Abstract

The $b$-jet tagging efficiency on jets containing charm hadrons ($c$-jets) has been measured using a sample of $D^{*+}$ mesons, reconstructed within a jet in the $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+\pi^+)$ final state. The measurement is based on 5 fb$^{-1}$ of data collected in 2011 by the ATLAS detector.

The $b$-tagging efficiency on $c$-jets has been extracted by comparing the yield of $D^{*+}$ mesons before and after the tagging requirement. The contamination with $D^{*+}$ mesons that result from $b$-hadron decays has been measured with a fit to the $D^0$ pseudo-proper time distribution.

The measurement of the $c$-tagging efficiency is provided in the form of jet $p_T$ and $\eta$ dependent scale factors that correct the $b$-tagging performance in simulation to that observed in data. The precision of the measurement depends on the tagging algorithm, operating point and jet $p_T$ bin. For the high-performance MV1 tagging algorithm at an operating point corresponding to a 70% $b$-tag efficiency in $t\bar{t}$ events, the total uncertainty ranges from 12% to 25%.
1 Introduction

The identification of jets originating from $b$-quarks is an important part of the LHC physics programme. In precision measurements in the top quark sector as well as in the search for the Higgs boson and new phenomena, the suppression of background processes that contain predominantly light-flavour jets using $b$-tagging is essential. It might also become critical to achieve an understanding of the flavour structure of any new physics (e.g. Supersymmetry) revealed at the LHC.

In order for $b$-tagging to be used in physics analyses, the efficiency with which a jet originating from a $b$-quark is tagged by a $b$-tagging algorithm must be determined. It is also necessary to evaluate the $c$-tag efficiency, which is the equivalent quantity for jets originating from $c$-quarks, and the mistag rate, which is the probability of mistakenly tagging a jet originating from a light-flavour parton ($u$, $d$, $s$-quark or gluon) as a $b$-jet. This note describes a $c$-tag efficiency measurement.

The $b$-tagging algorithms calibrated in this note are SV0, IP3D+SV1, JetFitterCombNN and MV1. More details about SV0 can be found in [1] while the IP3D+SV1 and JetFitterCombNN algorithms are described in [2]. The MV1 algorithm is a neural network-based algorithm that uses the output weights of IP3D, SV1 and JetFitterCombNN as inputs. For each $b$-tagging algorithm a set of operating points, corresponding to cut values applied to the $b$-tagging weights, are defined, based on the inclusive $b$-tag efficiency measured on simulated $\bar{t}t$ events. The operating points which are calibrated in this note are SV0 at 50%, IP3D+SV1 at 60, 70 and 80%, JetFitterCombNN at 57, 60, 70 and 80%, and MV1 at 60, 70, 75 and 85%. In the following, the MV1 tagger at the 70% operating point is used to show detailed results of the measurement, while results for the other taggers and operating points are summarized at the end in Table 4. The MV1 tagger is used as the default one due to its better performance, being a combination of three of the other taggers.

The necessary ingredients for the calibration of flavour-tagging algorithms are jet samples characterized by a strong predominance of a single flavour, whose fractional abundance can be measured from data. For charm jets, such samples can be obtained by reconstructing exclusive charm meson decays within a jet, such as $D^{\ast+} \rightarrow D^{0}(\rightarrow K^{-}\pi^{+})\pi^{+}1$. In this case, the signal excess is predominantly due to charm meson decays, with some contamination from $b \rightarrow c$ decays, while the combinatorial background can be controlled and subtracted by studying the mass sidebands. Thus, by requiring this decay to be reconstructed within a jet, a reasonably pure sample of charm jets is obtained, which can be used to cross-check different tagging algorithms and to measure their efficiency.

2 Data samples and event selection

The data sample used in this analysis corresponds to approximately 5 fb$^{-1}$ of 7 TeV proton-proton collision data collected by the ATLAS experiment during 2011. The event sample for the $c$-tagging efficiency measurement was collected using a logical OR of triggers which require one or more jets above certain $p_T$ thresholds. The combination of these triggers covers the entire jet $p_T$ range used in the analysis.

The objects used in the definition of all flavour tagging variables are the tracks reconstructed in the inner detector, the reconstructed primary vertex and the calorimeter jets. The tracks are associated with the calorimeter jets with a spatial matching in $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ [3]. The track-selection criteria depend on the specific $b$-tagging algorithm, and are detailed in [2, 4]. The jets are reconstructed with the anti-$k_t$ algorithm with a distance parameter of 0.4 [5–7], starting from energy clusters in the calorimeter reconstructed using the scale established for electromagnetic objects. These jets are then calibrated to the hadronic energy scale using $p_T$ and $\eta$-dependent correction factors obtained from simulation. The measurement of the jet energy, the jet energy scale determination and the specific cuts used to reject jets of

\[1\]
Charge conjugate states are always included.
bad quality are described in [8]. The jets are required to have \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.5 \). Events without a reconstructed primary vertex with at least two tracks are neglected. When extra \( pp \) interactions occur in the same bunch crossing as the triggered event (pile-up), the primary vertex is selected by requiring its constituent tracks to have the highest \( \sum p_T^2 \).

The analysis makes use of a Monte Carlo (MC) simulated sample of multijet events; each event in this sample is required to contain a \( D^*^+ \) meson, which is in turn forced to decay to \( D^0 (\rightarrow K^- \pi^+)\pi^+ \). The simulation of these jets has been carried out in six slices of \( \hat{p}_T \), the momentum of the hard scatter process perpendicular to the beam line, in order to cover the jet \( p_T \) spectrum up to a few hundred GeV. Approximately 1 million events have been simulated per slice of \( \hat{p}_T \). Moreover, to reproduce the pile-up conditions in the data, extra collisions have been superimposed on the simulated MC events. The sample is generated with PYTHIA 6 [9, 10], utilizing the ATLAS AMBT2B PYTHIA tune [11].

To simulate the detector response, the generated events are processed through a GEANT4 [12] simulation of the ATLAS detector, and then reconstructed and analyzed in the same way as the data [13]. The simulated geometry corresponds to a perfectly aligned detector and takes into account the list of detector modules which are disabled in real data taking.

To bring the simulation into agreement with data for distributions where discrepancies are known to be present, corrections have been applied to the jets in the simulated multijet samples. The \( p_T \) spectrum of jets in the multijet samples is harder in data than in simulation because the prescale of the low threshold triggers is not activated in simulation. Since the \( c \)-tag efficiency depends on the jet kinematics, the jet \( p_T \) distribution has been re-weighted to match that observed in data. Re-weighting on the average number of interactions per bunch crossing (\( \bar{\mu} \)) has also been performed to ensure good agreement in the number of reconstructed primary vertices between data and MC.

The labeling of the flavour of a jet in simulation is done by spatially matching the jet with generator-level partons: if a \( b \)-quark is found within \( \Delta R < 0.3 \) of the jet direction, the jet is labeled as a \( b \)-jet. If no \( b \)-quark is found the procedure is repeated for \( c \)-quarks and \( \tau \)-leptons. A jet for which no such association can be made is labeled as a light-flavour jet.

### 2.1 \( D^{*+} \) selection

\( D^{*+} \) mesons are reconstructed in the decay \( D^{*+} \rightarrow D^0 \pi^+ \), with \( D^0 \rightarrow K^- \pi^+ \). Pairs of oppositely charged tracks are considered for the \( D^0 \) candidates, assigning both kaon and pion mass hypotheses to them. Studies on simulated data confirm that only the correct combination of mass hypotheses produces a \( D^0 \) in the expected mass region. The \( D^0 \) candidates are then combined with charged particle tracks with opposite sign to that of the kaon candidate, assigning the pion mass to them.

The \( D^{*+} \) candidates must fulfill the following criteria:

- All tracks must have at least five hits in the silicon tracking detectors, at least one of them in the pixel detector.
- The transverse momenta of the kaon and pion candidates from the \( D^0 \) decay candidate have to fulfill \( p_T > 1 \text{ GeV} \).
- The reconstructed \( D^0 \) candidate mass \( m_{K^-\pi^+} \) must satisfy \( |m_{K^-\pi^+} - m_{D^0}| < 40 \text{ MeV} \), where \( m_{D^0} \) is the world average \( D^0 \) mass, \( m_{D^0} = 1864.83 \pm 0.14 \text{ MeV} \) [14].
- The transverse momentum of the \( D^{*+} \) candidate has to exceed 4.5 GeV.

The decay chain is fitted as follows: first the \( D^0 \) vertex is formed by fitting the kaon and pion candidates, and the resulting \( D^0 \) neutral track is reconstructed by combining the kaon and pion four-momenta; the \( D^0 \) neutral track is then extrapolated back and fitted with the pion candidate to form the \( D^{*+} \) vertex. The
decay chain is fitted with a tool allowing the simultaneous reconstruction and fit of both vertices. No requirements are made on the vertex fit $\chi^2$ probability in order to minimize the bias on the $b$-tagging.

The $D^{*+}$ candidate is in turn associated with a reconstructed jet requiring its direction to be within $\Delta R = 0.3$ of the jet direction. Finally, to reduce the amount of combinatorial background, the momentum of the $D^{*+}$ candidate projected along the jet direction has to exceed 30% of the jet energy.

The kinematics of the decay cause the $D^{*+}$ to release only a small fraction of energy to the prompt pion, usually called “slow pion”; for this reason the $D^{*+}$ signal is commonly studied as a function of the mass difference $\Delta m$ between the $D^{*+}$ and $D^0$ candidates. $D^{*+}$ mesons are expected to form a peak in the $\Delta m$ distribution around 145.4 MeV, while the combinatorial background forms a rising distribution, starting at the pion mass. Figure 1 shows the distributions of the mass difference for the $D^{*+}$ pairs associated with a reconstructed jet for four different jet $p_T$ intervals: [20, 30] GeV, [30, 60] GeV, [60, 90] GeV, [90, 140] GeV.

A fit of the $\Delta m$ distribution in each jet $p_T$ interval is done in order to determine the yield of the $D^{*+}$ mesons. The signal part of the $\Delta m$ distribution is fitted using a modified Gaussian ($\text{Gauss}^{\text{mod}}$), which provides a better description of the signal tails with respect to a simple Gaussian

$$S = \text{Gauss}^{\text{mod}} \propto \exp[-0.5 \cdot x^{(1+\frac{\Delta m}{\sigma})}],$$

where $x = |(\Delta m - \Delta m_0)/\sigma|$ and $\Delta m_0$ and $\sigma$, free parameters in the fit, are the mean and width of the $\Delta m$ peak. The combinatorial background is fitted with a power function multiplied by an exponential
The selection of $D^{\ast+}$ meson decays associated with jets allows background subtraction techniques to be used to perform comparisons between data and simulation in any variable related to the $D^{\ast+}$ mesons or jets, for the mixture of $b$ and $c$-jets present in data.

Signal and background regions are defined as the region within $3\sigma$ of the $\Delta m$ peak center and the region above 150 MeV respectively. The choice of the $\Delta m$ intervals for the signal and background regions aims at including almost all the signal events in the signal region and ensuring a negligible fraction of signal events in the background region.

For each variable, the data distribution extraction proceeds as follows: the distribution of events from the background region, normalized to the fitted background fraction in the signal region, is subtracted from the corresponding distribution in the signal region.

The procedure relies on the assumption that the distribution of the variable of interest is the same for the combinatorial background under the peak and in the sidebands. This assumption has been verified to be valid for simulated data and is supported by the observation that the distributions obtained from two different contiguous sideband regions ($\Delta m \in [150, 160]$ MeV and $\Delta m \in [160, 168]$ MeV) are compatible with each other within their statistical uncertainty.

### 3 Measuring the flavour composition in the $D^{\ast+}$ sample

The measurement of the flavour composition for the selected $D^{\ast+}$ sample is a key ingredient for its use in $b$-tagging calibration studies. The discriminating variable adopted in this note to identify beauty and charm components is the $D^0$ pseudo-proper time defined as:

$$t(D^0) = \text{sign}(L_{xy} \cdot p_{\text{PT}}(D^0)) \cdot m_{D^0} \cdot \frac{L_{xy}(D^0)}{p_{\text{PT}}(D^0)},$$

where $m_{D^0}$ is the $D^0$ meson mass, $p_{\text{PT}}(D^0)$ is the transverse momentum of the reconstructed $D^0$ candidate, $L_{xy}(D^0)$ is the distance, in the transverse plane, between its decay vertex and the primary vertex in the event, and the sign function is defined as $\text{sign}(x) = x/|x|$. 

<table>
<thead>
<tr>
<th>Jet $p_{\text{PT}}$ [GeV]</th>
<th>[20, 30]</th>
<th>[30, 60]</th>
<th>[60, 90]</th>
<th>[90, 140]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted number of candidates</td>
<td>4450 ± 330</td>
<td>6100 ± 236</td>
<td>2823 ± 136</td>
<td>2390 ± 133</td>
</tr>
<tr>
<td>$\Delta m_0$ [MeV]</td>
<td>145.24 ± 0.04</td>
<td>145.38 ± 0.02</td>
<td>145.41 ± 0.03</td>
<td>145.46 ± 0.04</td>
</tr>
<tr>
<td>$\sigma(\Delta m_0)$ [MeV]</td>
<td>0.69 ± 0.06</td>
<td>0.59 ± 0.03</td>
<td>0.62 ± 0.03</td>
<td>0.68 ± 0.04</td>
</tr>
<tr>
<td>$f_B/(f_B + f_S)$</td>
<td>0.86 ± 0.02</td>
<td>0.72 ± 0.02</td>
<td>0.62 ± 0.02</td>
<td>0.65 ± 0.02</td>
</tr>
</tbody>
</table>

Table 1: Fit results, including statistical uncertainties only, for $D^{\ast+}$ associated with jets in the different $p_{\text{PT}}$ bins.
The first step of the flavour composition fit is the extraction of charm and beauty templates from simulated data:

- The resolution on the $D^0$ pseudo-proper time, $R(t)$, is described by the sum of a simple Gaussian and a modified Gaussian. Since it shows no dependence on the $D^{*+}$ production mechanism, its parameters are fitted to the more abundant charm component.

- The $D^0$ pseudo-proper time distribution for the charm component, $F_c(t)$, is modelled as a single exponential function with a time constant equal to the measured $D^0$ lifetime [14], convolved with the pseudo-proper time resolution $R(t)$; no additional fits are needed to obtain the charm component model.

- The model for the $D^0$ pseudo-proper time distribution for the beauty component, $F_b(t)$, cannot be easily inferred from physics arguments, since the pseudo-proper time of $D^0$ candidates from beauty depends on many variables, such as the beauty hadron and $D^0$ lifetimes, the momenta and the angle between their flight paths. Therefore, $F_b(t)$ is modelled as the convolution of two exponential functions, further convolved with the pseudo-proper time resolution $R(t)$; this empirical model provides the best agreement with the simulated distribution. The time constants of the two exponential functions are fitted using the simulated distribution for the beauty component.

Once the models for charm and beauty components are fixed, their sum is built as

$$F(t) = f_b \cdot F_b(t) + (1 - f_b) \cdot F_c(t),$$

where $f_b$ is the fractional beauty abundance, and is used to fit simulated or real background-subtracted data. A binned maximum likelihood fit is performed leaving the $f_b$ parameter free and fixing the normalization of $F(t)$ to the integral of the fitted histogram.

A closure test of the fit procedure is performed by splitting the simulated sample into 40 sub-samples and repeating the pseudo-proper time fit on each sub-sample. The pull distribution of the fitted purity is found to be compatible with a Gaussian distribution centered on zero and with unit width, thus validating the fit procedure.

### 3.1 Fit results and systematic studies

The fit is done using the variable $crt(D^0)$, where $t(D^0)$ is the $D^0$ pseudo-proper time defined in Eq. 3, and $c$ the speed of light in vacuum, in the range [-1, 2] mm. The fit on background-subtracted real data, in the four bins of jet $p_T$, is shown in Figure 2 and results are summarized in Table 2.

<table>
<thead>
<tr>
<th>Jet $p_T$ [GeV]</th>
<th>[20, 30]</th>
<th>[30, 60]</th>
<th>[60, 90]</th>
<th>[90, 140]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted value</td>
<td>0.212 ± 0.010</td>
<td>0.315 ± 0.010</td>
<td>0.303 ± 0.015</td>
<td>0.315 ± 0.017</td>
</tr>
</tbody>
</table>

Table 2: Beauty fractions determined by fits to the data in four jet $p_T$ bins.

In order to cross-check the fit results, the distribution of the $D^0$ impact parameter, a variable sensitive to the beauty component, is analyzed. Figure 3 shows the comparison between background-subtracted data and Monte Carlo simulation for the impact parameter of the $D^0$ meson emerging from the $D^{*+}$ decay. The Monte Carlo distribution is obtained by summing the beauty and charm components according to the overall $f_b$ value given in Table 2. Data and simulation distributions are found to be in reasonable agreement.
Figure 2: Fitted $D^0$ pseudo-proper time distributions on background-subtracted $D^{*+}$ data samples in four jet $p_T$ bins.

Figure 3: Comparison between the $D^0$ impact parameter in the background-subtracted $D^{*+}$ data samples with the corresponding simulated samples; the beauty fraction in the simulation is fixed to the value obtained by the pseudo-proper time fit in the full jet $p_T$ range in data. The ratio between the two distributions is shown on the bottom of the plot.
4 \hspace{5pt} \textit{b}\text{-}tagging calibration with the $D^{*+}$ sample

Using the background subtraction technique described in Sec. 2.2, the shape of any variable in data can be compared to that in simulation. Figure 4 shows the distributions of the SV0 output weight, namely the decay length significance$^2$, the JetFitterCombNN output weight, the IP3D+SV1 output weight and the MV1 output weight in the background-subtracted $D^{*+}$ sample. They are found to be in good agreement with the expectations from Monte Carlo simulation.

![Graphs showing distribution comparisons](image)

Figure 4: Comparison between the weight distributions for the SV0, JetFitterCombNN, IP3D+SV1 and MV1 taggers on background-subtracted $D^{*+}$ data sample with the corresponding simulated samples; the beauty fraction in the simulation is fixed to the value obtained by the pseudo-proper time fit in the full jet $p_T$ range in data.

4.1 Measuring the $c\text{-}tagging$ efficiency using $D^{++}$ candidates

The selected sample can be used to measure the $c\text{-}tagging$ efficiency for jets associated with $D^{++}$ candidates, by performing a combined fit to the $\Delta m$ distributions for $D^{++}$ mesons in jets before and after applying the $b\text{-}tagging$ requirement.

The fit parameters describing the signal and the background shapes are required to be equal for the two distributions and the combined fit only introduces the $D^{*+}$ tagging efficiency $\epsilon_{D^{*+}}$ as an extra parameter accounting for the reduction in the $D^{*+}$ peak in the tagged jets. The procedure was tested in simulation and it has been verified that the measured efficiency on jets associated with a $D^{*+}$ meson is unbiased.

$^2$The significance is set to $-10$ when no secondary vertex is found.
Using the method described it is possible to obtain the efficiency to tag jets associated with a $D^{*+}$ candidate. This inclusive efficiency $\varepsilon_{D^{*+}}$ is then decomposed into the efficiency for $b$ and $c$-jets using:

$$\varepsilon_{D^{*+}} = f_b \varepsilon_b + (1 - f_b) \varepsilon_c,$$

where $f_b$ is the fraction of $D^{*+}$ coming from beauty, before the $b$-tagging selection, determined by the fit to the pseudo-proper lifetime. The efficiency to tag a $b$-jet, $\varepsilon_b$, is taken from simulation and corrected by the data-to-simulation scale factors obtained by the $p_{T}\text{rel}$ and System8 combination method [15]. Solving with respect to $\varepsilon_c$ yields the following relation

$$\varepsilon_c = \frac{\varepsilon_{D^{*+}} - f_b \varepsilon_b}{1 - f_b}. \quad (6)$$

5 Systematic Uncertainties

The dominant systematic uncertainties affecting the method presented in this note are those related to the fit of the yield of $D^{*+}$ mesons, to the extractions of the fraction of $D^{*+}$ mesons originating from beauty hadrons and to the extrapolation of the $c$-tag efficiency scale factor measured on jets associated with a $D^{*+}$ meson to that of an inclusive $c$-jet sample.

The systematic and statistical uncertainties on the $c$-tag efficiency scale factors of the MV1 tagging algorithm at 70% efficiency are shown in Table 3. Each of the systematic sources listed in the table is explained below.

<table>
<thead>
<tr>
<th>Source</th>
<th>Jet $p_T$[GeV]</th>
<th>[20,30]</th>
<th>[30,60]</th>
<th>[60,90]</th>
<th>[90,140]</th>
</tr>
</thead>
<tbody>
<tr>
<td>beauty fraction fit</td>
<td></td>
<td>±5</td>
<td>±2</td>
<td>±2</td>
<td>±2</td>
</tr>
<tr>
<td>$b$-tagging efficiency scale factor</td>
<td></td>
<td>±4</td>
<td>±5</td>
<td>±5</td>
<td>±8</td>
</tr>
<tr>
<td>$D^{*+}$ mass peak width</td>
<td></td>
<td>±16</td>
<td>±4</td>
<td>±5</td>
<td>±10</td>
</tr>
<tr>
<td>background parametrization</td>
<td></td>
<td>±1</td>
<td>±1</td>
<td>±1</td>
<td>±2</td>
</tr>
<tr>
<td>jet energy scale</td>
<td></td>
<td>±4</td>
<td>±2</td>
<td>±1</td>
<td>±3</td>
</tr>
<tr>
<td>pile-up</td>
<td></td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>±2</td>
</tr>
<tr>
<td>extrapolation $D^0$</td>
<td></td>
<td>+0</td>
<td>+0</td>
<td>+0</td>
<td>+0</td>
</tr>
<tr>
<td>extrapolation baryons-HERA</td>
<td></td>
<td>+8</td>
<td>+8</td>
<td>+0</td>
<td>+0</td>
</tr>
<tr>
<td>extrapolation baryons-LEP</td>
<td></td>
<td>+12</td>
<td>+12</td>
<td>+6</td>
<td>+9</td>
</tr>
<tr>
<td>extrapolation others</td>
<td></td>
<td>+5</td>
<td>+4</td>
<td>+3</td>
<td>±1</td>
</tr>
<tr>
<td>total systematic</td>
<td></td>
<td>±12</td>
<td>±12</td>
<td>±12</td>
<td>±11</td>
</tr>
<tr>
<td>statistical</td>
<td></td>
<td>±13</td>
<td>±9</td>
<td>±11</td>
<td>±12</td>
</tr>
</tbody>
</table>

Table 3: Relative systematic and statistical uncertainties, in %, on the data-to-simulation $c$-tag efficiency scale factors for the MV1 tagging algorithm at 70% efficiency.

5.1 Beauty fraction fit

To study the effects of imperfect modelling of the pseudo-proper time resolution in simulation and the beauty lifetime uncertainty, the following procedure is adopted:

- Resolution systematics: the fit results have a weak dependence on the assumed resolution functions, and a conservative systematic uncertainty is assigned by fixing the Gaussian and modified
Gaussian widths to 0.5 and 1.5 times the resolution fitted on the simulated sample. This mainly affects small pseudo-proper time values, while the fit results are mainly influenced by the beauty tails at high positive values.

- Lifetime uncertainty: the lifetimes of the two exponentials used in modelling the beauty component are each varied by the fractional error on the inclusive $b$-hadron lifetime world average [14].

In both cases the maximum positive and negative variations in the beauty fraction central value are taken as an estimate of the corresponding systematic uncertainty. The total uncertainty on the beauty fraction is calculated by combining the fit statistical error together with the resolution and lifetime systematics, and is used to evaluate the systematic uncertainty on the $c$-tag efficiency.

5.2 $b$-tagging efficiency scale factor

The tagging efficiency for $b$-jets is evaluated by multiplying the value found in simulation by the scale factor measured with the $p_T^{rel}$ and System8 combination method [15]. The variation of this scale factor within its error is propagated to the final results as a systematic uncertainty.

5.3 $D^{*+}$ mass fit

The systematic uncertainty in the mass fit is evaluated by removing the constraint that the width of the $D^{*+}$ mass peak and the parametrization of the background shape are the same in the pre-tagged and tagged sample. The fit is separately repeated with and without these assumptions and the efficiency variations are taken as two separate systematic uncertainties. The obtained uncertainties, by definition single sided, have been symmetrized assuming that a similar variation could have been observed also in the opposite direction.

5.4 Jet energy scale

The systematic uncertainty originating from the jet energy scale is obtained by scaling the $p_T$ of each jet in the simulation up and down by one standard deviation, according to the uncertainty of the jet energy scale [8]. This systematic uncertainty impacts both the true $c$-tag efficiency and the pseudo-proper time templates.

5.5 Pile-up

During 2011, the average number of interactions per bunch crossing, referred to as $\mu$, increased from less than 5 to above 20. To model the pile-up activity, the $\mu$ distribution in simulation is reweighted to agree with that in data. In order to also have a satisfactory level of agreement with the data in the number of reconstructed primary vertices per event, the $\mu$ values in simulation have been rescaled, prior to the $\mu$ reweighting, by a factor of 0.97, with a related uncertainty of 1%. Therefore, as a systematic uncertainty the measurement has been repeated by scaling up and down by 1% the $\mu$ values in simulation prior to reweighting.

5.6 Extrapolation to inclusive charm

By construction, the method described measures the $b$-tagging efficiency scale factors for $c$-jets associated with a $D^{*+}$ meson decaying to $D^{0}(\rightarrow K^-\pi^+)\pi^+$. To evaluate the additional uncertainty caused by interpreting this scale factor as an inclusive $c$-tag efficiency scale factor, possible systematic contributions to the extrapolation to the inclusive $c$-jet sample have to be considered.
The efficiency extrapolation factors, $X$, for data and simulation, can be expressed through

\[ \varepsilon_c^{\text{data}}(\text{incl}) = X^{\text{data}} \cdot \varepsilon_c^{\text{data}}(D^{*+}), \]
\[ \varepsilon_c^{\text{MC}}(\text{incl}) = X^{\text{MC}} \cdot \varepsilon_c^{\text{MC}}(D^{*+}), \]

where $\varepsilon_c(D^{*+})$ is the $c$-tag efficiency measured in this analysis using jets associated with $D^{*+}$ mesons and $\varepsilon_c(\text{incl})$ is the $c$-tag efficiency on an inclusive sample of $c$-jets.

Charm jets containing a $D^{*+}$ meson are tagged more often than the generic charm jets because of the requirement of having at least three reconstructed charged tracks. The typical values of $X^{\text{MC}}$, evaluated for the MV1 tagger, range between 0.5 and 0.7, depending on the working point. The inclusive $c$-tagging scale factor is given by

\[ SF_c(\text{incl}) = \frac{\varepsilon_c^{\text{data}}(\text{incl})}{\varepsilon_c^{\text{MC}}(\text{incl})} = \frac{X^{\text{data}}}{X^{\text{MC}}} SF_c(10), \]

where $SF_c(D^{*+})$ is the measured $c$-tag efficiency scale factor on jets associated with $D^{*+}$ mesons originating from $c$-quarks.

Even if the data-to-simulation scale factors come out close to unity for a sample of $D^{*+}$ mesons, the inclusive scale factors in data can be different from those in simulation either because the fragmentation fractions of the various charm hadron species is different in data and simulation or because of differences in the charged track multiplicity of a given charm hadron decay. By varying both the fragmentation fraction and branching ratios between the values in the ATLAS simulation and those of the PDG [14], weighting each component by its corresponding tagging efficiency, the effect on the inclusive $c$-tag efficiency from the possible mismodelings of the above quantities can be estimated.

Therefore the extrapolation ratio can be expressed as

\[ X^{\text{data}} = \frac{\sum \alpha_i \beta_{ij} \varepsilon_{ij}^{\text{data}}}{\sum \alpha_i \beta_{ij} \varepsilon_{ij}^{\text{MC}}} = \frac{X^{\text{MC}}}{X^{\text{MC}}} SF_c(D^{*+}), \]

where $\alpha_i$ is the fragmentation fraction of a given charm hadron species, $\beta_{ij}$ is the branching ratio of that charm hadron species to a $j$-prong final state and $\varepsilon_{ij}$ the corresponding $b$-tag efficiency.

The ratio of the extrapolation factors is assumed to be equal to unity, and possible differences between data and Monte Carlo simulation are accounted in the ratio uncertainty. Possible differences between the $c$-tagging efficiency measured on data and Monte Carlo for the $D^{*+}$ sample are attributed to detector effects, and assumed to be similar for inclusive charm hadron decays. The remaining uncertainty on the extrapolation factors are therefore obtained by varying $\alpha$ and $\beta$ in the Monte Carlo simulation according to the best experimental knowledge. In particular, for the fragmentation fractions we refer to the HERA and LEP measurements [16], and for the $D^0$ branching ratios to $j$-prong final states, to the values reported by the PDG [14]. For the other charm species, a 10% variation on the most populated $j$-prong final states are assumed.

For each contribution, the Monte Carlo simulation has been re-weighted to match the experimental value and the maximal variation of the extrapolation factor ratio has been assumed as a corresponding systematic uncertainty.

Since the main discrepancies between the Monte Carlo simulation and the experimental knowledge are in the $\Lambda_c^+$ fragmentation fraction and in the description of the $D^0$ decays, their contribution is quoted separately, but only the largest between HERA and LEP $\Lambda_c^+$ fragmentation systematic uncertainties is accounted in the overall systematic uncertainty quoted in Table 3. The effects coming from meson fragmentation fractions and $D^+$, $D^0$ and $\Lambda_c^+$ decays are instead summed in quadrature together.

The asymmetry of the ratio uncertainty is due to the fact that the charm-baryon fraction in simulation is lower than both HERA and LEP measurements. The branching fractions of the $D^0$ meson into $j$ prongs
also has a single-sided uncertainty since the 0-prong branching fraction in simulation is below the range allowed by experimental measurements.

The results obtained are based on a specific simulation, and therefore the systematic due to the extrapolation to inclusive $c$-jets must be scaled in Monte Carlo samples produced using generators with different charm fragmentation fractions or charm decay branching ratios. Nevertheless taking into account the other systematic contributions the total error is only slightly asymmetric and hence the rescaling to different generator parameters is not expected to change the total error significantly.

6 Results

The measured $c$-tag efficiencies in data, the $c$-tag efficiencies in simulation and the resulting data-to-simulation scale factors for the MV1 tagging algorithm at 70% efficiency are shown in Figure 5. Results for other tagging algorithms and operating points can be found in Table 4.

![Figure 5: The $c$-tag efficiency in data and simulation (left) and the data-to-simulation scale factor (right) for MV1-70.](image)

The scale factors in all $p_T$ bins are compatible with unity within uncertainties. No significant $p_T$ dependence of the scale factor is observed.

7 Conclusions

Reconstructed $D^{*+}$ mesons associated with jets have been used to measure the $c$-tag efficiency of several $b$-tagging algorithms with 5 fb$^{-1}$ of data from the ATLAS detector. The same sample has also been used to cross-check the output weight distributions of the various tagging algorithms. The measurement presented in this note represents the first determination of the $b$-tagging efficiency on $c$-jets from data.

The results are expressed in terms of scale factors, correcting the $c$-tag efficiency in simulated events to those measured in data. The scale factors are consistent with unity for all the taggers and operating points with uncertainties varying, depending on the jet $p_T$, from 10% to 40%.

References

Table 4: $c$-tag efficiency scale factors on $c$-jets, determined with the $D^{*+}$ method, as a function of jet $p_T$ for $|\eta| < 2.5$ and for different $b$-tagging algorithms and operating points.

<table>
<thead>
<tr>
<th>Tagger</th>
<th>$\varepsilon_b(%)$</th>
<th>$p_T$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[20, 30]</td>
<td>[30, 60]</td>
</tr>
<tr>
<td>SV0</td>
<td>50</td>
<td>0.99±0.22</td>
</tr>
<tr>
<td>IP3D+SV1</td>
<td>60</td>
<td>0.98±0.25</td>
</tr>
<tr>
<td>IP3D+SV1</td>
<td>70</td>
<td>0.99±0.24</td>
</tr>
<tr>
<td>IP3D+SV1</td>
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<td>1.03±0.16</td>
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<tr>
<td>JetFitterCombNN</td>
<td>57</td>
<td>0.90±0.18</td>
</tr>
<tr>
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<td>0.89±0.23</td>
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<td>0.95±0.23</td>
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<tr>
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<tr>
<td>MV1</td>
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<td>0.90±0.23</td>
</tr>
<tr>
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</tr>
<tr>
<td>MV1</td>
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<tr>
<td>MV1</td>
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