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Calibration of light-flavour jet b-tagging rates on ATLAS data at $\sqrt{s} = 13$ TeV

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A variety of algorithms have been developed to identify jets originating from b-quark hadronization within the ATLAS experiment at the Large Hadron Collider. We describe the measurement of the false positive rate of the algorithm most commonly used in the LHC Run 2 ATLAS analyses, i.e. the misidentification rate of jets containing no b- nor c-hadrons. The measurement is based on the full data sample collected at a centre-of-mass energy of $\sqrt{s} = 13$ TeV by the ATLAS detector during the year 2015 and 2016 and is performed in various ranges of jet transverse momenta and pseudorapidities. The final data sample used to extract the results is enriched in jets originating from light-flavour quark and gluon hadronization with the application of a dedicated algorithm reversing some of the criteria used in the nominal identification algorithm. The results are compared to the false positive rate predicted by the nominal ATLAS simulation in order to calibrate them.

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1. Introduction

The identification of jets originating from the b-quark hadronization (b-tagging) is an important element of a number of prominent analyses performed with the ATLAS detector [1] at the Large Hadron Collider (LHC): Standard Model measurements aiming to constrain the heavy-flavour (HF) parton density functions [2], studies of the top quark [3] and the Higgs-boson [4, 5], exploration of New Physics scenarios [6, 7].

The b-tagging of a jet relies on the property of the b-hadrons to have long lifetime τ ($\tau \sim 1.5$ ps, corresponding to a proper decay length of about $c\tau \sim 450$ μm) and large mass, resulting in the production of tracks with non-zero impact parameters, secondary decay vertices and a large multiplicity of decay products inside the jet cone. These observables are reconstructed with the help of the charged-particle tracking capability of the ATLAS inner detector [8]. The information is then combined using a multi-variate algorithm able to enhance the discrimination of a jet containing b-hadrons (b-jet) with respect to one containing only c-hadrons (c-jet) or one containing none of them (LF-jet, LF standing for light-flavour). Specific selections on the output weight distribution of a given b-tagging algorithm are called working points (WP) and defined as a function of the average efficiency of tagging a b-jet as measured in a $t\bar{t}$ simulated sample [9]. The algorithm most commonly used in the Run 2 ATLAS analyses is called MV2. The 2016 version of MV2, which is the one considered in this study, is trained with a background sample including 7% of c-jets and 93% of LF-jets. It is denoted MV2c10 in the following.

The performance of a b-tagging algorithm is characterised by the probability of tagging a b-jet (ε_b) and the probabilities of mistakenly tagging as a b-jet a c-jet (ε_c) or a LF-jet (ε_l), referred to as "mistag rates" in the following. Ideally, Monte Carlo (MC) simulations including the various quark flavours could be used to evaluate the b-tagging performance. However, additional calibration is often needed to account for differences between data and simulation, originating for instance from an imperfect description of the inner detector material in the simulation. In practice, each working point of the algorithm is calibrated as a function of the jet transverse momentum ($p_{\mathrm{T}}^{\mathrm{jet}}$) and absolute pseudorapidity ($|\eta^{\mathrm{jet}}|$).[1] This document presents the measurements of the LF-jet mistag rate in ATLAS data recorded at $\sqrt{s} = 13$ TeV for the MV2c10 working points listed in Table 1 [10].

WP	Cut value X	$\varepsilon_b^{\mathrm{MC}}$	c-jet rejection	LF-jet rejection
85%	0.18	85%	3	34
77%	0.65	77%	6	134

Table 1: b-tagging MV2c10 working points considered in this document. Each WP is defined by a cut value X on the MV2c10 output weight distribution (MV2c10 Output $> X$, MV2c10 Output $\in [-1, 1]$). The resulting b-tagging efficiency ($\varepsilon_b^{\mathrm{MC}}$), c- and LF-jet rejection rates ($1/\varepsilon_c$, $1/\varepsilon_l$) as measured in a $t\bar{t}$ simulated sample are also shown.

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

2. The negative tag method

In this analysis, the full proton-proton collision data sample recorded by the ATLAS detector during the year 2015 and 2016 is used. Data were recorded if at least one hadronic jet was present in the event.[2] Given the very high rates of such events at the LHC, only a fraction of events satisfying this requirement were recorded at low and medium $p_{\mathrm{T}}^{\mathrm{jet}}$ due to computation power and data storage limitations. The integrated luminosity of the data sample therefore depends on $p_{\mathrm{T}}^{\mathrm{jet}}$ and ranges from 0.02 pb^{-1} (20 GeV $< p_{\mathrm{T}}^{\mathrm{jet}} <$ 60 GeV) to 36.1 fb^{-1} ($p_{\mathrm{T}}^{\mathrm{jet}} >$ 500 GeV).

Events with at least two jets reconstructed within the ATLAS inner detector pseudorapidity acceptance ($|\eta^{\mathrm{jet}}| < 2.5$), coming from the primary hard interaction and satisfying $p_{\mathrm{T}}^{\mathrm{jet}} > 20$ GeV after the final calibration are selected. A complete description of the jet energy calibration procedure can be found in [13]. If more than two jets satisfy these criteria, the two jets with the highest transverse momenta are selected and the others are disregarded. A good angular separation between the two jets in the transverse plane ($\Delta\phi_{jj} > 2$ rad.) is also required in order to reject events originating from the splitting of a gluon into two quarks ($g \to q\bar{q}$), more likely to contain c- and b-jets, and to reduce the beam-induced backgrounds [14]. According to the simulation, the selected jets in the final sample are composed by 1 to 4% of b-jets and 4 to 8% of c-jets, depending on $p_{\mathrm{T}}^{\mathrm{jet}}$ and $|\eta^{\mathrm{jet}}|$. ε_b and ε_c being typically an order of magnitude higher than ε_l, a direct measurement of ε_l would suffer a lot from the HF fraction in the sample, which is rather uncertain because it is inferred from simulation. Therefore, an alternative method called the "negative-tag method", described previously by the ATLAS collaboration [8], is used.

The negative-tag method relies to a large extent on the assumption that LF-jets are mistagged as b-jets mainly because of the finite resolution of the inner detector track parameters. A jet axis is defined for each jet as the direction of the vector sum of its associated constituents. The signed impact parameter of a track associated with a jet is defined as the closest distance between the track and the primary vertex. In case only the distance in the transverse plane (r,ϕ) is considered, it is referred to as the transverse impact parameter (d_0). The impact parameter sign is set to positive (negative) if the track and the jet axis cross in front of (behind) the primary vertex in the plane containing both of them, see Figure 1, left. Due to the long lifetime of b- and c-hadrons, the impact parameter distributions of the tracks associated with b- and c-jets are expected to show a high tail at large positive values. Assuming the negative-tag method assumption to be true, the distribution is expected to be symmetric for LF-jet. These properties are observed in simulated events, as shown in Figure 1, right. The inclusive tag rate obtained by re-running the MV2c10 algorithm after reversing the impact parameter significance sign of tracks is therefore expected to be a good approximation of the LF-mistag rate for this observable. Moreover, the b-, c- and LF-jets impact parameter distributions being much more similar on the negative side than on the positive side, one expects that inclusive tag rate to be comparable for the three flavors. The same kind of features are expected for the signed decay length significance of reconstructed secondary vertices, also used as an input in MV2 [9]. A new algorithm implementing these modifications and denoted MV2c10Flip in the following is defined. A jet is then considered negatively tagged if the tag weight discriminant

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[2] Hadronic jets are reconstructed from clustered energy deposits [11] in the ATLAS calorimeter with the anti-k_t algorithm [12] and a parameter $R = 0.4$.

variable computed by MV2c10Flip satisfies the normal weight criterion. The training and inputs variables used in the MV2c10Flip algorithm are unchanged with respect to the nominal algorithm.

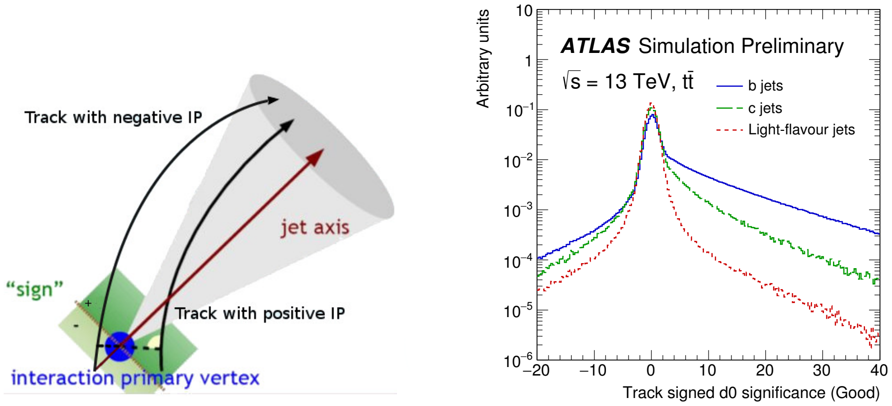

Figure 1: (left) Schematic diagrams of a jet associated with tracks of positive and negative impact parameter. (right) Distribution of the signed transverse impact parameter (d_0) significance (i.e. divided by its error) for *b*-. *c*- and LF-jets [9].

However, LF jets can be tagged as *b*-jets also because of the presence of tracks from displaced vertices of long-lived particles (e.g. K_S or Λ) and material interactions (hadronic interactions and photon conversions), which bias slightly towards positive value the d_0 distribution. The *b*-, *c*- and LF-jets negative tag rate are also expected to show some differences. Hence, the negative-tag method consists in measuring the negative tag efficiency of the jets in the selected data sample and applying the relevant corrections (extracted from MC simulation) to account for *b*- and *c*-jet in the sample and the presence of tracks from displaced vertices of long-lived particles and material interactions associated with LF-jets. The performances of the MV2c10 and MV2c10Flip algorithm are evaluated from a simulated multi-jet sample obtained from Pythia 8 events [15] processed through the nominal ATLAS detector simulation [16] and shown in Figure 2. As expected, (i) the LF shape is comparable between the two algorithms and (ii) the MV2c10Flip algorithm shows a much lower discrimination between the three flavors than MV2c10. While (i) allows to get a good estimate of the LF-jet mistag rate with the negative tag rate, (ii) limits the impact of the *b*- and *c*-jet sample contamination on the measurement with respect to a direct measurement based on the MV2c10 output weight.

3. Results

The measurements of the LF-jet mistag rates with the negative tag method for the 85% and 77% working point of the MV2c10 algorithm are presented and compared to the rates predicted by Pythia 8 events processed with the nominal ATLAS detector simulation in Figure 3. They range respectively between 1% and 16% (negative tag method) and 0.5% and 8% (Pythia 8 events + ATLAS simulation). The resulting data to simulation correction factors, approximately constant as a function of both p_T^{jet} and $|\eta^{\text{jet}}|$, are close to 2 and shown in Figure 4. The MC correction factors accounting for *b*- and *c*-jet contamination ranges between 0.9 and 0.3, while the ones related to

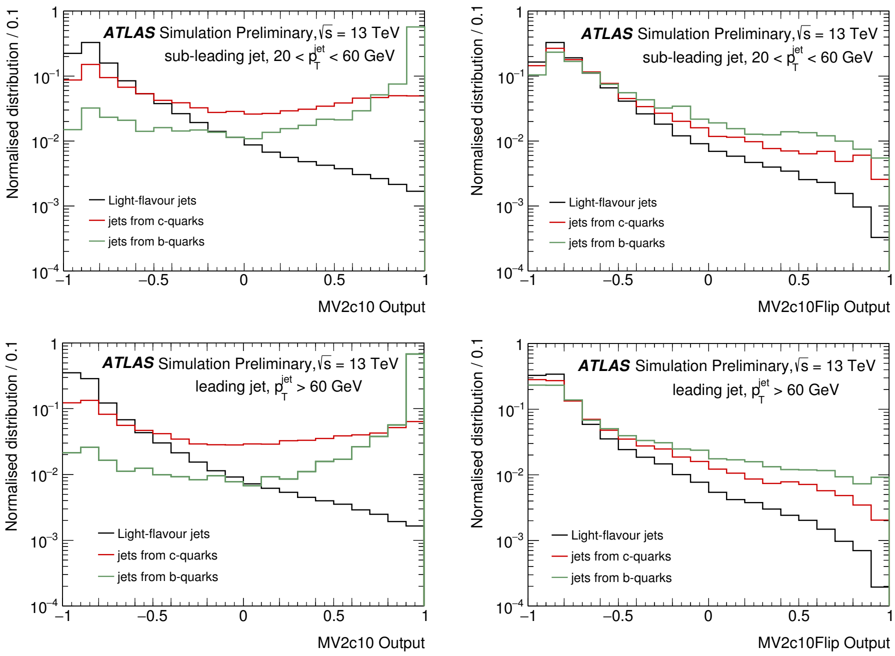

Figure 2: Normalized MV2c10 (left) and MV2c10Flip (right) output weight distributions for LF, *c*- and *b*-jets in a simulated multi-jet sample. The second highest p_T^{jet} in the event is shown when this jet satisfies 20 GeV $< p_T^{\text{jet}} <$ 60 GeV (top), otherwise the highest p_T^{jet} in the event is shown (bottom). Sub-leading jets are used at low p_T^{jet} to avoid trigger biases when running the analysis on data [10].

material interactions and long-lived mesons ranges extends from 1.3 to 5. They are both included in the measurements showed in Figures 3 and 4. The MC corrections increases with p_T^{jet} and $1/\varepsilon_l$. The total uncertainty on the data to simulation correction factors ranges from 10% (low p_T^{jet}, 85% WP) to 35% (high p_T^{jet}, 77% WP). It is dominated by the track impact parameter resolution difference between data and simulation (detector simulation) and the uncertainty in the sample composition (MC generator).

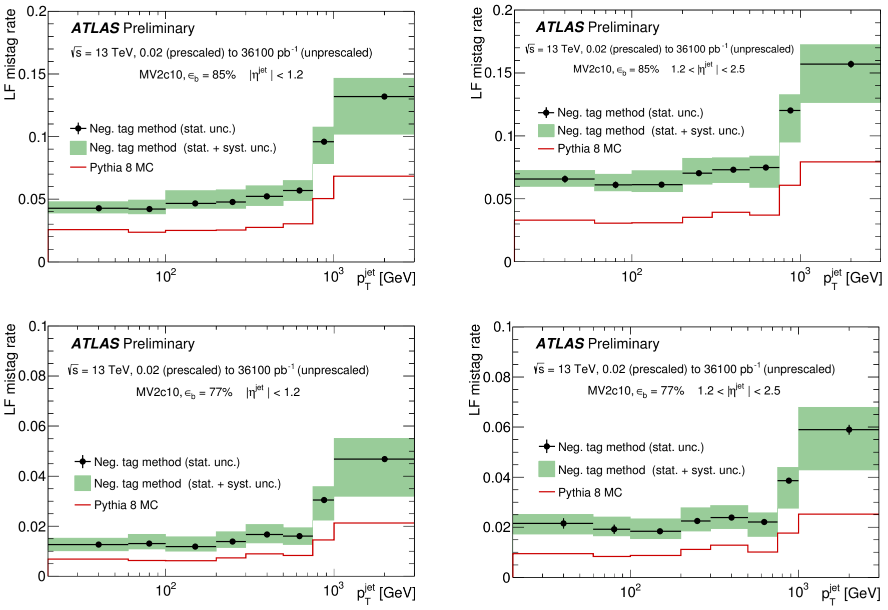

Figure 3: LF-jet mistag rate for the 85% (top) and 77% WP (bottom) as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$ for $|\eta^{\mathrm{jet}}| < 1.2$ (left) and $1.2 < |\eta^{\mathrm{jet}}| < 2.5$ (right) as measured by the negative tag method and as simulated using the Pythia 8 event generator passed through the nominal ATLAS detector simulation. The negative tag measurements include simulation-based corrections for heavy flavour jet contamination and light-flavour jets with true secondary vertices. The statistical uncertainty associated with the negative tag method measurements represents the sum in quadrature of data and MC statistical uncertainties. The data used in the negative tag method measurements was recorded using a set of prescaled and unprescaled jet triggers [10].

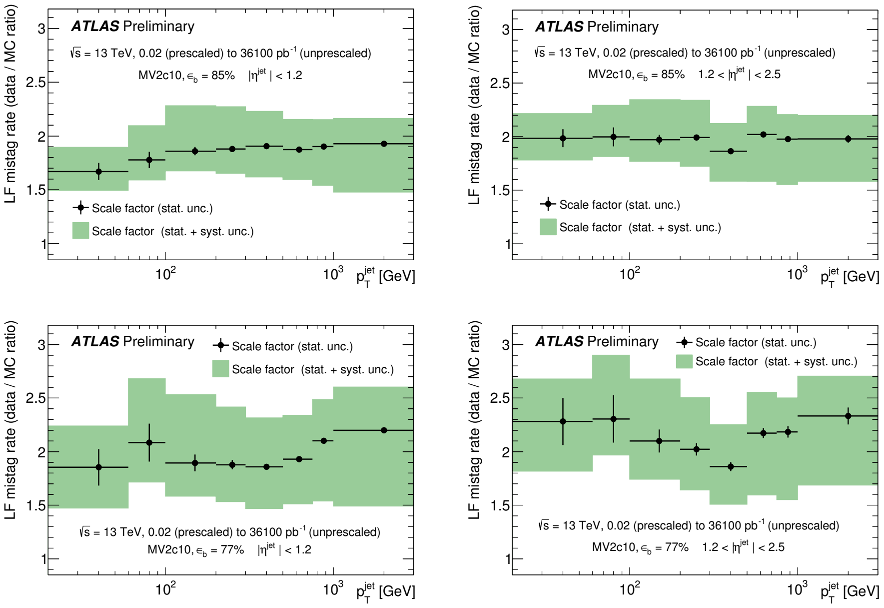

Figure 4: Ratio between the LF mistag rate measured from data with the negative tag method and the one simulated using the Pythia 8 event generator passed through the nominal ATLAS detector simulation for the 85% (top) and 77% (bottom) WP, as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$ for $|\eta^{\mathrm{jet}}| < 1.2$ (left) and $1.2 < |\eta^{\mathrm{jet}}| < 2.5$ (right). The statistical uncertainty represents the sum in quadrature of data and MC statistical uncertainties. The data sample used for the measurement was recorded using a set of prescaled and unprescaled jet triggers [10].

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