

Top quark pair production measurements in the single lepton channel using the ATLAS detector

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List of acronyms

4FS	four flavour scheme	38
5FS	five flavour scheme	38
BS	ByteStream	67
CERN	European Organization for Nuclear Research	43
CSC	Cathode Strip Chambers	60
CSM	Chamber Service Module	78
CST	calorimeter-based soft term	101
CTP	Central Trigger Processor	67
DCS	Detector Control System	69
e^+e^-	electron-positron	23
EF	Event Filter	71
EMEC	Electromagnetic End-cap Calorimeter	57
ep	electron-proton	24
EW	electroweak	35
FCal	Forward Calorimeter	57
FSR	final-state radiation	24
FTK	Fast Tracker	68
HEC	Hadronic End-cap Calorimeter	57
HLT	High Level Trigger	53
IBL	Insertable B-Layer	54
ID	Inner Detector	54
IP	Interaction Point	51
IR	Interaction Region	43
ISR	initial-state radiation	24

JER	jet energy resolution	138
JES	jet energy scale	138
JVT	Jet Vertex Tagger	95
L1	Level-1	53
L2	Level-2	71
L1 Topo	Level-1 Topological trigger	68
LAr	liquid argon	57
LHC	Large Hadron Collider	24
LO	leading order	35
LS1	Long Shutdown 1	48
MC	Monte Carlo	29
MDT	Monitored Drift Tubes	60
MET	missing transverse energy	28
MPI	multi-parton interaction	24
MS	Muon Spectrometer	60
MVA	multivariate analysis	86
NLO	next-to-leading order	35
NNLO	next-to-next-to-leading order	35
PbPb	lead-lead	47
PDF	parton distribution function	24
<i>pp</i>	proton-proton	23
<i>p$\bar{p}$</i>	proton-antiproton	23
<i>pPb</i>	proton-lead	47
PRD	PrepRawData	72
PS	parton shower	29
QCD	quantum chromodynamics	19
RDO	Raw Data Object	72
ROB	Readout Buffer	67

ROD	Readout Driver	67
ROS	Readout System	67
RoI	Region of Interest	67
RPC	Resistive Plate Chambers	60
SCT	Semiconductor Tracker	55
SM	Standard Model	19
TDAQ	Trigger and Data Acquisition	65
TGC	Thin Gap Chambers	60
TRT	Transition Radiation Tracker	55
TST	track-based soft term	101

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Abstract

Three measurements of top-quark pair production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV using data collected by the ATLAS experiment are presented. The single-lepton final states are used, where one electron or muon, two b -jets and two other jets can be identified. The inclusive $t\bar{t}$ production cross section is measured to be $\sigma_{t\bar{t}} = 817 \pm 13$ (stat.) ± 103 (syst.) ± 88 (lum.) pb, which is in good agreement with predictions and with other measurements. Absolute and relative differential cross sections of $t\bar{t}$ production are also measured, showing an overall good agreement with predictions, except for the top-quark transverse momentum distribution. As already reported in measurements at lower proton-proton collision energies, this distribution is shifted towards higher momenta in all predictions with respect to the observations. Total and differential fiducial cross sections of $t\bar{t}$ production in association with heavy-flavour jets are also presented. All tested models are found to agree with data within the uncertainties of these measurements.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Rafał P. Bielski

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I am also grateful to my parents for their endless support throughout the my whole education. Finally and most importantly, I thank my wife, Hanna, who brings balance, love, joy and sense to my life. Without her, I would have not survived this arduous adventure called PhD.

Preface

The work presented in this thesis is a result of a collaborative effort of thousands of individuals involved in the ATLAS experiment, and in particular of the ATLAS Top Physics Working Group. However, more emphasis is placed on aspects with significant contributions from myself. In particular, Section 3.3 presents a software-development project I realised during the first year of my PhD programme. I continued to maintain the corresponding software packages and provide expertise in the area in the subsequent years. My dedicated involvement in the operation of the ATLAS Trigger system throughout the past three years is not reflected in this thesis, although it shaped a significant portion of my PhD programme. My main contribution to the inclusive cross-section measurement presented in Chapter 5 was the estimation of the fake/non-prompt lepton and W +jets backgrounds. I have also worked on the fake/non-prompt lepton background estimate for the differential measurements presented in Chapter 6. These developments are reflected by a detailed description of the corresponding methods in Section 4.5. It is complemented by a study of a modification to the matrix method using a probabilistic approach, which was proposed by me. My contributions to the $t\bar{t} + b$ -jets cross-section measurements reported in Chapter 7 include the implementation of the flavour-composition fit and all related studies, as well as the measurements of the total fiducial cross sections. Additional studies I performed on $t\bar{t}b\bar{b}$ system reconstruction algorithms for the differential measurements are presented in Appendix B.3.

Chapter 1

Introduction

With the largest mass among all fundamental particles, the top quark is characterised by unique properties and plays a special role in the Standard Model of particle physics. Twenty-three years after its discovery at the Tevatron proton-antiproton collider, top quark physics research is currently focused on precise measurements of its properties and searches for both rare Standard-Model processes and new phenomena involving top quarks. The vast amount of top-antitop pairs produced daily in proton-proton collisions at the Large Hadron Collider facilitates the most precise differential or even double-differential measurements of $t\bar{t}$ production cross sections. Observation of rare associated production of $t\bar{t}$ pairs with W , Z and Higgs bosons is also becoming possible.

Run 2 of the Large Hadron Collider has opened new opportunities for precise measurements in a never-before reached energy regime. Early datasets recorded in the first few weeks of proton-proton collisions at $\sqrt{s} = 13$ TeV in summer 2015 were used to establish inclusive cross sections of a number of benchmark Standard-Model processes including $t\bar{t}$ production. The initial measurements with lower precision were motivated by the fact that new particles produced at 13 TeV and decaying into top quark pairs could enhance the cross section above the Standard Model expectation. Rapidly

growing datasets allowed for the first differential measurements of $t\bar{t}$ production cross section already after a few months of operation. These studies focused again on establishing whether non-Standard-Model particles appear at the new energy and on investigation of discrepancies observed in Run 1 data in modelling of $t\bar{t}$ kinematic distributions. In the following years, further focus has been put on associated production of top quark pairs with bosons. Beside measurements of $t\bar{t}W$ and $t\bar{t}Z$ cross sections, this lead also to the first evidence and observation of $t\bar{t}H$ production. Despite the highest branching fraction of the Higgs boson to a $b\bar{b}$ pair, the significance of this channel remains low due to the difficulties in modelling of its largest background, $t\bar{t}$ production in association with $b\bar{b}$ originating from gluon radiation. The $t\bar{t}b\bar{b}$ process is therefore also a subject of particular interest for top quark research in Run 2 of the Large Hadron Collider.

The first measurements of inclusive and differential $t\bar{t}$ production cross sections in proton-proton collisions at $\sqrt{s} = 13\text{ TeV}$ using data collected by the ATLAS experiment are reported in this thesis. In addition, total and differential fiducial cross-section measurements of $t\bar{t}$ production in association with heavy-flavour jets are also presented. All the reported analyses use the single-lepton final state, where an electron or muon, two b -jets and two other jets can be identified. The results are discussed in the context of other measurements performed in the past or in parallel by both ATLAS and CMS Collaborations. Their impact on the current understanding and modelling of top quark production is also discussed.

Chapter 2 presents a brief history of the Standard Model and modern particle physics from an experimental point of view, followed by characteristics of hadron collider experiments. Top physics is then introduced discussing recent developments in $t\bar{t}$ production modelling and motivating the pre-

sented measurements. Chapter 3 describes the experimental basis, focusing on operation and performance of the Large Hadron Collider. The design of the ATLAS experiment is presented and all major elements of the detector are shortly discussed. This is followed by a detailed description of software developments implemented in the High-Level Trigger muon algorithms in preparation for Run 2. Chapter 4 presents the fundamental elements of all three measurements, including physics object reconstruction algorithms, signal and background process simulations, event selection, data-driven methods of background estimation, detector-effect corrections, and finally the evaluation of uncertainties. Chapter 5 reports on one of the first measurements of the inclusive $t\bar{t}$ production cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV. Chapter 6 presents differential measurements of $t\bar{t}$ production using all data collected by ATLAS in 2015. Chapter 7 describes measurements of total and differential fiducial production cross sections of $t\bar{t}$ pairs in association with heavy-flavour jets. This measurement makes use of a larger dataset including all proton-proton collision events recorded by ATLAS in 2015 and 2016. Chapter 8 summarises all the reported results, discusses their impact and presents prospects for further measurements in the near future.

Chapter 2

Background and motivation

2.1 Standard Model of particle physics

The Standard Model (SM) of particle physics is a prominent quantum field theory framework successfully describing fundamental (to our current knowledge) particles and their interactions, where the particles are described as excited states of the respective fields. According to the SM, all matter is composed of twelve fermions (half-integer spin particles) which can interact by exchanging one of five bosons (integer spin particles). All seventeen particles are presented in Figure 2.1, grouped by type and properties.

There are three fundamental forces of nature incorporated in the SM – the electromagnetic force mediated by neutral and massless photons, the weak force mediated by massive neutral Z bosons and charged W bosons, and the strong force mediated by massless and electrically-neutral gluons carrying another type of charge called colour. The electromagnetic and weak interactions can be both described by a unified electroweak theory, whereas the strong interactions are described by a theory named quantum chromodynamics (QCD). The gravitational force is not included in the SM as there is currently no complete quantum theory of gravity. Gluons, photons, W and Z are vector bosons with spin 1. The Standard Model also includes a scalar (spin 0) Higgs boson, which arises from an additional field

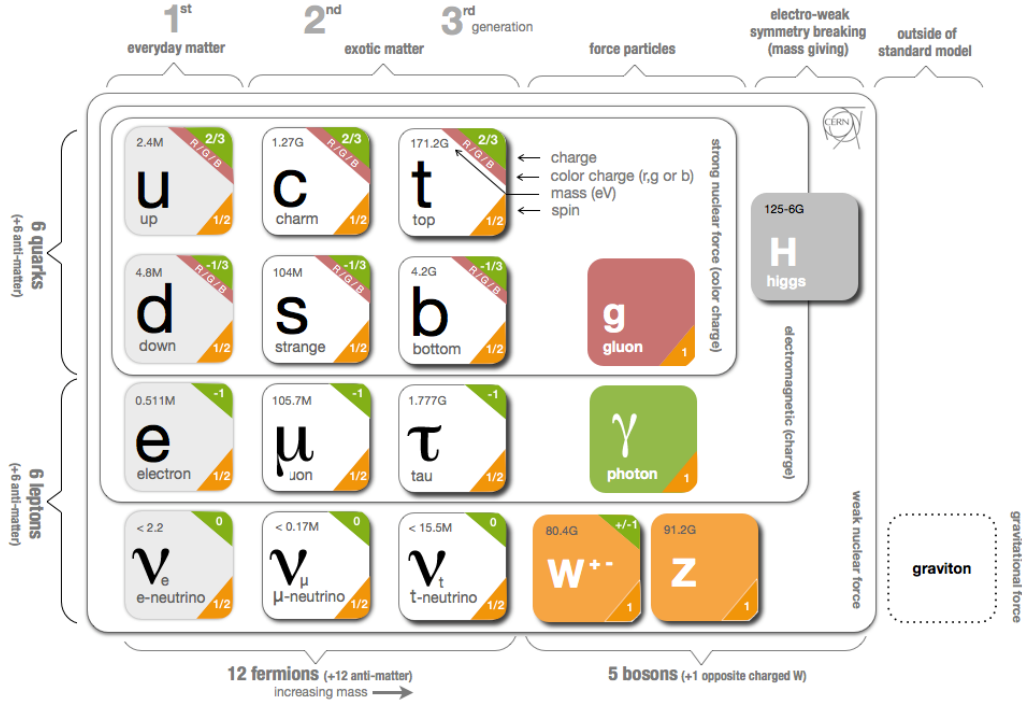


Figure 2.1: Infographic presenting the particles of the Standard Model [1].

in the electroweak theory providing a mechanism through which particles acquire their mass.

The fermions can be divided into two types – quarks carrying a fractional electric charge $\pm 1/3$ or $\pm 2/3$ and a colour charge, and colourless charge-1 or neutral leptons. Quarks are the only fermions able to interact with all three types of fundamental forces. Charged leptons interact electromagnetically and weakly, whereas the neutral leptons – neutrinos – interact exclusively with the weak force. Quarks and leptons can be further divided into three generations differing only in mass and sharing all other properties.

The foundations of the Standard Model were developed in the 1960s and 1970s in an attempt to organise and unify models describing the abundance of new particles and processes discovered in the preceding years, and the symmetries observed between them. Particularly significant contribu-

tions to the electroweak theory formulation came from Brout, Englert and Higgs [2, 3] as well as Glashow, Salam and Weinberg [4–6]. The first three provided a mathematical model giving mass to the weak force mediators and predicted the existence of a new scalar boson associated with a new field they introduced. The latter three provided a unified description of the electromagnetic and weak interactions incorporating the Brout-Englert-Higgs mechanism. The theory of strong interactions was being developed at the same time using similar mathematical concepts by numerous physicists including Gell-Mann and Zweig [7, 8] who first proposed the concept of quarks as fundamental building blocks of strongly-interacting matter. Several years later, Gross, Politzer and Wilczek [9, 10] developed a breakthrough concept of asymptotic freedom (a decreasing interaction strength at very small distances) defining the nature of the strong interaction where quarks form colourless bound states (hadrons) very quickly and bare quarks cannot be directly observed in nature.

The formulation of the Standard Model proceeded in parallel to experimental programmes carried out across Europe and the USA. The theoretical advancements and precise predictions motivated the design of some experiments, e.g. the Super Proton-Antiproton Synchrotron with a specific goal of observing a resonance production of the W and Z bosons and confirming their predicted masses [11] (achieved in 1983). Other experiments performing general searches for new states successively confirmed concepts postulated by the theorists like the existence of charm quarks and later the existence of the third generations of quarks and leptons. By mid-1980s the SM was a well-developed theory successfully passing numerous experimental tests with most of the predicted particles already discovered. The only remaining ones were the top quark, the tau neutrino and the Higgs boson, all discovered much later in 1995, 2000 and 2012 respectively.

Despite all fundamental particles of the SM being discovered and the decades of thorough experimental tests showing no major deviations from its predictions¹, it is clear the Standard Model does not provide a full description of the constituents and forces of nature. In addition to neglecting gravity, it also does not provide any particles explaining the dark matter seen in cosmological observations and it cannot fully explain the matter-antimatter asymmetry in the universe. Furthermore, the Standard Model includes a large number of free parameters (over 20), which have to be provided by measurements, it lacks unification between electroweak and strong forces, and provides no explanation for charge quantisation or the number of fermion generations.

2.2 Collider experiments

As in the 1970s, today's particle physics experiments focus on precision measurements of the SM parameters and on searches for new particles guided by theoretical models aiming to answer the open questions. This can be achieved either by studying particles coming from space (neutrinos, photons or atmospheric showers) which opens access to very high energies, however at small rates, or by creating new particles in terrestrial laboratories. The latter approach allows to control the energy and rate of the produced particles, as well as to design experiments aiming to produce and detect particular states. However it is constrained by the available technology and resources. Controlled production of particles is typically achieved by accelerating a beam of charged particles (either electrons, positrons, protons, antiprotons or ions) and colliding them with either a fixed target or

¹The non-zero masses and mixing of neutrinos, although not initially predicted by the SM, can be easily incorporated using similar mechanisms to those describing electroweak interactions of quarks.

another beam of particles. The beam-target collisions offer a high rate of interactions and a simpler accelerator design, whereas the beam-beam collisions offer higher centre-of-mass energy, particularly important in searches for new heavy states. Particle detectors with automated electronic readout are built around the collision points to detect the newly produced particles or their decay products. These usually consist of tracking detectors recording trajectories of charged particles within a magnetic field and calorimeters used to absorb particles and measure their energy. A specific type of particle physics experiments focusing on measurements of neutrino properties will not be discussed in this thesis.

Beam-beam colliders most commonly operate with electron-positron (e^+e^-), proton-proton (pp) or proton-antiproton ($p\bar{p}$) beams. Hadron beams can be accelerated to much higher energies in circular accelerators thanks to lower energy loss from synchrotron radiation (which has a $\frac{1}{m^4}$ dependence on the particle mass). Hence, they are better suited as discovery machines allowing to reach higher masses of particles produced in the collisions. The main disadvantage of hadron colliders is the compositeness of the collided objects. At high energy, the interactions occur between constituents of the proton or antiproton (called partons) which carry an unknown fraction of the total hadron momentum. As a result, the total longitudinal momentum of the colliding system is different from zero and cannot be determined. In addition, colliding strongly interacting particles produces vast amounts of already-known hadrons creating a challenging background in searches for new particles. Electron-positron colliders, on the other hand, provide much cleaner final states and a well-defined initial state, making it easier to robustly select and reconstruct the interesting events. Therefore, they are typically used for precision measurements requiring a large number of events and low backgrounds. Two notable exceptions from the common types of

colliders are HERA and RHIC. HERA was an electron-proton (ep) collider operating in 1992–2007 which contributed greatly to our understanding of the proton structure. RHIC, operating since 2000, collides various types of heavy ion beams (e.g. gold or copper) and is focused on studying the properties of hot and dense strongly interacting matter created in these collisions. RHIC and the LHC (Large Hadron Collider, colliding protons or heavy ions and described in details in Chapter 3) are the only currently operating accelerators colliding hadron beams in the world.

2.2.1 Physics of proton-proton collisions

A high-energy proton-proton collision is a complex event including multiple particle interactions and decays, producing a large number of final-state particles (stable products of the interaction). Since protons are composite particles, high-energy interactions occur between their components – quarks and gluons, collectively called partons – rather than whole protons. The structure of a proton is described by parton distribution functions (PDFs) describing the probability for a given type of parton to carry a given fraction, x , of the full momentum of a proton. PDFs are universal, do not depend on a type of collision (pp , $p\bar{p}$, ep) and can be factorised from other elements of cross-section calculations for a given process, e.g. $p\bar{p} \rightarrow t\bar{t}$. High momentum transfer interactions between two incoming partons are referred to as the hard scattering and are usually the point of interest in the experiment (e.g. the production of a Z boson in a quark-antiquark annihilation). Due to the nature of strong interactions, the hard process is always accompanied by an emission of soft (low-momentum) gluons from high-energy coloured particles either in the initial or final states. The emissions are referred to as the initial-state radiation (ISR) and final-state radiation (FSR). It is also possible for more than one pair of partons to interact and produce particles observed in detectors, which is called the multi-parton interaction (MPI).

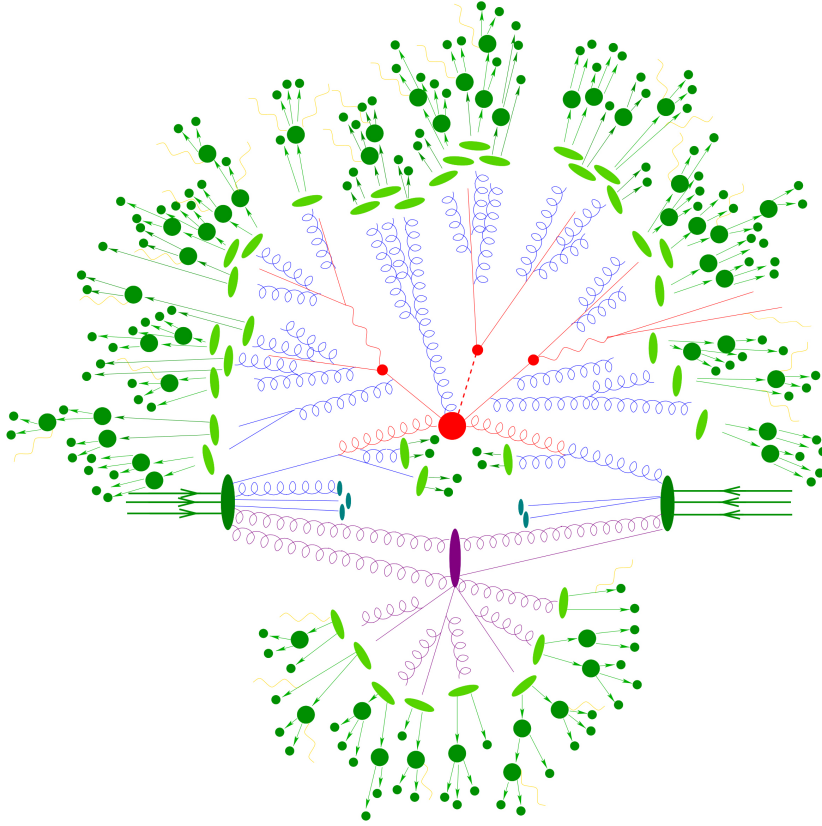


Figure 2.2: A sketch of a proton-proton collision resulting in the production of a Higgs boson in association with a top-antitop quark pair, with subsequent $H \rightarrow b\bar{b}$ and $t\bar{t} \rightarrow b\ell\nu\bar{b}q\bar{q}$ decays [12]. The hard process is depicted in red. Purple lines represent MPI, whereas blue lines represent ISR, FSR and parton showering. Hadronisation is shown in green and photon emissions in yellow.

An example course of processes in a pp collision including all the described types of processes is outlined in Figure 2.2.

Cross-section calculations and event simulations for hadron collisions are possible thanks to the fact that soft and hard interactions can be factorised and evaluated independently [13–15]. QCD calculations for hard processes exploit perturbative methods with functions expanded around the strong coupling ‘constant’, α_s , which is small at high energies thanks to the asymptotic freedom of QCD. This is, however, not the case for soft interactions

and other estimation methods have to be explored, requiring many inputs from experimental measurements.

Final-state quarks and gluons emit further soft gluons, which then create quark-antiquark pairs forming longer-lived hadrons (a process called hadronisation) resulting in collimated showers of particles observed in detectors. An example event display from the ATLAS experiment showing two such showers is presented in Figure 2.3. As the soft gluon emissions cannot be described perturbatively, theoretical cross-section calculations and experimental measurements make use of collective objects describing the final state, called *jets*, which include all particles originating from a quark or a gluon within a certain angular area. Jets can be reconstructed in experimental data with a number of algorithms from two general classes – cone algorithms looking for the highest-energy constituents and assigning close-by particles to them, and sequential recombination algorithms merging objects that are the closest to each other with different definitions of the distance. Both can be characterised by a maximum angular distance parameter R , beyond which objects cannot be merged. The key property of a jet reconstruction algorithm should be that its results are invariant with respect to collinear splitting of partons and to emissions of infinitely soft particles. These two properties are referred to as the collinear and infrared safety and allow meaningful perturbative cross-section calculations for hadronic final states which can be related to experimental results. The *anti- k_t* algorithm [16] ensures these properties and thus, is the most widely used algorithm nowadays. It is a sequential recombination algorithm where the distance between two objects i and j (particles or energy deposits) is defined as:

$$d_{ij} = \min \left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2} \right) \frac{\Delta_{ij}^2}{R^2},$$

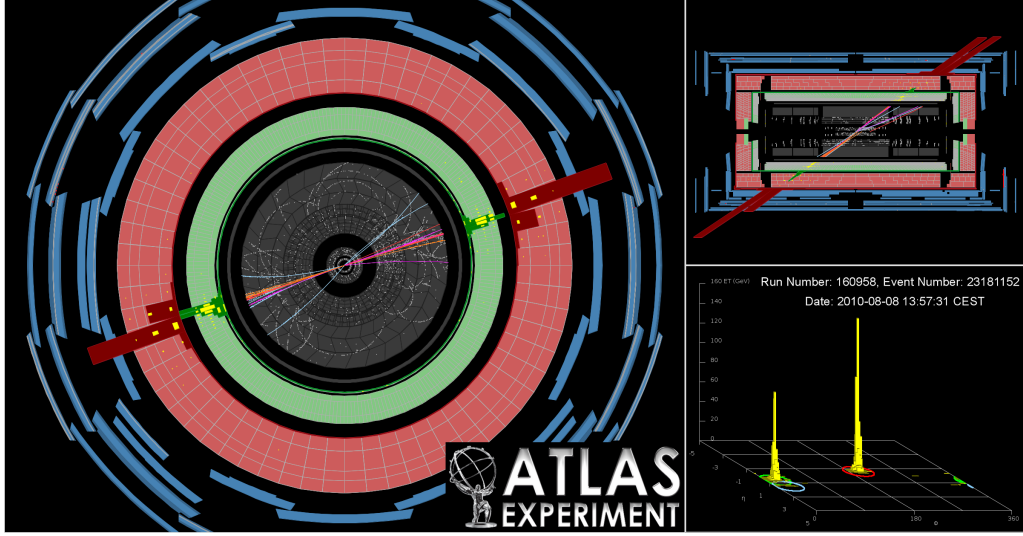


Figure 2.3: Display of an event with two jets recorded by the ATLAS experiment in 2010 [17]. Multiple close-by charged particle tracks can be observed in the inner tracking detectors, pointing to two very large and localised energy deposits in calorimeters.

where k_t is the transverse momentum of the object and Δ_{ij} is the angular distance between objects.

Although the particle content of jets is usually not considered in experimental data analysis, identification of their origin is often profitable for identification of the hard process and background suppression. Discrimination between jets originating from a b quark and from lighter quarks or gluons (b -tagging) is the most commonly used and easiest jet identification technique. It is possible thanks to the relatively high mass and long lifetime of b -hadrons², causing them to decay into many particles after travelling a measurable distance (a few hundred micrometres) from the primary vertex (hard interaction point). Variables related e.g. to the distance of

²The term *b-hadron* is used throughout the thesis to refer to any hadron containing a b quark. Similarly, the term *c-hadron* is used to describe any hadron containing a c quark.

the tracks reconstructed within a jet from the primary vertex, track multiplicity of a secondary vertex or the number of two-track vertices within a jet can be combined in a multivariate discriminant robustly differentiating between b -jets and light jets. Algorithms identifying c -jets or discriminating between gluon- and quark-initiated jets are also being explored [18–20], however their use is not as common as b -tagging algorithms.

An additional event-level object specific to experiments at hadron colliders covering a large solid angle is the missing transverse energy³, $E_{\text{T}}^{\text{miss}}$ or MET. It is defined as the negative vectorial sum of the transverse (to the beam direction) momenta of all observed particles and jets as well as tracks and/or calorimeter energy deposits unassociated to any reconstructed physics object. In light of the inaccessibility of information about the total momentum of the colliding system, $E_{\text{T}}^{\text{miss}}$ provides a good probe of particles escaping the detector without interaction. In SM measurements it is typically associated with high-momentum neutrinos from the hard process, whereas in beyond-SM physics searches it can serve as a probe of a hypothetical new non-interacting particle.

Using the above definitions, the proton-proton collision depicted in Figure 2.2 can be described as containing one lepton, missing transverse energy (from the neutrino), four b -jets and two other jets produced in the hard process. Additional objects, typically lower-momentum jets, may be present due to the QCD radiation and MPI.

2.2.2 Monte Carlo simulation

The abundance of non-perturbative processes at particle colliders makes it difficult to develop analysis techniques and to compare measurements

³The term *missing transverse momentum* is also used interchangeably since the definition assumes negligible mass of the undetected particles.

to predictions. To overcome these difficulties and facilitate the research methods, large samples of collision events can be simulated using so-called Monte Carlo (MC) computer programs producing the possible outcomes by randomly sampling the underlying (assumed or measured) probability density functions. MC simulations are widely used not only to assist the physics measurements, but also to produce predictions defining the design of new experiments, as well as to help in calibration and understanding of the existing detectors.

Thanks to the factorisation of hard and soft processes, the simulation may be performed in two distinct steps. The processes of interest are usually hard interactions with two initial-state and a few final-state particles, where perturbative calculation methods are applicable, and the production cross sections can be calculated to a greater precision than for soft interactions. Simulation of the hard process, incorporating the PDFs in case of hadron collisions, is usually the first step of an MC simulation. The particles produced in the hard process are further interfaced to programs simulating soft interactions in the non-perturbative regime, including parton showering (ISR and FSR) and hadronisation. The parton shower (PS) simulation is based on a probabilistic emission of partons with a decreasing momentum transfer in subsequent emissions. The hadronisation simulation is typically based either on the Lund string model [21], for example in the PYTHIA generator [22], or on the cluster model [23], for example in HERWIG [24]. In all currently used generators, the dependence of the predicted cross sections on the factorisation scale, below which particles are simulated with non-perturbative models, is based on leading-order perturbative calculations.

The outcomes of the hard process simulation, which include coloured partons subject to further fragmentation and hadronisation, are often referred

to as the *parton level* predictions. Including the PS and hadronisation, and considering only long-lived particles which can be directly observed in a detector defines the *particle level* simulation. In order to directly compare simulated distributions to the observations, they have to be further processed by programs simulating the response of a specific detector configuration. This includes electromagnetic interactions of charged particles with detector material, as well as the evolution of hadronic showers within calorimeters. The outputs of the full simulation, directly comparable to data, are often called the *detector level* distributions. Each step of the simulation convolutes the underlying predictions introducing additional uncertainty due to the assumptions and choice of parameters within the programs, which have to be taken into account when using the simulation in a measurement. The MC simulation is often used to correct the observed distributions for detector effects by *unfolding* them to particle level. This procedure makes the observations directly comparable to results from different experiments and to other simulations without the need of simulating the detector response again (which often requires large computing resources). Measurements can be also unfolded to parton level, which has the advantage of being comparable directly to perturbative calculations which are often available at higher accuracy than full MC simulations. However, correcting for radiation and hadronisation effects using simulation makes the result dependent on the used models of the non-perturbative effects and the underlying tunable parameters, which are associated with large uncertainties.

2.3 Top quark physics

The mass of the top quark, around 173 GeV [25], makes it the heaviest fundamental particle of the Standard Model and defines its unique properties and role. Its extremely short lifetime of around 5×10^{-25} s is one

order of magnitude shorter than typical hadronisation time and two order of magnitude shorter than effects leading to spin decorrelation in bound states. This means it decays before forming a hadron and its spin can be directly probed through its decay products. The top quark decays almost exclusively into a W boson and a b quark, as given by the V_{tb} element of the CKM matrix describing the strength of flavour-changing weak decays. The average of Tevatron and LHC measurements gives the $|V_{tb}|$ value of 1.009 ± 0.031 with the uncertainty dominated by jet flavour tagging and jet energy scale/resolution uncertainties [25]. The most precise value can be obtained from a global fit for all CKM matrix elements using all available measurements and imposing an SM constraint of the matrix unitarity for three quark generations. The fit gives $|V_{tb}| = 0.99915 \pm 0.00005$ [25], proving that $t \rightarrow Ws$ and $t \rightarrow Wd$ decays are highly suppressed. Flavour-changing neutral currents are not allowed in the Standard Model, making top decays into charm or up quarks impossible and leaving $t \rightarrow Wb$ the almost exclusive decay mode.

The decay modes of the W boson define the final-state composition of the top quark decay. In case of $t\bar{t}$ pair production, which is dominant over single top production in high-energy hadron collisions, the final state can be identified as either dileptonic, where both W bosons decay into a charged lepton and a neutrino, monoleptonic (usually denoted ℓ +jets), where one W boson decays leptonically and the other into $q\bar{q}'$, or all-hadronic where both W bosons decay into quarks. The respective branching fractions are presented in Figure 2.4.

The large mass of the top quark also implies the largest coupling to the Higgs boson, making top-quark loops the dominant contributions to Higgs boson production via gluon-gluon fusion and to Higgs boson decay into two

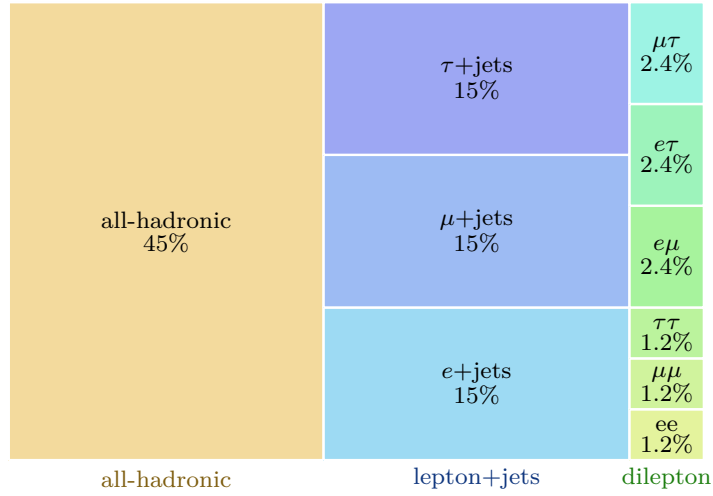


Figure 2.4: Mosaic plot presenting branching fractions for all $t\bar{t}$ decay final states defined by the subsequent W decays. The area of each rectangle corresponds to the respective branching fraction. The two jets coming from b quarks in the dilepton channel are usually omitted in the labelling.

photons. The Higgs – top quark coupling, which is a yet-unmeasured free parameter of the Standard Model, can be directly measured through the cross section for associated production of a Higgs boson with a $t\bar{t}$ pair. In addition to precision measurements and tests of the Standard Model achievable with top quarks, their production and properties are also sensitive to beyond-SM physics and can be distorted by the existence of new particles.

In hadron collisions, top quarks are produced predominantly in $t\bar{t}$ pairs via a high-energetic gluon produced either in quark-antiquark annihilation or in a gluon-gluon fusion (dominant at the LHC energy). The s -, t - and u -channel gluon-gluon fusion production processes are indistinguishable experimentally. Tree-level (i.e. corresponding to the leading order in perturbative calculations) Feynman diagrams⁴ for these processes are presented

⁴All Feynman diagrams presented in this thesis were created using the TikZ-Feynman L^AT_EX package [26].

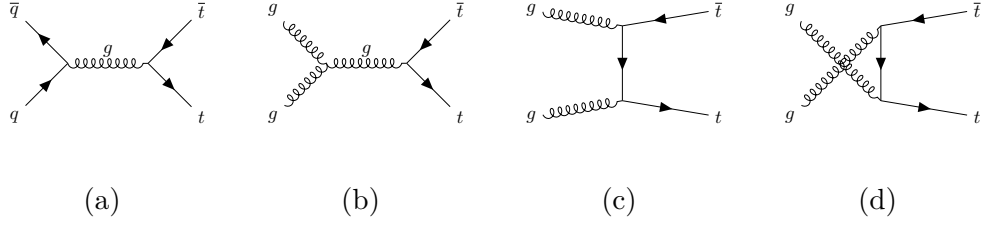


Figure 2.5: Tree-level Feynman diagrams for the dominant $t\bar{t}$ production processes in hadron collisions: (a) quark-antiquark annihilation, (b) s -channel gluon-gluon fusion, (c) t -channel gluon-gluon fusion, (d) u -channel gluon-gluon fusion.

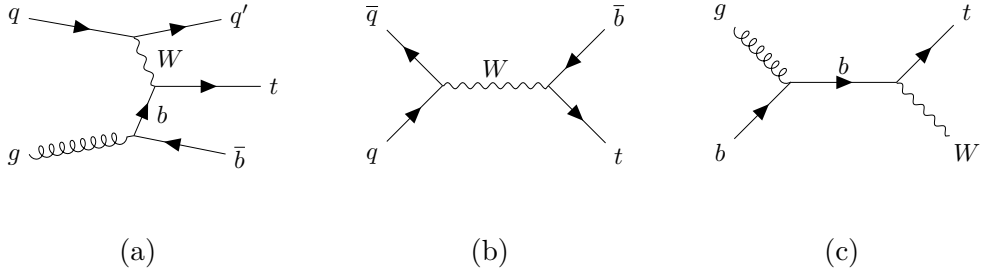


Figure 2.6: Tree-level Feynman diagrams for the dominant single top production processes in hadron collisions: (a) t -channel production, (b) s -channel production, (c) associated production with a W boson.

in Figure 2.5. Single top production in hadron collisions is characterised by a few times lower cross section and is possible through either t -channel, s -channel or a tW associated production as shown in Figure 2.6.

As the heaviest fundamental particle, the top quark remained undiscovered for a relatively long time even though broadly anticipated following the discovery of the lighter third generation quark, the b , in 1977 [27]. Despite the continuous development of the Tevatron $p\bar{p}$ collider pushing the centre-of-mass collision energy ($\sqrt{s}$) beyond 1 TeV throughout the 1980s, it was not until the mid-1990s when enough data were collected to reach the discovery. Shortly after the D0 Collaboration set the lower limit for the top mass at

131 GeV in 1994 [28], the CDF Collaboration announced the first evidence for the existence of a top quark at the mass of around 174 GeV (a 2.8σ deviation from a background-only hypothesis) [29]. Only a few months later, in March 1995, both collaborations announced the direct observation of a top quark with the significance of 4.8σ (CDF) and 4.6σ (D0) and the measured mass of 176 ± 13 GeV and 199^{+29}_{-30} GeV respectively [30, 31].

As in the case of other fundamental particle discoveries, the observation of the top quark opened a new field of particle physics focused on precise measurements of its properties and production cross sections. This new area of research soon started to provide new stringent tests of the Standard Model with Tevatron Run II data and later also with the LHC. Particular focus in this thesis is put on the $t\bar{t}$ pair production cross sections, introduced in the next section. A selection of top quark properties measured over the course of the past 23 years is presented in Table 2.1. No significant deviations from the SM predictions have been found so far. Although some tensions have been reported in the past, they are all believed to come from problems in precise prediction calculations rather than from new physics effects and tend to decrease as the predictions are improved over time. These include, for example, the forward-backward asymmetry in $t\bar{t}$ production in $p\bar{p}$ collisions [32] and the differential $t\bar{t}$ production cross section as a function of top quark transverse momentum [33].

2.3.1 Top quark pair production cross sections

Measurements of $t\bar{t}$ production cross sections offer advancements at multiple frontiers of fundamental particle physics. With the LHC delivering as many as 12 $t\bar{t}$ pairs per second⁵, large datasets allowing increasingly precise measurements quickly become available. The results can be compared

⁵Typical running conditions in late 2017 at $\mathcal{L} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (see Section 3.1.3)

Property	Value	Reference
Mass	$m_t = 173.1 \pm 0.6 \text{ GeV}$	World average [25]
Decay width	$\Gamma_t = 1.41^{+0.19}_{-0.15} \text{ GeV}$	World average [25]
Electric charge	$q_t = 0.64 \pm 0.08 \text{ e}$	ATLAS [34]
$t\bar{t}$ mass difference	$m_t - m_{\bar{t}} = -0.2 \pm 0.5 \text{ GeV}$	World average [25]
$t\bar{t}$ forward-backward asymmetry ($p\bar{p}$)	$A_{\text{FB}} = (11.8 \pm 2.8)\%$	D0 [35]
$t\bar{t}$ charge asymmetry (pp , 8 TeV)	$A_{\text{C}}^{\text{LHC8}} = 0.0055 \pm 0.0034$	ATLAS and CMS [36]
$t\bar{t}$ spin correlation	$f_{\text{SM}} = 1.20 \pm 0.14$	ATLAS [37]

Table 2.1: Selection of top quark properties with the most precise measured values to date or a combination of results where available.

to state-of-the-art perturbative QCD predictions providing a stringent verification of the SM and the challenging calculations. Development of the predictions, particularly for differential cross sections as a function of top quark or $t\bar{t}$ system kinematic properties, requires a significant effort to produce results describing the measured distributions. It has become clear in recent years that next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) corrections in perturbative calculations are relatively large and crucial to reach agreement between data and predictions. The most pronounced discrepancy has been found in the top (or antitop) quark transverse momentum (p_{T}) distribution. As seen in Figure 2.7a, the inclusion of NLO and NNLO corrections brings the predicted shape closer to the experimental data, however does not yet fully explain the difference. It has been also demonstrated recently [38] that the addition of electroweak (EW) corrections on top of the NNLO predictions (Figure 2.7b) may improve the agreement even further.

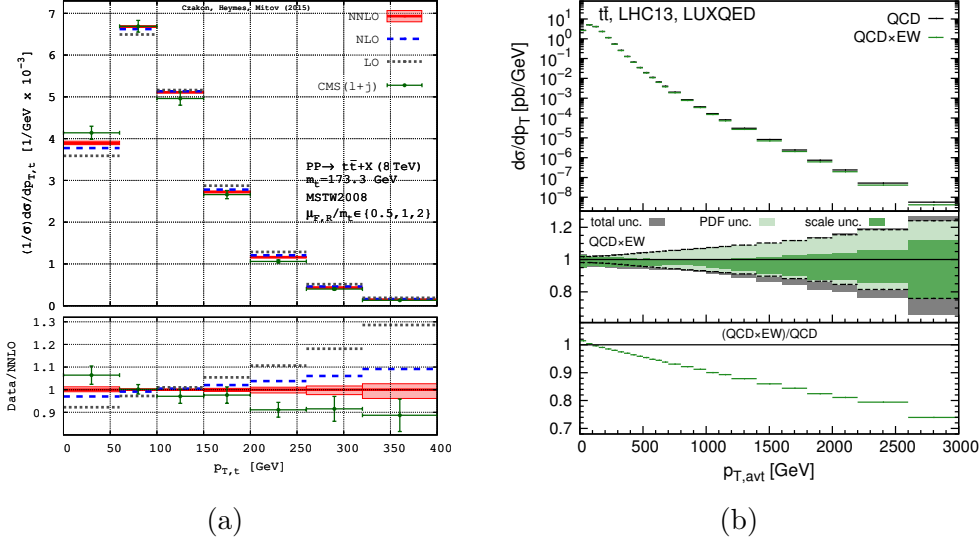


Figure 2.7: Normalised differential cross section for $t\bar{t}$ production in pp collisions as a function of top quark p_T (averaged between top and antitop). (a) CMS measurements at $\sqrt{s} = 8$ TeV compared to LO, NLO and NNLO predictions [33]. (b) Comparison of the 13 TeV NNLO predictions with and without electroweak corrections included [38].

Even though NNLO+EW corrections are available for the commonly measured distributions, it is not straightforward to incorporate them in MC event generators and allow particle level comparison in an arbitrary kinematic selection. This is because the PS and hadronisation simulation relies on leading order calculations and interfacing it to higher order hard process predictions requires careful treatment of possibly double-counted effects. One example would be an FSR emission of a relatively high momentum gluon off a top quark, which comes as an NLO correction but is also generated by the parton shower program. Two matching methods – MC@NLO and POWHEG – were developed [39, 40] and applied to top quark production [41, 42] in the 2000s. They were later automated in popular MC generators and are widely used nowadays. However, no method currently exists to match NNLO predictions to parton shower generators, thus parti-

cle production in exclusive selections cannot yet be simulated with NNLO precision.

Another limitation of MC simulations comes from the number of free parameters of the implemented models which attempt to approximate higher order effects or describe non-perturbative processes phenomenologically. The parameters have to be optimised using measured distributions sensitive to their modification. The process of parameter optimisation is commonly known as MC *tuning* and a chosen set of parameters is often referred to as a *tune*. Differential $t\bar{t}$ cross-section measurements are crucial in improving MC modelling of processes involving top quarks and verification of their implementation in the relevant programs. Such modelling studies are, for example, regularly carried out by the ATLAS and CMS collaborations [43–45].

Further motivation for top quark pair production measurements is the potential sensitivity of some distributions to new physics effects. The most straightforward would be an observation of a peak or a peak-dip structure in the $t\bar{t}$ invariant mass spectrum which could come from a resonant production of a new particle [46]. Transverse momentum and angular distributions may be also modified, even in case of no peak observation [47]. Moreover, top quark pair production constitutes the main background in various searches for new physics, for example supersymmetry (top squarks) [48] or heavy vector-like quarks [49]. Therefore, improvements in $t\bar{t}$ modelling may have a direct impact on the sensitivity of these searches. Since $t\bar{t}$ production at the LHC occurs primarily via gluon-gluon fusion, the cross-section measurements are also sensitive to the distribution of gluons within protons and can help constrain the gluon PDF [50].

2.3.2 $t\bar{t}$ +jets production

Production of $t\bar{t}$ pairs in association with additional high-momentum jets, particularly b -jets, is a process of significant interest in recent years. The main motivation for seeking improvements in its understanding comes from the fact that $t\bar{t}b\bar{b}$ production (Figure 2.8) is the main source of irreducible background in searches for the $t\bar{t}H$ process, where the Higgs boson decays to a $b\bar{b}$ pair (its highest branching fraction decay mode) [51, 52]. With significant uncertainties and modelling differences observed in the predictions [53], and insufficient experimental data to constrain the models, inputs from both the theory and experimental communities are highly anticipated.

The calculation of NLO corrections for $t\bar{t}b\bar{b}$ production was completed shortly before the LHC started delivering physics data in 2010 [54–56] and showed significant reduction in the theoretical uncertainty and a factor of 1.8 increase in central value with respect to the LO prediction. Developments on matching the predictions to PS generators were first presented a few years later, already after the end of LHC Run 1⁶ with two different approaches. One used the POWHEG matching method and assumed the b quark mass to be negligible (so-called five flavour scheme, 5FS) [57, 58], whereas the other utilised the MC@NLO method and included finite b quark mass effects (four flavour scheme, 4FS) [59]. In the latter, it was also shown that events with two gluon emissions producing collinear $b\bar{b}$ pairs which are unresolved by the jet clustering algorithm, thus producing two final state b -jets (Figure 2.9), may produce a sizeable enhancement in high- m_{bb} regions. This is presented in Figure 2.10, where the MC@NLO prediction includes the double-splitting effects and the MC@NLO_{2b} prediction excludes them. The $t\bar{t}b\bar{b}$ cross section in the Higgs boson mass region, around $m_{bb} = 125$ GeV, is approx-

⁶LHC Run 1 was an operation period in 2010-2012 as described in Section 3.1.1

imately 20 % different between the two predictions. Further comprehensive modelling studies performed by the LHC Higgs Cross Section Working Group [53] showed that 5FS and 4FS models may provide similar cross section predictions across the investigated kinematic distributions. However, large differences were observed between different matching approaches and hard process generators in some phase-space regions. It can be observed in Figure 2.11, where the 5FS POWHEL+PYTHIA8 simulation provides results consistent with the 4FS SHERPA+OPENLOOPS, however significantly different from another 5FS simulation using MG5_aMC@NLO. Additional very recent studies using 4FS NLO predictions matched to PS with the POWHEG method [60] have emphasised the importance of the $g \rightarrow b\bar{b}$ splitting of final state gluons in both, the collinear and the resolved case. It was also confirmed that the size of the NLO corrections over the LO prediction reaches a factor of ~ 2 and the theory uncertainty of the NLO prediction is around 25–30 %, dominated by the renormalisation scale variations. Further studies of the various predictions, matching techniques and their parameters along with a comparison to experimental data are required to improve the understanding of $t\bar{t}b\bar{b}$ production and help to reduce the uncertainties associated with the predictions.

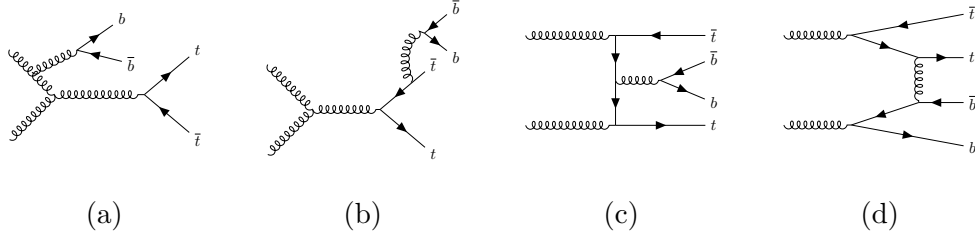


Figure 2.8: Four examples out of over forty LO $t\bar{t}b\bar{b}$ production Feynman diagrams. (a) ISR gluon emission, (b) FSR gluon emission, (c) t -channel production, (d) t -channel production through double gluon splitting. Diagrams (b) and (c) with the gluon replaced by a Higgs boson correspond to the dominant $t\bar{t}H(b\bar{b})$ production processes.

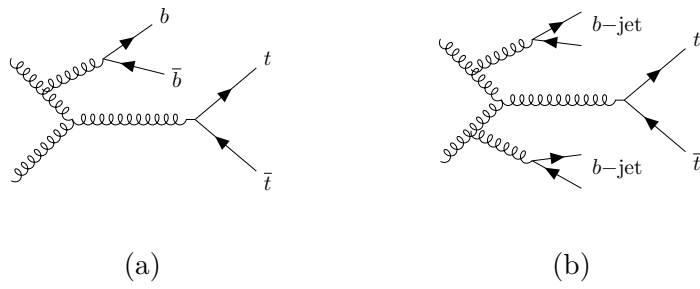


Figure 2.9: Tree topologies corresponding to $t\bar{t}b\bar{b}$ production via (a) single hard or (b) double collinear $g \rightarrow b\bar{b}$ splitting.

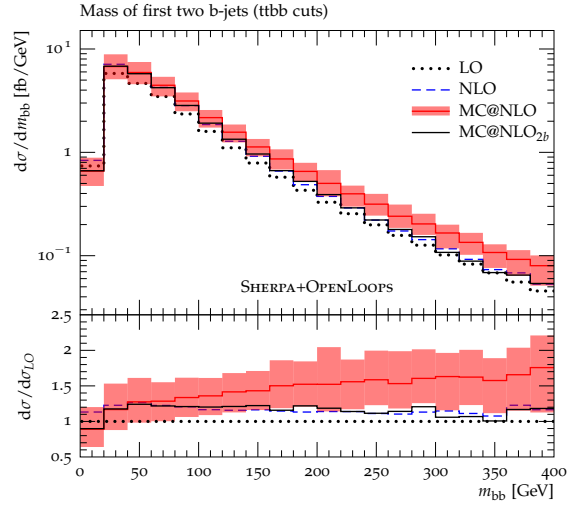


Figure 2.10: Invariant mass of the additional $b\bar{b}$ pair at LO, NLO and NLO matched to PS with the MC@NLO approach. The MC@NLO_{2b} curve was obtained by disabling the $g \rightarrow b\bar{b}$ splittings in the parton shower [59].

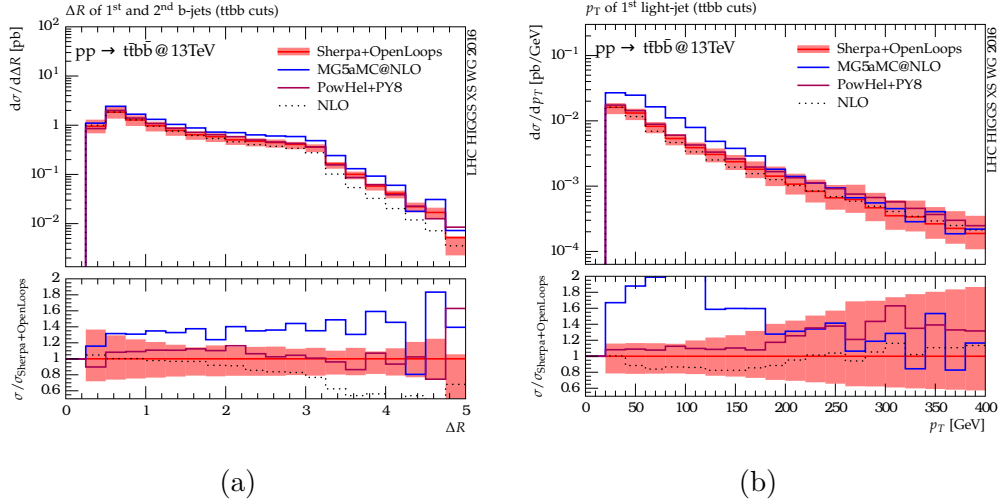


Figure 2.11: Angular separation of the $b\bar{b}$ pair and the p_T of the hardest light jet in the $t\bar{t}b\bar{b}$ selection. NLO prediction is presented along three NLO+PS curves. SHERPA+OPENLOOPS is a 4FS prediction matched to the SHERPA parton shower, MG5_aMC@NLO is a 5FS prediction matched to the PYTHIA8 PS, both using the MC@NLO method, whereas POWHEL+PYTHIA8 is a 5FS prediction matched to PYTHIA8 using the POWHEG method. While most $t\bar{t}b\bar{b}$ kinematic distributions, including ΔR_{bb} , are described consistently by the three simulations, some, like $p_T^{j_1}$ show significant discrepancies, particularly between MG5_aMC@NLO and the other two curves [53].

Chapter 3

ATLAS Experiment at the Large Hadron Collider

3.1 Large Hadron Collider

The Large Hadron Collider (LHC) [61] is a 27 km-circumference circular particle accelerator and collider installed at the European Organization for Nuclear Research (CERN) on the border of Switzerland and France in the vicinity of Geneva. It is capable of accelerating two beams of either protons or heavy nuclei in opposite directions to the highest energy ever reached in a laboratory and enables their head-on collisions in four beam-crossing points. Although the tunnel design allows eight Interaction Region (IR), four have been dedicated to beam stability instrumentation. Four large and three small experiments operate at the four IRs providing collisions: ATLAS and LHCf at IR1, ALICE at IR2, CMS and TOTEM at IR5, LHCb and MoEDAL at IR8.

ATLAS and CMS are large multi-layered general-purpose particle detectors of a 4π -type, i.e. covering as much solid angle around the particle collision point as possible. Their design goals include searching for new physics phenomena, precise measurements of Standard Model properties and the already-achieved discovery of the Higgs Boson. LHCb is a one-arm

spectrometer-type detector (covering a small solid angle) focusing on the physics of b and c quarks, which are produced predominantly in the forward direction and decay at displaced vertices. The latter fact was a motivation for constructing its state-of-the-art Vertex Locator sub-detector providing excellent identification of primary and secondary vertices. ALICE is another 4π -type detector, designed primarily for studies of heavy ion collisions and providing notable particle identification and tracking at high multiplicities and low momenta achieved by its exceptionally large Time Projection Chamber. The three smaller LHC experiments are located at a further distance from the interaction points. LHCf focuses on neutral particle production in the very forward region, TOTEM measures the total pp interaction cross section, whereas MoEDAL searches for magnetic monopoles and highly ionising stable massive particles.

Besides two beam pipes maintained with ultra-high vacuum, the LHC consists mainly of dipole magnets bending the beams, higher multipole magnets for focusing, and radio frequency cavities for acceleration. The magnets are designed in a widely-used NbTi superconducting technology. However, unlike in other accelerators, they are cooled to a temperature below 2 K using superfluid helium, which allows them to operate at fields above 8 T. The extreme bending power of the magnets allows to accelerate protons to the maximum design energy of 7 TeV resulting in collisions at the centre-of-mass energy of $\sqrt{s} = 14$ TeV. Particles circulating within the LHC beams are grouped in bunches of typically $\sim 10^{11}$ protons, which are further organised in bunch trains. Trains consist of up to 144 bunches separated in time by 25 ns. A typical train separation is 200–1000 ns. Nominally, the LHC can be filled with up to 2808 bunches in each ring at the same time, but the highest number used in physics runs so far was 2556 due to safety and stability requirements.

The machine operates in *fills* – a fill begins when the desired number of bunches is injected into the rings. The beams are then accelerated and focused at the four IRs and begin to collide. After ensuring the colliding beam conditions are safe and stable, *stable beams* are declared to the experiments, which allows them to start collecting physics data. The period when data are recorded, typically corresponding to one LHC fill, is referred to as a *run* within the experiments. As the beams collide throughout a fill, the collision rate decreases exponentially due to both the particles being lost in head-on collisions and beam losses outside of IRs. The latter are caused mainly by particle interactions within a bunch and interactions with residual gas particles in the beam pipes. The inverse of the exponent coefficient is termed the *average luminosity lifetime* and its typical value in LHC proton-proton fills is in the range 10–20 h. In absence of any operational problems or scheduled maintenance, a fill is usually finished after approximately one average luminosity lifetime. At this point, the collision rate decreases enough so that spending 2–3 h on preparing a new fill and restarting collisions at high rate results in a larger total number of delivered collisions than continuing the current fill at a low rate. In practice, the average duration of stable beams does not exceed 10 h, however there are periods of regular 24 h fill operation.

Luminosity is one of the key parameters of a particle collider, defined as:

$$\mathcal{L} = \frac{1}{\sigma} \frac{dN}{dt},$$

where σ is the interaction cross section and dN/dt is the rate of events. In case of a *pp* collider, both numbers refer to inelastic *pp* collisions. For a bunched beam with the number of colliding bunches n_b (typically 2000–2500 in ATLAS and CMS during 2016–2017 LHC *pp* runs), the revolution frequency f_r (11 245.5 Hz at the LHC), the average number of particles in

two colliding bunches n_1 and n_2 ($\sim 10^{11}$ each), and the transverse particle density distributions $\hat{\rho}_1(x, y)$ and $\hat{\rho}_2(x, y)$, the absolute luminosity can be expressed as

$$\mathcal{L} = n_b f_r n_1 n_2 \int \hat{\rho}_1(x, y) \hat{\rho}_2(x, y) dx dy$$

assuming the beams collide at a zero crossing angle [62]. Due to the small bunch spacing in the LHC, the beams have to be crossed at an angle of around $300 \mu\text{rad}$ to avoid unwanted interactions outside the nominal collision point. For small angles, the luminosity reduction from the smaller bunch overlap can be approximately calculated as

$$S = \frac{1}{\sqrt{1 + \left(\frac{\sigma_s \phi}{\sigma_x}\right)^2}},$$

where σ_s is the bunch length, σ_x is the transverse size of a bunch and ϕ is the crossing angle. With $\sigma_s = 7.7 \text{ cm}$, $\sigma_x = 17 \mu\text{m}$ and $\phi = 300 \mu\text{rad}$ at the LHC, this evaluates to $S = 0.83$ [63].

Whilst the instantaneous luminosity is a vital parameter for collider and detector operation, its value integrated over time, $\mathcal{L}^{\text{int}} = \int \mathcal{L} dt$, is the quantity which is crucial for physics measurements and searches. It is directly proportional to the number of events with a certain process produced over a given period of time, $N = \sigma \mathcal{L}^{\text{int}}$, where σ is the cross section of the process. Hence, the higher the integrated luminosity, the lower the statistical uncertainty on a physics measurement or search and the greater the discovery potential for rare processes.

3.1.1 Run 1 performance

The LHC started regular operation in 2010 after a year-long delay caused by a catastrophic incident during the commissioning phase. The unforeseen

event was caused by a faulty superconducting cable interconnection [64] and resulted in a major damage to the machine components. Following the incident, it was decided to pursue the first three-year long part of the physics programme, *Run 1*, at half of the design beam energy. The accelerator operated almost incessantly between March 2010 and March 2013 providing vast amounts of data for all experiments. The majority of this time was dedicated to proton-proton operation, which is the primary design purpose of the machine. Moreover, the LHC provided two 4-week periods of lead-lead (PbPb) collisions in November 2010 and November 2011, as well as proton-lead (*p*Pb) collisions in early 2013. Additional two short *pp* runs at a lower energy took place to deliver reference data for heavy ion research.

A number of beam parameters have been continuously changing throughout the Run 1 *pp* operation, gradually increasing the instantaneous luminosity up to the record peak luminosity of $7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ reached in August 2012. The evolution of the peak luminosity delivered to ATLAS in *pp* runs of 2010, 2011 and 2012 is presented in Figure 3.1. The modified beam parameters include the total number of bunches per ring (from 2 up to 1380), the bunch spacing (from 150 ns down to 50 ns), the number of protons per bunch (from 2×10^{10} up to 1.7×10^{11}), and the β^* parameter related to the transverse size of the beams at the collision point (from 3.5 m down to 0.6 m). The beam energy was also increased between 2011 and 2012 from 3.5 TeV to 4 TeV, increasing the centre-of-mass *pp* collision energy from 7 to 8 TeV.

High instantaneous luminosity at the LHC is produced at the cost of introducing multiple proton-proton interactions per bunch crossing (so-called pile-up). The average number of inelastic *pp* collisions in each bunch crossing, $\langle \mu \rangle$, was reaching up to 37 at fill start by the end of Run 1 and the

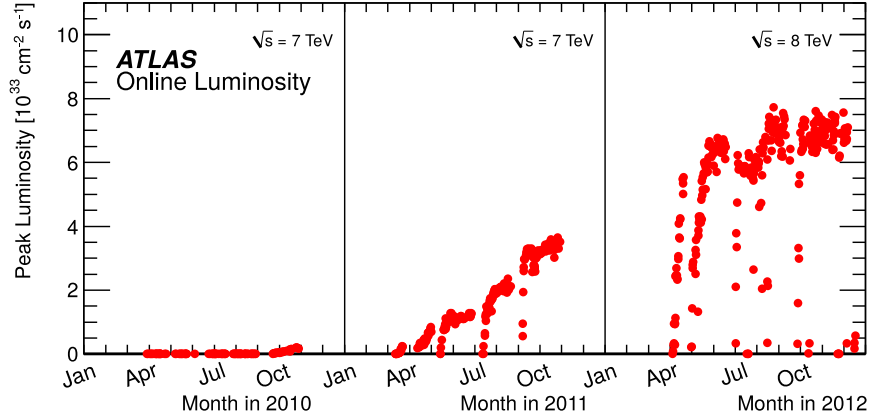


Figure 3.1: The peak instantaneous luminosity delivered to ATLAS versus time during the pp runs of 2010, 2011 and 2012 [66].

value averaged over the whole 2012 pp dataset is $\langle\mu\rangle = 20.7$. In total, the LHC delivered pp collision data corresponding to the integrated luminosity of 5.6fb^{-1} at the collision energy of 7 TeV and 23.3fb^{-1} at 8 TeV [65].

3.1.2 Long Shutdown 1

After the successful Run 1, the LHC ceased its operation for a two-year period termed the Long Shutdown 1 (LS1), executing a scheduled maintenance and upgrade programme. One of the major tasks performed during this time was the consolidation of over ten thousand superconducting splices in magnet interconnections, replacing the technology which caused the incident delaying the start of Run 1. In parallel, the experiments performed numerous repairs and detector upgrades improving their performance for Run 2.

3.1.3 Run 2 performance

During the LS1, a decision was made to restart operations at a pp collision energy of 13 TeV rather than the nominal 14 TeV. It was motivated by the need of much longer preparation of the dipole magnets to reach the

maximum energy, which would have delayed the physics programme and reduced the amount of data collected. The first stable-beam collisions at the new energy started in June 2015 at low intensity and with the Run-1 bunch spacing of 50 ns. After the initial beam commissioning period, the bunch spacing was changed to the nominal 25 ns. Similarly as in Run 1, other beam parameters have been also gradually improved and optimised increasing the instantaneous luminosity.

Despite intermittent problems affecting beam stability, including pollution inside a beam pipe in 2015 and 2016, and trapped gas in one of the sectors in 2017, the LHC managed to surpass its performance goals for 2016 and 2017 breaking many of its own records. By the end of the 2017 pp run, the machine proved to be able to deliver collisions at double the design instantaneous luminosity, reaching $\mathcal{L} = 2.06 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with a pile-up of $\langle\mu\rangle = 79$. The maximum integrated luminosity delivered in 7 days reached $\mathcal{L}^{\text{int}} = 5.2 \text{ fb}^{-1}$ and in one day $\mathcal{L}^{\text{int}} = 0.88 \text{ fb}^{-1}$.

The excellent performance of the LHC became challenging for the two high-luminosity experiments, ATLAS and CMS, which were designed to operate at $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and $\langle\mu\rangle \approx 20$ [67, 68]. Both had to explore mitigation techniques to manage the amount of data delivered by the LHC. One such technique is to tighten the trigger requirements deciding whether to record data for a particular event, mainly by increasing the energy and momentum thresholds of interesting objects (leptons, jets). This however constrains the phase space available to physics analyses and may have adverse effects on their precision and sensitivity. Another technique, employed since October 2017, is the *luminosity levelling* where the bunches are collided non-centrally, decreasing the instantaneous luminosity. The bunch overlap is continuously and automatically increased, correcting for the ex-

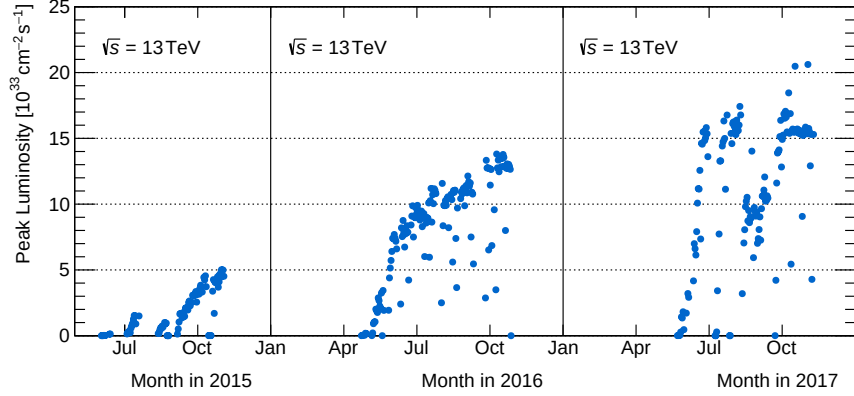


Figure 3.2: The peak instantaneous luminosity delivered to ATLAS versus time during the pp runs of 2015, 2016 and 2017.

ponential decrease of the beam intensity and resulting in a constant instantaneous luminosity over a long period of time. This procedure allows to maximise the integrated luminosity while keeping the instantaneous value at a manageable level. Although the luminosity levelling results in a small loss of integrated luminosity in comparison to full head-on collisions due to the non-collision beam intensity losses, it allows for a good production efficiency without further limiting the analysis phase space. Levelling has been used in the low-luminosity experiments at IR2 and IR8 throughout the whole period of LHC pp operation. In late 2017, the collision rate at ATLAS and CMS was levelled at $\mathcal{L} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and $\langle \mu \rangle = 59$ in the first ~ 2 h of each run, until the beam intensity decreased enough to reach these values in head-on collisions.

In total, the LHC delivered over 90 fb^{-1} of 13 TeV pp collisions to each high-luminosity experiment in the years 2015–2017. The evolution of the peak luminosity delivered to ATLAS in these runs is presented in Figure 3.2. In addition, the programme included one week of PbPb collisions at $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$ in 2015, as well as one week of $p\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$

and two weeks at $\sqrt{s_{\text{NN}}} = 8 \text{ TeV}$ in 2016. Several weeks were devoted to pp collisions at a lower energy of 5 TeV. Two days in 2017 were exceptionally dedicated to Xenon ion collisions, proving the LHC is capable of operating with types of beams never considered during its design. Run 2 will continue until the end of 2018 aiming at $\sim 150 \text{ fb}^{-1}$ of 13 TeV pp data and will be followed by another long shutdown dedicated to both machine and experiment upgrades.

3.2 ATLAS Experiment

ATLAS [67] is a barrel-shaped, multi-purpose particle detector built at one of the four LHC beam crossing regions, IR1. The nominal beam crossing point (the Interaction Point, IP) defines the origin of a right-handed coordinate system used in the experiment and in this thesis hereafter. The z -axis is directed along the beam pipe, the y -axis points upwards, and the x -axis points toward the centre of the accelerator ring. Cylindrical coordinates (R, ϕ) are used in the plane transverse to the beam direction (xy), where the direction $\phi = 0$ is aligned with the positive x -axis. The pseudorapidity η is defined in terms of the polar angle θ as $\eta = -\ln(\tan(\theta/2))$. It is commonly used instead of the polar angle due to its similarity to the particle rapidity, $y = (1/2) \ln((E + p_z)/(E - p_z))$. The two quantities are equivalent for massless particles. Rapidity differences are invariant under Lorentz boosts along the beam direction, which is a favourable property in studies of hadron collision products. Particles produced in the initial parton-parton interaction are subject to such a boost because of the difference in parton momenta. The positive- η side of ATLAS is conventionally referred to as the A-side, whereas the negative- η side as the C-side.

The design of the detector and its subsystems was driven by a range of processes predicted to be potentially observable at the TeV interaction

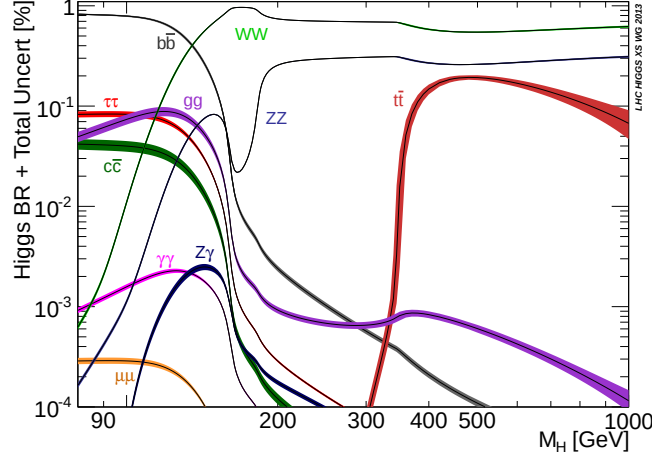


Figure 3.3: Higgs boson decay branching ratios for the boson mass between 80 and 1000 GeV [69].

scale [70]. One of the main goals of the experiment was the discovery of the Higgs boson and establishing whether its properties are consistent with the predictions of the Standard Model or one of its extensions. The full range of possible Higgs boson masses and the corresponding possible decay modes (presented in Figure 3.3) was considered at the design phase. A low-mass Higgs boson would decay predominantly into $b\bar{b}$, gg or $\tau\tau$ pairs hindering its discovery potential in the main decay channels due to a high irreducible QCD background. Therefore, the most likely discovery channel would be the $\gamma\gamma$ decay, requiring the experiment to have a high-granularity calorimeter system with a good energy resolution in the range of tens of GeV. Higher Higgs boson masses open the WW and ZZ decay channels, where leptonic decays of the vector bosons provide a clean signature of the process. Detection and reconstruction of these final states required dedicated muon detectors outside the calorimeter system (to reduce contamination from other charged particles) and additional tracking detectors before the calorimeters to measure electron momenta. Very high Higgs boson masses would open the $t\bar{t}$ decay channel resulting in final states involving jets,

b -jets, charged leptons and neutrinos. Associated production of the Higgs boson with a $t\bar{t}$ pair or a W/Z boson with a subsequent $H \rightarrow b\bar{b}$ decay were also among processes considered during the design phase. Moreover, the production of forward jets in vector boson fusion (one of the Higgs boson production processes) motivated the installation of additional calorimeters in the high- η regions. Other potential physics analyses considered in the detector design include precision measurements of $t\bar{t}$ production and top quark properties, as well as searches for new heavy gauge bosons, quark compositeness, flavour-changing neutral currents, lepton flavour violation, supersymmetric particles and gravitons.

ATLAS comprises three main categories of detectors and two types of magnets, placed in consecutive layers of the barrel and in two end-caps. The innermost part, placed inside a solenoid magnet, utilises three types of tracking detectors – silicon pixels, silicon microstrips and straw tubes. The system facilitates high-precision reconstruction of charged particle tracks and allows to measure the particle momenta. The electromagnetic and hadronic calorimeters placed outside the solenoid are designed to absorb all photons, electrons, protons, neutrons, pions and kaons, measuring their energy. The outermost layers of the detector include 24 large air-core magnets (eight in the barrel and eight in each end-cap) producing a toroidal field, and a set of gaseous tracking detectors allowing the measurement of muon momenta. ATLAS uses an advanced trigger system composed of two parts – a hardware-based Level-1 (L1) Trigger and a software-based High Level Trigger (HLT). An overview of the detector and its main subsystems is presented in Figure 3.4. In addition, ATLAS features several smaller specialised detectors not shown in the figure and described in Section 3.2.2.

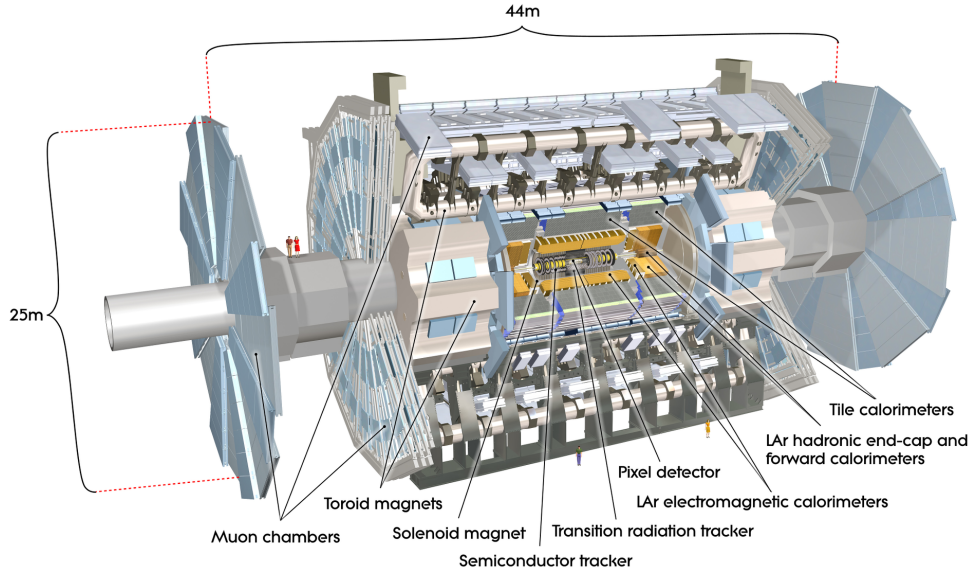


Figure 3.4: Cut-away view of the full ATLAS detector [67].

3.2.1 Inner Detector

The ATLAS Inner Detector (ID), presented in Figure 3.5, is a robust device for detecting tracks of charged particles allowing the determination of their momenta and reconstruction of primary and secondary interaction vertices with great precision. It is composed of three types of tracking detectors contained within a solenoidal magnetic field of 2 T. The central part of the detector comprises coaxial cylindrical layers, whereas higher z values are facilitated with disk-shaped end-caps.

The space closest to the beam crossing point was originally covered with pixel modules arranged in three barrel layers and three end-cap layers on each side. The placement of the layers ensured that a particle produced at the Interaction Point typically hit three of them. During the LS1, the barrel was supplemented with another layer of pixel detectors – the Insertable B-Layer (IBL) – between the new narrower beam pipe and the previously

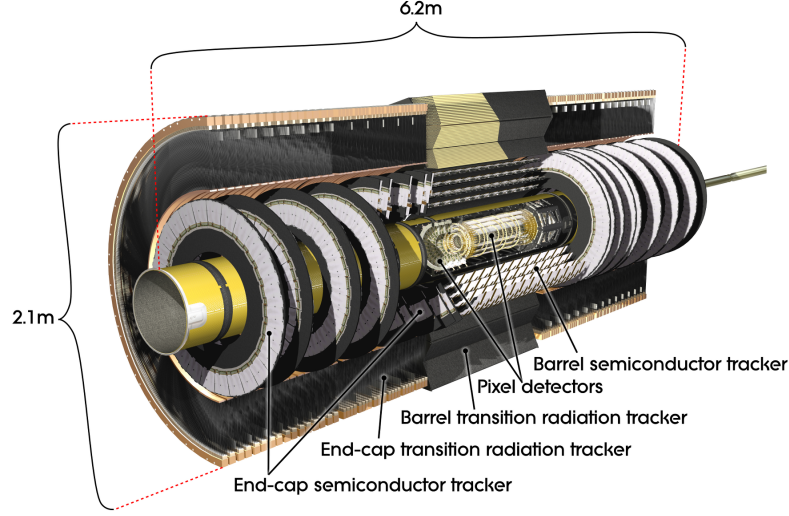


Figure 3.5: Cut-away view of the ATLAS Inner Detector [67].

innermost layer (B-Layer) [71, 72]. The upgrade was motivated by the radiation damage of the B-Layer expected to impede vertex reconstruction precision in Run 2 and 3 and was designed as an alternative to the initially planned replacement of the B-Layer.

The Semiconductor Tracker (SCT) is a silicon microstrip detector surrounding the pixels and designed in a similar geometry with modules arranged in four barrel layers and nine disks in each end-cap. Each SCT module consists of two layers of strips glued together back-to-back and sharing the support structure and front-end electronics. One layer is aligned with the measurement direction and the other is rotated by 40 mrad . This small stereo angle ensures a better resolution along the strips and a lower rate of fake tracks due to noise coincidence.

The outermost part of the Inner Detector holds the Transition Radiation Tracker (TRT) which is a straw tube gaseous tracking detector where an aluminium coating of the inner tube surface serves as the cathode and an

axially placed tungsten wire is the anode. The whole detector is composed of up to 73 layers of tubes in the barrel and 160 in each end-cap, compensating the lower resolution in comparison to silicon detectors with a large number of hits per track. In addition to providing continuous tracking at high radii, the TRT has a unique capability among the LHC experiments to detect the transition radiation emitted by electrons. The radiation is provoked by polypropylene radiators – thin fibres filling the space between tubes in the barrel and layers of foil between the end-cap disks. The transition radiation photons, predominantly in the X-ray energy regime, are efficiently absorbed by the xenon gas mixture within the tubes. The TRT front-end electronics are designed to detect hits at two thresholds – low threshold adjusted for minimum ionising particles and high threshold to detect high γ -factor particles associated with transition radiation (high- p_T electrons). During Run 2, some higher-occupancy layers of the detector (the inner barrel layers and a few selected end-cap layers) were operated using an argon mixture instead of xenon due to the better resulting position resolution, however at the cost of lower transition radiation absorption.

The Inner Detector provides charged particle momentum measurements in the range 0.5–150 GeV within $|\eta| < 2.5$ and electron identification within $|\eta| < 2.0$. Single-module hit position accuracy reaches 10 μm for the pixels and 17 μm for the strips in the $R - \phi$ direction. The perpendicular direction (z in the barrel and R in the end-caps) is measured with 115 μm accuracy in the pixel detectors and 580 μm in the SCT. The TRT tubes reach a 130 μm accuracy. The detector provides a track impact parameter resolution down to 80 μm along the beam direction and 20 μm in the transverse plane for central high- p_T tracks [73].

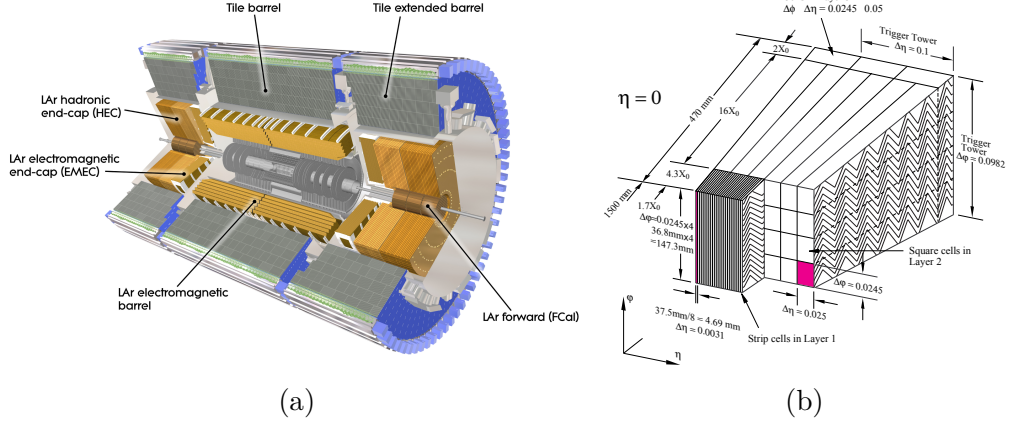


Figure 3.6: (a) Cut-away view of the ATLAS calorimeter system [67]. (b) Sketch of a liquid argon electromagnetic calorimeter barrel module [67].

3.2.2 Calorimeters and forward detectors

The primary aim of the ATLAS calorimeter system is to absorb virtually all particles except for muons and neutrinos in the maximal possible solid angle in order to measure their energy. This is achieved with the use of several calorimetry systems in two general categories – electromagnetic (for electrons and photons) and hadronic (for protons, neutrons, pions and kaons). Their arrangement is presented in Figure 3.6a. There are three hadronic calorimeter subsystems: Tile barrel, Tile extended barrel and Hadronic End-cap Calorimeter (HEC), whereas the electromagnetic calorimeter comprises two parts: the barrel and the Electromagnetic End-cap Calorimeter (EMEC). In addition, a three-layer Forward Calorimeter (FCal) is placed at the highest η on both sides.

The electromagnetic calorimeters are composed of liquid argon (LAr) active layers and lead absorbers folded in an accordion geometry (Figure 3.6b), which provides a full ϕ coverage avoiding azimuthal cracks between individual cells. Several layers of such structured detectors are used – three in the precision measurement region $|\eta| < 2.5$ and two at higher pseudorapidities.

A fine segmentation of the first layer in the central region allows an accurate determination of an electromagnetic cluster position. Furthermore, in the $|\eta| < 1.8$ region, the detector is complemented by an additional thin LAr layer – the presampler – providing a measurement of the energy lost in front of the electromagnetic calorimeter.

The Tile hadronic calorimeter includes three independent parts – one central barrel covering the range $|\eta| < 1.0$ and two extended barrels between $|\eta| = 0.8$ and 1.7 . It uses steel as the absorber and scintillating tiles (polystyrene doped with wavelength-shifting fluors) as the active medium. Higher- η regions are covered by HEC, which consists of two independent wheels on each side extending over $1.5 < |\eta| < 3.2$. It uses copper plates as the absorber and, similarly to EMEC, liquid argon as the active material.

FCal comprises three calorimeter layers in each end-cap at the highest η – one electromagnetic and two hadronic. The detectors are placed between HEC and the beam pipe and cover angles up to $|\eta| = 4.9$. The FCal layout is based on absorber rods situated within copper tubes with a sub-millimetre gap in between filled with liquid argon. Each layer consists of a matrix of tubes placed parallel to the beam pipe and separated by additional absorber material. A plastic fibre collecting the scintillation light is woven around each rod within the LAr layer. The small size of the active material gaps is required to avoid ion build-up caused by the high particle flux in this forward region. The electromagnetic layer uses copper as the absorber, whereas tungsten is used in the hadronic layers. The common active material used in EMEC, HEC and FCal allowed to install them within a single cryostat module on each side, minimising the energy losses in cracks between the systems and reducing the backgrounds reaching the muon detectors.

ATLAS also features several smaller specialised sub-detectors placed in the

very forward regions. A series of small diamond detectors placed close to the beam pipe within the Inner Detector serve as monitors of the beam conditions and can trigger a beam dump if a dangerous instability is detected. In addition, they provide a measurement of beam backgrounds and support online luminosity measurements. The Minimum Bias Trigger Scintillators (MBTS) composed of 32 scintillator counters distributed over two disks in the ATLAS end-caps ($2.09 < |\eta| < 3.84$) were designed for triggering in the early low-luminosity runs. This simple yet robust device is still operational and used during Run 2 in low pile-up special physics runs. LUCID (LUminosity measurement with Cherenkov Integrating Detector) consists of an array of Cherenkov tubes placed at $z = \pm 17$ m within the beam pipe support structures between the main ATLAS volume and the outer muon wheels. It is the primary source of online luminosity measurement and plays a crucial role in the offline determination of the integrated luminosity. The Zero-Degree Calorimeter (ZDC), installed at $z = \pm 140$ m between the two already-separated beam lines, is designed primarily to detect forward neutrons with $|\eta| > 8.3$ in heavy-ion collisions. The ATLAS Forward Proton (AFP) detector [74] is a new device installed and commissioned in 2016 and 2017 aimed to detect protons from diffractive pp interactions with exclusive jet production (where the jets are detected within the main ATLAS volume). It comprises silicon trackers and time-of-flight detectors based on Cherenkov light detection placed in two stations at each side around $z = \pm 210$ m. ALFA (Absolute Luminosity For ATLAS) is a detector placed the furthest from the IP and consists of two stations per side placed around $z = \pm 240$ m equipped with tracking detectors based on scintillating fibres. Its main purpose is the measurement of the total pp interaction cross section in ATLAS at the LHC collision energy (7, 8, 13 TeV), which is achieved in special low-intensity runs with the average number of interactions per

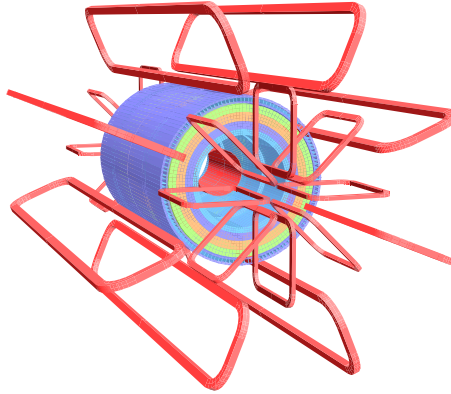


Figure 3.8: Geometry of the toroid and solenoid magnet windings (red) and the Tile Calorimeter steel (coloured layers) [67].

Each MS barrel layer is composed of eight small and eight large detector stations alternating in ϕ as presented in Figures 3.9 and 3.10, and containing several rectangular MDT chambers along the z direction. The middle layer MDT chambers are sandwiched by two layers of RPC. Additional RPC modules are placed in the outer barrel layer, on the outer side of the large stations and the inner side of the small stations. The three end-cap wheels on each side are composed largely of trapezoidal MDT chambers as shown in Figures 3.9 and 3.10. Due to the high rate of particles produced in the forward direction in pp collisions, the high- η regions of the innermost wheels are equipped with CSC instead of MDT as they provide higher granularity and better high-rate performance. The TGC trigger chambers are organised in one inner layer in front of each small wheel and three layers in each middle wheel.

Precision-measurement chambers

The basic element of an MDT chamber is a 3 cm diameter aluminium tube filled with an argon gas mixture. The tube serves as a cathode and a thin tungsten-rhenium anode wire at a high electric potential is placed in the

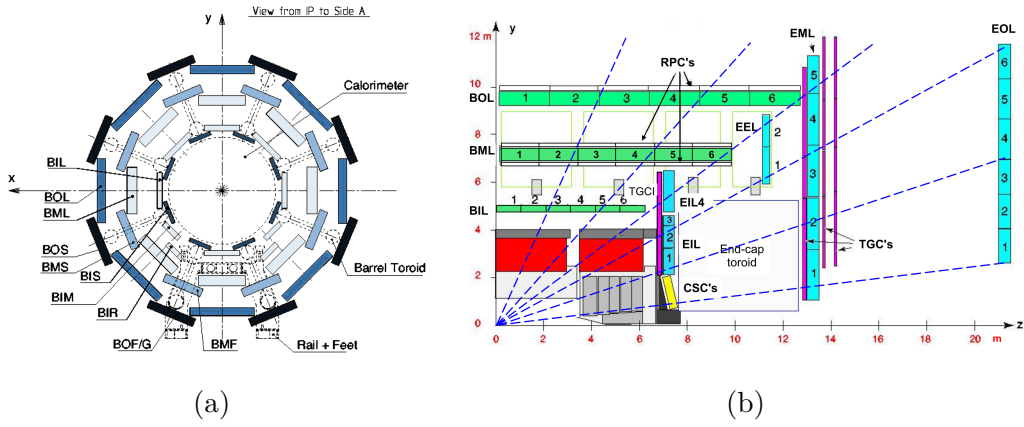


Figure 3.9: (a) Cross section of the barrel muon system perpendicular to the beam axis (non-bending plane) [67]. (b) Cross section of the muon system in a plane containing the beam axis (bending plane) [67]. MDT chambers are shown in green (barrel) and blue (end-cap), CSC in yellow, RPC in white and TGC in purple. Dashed lines represent infinite-momentum muon trajectories crossing typically three stations.

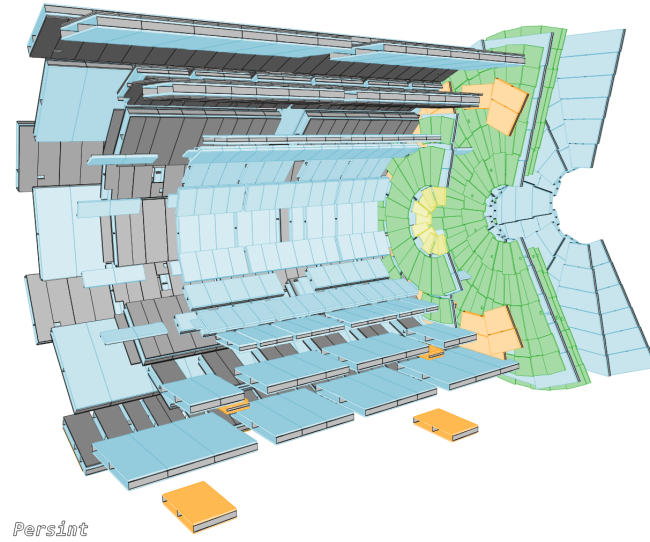


Figure 3.10: Cut-away view of the ATLAS Muon Spectrometer modules generated with the Persint visualisation program [75]. MDT chambers are shown in blue, RPC in black, TGC in green and CSC in yellow. New MDT and RPC modules commissioned during the LS1 are shown in orange.

centre. Three or four layers of tubes form a multi-layer and two multi-layers separated by aluminium spacers form a single chamber. The average spatial resolution of a single MDT tube along the wire is $80\text{ }\mu\text{m}$.

MDT can be safely operated up to the rate of around 150 Hz/cm^2 , which was expected to be exceeded in the region $|\eta| > 2$ of the innermost end-cap layer in the nominal LHC operating conditions. In order to allow measurements in this area, it was facilitated with CSC which maintain high spatial and time resolution, while being able to withstand rates up to 1 kHz/cm^2 . A single CSC module is a multiwire proportional chamber comprising four planes, providing independent measurements in η and ϕ . Each plane consists of a layer of anode wires sandwiched by two layers of cathode strips oriented orthogonally to each other. The strip segmentation in the bending direction (η) is much finer than in the non-bending direction (ϕ) resulting in the average spatial resolution per chamber of $60\text{ }\mu\text{m}$ and 5 mm respectively. The track position measurement in each cathode plane is based on interpolation between charges induced on neighbouring strips.

Trigger chambers

The MS trigger chambers are designed to provide fast information on muon tracks allowing event discrimination on muon p_T in the hardware trigger, and to give a coarse tracking information for the software trigger. In addition, they complement the MDT measurement with a second coordinate information in the non-bending direction, ϕ . Two different technologies have been used for the barrel and the end-caps, as the latter region requires an increased granularity dependent on η due to the high rates and lower ratio of bending power to the total momenta of high- p_T muons. The layout of the RPC and TGC chambers is presented in Figure 3.11. Operation of the L1 Trigger is based on comparing hits in the reference layer – RPC2 in the

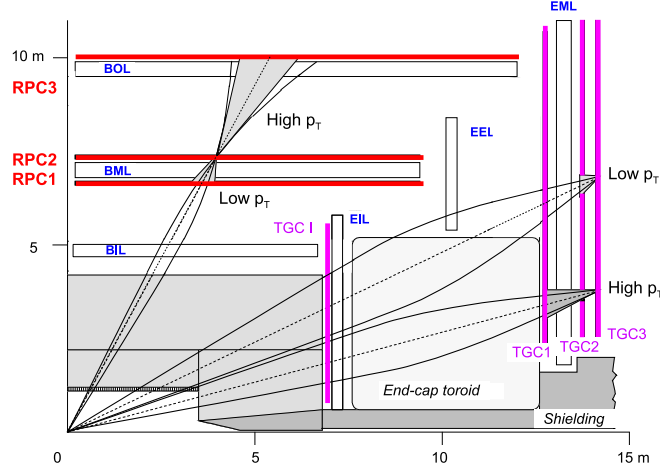


Figure 3.11: The trigger chamber layout in the Muon Spectrometer [67].

barrel or TGC3 in the end-caps – with hits in other layers and a quick estimate of the track curvature. For low- p_T triggers, the comparison is made with RPC1 or TGC2, whereas for high- p_T RPC3 or TGC1 is used.

The Thin Gap Chambers are multiwire proportional chambers characterized by a wire-to-cathode distance smaller than the distance between the wires (1.4 mm and 1.8 mm respectively) – hence the name. This feature in combination with a highly-quenching gas mixture of n -pentane and CO_2 allows fast and safe operation at high particle flux. The signal read from the wires provides a bending direction position measurement with a few-mm accuracy. Copper strips separated from a graphite cathode plane by a flame-resistant material layer provide an azimuthal measurement with a similar accuracy. Each end-cap comprises nine layers of TGC gas volumes in total – a doublet in each TGC1, TGC2 and TGC3, and a triplet in TGC1 for better background rejection.

RPC, unlike the other three MS technologies, do not utilise wires to generate the avalanche-forming electric field. A single detector module is composed of two parallel plastic resistive plates separated by a 2 mm gap created

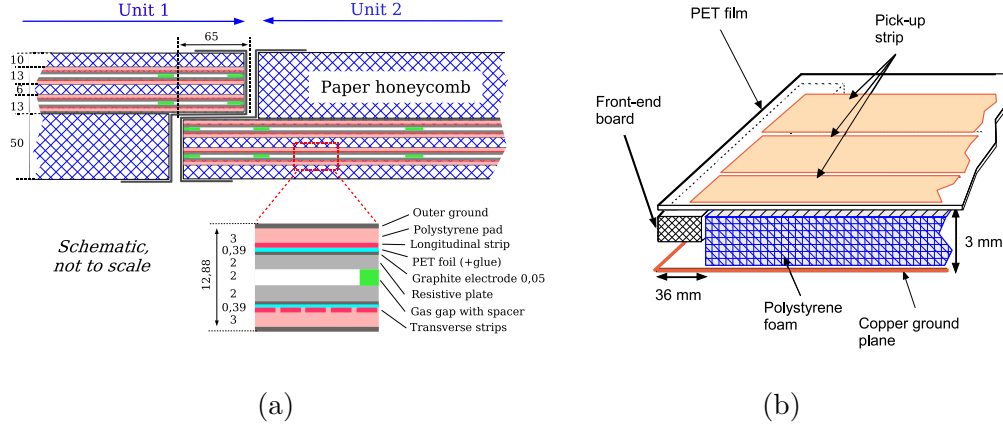


Figure 3.12: (a) Cross section through an RPC module, where two units are joined to form a chamber [67]. Dimensions are given in mm. (b) Layout of an RPC readout strip plane [67].

with insulating spacers and sandwiched by graphite electrode planes, as presented in Figure 3.12a. The gap between the resistive plates is filled with a freon-based gas mixture, which is non-flammable, low-cost and allows relatively low operating voltage. The signal is read out from two layers of orthogonal copper strips separated from the electrodes by a thin plastic foil (Figure 3.12b), providing a 10 mm accuracy in both directions. A single RPC chamber comprises two neighbouring units, each including two parallel gas volumes, such that the full RPC system provides six measurement points for a muon track traversing the MS barrel.

3.2.4 Trigger and Data Acquisition

The average LHC collision rate reaching up to 30 MHz produces amounts of data largely exceeding the storage capabilities of ATLAS data disks. In addition, the majority of pp collisions at 13 TeV produce only soft interactions with no signatures of processes targeted by the physics programme of the experiment. The ATLAS Trigger and Data Acquisition (TDAQ) system is designed to efficiently select and record potentially interesting events,

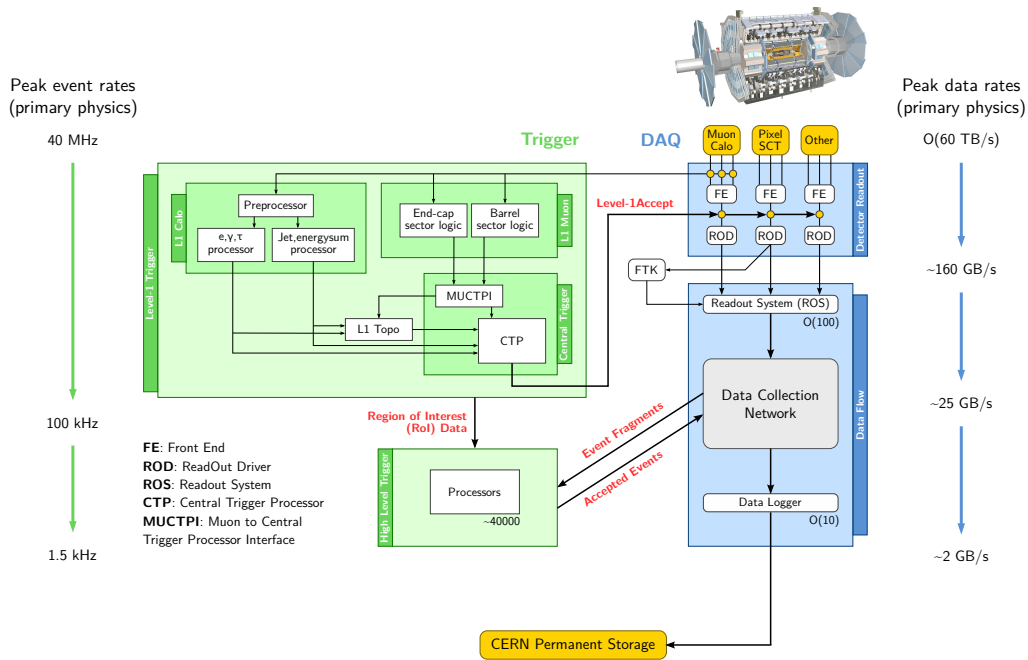


Figure 3.13: Simplified layout of the ATLAS Trigger and Data Acquisition hardware in Run 2 and the flow of data through the system. Rates indicated on the left and the right refer to what is called the *physics main* stream with full events and exclude calibration data and streams saving only part of the event information.

reducing the output rate to a manageable level. It is composed of a hardware Level-1 (L1) Trigger based on purpose-built electronics, a software High Level Trigger (HLT) exploiting a computing farm built with industry-standard components, and a series of elements interfacing the levels and facilitating the data flow from the detectors to the disks.

The flow of data through the system is outlined in Figure 3.13. The signals from individual modules of all detectors are first buffered in their front-end electronics while signals from the calorimeters and muon trigger chambers are directed into the respective L1 Trigger components. After pre-processing in the individual L1 Calo and L1 Muon systems, the information is di-

rected into the Central Trigger Processor (CTP) which forms the final L1 accept decision. The CTP is also responsible for applying a preventive dead-time to avoid overlapping readout windows and overflow of the front-end buffers. Upon a positive L1 decision, the buffered data are sent through the Readout Drivers (RODs), which form the data into a unified ATLAS ByteStream (BS) format, to the Readout System (ROS) and stored in the Readout Buffers (ROBs) where they are accessible by the HLT and wait for its decision.

Predefined sequences of HLT algorithms refine the L1 selection using additional data from finer-granularity calorimeter cells, MS precision measurement chambers and the ID. Most sequences include two distinctive stages – one with fast tracking and object reconstruction for a rapid background rejection and another using reconstruction algorithms similar to or the same as in the offline data processing. This structure originates from the Run 1 ATLAS trigger system, where the two stages were fully separated at the hardware level. Merging them into a single software trigger stage simplified the system and removed rate and bandwidth limitations between the two steps. The duplication of certain stages, e.g. the pattern recognition for track finding, was also removed. Both types of trigger algorithms can now exploit the Region of Interest (RoI) information defined by the L1, which includes the types and rough angular coordinates (η, ϕ) of objects triggering the L1 accept decision. The RoI is used to define which event fragments are read from the ROBs and used in trigger-level object reconstruction. Reading data only from detector modules intersecting with the RoI speeds up the algorithm execution without compromising the reconstruction quality. Some full-scan trigger sequences using the full detector data are still executed at lower rates to study the performance of the selection.

The complete set of all trigger chains, referred to as the *trigger menu* consists of around 3000 combinations of different L1 triggers with numerous reconstruction and hypothesis algorithms at the HLT. Due to data bandwidth constraints, not all chains can be executed at full rate. The menu defines a set of primary physics chains comprising mainly chains accepting events with high- p_T electrons, muons or jets, which can be always executed at full rate. These primary chains allocate up to 2 GB/s of the bandwidth. The rest, around 800 MB/s is allocated to lower p_T -threshold triggers which are *prescaled*, which means only one in every N events accepted by them is recorded and the others are discarded. The number N is called the *prescale factor* and can be defined for each chain individually. The prescale factors are regularly reduced throughout a run as the overall rates decrease with the decreasing instantaneous luminosity and more bandwidth becomes available. The prescaling technique allows to record reduced samples of events with lower- p_T objects required for detector calibration, performance studies, background estimation and physics analyses focusing on low-mass states, e.g. B -mesons. Primary physics chains remain unprescaled at all times, i.e. their prescale factor equals 1.

The TDAQ system is one of the most modified components of ATLAS throughout Run 1 and Run 2. Nearly all of its elements were subject to upgrades, replacement and redesign during the LS1 to allow efficient data taking with the increasingly challenging conditions. The upgrade programme included the installation of two new functional elements of the trigger system – the Level-1 Topological trigger (L1 Topo) [76] and the Fast Tracker (FTK) [77], both indicated in Figure 3.13. L1 Topo is a new component of the Central Trigger Processor which receives signals from the L1 Calo and Muon processors and constructs topological and kinematic quantities from multiple objects, allowing to discriminate events on variables like ΔR between

jets or dimuon invariant mass. The processor was commissioned throughout 2015 and 2016 and the first topological triggers for use in physics analysis were in operation in 2017. The FTK is a hardware system operating in parallel to the Level-1 Trigger, reading data from the pixel and SCT detectors and reconstructing particle tracks within a latency short enough for them to be used as an additional input to the HLT. The track reconstruction is implemented using a dedicated associative memory chip matching the observed hit combinations to preloaded patterns. The system integration with ATLAS is still under commissioning with the first tracks reconstructed and saved within the ATLAS data stream in November 2017.

3.2.5 Detector Control System

Stable and safe operation of the ATLAS detector is ensured by the Detector Control System (DCS) [78] organised in two main parts – the front-end systems and back-end control, as presented in Figure 3.14. The front-end is composed of a broad range of hardware control devices, from simple sensors to complex instruments such as software controlled power supplies. Although commercial solutions are applied as widely as possible in the DCS, their usage is limited within the ATLAS cavern due to the high magnetic field and ionising radiation level. To overcome this issue without sacrificing the homogeneity and simplicity of the system, a general-purpose I/O concentrator board – the Embedded Local Monitor Board – has been designed and widely used across the DCS front-end systems. There are approximately 5000 of these boards across ATLAS, controlled using industry-standard servers and protocols.

The DCS back-end comprises over 150 computers connected in a distributed three-layer system. The Local Control Stations connect to the front-end of specific controlled systems in three underground electronics rooms, the

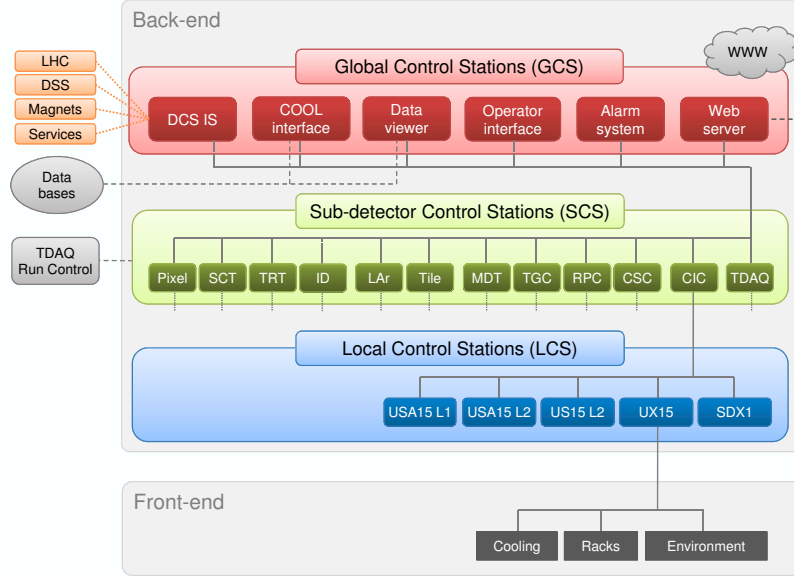


Figure 3.14: Architecture of the ATLAS Detector Control System [78].

ATLAS cavern and the TDAQ computer rooms. They are responsible for processing and archiving the respective data. The Subdetector Control Stations facilitate full operation of each subdetector independently and provide a user interface to control its subsystems. The Global Control Stations provide the tools necessary for monitoring and controlling operation of the whole experiment from the ATLAS control room, as well as a status summary available remotely via the World Wide Web.

The DCS systems are organised in a single, distributed, tree-like finite state machine. The state of each single subsystem is propagated upwards, whereas a command changing a certain parameter can be propagated from the top down to the specific hardware.

3.3 Muon Spectrometer data decoding

Merging the Level-2 (L2) and Event Filter (EF) software trigger steps into the single HLT during LS1 (see Section 3.2.4) raised the necessity to adapt the EF algorithms for a new input concept. Previously run after full event building, the EF algorithms used information from the whole detector. However, in the Run-2 configuration they need to follow an L2-like behaviour of using event fragments read from ROS. This section describes the principles of HLT muon algorithms operation and the changes applied for Run 2. This is followed by technical details of problems encountered during the implementation of these changes and the applied solutions.

3.3.1 Muon trigger algorithms

The aims of the HLT muon algorithms, both L2 and EF, are fast reconstruction of muon tracks, extraction of their features and a time-efficient decision on whether to accept or reject an event. Two types of tracks are created and processed – *standalone* tracks built using MS-only data and *combined* tracks including also information from the ID. The combined tracks can be constructed in two ways – by extrapolating a standalone track to the ID and adjusting it to include a previously built ID track (the *outside-in* algorithm) or by extrapolating an ID track and matching it to a standalone MS track (the *inside-out* algorithm). Both approaches are also used to reconstruct muons in offline data processing, as described in Section 4.1.2.

In Run 1, two EF muon algorithms were used: an outside-in `TrigMuonEF` and an inside-out `TrigMuGirl` based on `MuGirl` – one of the offline muon reconstruction algorithms. In order to decrease the EF processing time, a ‘smart OR’ of the two is used in Run 2. It is implemented as a wrapper algorithm `TrigMuSuperEF`, which executes `TrigMuonEF` by default and

only in the case when no muon is found, it executes the `MuGirl` offline-reconstruction software tool. With this change, `TrigMuGirl` became obsolete and was removed in Run-2 muon trigger software.

Regardless of the track type to be used, the `TrigMuonEF` execution begins with building a standalone track using `TrigMuonEFStandaloneTrackTool`. It is a tool which uses pattern-finding algorithms to build track segments from hits in different muon detectors and combines them into standalone muon tracks. Before the track segments can be created, raw data corresponding to the hit information has to be converted into a suitable object-oriented format. This is achieved using a set of detector-specific tools commonly called the *decoders*. Raw data in the `ByteStream` format are first converted into the Raw Data Object (RDO) format which is further converted into `PrepRawData` (PRD). Both RDO and PRD data are organised in collections. The RDO collections correspond to the layout of front-end electronics and the physical readout path, whereas the PRD collections follow the detector geometry and usually correspond to several RDO collections. For example, each PRD collection for the RPC detectors corresponds to data collected from one RPC layer in one MS barrel station (two units with two gas volumes each). The MS decoders comprise four sets of tools, one for each detector technology. These include `XxxRdoToPrepDataTool`, `XxxRawDataProviderTool` and `XxxRDO_Decoder`, where `Xxx` is either `Mdt`, `Rpc`, `Tgc` or `Csc`. The decoding process is explained in Figure 3.15 using the example of RPC. It makes an extensive use of the Event Store, which is a transient storage for data related to the currently processed event. The main difference between the Run-1 and Run-2 software is the implementation of the ROB data provider service, which previously operated on full event data stored in the EF system memory after event building. In the new merged HLT, an L2-like ROB data provider service is used, which requests

the event fragments directly from ROS. The two main tasks required for the implementation of the new system in the muon trigger algorithms are detailed below.

Task 1: Use RoI-driven decoding in TrigMuonEF

This major change in the **TrigMuonEF** decoding is aimed at significant reduction of the amount of processed data. In Run 1, all data from the whole MS were decoded (so-called *full decoding* mode). This was natural, as the EF was run after the full event data were already read from ROS and directly available. However, as EF is part of the trigger, only the decoded data corresponding to the currently processed RoI were used to build track segments, and the remaining data from outside of the RoI were not used. The full decoding was not an optimal approach due to the large time spent on decoding of the unused data. Moreover, the extra data remained in the Event Store until the final EF decision, increasing the memory usage. In Run 2, the decoders are used to process data only from the detector modules which have non-zero intersection with the RoI (which is known as the *seeded* or *RoI-driven decoding*). This functionality has already been implemented in the decoders, however has not been used in **TrigMuonEF**. The method `decode` of the RDO-to-PRD conversion tool, which is called by the standalone track tool, typically takes a vector of PRD collection identifiers as an input. The decoding is then performed only for these collections. If an empty vector is provided, the method decodes all possible PRD collections, i.e. data from the whole subdetector. In principle, the only change needed for Run 2 was to provide a valid input vector for the decoders, which would contain collection identifiers corresponding to the RoI.

Such functionality is provided by a general-use service, the Region Selector (**RegSelSvc**). It stores a simple look-up table for each ATLAS subdetector

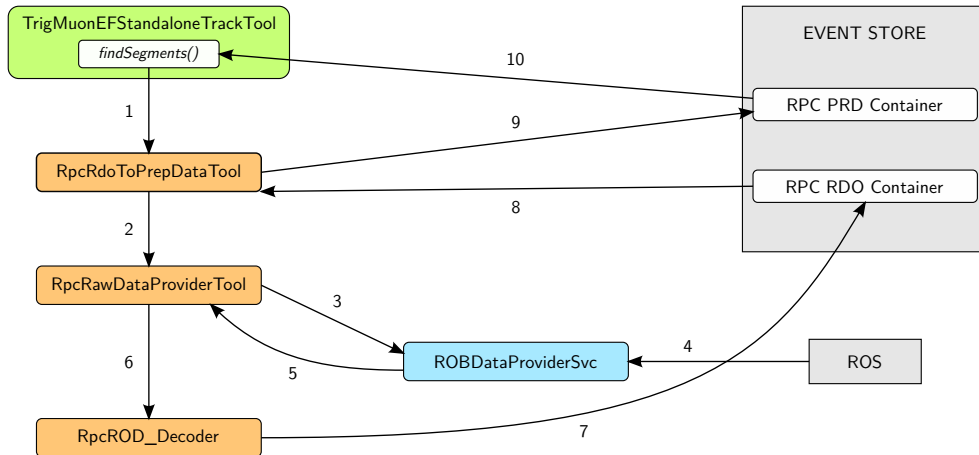


Figure 3.15: Schematic representation of the RPC data decoding process. At first, the track-segment finding method calls the RDO-to-PRD conversion tool (1). If the requested data are already decoded, the tool does nothing and the process goes immediately to step 10. Otherwise, the raw data provider is called (2) which requests the appropriate event fragments from the ROB data provider service (3). The service obtains the raw data from the corresponding ROBs in ROS (4) and returns them to the raw data provider (5). They are further passed to the ROD decoder (6), which performs the BS-to-RDO conversion and writes the converted data into RDO collections within their designated container in the Event Store (7). The RDO-to-PRD tool can then obtain these data (8), convert them and save the decoded PRD collections back into the Event Store (9). When all data are converted, the segment finder can retrieve them (10), build and pass them to the pattern-finding algorithm.

in the form $(z_{min}, z_{max}, r_{min}, r_{max}, \phi_{min}, \phi_{max}, \text{robId}, \text{prdId})$, i.e. assigns a geometrical region to each detector module corresponding to a single PRD collection and connected to a single ROB. The look-up tables are filled during initialisation of the service using software packages specific for each detector. The Region Selector provides methods which take an RoI descriptor object as an input and return a list of corresponding ROBs or PRD collections for a chosen subdetector.

Task 2: ROB predeclaration in TrigMuSuperEF

The ROB data access in the new HLT system is organised in the same way as in the old L2. The ROB data required during an algorithm execution are requested over the network from ROS and sent to the specific HLT computing node. Adopting all EF algorithms to this model increases the ROB data request rates which could become a limiting factor for the HLT throughput. This problem is partially addressed by a hardware upgrade of the ROS boards which are now able to process more requests in the same time. However, a software-side optimisation of the requests is also required. In general, grouping the required ROBs together and retrieving them in one request is more efficient than multiple individual requests. In order to achieve this behaviour, all L2 and EF algorithms executed in a certain trigger step are required to predeclare the list of ROBs from which they will read the data, knowing the coordinates of the RoI they need to process. All ROB data for this step are then sent from ROS and cached in the HLT node memory. Technically, the predeclaration is achieved by overriding a virtual method `prepareRobRequests` from the HLT algorithm base class, and is implemented in `TrigMuSuperEF` using ROB lists given by the Region Selector.

3.3.2 Problems

The usage of the Region Selector, seeded decoding and ROB predeclaration in `TrigMuSuperEF/TrigMuonEF` was implemented in the first year of LS1. During tests of the new features two problems were identified, as detailed below.

Problem 1: Seeded and full decoding give different results

When running `TrigMuonEF` in seeded and full decoding modes, it was observed that the two gave different results. Further investigation showed that the set of decoded PRD collections used for track-segment finding differs between the two modes. This should never happen, as the list of collections to be used by the segment finder is the very same list passed as input to the decoders in seeded mode. This issue introduced an unphysical bias in the kinematic properties of muons reconstructed by `TrigMuonEF`, as presented in Figure 3.16. The problem was tracked down to an unwanted behaviour of the `decode` methods of the respective RDO-to-PRD converters for three out of four MS subdetectors – MDT, RPC and CSC. The three problems turned out to be detector-specific and unrelated to each other. The introduced bias was different for each of the decoders and the situation seen in Figure 3.16 is a convolution of the three. It was later shown, for example, that the CSC decoder by itself was producing an excess of high- p_T tracks in the seeded mode, which is hidden here by other biases.

Problem 2: Region Selector does not provide ROB identifiers

Another issue was identified in the usage of the Region Selector to provide a list of ROBs for predeclaration in `TrigMuSuperEF`. It was realised that the ROB identifiers were never implemented in the Region Selector look-up tables for the MS subdetectors, as there has never been a need to

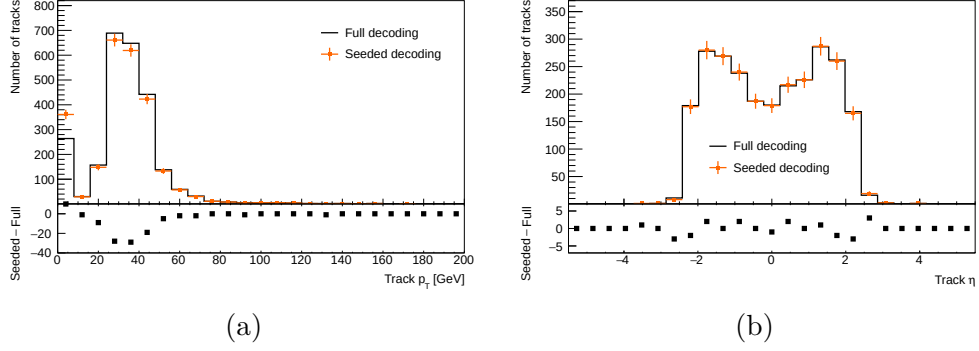


Figure 3.16: Transverse momentum (a) and pseudorapidity (b) distributions of tracks built by `TrigMuonEFStandaloneTrackTool` with the full and seeded decoding before fixes were applied. The bottom panels show the difference between number of tracks reconstructed with seeded and full decoding in each bin.

use them. There are four classes implementing the respective table creation called `XXX_RegionSelectorTable`, where `XXX` is either `MDT`, `RPC`, `TGC` or `CSC`. The table creation methods iterate over all detector modules and for each of them create a `RegSelModule` with corresponding geometrical parameters, ROB identifier and PRD collection identifier. Detector and layer identifiers are provided as well, but they are irrelevant for the developments described in this report. Each `RegSelModule` is then added to the look-up table, which is attached to the Region Selector service. For all four MS subdetectors, the ROB identifiers passed to the `RegSelModule` constructor were always zero. To meet the Run 2 trigger software requirements, valid ROB identifiers needed to be provided in each case, using specific detector-description software which also needed to be extended in some cases.

Summary of the solutions

Individual solutions were developed for each subdetector before the start of Run-2 physics data taking. The solutions for RPC, which turned out to be

the most complex, are described in detail in the following subsections¹. The most straightforward fix was provided for TGC, as there was no problem in decoding and the detector-description software could easily provide the ROB identifiers for the look-up table creator. CSC problems were slightly more complicated due to an upgrade of the CSC readout during the LS1, in which the number of RODs and ROBs was increased from 16 to 32. The new code had to provide correct results for both the Run-1 and Run-2 layouts, as the software tests could only be performed using Run-1 data at the time. The decoding problem was identified to be caused by an unhandled exceptional PRD collection identifier processed by the `decode` method. The discrepancies in MDT decoding were linked to the case when two chambers are read by one Chamber Service Module (CSM) and only data from the second chamber is requested for decoding. The data from one CSM could be only split when the first chamber was requested. In order to fix this issue, it was decided to use a different approach in the seeded decoding. Instead of using a method which decodes requested PRD collections corresponding to individual chambers, a new method was implemented which takes a vector of ROB identifiers, as an input and performs decoding of all data from the given ROBs, which corresponds to a single CSM. This approach was another motivation for resolving the Region Selector problem, as a valid list of ROB identifiers had to be provided for decoding. All solutions were thoroughly validated and proved to work well.

The data decoding and ROB predeclaration are similarly used in L2 algorithms, thus they were also affected by the same problems. Appropriate changes were applied to the L2 muon algorithm, **MuFast**, adapting the EF solutions and keeping consistency between the two.

¹The solutions for RPC were implemented by the author of this thesis, who also provided consultation for the CSC and TGC software modifications.

3.3.3 Improvements in RPC decoding

The specific role of RPC as an L1 Trigger detector is reflected in its readout hardware. The main segment of RPC front-end electronics is a PAD which processes signals from η and ϕ strips in all three RPC layers in a small $\eta - \phi$ region called a trigger tower. Each PAD consists of eight chips looking for hit coincidences between the reference layer and the high- and low- p_T layers. Each ROD processes information from several PADs and the data sent to ROS reflect the detector segmentation in η and ϕ , but not in R . The organisation of readout electronics and the raw data format allows for an unambiguous determination of the layer and gas volume from which an η -strip hit comes. However, the ϕ -strip hits are ambiguous and their exact location has to be resolved on the software side, which is performed in the RDO-to-PRD decoder. The ambiguity is resolved by matching a fired ϕ -channel to a fired η -channel within the same gas volume. If no matching η -hit is found, all possible ϕ -hit locations are recorded. All the recorded ϕ -hits are then passed to the segment finder, even though all but one are likely fake (caused by electronic noise). The ambiguous hits are in different RPC layers, hence also in different PRD collections. In full decoding, all η -hits were decoded and processed, thus when there was a matching hit, it was always found. The ambiguities were rare and did not affect the overall track reconstruction efficiency. The seeded mode introduced a case when a matching hit was part of an unrequested collection, thus was not decoded and could not be found, which increased the number of ambiguities.

The problem of additional ambiguities was resolved by adding an extra loop in the RDO-to-PRD decoder. In seeded mode, when ambiguities are found, decoding is performed again for the ambiguous PRD collections including those which were not requested, but may contain the missing matching η -

hits. The solution was applied and thoroughly validated in December 2014. Several additional fixes were also provided for minor, but related bugs. It was proved that after the fixes the full and seeded modes give exactly the same results, as presented in Figure 3.17.

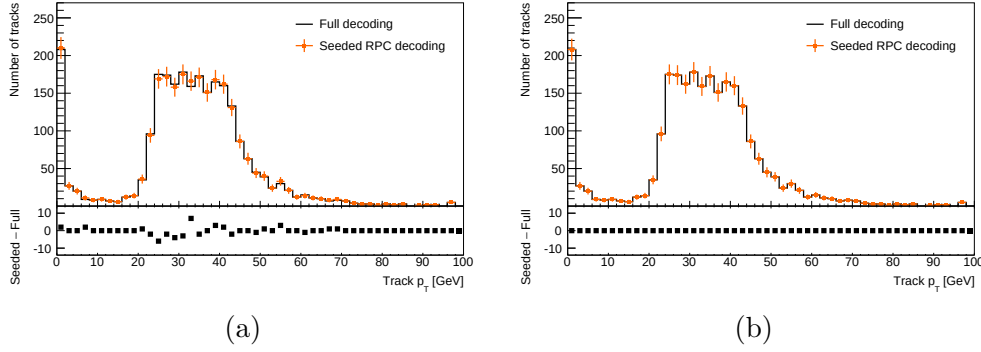


Figure 3.17: Transverse momentum distributions of tracks built by `TrigMuonEFStandaloneTrackTool` before (a) and after (b) the RPC decoding fixes were applied. Black lines represents the full decoding mode, whereas orange points represent the seeded decoding of RPC with full decoding of other subdetectors. The bottom panels show the difference between the two.

Although the PRD-based seeded decoding was fixed and works correctly, it was later shown that it cannot be used along with ROB predeclaration in `TrigMuSuperEF`. Due to an unusual layout of readout links between RPC front-end electronics and RODs explained in the next subsection, each PRD collection (i.e. a detector module) corresponds to two ROBs. If an RoI covered a part of a detector module read by one ROB, then only this ROB would be predeclared. The PRD-based decoding method would try to decode data from the whole module, requesting also data from the other – undeclared – ROB. The situation is depicted in Figure 3.18a. In order to resolve this problem, a ROB-based decoding method, similar as for MDT, was implemented in `TrigMuonEF` for Run 2. With this change, a set of RPC hits used to build a track segment is different (e.g. all hits from ROB #3 as

opposed to all hits from modules D, E, F in Figure 3.18a), which introduces a small bias. However, the only difference is due to noise hits which are close to the RoI but outside of it. The bias is therefore negligible and it was validated that the overall performance of **TrigMuonEF** is not affected. In addition, the problem of extra ambiguities in the seeded mode disappears in the ROB-based method, because full trigger towers are always decoded.

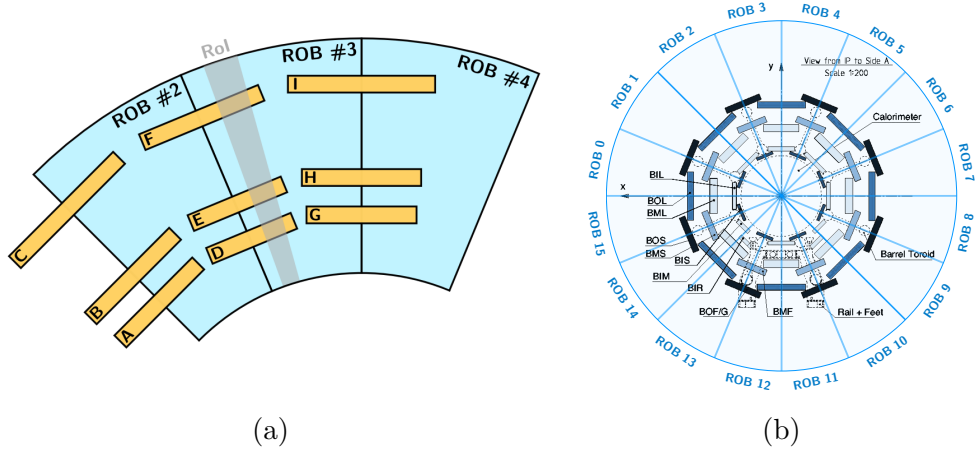


Figure 3.18: (a) Schematic example of an RoI covering only one ROB. (b) RPC ROB segmentation overlaid on a cross section of the MS barrel.

3.3.4 RPC ROBs in Region Selector

In order to provide valid RPC ROB identifiers in the Region Selector look-up table, it was required to implement a method mapping a PRD collection identifier into a single ROB identifier within the RPC detector description software. However, it turned out to be impossible due to the layout of the RPC readout system in which every detector module is read out by two different RODs, each connected to a separate ROB. During the detector design and construction, it has been decided to segment the readout system in sixteen more-or-less equal parts in ϕ , starting from the x -axis, and in two parts in z (positive and negative). This is indicated in Figure 3.18b. For each of the 32 regions, all PADs within the region are connected to one

ROD, which is then connected to one ROB in ROS. The choice was made many years ago when the detectors were first installed. It is currently recognised that segmentation shifted in ϕ by 11.25° would be more optimal for decoding, yet it has not been realised until recently that the present layout would cause significant problems. The layout could be changed fairly easily by swapping some of the links between PADs and RODs. However, when the problem emerged, the ATLAS cavern was already closed in preparation for Run 2. Therefore, the issue had to be resolved on the software side.

The constructor method of `RegSelModule` can only take a single ROB identifier as a parameter, thus implementation of ambiguous PRD-ROB mapping in the look-up table was not a trivial task. Several solutions were discussed:

- implementing two times smaller Region Selector modules, each corresponding to a unique PRD-ROB combination;
- creating two separate look-up tables – one for PRD collections and one for ROB;
- using RPC detector description software directly in `TrigMuonEF` instead of Region Selector;
- modifying `RegSelModule` to allow for multiple ROB per module.

The first solution was chosen as the most optimal, although not free of caveats. The Region Selector internally creates also inverse look-up tables indexed by PRD collection identifiers. Therefore, the look-up table cannot contain two modules with the same identifier. To overcome this issue, masking of the identifiers was applied by adding a number shifted by 16 bits. The old modules have been divided in two equal parts in ϕ , which is a good approximation of the readout segmentation. In order to ensure that the Region Selector returns valid PRD collection identifiers, a new class derived

	Old module	New modules	
r [mm]	[7477.54, 7563.44]	[7477.54, 7563.44]	[7477.54, 7563.44]
z [mm]	[3550.45, 5230.44]	[3550.45, 5230.44]	[3550.45, 5230.44]
ϕ [°]	[70.461, 96.2921]	[70.461, 83.3766]	[83.3766, 96.2921]
ROB id.	0x0	0x650003	0x650004
PRD coll. id.	0x8b	0x1008b	0x2008b

Table 3.1: Example of splitting one old `RegSelModule` into two new modules.

from the original look-up table class was implemented. It overrides methods returning identifiers and unmask them. An example of the module splitting is presented in Table 3.1 and a full visualisation of the old and new modules is shown in Figure 3.19.

3.3.5 Summary

During the implementation of new data access model in the merged HLT system, a number of problems related to muon detectors data decoding were encountered. The solutions required the implementation of new ROB-based decoding methods for MDT and RPC and modifications of the RPC detector description software. The new seeded decoding including the ROB-based methods, as well as the ROB predeclaration in `TrigMuSuperEF`, have been successfully used throughout Run 2. Further modifications of the decoders are foreseen for Run 3 in order to adopt them to a new multithreaded framework, where an explicit algorithm-level (rather than tool-level) RoI-based data access is required. In addition, new decoders have to be developed for new muon detectors planned to be installed in ATLAS during the next Long Shutdown [79].

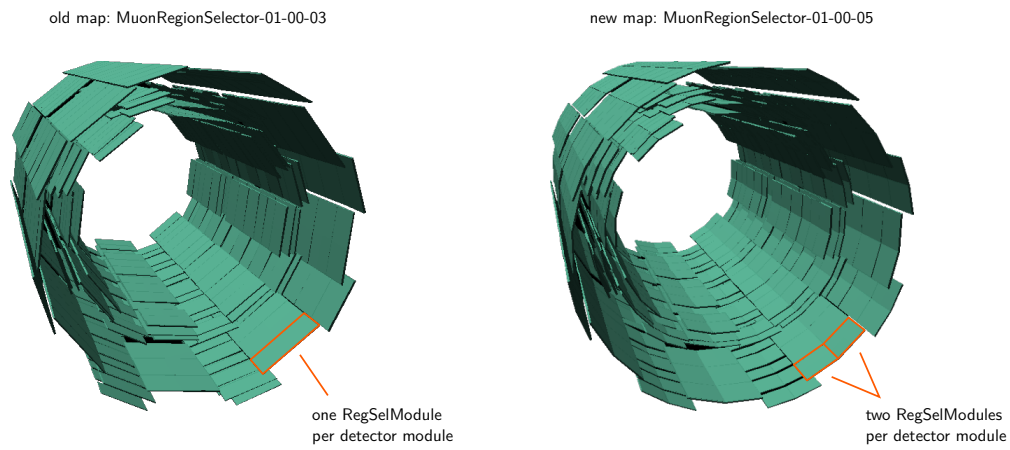


Figure 3.19: Visualisation of the `RegSelModules` in RPC Region Selector look-up table before and after changes including module splitting. `MuonRegionSelector` is the name of the software package containing look-up table creators for the MS subdetectors. The numbers tag the respective versions of this package.

Chapter 4

Analysis tools and methods

4.1 Object reconstruction

Raw data saved to ATLAS disks after online selection (trigger) are subsequently converted into object-oriented formats describing hits and energy deposits serving as an input to physics object reconstruction algorithms. The reconstructed objects include electrons, photons, muons, taus, jets and MET. In the following subsections, the reconstruction and identification of electrons, muons, jets and MET are described. The words *electrons* and *muons* are used throughout the document to collectively refer to both positively and negatively charged leptons of each generation. Photons and taus are omitted as they are not used in the analyses presented in this thesis, however the relevant reconstruction techniques and evaluation of their performance can be found in References [80–83]. Each of the following subsections summarises also the techniques of object calibration, which includes optimisation of reconstruction algorithm parameters as well as the derivation of correction factors for the relevant objects in MC simulation. The correction factors account for imprecision in detector simulation and local or temporary data-taking inefficiencies. This is crucial for measurements and searches relying on MC simulation to define kinematic cuts, calculate selection efficiency or unfold the observed distributions to particle level.

4.1.1 Electrons

Detailed performance studies of ATLAS electron reconstruction and identification techniques are available in References [84, 85]. Detector elements and concepts used in the procedure are presented schematically in Figure 4.1. The reconstruction starts with seeking cluster seeds with an energy above 2.5 GeV in the electromagnetic calorimeter using a sliding window with a size of $\Delta\eta \times \Delta\phi = 3 \times 5$ units, 0.025×0.025 each. Extended size clusters (3×7 in the barrel and 5×5 in the end-cap) are formed around the seeds and duplicates are removed. Tracks reconstructed using the Inner Detector information are extrapolated to the calorimeter region accounting for bremsstrahlung (up to 30 % energy loss is allowed at each material surface) and matched to the clusters. If multiple tracks are matched to a single cluster, tracks with a larger number of hits in silicon layers and closer to the cluster energy centre are prioritised. Clusters without any associated tracks are considered unconverted photon candidates. The angular coordinates of the reconstructed electron are defined by the matched track parameters at the primary interaction vertex. Its energy is reconstructed from the cluster energy deposit accounting for the energy loss before the calorimeter and for energy leakage outside of the cluster. The energy corrections are derived using multivariate analysis (MVA) techniques based on MC simulations. [86].

In addition to prompt electrons, background objects including hadrons and converted photons may be also reconstructed as electron candidates. Their contribution is minimised by using an MVA method where a likelihood-based discriminant $d_{\mathcal{L}} = \mathcal{L}_{\mathcal{S}} / (\mathcal{L}_{\mathcal{S}} + \mathcal{L}_{\mathcal{B}})$ is employed. $\mathcal{L}_{\mathcal{S}}$ and $\mathcal{L}_{\mathcal{B}}$ are signal and background likelihood functions defined as products of probability distributions of variables related to track-cluster matching, shower shapes in each electromagnetic calorimeter layer, energy leakage into the hadronic

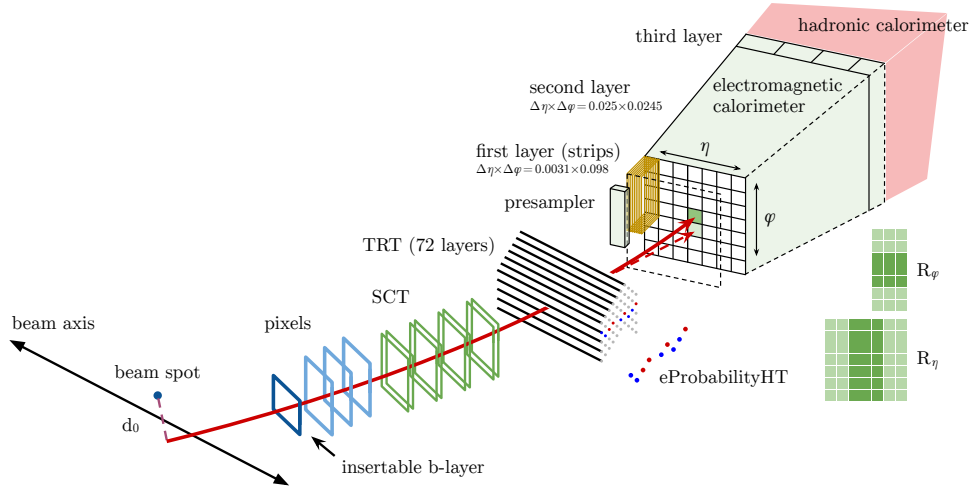


Figure 4.1: Elements of the electron reconstruction and identification algorithms [85].

calorimeters and the transition radiation in the TRT. Additional simple selection criteria are applied to the number of hits in different silicon layers. Three levels of identification operating points are defined – *Loose*, *Medium* and *Tight* – corresponding to different background rejection and signal efficiency. In order to further suppress the background from photon conversions and secondary particles, track-to-vertex association requirements are imposed, ensuring the distance of closest approach of an electron candidate track to the primary interaction vertex is sufficiently small.

Electrons are reconstructed and identified in the central region of ATLAS, $|\eta| < 2.47$, covered by both the Inner Detector and the calorimeters. A transition region between the barrel and end-cap electromagnetic calorimeters, $1.37 < |\eta| < 1.52$, is usually excluded from physics measurements and searches as it is characterised by large material budget resulting in low signal efficiency and impaired MC modelling. The signal efficiency is measured in data and simulation using the *tag-and-probe* method based on $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ events. In a sample of events with at least two electron

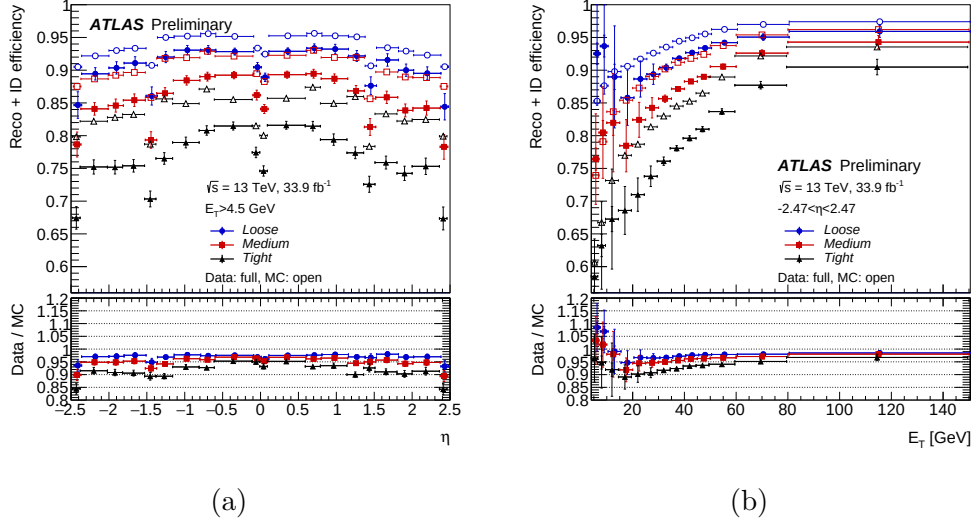


Figure 4.2: Electron reconstruction and identification efficiency measured in $Z \rightarrow ee$ events as a function of (a) pseudorapidity and (b) transverse energy. Only electrons with $E_T > 4.5$ GeV are considered and the three likelihood-based working points, Loose, Medium and Tight, are presented [87]. The dataset corresponds to $\mathcal{L}^{\text{int}} = 33.9 \text{ fb}^{-1}$ collected by ATLAS in 2016.

candidates, strict selection requirements are applied to one of them called the *tag*. The other candidate is considered a *probe* if the invariant mass of the two falls into a narrow window around either Z or J/ψ mass. The procedure provides an unbiased selection of probe electrons and allows to measure the signal efficiency in the E_T range 4.5–200 GeV. If the probe also satisfies the tag selection criteria, the pair is considered twice – as a tag-probe and a probe-tag pair. The combined reconstruction and identification efficiency measured for each of the three working points is presented in Figure 4.2. The observed discrepancy between data and simulation comes from an incomplete representation of TRT gas conditions and a mismodelling of calorimeter shower shapes in the MC, and is corrected in subsequent physics analysis by applying η - and E_T -dependent scaling factors.

An additional method of increasing the electron sample purity is to require their isolation, which is the lack of activity around the electron candidate. Isolation requirements can be defined for both, the calorimeter clusters and the ID tracks. In the first case, the variable $E_T^{\text{cone0.2}}$ is used, defined as the sum of calibrated transverse energy ($E_T = E \sin \theta$) contributions within $\Delta R < 0.2$ from the candidate cluster centre minus the cluster energy. The estimated energy leakage from the central cluster and the pileup contribution are also taken into account. The track isolation is based on $p_T^{\text{varcone0.2}}$, defined as the p_T -sum of all tracks within $\Delta R = \min(0.2, 10 \text{ GeV}/E_T)$ around the electron candidate track. The decreasing cone size helps to recover signal inefficiency for high- p_T electrons while providing good rejection of electrons coming from semileptonic decays of b - and c -hadrons. The tracks are required to originate from the primary vertex and the electron candidate together with the associated converted bremsstrahlung photons are excluded. Requirements on $E_T^{\text{cone0.2}}/E_T$ and $p_T^{\text{varcone0.2}}/E_T$ varying as a function of the electron transverse energy are optimised for a specific signal efficiency at $E_T = 25$ and 60 GeV . A working point corresponding to 90 % and 95 % efficiency respectively is called the default *gradient* isolation working point. The word *gradient* refers to the variation of the signal efficiency as a function of electron E_T . Isolation requirements are beneficial in analyses using final states with one electron or multiple electrons with large angular separation, but disadvantageous in selections where close-by electrons are considered signal.

4.1.2 Muons

The reconstruction of muons, explained comprehensively in Reference [88], starts from local straight-line pattern finding. A Hough transform [89] is used to search for particle tracks in the bending plane using hits from a single MDT chamber and the adjacent trigger chambers. In addition, the

non-bending direction is extracted from the RPC and TGC hits. The CSC pattern recognition employs an alternative algorithm incorporating the η and ϕ information as well as loose constraints on track to Interaction Point association. The individual track segments are subsequently fit to form candidate tracks across all detector layers. Combinations with the closest segment-to-track distance and the largest number of hits are prioritised and overlapping track candidates are removed. The MS tracks are then refit removing hits with large χ^2 and including additional hits if they are found to be compatible with the trajectory. In the next step, the tracks are extrapolated towards the centre of the detector and combined with tracks reconstructed independently in the ID. The reconstruction algorithms provide four types of muons:

Combined muons are formed by a global refit including hits from both, the MS and the ID. The MS tracks are first extrapolated inwards and matched to the tracks found in the ID reconstructing the majority of combined muons. A complementary matching starting from the ID and matching MS hits to extrapolated ID tracks is used to recover a small number of low- p_T tracks which did not form an MS track segment in the first approach.

Segment-tagged muons include only one MDT or CSC track segment matched to a track extrapolated from the ID. The algorithm recovers low- p_T muons reaching only the first MS layer and those passing through low-acceptance regions of the system.

Calorimeter-tagged muons are constructed by matching an ID track to a calorimeter energy deposit consistent with a minimum ionising particle. Although this type of muons suffers from large backgrounds, it is helpful to regain reconstruction efficiency in the $|\eta| < 0.1$ region only partially instrumented with muon chambers due to the presence of support structures

and cables.

Extrapolated muons are reconstructed using only MS hits and assume the track origin is close to the IP. They are used in regions beyond the ID acceptance, $2.5 < |\eta| < 2.7$.

The overlap between different types of muons sharing the same ID track is removed by giving the highest priority to combined muons, lower to segment-tagged and the lowest to calorimeter-tagged. The overlap with extrapolated muons is resolved basing on the goodness of fit and the number of hits.

The main source of background for prompt muon candidates are muons originating from decays of light hadrons (kaons and pions) within the ID. Four sets of identification criteria aiming to minimise the background and optimised for different use cases are defined: *Loose*, *Medium*, *Tight* and *High- p_T* . Medium muons serve as the baseline and include only combined muons within the ID acceptance, $|\eta| < 2.5$, and extrapolated muons in the range $2.5 < |\eta| < 2.7$. Further requirements are applied on the number of MS hits for each type of track and on the compatibility of the combined track charge-to-momentum ratio between the MS and the ID. Tight muons are optimised for the highest prompt muon purity at the cost of efficiency. They include only combined Medium muons with more stringent criteria applied on the MS-ID track compatibility. A low normalised χ^2 of the track fit is also required. Loose muons include all Medium muons with the addition of segment-tagged and calorimeter-tagged muons in the $|\eta| < 0.1$ region. The Loose selection provides the highest overall signal efficiency and was designed for the analysis of multi-muon decay modes, for example $H \rightarrow ZZ \rightarrow 4\mu$. The High- p_T identification working point is optimised for use in searches for new heavy gauge bosons Z' and W' and reach the best

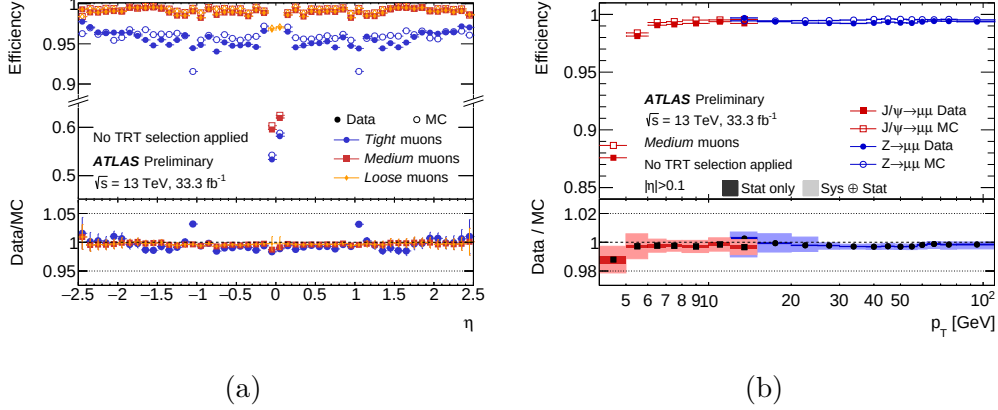


Figure 4.3: Muon reconstruction and identification efficiency measured in simulation and data collected by ATLAS in 2016 corresponding to $\mathcal{L}^{\text{int}} = 33.3 \text{ fb}^{-1}$ [90]. (a) The efficiency measured as a function of muon η for Loose, Medium and Tight muons with $p_T > 10 \text{ GeV}$ coming from $Z \rightarrow \mu\mu$ decays. (b) The Medium muon efficiency measured as a function of its p_T using muons from $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ decays. The $|\eta| < 0.1$ region is excluded.

momentum resolution for muons with $p_T > 100 \text{ GeV}$. They are based on combined Medium muons requiring hits in three MDT stations and excluding regions with suboptimal detector alignment.

Muon reconstruction and identification efficiency is measured in data and simulated samples in an analogous way to the electron measurements. The tag-and-probe method using dimuon decays of Z and J/ψ is employed. The efficiency measured as a function of muon η and p_T is presented in Figure 4.3. The discrepancy between data and simulation is smaller in comparison to electrons and comes mainly from local misalignments and data taking inefficiencies. The data/MC efficiency ratio serves as a correction to the simulation used for physics analysis.

A fraction of muons coming from semileptonic decays of heavy flavour hadrons may also satisfy the above reconstruction and identification criteria.

Since they are typically produced in the same direction as the hadronic decay products, this type of background can be significantly reduced by applying muon isolation criteria. Variables and working point definitions similar to the previously described electron isolation are used. The track isolation is based on $p_{\text{T}}^{\text{varcone0.3}}$ where the track transverse momenta are summed within a cone of $\Delta R = \min(0.3, 10 \text{ GeV}/E_{\text{T}})$ around the muon. Calorimeter isolation utilises the $E_{\text{T}}^{\text{cone0.2}}$ variable accounting for the muon energy deposit and pileup effects. The default gradient isolation working point is optimised for 90% efficiency at $p_{\text{T}} = 25 \text{ GeV}$ and 99% at 60 GeV .

4.1.3 Jets

The standard ATLAS jet reconstruction algorithm builds jets from *topo-clusters*, which are three-dimensional clusters of topologically connected calorimeter cells with high signal significance defined as the ratio of the deposited energy to the average noise level [91]. The noise thresholds are estimated from measured electronic noise and simulated pileup effects. Cell energies are measured at the scale corresponding to the energy deposited by electromagnetically interacting particles. The topo-clustering algorithm performs an implicit noise suppression and takes advantage of the fine segmentation of ATLAS calorimeters. The resulting topo-clusters are used as an input to the anti- k_t jet clustering algorithm [16] (see also Section 2.2.1) as implemented in the FASTJET software package [92]. The standard ATLAS jets are reconstructed with a radius parameter $R = 0.4$ and a transverse momentum of at least 7 GeV .

Reconstructed jet four-momenta are calibrated to correspond to those of particle-level jets in MC simulation (also called *truth* jets), defined by the anti- k_t algorithm applied to stable final-state particles (lifetime $c\tau > 10 \text{ mm}$). Muons, neutrinos and particles originating from pileup interactions are ex-

cluded from the truth jet definition. Several MC-based methods are employed to correct the detector-level jets for features of the detector, the clustering algorithm, jet fragmentation and pileup [93]. In addition, *in situ* techniques are used to determine and correct the differences between data and simulation. The MC-based calibrations are applied to both, data and simulation, whereas the *in situ* corrections are applied only to data. All stages of jet calibration are summarised in Figure 4.4.

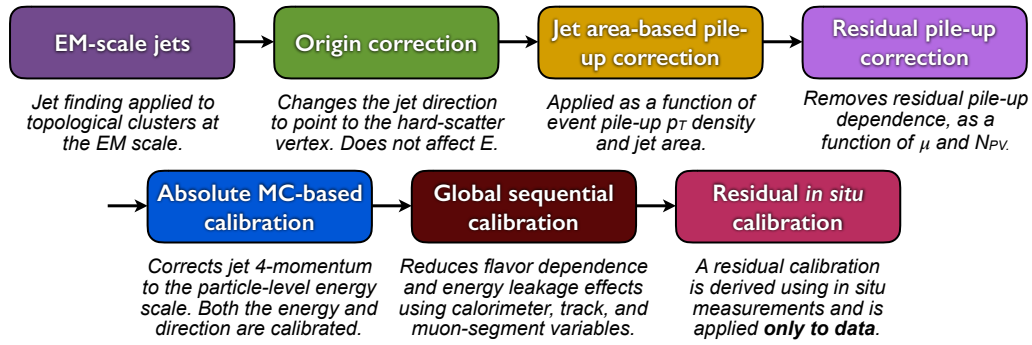


Figure 4.4: The stages of jet calibration in ATLAS [93].

During reconstruction, jets are assumed to originate from the nominal Interaction Point. In the first step of the calibration, their three-momenta are adjusted to point towards the hard interaction vertex, which improves the jet η -resolution, particularly for high- p_T jets. The jet energy remains unchanged in this step. The pileup contribution is then subtracted using the jet area method [94]. Since the jet p_T density used in the subtraction is calculated only in the central lower-occupancy regions of the detector, a residual pileup dependence of the jet p_T remains and is largest in the forward regions. It is removed by applying a correction derived in MC simulation and validated using independent *in situ* techniques. In the next step, two MC-based corrections are applied bringing the absolute reconstructed jet energy to the particle-level scale and removing an η -bias in the detector transition regions between the barrel and the end-caps as well as

between the main end-cap calorimeters and FCal. Further improvements are obtained with the global sequential calibration procedure removing the jet energy dependence on five observables sensitive to the type of initiating particles (quarks or gluons). The observables include the fractions of jet energy measured in the third electromagnetic LAr calorimeter layer and the first hadronic Tile layer, the number of ID tracks matched to the jet and their average distance from the jet axis, as well as the number of matched MS track segments. The average jet energy in the event is conserved in each of these corrections.

In the last calibration step, *in situ* corrections are derived to remove the residual discrepancy between data and simulation arising from imperfect description of the detector geometry and material, as well as the physical processes involved in jet production, fragmentation and interaction with the detector. The data-simulation difference is determined by balancing jet p_T against the p_T of other well-measured objects and evaluating the response $\mathcal{R}_{in\ situ}$ defined as the p_T ratio of the jet to the reference object. The correction factor is defined as the $\mathcal{R}_{in\ situ}$ ratio between data and simulation:

$$c = \frac{\mathcal{R}_{in\ situ}^{\text{data}}}{\mathcal{R}_{in\ situ}^{\text{MC}}}$$

and is evaluated as a function of jet p_T and η . The method is used with four types of reference objects. Central jets are used as the reference in calibration of forward jets in dijet events (a technique called the η -intercalibration), as presented in Figure 4.5a. Z bosons, photons or jets in a multijet system are used in complementary calibration studies focusing on different p_T ranges, which are later combined to obtain a single p_T -dependent correction as presented in Figure 4.5b

The amount of selected jets arising from pileup interactions may be further minimised using the Jet Vertex Tagger (JVT) algorithm [95], which provides

a likelihood discriminant based on tracking information. Three working points are defined, corresponding to a signal efficiency of around 85%, 92% and 97%. The JVT selection criteria are applied to central low- p_T jets only ($|\eta| < 2.4$, $p_T < 50$ GeV in 2015 or 60 GeV in 2016).

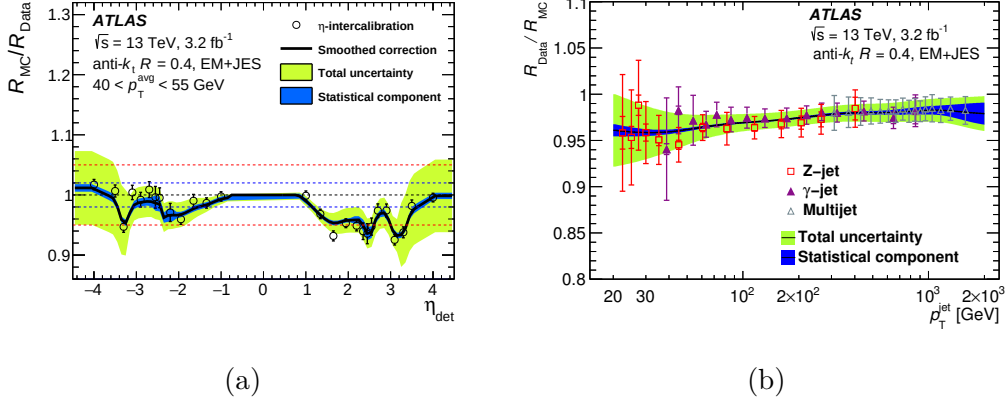


Figure 4.5: Data-to-simulation jet p_T response correction factor measured with the *in situ* calibration techniques [93]. (a) The result of the η -intercalibration correcting the forward jet response. (b) The Z boson, photon and multijet system calibrations as a function of jet p_T . The combined correction factor is presented as a black line with statistical and systematic uncertainty intervals.

4.1.4 b -jet tagging

Jets originating from decays of b -hadrons, commonly referred to as b -jets, may be identified thanks to the high mass and long lifetime of the hadrons. Their characteristic features include large multiplicity of tracks originating from a vertex measurably displaced from the primary hard interaction point and a high invariant mass of these tracks. A multivariate discriminant MV2 is constructed to identify b -jets in ATLAS using the boosted decision trees algorithm with the tracking and vertex information provided as the input [96]. The algorithm is trained on a simulated sample of b -jets, c -jets and light (u , d , s or gluon) jets produced in $t\bar{t}$ events. The initial Run 2 optimisation was performed using three background composition variants with

the c -jet (light jet) fractions of 20% (80%), 10% (90%) and 0% (100%). Their outputs are referred to as the MV2c20, MV2c10 and MV2c00 discriminants respectively. MV2c20 was found to provide the best background rejection at a given signal efficiency and was used as the standard b -tagging discriminant in the analysis of 2015 data. The multivariate algorithm was refined in 2016 and a new training with reduced charm contributions of 15% and 7% for MV2c20 and MV2c10 (the nomenclature remained unchanged) was performed [97]. The MV2c10 variant was then chosen as the standard b -tagging algorithm providing a similar light jet rejection and an improved c -jet rejection compared to the 2015 MV2c20 optimisation. The 2016 MV2c10 discriminant distribution for the three types of jets is presented in Figure 4.6. Figure 4.7 presents a comparison of the 2015 and 2016 background rejection performance.

A precise evaluation of the b -tagging efficiency, the probability of a c -jet or a light jet to be b -tagged (also called the *mistag* rates), and the systematic uncertainties associated with the three values is a crucial input for measurements and searches involving b -jets. In particular, the related uncertainties are among the main factors limiting the $t\bar{t}H(b\bar{b})$ search sensitivity [52] and the precision of $t\bar{t}b\bar{b}$ cross section measurements (Chapter 7). Several techniques to measure these efficiencies in data and derive the respective correction factors for simulated samples have been developed for Run 1 [98] and reused in Run 2. All Run 2 calibrations were performed for four working points corresponding to a signal efficiency of 60%, 70%, 77% and 85% as measured in the remaining part of the $t\bar{t}$ MC sample used for training. The corresponding cut values and background rejection rates are presented in Table 4.1.

The b -tagging signal efficiency is measured in dilepton $t\bar{t}$ events with two

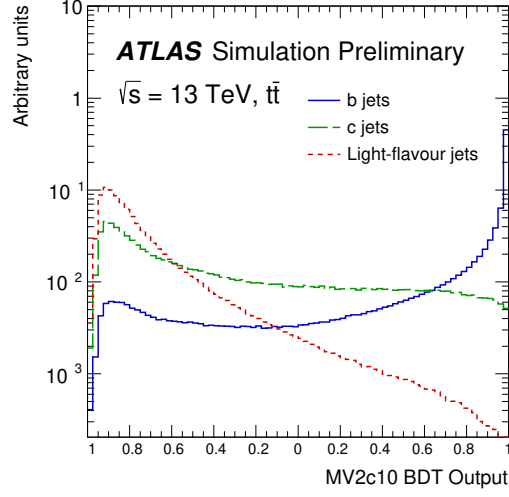


Figure 4.6: The 2016 MV2c10 discriminant distribution for b -, c - and light jets in simulated $t\bar{t}$ events [97].

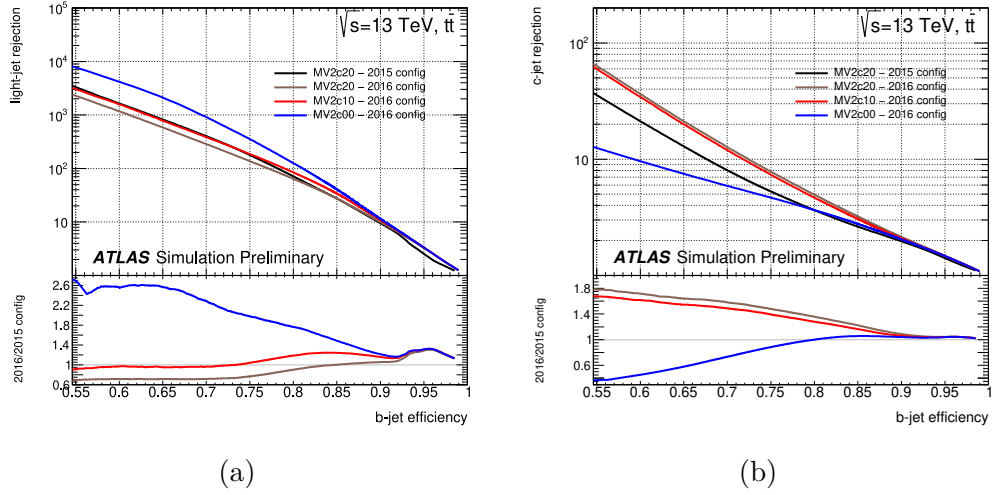


Figure 4.7: Light jet (a) and c -jet (b) rejection versus b -jet selection efficiency for the 2015 MV2c20 configuration compared to the three 2016 configurations [97].

BDT cut value	b -jet efficiency [%]	c -jet rejection	light jet rejection	τ rejection
0.9349	60	34	1538	184
0.8244	70	12	381	55
0.6459	77	6	134	22
0.1758	85	3.1	33	8.2

Table 4.1: Operating points for the MV2c10 b -tagging algorithm with the 2016 optimisation and training. Benchmark numbers for the efficiency and rejection factors extracted from $t\bar{t}$ events using jets with $p_T > 20$ GeV are also presented [97].

methods. One method is a tag-and-probe technique [99] where events with two leptons and exactly two jets are selected, and one of the jets (the *tag*) is required to be b -tagged. The tagging efficiency of the other jet (the *probe*) is measured and compared to the efficiency obtained from MC simulation. A selection based on kinematic properties of the event minimises the backgrounds and results in a pure sample of probe jets. Another signal efficiency calibration technique uses a combinatorial likelihood approach [98, 100] where an unbinned likelihood fit to data is performed. The likelihood function combines probability distribution functions for the b -tagging discriminant and p_T of the jets. The results of the two methods were found to be consistent within the estimated uncertainty intervals.

The c -jet mistag rate in Run 1 and at the beginning of Run 2 was determined using two techniques focusing on $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$ decays and on the associated production of a charm quark with a leptonically decaying W boson [98]. Both methods are based on exclusive c quark decays in topologies different from most ATLAS measurements and searches, and require evaluation of extrapolation factors introducing additional sources of systematic uncertainty. Moreover, their specific event selections provide

relatively low statistics compared to the benchmark $t\bar{t}$ process. A new calibration method was developed during Run 2 using c -jets from W decays in single lepton $t\bar{t}$ events [101]. Events with one electron or muon and exactly four jets are selected, and a kinematic likelihood technique is used to assign the jets to the $t\bar{t}$ decay products. A likelihood fit is then performed using the two jets from W to extract the c -jet tagging efficiency. Although the results are consistent with the previous methods within the uncertainty intervals, the data-to-MC scale factors were found to be systematically higher across all working points and jet p_T ranges, with a noticeably smaller uncertainty.

Light jets can be misidentified as b -jets mainly due to the finite resolution of the ID or interaction of particles with the detector material changing their trajectories. The amount of light jets coming from vertices behind and in front of the primary vertex (relative to the jet propagation direction) is therefore equal. This symmetry provides a base for the negative tag method [98, 102], where a ‘negative tagging’ algorithm is defined by inverting the internal track impact parameter and decay length selections in the nominal algorithm. The light jet mistag rate is then approximated by the negative tag rate in an inclusive jet sample.

4.1.5 Missing transverse energy

The transverse momentum conservation implies that the vector sum of transverse momenta of all final state particles produced in a proton-proton collision should equal zero. An imbalance in this sum, referred to as the missing transverse momentum, E_T^{miss} (see also Section 2.2.1), can be associated with undetected weakly interacting stable particles (neutrinos in the context of the SM). It is calculated using two types of contributions, the hard and the soft term:

$$\mathbf{E}_T^{\text{miss}} = \mathbf{E}_T^{\text{miss, hard}} + \mathbf{E}_T^{\text{miss, soft}},$$

where the hard term is a negative vectorial p_T sum of all hard objects selected and calibrated in a particular physics analysis. This ensures the best available calibration is used for the largest contributions in the sum. The soft term aims to account for all particles from the hard interaction which do not enter $\mathbf{E}_T^{\text{miss,hard}}$. It can be calculated either using calorimeter topoclusters or tracks matched to the primary interaction vertex, both unassociated to any of the selected hard objects [103]. The two approaches are referred to as the calorimeter-based soft term (CST) and the track-based soft term (TST). The former approach is more inclusive as it accounts for neutral particles and has access to the forward regions of the detector. However, it is susceptible to pileup contributions distorting the information about the total transverse momentum of objects produced in the hard interaction. The large pileup in Run 2 pp collisions in ATLAS led to the choice of the TST E_T^{miss} calculation as the standard procedure applied in the 13 TeV data analysis. Although it does not include contributions from neutral or forward ($|\eta| > 2.5$) particles, it is preferable thanks to its robust pileup independence coming from the good vertex identification ability of the Inner Detector.

The performance of E_T^{miss} reconstruction is typically studied in $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ events [104] which can be both robustly identified in data. The $Z \rightarrow \ell\ell$ process is expected to produce very low E_T^{miss} and provides a good environment to study the inherent bias of the reconstruction methods as well as the E_T^{miss} resolution. $W \rightarrow \ell\nu$ events feature a relatively high expected E_T^{miss} from the hard neutrino and allow to verify the reconstruction performance and the agreement between data and simulation. The TST E_T^{miss} scale and resolution measured in 2016 data using $Z \rightarrow ee$ events are presented in Figure 4.8.

4.2 Data and simulated samples

Measurements presented in the following chapters are based on three subsets of 13 TeV pp collision data collected by the ATLAS experiment in Run 2. The *early data* include events recorded in June and July 2015 with a 50 ns bunch spacing, corresponding to an integrated luminosity of 85 pb^{-1} . The 2015 and 2016 datasets include all events recorded in 13 TeV pp collisions with 25 ns bunch spacing in the respective years. Only data collected during stable beam conditions with a fully operational detector are considered. The 2015 and 2016 datasets correspond to an integrated luminosity of 3.2 fb^{-1} and 32.9 fb^{-1} respectively, thus their combination corresponds to 36.1 fb^{-1} . The average number of inelastic pp interactions per bunch crossing is 19 in the early data, 13 in the 2015 25 ns data and 24.5 in the 2016 data. The combination of 2015 and 2016 data is dominated by the latter, resulting in an average pileup of 23.5. The distribution of the average number of pp collisions per bunch crossing in each dataset is presented in Figure 4.9.

Simulated samples of $pp \rightarrow t\bar{t} + X$ signal events and several background processes are used in the presented measurements to estimate the signal and background composition, optimise the event selection, derive correction factors for the detector acceptance and resolution, and to estimate systematic uncertainties. Pileup is modelled by overlaying each sample with multiple inelastic pp collisions simulated with the PYTHIA 8.186 event generator [105] using the A2 parameter tune [106] and the MSTW2008LO set of PDFs [107]. The simulated pileup distributions were chosen to roughly correspond to those observed in data. Additional weights are assigned to all simulated events such that the pileup distribution of each simulated sample matches the analysed dataset closely. The total cross section of each generated sample is rescaled to the highest-order available calculation for the hard

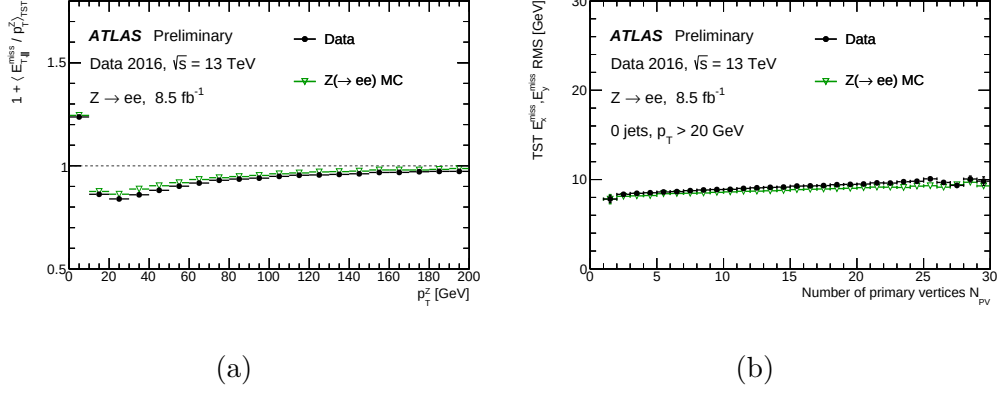


Figure 4.8: TST E_T^{miss} (a) scale and (b) resolution for a selection of $Z \rightarrow ee$ events in MC simulation and 2016 ATLAS pp collision data corresponding to $\mathcal{L}^{\text{int}} = 8.5 \text{ fb}^{-1}$ [104]. The scale is defined as the $\mathbf{E}_T^{\text{miss}}$ vector projection on the Z boson $\mathbf{p}_T$, shifted by one. Its deviation from unity is accounted to the loss of information from neutral particles and the limited ID acceptance in the TST evaluation.

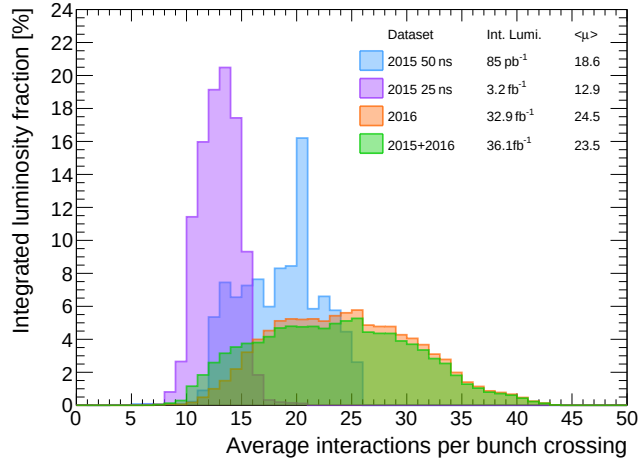


Figure 4.9: Distributions of the average number of interactions per bunch crossing (pileup) in the analysed datasets. Each distribution is normalised to 100%.

process. All MC samples are interfaced to a detector simulation [108] using the GEANT4 framework [109]. Two types of detector simulation are used – *full*, where the response of all detector elements is simulated with GEANT4, and *fast* which relies on a parametrisation of the calorimeter response [110]. The ID and MS are fully simulated in both approaches. Simulated events are processed using the same reconstruction algorithms and analysis chain as the data. Mismodelling in object reconstruction is corrected with calibration scale factors.

4.2.1 Top pair production

The early and full 2015 data measurements (Chapters 5 and 6) make use of samples of $t\bar{t}$ events generated with the POWHEG-BOX v2 NLO generator [111] using the CT10 PDF set [112] and interfaced to PYTHIA 6.428 [22] for parton showering. The EVTGEN package [113] is used to simulate the decays of charm and bottom hadrons. The h_{damp} parameter of the POWHEG method controlling the p_T of the first additional emission, against which the $t\bar{t}$ system recoils, is set to the mass of the top quark, $m_t = 172.5 \text{ GeV}$. It was found to be the optimal setting in studies based on 7 TeV ATLAS $t\bar{t}$ differential cross section measurements [114]. The renormalisation and factorisation scales are set to $\mu = \sqrt{m_t^2 + p_{T,t}^2}$. The underlying event description is based on the Perugia2012 tune [115] with the CTEQ6L PDF set [116]. Since only the ℓ +jets channel is considered, filtered samples with discarded all-hadronic $t\bar{t}$ events are used.

The uncertainties arising from the particular choice of MC models are estimated by comparing the nominal configuration to alternative samples. The effects associated with ISR and FSR are evaluated using two variations of the nominal POWHEG+PYTHIA6 sample – one with $h_{\text{damp}} = 2m_t$, the renormalisation and factorisation scales set to half the nominal value and

using the Perugia2012 ‘radHi’ tune, and another with $h_{\text{damp}} = m_t$, renormalisation and factorisation scales set to twice the nominal value and using the ‘radLo’ Perugia2012 variation. PS algorithm effects are estimated using a sample where the nominal POWHEG-BOX configuration is interfaced to HERWIG++ 2.7.1 [24] with the UE-EE-5 tune [117] and the CTEQ6L PDFs. The impact of the hard process NLO generator choice is evaluated using MADGRAPH5_aMC@NLO 2.1.1 [118] interfaced to the same HERWIG++ configuration.

The $t\bar{t}$ simulation configuration was updated and reoptimised in 2016 [43] and the new set of samples was used in the measurement presented in Chapter 7. The nominal sample is generated with POWHEG-BOX v2 interfaced to PYTHIA 8.210 [119] with $h_{\text{damp}} = 1.5m_t$ and the same renormalisation and factorisation scale settings as previously. The NNPDF3.0NLO PDF set [120] is used for the NLO generator, whereas the PS program uses NNPDF2.3LO [121] with the corresponding A14 set of tunable parameters [122]. Similarly to the 2015 configuration, the EVTGEN package is employed to simulate the decays of charm and bottom hadrons. Radiation effects are estimated using a sample with $h_{\text{damp}} = 3m_t$, half the nominal scale values and the A14Var3cUp tune variation, and a sample with $h_{\text{damp}} = 1.5m_t$, twice the nominal scale values and the A14Var3cDown tune. Uncertainties corresponding to the choice of the PS algorithm are evaluated with a sample generated with the nominal POWHEG-BOX configuration interfaced to HERWIG 7.01 [123] using the authors’ H7UE tune and the MMHT2014lo68cl PDFs [124]. The NLO generator uncertainty estimate makes use of a sample generated with MADGRAPH5_aMC@NLO 2.3.3 [118] and the NNPDF3.0NLO PDF set, interfaced to the nominal PYTHIA 8 configuration with EVTGEN.

Two additional samples were generated to compare against the $t\bar{t}b\bar{b}$ production cross section measurements described in Chapter 7, both utilising the SHERPA 2.2.1 generator [125]. One sample simulates inclusive $t\bar{t}$ production where the hard process generator describes events with zero or one additional jet (from QCD radiation) with NLO precision and events with up to four additional jets at LO. It exploits the MEPS@NLO matching method [126] which is an extension of MC@NLO designed specifically to match NLO predictions for multijet final states to parton shower generators. The other sample simulates the $t\bar{t}b\bar{b}$ production exclusively, following the methods outlined in Reference [59], where the COMIX [127] and OPEN-LOOPS [128] NLO generators are interfaced to SHERPA parton showering using the MC@NLO method. Both samples make use of the NNPDF3.0NNLO set of PDFs.

In all configurations, the $t\bar{t}$ samples are normalised to the total cross section of $\sigma_{t\bar{t}} = 832_{-51}^{+46}$ pb calculated to the NNLO precision with the Top++ 2.0 program [129] assuming the top quark mass $m_t = 172.5$ GeV. The nominal samples are simulated with both, full and fast detector simulation, whereas the alternative samples use the fast simulation only. The full-simulation nominal samples are used to derive efficiency and acceptance corrections for the measurements and in unfolding. The signal modelling uncertainties are evaluated by comparing fast-simulation alternative samples to fast-simulation nominal samples.

4.2.2 Other top quark processes

Single top production, one of the dominant backgrounds in $t\bar{t}$ measurements, is simulated separately in each of the three channels presented in Figure 2.6: the t -channel, the s -channel and the tW associated production. The tW and s -channel processes are generated with POWHEG-BOX v2 using the CT10 PDF set, whereas the electroweak t -channel simulation is based

on a 4FS NLO calculation implemented in POWHEG-BOX v1 with a dedicated CT10f4 PDF set. MADSPIN [130] is used to model top quark decays preserving spin correlations. The parton showering for all three processes is simulated with the same PYTHIA6 configuration as in the early Run 2 nominal $t\bar{t}$ sample described above. EVTGEN is used to simulate the decays of heavy flavour hadrons. Since the tW process interferes with $t\bar{t}$ production, the overlap has to be removed by applying either the *diagram removal* or the *diagram subtraction* mechanism [131]. The former is used to generate the nominal tW sample, whereas a sample implementing the latter approach is used to assess the systematic uncertainty due to the overlap removal prescription. The effects of initial- and final-state radiation are estimated using ‘radHi’ and ‘radLo’ samples with modified h_{damp} , analogous to those used in $t\bar{t}$ simulation.

Processes involving the production of a W , Z or a Higgs boson in addition to a $t\bar{t}$ pair are simulated using the MADGRAPH5_aMC@NLO generator with the NNPDF3.0NLO PDF set interfaced to PYTHIA 8 with the A14 tune and the NNPDF2.3LO PDFs. Top quarks are decayed by MADSPIN to preserve the spin correlation information. In case of the $t\bar{t}H$ process, the Higgs boson decays are simulated by PYTHIA 8, allowing all possible decay modes. All samples are normalised to NLO production cross-sections computed using MADGRAPH5_aMC@NLO. Details of this simulation are available in Reference [132].

4.2.3 Vector boson production in association with jets

W +jets, Z +jets and diboson ($WW/ZZ/WZ$) backgrounds in the measurements based on the 2015 datasets are estimated using samples simulated with the COMIX and OPENLOOPS NLO generators matched to SHERPA

2.1.1 PS using the MEPS@NLO method. The CT10 PDF set is used together with the underlying event tune provided by SHERPA. ATLAS measurements including the 2016 dataset make use of an updated W +jets and Z +jets simulation where the SHERPA version 2.2.1 is used, including an improved tune and the NNPDF3.0NNLO PDF set. The V +jets cross sections are normalised to NNLO calculations, whereas the diboson samples use the generator-level NLO cross sections. Details of all V +jets and diboson simulations can be found in References [133, 134].

4.3 Object and event selection

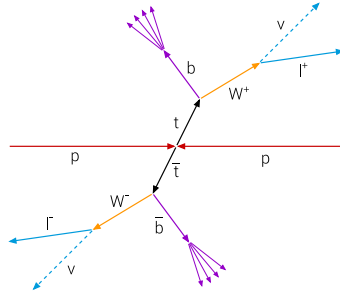
Measurements involving $t\bar{t}$ pairs explore all three decay channel categories – dilepton, ℓ +jets and all-hadronic. Typical event selections in each channel require the presence of two high- p_T b -jets and 2, 1 or 0 leptons respectively. At least 0, 2 or 4 additional jets are required from the hadronic decays of the W bosons. In the leptonic channels, only electrons and muons are usually considered due to the short lifetime and difficult reconstruction of tau leptons, which may decay both leptonically and hadronically. Although dedicated measurements with final-state taus have been performed in the past [135–138], they are normally omitted and contribute implicitly to the signal (for leptonic τ decays) or the background (for hadronic τ decays).

The discrepancy between measurements and models observed in the top quark p_T distribution as well as the new physics sensitivity of high- p_T top pairs (see Section 2.3.1) motivated the development of techniques increasing the high- p_T reach of $t\bar{t}$ cross section measurements. The loss of acceptance in events with high- p_T top quarks arises mainly from the small angular separation of their boosted decay products. Measurements exploring the boosted regime of hadronic top decays exploit an alternative jet clustering approach, where a single large- R (typically $R = 1.0$) jet is reconstructed

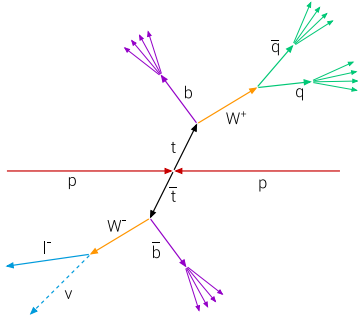
encompassing all decay products of the top quark (bqq'). Algorithms using information about the substructure of the large-R jets are employed to discriminate between top-like and background (mostly W -like) jets [139, 140] – a technique called *top-tagging*. Typical event topologies where all $t\bar{t}$ decay products can be resolved as well as the boosted topologies are presented in Figure 4.10.

The measurements presented in this thesis all focus on the resolved ℓ +jets topology. To select a clean sample of $t\bar{t}$ decays in this channel, events are first required to pass a combination of trigger chains corresponding to the lowest-threshold unprescaled single electron and single muon triggers. Since both types of single lepton triggers include trigger-level isolation criteria leading to a small inefficiency at high p_T , they are combined with higher-threshold triggers without isolation requirements to recover the full efficiency. In addition, looser identification criteria are used in the high-threshold electron triggers. All trigger requirements applied to the analysed datasets are summarised in Table 4.2.

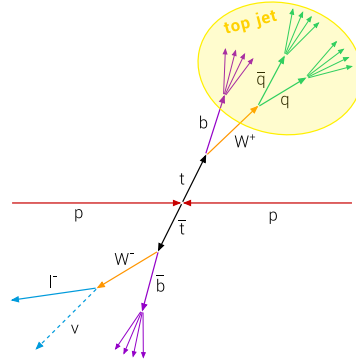
The early-2015 electron trigger selection requires events to be triggered by single electron chains with either 24 GeV or 60 GeV p_T thresholds. The latter chain does not apply any isolation criteria, whereas the former includes a $p_T^{\text{cone20}}/E_T < 0.1$ track isolation requirement and a Level-1 veto on any corresponding activity in the hadronic calorimeter. Both chains make use of the Medium identification working point (see Section 4.1.1). In the selections applied to 2015 data collected during collisions with 25 ns bunch spacing, the track isolation criterion is not applied. In addition, another high- p_T electron chain is added to recover signal electrons failing the Medium identification at trigger level. It makes use of the Loose identification criteria and requires p_T of at least 120 GeV. The same 60 GeV and 120 GeV chains



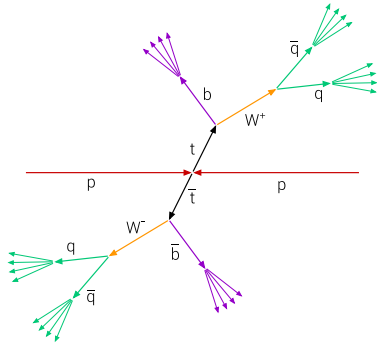
(a)



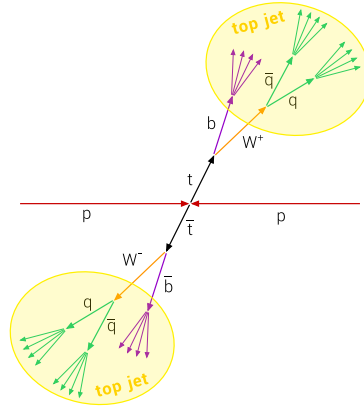
(b)



(c)



(d)



(e)

Figure 4.10: Five typical event topologies used in $t\bar{t}$ measurements: (a) dilepton, (b) ℓ +jets resolved, (c) ℓ +jets boosted, (d) all-hadronic resolved, (e) all-hadronic boosted.

were also used in 2016 selections, however the lowest unprescaled trigger had to be changed due to the increased instantaneous luminosity. It requires a p_T of at least 26 GeV and Tight identification, and includes both the track isolation criterion and the L1 veto on hadronic activity.

Identical muon trigger selections are applied to the early and full 2015 datasets, consisting of a logical combination of 20 GeV and 50 GeV threshold chains. The lower-threshold chain includes a loose track isolation requirement $p_T^{\text{cone20}}/p_T < 0.12$, whereas the higher-threshold chain does not apply any isolation criteria. The same high-threshold chain is also used in 2016 data selections, however, it is combined with a 24 GeV threshold chain including medium track isolation requirement $p_T^{\text{varcone30}}/p_T < 0.07$. All the exploited muon chains require the combined type of muon at the trigger level (see Section 4.1.2).

All events are required to be recorded during stable beam conditions when all detector and magnet subsystems were fully operational. The primary vertex has to be reconstructed with at least two associated tracks. An event is rejected if at least one jet is identified as coming from beam-induced backgrounds, cosmic shower or large coherent calorimeter noise, using the loose criteria discussed in Reference [141].

Only Tight electrons and Medium muons with $p_T > 25$ GeV are considered in the signal selections. Both types of leptons are required to pass the default gradient isolation criteria. Only muons within the pseudorapidity range $|\eta| < 2.5$ are used, whereas electrons are required to have their associated calorimeter cluster within $|\eta| < 2.47$ excluding the barrel to end-cap transition region $1.37 < |\eta| < 1.52$. The baseline $t\bar{t}$ selection requires the presence of exactly one such lepton, which also has to be matched geometrically to the corresponding trigger-level object. Due to the raised trigger

Dataset	Lepton	Threshold [GeV]	Identification	Isolation
2015 50 ns	e	24	Medium LH	L1 had. veto, $p_T^{\text{cone20}}/E_T < 0.1$
		60	Medium LH	–
2015 25 ns	e	24	Medium LH	L1 had. veto
		60	Medium LH	–
		120	Loose LH	–
2015	μ	20	Combined	$p_T^{\text{cone20}}/p_T < 0.12$
		50	Combined	–
2016	e	26	Tight LH	L1 had. veto, $p_T^{\text{varcone20}}/E_T < 0.1$
		60	Medium LH	–
		120	Loose LH	–
2016	μ	24	Combined	$p_T^{\text{varcone30}}/p_T < 0.07$
		50	Combined	–

Table 4.2: Trigger requirements applied to the 2015 and 2016 datasets. *LH* refers to the likelihood-based electron identification working points. *L1 had. veto* is a veto on a corresponding activity in the hadronic calorimeter applied in the Level-1 trigger. The $p_T^{(\text{var})\text{coneRR}}$ variables refer to the electron and muon track isolation defined in Sections 4.1.1 and 4.1.2.

p_T thresholds in 2016, the 2015+2016 measurement requires the leading lepton p_T to be above 27 GeV, which is in the nearly-full trigger efficiency region. A 25 GeV threshold is still applied for the sub-leading lepton veto. Dilepton events where one of the leptons has a $p_T < 25$ GeV are therefore included and constitute approximately 5 % of signal events in the baseline $t\bar{t}$ selection.

Jets are reconstructed using the anti- k_t algorithm [16] with $R = 0.4$ and are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. Different b -tagging working points are used in each measurement, as described in the respective chapters. One lepton, two b -jets and two other jets are required to select a pure sample of $t\bar{t}$ events. Further modifications from these selection requirements are

discussed in the subsequent chapters.

Due to the independent reconstruction of leptons and jets, a single object may be reconstructed as both. An *overlap removal* procedure is employed to minimise such double-counting. Electron clusters considered as jets are first removed by discarding the jet which is the closest to an electron, if the distance $\Delta R(e, j)$ is smaller than 0.2. Subsequently, the impact of non-prompt electrons is minimised by discarding all electrons within $\Delta R < 0.4$ from any jet. If less than three tracks are associated to a jet and the jet is within $\Delta R < 0.4$ from a muon, then the jet is discarded. Finally, if there is a muon within $\Delta R < 0.4$ from a jet with at least three tracks, the muon is removed. The association of tracks to jets is performed with the ghost matching method [142], where the track momenta are scaled to a negligible value and their four-vectors are included in the jet clustering algorithm. Tracks clustered as jet constituents are then defined to be associated with the jet.

4.4 Particle-level definitions

Differential and inclusive fiducial cross section measurements make use of particle-level simulated signal events to define the fiducial phase space and correct the observations for detector effects. The particle-level event selection includes only stable final-state particles with a lifetime $\tau > 30$ ps and follows the detector-level definitions closely.

Electrons and muons are required to not originate from a hadron (either directly or through a τ decay) resulting in a sample of electroweakly produced leptons without the need for a direct matching to W bosons. Four-momenta of photons within $\Delta R < 0.1$ from an electron or a muon are added to the lepton four-momentum to account for their final-state radiation. The lep-

tons are required to be within $|\eta| < 2.5$ and the same p_T selections as at the detector level are applied (either 25 or 27 GeV). The particle-level electron pseudorapidity selection does not exclude the barrel to end-cap calorimeter transition region, thus the simulation-based corrections extrapolate the measurement to the full $|\eta| < 2.5$ range.

Stable-particle four-momenta serve as an input to the anti- k_t jet clustering algorithm with the radius parameter $R = 0.4$ defining particle-level jets used in the measurements. Electrons, muons, their associated radiation photons, and neutrinos are not included in the jet clustering unless they originate from a hadron decay. The resulting jets are required to be within $|\eta| < 2.5$ and have $p_T > 25$ GeV. All jets from the hard process and the underlying event are included, whereas pileup jets are not considered. Particle-level b -jets are defined by requiring at least one b -hadron to be ghost-matched [142] to the jet. If no b -hadron, but at least one c -hadron is matched, the jet is considered a c -jet. The missing transverse momentum is defined as the vectorial p_T sum of all neutrinos in the event which do not originate from a hadron, either directly or through a τ decay.

The same lepton, jet and b -jet multiplicity requirements are applied at particle and detector level. No particle-level overlap removal is applied in the 2015 measurement (Chapter 6), whereas the 2015+2016 measurement (Chapter 7) requires the selected leptons to be separated from the selected jets by $\Delta R(\ell, j) > 0.4$. This requirement was overlooked in the 2015 measurement, which may slightly enhance signal modelling uncertainties as the corrections from detector level to particle level have to account for a larger difference between the two. However, the effect is expected to be small.

4.5 Background estimation

Events with processes other than $t\bar{t}$ production may also meet the selection criteria outlined in Section 4.3. The three dominant background sources comprise:

single top production (mainly in the tW and t-channel) with an additional jet coming from radiation, multi-parton interaction or pileup;

W boson production in association with multiple jets (two of which originate from b quarks or are misidentified as b -jets) where the boson decays leptonically;

multijet production, often called the *non-prompt and fake lepton* background, where the lepton comes from a semileptonic decay of a heavy flavour hadron, interactions of prompt particles with the detector material, or misidentification of a hadron as a lepton.

Sub-leading processes often also considered in the background estimate include the Z + jets and diboson production as well as the $t\bar{t}$ production in association with a vector boson ($t\bar{t}V$). The single top, Z + jets, diboson and $t\bar{t}V$ contributions are evaluated using MC simulations described in Section 4.2.2. The W + jets and multijet backgrounds are estimated using data-driven techniques outlined below.

4.5.1 W + jets

The production of W bosons with jets (in particular heavy-flavour jets) has been known to be associated with large modelling uncertainties increasing with the number of jets since before the start of the LHC [143], and large differences between models have been shown in the first ATLAS and CMS measurements [144, 145]. Therefore, starting from the very first ATLAS

measurements of $t\bar{t}$ production in the ℓ +jets channel [146, 147], data-driven techniques have been employed to estimate the amount of this background in the signal selection.

The samples described in Section 4.2.3 simulate the W +jets production at NLO for 0, 1 and 2 jets, and at LO for 3 and 4 jets in the hard process generator. Higher jet multiplicities are described by the PS simulation. Thanks to the implementation of internal generator weights for scale and PDF variations in the SHERPA 2.2 samples, a consistent evaluation of the theory uncertainties became possible. Detailed studies of V +jets modelling using these samples [148] show that the cross section uncertainty for the production of a W boson with at least four jets, relevant for the $t\bar{t}$ selections, is around 30–50%. The $t\bar{t}b\bar{b}$ cross section measurement, which uses the SHERPA 2.2 samples and is affected by the W +jets background to a smaller extent than $t\bar{t}$ measurements, uses only the MC predictions with the associated scale and PDF uncertainties. Both $t\bar{t}$ cross section measurements use distribution shapes predicted by the SHERPA 2.1 simulation with a data-driven overall normalisation correction. In addition, the differential measurement presented in Chapter 6 applies a flavour composition correction where the fractions of $W + b\bar{b}$, $W + c\bar{c}$, $W + c$ and W + light jets events are adjusted in a data control region.

The overall normalisation correction is based on the charge asymmetry in W boson production in pp collisions [149], which is well predicted and less sensitive to uncertainties than absolute W +jets yields. It can be quantified using the number of single-lepton events with positive and negative leptons:

$$\mathcal{A}_W^\ell = \frac{N_W^+ - N_W^-}{N_W^+ + N_W^-}.$$

Since $t\bar{t}$ events are expected to be charge-symmetric, the difference between the number of data events with positive and negative leptons, $N_{\text{data}}^+ - N_{\text{data}}^-$

arises mainly from W +jets events and can be used to estimate their number. Single top, $t\bar{t}V$ and diboson events can also contribute to the charge asymmetry by a small amount, thus their yields obtained from MC simulation are subtracted. The number of W +jets events can be therefore expressed as:

$$N_{W,DD} = \frac{(N_{\text{data}}^+ - N_{\text{MC,non-W}}^+) - (N_{\text{data}}^- - N_{\text{MC,non-W}}^-)}{\mathcal{A}_W^\ell},$$

where $\mathcal{A}_W^\ell$ is calculated using the nominal W +jets MC sample. The subscript DD denotes the data-driven yield estimates, whereas the subscript MC represents the simulated yields. The normalisation correction defined as the ratio of the data-driven to the simulated yields, $C_A = N_{W,DD}/N_{W,MC}$, is derived in control regions without any b -tagging requirements, dominated by W +jets events. It is then extrapolated to b -tagged selections using the MC simulation.

The flavour composition corrections are obtained using events with exactly two jets, one of which is b -tagged, after deriving the normalisation correction. The sample is split into four flavour categories ($W + b\bar{b}$, $W + c\bar{c}$, $W + c$, $W + \text{light jets}$) using information from the MC simulation and further divided into events with positive and negative leptons. The ratio of $W + b\bar{b}$ to $W + c\bar{c}$ contributions is fixed to a value obtained from the simulation.

A system of three equations:

$$\begin{pmatrix} C_A(N_{W^-,MC}^{b\bar{b}} + N_{W^-,MC}^{c\bar{c}}) & C_A N_{W^-,MC}^c & C_A N_{W^-,MC}^{\text{light}} \\ (f_{b\bar{b}} + f_{c\bar{c}}) & f_c & f_{\text{light}} \\ C_A(N_{W^+,MC}^{b\bar{b}} + N_{W^+,MC}^{c\bar{c}}) & C_A N_{W^+,MC}^c & C_A N_{W^+,MC}^{\text{light}} \end{pmatrix} \begin{pmatrix} K_{b\bar{b},c\bar{c}} \\ K_c \\ K_{\text{light}} \end{pmatrix} = \begin{pmatrix} N_{\text{data}}^+ \\ 1 \\ N_{\text{data}}^- \end{pmatrix} \quad (4.1)$$

is then solved to obtain the correction factors K_i for each category. The procedure follows that of Reference [150]. Taking into account the flavour composition corrections, the overall normalisation factor is derived again and this iterative procedure is repeated until the W +jets yield prediction agrees with data in the 2-jet region within 0.1%.

4.5.2 Non-prompt and fake leptons

Non-prompt leptons in events satisfying $t\bar{t}$ event selection requirements come mainly from semileptonic decays of heavy flavour hadrons within jets, where the lepton appears to be isolated. In addition, non-prompt electrons may arise from conversion of photons, whereas fake electrons are produced by misidentification of a jet with high electromagnetic energy (from the hadronisation to π^0 or early showering in the calorimeter). Non-prompt muons are also created by charged hadron decays within the ID. Fake muons may be produced by particles from high-energy hadronic showers escaping the hadronic calorimeter into the muon detectors (so-called ‘punch-through’ particles). The non-prompt and fake lepton background is considered an instrumental background as all these production mechanisms relate to subtle detector-specific effects. Although the described processes are relatively rare, they occur in multijet events produced with several orders of magnitude higher cross section than $t\bar{t}$ production, therefore can contribute significantly to $t\bar{t}$ signal selections. All-hadronic $t\bar{t}$ events with misidentified leptons also contribute to this background. Due to the difficult cross-section calculations for multijet events and the large suppression factor requiring very high statistics, this type of background cannot be simulated with a sufficient precision. It is therefore estimated using data-driven techniques.

Two types of multijet background estimation techniques were used in ATLAS Run 1 $t\bar{t}$ measurements – an approach based on fitting data-based templates in control regions, and the *matrix method*. A comprehensive study of the two approaches performed after Run 1 [151] showed that while they are consistent, the matrix method offers smaller uncertainties, whereas the fit method suffers from large uncertainties due to modelling of the template

shapes. The matrix method is therefore the leading approach in Run 2 $t\bar{t}$ production measurements in ATLAS.

Matrix method

The matrix method is based on selecting a sample enriched in fake and non-prompt leptons by defining looser identification and isolation requirements, and measuring the probability of these leptons to pass the signal selection criteria. This approach was first used for multijet background estimation nearly twenty years ago, in the 1999 D0 measurement of the W boson decay width [152], however without mathematical formalisation and the name *matrix method*. In the following years it became a standard method applied in D0 and CDF $t\bar{t}$ measurements in the single lepton channel and is still widely used by ATLAS and CMS nowadays.

Two levels of lepton selection requirements are defined – *tight* which is used in the nominal selection as described in Section 4.3 and *loose* with less stringent identification and isolation requirements. Differences between the two are summarised in Table 4.3. An inclusive data sample S is selected by requiring exactly one loose lepton and a relevant number of jets (e.g. ≥ 4 for the $t\bar{t}$ signal region). It can be divided into two disjoint sets of tight events T and exclusively loose events L depending on whether the lepton passes the tight requirements or not. One can also define the subset of events with real leptons R and with fake/non-prompt leptons F , which are disjoint while $T + L = R + F = S$ holds. The relation between the subsamples is depicted schematically in Figure 4.11. Background events contributing to the analysis signal selection are defined by the intersection of T and F . The matrix method is based on the equation:

$$\begin{pmatrix} \langle n_T \rangle \\ \langle n_L \rangle \end{pmatrix} = \begin{pmatrix} \varepsilon_r & \varepsilon_f \\ \bar{\varepsilon}_r & \bar{\varepsilon}_f \end{pmatrix} \begin{pmatrix} n_R \\ n_F \end{pmatrix},$$

	Loose selection	Tight selection
Electron identification level	Medium LH	Tight LH
Muon identification level	Medium	Medium
Lepton isolation requirement	None	Gradient

Table 4.3: Summary of the differences between loose and tight lepton selection requirements.

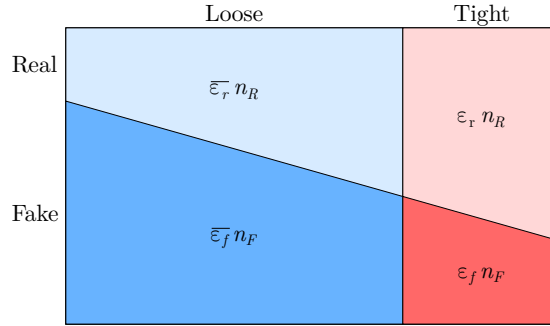


Figure 4.11: Schematic representation of the matrix method sample definitions.

which relates the expected number of tight and loose events, $\langle n_T \rangle$ and $\langle n_L \rangle$, to the unknown true number of real and fake events, n_R and n_F . The coefficient ε_r (ε_f) is defined as the probability of a real (fake) lepton to pass the tight selection criteria and it is called the *real (fake) efficiency*. The coefficients $\bar{\varepsilon}_i$ are defined as $\bar{\varepsilon}_i = 1 - \varepsilon_i$. The real (fake) efficiency is measured in a data control region dominated by real (fake) lepton events.

In order to estimate the number of fake leptons in the tight selection, $n_{TF} = \varepsilon_f n_F$, the equation can be inverted assuming $\varepsilon_r \neq \varepsilon_f$:

$$\begin{pmatrix} n_R \\ n_F \end{pmatrix} = \frac{1}{\varepsilon_r - \varepsilon_f} \begin{pmatrix} \bar{\varepsilon}_f & -\varepsilon_f \\ -\bar{\varepsilon}_r & \varepsilon_r \end{pmatrix} \begin{pmatrix} \langle n_T \rangle \\ \langle n_L \rangle \end{pmatrix} \quad (4.2)$$

and the estimator of n_{TF} can be constructed by using the observed numbers

of tight and loose events in place of the expectation values:

$$\hat{n}_{TF} = \varepsilon_f \hat{n}_F = \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} (\varepsilon_r (n_T + n_L) - n_T) . \quad (4.3)$$

To account for the dependency of the efficiencies ε_r and ε_f on the kinematic properties of events, they are parametrised in chosen observables and calculated per event accordingly. In practice, the estimation of the multijet background in a given bin of a certain distribution is realised by summing all loose and tight events i in that bin, weighted by:

$$w_i = \frac{\varepsilon_f^i}{\varepsilon_r^i - \varepsilon_f^i} (\varepsilon_r^i - \delta_{i \in T}) ,$$

where $\delta_{i \in T} = 1$ if the event passes the tight selection and 0 otherwise. The efficiencies ε_f^i and ε_r^i are taken from the parametrised measurements for the kinematic properties of the event i . The sum can be formally expressed as:

$$\hat{n}_{TF} = \sum_{i \in (L+T)} \frac{\varepsilon_f^i}{\varepsilon_r^i - \varepsilon_f^i} (\varepsilon_r^i - \delta_{i \in T}) . \quad (4.4)$$

Due to the difference $\varepsilon_r - \varepsilon_f$ appearing in the denominator, the results are the most stable if the difference is large. This has to be satisfied by the choice of sufficiently different loose and tight lepton selection criteria. The single-lepton case presented here can be generalised for use in the dilepton channel, where a 4×4 efficiency matrix is used and the expected numbers of events with either lepton being loose or tight are considered [151]. However, non-prompt and fake lepton events in the dilepton channel arise mostly from single-lepton $t\bar{t}$ or W +jets events where only the additional lepton is fake/non-prompt, and can be estimated using MC simulation with a data-driven normalisation correction.

Although the matrix method has been successfully used in numerous measurements, it has two known disadvantages. Firstly, it involves using observed numbers of loose and tight leptons in place of their expectation values, which in regions where $\langle n_L \rangle$ is small leads to negative predictions. To

illustrate it, one can consider an extreme example of $\langle n_L \rangle = 1$ in a certain selection, which is not a particularly unlikely scenario in high lepton p_T or high E_T^{miss} regions. The Poisson probability of observing 0 loose leptons is then equal to that of observing 1, which is around 37%. If $n_L = 0$ is used in Equation 4.3, it is clear the prediction will be negative. Negative predictions in certain bins of the measured distributions are usually forced to be zero, introducing differences in the total background yield estimate between different distributions.

Another difficulty of the matrix method is found in the parametrisation of the real and fake efficiency. Ideally, one has to identify all observables sensitive to the fake and non-prompt lepton production processes and measure the efficiencies differentially in all of them. N -dimensional differential measurements of these parameters are typically not feasible with the available statistics if $N > 2$, thus a combination of 1-dimensional and 2-dimensional measurements has to be developed. At least two combination methods have been used so far. One, documented in Reference [151], specifies two types of variables, x and y , and measures the efficiencies ε_k ($k = f, r$) differentially in all x -variables and one y -variable at a time, i.e. $\varepsilon_k = \varepsilon_k(x_1, \dots, x_N; y_j)$. The x -variables are discrete with a small number of bins (e.g. the number of jets and the number of b -jets in the event), whereas the y -variables are continuous with a larger number of bins (e.g. the lepton p_T). The combined efficiency is then calculated as:

$$\varepsilon_k(x_1, \dots, x_N; y_1, \dots, y_M) = \frac{1}{\varepsilon(x_1, \dots, x_N)^{M-1}} \prod_{j=1}^M \varepsilon_k(x_1, \dots, x_N; y_j),$$

where $\varepsilon(x_1, \dots, x_N)$ is averaged over all y -variables. This method is justified in Reference [151] as conserving correlations between the x -variables and each of the y -variables, although neglecting the correlations between different y -variables. It may, however, lead to pathological cases where the com-

bined efficiency is larger than unity. For example, if one considers the electron+jets channel and defines $\{x\} = \{N_{b\text{-jets}}\}$ and $\{y\} = \{p_{\text{T}}^e, \Delta\phi(\ell, E_{\text{T}}^{\text{miss}})\}$, where p_{T}^e is the electron p_{T} and $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$ is the azimuthal angle difference between the electron momentum and the $\mathbf{E}_{\text{T}}^{\text{miss}}$ vector, a likely scenario for a particular part of the phase space may be:

$$\varepsilon_r(N_{b\text{-jets}} = 2; p_{\text{T}}^e = 100 \text{ GeV}, \Delta\phi = 0.5) = \frac{1}{0.9^2} (0.99 \cdot 0.95) \approx 1.16.$$

An alternative approach is used in the measurements presented in Chapters 5 and 6, where no distinction between types of variables is made and a geometric mean of the efficiencies is used:

$$\varepsilon_k(x_1, \dots, x_N) = \sqrt[N]{\varepsilon_k(x_1) \cdot \varepsilon_k(x_2) \cdot \dots \cdot \varepsilon_k(x_N)}.$$

The geometric mean is always well-defined and never yields efficiencies outside the range $[0, 1]$. Furthermore, it is generally the preferred way of combining relative quantities [153]. Combinations between measurements in different number of dimensions are also possible with this method, for example:

$$\varepsilon_k(x_1, \dots, x_N) = \sqrt[M]{\varepsilon_k^{(1)}(x_1, x_2) \cdot \varepsilon_k^{(2)}(x_1, x_3) \cdot \varepsilon_k^{(3)}(x_4) \cdot \dots \cdot \varepsilon_k^{(M)}(x_N)},$$

where M is the number of combined measurements. The main disadvantage of combining lower-dimensional measurements into an N -dimensional estimate with either of the two methods is that strong dependencies are ‘washed out’ when combined with variables less sensitive to fake/non-prompt lepton production.

Study of a modified matrix method

During the background estimate developments for the differential $t\bar{t}$ cross section measurement, a modification to the matrix method was proposed

and briefly examined. Although it was not used in the final measurement, it is an interesting idea which could be further explored in the future.

The fake and real efficiencies introduced above can be formally defined as conditional probabilities:

$\varepsilon_r = P(T|R)$ – the probability of a real lepton to be identified as tight;

$\varepsilon_f = P(T|F)$ – the probability of a fake lepton to be identified as tight.

These are measured in F -dominated and R -dominated regions and can be calculated for different phase-space regions, i.e. parametrised. To estimate the number of fake leptons in the tight selection, n_{TF} , one can start from defining the probability of a tight lepton to be fake using the Bayes' theorem:

$$P(F|T) = \frac{P(T|F)P(F)}{P(T)}, \quad (4.5)$$

where $P(T|F) \equiv \varepsilon_f$. The probability of a lepton to be tight, $P(T)$, is the number of tight leptons divided by the total number of leptons in a particular phase-space region and can be named the *tight efficiency*:

$$\varepsilon_t = P(T) = \frac{\langle n_T \rangle}{\langle n_L \rangle + \langle n_T \rangle}.$$

Rather than evaluating ε_t per event, it can be measured and parametrised in a region close to the signal phase space, but with higher statistics, where the $\langle n_L \rangle \approx n_L$ approximation is valid. The last ingredient, $P(F)$, is the probability of a lepton to be fake, which is the number of fake leptons divided by the total number of leptons:

$$P(F) = \frac{n_F}{\langle n_L \rangle + \langle n_T \rangle},$$

where n_F is given by Equation 4.2, resulting in:

$$\begin{aligned}
P(F) &= \frac{n_F}{\langle n_L \rangle + \langle n_T \rangle} = \frac{1}{\langle n_L \rangle + \langle n_T \rangle} \frac{1}{\varepsilon_r - \varepsilon_f} (-\bar{\varepsilon}_r \langle n_T \rangle + \varepsilon_r \langle n_L \rangle) \\
&= \frac{1}{\langle n_L \rangle + \langle n_T \rangle} \frac{1}{\varepsilon_r - \varepsilon_f} (\varepsilon_r (\langle n_L \rangle + \langle n_T \rangle) - \langle n_T \rangle) \\
&= \frac{1}{\varepsilon_r - \varepsilon_f} \left(\varepsilon_r - \frac{\langle n_T \rangle}{\langle n_L \rangle + \langle n_T \rangle} \right) = \frac{\varepsilon_r - \varepsilon_t}{\varepsilon_r - \varepsilon_f}.
\end{aligned}$$

The above can be inserted into Equation 4.5, yielding:

$$\begin{aligned}
P(F|T) &= \frac{P(T|F)P(F)}{P(T)} = \frac{\varepsilon_f \varepsilon_r - \varepsilon_t}{\varepsilon_t \varepsilon_r - \varepsilon_f} \\
&= \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} \frac{\varepsilon_r - \varepsilon_t}{\varepsilon_t} = \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} \left(\frac{\varepsilon_r}{\varepsilon_t} - 1 \right).
\end{aligned}$$

Knowing the probability that a given tight lepton is fake, the number of fake tight leptons can be obtained through the sum:

$$\hat{n}_{TF} = \sum_{i \in T} P(F|T)_i = \sum_{i \in T} \frac{\varepsilon_f^i}{\varepsilon_r^i - \varepsilon_f^i} \left(\frac{\varepsilon_r^i}{\varepsilon_t^i} - 1 \right), \quad (4.6)$$

which in practice can be realised by iterating over the whole tight sample and filling a histogram in event i with $P(F|T)_i$ as the weight. For the results to be physical, the following conditions have to be met:

$$1 \geq P(F|T) \geq 0 \quad \Leftrightarrow \quad \varepsilon_r \geq \varepsilon_t \geq \varepsilon_f. \quad (4.7)$$

The similarity between Equations 4.4 and 4.6 is not accidental. It can be easily shown that the modified and standard matrix methods are exactly equivalent if constant efficiencies ε_k ($k = f, r, t$) averaged over all kinematic parameters are used in place of the parametrised ε_k^i . The two versions of the weighted sum of events may be written as:

$$\hat{n}_{TF}^{MM} = \sum_{i \in T} \frac{\varepsilon_f^i}{\varepsilon_r^i - \varepsilon_f^i} (\varepsilon_r^i - 1) + \sum_{i \in L} \frac{\varepsilon_f^i}{\varepsilon_r^i - \varepsilon_f^i} (\varepsilon_r^i - 0)$$

for the standard matrix method, and:

$$\hat{n}_{TF}^{MMM} = \sum_{i \in T} \frac{\varepsilon_f^i}{\varepsilon_r^i - \varepsilon_f^i} \left(\frac{\varepsilon_r^i}{\varepsilon_t^i} - 1 \right) + 0$$

for the modified version, highlighting the differences and similarities between the two. Using the constant (averaged) efficiencies, one obtains:

$$\begin{aligned}\hat{n}_{TF}^{MM} &= \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} (\varepsilon_r - 1) n_T + \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} \varepsilon_r^i n_L \\ &= \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} (\varepsilon_r n_T - n_T + \varepsilon_r n_L)\end{aligned}$$

and

$$\hat{n}_{TF}^{MMM} = \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} \left(\frac{\varepsilon_r^i}{\varepsilon_t^i} - 1 \right) n_T = \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} \left(\varepsilon_r \frac{n_L + n_T}{n_T} - 1 \right) n_T,$$

giving:

$$\hat{n}_{TF}^{MM} = \hat{n}_{TF}^{MMM} = \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} (\varepsilon_r (n_T + n_L) - n_T) .$$

The characteristic difference between the two methods is that the standard approach estimates the tight efficiency ‘on the fly’ when summing over all loose and tight events, whereas the modified version uses a tight efficiency measured in a higher-statistics region where the expectation values can be legitimately approximated by the observed values. Thanks to the probabilistic approach of the modified method, the event weights are always within the range $[0, 1]$ (given that the condition in Equation 4.7 is met) and negative yields are not possible. Example event weight distributions from the preliminary study are presented in Figure 4.12. It can be observed that the standard matrix method yields a large number of events with small negative weights and a moderate number of positively-weighted events distributed sparsely between 0 and 1, whereas only positive weights are given by the modified method.

A third intermediate approach can be defined by using the combined probability $P(F \cap T) = P(T|F)P(F)$ as the event weight, with the equivalent sum written as:

$$\hat{n}_{TF} = \sum_{i \in (T+L)} \frac{\varepsilon_f^i}{\varepsilon_r^i - \varepsilon_f^i} (\varepsilon_r^i - \varepsilon_t^i) .$$

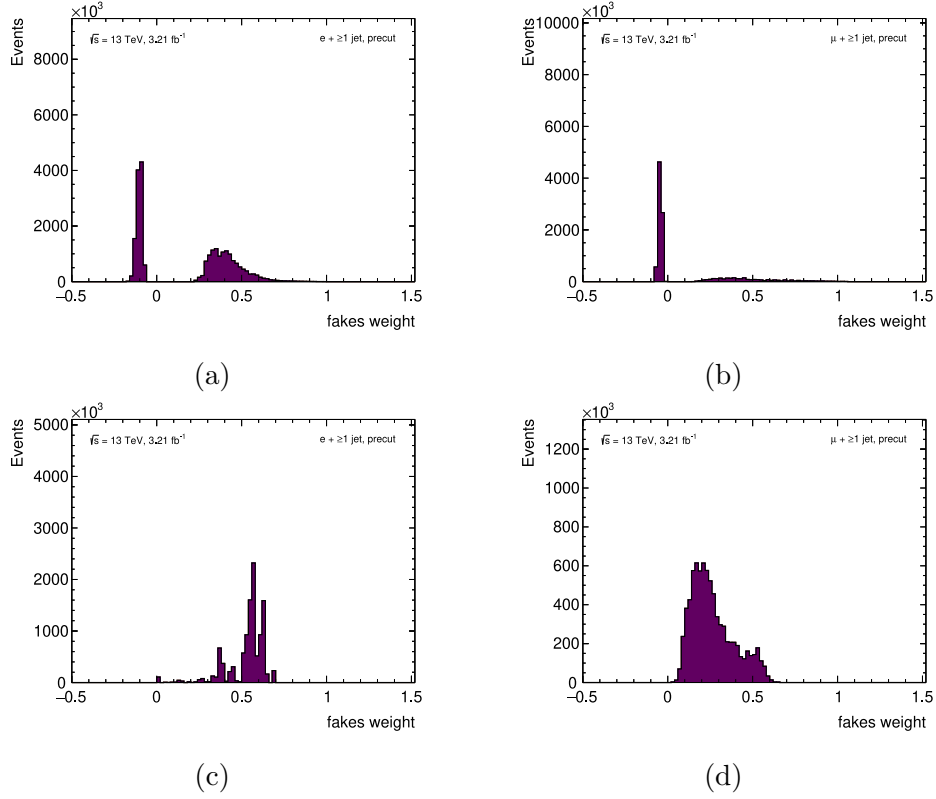


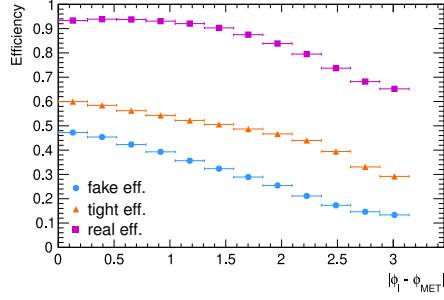
Figure 4.12: Example event weight distributions for fake/non-prompt lepton background estimation in the e +jets (a,c) and μ +jets (b,d) using the standard matrix method (a,b) and the modified version (c,d).

However, this approach was not investigated further.

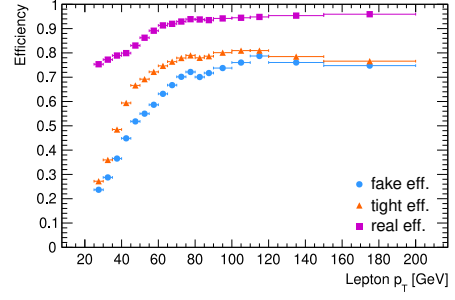
The efficiencies measured in this preliminary study are shown in Figures 4.13 and 4.14 for the e +jets and μ +jets channel respectively. The differences between the two channels are expected due to the different processes producing fake/non-prompt electrons and muons. The efficiency combinations used to obtain the distributions shown in Figure 4.12 are all calculated as a geometric mean of a few one-dimensional parametrisations. The muon channel combines the lepton p_T , E_T^{miss} , $\Delta\phi(\ell, E_T^{\text{miss}})$ and the number of b -tagged jets for both variants of the method. The electron channel uses the same combination for the standard matrix method, whereas only E_T^{miss}

and the number of b -tagged jets were combined for the modified version. The fake and real efficiencies are measured as described in Chapter 6. The tight efficiency is measured in an inclusive sample selected by requiring the presence of one lepton (loose or tight) and at least one jet without any b -tagging requirements. The study produced a number of predictions compared to data together with MC estimates of other processes in different validation regions. These included selections requiring at least one, exactly two, exactly three or at least four jets, and in the four-jet case also at least zero, one or two b -tags. A selection of results is presented in Figures 4.15 and 4.16. Here, m_T^W stands for the transverse mass of a W boson candidate, defined as $m_T^W = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos \Delta\phi(\ell, E_T^{\text{miss}}))}$. The figures show that the modified method can provide similar or better description of data in validation regions. In particular, the difference between the two methods is small in the $\mu + \geq 1$ jets region (Figure 4.15), whereas in the $\mu + \geq 3$ jets region (Figure 4.16) the modified method provides a better-matching normalisation. However, in both cases a residual discrepancy in the shape of the muon p_T distribution is present for both methods. The source of this discrepancy has not been investigated in details in this preliminary study. If similar discrepancy is observed in a measurement, it is often contained within the assigned systematic uncertainties.

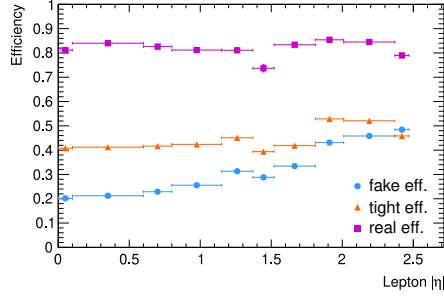
Three conclusions were drawn from the study. Firstly, the modified matrix method offers a promising alternative for the standard approach, especially in cases where negative predictions become problematic, and its implementation is feasible. The distributions presented in Figures 4.15 and 4.16 show the modified method provides equally good or better description of the data in validation regions as the standard method. Secondly, the introduction of a third efficiency emphasises the difficulties of the matrix method related to the efficiency measurements. The control regions where each efficiency



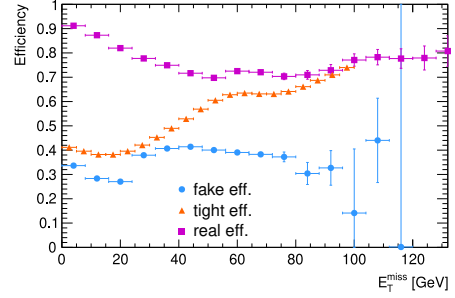
(a)



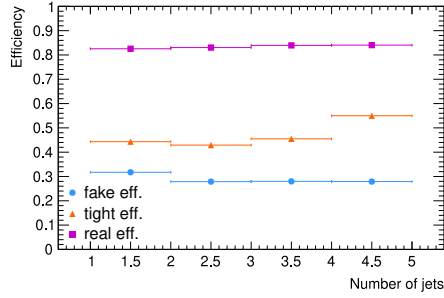
(b)



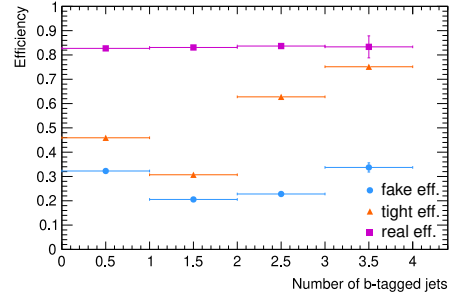
(c)



(d)

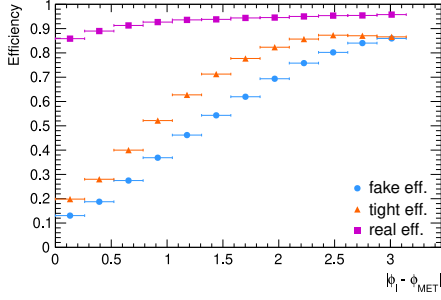


(e)

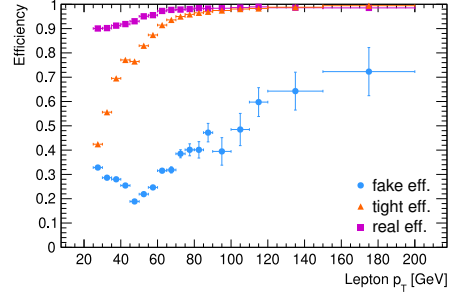


(f)

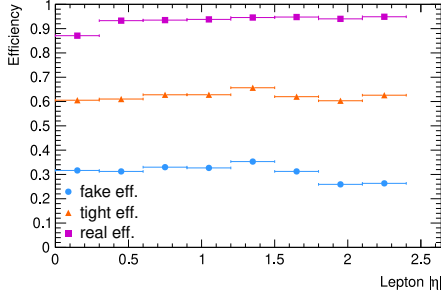
Figure 4.13: Example results of one-dimensional efficiency measurements for the $e+\text{jets}$ channel performed as part of the preliminary studies of the modified matrix method. Purple squares represent ε_r , orange triangles ε_t and blue circles ε_f .



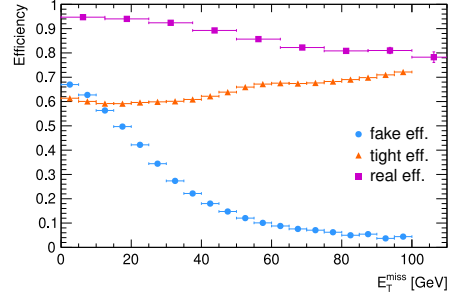
(a)



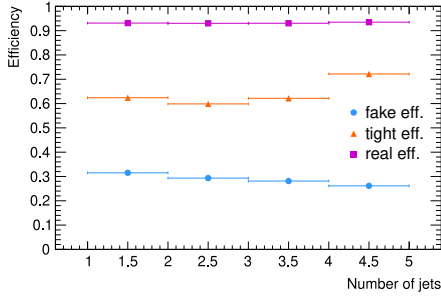
(b)



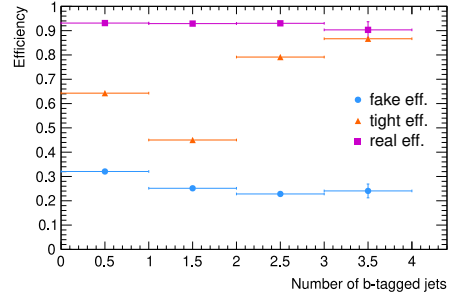
(c)



(d)



(e)



(f)

Figure 4.14: Example results of one-dimensional efficiency measurements for the μ +jets channel performed as part of the preliminary studies of the modified matrix method. Purple squares represent ε_r , orange triangles ε_t and blue circles ε_f .

is measured have to be chosen carefully to provide an appropriate sample composition and enough statistics, yet still be relatively close to the signal region such that the extrapolation is valid. Finally, it has been observed that the modified matrix method tends to predict multijet background distributions closely following the shape of the tight-lepton data sample in observables which are not directly considered in the parametrisation. It seems to be more sensitive to the choice of the combined parametrisations and the correlations between them. This feature can be seen particularly in Figures 4.16e and 4.16f, where the modified matrix method overestimates the amount of multijet background around the W peak in m_T^W and at high lepton p_T , where it is not expected. Although no further developments have been made beyond this study, it proves the method is promising and feasible, and after additional studies could be successfully used to estimate the fake/non-prompt lepton background in the ℓ +jets channel measurements.

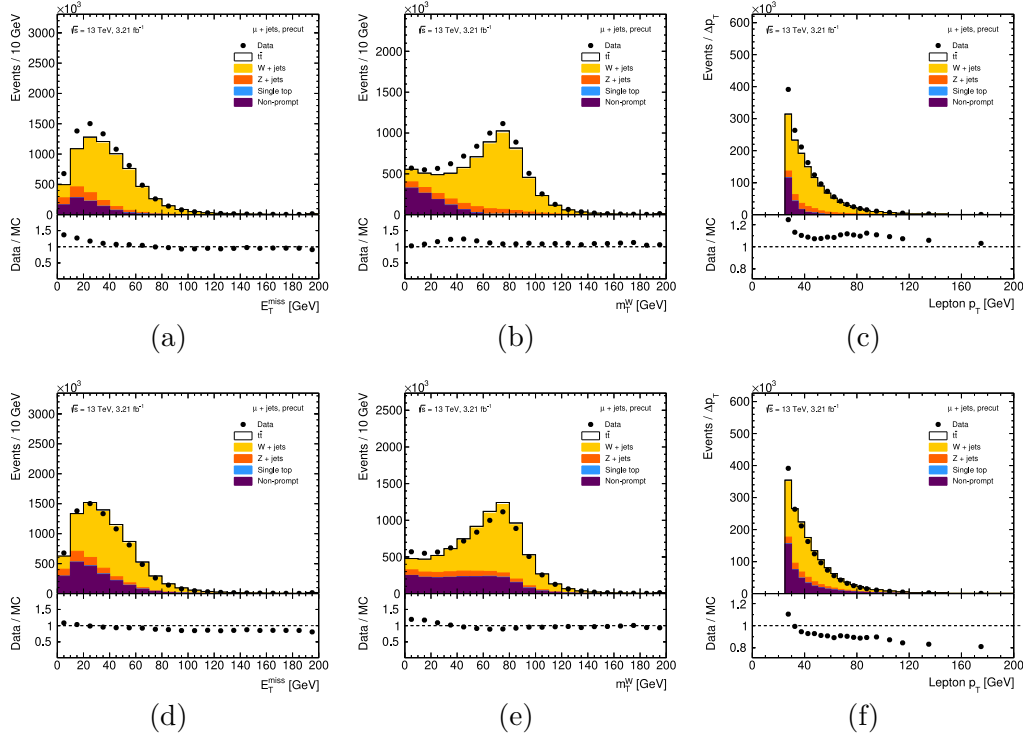


Figure 4.15: Control distributions for the μ +jets channel in a selection requiring the presence of one tight lepton and at least one jet without any b -tagging requirements. The top row (a, b, c) presents the results obtained using the standard matrix method, whereas the bottom row (d, e, f) shows the modified matrix method results.

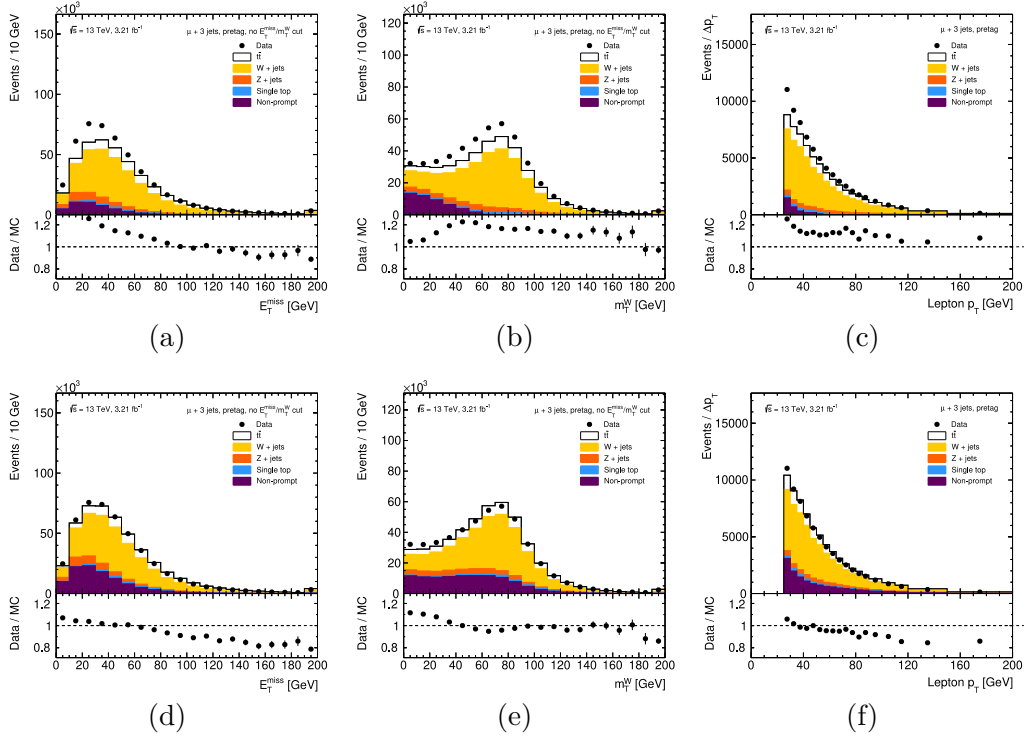


Figure 4.16: Control distributions for the μ +jets channel in a selection requiring the presence of one tight lepton and exactly three jets without any b -tagging requirements. The top row (a, b, c) presents the results obtained using the standard matrix method, whereas the bottom row (d, e, f) shows the modified matrix method results.

4.6 Unfolding

Measured differential distributions are often *unfolded* to either particle or parton level, which means they are corrected for detector effects, and optionally also for parton showering and hadronisation (see also Section 2.2.2). The particle-level distributions can be directly compared to similar results from different experiments, as well as to new simulated distributions without the need to re-simulate the detector response. Parton-level results have an additional advantage of being directly comparable to higher-order perturbative calculations, which cannot be easily incorporated in hadronisation simulations. The corrected effects are evaluated by a *migration matrix*, $\mathcal{M}$, describing bin migrations between the parton or particle level and the detector level.

The migration matrix could be simply inverted (if it is nonsingular) to obtain the desired corrections. This, however, could lead to problematic results due to similar sensitivity of the inversion to statistical fluctuations as presented for the multijet background estimation method presented in the previous section. A matrix equation describing the case of unfolding could be written as $\mathbf{E} = \mathcal{M}\mathbf{C}$, where $\mathbf{C}$ is a vector of the unknown true number of events in each bin and $\mathbf{E}$ is a vector of expectation values given the migrations described by $\mathcal{M}$. Estimating the true distribution by $\hat{\mathbf{C}} = \mathcal{M}^{-1}\mathbf{O}$ where the expectation values are $\mathbf{E}$ replaced by the observed spectrum $\mathbf{O}$ may seem attractive thanks to its simplicity, however may significantly enhance small fluctuations in data. The observed spectrum usually contains many bins and a large fraction of them may be associated with a sizeable statistical uncertainty. In particular, this often leads to large bin-to-bin anticorrelations. In extreme cases, it can also lead to negative yields.

In order to overcome the above problems, the effects of bin migrations (smearing) between the particle and detector level in the presented measurements are corrected using the iterative Bayesian unfolding method [154, 155] as implemented in the ROOUNFOLD software package [156]. It infers the posterior true distribution in the measurement starting from a prior which is the simulated particle-level spectrum, and updates it using the knowledge of the migration matrix. The bias towards the prior, which in general is not necessarily close to the unknown true distribution leading to the observations in data, is removed by repeating the procedure using the posterior of step n as the prior in step $n + 1$. This can be repeated several times further reducing the bias. However, large number of iterations may enhance statistical fluctuations in the unfolded result. The optimal number of iterations is individually adjusted in each measurement by selecting a number for which a χ^2 measure of compatibility between the prior and posterior reaches a plateau. At this point, further iterations do not bring the result closer to the true distribution, but only enhance statistical fluctuations in individual bins. The optimal number of iterations is typically found to be between 3 and 5.

Differential cross section measurements described in this thesis are presented at the particle level, corrected for detector acceptance, reconstruction efficiency and bin migrations. All corrections are derived using the signal MC simulation described in Section 4.2.1. Only events where the detector-level objects can be geometrically matched to their particle-level counterparts are considered in the migration correction. The matching requires $\Delta R < 0.02$ for electrons and muons and $\Delta R < 0.35$ for jets. The loss of events due to the matching is recovered by a correction factor $f_{\text{match}} = N_{\text{part \& reco \& matched}}/N_{\text{part \& reco}}$ calculated in each bin of the measured observable. Here, $N_{\text{part \& reco}}$ denotes the number of simulated events passing

both the particle-level and the detector-level selection criteria in that bin, whereas $N_{\text{part \& reco \& matched}}$ is the number of such events where the relevant objects are matched between the two levels. The matching correction varies typically between 0.5 and 0.9, depending on the observable and the analysis selection criteria. The acceptance correction $f_{\text{acc}} = N_{\text{part \& reco}}/N_{\text{reco}}$ accounts for events generated outside of the fiducial phase space at the particle level, but passing the detector-level selection. N_{reco} denotes the number of events passing the detector-level selection regardless of the particle level. The efficiency $\epsilon = N_{\text{part \& reco \& matched}}/N_{\text{part}}$ corrects for events which are generated within the fiducial phase space, but are not reconstructed at the detector level.

The differential cross section in bin i of a given particle-level observable x is calculated by applying all corrections and the iterative unfolding procedure to the background-subtracted observed spectrum:

$$\frac{d\sigma^{\text{fid}}}{dx^i} \equiv \frac{1}{\mathcal{L}^{\text{int}} \cdot \Delta x^i} \cdot \frac{1}{\epsilon^i} \cdot \sum_j \mathcal{M}_{ij}^{-1} \cdot f_{\text{match}}^i \cdot f_{\text{acc}}^i \cdot (N_{\text{reco}}^j - N_{\text{bkg}}^j),$$

where the index i refers to the particle-level bin and the index j iterates over the detector-level bins. N_{reco}^j is the number of events observed in data in the j -th bin and N_{bkg}^j is the corresponding estimated number of background events. Δx^i is the bin width and $\mathcal{L}^{\text{int}}$ is the integrated luminosity corresponding to the data sample. $\mathcal{M}^{-1}$ symbolises the iterative unfolding procedure and not a matrix inversion.

The unfolding procedure is validated using closure and stress tests. In the first case, two statistically independent MC samples are generated by randomly splitting the nominal signal sample. One part (sample A) is used to derive the migration matrix and the corrections, whereas the other part (sample B) is used as pseudo-data. The pseudo-data are unfolded using

the corrections from sample A and compared to particle-level distributions of sample B to verify the self-closure and stability of the method. Stress tests aim to ensure the unfolding procedure does not introduce a strong bias towards the distribution shapes of the nominal signal MC sample. They are performed by reweighting the sample at both particle and detector (pseudo-data) level, significantly changing the shape of a given distribution, for example by inserting a Gaussian peak in the $t\bar{t}$ system mass distribution. The reweighted pseudo-data are then unfolded using the nominal corrections and compared to the corresponding reweighted particle-level prediction.

4.7 Systematic uncertainties

Multiple sources of systematic uncertainty related to luminosity, object reconstruction and identification, background estimation, and signal modelling are considered in the presented measurements. The impact of each source on the final result is evaluated using the nominal simulated signal sample with exception of the signal modelling effects, which are determined by comparing the nominal sample to alternative models listed in Section 4.2.1. The effect of the 0.1 % beam energy uncertainty [157] is neglected, however it can be shown to be lower than 0.3 % for the inclusive $t\bar{t}$ cross section at 13 TeV. The individual sources of detector and background uncertainty and methods of their estimation are listed below. Signal modelling effects and propagation of all uncertainties to the final results in each of the presented measurements are described in their respective chapters. The dominant uncertainty sources typically observed in both inclusive and differential $t\bar{t}$ cross-section measurements are the signal modelling, jet energy scale measurement, and b -jet tagging and mistag efficiency.

Luminosity

The uncertainty on the integrated luminosity of the analysed datasets comes from calibration procedures using transverse (x and y) beam-separation scans [158] performed in several special runs throughout Run 2. The final calibration of 2015 luminosity, performed after the full data-taking period and applicable to both 50 ns and 25 ns data, yields an uncertainty of 2.1 %. However, at the time when the early-data measurement was performed (August 2015), only initial calibration studies were available, associated with an uncertainty of 9 %. The integrated luminosity of the 2016 dataset is evaluated with an uncertainty of 2.2 %. A partial correlation of the 2015 and 2016 uncertainties results in the final value of 2.1 % for the combined dataset.

Electrons and muons

Lepton reconstruction, identification and trigger efficiency scale factors as well as lepton momentum scales and resolutions are determined using $Z \rightarrow \ell\ell$ events selected in data and MC simulation, as described in Section 4.1. The associated uncertainties come from the methodology, background estimation, available statistics, and from detector alignment and performance. The effects of the lepton scale factors and their uncertainty are negligible compared to the dominant uncertainties in the ℓ +jets channel $t\bar{t}$ cross section measurements.

Jets and $E_{\text{T}}^{\text{miss}}$

The ℓ +jets channel is highly affected by jet energy scale (JES) and jet energy resolution (JER) uncertainties which modify the efficiency to select events with at least four jets having $p_{\text{T}} > 25$ GeV and influence the bin migrations in differential measurements. Up to 84 individual sources contributing to

the JES uncertainty are identified [93], most of which are related to the *in situ* calibration techniques described in Section 4.1.3. Other contributions include high- p_T jet response and pileup effects. The individual sources are combined into a reduced set of orthogonal nuisance parameters, defined differently for each of the three measurements presented in the following chapters. A single nuisance parameter is defined for the JER uncertainty coming from individual sources in both the MC-based and *in situ* measurement techniques. The uncertainty on the JVT selection efficiency is applied by varying the corresponding scale factor. It includes a statistical component as well as the uncertainty on the residual contamination from pileup in the efficiency measurement.

Another dominant category of uncertainties is related to b -tagging efficiency and b -jet misidentification rates. Similarly to other efficiency uncertainties, they are applied through variations in the scale factors correcting the MC simulation to reflect the efficiency measured in data. The largest components of the total uncertainty in efficiency measurements based on $t\bar{t}$ events include $t\bar{t}$ modelling and JES. The c -jet mistag rate measurements based on $W + c$ -jet and D^{*+} are most sensitive to uncertainties coming from c -jet signal identification and extrapolation of the results to a more inclusive phase space. Statistical uncertainties also play a key role in these measurements.

Systematic uncertainties affecting E_T^{miss} reconstruction come from the calibration of the hard objects included in its definition and modelling of the soft term. The latter is evaluated by comparing the E_T^{miss} scale and resolution using several different MC models and taking an envelope around their predictions.

Background modelling

Single top production is associated with a $\sim 5\%$ uncertainty on the inclusive cross section [159, 160]. Additional uncertainties come from the comparison of the nominal (diagram removal) tW sample to the one implementing the diagram subtraction scheme. ISR and FSR effects are estimated using samples with modified h_{damp} parameter and alternative PS tunes.

Different uncertainty evaluation methods are applied to the W +jets background depending on the simulated samples and on whether the data-driven normalisation and flavour composition correction are applied. The derivation of data-driven scale factors is repeated for each systematic variation coming from the object reconstruction uncertainties and the normalisation of other charge-asymmetric backgrounds. An additional uncertainty related to the modelling of W +jets kinematics is evaluated using an alternative sample simulated with POWHEG+PYTHIA8. Effects of the statistical uncertainty are also taken into account. In case of the SHERPA 2.2 sample used in the $t\bar{t}b\bar{b}$ cross-section measurement without data-driven corrections, theory uncertainties coming from scale and PDF variations are evaluated using internal generator weights.

Only normalisation uncertainties are assigned to the small background contributions coming from Z +jets and diboson processes, varying between 40 and 60% depending on the number of additional jets in the event. The contribution of $t\bar{t}V$ in the $t\bar{t}$ differential cross-section measurement is varied within the scale and PDF uncertainties evaluated with the NLO generator [118]. Due to the special treatment of $t\bar{t}V$ processes in the $t\bar{t}b\bar{b}$ measurement, the normalisation uncertainty is enlarged to 30% covering the uncertainty of the measured $t\bar{t}Z$ cross section [161].

Uncertainties related to the fake/non-prompt lepton background estimation are evaluated by varying definitions of the control regions for efficiency measurements as well as the choice of parametrisations. The effects of residual background from other processes in the fake efficiency measurement is evaluated by varying the subtracted MC prediction. The statistical component of each efficiency is also included. An additional normalisation uncertainty is added in the differential $t\bar{t}$ cross-section measurement presented in Chapter 6, covering the mismodelling observed in the validation regions. Due to the small size of this background in the $t\bar{t}b\bar{b}$ measurement, a detailed uncertainty evaluation is not performed and a 100 % normalisation uncertainty is used instead.

Chapter 5

Inclusive $t\bar{t}$ production cross section

The beginning of the LHC Run 2 offered the opportunity for the first cross-section measurements for benchmark Standard Model processes, including $t\bar{t}$ production, at the new pp collision energy of 13 TeV. The aim of the early-data measurements was to provide first quick verification of SM predictions in this previously unexplored regime. Any new non-SM particles could potentially decay into SM particles enhancing their production cross sections. The first ATLAS ℓ +jets channel measurement of the inclusive $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 13$ TeV is presented in this chapter. The results of this measurement were published in a conference note [162] and presented at the 8th International Workshop on Top Quark Physics in September 2015, together with a parallel measurement in the same-flavour dilepton channel. These two complementary channels were explored together in the early Run-2 data analyses as they provide clean $t\bar{t}$ samples with simple selection criteria, comparable overall precision and are statistically independent. The ℓ +jets channel suffers from larger backgrounds and larger systematic uncertainties, however provides larger number of events compared to dilepton, gaining in statistical precision. In small datasets, they are also comparable to the $e\mu$ channel measurements,

which are limited by statistical uncertainties until large amount of data is accumulated. The complementary $e\mu$ result was presented earlier, in July 2015 [163].

The ℓ +jets analysis presented in this chapter is based on the early-2015 dataset collected with a 50 ns bunch spacing and makes use of the signal and background MC simulation samples described in Section 4.2. The following sections present specific studies and choices regarding background estimation and event selection, expanding on the information presented in Chapter 4. The measurement method is then presented, followed by the evaluation of the corresponding uncertainties and a discussion of the results.

5.1 Background estimation

5.1.1 W +jets

The estimation of the W +jets background is based on the SHERPA 2.1 MC samples with a data-driven normalisation factor derived with the charge-asymmetry method. The number of W +jets events is estimated in data in a selection requiring the presence of exactly one lepton, zero b -tagged jets and either one, two, three, or at least four jets. The resulting numbers are then extrapolated to selections with at least one b -jet using the ratio of $0b$ to $\geq 1b$ events in the simulation:

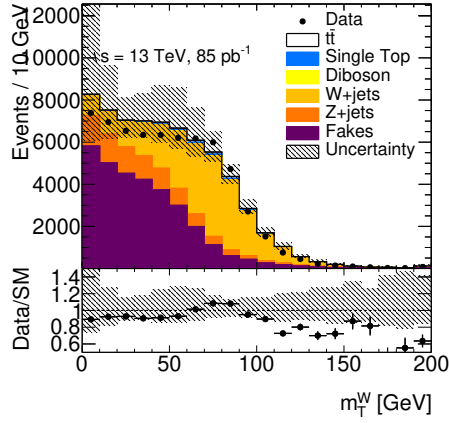
$$N_{W,\text{DD}}^{\geq 1b} = N_{W,\text{DD}}^{0b} \frac{N_{W,\text{MC}}^{\geq 1b}}{N_{W,\text{MC}}^{0b}},$$

where $N_{W,\text{DD}}$ stands for the data-driven numbers and $N_{W,\text{MC}}$ comes from MC simulation. The normalisation is evaluated separately in the electron and muon channels.

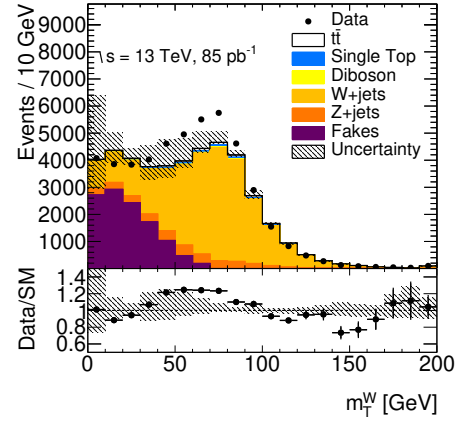
The intermediate quantities involved in the normalisation procedure and its final results for the $t\bar{t}$ signal selection (discussed in the next section) are presented in Table 5.1. The numbers are presented for the nominal SHERPA 2.1 sample as well as for the alternative POWHEG+PYTHIA8 sample which is used to evaluate the W +jets modelling uncertainty. The resulting estimated number of W +jets events in the b -tagged selection is consistent between the two models, taking into account the statistical uncertainty of 22 %. However, the scale factor (ratio of the data-driven to MC-only estimate) is very different due to an underestimation of the $W + \geq 4$ jets cross section in the POWHEG+PYTHIA8 simulation. Event kinematics modelling after application of the scale factors does not differ significantly between the two models, as seen in Figure 5.1.

Channel	Model	$\mathcal{A}_W^\ell$	$\frac{N_{W,MC}^{0b}}{N_{W,MC}^{\geq 1b}}$	$N_{W,DD}^{0b}$	$N_{W,DD}^{\geq 1b}$	Scale factor
e +jets	SHERPA 2.1	0.119	0.132	2605	343	1.03
	POWHEG+PYTHIA8	0.118	0.125	2632	328	3.91
μ +jets	SHERPA 2.1	0.155	0.131	1771	232	0.67
	POWHEG+PYTHIA8	0.141	0.116	1953	226	3.05

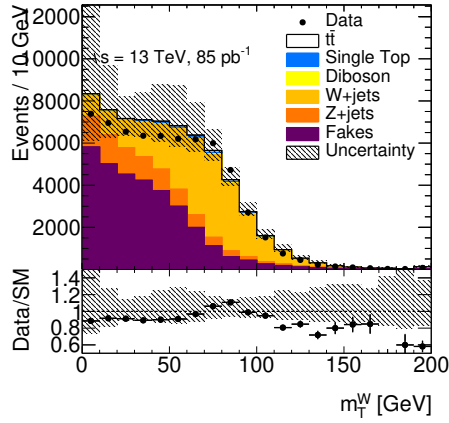
Table 5.1: Ingredients and results of the data-driven W +jets background normalisation as calculated with the nominal SHERPA and the alternative POWHEG+PYTHIA samples for the e +jets and μ +jets channels. The statistical uncertainty on $N_{W,DD}^{\geq 1b}$ is around 22 %.



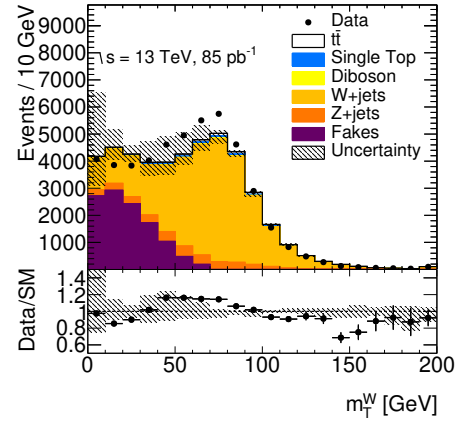
(a) $e + 2$ jets, SHERPA



(b) $\mu + 2$ jets, SHERPA



(c) $e + 2$ jets, POWHEG+PYTHIA



(d) $\mu + 2$ jets, POWHEG+PYTHIA

Figure 5.1: Distributions of the W candidate transverse mass, m_T^W , in the $e + 2$ jets and $\mu + 2$ jets selections showing the SHERPA and POWHEG+PYTHIA W +jets predictions with the corresponding data-driven normalisation applied.

5.1.2 Non-prompt and fake leptons

The non-prompt and fake lepton background is estimated using the matrix method as described in Section 4.5.2. The fake efficiency is measured in control regions dominated by the multijet background, which are different for the electron and muon channels due to the different fake/non-prompt lepton composition and origin. In both cases, events are required to contain exactly one loose or tight lepton and at least one jet. The electron channel ε_f control region is defined by requiring $E_T^{\text{miss}} < 40 \text{ GeV}$ and $m_T^W < 50 \text{ GeV}$, whereas the muon channel uses a definition based on the significance of the transverse impact parameter of the muon track. The requirement $|d_0^{\text{sig}}| > 5$ is an inversion of one of the track-to-vertex association criteria used in the differential $t\bar{t}$ and $t\bar{t}b\bar{b}$ cross-section measurements presented in Chapters 6 and 7. The choice of the control regions was driven by the observed disagreement between data and MC-only prediction in these regions, expected to arise from the multijet background. Distributions of the observables defining the control regions before and after the inclusion of the background estimate are presented in Figure 5.2. Up to seven times more data events than predicted by MC-only estimates are observed in low- E_T^{miss} and low- m_T^W regions in the e +jets channel. The high- $|d_0^{\text{sig}}|$ regions in the μ +jets channel show up to 10–20 times more events in data than expected from the simulated processes only. After including the estimated multijet contribution, the agreement between data and predictions remains within 50 %. Therefore, the regions selected for the fake efficiency measurements are shown to be dominated by fake/non-prompt lepton events.

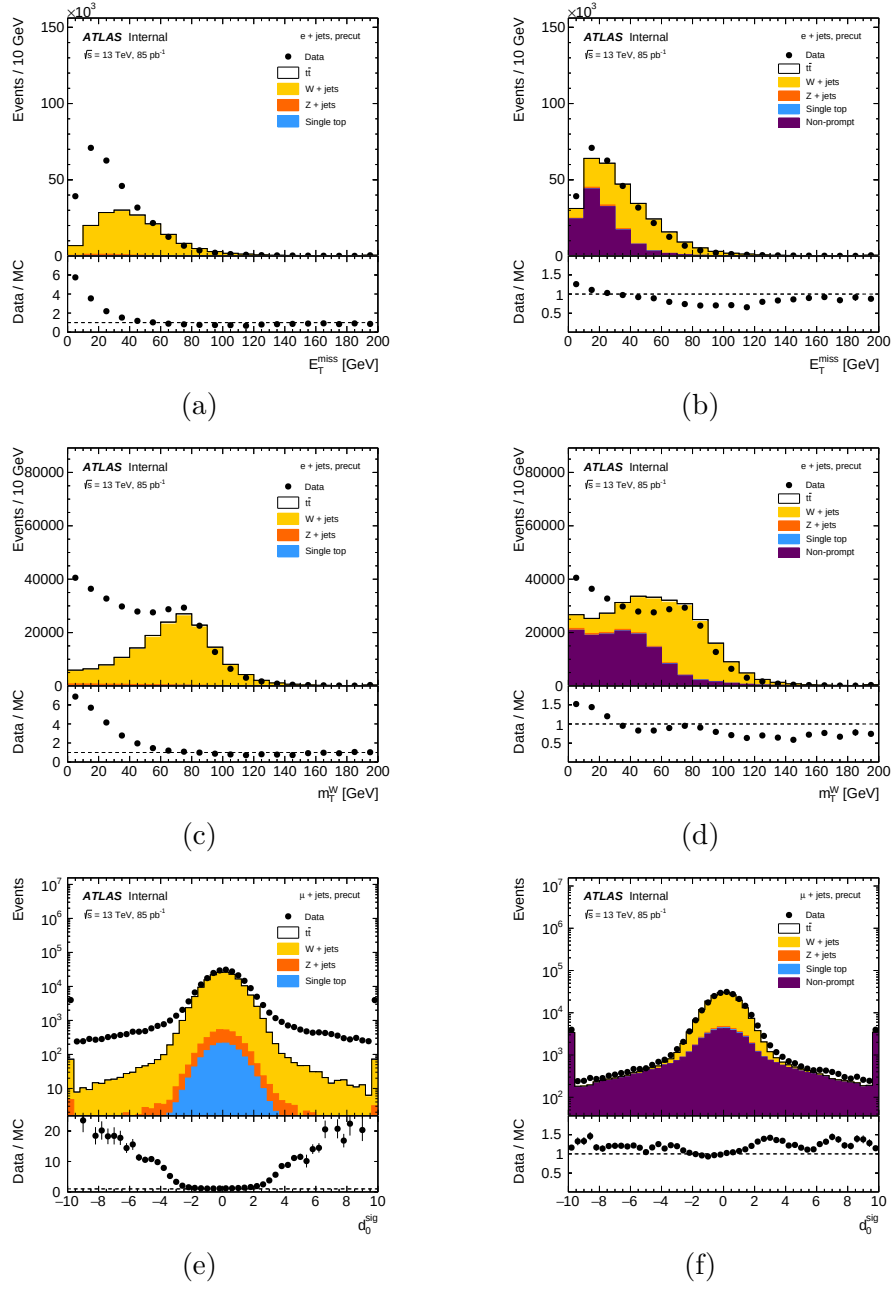


Figure 5.2: Distributions of the observables defining the control region for the fake efficiency measurement: E_T^{miss} (a, b) and m_T^W (c, d) in the $e + \geq 1$ jets selection, and d_0^{sig} (e, f) in the $\mu + \geq 1$ jets selection. The left column (a, c, e) presents the distributions before including the fake/non-prompt lepton estimate, whereas the right column (b, d, f) shows them including the estimate.

To account for the dependency of the fake efficiency on event kinematics, it is measured separately as a function of two discrete and six continuous variables:

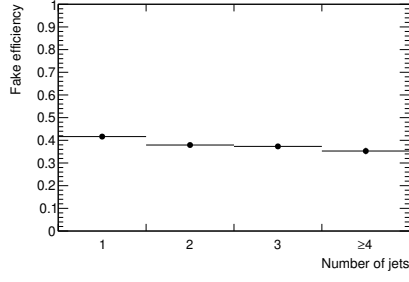
- number of jets,
- number of b -tagged jets,
- lepton p_T
- lepton $|\eta|$,
- $\Delta\phi(\ell, E_T^{\text{miss}})$,
- leading jet p_T ,
- minimum $\Delta R(\ell, \text{jet})$,
- E_T^{miss} (μ +jets channel only¹).

The fake efficiency ε_f in a bin i of a given variable is calculated as the number of tight events in this bin divided by the number of loose-or-tight events in this bin, $\varepsilon_f^i = N_T^i/N_{L+T}^i$, after subtracting the residual real lepton contribution estimated with MC simulation. The real lepton contamination is found to be less than 1 % in the μ +jets channel and around 13 % in the e +jets channel, dominated by the W +jets process. The resulting efficiency measurements are presented in Figures 5.3 and 5.4. The largest modifications of the fake efficiency are observed as a function of lepton p_T , leading jet p_T , $\Delta\phi(\ell, E_T^{\text{miss}})$ and E_T^{miss} . The lepton- p_T dependence shows high- p_T fake/non-prompt leptons are far more likely to be identified as tight. Higher efficiency is also observed for events with only low- p_T jets. Fake/non-prompt muons are less likely to pass the signal selection criteria in events with high E_T^{miss} . A particularly interesting feature is observed in the $\Delta\phi(\ell, E_T^{\text{miss}})$ dependence showing opposite trends for the two channels. Low- $\Delta\phi(\ell, E_T^{\text{miss}})$ regions are believed to be dominated by non-prompt leptons from heavy-

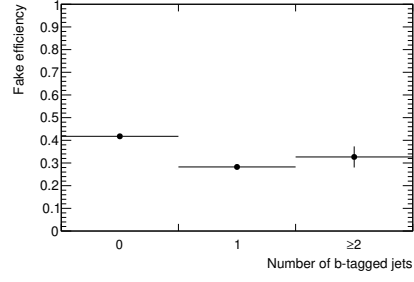
¹The fake efficiency cannot be measured as a function of E_T^{miss} in the e +jets channel because it is used to define the control region.

flavour hadron decays, which are produced with a corresponding neutrino. Other non-prompt/fake lepton production processes are thought to be uncorrelated to $\Delta\phi(\ell, E_T^{\text{miss}})$, contributing equally in the full range $[0, \pi]$. The observed trends suggest muons from heavy-flavour hadron decays are efficiently rejected by the signal selection criteria, whereas others, probably dominated by punch-through particles, are often identified as tight. At the same time, electrons from heavy-flavour hadron decays are difficult to identify since the calorimeter deposits from the corresponding jet may be misidentified as coming from the electron. High- $\Delta\phi(\ell, E_T^{\text{miss}})$ electrons are probably dominated by photon conversions which can be more easily rejected using tighter identification requirements. The continuous-variable parametrisations are fitted with functions summarised in Table 5.2. Using a smooth function rather than a binned efficiency has the advantage of minimising the effect of statistical fluctuations and avoiding large steps in steeply changing dependencies. The small discrepancies between the data and the fitted functions seen in the figures have a negligible impact on the resulting background yield predictions and no impact on the measured $t\bar{t}$ cross section.

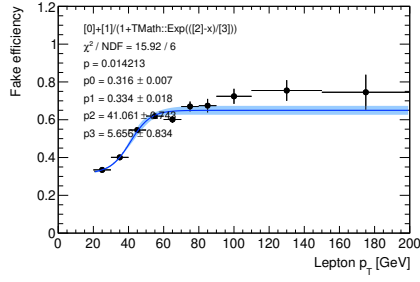
Since the real efficiency is generally much closer to 1 than the fake efficiency, and it is found to have a smaller effect on the predicted background yields, all efficiency parametrisation studies were performed assuming $\varepsilon_r = 1$ and varying only ε_f . Background predictions resulting from different parametrisation choices were compared to data in validation regions requiring exactly two or exactly three jets. The combination found to describe the data best is the geometric mean of $\Delta\phi(\ell, E_T^{\text{miss}})$ and the number of b -tagged jets (N_b) in the electron channel, and the geometric mean of $\Delta\phi(\ell, E_T^{\text{miss}})$ and E_T^{miss} in the muon channel. In each case, the two parametrisations combined in the nominal prediction are used separately to estimate the systematic uncer-



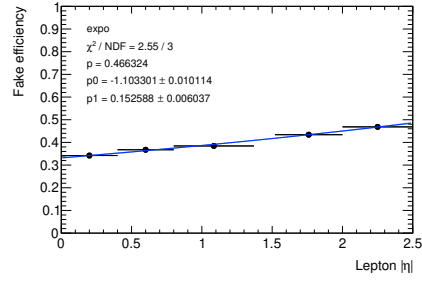
(a) number of jets



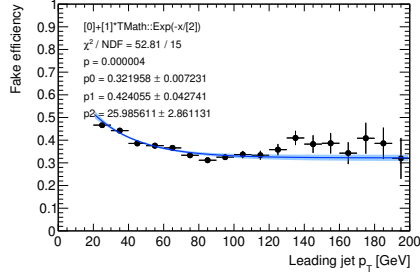
(b) number of b -tagged jets



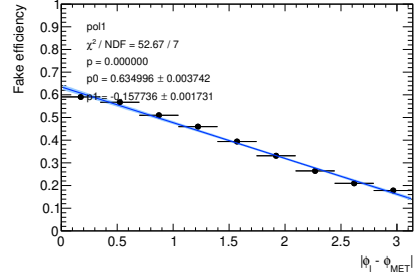
(c) lepton p_T



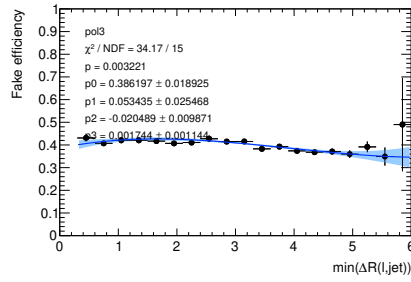
(d) lepton $|\eta|$



(e) leading jet p_T

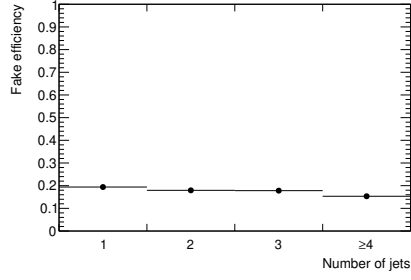


(f) $\Delta\phi(\ell, E_T^{\text{miss}})$

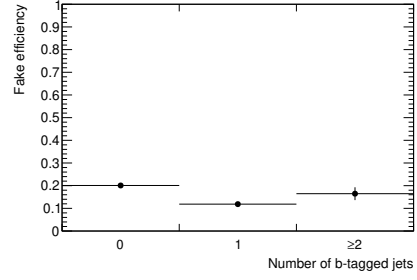


(g) minimum $\Delta R(\ell, \text{jet})$

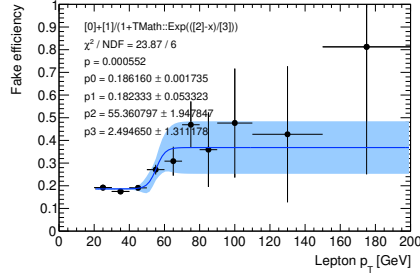
Figure 5.3: Measured e +jets channel fake efficiency parametrisations with the fitted functions. The blue bands represent a 1σ statistical uncertainty on the function parameters.



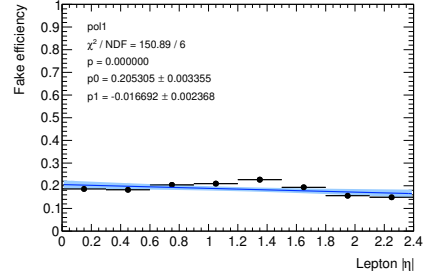
(a) number of jets



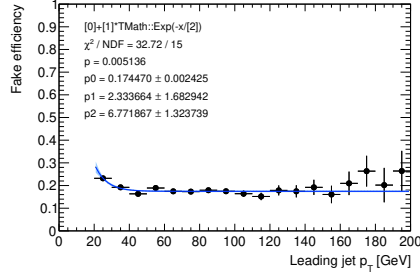
(b) number of b -tagged jets



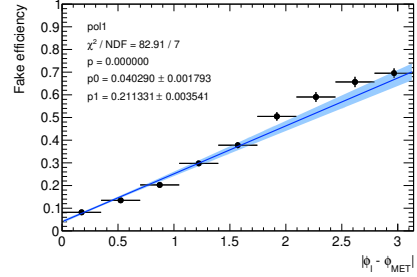
(c) lepton p_T



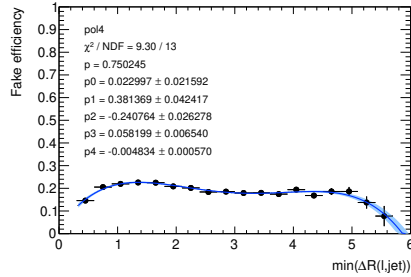
(d) lepton $|\eta|$



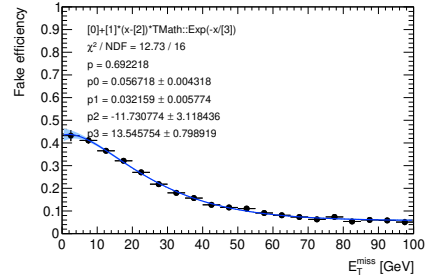
(e) leading jet p_T



(f) $\Delta\phi(\ell, E_T^{\text{miss}})$



(g) minimum $\Delta R(\ell, \text{jet})$



(h) E_T^{miss}

Figure 5.4: Measured μ +jets channel fake efficiency parametrisations with the fitted functions. The blue bands represent a 1σ statistical uncertainty on the function parameters.

tainty on the background prediction. Multijet background yields predicted by various parametrisations, including the nominal and the two systematic variations referred to as *systA* and *systB*, are presented in Figures 5.5 and 5.6 for the e +jets and μ +jets channel respectively. The distributions are shown for variables sensitive to this background in the validation region defined by requiring exactly two jets without any b-tagging requirement. It can be observed that the systematic variations bracket the nominal prediction symmetrically and in many observables the other parametrisations also remain within the systematic variation interval. The only exception is the electron- p_T parametrisation in the e +jets channel (Figure 5.5), which stands out the most from other parametrisations in this channel. It was decided to define the systematic variations by dropping one of the components at a time from the combined parametrisation describing the data best, rather than to switch to the uncorrelated p_T parametrisation since the latter was found to provide a largely inadequate background prediction (with a large normalisation offset). The same argument does not apply to the $\Delta\phi(\ell, E_T^{\text{miss}})$ parametrisation in the μ +jets channel (Figure 5.6) since it is one of the components of the nominal combined parametrisation and is crucial to describe the background distribution shapes correctly.

The real efficiency is measured using the $Z \rightarrow \ell\ell$ tag-and-probe technique in a data sample selected by requiring the presence of exactly two loose or tight leptons of the same flavour and opposite charge, and at least one jet. The invariant mass of the dilepton system is required to be between 80 and 100 GeV, resulting in a pure sample of $Z \rightarrow \ell\ell$ events. The real efficiency is parametrised in the same way as the fake efficiency with fits performed separately for the three continuous observables. The resulting efficiencies are presented in Figure 5.7, whereas the fitted functions and their parameters are summarised in Table 5.3. All dependencies follow the

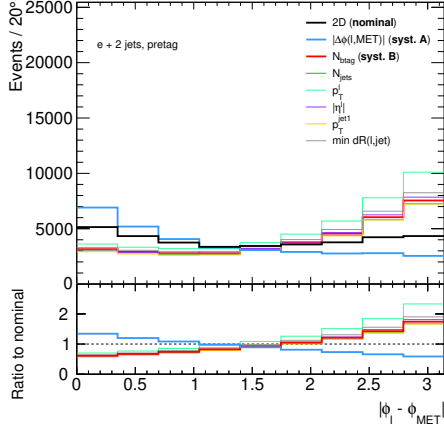
same trends as for the fake efficiency, however, remain above 80 % in almost all measured bins.

5.1.3 Other backgrounds

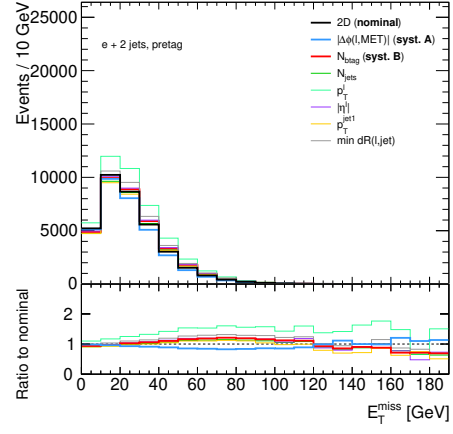
The contribution of single top, Z + jets and diboson processes to the signal selection is estimated using simulated samples normalised to the highest-order available inclusive cross-section calculation, as described in Section 4.5. The effect of $t\bar{t}V$ processes on the measured cross section is negligible compared to the achieved precision, thus they are not considered either as signal or background.

Variable	Electron channel	Muon channel
Lepton p_T	Fermi function	Fermi function
Lepton $ \eta $	Exponential	Linear
Leading jet p_T	$A + Be^{-x/C}$	$A + Be^{-x/C}$
$\Delta\phi(\ell, E_T^{\text{miss}})$	Linear	Linear
$\min\Delta R(\ell, \text{jet})$	3 rd order pol.	4 th order pol.
E_T^{miss}	–	$A + B(x - C)e^{-x/D}$

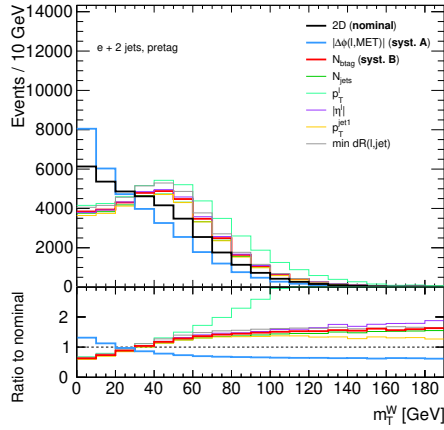
Table 5.2: Functions chosen to fit the fake efficiency parametrisations in the continuous variables.



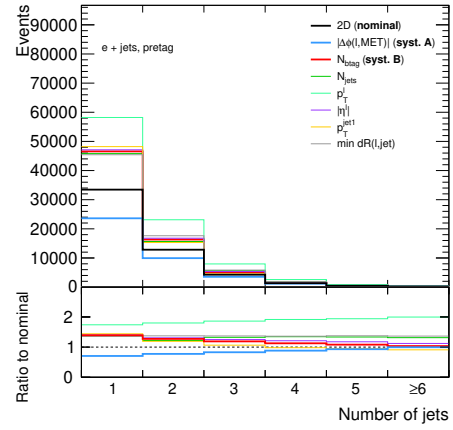
(a)



(b)



(c)



(d)

Figure 5.5: Comparison of fake/non-prompt lepton background yields in the electron channel estimated with different parametrisations of the fake efficiency and $\varepsilon_r = 1$. The black line represents the nominal 2D parametrisation and coloured lines represent different 1D parametrisations. Figures (a, b, c) show the estimates for the $e + 2$ jets selection, whereas Figure (d) corresponds to the $e + \geq 1$ jets selection.

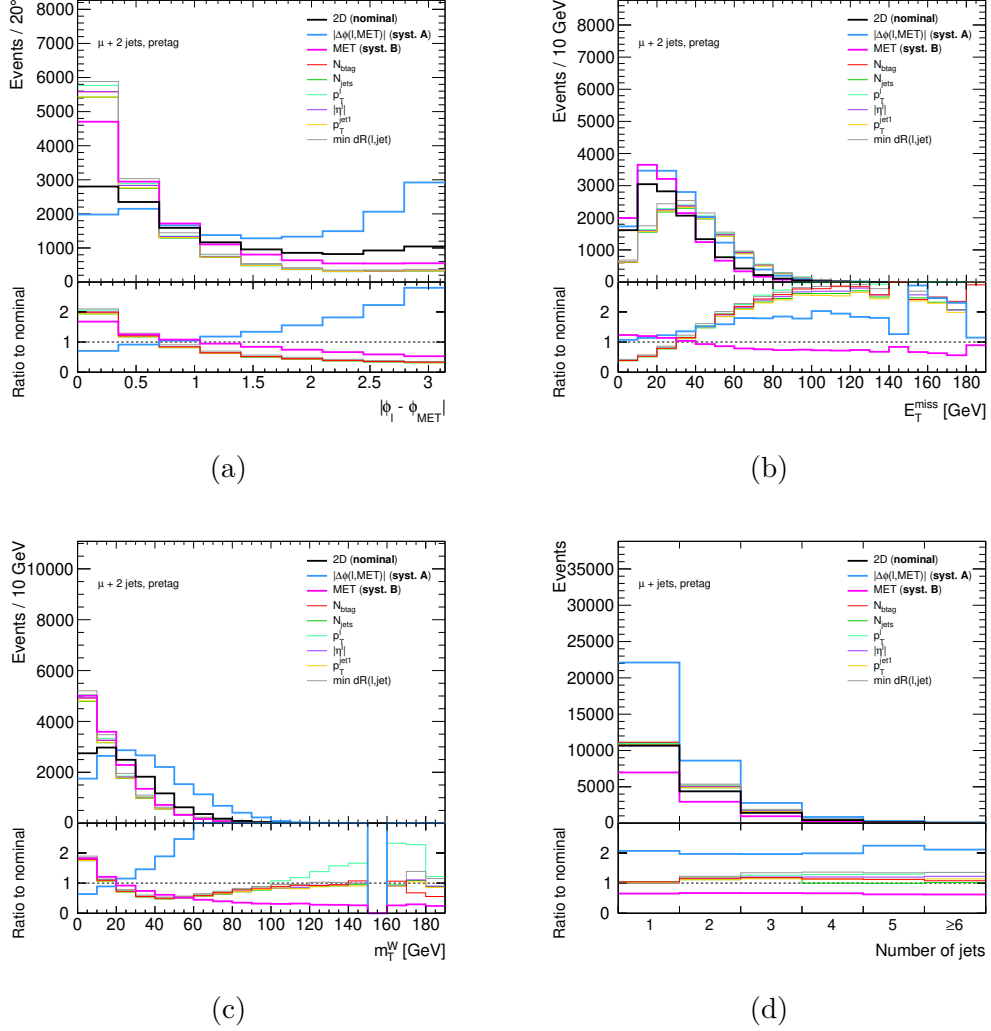
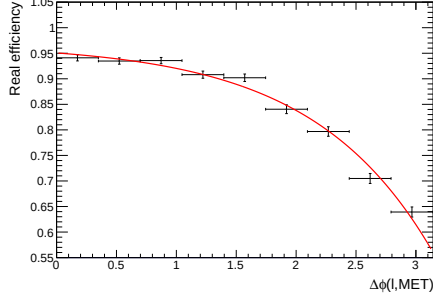
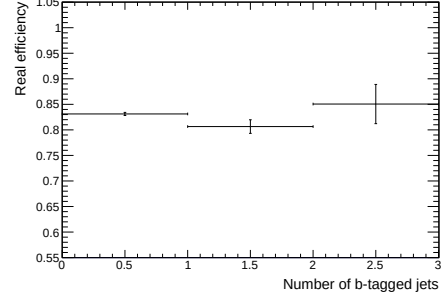


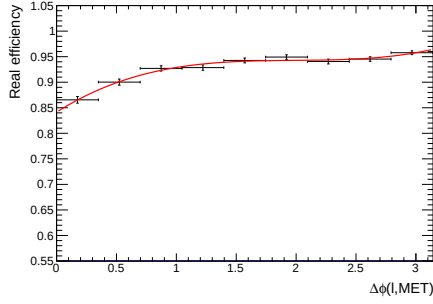
Figure 5.6: Comparison of fake/non-prompt lepton background yields in the muon channel estimated with different parametrisations of the fake efficiency and $\varepsilon_r = 1$. The black line represents the nominal 2D parametrisation and coloured lines represent different 1D parametrisations. Figures (a, b, c) show the estimates for the $\mu + 2$ jets selection, whereas Figure (d) corresponds to the $\mu + \geq 1$ jets selection.



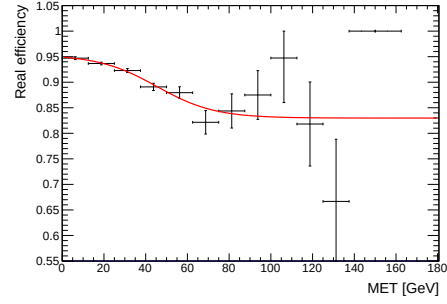
(a) $\Delta\phi(\ell, E_T^{\text{miss}})$, e +jets



(b) number of b -tagged jets, e +jets



(c) $\Delta\phi(\ell, E_T^{\text{miss}})$, μ +jets



(d) E_T^{miss} , μ +jets

Figure 5.7: Parametrisations of the real efficiency, ε_r , used in the fake/non-prompt lepton background estimate.

Channel	Variable	Function	Parameters
e +jets	$\Delta\phi(\ell, E_T^{\text{miss}})$	$A + B \exp(x)$	0.968, -0.0176
	N_b	Binned values are used	
μ +jets	$\Delta\phi(\ell, E_T^{\text{miss}})$	$A + Bx + Cx^2 + Dx^3$	0.841, 0.149, 0.0739, 0.0124
	E_T^{miss}	$A + B / \left(1 + \exp\left(\frac{x-C}{D}\right)\right)$	0.830, 0.124, 45.4, 13.9

Table 5.3: Functions chosen to fit the real efficiency parametrisations.

5.2 Event selection and inclusive cross-section extraction

The inclusive $t\bar{t}$ production cross section is measured in a signal region defined by requiring the presence of exactly one lepton (electron or muon) and at least four jets. At least one of the jets is required to be b -tagged using the MV2c20 discriminant cut corresponding to a 70 % signal efficiency. Including events with only one b -jet (rather than ≥ 2) in the signal region provides a higher signal selection efficiency, which is important due to the small size of the early-2015 dataset. Furthermore, it reduces the signal modelling uncertainty related to the extrapolation to the inclusive phase space. To minimise the impact of the fake/non-prompt lepton background in this looser signal selection, additional requirements based on E_T^{miss} and m_T^W are explored. This type of background is found to dominate low values of both distributions, as seen in Figure 5.8, thus a triangular cut $E_T^{\text{miss}} + m_T^W > 60$ GeV rejecting the bottom-left corner of the 2D distribution is employed.

A number of validation regions are used to verify the background modelling, where the $E_T^{\text{miss}} + m_T^W$ and b -tagging requirements are not applied. These include selections with exactly two, exactly three, or at least four jets. In

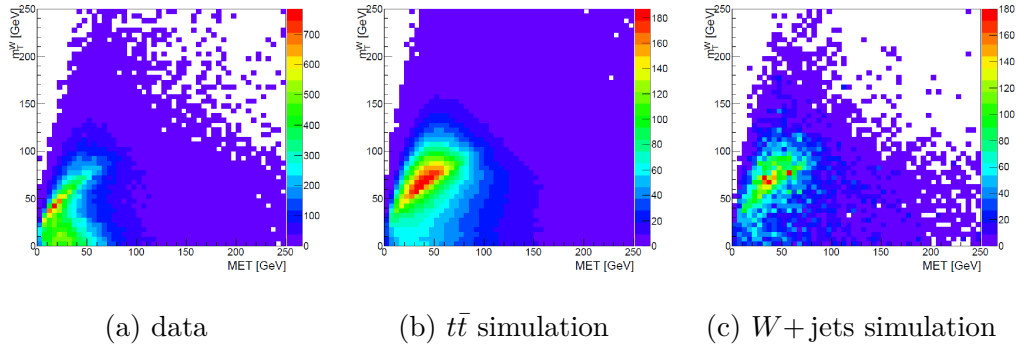


Figure 5.8: The two-dimensional distribution of E_T^{miss} and m_T^W in $\mu + \geq 4$ jets events in data, $t\bar{t}$ simulation and W +jets simulation.

general, the predictions are found to describe the data well across all regions, with some mismodelling observed in the electron p_T distribution and m_T^W . These do not have an impact on the signal region modelling, where the overall background yields are small compared to signal. The source of the electron p_T discrepancy has not been identified since the effect is negligible compared to the overall precision of the measurement (due to unrelated systematic uncertainties). However, it is believed it may be related to the fact that the same triggers were used to select the fake lepton control region and the signal region, and they apply electron isolation requirements for low- p_T electrons. This removes a fraction of fake leptons from the sample, which is good for the signal selection, but makes the fake efficiency measurement less accurate. Chosen distributions from each validation region are presented in Figures 5.9 and 5.10 for the e +jets and μ +jets channel respectively. The distributions of the number of jets before b -tagging and the number of b -tagged jets in the ≥ 4 -jet region are well modelled (Figure 5.11) and a very good agreement between data and predictions is observed in the signal region (Figures 5.12 and 5.13). The numbers of predicted and observed events in each channel are presented in Table 5.4.

The inclusive $t\bar{t}$ production cross section is calculated as:

$$\sigma_{t\bar{t}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L}^{\text{int}} C_{t\bar{t}}}, \quad (5.1)$$

where N_{data} is the number of observed data events in the signal region, N_{bkg} is the predicted number of background events in the signal region, $\mathcal{L}^{\text{int}}$ is the integrated luminosity of the data sample, and $C_{t\bar{t}}$ is a correction factor accounting for the acceptance and the detector efficiency. The correction is evaluated using the signal MC simulation and defined as the number of reconstructed and selected events divided by the total number of events generated in the inclusive phase space.

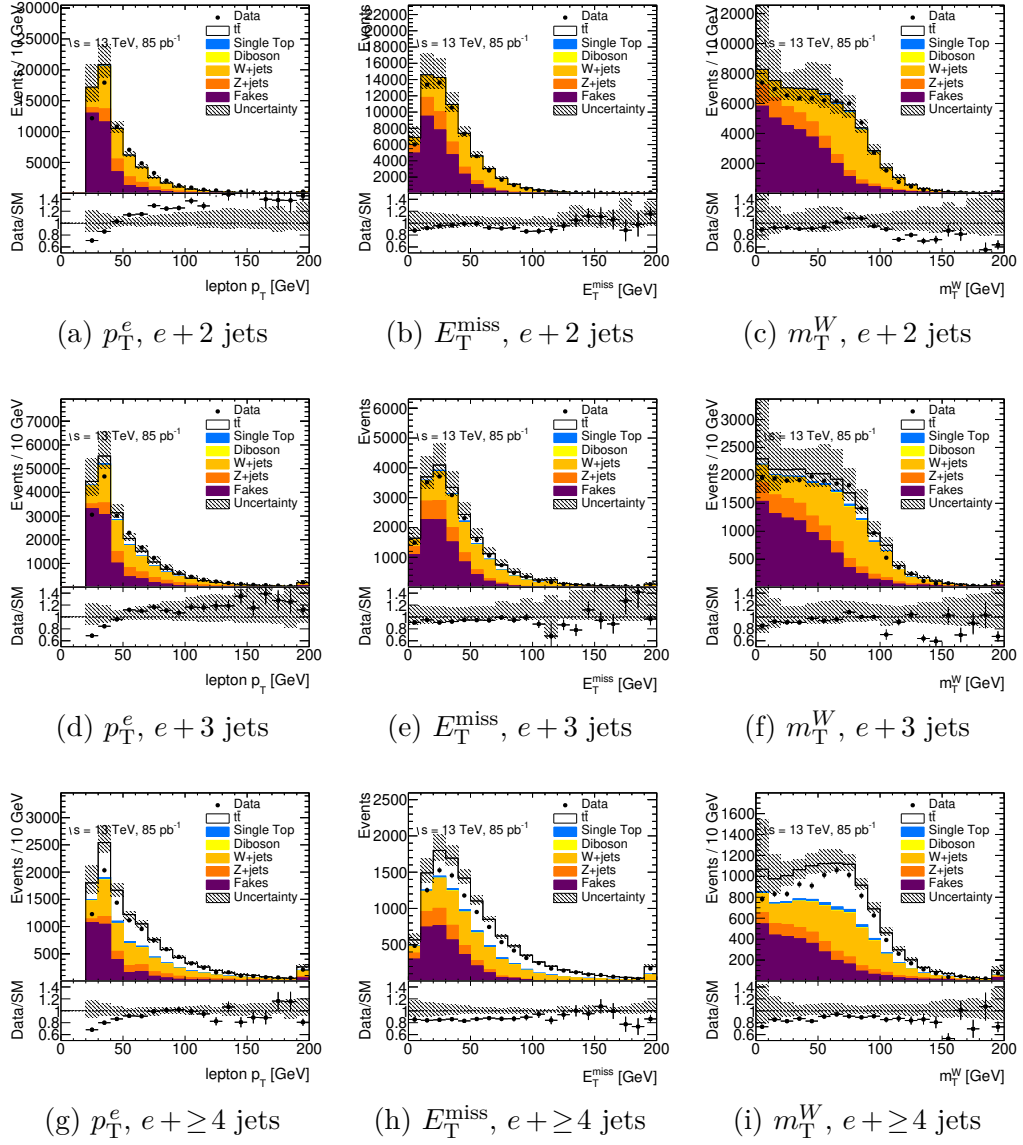


Figure 5.9: Distributions of the lepton p_T , E_T^{miss} and m_T^W in the e +jets channel in the validation regions requiring the presence of exactly two, exactly three or at least four jets. No E_T^{miss} , m_T^W or b -tagging requirements are imposed.

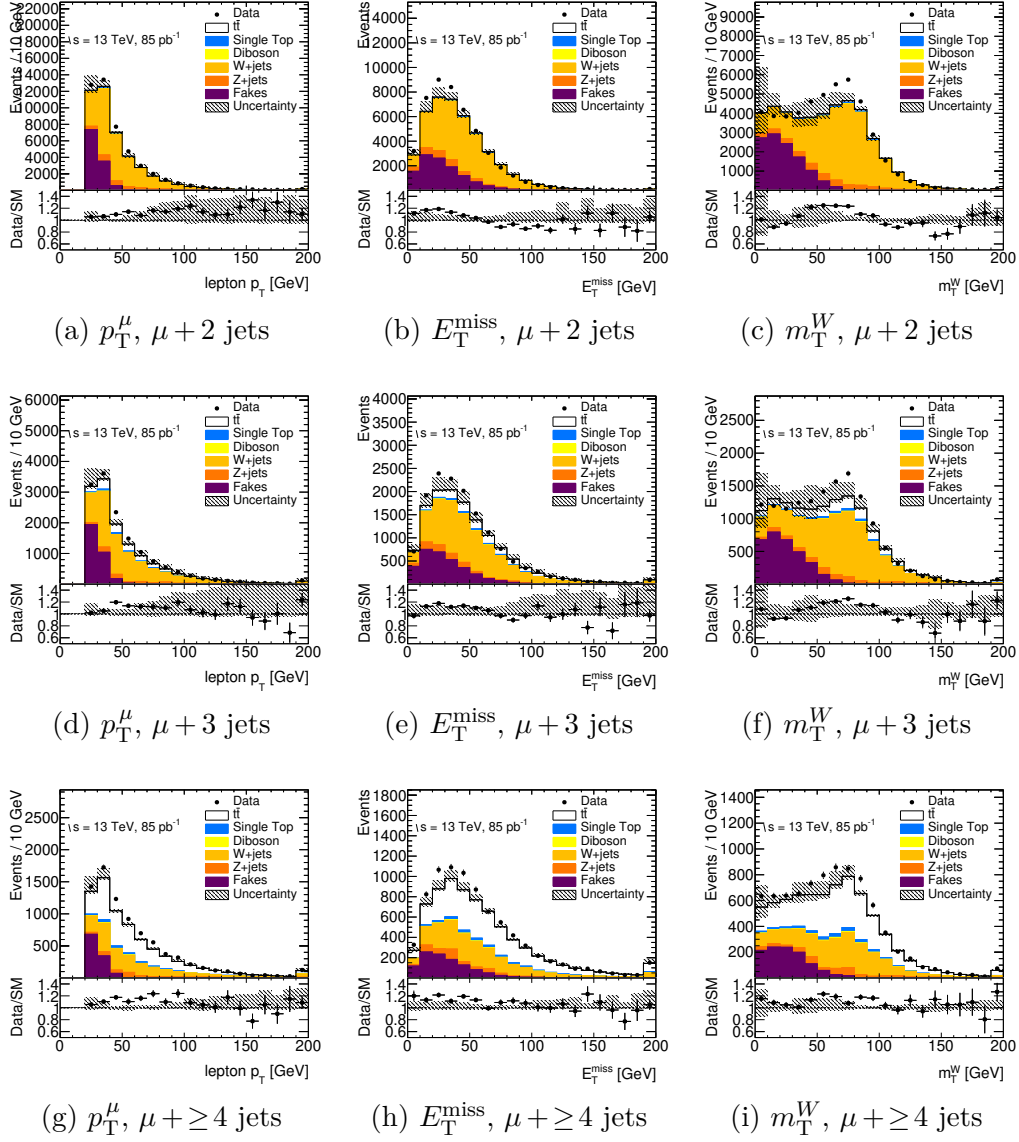
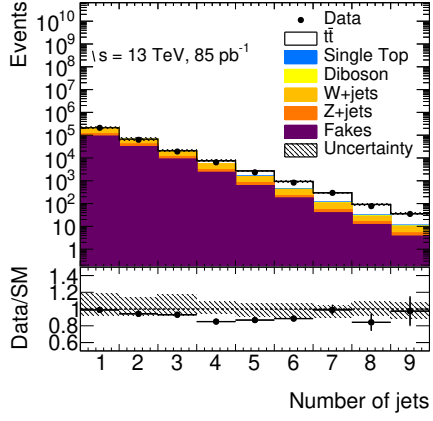
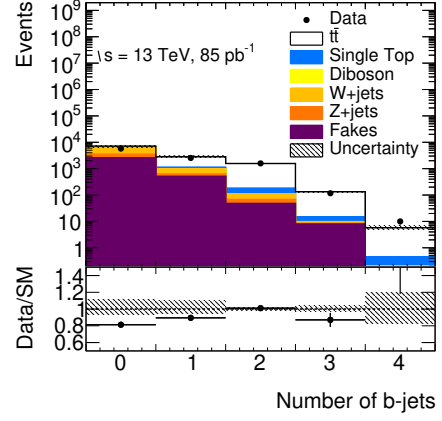


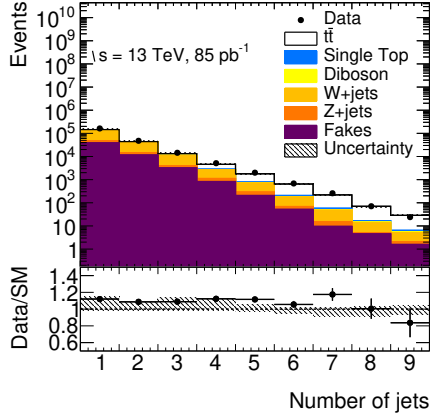
Figure 5.10: Distributions of the lepton p_T , E_T^{miss} and m_T^W in the μ +jets channel in the validation regions requiring the presence of exactly two, exactly three or at least four jets. No E_T^{miss} , m_T^W or b -tagging requirements are imposed.



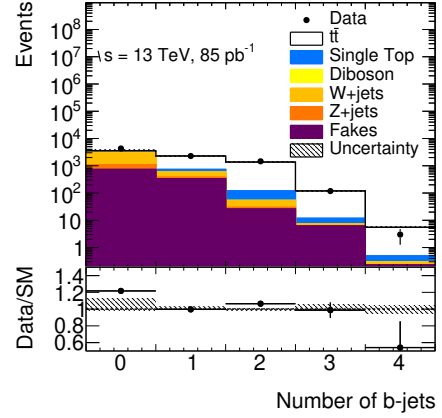
(a)



(b)

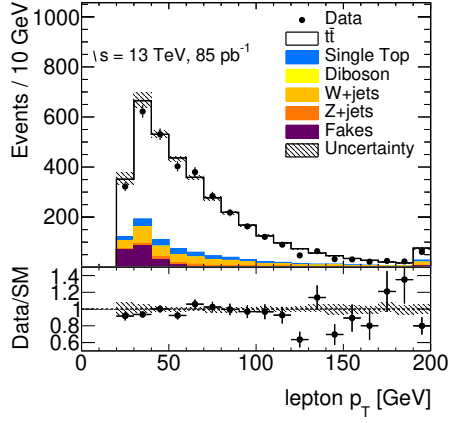


(c)

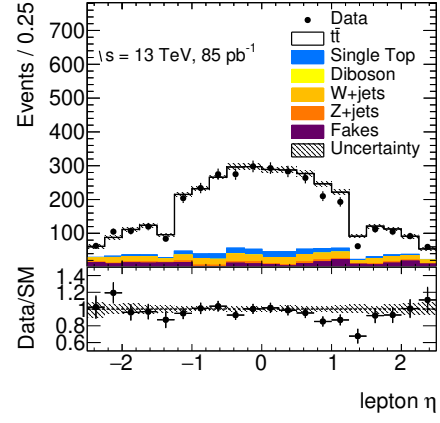


(d)

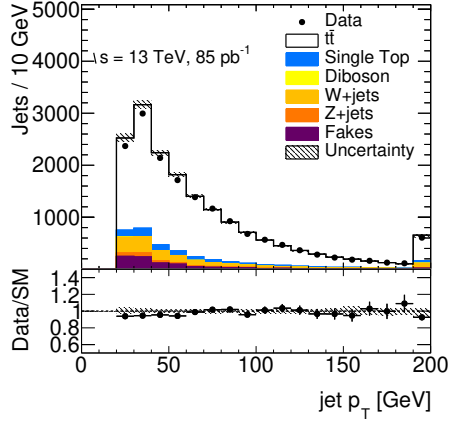
Figure 5.11: The number of jets in an inclusive pre-tag 1-jet selection (a, c) and the number of b -tagged jets in events with at least four jets (b, d) in the electron (a, b) and muon (c, d) channels. The $E_T^{\text{miss}} + m_T^W$ requirement is not applied.



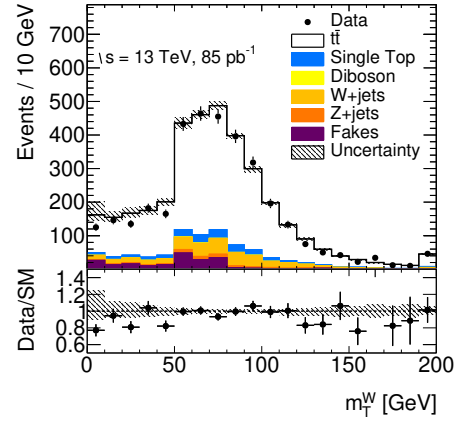
(a)



(b)

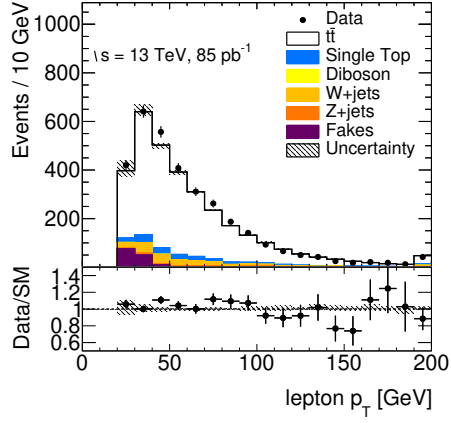


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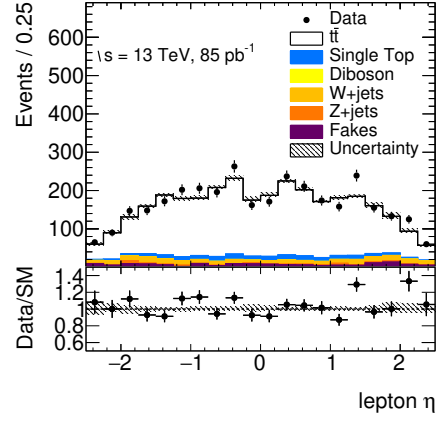


(d)

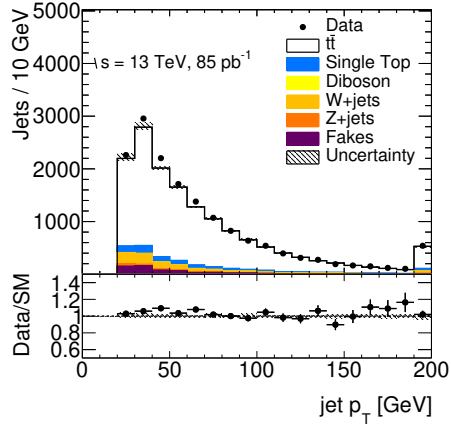
Figure 5.12: Signal region ($\geq 4j, \geq 1b, E_T^{\text{miss}} + m_T^W > 60 \text{ GeV}$) distributions of (a) lepton p_T , (b) lepton $|\eta|$, (c) inclusive jet p_T (histograms filled once per jet) and (d) m_T^W in the e +jets channel.



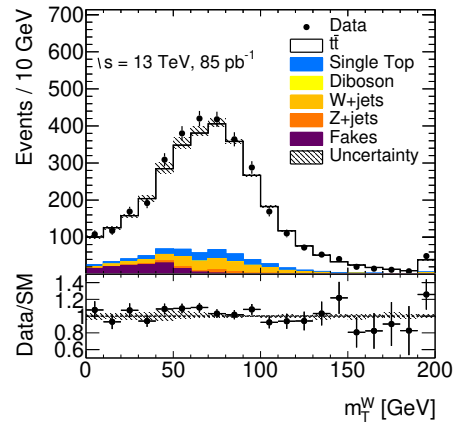
(a)



(b)



(c)



(d)

Figure 5.13: Signal region ($\geq 4j, \geq 1b, E_T^{\text{miss}} + m_T^W > 60$ GeV) distributions of (a) lepton p_T , (b) lepton $|\eta|$, (c) inclusive jet p_T (histograms filled once per jet) and (d) m_T^W in the μ +jets channel.

Sample	e +jets	μ +jets
$t\bar{t}$	2800 ± 400	2620 ± 340
W +jets	340 ± 100	230 ± 60
Multijet	200 ± 70	130 ± 60
Single top	192 ± 34	180 ± 30
Z +jets	71 ± 35	45 ± 22
Diboson	10 ± 5	10 ± 5
Total background	820 ± 130	600 ± 100
Total expected	3600 ± 500	3220 ± 350
Observed	3439	3314

Table 5.4: The number of events observed in data and predicted using MC simulation and data-driven techniques in the e +jets and μ +jets channels. The uncertainty on the predicted numbers includes both, statistical and systematic components.

5.3 Uncertainties

The impact of each source of systematic uncertainty on the measured cross section is evaluated by deriving all input parameters of Equation 5.1 with the corresponding variations and extracting the varied cross-section value. The procedure preserves correlations between the individual parameters of the formula. The total systematic uncertainty on $\sigma_{t\bar{t}}$ is evaluated by adding the contributions from each source in quadrature. The luminosity, object calibration and background modelling uncertainties are evaluated following the procedures described in Section 4.7. The effect of the luminosity uncertainty is slightly larger than the uncertainty on the absolute value of $\mathcal{L}^{\text{int}}$ because it enters the cross-section calculation also through the normalisation of the background MC samples. Electron and muon scale factors and corresponding uncertainties are evaluated using the early-2015 data [164, 165], whereas jet and b -jet uncertainties are based on 13 TeV MC studies and the knowledge from Run 1, and include additional components related to the extrapolation to 13 TeV data. The W +jets background uncertainty includes the statistical component and the systematic variation coming from the comparison between the SHERPA and POWHEG+PYTHIA models. The fake/non-prompt lepton background uncertainty comes from the parametrisation variations only.

Signal modelling uncertainties related to the NLO generator, the PS algorithm and the initial-/final-state radiation are evaluated by comparing the results obtained with the nominal simulations to results obtained using the alternative samples described in Section 4.2.1. The uncertainty coming from a limited knowledge of the proton PDFs is evaluated by reweighting a MADGRAPH5_aMC@NLO $t\bar{t}$ sample using error sets associated with the CT14 [166], MMHT2014nlo68cl [124] and NNPDF3.0NLO [120] PDFs. The

procedure follows the recommendations of the PDF4LHC working group [167]. A summary of all uncertainties affecting the final measured cross-section value in the combination of the e +jets and μ +jets channels is presented in Table 5.5. The largest contributions come from jet energy scale calibration, parton shower modelling in the signal simulation, b -tagging efficiency and luminosity. Due to only preliminary luminosity calibration being available at the time the measurement was performed, and the large effect of the corresponding uncertainty on the results, it is quoted separately from other systematic uncertainties.

5.4 Results, context and discussion

The inclusive cross section for $t\bar{t}$ production in pp collisions at $\sqrt{s} = 13$ TeV measured in the e +jets channel is:

$$\sigma_{t\bar{t}}^{e+\text{jets}} = 775 \pm 17 \text{ (stat.)} \pm 123 \text{ (syst.)} \pm 85 \text{ (lum.) pb,}$$

and in the μ +jets channel:

$$\sigma_{t\bar{t}}^{\mu+\text{jets}} = 862 \pm 18 \text{ (stat.)} \pm 93 \text{ (syst.)} \pm 94 \text{ (lum.) pb.}$$

The combination of the two channels gives the final result of:

$$\sigma_{t\bar{t}}^{\ell+\text{jets}} = 817 \pm 13 \text{ (stat.)} \pm 103 \text{ (syst.)} \pm 88 \text{ (lum.) pb.}$$

The presented result is one of the first $t\bar{t}$ inclusive cross-section measurements at the new pp collision energy in LHC Run 2. It agrees well with other ATLAS measurements using the early data and exploiting the same-flavour dilepton ($ee/\mu\mu$) channel [162] and the $e\mu$ channel [163]. The three results are also consistent with the early measurements presented by the CMS Collaboration using the $e\mu$ and ℓ +jets channels [168, 169]. All five results are

Uncertainty	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	1.5
$t\bar{t}$ parton showering	4.1
Initial-/final-state radiation	1.9
PDF	0.7
$t\bar{t}$ NLO modelling	0.6
Fake/non-prompt leptons	1.8
W +jets statistics	1.7
W +jets modelling	1.0
Z +jets cross section	1.0
Single top cross section	0.3
Diboson cross sections	0.2
Electron trigger	2.8
Electron identification	2.1
Electron isolation	0.4
Electron energy scale/resolution	0.1
Muon trigger	1.2
Muon isolation	0.3
Muon identification	0.2
Muon momentum scale/resolution	0.1
Jet energy scale	$^{+10}_{-8}$
b -tagging	4.1
Jet energy resolution	0.6
$E_{\text{T}}^{\text{miss}}$ scale/resolution	0.4
Analysis systematics	$^{+13}_{-11}$
Integrated luminosity	$^{+11}_{-9}$
Total uncertainty	$^{+17}_{-14}$

Table 5.5: Summary of the statistical, systematic and total uncertainties on the $t\bar{t}$ production cross section measured in the combined ℓ +jets channel.

presented in Table 5.6 and are shown to agree with an NNLO prediction in Figure 5.14a. The compatibility of all early-data results and the comparable size of the total uncertainties underline the complementarity of the different channels, where the limited statistical precision of the dilepton final states is balanced by a better control of the systematic uncertainties.

The precision of the presented analysis is largely dominated by the luminosity uncertainty, which can be greatly reduced in a longer term. Precise calibration of the luminosity measurement requires a detailed and time-consuming analysis and a use of special calibration runs to determine the transverse profile of the beam. The final ATLAS luminosity measurement for the 2015 pp collision data (both the early and full datasets) yields a 2.1 % uncertainty, which is several times smaller than the 9 % used here. Other dominant uncertainties include jet energy scale calibration and b -tagging signal and background efficiencies. These can also be reduced following more detailed and time-consuming studies profiting from larger datasets. However, as observed in subsequent differential $t\bar{t}$ cross section measurements presented in the next two chapters, they still remain among the main contributions to the total uncertainty. Another challenging source of uncertainty comes from the modelling of the signal process, impacting the evaluation of the signal selection efficiency. This type of uncertainty can be only reduced by improving the existing simulation software and tuning the associated parameters. This requires further differential cross-section measurements for processes involving top quarks, which can be used to verify the adjusted models and their parameters.

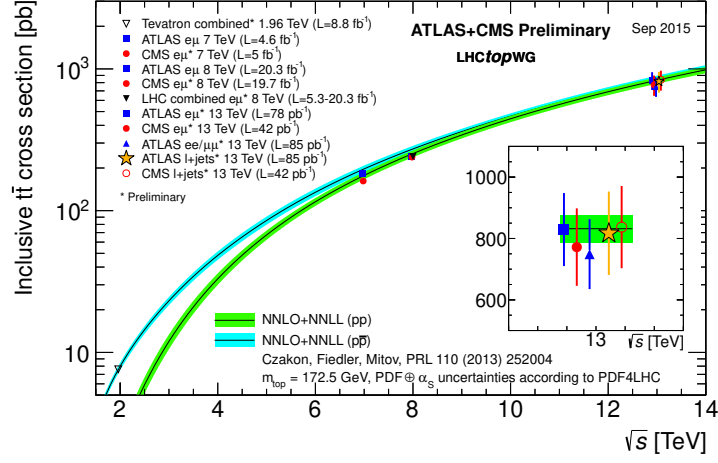
The complementary $e\mu$ and same-flavour dilepton channel measurements provide a similar, 14 % and 16 % overall precision respectively. Although they are less affected by jet-related uncertainties thanks to the lower num-

ber of jets in the final state and they do not suffer from the W +jets background, the dilepton measurements are characterised by a larger statistical uncertainty due to the lower branching fractions. Due to the reduction of jet-related uncertainties and the presence of two leptons in the signal region, the electron identification uncertainty also becomes significant. Very similar findings were also presented in the CMS $e\mu$ and ℓ +jets measurements, which both resulted in a 16 % precision.

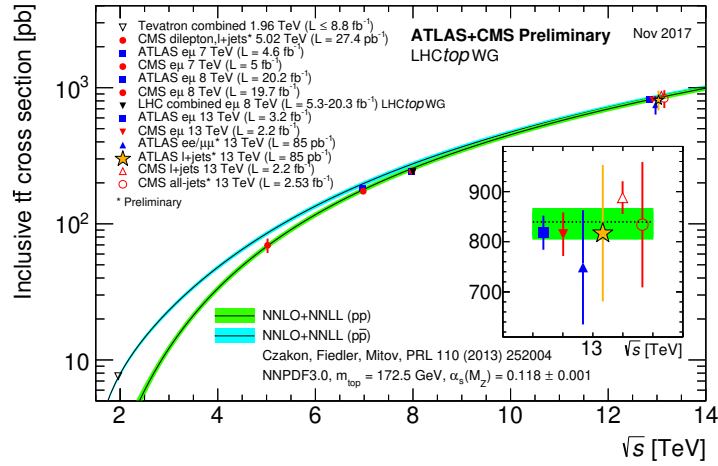
A $\sim 16\%$ measurement precision reached within a few weeks from the start of Run 2 proves the excellent performance of both experiments as well as the LHC. In addition, the good agreement of all results with the NNLO prediction shows the robustness of the perturbative QCD calculations. Although some of the early measurements were later superseded by analyses using larger datasets and profiting from a better understanding of the systematic uncertainties [170–172], the result presented here remains the only 13 TeV ATLAS measurement in the ℓ +jets channel (Figure 5.14b).

Measurement	$\sigma_{t\bar{t}}$ [pb]	Stat. unc. [pb]	Syst. unc. [pb]	Lum. unc. [pb]
ATLAS $e\mu$ [163]	825	49	60	83
ATLAS $ee/\mu\mu$ [162]	749	57	79	74
ATLAS ℓ+jets [162]	817	13	103	88
CMS $e\mu$ [168]	772	60	62	93
CMS ℓ +jets [169]	836	27	84	100

Table 5.6: Summary of the first Run-2 inclusive measurements of $t\bar{t}$ production cross section presented by ATLAS and CMS in 2015.



(a)



(b)

Figure 5.14: Summary of the LHC and Tevatron measurements of the $t\bar{t}$ production cross section as a function of the centre-of-mass energy compared to an NNLO QCD calculation. The measurements and the theory calculation are quoted at $m_t = 172.5 \text{ GeV}$. Measurements made at the same centre-of-mass energy are offset for clarity [173]. Figure (a) includes all results available in September 2015, whereas Figure (b) includes results up to November 2017. The measurement presented in this chapter is highlighted with an orange star in both figures.

Chapter 6

Differential $t\bar{t}$ production cross sections

The 13 TeV pp collisions dataset collected by ATLAS by the end of 2015 has already provided the opportunity to perform the first differential measurements of $t\bar{t}$ production in this new energy regime. One of the aims of these measurements was a search for possible indications of new physics processes, for example new heavy particles decaying into $t\bar{t}$ which could produce a peak structure in the $t\bar{t}$ system mass distribution. The measurements were also crucial to validate the challenging calculations of SM predictions. In particular, a verification of the top- p_T discrepancy observed in Run 1 was required (as discussed in Section 2.3.1, providing general motivation and historical background for $t\bar{t}$ cross-section measurements).

This chapter presents differential measurements of absolute and relative $t\bar{t}$ production cross sections in pp collisions at $\sqrt{s} = 13$ TeV using the ℓ +jets final state. The analysis is based on the full 2015 dataset collected by ATLAS during pp collisions with 25 ns bunch spacing. The data correspond to an integrated luminosity of 3.2 fb^{-1} after requiring stable beam conditions and a fully-operational detector. The measurement is focused on the resolved topology, however, it was performed in parallel with a boosted-regime measurement using the same data and consistent methods. Preliminary results

of both analyses were first presented at the 38th International Conference on High Energy Physics in August 2016 and reported in a corresponding conference note [174]. The final results were published later in the Journal of High Energy Physics [175]. The following sections present detailed information about the background estimation techniques, event reconstruction and validation of the unfolding framework. The evaluation and propagation of uncertainties is later discussed, followed by the presentation and discussion of the unfolded results.

6.1 Background estimation

6.1.1 $W + \text{jets}$

The $W + \text{jets}$ background distributions are simulated with SHERPA 2.1 and normalised using the iterative procedure described in Section 4.5.1 including both the charge-asymmetry normalisation and the flavour composition corrections. The charge-asymmetry scale factor is derived in selections with no b -tagging requirements and including exactly two, exactly three or at least four jets. It is extrapolated to the b -tagged selections using the MC simulation. The flavour composition corrections are evaluated using events with exactly two jets and at least one of them b -tagged. The correction factors K_i obtained using Equation 4.1 are then applied to the signal-region flavour fractions f_i .

6.1.2 Non-prompt and fake leptons

The fake/non-prompt lepton background is estimated using the data-driven matrix method discussed in Section 4.5.2. The fake efficiency is measured in data control regions defined similarly to those in Section 5.1.2. The electron-channel control region requires $E_{\text{T}}^{\text{miss}} < 30 \text{ GeV}$ and $m_{\text{T}}^W < 50 \text{ GeV}$, whereas the muon-channel control region includes only events with $|d_0^{\text{sig}}| > 5$. In

both cases, the presence of exactly one loose or tight lepton is required. Due to large differences in efficiency shapes observed between 1-jet and 2-jet selections, only events with at least two jets are included in the control region. This selection was found to produce predictions that describe the data better in validation regions with two, three or four jets. The residual real-lepton contamination in the control regions is around 14 % and 2 % in the e +jets and μ +jets channel respectively. The fake efficiency is measured as a function of the same eight observables as in the inclusive cross-section measurement (Section 5.1.2). These include the jet and b -jet multiplicity, lepton p_T and $|\eta|$, $\Delta\phi(\ell, E_T^{\text{miss}})$, minimum $\Delta R(\ell, \text{jet})$, and E_T^{miss} . However, thanks to the larger available statistics, two-dimensional measurements combining these variables are now also possible.

The fake efficiency parametrisation selected as describing the validation-region distributions best in the e +jets channel is:

$$\varepsilon_f = \sqrt[3]{\varepsilon_f^{2D}(p_T^\ell, N_b) \cdot \varepsilon_f^{2D}(\Delta\phi, |\eta^\ell|) \cdot \varepsilon_f^{2D}(\Delta\phi, p_T^\ell)},$$

where $\Delta\phi \equiv \Delta\phi(\ell, E_T^{\text{miss}})$ and the efficiencies $\varepsilon_f^{2D}(x, y)$ are measured double-differentially. Low- p_T background muons, believed to be produced mainly in semileptonic decays of heavy flavour hadrons, are found to show different sensitivity to E_T^{miss} than high- p_T fake muons, likely dominated by hadronic-calorimeter punch-through effects. A good description of the validation-region data is achieved with different fake efficiency parametrisations in these two regimes. The low- p_T parametrisation depends on the muon p_T as well as E_T^{miss} and $\Delta\phi(\ell, E_T^{\text{miss}})$:

$$\varepsilon_f^L = \sqrt{\varepsilon_f^{2D}(\Delta\phi, p_T^\ell) \cdot \varepsilon_f(E_T^{\text{miss}})},$$

whereas the high- p_T parametrisation depends on the muon p_T only:

$$\varepsilon_f^H = \varepsilon_f(p_T^\ell).$$

The two parametrisations are combined using a Fermi function with a 10 GeV width around a 60 GeV turning point:

$$\varepsilon_f = (1 - f) \cdot \varepsilon_f^L + f \cdot \varepsilon_f^H,$$

where:

$$f = f(p_T^\ell) = \left(1 + \exp \left(-\frac{p_T^\ell - 60 \text{ GeV}}{10 \text{ GeV}} \right) \right)^{-1}. \quad (6.1)$$

All measurements of the fake efficiency used in the parametrisations described above are presented in Figure 6.1. In double-differential cases, there are a few bins with no value, which arise from ill-defined efficiency due to statistical fluctuations at the tail of the p_T distribution. In these bins, the arithmetic mean of the neighbouring non-zero bins is taken as the efficiency value. This has no adverse effects on the final predictions, as it happens only in very few 2D bins at the highest p_T where the contribution of fake leptons is insignificant.

The real efficiency is measured with the $Z \rightarrow \ell\ell$ tag-and-probe method. Events with a pair of same-flavour opposite-sign loose or tight leptons and at least one jet are selected, requiring the invariant mass of the dilepton system to be between 60 and 120 GeV. If one of the two leptons passes the tight lepton requirements, it is considered a tag and the other lepton is considered a probe. In general, the denominator of the efficiency is the number of all probes, whereas the numerator is the number of probes which pass the tight criteria. If both leptons pass the tight criteria, the pair serves both as a tag-probe and as a probe-tag pair. The same observables as for the fake efficiency were considered for the parametrisation.

In order to correct the measurement for the residual amount of fake leptons in the selection (originating mostly from $t\bar{t} \rightarrow \ell + \text{jets}$ events with an

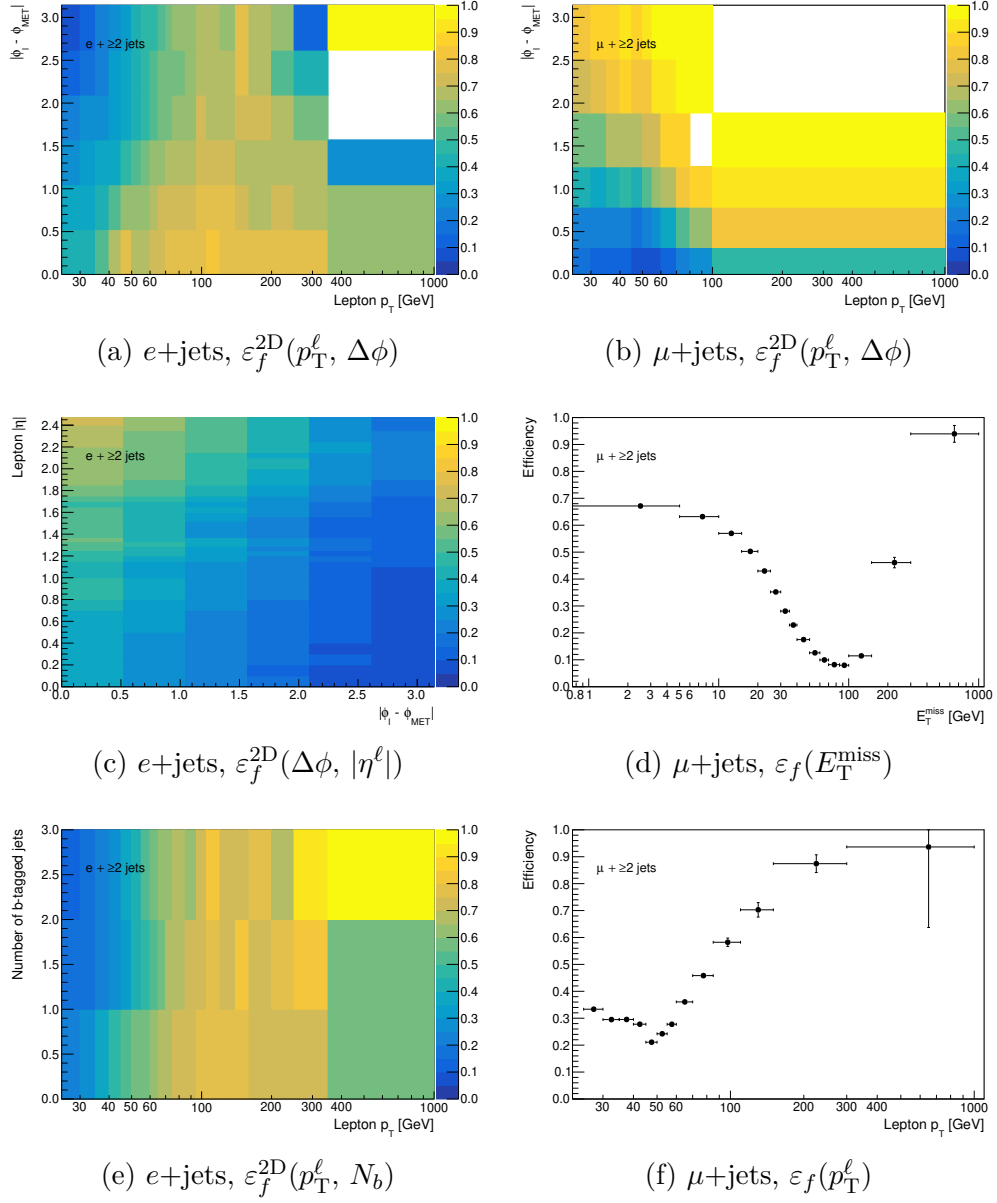


Figure 6.1: Fake efficiency measurements used in the multijet background estimate in the $e+\text{jets}$ and $\mu+\text{jets}$ channels.

additional fake lepton), a method based on an $m_{\ell\ell}$ fit is employed. For each bin of an observable x in which the efficiency is measured, a fit of the $m_{\ell\ell}$ distribution is performed with a signal+background model including events only from this bin. The amount of the $Z \rightarrow \ell\ell$ signal is calculated as the number of events within the range 80–100 GeV minus the integral of the background function over this range. The same procedure is done separately for the numerator and the denominator of the efficiency, and the resulting numbers are divided to obtain the real efficiency in a given bin of x . The signal model is a convolution of Breit-Wigner and Crystal Ball distributions, whereas the background is modelled with a linear function. Example fit results are presented in Figure 6.2. The fits are describing data well in all bins and the background contribution is found to be small.

In the e +jets channel, the real efficiency is parametrised only as a function of the lepton transverse momentum, $\varepsilon_r = \varepsilon_r(p_T^\ell)$, whereas in the μ +jets channel a p_T^ℓ -splitting is performed in the same way as for the fake efficiency. The same merging function (Equation 6.1) is used, and the corresponding components are calculated as:

$$\varepsilon_r^{\text{L}} = \sqrt{\varepsilon_r(\Delta\phi) \cdot \varepsilon_r(p_T^\ell)},$$

$$\varepsilon_r^{\text{H}} = \varepsilon_r(p_T^\ell).$$

The three real efficiency measurements used in the background estimate are presented in Figure 6.3. Low- p_T real leptons are found to be more likely to be rejected in the signal selection, which is expected due to p_T -dependent isolation criteria. Muons with lower $\Delta\phi(\ell, E_T^{\text{miss}})$ are also characterised by a lower real efficiency, which may be due to energy losses in less efficient detector regions.

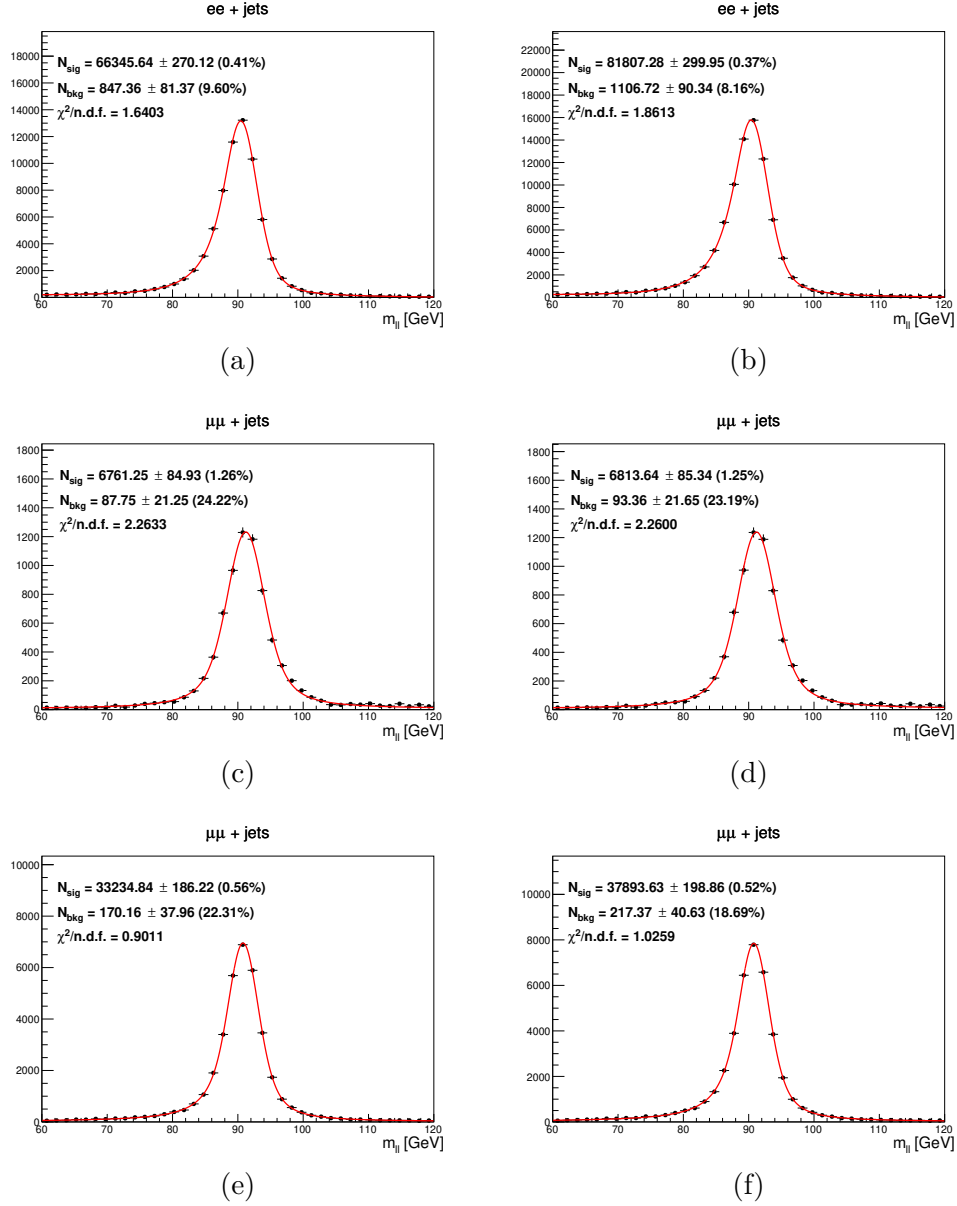
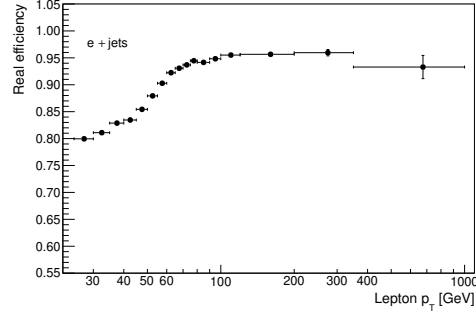
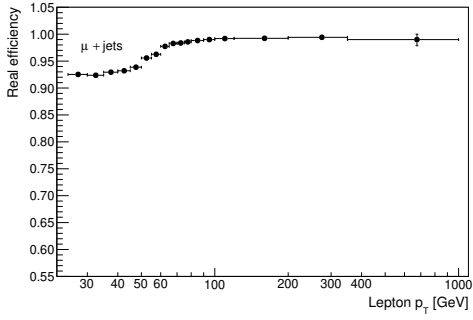


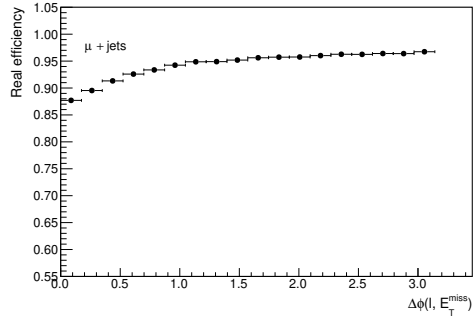
Figure 6.2: Example results of dilepton invariant mass fits for the numerator (a, c, e) and denominator (b, d, f) of the real efficiency. The top row (a, b) shows the electron p_T bin (35, 40) GeV, the middle row (c, d) shows the muon p_T bin (120, 200) GeV, and the bottom row (e, f) shows the muon $\Delta\phi(\ell, E_T^{\text{miss}})$ bin $(0, \frac{\pi}{18})$.



(a) $e+\text{jets}$, $\varepsilon_r(p_T^\ell)$



(b) $\mu+\text{jets}$, $\varepsilon_r(p_T^\ell)$



(c) $\mu+\text{jets}$, $\varepsilon_r(\Delta\phi)$

Figure 6.3: Real efficiency measurements used in the multijet background estimate in the $e+\text{jets}$ and $\mu+\text{jets}$ channels.

6.1.3 Other backgrounds

The contribution of single-top, $Z + \text{jets}$, diboson and $t\bar{t}V$ processes in the signal selection is estimated using simulated samples listed in Section 4.2.

6.2 Event selection and reconstruction

The signal region selection at the detector level includes events with exactly one lepton (electron or muon) and at least four jets, following the definitions from Section 4.1. At least two jets in the event are required to be b -tagged using an MV2c20 requirement corresponding to a 77 % signal efficiency and a 4.5 (140) rejection factor for c -jets (light jets). The particle-level definition of the fiducial phase space follows the detector-level selection closely, requiring the presence of exactly one electron or muon and at least four jets, with at least two of the jets identified as originating from a b -hadron. All particle- and detector-level event and object selection requirements are summarised in Table 6.1. A comprehensive set of figures showing kinematic distributions of leptons, jets and $E_{\text{T}}^{\text{miss}}$ in the signal region and in background-dominated validation regions is presented in Appendix A.1. Background and signal predictions agree well with data across all regions. Although a 10 % normalisation offset of data above the prediction is observed in the signal region, it remains within the uncertainty interval defined by the statistical, background and object reconstruction uncertainties.

Measurements of the top quark and $t\bar{t}$ system properties require the reconstruction of both, detector-level and particle-level objects corresponding to top-quark kinematics. The main challenges of the reconstruction are the determination of the neutrino momentum and the association of jets to the top-quark decay products. The so-called pseudo-top algorithm [176] is employed, where the underconstrained system is resolved using assumptions on the W boson mass and the momentum ordering of jets. Firstly, the leptonically-decaying W boson is reconstructed using the lepton four-momentum and the $\mathbf{E}_{\text{T}}^{\text{miss}}$ vector. Neglecting the neutrino mass, its longi-

	Particle level	Detector level
OBJECT SELECTION		
Leptons	$p_T \geq 25 \text{ GeV},$ $ \eta < 2.5$	$p_T \geq 25 \text{ GeV},$ $ \eta^\mu < 2.5, \eta^e \in [0, 1.37] \cup [1.52, 2.47]$ Track and calorimeter isolation, Track to primary vertex association, Trigger object matching
Jets	anti- k_t $R = 0.4,$ $p_T \geq 25 \text{ GeV},$ $ \eta < 2.5$	anti- k_t $R = 0.4,$ $p_T \geq 25 \text{ GeV},$ $ \eta < 2.5,$ JVT requirement
b -tagging	Ghost-matching	MV2c20 at 77 % WP
E_T^{miss}	Non-hadronic ν p_T -sum	TST E_T^{miss}
EVENT SELECTION		
N leptons	$= 1 \text{ } e \text{ or } \mu$	$= 1 \text{ } e \text{ or } \mu$
N jets	≥ 4	≥ 4
N b -tagged jets	≥ 2	≥ 2

Table 6.1: Summary of object and event selection requirements applied at the particle and the detector level.

tudinal momentum is obtained from a solution of the quadratic equation:

$$\left(E^\ell + E^\nu\right)^2 - \left(p_x^\ell + p_x^\nu\right)^2 - \left(p_y^\ell + p_y^\nu\right)^2 - \left(p_z^\ell + p_z^\nu\right)^2 = m_W^2,$$

where $p_x^\nu = E_x^{\text{miss}}, p_y^\nu = E_y^{\text{miss}}$ and m_W is fixed to the value used for the MC-samples generation, 80.399 GeV. A general solution of the above equation gives:

$$p_z^\nu = \frac{-b - \sqrt{b^2 - 4ac}}{2a},$$

where:

$$a = (E^\ell)^2 - (p_z^\ell)^2, \quad b = -2kp_z^\ell, \quad c = (E^\ell p_T^\nu)^2 - k^2$$

and

$$k = \frac{m_W^2 - m_\ell^2}{2} + (p_x^\ell p_x^\nu + p_y^\ell p_y^\nu) .$$

If there are two real solutions, the one with a smaller $|p_z^\nu|$ is used, and if the discriminant of the equation is negative, the neutrino longitudinal momentum is set to the location of the parabola vertex $p_z^\nu = -b/(2a)$. The top quark producing the leptonically-decaying W boson, hereafter called the *leptonic top*, is reconstructed by combining the W with a b -jet which is the closest in ΔR to the lepton. Only the two highest- p_T b -jets in an event are considered as the direct products of top quark decays. The other b -jet is assigned to the *hadronic top*, combining it with the two other jets which give a dijet invariant mass closest to m_W . The same algorithm is used to reconstruct the $t\bar{t}$ system at both, the particle and the detector level.

The differential cross sections are measured as a function of five observables – the transverse momentum and rapidity of the hadronic top ($p_T^{\text{t, had}}, y^{\text{t, had}}$), and the transverse momentum, rapidity and invariant mass of the $t\bar{t}$ system ($p_T^{t\bar{t}}, y^{t\bar{t}}, m^{t\bar{t}}$). The hadronic top is chosen over the leptonic due to a better resolution and correspondence between detector and particle level. It is also preferred for comparison with the parallel analysis using the boosted topology, where the large- R top-jet directly corresponds to the hadronic top. The choice of observables is driven by their sensitivity to the modelling of $t\bar{t}$ production and decays, and is in line with previous ATLAS and CMS ℓ +jets measurements at lower pp collision energies [176–182]. The p_T of the $t\bar{t}$ system is particularly sensitive to the underlying event description and higher-order corrections in perturbative calculations, since it corresponds to the opposite of the p_T of additional particles produced in the hard process “back-to-back” with the top quark pair. In leading order calculations (so called *tree-level*) there is no additional emission, thus $p_T^{t\bar{t}}$ is always zero to

conserve the total transverse momentum. In addition, it is also sensitive to beyond-SM physics as new heavy particles could decay into high-momentum top quark pairs. Such new particles could be also observed in the $t\bar{t}$ system mass distribution, motivating the cross-section measurement as a function of this observable. Top quark p_T distributions have also been shown to be highly sensitive to higher-order corrections in perturbative calculations in LHC Run-1 measurements and a significant data-model discrepancy was observed in comparison to LO and NLO predictions (see Section 2.3.1). The top quark and $t\bar{t}$ system rapidity distributions are particularly sensitive to the choice of PDFs and new measurements of these observables may help constrain the gluon PDF.

6.3 Unfolding

The detector-level distributions are unfolded to particle level following the procedure described in Section 4.6. The migration matrices and all corrections are derived using the nominal signal MC sample (POWHEG+PYTHIA6) and are presented for the hadronic top p_T distribution in Figure 6.4, along with its detector-level distribution. The migration matrix is normalised in rows for presentation, such that each bin value represents the probability of a given particle-level true value to result in a given detector-level observation. The values are expressed in percent. The intermediate- p_T regions are found to be the least affected by the reconstruction and selection efficiencies and provide the best matching efficiency. The loss of events at high p_T is attributed to the decreasing lepton isolation and to merging of jets. Low- p_T effects affecting the measurement are dominated by jets close to the fiducial definition boundaries, particularly particle-level jets with $p_T < 25$ GeV reconstructed as having $p_T > 25$ GeV or vice versa. Events in the e +jets and μ +jets channels are treated together as a combined ℓ +jets channel,

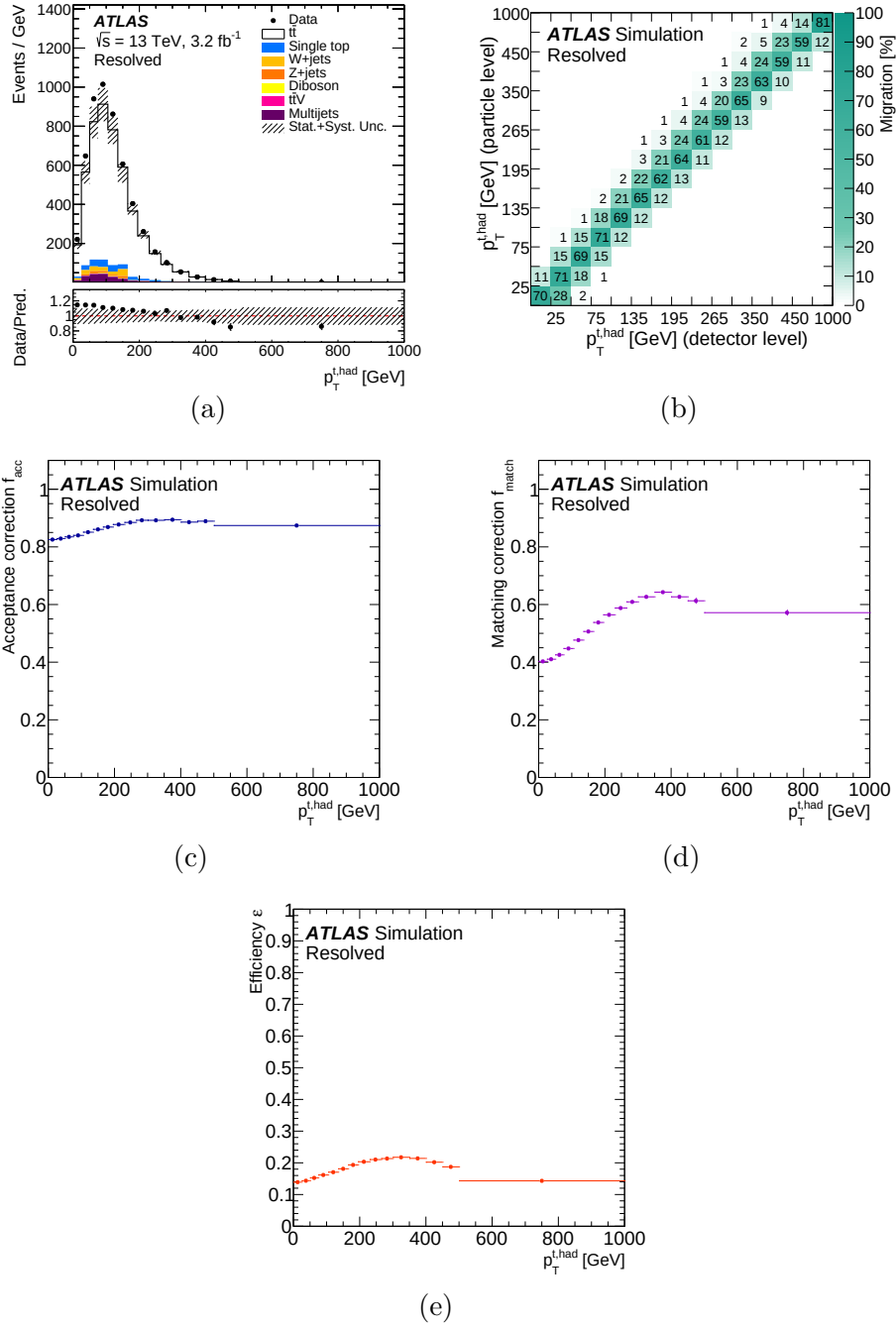


Figure 6.4: Detector-level distribution (a), migration matrix (b), acceptance correction (c), matching correction (d) and efficiency (e) for the hadronic top p_T . The migration matrix is normalised to unity in each row, thus the number in each bin represents the probability of a migration from a given particle-level bin to a particular detector-level bin [175].

which is justified by the similarity of the respective distributions and corrections. The binning in each observable is chosen to minimise off-diagonal migration matrix elements and ensure a sufficient number of events in each bin. The first property is ensured by requiring that each bin is at least 2σ wide, where σ corresponds to the variance of the detector-level distribution of a given observable in a narrow particle-level range around the bin centre. Some bins are widened later in case of large statistical fluctuations observed in closure tests. The number of iterations in the unfolding procedure was optimised to give consistent results with respect to the next iteration while minimising the statistical uncertainties in each unfolded bin, as described in Section 4.6. Four iterations are found to be a good compromise across all measured distributions.

The unfolding procedure is validated using closure and stress tests described in Section 4.6. In the stress tests, the p_T distributions are reweighted using a linear function, the rapidity by subtracting a zero-centred Gaussian with a width of 0.3, and the mass of the $t\bar{t}$ system by adding a Gaussian around 800 GeV with a width of 100 GeV. In all cases, a good agreement between the unfolded and particle-level distributions is observed. Results of the closure and stress tests performed all measured distributions are presented in Figures 6.5 and 6.6. In all cases, they show the procedure is stable and does not introduce a large bias towards the prior, thus would not hide new physics or signal mismodelling effects.

The unfolded results are presented as both absolute and relative differential cross section measurements, where *relative* means divided by the total fiducial cross section in the analysis selection. The latter approach is advantageous due to a partial cancellation of systematic uncertainties resulting in an increased sensitivity to distribution shape modelling regardless of the

total cross section.

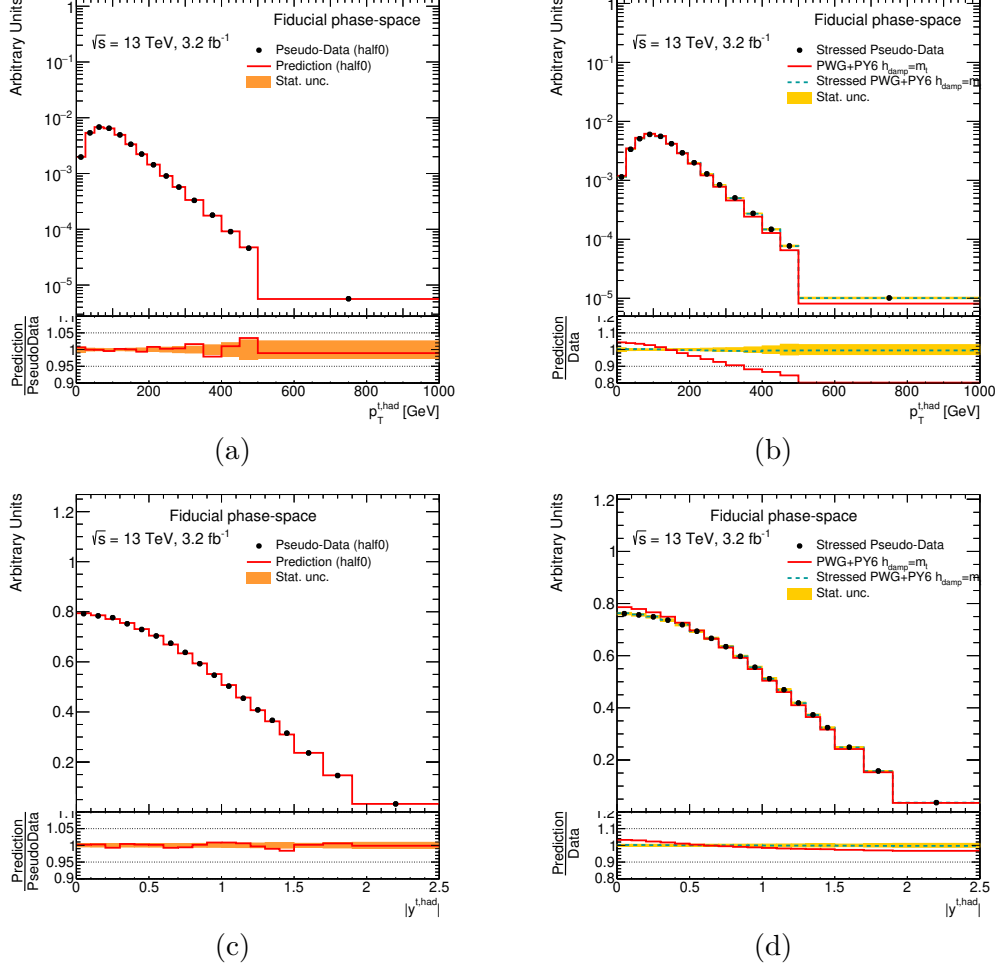
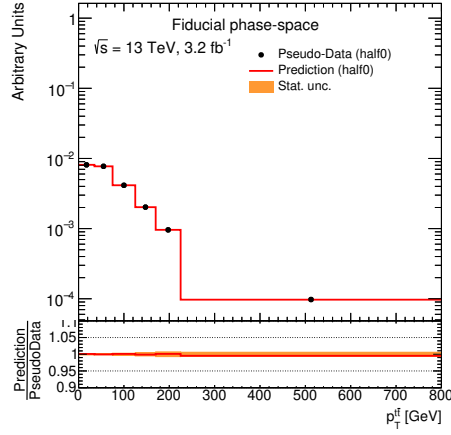
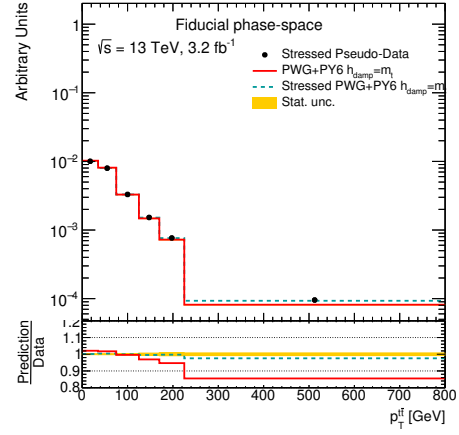


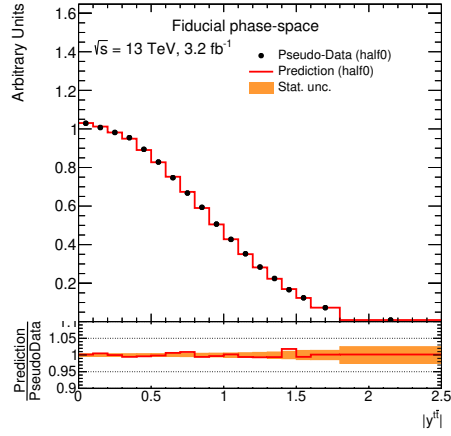
Figure 6.5: Results of the closure (a, c) and the stress (b, d) tests for the hadronic top p_T (a, b) and rapidity (c, d) distributions.



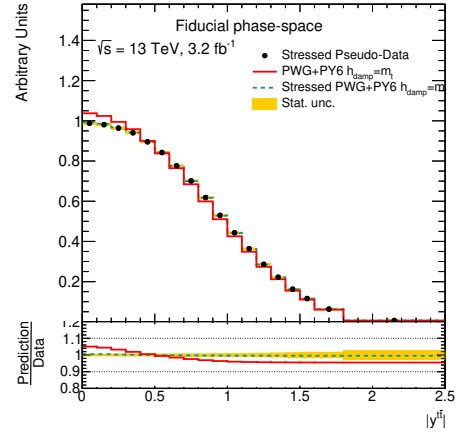
(a)



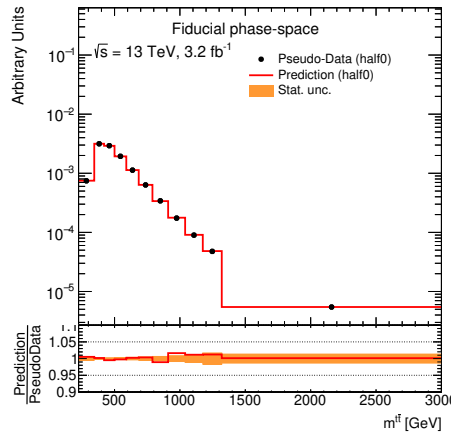
(b)



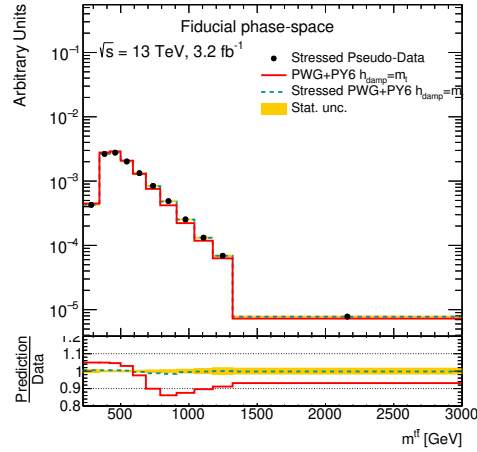
(c)



(d)



(e)



(f)

Figure 6.6: Results of the closure (a, c, e) and the stress (b, d, f) tests for the hadronic top p_T (a, b), rapidity (c, d) and mass (e, f) distributions.

6.4 Uncertainties

Individual systematic uncertainties associated with object reconstruction and MC-based background estimates are evaluated as described in Section 4.7. Uncertainties affecting the W +jets background estimate include the effects of object reconstruction and normalisation of other backgrounds, as well as a statistical component associated with each data-driven scale factor. The multijet background uncertainty includes contributions from variations of the fake efficiency control regions, normalisation of the residual real-lepton contamination in the fake efficiency measurement, and the statistical precision of both efficiency measurements. In addition, an overall 50 % normalisation uncertainty is added to cover an $E_{\text{T}}^{\text{miss}}$ and m_{T}^W mis-modelling observed in the validation regions. All of the above variations are propagated to the final results by unfolding the varied detector-level predictions using the nominal corrections and comparing them to the nominal particle-level distributions. The integrated luminosity of the analysed data sample, which additionally affects the scale of the absolute cross section measurements, is associated with a 2.1 % uncertainty.

Effects related to the choice of the signal hard process generator are evaluated by unfolding a MG5_aMC@NLO+HERWIG++ sample using corrections derived with POWHEG+HERWIG++. The unfolded result is compared to the particle-level spectrum of MG5_aMC@NLO+HERWIG++ and the relative difference is transferred to the nominal unfolded results. The parton shower uncertainty is determined by unfolding the POWHEG+HERWIG++ distributions with the POWHEG+PYTHIA corrections and comparing to the POWHEG+HERWIG++ particle level. In analogy, the effects of the initial- and final-state radiation are estimated using the ‘radHi’ and ‘radLo’ POWHEG+PYTHIA samples unfolded using the nominal corrections. The

PDF4LHC15 recommendations [183] are applied to evaluate the uncertainty related to the PDF set choice. Since the PDF variations affect the unfolding corrections, the nominal MG5_aMC@NLO+HERWIG++ sample is unfolded using differently PDF-reweighted corrections and the effects of the correction variations are transferred to the nominal results.

The statistical uncertainty due to the size of both data and MC samples is evaluated using pseudo-experiments. The event counts are varied independently in every bin before unfolding and the variations are propagated to the unfolded results. Pseudo-experiments are also used to obtain covariance matrices carrying information about the bin-to-bin correlations of the total uncertainty, which are presented along with the numeric results of the measurements.

Example distributions of the fractional uncertainty divided into several categories are presented in Figure 6.7. Low top-quark and $t\bar{t}$ -system p_T and low $m_{t\bar{t}}$ regions are particularly affected by the jet energy scale and resolution uncertainties, whereas the precision at higher values is limited by the flavour tagging effects. Uncertainties related to signal modelling and background estimation also have a significant contribution in several bins of the measured observables. The precision of the top-quark and $t\bar{t}$ -system rapidity measurements is similar across the full measured range and dominated by JES and flavour tagging effects. The total uncertainty associated with the absolute measurements varies within the range 10–20 %. A large uncertainty reduction, up to a factor of 3, is observed for the relative measurements with the overall values ranging between 5 and 15 %. In many bins, the normalised measurements become dominated by the uncertainties related to signal modelling. This is expected since the JES and flavour tagging uncertainties affect the object selection the most and signal distribution

shapes to a lower extent. JES variations cause jets with p_T close to 25 GeV to cross the requirement boundary, changing the number of signal events with at least four jets with $p_T \geq 25$ GeV. Similarly, variations affecting the b -tagging result affect the number of signal events with at least two b -jets.

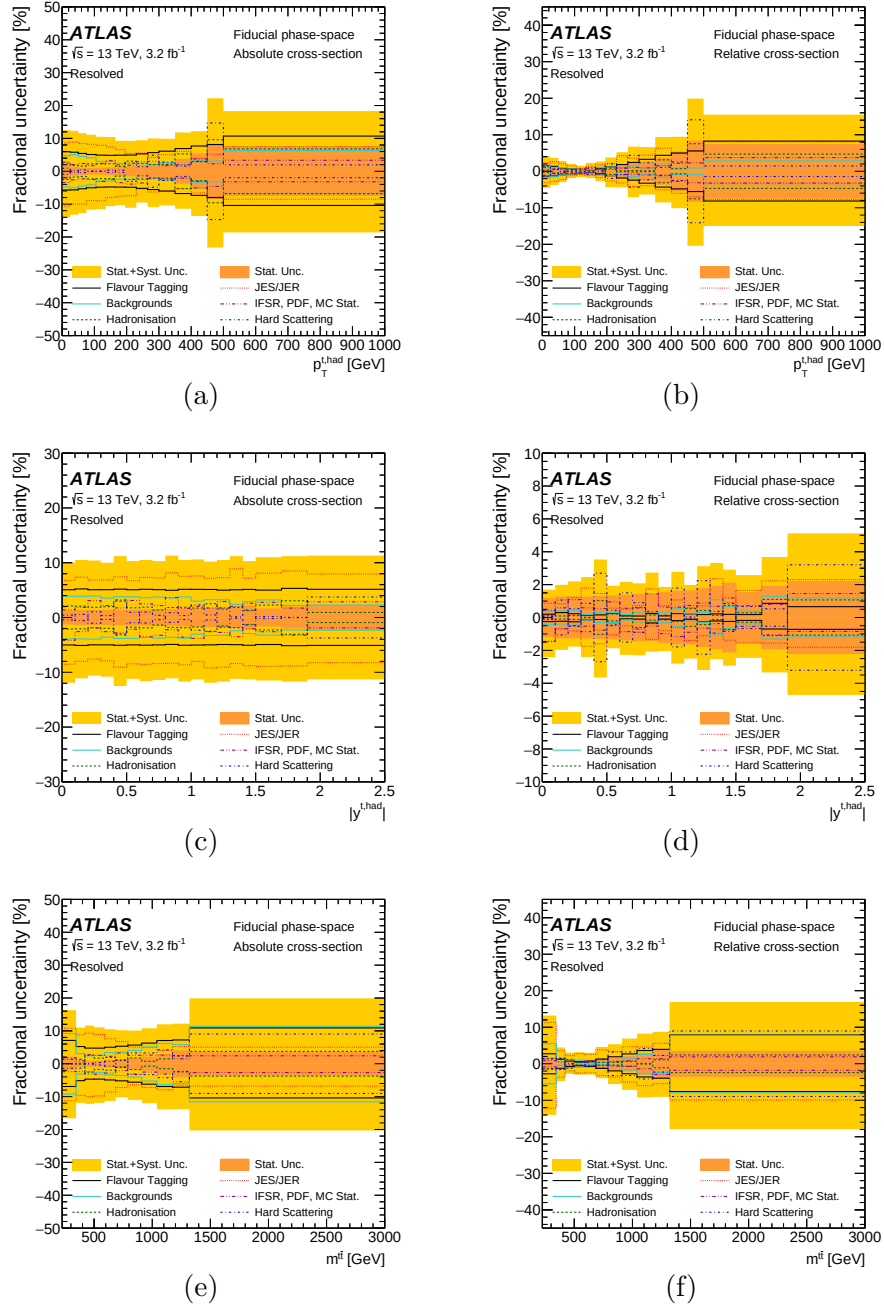


Figure 6.7: Uncertainties associated with the absolute (a, c, e) and relative (b, d, f) differential measurements of the $t\bar{t}$ production cross section as a function of the hadronic top p_T (a, b), hadronic top rapidity (c, d) and the mass of the $t\bar{t}$ system (e, f) [175].

6.5 Results, context and discussion

Results of the fiducial relative differential cross-section measurements in the five considered observables are presented in Figures 6.8 and 6.9. The corresponding results of the absolute cross-section measurements can be found in Appendix A.3. The unfolded data are compared to different Standard Model perturbative QCD predictions including the nominal and alternative samples used in the measurement. In addition, predictions obtained using the new $t\bar{t}$ samples generated in 2016 and listed in Section 4.2.1 are also presented. These include the new nominal configuration of POWHEG+PYTHIA8 and the alternative samples generated with POWHEG+HERWIG7 and with MG5_aMC@NLO+PYTHIA8. Parameters of the POWHEG-BOX NLO generator as well as the PYTHIA8 and HERWIG7 PS simulations were optimised using preliminary results of this analysis in addition to analogous 7 and 8 TeV ATLAS measurements [43]. The total fiducial cross-section values used to compute the relative measurements are presented in Table 6.2. Each generated $t\bar{t}$ sample is scaled to the same inclusive cross-section value obtained from NNLO calculations as described in Section 4.2.1, thus the differences originate exclusively from modelling of the fiducial acceptance.

The level of agreement between the measured distributions and each prediction is assessed by computing χ^2 values using the full covariance matrices of experimental uncertainties. The p -value is also evaluated for each comparison. It is the probability of χ^2 being equal or higher than the observed value, which corresponds to the probability of the disagreement being only due to fluctuations described by the uncertainties. The resulting χ^2 and p -values for the five relative measurements are presented in Tables 6.3 and 6.4.

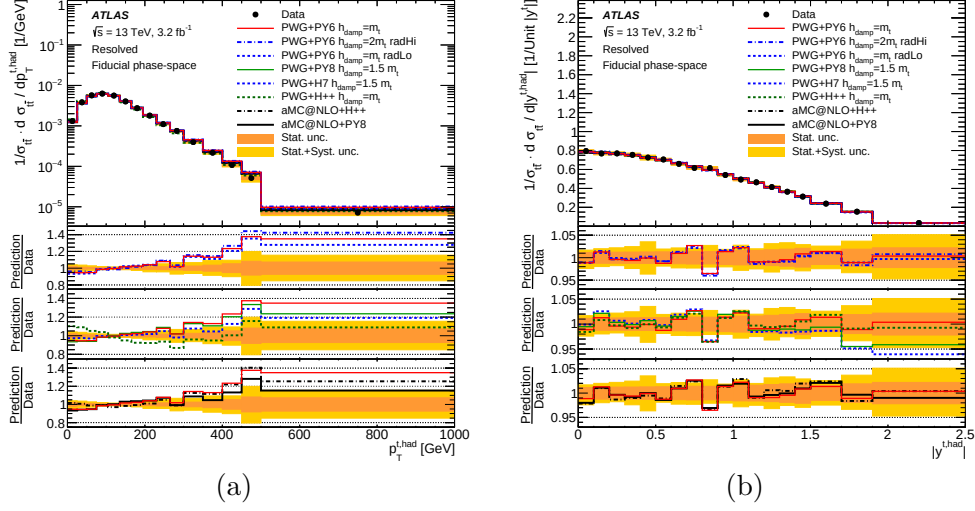


Figure 6.8: Fiducial relative differential cross-sections as a function of the hadronic top transverse momentum (a) and rapidity (b) [175].

MC model	σ_{tt}^{fid} [pb]
POWHEG+PYTHIA6	92.0
POWHEG+PYTHIA6 ‘radHi’	90.9
POWHEG+PYTHIA6 ‘radLo’	94.2
MADGRAPH5_aMC@NLO+HERWIG++	94.9
POWHEG+HERWIG++	93.5
POWHEG+PYTHIA8	97.5
POWHEG+HERWIG7	97.2
MADGRAPH5_aMC@NLO+PYTHIA8	98.5
Data	110^{+13}_{-14} (stat.+syst.)

Table 6.2: Fiducial cross sections measured in data and obtained with different signal models [175].

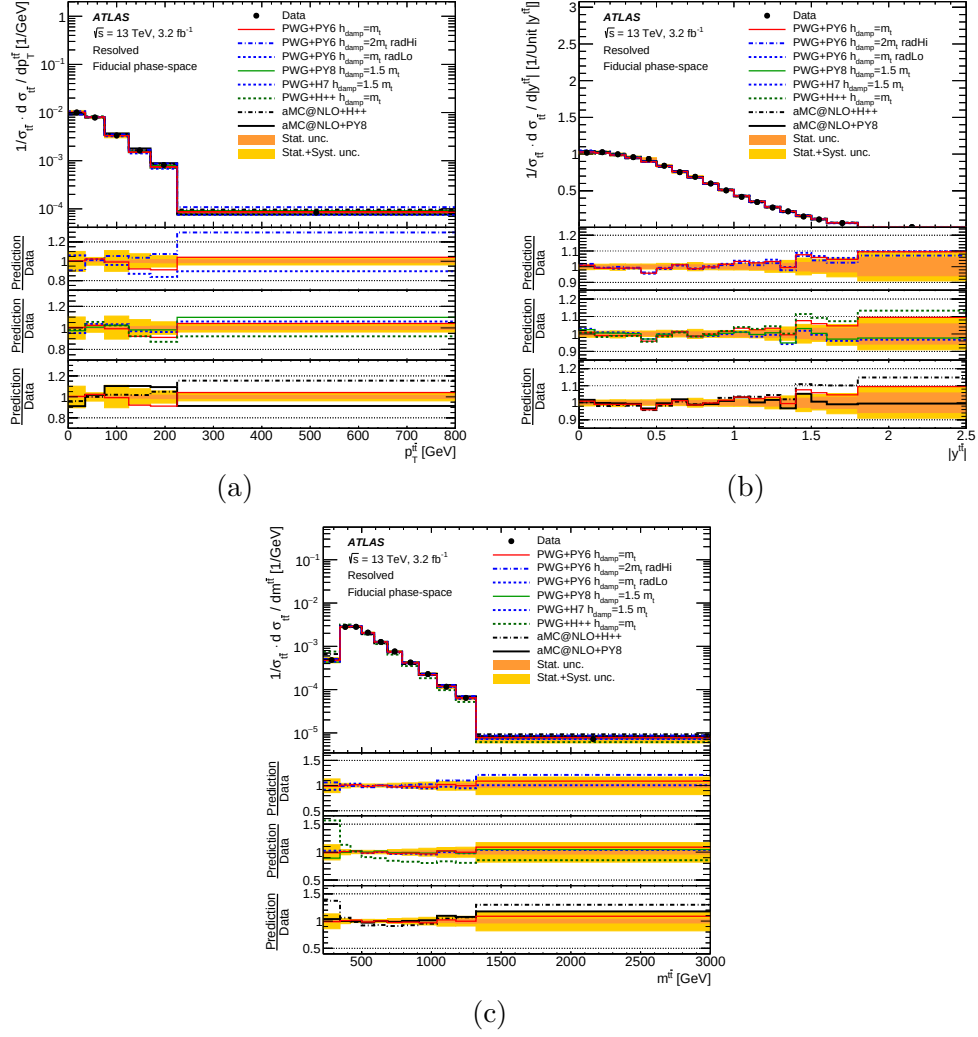


Figure 6.9: Fiducial relative differential cross-sections as a function of the $t\bar{t}$ system transverse momentum (a), rapidity (b) and mass (c) [175].

MC model	$p_T^{t,\text{had}}$		$ y^{t,\text{had}} $	
	χ^2/NDF	$p\text{-value}$	χ^2/NDF	$p\text{-value}$
POWHEG+PYTHIA6	23.0/14	0.06	8.1/17	0.96
POWHEG+PYTHIA6 ‘radHi’	23.8/14	0.05	8.5/17	0.95
POWHEG+PYTHIA6 ‘radLo’	25.9/14	0.03	7.5/17	0.98
MG5_aMC@NLO+HERWIG++	24.4/14	0.04	10.8/17	0.87
POWHEG+HERWIG++	24.0/14	0.05	7.4/17	0.98
POWHEG+PYTHIA8	21.5/14	0.09	9.6/17	0.92
POWHEG+HERWIG7	15.4/14	0.35	9.3/17	0.93
MG5_aMC@NLO+PYTHIA8	21.8/14	0.08	7.8/17	0.97

Table 6.3: Comparison of the measured fiducial relative differential cross sections as a function of hadronic top p_T and $|y|$ to the predictions from different MC models in terms of χ^2 divided by the number of degrees of freedom (NDF) and p -values [175].

MC model	$m^{t\bar{t}}$		$p_T^{t\bar{t}}$		$ y^{t\bar{t}} $	
	χ^2/NDF	$p\text{-value}$	χ^2/NDF	$p\text{-value}$	χ^2/NDF	$p\text{-value}$
POWHEG+PYTHIA6	6.3/10	0.79	7.7/5	0.17	22.5/17	0.17
POWHEG+PYTHIA6 ‘radHi’	7.7/10	0.66	5.1/5	0.41	19.3/17	0.31
POWHEG+PYTHIA6 ‘radLo’	8.2/10	0.61	20.4/5	<0.01	28.0/17	0.04
MG5_aMC@NLO+HERWIG++	23.6/10	<0.01	2.6/5	0.76	30.0/17	0.03
POWHEG+HERWIG++	37.9/10	<0.01	25.0/5	<0.01	32.8/17	0.01
POWHEG+PYTHIA8	6.5/10	0.77	1.1/5	0.96	14.0/17	0.67
POWHEG+HERWIG7	6.7/10	0.76	5.4/5	0.37	15.1/17	0.59
MG5_aMC@NLO+PYTHIA8	6.8/10	0.75	3.3/5	0.66	18.0/17	0.39

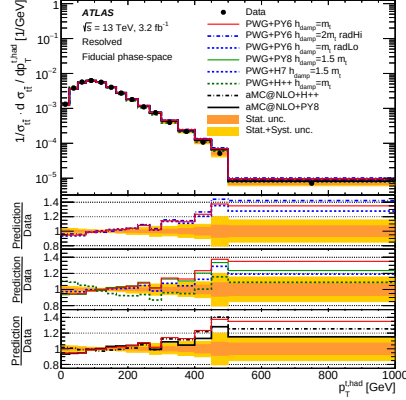
Table 6.4: Comparison of the measured fiducial relative differential cross sections as a function of $t\bar{t}$ system m , p_T and $|y|$ to the predictions from different MC models in terms of χ^2 divided by the number of degrees of freedom (NDF) and p -values [175].

None of the compared models manage to describe all five measured distributions well. In particular, most generators predict the hadronic top p_T distribution to be harder (i.e. shifted towards higher values) than observed in data. In addition, the configurations using the HERWIG++ PS simulation show a non-monotonic discrepancy with the observations, predicting higher relative yields in the lowest and the highest p_T regions with a deficit in between. The p_T of the $t\bar{t}$ system is adequately described by most models with the exceptions of the POWHEG+HERWIG++ and POWHEG+PYTHIA6 ‘radLo’ configurations, both showing opposite effects as for $p_T^{\text{t, had}}$ and resulting in p -values lower than 0.01. The observed shape of the $t\bar{t}$ mass spectrum differs significantly from the predictions using the HERWIG++ PS, however, all other predictions agree well with the measurement. The rapidity distributions are found to be in good agreement with all predictions. The only discrepant region is the high $t\bar{t}$ system rapidity, where multiple generators produce higher relative yields than observed. The modelling of this region was previously shown to be particularly sensitive to the choice of PDF sets [181]. Overall, the POWHEG+HERWIG++ model disagrees with the observations the most in the five measured observables. Due to this and similar observations in different $t\bar{t}$ decay channels, it is no longer in use by ATLAS. The nominal POWHEG+PYTHIA6 model provides a reasonable description of the data. The best overall agreement is found with the POWHEG+HERWIG7 predictions, however, this model also fails to describe the shape of the top p_T distribution. The ‘radLo’ and ‘radHi’ variations bracket the nominal prediction in almost all bins of the five distributions, as expected from samples aimed to estimate the effects of decreased and increased amounts of initial-/final-state radiation.

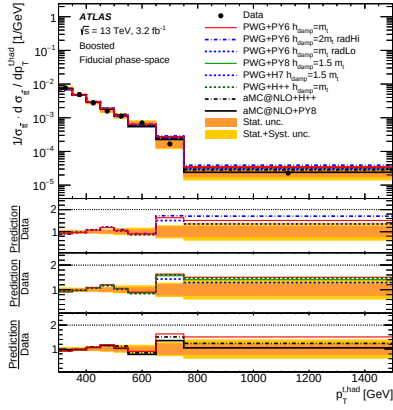
The results are consistent with previous ATLAS and CMS ℓ +jets measurements at lower collision energies [176–182] as well as with the CMS

measurement at $\sqrt{s} = 13 \text{ TeV}$ [184]. The same trends are observed at the particle and the parton levels, and similar features emerge in other $t\bar{t}$ decay channels [185, 186] and topologies. In particular, the linear discrepancy observed in the top quark p_T distribution can be observed across the full range of measurements, including all ATLAS measurements using the 2015 dataset, as presented in Figure 6.10. Despite the different definitions of the measured objects and fiducial phase space, all results sensitive to top-quark p_T show a similar behaviour. In particular, the complementarity and compatibility of the ℓ +jets resolved topology measurement with the boosted topology analysis presented in the same publication [175] is clearly seen in Figure 6.11 showing the ratios of the observed spectra to predictions obtained with the same nominal POWHEG+PYTHIA6 MC sample. The boosted topology allows to reach higher top-quark p_T values and provides results consistent with the resolved topology where the two overlap. As discussed in Section 2.3.1, the disagreement is found to decrease with the inclusion of higher-order perturbative QCD corrections and electroweak effects, however it is not yet fully understood and further developments in theory predictions, MC simulations and experimental measurements are anticipated.

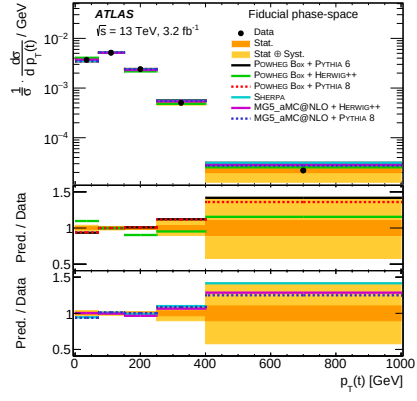
No new physics observations were made in the presented measurements and the Standard Model predictions were found to provide an overall good description of the measured differential cross sections. However, none of the studied models provide a perfect description of all observables together, and none of them can adequately describe the shape of the top p_T distribution. The latter observation confirms the results of similar measurements using LHC Run-1 data. The presented measurements were successfully used as an input for parameter tuning in top-quark process MC generators used in ATLAS [43]. They can be used in future in other similar studies and also



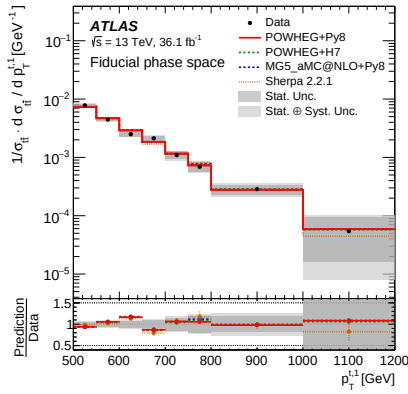
(a)



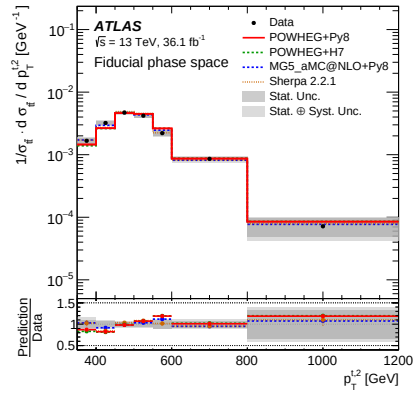
(b)



(c)



(d)



(e)

Figure 6.10: Fiducial relative differential cross-sections as a function of the transverse momentum of a particle-level top quark proxy object in the (a) ℓ +jets resolved [175], (b) ℓ +jets boosted [175], (c) $e\mu$ [185], (d,e) all-hadronic [186] channels.

in PDF fits, thus provide a crucial input to the global understanding of $t\bar{t}$ production in high-energy hadron collisions.

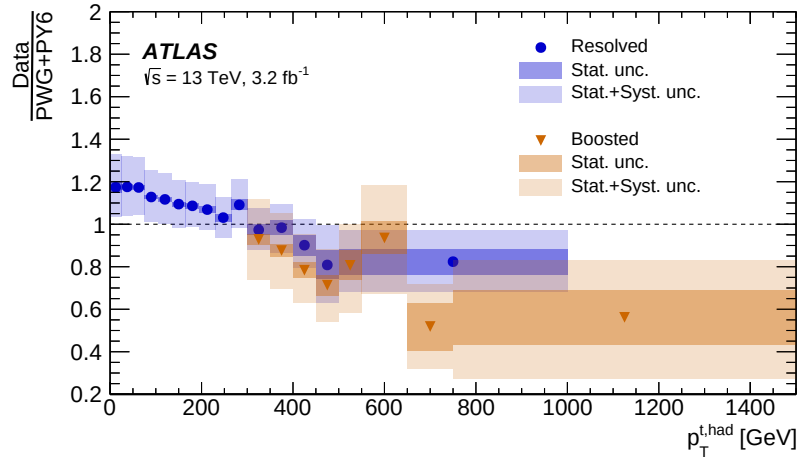


Figure 6.11: Ratios of the measured fiducial absolute differential cross sections to the prediction of the nominal POWHEG+PYTHIA6 sample in the resolved and boosted topologies as a function of their respective transverse momentum of the hadronic top quark [175].

Chapter 7

$t\bar{t}$ production in association with heavy-flavour jets

With the rapidly increasing amount of 13 TeV data throughout Run 2 of the LHC and with the lack of new physics observations, the focus of top physics research has extended towards cross section measurements of associated production of $t\bar{t}$ with vector bosons or with jets. One of the main goals for Run 2 for both ATLAS and CMS was also the observation of the $t\bar{t}H$ production, which was achieved in 2018 [187, 188]. However, the highest branching-fraction decay channel of the Higgs boson still provides low sensitivity to $t\bar{t}H$ production due to high uncertainty on the production cross section of $t\bar{t}b\bar{b}$, the main background for $t\bar{t}H(b\bar{b})$ [51, 52]. Improvements in $t\bar{t}b\bar{b}$ modelling require both further developments of the simulation programs and dedicated measurements to validate the models, as discussed in Section 2.3.2. Validation of the state-of-the-art perturbative QCD predictions matched to parton shower and hadronisation simulations is also interesting on its own.

This chapter reports on the first ATLAS Run-2 measurements of $t\bar{t}$ production in association with jets identified as originating from b quarks. Normalised differential cross-section measurements in a fiducial volume requiring at least two additional b -jets are complemented by total fiducial cross

section measurements in selections requiring exactly one, at least one, or at least two additional b -jets. The analysis reported here is performed in the ℓ +jets channel. A dilepton channel measurement is also performed in parallel, exploiting the same strategy and object definitions, and complementary phase spaces. Both measurements are based on the full 2015+2016 dataset collected by ATLAS in pp collisions with 25 ns bunch spacing. After selecting only periods with stable beam conditions and a fully-operational detector, the dataset corresponds to an integrated luminosity of 36.1 fb^{-1} . A journal publication presenting both analyses is in preparation, thus only work-in-progress results are reported in this thesis.

7.1 Event selection

The $t\bar{t} + b$ -jets cross section measurements are based on three particle-level fiducial volumes defined using objects described in Section 4.4. Both differential and total fiducial cross sections are measured in a $t\bar{t} + \geq 2b$ selection with exactly one lepton and at least six jets, four of which are identified to originate from b quarks. In addition, the total fiducial cross sections are measured in the exclusive $t\bar{t} + 1b$ and inclusive $t\bar{t} + \geq 1b$ selections requiring at least five jets and either exactly three or at least three b -tags. Events with only one additional b -jet in the fiducial volume originate mainly from $t\bar{t}b\bar{b}$ events where one of the b -jets has a p_{T} below 25 GeV. All particle-level and detector-level object and event selection criteria are summarised in Table 7.1.

The detector-level signal regions follow analogous definitions requiring the same jet and b -jet multiplicities as the particle-level selections. Signal and background modelling is verified in a $t\bar{t}$ -dominated validation region employing the baseline selection described in Section 4.3 including events with at least four jets and at least two b -tags. An additional control region

	Particle level	Detector level
OBJECT SELECTION		
Leptons	$p_T \geq 25 \text{ GeV},$ $ \eta < 2.5$	$p_T \geq 25 \text{ GeV},$ $ \eta^\mu < 2.5, \eta^e \in [0, 1.37] \cup [1.52, 2.47]$ Track and calorimeter isolation, Track to primary vertex association, Trigger object matching
Jets	anti- k_t $R = 0.4,$ $p_T \geq 25 \text{ GeV},$ $ \eta < 2.5$	anti- k_t $R = 0.4,$ $p_T \geq 25 \text{ GeV},$ $ \eta < 2.5,$ JVT requirement
b -tagging	Ghost-matching	MV2c10 at 60% WP
$t\bar{t} + 1b$ EVENT SELECTION		
N leptons	$= 1 e \text{ or } \mu$	$= 1 e \text{ or } \mu$
N jets	≥ 5	≥ 5
N b -tagged jets	$= 3$	$= 3$
$t\bar{t} + \geq 1b$ EVENT SELECTION		
N leptons	$= 1 e \text{ or } \mu$	$= 1 e \text{ or } \mu$
N jets	≥ 5	≥ 5
N b -tagged jets	≥ 3	≥ 3
$t\bar{t} + \geq 2b$ EVENT SELECTION		
N leptons	$= 1 e \text{ or } \mu$	$= 1 e \text{ or } \mu$
N jets	≥ 6	≥ 6
N b -tagged jets	≥ 4	≥ 4

Table 7.1: Summary of object and event selection requirements applied at the particle and the detector level.

with at least five jets and at least two b -tags is used to correct the flavour composition of the $t\bar{t}$ + jets simulation, as explained in the next section. All detector-level b -jet multiplicity requirements are based on the 60 % b -tagging efficiency working point of the MV2c10 discriminant, providing high c -jet and light-jet rejection factors (34 and 1538 respectively).

An excellent agreement between data and predictions is observed across the validation and signal regions for most observables, as presented in Figure 7.1 and additional figures in Appendix B.1. In particular, a large improvement of the jet multiplicity description in $t\bar{t}$ events between the previous POWHEG+PYTHIA6 and the new POWHEG+PYTHIA8 simulation can be observed comparing Figure A.3d to Figure 7.1a. This is attributed to the use of newer parameter tunes based on ATLAS data and the increase of the h_{damp} parameter value [43]. However, a mismodelling of the b -jet multiplicity can be clearly observed in Figure 7.1b resulting in a normalisation offset in selections requiring additional b -jets.

7.2 Signal and background yields extraction

Non- $t\bar{t}$ background contributions in the signal selections are estimated following similar techniques as in the previous two chapters. The single top, W + jets, Z + jets and diboson yields are computed using simulated samples listed in Section 4.2. The amount of fake and non-prompt lepton events is estimated with the matrix method using efficiencies and parametrisations optimised for a different measurement using the same dataset [189], which is focused on jet properties in $t\bar{t} \rightarrow \ell$ + jets events. The fake efficiency is measured in $\ell + \geq 1$ jet regions with $E_{\text{T}}^{\text{miss}} < 20$ GeV or $|d_0^{\text{sig}}| > 5$ for electrons and muons respectively. The real efficiency measurement exploits the $Z \rightarrow \ell\ell$ tag-and-probe method. Different combinations of parametrisations including the lepton $|\eta|$, b -jet multiplicity, leading jet p_{T} and $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$

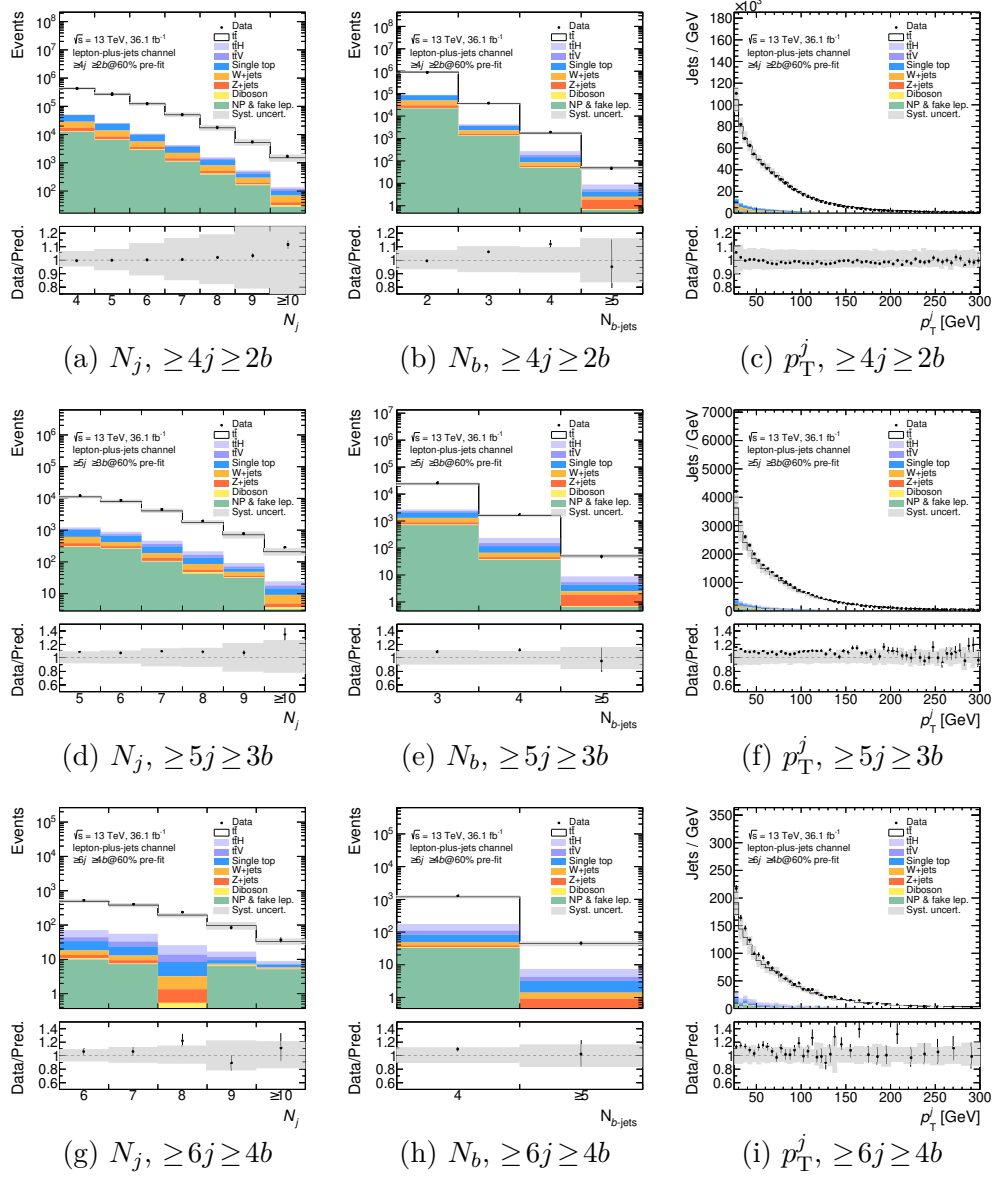


Figure 7.1: Jet multiplicity, b -jet multiplicity and jet p_T distributions in a $t\bar{t}$ control region requiring at least four jets with at least two b -tags and signal regions requiring at least one or at least two additional b -jets. The jet p_T histograms are filled once per jet, thus multiple times per event. The grey bands represent the sum in quadrature of uncertainties from background and detector effects, and simulation statistics.

are used for each channel and each year. The background estimates for 2015 and 2016 data are split due to the different triggers used in these two periods. All non- $t\bar{t}$ backgrounds constitute around 7–8 % of the total event yields in the signal regions, as presented in Table 7.2.

	$\geq 4j, \geq 2b$	$\geq 5j, \geq 2b$	$\geq 5j, \geq 3b$	$\geq 5j, =3b$	$\geq 6j, \geq 4b$
$t\bar{t}$	810000 ± 50000	426000 ± 42000	23000 ± 2200	21700 ± 2100	1030 ± 110
$t\bar{t}H$	1462 ± 52	1250 ± 58	437 ± 23	351 ± 18	68.3 ± 5.8
$t\bar{t}V$	2530 ± 100	2020 ± 110	250 ± 16	215 ± 14	28.3 ± 2.8
Single top	37100 ± 3000	16400 ± 2000	856 ± 99	803 ± 94	35.7 ± 6.5
W +jets	20000 ± 12000	8600 ± 5300	440 ± 270	410 ± 260	11.0 ± 6.9
Z +jets	7350 ± 890	2960 ± 480	164 ± 26	155 ± 26	5.9 ± 1.5
Diboson	1060 ± 120	529 ± 80	34.0 ± 5.6	32.0 ± 5.5	1.79 ± 0.58
Fakes	23000 ± 12000	11000 ± 5500	740 ± 380	710 ± 360	32 ± 21
$t\bar{t} + X$ sum	814000 ± 50000	429000 ± 42000	23700 ± 2200	22300 ± 2100	1130 ± 110
Non- $t\bar{t}$ sum	89000 ± 17000	39500 ± 7900	2230 ± 470	2110 ± 450	87 ± 23
Total pred.	903000 ± 52000	469000 ± 42000	26000 ± 2300	24400 ± 2200	1220 ± 110
Data	901899	469793	28167	26389	1316

Table 7.2: Predicted and observed event yields in the $t\bar{t}$ preselection, fit and signal regions. All systematic uncertainties are included except for the signal modelling.

The dominant and most challenging background affecting the measurements comes from $t\bar{t}$ events with additional light or c -jets misidentified as b -jets. This category, referred to as the *mistag background*, includes also events where the misidentified c -jet comes from the hadronically-decaying W boson produced by a top quark. Both the $t\bar{t}b\bar{b}$ signal and the $t\bar{t}c\bar{c}$ background production cross sections are poorly known (see Section 2.3.2) and the b -jet misidentification rates are also associated with a 10–20 % uncertainty [101, 102]. In order to reduce the impact of the $t\bar{t} + \text{jets}$ modelling and b -jet misidentification uncertainties on the measured cross sections, the normalisation of $t\bar{t}$ contributions with light, c - and b -jets is extracted from a template fit to data. Electroweak production of additional jets in $t\bar{t}$ final

states is treated in the same way as the strong production and categorised either as signal or as the mistag background. The electroweak signal contributions include events from the $t\bar{t}H(b\bar{b})$ and $t\bar{t}Z(b\bar{b})$ processes, whereas the mistag background includes, for example, $t\bar{t}H(c\bar{c})$ or $t\bar{t}H(WW)$ with both W bosons producing c quarks. As stated in Sections 4.2.1 and 4.2.2, $t\bar{t}$ events are simulated with POWHEG+PYTHIA8, whereas $t\bar{t}V$ and $t\bar{t}H$ events are simulated with MADGRAPH5_aMC@NLO+PYTHIA8.

The fit is performed in a control region with at least five jets and at least two b -tags, which is dominated by $t\bar{t}$ events with at least one additional jet. **Three templates** are defined by splitting the sum of $t\bar{t}$, $t\bar{t}H$ and $t\bar{t}V$ simulated samples into three categories based on the flavour of particle-level jets with $p_T > 25$ GeV and $|\eta| < 2.5$. If at least three such jets in an event are identified as b -jets (i.e. ghost-matched to at least one b -hadron), the event is categorised in the **$t\bar{t}b$ template**. If there are fewer than three b -jets and at least two c -jets, the event is categorised in the **$t\bar{t}c$ template**. If fewer than three b -jets and fewer than two c -jets are found, the event is considered in the **$t\bar{t}l$ template**. The sample of events with only one c -jet is dominated by $t\bar{t}$ production in association with light jets, where the c -jet comes from a W boson produced by a top quark, thus it is included in the $t\bar{t}l$ category and not in $t\bar{t}c$.

All detector-level jets in each event are sorted by the corresponding MV2c10 discriminant value and a two-dimensional distribution of the third and fourth highest values is constructed. The binning of this distribution corresponds to the calibrated working points summarised in Table 4.1. The distribution is then linearised into a one-dimensional combined ‘tag weight bin’ distribution, as presented in Figure 7.2. The three templates are then

fitted to data using all bins of this distribution according to:

$$\alpha N_{t\bar{t}b}^{\text{MC}} + \beta N_{t\bar{t}c}^{\text{MC}} + \gamma N_{t\bar{t}l}^{\text{MC}} + N_{\text{non-}t\bar{t}} = N^{\text{data}},$$

where the non- $t\bar{t}$ background contribution, $N_{\text{non-}t\bar{t}}$, is fixed and the parameters α , β , γ are the three flavour scale factors extracted from the fit. The shape of each template and their fractional contributions to the total prediction in each bin are presented in Figure 7.3. As expected (see Figure 4.6), the bins corresponding to low MV2c10 values dominating the $\geq 5j \geq 2b$ selection are composed in 80–90 % of $t\bar{t}l$ events. Events with additional b -jets dominate high MV2c10-value bins. In particular, the last bin corresponding to the $t\bar{t} + \geq 2b$ signal region consists in around 85 % of $t\bar{t}b$ events. Events in the $t\bar{t}c$ category contribute moderately to all bins, however their largest fraction, up to 20 %, can be found in the intermediate bins 6–11.

The pre-fit and post-fit b -tagging discriminant distributions are presented in Figure 7.4. The extracted scale factors are 1.11 ± 0.02 , 1.59 ± 0.06 and 0.962 ± 0.003 for the $t\bar{t}b$, $t\bar{t}c$ and $t\bar{t}l$ templates respectively, where the quoted uncertainties are statistical only. The fit results suggest a $\sim 10\%$ underestimation of the signal in the simulation. The largest effect of the fit is observed in the $t\bar{t}c$ normalisation, which may be related to problems either in the cross-section modelling or calibration of the flavour misidentification. All detector- and background-related systematic variations used in the final uncertainty evaluation are fitted independently resulting in a reduction of the total uncertainty observed in the lower panel of Figure 7.4. The extracted flavour scale factors are used to correct the measured cross sections for the mistag backgrounds as detailed in the next section. A comparison of example event and jet property distributions before and after the fit are presented in Figure 7.5. A more comprehensive set of figures is included in Appendix B.1. No effect on the shape of kinematic distributions is observed,

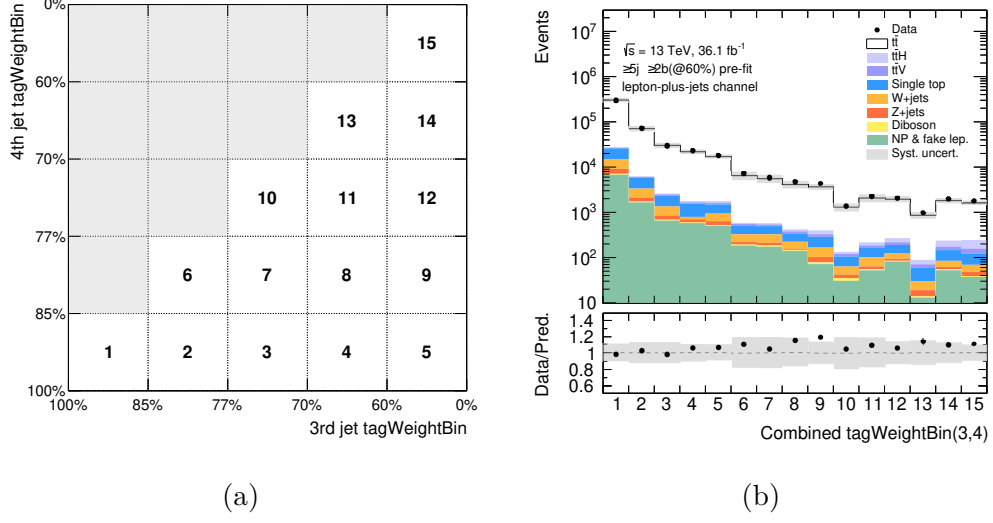


Figure 7.2: (a) Bin numbering definition for the one-dimensional pseudo-continuous b -tagging distribution of the third and fourth highest-MV2c10-score jets, presented in the two-dimensional space. The grey area represents combinations impossible due to sorting. (b) Distribution of the data and predicted event yields in the one-dimensional variable. The grey band represents the systematic uncertainty excluding the signal modelling.

whereas the normalisation offset found in high b -jet multiplicity selections is reduced. The stability of the fit procedure was verified in studies presented in Appendix B.2.

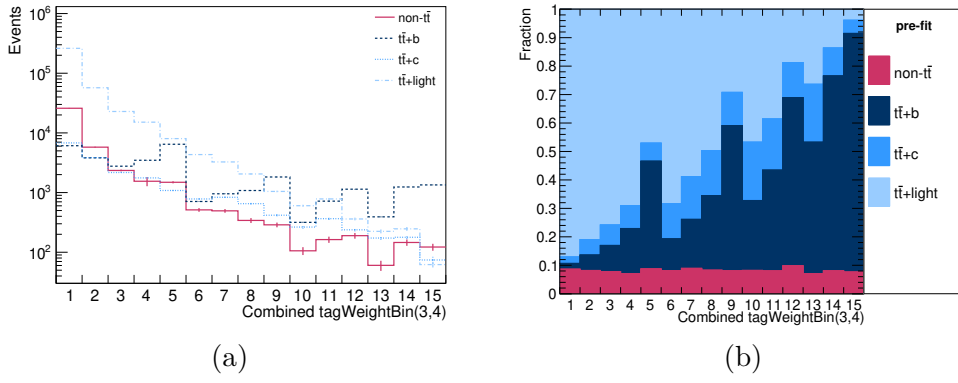


Figure 7.3: (a) The template shapes used in the fit of the pseudo-continuous b -tagging discriminant distribution. Vertical lines represent the statistical uncertainty. (b) The pre-fit fraction of events from each template in each bin of the fitted distribution.

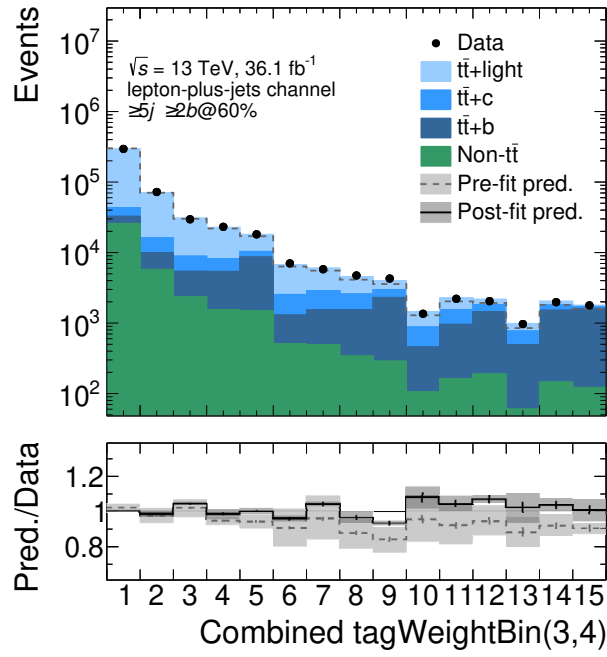
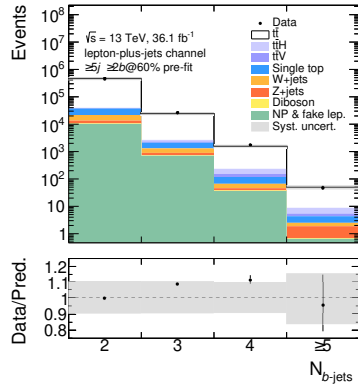
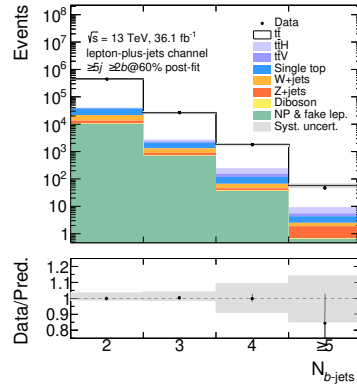


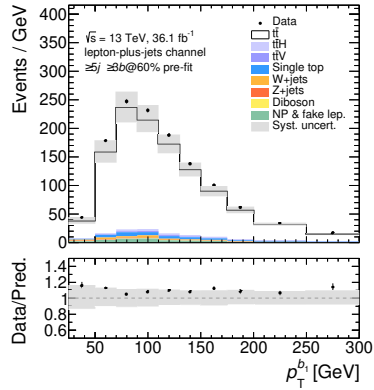
Figure 7.4: The pseudo-continuous b -tagging discriminant distribution of the third and fourth MV2c10-ranked jet before and after the fit. The ratios of the total pre- and post-fit predictions to the data are shown in the lower panel with the grey bands representing the detector and background systematic uncertainties added in quadrature to the statistical uncertainty. The statistical-only uncertainty is indicated by the vertical bars.



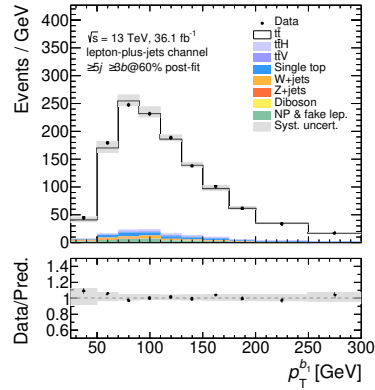
(a) $N_b, \geq 5j \geq 2b$



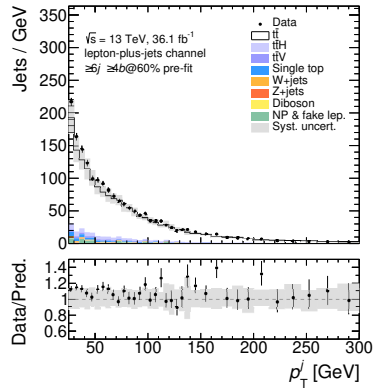
(b) $N_b, \geq 5j \geq 2b$



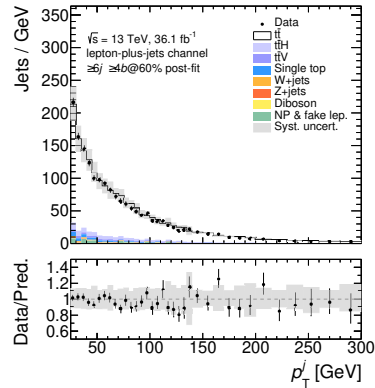
(c) $p_T^{b1}, \geq 5j \geq 3b$



(d) $p_T^{b1}, \geq 5j \geq 3b$



(e) $p_T^j, \geq 6j \geq 4b$



(f) $p_T^j, \geq 6j \geq 4b$

Figure 7.5: Pre-fit (a, c, e) and post-fit (b, d, f) distributions of b -jet multiplicity in the fit selection (a, b), leading b -jet p_T in the $t\bar{t} + \geq 1b$ signal region (c, d), and the inclusive jet p_T in the $t\bar{t} + \geq 2b$ signal region (e, f). The grey bands represent the sum in quadrature of uncertainties from background and detector effects, and simulation statistics.

7.3 Cross-section measurement methods

7.3.1 Total fiducial cross sections

The fiducial cross-section, σ_{fid} , is defined similarly to Equation 5.1 as

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L}^{\text{int}} C},$$

where N_{data} is the number of observed events in data, N_{bkg} is the predicted number of background events, $\mathcal{L}^{\text{int}}$ is the integrated luminosity and C is a correction factor accounting for detector inefficiencies and resolution. The correction is obtained from a comparison between particle- and detector-level yields in signal MC simulation. Hereafter the *signal* simulation refers to events categorised as $t\bar{t}b$ following the classification described in the previous section. The electroweak $t\bar{t}H$ and $t\bar{t}Z$ processes are therefore included in the definition.

The mistag background can be treated in two ways in this calculation. One can either subtract its predicted yield from the data as with the non- $t\bar{t}$ backgrounds or account for it in the correction factor. In the first case, C is defined as

$$C = \frac{N_{\text{reco}}^{t\bar{t}b}}{N_{\text{part}}^{t\bar{t}b}},$$

where $N_{\text{reco}}^{t\bar{t}b}$ is the number of signal events reconstructed and selected at the detector level and $N_{\text{part}}^{t\bar{t}b}$ is the number of particle-level signal events passing the fiducial volume selection. The fiducial cross section is then defined as

$$\sigma_{\text{fid}} = \frac{(N_{\text{data}} - \beta N_{t\bar{t}c}^{\text{MC}} - \gamma N_{t\bar{t}l}^{\text{MC}} - N_{\text{non-}t\bar{t}}) N_{\text{part}}^{t\bar{t}b}}{\mathcal{L}^{\text{int}} N_{\text{reco}}^{t\bar{t}b}}. \quad (7.1)$$

This technique will be referred to as the *subtractive approach* throughout this chapter. It is worth noting the fitted value of α is not used in this approach as it cancels in the numerator and denominator of C .

In the alternative method of the fiducial cross-section calculation, the mistag background is treated as a detector effect corrected by C defined as

$$C = \frac{\alpha N_{\text{reco}}^{t\bar{t}b} + \beta N_{\text{reco}}^{t\bar{t}c} + \gamma N_{\text{reco}}^{t\bar{t}l}}{\alpha N_{\text{part}}^{t\bar{t}b}} = \frac{N_{\text{reco}}^{t\bar{t}, \text{fitted}}}{\alpha N_{\text{part}}^{t\bar{t}b}}.$$

The fiducial cross section is thus calculated as

$$\sigma_{\text{fid}} = \frac{(N_{\text{data}} - N_{\text{non-}t\bar{t}})\alpha N_{\text{part}}^{t\bar{t}b}}{\mathcal{L}_{\text{int}} N_{\text{reco}}^{t\bar{t}, \text{fitted}}}. \quad (7.2)$$

The latter approach is the nominal method used to compute both the total and the differential fiducial cross sections in this analysis, and will be referred to as the *multiplicative approach*. A comparison of the two methods and the motivation to use the latter is discussed in the context of the total fiducial cross-section measurement results in Section 7.5.1.

7.3.2 Differential fiducial cross sections

Fiducial differential cross sections are measured in the $t\bar{t} + \geq 2b$ selection as a function of:

- the p_{T} of the four leading (highest- p_{T}) b -jets,
- the p_{T} of the leading light (non- b) jet,
- H_{T}^b , the scalar sum of the p_{T} of the four leading b -jets,
- $H_{\text{T}}^{\text{had}}$, the scalar sum of the p_{T} of all jets in the event,
- H_{T} , the scalar sum of $H_{\text{T}}^{\text{had}}$ and the lepton p_{T} ,
- m_{bb} , the invariant mass of two b -jets,
- ΔR_{bb} , the angular distance between two b -jets,
- $p_{\text{T}, bb}$, the p_{T} of the system of two b -jets.

The variables are chosen to describe basic kinematics properties of the $t\bar{t}b\bar{b}$ system using simple definitions without performing full event reconstruction, since it is difficult to precisely resolve the origin of all b -jets. Basic properties of $t\bar{t}b\bar{b}$ events are interesting as they were never measured before

and may provide a verification of current and future simulation models. The choice was also motivated by the studies presented in Reference [53] and discussed in Section 2.3.2. Each of the observables describing a system of two b -jets, denoted ‘ bb ’ throughout this chapter, is measured for two combinations – the two leading b -jets and the two b -jets which are closest to each other in terms of ΔR . These simple definitions allow to select bb systems with an enhanced probability to originate from top quark decays or from a $g \rightarrow b\bar{b}$ splitting of an ISR/FSR gluon without a need for a full $t\bar{t}$ system reconstruction. This is because the $b\bar{b}$ pairs from gluon splitting are produced predominantly at lower p_T and collinearly, whereas the b -jets originating from top quarks are typically high-energetic and produced closer to a back-to-back topology ($\Delta\phi(bb) \approx \pi$). Therefore, the pair of leading b -jets often originates from top-quark decays and the pair of closest b -jets often originates from the additional gluon. However, in both cases a significant fraction of the selected bb pairs is of a mixed origin. Further studies of the additional bb pair identification algorithms are presented in Appendix B.3.

The differential cross sections are computed following the unfolding procedure described in Section 4.6, including the matching, acceptance and efficiency corrections:

$$f_{\text{match}} = \frac{N_{\text{part \& reco \& matched}}}{N_{\text{part \& reco}}},$$

$$f_{\text{acc}} = \frac{N_{\text{part \& reco}}}{N_{\text{reco}}},$$

$$\epsilon = \frac{N_{\text{part \& reco \& matched}}}{N_{\text{part}}}.$$

No matching is required for H_T and H_T^{had} , thus in these cases $f_{\text{match}} = 1$. The b -jet momentum ordering has to be preserved between the particle and detector levels for the cross-section measurements as a function of jet p_T . This avoids large smearing in the migration matrix due to comparing two

different jets between the particle and detector level rather than evaluating detector resolution effects for a particular jet. In the case of the bb system observables, the two selected jets are allowed to swap order between the two levels.

Taking into account the flavour composition corrections obtained from the fit and using the multiplicative treatment of the mistag background, the number of all events reconstructed at the detector level can be redefined as

$$N_{\text{reco}} = N_{\text{reco}}^{t\bar{t}, \text{fitted}} = \alpha N_{\text{reco}}^{t\bar{t}b} + \beta N_{\text{reco}}^{t\bar{t}c} + \gamma N_{\text{reco}}^{t\bar{t}l}.$$

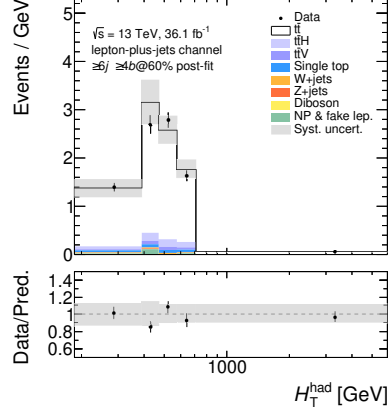
Since the $t\bar{t} + \geq 2b$ fiducial volume is a subset of the $t\bar{t}b$ category, only the α scale factor has to be included in the definitions of N_{part} , $N_{\text{part \& reco}}$ and $N_{\text{part \& reco \& matched}}$:

$$N_{\text{part}} = \alpha N_{\text{part}}^{t\bar{t}b},$$

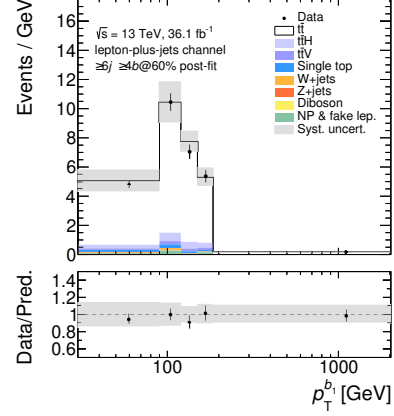
$$N_{\text{part \& reco}} = \alpha N_{\text{part \& reco}}^{t\bar{t}b},$$

$$N_{\text{part \& reco \& matched}} = \alpha N_{\text{part \& reco \& matched}}^{t\bar{t}b}.$$

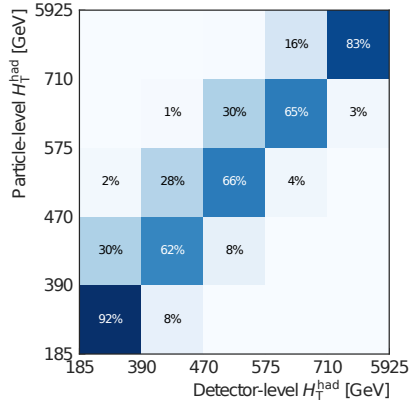
Binning of the measured distributions is optimised to ensure sufficient statistics in each bin using the nominal and the alternative signal MC samples. The measurement resolution is taken into account by requiring the diagonal bins of the migration matrix to include at least 60 % of the events from the corresponding row, which means the migration probability to a different detector-level bin is below 40 %. Two examples of detector-level distributions, migration matrices and unfolding corrections for the leading b -jet p_{T} and for $H_{\text{T}}^{\text{had}}$ are presented in Figure 7.6. Similar stability and bias tests to those described in Section 6.3 were implemented, showing good performance of the unfolding procedure. The number of iterations was chosen to be four, ensuring good compatibility of the prior and posterior distributions without enhancing the statistical uncertainties.



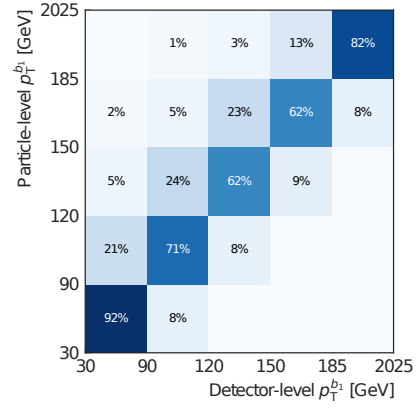
(a)



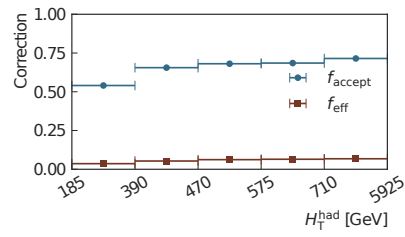
(b)



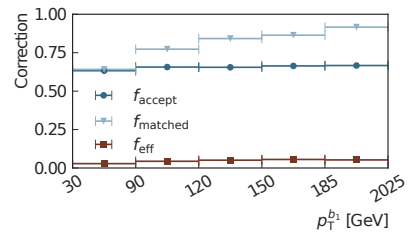
(c)



(d)



(e)



(f)

Figure 7.6: Detector-level distributions (a,b), migration matrices (c,d) and the unfolding correction factors (e,f) for the leading b -jet p_T (a,c,e) and the H_T^{had} (b,d,f).

7.4 Uncertainties

Luminosity, object reconstruction and MC-background uncertainties are evaluated as described in Section 4.7 and in the previous two chapters. The only differences are in the W +jets and fake/non-prompt lepton background estimates. The W +jets uncertainty is based on SHERPA internal generator weights evaluating effects of the scale and PDF variations. Since the fake/non-prompt lepton background is small in the signal regions, no detailed uncertainty studies were performed and a 100 % normalisation uncertainty is used instead. The signal modelling effects including contributions from the hard process generator, the parton shower simulation and the initial-/final-state radiation are estimated using the alternative MC samples listed in Section 4.2.1. The uncertainty associated to the choice of the PDF set is computed using the PDF4LHC15_30 error set [183] implemented as generator weights in the nominal $t\bar{t}$ MC sample. The $t\bar{t}H$ and $t\bar{t}V$ contributions are assigned a 100 % and 30 % normalisation uncertainty respectively, covering the experimental uncertainties of ATLAS $t\bar{t}H(b\bar{b})$ and $t\bar{t}Z$ measurements [52, 161].

The flavour composition fit is repeated for each systematic variation of the predicted signal and background yields. The total fiducial cross sections are then recalculated using the varied predictions and the corresponding new scale factors in Equation 7.2 to evaluate the corresponding uncertainty. The total systematic uncertainty is obtained by summing the individual contributions in quadrature. The statistical uncertainties on the total fiducial cross sections due to the limited size of the data and the MC samples are evaluated using pseudo-experiments. 1000 variations of the signal region data distributions are generated by assigning each event random weights following a Poisson distribution with the mean of 1. Each of the 1000 vari-

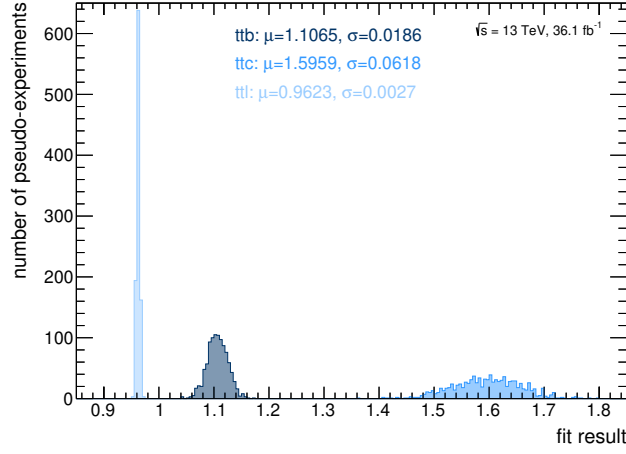


Figure 7.7: Flavour scale factor distributions in 1000 pseudo-experiments varying the fitted data spectrum. The quoted standard deviations correspond to the statistical uncertainty on the fit results due to the size of the dataset. However, the values are not used directly in the cross-section uncertainty evaluation. Instead, the cross sections are recomputed in each pseudo-experiment and the standard deviation of the final result distribution is used.

ations is then used to perform the flavour composition fit and calculate the corresponding cross sections. The standard deviation of the resulting cross-section distribution is quoted as the statistical uncertainty due to the size of the dataset. The same procedure is used to evaluate the statistical uncertainty due to the size of the MC samples, where random weights are assigned to each MC event. The distributions of the fitted scale factors in the 1000 data pseudo-experiments are presented in Figure 7.7. It can be observed that the $t\bar{t}l$ scale factor is the most stable, which is due to the large fraction of events falling into this category. The relatively large spread of the $t\bar{t}c$ scale factor can be attributed to the small fraction of $t\bar{t}c$ events in the fit control region.

A full covariance matrix including all bins of all measured differential cross sections is computed including both statistical and systematic uncertainties.

It is used to evaluate the global and per-distribution agreement between data and predictions. The components of the matrix related to the statistical and detector-related uncertainties are computed using 10 000 pseudo-experiments, where the observed data yields are varied following a Poisson distribution and smeared randomly following a Gaussian distribution with a width corresponding to the systematic uncertainty. The varied spectra are then unfolded using the nominal migration matrix and corrections, and compared to the nominal unfolded results. The signal modelling effects are accounted for using the same approach as in Chapter 6, where the alternative signal prediction is unfolded using the nominal corrections and compared to the corresponding alternative particle-level prediction. The total uncertainty in each measured bin is extracted from the diagonal elements of the covariance matrix. The statistical-only and full correlations of all measured bins are presented in Figures 7.8 and 7.9.

The contribution of different sources of systematic and statistical uncertainties to the total uncertainty on the total fiducial cross sections are presented in Table 7.3. The major components affecting the $t\bar{t} + 1b$ and $t\bar{t} + \geq 1b$ measurements include the $t\bar{t}$ PS and radiation modelling as well as uncertainties related to b -tagging. In particular, the largest contribution comes from the calibration of mistag rates for light and c -jets, reflecting the high sensitivity of the measurements to the mistag background. In the $t\bar{t} + \geq 2b$ measurement performed in a signal-rich selection, the b -tagging efficiency uncertainty dominates over the mistag rates and is larger than in the other two selections due to the higher number of required b -jets. The higher number of jets in the selection leads to an increased sensitivity to jet energy scale and resolution, which become the dominant uncertainty category. The effects of $t\bar{t}$ modelling still play a significant role in the overall precision. Although the radiation uncertainty appears to be half of that in the $t\bar{t} + 1b$

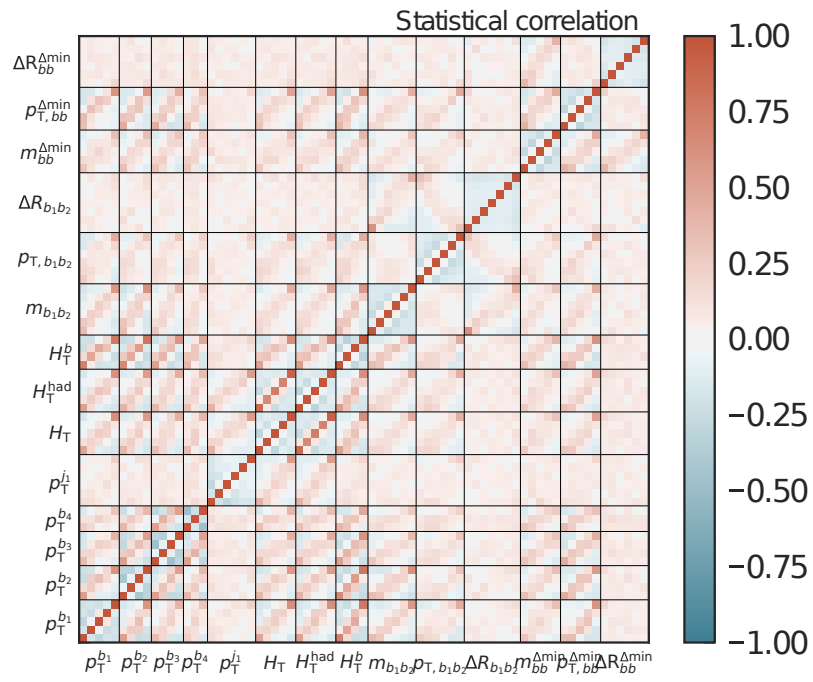


Figure 7.8: The full statistical correlation matrix including all bins of the measured normalised differential cross sections.

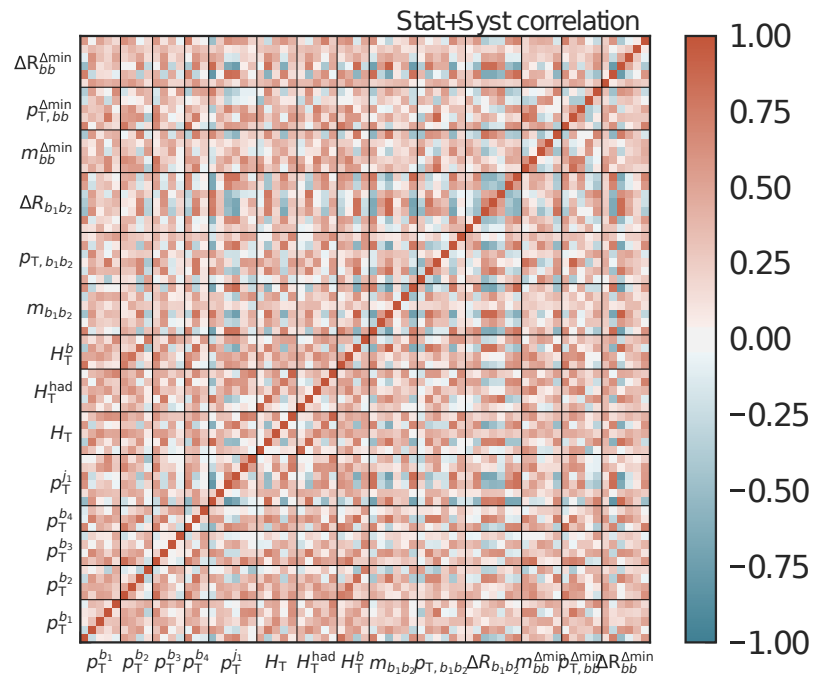


Figure 7.9: The full correlation matrix including all bins of the measured normalised differential cross sections. Both statistical and systematic effects are included.

and $t\bar{t} + \geq 1b$ measurements, the difference is not statistically significant. The statistical uncertainty of the generated MC samples becomes generally problematic in this strict selection, surpassing the statistical uncertainty due to data. A similar level of contributions of the dominant uncertainty categories is observed in the normalised differential cross-section measurements, as presented in Figure 7.10. Jet energy scale, b -tagging and $t\bar{t}$ modelling uncertainties dominate in the majority of bins.

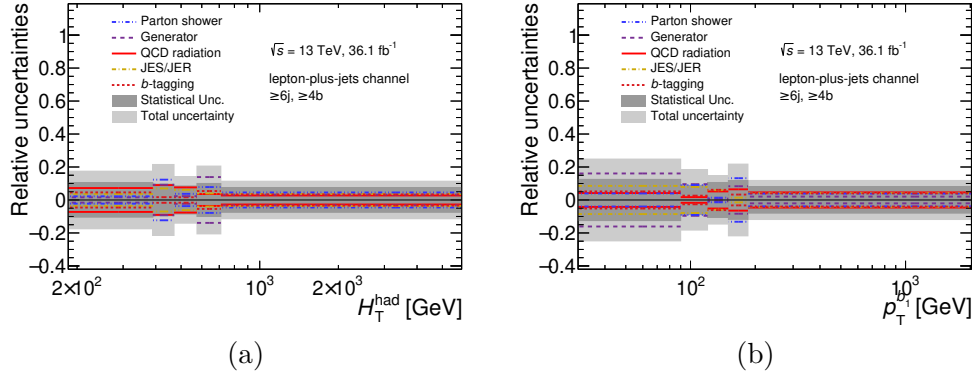


Figure 7.10: Relative systematic uncertainties of various signal modelling and experimental sources for the H_T^{had} (a) and leading b -jet p_T (b) distributions.

Uncertainty source	$\Delta\sigma_{t\bar{t}+1b}$ [%]	$\Delta\sigma_{t\bar{t}+\geq 1b}$ [%]	$\Delta\sigma_{t\bar{t}+\geq 2b}$ [%]
$t\bar{t}$ generator	2.2	1.6	1.0
$t\bar{t}$ parton shower	15	12	6.3
$t\bar{t}$ radiation	6.1	6.2	2.9
$t\bar{t}$ PDF	0.3	0.3	0.1
$t\bar{t}H/t\bar{t}V$ norm.	3.3	2.2	0.3
b -tagging (b)	4.9	5.0	6.0
b -tagging (c)	9.7	9.4	3.9
b -tagging (light)	13	13	4.8
Jets	3.5	3.6	7.2
Pileup	1.6	1.6	1.3
Electrons	0.4	0.4	0.5
Muons	0.8	0.7	0.7
Luminosity	2.3	2.3	2.2
W +jets	0.9	0.9	0.5
NP/fake leptons	1.5	1.5	1.3
MC statistics	1.4	1.2	4.3
All systematic	24	22	14
Data statistics	1.7	1.7	3.0

Table 7.3: Summary of the relative systematic and statistical uncertainties on the total fiducial cross sections for $t\bar{t} + 1b$, $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 2b$ production. Values presented in the table are symmetrised showing the larger of the up/down variations. The MC statistical uncertainty is included in the sum of systematic uncertainties.

7.5 Results

7.5.1 Total fiducial cross sections

The measured total fiducial cross section for a particular process should be independent of the b -tagging working point used in the detector-level selection. To verify the stability of the measurements, each fiducial cross section, $t\bar{t} + 1b$, $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 2b$, is measured in each of the fifteen MV2c10 bins used in the fitting procedure (see Section 7.2). The results are presented in Figure 7.11 for both the subtractive and the multiplicative approach, described by Equations 7.1 and 7.2 respectively. The nominal $t\bar{t} + \geq 2b$ detector-level signal selection requiring at least six jets with at least four b -tags using the 60 % efficiency working point corresponds to bin 15 in Figure 7.11c. Two additional bins are presented in each subfigure. Bin 16 corresponds to the selection including bins 5, 9, 12 and 14, whereas bin 17 includes all events from bins 15 and 16. The two additional bins correspond to the nominal $t\bar{t} + 1b$ and $t\bar{t} + \geq 1b$ detector-level selections in Figures 7.11a and 7.11b. It can be observed that the two cross-section calculations provide consistent results across all bins and between each other. However, the multiplicative approach is more stable and results in lower uncertainties in background-rich selections. These observations motivated the use of the multiplicative approach to compute both the total and the differential fiducial cross sections presented as the final results. Moreover, Figure 7.11 shows that the chosen detector-level selections for each measurement are among the most precise, minimising the effects of systematic uncertainties.

The $t\bar{t} + 1b$, $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 2b$ fiducial cross sections measured in the $\geq 5j = 3b$, $\geq 5j \geq 3b$ and $\geq 6j \geq 4b$ selections using the 60 % b -tagging efficiency

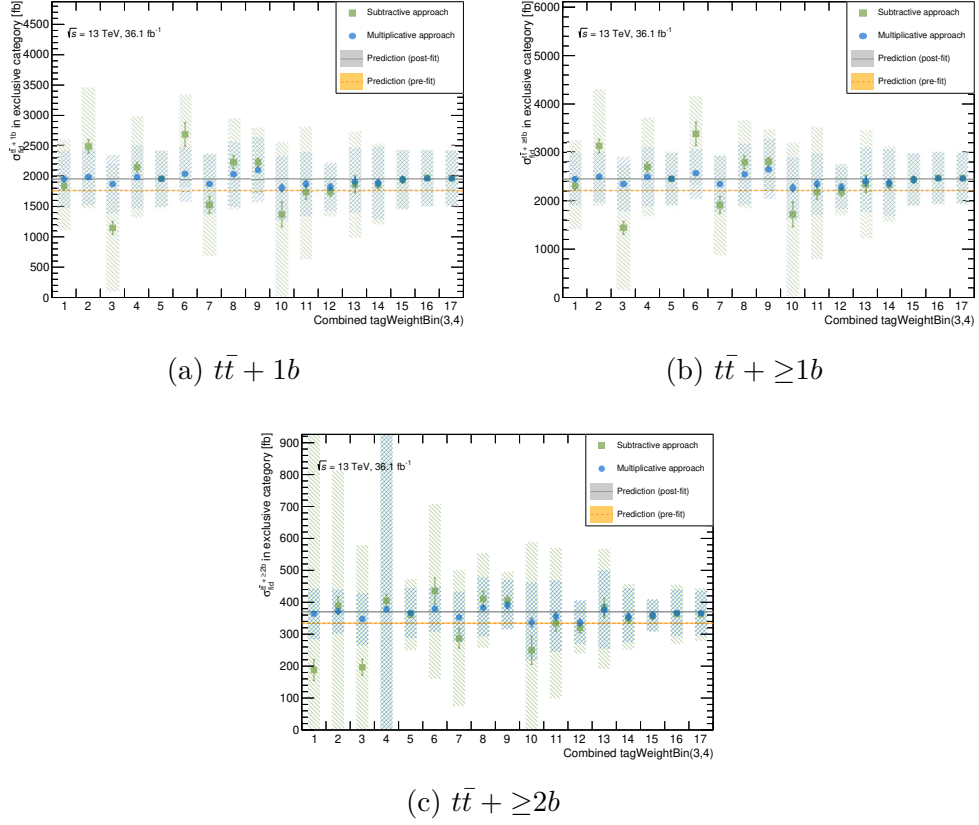


Figure 7.11: The total fiducial cross section measured in exclusive bins of the b -tagging discriminant for the three fiducial volumes. The $t\bar{t} + 1b$ (a) and $t\bar{t} + \geq 1b$ (b) measurements require at least five jets and two b -tags at the detector level, whereas the $t\bar{t} + \geq 2b$ (c) measurement requires at least six detector-level jets with at least two b -tags. The results are shown for the multiplicative and subtractive methods (the blue and green points respectively) described in the text. The error bars represent the statistical uncertainty and the hatched rectangles represent the combined statistical and systematic uncertainty.

working point are found to be:

$$\sigma_{\text{fid}}^{t\bar{t}+1b} = 1960 \pm 30 \text{ (stat)} \pm 450 \text{ (syst) fb},$$

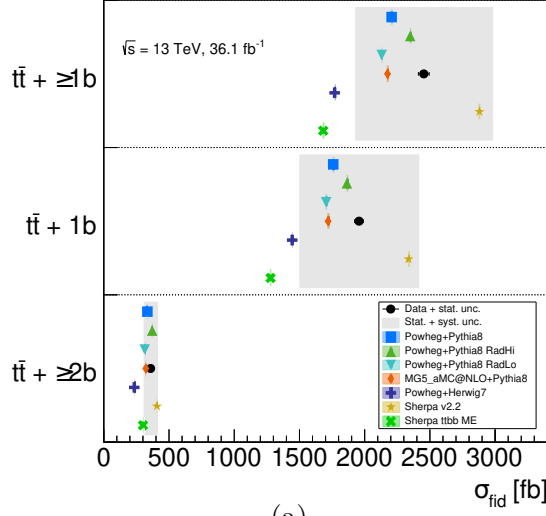
$$\sigma_{\text{fid}}^{t\bar{t}+\geq 1b} = 2450 \pm 40 \text{ (stat)} \pm 520 \text{ (syst) fb},$$

$$\sigma_{\text{fid}}^{t\bar{t}+\geq 2b} = 359 \pm 11 \text{ (stat)} \pm 50 \text{ (syst) fb}.$$

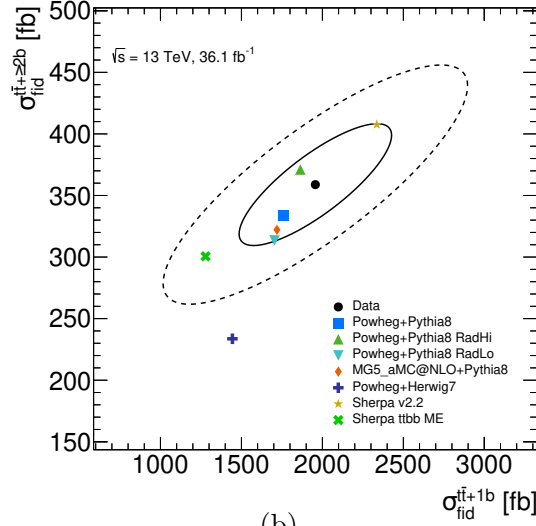
The above results are presented collectively in Figure 7.12 along with predictions using different hard process or parton shower generators, or tunes¹ to simulate the $t\bar{t}$ production in association with strongly-produced b -jets. The nominal $t\bar{t}H$ and $t\bar{t}V$ contributions are added to each prediction, contributing in 2% to the $t\bar{t} + 1b$ fiducial volume, 3% to $t\bar{t} + \geq 1b$ and 8% to $t\bar{t} + \geq 2b$. Figure 7.12b presents the $t\bar{t} + 1b$ and $t\bar{t} + \geq 2b$ results in a 2D space indicating their uncertainty correlation. The uncertainty band is constructed from the eigenvectors and eigenvalues of a covariance matrix calculated as a sum of covariance matrices from each uncertainty source. The Pearson correlation coefficient of the two measurements equals 73%.

The measured fiducial cross sections agree within the 1σ uncertainty interval with the nominal predictions presented in Table 7.4. The alternative predictions employing the PYTHIA8 PS simulation also remain within the 1σ interval and are close to each other. The inclusive $t\bar{t}$ +jets simulations using POWHEG+HERWIG7 and SHERPA underestimate the cross sections by a large amount. At the same time, the exclusive SHERPA $t\bar{t}b\bar{b}$ simulation is the only prediction slightly overestimating the production rate in all three fiducial volumes. However, no scale or PDF uncertainties are evaluated for the alternative predictions and it is expected that the significance of the discrepancies would be low if they were taken into account.

¹The two variants of the nominal POWHEG+PYTHIA8 sample using modified h_{damp} parameter values, modified scales, and the A14Var3cUp/Down tunes are referred to as the ‘radHi’ and ‘radLo’ samples throughout this chapter.



(a)



(b)

Figure 7.12: (a) Results of the total fiducial cross-section measurements in the $t\bar{t} + \geq 2b$, $t\bar{t} + 1b$ and $t\bar{t} + \geq 1b$ fiducial volumes (black dots) compared to predictions using different MC generators or tunes (coloured markers). Coloured bands around each prediction represent the statistical uncertainty only. (b) A two-dimensional representation of the $t\bar{t} + \geq 2b$ and $t\bar{t} + 1b$ fiducial cross-section measurements showing the uncertainty correlation between the two. The solid ellipse represents a 1σ uncertainty on the central value (black dot) and the dashed ellipse corresponds to 2σ . The coloured markers represent the same predictions as in Figure (a), with no uncertainty shown. All predictions include the nominal $t\bar{t}H$ and $t\bar{t}V$ contributions.

Process	$t\bar{t} + 1b$	$t\bar{t} + \geq 1b$	$t\bar{t} + \geq 2b$
$t\bar{t}$	$1720 \pm 8 \text{ (PDF)} \pm 38 \text{ (scale)}$	$2130 \pm 11 \text{ (PDF)} \pm 52 \text{ (scale)}$	$305 \pm 2 \text{ (PDF)} \pm 13 \text{ (scale)}$
$t\bar{t}H$	24	51	20
$t\bar{t}V$	14	25	8
Total	1759	2207	334

Table 7.4: $t\bar{t} + 1b$, $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 2b$ cross section predictions from nominal signal samples including $t\bar{t}$ PDF and scale uncertainties.

7.5.2 Differential fiducial cross sections

Results of the normalised fiducial differential cross-section measurements for four out of the fourteen variables, which show the largest discrimination between the compared models or the largest deviation with respect to data, are presented in Figures 7.13 and 7.14. The ten remaining results can be found in Appendix B.4. All results are compared to a number of MC predictions using different hard process or parton shower generators, or different tunes. The predictions do not include the $t\bar{t}H$ and $t\bar{t}V$ contributions, however, their effect on the shape of the normalised cross sections is presented in the lowest panel of each figure. The electroweak contributions are found to modify the shapes by less than 10 % with the largest effects observed at high H_T and $p_{T,bb}$, and at the mass of the closest bb pair around 100 GeV (close to the Higgs and Z bosons masses).

All predictions agree well with the data and with each other in most bins of the measured distributions. As expected, the two variants of the nominal POWHEG+PYTHIA8 sample modifying the amount of radiation bracket the nominal prediction in almost all bins. However, the effect of these variations is small. The largest discrepancy between different predictions is observed in the last bins of the H_T distributions. MG5_aMC@NLO+PYTHIA8 appears to underestimate the energy emitted in the transverse direction in

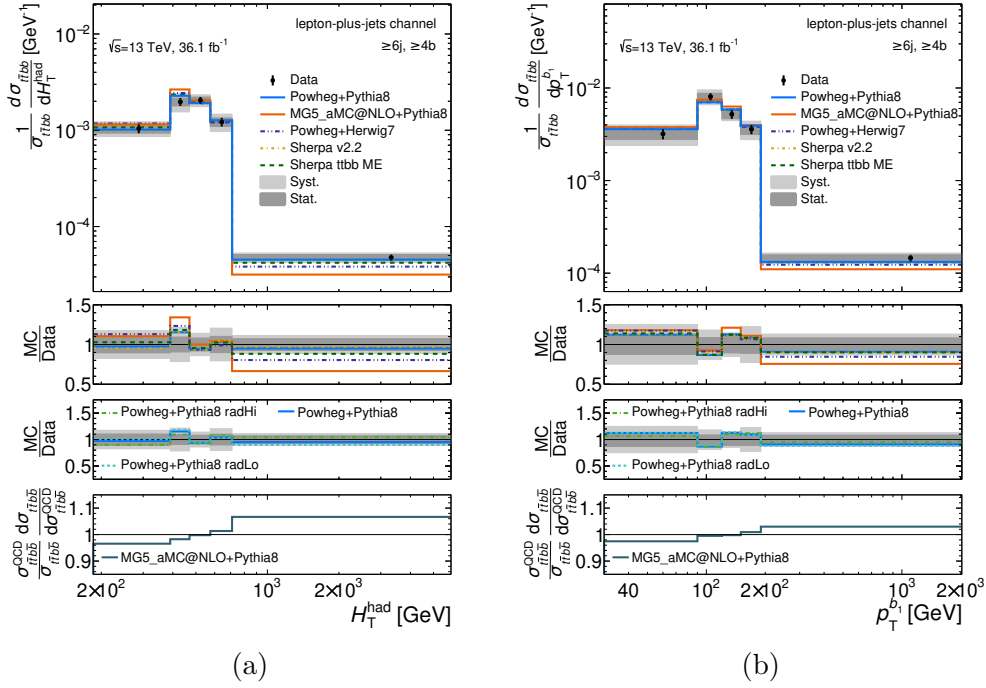


Figure 7.13: Relative differential cross sections as a function of (a) H_T^{had} and (b) leading b -jet p_T in the $t\bar{t} + \geq 2b$ fiducial volume compared to various MC generators. Three ratio panels are shown, the first two of which show the ratios of various predictions to data. The third panel shows the ratio of predictions of normalised differential cross sections from MG5_aMC@NLO+PYTHIA8 including (numerator) and not including (denominator) the contributions of $t\bar{t}V$ and $t\bar{t}H$ production.

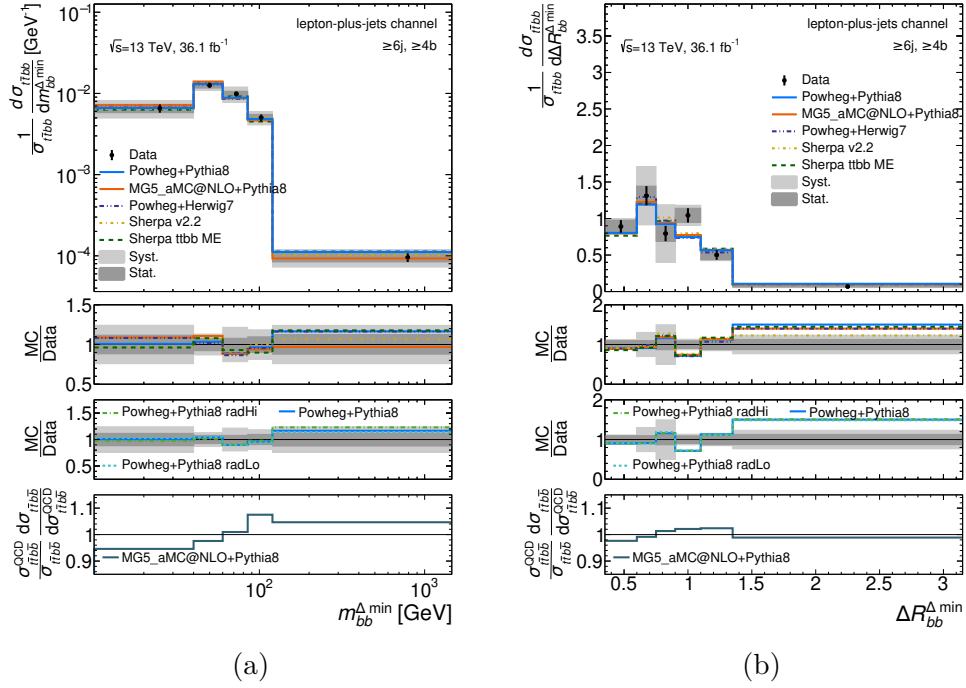


Figure 7.14: Relative differential cross sections as a function of (a) mass and (b) angular separation of the closest bb pair in the $t\bar{t} + \geq 2b$ fiducial volume compared to various MC generators. Three ratio panels are shown, the first two of which show the ratios of various predictions to data. The third panel shows the ratio of predictions of normalised differential cross sections from MG5_aMC@NLO+PYTHIA8 including (numerator) and not including (denominator) the contributions of $t\bar{t}V$ and $t\bar{t}H$ production.

$t\bar{t}b\bar{b}$ events, predicting more events at low H_T and fewer events at high H_T than observed in data. At the same time, the nominal POWHEG+PYTHIA8 simulation describes the H_T distributions well. No other shape differences between data and predictions are significant given the size of the statistical and systematic uncertainties. The statistical precision of the predictions is also limited due to the strict signal selection criteria and insufficient size of the generated samples.

The global agreement of each prediction with all measured distributions is evaluated in terms of χ^2 and p -values and presented in Table 7.5. The disagreements observed for the MG5_aMC@NLO+PYTHIA8 sample are reflected in the p -value which is smaller than 0.01. No other predictions give p -values lower than 0.10, confirming the overall agreement with observations. The two predictions describing the data best are the inclusive SHERPA $t\bar{t}$ +jets simulation and the nominal POWHEG+PYTHIA8 sample, resulting in p -values of 0.24 and 0.17 respectively.

MC model	χ^2 / NDF	p -value
POWHEG+PYTHIA8	58.37/49	0.17
MG5_aMC@NLO+PYTHIA8	86.52/49	< 0.01
SHERPA 2.2	55.56/49	0.24
POWHEG+HERWIG7	61.30/49	0.11
POWHEG+PYTHIA8 ‘radHi’	59.37/49	0.15
POWHEG+PYTHIA8 ‘radLo’	62.00/49	0.10

Table 7.5: Global χ^2 and p -values evaluated for various predictions considering all fourteen measurements of the normalised differential cross sections. The SHERPA exclusive $t\bar{t}b\bar{b}$ simulation is not included in these work-in-progress results.

7.5.3 Context and discussion

The measurements presented in this chapter are the first ATLAS measurements of $t\bar{t}$ production with additional b -jets in pp collisions at $\sqrt{s} = 13$ TeV and the first differential measurements of this process in ATLAS at any energy. The precision of the total fiducial cross-section measurements in the ℓ +jets channel is 14 % for the $t\bar{t} + \geq 2b$ selection, 22 % for the inclusive $t\bar{t} + \geq 1b$ selection and 24 % for the exclusive $t\bar{t} + 1b$ selection. The parallel analysis in the dilepton channel yields a precision of 14 % for the $t\bar{t} + \geq 1b$ measurement and 24 % for $t\bar{t} + \geq 2b$. The only previous ATLAS measurement of $t\bar{t}+b$ -jets production [190] focused on total fiducial cross sections at 8 TeV and reached a precision of 26 % for a $t\bar{t} + \geq 1b$ measurement in the ℓ +jets channel and around 36 % for $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 2b$ measurements in the dilepton channel. Both the previous and the current measurements are limited by uncertainties related to b -tagging efficiency, mistag rates, jet energy measurement and signal modelling. Statistical uncertainties also play a significant role in both cases. The first relative differential measurements yield a precision of 20–50 % in the $b\bar{b}$ system observables and 10–30 % in others.

Although no results so far allow for strong discrimination between different models, a preference towards certain predictions can be observed. When published, the results can be used to compare against new $t\bar{t}b\bar{b}$ predictions and help to constrain the model parameters and choices. The differential results shed an experimental light at some of the observables identified as sensitive to $t\bar{t}b\bar{b}$ production modelling in the LHC Higgs Cross Section Working Group report presented in 2016 [53]. An additional potential to discriminate between models is found in event-level observables like H_T and H_T^{had} .

The CMS Collaboration has presented measurements of the ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ production cross sections at 8 and 13 TeV as well as the inclusive $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ production cross sections at 13 TeV [191, 192]. The precision of the presented measurements reaches 25–30 % for the ratio and 36 % for the inclusive $t\bar{t}b\bar{b}$ production cross section. In addition, CMS has presented a comprehensive set of differential $t\bar{t}$ +jets production measurements at 8 TeV including also events with additional b -jets [193]. Some of the observables reported in this chapter have also been measured, however with very limited statistical precision due to the smaller $t\bar{t}b\bar{b}$ cross section at the lower collision energy.

The results from the two experiments are complementary and both provide a verification of various models. However, the precision of all measurements so far is insufficient to effectively discriminate between different model choices and to help constrain the theory uncertainties associated with $t\bar{t}b\bar{b}$ production in the nearest future. Nevertheless, they prove the current models are correct within their associated uncertainties and provide an excellent groundwork for future measurements with increased precision. Improvements in future measurements will come from the increased statistics in data, as well as further dedicated studies of jet energy scale measurement and flavour tagging efficiency. New flavour tagging techniques may provide an improved mistag background rejection and more precise evaluation of the efficiencies. Future double-differential measurements of $t\bar{t}$ production cross section profiting from the large datasets may provide input for more precise tuning of simulation parameters and lead to a decrease of the modelling uncertainties. Careful planning of dedicated production of simulation samples will be also crucial to ensure that simulation statistical uncertainties may be minimised.

Chapter 8

Conclusions

Three ATLAS measurements of top quark pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV using the ℓ +jets final states were presented. Successively larger datasets collected throughout the first year and a half of LHC Run 2 allowed to measure these processes in increasingly exclusive phase spaces and to reach and surpass the precision achieved in Run 1.

In the first few weeks of 13 TeV pp collisions, the LHC delivered sufficient amount of data to establish that the inclusive $t\bar{t}$ production rates are in good agreement with the predictions. The presented ℓ +jets channel measurement result:

$$\sigma_{t\bar{t}}^{\ell+\text{jets}} = 817 \pm 13 \text{ (stat.)} \pm 103 \text{ (syst.)} \pm 88 \text{ (lum.) pb.}$$

was found to agree also with similar same-flavour and different-flavour dilepton channel measurements, as well as with analogous results reported by the CMS Collaboration. Although further measurements with more data and increased precision were undertaken later using other channels, the presented result currently remains the only ATLAS ℓ +jets measurement at 13 TeV.

After confirming the expected inclusive production rates, the research focus shifted towards differential measurements. They were aimed at confirming

or disproving Run-1 observations and providing further information required to improve top-pair production modelling in simulations. The results of the ℓ +jets channel measurement using the resolved final-state topology were presented in parallel to a boosted-topology analysis and on a similar time scale to dilepton and all-hadronic channel measurements. Normalised and absolute particle-level differential cross sections were presented as a function of the p_T and rapidity of the hadronic top quark, as well as the p_T , rapidity and mass of the $t\bar{t}$ system. Similarly to Run 1 results, an overall good agreement between data and predictions was observed across all measured observables with the exception of the top-quark p_T distribution, which is softer in data. This can be partially attributed to the lack of NNLO and electroweak effects in the simulation. Further developments are anticipated both in state-of-the-art theoretical predictions and in simulations. New more precise differential and double-differential measurements exploiting the full Run-2 dataset may also be able to shed light on the origin of this discrepancy.

The increased $t\bar{t}$ production cross-sections at the new pp collision energy and the growing datasets collected throughout 2015 and 2016 allowed also for the first ATLAS measurements of differential cross sections of $t\bar{t}$ pair production in association with heavy-flavour jets. New total fiducial measurements of $t\bar{t} + b$ -jets production cross sections were also presented, exceeding the precision of the 8 TeV ATLAS results. Three fiducial cross sections were measured in regions selecting $t\bar{t}$ pairs with exactly one, at least one or at least two additional b -jets:

$$\sigma_{\text{fid}}^{t\bar{t}+1b} = 1960 \pm 30 \text{ (stat)} \pm 450 \text{ (syst) fb},$$

$$\sigma_{\text{fid}}^{t\bar{t}+\geq 1b} = 2450 \pm 40 \text{ (stat)} \pm 520 \text{ (syst) fb},$$

$$\sigma_{\text{fid}}^{t\bar{t}+\geq 2b} = 359 \pm 11 \text{ (stat)} \pm 50 \text{ (syst) fb}.$$

The $t\bar{t} + b$ -jets measurements are hoped to help constrain the large theory uncertainties associated with the corresponding predictions and improve the simulation models. Verification of the state-of-the-art predictions for this challenging process is interesting on its own, however, the main motivation comes from the $t\bar{t}H(b\bar{b})$ searches, where $t\bar{t}b\bar{b}$ background uncertainties are one of the main precision-limiting factors. Due to the large systematic uncertainties related to jet flavour tagging, jet energy scale measurement and signal modelling, as well as due to the limited statistical precision, the presented results are insufficient to discriminate between different models and effectively constrain the theory uncertainties. Similar observations apply to the previous ATLAS $t\bar{t} + b$ -jets measurements as well as the results reported by the CMS Collaboration. Nevertheless, the results provide an excellent groundwork for more precise measurements in the near future. The full Run-2 dataset, expected to be up to five times larger than the 2015+2016 sample, will undoubtedly provide much better statistical precision. Future measurements will also benefit from improved b -tagging algorithms developed recently [194]. The calibrations of jet energy scale and flavour tagging efficiencies are also expected to improve with the larger dataset. Ongoing studies of $t\bar{t}$ production modelling in simulations, exploiting the new differential and double-differential cross-section measurements, may also result in a reduction of the corresponding uncertainties. Thanks to all these improvements in measurement precision expected in the next two to three years, exploiting the full Run-2 dataset, a discrimination between different models may be achieved.

Appendices

Appendix A

Differential $t\bar{t}$ production cross sections

A.1 Signal and validation region kinematic distributions

Distributions sensitive to W +jets and multijet background modelling in validation regions enriched in these processes show good agreement of the predictions with data. Figure A.1 presents the lepton p_T , E_T^{miss} and m_T^W distributions in selections with at least three or at least four jets and without any b -tagging requirements. These regions are dominated by W +jets with a significant multijet contribution. Figure A.2 shows the lepton p_T , leading b -jet p_T and m_T^W distributions in selections with a comparable contribution of signal and the multijet background. At least three jets with at least two b -tags or at least four jets with at least one b -tag are required. In addition, events with E_T^{miss} above 30 GeV are rejected, maximising the fraction of multijet events in the selection. Both figures show the e +jets and μ +jets channels separately in order to verify the different multijet background estimates. Figure A.3 presents the signal-region jet multiplicity and kinematic distributions involving the lepton, the leading b -jet and E_T^{miss} in the combined ℓ +jets channel. An overall good shape modelling is observed, however with a normalisation offset of data above the total prediction, which increases

significantly at a higher jet multiplicity. Uncertainty intervals shown in the figures include all uncertainty sources except the signal modelling, which is only presented for the unfolded results.

A.2 Corrections and migration matrices

Figures A.4–A.7 present the detector-level distribution, migration matrix and correction for the rapidity of the top quark and the p_T , mass and rapidity of the $t\bar{t}$ system.

A.3 Absolute cross section results

Results of the fiducial absolute differential cross-section measurements are presented in Figures A.8 and A.9. An overall underestimation of the data by the predictions may be observed in all distributions, however it remains within the measurement uncertainty ranges. Shape differences follow the same trends discussed in the absolute measurement discussion (Section 6.5). In particular, a clear slope in hadronic top p_T distribution is observed for all predictions.

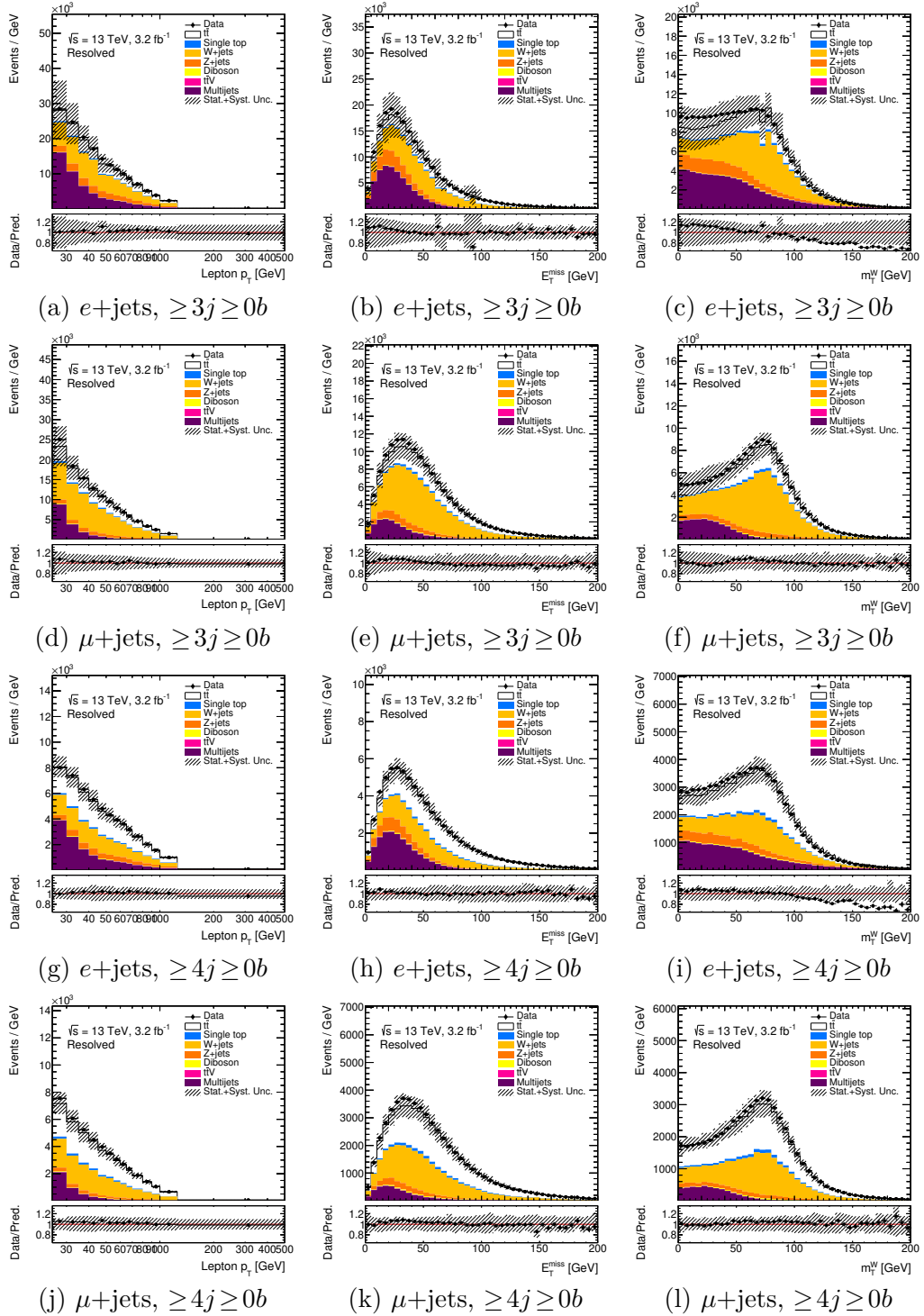


Figure A.1: Distributions of the lepton p_T (left column), E_T^{miss} (middle column) and m_T^W (right column) for the $e+\text{jets}$ and $\mu+\text{jets}$ channels in selections with at least three or at least four jets and no b -tagging requirements.

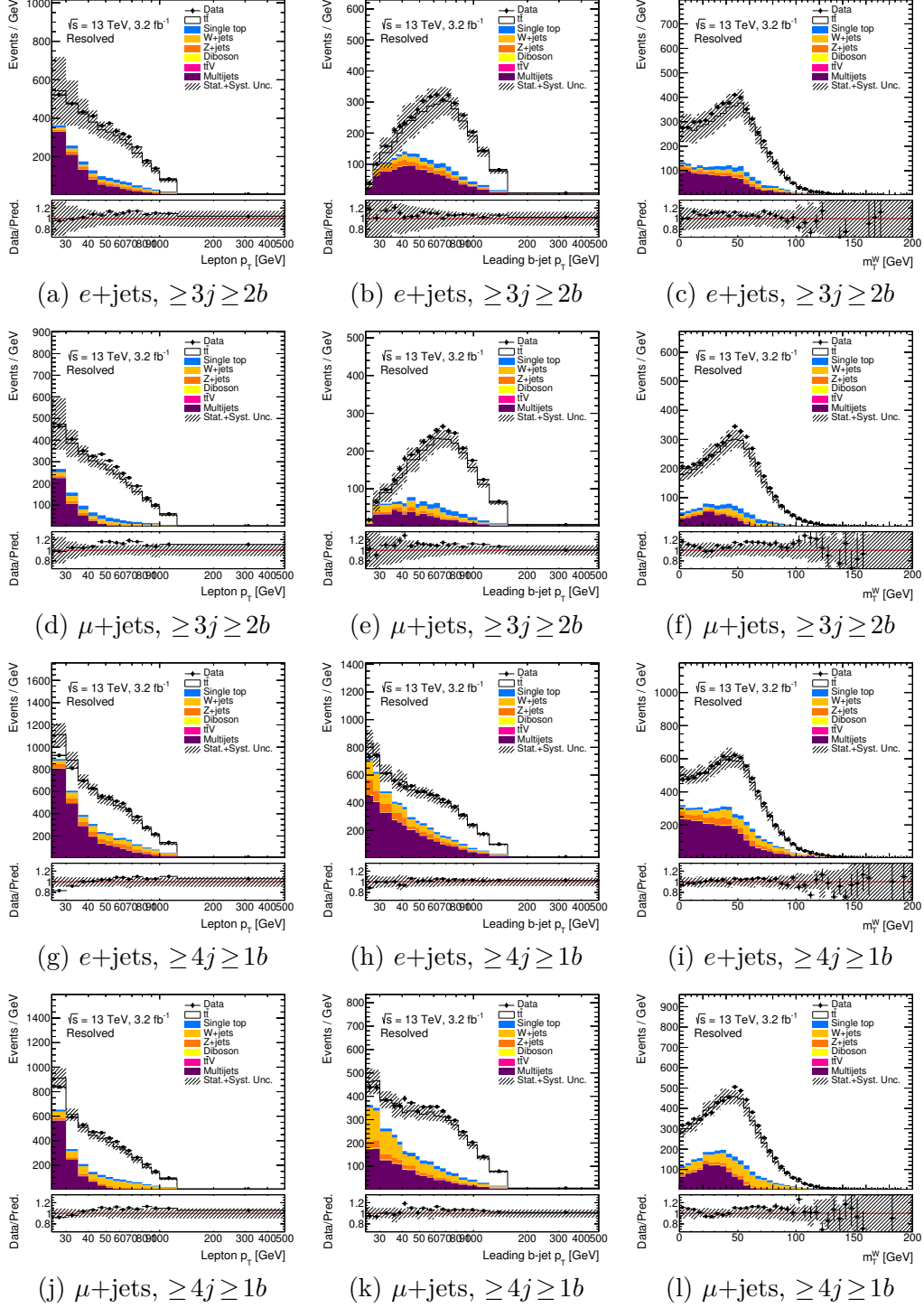
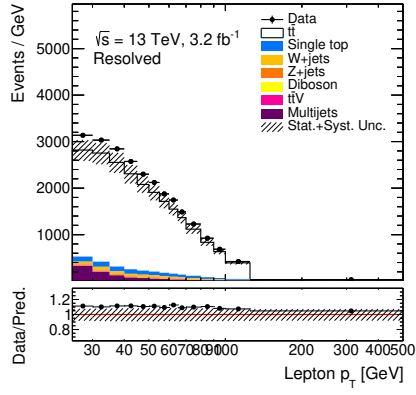
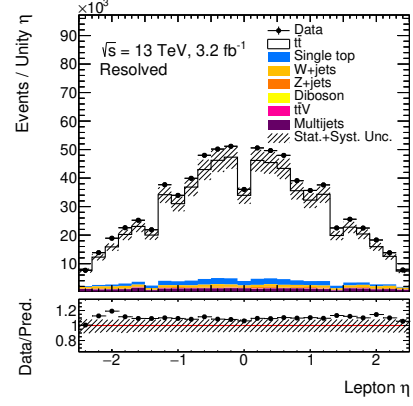


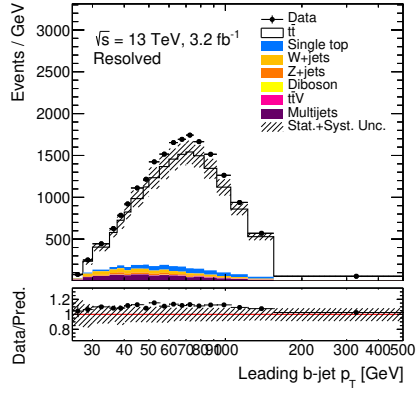
Figure A.2: Distributions of the lepton p_T (left column), leading b -jet p_T (middle column) and m_T^W (right column) for the $e+jets$ and $\mu+jets$ channels in $\geq 3j \geq 2b$ and $\geq 4j \geq 1b$ selections requiring $E_T^{\text{miss}} < 30$ GeV.



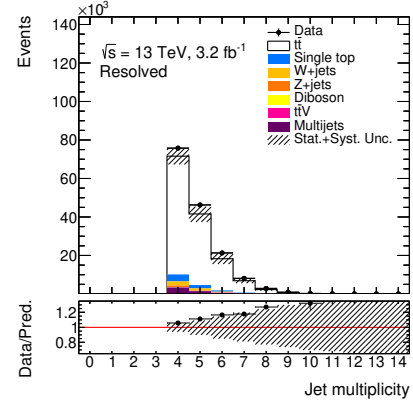
(a) p_T^ℓ



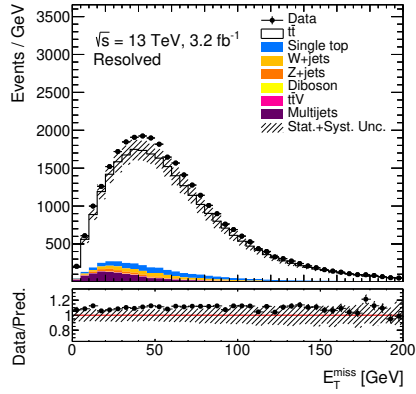
(b) η^ℓ



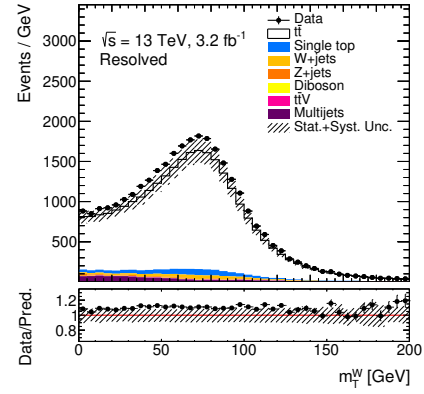
(c) $p_T^{b\text{-jet}1}$



(d) N_j



(e) E_T^{miss}



(f) m_T^W

Figure A.3: Signal-region distributions of lepton p_T and η , leading b -jet p_T , jet multiplicity, E_T^{miss} and m_T^W in the combined e +jets and μ +jets channels.

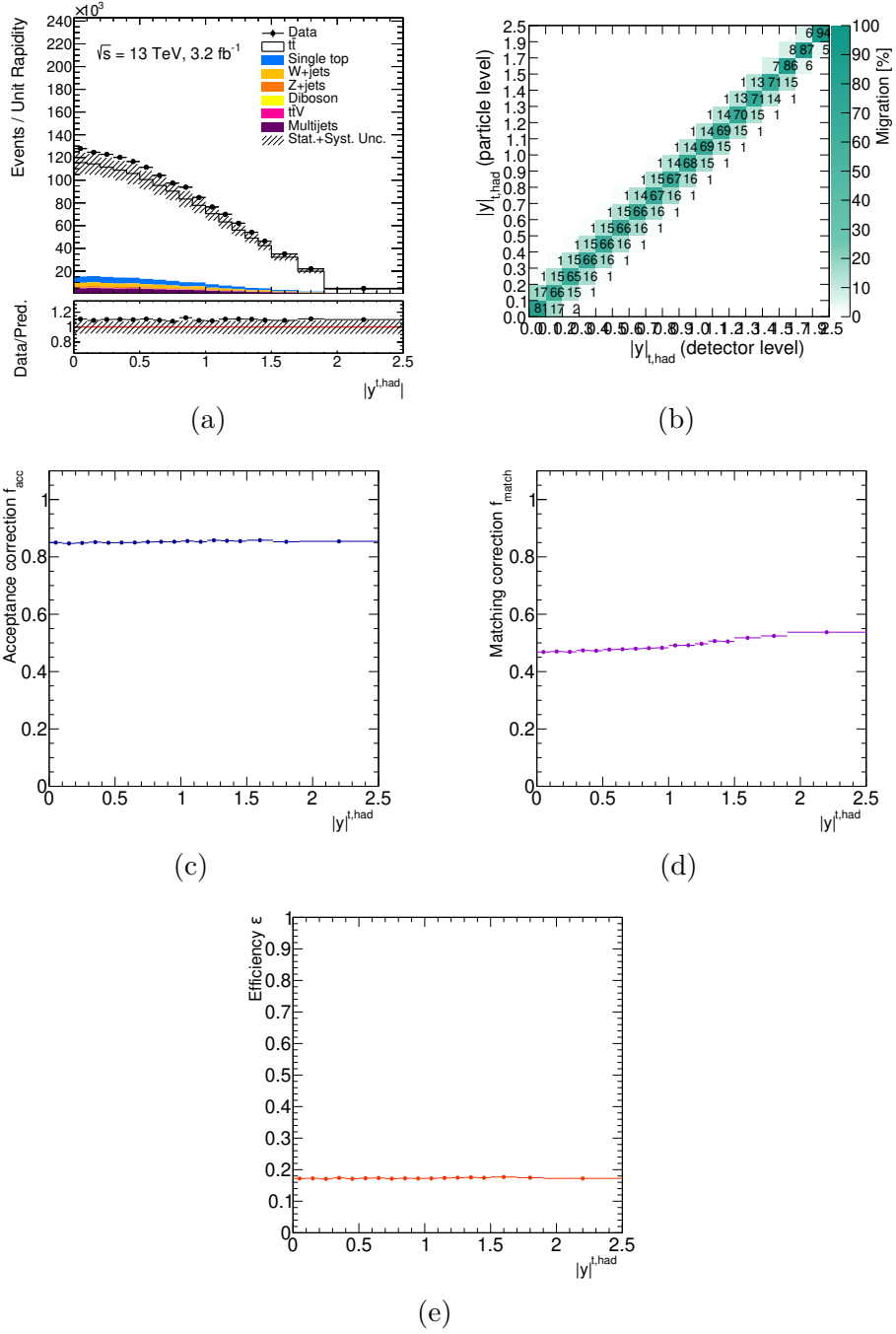


Figure A.4: Detector-level distribution (a), migration matrix (b), acceptance correction (c), matching correction (d) and efficiency (e) for the hadronic top rapidity. The migration matrix is normalised to unity in each row, thus the number in each bin represents the probability of a migration from a given particle-level bin to a particular detector-level bin.

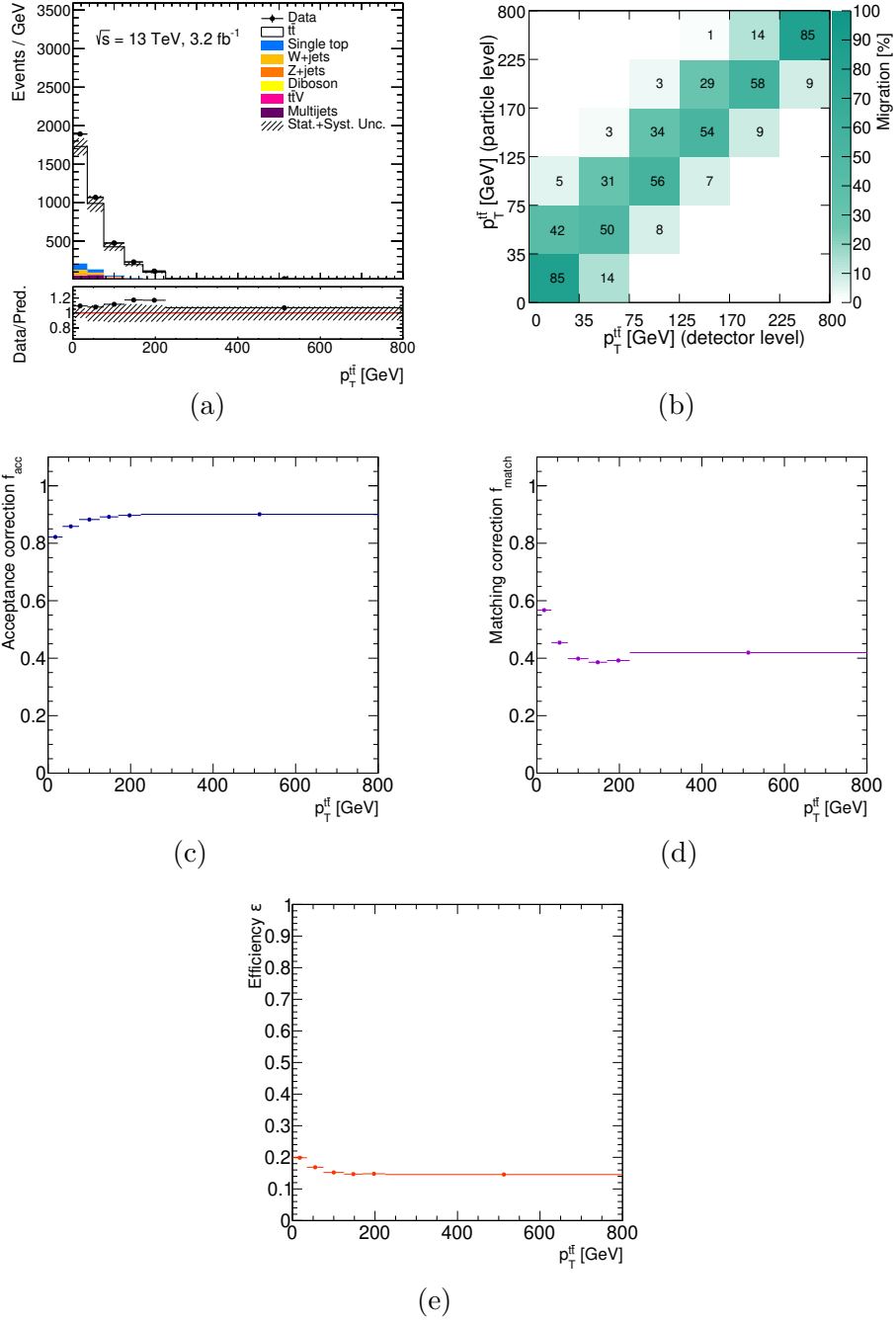


Figure A.5: Detector-level distribution (a), migration matrix (b), acceptance correction (c), matching correction (d) and efficiency (e) for the $t\bar{t}$ system p_T . The migration matrix is normalised to unity in each row, thus the number in each bin represents the probability of a migration from a given particle-level bin to a particular detector-level bin.

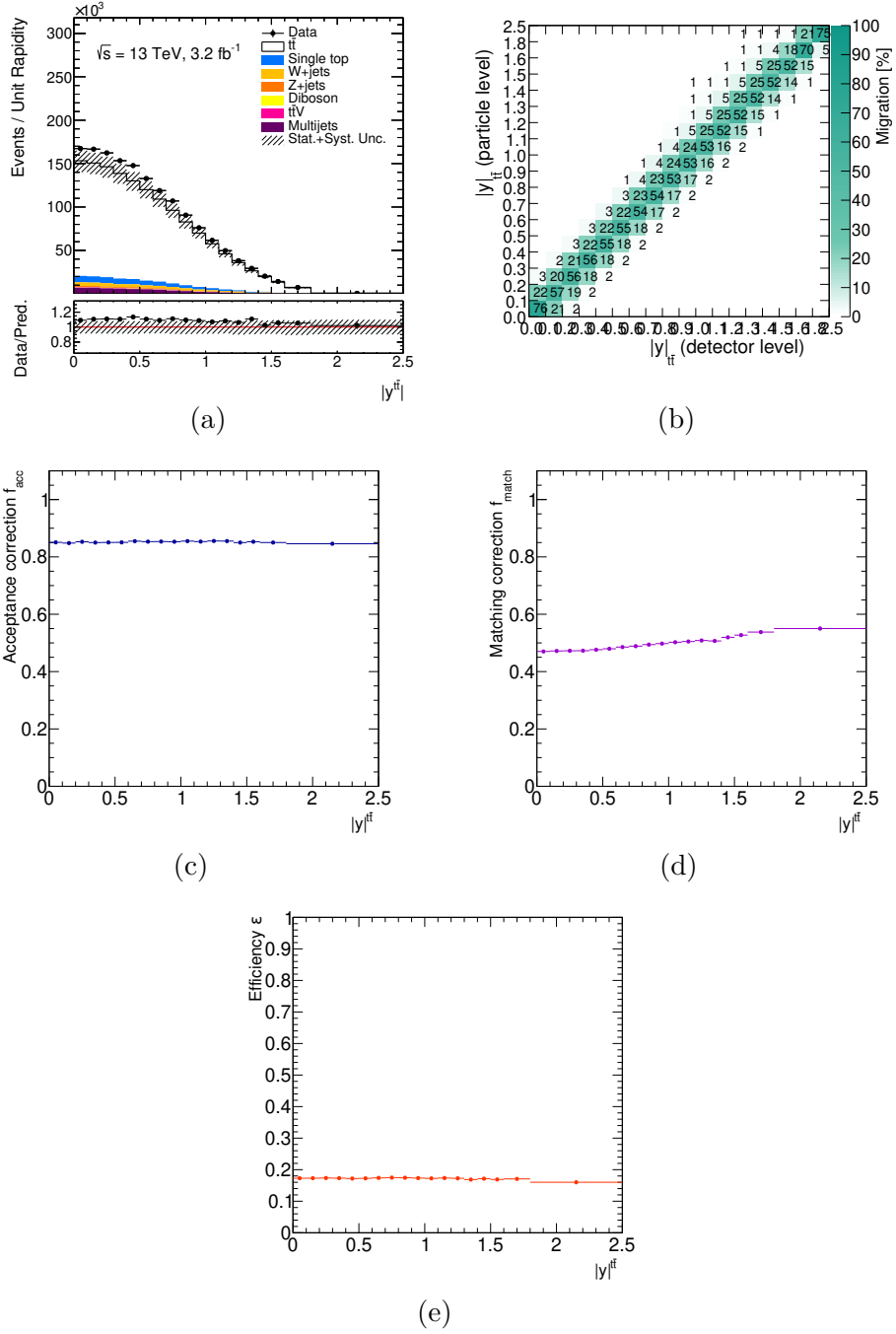


Figure A.6: Detector-level distribution (a), migration matrix (b), acceptance correction (c), matching correction (d) and efficiency (e) for the $t\bar{t}$ system rapidity. The migration matrix is normalised to unity in each row, thus the number in each bin represents the probability of a migration from a given particle-level bin to a particular detector-level bin.

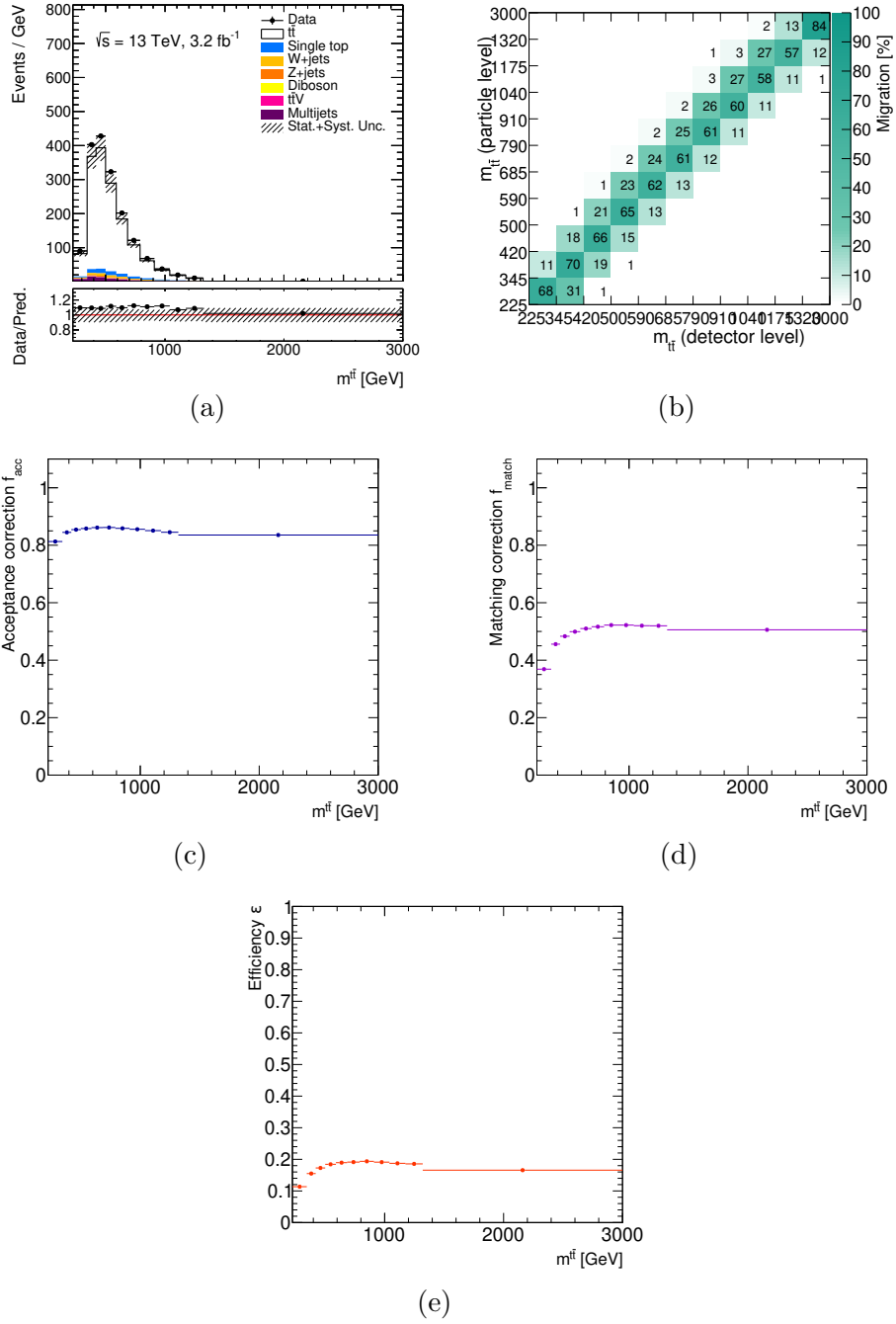


Figure A.7: Detector-level distribution (a), migration matrix (b), acceptance correction (c), matching correction (d) and efficiency (e) for the $t\bar{t}$ system mass. The migration matrix is normalised to unity in each row, thus the number in each bin represents the probability of a migration from a given particle-level bin to a particular detector-level bin.

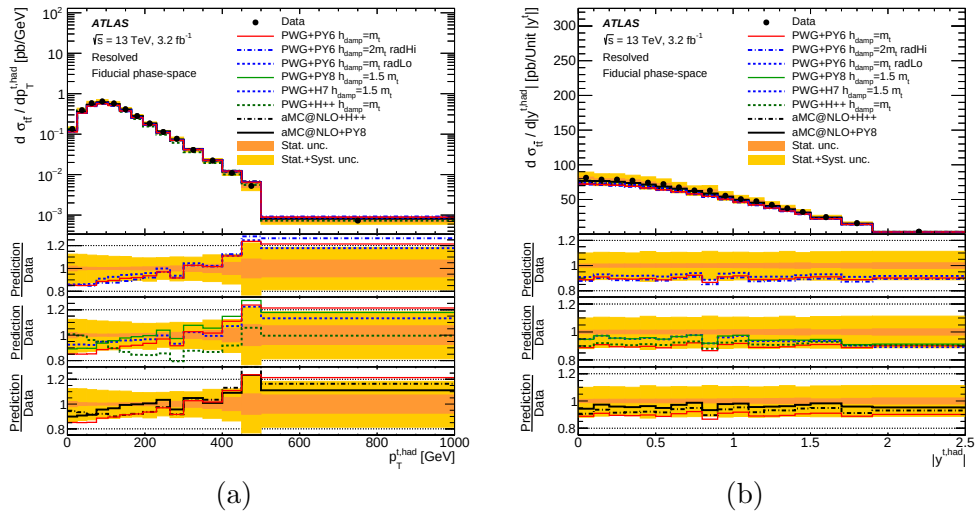


Figure A.8: Fiducial absolute differential cross-sections as a function of the hadronic top transverse momentum (a) and rapidity (b) [175].

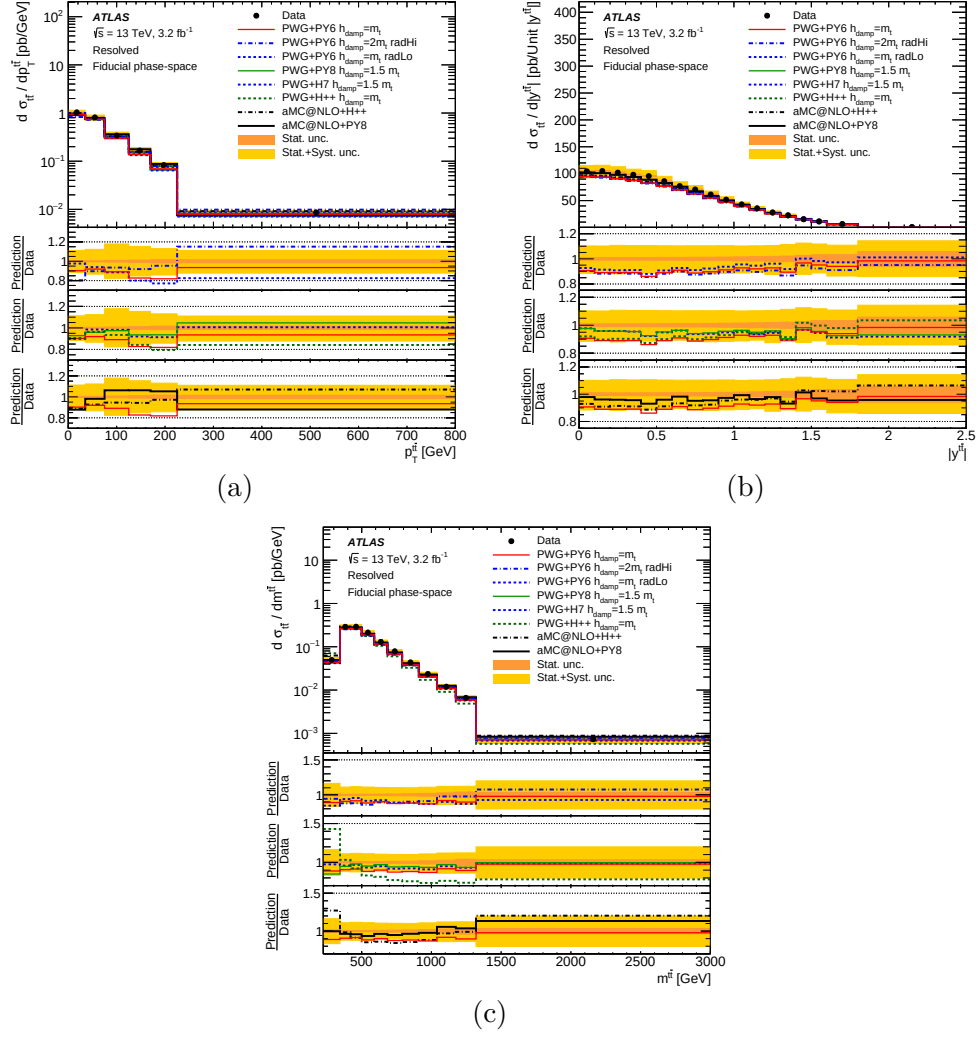


Figure A.9: Fiducial absolute differential cross-sections as a function of the $t\bar{t}$ system transverse momentum (a), rapidity (b) and mass (c) [175].

Appendix B

$t\bar{t}$ production in association with heavy-flavour jets

B.1 Signal and validation region kinematic distributions

Figures B.1–B.4 present distributions validating agreement between data and predictions before the flavour-composition fit in the $\geq 4j \geq 2b$, $\geq 5j \geq 2b$, $\geq 5j \geq 3b$ and $\geq 6j \geq 4b$ selections. A good overall agreement is observed with the exception of a normalisation offset increasing with the number of b -jets in the event. The same distributions after applying the fitted flavour scale factors are presented in Figures B.5–B.7 for the $\geq 5j \geq 2b$, $\geq 5j \geq 3b$ and $\geq 6j \geq 4b$ selections. No shapes are affected by the flavour composition correction except for the number of b -tagged jets in the event, which is improved. The normalisation offset observed in high b -jet multiplicity regions is thus reduced and an improved overall data-prediction agreement is observed. Since the fit is repeated for every systematic variation, the total uncertainty is also reduced.

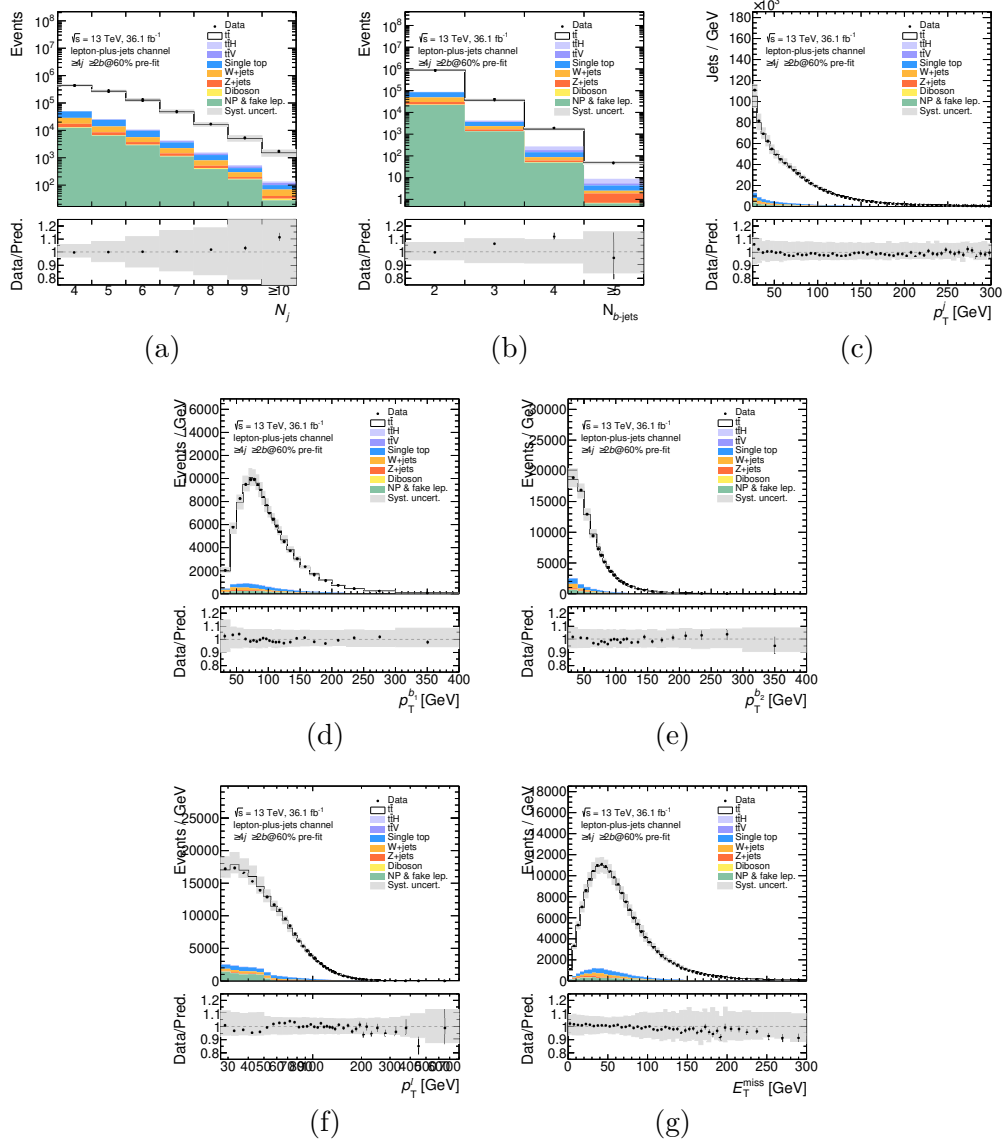


Figure B.1: Pre-fit jet and b -jet multiplicity, jet, b -jet and lepton p_T , and E_T^{miss} distributions in the selection requiring at least four jets with at least two b -tags.

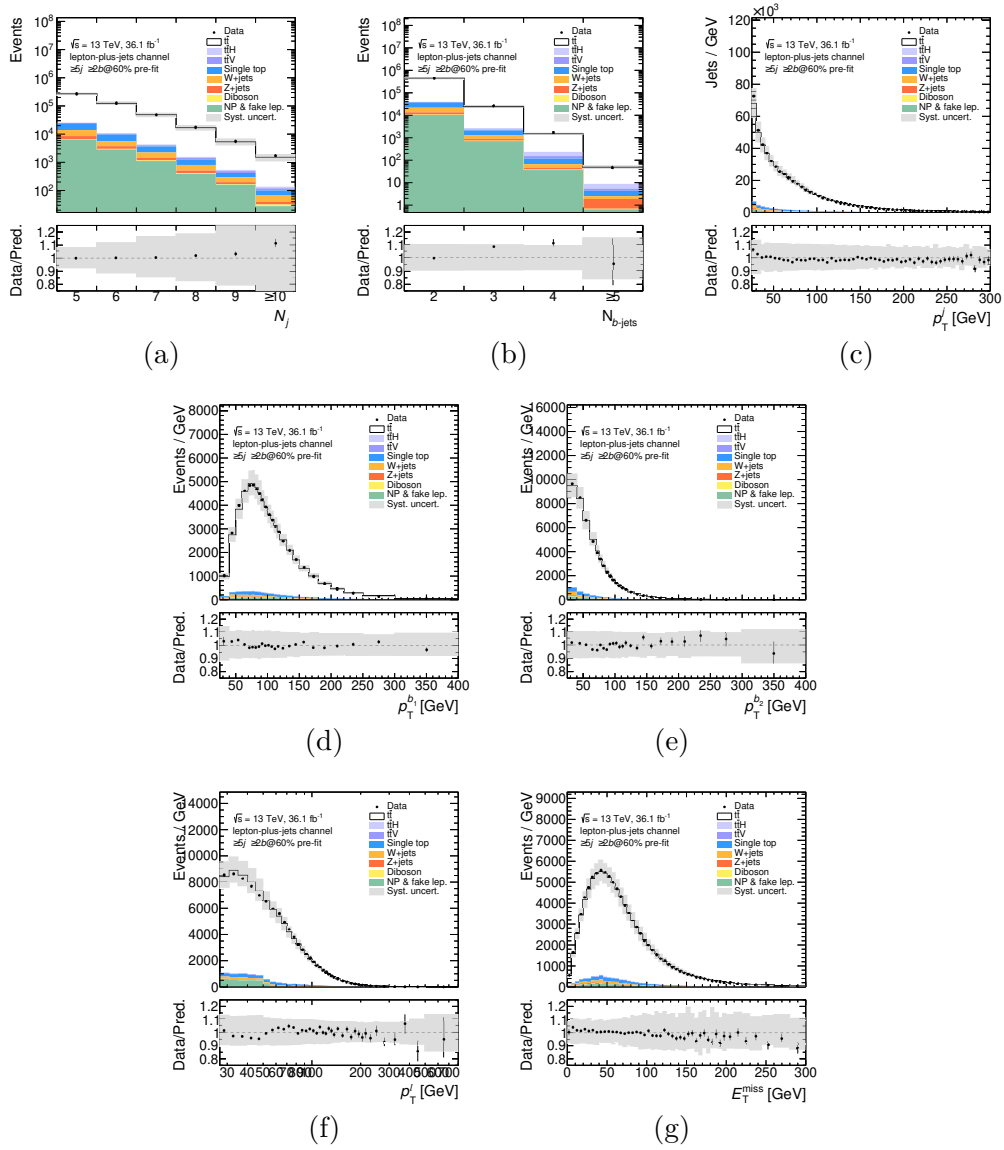


Figure B.2: Pre-fit jet and b -jet multiplicity, jet, b -jet and lepton p_T , and E_T^{miss} distributions in the selection requiring at least five jets with at least two b -tags.

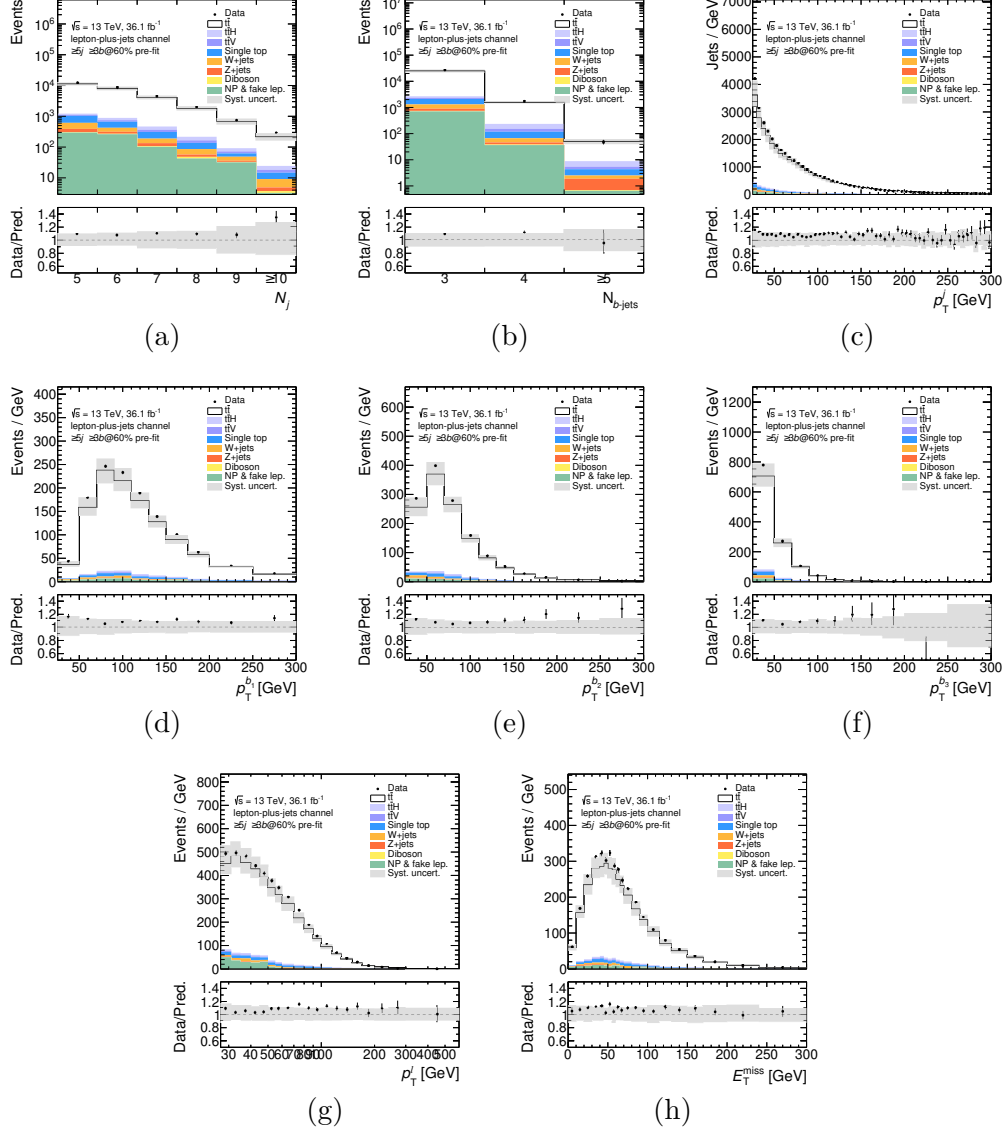


Figure B.3: Pre-fit jet and b -jet multiplicity, jet, b -jet and lepton p_T , and E_T^{miss} distributions in the selection requiring at least five jets with at least three b -tags.

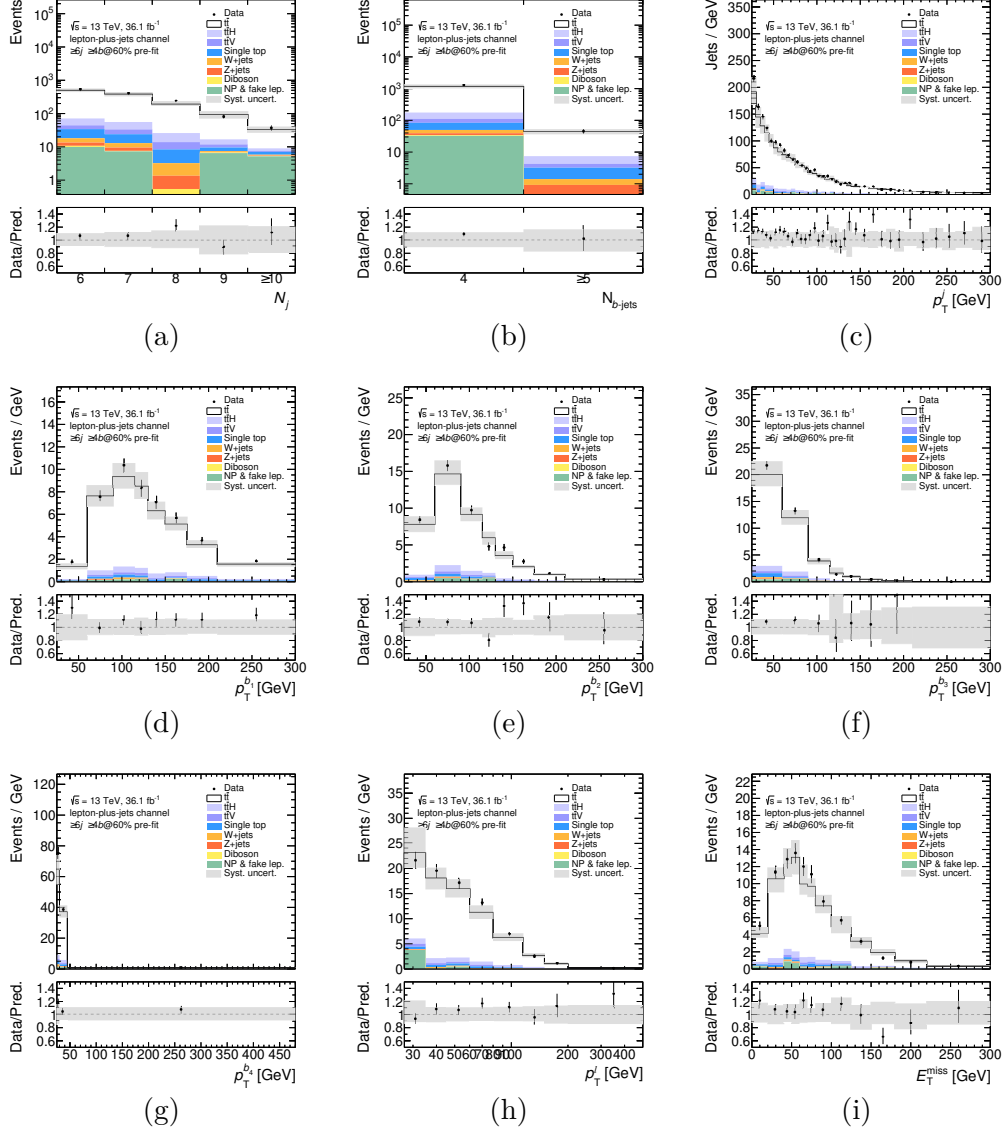


Figure B.4: Pre-fit jet and b -jet multiplicity, jet, b -jet and lepton p_T , and E_T^{miss} distributions in the selection requiring at least six jets with at least four b -tags.

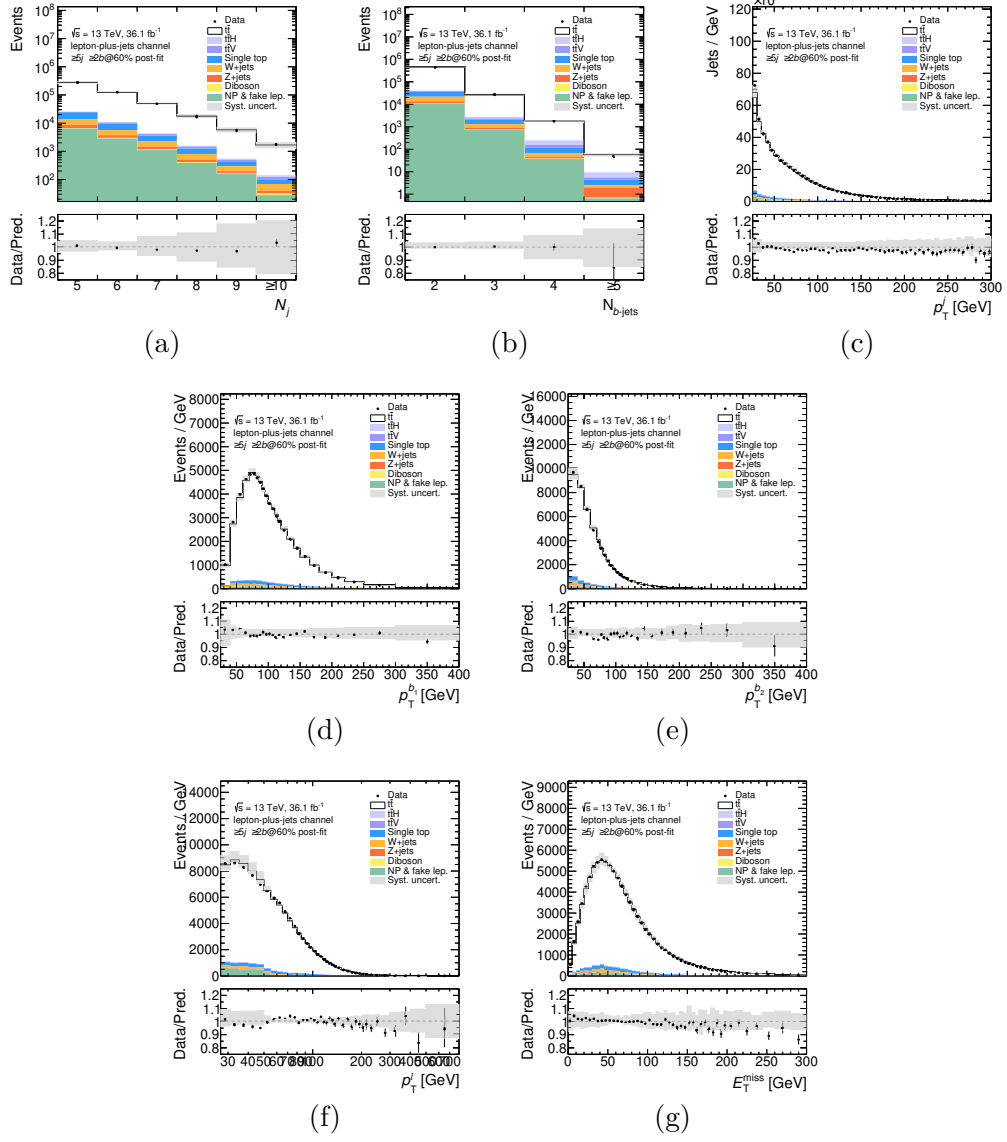


Figure B.5: Post-fit jet and b -jet multiplicity, jet, b -jet and lepton p_T , and E_T^{miss} distributions in the selection requiring at least five jets with at least two b -tags.

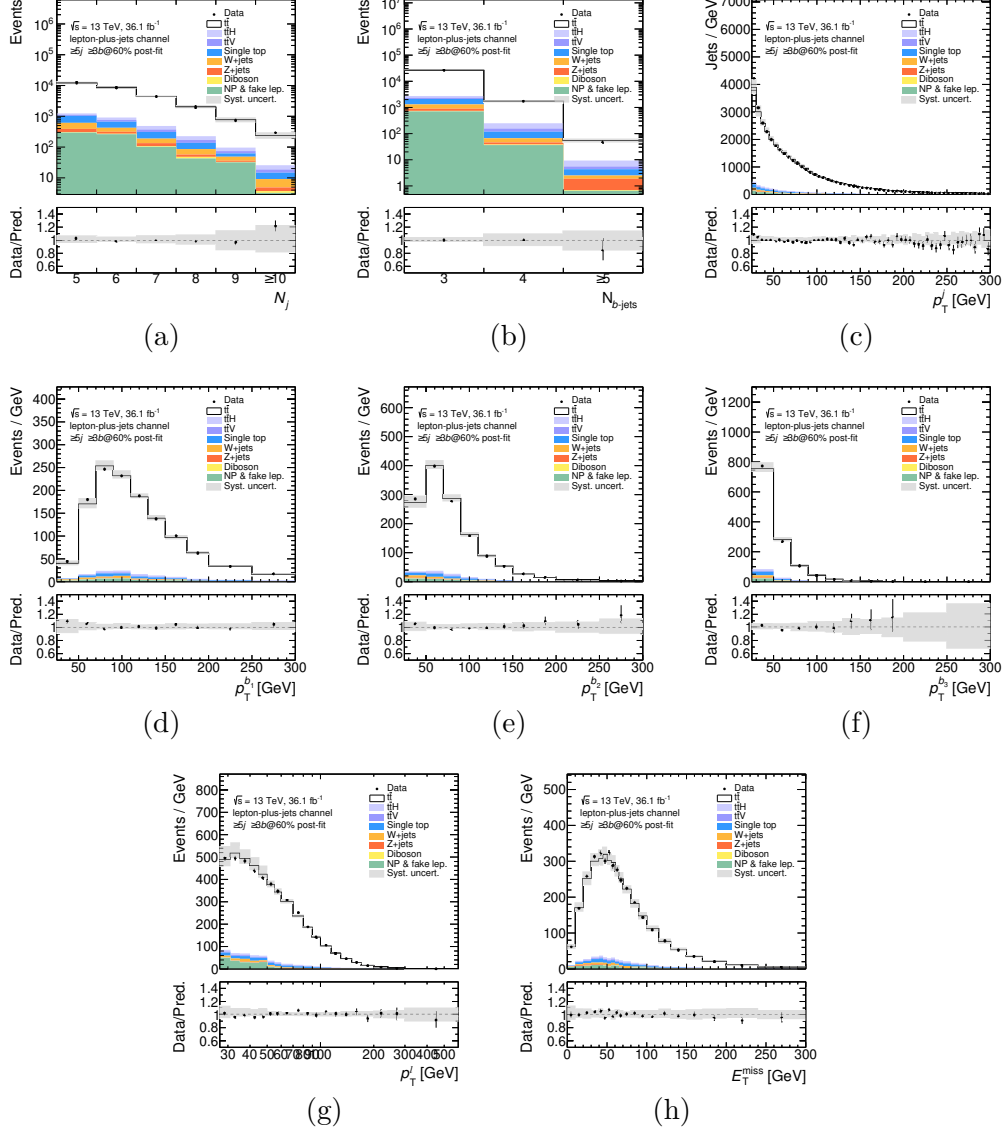


Figure B.6: Post-fit jet and b -jet multiplicity, jet, b -jet and lepton p_T , and E_T^{miss} distributions in the selection requiring at least five jets with at least three b -tags.

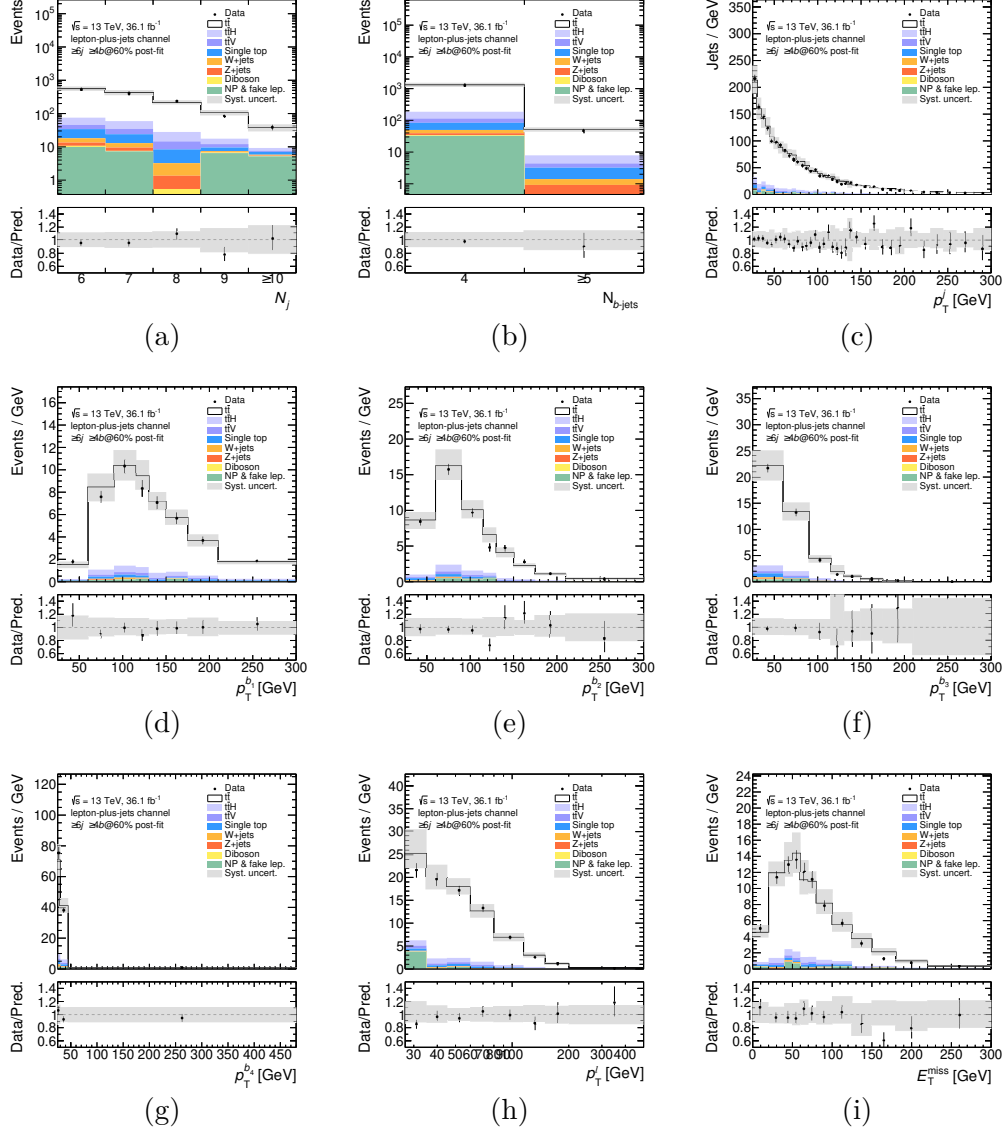


Figure B.7: Post-fit jet and b -jet multiplicity, jet, b -jet and lepton p_T , and E_T^{miss} distributions in the selection requiring at least six jets with at least four b -tags.

B.2 Fit stability studies

Alternative classifications

The analysis was initially performed with a different flavour-category classification and some of the comparisons and checks in this appendix are using the previous definitions. The previous classification is based on the number of b - and c -hadrons ghost-matched to particle-level jets within the fiducial volume. Each jet matched to more than one b -hadron is counted as two b -jets and, if no b -hadrons and more than one c -hadron is matched, the jet is counted as two c -jets. In the current definition, each particle-level jet is always considered as a single b -, c - or light-jet. In both classifications an event is classified as $t\bar{t}b$ if it contains at least three b -jets and as $t\bar{t}c$ if it contains less than three b -jets and at least two c -jets. Events not falling into any of these two categories are classified as $t\bar{t}l$ events. The change in the classification definitions effectively moves a fraction of events from the $t\bar{t}c$ category to $t\bar{t}l$, as seen in Table B.1. The table also presents the fit results and the fiducial cross sections for both cases, showing that the effect of the change on the final results is small.

The nominal fit was also repeated with a categorisation where $t\bar{t} + \text{light jet}$ events with a single c -jet, assumed to be coming from W from top, are separated out from the other $t\bar{t} + \text{light jet}$ events. The nominal $t\bar{t}l$ category is split into $t\bar{t}l$ and $t\bar{t}c$ where the latter designates events with exactly one particle-level c -jet. The nominal $t\bar{t}c$ category is renamed to $t\bar{t} + cc$. The fit results, presented in Figure B.8, are consistent with the assumption of the single c -jet events being in fact $t\bar{t} + \text{light jet}$ events where the c -jet comes from the top quark decay chain. The resulting scale factors for $t\bar{t}b$ and $t\bar{t}l$ are unchanged with respect to the equivalent fit performed with three templates. The new $t\bar{t}c$ category scale factor is close to $t\bar{t}l$ and the $t\bar{t} + cc$

classification	hadron-based			jet-based		
fiducial volume	$t\bar{t} + 1b$	$t\bar{t} + \geq 1b$	$t\bar{t} + \geq 2b$	$t\bar{t} + 1b$	$t\bar{t} + \geq 1b$	$t\bar{t} + \geq 2b$
$N_{t\bar{t}b}^{\text{MC, reco}}$	10878	12225	1049	10704	12055	1053
$N_{t\bar{t}c}^{\text{MC, reco}}$	3092	3172	50	1922	1995	46
$N_{t\bar{t}l}^{\text{MC, reco}}$	8283	8336	31	9715	9777	37
α_b	1.10	1.10	1.10	1.10	1.10	1.10
α_c	1.44	1.44	1.44	1.59	1.59	1.59
α_l	0.96	0.96	0.96	0.96	0.96	0.96
σ_{fid} [fb]	1930^{+460}_{-440}	2420^{+530}_{-510}	360 ± 48	1960 ± 450	2450 ± 520	359 ± 51

Table B.1: Comparison of the predicted number of $t\bar{t}$ +jets events, fit results and fiducial cross sections obtained with two event categorisations – one considering doubly-tagged particle-level heavy flavour jets as two jets (hadron-based) and one treating them as single jets (jet-based).

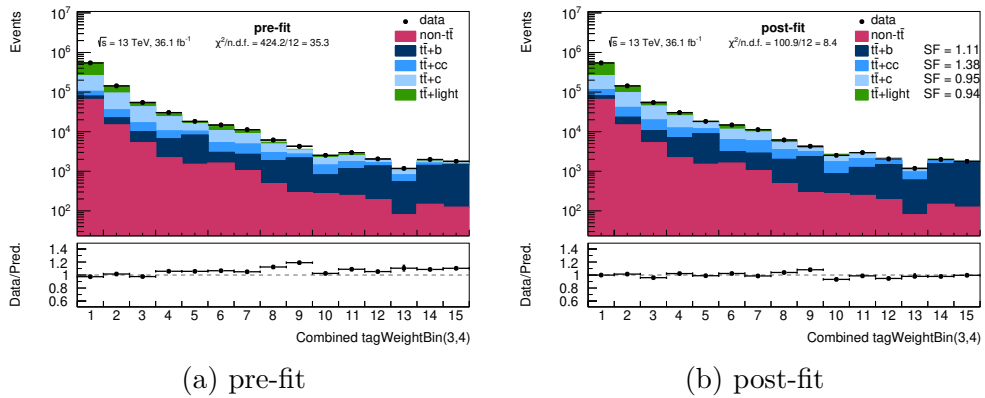


Figure B.8: Pre- and post-fit MV2c10 distribution for the four-category fit where $t\bar{t} + \text{single } c\text{-jet}$ events are separated out from $t\bar{t} + \text{light jet}$.

scale factor is close (slightly lower) to its nominal value, proving that the majority of the $t\bar{t}c$ events belong to the $t\bar{t}l$ category.

Alternative fit regions

In order to check the stability of the fits with respect to the fit-region definition, the fit was repeated with several selections. Combinations of different number-of-jets requirements (either ≥ 5 or ≥ 6) and the b -tagging working point to select the first two b -jets (either 77% or 60%) were tested. The same fits were also repeated including or excluding the $t\bar{t}b\bar{b}$ signal region ($\geq 4b$ at 60%) corresponding to bin 15. The results are summarised in Figure B.9 showing small modifications between the different regions.

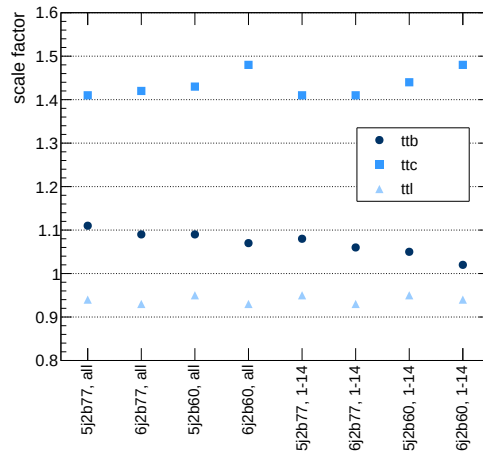


Figure B.9: Summary of fit results in different jet selections, using different b -tagging working points and including or excluding bin 15.

Fits to systematic variations

The fit procedure is repeated for each systematic variation and the resulting scale factors are used to reweight the varied distributions when evaluating the uncertainty on the results. The full list of scale factors obtained in fits to each systematic variation is not presented here, as there are nearly 500 systematic variations considered. Several examples of pre-fit and post-fit distributions for the variations most different from the nominal result are presented in Figures B.10–B.15. The difference between the variation-fit and the nominal-fit flavour scale factors does not constitute an uncertainty on its own. Only comparing the varied prediction reweighted with the varied scale factors to the nominal sample reweighted with the nominal scale factors carries information about a specific systematic uncertainty. It can be observed that even large modifications to the fitted templates result in a similar good post-fit agreement between predictions and data.

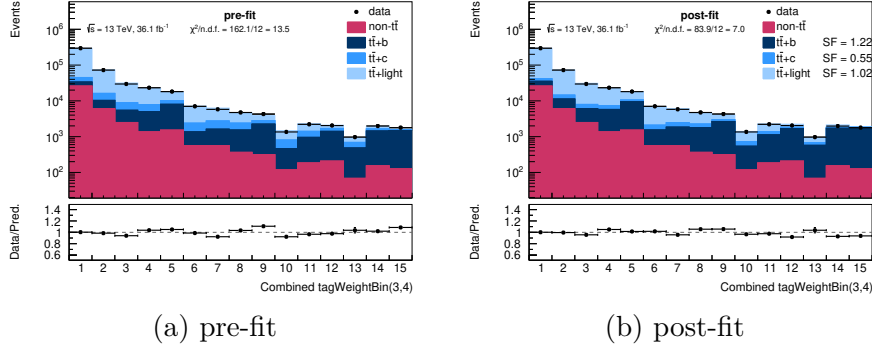


Figure B.10: Pre- and post-fit MV2c10 distribution for the `bTagSF_Continuous_eigenvars_Light_down_0` systematic variation.

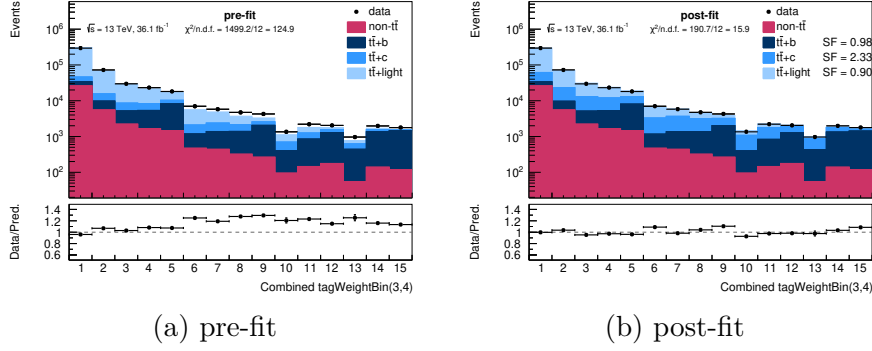


Figure B.11: Pre- and post-fit MV2c10 distribution for the `bTagSF_Continuous_eigenvars_Light_up_0` systematic variation.

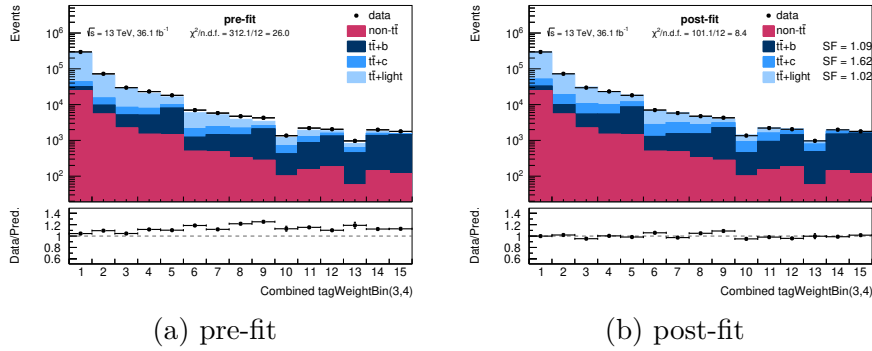


Figure B.12: Pre- and post-fit MV2c10 distribution for the `JET_21NP_JET_Flavor_Composition_1down` systematic variation.

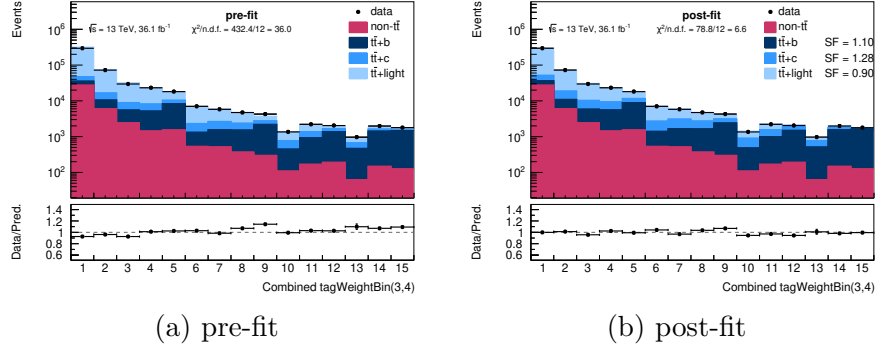


Figure B.13: Pre- and post-fit MV2c10 distribution for the JET_21NP_JET_Flavor_Composition_1up systematic variation.

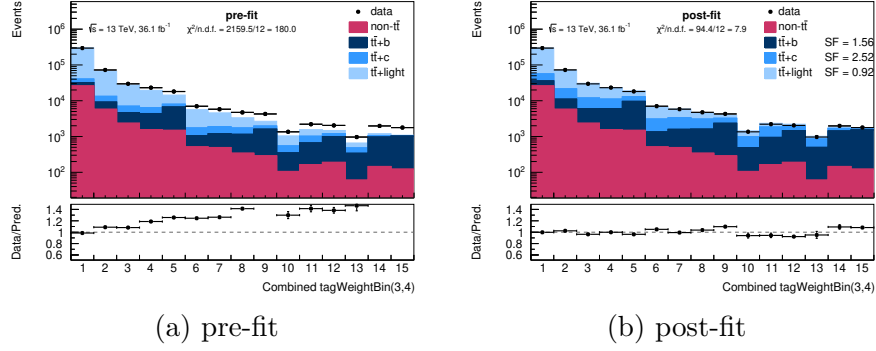


Figure B.14: Pre- and post-fit MV2c10 distribution for the parton shower generator systematic variation.

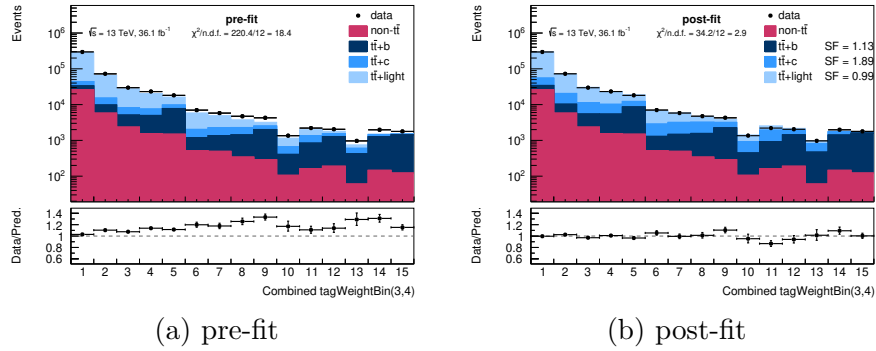


Figure B.15: Pre- and post-fit MV2c10 distribution for the hard process generator systematic variation.

B.3 $t\bar{t}b\bar{b}$ event reconstruction studies

Differential measurements of $t\bar{t}b\bar{b}$ production as a function of the additional $b\bar{b}$ pair kinematics have the potential to discriminate between different modelling choices and constrain the corresponding theory uncertainties [53]. However, identification of the additional $b\bar{b}$ pair out of at least four b -jets in an event is a challenging task. Several algorithms based on simple observables and well-known $t\bar{t}$ system reconstruction methods have been tested and the results are reported below. The fraction of correctly identified non-top $b\bar{b}$ pairs is evaluated using truth-level information about the b -jet origin in the nominal signal MC simulation. In addition, the fractions of selected $b\bar{b}$ pairs where one or both b -jets originate from top quarks are also evaluated. The results of this study are presented in Figure B.16. It shows the distribution of all $b\bar{b}$ pairs selected by a given algorithm as coming from additional radiation in bins indicating their true origin. The correctly selected additional $b\bar{b}$ pairs are in the third bin, highlighted in blue. The first bin corresponds to $b\bar{b}$ pairs, where both b -jets originate from the decays of top quarks, whereas the second bin corresponds to $b\bar{b}$ pairs where one b -jet comes from a top decay and one comes from additional radiation. The last bins includes events where at least one of the selected b -jets could not be matched to any true b -jet in the MC record.

The comparison considers two types of algorithms – one selecting the b -jet pair based on their p_T , and one using angular information about the b -jets and other objects in the event. Both algorithms are presented with several modifications, resulting in the total number of eight tested combinations. The simplest algorithm, denoted ‘ p_T ’, selects the third and fourth highest- p_T b -jets in the event, regardless of anything else. A modification of this algorithm labelled ‘ p_T + pseudo-top veto’ employs the pseudo-top algorithm

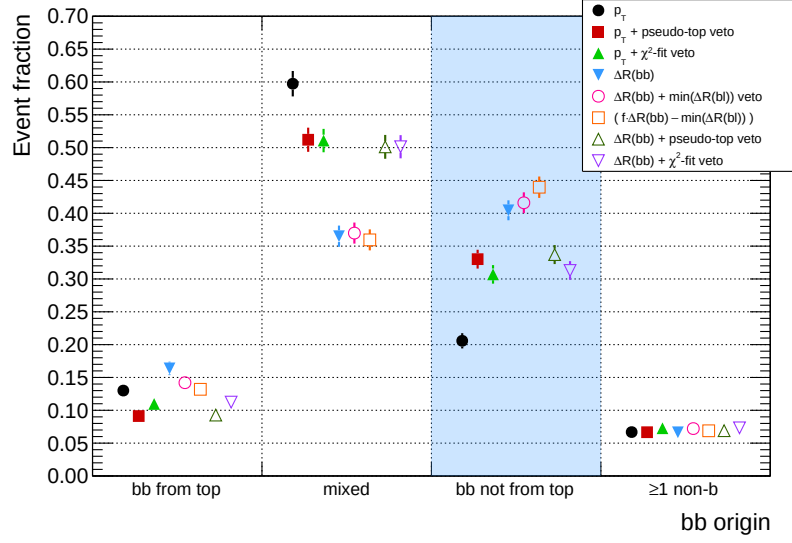


Figure B.16: Fraction of bb pairs coming from $t\bar{t}$, from additional radiation, or of mixed origin selected by different reconstruction algorithms. The rightmost bin includes events where at least one of the selected detector-level b -jets corresponds to a light jet or c -jet at the particle level.

described in Section 6.2. The $t\bar{t}$ system is reconstructed from the lepton, two leading b -jets and two other jets giving an invariant mass closest to m_W regardless of their b -tagging score. The four jets assigned to the $t\bar{t}$ system are excluded from the event and the two lowest- p_T b -jets out of the remaining ones are selected as the additional bb pair. A similar approach using the χ^2 -fit $t\bar{t}$ reconstruction method [195] instead of the pseudo-top algorithm is referred to as the ‘ $p_T + \chi^2$ -fit veto’ algorithm.

The algorithms based on angular information exploit the ΔR distance between b -jets or between a b -jet and the lepton. The simplest algorithm from this category, denoted ‘ $\Delta R(b, b)$ ’, selects the two b -jets in the event which are the closest to each other. This algorithm is used in the differential measurements presented in this thesis. The motivation for this choice is presented in Figure B.17a, showing that the bb pair from additional radiation is characterised by small $\Delta R(b, b)$, whereas the same distribution for the

$b\bar{b}$ pair from $t\bar{t}$ peaks around 3. Additional discrimination can be obtained using the angular distance between b -jets and the lepton, presented for any of the two b -jets in Figure B.17b. The $\Delta R(\ell, b)$ distribution peaks around 3 for b -jets from additional radiation, whereas two distinctive peaks are observed for b -jets from top quarks. One peak, at low values, corresponds to the b -jet from the leptonic top and the other, around 3, to the b -jet from the hadronic top. Therefore using the lower value of $\Delta R(\ell, b)$ from the two selected b -jets, $\min \Delta R(\ell, b)$, one can distinguish easily between $b\bar{b}$ pairs containing or not containing the b -jet from the leptonic top. A simple modification of the ‘ $\Delta R(b, b)$ ’ algorithm, denoted ‘ $\Delta R(b, b) + \min \Delta R(\ell, b)$ veto’ selects the two closest b -jets after excluding the b -jet which is closest to the lepton.

Further studies of the $\Delta R(b, b)$ and $\min \Delta R(\ell, b)$ distributions in two dimensions, presented in Figure B.18, uncover the discriminating power of their combination thanks to the lack of correlation between the two observables. The highest separation is obtained along the direction perpendicular to the $\Delta R(b, b) = \min \Delta R(\ell, b)$ line, i.e. using the difference $\Delta R(b, b) - \min \Delta R(\ell, b)$. The direction can be further rotated by a factor f in order to search for the maximal discrimination. The discrimination along the $f \cdot \Delta R(b, b) - \min \Delta R(\ell, b)$ direction for $f = 0.5, 1$ and 1.2 is presented in Figure B.19. The $b\bar{b}$ pair selection algorithm exploiting this observable selects the pair with the lowest value of $f \cdot \Delta R(b, b) - \min \Delta R(\ell, b)$ to be the additional $b\bar{b}$ pair. Results of a systematic search along f values between 0.5 and 2.0 are presented in Figure B.20, showing that $f = 1.2$ allows to correctly select the additional $b\bar{b}$ pair in around 44 % cases. This is the best result achieved among all algorithms presented in Figure B.16. Due to the large size of the statistical uncertainty on this fraction and fluctuations seen in Figure B.20, it is believed that the increased discrimination for $f = 1.2$

may be accidental. In this case, the simpler choice of $f = 1$ is considered equally good.

Algorithms combining the angular and momentum information, including the pseudo-top or χ^2 -fit veto in the ΔR selection are found to provide worse results than angular-only algorithms. The simple ‘ ΔR ’ algorithm was used in the differential measurements due to its simplicity in comparison to the $f \cdot \Delta R(b, b) - \min \Delta R(\ell, b)$ algorithm. The loss of correct-matching efficiency due to this is small, and the correct bb pair is selected in 41 % of events.

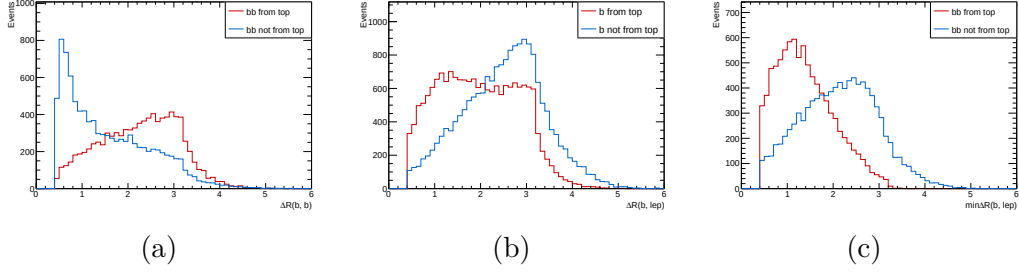


Figure B.17: Distributions of ΔR between two b -jets (a), ΔR between the lepton and any of the two b -jets (b) and ΔR between the lepton and the closest of the two b -jets (c) for bb pairs originating from $t\bar{t}$ (red) and from additional radiation (blue).

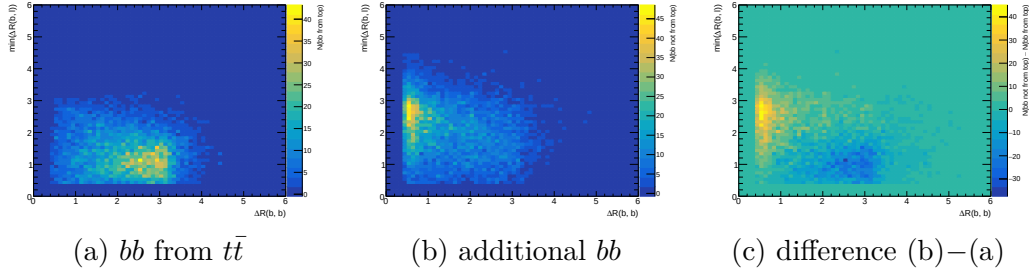


Figure B.18: Two-dimensional distribution of $\Delta R(b, b)$ and $\min \Delta R(\ell, b)$ for bb pairs from $t\bar{t}$ (a) and from additional radiation (b). Figure (c) shows the difference between the two distributions.

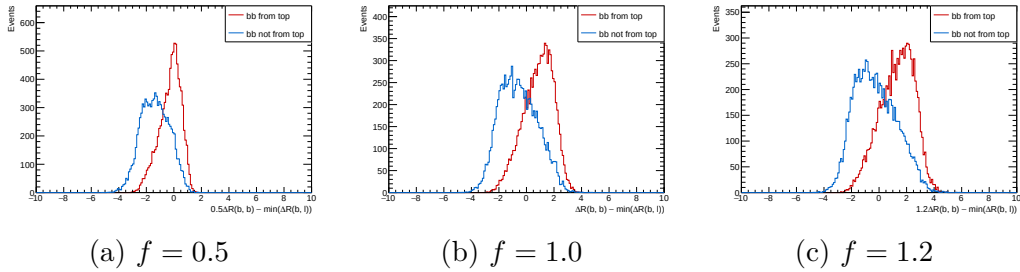


Figure B.19: Distributions of $f \cdot \Delta R(b, b) - \min \Delta R(\ell, b)$ for bb pairs from $t\bar{t}$ (red) and from additional radiation (blue) for $f = 0.5, 1.0$ and 1.2 .

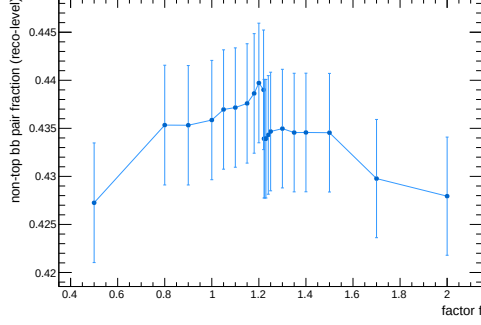


Figure B.20: The fraction of correctly selected additional bb pairs using the $f \cdot \Delta R(b, b) - \min \Delta R(\ell, b)$ algorithm with different values of f . The error bars represent the statistical uncertainty.

B.4 Differential cross-section measurement results

Figures B.21 and B.22 present the ten normalised differential fiducial cross-section measurement results not included in Section 7.5.2. The lowest panel of each figure shows the ratio of predictions of normalised differential cross sections from MG5_aMC@NLO+PYTHIA8 including (numerator) and not including (denominator) the contributions of $t\bar{t}V$ and $t\bar{t}H$ production. The discussion in Section 7.5.2 applies also to the results presented here.

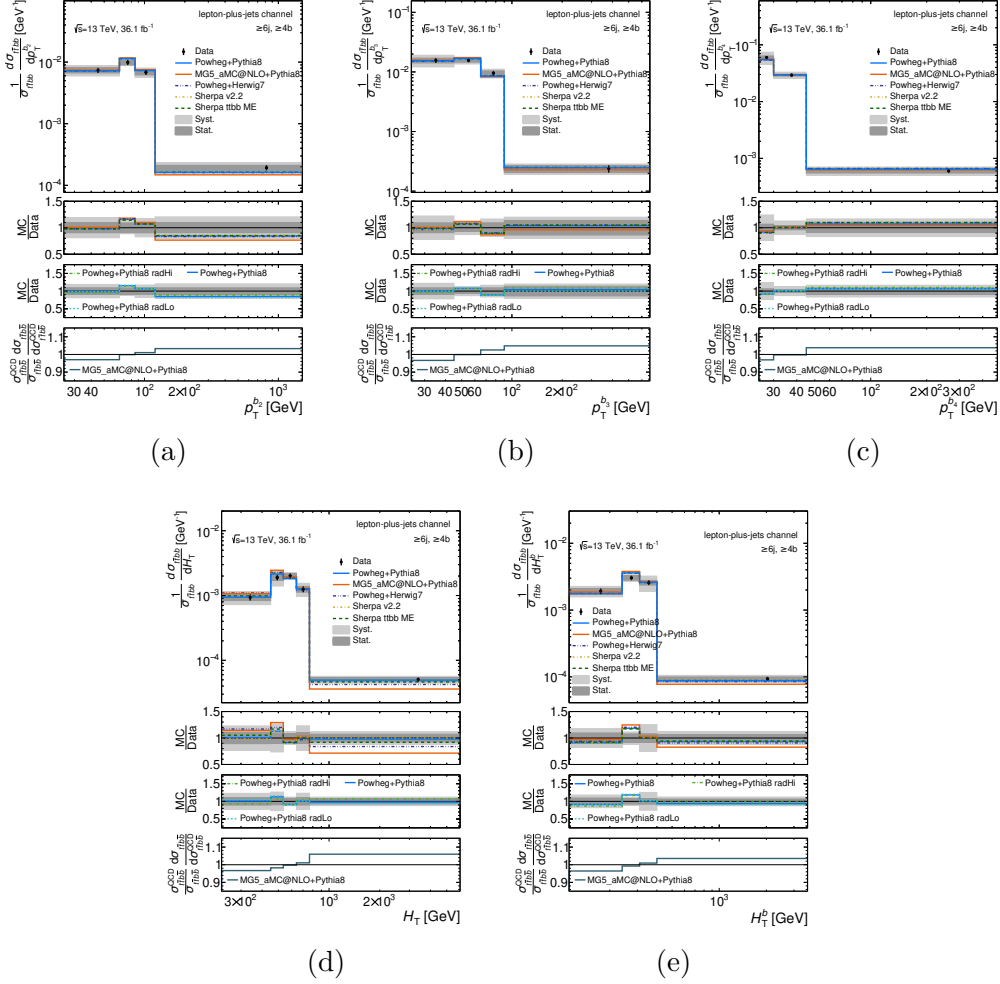


Figure B.21: Relative differential cross sections as a function of the p_T of the (a) sub-leading, (b) third and (c) fourth b -jet, and the (d) H_T and (e) H_T^b variables. The results are presented in the $t\bar{t} + \geq 2b$ fiducial volume and compared to various MC generators. The lowest panel shows the relative effect of the electroweak contributions on the shape of the normalised cross section.

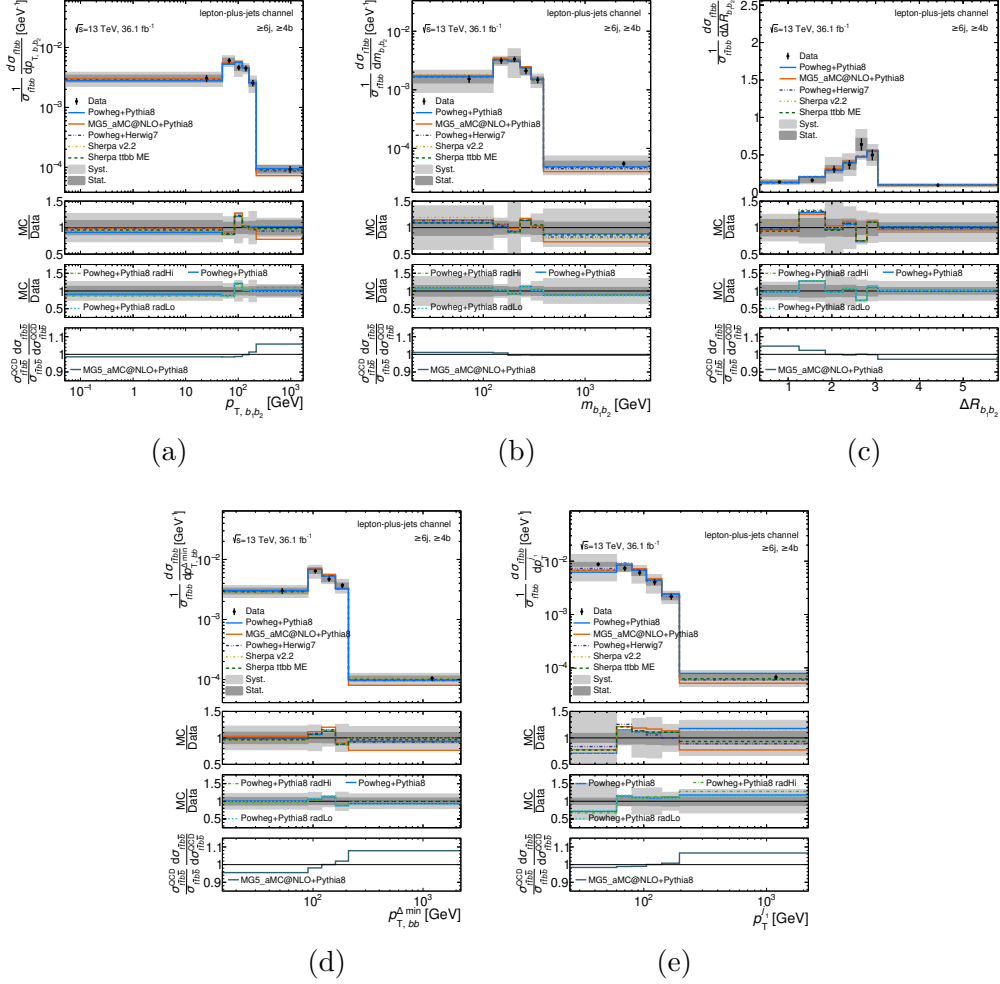


Figure B.22: Relative differential cross sections as a function of the (a) p_T , (b) mass and (c) angular separation of the leading bb pair, as well as (d) the p_T of the closest bb pair and (e) the leading non- b -jet p_T . The results are presented in the $t\bar{t} + \geq 2b$ fiducial volume and compared to various MC generators. The lowest panel shows the relative effect of the electroweak contributions on the shape of the normalised cross section.

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