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In Situ Measurements of the Jet Energy Scale in ATLAS

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Abstract. Hadron jets are the most commonly observed objects in p-p collisions at the Large Hadron Collider at CERN. Because of this, they are part of the final state of almost any process, and are an important probe in searches for extensions of the Standard Model.

A precise knowledge of the energy calibration for jets is difficult to ascertain for a number of reasons, and is a necessary ingredient in the ATLAS experimental program. This report presents in situ techniques and results for the jet energy scale at ATLAS using recent collision data. This report demonstrates an understanding of the necessary jet energy corrections to within $\approx 4\%$ in the central region of the calorimeter.

1. Introduction

Over the course of 2010, the ATLAS detector [1] collected data from proton-proton collisions delivered by the Large Hadron Collider (LHC) at a center-of-mass energy of $\sqrt{s} = 7$ TeV. Understanding and measuring the performance of jets in these data is crucial for many measurements with ATLAS. Indeed, the uncertainty of the jet energy scale (JES) is the dominant experimental uncertainty for numerous physics results, for example the cross-section measurement of the inclusive jets, dijets [2] and multijets, vector boson accompanied by jets [3], and for new physics searches with jets in the final state as in [4], to name a few.

An estimate of the JES uncertainty has been derived in Ref. [5] using in situ measurements of the single hadron response [6]. This report summarizes the JES systematic uncertainty based on analysis of the first year of ATLAS data, and results from the JES uncertainty validation using in situ techniques.

1.1. The ATLAS Detector

The ATLAS detector consists of a tracking system immersed in a 2 T solenoidal magnetic field up to a pseudorapidity[1] $|\eta| < 2.5$, sampling electromagnetic and hadronic calorimeters up to $|\eta| < 4.9$, and muon chambers in a toroidal magnetic field. A more detailed description of the ATLAS experiment can be found elsewhere [1]. Jets are reconstructed using the ATLAS calorimeters. The electromagnetic calorimeters use liquid argon as the active material and lead for the absorbers, and they cover the fiducial region up to $|\eta| < 3.2$. Liquid argon presamplers

[1] The ATLAS Coordinate System is a right-handed system with the x-axis pointing to the centre of the LHC ring, the y-axis pointing upwards and the z-axis following the beam direction. The pseudorapidity η is an approximation for rapidity y in the high energy (massless) limit, and is related to the polar angle θ by $\eta = -\ln(\tan \frac{\theta}{2})$.

situated in front of the electromagnetic calorimeter allow for corrections of upstream energy loss due to the presence of the barrel solenoid and inner detector cryostat. The hadronic calorimeters employ plastic scintillator and steel for the barrel and extended barrels (covering $0 < |\eta| < 0.8$ and $0.8 < |\eta| < 1.7$, respectively), and liquid argon and copper for the endcaps ($1.5 < |\eta| < 3.2$). The forward calorimeter is a liquid argon and tungsten/copper detector, and extends the calorimetry up to $|\eta| < 4.9$ for nearly hermetic coverage.

1.2. Jet Reconstruction

Jets are reconstructed by the FastJet software [7], using the anti-k_t algorithm [8] with distance parameters $R = 0.6$ and $R = 0.4$. In the following, jets with distance parameter $R = 0.6$ are discussed. The results for jets with $R = 0.4$ are similar and are excluded for brevity. The constituents of calorimeter jets are topological clusters (topo-clusters) [9] that group together calorimeter cells and are designed to follow the shower development. The topo-cluster algorithm starts from a seed cell, whose signal-to-noise ratio is above a threshold of 4. Cells that are topologically connected to the seed and that have a signal-to-noise ratio of at least 2 are included iteratively, and finally all directly neighboring cells are added to the topo-cluster. A topo-cluster is defined to have an energy equal to the energy sum of all the included cells, zero mass and a reconstructed direction along the unit vector originating from the center of the detector, pointing to the energy-weighted topo-cluster barycenter. Note that the ATLAS calorimetry is designed with a pointing geometry that projects to the center of the coordinate system.

2. Calibration of the Jet Energy Scale

The goal of the JES calibration is to correct the E and $\vec{p}$ of jets measured in the calorimeter, to the corresponding particle reference jets (which are jets built from all final state particles in an event, except muons and neutrinos). This calibration must account for a number of detector effects:

- calorimeter response non-compensation ($e/h > 1.3$ in ATLAS);
- inactive regions (sometimes known as dead material) and punch through, in which the calorimeter does not fully contain the shower;
- calorimeter signal definition inefficiencies due to clustering noise thresholds, or jet width parameter;
- additional energy deposited in the reconstructed jet from pileup.

For the 2010 analyses, ATLAS has employed a technique, known as `EMJES`, which is based on calibration factors derived from Monte Carlo simulations. The steps involved in this scheme are shown in Figure 1. The calibration begins at the calorimeter electromagnetic scale, which is validated with $Z^0 \rightarrow e^+e^-$ events and minimum-ionizing muons. Then, a correction to account for the additional energy contribution due to pileup is applied. This correction is derived from minimum bias data as a function of the number of reconstructed primary vertices in the event and the jet η. It takes into account the average additional energy deposited in a fixed grid of 0.1×0.1 in the (η, ϕ)-plane (called towers) and the average number of such towers in a jet. The average energy deposition per tower and average tower multiplicity per jet are shown in Figure 2.

Because the jet reconstruction is performed using topoclusters assuming an interaction point at $(x, y, z) = (0, 0, 0)$, an additional correction is needed to adjust the momentum of the jet such that the momentum unit vector points from the leading primary vertex in the event[2] from which the jet originates.

[2] The leading primary vertex is defined here as the reconstructed vertex with the highest $\sum_{i \in \{\text{tracks}\}} \left(p_T^{(i)}\right)^2$.

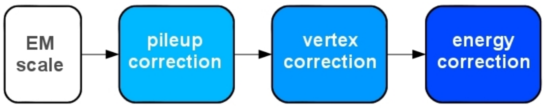

Figure 1. The various steps involved in the EMJES calibration scheme: the raw electromagnetic scale, a correction for pileup, a correction to the primary vertex from the detector centroid (0, 0, 0), and finally a correction for the calorimeter response.

The final step of the EMJES jet calibration restores the reconstructed jet energy to the energy of the reference jet in the Monte Carlo simulations. Since pile-up effects have already been corrected for, the simulation samples used to derive the calibration do not include multiple proton-proton interactions within the same bunch crossing. The correction is defined in a fine η segmentation and is applied as a simple scaling factor $C = C(E, \eta)$, where E and η are the energy and pseudo-rapidity of the jet with the first two corrections applied. This correction is shown in Figure 3.

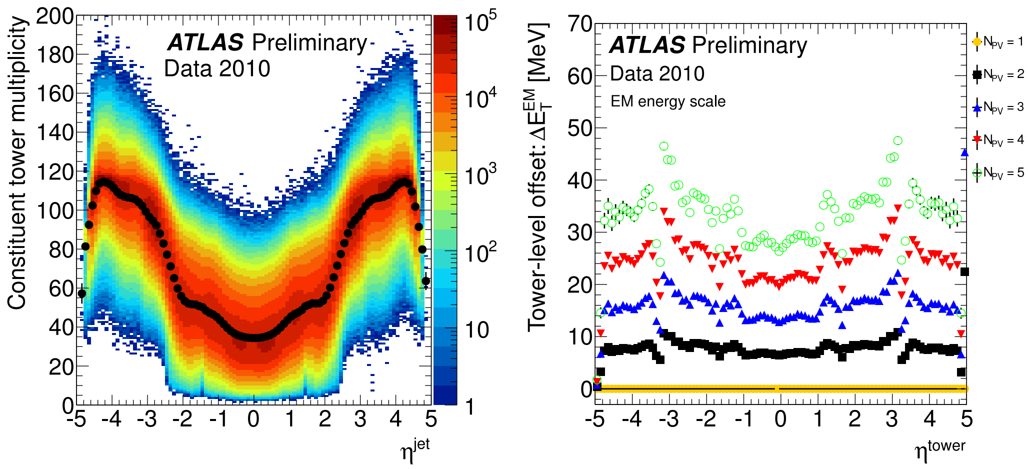

Figure 2. The average tower multiplicity in each jet as a function of pseudo-rapidity (left) and the average tower offset E_T in minimum bias events, shown for various numbers of reconstructed primary vertices (i.e., different levels of pileup), and as a function of the η centroid of the tower (right).

3. Systematic Uncertainties

The overall strategy used to ascertain the validity of the calibration procedure [10], is to evaluate the jet energy scale by roughly factorizing the components of EMJES, verifying that the Monte Carlo description of each component in the data is correct. In other words, the role of the in situ measurements is to provide systematic uncertainties on the jet energy scale. Contributions to the overall JES systematic uncertainty arising from non-closure of the calibration in the simulations, jet fragmentation uncertainty, effects of the noise thresholds used in clustering, or from mismodeling of the inner detector in the detector simulation, are derived from dedicated simulation studies. The largest components of the uncertainty, arising from description of the calorimeter response, are derived with two data-driven techniques: single particle response from E/p and test-beam measurements in the central region ($|\eta| < 0.8$), and relative calibration with QCD dijet events for the endcap and forward regions ($|\eta| > 0.8$).

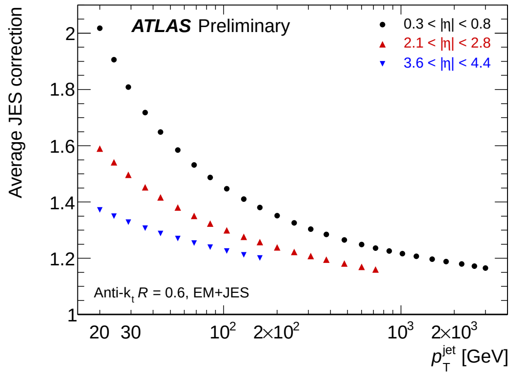

Figure 3. The energy correction factor C described in the text, shown as a function of jet p_T for various η ranges.

3.1. Single Particle Response

The core idea is to measure the response for isolated single particles by comparing the energy (calorimeter) and momentum (tracking) measurements, namely E/p. Then, pseudo experiments in Monte Carlo simulations are employed to extrapolate the single particle response uncertainty to a jet response uncertainty. Although the translation from single particles to a jet context is non-trivial, it has been exhaustively cross-checked and found to have small uncertainty.

For charged particles in the momentum range $0.5 < p < 20$ GeV the E/p measured in situ is used to determine the response [6]. In order to account for the neutral background component to the measured E/p, the background is estimated by looking in an annulus $0.1 < \Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.2$ around minimum ionizing particles in the EM calorimeter. This contribution is then subtracted from the measured E/p ratio. A comparison of E/p in data to that in Monte Carlo is shown in Figure 4.

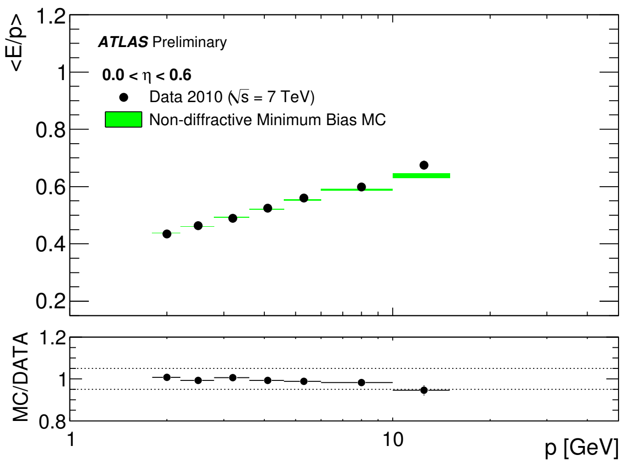

Figure 4. The E/p measured in data (black points) compared to the same measurement in Monte Carlo simulations (shaded green histogram), as a function of particle momentum. The ratio of data to Monte Carlo is also shown, in which the dashed lines are located at $\pm 5\%$ of unity.

The response for charged particles in the momenutm range $20 < p < 400$ GeV is estimated from test-beam measurements using a nearly exact replica of a slice of the ATLAS detector. An uncertainty that accounts for the differences in the test-beam setup compared to the ATLAS detector "as built" is included in this measurement.

Additional uncertainties that are included in the single particle extrapolation account for effects related to the calorimeter acceptance, uncertainties related to particles with $p > 400$ GeV, and uncertainties for the response of neutral hadrons.

3.2. QCD Dijet Relative Response

For jets in the region $|\eta| > 0.8$, the response for the central region is extrapolated using a dijet balance technique [11]. This procedure derives a calibration for a jet under the assumption of momentum balance of the dijet system at the particle (reference) level. Supposing that in a QCD dijet event one of the jets lands in η bin i and the other in bin j, one can define an event asymmetry

$$A_{ij} = \frac{p_T^i - p_T^j}{\frac{1}{2}\left(p_T^i + p_T^j\right)} \tag{1}$$

so that $R_{ij} = \frac{2-\langle A_{ij}\rangle}{2+\langle A_{ij}\rangle}$ is the average ratio of the relative response coefficients, α_i/α_j, over many events. After selecting events with a QCD dijet topology, one can calculate a matrix R_{ij} and minimize

$$S = \sum_{i<j}\left(\frac{1}{\Delta R_{ij}}(\alpha_j\, R_{ij} - \alpha_i)\right)^2 + \chi(\{\alpha_i\}), \tag{2}$$

where χ is a constraint on the central response corrections (which are set to unity, since the central response is fixed) and ΔR_{ij} is the matrix of statistical uncertainties for R_{ij}. Minimizing S results in coefficients $\{\alpha_i\}$ that equalize the calorimeter response in all η bins to the central region. This procedure is applied in bins of transverse momenta to derive corrections $\{\alpha_i(p_T)\}$.

For the relative response measurement a combination of minimum bias and jet triggers are chosen to ensure that only events on the plateau of each trigger are used in the analysis, and events are then selected that contain two jets well-separated in ϕ, and with no high p_T third jet.

An inconsistency is noticed in the relative response coefficients calculated with different Monte Carlo generators. Since there is no a priori reason to select one generator over another, the RMS deviation between Monte Carlo and data is taken as the systematic uncertainty in the dijet balance. Then the total uncertainty in the endcap region is given as

$$\sigma_{|\eta|>0.8} = \sigma_{|\eta|<0.8} \oplus \sigma_{\text{dijet}}.$$

The systematic uncertainty from dijet balance is shown in Figure 5.

4. In Situ Validations

In order to validate the overall jet energy scale uncertainty, various measurements are performed that are directly sensitive to the JES. Comparisons of these measurements between Monte Carlo and data provide validation that the JES uncertainty estimate is correct.

4.1. Photon + Jet Results

Because photons are well-measured objects, one can directly measure the jet response by using the principle of momentum balance between a photon and recoil jet in photon + jet events [12]. Two techniques are used: the missing E_T projection fraction (MPF) method and the direct balance method. The two are in some sense complementary: the MPF method measures the total calorimeter response, whereas the direct balance method is also sensitive to the leakage of energy outside of the calorimeter jet. The ratio of data to Monte Carlo for the MPF and direct balance measurements are shown in Figure 6, along with the associated systematic and statistical uncertainties. The Monte Carlo and data agree within 5% for $25 < p_T < 250$ GeV in the central region.

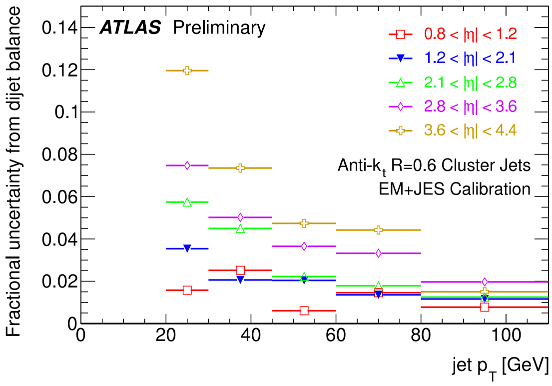

Figure 5. Systematic uncertainty derived for the relative correction using dijet balance as a function of jet p_T.

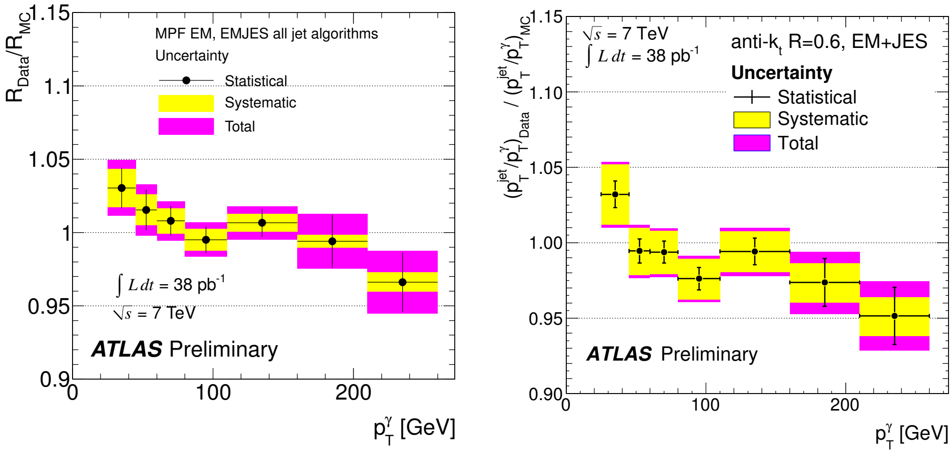

Figure 6. The ratio of data to Monte Carlo for the MPF (left) and direct balance (right) as a function of photon p_T in photon + jet events. The yellow band indicates the size of the systematic uncertainty due to dijet background, photon energy scale and gluon radiation modeling.

4.2. QCD Multijet Balance

If jets at low transverse momentum are well calibrated, one can assess the calibration of jets at high p_T by balancing against a recoil system of at least two lower p_T jets, both of which are in a region for which a calibration is known [13]. This method allows probing the jet energy scale up to the TeV regime. A multi-jet topology is selected by demanding that events contain at least three jets and that the p_T of the recoil system is evenly distributed. The recoil system and leading jet are also required to be well-separated in ϕ. Considering effects due to calibration of low p_T jets, gluon radiation, and the presence of nearby jets on the response, the total systematic effects are evaluated to be 4%. The ratio of the multi-jet balance in data to Monte Carlo for the region $0 < |\eta| < 2.8$ is shown in Figure 7.

5. Summary

The jet energy scale uncertainty for jets reconstructed with the anti-k_t algorithm with distance parameters $R = 0.4$ and $R = 0.6$, has been estimated in ATLAS. The JES and its uncertainty are evaluated up to the kinematic limit (jet energies up to 3.5 TeV) and for pseudorapidities $|\eta| < 4.5$. Uncertainties are derived using primarily data-driven approaches. The results are

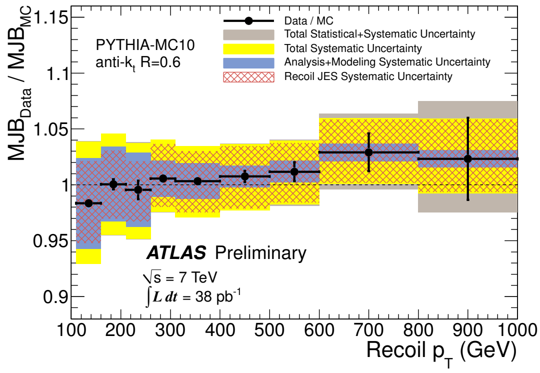

Figure 7. The ratio of the multi-jet balance in data to Monte Carlo as a function of the p_T of the recoil system. The data and Monte Carlo agree within systematic and statistical uncertainties.

further verified using photon + jet and multijet balancing methods in situ. A summary of all the validation methods and the JES uncertainty is shown in Figure 8.

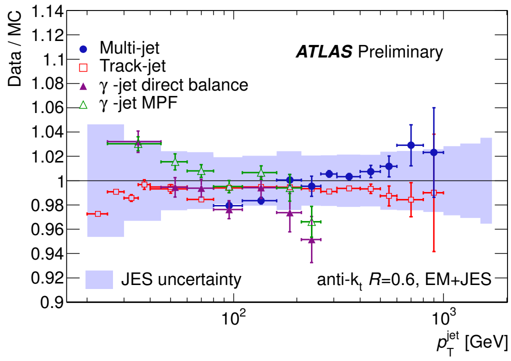

Figure 8. The jet energy scale uncertainty (blue band) in the central region compared to data and Monte Carlo ratios calculated in various validation measurements. The JES uncertainty agrees with the measurements over a large range of transverse momenta.

References

[1] ATLAS Collaboration 2008 The ATLAS Experiment at the CERN Large Hadron Collider *JINST* **3** S08003.

[2] ATLAS Collaboration 2011 Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy with the ATLAS detector *Eur. Phys. J. C* **71** 1512 (*Preprint* arXiv:1009.5908).

[3] ATLAS Collaboration 2010 Measurement of the production cross section for W-bosons in association with jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector *Phys. Lett. B* (*Preprint* arXiv:1012.5382).

[4] ATLAS Collaboration 2010 Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC *Phys. Rev. Lett.* **105** 161801 (*Preprint* arXiv:1008.2461).

[5] ATLAS Collaboration 2011 Update on the jet energy scale systematic uncertainty for jets produced in proton-proton collisions at $\sqrt{s} = 7$ TeV measured with the ATLAS detector *ATLAS-CONF-2011-007*.

[6] ATLAS Collaboration 2010 ATLAS calorimeter response to single isolated hadrons and estimation of the calorimeter jet scale uncertainty *ATLAS-CONF-2010-052*.

[7] M. Cacciari and G. P. Salam 2006 Dispelling the N^3 myth for the k_t jet-finder *Phys. Lett. B* **641** no. 1, 57 - 61.

[8] M. Cacciari, G. P. Salam, and G. Soyez 2008 The anti-kt jet clustering algorithm *JHEP* **04** 063 (*Preprint* arXiv:0802.1189).

[9] W. Lampl et al. 2008 Calorimeter clustering algorithms: description and performance *ATL-LARG-PUB-2008-002*.

[10] ATLAS Collaboration 2011 Jet energy scale and its systematic uncertainty in proton-proton collisions at $\sqrt{s} = 7$ TeV with ATLAS 2010 data *ATLAS-CONF-2011-032*.

[11] ATLAS Collaboration 2011 In-situ pseudorapidity intercalibration for evaluation of jet energy scale uncertainty using dijet events in proton-proton collisions at $\sqrt{s} = 7$ TeV *ATLAS-CONF-2011-014*.

[12] ATLAS Collaboration 2011 Determination of the jet energy measurement uncertainty using photon-jet events in proton-proton collisions at $\sqrt{s} = 7$ TeV *ATLAS-CONF-2011-031*.

[13] ATLAS Collaboration 2010 Measurements of multijet production cross sections in proton-proton collisions at 7 TeV center-of-mass energy with the ATLAS Detector *ATLAS-CONF-2010-084*.