MEASUREMENT OF JET ENERGY SCALE AND RESOLUTION AT ATLAS AND CMS AT $\sqrt{s} = 8$ TeV*

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A summary of the jet energy calibration efforts of the ATLAS and CMS collaborations is presented. Both experiments have recorded data corresponding to an integrated luminosity of 20 fb^{-1} of proton–proton collisions at a centre-of-mass energy of 8 TeV. Different procedures to handle the effects from pileup collisions are carried out. Data-driven estimations of jet energy scale and resolution are performed with balancing methods in dijet, photon+jet, Z+jet and multijet samples. Novel techniques are explored to measure the differences between jets originating from partons with different flavours. The resulting uncertainty on the jet energy scale is at the level of only a few percent.

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1. Introduction

Particle jets are among the most common objects in high-energetic hadron collisions. As the experimental signatures of quarks and gluons, they are important for the reconstruction of many physics processes.

However, the measurement of jets is biased by a multitude of systematic effects: event pileup due to additional interactions in the same or adjacent bunch crossing, initial and final state radiation, nonlinear calorimeter response, out-of-cone effects or detector noise and miscalibration. The uncertainty on the jet energy scale is the largest experimental uncertainty in many physics analyses.

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A thorough understanding and correction of these effects is necessary. Both the ATLAS [1] and CMS [2] collaborations have developed a multitude of sophisticated techniques to correct for systematic biases and measure the jet energy scale with high precision.

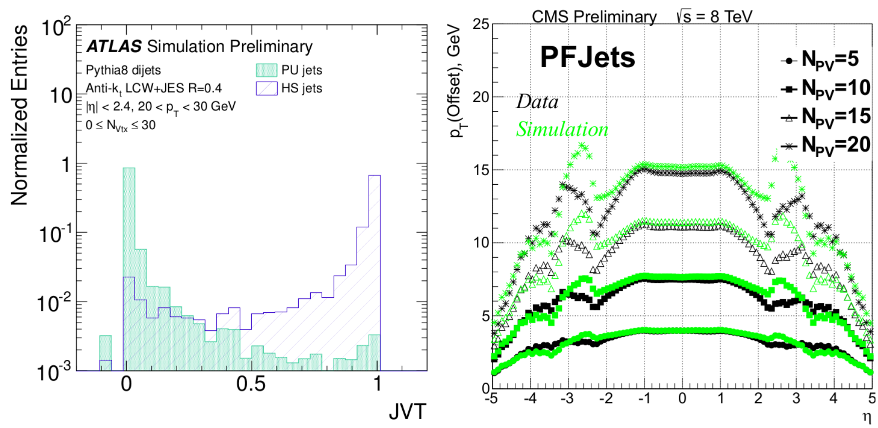
The CMS Collaboration uses the Particle-Flow [3] method of event reconstruction: information from all detector subsystems is combined to reconstruct particle candidates. The jet clustering algorithm is then applied to the candidate collection. The ATLAS Collaboration uses calorimeter topo-clusters as an input for the jet algorithms, with dedicated energy corrections being applied to the calorimeter cells and clusters.

2. Pileup correction and mitigation techniques

In addition to any hard scattering processes, every LHC bunch crossing leads to around 20 soft proton–proton collisions, referred to as *pileup*.

Particles from these pileup interactions might be added to the jet by the clustering algorithm. This increases the measured jet energy with respect to the original energy from the hard interaction. To counter this systematic bias, *mitigation* and *correction* techniques are applied.

Mitigation techniques aim to remove as much pileup as possible from the event. The CMS Collaboration removes charged hadrons that can be traced back to pileup vertices prior to jet clustering. The ATLAS Collaboration has developed a multivariate discriminator [5], mainly based on track-vertex-association, to tag jets originating from pileup vertices, see Fig. 1 (a).



(a) (b)

Fig. 1. (a) ATLAS: distribution of the jet-vertex-tagger for pileup and hard-scatter jets [5]. (b) CMS: offset from pileup as a function of jet pseudorapidity. The offset increases for a higher number of primary vertices in the event [6].

Further *correction* methods subtract the remaining pileup energy from the jet. The jet area method [4] combines the event energy density and the jet area in η-ϕ-space to achieve the most precise estimation of the pileup offset per jet, see Fig. 1 (b).

3. Jet energy scale corrections from simulation

Corrections derived from simulation often constitute the largest part of the total calibration. Their purpose is to correct for all known systematic reconstruction biases.

Simulated jets before (*gen*-level) and after (*reco*-level) the detector simulation are matched. Pileup corrections are applied to the reco-level jets beforehand. From the ratio $p_{\mathrm{T}}^{\mathrm{reco}}/p_{\mathrm{T}}^{\mathrm{gen}}$, the jet energy scale can be determined. The result from the CMS Collaboration is shown in Fig. 2. The corrections are derived as the inverse of the measured jet response depending on jet η and p_{T}.

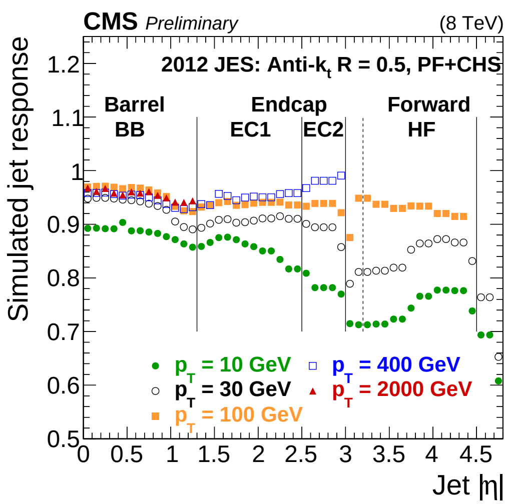


Fig. 2. The CMS Collaboration: jet response from simulation as a function of $|\eta_{\mathrm{jet}}|$ for different values of jet p_{T} [13].

While the corrections from simulation cover all understood systematic effects, additional data-driven corrections are mandatory due to simulation imperfections or unknown features.

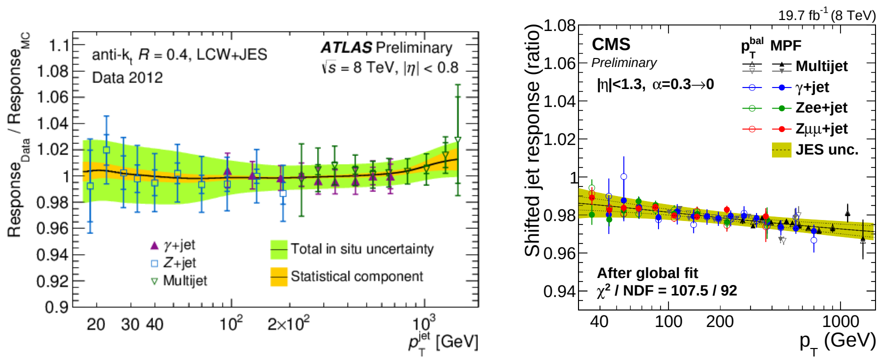
4. Measurements of the jet energy scale with balancing methods

The data-driven calibration methods rely on balancing techniques: In a balanced topology, a probe jet and a well-measured reference object are correlated via momentum conservation, as the average transverse momentum in the initial state is zero. This relation can be exploited to calibrate the probe jet.

This method is applied in several ways:

1. dijet balancing to calibrate jets in the forward and endcap regions,
2. Z+jet and γ+jet balancing to measure the absolute scale,
3. multijet balancing to measure the jet response at high transverse momenta.

The results from the different measurements can then be combined, see Fig. 3. The ATLAS Collaboration uses a weighted average in bins of jet p_{T} and applies a smoothing procedure [11]. The CMS Collaboration performs a global fit to the results of all channels after corrections for initial and final state radiation.



(a) (b)

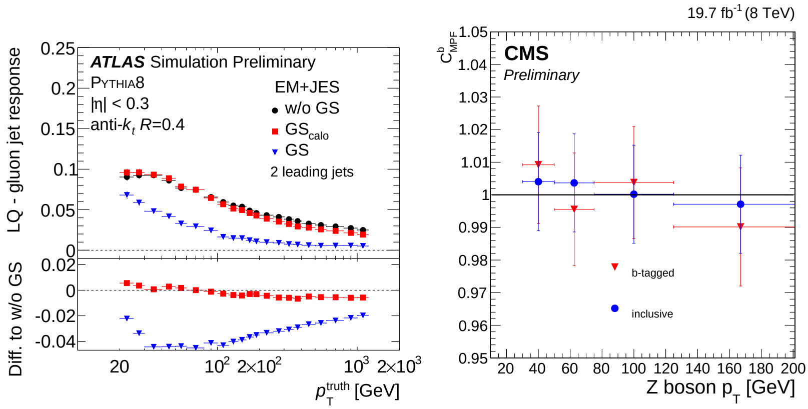
Fig. 3. Combination of data-driven jet energy scale measurements for: (a) ATLAS [7], (b) CMS [13].

Employing these combination procedures, the differences between data and simulation are determined very precisely. The ratio between data and simulation is close to unity within a couple of percent, confirming the high level of simulation accuracy and detector understanding achieved by the both experiments.

5. Jet flavour studies

The jet response depends on the flavour of the originating parton: gluon jets fragment into a wider cone with softer particles, b-jets have a lower response due to neutrinos from semileptonic b-decays escaping the detector. These differences are small on average, but they must not be neglected in the era of precision measurements.

To achieve the best estimate of response differences between flavours, several studies have been carried out to measure response differences between flavours. The ATLAS Collaboration has shown that applying the full correction scheme decreases the difference between gluon and light-quark induced jets, see Fig. 4 (a). The CMS Collaboration has published a data-driven study on b-jet response [8], which found that no additional corrections are needed, as illustrated by Fig. 4 (b).

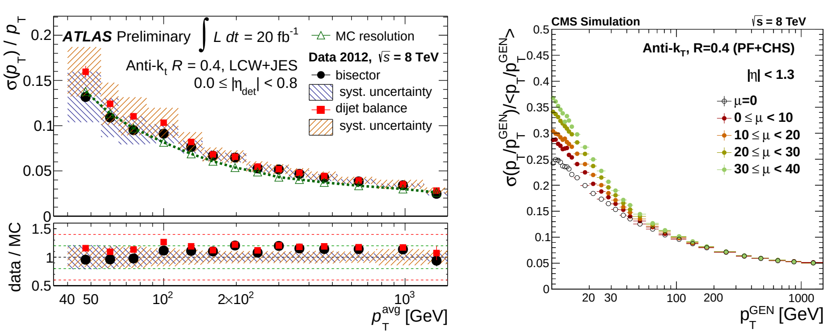


(a) (b)

Fig. 4. Flavour studies: (a) ATLAS gluon *vs.* light quark response difference before and after full correction [12], (b) CMS b-jet response compared to inclusive jet response [8].

6. Jet energy resolution measurements

The width of the jet response distribution, the jet p_T resolution, is also important for jet measurements and the estimation of systematic uncertainties.



(a) (b)

Fig. 5. Jet p_T resolution: (a) CMS study for different pileup scenarios [10], (b) ATLAS *in situ* measurement with bisector method [9].

The ATLAS Collaboration has used the bisector method [9] to perform an *in situ* measurement of the jet response and compare it to the resolution determined from dijet balancing, see Fig. 5 (a). The measured jet energy resolution is only slightly worse with respect to the resolution in simulation.

The CMS Collaboration has studied the jet response as a function of jet p_{T} for different pileup scenarios. It was found that the effects from additional pileup worsen the resolution only slightly at low p_{T}, see Fig. 5 (b).

7. Jet energy uncertainties

Combining all uncertainty sources, the total uncertainty amounts to around 1% in the central detector region at medium p_{T} (a few hundred GeV), see Fig. 6. It rises to a few percent at other regions of phase-space where calibration is more difficult.

At low p_{T}, the uncertainties from pileup and flavour effects dominate. In the high-p_{T} regime, the absolute scale uncertainty becomes the main contribution to the total uncertainty. The uncertainty on the relative scale is dominant at higher values of the absolute pseudorapidity, *i.e.* in the endcap and forward detector regions.

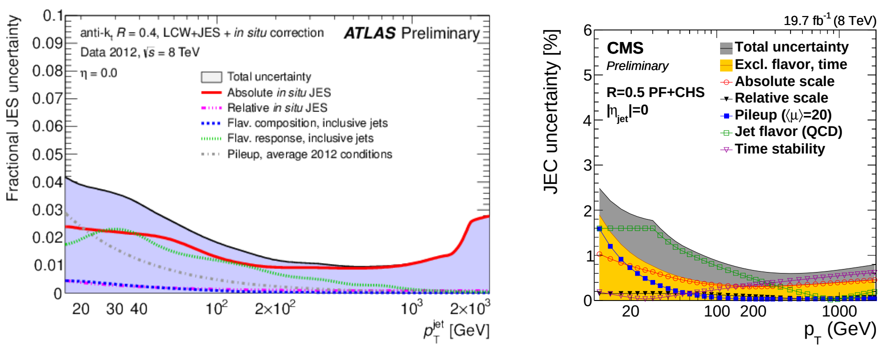


Fig. 6. Jet energy uncertainty sources for central jets as a function of jet p_{T} for: (a) ATLAS [7], (b) CMS [13].

8. Conclusion

The ATLAS and CMS experiments have demonstrated an outstanding performance in jet calibration in the LHC Run 1 data. Different techniques have been combined to achieve a jet energy scale precision better than 1%. Many novel techniques have been explored to tackle the challenges at the high-energy, high-luminosity frontier.

REFERENCES

[1] ATLAS Collaboration, *JINST* **3**, S08003 (2008).

[2] CMS Collaboration, *JINST* **3**, S08004 (2008).

[3] CMS Collaboration, Commissioning of the Particle-flow Event Reconstruction with the First LHC Collisions Recorded in the CMS Detector, CMS-PAS-PFT-10-001 (2010).

[4] M. Cacciari, G.P. Salam, *Phys. Lett. B* **659**, 119 (2008) [arXiv:0707.1378 [hep-ph]].

[5] ATLAS Collaboration, Tagging and suppression of pileup jets, ATLAS-CONF-2014-018 (2014).

[6] CMS Collaboration, 8 TeV Jet Energy Corrections and Uncertainties based on 19.8 fb^{-1} of data in CMS, CMS-DP-2013/033 (2013).

[7] ATLAS Collaboration, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013JESUncertainty

[8] CMS Collaboration, Calculation of Residual Energy Correction for b-jets Using $Z + b$ Events in 8 TeV pp Collisions, CMS-PAS-JME-13-001 (2013).

[9] ATLAS Collaboration, Data-driven Determination of the Energy Scale and Resolution of Jets Reconstructed in the ATLAS Calorimeters Using Dijet and Multijet Events at $\sqrt{s} = 8$ TeV, ATLAS-CONF-2015-017 (2015).

[10] CMS Collaboration, https://twiki.cern.ch/twiki/bin/view/CMSPublic/MultipleConeSizes14

[11] ATLAS Collaboration, *Eur. Phys. J. C* **75**, 17 (2015).

[12] ATLAS Collaboration, Jet Global Sequential Corrections with the ATLAS Detector in Proton–Proton Collisions at $\sqrt{s} = 8$ TeV, ATLAS-CONF-2015-002 (2015).

[13] CMS Collaboration, CMS JEC Run 1 Legacy Performance Plots, CMS-DP-2015/044 (2015).