Performance of Jets and Missing Transverse Energy in CMS

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A summary of the measurements of jet energy calibration and missing transverse energy calibration and resolution is presented. The jet energy calibration is performed with data samples collected in proton-proton collisions at a centre-of-mass energy of 8 TeV corresponding to an integrated luminosity of $1.6\,\text{fb}^{-1}$. The final jet energy calibration is based on dijet, γ+jet and Z+jet events. The results are presented for the "Particle Flow" approach, which attempts to reconstruct all stable particles in the event individually, prior to the jet clustering, based on information from all relevant subdetectors. We discuss the effect of pile-up interactions and the state of the art mitigation techniques used in CMS. Furthermore, we describe the main uncertainty sources for the jet energy calibration. Finally, the results of comprehensive studies of the missing transverse energy are presented, performed with $0.7\,\text{fb}^{-1}$ of $Z(\to \mu\mu)$+jets events collected at 8 TeV.

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1. Reconstruction of Jets and Missing Transverse Energy in CMS

CMS has achieved a thorough understanding of jets and missing transverse energy E_T^{miss} on a time scale that has never been reached before. The increased number of pile-up interactions and the mitigation of their effects is the major challenge in 2012.

Within the CMS Collaboration, the "Particle Flow" approach [1] is used for the event reconstruction. It combines information from all detector components prior to jet clustering, E_T^{miss} calculation and further processing. This yields a higher response and an improved resolution compared to purely calorimeter-based jet and E_T^{miss} reconstruction. Furthermore, it allows to distinguish contributions to the reconstructed jet energy from different detector components.

2. Jet Energy Corrections

The CMS Collaboration uses a factorised approach for jet calibration to combine the advantages of Monte-Carlo simulation based studies with robust data-driven methods. The procedure is described in detail in [2]. The correction levels are:

- corrections for pile-up and electronic noise;

- corrections for detector calibration effects and reconstruction efficiencies based on Monte-Carlo simulation;

- corrections for residual dependencies on the pseudorapidity η and transverse momentum p_T directly derived from data.
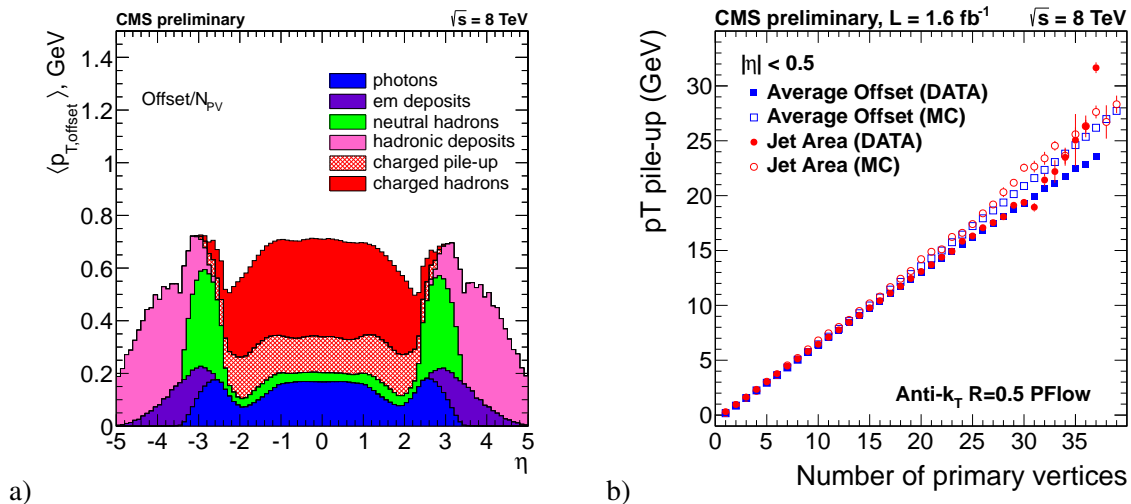
2.1 Pile-Up Corrections

Figure 1: Pile-up corrections: a) Average p_T^{offset} due to pile-up as a function of η, broken down to contributions from different components as given by the Particle Flow reconstruction algorithm. b) The pile-up contribution to the jet p_T rises linearly with the number of primary vertices in the event [5].

Dedicated corrections are defined to account for the effects of multiple proton collisions in the same bunch crossing (pile-up). Two methods are used in CMS: the first subtracts from a jet

the transverse momentum emerging from pile-up as a function the number of primary vertices N_{PV} reconstructed in the event. The second method extends this approach by taking into account the jet area of the considered jet and the amount of transverse momentum per unit area added to the event by pile-up [4]. The latter is the default method for Particle Flow jets.
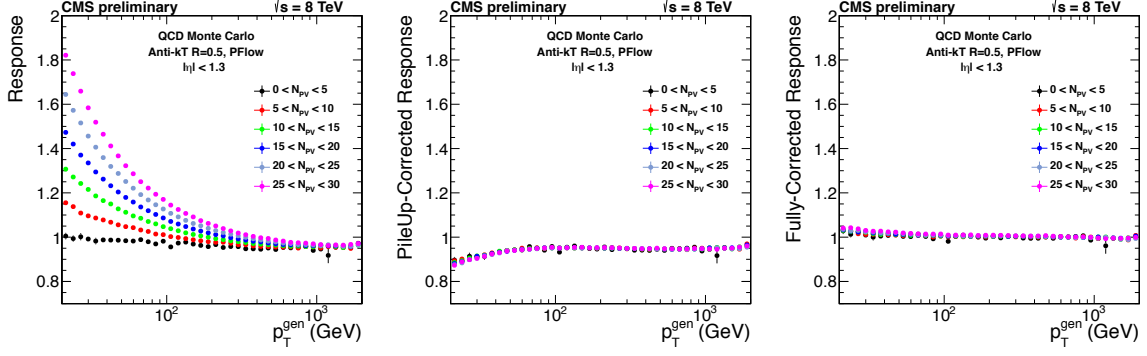
2.2 Corrections Based on MC Simulation

Figure 2: MC based corrections (*from left to right*): Uncorrected jets show a clear dependence on the number of primary vertices N_{PV}, especially at low p_T. This is successfully removed by the pile-up corrections. The corrections to the generator jet show closure over the whole p_T range [5].

After being corrected for the effect of pile-up, jets are corrected to the generator level based on Monte-Carlo simulation of QCD events. This correction step accounts for reconstruction efficiencies and the limited detector resolution. The jet energy scale for various jet flavours differs only by up to 3% in the central part of the detector. Therefore, flavour corrections are not applied by default. The corrected response reaches unity in simulated events over the whole p_T and η range, as is shown in Fig. 2 for jets in the barrel region ($|\eta| < 1.3$).

2.3 Data-Driven Residual Corrections

This chain of corrections is completed by the residual corrections in data. Relative differences in the jet energy scale between jets in the central part of the detector and jets with arbitrary η are determined from dijet events in collision data. The jets are then corrected to the absolute jet energy scale which is measured in topologies where a well-calibrated reference object is balanced to a jet. Measurements in three different channels are combined: $Z(\to \mu\mu)$+jet, $Z(\to ee)$+jet and γ+jet. Events of those topologies are selected by requiring additional jets besides the balanced jet to have small transverse momenta compared to the hard scattering scale of the event. Extrapolation techniques are employed to study the ideal case of no additional jet activity in the event. As Fig. 3 depicts, residual corrections are especially needed in the forward region of the detector. The different channels in the determination of the absolute jet energy scale agree within uncertainties.

2.4 Uncertainties of the Jet Energy Corrections

The uncertainties on the transverse momentum of a corrected jet strongly depends on its p_T and η (Fig. 4). The uncertainty resulting from the difficulty to distinguish pile-up interactions from the hard process affects especially low energy jets, whereas statistical uncertainties due to trigger
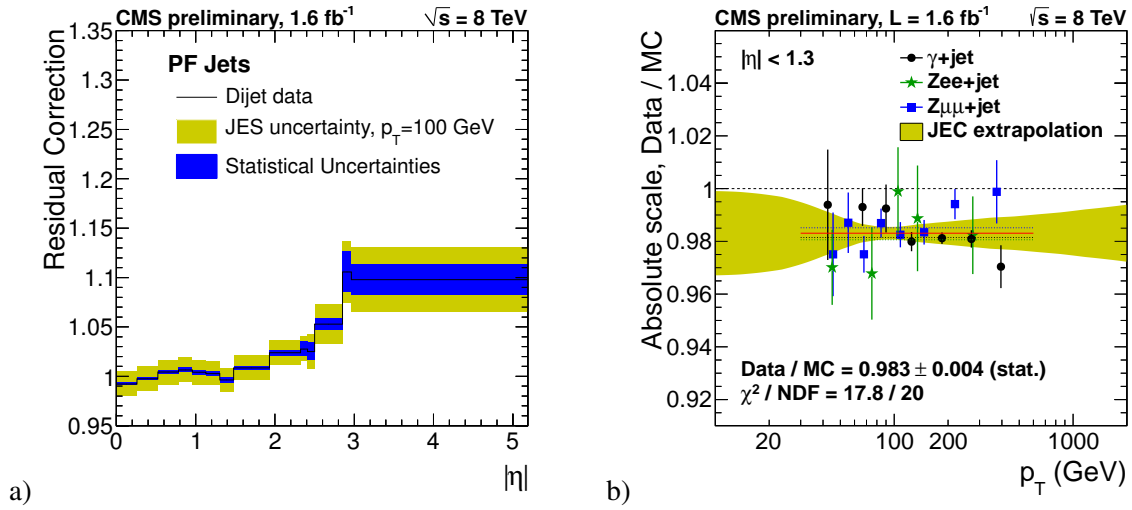
Figure 3: Residual corrections: a) Residual corrections are particularly needed in the forward region. b) The absolute scale in data is slightly lower in data which leads to residual corrections of the absolute p_T [5].
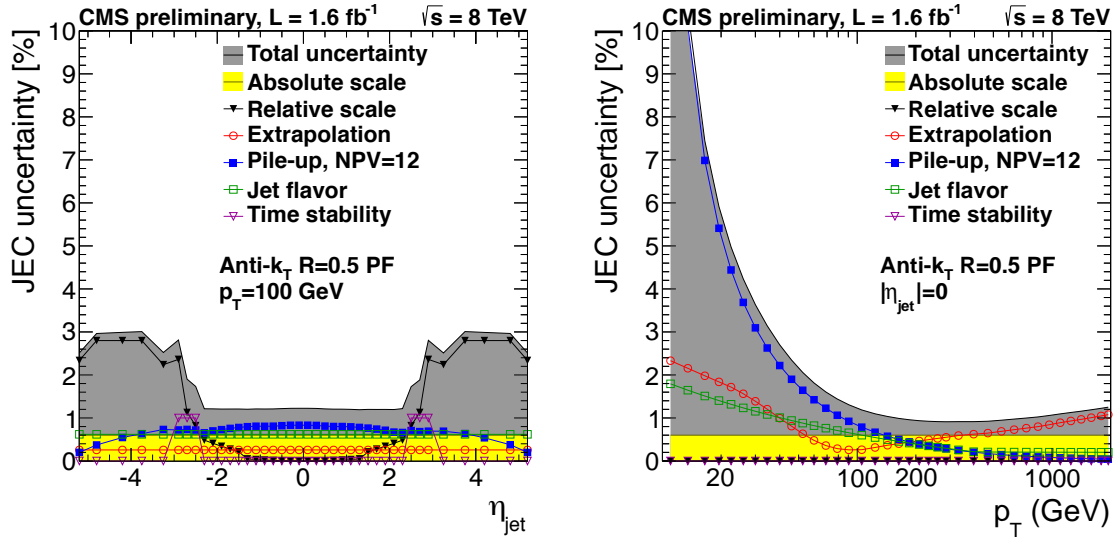

Figure 4: Uncertainty of the final jet energy corrections as a function of p_T (*left*) and η (*right*) split up into the considered sources of systematic uncertainties [5].

settings and systematic uncertainties of the relative corrections limit the precision in the forward region. In the central part of the detector, the jet energy scale is determined with a precision of about 1%.

3. Missing Transverse Energy

Robust missing transverse energy calibration and validation methods have been developed and established in CMS [3]. In 2012, the measurements are performed with $Z(\to \mu\mu)$ events [6], taking advantage of the absence of intrinsic E_T^{miss} and the very high resolution of CMS in the reconstruction of muon four-momenta. Considering the uncertainties, the distribution of the missing
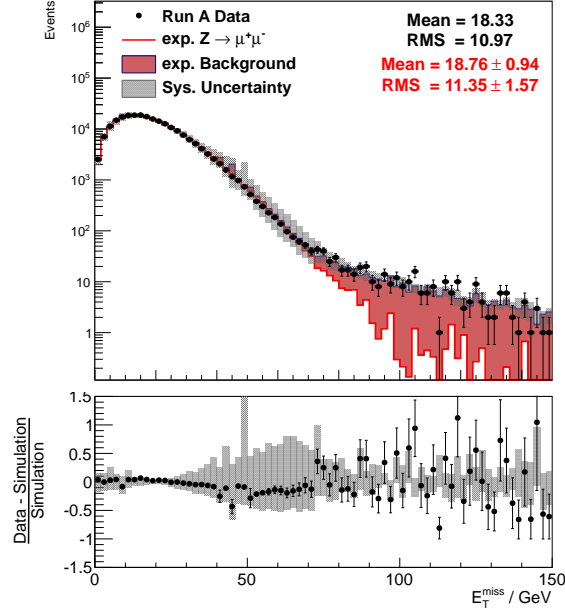
Figure 5: The distribution of the missing transverse energy E_T^{miss} in data agrees with the expectations from Monte-Carlo simulation [6].

transverse energy in data agrees with the expectations from Monte-Carlo simulation over the whole p_T range, as shown in Fig. 5.

The projection of the transverse momentum of the hadronic recoil u on the one of the Z boson q_T is used as a measure for the E_T^{miss} scale. The E_T^{miss} resolution is determined as the standard deviation of the perpendicular projection of the hadronic recoil to the Z transverse momentum.

$$E_T^{miss} \text{ scale} = \left\langle -\frac{u_{\parallel}}{q_T} \right\rangle \qquad\qquad E_T^{miss} \text{ resolution} = \sigma(u_{\perp}) \qquad (3.1)$$

Compared to previous data taking periods, an improved resolution for a fixed number of primary vertices was achieved in 2012 by the use of dedicated pile-up corrections. Furthermore, improved ECAL and HCAL reconstruction techniques have reduced the impact of pile-up from preceding and following bunch crossings on the E_T^{miss} measurements. The E_T^{miss} resolution degradation per additional primary vertex only amounts to 3 GeV. The E_T^{miss} resolution as a function of the number of primary vertices is shown in Fig. 6a.

There are ongoing efforts to reduce the effect of pile-up on the reconstructed missing energy. However, already with these results, CMS can keep up with the increasing luminosity during the 2012 data taking period.

The correction applied to jets can be propagated to E_T^{miss} to restore the consistency of the event. As Fig. 6b shows, this corrected E_T^{miss} response is very close to unity over a wide p_T range and the results in data agree with Monte-Carlo simulation.
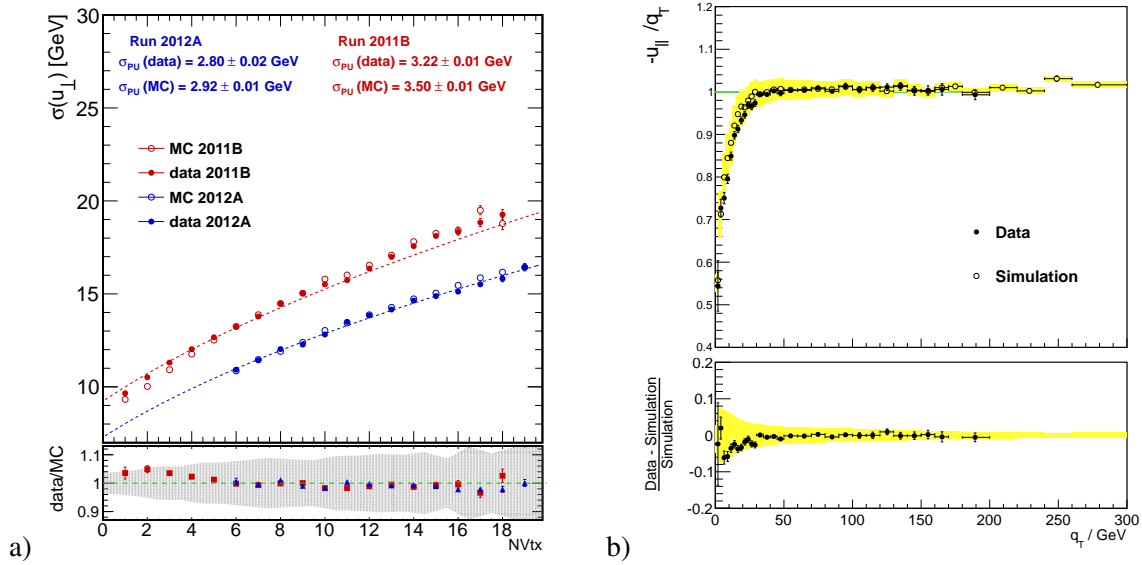
Figure 6: a) $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution $\sigma(u_\perp)$ as a function of the number of primary vertices N_{Vtx} and b) the corrected $E_{\mathrm{T}}^{\mathrm{miss}}$ response $-\frac{u_\parallel}{q_{\mathrm{T}}}$ as a function of transverse momentum of the Z boson q_{T} [6].

4. Conclusion

The CMS Collaboration successfully uses a factorised approach for jet energy corrections. Jets are measured with a precision as good as 1% in CMS, thanks to the extensive use of robust data-driven techniques. The missing transverse energy is well understood and calibrated. The effects of additional proton-proton collisions in the event are successfully removed from jets and missing energy.

References

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