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Measurement of the b-jet tagging efficiency using top quark pair events with ATLAS data

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Many physics analyses of LHC data have jets originating from b-quarks in the final state. Algorithms that allow to identify such jets are thus of great importance and it is crucial to calibrate their performance directly in data by measuring the tagging efficiencies and fake rates. Since the top quark almost exclusively decays to a W boson and a b-quark, a sample of top quark pair events ($t\bar{t}$) is ideal for studying the b-tagging performance. The calibration methods based on top quark pair events are especially important because they can provide measurements of the b-tagging efficiency for jets with high transverse momentum which are beyond the reach of muon-based methods. Final states containing one or two leptons recorded with the ATLAS detector have been used to measure the b-tagging efficiency, either by counting the number of b-tagged jets, by exploiting the kinematics of top quark pair decays and flavour composition, or by applying a kinematic fit to extract a sample rich in b-jets. Results of calibration are per event scale factors. For all the b-tagging algorithms calibrated, the scale factors measured with these methods are consistent and close to 1. The total uncertainties on the scale factors range from 5% to 15% for jet p_{T} in the range from 25 GeV to 300 GeV.

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1. Introduction

The performance of b-tagging algorithms has to be measured using data, in order to correct for mismodelings in Monte Carlo simulations. The b-tagging efficiency calibration methods used in ATLAS [1] so far relied on a sample of jets containing muons from b-hadron decay [2]. At the LHC at collisions with $\sqrt{s} = 7$ GeV, the large $t\bar{t}$ production cross section offers an alternative source of events enriched in b-jets. The distinctive topology with high p_{T} leptons, multiple jets, and large missing transverse momentum is relatively easy to trigger on and to reconstruct. With the integrated luminosity of 4.7 fb^{-1} collected during 2011 with collisions at center of mass energy $\sqrt{s} = 7$ GeV, the methods based on $t\bar{t}$ selections have become competitive for the first time. In addition to providing b-tagging calibration measurements in an inclusive b-jet sample rather than a sample of semileptonic b-jets, these methods also allow to extend the calibrated jet p_{T} range.

The results of calibration are presented in the form of p_{T}-dependent scale factors defined as

$$\kappa_{\varepsilon_b}^{\mathrm{data/sim}}(p_{\mathrm{T}}) = \frac{\varepsilon_b^{\mathrm{data}}(p_{\mathrm{T}})}{\varepsilon_b^{\mathrm{sim}}(p_{\mathrm{T}})}, \tag{1.1}$$

where $\varepsilon_b^{\mathrm{sim}}$ ($\varepsilon_b^{\mathrm{data}}$) is the fraction of b-jets which are tagged in simulated (collision) data. In simulation the jet flavour is defined by matching to generator level partons. The $\varepsilon_b^{\mathrm{data}}$ is estimated with one of three methods described in the next section. In physics analyses, these p_{T}-dependent scale factors are then applied as weights per jet to reweigh the Monte Carlo simulation, to correct the b-tagging efficiency to the values measured in data.

2. b-tagging calibration methods

These proceedings present results of three calibration methods: tag counting, kinematic selection and kinematic fit. The first two can be successfully applied in both single lepton and dilepton $t\bar{t}$ channel, while the last one is by construction restricted to single lepton. They are described in Reference [3], where details about Monte Carlo samples used, event and object selection as well as background estimation can be found. In total twelve working points for four b-tagging algorithms were calibrated, here however only results for the MV1 b-tagging algorithm at an operating point corresponding to an average tagging efficiency on b-jets of 70% are presented. The MV1 algorithm is a neural network algorithm that uses as inputs information about secondary vertices and impact parameter of tracks associated with a jet. Because of its excellent performance it is the most commonly used b-tagging algorithm in ATLAS.

2.1 Tag counting method

The tag counting method makes use of the fact that each $t\bar{t}$ event is expected to contain exactly two b-jets. If there were no other sources of b-jets and if only b-jets were b-tagged, the expected number of events with two b-tagged jets would be $\varepsilon_b^2 N_{\mathrm{sig}}$ while the number of events with one b-tagged jet would be $\varepsilon_b(1-\varepsilon_b)2N_{\mathrm{sig}}$, where N_{sig} is the number of $t\bar{t}$ signal events.

In reality, the mean number of reconstructed (or tagged) b-jets in a $t\bar{t}$ event is not exactly two, since the b-jets from the top quark decays can be out of the detector acceptance, and additional b-jets can be produced through gluon splitting. Moreover, c-jets and light flavour jets can be tagged as b-jets and consequently contribute to the number of b-tagged jets in the event. These effects are taken into account by evaluating the expected fractions, F_{ijk}, of events containing i b-jets, j c-jets and k light-flavour jets that pass the event selection. The F_{ijk} fractions are estimated from Monte Carlo simulation and are derived separately for the $t\bar{t}$ signal and various background processes. The expected number of events with n b-jets is calculated as the sum of all contributions. The b-tagging efficiency can be extracted by fitting the expected event counts to the observed counts.

The expected number of $t\bar{t}$ signal events with n b-tagged jets, $< N_n >$, is calculated as

$$< N_n > = \sum_{i,j,k} \Bigg\{ (\sigma_{t\bar{t}} \mathscr{B} A_{t\bar{t}} \mathscr{L} F^{t\bar{t}}_{ijk} + N_{\text{bkg}} F^{\text{bkg}}_{ijk}) \times \\ \sum_{i'+j'+k'=n} \binom{i}{i'} {\varepsilon_b}^{i'} (1-\varepsilon_b)^{i-i'} \binom{j}{j'} {\varepsilon_c}^{j'} (1-\varepsilon_c)^{j-j'} \binom{k}{k'} {\varepsilon_l}^{k'} (1-\varepsilon_l)^{k-k'} \Bigg\}, \quad (2.1)$$

where i, j and k (i', j' and k') represent the number of pretagged (tagged) b-, c- and light-flavour jets. $\mathscr{B}$ is the branching fraction to each final state, $A_{t\bar{t}}$ is the event selection efficiency for that particular final state and $\mathscr{L}$ is the integrated luminosity. The binomial coefficients account for the number of combinations in which the n-tags can be distributed. The efficiencies to mis-tag a c-jet or light-flavour jet as a b-jet, ε_c and ε_l respectively, are fixed to the values found in Monte Carlo simulation but with data driven scale factors applied [4]. N_{bkg} is the number of background events.

To measure b-tagging efficiency as a function of p_{T}, the n-tag distributions and F_{ijk} fractions are computed in p_{T} bins using only the jets in each event that fall in a given p_{T} bin. Independent fits are performed for each p_{T} bin. Since a single event can contribute to several p_{T} bins, this method maximises the use of the available jets in the sample.

2.2 Kinematic selection method

The kinematic selection method relies on the knowledge of the flavour composition of the $t\bar{t}$ signal and background samples, and extracts the b-tagging efficiency by measuring the fraction of b-tagged jets in data, $f_{b-\text{tag}}$. Given an expected fraction of b-, c- and light-flavour jets, as well as the c- and light-flavour jet mis-tag efficiencies, the b-tagging efficiency of b-jets in data can be expressed as

$$\varepsilon_b = \frac{1}{f_{b-\text{jets}}} \cdot \left(f_{b-\text{tag}} - \varepsilon_c f_{c-\text{jets}} - \varepsilon_l f_{l-\text{jets}} - \varepsilon_{\text{fake}} f_{\text{fake}} \right). \quad (2.2)$$

Here, $f_{b-\text{jets}}$, $f_{c-\text{jets}}$ and $f_{l-\text{jets}}$ are the expected fractions of b-, c- and light-flavour jets from simulated events and the ε_c and ε_l are the mis-tag efficiencies as described in Section 2.1. f_{fake} is the fraction of jets from the fake lepton (in the dilepton channel) or multijet (in the single lepton channel) background and is determined from data. The flavour fractions are calculated with respect to the sum of jets from Monte Carlo simulation and follow the relation $f_{b-\text{jets}} + f_{c-\text{jets}} + f_{l-\text{jets}} + f_{\text{fake}} = 1$. The expected fraction of b-tagged fake lepton or multijet events, $\varepsilon_{\text{fake}}$, is estimated from data control regions enriched in events with fake leptons or multijet events respectively. In the single lepton channel is it a region of low $E_{\text{T}}^{\text{miss}}$ and in dilepton channel events in which the charge of both leptons have the same sign are used.

To increase the signal-to-background ratio as well as the purity of the analysed sample, the events in the single lepton channel are additionally required to have at least one jet b-tagged with the

MV1 algorithm at operating point of 70%. In the dilepton analysis, the b-jet fraction of the sample is increased by using only the two leading jets in each event, as this reduces the contamination of c- and light-flavour jets originating from gluon radiation.

2.3 Kinematic fit method

The kinematic fit method is based on the selection of a high purity b-jet sample by applying a kinematic fit to the events passing some basic $t\bar{t}$ selection criteria. The kinematic fit performed with the hypothesis of a single lepton $t\bar{t}$ decay event topology provides a mapping between the reconstructed jets to the quarks originating from the hard process. The fit, based on a χ^2 minimization, infers a best estimate for the measured observables. Obeying constraints from the invariant masses of both top quarks and W bosons, and assuming the missing transverse momentum to be solely due to the neutrino, leaves its transverse component as the only unmeasured parameter. All permutations of four jets out of the six leading jets are fitted and the one with the lowest value of χ^2 is retained.

While the kinematic fit selects the correct jet association with a good efficiency, the permutation with the lowest χ^2 in the event is not always the correct one. In addition to the combinatorial background the sample still contains physics background, such as single top and W+jets events. The single lepton sample can be further purified using using an in situ background estimate. Here, the sample is divided into two orthogonal subsamples based on the tag weights of the jets on the hadronic side of the event (where $W \to jj$): the first subsample (*signal sample*) is enriched in correct permutations, while the second subsample (*background sample*) is enriched in incorrect mappings. The amount of background is estimated by normalizing the χ^2 distributions of both samples and the shape is taken from the background sample. The b-tagging efficiency is measured from background-subtracted tag weight distribution of the jet assigned to the b-quark of leptonic side of the event (where $W \to l\nu$).

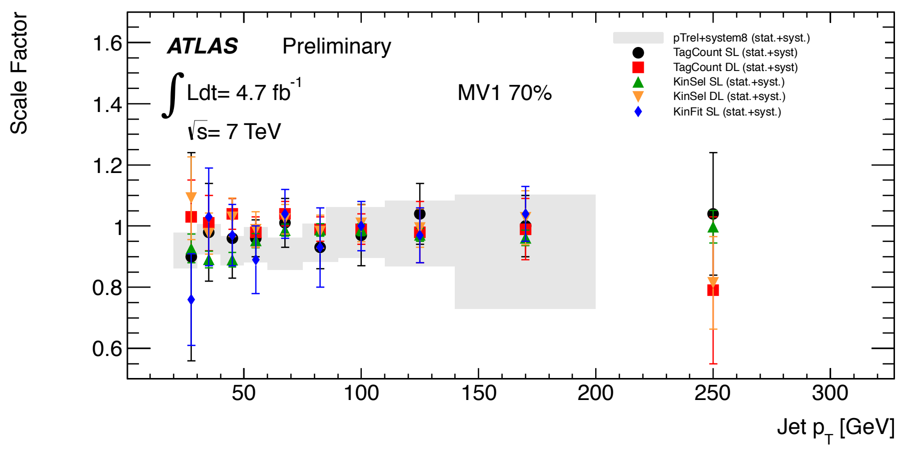

Figure 1: Comparison of all $t\bar{t}$-based scale factors with the scale factor from the combination of system8 and $p_{\mathrm{T}}^{\mathrm{rel}}$ calibration methods, which are based on dijet events [3].

3. Results

The scale factors, including all systematic and statistical uncertainties, are summarised in Table 1 and the highest and lowest values of statistical and total systematic uncertainty are presented in Table 2. Figure 1 demonstrates the compatibility of all calibration methods. The individual $t\bar{t}$ based calibration methods, using different selections (single lepton and dilepton) and based on different calibration methods (tag counting, kinematic selection and kinematic fit), are consistent with each other within uncertainties. Furthermore, all results are in good agreement with the earlier calibration methods based on dijets and extend the range of the scale factors in p_{T} up to 300 GeV. The results of the combination of the system8 and $p_{\mathrm{T}}^{\mathrm{rel}}$ methods [2] based on a dijet sample are also shown in Figure 1.

p_{T} [GeV]	TagCount SL	TagCount DL	KinSel SL	KinSel DL	KinFit SL
25-30	0.90±0.34	1.03±0.12	0.93±0.10	1.04±0.13	0.76±0.15
30-40	0.98±0.16	1.01±0.09	0.89±0.05	0.96±0.07	1.03±0.16
40-50	0.96±0.13	1.04±0.05	0.89±0.05	1.01±0.06	0.97±0.10
50-60	0.96±0.06	0.98±0.05	0.95±0.05	0.97±0.06	0.89±0.11
60-75	1.01±0.08	1.04±0.04	0.98±0.05	1.01±0.05	1.04±0.08
75-90	0.93±0.07	0.99±0.04	0.98±0.05	0.96±0.06	0.93±0.13
90-110	0.97±0.10	0.99±0.05	0.98±0.05	0.98±0.06	1.00±0.08
110-140	1.04±0.10	0.98±0.10	0.97±0.05	0.98±0.06	0.97±0.09
140-200	1.00±0.10	0.99±0.10	0.97±0.07	0.99±0.09	1.04±0.09
200-300	1.04±0.20	0.79±0.24	1.00±0.12	0.82±0.15	

Table 1: Scale factors for the MV1 algorithm at 70% working point measured with data of integrated luminosity of 4.7 fb^{-1} at the center of mass energy $\sqrt{s} = 7$ TeV with the tag counting (TagCount), kinematic selection (KinSel) and kinematic fit (KinFit) method in single lepton (SL) and dilepton (DL) channels. The uncertainties are symmetrised and include the statistical uncertainty and all systematic uncertainties.

	TagCount SL	TagCount DL	KinSel SL	KinSel DL	KinFit SL
Stat. unc.	3.7% – 6.4%	2.9% – 9.4%	1.9% – 5.1%	2.1% – 10.7%	5.5% – 17.6%
Syst. unc.	6.5% – 27.2%	5.1% – 23.8%	4.3% – 10.6%	4.2% – 15.1%	6.1% – 12.5%

Table 2: The range of relative statistical and systematic uncertainties throughout the jet p_{T} bins for tag counting (TagCount), kinematic selection (KinSel) and kinematic fit (KinFit) method in single lepton (SL) and dilepton (DL) channels.

4. Systematic uncertainties

In this part only the most relevant systematic uncertainties on the measured scale factors are discussed, the full list can be found in Reference [3].

Jet energy scale [5], jet energy resolution and jet reconstruction efficiency variations may cause jet to migrate between p_{T} bins, which not only affects the numbers of jets in particular bins, but

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also influences correction factors that are applied to simulations, such as corrections of the tagging efficiencies for light and c-jets, ε_l and ε_c, which depend on p_{T} and η of jet [6, 7]. As a result jet energy scale, jet energy resolution and jet reconstruction efficiency are the dominant uncertainties. The uncertainties caused by variations of ε_l and ε_c are smaller, but also significant.

All methods apart from the kinematic fit strongly depend on simulations and thus uncertainties related to parton shower modeling, choice of generator, amount of initial and final state radiation are high and can lead to 10-15% relative uncertainty on the measured scale factor.

Another significant uncertainty comes from factors that change the flavour composition of analysed sample, such as background description. In all analyses, the dominant backgrounds are estimated using data driven techniques. However, the flavour composition of all background samples except W+jets is taken from simulation and not assigned a systematic uncertainty. To estimate the uncertainty originating from flavour composition of W+jets background, fractions of $Wb\bar{b}$+jets, $Wc\bar{c}$+jets, Wc+jets and W+light jets are varied within their uncertainties.

5. Conclusion

The b-tagging efficiency scale factors are close to unity for all values of jet p_{T}. The total uncertainties are ranging from 5% to 15% when subdividing the data into bins of jet p_{T}. With the integrated luminosity of 4.7 fb^{-1} collected in 2011 at the center of mass energy $\sqrt{s} = 7$ TeV the tag counting and kinematic selection methods are dominated by systematic uncertainties while the measurement using the kinematic fit method is statistically limited. It is the first time when the $t\bar{t}$ calibration methods became competitive with methods based on dijet events.

References

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