Determination of the Jet Energy Scale in CMS

Henning Kirschenmann, on behalf of the CMS collaboration

University of Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, 22761 Hamburg, Germany

E-mail: henning.kirschenmann@desy.de

Abstract. Measurements of the jet energy scale in CMS and the status of the jet energy corrections for 2011 analyses are presented. The measurements have been performed with a data sample collected in proton-proton collisions at a centre-of-mass energy of 7 TeV, corresponding to an integrated luminosity of $4.9\,\mathrm{fb}^{-1}$. Dijet and photon/Z+jets events are used to measure the jet energy response in the CMS detector. The results are presented for the Particle Flow approach, which attempts to reconstruct individually each particle in the event, prior to the jet clustering, based on information from all relevant subdetectors.

1. Introduction

Jets are the experimental signatures of quarks and gluons produced in high-energy processes such as hard scattering of partons in proton-proton collisions. The jet energy corrections relate the energy of reconstructed jets - on average - to the true particle level energy, which is independent of the detector response. The detailed understanding of the jet energy scale is of crucial importance for many physics analyses.

The measurements discussed here have been performed by the Compact Muon Solenoid (CMS) collaboration at the CERN Large Hadron Collider (LHC). The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. A detailed account of the detector can be found in [1].

The techniques for the determination of the jet energy scale and transverse momentum resolution at CMS have been discussed in detail in Ref. [2]. In the following, we summarize the current status of jet energy corrections and present the 2011 results on the determination of the energy scale in data.

2. Jet-types used at CMS

Within CMS, three different methods to reconstruct jets have been commissioned (see Ref. [3]): a calorimeter-based approach, the "Jet-Plus-Track" approach, which improves the measurement of calorimeter jets by exploiting the associated tracks, and the Particle Flow (PF) approach, which attempts to reconstruct individually each particle in the event, prior to the jet clustering, based on information from all relevant subdetectors. The resulting jet energy resolutions from simulation are depicted in Fig. 1.

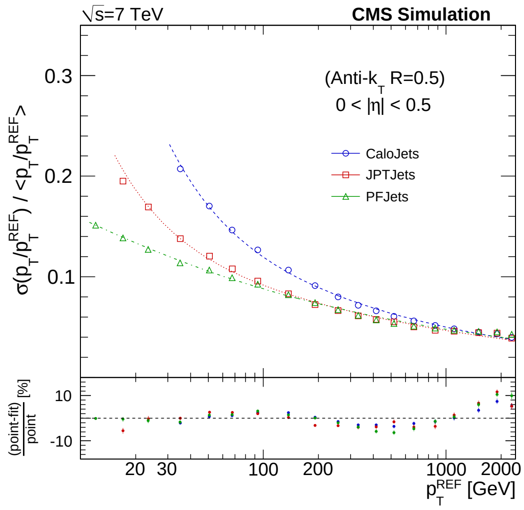

Figure 1. Jet energy resolution from simulation for the three types of reconstructed jets at CMS supplied with jet energy corrections: Calorimeter jets, Jet-Plus-Track jets, and Particle Flow jets. Taken from Ref. [4]

The improvement of the jet energy resolution and the more uniform and linear energy response of PF-objects indicate that the Particle Flow approach offers advantages with respect to the other jet types. As expected for the fragmentation of partons to jets, about 65% of the energy of PF-jets at central rapidity and $p_T \approx 100\,\text{GeV}$ is carried by charged hadrons, 25% by photons, and 10% by neutral hadrons. For charged hadrons the tracker information is relevant ($\sigma_{tracker}(p_T)/p_T \approx 1\%$), while photons are reconstructed from isolated ECAL clusters ($\sigma_{ECAL}(E)/E \approx 1\%\sqrt{E} \oplus 0.3\%$) and only the remaining neutral hadrons are reconstructed from HCAL-information alone, leading to the aforementioned significant improvement of the jet energy resolution in comparison to the other jet-types. The study of the energy composition of PF-jets, i.e. the energy fractions of the different particle candidate classes, provides an important additional handle on the quality of the simulation of the detector and understanding of the PF algorithm. It is performed using a tag-and-probe in dijet events. The results in Fig. 2 show that the differences in the observed energy fractions between data and simulation are below 1% in the central detector region.

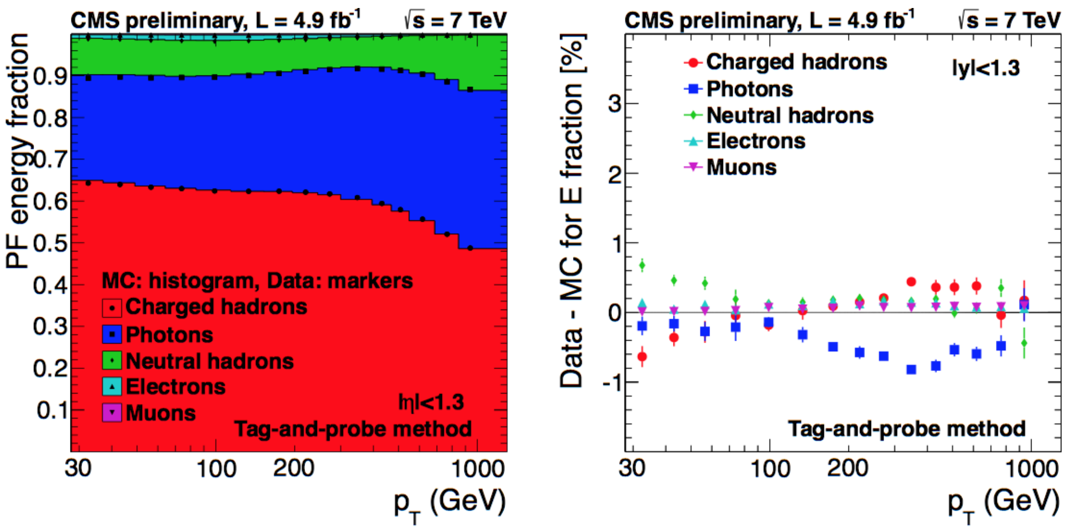

Figure 2. PF energy fractions in the central detector region. Taken from Ref. [5]

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3. Factorized jet energy corrections

The success of the CMS simulation in describing the jet properties (see Ref. [4]) allows its effective use in a factorized approach to jet energy corrections (JEC) that CMS has adopted. After the first level correction, which subtracts the additional energy in the event induced by pileup effects (additional minimum bias events), the reconstructed jets are corrected to compensate for the non-linear response of the calorimeters (as a function of p_T) and variations of the response in η. These corrections are derived from simulation.

Subsequently, small residual corrections are applied which are based on measurements of the relative scale as a function of η from dijet events and the absolute scale in the central detector region ($|\eta| < 1.3$) from Z+jet and γ+jet events.

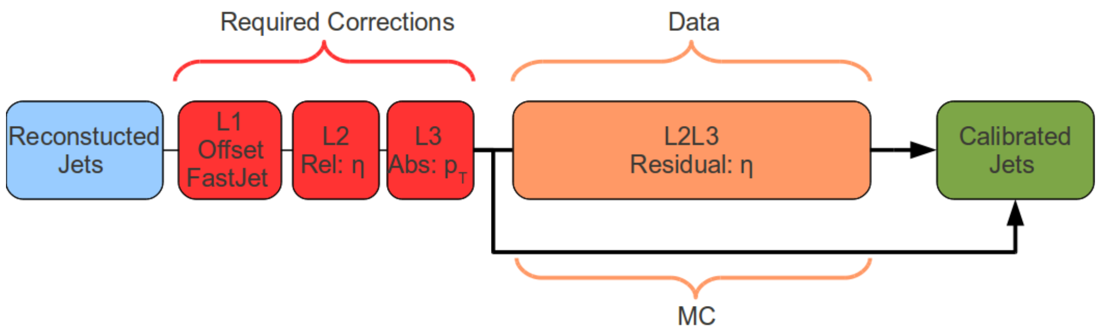

Figure 3. Sketch of the mandatory jet energy correction levels at CMS.

3.1. L1 - Pileup corrections

Corrections for pileup effects have become increasingly important during the LHC-running. The mean number of primary vertices in 2011 data has been $\langle N_{PV} \rangle \approx 7$ and increases to more than 20 in 2012. The average energy offset amounts to $\Delta p_T = 0.72\,\mathrm{GeV}/N_{PV}$ for central PF-jets. For each event, an average p_T density ρ per unit area is estimated which characterizes the soft jet activity and is a combination of the underlying event, the electronic noise and the pileup. Following the jet area approch described in [8, 9], ρ and the jet-area A are used to calculate an η-dependent correction factor to subtract the offset energy of individual jets on an event-by-event basis.

3.2. L2L3 - MC truth corrections

The L2L3-corrections are based on simulation and correct the energy of the reconstructed jets such that it equals - on average - the energy of the jets at particle level. Simulated jet events, generated with PYTHIA6 [6], tune Z2 and processed through the full, GEANT4 [7] detector simulation are used for the derivation of these corrections. The generated and reconstructed jets are matched spatially and the transverse momentum of the reconstructed jet p_T^{reco} and the response $p_T^{\mathrm{reco}}/p_T^{\mathrm{gen}}$ are determined in fine bins of p_T^{gen} and η^{gen}. The correction factor is then determined as the inverse of the mean response as a function of p_T^{reco} in fine η-bins.

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4. Residual corrections from data-driven techniques

The corrections from simulated data are the foundation of the jet energy correction chain in CMS. To complete the chain, these corrections are applied to data and simulated data in order to validate the jet energy scale. Response estimators from the p_T balance and the MPF[1] method (used extensively at [10]) are used to determine the mean response in data and simulated data.

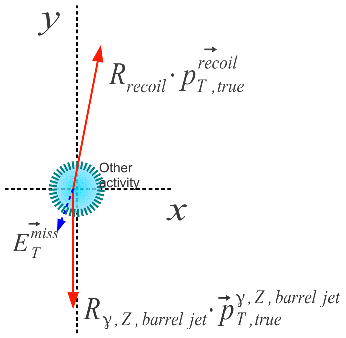

Figure 4. Sketch of MPF-method

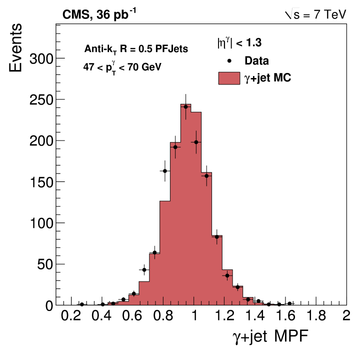

Figure 5. Sample MPF-distribution for γ+jet events

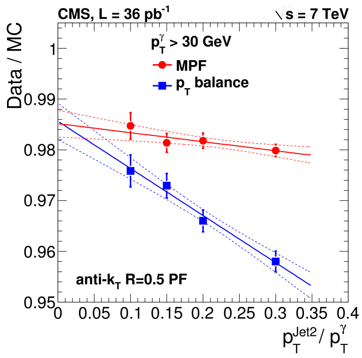

Figure 6. Extrapolation to zero additional event activity for γ+jet

4.1. Absolute scale from Z+jet and γ+jet

Z+jet and γ+jet events provide a very clean signature with a well understood and precisely measured reference object balancing the jet. The jets are selected to be in the barrel region ($|\eta| < 1.3$) and back to back to the reference object.

The response estimators are defined as

$$\mathcal{R}_{\text{balance}} = \frac{p_T^{jet}}{p_T^{\gamma,Z}} \tag{1}$$

for the p_T-balance method and as

$$\mathcal{R}_{\text{recoil}} = \mathcal{R}_{\gamma,\text{Z}} + \frac{\vec{\not{E}}_T \cdot \vec{p}_{\text{T}}^{\,\gamma,\text{Z}}}{(\vec{p}_{\text{T}}^{\,\gamma,\text{Z}})^2} \equiv R_{\text{MPF}} \equiv \mathcal{R}_{\text{probe}} \tag{2}$$

for the MPF-method, where $\vec{\not{E}}_T$ is the missing transverse energy and $\mathcal{R}_{\gamma,\text{Z}}$ the response of the reference photon or Z-boson. The idea underlying the MPF response estimator (see Fig. 4) is that there is no intrinsic $\vec{\not{E}}_T$ in such events and that the measured $\vec{\not{E}}_T$ is instead induced by mismeasurents of the hadronic recoil. The projection of $\vec{\not{E}}_T$ along the reference object axis can then be used to yield a MPF response estimator.

In order to determine the energy scale as a function of p_T, the distributions of the previously defined response estimators $\mathcal{R}_{\text{balance}}$ and $\mathcal{R}_{\text{MPF}}$ are evaluated. An example distribution is shown in Fig. 5. The mean of the estimated response is determined in bins of p_T for different values of the requirement on the maximum of the relative second jet p_T. The ratio of data to simulation of $\mathcal{R}_{\text{balance}}$ and $\mathcal{R}_{\text{MPF}}$ is extrapolated to zero additional event activity (corresponding to $p_T^{Jet2}/p_T^{\gamma} = 0$) to suppress the influence of soft radiation on the results. An example of such an

[1] Missing transverse energy projection fraction

extrapolation is shown in Fig. 6 and illustrates the significantly reduced dependence of $\mathcal{R}_{\mathrm{MPF}}$ on the radiation modeling in simulation with respect to the p_T balance method. The resulting ratio of data to simulation as a function of p_T is depicted in Fig. 7 and corresponds to a scale deviation of $\approx 1\%$ in the central detector region.

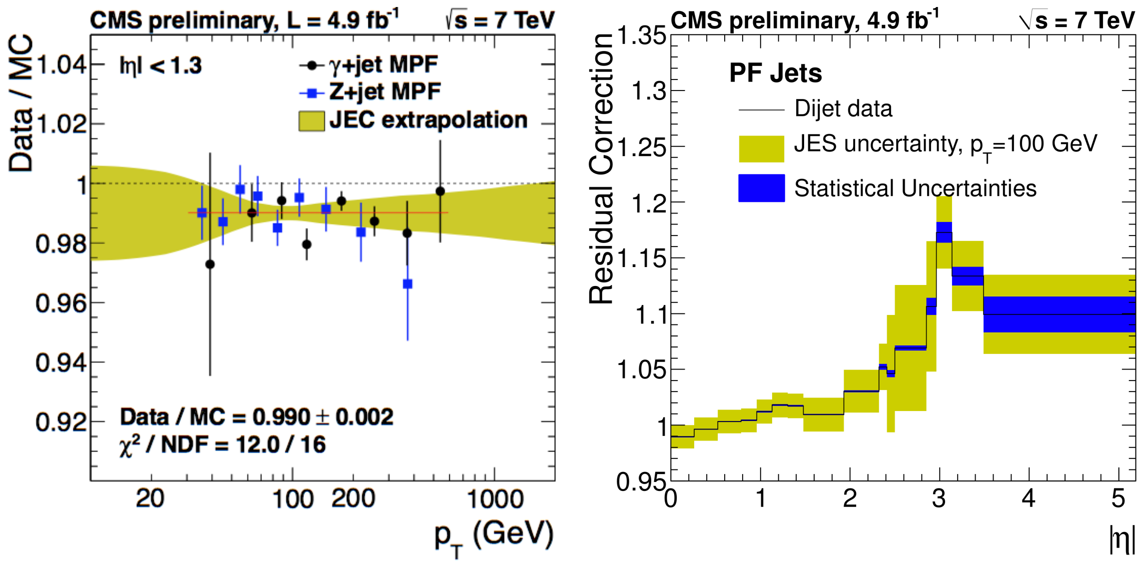

Figure 7. Absolute scale determined from Z+jet and γ+jet and the relative residual correction factor determined from dijet data. Taken from Ref. [5]

4.2. Relative scale from dijet events

With the absolute scale being verified in the central detector region, the missing component is the relative scale. This is determined using dijet events which provide a large number of events and a high p_T-reach. The two leading jets are required to be back-to-back in the azimuthal angle φ and at least one of the jets is required to be in the central ($|\eta| < 1.3$) detector region.

With this selection, the energy scale can be constrained relative to the central detector region by response estimators, i.e. the relative response

$$\mathcal{R}_{\mathrm{rel}}(\eta^{probe}, p_{\mathrm{T}}^{\mathrm{ave}}) = \frac{1 + \langle \mathcal{A} \rangle}{1 - \langle \mathcal{A} \rangle}, \text{ with } \mathcal{A} = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{probe} + p_T^{barrel}} \tag{3}$$

and $\mathcal{R}_{\mathrm{MPF}}$ as before. As depicted in Fig. 7, these relative differences are very small in the central detector region and below 5% in the region up to $|\eta| < 2.5$. These small remaining differences observed in Z/γ+jet and dijet events are explicitly corrected for in data in the L2L3Residual correction step which completes the previously discussed jet energy correction chain. A significant advantage of this approach is that biases inherent to data-driven methods are canceled to first order by determining only the ratio of data to simulation.

5. Conclusions

As a result of the factorized calibration procedure outlined above, the energy scale is known to the percent level over a wide range of the available phase space (compare Fig. 8) and as precise as 1% at 200 GeV for a central jet. A better understanding of the scale uncertainties allows many physics analyses to improve on their JEC-related systematic uncertainties in turn,

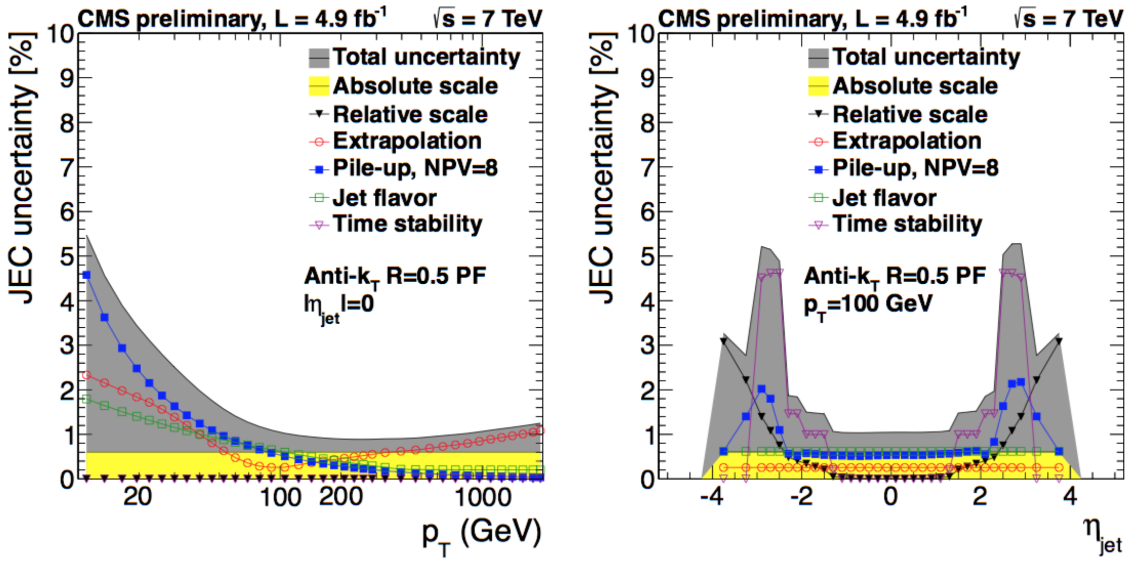

Figure 8. Jet energy scale uncertainties as a function of p_T and η. Taken from Ref. [5]

leading to more precise results in measurements involving jets. More details on pileup-mitigation techniques and on how to reduce the impact of jet energy scale uncertainties on measurements are covered in the corresponding contributions in these proceedings [11, 12].

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