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Simultaneous efficiency measurements of b- and c-jets in $t\bar{t}$ events from $\sqrt{s}$ = 13.6 TeV pp collision data collected with the ATLAS detector

The ATLAS Collaboration

This paper reports simultaneous measurements of the efficiencies with which b-jets are identified, and c-jets are misidentified as b-jets, by the single-transformer-based GN2 tagger that is currently used in the ATLAS experiment at the LHC. The measurements use $t\bar{t}$ events where one of the W bosons decays into an electron or muon and a neutrino, and the other decays into a quark–antiquark pair, together with the known $t \to bW$ and $W \to cs$ branching fractions. The data were collected from $\sqrt{s}$ = 13.6 TeV proton–proton collisions by the ATLAS detector and correspond to an integrated luminosity of 56 fb^{-1}. Events are reconstructed using a kinematic likelihood technique which maps the jets to the $t\bar{t}$ decay products. The b-jet tagging efficiency is measured from jets arising from leptonically decaying top quarks and the c-jet mistagging efficiency is obtained from jets arising from hadronic W decays. The efficiencies are measured as a function of jet transverse momentum in intervals of the tagging-variable distribution. The b-jet (c-jet) tagging efficiency measurements reach a precision of better than 2% (5%). Each b-jet efficiency is combined with an independent measurement using $t\bar{t}$ events where both W bosons decay leptonically.

Contents

1 Introduction

In many analyses at the Large Hadron Collider (LHC) [1] it is crucial to identify which jets originate from a bottom or charm quark; recent examples using data collected by the ATLAS experiment [2] are a measurement of Higgs bosons decaying to bottom quarks and search for Higgs bosons decaying to charm quarks [3], measurements of top-quark pair production with additional b-jets [4] or c-jets [5], and searches for Higgs boson pair production [6] and Higgs boson production in association with top quarks [7].

The algorithms which identify jets that originate from a bottom quark are known as b-tagging algorithms. The performance of these algorithms depends crucially on whether the jets that are identified contain b-hadrons (b-jets), c-hadrons (c-jets), or neither of them (light-flavour jets). Monte Carlo (MC) simulation provides an estimate of the probability that a jet fulfils the requirements of the b-tagging algorithm, i.e. the tagging efficiency for b-jets and the mistagging efficiency[1] for c-jets, light-flavour jets or jets formed from the products of hadronically decaying τ-leptons. However, since the simulation is not perfect, the (mis)tagging efficiency is measured in data. Simulation-to-data scale factors (SFs), which are defined as the ratio of the efficiency measured in data to that in simulation, are used to correct the simulation, assuming that the SFs are independent of the physics process. Analyses that use b-tagging apply a weight to each simulated event, calculated as the product of the SFs for all jets in the event.

ATLAS recently measured the SFs for b-jets [8] in data proton-proton (pp) data at a centre-of-mass energy of 13 TeV from 2015-2018 (LHC Run 2). That measurement used dileptonic top-quark pair production ($t\bar{t}$) where the W bosons from both top-quark decays produce an electron or a muon plus the corresponding neutrino. Measurements of SFs for c-jets used a method similar to that presented in this paper, utilising $t\bar{t}$ semileptonic events where the W boson originating from one of the top quarks decays leptonically into an electron or a muon plus the corresponding neutrino ($t \to Wb \to \ell\nu b$) and the other decays hadronically

[1] Mistagging efficiency is the efficiency for an object other than a b-jet to be identified as a b-jet by the b-tagging algorithm.

($t \to Wb \to qq'b$) [9]. The SFs for the mistagging efficiency for light-flavour jets were measured in Z+jet events [10].

This paper is the first to report simultaneous measurements of the b-jet and c-jet SFs using $t\bar{t}$ semileptonic events. The measurements use data from 13.6 TeV pp collisions recorded with the ATLAS detector during part of Run 3 in 2022 and 2023, corresponding to an integrated luminosity of 56 fb^{-1} [11, 12]. The method for extracting the c-jet SFs was updated for use with an improved transformer-based graph neural-network flavour tagger, since this tagger's lower c-jet mistagging efficiency [13] makes the measurements of these SFs more challenging. A likelihood-based method is used to select a high-purity semileptonic $t\bar{t}$ sample. The leptonically decaying top quark is used to determine the b-jet SFs. The known branching fraction of the W boson to a final state with a c-quark, approximately 33% [14], allows the c-jet mistagging efficiency to be determined from the data by using the W boson from the hadronically decaying top quark. The SFs are determined as a function of jet transverse momentum (p_{T}), as is also the case in Ref. [9].

2 ATLAS detector

The ATLAS experiment [2, 15] at the LHC uses a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.[2] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID-2 detector, which is located close to the beam pipe. A two-level trigger system is used to select events [16]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 3 kHz on average, depending on the data-taking conditions. A software suite [17] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and simulated event samples

The data analysed in this paper correspond to 56 fb^{-1} of pp collision data collected by the ATLAS detector in 2022 and 2023 with a centre-of-mass energy of 13.6 TeV and a 25 ns proton bunch crossing interval. The

[2] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = (1/2)\ln[(E + p_z)/(E - p_z)]$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

data sample was collected using a set of single-electron and single-muon triggers with lowest p_T thresholds of 26 GeV for electrons and 24 GeV for muons [16, 18, 19]. All detector subsystems were required to be operational during data-taking [20]. Events with noise bursts or coherent noise in the calorimeters are removed. The presence of additional interactions in the same or a neighbouring bunch crossing, referred to as pile-up, is characterised by the average number of such interactions, $\langle\mu\rangle$, which was 42 (51) during 2022 (2023).

Simulated event samples are used to model Standard Model processes and to estimate the expected signal yields. All samples were produced using the ATLAS simulation infrastructure [21] and Geant4 [22]. The simulated events are reconstructed with the same algorithms as used for data, and contain a realistic modelling of pile-up interactions. The pile-up profiles in the simulation match those of the data and were obtained by overlaying the hard-scatter events with minimum-bias events simulated using the soft QCD processes generated from a mix of Epos 2.0.1.4 [23] and Pythia 8.308 [24]. The Epos events were generated with parameter values from the Epos LHC tune [25] and the Pythia events with the A3 tune [26] and the NNPDF2.3lo [27] set of parton distribution functions (PDFs). Pythia pile-up events include either a high-p_T jet, a prompt photon, or a lepton from a b-hadron decay, while Epos was filtered to simulate all remaining pile-up events in the overlay sample. For all samples, with the exception of those generated using Sherpa [28], the decays of bottom and charm hadrons were performed by EvtGen [29].

The events used in this study originate mostly from $t\bar{t}$ production. This process was modelled using the Powheg Box v2 [30–33] generator at next-to-leading order (NLO) with the NNPDF3.0nlo PDF set [34] and the h_{damp} parameter[3] set to $1.5 \times m_{top}$ [35], where m_{top} denotes the mass of the top quark. The events were interfaced to Pythia 8.308 to model the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune [36] and using the NNPDF2.3lo set of PDFs [34]. The production was split into three parts: semi-leptonic decays, dileptonic decay and a high statisics sample for events with the decay to $W \to cb$, which was produced for the measurement of the CKM element V_{cb} [37].

The uncertainty due to initial-state radiation (ISR) is estimated by varying the h_{damp} parameter and the renormalisation and factorisation scales, and choosing the Var3c up/down variants of the A14 tune as described in Ref. [36]. The impact of final-state radiation (FSR) is evaluated by varying the renormalisation scale for emissions from the parton shower by a factor two. The impact of using a different parton shower and hadronisation model is evaluated by comparing the nominal $t\bar{t}$ sample with another $t\bar{t}$ sample generated by Powheg Box v2 using exactly the same parameter values but interfaced with Herwig 7.13 [38, 39], using the default tune [39, 40] and the MMHT2014lo PDF set [41]. Finally, the matrix element matching uncertainty was evaluated by setting the $p_{T,hard}$ parameter to 1 instead of its nominal value of 0 [35].

In addition to $t\bar{t}$ production, some minor backgrounds contribute to the final event sample used for the calibration. These backgrounds consist mostly of single-top and diboson production, the production of $t\bar{t}$ in association with a vector boson and the production of a vector boson in association with jets. Details of the modelling of these samples are given in the following.

Single-top s-channel production was modelled using the Powheg Box v2 generator [42] at NLO in QCD in the five-flavour scheme with the NNPDF3.0nlo PDF set. Single-top t-channel production was modelled using the Powheg Box v2 generator [42] at NLO in QCD, using the four-flavour scheme and the corresponding NNPDF3.0nlo set of PDFs. The associated production of a single top quark and a W boson (tW) was modelled using the Powheg Box v2 generator [43] at NLO in QCD, using the five-flavour scheme and the NNPDF3.0nlo set of PDFs. The diagram removal scheme [44] was used to remove interference

[3] The h_{damp} parameter is a resummation damping factor and one of the parameters that control the matching of Powheg matrix elements to the parton shower and thus effectively regulate the high-p_T radiation against which the $t\bar{t}$ system recoils.

and overlap with $t\bar{t}$ production. The events for all single-top production channels were interfaced to Pythia 8.308, which used the A14 tune and the NNPDF2.3lo set of PDFs.

The production of Z+jets and W+jets events was simulated with the Sherpa 2.2.14 generator using NLO matrix elements for up to two partons, and leading-order (LO) matrix elements for up to five partons calculated with the Comix [45] and OpenLoops [46–48] libraries. They were matched with the Sherpa parton shower [49] using the MEPS@NLO prescription [50–53] and the set of tuned parameters developed by the Sherpa authors. The NNPDF3.0nnlo set of PDFs [34] was used and their predictions were normalised to a next-to-next-to-leading-order (NNLO) prediction [54].

Samples of events with diboson final states (VV) were simulated with the Sherpa 2.2.14 generator, including off-shell effects and Higgs boson contributions where appropriate. Fully leptonic final states and semileptonic final states, where one boson decays leptonically and the other hadronically, were generated using matrix elements at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions. The matrix element calculations were matched and merged with the Sherpa parton shower based on Catani–Seymour dipole factorisation using the MEPS@NLO prescription. The virtual QCD corrections were provided by the OpenLoops library. The NNPDF3.0nnlo set of PDFs was used, along with the dedicated set of tuned parton-shower parameters developed by the Sherpa authors.

Production of $t\bar{t}$ in association with a vector boson was modelled using the MadGraph5_aMC@NLO 3.5.1 [55] generator at NLO with the NNPDF3.0nlo PDF set. The events were interfaced to Pythia 8.309 [56] using the A14 tune and the NNPDF2.3lo PDF set.

4 Object selection

Selected events are required to contain at least one vertex having at least two associated tracks with $p_T > 500$ MeV, and the primary vertex is chosen to be the reconstructed vertex with the largest Σp_T^2 of its associated tracks.

Electron candidates are reconstructed by matching inner-detector tracks to clusters of energy deposited in the EM calorimeter. Electrons must have $p_T > 27$ GeV and $|\eta| < 2.47$. The associated track must have $|d_0|/\sigma_{d_0} < 5$ and $|z_0| \sin\theta < 0.5$ mm, where d_0 (z_0) is the transverse (longitudinal) impact parameter relative to the primary vertex, σ_{d_0} is the uncertainty in d_0, and θ is the polar angle of the track. Candidates are identified with a likelihood method and must satisfy the 'medium' identification criteria described in Ref. [57]. The likelihood relies on the shape of the EM shower measured in the calorimeter, the quality of the track reconstruction, and the quality of the match between the track and the cluster. To suppress electrons originating from photon conversions, hadron decays, or jets misidentified as electrons, candidates are required to satisfy the Tight_VarRad isolation criteria defined in Ref. [58]. These criteria are based on constraints on the energy deposited in the calorimeter and the sum of the track transverse momenta in a variable-size cone around the electron candidate. The electron energy and reconstruction, identification and trigger efficiencies are calibrated as described in Refs. [58, 59].

Muon candidates are reconstructed in the range $|\eta| < 2.5$ by combining tracks in the inner detector with tracks in the muon spectrometer. All muon candidates must have $p_T > 27$ GeV, $|d_0|/\sigma_{d_0} < 3$, and $|z_0| \sin\theta < 0.5$ mm. The 'medium' quality requirements are used and muons from hadron decays are suppressed by imposing the 'tight' isolation requirement with a variable-size cone as described in Ref. [60].

The muon momentum is calibrated as described in Ref. [61], and the reconstruction efficiency in the simulation is corrected to agree with that measured for muons from $Z \to \mu\mu$ decays in data [60].

Jets are formed using objects from a particle-flow algorithm, which combines energy deposits in the calorimeter with inner detector tracks [62]. The particle-flow objects are combined into jets using the anti-k_t algorithm [63, 64] with a radius parameter R of 0.4. Only jets within the range in the range $|\eta| < 2.5$ and $p_{\mathrm{T}} > 20$ GeV are used for the results presented in this paper. A jet-vertex-tagging technique using a multivariate likelihood [65, 66] is applied to jets with $p_{\mathrm{T}} < 60$ GeV to suppress jets that are not associated with the event's primary vertex. Jets are further calibrated according to in situ measurements of the jet energy scale [67].

The labelling scheme used to define the flavour of a jet in a simulated event is applied by matching reconstructed jets to generator-level b- or c-hadrons with $p_{\mathrm{T}} > 5$ GeV within a cone of size $\Delta R = 0.3$ around the jet axis. Jets that contain a b-hadron are called b-jets. Remaining jets containing a c-hadron are called c-jets. Jets with a hadronically decaying τ-lepton are called τ-jets, and all remaining jets are called light-flavour jets.

The larger mass and longer lifetime of the b-hadron are used to distinguished b-jets from other jets . The b-tagging algorithm studied in this paper is called GN2 and is described in detail in Ref. [13]. GN2 differs from previous taggers used in the ATLAS experiment in that track and jet information is used directly in the training, without running dedicated secondary-vertex reconstruction algorithms. The GN2 tagger uses a single-transformer model [68] with a single discriminant as output. The GN2 tagger is used in discrete intervals defined by the efficiency to tag b-jets in simulated $t\bar{t}$ events [8]: 0–65%, 65–70%, 70–77%, 77–85%, 85–90% and 90–100%. The 90–100% interval is where most of the light-flavour jets are found and is referred to as the untagged bin. Jets with GN2 values that do not lie in this interval are described as tagged.

Significant differences are seen between the simulated (mis)tagging efficiency for different fragmentation models [8]. To account for these differences, simulation-to-simulation SFs are applied to those simulated samples that have a fragmentation model and decay different from the one used to derive the SFs. In the present paper the $t\bar{t}$ simulation (see Section 3) uses Pythia 8 and EvtGen, which is the reference MC fragmentation program for all the measured SFs.

Overlaps between reconstructed objects are removed using a procedure based on the angular separation between different final-state objects. The procedure is the same as the one described in Ref. [69].

The event's missing transverse momentum $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$, whose magnitude is denoted by $p_{\mathrm{T}}^{\mathrm{miss}}$, is computed as the negative vectorial sum of the transverse momenta of leptons, jets and a track-based soft term [70] accounting for the contribution from particles from the primary vertex that are not already included. The jets employed in the $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$ calculation include particle-flow jets and, in addition, jets with $p_{\mathrm{T}} > 30$ GeV and $2.5 < |\eta| < 4.5$, which are formed solely with calorimeter energy clusters.

5 Event selection

The analysis aims to obtain a pure sample of semileptonic $t\bar{t}$ events. Exactly one electron or one muon, denoted by ℓ, is required. The events are also required to have $p_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, and the transverse mass m_{T}

of the lepton and $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$ must satisfy

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}p_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\Delta\phi)} > 40\ \mathrm{GeV},$$

where $\Delta\phi = \phi(\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) - \phi(\ell)$ is the azimuthal angle between the lepton and $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$.

In order to accept events with a high number of jets covering a large range in p_{T}, while reducing the non-$t\bar{t}$ background and the number of jets arising from initial- and final-state QCD radiation (ISR and FSR), requirements are made such that either of the following selections is true:

- the event contains exactly four jets with $p_{\mathrm{T}} > 25$ GeV
- the event contains at least three jets with $p_{\mathrm{T}} > 25$ GeV and exactly one jet with $20 < p_{\mathrm{T}} < 25$ GeV

The first selection accepts ISR/FSR jets at a relatively low rate because it requires exactly four jets with a moderate p_{T} threshold. The second selection allows measurements of events with a jet with p_{T} of 20–25 GeV, while minimising the non-$t\bar{t}$ background, which is more likely to have multiple low-p_{T} jets. In order to improve the statistics at higher p_{T} in the c-jet SF determination, events with more than four jets are allowed if

- the event contains at least five jets with $p_{\mathrm{T}} > 25$ GeV and at least one of these jets has $p_{\mathrm{T}} > 70$ GeV.

The $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$ and the four-momenta of the four highest-p_{T} jets and the lepton are used as inputs to a likelihood-based $t\bar{t}$ event reconstruction algorithm, which minimises deviations of the invariant masses of the top quarks and W bosons from their true values and is described in more detail in Ref. [71]. This algorithm uses a likelihood function to assign the four jets to the $t\bar{t}$ decay topology. In particular, the algorithm assigns one jet to the b-jet from the leptonically decaying top quark, another jet to the b-jet from the hadronically decaying top quark and the remaining two jets to the jets that come from the hadronic W boson decay. The jet assignment does not use any b-tagging information. The following notation is used: the jets that are assigned as the decay products of the W boson are referred to as W-jets and the remaining two jets are referred to as the leptonic top-jet and hadronic top-jet.

Among all the possible four-jet permutations, the one with the highest likelihood is selected. The logarithm of the likelihood is required to be greater than −48 [9] so as to increase the fraction of events where the top-quark decay products are correctly assigned.

6 Simultaneous efficiency measurements of b- and c-jets in $t\bar{t}$ events

6.1 Analysis strategy

The b-jet efficiency SFs $b^t(i)$ and c-jet mistagging efficiency SFs $c^t(i)$ are determined in jet-p_{T} intervals i, with boundaries at 20, 40, 65, 140 and 250 GeV, and tagging intervals t, where $t = 0$ is the untagged bin (90−100% interval), $t = 1$ is the 85−90% interval and so on until $t = 5$, which corresponds to the 0−65% interval. In all events the hadronic top-jet is required to be tagged in the tightest (0−65%) interval, in order to reduce both the rate of top-quark decays with wrongly assigned jets and the non-$t\bar{t}$ background. The light-flavour jet SFs $l^t(i)$ are determined independently of the analysis presented here, but using the same dataset and tagger, using jets produced in association with a Z boson and a method similar to that described in Ref. [10]; they are applied in all distributions shown in this paper. The method described below is for the 'pseudo-continuous' calibration where the efficiency is defined as the fraction of jets that have a GN2 discriminant value that lies between the boundaries of each tagging interval, i.e. above the 65% boundary (as illustrated in Figure 1), between the 70% and 65% boundaries, etc. Two different event selections targeting $b^t(i)$ and $c^t(i)$ are employed, with some events common to both, as described below. All parameters of interest are determined in a single fit by minimising a total χ^2 defined as

$$\chi^2 = \chi_b^2 + \chi_c^2 + \chi_\epsilon^2, \tag{1}$$

with the terms defined below.

The $b^t(i)$ SFs are mainly constrained by comparing the fraction of events where the leptonic top-jet lies within each of the GN2 discriminant intervals with the expectation from MC simulation. Both W-jets are required to be untagged to reduce the rate of top-quark decay-product misidentification. However, even after this selection there remains a sizeable fraction of light-flavour jets whose normalisation is not described well by the simulation, as can be seen in Figure 1(a). In order to normalise the light-flavour jet contribution, the untagged bin is divided into four intervals according to the invariant mass of the charged lepton and leptonic top-jet, m_{jl}, with boundaries at 60, 100 and 150 GeV, as shown in Figure 2(a). The quantity m_{jl} is chosen because it offers discrimination between light-flavour jets and b-jets and is uncorrelated with the GN2 discriminant. The intervals in m_{jl} are labelled with an index s, such that $s = -3, -2, -1, 0$ for $t = 0$ and $s = t$ for $t > 0$. The number of data events in each bin is denoted by $N^s_{\text{data}}(i)$.

The number of simulated 'signal' events in each bin, $N^s_B(i)$, corresponds to those events where the leptonic top-jet is a b-jet. There are two sources of 'background' events, defined as events where the leptonic top-jet is either a light-flavour jet or c-jet, contributing $N^s_L(i)$ or $N^s_C(i)$ events respectively. The relative normalisation $L(i)$ of the light-flavour jet contribution is allowed to vary in the fit in each jet-p_{T} bin. The relative contribution from c-jets is small and set to the expectation from simulation multiplied by $c^t(i)$. The overall normalisation of events, $k_b(i)$, in each jet-p_{T} bin is also allowed to vary in the fit.

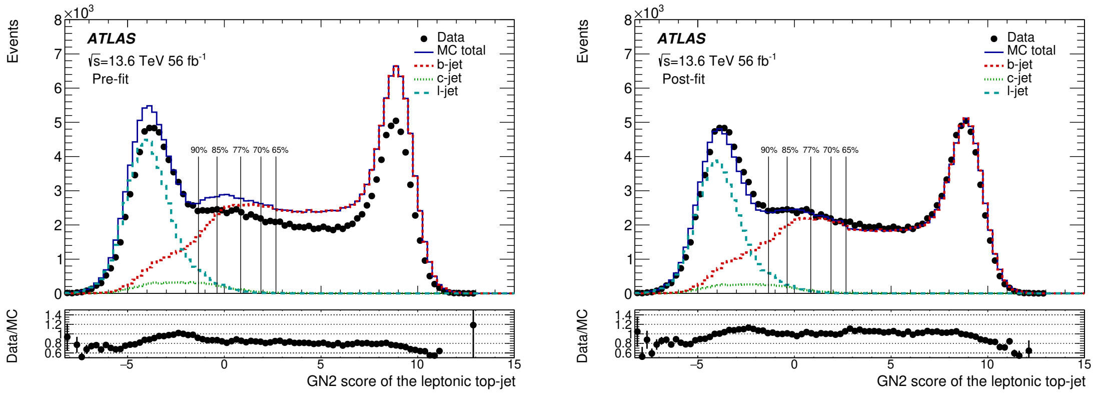
Some events are common to the χ_b^2 and χ_c^2 determinations, specifically those where both W-jets are untagged and the leptonic top-jet lies within the 0–65% tagging interval. The statistical correlation between the b-jet and c-jet SFs is therefore not precisely determined in the method presented above. However, the fit uses different properties of the events in common, so the statistical correlation is expected to be much smaller than the systematic correlation.

The χ_b^2 contribution is given by

$$\chi_b^2 = \sum_{i=1}^{4} \sum_{s=-3}^{5} \left[N^s_{\text{data}}(i) - k_b(i) \left(L(i) l^t(i) N^s_L(i) + c^t(i) N^s_C(i) + b^t(i) N^s_B(i) \right) \right]^2 / N^s_{\text{data}}(i).$$

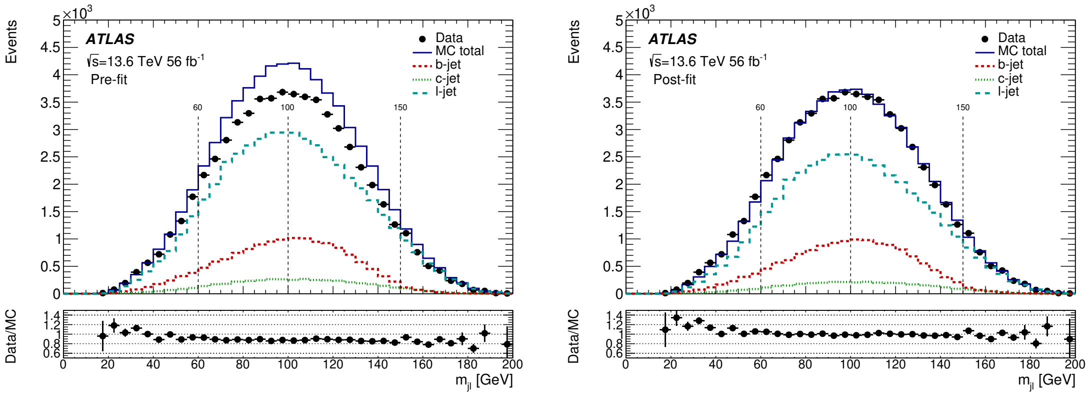
The $c^t(i)$ SFs are mainly constrained by comparing the fraction of events where one of the W-jets lies within each of the GN2 discriminant intervals with the expectation from MC simulation. To simplify the fit, events where both W-jets are tagged, making up 0.7% of the total number of events, are discarded. In order to reduce the number of wrongly assigned b-jets, both top-jets must be tagged with the tightest (0–65%) requirement. The GN2 discriminant of the tagged W-jet is shown in Figure 3(a). It can be seen that the expectation from simulation is dominated by c-jets, with sizeable contributions from light-flavour jets at low GN2 values and b-jets at high GN2 values.

Events are classified according to the p_{T} bin of the tagged W-jet (labelled i) and the p_{T} bin of the untagged W-jet (labelled j). In events where both W-jets are untagged, the higher-p_{T} jet is denoted by j, so $j \geq i$.



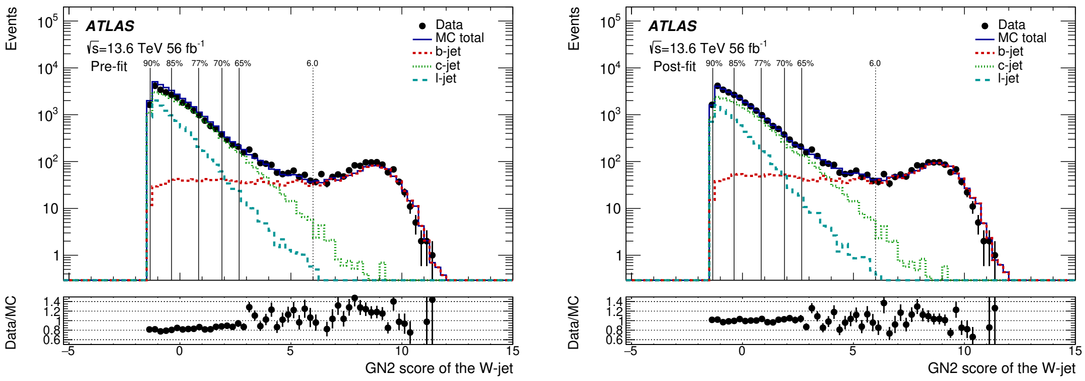
(a) Pre-fit (b) Post-fit

Figure 1: Distributions of the GN2 discriminant of the leptonic top-jet for events where the hadronic top-jet is tagged in the 0−65% interval and both W-jets are untagged. The simulation is split according to the flavour of the jet. The normalisations and b-jet tagging and c-jet mistagging efficiency scale factors, determined in the fit described in this section, are not applied to the simulation in (a) but are applied in (b). The distributions are shown without systematic errors. The dashed vertical lines demarcate the tagging intervals in which the measurements of the (mis)tagging efficiency scale factors are made.



(a) Pre-fit (b) Post-fit

Figure 2: Distributions of the invariant mass of the charged lepton and leptonic top-jet for events where the hadronic top-jet is tagged in the 0–65% interval and the leptonic top-jet and both W-jets are untagged. The simulation is split according to the flavour of the jet. The normalisations and b-jet tagging and c-jet mistagging efficiency scale factors, determined in the fit described in this section, are not applied to the simulation in (a) but are applied in (b). The distributions are shown without systematic errors. The dashed vertical lines demarcate the intervals into which the events are separated.



(a) Pre-fit

(b) Post-fit

Figure 3: Distributions of the GN2 discriminant of the tagged W-jet for events where the other W-jet is untagged and both top-jets are tagged with a value in the 0−65% interval. The simulation is split according to the flavour of the jet. The normalisations and b-jet tagging and c-jet mistagging efficiency scale factors, determined in the fit described in this section, are not applied to the simulation in (a) but are applied in (b). The distributions are shown without systematic errors. The solid vertical lines demarcate the tagging intervals in which the measurements of the (mis)tagging efficiency scale factors are made. The dashed vertical line denotes the extra splitting in the tightest tagging interval, which is used to help determine the background normalisation.

Contributions from b-jets can arise from misidentified top-jets and also $t\bar{t}$ production with additional b-jets. These contributions may not be well described by simulation, so the relative normalisation is allowed to vary with a normalisation factor B. To determine B, the bin with the 0–65% tagging interval ($t = 5$) is split into two for GN2 discriminant values above or below 6. An index u is used to label events such that $u = t$ for $t < 5$ and $u = 5, 6$ for $t = 5$. The relative fraction of b-jets in the two regions of the 0–65% tagging interval is adjusted in simulation to that observed in data by examining the fraction for the hadronic top-jet. As can be seen in Figure 4, this region is dominated by b-jets. The fraction is evaluated in each of the four jet-p_{T} intervals and the mean value is taken as the central value. The uncertainty is taken as the largest deviation from the mean in any of the jet-p_{T} intervals. The resulting correction either decreases the event weight in the simulation by $(2.4 \pm 1.9)\%$ or increases it by $(5.1 \pm 1.9)\%$ depending on whether the GN2 discriminant is above or below 6. This correction is only applied to the tagged W-jet and not to the top-jets.

The number of data events in each bin is $N^u_{\mathrm{data}}(i, j)$ and the expected numbers of light-flavour jet, c-jet and b-jet events are $N^u_L(i, j)$, $N^u_C(i, j)$ and $N^u_B(i, j)$ respectively. The overall normalisation of events, $k_W(i, j)$, in each bin is also allowed to vary in the fit.

The $c^t(i)$ SFs are determined by minimising the partial χ^2 defined as

$$\chi^2_c = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{u=0}^{6}\left[N^u_{\mathrm{data}}(i, j) - k_W(i, j)l^0(j)\left(l^t(i)N^u_L(i, j) + c^t(i)N^u_C(i, j) + Bb^t(i)N^u_B(i, j)\right)\right]^2 / N^u_{\mathrm{data}}(i, j).$$

It should be noted that the SF $l^0(j)$ is only applied if the untagged W-jet is a light-flavour jet; to simplify the fit, this SF is ignored if the untagged jet is a b-jet or c-jet.

The sum of the efficiencies for the untagged bin and all tagged bins is constrained to unity by including in the total χ^2 the following terms, which have an arbitrary tolerance of 1%:

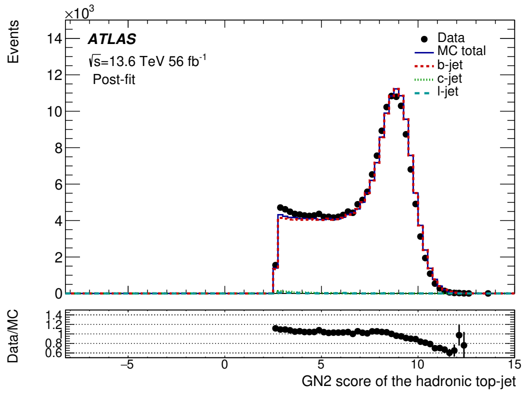


Figure 4: Distribution of the GN2 discriminant for the 0–65% tagging interval for the hadronic top-jet for events where both W-jets are untagged. The simulation is split according to the flavour of the jet. The normalisations and b-jet tagging and c-jet mistagging efficiency scale factors, determined in the fit described in this section, are applied to the simulation. The distributions are shown without systematic errors.

$$\chi^2_\epsilon = \sum_{i=1}^{4}\left(1 - \sum_{t=0}^{5} b^t(i)\epsilon^t_{b\mathrm{MC}}(i)\right)^2 /(1\%)^2 + \sum_{i=1}^{4}\left(1 - \sum_{t=0}^{5} c^t(i)\epsilon^t_{c\mathrm{MC}}(i)\right)^2 /(1\%)^2,$$

where $\epsilon^t_{b\mathrm{MC}}(i)$ and $\epsilon^t_{c\mathrm{MC}}(i)$ are the MC efficiencies in each tag and p_T bin for b-jets and c-jets respectively. With this constraint the maximum deviation of the sum of the b-jet (c-jet) efficiencies from unity is 0.12% (0.017%) for any p_T interval, which is much smaller than the total uncertainty on any of the measured efficiencies.

The SFs $c^t(i)$ and $b^t(i)$ and the normalisation parameters $k_b(i)$, $k_W(i, j)$, $L(i)$, B are free parameters in the fit.

The b-jet efficiency SFs were also measured in $t\bar{t}$ dileptonic events as reported in Ref. [72]. A relatively simple way of combining these SFs with those measured in the present analysis is to use the $t\bar{t}$ dileptonic measurements, $b^t_\mathrm{DL}(i)$ with statistical uncertainty $\Delta b^t_\mathrm{DL}(i)$, as a prior. This is done by adding

$$\chi^2_\mathrm{DL} = \sum_{i=1}^{4}\sum_{t=0}^{5}[\,(b^t_\mathrm{DL}(i) - b^t(i))/\Delta b^t_\mathrm{DL}(i)\,]^2$$

to the χ^2 defined in Eq. (1).

6.2 Systematic uncertainties

Several sources of experimental and MC modelling systematic uncertainty affecting the efficiency SFs are considered. The uncertainty from each source is evaluated by and repeating the fit after making the corresponding change to the MC model to produce new templates for the semileptonic or shifting the dileptonic data points for the combined fit. Each systematic error source is thus correlated between the tagging and jet-p_T intervals, between bottom tagging and charm mistagging SFs and between the semileptonic and dileptonic analyses. The total systematic uncertainty for each interval is evaluated by adding the individual uncertainties in quadrature. The uncertainties of the b-jet SFs are largest in the 90−100% interval, where the light-flavour jet background is the largest, while the c-jet SF uncertainties are largest in the 0−65% interval, where the b-jet background is the largest.

The uncertainties in the jet energy scale and resolution are derived by combining information from data and simulation [67], resulting in many independent model variations. In this analysis, 11 such variations are found to have a significant effect: the largest leads to changes of up to 15% (8%) in the b-jet (c-jet) SFs. The uncertainty due to pile-up modelling [66] leads to changes of up to 5% (11%) in the b-jet (c-jet) SFs.

The uncertainties in the light-flavour jet mistagging SFs are accounted for by changing the SFs by each component of the total uncertainty, and where appropriate including the correlation between this and the uncertainty used in the c-jet SF determination. The most important uncorrelated uncertainties originate from changing the model used for the simulation of Z+jets, giving uncertainties of up to 1% (5%), and the MC sample sizes, giving uncertainties of up to 2% (5%) in the b-jet (c-jet) SFs [10]. The uncertainty in the b-jet fraction reweighting in the tightest tagging interval, described in Section 6.1, leads to a maximum uncertainty of 2% in the c-jet SF.

Uncertainties from the modelling of $t\bar{t}$ are estimated by replacing the nominal MC sample by alternative MC samples. The uncertainty due to the choice of parton shower and hadronisation model is estimated by replacing the standard Pythia 8 model with Herwig. This is known to have a large effect in the differential distributions [73] and it is the largest source of uncertainty in this analysis, leading to changes of up to 26% (13%) in the b-jet (c-jet) SFs.

The uncertainty from the modelling of ISR/FSR is assessed by increasing the radiation by doubling the h_{damp} parameter [35]. The resulting uncertainty in the b-jet (c-jet) SFs is at most 18% (21%). Finally, the effect of the matrix-element matching uncertainty on the b-jet (c-jet) SFs is at most 14% (13%).

Uncertainties in the normalisation of backgrounds other than $t\bar{t}$ are accounted for by scaling the MC expectation by ±25%, which is approximately the maximum difference seen between data and simulation in dedicated measurements [74, 75]. The resulting uncertainty in the b-jet (c-jet) SFs is at most 13% (1%).

6.3 Results

The measured b-jet pseudo-continuous tagging efficiency SFs together with the total, statistical and systematic uncertainties are listed in Table 1 and shown in Figure 5 for the six tagging intervals. The fitted normalisation factors $k_b(i)$ lie in the range 0.75 to 0.83, and the fitted light-flavour jet background normalisation factors $L(i)$ lie between 0.97 and 1.16. The contributions to the systematic uncertainty are listed in Table 2. It can be seen that the largest uncertainties arise from $t\bar{t}$ modelling and jet reconstruction and are largest in the untagged interval, where the light-flavour jet background is large. The SFs do not have a strong jet-p_{T} dependence. The total uncertainty varies from 2% to 44% and is dominated by the systematic uncertainty except in the highest p_{T} bin.

Also shown in Figure 5 are the measurements of the $t\bar{t}$ dileptonic b-jet tagging efficiency SFs [72]. It can be seen that the two measurements are in good agreement. The combination of the two measurements, obtained using the method described in Section 6.1, is also shown. As is also seen in the individual measurements, there is no clear p_{T} dependence, but the SF differs from unity in some tagging intervals.

The measured c-jet pseudo-continuous mistagging efficiency SFs together with the total, statistical and systematic uncertainties are listed in Table 3 and shown in Figure 6 for the six tagging intervals. The fitted

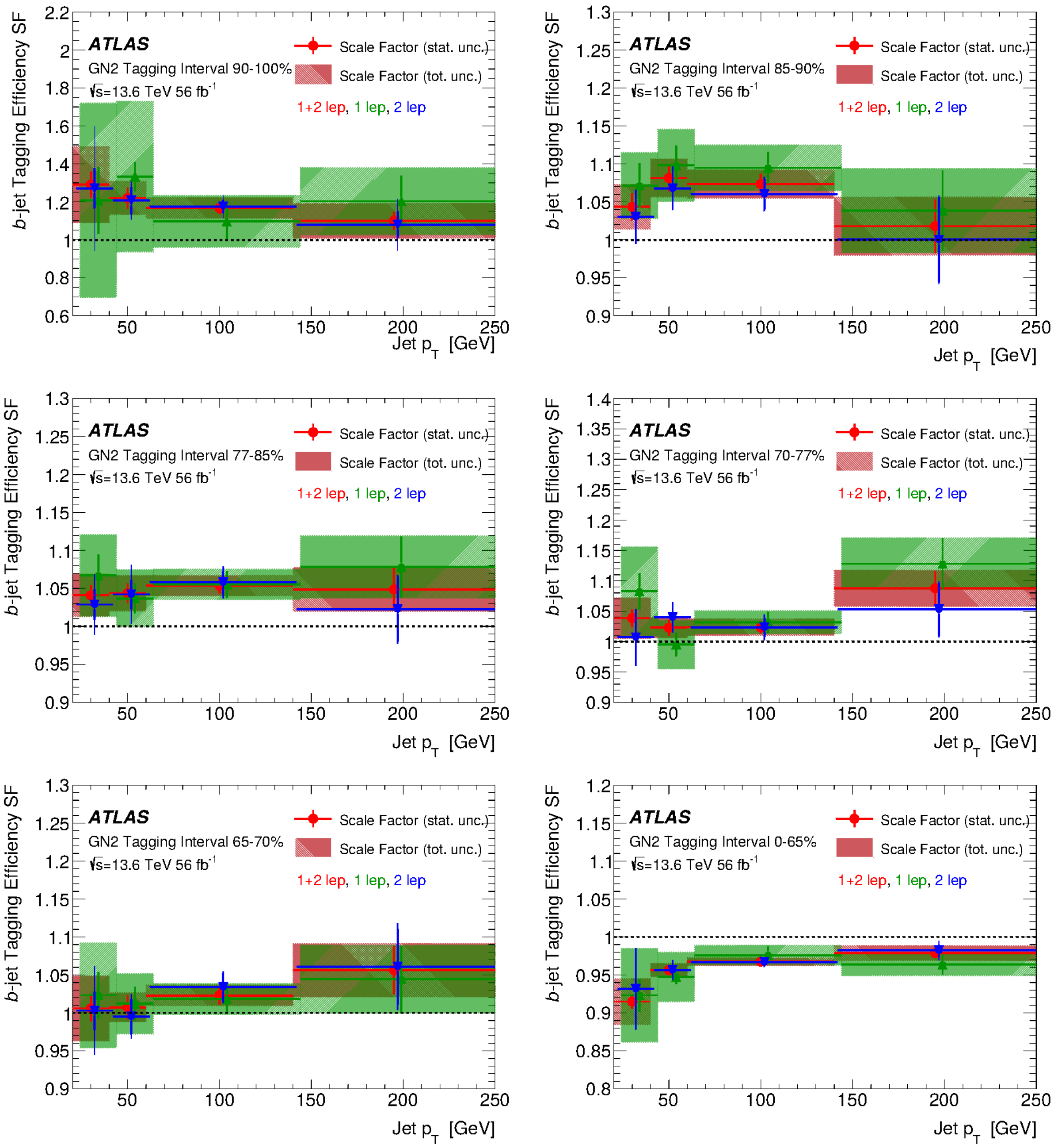


Figure 5: The b-jet pseudo-continuous tagging efficiency SFs measured in semileptonic (1 lep) $t\bar{t}$ events shown as a function of jet p_{T} for the six tagging intervals. Also shown are the measurements made in dileptonic (2 lep) $t\bar{t}$ events and the combination (1+2 lep). The SFs are shown for the PYTHIA 8 + EVTGEN fragmentation model.

normalisation factors $k_W(i, j)$ lie in the range 0.75 to 0.84 and the b-jet background normalisation factor is $B = 1.56 \pm 0.05\,(\text{stat.}) \pm 0.21\,(\text{syst.})$. The contributions to the systematic uncertainty are listed in Table 4. The SFs do not have a strong jet-p_T dependence. In the tightest tagging interval the efficiency is higher in data than in MC simulation. The total uncertainty varies from 2% to 41%.

Table 1: The measured b-jet pseudo-continuous tagging efficiency SFs measured in semileptonic $t\bar{t}$ events, listed with the total, relative statistical and relative systematic uncertainties for each tagging and jet-p_T interval. The SFs are listed for the Pythia 8 + EvtGen fragmentation model.

			SF uncertainty		
Tagging interval	Jet p_T range [GeV]	SF	Total	Stat.	Syst.
90–100%	20–40	1.206	43%	14%	41%
90–100%	40–60	1.335	31%	13%	28%
90–100%	60–140	1.096	15%	8.5%	12%
90–100%	140–250	1.200	14%	11%	8.3%
85–90%	20–40	1.068	4.8%	3.0%	3.8%
85–90%	40–60	1.092	5.1%	2.8%	4.3%
85–90%	60–140	1.095	2.4%	2.0%	1.2%
85–90%	140–250	1.035	4.8%	4.6%	1.3%
77–85%	20–40	1.063	6.4%	3.0%	5.7%
77–85%	40–60	1.031	5.1%	2.6%	4.4%
77–85%	60–140	1.055	2.5%	1.8%	1.7%
77–85%	140–250	1.075	4.0%	3.8%	1.2%
70–77%	20–40	1.079	8.1%	3.2%	7.5%
70–77%	40–60	0.990	5.1%	2.7%	4.4%
70–77%	60–140	1.032	2.1%	1.8%	1.1%
70–77%	140–250	1.125	3.9%	3.8%	0.9%
65–70%	20–40	1.020	8.7%	3.4%	8.0%
65–70%	40–60	1.007	5.1%	2.9%	4.2%
65–70%	60–140	1.018	2.3%	2.0%	1.2%
65–70%	140–250	1.041	4.5%	4.3%	1.1%
0–65%	20–40	0.920	8.5%	2.8%	8.0%
0–65%	40–60	0.942	4.6%	2.1%	4.0%
0–65%	60–140	0.976	1.7%	1.3%	1.1%
0–65%	140–250	0.961	1.7%	1.5%	0.8%

The corresponding measured b-tagging efficiencies and c-mistagging efficiencies, shown in Figure 7, are obtained by multiplying the tagging efficiencies from simulation by the SFs. It can be seen that the b-tagging efficiency is larger than the c-mistagging efficiency in the three tightest tagging intervals, whereas the c-mistagging efficiency is larger in the three loosest intervals.

Post-fit plots of the GN2 discriminant are shown in Figure 1(b) and Figure 3(b) after applying the fitted normalisation and c-jet and b-jet SFs. It can be seen that the fit greatly improves the description. In particular the normalisation of the light-flavour jet background is reasonable even though these distributions are not directly used to constrain it. A post-fit plot of the m_{jl} distribution of the charged lepton and leptonic top-jet, displayed in Figure 2(b), shows good agreement between data and simulation, giving further confidence in the normalisation of the light-flavour jet background.

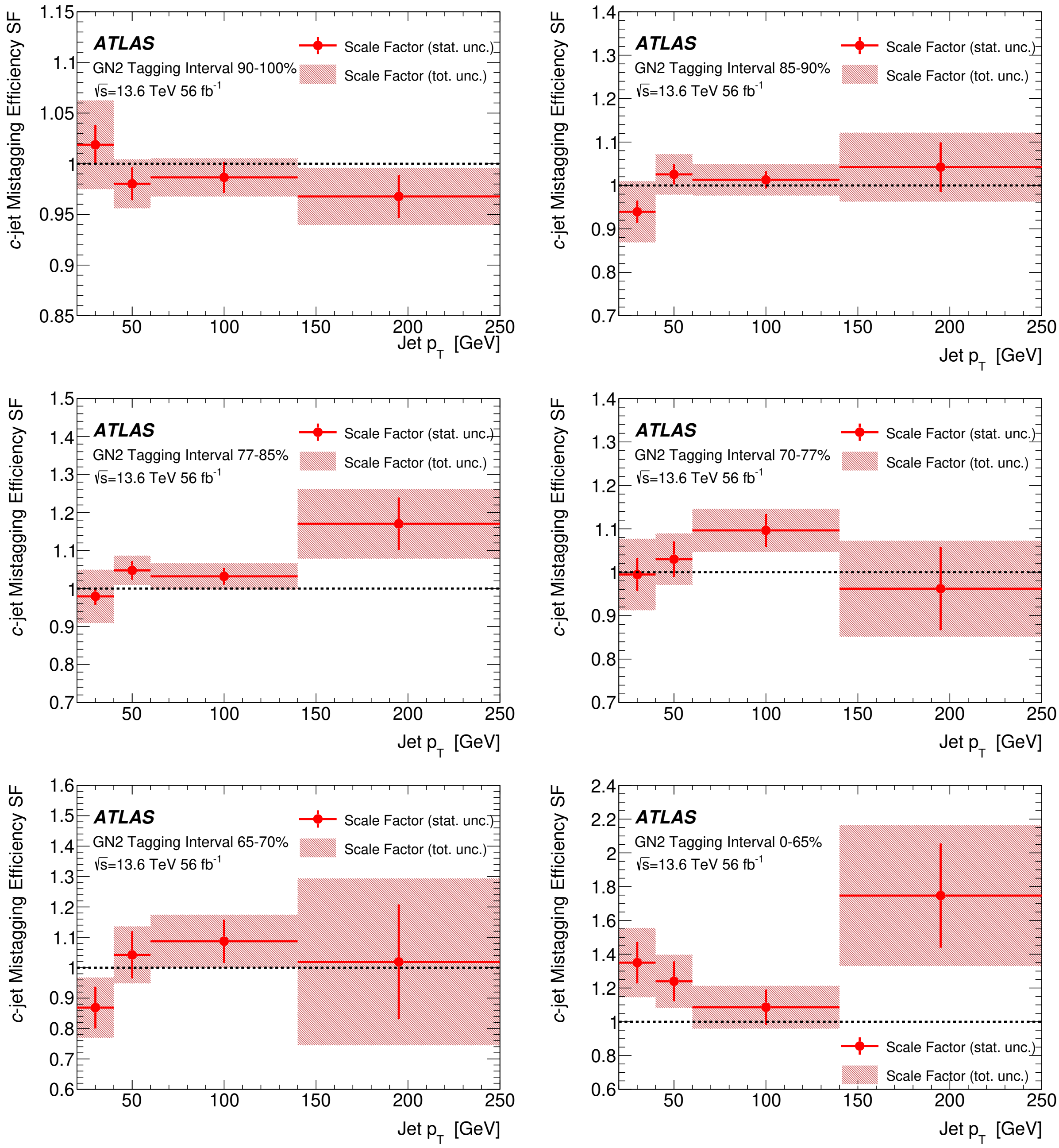


Figure 6: The c-jet pseudo-continuous mistagging efficiency SFs measured in semileptonic $t\bar{t}$ events shown as a function of jet p_{T} for the six tagging intervals. The SFs are shown for the Pythia 8 + EvtGen fragmentation model.

Table 2: The contributions to the b-jet pseudo-continuous tagging efficiency SF systematic uncertainties measured in semileptonic $t\bar{t}$ events, listed as a function of jet p_{T} for six tagging intervals. Included are the relative uncertainties related to the $t\bar{t}$ modelling, the jets and $p_{\mathrm{T}}^{\mathrm{miss}}$, the light-flavour jet SF and all other sources.

		SF systematic uncertainty			
Tagging interval	Jet p_{T} range [GeV]	$t\bar{t}$ mod.	Jet & $p_{\mathrm{T}}^{\mathrm{miss}}$	Light tag	Other
90–100%	20–40	32%	22%	2.4%	13%
90–100%	40–60	22%	17%	1.8%	8.1%
90–100%	60–140	9.1%	4.1%	2.7%	5.5%
90–100%	140–250	5.6%	5.8%	1.3%	1.4%
85–90%	20–40	2.7%	1.6%	0.9%	1.9%
85–90%	40–60	2.1%	3.5%	0.5%	1.2%
85–90%	60–140	0.9%	0.6%	0.0%	0.6%
85–90%	140–250	1.0%	0.7%	0.0%	0.5%
77–85%	20–40	4.4%	2.6%	0.2%	2.4%
77–85%	40–60	3.6%	2.2%	0.2%	1.2%
77–85%	60–140	1.5%	0.5%	0.2%	0.6%
77–85%	140–250	1.1%	0.5%	0.0%	0.2%
70–77%	20–40	5.5%	4.5%	0.4%	2.4%
70–77%	40–60	3.2%	2.7%	0.2%	1.2%
70–77%	60–140	0.9%	0.4%	0.2%	0.5%
70–77%	140–250	0.6%	0.6%	0.0%	0.1%
65–70%	20–40	6.5%	3.9%	0.6%	2.4%
65–70%	40–60	3.3%	2.3%	0.2%	1.1%
65–70%	60–140	0.9%	0.5%	0.2%	0.5%
65–70%	140–250	1.0%	0.5%	0.0%	0.1%
0–65%	20–40	6.4%	4.2%	0.6%	2.3%
0–65%	40–60	3.1%	2.4%	0.2%	1.1%
0–65%	60–140	0.9%	0.5%	0.3%	0.5%
0–65%	140–250	0.6%	0.5%	0.0%	0.1%

Table 3: The measured c-jet pseudo-continuous mistagging efficiency SFs measured in semileptonic $t\bar{t}$ events, listed with the total, relative statistical and relative systematic uncertainties for each tagging and jet-p_T interval. The SFs are listed for the Pythia 8 + EvtGen fragmentation model.

			SF uncertainty		
Tagging interval	Jet p_T range [GeV]	SF	Total	Stat.	Syst.
90–100%	20–40	1.019	3.9%	1.9%	3.4%
90–100%	40–60	0.980	2.7%	1.7%	2.1%
90–100%	60–140	0.987	1.9%	1.6%	1.2%
90–100%	140–250	0.968	3.0%	2.2%	2.0%
85–90%	20–40	0.939	7.1%	2.7%	6.5%
85–90%	40–60	1.026	5.2%	2.3%	4.7%
85–90%	60–140	1.013	3.7%	2.0%	3.1%
85–90%	140–250	1.042	9.5%	5.7%	7.7%
77–85%	20–40	0.979	6.1%	2.4%	5.6%
77–85%	40–60	1.048	4.5%	2.4%	3.7%
77–85%	60–140	1.032	4.1%	2.1%	3.5%
77–85%	140–250	1.170	7.3%	6.1%	4.1%
70–77%	20–40	0.995	9.8%	3.8%	9.0%
70–77%	40–60	1.030	6.2%	4.1%	4.7%
70–77%	60–140	1.096	4.8%	3.5%	3.3%
70–77%	140–250	0.962	12%	10%	6.4%
65–70%	20–40	0.868	12%	8.1%	9.2%
65–70%	40–60	1.042	9.5%	7.6%	5.7%
65–70%	60–140	1.086	15%	6.6%	14%
65–70%	140–250	1.019	32%	18.9%	25%
0–65%	20–40	1.342	17%	9.6%	14%
0–65%	40–60	1.234	17%	11%	12%
0–65%	60–140	1.074	12%	10%	6.3%
0–65%	140–250	1.740	32%	18%	26%

Table 4: The contributions to the c-jet pseudo-continuous mistagging efficiency SF systematic uncertainties measured in semileptonic $t\bar{t}$ events, listed as a function of jet p_T for six tagging intervals. Included are the relative uncertainties related to the $t\bar{t}$ modelling, the jets and p_T^{miss}, the light-flavour jet SF, the b-jet SF, and all other sources.

		SF systematic uncertainty				
Tagging interval	Jet p_T range [GeV]	$t\bar{t}$ mod.	Jet & p_T^{miss}	Light tag	b-tag	Other
90–100%	20–40	1.3%	2.5%	1.9%	0.0%	0.0%
90–100%	40–60	1.2%	1.3%	1.0%	0.0%	0.0%
90–100%	60–140	0.8%	0.5%	0.7%	0.0%	0.0%
90–100%	140–250	1.7%	0.5%	0.8%	0.0%	0.3%
85–90%	20–40	1.9%	4.8%	4.0%	0.0%	0.3%
85–90%	40–60	2.9%	3.0%	2.1%	0.0%	0.5%
85–90%	60–140	1.9%	1.7%	1.8%	0.0%	0.0%
85–90%	140–250	6.8%	1.9%	2.4%	0.0%	1.8%
77–85%	20–40	2.3%	4.2%	3.0%	0.0%	0.0%
77–85%	40–60	2.9%	1.7%	1.6%	0.0%	0.0%
77–85%	60–140	2.8%	1.6%	1.3%	0.0%	0.0%
77–85%	140–250	3.4%	1.3%	1.6%	0.0%	0.7%
70–77%	20–40	7.3%	3.3%	4.1%	0.1%	0.3%
70–77%	40–60	2.8%	2.8%	2.5%	0.0%	0.0%
70–77%	60–140	2.3%	0.9%	2.1%	0.0%	0.4%
70–77%	140–250	5.6%	1.6%	2.5%	0.0%	0.0%
65–70%	20–40	6.7%	4.3%	4.3%	0.3%	1.6%
65–70%	40–60	3.3%	2.8%	2.8%	0.2%	2.5%
65–70%	60–140	13%	1.5%	3.6%	0.2%	1.7%
65–70%	140–250	18%	12%	8.1%	0.2%	11%
0–65%	20–40	9.3%	9.3%	2.5%	1.8%	3.3%
0–65%	40–60	9.4%	7.2%	1.8%	1.9%	0.9%
0–65%	60–140	2.6%	3.2%	4.3%	2.0%	0.7%
0–65%	140–250	24%	8.5%	2.5%	1.1%	6.0%

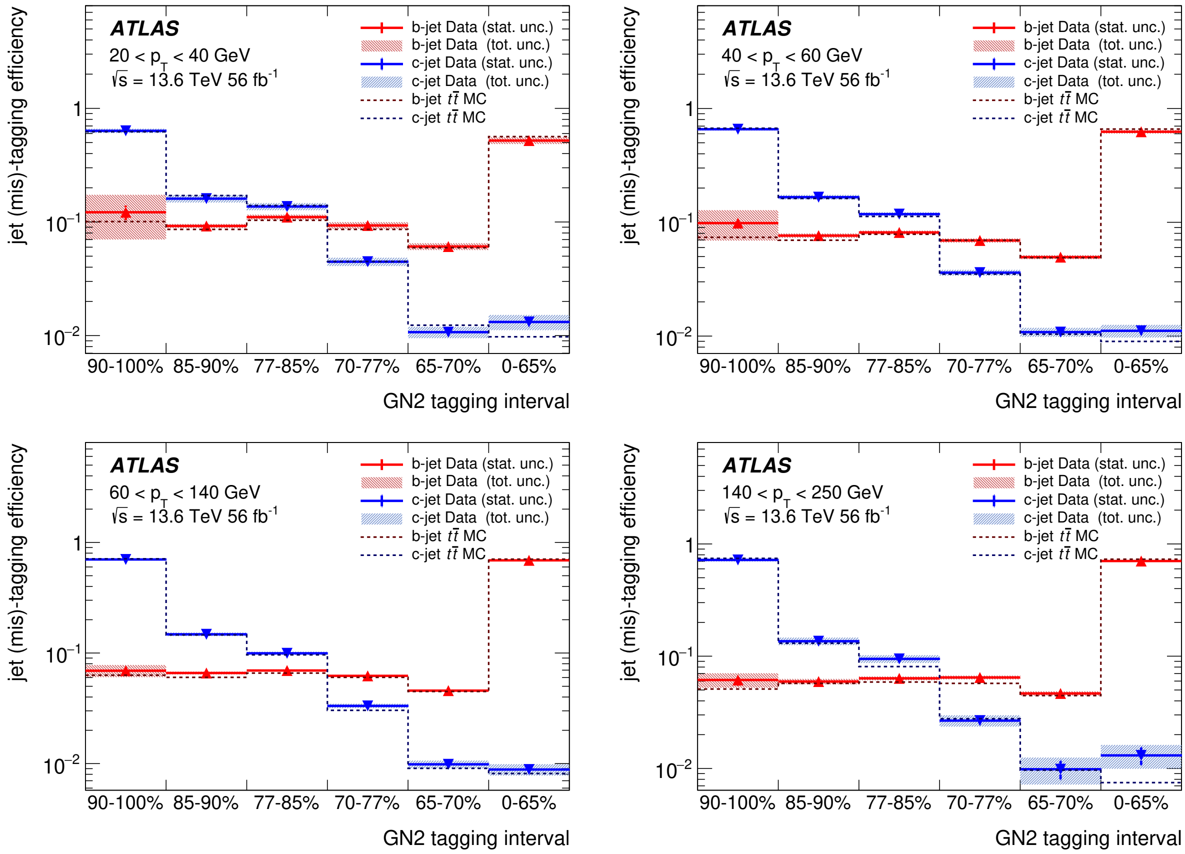


Figure 7: The b-jet (c-jet) pseudo-continuous (mis)tagging efficiencies measured in semileptonic $t\bar{t}$ events shown as points as a function of tagging interval for the four jet-p_{T} ranges. Included in the plots are the corresponding MC efficiencies when using the Pythia 8 + EvtGen fragmentation model.

7 Conclusion

Simultaneous measurements of the b-jet tagging and c-jet mistagging efficiencies of the ATLAS GN2 b-tagging algorithm are presented for the first time. The measurements use semileptonic $t\bar{t}$ events selected from 56 fb^{-1} of $\sqrt{s}$ = 13.6 TeV pp collision data collected with the ATLAS detector at the LHC during 2022 and 2023. The efficiencies were measured as a function of jet p_{T} in the range 20–250 GeV, with boundaries corresponding to 65%, 70%, 77%, 85% and 90% efficiency to tag b-jets in simulated $t\bar{t}$ events. The measured b-jet tagging efficiencies have a total uncertainty of less than 2% for jet $p_{\mathrm{T}} > 60$ GeV in the tightest tagging interval. Several c-jet tagging efficiency measurements have a precision of better than 5%. These are found in various jet p_{T} intervals in the four loosest tagging intervals.

Good agreement is observed between the measured b-jet efficiencies and those obtained with an independent measurement using dileptonic $t\bar{t}$ events. A combination of the two measurements is also presented.

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