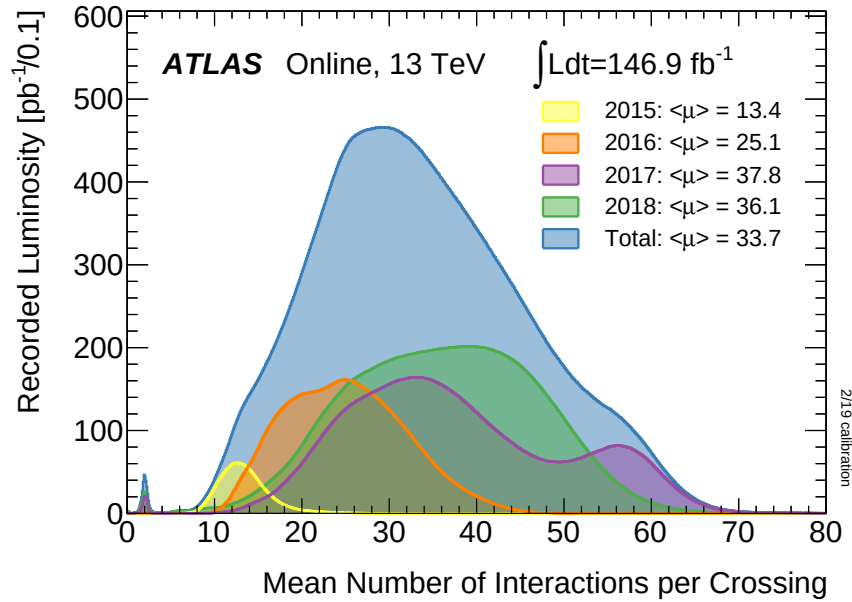


Figure 3.9: Mean number of interactions per beam crossing at ATLAS during Run 2 separated by year [11].

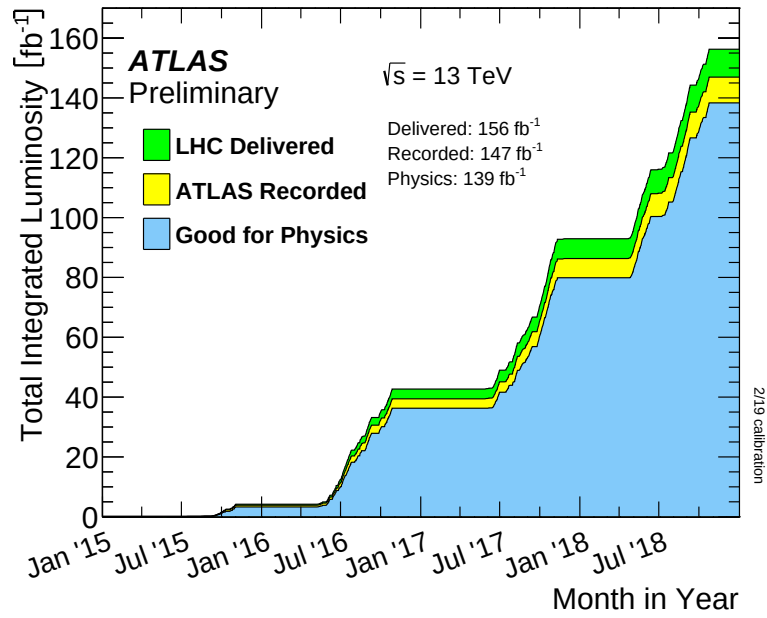


Figure 3.10: Cumulative integrated luminosity and data quality at ATLAS during Run 2 [11].

Chapter 4

Physical Object Reconstruction and Event Simulation

4.1 Reconstruction at ATLAS

In events meeting the trigger requirements the readouts from the detectors described in Section 3.2 are used to reconstruct physics objects on which physics analyses are performed.

4.1.1 Tracks

Tracks are the paths of charged particles recorded as they pass through the inner detector. They are built from the multiple hits that charged particles leave along their path. Tracks are a building block of a number of other reconstructed physics objects. Several algorithms are used to reconstruct tracks but the main algorithm is the inside-out algorithm [45]. This consists of the following steps:

- **Formation of space-points:** Clusters are formed from hits detected in the Pixel and SCT, and drift circles are formed from hits in the TRT. Drift circles are circles somewhere along which an interaction occurred, these are formed because only information on the distance of the interaction from the anode is available rather than the exact point. The clusters are then converted into 3D space-points.
- **Track finding:** Seed tracks are formed from sets of three space-points in the Pixel and SCT, and then required to pass p_T and impact parameter resolution cuts. The seed must also match a fourth space-point compatible with the seed's trajectory. Additional compatible space-points are then

combined with the seeds to form track candidates using a combinatorial Kalman filter [46].

- **Ambiguity solving:** The track candidates are then given a track score which is a measure of the track quality [47]. Tracks with higher scores are favoured and have the ambiguity solving process applied to them first. A number of factors are considered to determine the track score including the numbers of space-points in the track, the distribution of the space-points between sub-detectors, any gaps in the track in areas with sensitive detector elements, and the χ^2 of the track fit. The logarithm of the track momentum is also included; this helps reduce the number of tracks with incorrectly assigned space-points which typically have a lower p_T . The ambiguity solver only allows space-points to be shared by two tracks and one track may only have two shared space-points. If a track candidate cannot fulfil these requirements then the space-points are removed from the track candidate and its track score is re-evaluated. After this process track candidates are accepted if they meet basic quality criteria [47].
- **TRT extension:** The track candidates are then extended to the TRT if there are valid sets of matching drift circles. Refitting the track with the drift circles then improves the track momentum resolution.

The tracks reconstructed using the inside-out algorithm are required to satisfy the following requirements [48]:

- $p_T > 400 \text{ MeV}$
- $|\eta| < 2.5$
- Number of Pixel and SCT clusters on track ≥ 7
- Number of modules used by more than one track ≤ 1
- Number of SCT holes (modules along the track without a hit) ≤ 2
- Number of Pixel holes ≤ 1

4.1.2 Vertices

The primary vertex (PV) of an event is a point where a proton-proton collision occurred [49]. The hard scatter vertex is the primary vertex with the largest sum of p_T^2 associated with it. Secondary vertices (SVs) are the locations of the subsequent decays of particles produced in the collision.

The luminous region or beam spot is the region where the proton beams collide and so where primary vertices should be located. The luminous region

during Run 2 was typically around 14 μm in the transverse direction and 45 mm in the longitudinal direction.

Primary vertex reconstruction is performed using reconstructed particle tracks from the ID. The tracks must first meet a set of basic quality requirements [49]. A seed position is then selected based on the tracks passing the requirements. An iterative fit is then performed, down-weighting tracks which are less compatible with the vertex position and recomputing the vertex position. Tracks found to be incompatible with the vertex are used in the determination of another vertex with each vertex requiring at least two compatible tracks.

Secondary vertex reconstruction only considers tracks within jets [50]. This is because the primary use of secondary vertices is in jet flavour identification. The vertex finding algorithm uses the jet axis direction, the primary vertex position and the tracks associated with the jet. The algorithm returns a single secondary vertex for each jet; in the case of multiple SVs these will either be combined if close or the vertex with the largest track multiplicity will be selected. The choice to reconstruct only a single SV per jet is due to the finite tracking resolution of ATLAS.

4.1.3 Topological Clusters

Topological clusters or topo-clusters are another important building block for objects including jets and electrons. Topo-clusters are 3D objects formed by showers in the calorimeter system. First a calorimeter cell is required to have a hit with energy at least 4 times that of the expected cell noise this is the seed cell. Cells neighbouring this first cell that have a hit with energy at least twice that of the expected cell noise are then added to the first cell to form a proto-cluster. These newly added cells become seed cells themselves in the next iteration adding more cells to the proto-cluster. If during these iterations two proto-clusters share a cell the proto-clusters are merged. Once all iterations are complete there is a final step where any neighbouring cells with energy greater than 0 are added to the proto-cluster. This is known as “4-2-0” topo-cluster reconstruction. Proto-clusters with two or more local maxima can be split into separate clusters. The local maxima must have $E_{cell}^{EM} > 500 \text{ MeV}$, the maximum cell must have at least four neighbours and these neighbours must not have a larger signal [12].

4.1.4 Electrons

The signature of electrons in the detector is a track in the ID and a compatible shower in the electromagnetic calorimeter. There should not be a significant shower in the hadronic calorimeters.

Reconstructing electrons uses the topo-clusters described in Section 4.1.3.

However, these topo-clusters are reconstructed throughout the entire calorimeter system while electrons do not generate significant showers in the hadronic calorimeter. Clusters which are primarily the result of showers in the EM calorimeter are isolated using a selection cut on the fraction of the topo-cluster energy located in the EM calorimeter. The fraction of energy located in the EM calorimeter is required to be greater than 50% [12].

The selected clusters are then matched with tracks in the ID. If the tracks have silicon hits loosely matched to EM clusters they are refitted using a Gaussian Sum Filter fitter [51], a non-linear generalisation of the Kalman filter initially used. This gives improved track parameter estimation. These refitted tracks are then matched to EM clusters with tighter requirements in η and ϕ . In some cases multiple tracks will match with a cluster: in those cases tracks with hits in the pixel detector are preferred, followed by tracks with hits in the SCT. If multiple tracks have hits in the same detector then the track with the smallest distance in the η - ϕ plane (ΔR) to the cluster barycentre is chosen, unless the difference is less than 0.01 in which case the track with the greater number of hits is chosen [52].

To avoid losses due to bremsstrahlung radiation some topo-clusters are then grouped together to form superclusters. Each supercluster consists of a seed cluster and satellite clusters close to the seed cluster, a simple example is given in Figure 4.1. First, potential seed clusters are identified and ordered by descending p_T . Satellite clusters will always have a lower p_T than the seed cluster. Electron seed clusters must have a minimum energy of 1 GeV and be matched to a track with ≥ 4 hits in the silicon detectors. Each candidate seed cluster is considered in turn and potential satellite clusters are identified from all remaining unused clusters. Clusters within a $\Delta\eta \times \Delta\phi = 0.075 \times 0.125$ window of the seed cluster barycentre are assigned as satellite clusters. A search is also performed in a wider $\Delta\eta \times \Delta\phi = 0.125 \times 0.3$ window around the seed cluster barycentre. If a cluster in this window has ≥ 1 matched tracks such that its best-matched track is the same as the seed cluster it will be assigned as a satellite cluster. Clusters assigned as satellites are not considered in future iterations as seed clusters or satellite clusters.

Whether an electron candidate is identified as an electron in an analysis is determined by a likelihood discriminant which uses measurements from the tracking system, the calorimeter system and quantities depending on both systems [2]. These variables are summarised in Table 4.1. Signal and background probability density functions of the discriminating variables are multiplied to define an overall likelihood that an object is signal $\mathcal{L}_S$ and an overall likelihood that the object is background $\mathcal{L}_B$. The likelihood discriminant

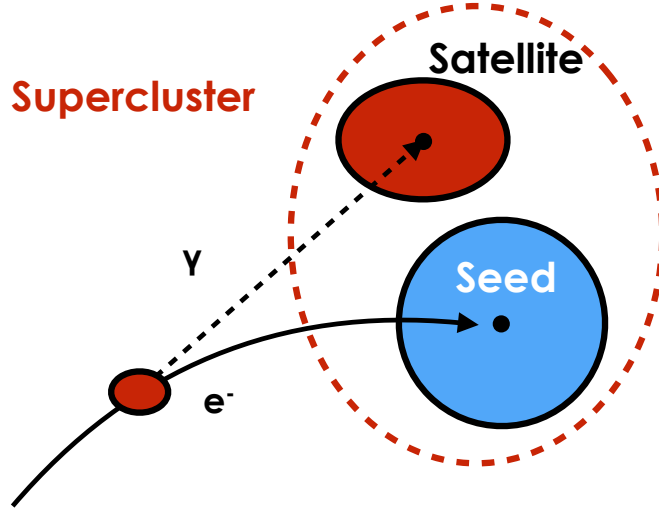


Figure 4.1: Example of a supercluster showing a seed electron cluster and a satellite photon cluster caused by bremsstrahlung radiation [12].

is then defined as:

$$d_{\mathcal{L}} = \frac{\mathcal{L}_S}{\mathcal{L}_S + \mathcal{L}_B} \quad (4.1)$$

By choosing different minimum values of the discriminant for a candidate to be identified as an electron, different working points can be defined with a trade-off between efficiency in identifying electrons and the efficiency of mis-identifying backgrounds as electrons. ATLAS defines three working points in order of increasing electron efficiency: “tight”, “medium”, “loose”. The efficiencies of these working points are shown in Figure 4.2. To correct for differences in the efficiency of identifying electrons as electrons in Monte Carlo (MC) simulation compared to data, the efficiencies are measured as a function of p_T and η in $Z \rightarrow e^+e^-$ and $J/\psi \rightarrow e^+e^-$ events. This allows scale factors to be derived to correct for any differences between MC simulation and data.

4.1.5 Muons

The typical signature of a muon in the detector is a track in both the ID and the muon spectrometer (MS). Muons also leave small energy deposits in the calorimeters consistent with a minimum ionising particle. As such, muon reconstruction primarily uses tracks reconstructed in the ID as described in Section 4.1.1 as well as tracks reconstructed in the MS.

The process of reconstructing tracks in the MS begins by identifying short straight-line track segments reconstructed from hits in an individual MS station [13]. These track segments are identified using a Hough transform [53]. Track segments are then combined based on the interaction point and a parabolic trajectory to form preliminary track candidates. A global χ^2 fit is performed

Category	Description
Hadronic leakage	Ratio of E_T in first layer of the hadronic calorimeter to E_T of the EM cluster
Back layer of EM calorimeter	Ratio of the energy in the back layer to the total energy in the EM accordion calorimeter
Middle layer of EM calorimeter	Lateral shower width within a window of 3×5 cells Ratio of the energy in 3×3 cells to the energy in 3×7 cells centred at the electron cluster position Ratio of the energy in 3×7 cells to the energy in 7×7 cells centred at the electron cluster position
Strip layer of EM calorimeter	Shower width in a window of $\Delta\eta \times \Delta\phi \approx 0.0625 \times 0.2$ Ratio of the energy difference between the maximum energy deposit and the energy deposit in a secondary maximum in the cluster to the sum of these energies Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter
Track conditions	Transverse impact parameter with the respect to the beamline Significance of transverse impact parameter Momentum lost by the track between the perigee and the last measurement point divided by the original momentum
TRT	Likelihood probability based on transition radiation in the TRT
Track-cluster matching	$\Delta\eta$ between the cluster position in the strip layer and the extrapolated track $\Delta\phi$ between the cluster position in the middle layer and the track extrapolated from the perigee

Table 4.1: Table of electron discriminating variables used in electron likelihood discriminant. Modified from [2].

on the muon trajectory through the magnetic field. Using the trajectory given by this fit outlier hits can be removed and hits along the trajectory previously not included can be added to the track. The track is then refitted with these changes. Tracks which share a large fraction of hits with a higher-quality track are removed. Finally, the tracks are refitted with a loose impact parameter constraint and while taking account of any energy lost in the calorimeters the track is extrapolated back to the beam line.

Reconstructed muons can be separated into five types depending on the reconstruction strategy used [13]:

- **Combined (CB):** A combined track fit is performed by matching MS tracks to ID tracks and then performing a fit to the hits in both the ID

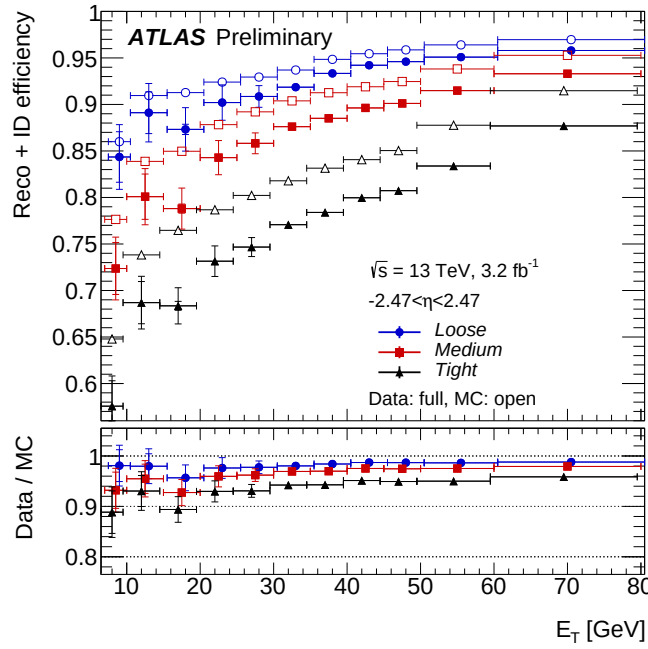


Figure 4.2: Combined electron reconstruction and identification efficiencies in $Z \rightarrow e^+e^-$ events [2].

and MS.

- **Inside-out combined (IO):** An inside-out algorithm is used which extrapolates ID tracks to the MS and searches for at least three loosely-aligned MS hits. These hits, along with the ID hits and the energy lost in the calorimeter, are used in a combined track fit. This algorithm does not use a MS track.
- **Muon spectrometer extrapolated (ME):** If the MS track cannot be matched with an ID track then the MS track extrapolated back to the beamline is used to define an ME muon. This allows muons to be detected in the $2.5 < |\eta| < 2.7$ range which the ID does not cover but the MS does.
- **Segment-tagged (ST):** An ID track is extrapolated to the MS and is required to satisfy tight angular matching requirements to at least one MS track segment. The properties of the reconstructed muon are taken from the ID track.
- **Calorimeter-tagged (CT):** An ID track is extrapolated through the calorimeters and a search is performed along the track for energy deposits consistent with a muon. These are used to identify the track as a muon. The properties of the reconstructed muon are taken from the ID track. A higher p_T threshold is used for CT muons since there are large

backgrounds at low p_T . CT muons allow coverage in areas the MS does not fully cover, in particular the $|\eta| < 0.08$ region.

Whether a muon candidate is assigned as a muon is determined by the working point used. As with electrons these working points vary in their trade-off between their efficiency of correctly identifying muons and their efficiency of misidentifying backgrounds as muons. Three standard working points are defined in order of increasing muon efficiency: Tight, Medium and Loose. There are two additional working points optimised for low and high p_T muons. Different working points use different numbers of muon types with specific sets of requirements on properties such as the number of hits in different ID sub-detectors for each muon type [13].

In this work the Tight working point is used to select muons while the Loose working point is used to define a veto. The Tight working point only uses CB and IO muons. Among other requirements the fit to the combined track must have a normalised χ^2 less than 8 and the track must have at least two MS stations with at least three hits (precision stations). The Loose working point includes CT and ST muons in the $|\eta| < 0.1$ range. IO muons in the range $|\eta| < 1.3$ are only required to have one precision station if they are also reconstructed as ST muons. There is no χ^2 requirement. All working point requirements are specified in [13]. The efficiencies of the working points are measured in data using $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ events and these measurements are used to correct for differences in performance between data and simulated Monte Carlo as a function of p_T . Figure 4.3 shows the performance of the different working points as a function of p_T in $J/\psi \rightarrow \mu\mu$ events.

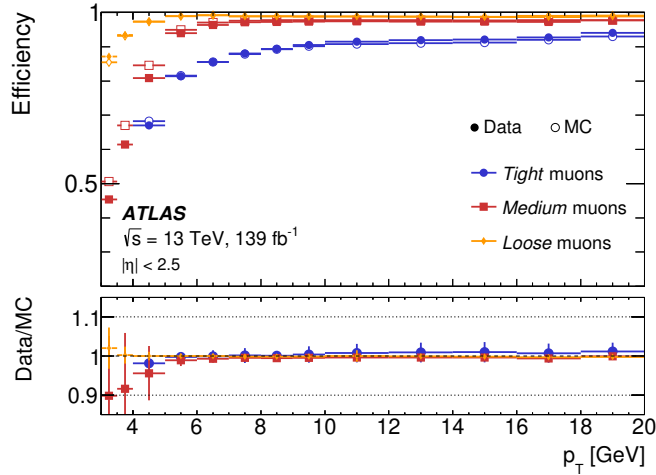


Figure 4.3: Muon reconstruction efficiencies for different working points compared between data and Monte Carlo in $J/\psi \rightarrow \mu\mu$ events [13].

4.1.6 Jets

Jets are narrow cones of particles produced by the fragmentation and hadronisation of a quark or gluon. They are used to infer the presence of quarks from the decay of particles produced in the collision of protons at ATLAS. Jets at ATLAS are reconstructed using the anti- k_t algorithm [54]. This is an infrared and collinear (IRC) safe algorithm. Collinear splittings occur in jets and to be collinear safe means that replacing a parton with a set of partons with the same total momentum will not change the jet properties. Infrared safety means that the addition of a soft emission will not change the properties of the jet [55]. This property is important to ensure theoretical predictions can be more easily compared with experimental results. The anti- k_t algorithm is a sequential recombination algorithm. Two distance parameters are defined: d_{ij} which is a distance measure between objects i and j , and d_{iB} which is a distance measure between an object i and the beam. These are defined in equations 4.2 and 4.3:

$$d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2}) \frac{\Delta_{ij}^2}{R^2} \quad (4.2)$$

$$d_{iB} = p_{Ti}^{-2} \quad (4.3)$$

where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, y_i is the rapidity of particle i and ϕ_i its azimuthal angle. R is the radius parameter which in this work is set to $R = 0.4$. The algorithm iterates through each object i and evaluates d_{ij} for every other object j . The smallest value of d_{ij} found is compared to d_{iB} . If d_{ij} is smallest then objects i and j are combined, if d_{iB} is smallest then i is a completed jet and it is removed from the list of objects.

Within this work particle-flow or p-flow jets are used [56]. Here, tracks from the ID and topo-clusters are used for the reconstruction of jets. To avoid double-counting the energy of particles, if a particle's track is used then the corresponding energy is removed from the calorimeter measurement. The particle flow algorithm performs matching between tracks and calorimeter topo-clusters to perform this energy subtraction procedure and then outputs a list of tracks and modified topo-clusters which are used as inputs to the anti- k_t algorithm.

Jet energy scale calibration

A number of jet energy scale (JES) calibrations have been performed. These ensure that the four-momentum of a jet reconstructed using inputs from the ATLAS detector matches that of a jet reconstructed using simulated stable particles within the jet as input to the anti- k_t algorithm. Stable particles are

defined as those with $c\tau > 10$ mm [57]. These calibrations are applied to the jets as follows:

1. p_T -density based pile-up correction: A subtraction of p_T from the jet p_T based on the per-event pile-up contribution to the jet p_T .
2. Residual pile-up correction: Removes remaining pile-up dependence based on the difference between the p_T of the jet reconstructed in the detector and the jet reconstructed directly from the simulated stable particles.
3. Absolute MC-based calibration: Corrects the jet energy and direction to the particle-level energy scale. accounts for energy losses in passive material and biases in the jet η reconstruction.
4. Global sequential calibration: Reduces flavour dependence and energy leakage effects using calorimeter, track and muon-segment variables.

A separate set of calibrations are performed to ensure that the jet response is consistent in data and MC simulation [57]. These *in-situ* calibrations are summarised as:

1. η intercalibration: Corrects the energy scale of forward ($0.8 \leq |\eta| < 4.5$) jets to match those of central jets ($|\eta| < 0.8$) using dijet events.
2. Hadronic recoil balancing: Calibrated Z boson or photon in $Z + \text{jet}$ or $\gamma + \text{jet}$ events are used to calibrate the hadronic recoil.
3. Multijet balancing: A system of well calibrated low- p_T jets are used to calibrate a single high- p_T jet.

Jet energy resolution

The jet energy resolution(JER) is measured in dijet events [57]. Dijet events are used because the transverse momenta of the jets should equal zero. This allows one jet in a well-calibrated region of the detector to be used as a reference object to the other jet for which the resolution is to be measured. The effect of noise on the JER is measured by measuring the fluctuations in energy deposits due to pileup in data samples using random unbiased triggers. These two measurements are combined to give the final measurement of the JER.

Jet vertex tagger

The jet vertex tagger (JVT) [14] is designed to help exclude reconstructed jets which come from pileup activity rather than hard-scattering. Two variables are used to create a two dimensional likelihood fit which forms the JVT discriminant: R_{pT} and corrJVF. R_{pT} is the scalar p_T sum of all tracks associated with the jet

that originate from the hard-scatter vertex divided by the fully calibrated jet p_T . The fully calibrated jet p_T includes pileup subtraction. corrJVF is defined as:

$$\text{corrJVF} = \frac{\sum_k p_T^{\text{trk}_k}(\text{PV}_0)}{\sum_l p_T^{\text{trk}_l}(\text{PV}_0) + \frac{\sum_{n \geq 1} \sum_l p_T^{\text{trk}_l}(\text{PV}_n)}{k \cdot n_{\text{trk}}^{\text{PU}}}} \quad (4.4)$$

where $\sum_k p_T^{\text{trk}_k}(\text{PV}_0)$ is the scalar sum of the p_T of tracks associated with the jet and that originate from the hard-scatter vertex. $\sum_{n \geq 1} \sum_l p_T^{\text{trk}_l}(\text{PV}_n)$ is the scalar p_T sum of tracks associated with the jet originating from any pileup interactions. $n_{\text{trk}}^{\text{PU}}$ is the total number of pileup tracks per event while $k = 0.01$. For each point in the two dimensional R_{pT} -corrJVF plane the relative probability for a jet at that point to be signal is calculated as the ratio of the number of hard-scatter jets divided by the number of hard-scatter plus pileup jets found around that point. The likelihood is shown in Figure 4.4a while Figure 4.4b shows the JVT score of pileup and hard-scatter jets at low p_T .

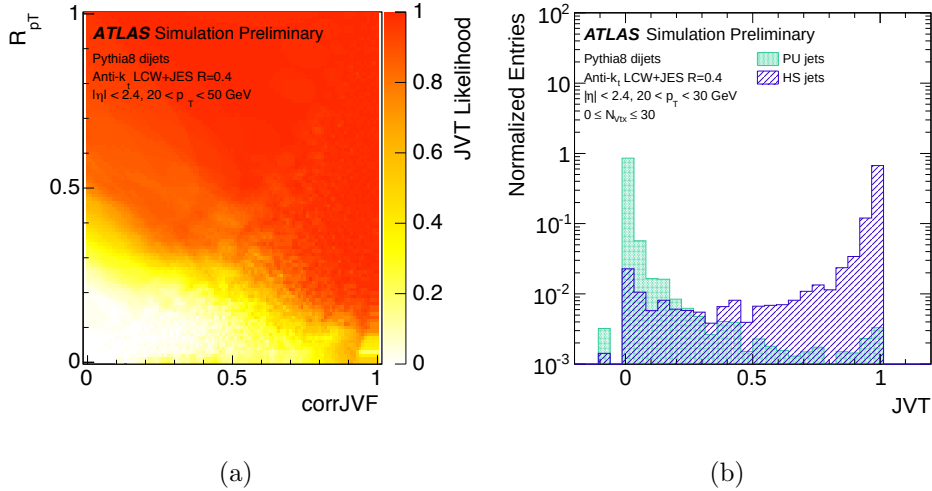


Figure 4.4: (a) The 2-dimensional JVT likelihood as a function of corrJVF and R_{pT} . (b) The distribution of the JVT score for pileup and hard-scatter jets with $20 < p_T < 30 \text{ GeV}$ and $|\eta| < 2.4$ [14].

Scale-factors to correct for discrepancies in the JVT discriminant between data and MC simulation in hard-scatter jets are derived using $Z(\rightarrow \mu\mu) + \text{jets}$ events [14]. Pile-up activity is more likely to mimic low- p_T jets and as such jets in this analysis with $p_T < 60 \text{ GeV}$ and $|\eta| < 2.5$ are required to have a JVT score > 0.5 .

Jet flavour definition

There are multiple ways to label the flavour of a jet. Ideally the flavour will correspond to the flavour of the quark that the jet originated from, although this is not unambiguous. The standard flavour labelling system used at ATLAS

is that if a jet has a b -hadron with $p_T > 5 \text{ GeV}$ within $\Delta R < 0.3$ of the jet's centre it is a b -jet. If no b -hadrons are found the procedure is repeated with c -hadrons, if no c -hadrons are found the procedure is repeated with τ leptons. If the jet is not labelled as b, c or τ it is labelled as a light jet [58].

An alternative labelling is referred to as the parton label in this thesis. This labels the jet as having the same flavour as the highest energy parton in the jet. This definition differentiates between each flavour of quark and also allows a jet to be labelled as a gluon jet.

4.1.7 Taus

Tau leptons decay before reaching the active parts of the ATLAS detector due to their short lifetime ($2.9 \times 10^{-13} \text{ s}$ [1]). Thus it is the decay products of the tau leptons that are detected rather than the taus themselves. Tau leptons decay leptonically ($\tau \rightarrow l \nu_l \nu_\tau$) in 35% of cases and hadronically the remainder of the time. It is hard to distinguish leptonic decays from normal leptons but in hadronic decays the shape of jets can be used to identify taus [59].

Jets considered as possible tau candidates must have $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$. Jets in the transition region between the barrel and forward calorimeters $1.37 < |\eta| < 1.52$, are not considered. The candidate track vertex with the largest fraction of momentum within $\Delta R < 0.2$ is taken as the tau vertex. Tracks passing quality requirements [59] are associated to the core ($\Delta R < 0.2$) or isolation ($0.2 < \Delta R < 0.4$) regions of the tau candidate. A dedicated energy calibration is performed on tau candidates to correct the energy deposition measured in the detector compared to the true energy of the tau. This is done separately for one and three prong candidates and binned in p_T and $|\eta|$.

The identification of tau leptons use Boosted Decision Trees (BDTs). These BDTs use shower shape variables to identify taus and are trained with simulated $Z/\gamma^* \rightarrow \tau\tau$ events for signal and dijet events for backgrounds. Separate BDTs are defined for tau candidates associated with one and three tracks. Loose, medium and tight working points are defined depending on the BDT score threshold above which a tau candidate is called a tau lepton.

4.1.8 Missing Transverse Energy

The missing transverse energy (MET) is ideally given by $E_T^{\text{miss}} = -\sum \vec{p}_T$, where $\sum \vec{p}_T$ is the vector sum over all detected transverse momenta. The reconstructed MET at ATLAS has two contributions. The first contribution is from hard-event signals which are fully reconstructed and calibrated particles and jets. These particles are electrons, photons, τ -leptons and muons. The second contribution comes from soft-event signals which are reconstructed charged-particle tracks associated with the hard-scatter vertex [60].

The calculation of the MET is complicated by the fact that dedicated reconstruction procedures are performed for each of the reconstructed physics objects which can result in the same energy deposits or tracks contributing to multiple physics objects. To avoid double-counting an explicit signal ambiguity resolution procedure is applied. This works by prioritising some objects above others and not including lower priority objects if there is overlap. In general electrons have the highest priority, followed by photons, then taus and finally jets. Since muons are primarily reconstructed from the ID and MS they generally do not overlap with other objects.

The MET in the x and y directions is calculated as

$$E_{x(y)}^{\text{miss}} = - \sum p_{x(y)}^e - \sum p_{x(y)}^\gamma - \sum p_{x(y)}^\tau - \sum p_{x(y)}^\mu - \sum p_{x(y)}^{\text{jet}} - \sum p_{x(y)}^{\text{tracks}} \quad (4.5)$$

with the final term referring to tracks associated with the hard scatter vertex but not any reconstructed object included in the calculation. Using tracks rather than residual calorimeter deposits for the soft term gives better performance since neutral calorimeter deposits suffer from significant pile-up contributions.

4.1.9 Flavour Tagging

Identifying whether jets contain b or c hadrons is incredibly important in this work and in many other ATLAS analyses. Flavour tagging algorithms have been developed for this purpose. These exploit the unique properties of b and c -hadrons. b -hadrons have a longer lifetime (around 1.5 ps [1]) compared to strongly decaying lighter hadrons and so travel a non-negligible distance before decaying. This leads to a displaced vertex relative to the hard-scatter collision point. Algorithms also exploit the long lifetime, high mass and high decay multiplicity of b -hadrons [58]. Charm hadrons have a comparable decay length to b -hadrons and have a single secondary vertex with intermediate charged decay multiplicity [61].

In this work the DL1r algorithm [62] is used for flavour tagging jets. The DL1r algorithm is an updated version of the DL1 algorithm described in Ref. [58]. The DL1r algorithm is based on a deep feed-forward neural network and takes the outputs of a number of low-level tagging algorithms as input. It includes the output of the RNNIP algorithm which is described below and in Ref. [61] as an additional input. These low-level tagging algorithms are as follows:

- **IP2D and IP3D:** The IP2D tagger uses the signed transverse impact parameter significance of tracks, while IP3D also uses the signed longitudinal impact parameter significance. The significance is defined as the parameter divided by its uncertainty. The signed impact parameter is

positive if the angle between the jet direction and the line joining the primary vertex to the point of closest approach to the track is less than $\pi/2$ and negative otherwise. Probability density functions (pdfs) of the impact parameter significances of tracks associated with b -jets, c -jets and light-jets are derived from simulation. These are used to calculate ratios of the probabilities of each track being b, c , or light. Three log-likelihood ratio discriminants are found using these ratios to separate b , c and light jets. For example the log-likelihood ratio discriminating between b and light-jets is given by: $\sum_{i=1}^N \log(p_b/p_u)$ where N is the number of tracks associated with the jet and $p_{b/u}$ is the template pdf of the b /light-jet hypothesis. These three discriminants from both taggers are used as inputs to the DL1r algorithm.

- **SV1:** This secondary vertex tagging algorithm reconstructs a single displaced secondary vertex in a jet. The algorithm finds all two-track vertices built with tracks associated with the jet. Tracks compatible with the decay of long-lived particles, photon conversions or hadronic interactions with the detector material are rejected. The algorithm tries to fit a single secondary vertex from all of the reconstructed two track vertices. The track-to-vertex association is evaluated using a χ^2 test. If the χ^2 is too large or the vertex invariant mass is greater than 6 GeV the track with the largest χ^2 is removed and the process is repeated. Eight variables from the reconstructed secondary vertex are used as input to the DL1r algorithm, which include the number of tracks associated with the vertex, the invariant mass of the vertex and its three-dimensional decay length significance.
- **JetFitter:** The JetFitter [63] algorithm attempts to reconstruct the full b -hadron decay chain. A Kalman filter [46] is used to approximate the flight path of the b -hadron and the vertex positions. This allows the b and c vertices to be found even if they are only associated with one track. Eight b -tagging variables are passed to the DL1r tagger including the track multiplicities at displaced vertices and the invariant mass of those tracks. Another eight c -tagging variables are passed to the DL1r tagger, which include the distance of the second or third vertex from the primary vertex and the invariant mass of tracks associated with those vertices [58].
- **RNNIP:** The RNNIP algorithm is a recurrent neural network that exploits correlations between the tracks' impact parameters. The track parameters and information from the IP2D and IP3D algorithms are fed to the network. The algorithm outputs four tagging probabilities equal

to the probability of the jet being a b -jet, c -jet, light jet or a τ -jet [61]. These four probabilities are used as inputs to the DL1r tagger.

The final outputs of the DL1r algorithm are three probabilities p_b , p_c , p_l , the probabilities of the jet being a b -jet, c -jet, or light flavoured jet respectively. Discriminants D_b and D_c are defined to determine if a jet is b or c -tagged respectively:

$$D_{b/c} = \ln \left(\frac{p_{b/c}}{f_{c/b} \cdot p_{c/b} + (1 - f_{c/b}) p_l} \right). \quad (4.6)$$

A value of the discriminant is chosen above which the jet is b/c tagged, which alongside the value of $f_{c/b}$, defines the tagging working point. $f_{c/b}$ is a parameter taking values between 0 and 1 which varies the importance of rejecting c/b -jets relative to rejecting light-jets. The discriminant merely decides whether a jet is tagged or is not and so if an analysis uses both b and c -tagging one must take priority over the other. In this work two working points are used: one where charm tagging takes priority and one where b -tagging takes priority. If the value of both the b and c discriminant is such that the jet would be both b and c tagged it is only tagged as whichever tagger is given priority.

In order to ensure that the performance of tagging is consistent in MC simulation and data calibrations are performed. These calibrations find the tagging efficiencies as functions of p_T between MC and data, from which correction scale-factors are derived. Calibrations are performed for b -jets, c -jets and light jets. The b -jet calibration is performed using the b -jets present in dileptonic $t\bar{t}$ events. A combinatorial likelihood fit approach is used to measure the tagging efficiency [58]. The c -jet calibration uses $W \rightarrow cs$ decays in semi-leptonic $t\bar{t}$ events. A fit is performed to the fraction of events where either of the jets coming from the W are tagged [62].

The light jet calibration is performed in $Z + \text{jets}$ events [64]. The rate of tagging light-jets as b or c is very low and tagged jets will be dominated by heavy-flavour jets. This makes calibrating the rate of mis-tagging light jets in this sample hard. To overcome this problem light jets are assumed to be mis-tagged as heavy flavour jets due to the finite resolution of tracks and impact parameters. Under this assumption the signed impact parameter distribution of tracks in light jets will be symmetric about zero while tracks associated with b or c -hadrons will be skewed towards positive impact parameters due to their long lifetime. A flipped tagger is defined, the details of which are in Ref. [64], but the main difference is the flipping of the sign of the signed impact parameter. This flipped tagger accepts similar number of light jets due to the symmetry of the signed impact parameter but accepts much lower numbers of heavy flavour jets. The working points to be calibrated are used with this

flipped tagger to give samples with large numbers of tagged light jets. With some corrections for the difference between the standard and flipped taggers performance the scale-factors can then be derived.

4.2 Signal and Background Modelling

Monte Carlo (MC) simulations are used to provide the templates of the signal and background processes used in the fit described in Chapter 6. Simulating events is a multistep process. The first step is calculating the matrix elements of the events as a function of the momenta of the initial and final-state particles. Parton distribution functions (PDFs) describe the initial momentum distribution of the particles within the colliding protons and MC techniques are used to simulate the momenta of the resulting particles across a large number of events.

The next step is simulating the parton shower and the hadronisation of particles. The high momentum quarks and gluons produced in the hard-scatter interaction emit gluons which split to $q\bar{q}$ pairs or more gluons and these new particles may continue the process. Eventually the quarks must hadronise due to colour confinement. If the hadrons that form are unstable then their decay must also be simulated.

The final step is the simulation of the ATLAS detector response. This is done using the GEANT4 framework [65, 66]. GEANT4 simulates the detector geometry and the passage of particles through the materials making up the detector components. Hits are recorded in areas where particles deposit energy. These hits are then converted into voltages and currents which are used to simulate the response of the relevant sub-detectors to these hits. The same reconstruction software is then applied to the simulated events as is applied to data.

In addition to the main hard-scatter process simulated, the simulated data must also include the effect of pileup. Pileup refers to the products of proton-proton collisions other than the collision of interest. These are primarily either in-time pileup where the collisions occur in the same bunch-crossing as the collision of interest or out-of-time pile-up where the collisions occur in the bunch-crossing before or after the collision of interest. Pileup is simulated as minimum-bias pp collisions using Pythia8 [67, 68] which are superimposed onto the hard-scatter collisions of interest. The simulated MC events are reweighted such that the pileup in simulation matches the observed pileup for a given year as seen in Figure 3.9.

The MC simulation is separated into three production campaigns with MC16a corresponding to data taken in 2015 and 2016, MC16d corresponding to data taken in 2017, and MC16e corresponding to data taken in 2018. The

simulated data is normalised based on the cross-section of the process and the measured integrated luminosity of the data-taking period.

4.2.1 $t\bar{t}$

The nominal $t\bar{t}$ sample used contains “non all-hadronic” $t\bar{t}$ events, that is it contains decays where one W decays leptonically and decays where both W bosons decay leptonically. This sample is generated using the POWHEG-BOX v2 NLO generator [69, 70] with the NNPDF3.0 PDF set [71] and a top quark mass of 172.5 GeV. The h_{damp} parameter which controls the p_T of the emission of the first gluon is set to 1.5 times the top mass. The decays of heavy flavour hadrons are simulated by the EvtGen program [72]. The parton shower and hadronisation is modelled using Pythia 8.2 [73] with the *A14* tune [74] and the NNPDF2.3LO PDF set [71]. The cross-section of all $t\bar{t}$ events is taken to be the top++2.0 [75] theoretical cross-section of 832 pb, this is calculated at next-to-next-to-leading-order (NNLO) in QCD and includes the resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms [76–79]. However, it is worth noting that the normalisation of the semi-leptonic and fully leptonic $t\bar{t}$ decays is free to vary in the fit as set out in Section 6.2.

$t\bar{t}$ events where additional heavy flavour jets not directly from the top or W boson decay are present are considered carefully in this analysis. Additional samples are generated with a filter requiring additional b or c jets to ensure that there are enough simulated events of this type in all regions of the fit. To avoid double-counting, events passing the requirements of this filter are removed from the main sample. The specially generated samples, which have a higher number of unweighted events, are then correctly weighted and combined with the main sample to give the nominal $t\bar{t}$ sample used in this analysis.

Alternative $t\bar{t}$ samples are used to estimate uncertainties due to the simulated parton shower. The generator is identical to that of the nominal sample but the parton shower and hadronisation is modelled using Herwig 7.0.4 [80]. As with the nominal sample additional samples are generated to ensure that there are enough events with additional heavy flavour jets in all regions of the fit.

The $t\bar{t}$ events are separated into categories depending on the flavour of partons matched to jets not originating from the decay of the $t\bar{t}$ system. Truth jets are reconstructed from all stable particles in the simulated event and are required to have $p_T > 15$ GeV and $|\eta| < 2.5$. Hadrons are matched to the jets if the centre of the jet is within $\Delta R < 0.3$ of the hadron. If a jet is matched to a b -hadron with $p_T > 5$ GeV not originating from the decay of a top quark the event is labelled as $t\bar{t}+ \geq 1b$. If not meeting this criteria then if a jet is matched to a c -hadron with $p_T > 5$ GeV not originating from a W boson decay

the event is labelled as $t\bar{t} + \geq 1c$. All other $t\bar{t}$ events including those with no additional jets are labelled as $t\bar{t}$ +light-jet events. This categorisation scheme was chosen to remain consistent with recent ATLAS analyses in particular studies of the decay of a hypothetical charged Higgs boson in $t\bar{t}$ events [81, 82].

The $t\bar{t}$ samples described in this section do not contain events with $W \rightarrow cb$. Dedicated samples are used for the $W \rightarrow cb$ which exclusively contain semi-leptonically decaying $t\bar{t}$ events with one $W \rightarrow cb$. These samples are otherwise generated identically to the nominal and alternative $t\bar{t}$ samples. The nominal dedicated sample will be referred to as the $|V_{cb}|$ sample in this thesis.

4.2.2 Single-top Background

The single-top background consists of six separate samples, the samples are separated by production channel and whether a top or anti-top quark is produced. The channels generated are the s-channel, t-channel and Wt channel, leading order Feynman diagrams of the processes are shown in Figure 4.5. As with the nominal $t\bar{t}$ sample each of these samples is generated using the POWHEG-BOX v2 generator interfaced with Pythia 8.2 using the *A14* tune and the NNPDF2.3LO PDF set. The decays of heavy flavour hadrons are simulated by the EvtGen program. The diagram-removal technique [83] is used to account for overlaps between the final states of the Wt channel and $t\bar{t}$ events. The samples are normalised to their approximate NNLO theory cross-sections [84–86]. As for the $t\bar{t}$ sample an alternative sample using Powheg 7.0.4 for parton shower simulation is used to evaluate uncertainties in the parton shower modelling.

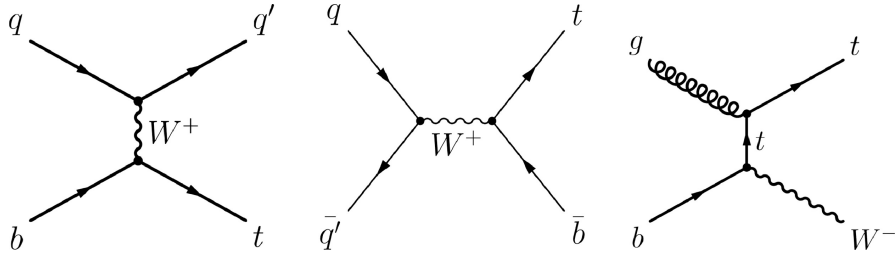


Figure 4.5: Leading order Feynman diagrams of the t-channel (left), s-channel (centre), and Wt channel (right) [15].

4.2.3 $V + \text{Jets}$ Backgrounds

The $W + \text{jets}$ and $Z + \text{jets}$ backgrounds are both generated with the SHERPA 2.2.1 generator [87], SHERPA simulates both the matrix element, the parton shower and the hadronisation. The matrix element calculation is performed at NLO for up to two partons and at LO for up to four and uses the NNPDF3.0 NNLO

pdf set. These calculations use the Comix [88] and OPENLOOPS [89] libraries. Both samples are normalised to their NNLO theoretical cross-section [90].

4.2.4 Diboson Backgrounds

Diboson backgrounds are $WW/WZ/ZZ$ +jets events. They are generated using SHERPA 2.2.2 with the NNPDF3.0 NNLO pdf set. The matrix element calculation is performed at NLO without any partons and at LO with up to three partons. The samples are normalised to their NLO QCD theoretical cross-sections.

Chapter 5

Event Selection and Reconstruction

5.1 Initial Selection Requirements

Before being subject to any other selection requirements events must pass a single-lepton trigger. Single-lepton triggers select events where the trigger has detected either an electron or a muon. This trigger level lepton must then be matched with a fully-reconstructed lepton. The names of the triggers used are summarised in Table 5.1 while the requirements of the triggers are shown in Table 5.2. The electron triggers use a likelihood determinant which is designed to be as close as possible to the likelihood discriminant used in the offline reconstruction of electrons described in Section 4.1.4 [4]. However, the discriminant used by the trigger does not include the momentum lost by the track between the perigee and the last measurement point. The trigger likelihood has four working points “very loose”, “loose”, “medium” and “tight.” Some triggers have isolation requirements on the lepton

Year	Lepton	Trigger Name
2015	Electron	e24_lhmedium_L1EM20VH OR e60_lhmedium OR e120_lhloose
	Muon	mu20_iloose_L1MU15 OR mu50
2016-2018	Electron	e26_lhtight_nod0_ivarloose e60_lhmedium_nod0 OR e140_lhloose_nod0
	Muon	mu26_ivarmedium OR mu50

Table 5.1: Names of the single lepton triggers used, split by data-taking year and lepton type. Trigger detail in Table 5.2 and Ref [3–5].

Events passing the trigger requirements of Table 5.1 are then required to have:

- Exactly 1 electron or muon passing the tight reconstruction requirements

Trigger Name	Trigger Requirements
e24_lhmedium_L1EM20VH	$E_T > 24$ GeV, Medium LH WP, Veto events with HCal energy deposit behind electron candidate
e60_lhmedium	$E_T > 60$ GeV, Medium LH WP
e120_lhloose	$E_T > 20$ GeV, Loose LH WP
e26_lhtight_nod0_ivarloose	$E_T > 26$ GeV, Tight LH WP, Isolation: $\sum p_T$ of tracks in $\Delta R < 0.2$ cone must be less than 10% of electron p_T
e60_lhmedium_nod0	$E_T > 60$ GeV, Medium LH WP
e140_lhloose_nod0	$E_T > 140$ GeV, Loose LH WP
mu20_iloose_L1MU15	$E_T > 20$ GeV, Isolation: $\sum p_T$ of tracks in $\Delta R < 0.2$ cone must be less than 12% of muon p_T
mu50	$E_T > 50$ GeV
mu26_ivarmedium	$E_T > 26$ GeV, Isolation: $\sum p_T$ of tracks in $\Delta z < 6$ mm must be less than 7% of muon p_T

Table 5.2: Summary of the requirements of the single lepton triggers used in the analysis. Complete details of working points can be found in Refs [3–5]. E_T is the transverse energy, LH WP refers to the working points of the electron trigger’s likelihood discriminant.

with $p_T > 25$ GeV, $|\eta| < 2.5$

- Exactly 4 jets with $p_T > 25$ GeV, $|\eta| < 2.5$

5.2 Flavour Tagging Working Points

Two different flavour tagging working points are used in this thesis, the details of which are described in the following sub-sections. All events are required to have at least one b -tagged jet to be selected. In the remainder of this chapter this will be using the optimised working point described in section 5.2.1 unless otherwise specified.

5.2.1 Analysis-optimised working point

The first working point used was optimised for the measurement of $|V_{cb}|$ using a cut-and-count method set out in Ref. [16]. This was the method originally envisaged for this analysis: $|V_{cb}|$ is measured by counting the number of events in different tagging bins. This contrasts with the binned template profile likelihood fit now used as set out in Chapter 6. The working point uses a b -tag veto such that if a jet passes the b -tagging threshold it will not also be c -tagged even if it passes the c -tagging score threshold. In Ref. [16] the equation for the

fractional error on $|V_{cb}|^2$ is given as

$$\frac{\Delta|V_{cb}|^2}{|V_{cb}|^2} \approx \frac{1}{\epsilon_b \sqrt{23\mathcal{L}\epsilon_c\epsilon_b}} \oplus \frac{\left[f_{lb} + f_{lc}\tilde{f}_{cb} \left(1 + f_{lc} + \tilde{f}_{cb} \right) \right]^{\frac{1}{2}}}{\epsilon_b^2 |V_{cb}| \sqrt{23\mathcal{L}\epsilon_c}} \oplus \delta_{\epsilon_b} \oplus \frac{f_{lb}}{\epsilon_b |V_{cb}|^2} \delta_{\mathcal{B}_1}, \quad (5.1)$$

where ϵ_a is the efficiency of identifying a jet due to a quark of flavour a as flavour a , while f_{ab} is the probability of a jet due to a quark of flavour a being identified as flavour b . $\tilde{f}_{cb} = f_{cb}/\epsilon_c$. δ_{ϵ_b} is the fractional error on the b efficiency and $\delta_{\mathcal{B}_1}$ the fractional error on the number of events of a background $\mathcal{B}_1$. This is defined as the background from $t\bar{t}$ events where a W decays to a light-jet and a charm jet but the light jet is mis-identified as a b -jet meaning that the event appears to be a signal event. Since δ_{ϵ_b} cannot be found without calibrating the working point the third term was excluded from the optimisation, since δ_{ϵ_b} varies relatively little between working points this will not have a large effect on the optimisation. In Ref. [16] this term was estimated as 0.03. The fourth term was also excluded due to $\delta_{\mathcal{B}_1}$ requiring the calculation of all systematics to be found, an estimate of $\delta_{\mathcal{B}_1}$ in Ref. [16] was given as 0.1. The fourth term is only directly sensitive to changes in the b -tagging working point and so its exclusion only affects the optimisation in the case where both the b and c tagging working points are allowed to vary.

The optimisation was performed allowing the cut on the discriminants $D_{b/c}$ and the fractions $f_{c/b}$ as defined in Eq. 4.6 to vary freely and minimising the fractional error. This was then repeated but with the b -tagging variables D_b and f_c fixed to a standard ATLAS 60% efficiency working point. The results are shown in Table 5.3. Given the very small difference in the fractional error the working point using the standard ATLAS 60% working point was chosen such that it was only the c -tagging working point that required calibration. The c -tagging WP has an efficiency of approximately 32%. For this working point and using the estimates of δ_{ϵ_b} and $\delta_{\mathcal{B}_1}$ given in Ref. [16], the terms of Eq. 5.1 are in order, 0.063, 0.082, 0.033, 0.089.

	f_c	D_b cut	f_b	D_c cut	Error
Fully optimised	0.024	5.24	0.015	1.48	0.099
Using 60% b WP	0.018	4.565	0.01	2.13	0.104

Table 5.3: Fractions and discriminant cuts for flavour tagging working points optimised to counting version of analysis.

Despite being optimised for a different method of measuring $|V_{cb}|$ this working point outperforms any other c -tagging working point used by ATLAS. This working point is expected to be relatively well optimised for the likelihood fit because the statistical error in both the cut-and-count method and the likelihood fit method primarily determined by the ratio of the signal over the

square root of the background in events with 3 b -tags and 1 c -tag.

Preliminary work was done to calibrate this working point. However, the calibration of non-standard flavour tagging working points remains a long and complicated process at ATLAS. As such due to the small size of the analysis team working on measuring $|V_{cb}|$ and time constraints it was decided that a less optimised working point being calibrated by another analysis should be considered. This working point is described in the next section.

There is ongoing work in the ATLAS collaboration to calibrate the p_b, p_c, p_l scores rather than specific cuts on the DL1r discriminants as is currently done. This would allow an arbitrary working point to be selected which would not require further calibration. Thus future iterations of this measurement should be able to use this optimised working point or a working point entirely optimised to the profile likelihood-fit approach.

5.2.2 Alternative working point

An alternative working point was provided by an analysis studying $t\bar{t} + c\bar{c}$ events. This working point uses a c -tag veto prioritising the c -tag if a jet could be both b and c -tagged.

The b -tagging working point uses $f_c = 0.018$ and the cut is then defined as a cut of 0.99 on the sigmoid¹ of the DL1r score. This is equivalent to a cut of 4.595 on the DL1r score and is very similar to the previous optimised working point.

The c -tagging working point uses a different definition of the DL1r discriminant compared to the usual definition of Eq. 4.6. It is defined as:

$$D_c = \ln \left(\frac{p_c}{p_b + 1.5p_u} \right). \quad (5.2)$$

Again, the cut is defined in terms of the sigmoid of the discriminant with the sigmoid of the discriminant required to be greater than 0.625 for a jet to be c -tagged.

A comparison between the statistical errors using the two flavour-tagging working points is made in Section 6.5.

5.3 Kinematic Chi-squared Quality Metric

In order to select as pure a sample of semi-leptonic $t\bar{t}$ events as possible and to assign each of the jets to one of the quarks in the original decay independent of flavour tag a kinematic χ^2 was created. Each permutation of the four jets is considered and the χ^2 score evaluated; the permutation with the lowest χ^2 is

¹The sigmoid of value x is defined as $S(x) = \frac{1}{1+e^{-x}}$

selected. Each term of the χ^2 will be described in detail in this section but the overall form is given by:

$$\chi_{\text{total}}^2 = \chi_{m_t^{\text{lep}}}^2(E_{\text{b-jet}}) + \chi_{y'}^2 + \chi_{x'}^2(y') (+\chi_{m_W^{\text{lep}}}^2). \quad (5.3)$$

The first term is described in Section 5.3.4 and is a contribution from the reconstruction of the leptonically decaying top quark, the second and third terms are described in Section 5.3.5, these are contributions due to the reconstruction of the hadronically decaying top and its corresponding W boson. The final term is from cases where the reconstruction of the neutrino does not give real solutions, this results in a shift of the leptonically decays W mass as is explained in Section 5.3.3. The complementary cumulative distribution function (cdf) of the χ^2 is determined based on the number of terms and is required to be greater than 0.1 for the event to pass selection.

5.3.1 Chi-squared calibration sample definition

The distributions used to calibrate the χ^2 require that jets in MC simulation are truth-matched with the initial quarks of the $t\bar{t}$ system. Truth information is used to select events in the nominal $t\bar{t}$ Powheg Pythia8 sample which are generated as semi-leptonic events with the lepton being an electron or muon. Events are required to have exactly 4 reconstructed jets and these jets cannot have a gluon parton label. The quarks must all fall within the $|\eta| < 2.5$ range.

The ΔR distance between each of the quarks and jets is calculated and a matching is chosen such that the sum of all ΔR is minimised. The four ΔR are put in ascending order and are then required to be less than $\{0.07, 0.2, 1, 1\}$ respectively. Events not satisfying this requirement are not included in the truth matched sample. The reconstructed lepton must be within $\Delta R < 0.3$ of the true lepton.

5.3.2 MET Correction

A correction is applied to the reconstructed MET of the events such that it more closely matches the simulated neutrino transverse momentum. The difference between the MET and the simulated neutrino p_T is plotted as a function of the reconstructed lepton p_T . This defines a function which is subtracted from the MET to give the corrected MET used in the reconstruction of the $t\bar{t}$ event.

Figure 5.1 shows the difference between the reconstructed MET and the neutrino p_T ; the 1D histogram shows that the MET is skewed such that the MET is larger than the neutrino p_T . Figure 5.2 shows the profile of Figure 5.1a along the x -axis before and after the MET correction.

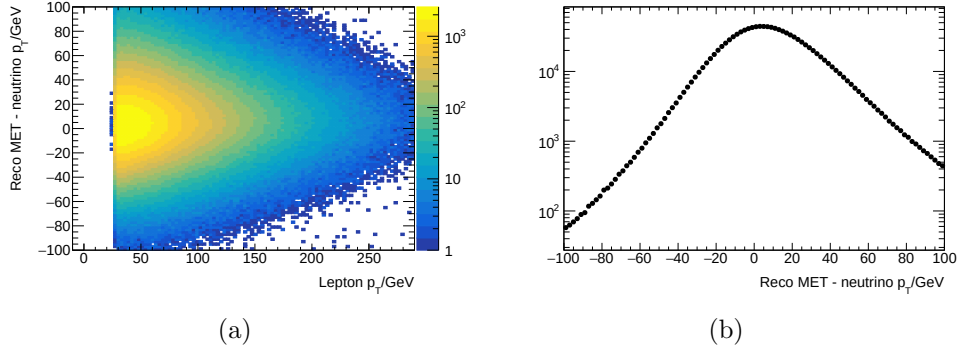


Figure 5.1: Histogram of the difference between the reconstructed MET and the neutrino p_T vs reconstructed lepton p_T , and a 1D histogram of the difference.

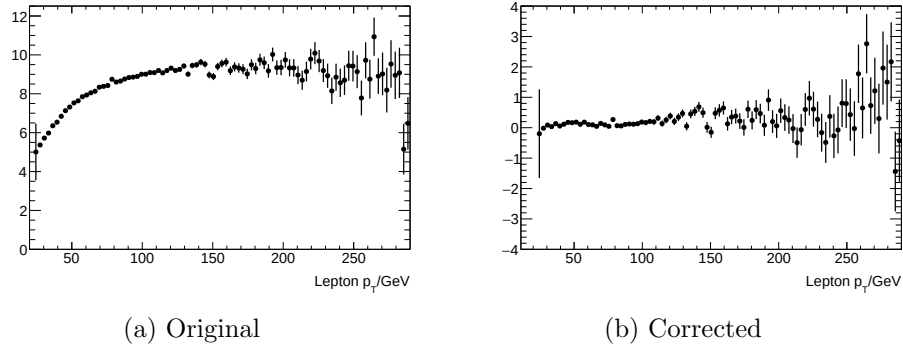


Figure 5.2: Profile of Figure 5.1a with and without the MET correction.

5.3.3 Neutrino reconstruction

The neutrino's longitudinal momentum is reconstructed by requiring that the charged lepton and the neutrino's four-momenta combine to reconstruct the W mass. Defining the lepton and neutrino's four momenta:

$$\mathbf{p}^\nu = \left(\sqrt{E_T^2 + p_z^2}, E_T \cos(\phi), E_T \sin(\phi), p_{z_\nu} \right), \quad (5.4)$$

$$\mathbf{p}^l = (E_l, p_{x_l}, p_{y_l}, p_{z_l}) \quad (5.5)$$

where p_{z_ν} is to be determined and ϕ is the azimuthal angle of the missing transverse energy E_T .

Define:

$$2A = m_\nu^2 + m_l^2 - m_W^2 - 2p_{x_l} E_T \cos(\phi) - 2p_{y_l} E_T \sin(\phi). \quad (5.6)$$

The solution for p_{z_ν} to reconstruct the correct W mass is then given by:

$$p_{z_\nu} = \frac{-Ap_{z_l} \pm E_l \sqrt{E_T^2 (p_{z_l}^2 - E_l^2) + A^2}}{E_l^2 - p_{z_l}^2}. \quad (5.7)$$

In approximately 75% of cases this equation has a real discriminant and as such there are two possible solutions; in this case the solution which is smaller in magnitude is chosen as has been done in other analyses [91]. In simulation the smaller solution is found to be closest to the true longitudinal neutrino momentum in 64% of cases. If the discriminant is negative thus giving imaginary solutions then the discriminant is set to zero to give one real solution. The effect of this is to shift the W mass upwards as seen in Figure 5.3. In these cases the shifted W mass contributes a term to the χ^2 . This term comes from taking the value of the cumulative distribution function of a Gaussian fitted to Figure 5.3 and converting this into the corresponding value of a single χ^2 contribution. If the W mass shifts above 160 GeV then the event is vetoed.

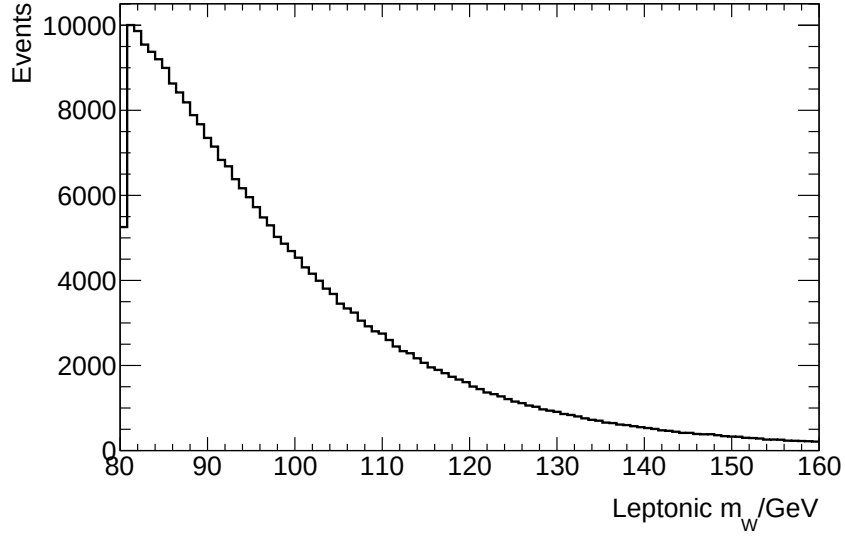


Figure 5.3: Reconstructed leptonic side W mass in the case where the discriminant of eq. 5.7 is negative.

5.3.4 Leptonically decaying top

The mass of the leptonically decaying top ($t \rightarrow b\ell\nu_l$) is reconstructed by adding the four-momenta of the reconstructed neutrino, charged lepton and the jet assigned as coming from the leptonic bachelor b .

To define the χ^2 contribution of the leptonic top the reconstructed mass of the leptonic top is plotted against the energy of the leptonic bachelor in the truth matched events as seen in Figure 5.4. 19 slices are taken along the x -axis between 25 and 500 GeV and projected onto the y -axis, giving plots of the top mass to which Crystal Ball functions [92] are fitted. The Crystal Ball function

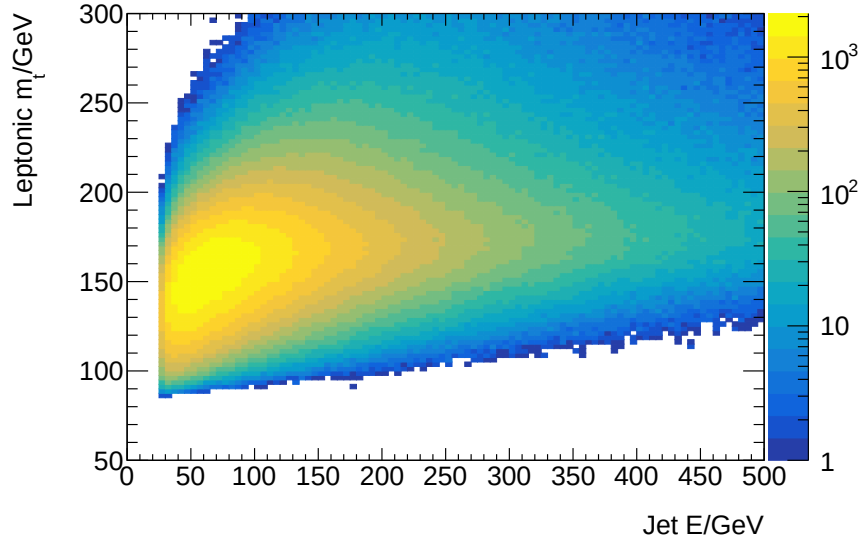


Figure 5.4: Reconstructed leptonic top mass as a function of b -jet energy.

here is defined as

$$f(x; \alpha, n, \bar{x}, \sigma) = N \cdot \begin{cases} \exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right), & \text{for } \frac{x-\bar{x}}{\sigma} < -\alpha \\ A \cdot (B - \frac{x-\bar{x}}{\sigma})^{-n}, & \text{for } \frac{x-\bar{x}}{\sigma} \geq -\alpha \end{cases}, \quad (5.8)$$

where

$$A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right), \quad (5.9)$$

$$B = \frac{n}{|\alpha|} - |\alpha|$$

and N is a normalisation factor. The means, standard deviations and alphas of these Crystal Ball functions are plotted as a function of b -jet energy and a polynomial is fitted to each of them such that there is a Crystal Ball function defined for every b -jet energy. Figure 5.5 shows two examples of the fitted slices while Figure 5.6 shows the fitted parameters of the Crystal Ball functions. The n parameter which determines the rate of decay of the Crystal Ball tail is set to 5 in all cases, a constraint which was needed to aid the stability of the fit while not degrading significantly the fit qualities. There are near degeneracies in the minima of the fit meaning that without this constraint n could vary drastically between slices and the parameters would not vary smoothly as seen in Figure 5.5.

Events where the b -jet energy is greater than 400 GeV are vetoed. Otherwise the b -jet energy is used to select the parameters of the Crystal Ball function using the fits of Figure 5.6. From this Crystal Ball function the value of the cdf relative to the mean is determined and this is converted into the corresponding value of a single parameter χ^2 function which is the contribution

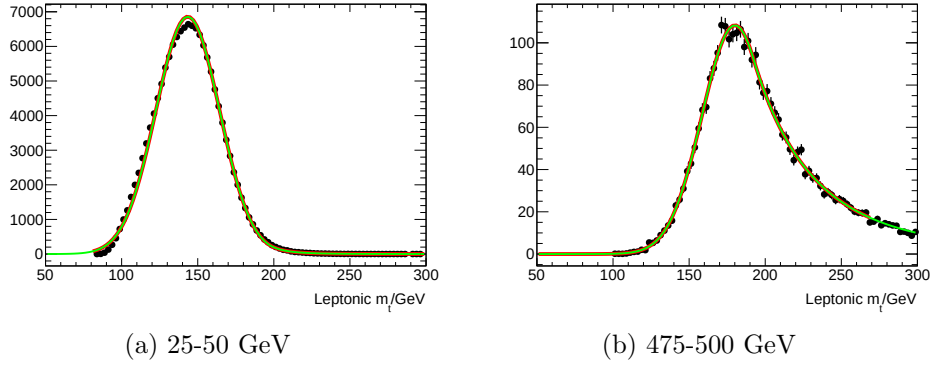


Figure 5.5: 25 GeV slices along the x -axis of Figure 5.4. The red line shows the Crystal Ball fit over the range used for the fit while the green line shows the fit over the entire range of masses.

of the leptonically decaying top to the χ^2 .

5.3.5 Hadronically decaying top

The masses of the hadronically decaying top $t \rightarrow bqq'$ and W are reconstructed by adding the appropriate jet four-momenta. The masses of the reconstructed top vs W boson are plotted and then rotated such that the axis with minimal variance is aligned with the x -axis. This is illustrated in Figure 5.7 where the rotated masses are referred to as x' and y' .

Figure 5.7b is split into 14 slices along the y' axis between $y' = -90$ and $y' = 70$. Similar to the leptonic top case these slices are projected onto the x' axis and Gaussian's are fitted to the histograms. The means and widths of those histograms are plotted and a fit is performed such that for every value of y' there is a corresponding Gaussian mean and width for x' . These are seen in Figure 5.8. If the value of y' falls outside of the fitted range the mean and standard deviation are set to those corresponding to $y' = -90$ or $y' = 70$.

y' is treated more straightforwardly with a Gaussian fitted to the projection without any slicing. The χ^2 contributions of x' and y' are simply the square of the difference between the mean and the reconstructed value divided by the standard deviation squared.

5.3.6 Jet assignment performance

Although only the cdf of the χ^2 is used in this iteration of the analysis rather than which jet has been assigned to which $t\bar{t}$ decay product Table 5.4 shows the efficiency with which the kinematic χ^2 assigns the reconstructed jets to the correct quark in the calibration sample.

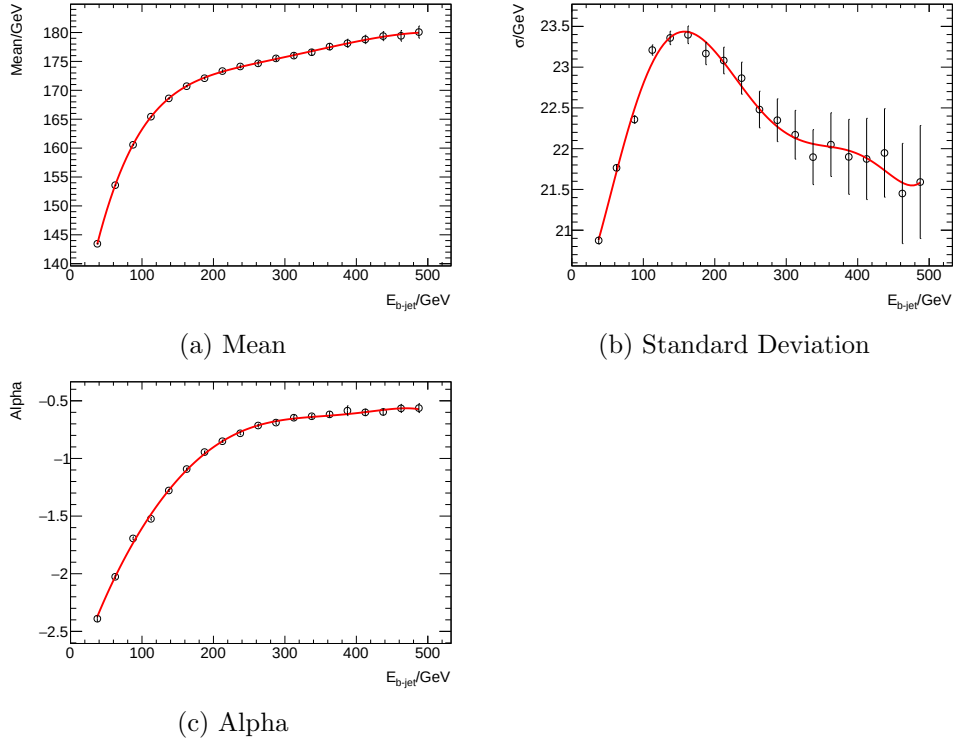


Figure 5.6: Fits to the parameters of the Crystal Ball functions fitted to the slices of Figure 5.4.

	Assigned Order	Efficiency
True Order	$W_D W_D b_{had} b_{lep}$	0.55
	$W_D W_D b_{lep} b_{had}$	0.050
	$W_D b_{had} W_D b_{lep}$	0.23
	$W_D b_{lep} W_D b_{had}$	0.039
	$b_{had} b_{lep} W_D W_D$	0.038
	$W_D b_{had} b_{lep} W_D$	0.046
	$W_D b_{lep} b_{had} W_D$	0.041

Table 5.4: Performance of χ^2 jet assignment in calibration sample. The first row corresponds to the correct ordering. W_D refer to the daughters of the hadronically decaying W , b_{had} is the b from the hadronically decaying top ($t \rightarrow b_{had} W_D W_D'$) and b_{lep} is the b from the leptonically decaying top ($t \rightarrow b_{lep} l \nu_l$).

5.4 Excluding Fully-leptonic $t\bar{t}$ Decays

The largest background passing the requirements set out so far is due to fully-leptonic $t\bar{t}$ decays where both W bosons decay leptonically. In order for these “lep-lep” events to pass the selection requirements then one charged lepton must not be detected and two additional jets not corresponding directly to the b -quarks in the $t\bar{t}$ decay must be detected and reconstruct a W mass within errors.

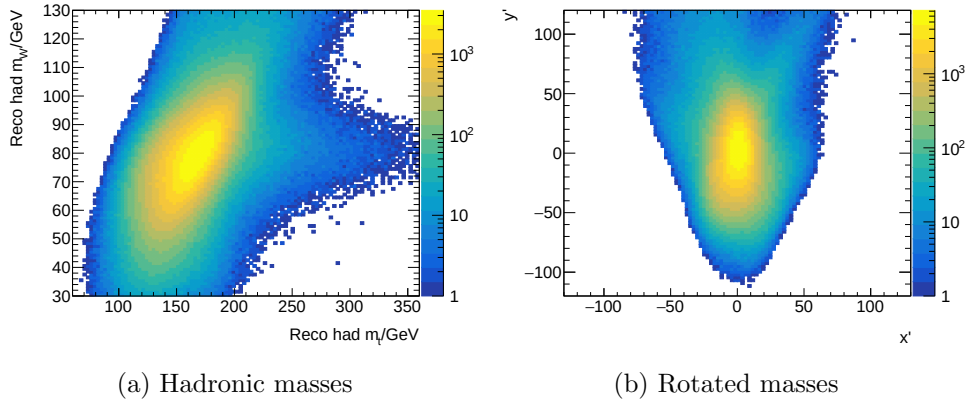


Figure 5.7: Scatter plots of the reconstructed hadronic W mass vs the hadronic top mass and the same plot rotated and centred to minimise the variance along the x' axis.

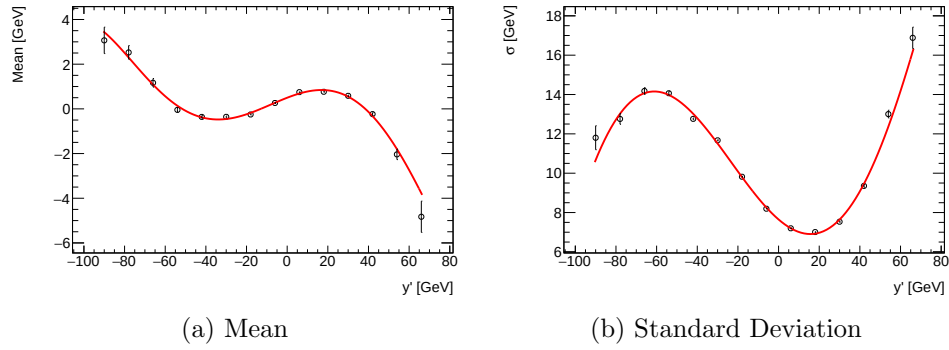


Figure 5.8: Fits to the parameters of the Gaussians fitted to the slices of Figure 5.7b.

The p_T of the undetected lepton in lep-lep events that pass the event selection requirements is plotted in Figure 5.9. This shows that a large number of the missed leptons fall below the 25 GeV requirement for the lepton to be considered. The steep increase in the number of missed leptons below 25 GeV suggests at least some lep-lep events could be removed if leptons below this threshold were considered. This leads to the first change in the event selection: if an event has an additional charged lepton with p_T between 10 and 25 GeV the event is vetoed.

In Figure 5.10 the p_T of the undetected lepton in lep-lep events is plotted against its pseudorapidity. In Figure 5.11 the same plots are created for leptons satisfying “loose” reconstruction requirements that are present in events passing the event selection requirements. This shows that some of the muons missed around $|\eta| = 0$ can be recovered, this is due to the loose working point including calorimeter-tagged muons to cover gaps in the muon spectrometer as described in Section 4.1.5. Some electrons are also recovered but not in the transition region between the barrel and end-cap where electrons are not reconstructed.

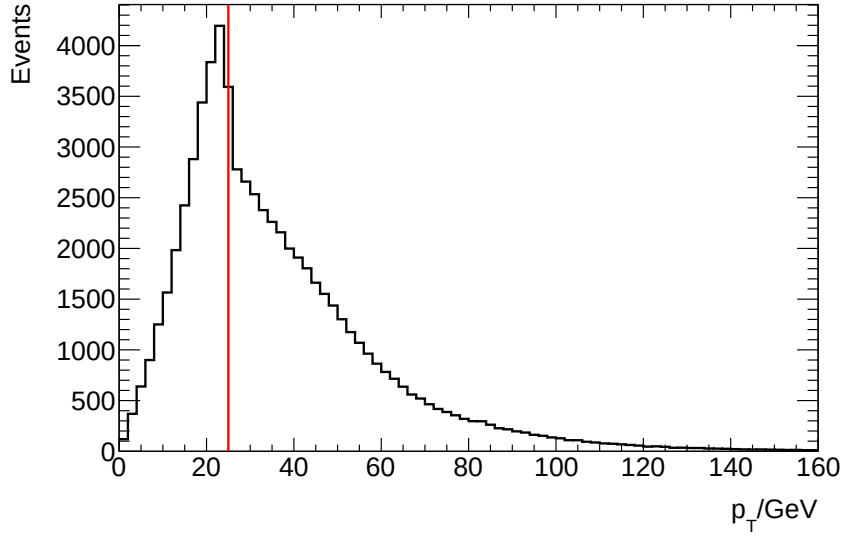


Figure 5.9: Transverse momentum of undetected leptons in lep-lep events passing other selection requirements. The vertical red line is at 25 GeV the minimum p_T required for leptons to be counted.

This motivates another modification of the event selection; events which have more than one lepton meeting the loose reconstruction requirements are not selected.

Figures 5.12 show the pseudorapidity of the missed leptons while Figures 5.13 show the pseudorapidity of jets with a parton label of -1 in lep-lep events passing the selection cuts. A parton label of -1 signifies no partons are present and therefore the jet has to have been caused by electromagnetic interactions. It is clear that in many cases the undetected leptons are instead reconstructed as jets. Figure 5.14 shows that in the majority (93%) of cases missed leptons are found within a jet. Given the peak in the transition region between the barrel and the end-caps for missed electrons an additional requirement is added: events with jets with $1.37 < |\eta| < 1.52$ and $p_T < 150$ GeV are not selected. It was decided not to veto jets in the $|\eta| = 0$ region since some of these missing muons are recovered by the veto of events with more than one loose lepton.

The effect of the additional requirements outlined in this section on the pseudorapidity of leptons can be seen in Figure 5.15. Contrasted with Figure 5.12 the number of lep-lep events has been significantly reduced.

Another source of lep-lep events is events where one of the leptonic decays is to a tau lepton which decays hadronically leading to a jet. In order to avoid these, events where jets are tagged as coming from a tau lepton are also vetoed.

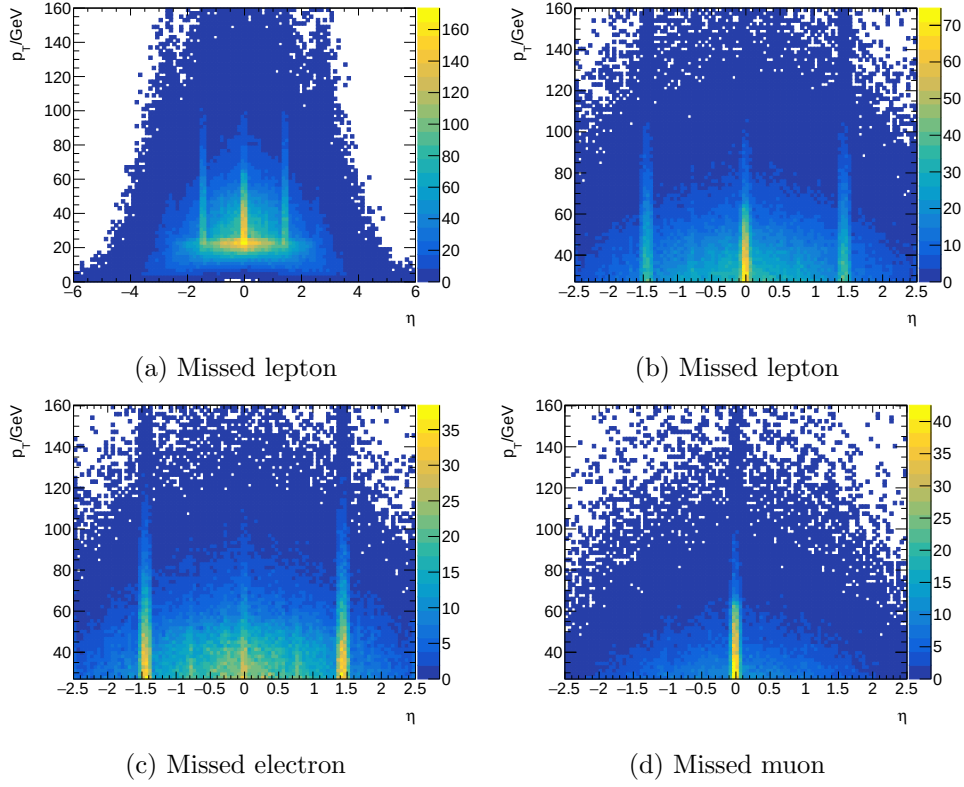


Figure 5.10: The transverse momentum plotted against pseudorapidity of undetected leptons in lep-lep events passing other selection requirements.

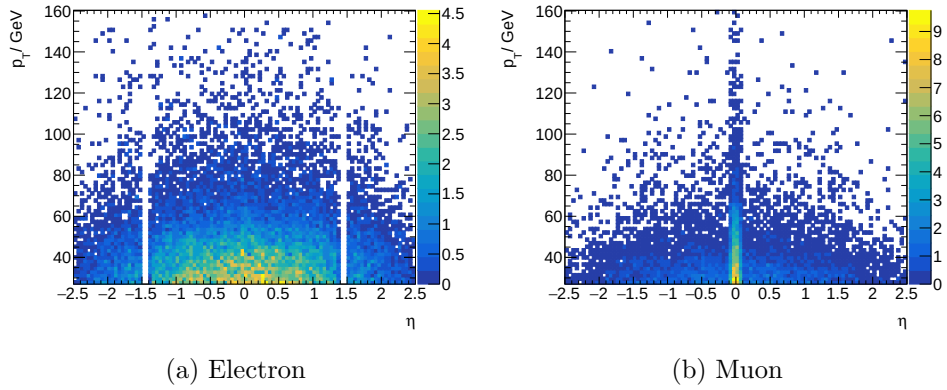
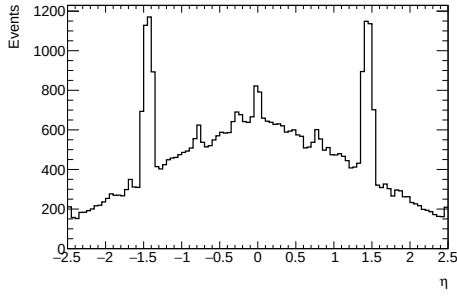
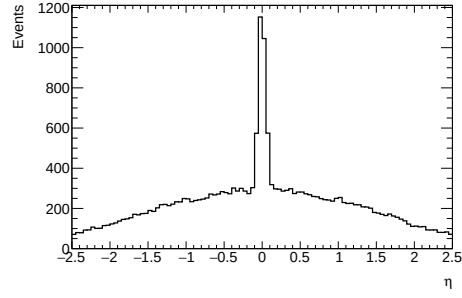


Figure 5.11: The transverse momentum plotted against pseudorapidity of leptons satisfying the loose reconstruction requirements but not the tight requirements in lep-lep events which satisfy event selection criteria.

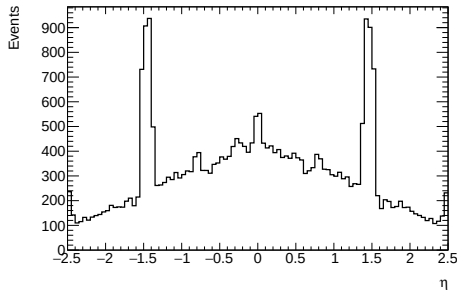


(a) Electron

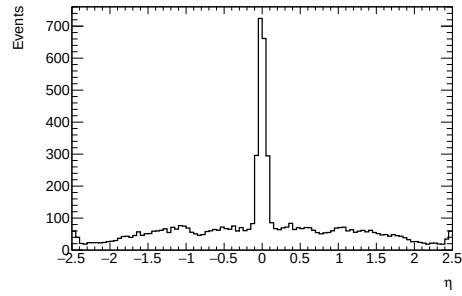


(b) Muon

Figure 5.12: The pseudorapidity of undetected leptons in lep-lep events passing other selection requirements.

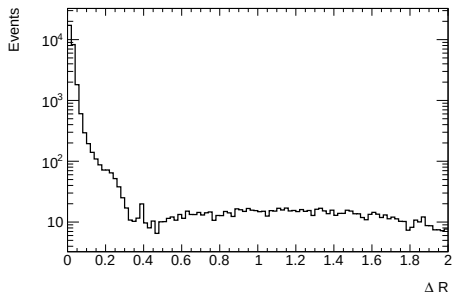


(a) Electron

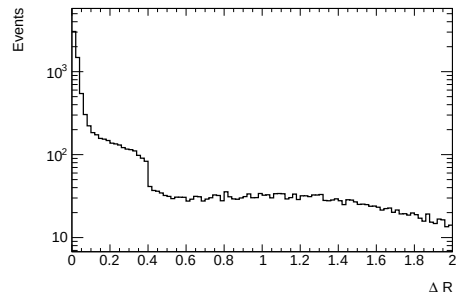


(b) Muon

Figure 5.13: The pseudorapidity of jets with a parton label of -1 signifying no partons are present in the jet. These are in lep-lep events and the figure captions show which flavour of lepton has not been detected.

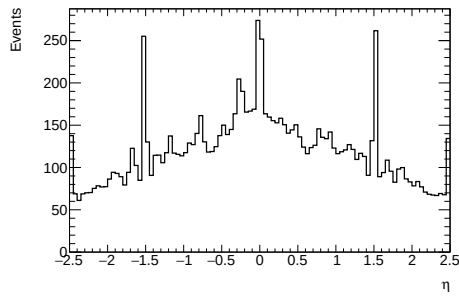


(a) Electron

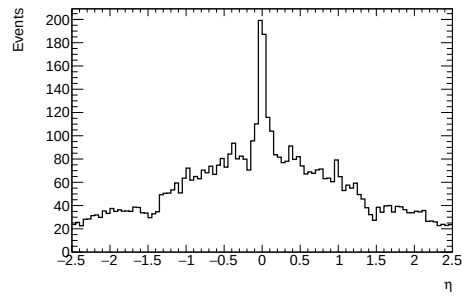


(b) Muon

Figure 5.14: The angular distance between the undetected lepton and the closest jet.



(a) Electron



(b) Muon

Figure 5.15: The pseudorapidity of undetected leptons in lep-lep events passing selection requirements including the additional requirements added in this section.

5.5 Reducing Gluon Contamination

Table 5.5 shows the number of simulated lep-had events passing the cuts specified thus far but also allowing events with more than four reconstructed jets. In these cases the χ^2 is evaluated for all subsets of four jets and the events are accepted if one of these subsets passes the cdf requirement. A large number of events have more than the four jets expected from the four quarks of the $t\bar{t}$ decay.

Number of jets	4	5	6	7
Number of events ($\times 10^6$)	1.66	1.29	0.588	0.210

Table 5.5: Numbers of events satisfying the event selection requirements as a function of the number of jets detected. Events with more than 4 jets are accepted if a subset of the jets pass the selection requirements.

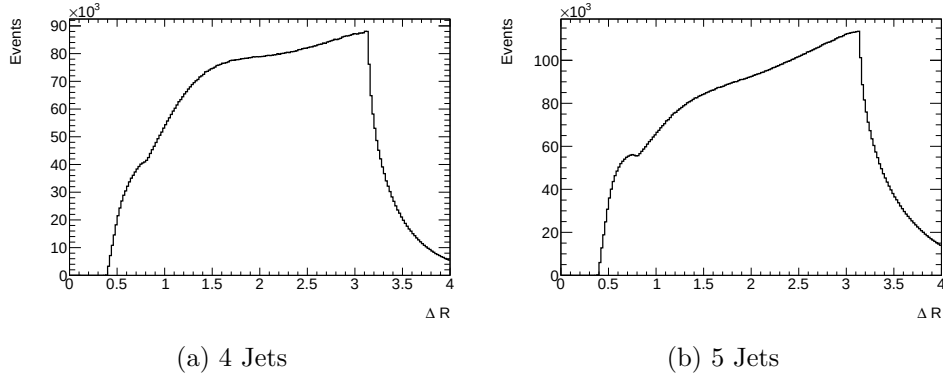


Figure 5.16: The ΔR between all reconstructed jets in 4 and 5 jet $t\bar{t}$ events passing reconstruction requirements.

In order to gain a better understanding of events with greater than four jets, comparisons were made between the kinematics of four and five jet events. Figure 5.16 shows the ΔR between all pairs of jets in four and five-jet $t\bar{t}$ events. It can be seen that there is a more pronounced peak in events at low ΔR in five-jet events which would suggest an increase in events where one jet is split due to gluon radiation or other effects.

Figure 5.17 shows the angle and invariant mass between all pairs of jets. In addition to the expected W mass peak there is clearly a second region of low-mass low-angle pairs. This is more prominent in the four-jet events but clearly present in both cases. Figures 5.18 and 5.19 separate the 2D angle vs invariant mass plots based on the parton label of the pairs of jets. Pairs of jets including a gluon or pairs of the same flavour have strong peaks in the low-mass low-angle region. This suggests that many of the pairs of jets in this region are caused by a gluon radiating from a quark leading to a small angle between a jet caused by the gluon and the jet caused by the quark. In

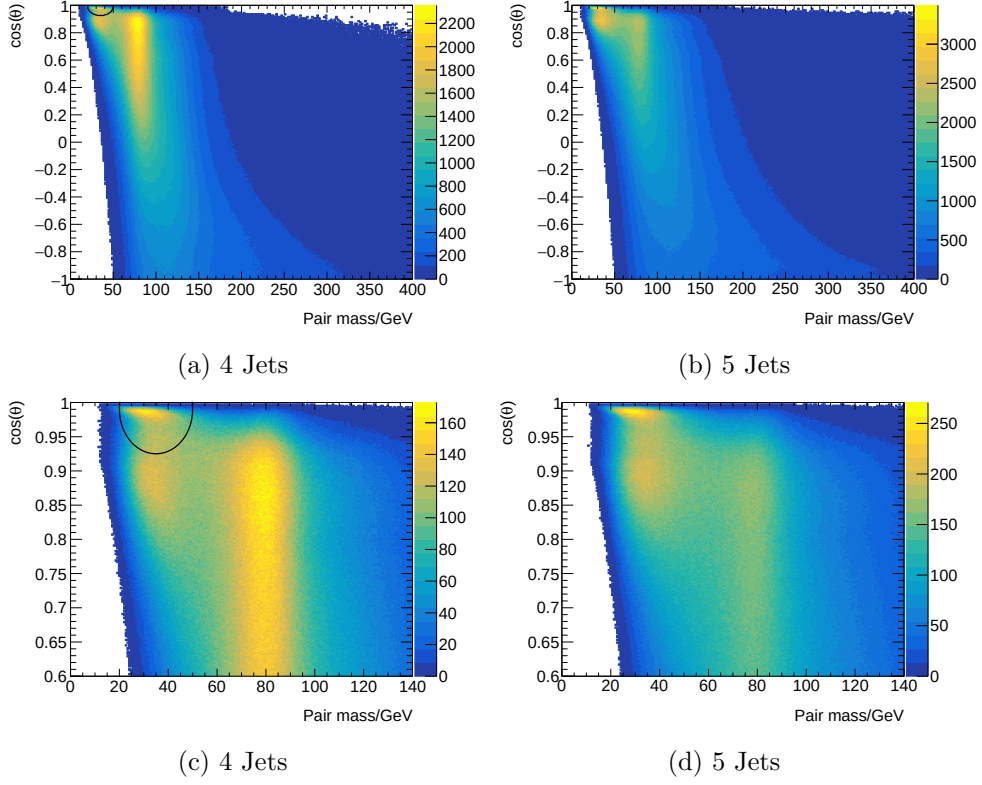


Figure 5.17: The cosine of the angle between all pairs of jets vs the pair's reconstructed mass in four and five jet $t\bar{t}$ events passing reconstruction requirements. Sub-figs. c) and d) are zoomed in versions of Sub-figures a) and b) respectively. The black lines are the ellipse defined in Eq. 5.10.

some cases the gluon splitting into a quark, anti-quark pair may create two jets leading to the low-mass low angle peaks in the $2c$ and $2b$ histograms.

To help ensure that the four selected jets in events correspond to the four quarks from the $t\bar{t}$ decay an ellipse-shaped cut in the pair mass-cos(pair angle) plane is introduced. Events are removed if they have pairs of jets falling within the ellipse defined by:

$$\frac{(m - 35)^2}{15^2} + \frac{(\cos \theta - 0.99)^2}{0.065^2} = 1 \quad (5.10)$$

where m is the pair mass and θ the angle between the jets. This ellipse is drawn onto the four jet plots of Figure 5.17.

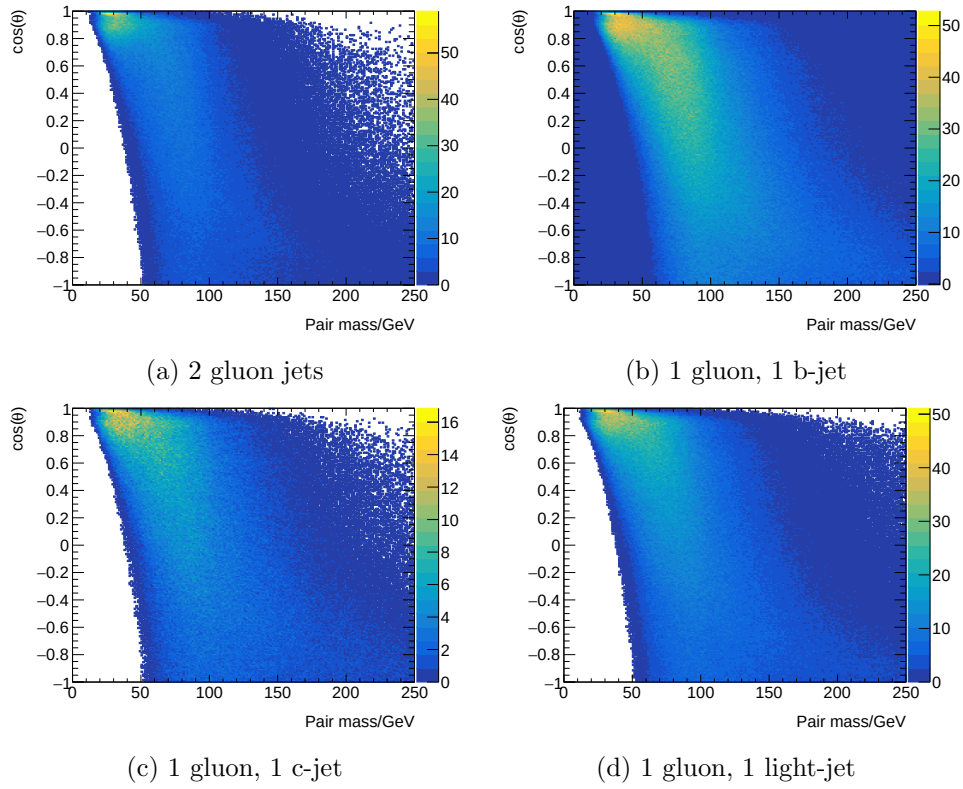


Figure 5.18: The cosine of the angle between all pairs of jets vs the pair's reconstructed mass in 4 jet $t\bar{t}$ events passing reconstruction requirements, separated by the jets' parton label.

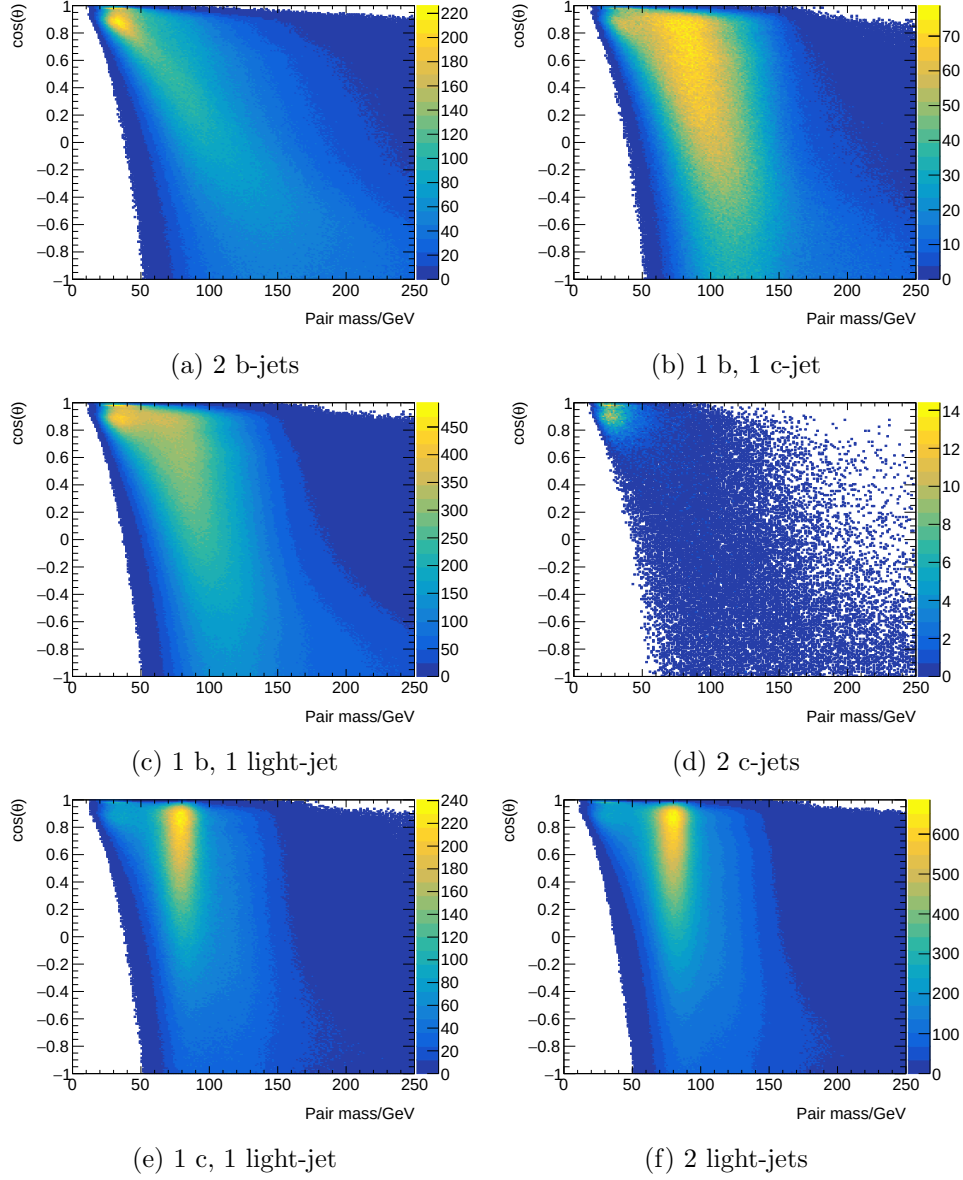


Figure 5.19: The cosine of the angle between all pairs of jets vs the pair's reconstructed mass in 4 jet $t\bar{t}$ events passing reconstruction requirements, separated by the jets' parton label.

5.6 Summary

The requirements for events to be selected after passing the single lepton triggers are summarised as:

- Exactly 1 muon or lepton passing the tight reconstruction requirements with $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$
- Exactly 4 jets with $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$
- At least 1 b -tagged jet
- $\chi^2 \text{ cdf} > 0.1$
- Veto events with an additional electron or muon satisfying loose reconstruction requirements
- Veto events with an additional charged lepton with $10 \leq p_T < 25 \text{ GeV}$
- Veto events with jets between $1.37 < |\eta| < 1.52$ and also a $p_T < 150 \text{ GeV}$
- Veto events with a tau tagged jet
- Veto events with any pair of jets lying within the ellipse in the mass- $\cos\theta$ plane defined by Eq. 5.10

Tables 5.6 and 5.7 summarise the percentage of events that pass each selection along with the total number of events passing selection for different $t\bar{t}$ and non- $t\bar{t}$ samples. Appendix A contains tables showing the number of simulated events of each sample passing the selection requirements split by the number of b and light(l)-tags.

Selection	Percentage surviving cut		
	lep-had	lep-lep	$ V_{cb} $
Exactly 4 jets	49.8%	61.0%	50.6%
$\chi^2 \text{ cdf} > 0.1$	61.9%	30.5%	61.4%
Loose lepton veto	96.5%	73.9%	95.7%
Low p_T lepton veto	99.9%	88.9%	99.8%
Transition jet veto	80.8%	75.2%	81.2%
Tau veto	99.5%	91.8%	99.6%
Jet mass-angle veto	93.4%	89.0%	93.4%
Cumulative %	22.3%	7.5%	22.4%
# Events	1.55×10^6	6.75×10^4	1480

Table 5.6: Table of the percentage of $t\bar{t}$ events passing cumulative selection requirements relative to the previous requirement. The initial selection requires at least 4 jets with 1 b -tag, and exactly 1 electron or muon with $p_T > 25 \text{ GeV}$.

Selection	Percentage surviving cut			
	Single top	W + jets	Z + jets	Diboson
Exactly 4 jets	63.0%	63.9%	65.6%	56.0%
χ^2 cdf > 0.1	42.6%	33.4%	40.2%	36.3%
Loose lepton veto	96.0%	97.6%	60.5%	90.9%
Low p_T lepton veto	99.7%	99.9%	82.4%	97.7%
Transition jet veto	80.6%	80.0%	70.2%	79.1%
Tau veto	99.5%	99.8%	97.7%	99.3%
Jet mass-angle veto	90.8%	86.6%	87.2%	89.1%
Cumulative %	18.7%	14.4%	7.9%	12.6%
# Events	9.22×10^4	7.73×10^4	1.15×10^4	2.85×10^3

Table 5.7: Table of the percentage of background events passing cumulative selection requirements relative to the previous requirement . The initial selection requires at least 4 jets with 1 b -tag, and exactly 1 electron or muon with $p_T > 25$ GeV.

Chapter 6

Fit

6.1 Likelihood fit

The fits in this work are performed using a binned likelihood fit with likelihood profiling used to incorporate systematic uncertainties in the fit. Templates of the distribution of events in MC simulation of different (signal or background) samples are used to fit the fraction of events in data made up of these samples. Consider a simplified case of signal S with signal strength μ (such that $\mu = 0$ corresponds to the background only hypothesis and $\mu = 1$ corresponds to the nominal signal hypothesis) and one background B which is not allowed to vary. The binned likelihood would be given by:

$$\mathcal{L}(\mathbf{n}|\mu, \boldsymbol{\theta}) = \prod_{i \in \text{bins}} \mathcal{P}(n_i | \mu S_i(\boldsymbol{\theta}) + B_i(\boldsymbol{\theta})) \quad (6.1)$$

where $\mathcal{P}$ is a Poisson distribution. S_i and B_i are the expected number of signal and background events in bin i while n_i are the observed number of events in that bin. $\boldsymbol{\theta}$ is a vector of parameters that affect the shape and size of the signal and background. μ would be allowed to vary until $\mathcal{L}$ is maximised, it is common to instead minimise $-\ln(\mathcal{L})$ since the product becomes a sum of logs.

The systematic uncertainties in the fit are included by using likelihood profiling [93]. Systematics are included in the fit as nuisance parameters. Systematic uncertainties are treated as being due to imperfect knowledge of parameters of the model. For some parameter of the model $\theta = \theta_0 \pm \Delta\theta$ the inputs to the fit are the nominal histograms corresponding to those at $\theta = \theta_0$, and histograms for $\theta = \theta_0 - \Delta\theta$ and $\theta = \theta_0 + \Delta\theta$. It is conventional to label $\theta_0 = 0$ and $\Delta\theta = 1$. How the histograms change with θ is then interpolated and extrapolated for any value of θ . The knowledge of θ is interpreted as being from an auxiliary measurement which constrains θ . This is usually treated as Gaussian with $\pm\Delta\theta$ being ± 1 Gaussian standard deviations. The binned likelihood is then given by:

$$\mathcal{L}(\mathbf{n}|\mu, \boldsymbol{\theta}) = \prod_{i \in \text{bins}} \mathcal{P}(n_i | \mu S_i(\boldsymbol{\theta}) + B_i(\boldsymbol{\theta})) \times \prod_{j \in \text{syst}} \mathcal{G}(\theta_j | \theta_j^0, \Delta\theta_j). \quad (6.2)$$

The Gaussian constraint is given by

$$\mathcal{G}(\theta_j | \theta_j^0, \Delta\theta_j) = \frac{1}{\sqrt{2\pi}\Delta\theta_j} \exp\left(-\frac{(\theta_j - \theta_j^0)^2}{2(\Delta\theta_j)^2}\right) \quad (6.3)$$

and acts to penalise parameters θ_j moving from their nominal values θ_j^0 in the fit. In some cases the data has enough statistical power to constrain the value of θ_j in the fit. This has the effect of reducing the systematic uncertainty in that parameter compared with the input histograms.

Additional nuisance parameters included in the fit are *normalisation factors*. These are linear multiplicative factors which scale the normalisation of signal or background samples. In the examples given so far μ is the normalisation factor of the signal.

Statistical uncertainties are also included to account for any cases where the limited number of MC simulation events in a bin mean that the template histograms may not be good descriptions of the underlying distribution [94]. The contribution to the statistical model from all bins which is multiplied with Eq. 6.1 to give the total likelihood is

$$\prod_{b \in \text{bins}} \mathcal{P}(n_b | \nu_b(\boldsymbol{\alpha}) + \gamma_b \nu_b^{MC}(\boldsymbol{\alpha})) \mathcal{P}(m_b | \gamma_b \tau_b). \quad (6.4)$$

where n_b is the number of events observed in a bin. The total number of events expected in the bin would be given by $\nu_b(\boldsymbol{\alpha}) + \nu_b^{MC}(\boldsymbol{\alpha})$ where $\nu_b(\boldsymbol{\alpha})$ is the number of events unaffected by MC statistical uncertainties (due for instance to being data-driven) and $\nu_b^{MC}(\boldsymbol{\alpha})$ is the number of events estimated using MC techniques where the statistical uncertainty needs to be taken into account. $\boldsymbol{\alpha}$ are parameters affecting the number of events. γ_b is the nuisance parameter introduced to reflect that the true rate may differ from that of the MC estimate $\nu_b^{MC}(\boldsymbol{\alpha})$, it takes a value of 1 if the true rate does not differ from that of the MC estimate. For a total statistical uncertainty δ_b the relative statistical uncertainty is given by ν_b^{MC}/δ_b which corresponds to a total MC sample in that bin of size $m_b = (\delta_b/\nu_b^{MC})^2$. The MC estimate is treated as an auxiliary measurement giving the Poisson constraint term $\mathcal{P}(m_b | \gamma_b \tau_b)$ for $\tau_b = (\nu_b^{MC}/\delta_b)^2$ which is treated as being fixed.

The likelihood fits were performed using the TRExFitter framework [95] used by many analyses within the ATLAS collaboration. TRExFitter builds its statistical models using the HistFactory [94] format. It uses statistical

modelling from RooFit [96] along with tools from the RooStats project [97].

6.2 Fit Parameters

Three normalisation factors are defined in the fit which affect $t\bar{t}$ samples:

- $n_{V_{cb}Rat}$: Scales the V_{cb} sample
- n_{LH} : Scales all $t\bar{t}$ lep-had samples including the V_{cb} sample
- n_{LL} : Scales all $t\bar{t}$ lep-lep samples

The V_{cb} sample scales with two normalisation factors and the result of this is that $n_{V_{cb}Rat}$ measures how the V_{cb} sample scales relative to the $t\bar{t}$ lep-had sample. This means that the fractional error on $n_{V_{cb}Rat}$ is the fractional error on the measurement of $|V_{cb}|^2$.

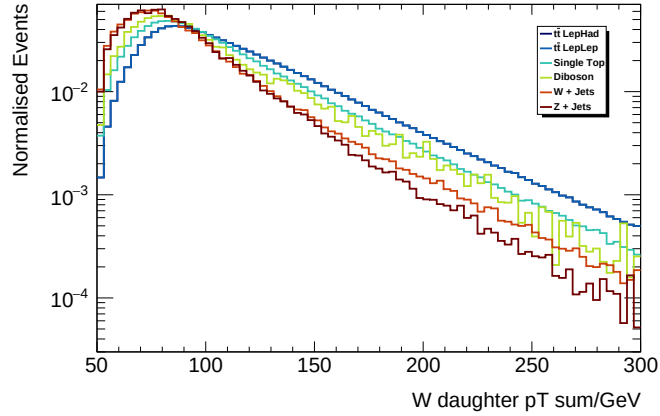
The remaining backgrounds do not have normalisation factors associated with them. However, as outlined in Chapter 7 the backgrounds have cross-section uncertainties which can be constrained in the fit; this constraint can cause the central value to change resulting in a change of the normalisation of the background.

Due to the low number of Z + jets and diboson events passing the event selection requirements as seen in Table 5.7 it was decided to combine these backgrounds for the purpose of the fit. This has been done in previous analyses such as in the measurement of the $t\bar{t}$ cross-section in semi-leptonic decays [98].

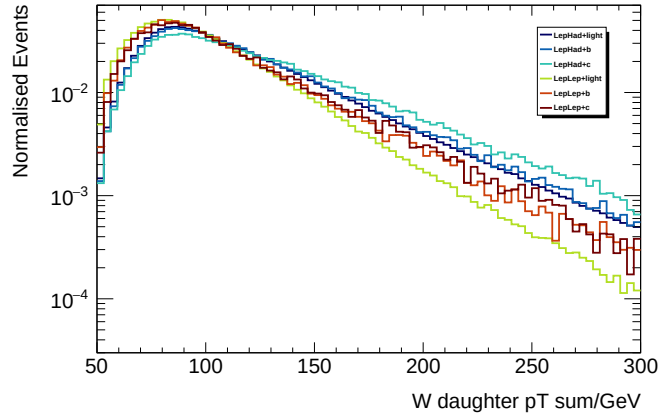
6.3 Fit Variable

Suitable variables to use in the fit were identified by looking at how well they differentiated between $t\bar{t}$ lep-had and lep-lep events. Given the large uncertainties associated with the heavy flavour $t\bar{t}$ samples outlined in Section 7.2 the differentiation between those samples was also considered. Two variables which separated the lep-lep and lep-had events were the scalar sum of the transverse momenta of the jets assigned as W daughter (the W daughter p_T sum) and the cdf of the χ^2 . Figure 6.1a shows the W daughter p_T sum of lep-had and lep-lep $t\bar{t}$ samples along with the non- $t\bar{t}$ samples while Figure 6.1b breaks the $t\bar{t}$ samples down into their heavy flavour categories as defined in Section 4.2.1. Figure 6.2 plots the χ^2 cdf of the different samples.

Initial fits were performed using the W daughter p_T sum but it was found that using the χ^2 cdf better constrained the uncertainties in the normalisation of the heavy flavour samples as outlined in Section 7.2. As such the χ^2 cdf is the variable fitted to in each of the fit regions.



(a) Background comparison



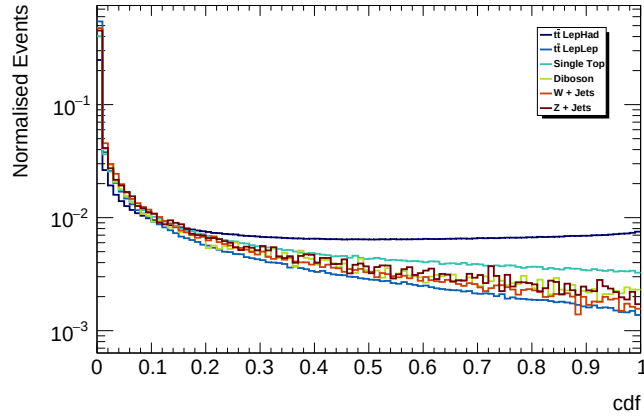
(b) Heavy flavour comparison

Figure 6.1: The sum of the transverse momenta of the jets assigned as W daughters of events from different samples. Each histogram is normalised such that the total number of events sum to 1.

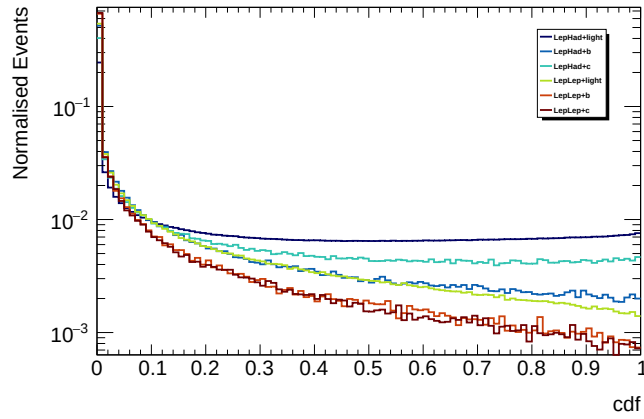
6.4 Fit Regions

The regions of the fit are defined by the number of b and c -tags with each unique combination defining a region. With the selection requirement that all events have at least 1 b -tag this gives 10 regions from $1b0c$ to $4b0c$. It is the difference in the distribution of events between these flavour tagging regions in $|V_{cb}|$ events compared to other $t\bar{t}$ lep-had events that allows $n_{V_{cb}Rat}$ to be determined in the fit.

The $1b0c$ region was found to be particularly susceptible to non- $t\bar{t}$ backgrounds including multi-jet backgrounds not from single-top, diboson, $Z + \text{jets}$ or $W + \text{jets}$. This is discussed in Chapter 8. As such the region was excluded from the fits reducing the number of regions in the fit to 9. In this way, all fit regions have at least two heavy quark jet candidates. The fit regions are summarised in Table 6.1.



(a) Background comparison



(b) Heavy flavour comparison

Figure 6.2: The cdf of the χ^2 of events from different samples. Each histogram is normalised such that the total number of events sum to 1.

	$0c$	$1c$	$2c$	$3c$
$1b$	-	$1b1c$	$1b2c$	$1b3c$
$2b$	$2b0c$	$2b1c$	$2b2c$	
$3b$	$3b0c$	$3b1c$		
$4b$	$4b0c$			

Table 6.1: Summary of the flavour tagged regions used in the fit.

6.5 Statistics-only Fit

Table 6.2 shows the statistical errors on the normalisation factors in the fit for the two flavour tagging working points. The error on n_{VcbRat} is the important error for the measurement and it can be seen that the optimised working point does give better performance than the $t\bar{t} + c$ working point.

	n_{VcbRat}	n_{LH}	n_{LL}
Optimised WP	0.26	0.0025	0.055
$t\bar{t} + c$ WP	0.32	0.0027	0.059

Table 6.2: Statistical errors on the normalisation factors given by Asimov fits. The results of the fit using the optimised tagging flavour tagging working point and the $t\bar{t} + c$ working point are compared. These working points are defined in Section 5.2.

Chapter 7

Systematic Uncertainties

7.1 Experimental

7.1.1 Pile-up reweighting

The simulated events are reweighted to account for differences between the simulated pile-up profile and the profile seen in data. The uncertainties due to this reweighting are found by varying the weights within their uncertainties.

7.1.2 Charged Leptons

There are a number of uncertainties which affect electrons, muons and tau leptons.

The first set of uncertainties are associated with the efficiency of the triggering, reconstruction, identification and isolation of leptons [2, 13, 59]. As described for the reconstruction efficiency in Sections 4.1.4 and 4.1.5 the efficiency of the trigger, reconstruction, identification and isolation is calibrated using data to derive scale-factors applied to the MC simulation. The uncertainties on these calibrations give uncertainties on the scale-factors which are included in the fit.

The second set of uncertainties are from corrections applied to the lepton momentum scale and resolution. The lepton momentum scale and resolution are measured using reconstructed distributions of the $Z \rightarrow l^+l^-$ and $J/\psi \rightarrow l^+l^-$ masses. For electrons E/p is also measured in $W \rightarrow e\nu$ events where E and p are the electron energy and momentum as measured by the calorimeter and the tracker respectively. In the case of muons the uncertainties on the momentum scale and resolution in the inner detector and the muon spectrometer are considered and varied separately. In the case of taus uncertainties in the energy do not need to be considered since tau identification is only used to veto events independent of the energy of the tau lepton.

7.1.3 Flavour Tagging

As described in Section 4.1.9, flavour tagging working points have to be calibrated such that the performance seen in MC simulation matches that in data. This calibration process gives scale factors which depend on p_T and correct for any differences in performance. These scale factors have uncertainties associated with them stemming from statistical and systematic uncertainties in the calibration process. Each of the three (b , c and light) calibrations have a number of uncertainties associated with them. An eigenvector variation method [99] is used to reduce the number of nuisance parameters, which results in nine systematics for b -jets, five for c -jets and five for light jets. In addition to these uncertainties there is an additional extrapolation uncertainty from extrapolating tagging performance beyond the calibrated range to $p_T > 300$ GeV as described in Ref. [58].

The uncertainties of the $t\bar{t}+c$ flavour tagging working point are not currently available due to the calibration still being in progress and as such the flavour tagging uncertainties cannot currently be included. In the case of the optimised working point the b -tagging working point used is a standard ATLAS working point and the uncertainties associated with it can be included. However, the c -tagging working point is not calibrated and thus the total flavour tagging uncertainty is not available.

7.1.4 Jets

Uncertainties associated with jets come from uncertainties in the jet energy scale (JES), jet energy resolution (JER) and the jet vertex tagger (JVT).

The calibration of the JES is outlined in Section 4.1.6. The calibration results in a large number of systematic uncertainties which are decorrelated using the same eigenvector variation method as the flavour tagging systematics [99]. This results in 30 nuisance parameters: 16 are from the in-situ calibration, six are from the η intercalibration, four are from uncertainties on the pileup, two are uncertainties relating to the jet flavour, one is from the uncertainty on jet punch-through (when a jet does not deposit all of its energy in the calorimeters) modelling and one describes uncertainties in high- p_T jets.

The two JES uncertainties relating to jet flavour are the jet flavour composition and the jet flavour response. These uncertainties relate to the fact that jets originating from quarks have different properties to jets originating from gluons. The jet flavour composition uncertainty is an uncertainty in what fraction of jets are gluon-initiated and what fraction are quark-initiated. The jet flavour response uncertainty is an uncertainty due to differences in the response to gluon jets between MC generators. By default the fraction of jets which are quark-initiated is set to 0.5 ± 0.5 a very conservative estimate. This

estimate was improved by measuring the quark-gluon jet fraction in MC simulation for $t\bar{t}$ events passing the event selection requirements. The uncertainty was estimated by comparing the results with alternative $t\bar{t}$ MC simulation samples. The nominal Powheg Pythia8 sample was compared with a Powheg Herwig7 sample to account for uncertainties in the showering and compared with a MadGraph5_aMC@NLO Pythia8 sample to account for uncertainties in the event generator. This gave the fraction of jets that are quark-initiated fraction with uncertainties in bins of p_T and $|\eta|$ which was applied to all $t\bar{t}$ MC simulation samples and reduced the effect of the jet flavour uncertainties.

The eigenvector variation method is also applied to the systematics of the JER measurement. This results in seven systematics which smear the jet p_T . Uncertainties from the calibration of the JVT are combined to give a single scale-factor uncertainty applied to the analysis.

7.1.5 MET

As described in Section 4.1.8 the MET has contributions from fully reconstructed and calibrated particles and jets as well as soft-event signals from charged particle tracks. Uncertainties associated with the reconstructed objects are propagated to the MET and as such are accounted for by the uncertainties described earlier in this chapter. However, the soft term needs to be accounted for. The uncertainties associated with the soft term come from comparisons of data to MC simulation in $Z \rightarrow \mu\mu$ events. In these events no missing transverse energy would be expected and so the soft term should cancel the hard term. As such for the purpose of calibration the soft term is projected along the direction anti-parallel to the hard term. Three quantities of the soft term are measured each with an associated uncertainty: the energy scale parallel to the axis, the resolution parallel to the axis and the resolution perpendicular to the axis [60].

7.2 Normalisation

Uncertainties in the luminosity and the cross-sections of background processes are a source of uncertainty in the measurement.

7.2.1 Luminosity

There is an uncertainty of 1.7% on the luminosity at ATLAS during Run 2 [44]. As such an uncertainty of 1.7% is applied to the normalisation of all samples; this uncertainty is fully correlated between all samples and so should have a very small effect on the error on $|V_{cb}|$.

7.2.2 Non- $t\bar{t}$ background cross-sections

The largest contribution to uncertainty in the single-top cross-section is from the tW production channel. There is a theoretical uncertainty of 5.4% in the tW cross-section [86, 100] and as such a 5.4% normalisation uncertainty is applied to the entire single-top background.

The W + jets background is given a cross-section uncertainty of 45%. This is consistent with the uncertainty used in other ATLAS studies of semi-leptonic $t\bar{t}$ decays [98, 81]. In those analyses the uncertainty was derived by varying the renormalisation (μ_R) and factorisation (μ_F) scales. This uncertainty is treated as uncorrelated between tagging regions.

The combined Z + jets and diboson background has an uncertainty of 50% in its cross-section. This is again consistent with the ATLAS measurement of the cross-section of semi-leptonic $t\bar{t}$ events [98] and derived by varying μ_R and μ_F .

7.2.3 Heavy flavour $t\bar{t}$ cross-sections

It is known that the MC modelling tends to underestimate the number of $t\bar{t}$ events in association with additional heavy flavour jets [101]. Thus additional normalisation uncertainties of 50% are applied to the $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 1c$ samples. The choice of uncertainty on the $t\bar{t} + \geq 1b$ is motivated by the expected level of agreement between data and MC [101]. The uncertainty on $t\bar{t} + \geq 1c$ is a conservative estimate which is constrained in the fit and is consistent with the approach of other ATLAS studies [81].

7.3 Modelling

It is important to account for uncertainties associated with the modelling of the $t\bar{t}$ MC simulation. Since it was the most significant non- $t\bar{t}$ background the same modelling systematics were also applied to the single-top background. The latest recommendations of the ATLAS physics modelling group (PMG) were followed in evaluating these uncertainties. Uncertainties due to the modelling of the parton shower and hadronisation are accounted for by comparing the nominal samples generated by Powheg and showered using Pythia8 with samples generated using Powheg but showered using Herwig7. Variation in the initial state radiation (ISR) and final state radiation (FSR) are accounted for by varying the factorisation and renormalisation scales (μ_F/μ_R), the FSR rate and the ISR α_s parameter between 0.5 and 2 times their nominal values.

These modelling uncertainties are treated as uncorrelated between the $t\bar{t} + \geq 1l$, $t\bar{t} + \geq 1c$ and $t\bar{t} + \geq 1b$ samples. This is motivated by the fact that

different diagrams contribute to these different sub-samples. This approach also remains consistent with other ATLAS studies [81].

Chapter 8

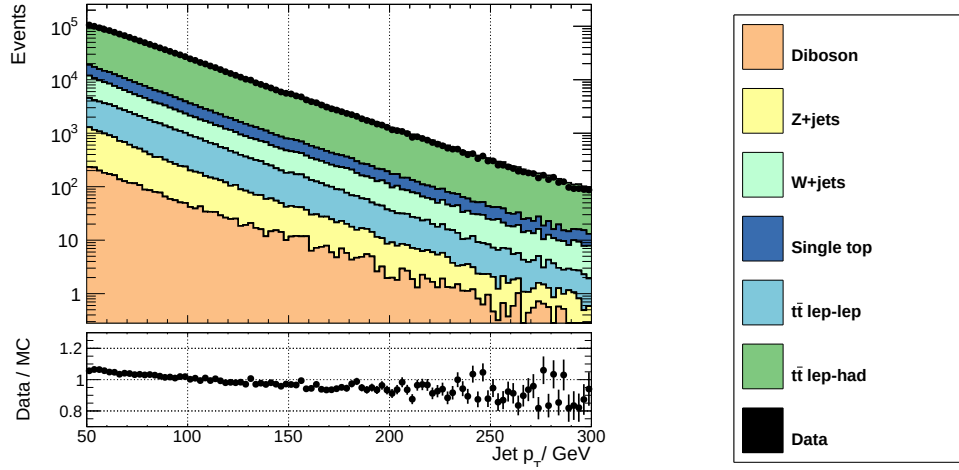
Control Region Studies

To ensure the analysis backgrounds were properly considered studies were performed comparing data with simulation in regions not sensitive to $|V_{cb}|$. The regions studied were the $1b0c$, $1b1c$ and $2b0c$ regions. The results presented here are for the optimised flavour tagging working point. The ratio between data and MC simulation is presented for each of the plots. This ratio includes statistical errors but not systematic errors.

8.1 Transverse Momentum Re-weighting

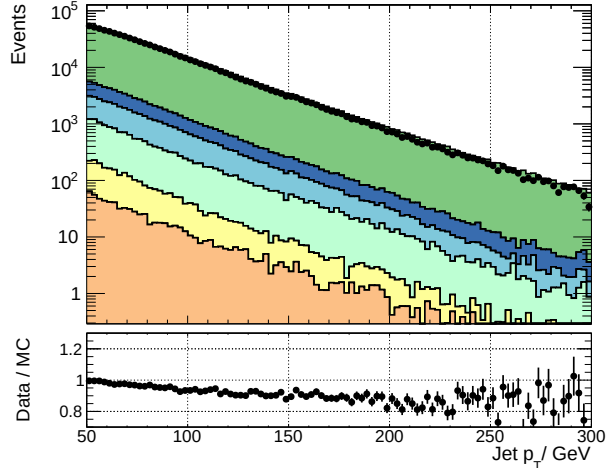
The distributions of a large number of kinematic variables were plotted across the three regions. Some examples are shown in Figure 8.1 where plots of the transverse momentum of all jets in each of the studied tagging regions are shown and Figure 8.2 where the MET and both reconstructed top masses are plotted. A slope in the data/MC ratio can be seen in each of the plots. This has been observed in other analyses [81, 82, 102] and the cause is mis-modelling in the Powheg+Pythia8 $t\bar{t}$ sample. Data-based corrections are generally applied to fix this discrepancy. The source of the discrepancy is assumed to be due to additional radiation in the parton shower which is independent of the flavour of the jets, thus a correction can be derived in one flavour tagging region and applied to all others.

It is worth noting that Figure 8.3 which plots the χ^2 cdf of events shows only a very subtle slope in the data/MC ratio. Since this is the variable fitted to in the different flavour tagging regions this may show that this mis-modelling does not have a large effect on our fit. Despite this it will likely be sensible to include a data-based correction in the final iteration of this analysis. This correction is not included in the results presented in this thesis but a first iteration using the $1b1c$ region for calibration is presented below.

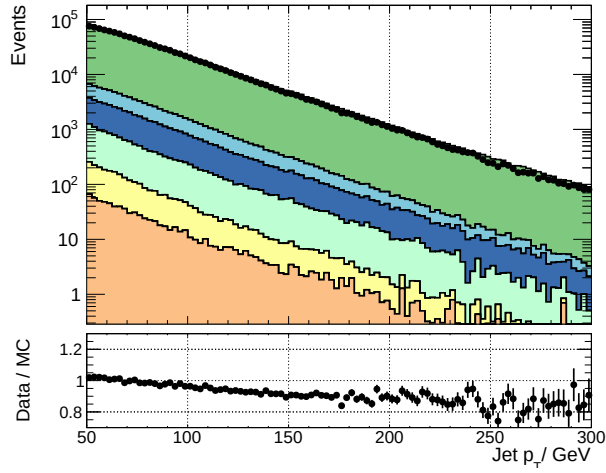


(a) 1b0c

(b) Legend



(c) 1b1c



(d) 2b0c

Figure 8.1: The transverse momentum of all jets separated by tagging region.

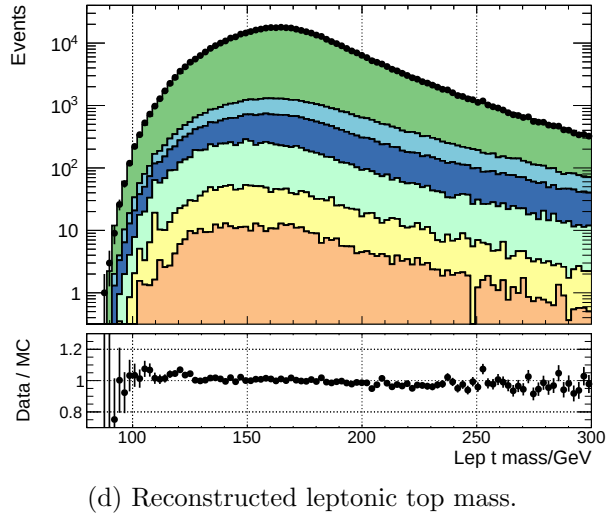
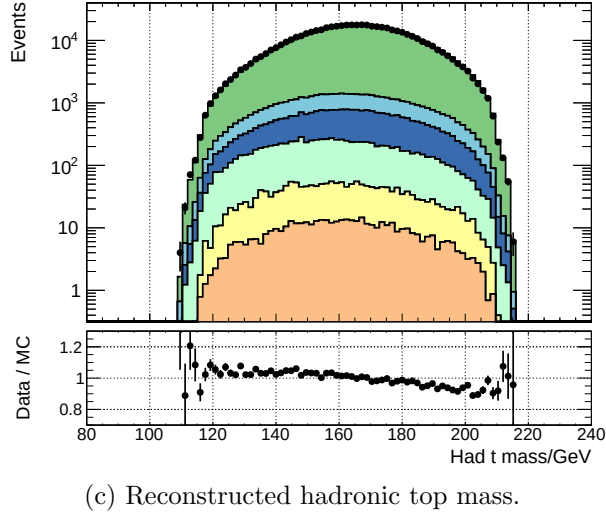
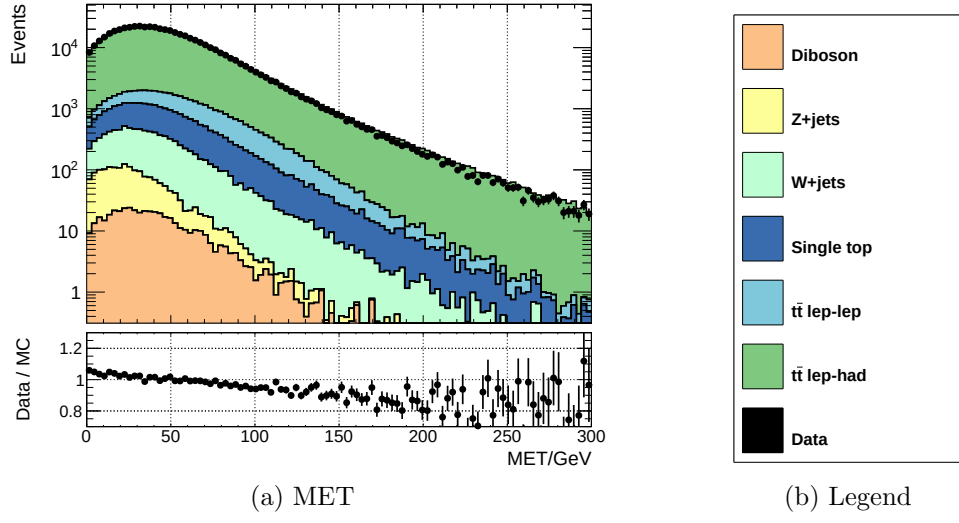
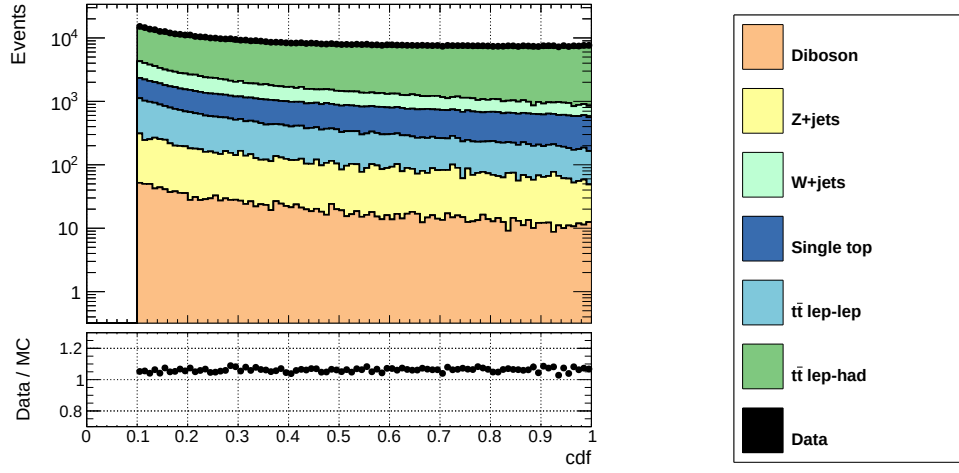
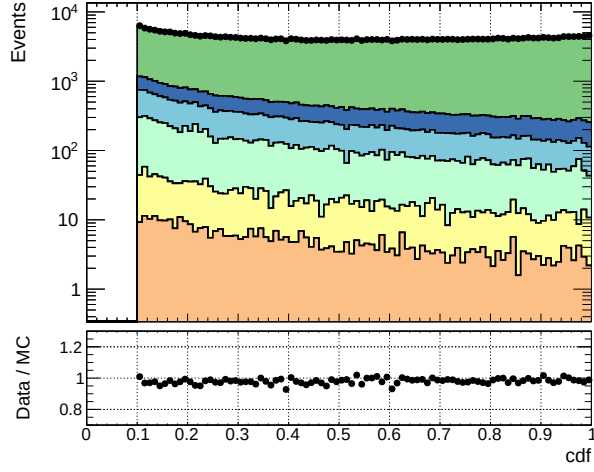


Figure 8.2: Plots of different reconstructed quantities in the $2b0c$ region.

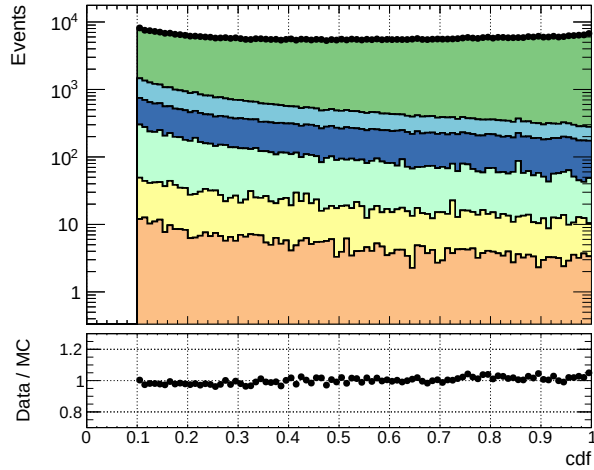


(a) 1b0c

(b) Legend



(c) 1b1c



(d) 2b0c

Figure 8.3: The χ^2 cdf of events in data and MC simulation in specific flavour tagging regions.

The re-weighting procedure derives a correction factor to be applied to $t\bar{t}$

MC simulation expressed as:

$$\mathcal{R}(x) = \frac{\text{Data}(x) - \text{MC}^{\text{non-}t\bar{t}}(x)}{\text{MC}^{t\bar{t}}(x)} \quad (8.1)$$

where x is the variable used to fix the mis-modelling. The effective mass m_{eff} which is the scalar sum of all jet and lepton p_T as well as the MET is a good variable to choose since it includes all transverse momenta. The effective mass of the $1b1c$ region is plotted in Figure 8.4, note that the bins are not of equal width to ensure no bins have large uncertainties but the bins are also not normalised based on their width. By subtracting the non- $t\bar{t}$ MC simulation events from the data one is left with the number of $t\bar{t}$ events in data within the normalisation errors of the background samples. By taking the ratio of these events with the number of $t\bar{t}$ MC simulation events the correction factor is derived. A function is then fitted to the ratio to give a continuous distribution of correction factors as a function of m_{eff} . The function fitted is $f(x) = p_0 + p_1/(x/300)^{p_2}$. The re-weighting factor derived in the $1b1c$ region is shown in Figure 8.5.

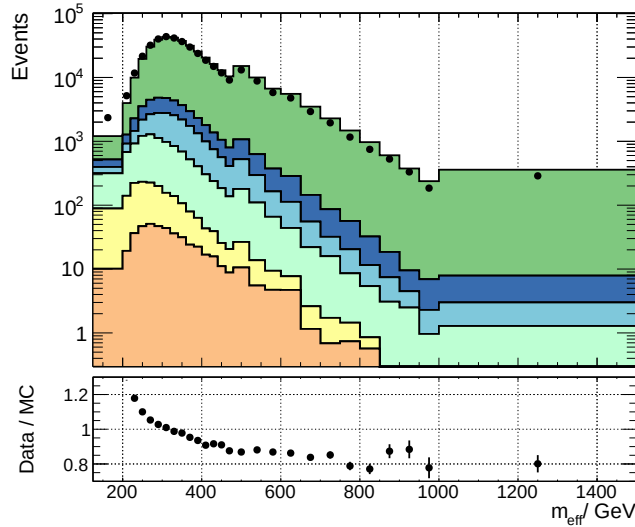


Figure 8.4: The effective mass in the $1b1c$ region. Note that the bins are not of an equal width and have not been normalised based on their width.

The results of applying this re-weighting factor to the previously plotted jet p_T and $2b0c$ kinematics are shown in Figures 8.6 and 8.7. The effect on the jet p_T and MET is clear with the Data/MC ratio in these plots now appearing flat. The reconstructed top masses also have improved Data/MC ratio plots.

This is the first iteration of this re-weighting procedure and is not used in the error estimates presented in this thesis. When applying the procedure to the analysis it will be important to consider systematic errors associated with it. These include three uncertainties from the three parameters of the function

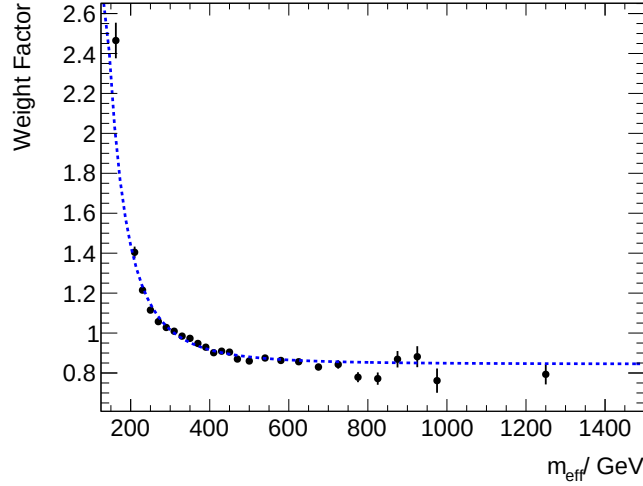


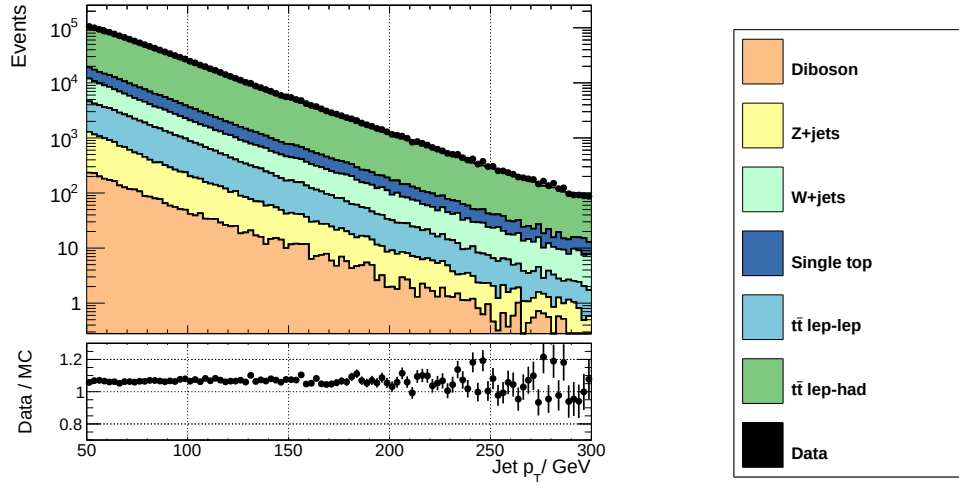
Figure 8.5: The re-weighting factor for $t\bar{t}$ events derived in the $1b1c$ region as a function of the effective mass.

fitted in Figure 8.5 and uncertainties in the normalisation of the backgrounds which will affect the denominator of the re-weighting factor in Eq. 8.1. Since the region used to calibrate the re-weighting process cannot be used in the fit it will also be important to optimise the selection of the calibration region to minimise any impact removing a region has on the measurement uncertainty.

8.2 Multi-jet Background

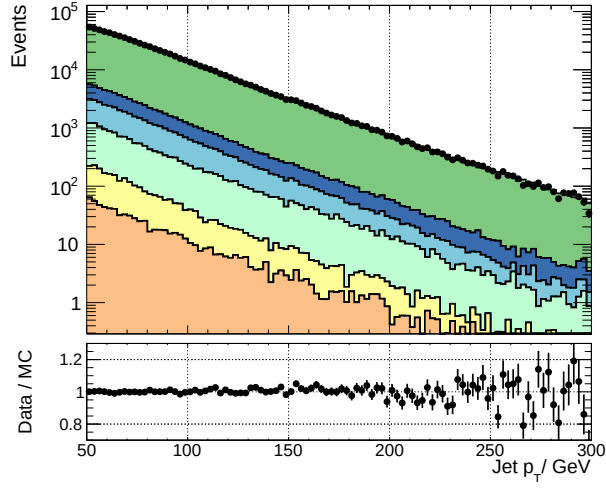
Studying the χ^2 cdf plot in Figure 8.3 again it can be seen that the cdf appears to be well modelled with a Data/MC ratio close to one in both the $1b1c$ and $2b0c$ regions. However, in the case of the $1b0c$ region there are consistently approximately 5% more events observed in data compared to simulation. It is possible that such a difference in the normalisation could come from systematic uncertainties in the flavour tagging performance, however due to the consistency seen in other regions the possibility of an additional background was considered.

The most likely candidate was considered to be the multi-jet background. This background consists of a number of jets not from the decay of a specific particle. This background is hard to model and if it needs to be accounted for, a data driven method is generally used to estimate its contribution to the background [98, 103]. This data driven method is based on the fact that to pass the single lepton selection the multi-jet background must either have a non-prompt lepton, a mis-identified photon or a jet depositing a large fraction of its energy in the EM calorimeter. The number of events passing loose lepton reconstruction requirements and those passing tight lepton reconstruction requirements are compared. By using the known efficiencies of identifying real leptons and fake leptons the number of non-prompt and fake leptons can be

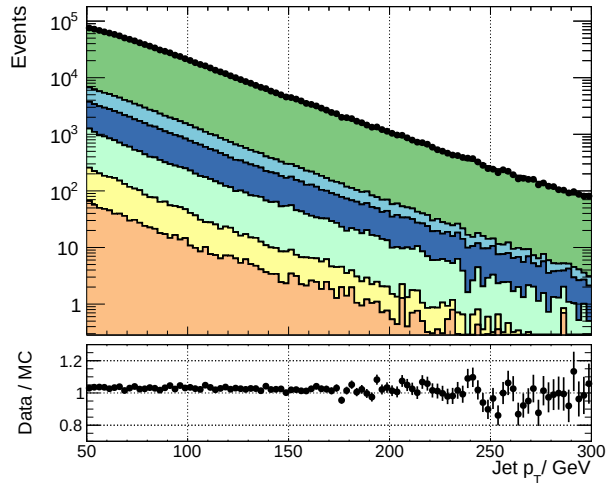


(a) $1b0c$

(b) Legend

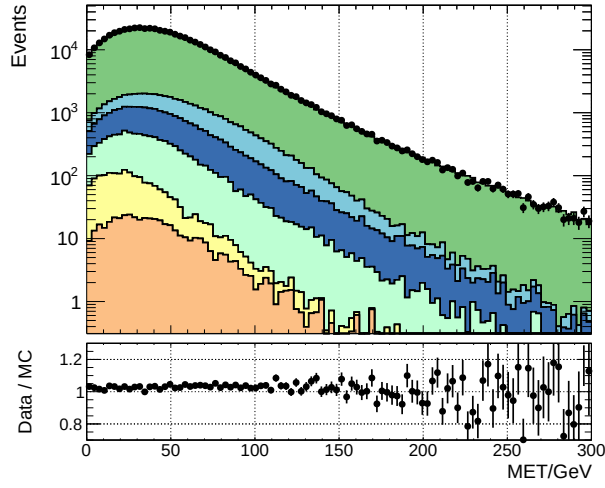


(c) $1b1c$



(d) $2b0c$

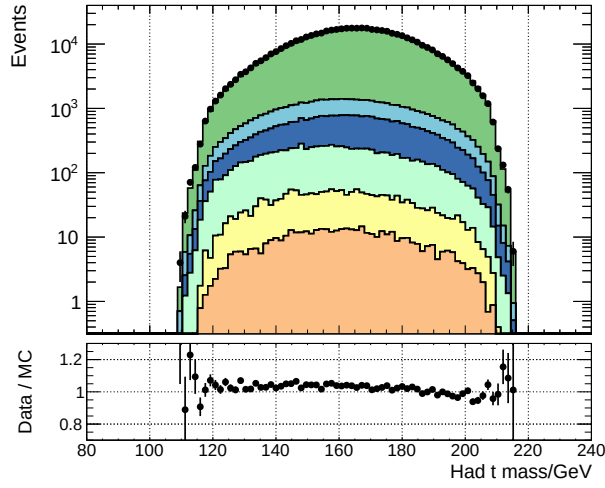
Figure 8.6: The transverse momentum of all jets separated by tagging region. The $t\bar{t}$ MC simulation has been re-weighted as described in Section 8.1.



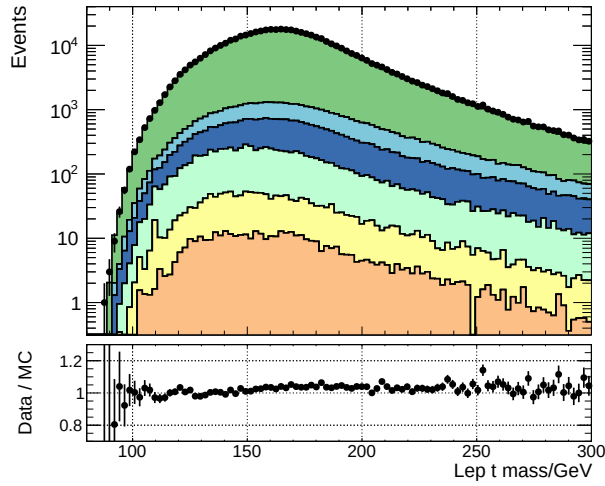
(a) MET



(b) Legend



(c) Reconstructed hadronic top mass.



(d) Reconstructed leptonic top mass.

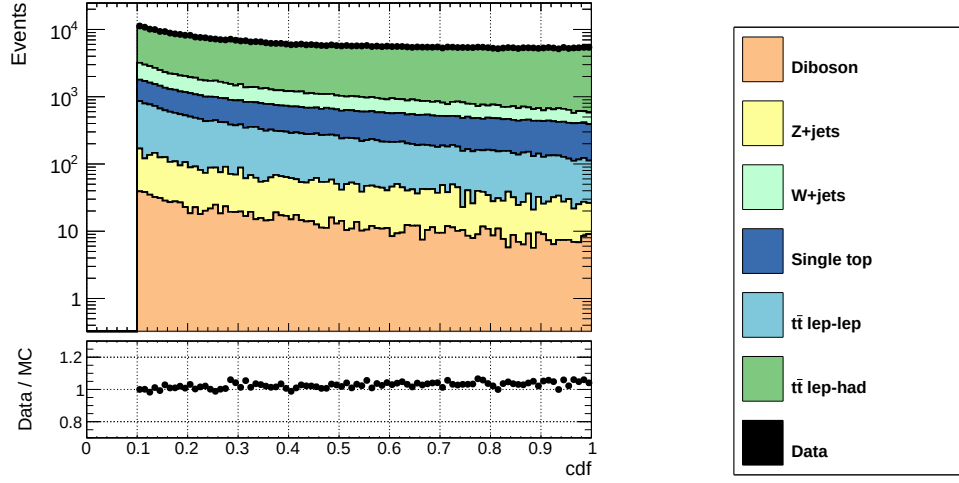
Figure 8.7: Plots of different reconstructed quantities in the $2b0c$ region. The $t\bar{t}$ MC simulation has been re-weighted as described in Section 8.1.

estimated. This gives an estimate of the multi-jet background.

The multi-jet background would not be expected to have any missing transverse energy. It is therefore common for analyses to require the MET to be above a certain value to suppress the multi-jet background. It is also common to have requirements for the transverse mass of the W boson. This is defined as $m_T^W = \sqrt{2p_T^l E_T^{miss}(1 - \cos \Delta\phi)}$ where p_T^l is the transverse momentum of the charged lepton and $\Delta\phi$ is the azimuthal angle separation between the lepton and the MET. In Ref. [81] the requirements used were $E_T^{miss} \geq 20$ GeV and $E_T^{miss} + m_T^W > 60$ GeV. In that case this cut was found to be sufficient to not require any modelling of the multi-jet background. However, this requirement reduces the number of $t\bar{t}$ events passing the selection by approximately 25%. Applying this requirement to the statistical only fit for the $t\bar{t} + c$ flavour tagging working point increased the error on $|V_{cb}|^2$ to 0.37 from the value of 0.32 reported in Table 6.2. It is therefore desirable to avoid using such a requirement if possible.

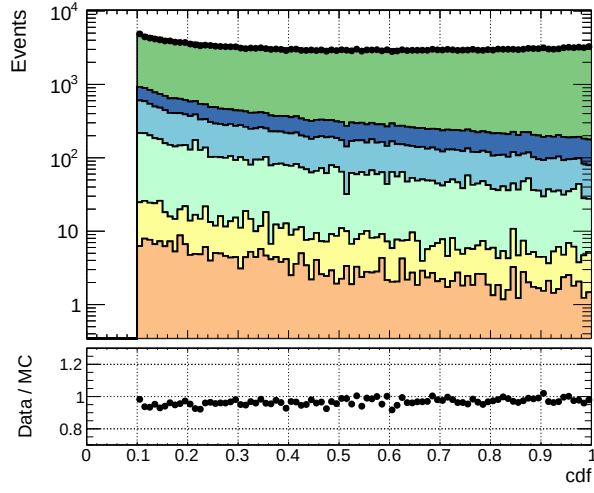
Figure 8.8 shows the χ^2 cdf distributions with the addition of the $E_T^{miss} \geq 20$ GeV and $E_T^{miss} + m_T^W > 60$ GeV requirement. The $1b0c$ region sees a reduction in the Data/MC ratio suggesting that the multi-jet background was contributing to the discrepancy between data and simulation. There is also a small reduction in the $1b1c$ region. Figure 8.9 plots the $E_T^{miss} + m_T^W$ distribution. This figure includes the re-weighting of the $t\bar{t}$ sample to aid readability since without it the ratio plot has a significant slope. There is a clear excess of events at low values of $E_T^{miss} + m_T^W$ in the $1b0c$ region which again suggests the presence of a significant multi-jet background. To avoid biasing the $1b1c$ plot this was re-weighted using a calibration in the $2b0c$ region rather than the $1b1c$ region. The $1b1c$ and $2b0c$ regions appear to be flat apart from a small peak at very low values in the $2b0c$ plot which may be due to a small number of multi-jet events.

Given the clear evidence of the multi-jet background in the $1b0c$ region it was decided to exclude it from the fit. The multi-jet background appears to have less of an effect on the other regions and so no additional cuts were introduced to suppress the multi-jet background. Multi-jet backgrounds are not expected to have large numbers of heavy flavour jets and as such they would be expected to have a smaller effect on regions with larger numbers of b and c tags.

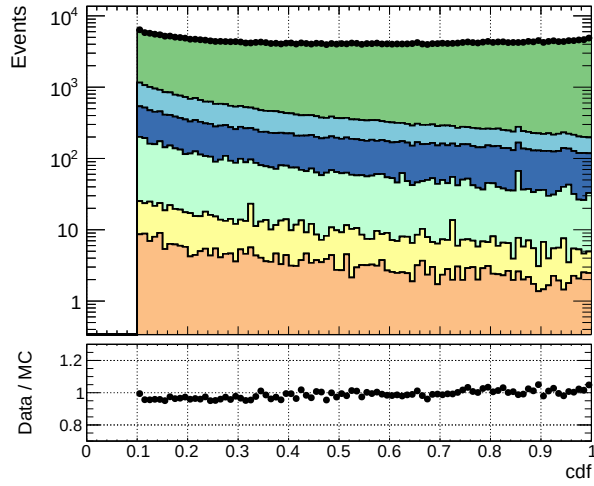


(a) 1b0c

(b) Legend

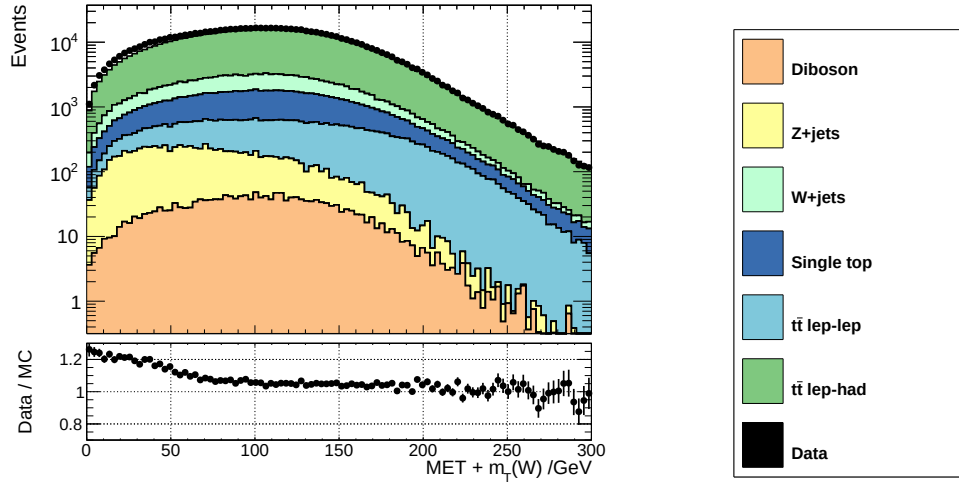


(c) 1b1c



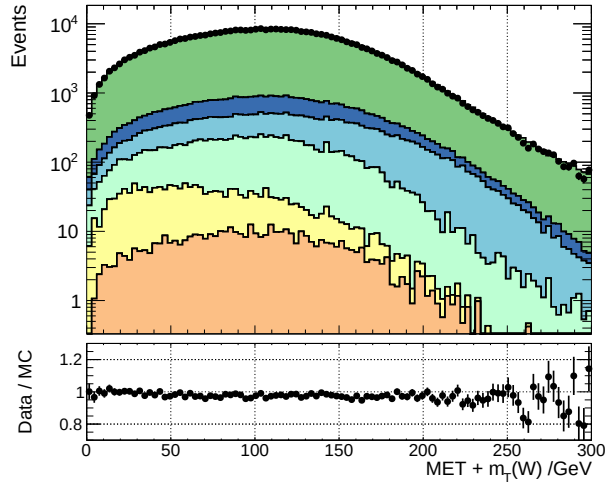
(d) 2b0c

Figure 8.8: The χ^2 cdf of events in data and MC simulation in specific flavour tagging regions with the additional requirement that $E_T^{miss} \geq 20$ GeV and $E_T^{miss} + m_T^W > 60$ GeV.

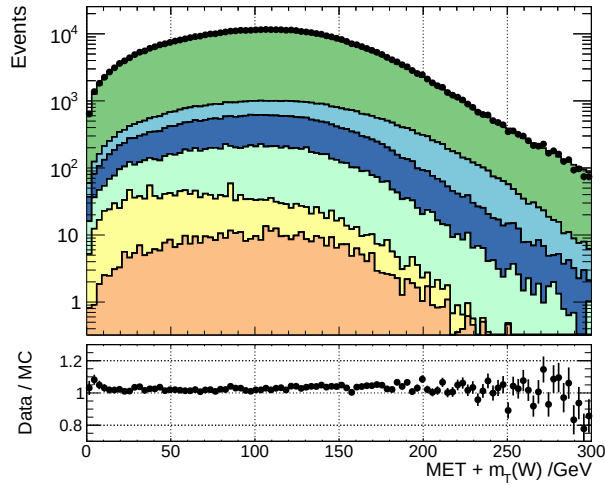


(a) 1b0c

(b) Legend



(c) 1b1c



(d) 2b0c

Figure 8.9: The $E_T^{miss} + m_T^W$ of events passing the selection requirements in data and MC simulation in specific flavour tagging regions. The $t\bar{t}$ MC simulation has been re-weighted as described in Section 8.1. In the case of the 1b0c and 2b0c regions this re-weighting is based on the calibration in the 1b1c region but in the case of the 1b1c region the re-weighting is based on a calibration in the 2b0c region.

Chapter 9

Asimov Results and Discussion

9.1 Results

In this section the results of fits to the Asimov dataset are presented. In the Asimov dataset all observed quantities are set to the value predicted by the simulated data. The fits are run as described in Chapter 6 including the uncertainties described in Chapter 7. Three fits are presented for the two flavour-tagging WPs defined in Section 5.2: the first uses the $t\bar{t} + c$ flavour-tagging WP without any flavour tagging systematics, the second uses the optimised WP without any flavour-tagging systematics and the third uses the optimised WP with the available b -tagging systematics but no c -tagging systematics. A summary of the total error for each WP can be found in Table 9.3 at the end of this section.

9.1.1 $t\bar{t} + c$ tagging working point

Figures 9.1 and 9.2 show a breakdown of the composition of the flavour tagging regions and the fraction of $|V_{cb}|$ events in each region. The $3b1c$ region has the largest fraction of $|V_{cb}|$ events as would be expected since the initial decay contains three b -quarks and one c -quark.

Figure 9.3 shows how the systematic uncertainties of the fit are constrained. Figure 9.4 ranks the post-fit impact of the 20 systematics having the largest impact on the measurement. The impact $\Delta\mu$ of a nuisance parameter θ is given by the shift in $n_{V_{cb}Rat}$ between the nominal fit where all parameters take their nominal values $\hat{\theta}$ and another fit where the nuisance parameter is fixed to a value of $\hat{\theta} \pm \Delta\theta$. The pre-fit impact is found by not constraining the uncertainty $\Delta\theta$, the post-fit impact is found by using the constrained value of $\Delta\theta$ if the uncertainty is constrained in the fit.

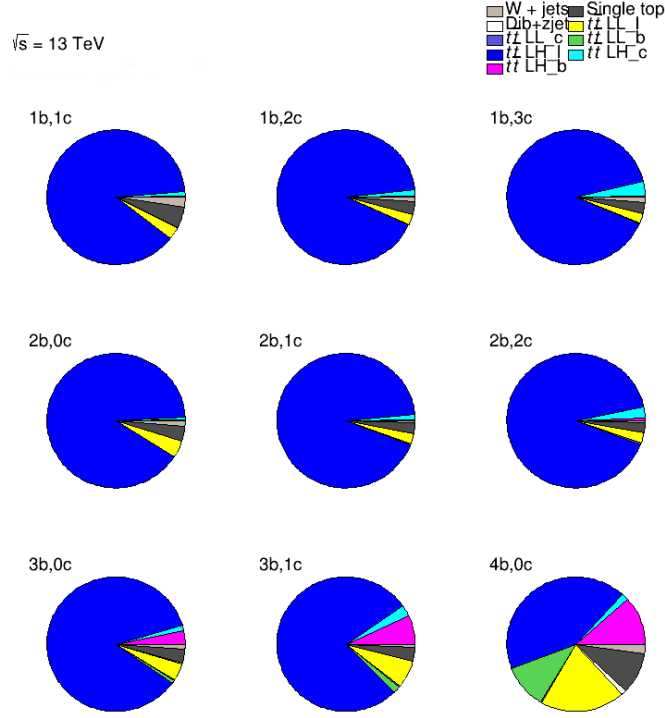


Figure 9.1: Composition of tagging regions excluding $|V_{cb}|$ events for the $t\bar{t} + c$ WP.

The total errors of the three normalisation factors of the fit are summarised in Table 9.1. Using the statistical errors previously shown in Table 6.2 the fractional error on $|V_{cb}|^2$ is given by:

$$\frac{\Delta|V_{cb}|^2}{|V_{cb}|^2} = 0.32(\text{stat.}) \oplus 0.31(\text{syst}) = 0.45, \quad (9.1)$$

or equivalently

$$\frac{\Delta|V_{cb}|}{|V_{cb}|} = 0.16(\text{stat.}) \oplus 0.16(\text{syst}) = 0.22. \quad (9.2)$$

	$n_{V_{cb}Rat}$	n_{LH}	n_{LL}
Total Uncertainty	0.45	0.11	0.24

Table 9.1: Total uncertainty on the normalisation factors given by Asimov fits using the $t\bar{t} + c$ working point.

$\sqrt{s} = 13 \text{ TeV}, 139 \text{ pb}^{-1}$

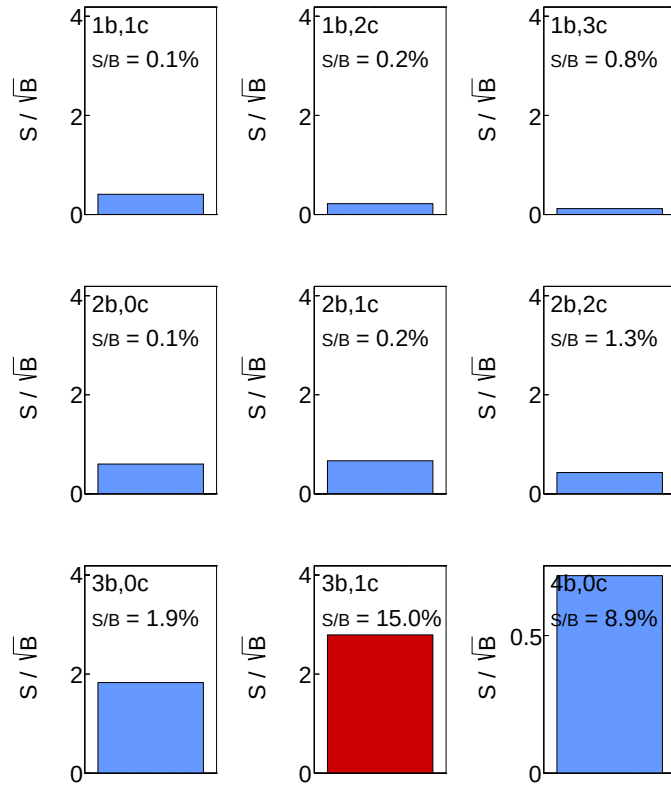


Figure 9.2: Signal/Background and $S/\sqrt{B}$ in flavour tagging regions for the $t\bar{t} + c$ WP.

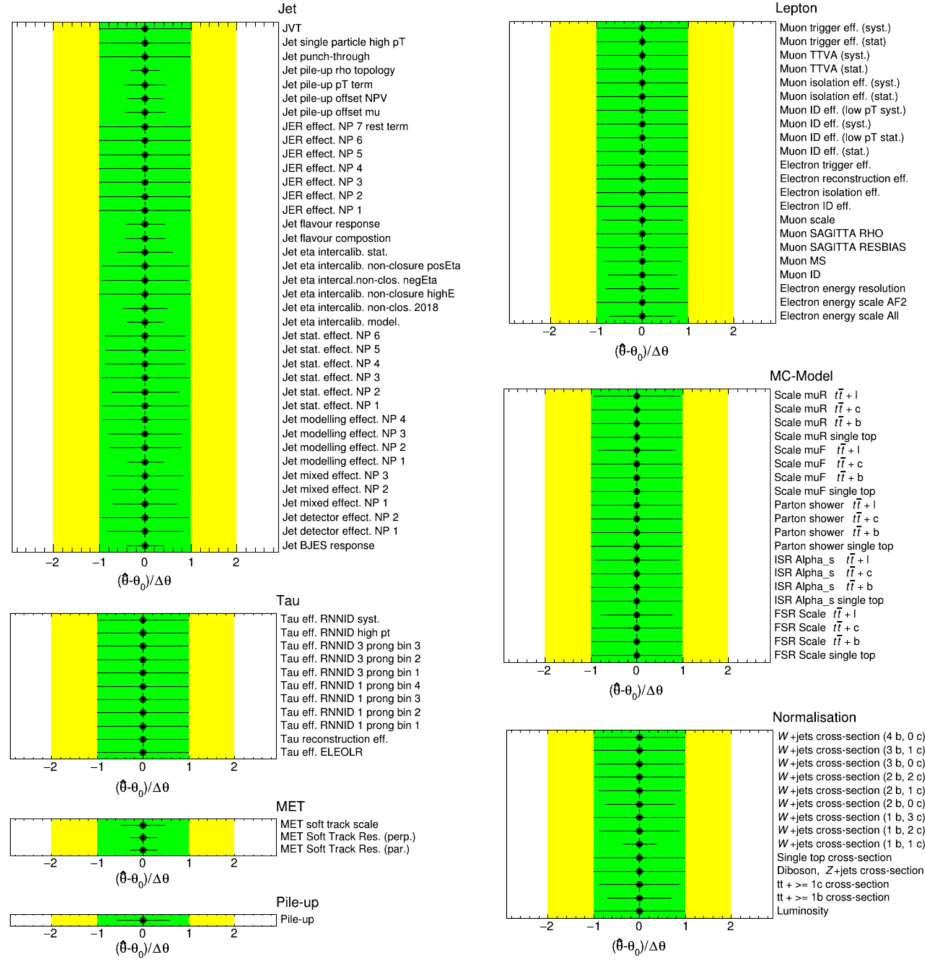


Figure 9.3: Plot of the constraints imposed on the NPs of the fit using the $t\bar{t} + c$ WP. The green band corresponds to one standard-deviation pre-fit. The central values are not pulled at all since the fit is to Asimov data.

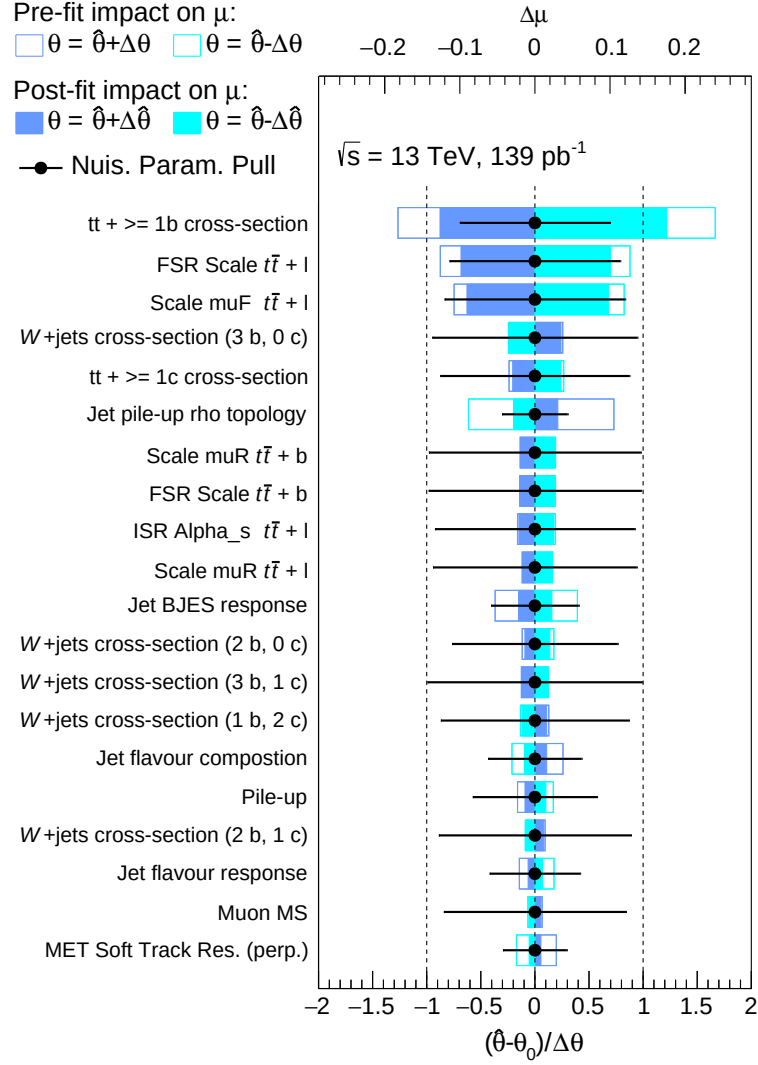


Figure 9.4: Plot of the systematic uncertainties having the largest impact on the measurement of $|V_{cb}|$ in the fit using the $t\bar{t} + c$ WP. The black lines show how much the NPs have been constrained in the fit. The blue bars show the impact of the NPs before and after the fit. The central values are not pulled at all since the fit is to Asimov data.

9.1.2 Optimised tagging working point

Figures 9.5 and 9.6 show the composition of the flavour tagging regions and the fraction of $|V_{cb}|$ events in each region for the optimised flavour tagging working point. These figures are very similar to those using the $t\bar{t} + c$ WP but there is a higher signal purity in the $3b1c$ region.

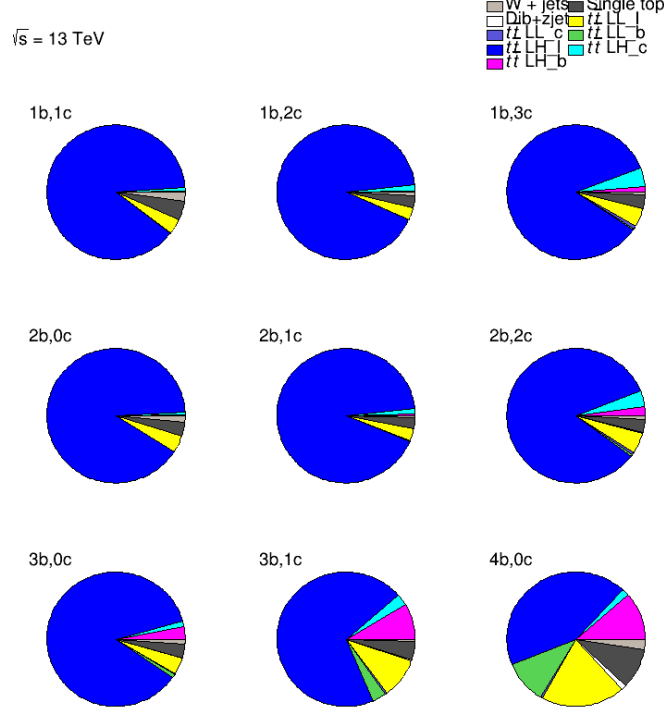


Figure 9.5: Composition of tagging regions excluding $|V_{cb}|$ events for the optimised WP.

For the fit to the optimised working point not including flavour tagging systematics Figure 9.7 shows how the systematic uncertainties of the fit are constrained while Figure 9.8 shows the 20 uncertainties with the largest impact on the measurement systematic error and the size of the impact pre and post-fit. Figures 9.9 and 9.10 show the same for the fit including b -tagging systematics.

The total uncertainties on each of the normalisation factors in both fits using the optimised WP are shown in Table 9.2. The fractional error on $|V_{cb}|^2$ using the optimised working point and including the b -tagging systematics is given by:

$$\frac{\Delta|V_{cb}|^2}{|V_{cb}|^2} = 0.26(\text{stat.}) \oplus 0.27(\text{syst}) = 0.38, \quad (9.3)$$

or equivalently

$$\frac{\Delta|V_{cb}|}{|V_{cb}|} = 0.13(\text{stat.}) \oplus 0.13(\text{syst}) = 0.19. \quad (9.4)$$

$\sqrt{s} = 13 \text{ TeV}, 139 \text{ pb}^{-1}$
Optimised WP

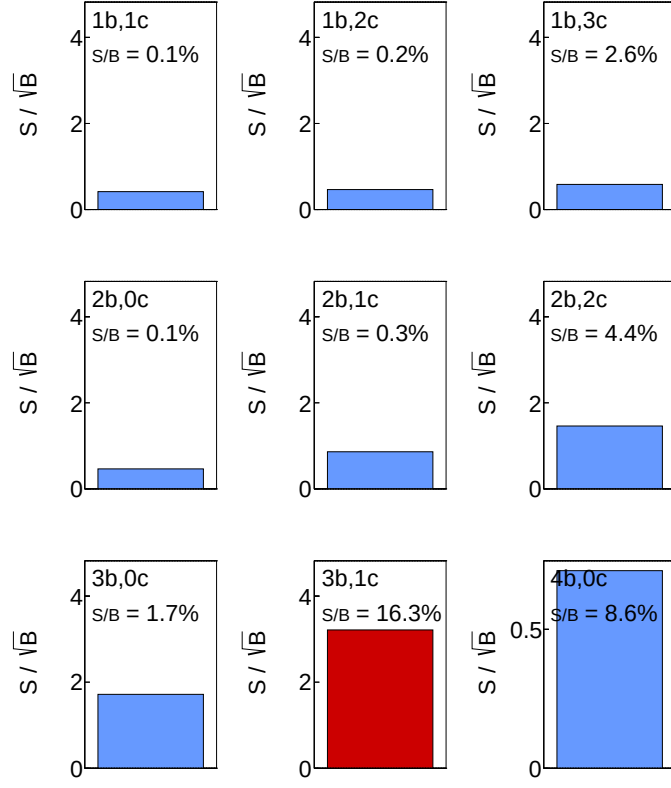


Figure 9.6: Signal/Background and $S/\sqrt{B}$ in flavour tagging regions for the optimised WP.

	n_{VcbRat}	n_{LH}	n_{LL}
No tagging syst.	0.369	0.066	0.12
b -tagging syst.	0.375	0.065	0.12

Table 9.2: Total uncertainty on the normalisation factors given by Asimov fits using the optimised WP.

	$\Delta V_{cb} / V_{cb} $
$t\bar{t} + c$ WP	0.22
Optimised WP no tag	0.18
Optimised WP b -tag	0.19

Table 9.3: Summary of the total fractional uncertainties on $|V_{cb}|$ for the different flavour tagging WPs.

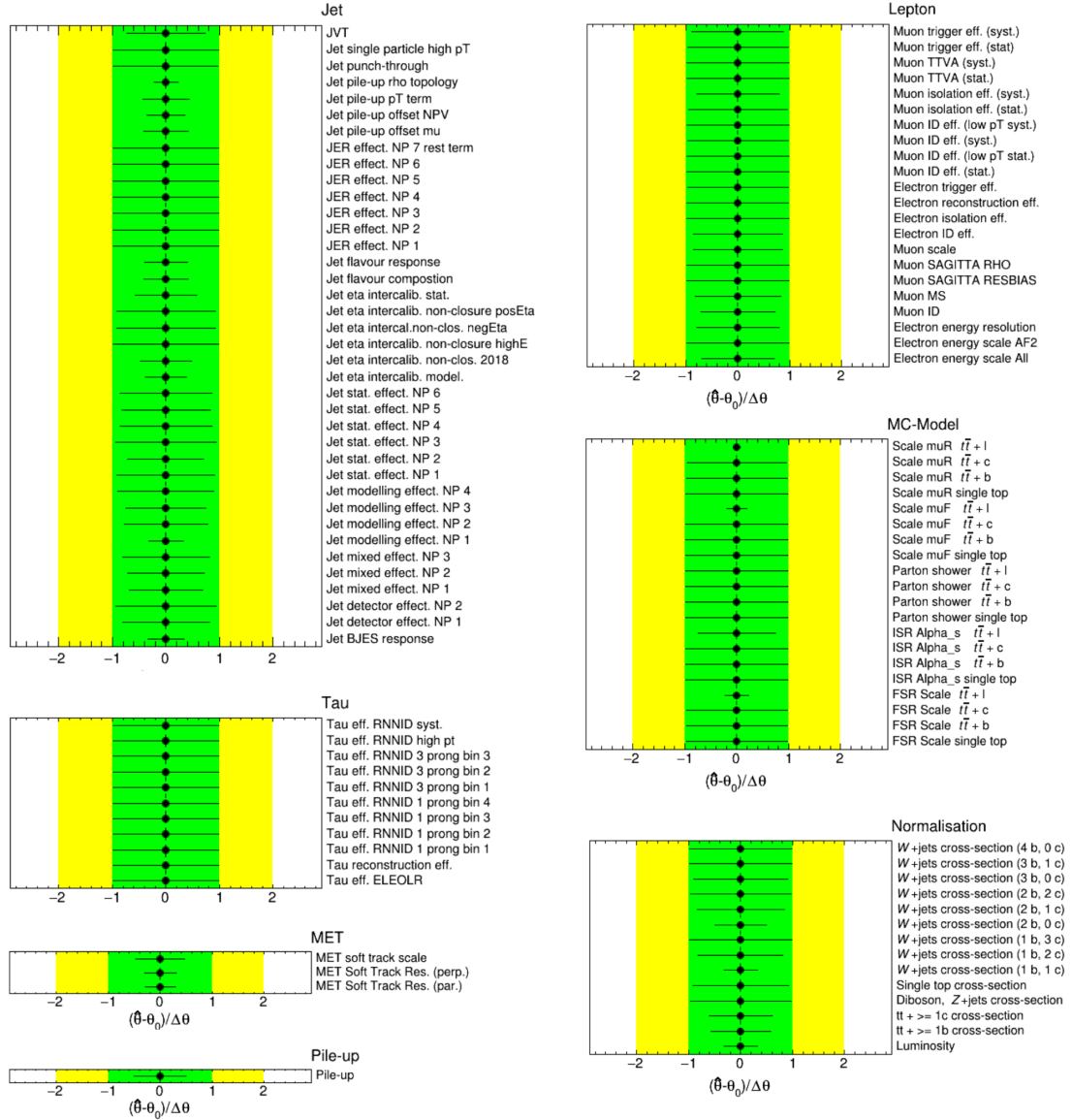


Figure 9.7: Plot of the constraints imposed on the NPs of the fit using the optimised WP and not including any tagging systematics. The green band corresponds to one standard-deviation pre-fit. The central values are not pulled at all since the fit is to Asimov data.

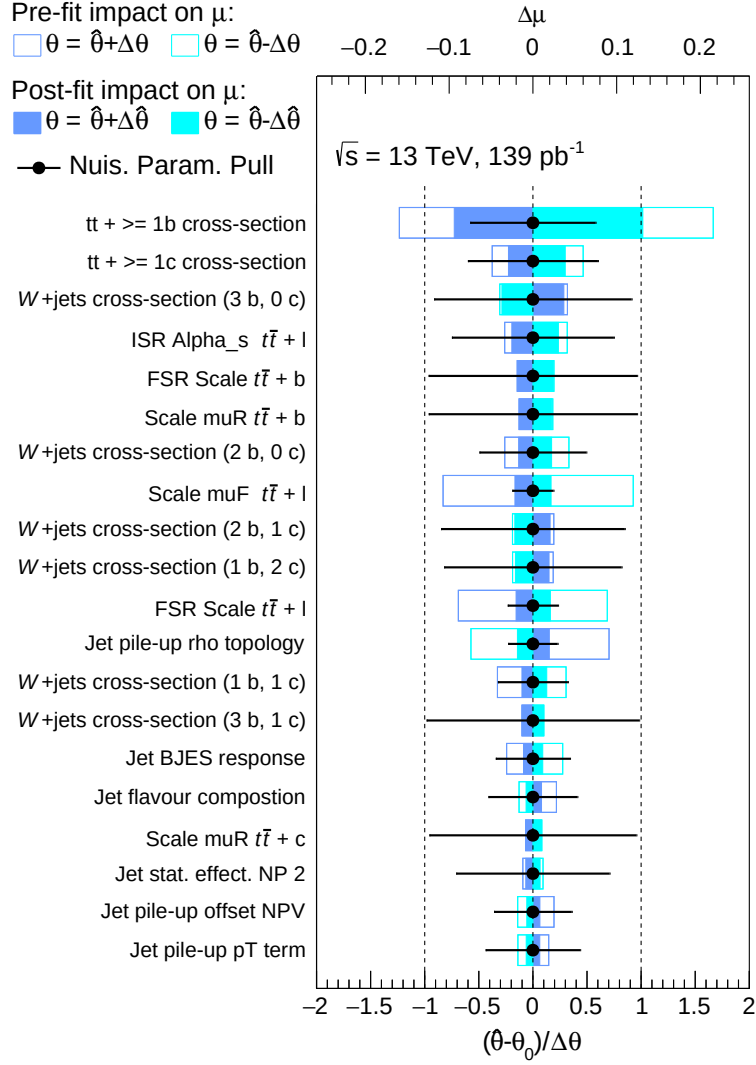


Figure 9.8: Plot of the systematic uncertainties having the largest impact on the measurement of $|V_{cb}|$ in the fit using the optimised WP and not including any tagging systematics. The black lines show how much the NPs have been constrained in the fit. The blue bars show the contribution of the NPs to the error on $|V_{cb}|^2$ before and after the fit. The central values are not pulled at all since the fit is to Asimov data.

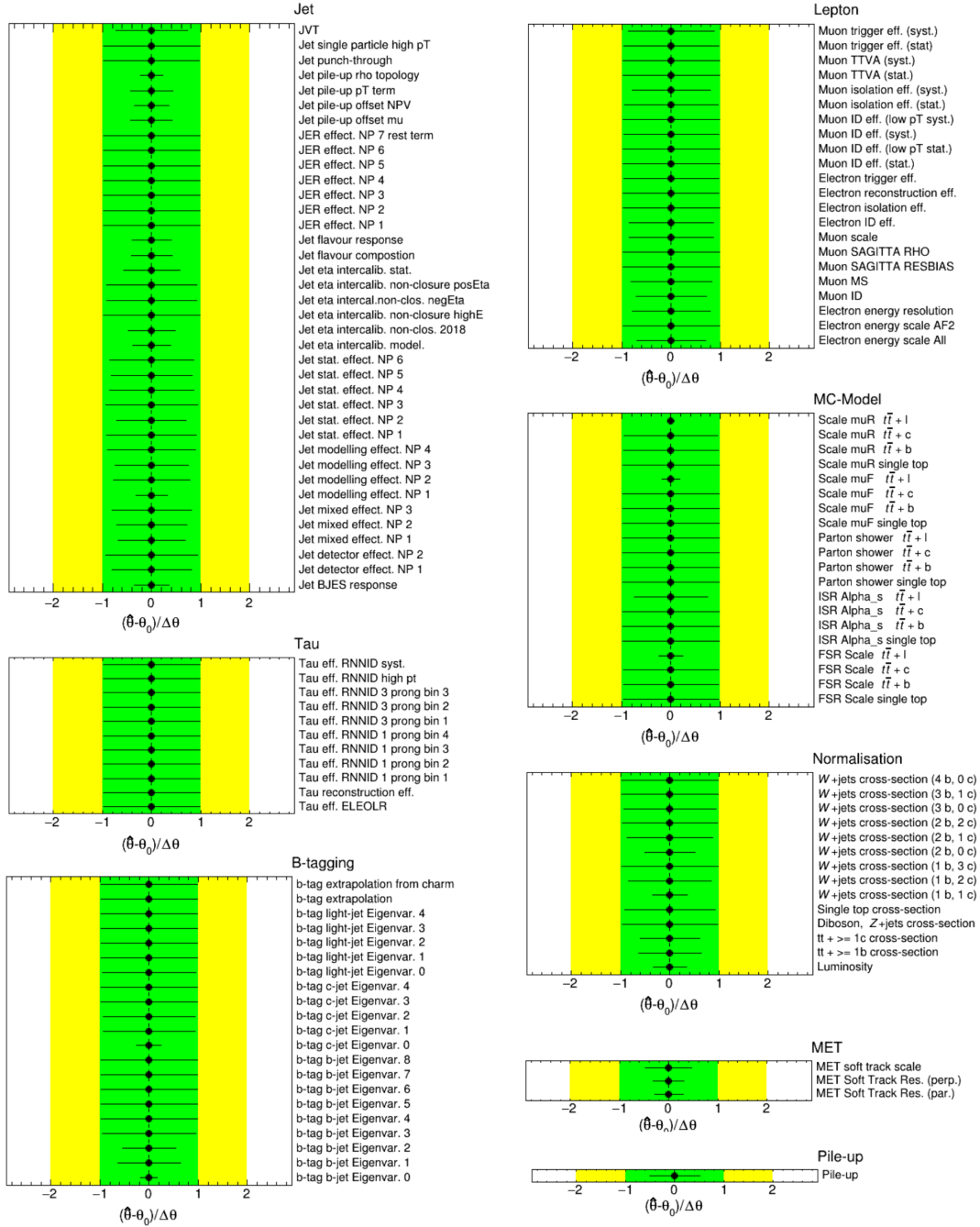


Figure 9.9: Plot of the constraints imposed on the NPs of the fit using the optimised WP and including b -tagging systematics. The green band corresponds to one standard-deviation pre-fit. The central values are not pulled at all since the fit is to Asimov data.

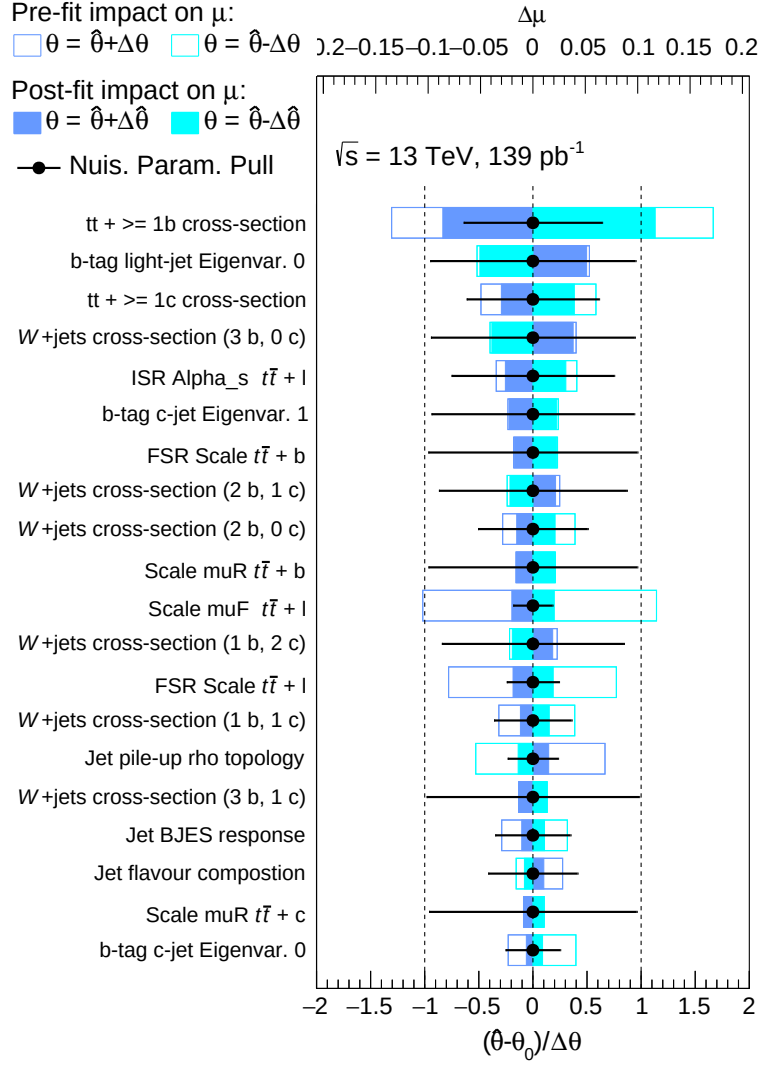


Figure 9.10: Plot of the systematic uncertainties having the largest impact on the measurement of $|V_{cb}|$ in the fit using the optimised WP and including b -tagging systematics. The black lines show how much the NPs have been constrained in the fit. The blue bars show the impact of the NPs before and after the fit. The central values are not pulled at all since the fit is to Asimov data.

9.2 Discussion

Across all three fits the normalisation uncertainty of the heavy flavour $t\bar{t} + \geq 1b$ events is the largest uncertainty and the $t\bar{t} + \geq 1b$ normalisation uncertainty is also significant across all fits. These uncertainties are able to be somewhat constrained by the fit. In the case of the $t\bar{t} + c$ WP the next most significant systematics are those from the modelling of the $t\bar{t}$ sample followed by an uncertainty in the $W + \text{jets}$ cross-section. The fits using the optimised flavour tagging WP are better able to constrain the $t\bar{t}$ modelling systematics and as such the uncertainty in the $W + \text{jets}$ cross-section is more significant than the $t\bar{t}$ modelling systematics. When including the b-tagging systematics an uncertainty in the light jet mis-tagging rate is the second most significant uncertainty.

Although the flavour-tagging systematics are significant the effect on the total uncertainty of adding them to the fit is relatively small. Part of the reason for this is that *b-tag b-jet Eigenvar. 0* and *b-tag c-jet Eigenvar. 0* are heavily constrained in the fit as can be seen in Figure 9.9.

The three fits presented here were also performed excluding the modelling systematics of the $t\bar{t}$ and single-top samples. Those fits are not presented here but showed that the total effect of including the modelling systematics is small and a little inconsistent between the two flavour tagging working points. In the case of the optimised WP there was no effect to three significant figures while for the $t\bar{t} + c$ WP the uncertainty increased by 1 percentage point. This is due to the previously mentioned fact that the modelling uncertainties are able to be better constrained when using the optimised working point.

If treating the $|V_{cb}|$ sample as a signal the significance of the signal when using the $t\bar{t} + c$ WP is 2.3σ while for the optimised WP this is 2.7σ . It is worth noting that this is the significance on the measurement of $|V_{cb}|^2$ rather than $|V_{cb}|$. These expected significances would be unsatisfactory if the aim of this measurement was to prove the existence of the $W \rightarrow c\bar{b}$ decay. However, the aim of this measurement is instead to measure $|V_{cb}|$, a quantity previously measured by a number of experiments, using a new method. This is similar to the measurement of $|V_{cs}|$ using flavour tagged jets in W decays made at DELPHI [104] where $|V_{cs}| = 0.94^{+0.32}_{-0.26}(\text{stat.}) \pm 0.13(\text{syst.})$. This corresponds to a signal significance for $|V_{cs}|^2$ of approximately 1.5σ . The DELPHI measurement has a significantly larger uncertainty than other measurements of $|V_{cs}|$ but remains important because it measures $|V_{cs}|$ directly [30]. The measurement reported in this thesis will directly measure $|V_{cb}|$ with a lower uncertainty than DELPHI's direct measurement of $|V_{cs}|$ despite $|V_{cb}|^2$ being three orders of magnitude smaller than $|V_{cs}|^2$.

Across all of the fits the statistical and systematic uncertainties are ap-

proximately equal. The predicted uncertainties on the measurement of $|V_{cb}|$ summarised in Table 9.3 are of order 10 times greater than the current uncertainties on measurements from the decay of B -mesons. Nevertheless, once complete this will be the first measurement of $|V_{cb}|$ from on-shell W -bosons and will provide an independent measure unaffected by the theoretical uncertainties which limit the measurements using B -mesons. Hopefully, future iterations of the analysis will allow both the systematic and statistical uncertainties to be reduced.

9.3 Analysis Completion

There are two remaining steps anticipated to be required in order to unblind this analysis and measure $|V_{cb}|$:

1. **A fully calibrated flavour tagging working point:** This is required so that systematic uncertainties in the flavour tagging performance can be fully accounted for. In the short term the $t\bar{t} + c$ WP will offer a fully calibrated working point that can be used. Longer term the ongoing work at ATLAS to calibrate the raw tagging scores should allow a fully optimised working point to be used which will reduce the statistical error on the measurement.
2. **Fully implemented re-weighting procedure:** As set out in Section 8.1 there is a known discrepancy in the modelling of $t\bar{t}$ in simulation compared to in data. A first attempt at implementing the re-weighting procedure is presented in Section 8.1 but this will need to be fully-implemented including systematic uncertainties in the procedure.

9.4 Future Prospects

Alongside the essential steps outlined in the last section there are further improvements to the analysis which could either be implemented prior to the first measurement of $|V_{cb}|$ in $t\bar{t}$ events or in the next iteration of the analysis. These include:

1. **Improved $t\bar{t}$ selection:** The ability of the kinematic χ^2 quality metric to select semi-leptonically decaying $t\bar{t}$ events and reject all other backgrounds could be improved. Using a neural network to select events may well allow an improvement in the purity of the events selected. This should reduce the statistical error and reduce the effect of the $W + \text{jets}$ cross-section systematic in the fit. Given the dominance of $t\bar{t} + \text{HF}$ systematic uncertainties the possibility of identifying and excluding these events could also be considered.

2. **Improved jet origin assignment:** Currently each jet is assigned to one of the quarks in the original decay during the χ^2 reconstruction. However, this information is not used in the fit. If the performance of the assignment of the jet origin could be improved then including this information in the fit could reduce the statistical errors of the fit. Again neural networks may offer a method of improving the jet assignment performance.
3. **Inclusion of events with more than 4 jets:** As shown in Table 5.5 a large number of lep-had $t\bar{t}$ events have greater than four detected jets. Including 5 jet events would increase the statistics by 78% while including 5 and 6 jet events would increase the statistics by 110%. The events would be added into the fit as a set of additional flavour tagging regions. Potential improvements in the $t\bar{t}$ selection and jet origin assignment would be very helpful to reduce the effects of backgrounds in events with more jets.

Beyond this iteration of the analysis reductions in the statistical error will come from using the data collected during Run 3 of the LHC. The standard ATLAS flavour tagger will also move from the current DL1r to DL1d which in the case of b -tagging offers significantly improved light and c -jet rejection. For a 60% efficiency b -tagging working point the number of c -jets mis-tagged as b is expected to reduce by approximately 25% while the number of light-jets mis-tagged as b is expected to reduce by approximately 50%. This should allow a higher signal purity in the main $3b1c$ signal region further reducing the statistical error. Better $t\bar{t}$ modelling and measurements of the cross-sections of $t\bar{t} + \text{HF}$ events in the future should allow a reduction in the dominant $t\bar{t} + \text{HF}$ uncertainties and the significant modelling uncertainties.

In Figure 9.11 a rough extrapolation of the uncertainty on the measurement of $|V_{cb}|$ is plotted against the integrated luminosity if no improvements were made to the current method. This was derived by multiplying the weights of all events in the fits by set numbers. For the purpose of these fits uncertainties due to the limited number of MC simulation events were excluded. Because the likelihood fit is able to constrain systematic uncertainties greater statistics reduces the systematic uncertainty as well as the statistical uncertainty. In practice as larger statistics became available the dedicated calibrations which provide many of the systematic uncertainties would be re-run and their uncertainties reduced in these dedicated fits rather than being increasingly constrained by the fit of this analysis. These dedicated calibrations would be better optimised to reduce the uncertainties and so the reductions in the systematic uncertainty would be expected to be greater. Figure 9.11 suggests that without other improvements to the analysis method it would require a luminosity close to

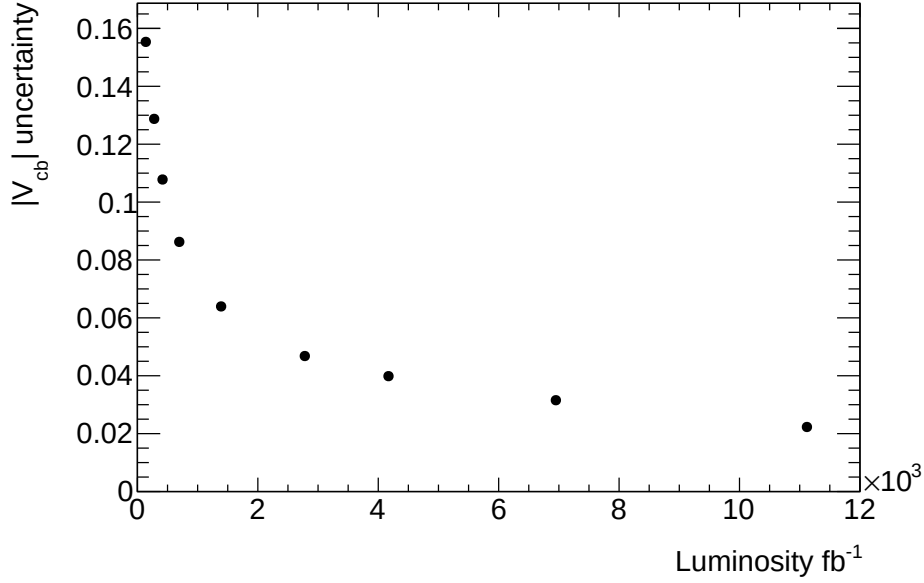


Figure 9.11: Extrapolation of the uncertainty in the measurement of $|V_{cb}|$ to higher luminosities using the optimised WP. Extrapolation is made by multiplying the weights of simulated events by a set of multipliers and performing a fit.

10^4 fb^{-1} for this measurement's uncertainty to be comparable with current measurements made in the decay of B -mesons. This demonstrates that it is important to make the improvements beyond more data if trying to make a competitive measurement.

Further into the future the best opportunities to measure $|V_{cb}|$ in on-shell W boson decays will come from WW production at high energy electron-positron colliders such as the proposed Future Circular Collider (FCC-ee) [105, 106]. By operating at a centre of mass energy $\sqrt{s} \approx 160 \text{ GeV}$ the FCC-ee would be expected to produce 10^8 WW pairs over its runtime [105]. This will provide a much cleaner sample than the $t\bar{t}$ sample used in this analysis because the collision of two leptons is a QED initial state with known kinematics. The sample will have a much smaller QCD background. All jets detected will come directly from the decay of the W bosons. The method presented in this thesis could be modified to measure $|V_{cb}|$ in these events. In events with one leptonic and one hadronic W decay, two jets would be expected from the hadronically decaying W significantly simplifying the fit compared to $t\bar{t}$ events where four jets are expected. Experience gained measuring $|V_{cb}|$ in $t\bar{t}$ decays as presented in this thesis should be able to be applied to these future measurements at electron-positron colliders.

Chapter 10

Conclusions

A method of measuring $|V_{cb}|$ in semi-leptonically decaying $t\bar{t}$ events was presented. This method is designed to use data collected by the ATLAS detector during Run 2 of the LHC at a centre of mass energy of $\sqrt{s} = 13$ TeV and integrated luminosity of 139 fb^{-1} . Events are separated into regions based on how jets are flavour-tagged and a profile-likelihood fit is performed using the cumulative distribution function of a kinematic χ^2 metric designed to select semi-leptonically decaying $t\bar{t}$ events. This method was used in fits to MC simulation to put lower limits on the uncertainty of the measurement. Using a flavour-tagging working point optimised for another analysis and not including any flavour-tagging systematics an estimate of the uncertainty is given by:

$$\frac{\Delta|V_{cb}|}{|V_{cb}|} = 0.16(\text{stat.}) \oplus 0.16(\text{syst}) = 0.22. \quad (10.1)$$

Using a flavour tagging working point optimised for a cut-and-count version of this analysis and including b -tagging systematics gives:

$$\frac{\Delta|V_{cb}|}{|V_{cb}|} = 0.13(\text{stat.}) \oplus 0.13(\text{syst}) = 0.19. \quad (10.2)$$

These uncertainties are of order 10 times larger than those measured in B -meson decays but this would be the first measurement of $|V_{cb}|$ in $t\bar{t}$ events or indeed from on-shell W decays.

To unblind the analysis and make a measurement using data will require: a fully calibrated flavour tagging working point and a fully implemented re-weighting of $t\bar{t}$ events to account for known modelling discrepancies.

Appendix A

Numbers of Events By Region

In this appendix the numbers of events of each MC simulation sample passing the selection cuts of Chapter 5 are presented separated by flavour tagging region. For ease of presentation they are shown in terms of the number of b -tags and light(l)-tags rather than b -tags and c -tags. Tables are presented for both the optimised flavour tagging working point and the $t\bar{t} + c$ working point as defined in Section 5.2.

	$3l$	$2l$	$1l$	$0l$
Lep-Had	(10^5)	(10^5)	(10^4)	
$1b$	7.31	2.10	1.62	202
$2b$	-	4.84	7.48	1030
$3b$	-	-	0.858	302
$4b$	-	-	-	36.7
Lep-Lep	(10^4)	(10^4)		
$1b$	3.20	0.708	458	5.68
$2b$	-	2.19	2100	33.1
$3b$	-	-	494	29.8
$4b$	-	-	-	20.2
$ V_{cb} = 1$				
$1b$	359.5	198	28.9	1.75
$2b$	-	439	188	14.3
$3b$	-	-	179	51.9
$4b$	-	-	-	5.81

Table A.1: Numbers of events in $t\bar{t}$ samples passing cuts, classified according to the total numbers of flavour tags. Using the flavour tagging working point of the $t\bar{t} + c$ analysis.

	$3l$	$2l$	$1l$	$0l$
Single-top	(10^4)	(10^4)		
$1b$	5.91	1.15	536	5.8
$2b$	-	1.79	1990	25.3
$3b$	-	-	321	10.9
$4b$	-	-	-	6.40
Diboson				
$1b$	1990	289	12.5	0
$2b$	-	469	30.4	0.36
$3b$	-	-	11.9	0.22
$4b$	-	-	-	0.87
$W + \text{ Jets}$	(10^4)			
$1b$	6.19	5840	185	2.6
$2b$	-	7650	426	6.1
$3b$	-	-	116	2.9
$4b$	-	-	-	1.5
$Z + \text{ Jets}$				
$1b$	8440	868	32.7	0.20
$2b$	-	1340	73.1	0.96
$3b$	-	-	33.5	0.73
$4b$	-	-	-	0.54

Table A.2: Numbers of events in background samples passing cuts, classified according to the total numbers of flavour tags. Using the flavour tagging working point of the $t\bar{t} + c$ analysis.

	$3l$	$2l$	$1l$	$0l$
$t\bar{t} + \text{light-jets}$	(10^5)	(10^5)	(10^4)	
$1b$	7.2	2.1	1.6	194
$2b$	-	4.79	7.4	995
$3b$	-	-	0.815	268
$4b$	-	-	-	28.0
$t\bar{t} + \geq 1b$	(10^3)	(10^3)		
$1b$	1.22	0.352	30.8	0.611
$2b$	-	1.15	206	7.22
$3b$	-	-	302	24.2
$4b$	-	-	-	7.6
$t\bar{t} + \geq 1c$	(10^3)	(10^3)		
$1b$	6.55	2.82	284	7.5
$2b$	-	3.11	980	29.2
$3b$	-	-	132	9.51
$4b$	-	-	-	1.1

Table A.3: Numbers of events in $t\bar{t}$ lep-had heavy flavour sub-samples passing cuts, classified according to the total numbers of flavour tags. Using the flavour tagging working point of the $t\bar{t} + c$ analysis.

	$3l$	$2l$	$1l$	$0l$
$t\bar{t} + \text{light-jets}$	(10^4)	(10^4)	(10^3)	
$1b$	3.15	6.88	0.433	4.86
$2b$	-	2.15	2.01	28.2
$3b$	-	-	0.397	22.6
$4b$	-	-	-	13.1
$t\bar{t} + \geq 1b$				
$1b$	134	38.3	3.63	0.10
$2b$	-	174	31.0	1.1
$3b$	-	-	83.9	6.20
$4b$	-	-	-	6.9
$t\bar{t} + \geq 1c$				
$1b$	383	158	21.9	0.600
$2b$	-	197	62.6	3.9
$3b$	-	-	13.5	0.81
$4b$	-	-	-	0.23

Table A.4: Numbers of events in $t\bar{t}$ lep-lep heavy flavour sub-samples passing cuts, classified according to the total numbers of flavour tags. Using the flavour tagging working point of the $t\bar{t} + c$ analysis.

	$3l$	$2l$	$1l$	$0l$
Lep-Had	(10^5)	(10^5)	(10^4)	
$1b$	5.80	3.47	4.36	455
$2b$	-	4.79	8.50	969
$3b$	-	-	0.888	317
$4b$	-	-	-	38.1
Lep-Lep	(10^4)	(10^4)		
$1b$	2.43	1.41	1430	28.2
$2b$	-	2.15	2840	67.7
$3b$	-	-	486	51.9
$4b$	-	-	-	20.8
$ V_{cb} = 1$				
$1b$	214	259	100	13.1
$2b$	-	337	260	48.1
$3b$	-	-	170	63.4
$4b$	-	-	-	5.87

Table A.5: Numbers of events in $t\bar{t}$ samples passing cuts, classified according to the total numbers of flavour tags. Using the optimised tagging working point.

	$3l$	$2l$	$1l$	$0l$
Single-top	(10^4)	(10^4)		
$1b$	5.24	1.77	1350	16.0
$2b$	-	1.78	2330	33.9
$3b$	-	-	323	17.0
$4b$	-	-	-	6.54
Diboson				
$1b$	1850	447	25.2	0.48
$2b$	-	465	38.3	1.11
$3b$	-	-	11.6	1.04
$4b$	-	-	-	0.87
$W+$ Jets	(10^4)			
$1b$	6.00	8440	393	3.5
$2b$	-	7703	487.9	9.7
$3b$	-	-	119	2.4
$4b$	-	-	-	1.7
$Z+$ Jets				
$1b$	8060	1340	68.7	0.90
$2b$	-	1340	92.7	2.7
$3b$	-	-	34.0	1.3
$4b$	-	-	-	0.54

Table A.6: Numbers of events in background samples passing cuts, classified according to the total numbers of flavour tags. Using the optimised flavour tagging working point.

	$3l$	$2l$	$1l$	$0l$
$t\bar{t}$ +light-jets	(10^5)	(10^5)	(10^4)	
$1b$	5.74	3.43	4.27	425
$2b$	-	4.75	8.34	904
$3b$	-	-	0.845	272
$4b$	-	-	-	29.1
$t\bar{t}+ \geq 1b$				
$1b$	840	634	132	6.21
$2b$	-	977	372	23.2
$3b$	-	-	299	33.4
$4b$	-	-	-	7.8
$t\bar{t}+ \geq 1c$	(10^3)	(10^3)		
$1b$	5.18	3.75	738	22.9
$2b$	-	2.93	1200	41.4
$3b$	-	-	138	11.0
$4b$	-	-	-	1.2

Table A.7: Numbers of events in $t\bar{t}$ lep-had heavy flavour sub-samples passing cuts, classified according to the total numbers of flavour tags. Using the optimised flavour tagging working point

	$3l$	$2l$	$1l$	$0l$
$t\bar{t}$ +light-jets	(10^4)	(10^4)	(10^3)	
$1b$	2.40	1.38	1.36	23.2
$2b$	-	2.12	2.69	54.7
$3b$	-	-	0.394	37.7
$4b$	-	-	-	13.4
$t\bar{t}+ \geq 1b$				
$1b$	78.5	76.1	20.7	1.3
$2b$	-	131	71.3	6.4
$3b$	-	-	78.8	12.7
$4b$	-	-	-	7.14
$t\bar{t}+ \geq 1c$				
$1b$	284	225	55.3	3.8
$2b$	-	177	84.5	6.58
$3b$	-	-	13.3	1.5
$4b$	-	-	-	0.26

Table A.8: Numbers of events in $t\bar{t}$ lep-lep heavy flavour sub-samples passing cuts, classified according to the total numbers of flavour tags. Using the optimised flavour tagging working point.

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