Jet Energy Scale Uncertainties in ATLAS

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Abstract. The first proton-proton collisions at a centre of mass energy of \( \sqrt{s} = 7 \) TeV have been used by the ATLAS experiment to achieve an accuracy of the jet energy measurement between 2% and 4% for jets transverse momenta between 20 GeV and 2 TeV and in the absolute pseudorapidity range up to 4.5. The jet energy scale uncertainty is derived from measurements in situ of the calorimeter single response to hadrons together with systematic variations in the Monte Carlo simulation. The transverse momentum balance between a central and a forward jet in events with two high transverse momenta jets is used to set the jet energy uncertainty in the forward region. The obtained uncertainty is confirmed by in-situ measurements. Jets in the TeV energy range have been tested using a system of well calibrated jets at low transverse momenta against high transverse momenta jets. A further reduction of the jet energy scale uncertainty between 1% and 2% for jets transverse momenta above 30 GeV has been achieved using data from the 2011 run based on an integrated luminosity of 5 fb\(^{-1}\).

1. Introduction
Since Spring 2010, the ATLAS detector [1] has been collecting data from proton-proton (p-p) collisions at a center-of-mass energy \( \sqrt{s} = 7 \) TeV delivered by the Large Hadron Collider (LHC) at CERN. Understanding and measuring the performance of jets is crucial for the physics at LHC: the energy of jets (jet energy scale, or JES) is input to many analyses, and its uncertainty is the dominant experimental uncertainty for measurements such as the di-jet cross section, the top quark mass and new physics searches with jets and missing transverse momentum in the final state. In the following, the determination of the jet energy scale and its systematic uncertainty for inclusive jets in the ATLAS experiment is described. Sections 2-4 of this note describe the calorimeters, the Monte Carlo (MC) simulation framework, and the jet reconstruction. Sections 5-6 describe the technique used to calibrate the JES. Sections 7-8 describe the sources of systematic uncertainties for the JES and their derivation using simulated and collision data, the conclusions are given at the end.

2. The ATLAS Detector
The ATLAS detector [1] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and nearly \( 4\pi \) coverage in solid angle. The layout of the detector features four superconducting magnet systems, which comprise a thin solenoid surrounding the inner tracking detectors and three large toroids supporting a large muon spectrometer. The calorimeters are of particular importance to the work here presented. In the pseudorapidity region \( |\eta| < 3.2 \), high-granularity liquid-argon (LAr) electromagnetic sampling calorimeters are used. An iron-scintillator tile calorimeter provides hadronic coverage over \( |\eta| < 1.7 \). The end-cap and forward regions, spanning \( 1.5 < |\eta| < 4.9 \), are instrumented with LAr calorimetry for both electromagnetic and hadronic measurements.
3. Data and Monte Carlo simulation

The analysis here presented is based on data collected in the 2010 run at $\sqrt{s} = 7$ TeV for a total integrated luminosity of 38 pb$^{-1}$. Preliminary results obtained using the 2011 run for a total integrated luminosity of 5 fb$^{-1}$ are also briefly presented.

The MC simulated events (default MC) are produced with various event generators. The inclusive quantum chromodynamics (QCD) jet events are generated using PYTHIA [2] and ALPGEN [3].

PYTHIA is an event generator used to simulate non-diffractive p-p collisions. The parton distribution function (PDF) set used in PYTHIA is MRST LO* [4]. The tune of PYTHIA is done by a set of parameters denoted as ATLAS MC10 and is described elsewhere [5]. An independent tune of PYTHIA is PERUGIA2010 that better reproduces jet shapes and hadronic event shapes [6].

ALPGEN is a leading order matrix-element generator for hard multi-parton processes in hadronic collisions. It is interfaced to the HERWIG generator [7] to produce parton showers in leading-log approximation. Parton showers are matched to the matrix-element with the MLM matching scheme [8]. Soft multiple parton interactions are modelled using JIMMY [9] and the ATLAS MC09 tune [10]. The PDF set used in ALPGEN is CTEQ6L1 [11].

After all the MC events are generated, the GEANT4 software toolkit [12] is used to propagate the particles through the detector and to simulate their interactions with the detector material. The simulated detector signals are then reconstructed with the same reconstruction software used for the data.

4. Jet reconstruction

Jets are reconstructed [13] using the anti-$k_T$ algorithm [14] with values of the radius parameter $R = 0.4$ or $R = 0.6$. The four-momentum recombination scheme is used. Jet finding is done using the event-coordinates $y-\phi$, while jet corrections and performance studies are often done using the detector coordinates $\eta-\phi$. The threshold on the jet transverse momentum ($p_T^{\text{jet}}$) reconstruction is $p_T^{\text{jet}} > 7$ GeV. The input to jets reconstructed in the calorimeter (called calorimeter jets) can be topological energy clusters (topo-clusters) [15] or towers [13] of calorimeter cells. In the following only results with jets built from topo-clusters are presented. In addition to calorimeter jets, track jets built from charged particle tracks originating from the primary hard scattering vertex are used to study close-by jet effects. These jets are less sensitive to effects of multiple p-p collisions within the same bunch crossing (pile-up). Finally MC simulation jets (called truth jets) are built from stable particles defined to have a proper lifetime longer than 10 ps, excluding muons and neutrinos.

5. Jet energy calibration scale

Reconstructed jets are first calibrated to the electromagnetic (EM) scale. The EM energy scale is established using test-beam measurements [16, 17, 18, 19, 20]. This EM energy scale accounts correctly for the energy of photons and electrons, but it does not correct for instrumental (detector) effects including calorimeter non-compensation, energy losses in inactive regions of the detector (dead material), particles which are not totally contained in the calorimeter (leakage), particles that fall out of the reconstructed jet but are included in the truth jet, and inefficiencies in calorimeter clustering and jet reconstruction. The goal of the JES calibration is to correct the energy and momentum of the jets measured in the calorimeter. The choice of JES calibration for the first ATLAS data is a jet by jet correction applied as a function of the $p_T^{\text{jet}}$ and $|\eta|$ (called simply JES). Beside the above described EM calibrated jets, there are other more sophisticated jet calibration schemes developed in ATLAS like the local calibration weighting (LCW) scheme [21], and the global sequential calibration scheme [13]. All these methods require a final JES calibration, with the resulting final calibrated jets referred to as
EM+JES, or LCW+JES jets, etc. The more sophisticated jet calibration methods mentioned above are under commissioning and will be part of the default energy scale in future.

6. Jet energy calibration in the EM+JES scheme
The EM+JES calibration scheme applies $p_T^{jet}$ and $|\eta|$ corrections to jets reconstructed at the EM scale. The additional energy due to pile-up is corrected before the hadronic energy scale is restored. The EM+JES calibration scheme consists of three main subsequent steps. As a first step the average additional energy due to pile-up is subtracted from the energy measured in the calorimeters using correction constants obtained from in situ measurements. In the second step the direction of the jet is corrected such that the jet originates from the main primary vertex of the interaction instead of the geometrical centre of the detector (vertex correction). Finally in the third step the jet energy and direction as reconstructed in the calorimeters are corrected using constants derived from the comparison of the kinematic observables of reconstructed jets and those from truth jets (jet energy and direction correction). Once the jet origin and energy corrections are made, the origin-corrected jet $\eta$ is further corrected for a bias due to poorly instrumented regions of the calorimeter [13]. This correction is in general small ($\Delta \eta < 0.01$) for most regions of the calorimeter but larger in the transition region between the barrel and end-cap calorimeters.

7. Jet energy scale uncertainties for the EM+JES scheme
The systematic uncertainty in the well-understood central barrel region is derived combining information from the single hadron response measured in situ and single pion test-beam measurements [13], uncertainties on the amount of material of the detector, the description of the electronic noise, and the MC modelling used in the event generation. Dedicated MC samples are generated with different conditions with respect to the standard MC sample. These variations are expected to provide an estimate of the systematic effects contributing to the JES uncertainty. The $\eta$ bins used for the estimate of the JES uncertainty divide the detector in eight main $\eta$-regions [13]. The JES systematic uncertainty for all jets with $|\eta| > 0.8$ is determined using the JES uncertainty for the central barrel region $(0.3 < |\eta| < 0.8)$ as a baseline. This choice is motivated by the good knowledge of the detector geometry in the central region, and by the use of pion response measurements in beam tests [16, 17, 18, 19, 20]. This section describes the sources of systematic uncertainties and their effect on the response of EM+JES calibrated jets.

7.1. Uncertainty in the JES calibration
After the jets are calibrated, the jet energy and the jet response still show at low $p_T$ slight deviations from unity when the MC simulated jet is compared to its matched truth jet. Any deviation from unity in the jet energy or $p_T^{jet}$ response after the application of the JES to the MC simulated sample implies that the kinematic observables of the calibrated calorimeter jet are not restored to that of the corresponding truth jet (non-closure). The non-closure is mainly due to the application of the same correction factor for jet energy and $p_T^{jet}$. The systematic uncertainty due to the non-closure of the JES calibration is taken as the larger deviation of the response in either jet energy or $p_T^{jet}$ from unity.

7.2. Uncertainty on the calorimeter response
The response and corresponding uncertainties for single particles interacting in the calorimeters can be used to derive the JES uncertainty in the central calorimeter region as detailed in Ref [22]. In the simulation the true calorimeter energy deposits in each calorimeter cell can be traced to the particles generated in the collision. The uncertainty in the calorimeter response to jets can
then be obtained from the response uncertainty of the individual particles constituting the jet. The *in situ* measurement of the single particle response detailed in Ref. [22] significantly reduces the uncertainty due to the limited knowledge of the detector geometry, in particular that due to the description of the dead material, and the modelling of the way particles interact in the detector.

### 7.3. Uncertainties due to the detector simulation

The topo-clusters used to build jets are constructed based on a signal-to-noise ratio of energy. Discrepancies between the simulated noise and the real noise in data can lead to differences in the cluster shapes and to the presence of fake topo-clusters. For data, the noise can change over time, while the noise RMS used in the simulation is fixed at the time of the production of the simulated data sets. These effects can lead to biases in the jet reconstruction and calibration. The effect of the calorimeter cell noise mis-modelling on the jet response is estimated by reconstructing topo-clusters in MC using the noise RMS measured from data. The response for jets reconstructed with modified noise thresholds are compared with the response for jets reconstructed in the same sample using the default MC noise thresholds. The maximal observed change in jet energy or $p_T^{jet}$ response is used to estimate the uncertainty on the jet energy measurement due to the calorimeter cell noise modelling. The JES is also affected by possible deviations in the material description and in the geometry assumed for the detector as simulated in the default MC sample. Specific MC simulation samples have been produced using distorted geometries. The uncertainty contribution due to the description of the detector material is estimated by comparing the EM+JES jet response in the default MC simulation sample with the jet response in MC simulation samples with distorted geometries.

### 7.4. Uncertainties due to the event modelling in Monte Carlo generators

The contributions to the JES uncertainty from the modelling of the fragmentation, the underlying event and other choices in the event modelling of the MC event generator are obtained from samples based on ALPGEN+HERWIG+JIMMY and the PYTHIA PERUGIA2010 tune. By comparing the baseline PYTHIA sample to the PYTHIA PERUGIA2010 tune, the effects of soft physics modelling are tested. The ALPGEN MC uses different theoretical models for all steps of the event generation and it is used to estimate additional systematic variations. The ratios of the baseline MC simulated jet to that of the two above MC jet samples are used to estimate the systematic uncertainty to the JES.

### 7.5. In situ intercalibration using events with di-jet topologies

The response of the calorimeters to jets depends on the jet direction, due to the different calorimeter technology and to the varying amounts of material in front of the calorimeters. A calibration is therefore needed to ensure a uniform calorimeter response to jets. Since this is achieved by applying correction factors derived from MC simulations, such corrections need to be validated *in situ*. The relative jet calorimeter response and its uncertainty is studied by comparing the $p_T^{jet}$ of a well-calibrated central jet and a jet in the forward region in events with only two high $p_T^{jet}$ (di-jets). The JES uncertainty in the region $|\eta| < 0.8$ obtained using the single particle response and systematic variations of the MC simulations, is transferred to the forward regions using the results from the di-jet balance method (\(\eta\)-intercalibration method). These uncertainties are then included in the final uncertainty [13]. The uncertainty measurements are performed with average $20 \text{ GeV} < p_T^{jet} < 110 \text{ GeV}$. The uncertainty for $p_T^{jet} > 100 \text{ GeV}$ is taken as the uncertainty of the last available $p_T^{jet}$-bin. The uncertainties are evaluated separately for anti-\(k_T\) jets with $R = 0.4$ and $R = 0.6$, and are found to be slightly larger for $R = 0.4$. 

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7.6. Uncertainties due to multiple proton-proton collisions

The uncertainty for the pile-up corrections can be obtained by studying the jet response with respect to the transverse momenta ($p_T$) of the track jets as a function of the number of primary vertices (NPV). In the case of NPV = 2 the uncertainty due to pile-up for central jets with $p_T = 20$ GeV and $|\eta| < 0.8$ is about 1%, while it amounts to about 2% for jets with $2.1 < |\eta| < 2.8$ and to less than 2.5% for all jets with $|\eta| < 4.5$. In the case NPV = 3 the pile-up uncertainty is approximately twice that of NPV = 2, and with NPV = 4 the uncertainty for central, endcap and forward jets is less than 3%, 6% and 8%, respectively. The pile-up uncertainty needs to be added separately to the estimate of the total JES uncertainty.

7.7. Summary of JES systematic uncertainties

The total JES uncertainty is derived by considering all the individual contributions described in the previous sections. In the central region ($|\eta| < 0.8$) for each ($p_T^{jet}$, $\eta$)-bin, the uncertainty contributions from the calorimeter, the jet non-closure, and systematic MC simulation variations are added in quadrature. For $|\eta| > 0.8$ the $\eta$-intercalibration contribution is estimated for each $\eta$ bin in the endcap region. The $\eta$-intercalibration contribution is added in quadrature to the total JES uncertainty determined in the 0.3 < $|\eta|$ < 0.8 region to estimate the JES uncertainty for jets with $|\eta| > 0.8$, with the exception of the non-closure term that is taken from the specific $\eta$-region. For $p_T^{jet} < 45$ GeV, this choice leads to partially double counting the contribution from the dead material uncertainty, but it leads to a conservative estimate in a region where it is difficult to estimate the accuracy of the material description. The contribution to the uncertainty due to pile-up is added separately, depending on the NPV in the event. Figure 1 shows the final fractional JES systematic uncertainty and its individual contributions as a function of $p_T^{jet}$ for anti-$k_{\perp}$ jets with $R = 0.6$ for three selected $\eta$ regions. The fractional JES uncertainty in the central region amounts to 2% - 4% for $p_T^{jet} < 60$ GeV, and it is between 2% and 2.5% for 60 GeV < $p_T^{jet}$ < 800 GeV. For jets with $p_T^{jet} > 800$ GeV, the uncertainty ranges from 2.5% to 4%. The uncertainty amounts to up to 7% and 3%, respectively, for $p_T^{jet} < 60$ GeV and $p_T^{jet} > 60$ GeV in the endcap region, where the central uncertainty is taken as a baseline and the uncertainty due to the intercalibration is added. In the forward region, a 13% uncertainty is assigned for $p_T^{jet} = 20$ GeV. The increased uncertainty is dominated by the modelling of the soft physics in the forward region that is accounted for in the $\eta$-intercalibration contribution. This uncertainty contribution is estimated conservatively. The same study has been repeated for anti-$k_{\perp}$ jets with $R = 0.4$ and the JES uncertainty for these jets is comparable to that obtained for anti-$k_{\perp}$
jets with $R = 0.6$, it is between $\approx 4\%$ (8\%, 14\%) at low $p_T^{jet}$ and $\approx 2.5\%$ - 3\% (2.5\% - 3.5\%, 5\%) for jets with $p_T > 60$ GeV in the central (endcap, forward) region. These results have been confirmed by in-situ validation studies [22].

Recent studies done using the 2011 $5 \text{fb}^{-1}$ data with increased pile-up conditions and the in-situ direct transverse momentum balance method described in Ref. [23], show for anti-$k_T$ jets with $R = 0.4$ JES uncertainties between 1\% and 2\%. The precision achieved with this in situ method is about 10\% at low $p_T^{jet}$ and 1\% to 2\% for $p_T^{jet} > 30$ GeV. Similar results are obtained using EM+JES or LCW+JES jets.

8. Conclusions

The JES calibration and its relative systematic uncertainty have been estimated for inclusive jets produced in p-p collisions at $\sqrt{s} = 7$ TeV. The jets are reconstructed with the anti-$k_T$ algorithm applied to topological energy clusters reconstructed in the ATLAS calorimeters. The method used to estimate the JES and its uncertainty relies on the MC simulation of inclusive QCD jets events. The procedure to calibrate the JES in different ranges of the jet kinematic variables has been described step-by-step for $20 \text{GeV} < p_T^{jet} < 800$ GeV and $|\eta| < 4.5$. The contributions to the relative systematic uncertainty from the jet kinematic variables, the detector performance, the MC simulation model and the data taking conditions have been described and analyzed. For the low pile-up conditions of the 2010 data taking period, the JES relative uncertainty is on average $(3 - 4)\%$ and is maximum $(\sim 10\%)$ for jets with $p_T^{jet}$ of about 20 GeV in the forward region, $|\eta| > 3.2$. In situ studies have been performed using the much larger data sample collected in 2011 reaching a JES precision of about 10\% at low $p_T^{jet}$ and 1\% to 2\% for $p_T^{jet} > 30$ GeV.

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