Jet Energy Calibration and Transverse Momentum Resolution at CMS

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For the CMS Collaboration
Outline

- Introduction
- Jet energy calibration
  - Calibration strategy
  - MC-truth calibration
  - In-situ calibration
- Jet energy resolution
  - Core resolution studies
  - Full resolution shape and tail studies

Majority of physics analyses relay on precise Jet Energy Calibration

- **Precision measurements:**
  - Jet cross sections. A 1% uncertainty on the JES translates to ~10% uncertainty at $p_T = 500$ GeV
  - Top mass measurement. A 1% uncertainty on the JES leads to $O(1\%)$ uncertainty on the top mass.

- **Searches:** need uniform jet response, good data / MC agreement for JES.

Precision knowledge of jet energy resolutions required for

- Unfolding jet spectra
- Predicting missing $E_T$ tails in SUSY searches
Jet Flavors and types

- **CaloJets**
  Calorimeter energy depositions grouped in CaloTowers.

- **JetPlusTrack**
  Calorimeter jets whose energy has been corrected with jet-track association.

- **PFlow Jets**
  Individually reconstructed particles (PF particles) by combination of multiple detector inputs (excellent tracking, 3.8 T magnetic field, fine granular EM calorimeter).

- **GenJets**
  Stable simulated particles (after hadronization and before interaction with the detector).
Jet Energy Calibration (JEC) Overview

- JEC corrects on average the energy of a reconstructed jet to the GenJet level.  
  - the correction scales jet 4-vector
- Offset correction to account for noise & pile-up
- Jet calibration starting from the MC truth JEC.
- Small residual correction is applied on top of MC truth, based on in-situ measurements
  - relative JES from dijet $p_T$ balance
  - absolute JES from $\gamma/Z+\text{jet } p_T$ balance
- the default JEC refers to the QCD flavor composition.

$$C = C_{\text{off}}(p_T^{\text{raw}}) \cdot C_{\text{MC}}(p_T', \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}$$
Offset correction

- **Tevatron method**: average $p_T$ in a jet cone due to noise and Pile-Up (PU). Measured in Zero Bias data.


- Parametrized as a func. of $\eta$ and $N_{PV}$:

  $$C_{off}(N_{PV}, \eta, E^{raw}) = 1 - (N_{PV} - 1) \frac{O_E(\eta)}{E^{raw}}$$

- Applies to all jets algorithms through the calculation of the jet area:

  $$C_{off}(\rho, A^{jet}, p_T^{raw}) = 1 - \frac{(\rho - \rho_{UE}) \cdot A^{jet}}{p_T^{raw}}$$
Offset correction

- **Hybrid Jet Area method**: imports $\eta$-dependence from Tevatron method into Jet Area Method.

- **Offset uncertainty**:
  - $\sim 1\%/N_{PV}$ at $p_T=20$ GeV. Negligible at $p_T=100$ GeV.
  - Estimated from comparison between Tevatron method and jet area method.
The MC truth correction is derived from Pythia QCD events
- geometrically matching the reconstructed jets to the GenJets
- response $R = \frac{p_T^{\text{reco}}}{p_T^{\text{gen}}}$, correction defined as $1/\langle R \rangle$ vs $\langle p_T^{\text{reco}} \rangle$

Jet types using tracking (PF, JPT) require small corrections in the tracking coverage region ($|\eta|<1.5$)

All jet types have similar behavior in Forward Hadronic Calorimeter region of $|\eta|>3.0$. 
Relative (vs. $\eta$) JEC

- Relative JEC measured with back-to-back dijet events using $p_T$ balance method

$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

- Resolution bias: steeply falling QCD spectrum + resolution difference between barrel and probe jets $\Rightarrow$ higher measured response in the direction of the jet with the worst resolution

- ISR+FSR effect: the extra jet activity biases measured response – $P_T$ threshold on 3rd jet varied and extrapolated to 0.
Relative (vs. $\eta$) JEC

- To account for the data/MC differences, a residual correction is derived from the MC/data response ratio. Includes corrections for:
  - plus/minus $\eta$ asymmetry
  - extra jet activity

\[ C_{\text{res}}(\pm \eta) = \frac{k_{\text{FSR}}(\eta) \cdot C_{\text{sym}}(|\eta|)}{1 \mp A(|\eta|)} \]

- Measurement precision
  - Limited by systematic uncertainty
  - Dominant uncertainty from the resolution bias modeling in the MC -- estimated by varying the resolution and the QCD spectrum slope
  - Other sources (PU, ISR+FSR, Asymmetry Statistics) are negligible
Absolute (vs. $p_T$) JEC

- Measured in back-to-back $\gamma$+jet and $Z(\rightarrow ee/\mu\mu)$+jet events using Missing $E_T$ Projection Fraction (MPF) method

$$R_{MPF} = \frac{R_{recoil}}{R_\gamma} = 1 + \frac{E_{miss} \cdot p_{T,\gamma}}{(p_{T,\gamma})^2}$$

- $p_T$-balancing method used for cross-checks.
- MPF method ideally suited for PFJets
  - the measurement performed exclusively for PFJets and then “transferred” to the other jet types by direct jet-by-jet matching

- Measured response in data/MC corrected for ISR+FSR by extrapolating 2nd jet $p_T$ to zero.
- Final (ISR+FSR corrected) response lower in data by 1.5 % compared to MC.
- Results consistent between three calibration samples.
Absolute JEC Uncertainties

- MPF method
  - secondary jets
  - flavor mapping from photon+jet to QCD composition
  - parton correction
  - QCD background
  - proton fragments
- Photon energy scale
- MC extrapolation beyond the reach of the measurement
  - single particle response
  - fragmentation modeling
- Average offset
- Residuals
  - MCtruth closure
  - jet-by-jet-matching
- flavor dependence
Total JEC Uncertainties
Jet Energy resolutions

- $P_T$ asymmetry method applied in dijet sample
  \[ A = \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2}, \quad \frac{\sigma(p_T)}{p_T} = \sqrt{2}A \]

- $P_T$ balancing method applied in $\gamma$+jet sample
  \[ \sigma \left( \frac{p_T^{\text{jet}}}{p_T^{\gamma}} \right) = \sigma \left( \frac{p_T^{\text{jet}}}{p_T^{\text{Genjet}}} \right) \oplus \sigma \left( \frac{p_T^{\text{Genjet}}}{p_T^{\gamma}} \right) \]

- Bias corrections
  - soft-radiation correction for both methods/samples
  - Particle level imbalance correction in $p_T$ asymmetry method
  - Genjet-$\gamma$ imbalance correction in $p_T$ balancing method

- Measurement systematics
  - the bias corrections
  - MC closure
  - data/MC scaling
Resolution tails measured from both dijet and $\gamma$+jet events.

- Counting events in tail regions of asymmetry/$p_T$ balancing distributions

\[ f_A = \frac{\text{Events in window}}{\text{total events}} \]

Data/MC ratios for $f_A$ measured after adjusting MC core distribution to match it to data.
Summary

- In-situ measurement of the Jet Energy Scale in CMS is in good agreement with the simulation.
  - jet calibration is based on MC simulation with small residual corrections to account for the small differences between data and MC.
  - the calibration chain also includes an offset corrections removing the additional energy inside jets due to Pile-Up.

- For all jet types, total Jet Energy Scale uncertainty is smaller than 3% for $p_T>50$ GeV in the $|\eta|<3$ region.

- Jet energy resolutions have been studied in dijet and $\gamma+$jet samples.
  - estimates of the core as well as the tails of the jet energy resolutions agree between the two samples
  - the core of the measured resolution in data is somewhat broader than in simulation