ATLAS NOTE

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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

The ATLAS collaboration

Abstract

An update to the jet energy scale systematic uncertainty for inclusive jets measured in the ATLAS detector and produced in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV is described. The jet energy scale (JES) systematic uncertainty for jets reconstructed with the anti-k_t algorithm with distance parameters of $R = 0.4$ and $R = 0.6$ is evaluated for transverse momentum $p_T > 20$ GeV and for a calorimeter coverage up to pseudo-rapidities of $|\eta| = 4.5$. The JES uncertainty is estimated using a combination of in-situ techniques and systematic variations of Monte Carlo simulations, and it is found to be similar for both distance parameters studied.

The JES uncertainty for central jets ($|\eta| < 0.8$) is lower than 6.5% for $p_T < 60$ GeV and decreases to 4% for $p_T > 200$ GeV. In the endcap ($0.8 < |\eta| < 3.2$) and forward region ($3.2 < |\eta| < 4.5$) the uncertainty for jets with $p_T < 60$ GeV amounts to about 9% and 15% respectively, while in the endcap jets with $p_T > 200$ GeV have an uncertainty smaller than 4.5%. The additional uncertainty contribution due to multiple proton-proton interactions is included as a separate contribution to the systematic uncertainty and it is evaluated as a function of the number of primary vertices in the event. For events with two primary vertices, it is shown to contribute less than 2% in the central region and less than 16% in the endcap and forward region and it is negligible for jets with $p_T > 200$ GeV and $|\eta| < 2.8$.

1 Introduction

The jet energy scale (JES) systematic uncertainty is a large contribution to the total uncertainty for many measurements involving jets. This note concerns the estimate of the JES systematic uncertainty for jets produced in proton-proton collisions at a centre-of-mass energy of 7 TeV with the ATLAS detector. A first estimate of the JES uncertainty was based on information available before the first LHC collisions and exploiting transverse momentum balance in di-jet events, and described in [1]. This note presents an updated determination of the JES systematic uncertainty in light of the increased knowledge of the detector performance gained during the analysis of the first year of LHC data [2–9]. In particular, the in-situ measurements of the single hadron response [2,3] allow a significant reduction of the JES uncertainty in the central detector region. The JES uncertainty in the endcap and forward region is determined from events where only two jets are produced by balancing the transverse momentum of a central and an endcap/forward jet (di-jet balance).

The estimate of the JES uncertainty described in this note follows closely the procedure described in [1]. A reduction in the overall JES uncertainty is achieved thanks to the improved understanding of the calorimeter response, the effect of the calorimeter cell noise thresholds and the combination of the individual uncertainty sources described in sections 3.1, 3.2 and 3.4. In the forward region, the di-jet balance analysis technique [9] is further exploited using a data-set corresponding to an integrated luminosity of 30 nb^{-1}. The resulting uncertainties are described in section 3.3. A summary of the JES uncertainty is given in section 4. The additional uncertainty due to multiple interactions in the same bunch crossing (pile-up) is estimated as a function of the number of primary vertices, as detailed in section 5.

2 Jet reconstruction, calibration and simulation in the ATLAS detector

The ATLAS detector simulation infrastructure and the Monte Carlo simulation samples used to estimate the JES uncertainty are described in [1]. The jet reconstruction and calibration procedures are described in sections 4 and 5 of [1].

Jets are reconstructed with the anti-k_t algorithm [10–12] starting from energy deposits in the calorimeters. In the Monte-Carlo simulation, jets are reconstructed either from event generator particles (true jets) or from energy deposits of particles after traversing the detector (calorimeter jets).

The calorimeter jets are calibrated with correction factors derived from Monte Carlo simulations that restore the calorimeter response of the reconstructed jet (measured at the electro-magnetic scale) to the true jet response. The use of the Monte Carlo simulation for the jet calibration is justified by the good description of the jet kinematic distributions and the good description of the internal jet structure. In particular, the momentum distribution of the individual particles forming the jet (jet fragmentation) as measured in the ATLAS inner detector and the topology of the energy depositions in the calorimeters are well described [4–8].

3 Jet energy scale uncertainties estimation

The determination of the JES systematic uncertainty relies on single hadron response measurements and on the comparison of the jet response of the ATLAS detector in Monte Carlo simulation samples with systematic variations. These Monte Carlo simulation samples used to estimate the contributions to the JES systematic uncertainty are detailed in sections 6.2, 6.3 and 6.4 of [1].

A significant reduction of the JES uncertainty is achieved thanks to the improvements in the following contributions:

- **Calorimeter response** The uncertainty on the calorimeter response due to the interaction of the particles belonging to the jet in the material before and within the calorimeters is estimated by propagating single particle response uncertainties to the JES uncertainty, as described in section 3.1;

- **Calorimeter cell noise thresholds** The uncertainty contribution due to the modeling of the calorimeter cell noise in the Monte Carlo simulation is estimated by applying constants relative to the cell noise suppression thresholds from data in the reconstruction of the Monte Carlo events, as outlined in section 3.2;

- **Closure test of the JES calibration** The revised evaluation of the correlation of the non-closure of the calibration[1] with the other uncertainty sources is explained in section 3.4.

3.1 Calorimeter response uncertainty

The response and corresponding uncertainties for single particles interacting in the ATLAS calorimeters can be propagated to the energy deposits comprised by jets. This can then be used to derive the calorimeter jet energy scale uncertainty in the central calorimeter region, as detailed in [3].

The ATLAS simulation infrastructure allows for linking the true calorimeter energy deposits in each calorimeter cell to the generated particles. The jet calorimeter response uncertainty can be obtained from the uncertainty on the response of each particle in the jet in simulated events. In this way the jet response can be deconvoluted from the response of the individual particles forming jets and the JES uncertainty can be determined using the single particle response uncertainties. The in–situ measurement of the single particle response reduces significantly the uncertainties due to the limited knowledge of the exact detector geometry, in particular those due to the presence of additional dead material, and the modeling of the interactions of particles in the detector.

The following single particle response measurements are used:

- the single hadron energy measured in a cone around an isolated track with respect to the track momentum (E/p) in the momentum range from $0.5 < p < 20$ GeV,

- the pion response measurements performed in the 2004 combined ATLAS test-beam, where a full slice of the ATLAS detector has been exposed to pion beams with momenta between 2 and 350 GeV [13].

From these measurements uncertainties for charged hadrons are estimated [3]. Since no test-beam measurements are available for neutral hadrons[2], their uncertainties are conservatively estimated, using single particle response studies, to contribute an additional 20% with respect to the uncertainty for charged hadrons.

Electrons, photons and hadrons with momenta $p > 20$ GeV are not included in the E/p measurements and therefore there is no in-situ estimate on the effect of additional material in front of the calorimeters. This uncertainty is estimated using dedicated Monte Carlo simulation samples described in section 6.2 of [1] where the detector material is systematically varied within the current uncertainty on the detector geometry knowledge. The relative contribution to the uncertainties due to additional dead material for electrons, photons and high transverse momentum hadrons is obtained by scaling the Monte Carlo-based dead material uncertainty by the average fraction of these particles within a jet as a function of transverse momentum and pseudorapidity.

[1] The non-closure uncertainty is defined as the difference with respect to unity of the jet response in the Monte Carlo sample that has been calibrated with the JES correction constants derived from the sample itself.

[2] Here, only neutral hadrons with a lifetime long enough to directly interact in the ATLAS detector are considered.

The absolute calorimeter energy scale uncertainties of 3% and 4% for the electromagnetic and hadronic calorimeter, respectively, are applied to particles not included in the single particle analysis, e.g. photons from π^0 decays, electrons and high momentum charged hadrons.

3.2 Uncertainty due to the noise description

Calorimeter cell noise in Monte Carlo simulation

The input to the jet reconstruction consists of energy deposit clustered in the ATLAS calorimeters, called topoclusters. Topoclusters follow the topology of calorimeter energy deposits and use fixed thresholds on the measured calorimeter cell noise to separate signal from noise [14]. Differences in the simulated noise with respect to the real noise in the data can lead to differences in the cluster shapes and to the presence of fake clusters, affecting jet reconstruction. The effect of the calorimeter cell noise modeling on the jet response is estimated by using noise constants taken from a cell noise table of a selected data run in the reconstruction of Monte Carlo jets. These constants are used for the noise suppression thresholds employed to reconstruct topoclusters.

The default Monte Carlo noise constants for the electromagnetic calorimeter follow a Gaussian model where the RMS is taken from calibration runs, while those for the hadronic calorimeter use a double Gaussian model. The constants used for the topocluster reconstruction in the simulation are fixed at the time of the production of the simulated data. Moreover, the conditions of single cells could change with time, and these effects would not be reflected in the modelling of the noise in the Monte Carlo samples [3].

By applying noise constants in the Monte Carlo topocluster reconstruction derived from a data sample from a recent data taking period, the effect of changes in the noise distribution of data can be assessed. The response of jets in the same Monte Carlo events using the default and data derived calorimeter cell noise constants is then compared to obtain an estimate of the systematic uncertainty on the jet energy scale.

Estimate of uncertainty due to calorimeter cell noise thresholds

The effect of applying data derived calorimeter cell noise constants in the reconstruction of Monte Carlo events is below 2% for the whole pseudo-rapidity range and is only present for jets with transverse momenta below 40 GeV, and negligible elsewhere.

The uncertainty assigned to jets with transverse momenta up to 40 GeV is estimated to be:

- 2% for 15 GeV $< p_T^{\text{jet}} <$ 20 GeV
- 1% for 20 GeV $< p_T^{\text{jet}} <$ 40 GeV.

3.3 Uncertainty for the endcap/forward region: η intercalibration

The JES uncertainty determined in the central detector region using the single particle response and systematic variations of the Monte Carlo simulations can be transfered to the forward regions by exploiting the transverse momentum balance of a central and a forward jet in events where only two jets are produced. Results from the relative η intercalibration using jets produced in proton–proton collisions in 2010 following the matrix method detailed in [9] are used to evaluate the JES uncertainty up to $\eta = 4.5$, as explained in section 6.2 of [1]. The procedure to include the intercalibration results in the total JES uncertainty are summarized below:

[3] This is the case in particular for cells in the electromagnetic calorimeter whose high voltage settings have changed over the course of the data taking.

- The total JES uncertainty in the central region $0.3 < \eta < 0.8$ is kept as a baseline [4];
- The difference from unity of the relative intercalibration in data is taken as an additional uncertainty for each η region under study and added in quadrature to the baseline (Data intercalibration contribution);
- The difference between intercalibration in data and Monte Carlo simulation is taken as an additional uncertainty, and added in quadrature as well (Monte Carlo intercalibration contribution).

With respect to the analysis in [9] a larger data-set corresponding to an integrated luminosity of approximately 30 nb^{-1} has been used. This allows a finer binning of the JES uncertainty and an extension of the upper kinematic limit up to jet transverse momenta p_T^{avg} of 110 GeV [5].

Both jet distance parameters of R=0.4 and R=0.6 have been included in these studies and similar results have been found. Figures 1 and 2 show a selection of intercalibration results for anti-k_t jets with $R = 0.6$. Figure 1 shows the relative intercalibration as a function of jet $|\eta|$ for events with two jets that have an average transverse jet momentum of $60 < p_T^{avg} < 80$ GeV in the data and in the Monte Carlo simulation. Figure 2 shows an example of the intercalibration uncertainties contributions for the $2.1 < |\eta| < 2.8$ region as a function of transverse momentum.

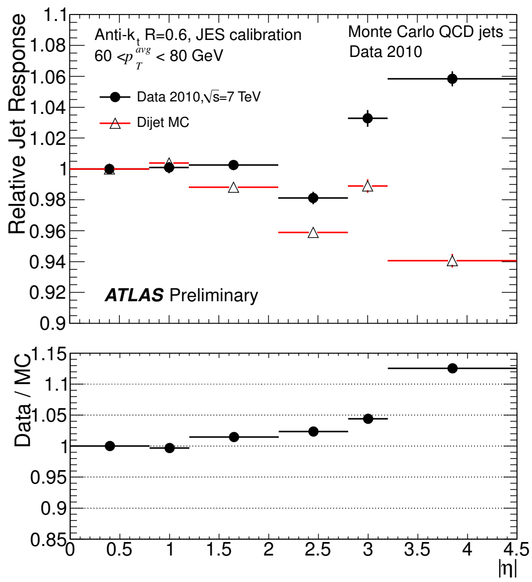

Figure 1: Relative intercalibration for data (diamonds) and Monte Carlo (triangles) for anti-k_t jets with $R = 0.6$ for $60 < p_T^{avg} < 80$ GeV as a function of the jet pseudo-rapidity.

3.4 Correlation of non-closure uncertainty

After the nominal inclusive jet Monte Carlo simulation sample is calibrated with the JES correction constants that were derived from the sample itself, the jet response still shows slight deviations from unity at low p_T (non-closure). This is mainly due to differences in the jet selection and topology between

[4] This is the largest fully instrumented $|\eta|$ region considered where combined test-beam results used to estimate the calorimeter uncertainty are available for the entire pseudorapidity range.

[5] For higher transverse momenta the uncertainties from the last bin of 80 to 110 GeV are used. This is justified, since the most relevant uncertainty contributions decrease with energy.

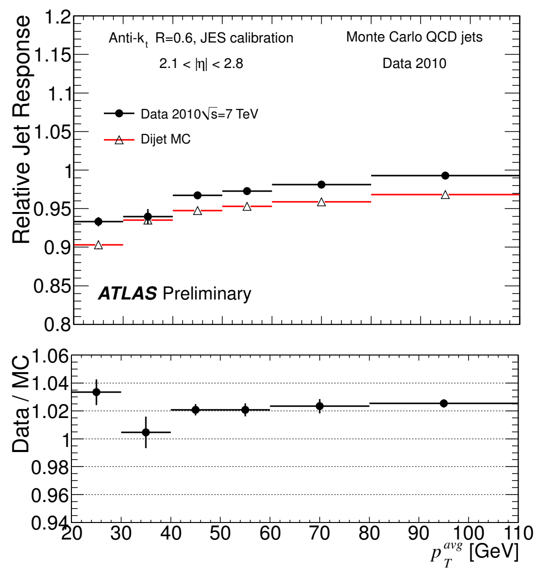

Figure 2: Relative intercalibration for anti-k_t jets with $R = 0.6$ within 2.1< $|\eta|$ <2.8 as a function of average jet transverse momentum.

the derivation of the constants and the analysis to estimate the JES systematic uncertainty. The deviation from unity of the jet response is taken as a source of systematic uncertainty.

Given that the same JES calibration constants are applied to all samples with systematic variations used for the derivation of the JES uncertainty, the correlation of the non-closure term with the other uncertainty components needs to be considered.

The non-closure uncertainty was conservatively considered fully correlated to the other components in [1] and added linearly to the other uncertainty components. However, this strategy has been revised given that:

1. the JES calibration constants vary slowly within the p_T bins used for the estimate of the JES uncertainty;

2. the systematic variations produce only small effects on the jet p_T spectrum within a bin.

For these reasons, the variation of the calibration constants due to systematic effects can be factorized from the variation of the jet energy. This variation will effectively cancel when taking the ratio of the jet response for any of the systematic samples and the jet response in the nominal sample. The non-closure term becomes then the only uncertainty source where the variation of the calibration constants is accounted for: it can therefore be considered uncorrelated to the other uncertainty contributions and added in quadrature to evaluate the total JES systematic uncertainty.

4 Summary of the jet energy scale systematic uncertainty

All the uncertainty sources mentioned in section 3 are added in quadrature to estimate the overall jet energy scale uncertainty. The estimate of the uncertainties related to the response of the ATLAS calorimeters, the noise thresholds and the JES calibration method have been described in the respective sections of this note (3.1, 3.2 and 3.4). The model uncertainties in the event generation (jet fragmentation, additional soft radiation, underlying event modeling) and the beam–spot conditions have been estimated from

Monte Carlo simulation samples described in section 6.2 and 6.4 of [1], and combined to form the overall uncertainty as explained in section 7 of [1]. The contributions detailed in [1] as hadronic shower model, additional dead material and electromagnetic scale of the calorimeters are now estimated propagating to jets the uncertainties on the in-situ response of single isolated hadrons.

The overall jet energy scale uncertainty is shown for anti-k_t jets with $R = 0.6$ in figures 3 and 4 for an example central ($0.3 < |\eta| < 0.8$) and endcap ($2.1 < |\eta| < 2.8$) region. The size of the JES uncertainty for anti-k_t jets with a distance parameter of $R = 0.4$ is similar to that of jets with a distance parameter of $R = 0.6$.

The JES uncertainty in the central region ($|\eta|$ <0.8) amounts to less than 6.5% for jet $p_T^{\text{jet}} < 60$ GeV, and 4% for $p_T^{\text{jet}} > 200$ GeV. The uncertainty is up to 9% and 4.5%, respectively, for $p_T^{\text{jet}} <$ 60 GeV and $p_T^{\text{jet}} > 200$ GeV in the endcap and to about 15% in the forward regions, where the uncertainty in the central region is taken as a baseline and the uncertainty due to the relative calibration (η intercalibration) is added. The dominant contributions to the uncertainty are the calorimeter response uncertainty in the central region and the relative calibration in the endcap ($\eta|$ <2.8) and forward ($|\eta|$ <4.5) region.

5 Pile-up uncertainty

Particles produced by multiple soft proton-proton interactions in the same bunch crossing (in-time pile-up) can produce additional energy deposits that are reconstructed within the hard scattering jet. As detailed in [1], no correction is applied yet to account for the average increase of the jet energy due to pile-up and an additional uncertainty is assigned instead.

The uncertainty due to pile-up is derived from data. The average additional jet energy is calculated from the additional calorimeter tower energy and the number of towers per jet [6]. The average additional tower energy is determined by studying the dependence on the number of vertices in mimimum bias collisions in each calorimeter rapidity region.

This updated estimate of the relative systematic uncertainty due to pile-up is derived from a data–set corresponding to an integrated luminosity of 15 nb^{-1}. The average number of interactions ranges from 0.5 to 2.1. The number of events within high luminosity runs that have an average of more than one reconstructed vertex is approximately 30%.

As in [1], the uncertainty due to pile-up is given as a function of jet pseudo-rapidity and transverse momentum, but, in addition, it is also estimated as a function of the number of reconstructed primary vertices. This allows this uncertainty contribution to be largely independent of the instantaneous luminosity. Furthermore, the uncertainty in the case of events with a low number of vertices is reduced with respect to the method explained in Section 8 of [1].

In case of two primary vertices per event, the uncertainty due to pile-up for jets with p_T=20 GeV and pseudorapidity $0.3 < |\eta| < 0.8$ is about 1.5%, while it amounts to about 6% for jets with pseudorapidity $2.1 < |\eta| < 2.8$. For jets with transverse momentum above 200 GeV, the pile-up uncertainty is negligible ($< 1\%$) for jets with $|\eta| < 2.8$, and below $< 2\%$ in the full pseudorapidity range ($|\eta| < 4.5$).

The effect of additional proton-proton interactions from different bunch crossings that can be caused by trains of consecutive bunches (out-of-time pile-up) has been studied separately. The effect of out-of-time pile-up on jet reconstruction has been found to be negligible.

[6] Anti-k_t jets with distance parameter R=0.6 have been used for this estimate, and the results extended to anti-k_t jets with a distance parameter of R=0.4.

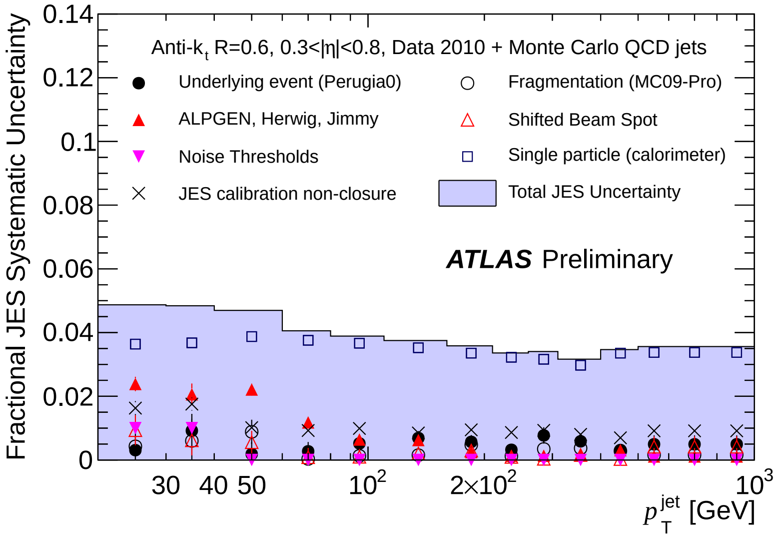

Figure 3: Fractional jet energy scale systematic uncertainty as a function of p_T^{jet} for jets in the pseudorapidity region $0.3 < |\eta| < 0.8$ in the calorimeter barrel. The total uncertainty is shown as the solid light blue area. The individual sources are also shown, with statistical uncertainties if applicable.

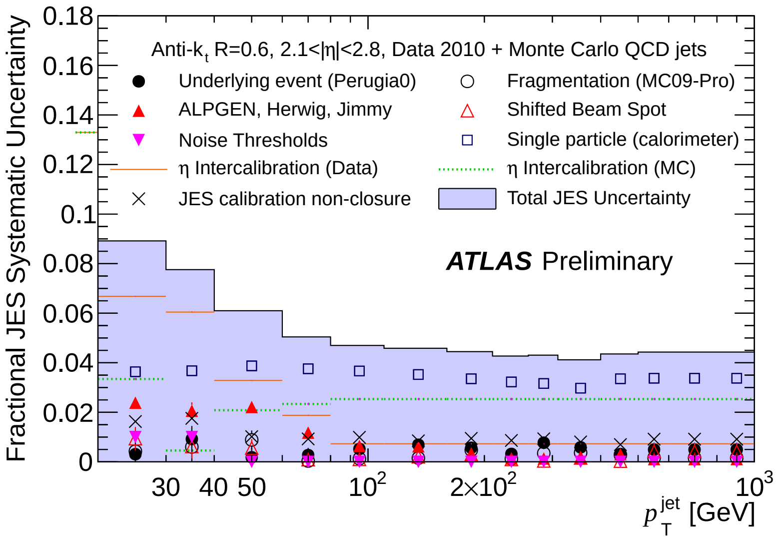

Figure 4: Fractional jet energy scale systematic uncertainty as a function of p_T^{jet} for jets in the pseudorapidity region $2.1 < |\eta| < 2.8$. The JES uncertainty for the endcap is extrapolated from the barrel uncertainty, with the contribution from the η intercalibration between central and endcap jets in data and Monte Carlo simulation added in quadrature. The total uncertainty is shown as the solid light blue area. The individual sources are also shown, with statistical uncertainties if applicable.

6 Conclusions

The jet energy scale uncertainty for inclusive jets measured in proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV has been estimated for the jet pseudo-rapidity range covered by the ATLAS detector ($|\eta| <4.5$). Jets have been reconstructed with the anti-k_t algorithm with a distance parameters equal to $R = 0.4$ and $R = 0.6$. Jets are calibrated with a simple factor restoring the true jet energy from the measured one in Monte Carlo simulation samples.

The jet energy scale uncertainty estimated in [1] has been significantly improved due to changes in the determination of the calorimeter response and calorimeter cell noise threshold contributions. The calorimeter response uncertainty is obtained propagating the uncertainty on the response of single isolated hadrons to jets. The calorimeter cell noise threshold uncertainty exploits the application of data-derived noise constants on jets reconstructed in the Monte Carlo simulation. The contribution of the JES non-closure has been reviewed and is now added quadratically to the overall JES uncertainty. A larger data-set has been used for the di-jet analysis of the JES uncertainty in the endcap and forward region.

The total jet energy scale uncertainty decreases with respect to the previous estimate in [1] by up to 3% in the central region and 1% in the endcap and forward region. The improvement is achieved by using in-situ measurements for the calorimeter response uncertainty and an improved noise understanding.

The jet energy scale uncertainty is found to be similar for both jet distance parameters of R=0.4 and R=0.6. In the central region ($|\eta| <0.8$) the uncertainty is lower than 6.5% for all jet momenta, while for jet momenta above 200 GeV the uncertainty is below 4%. In the endcap and forward region the relative intercalibration uncertainty dominates. The JES uncertainty amounts to a total of 15% for the most forward pseudo-rapidities up to $\eta = 4.5$.

The uncertainty due to pile-up is estimated separately as a function of the number of primary vertices. In the case of two primary vertices per event, the uncertainty due to pile-up for jets with p_T=20 GeV and pseudorapidity $0.3 < |\eta| < 0.8$ is about 1.5% while it amounts to about 6% for jets with pseudorapidity $2.1 < |\eta| < 2.8$. For jets with transverse momentum above 200 GeV, the uncertainty due to pile-up is negligible (< 1%) for jets with $|\eta| < 2.8$, and below < 2% in the full pseudorapidity range ($|\eta| < 4.5$).

Appendix A: jet energy scale uncertainty plots for comparison with ATLAS-CONF-2010-056

This section contains the JES uncertainty summary plots of section 4 with the same axis range as [1] for easier visual comparison.

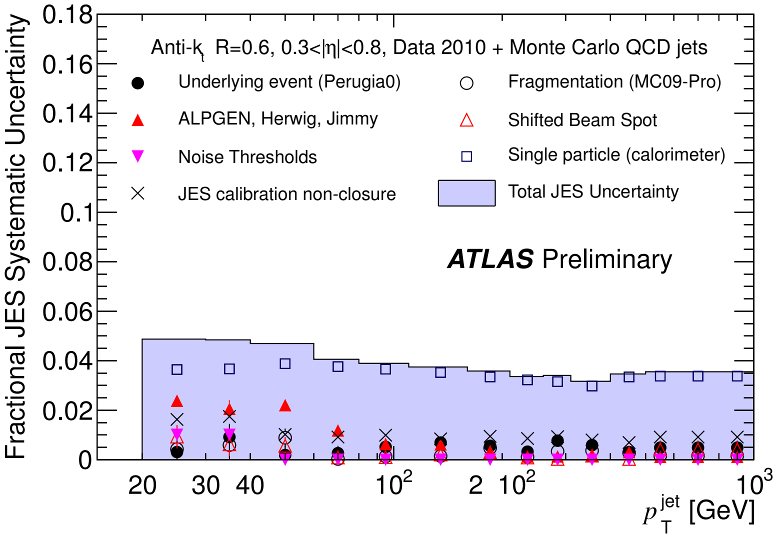

Figure 5: Fractional jet energy scale systematic uncertainty as a function of p_T^{jet} for jets in the pseudo-rapidity region $0.3 < |\eta| < 0.8$ in the calorimeter barrel. The total uncertainty is shown as the solid light blue area. The individual sources are also shown, with statistical uncertainties if applicable.

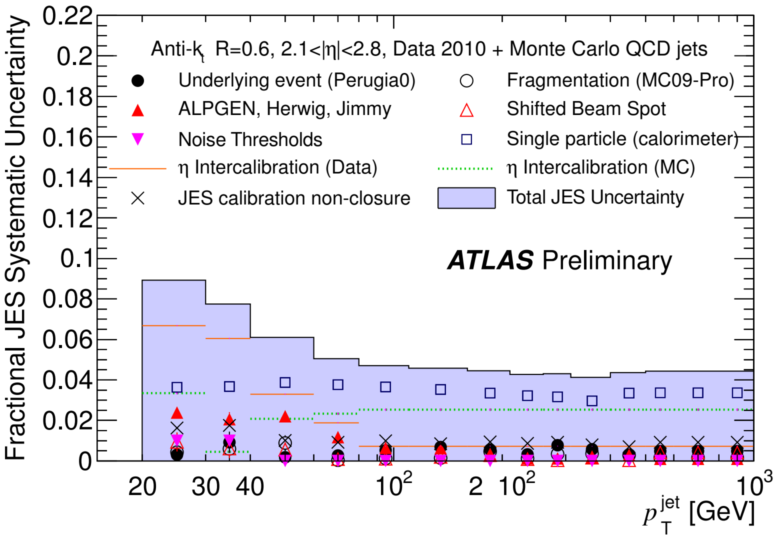

Figure 6: Fractional jet energy scale systematic uncertainty as a function of p_T^{jet} for jets in the pseudo-rapidity region $2.1 < |\eta| < 2.8$. The JES uncertainty for the endcap is extrapolated from the barrel uncertainty, with the contribution from the η intercalibration between central and endcap jets in data and Monte Carlo simulation added in quadrature. The total uncertainty is shown as the solid light blue area. The individual sources are also shown, with statistical uncertainties if applicable.

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