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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

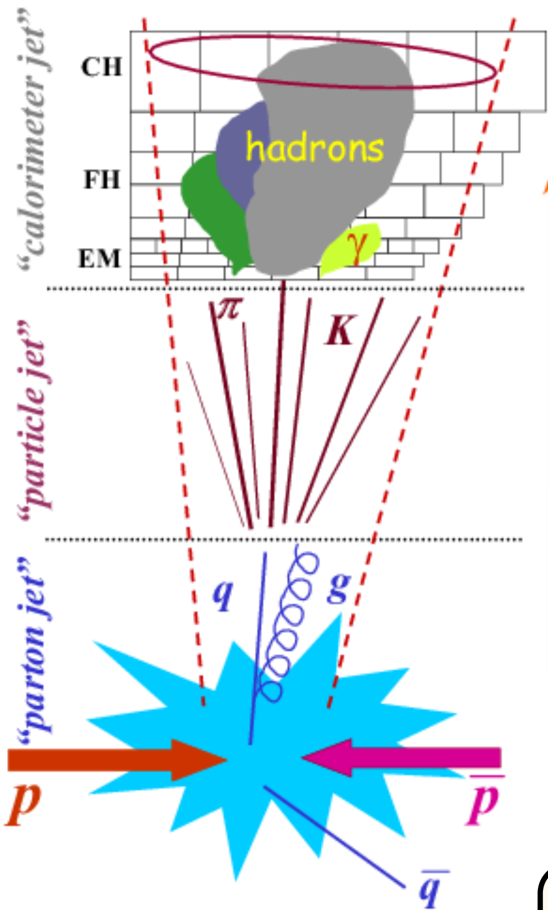
  Calorimeter jets whose energy has been corrected with jet-track association.
- PFlow Jets

  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).

Particles, CaloTowers, PF, Tracks → Jet Algorithm (Anti-kT with R=0.5) → GenJets, CaloJets, PFJets, JetPlusTrack

Jet Energy Calibration (JEC) Overview

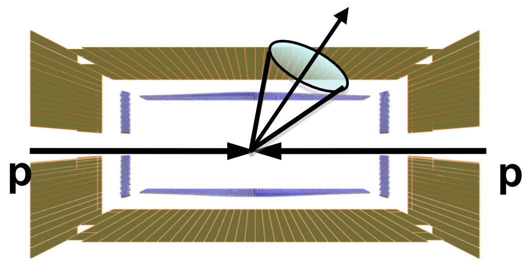


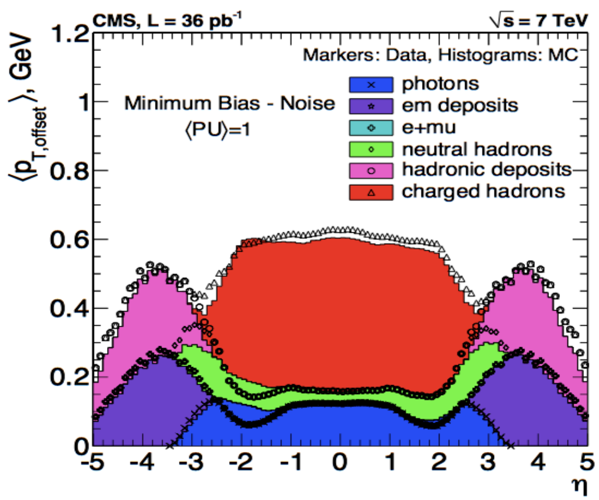
- JEC corrects on average the energy of a reconstructed jet to the GenJet level.
  - the correction scales jet 4-vector
- Offset correction to account for noise & pile-up
- Jet calibration starting from the MC truth JEC.
- Small residual correction is applied on top of MC truth, based on in-situ measurements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

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

Offset correction

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

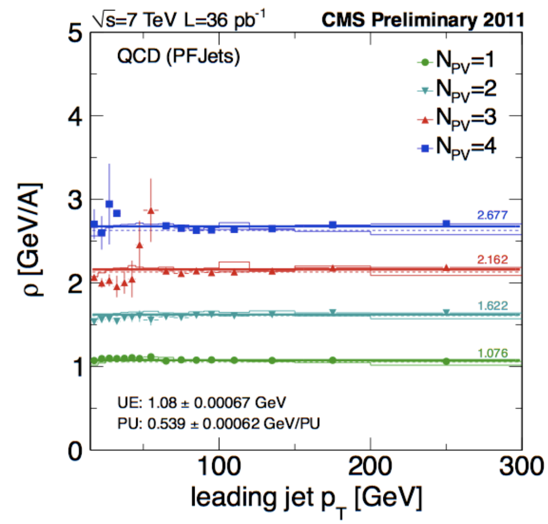




- Parametrized as a func. of η and N_{pv}:

$$C_{\rm off}(N_{\rm PV}, \eta, E^{raw}) = 1 - (N_{\rm PV} - 1)\frac{\mathcal{O}_E(\eta)}{E^{raw}}$$

- Jet Area method: average p_T density per unit jet area. Measured in-situ in high p_T physics events. Takes into account event-by-event and jet-by-jet fluctuations

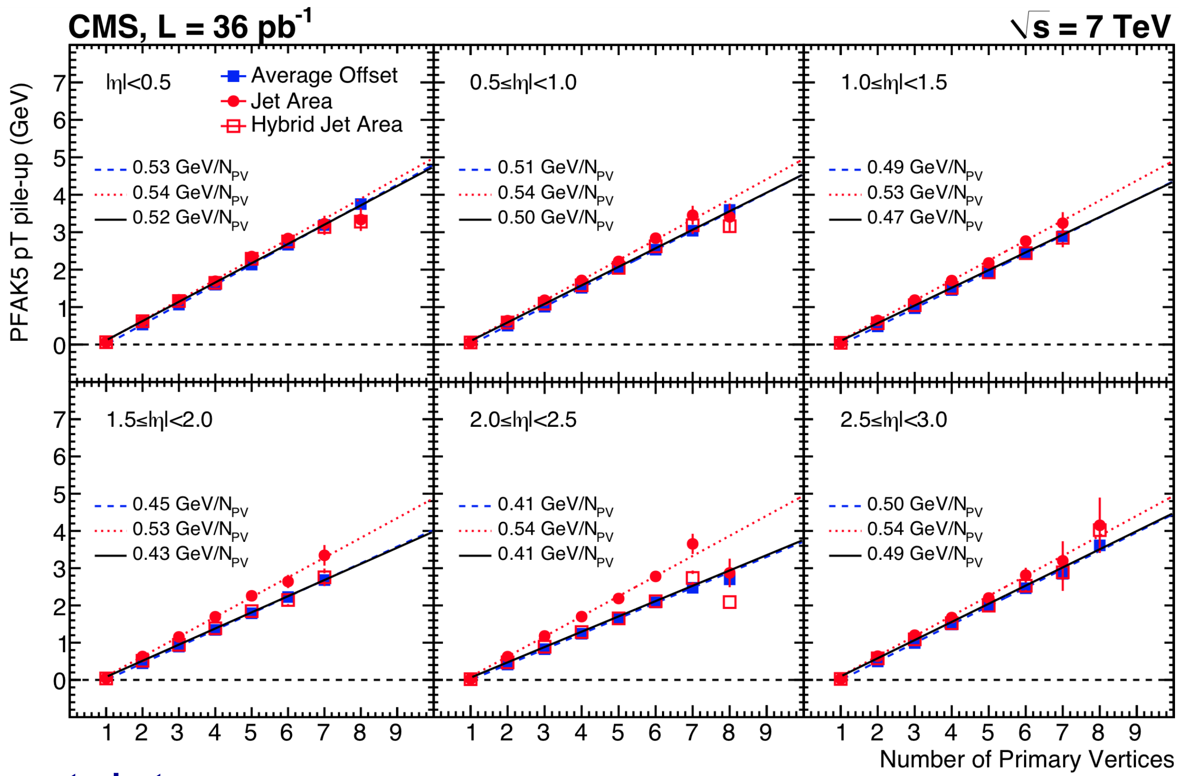


- Applies to all jets algorithms through the calculation of the jet area:

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

Offset correction

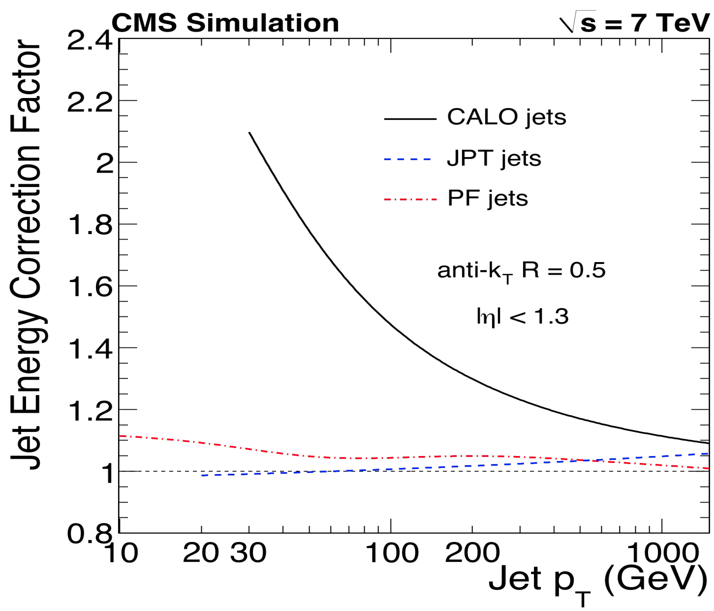
- Hybrid Jet Area method: imports η-dependence from Tevatron method into Jet Area Method

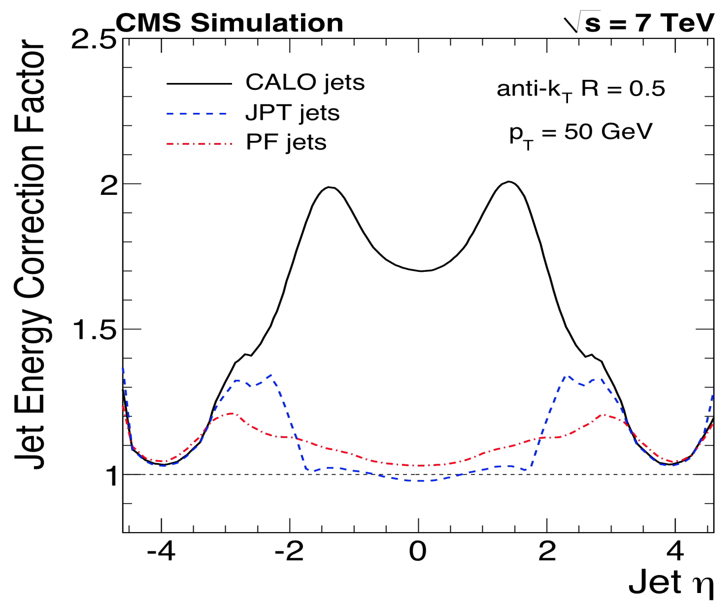


- Offset uncertainty:
  - ~1%/N_{PV} at p_T=20 GeV. Negligible at p_T=100 GeV.
  - Estimated from comparison between Tevatron method and jet area method.

MC Truth JEC

- The MC truth correction is derived from Pythia QCD events
  - geometrically matching the reconstructed jets to the GenJets
  - response R = p_T^{reco}/p_T^{gen}; correction defined as 1/<R> vs <p_T^{reco}>





- 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 $|\eta|>3.0$.

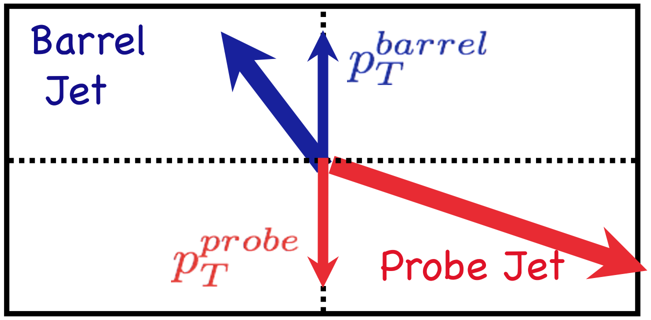
Relative (vs. η) JEC

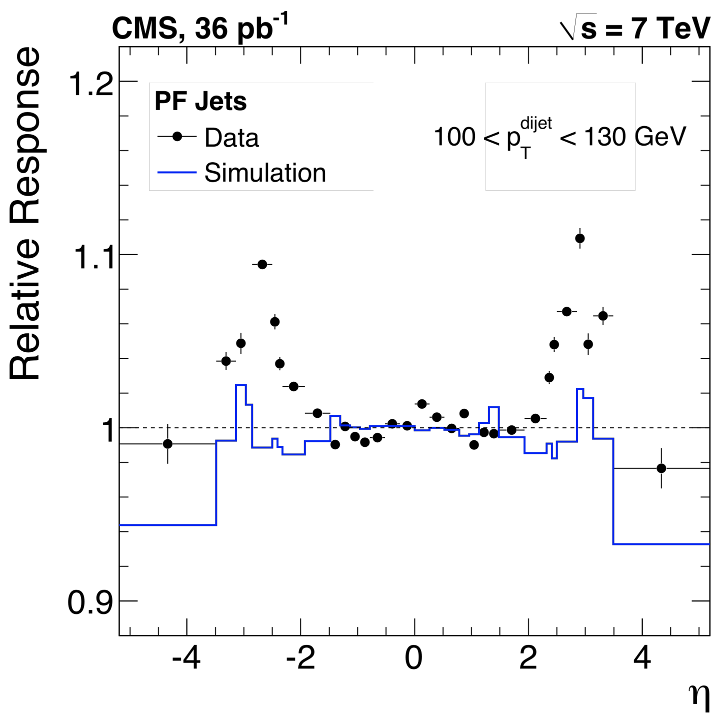
- Relative JEC measured with back-to-back dijet events using p_T balance method

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

$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$





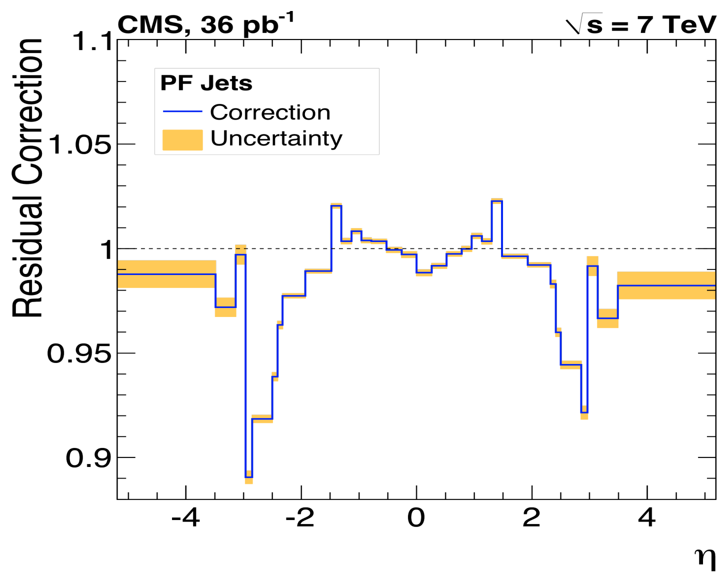
- Resolution bias: steeply falling QCD spectrum + resolution difference between barrel and probe jets ➔ higher measured response in the direction of the jet with the worst resolution

- ISR+FSR effect: the extra jet activity biases measured response – P_T threshold on 3rd jet varied and extrapolated to 0.

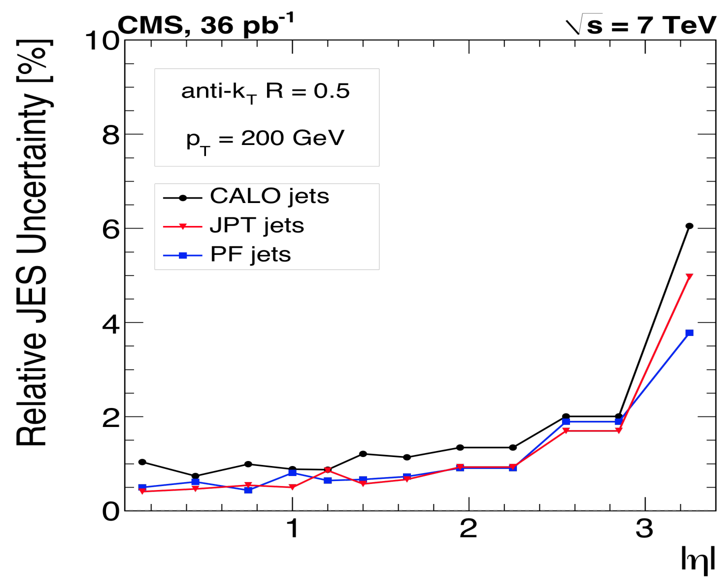
Relative (vs. η) JEC

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

$$C_{\rm res}(\pm\eta) = \frac{k_{\rm FSR}(\eta)\cdot C_{\rm sym}(|\eta|)}{1 \mp A(|\eta|)}$$



- 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

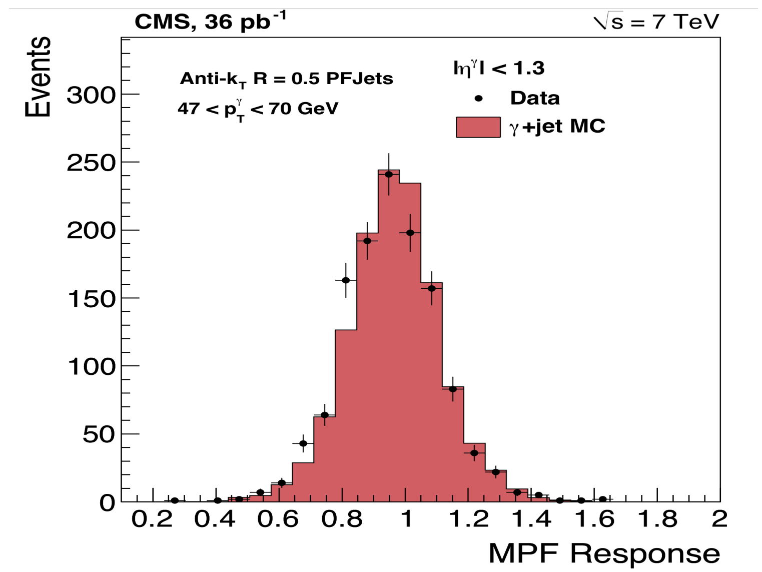


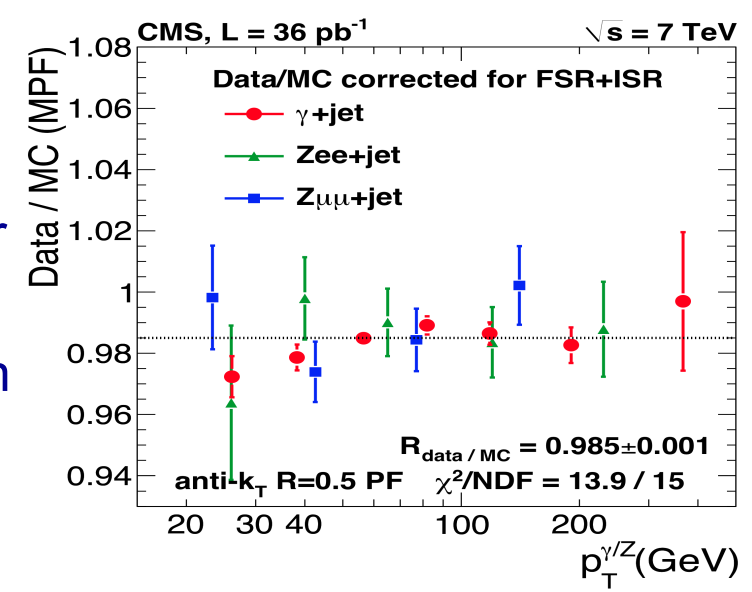
Absolute (vs. p_T) JEC

- Measured in back-to-back γ+jet and Z(->ee/μμ)+jet events using Missing E_T Projection Fraction (MPF) method

$$R_{MPF} \equiv \frac{R_{recoil}}{R_\gamma} = 1 + \frac{\vec{E}_T^{miss} \cdot \vec{p}_{T,\gamma}}{(p_{T,\gamma})^2}$$

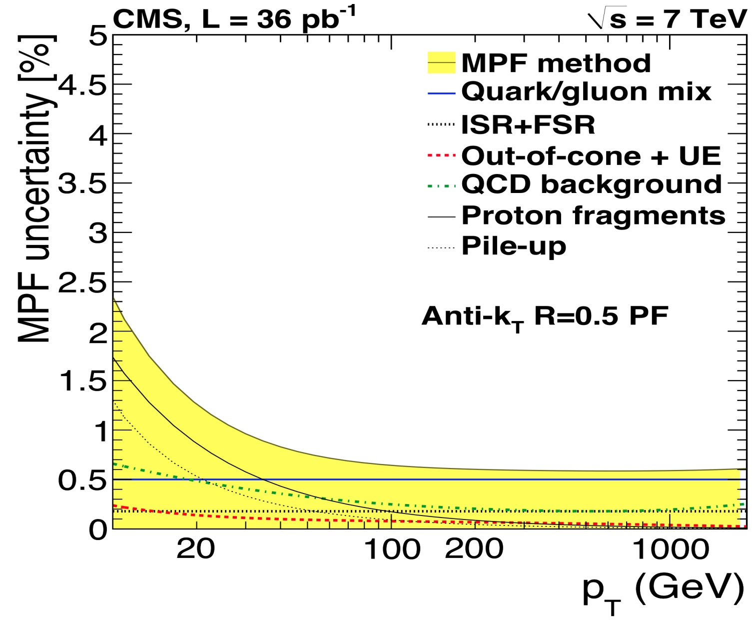
- P_T-balancing method used for cross-checks.
- MPF method ideally suited for PFJets
  - the measurement performed exclusively for PFJets and then “transferred” to the other jet types by direct jet-by-jet matching
- Measured response in data/MC corrected for ISR+FSR by extrapolating 2nd jet P_T to zero.
- Final (ISR+FSR corrected) response lower in data by 1.5 % compared to MC.
- Results consistent between three calibration samples.

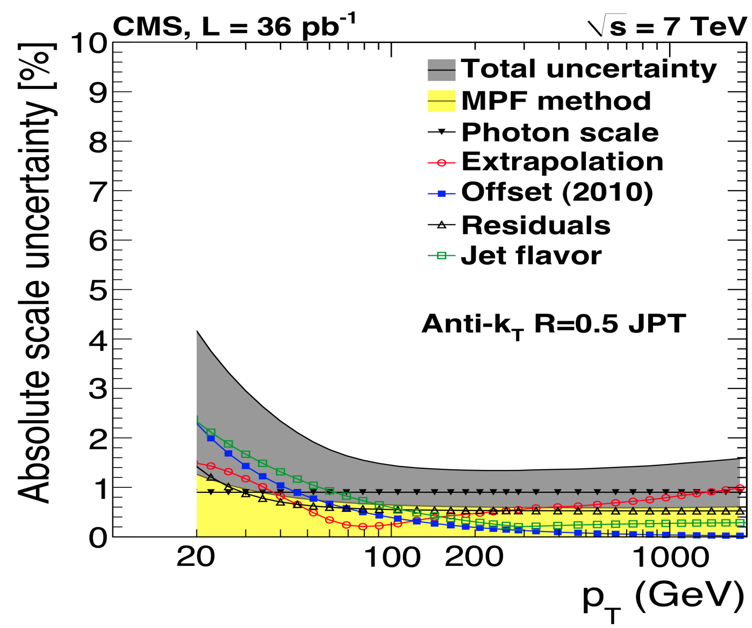




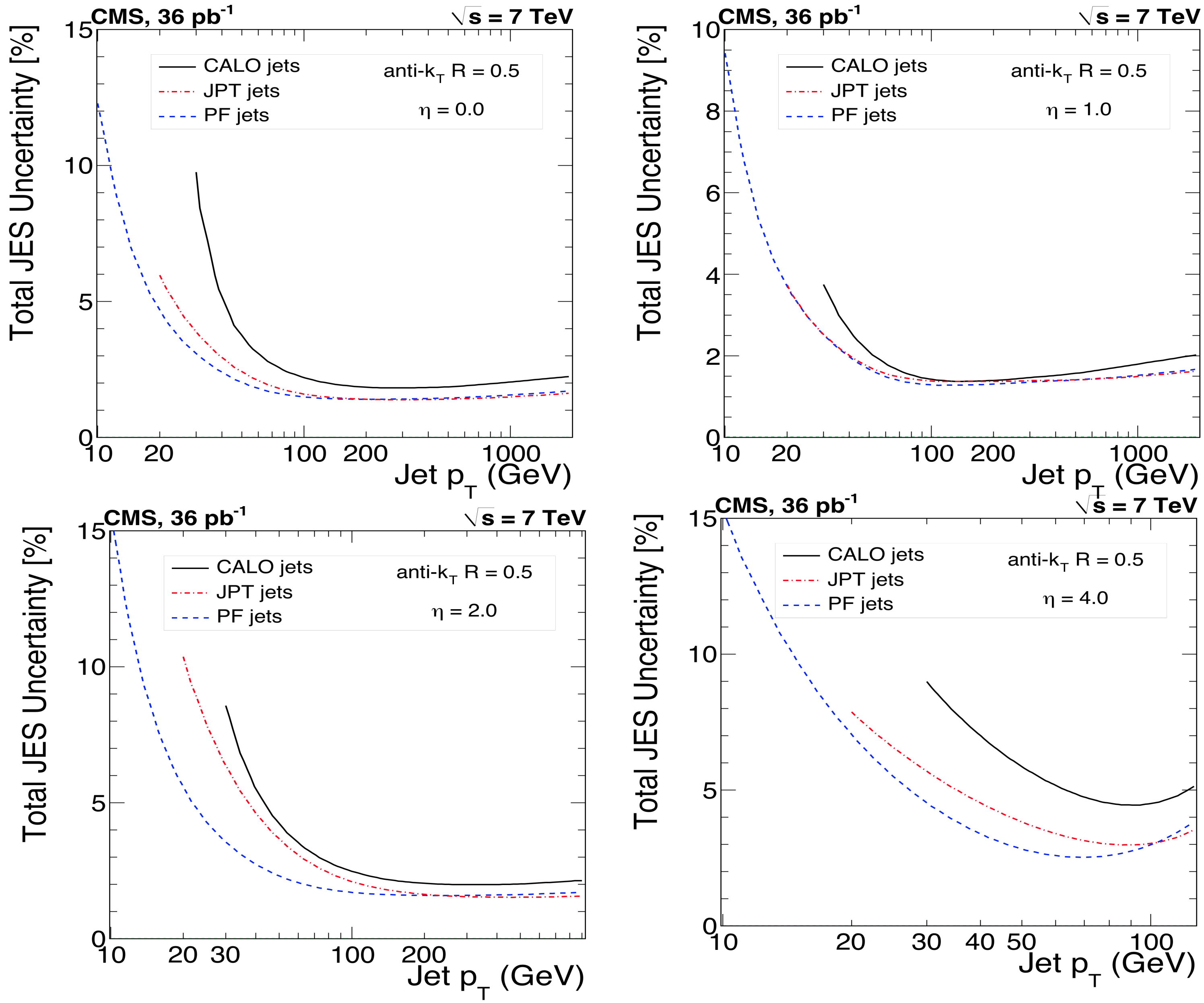
Absolute JEC Uncertainties

- ❑ 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

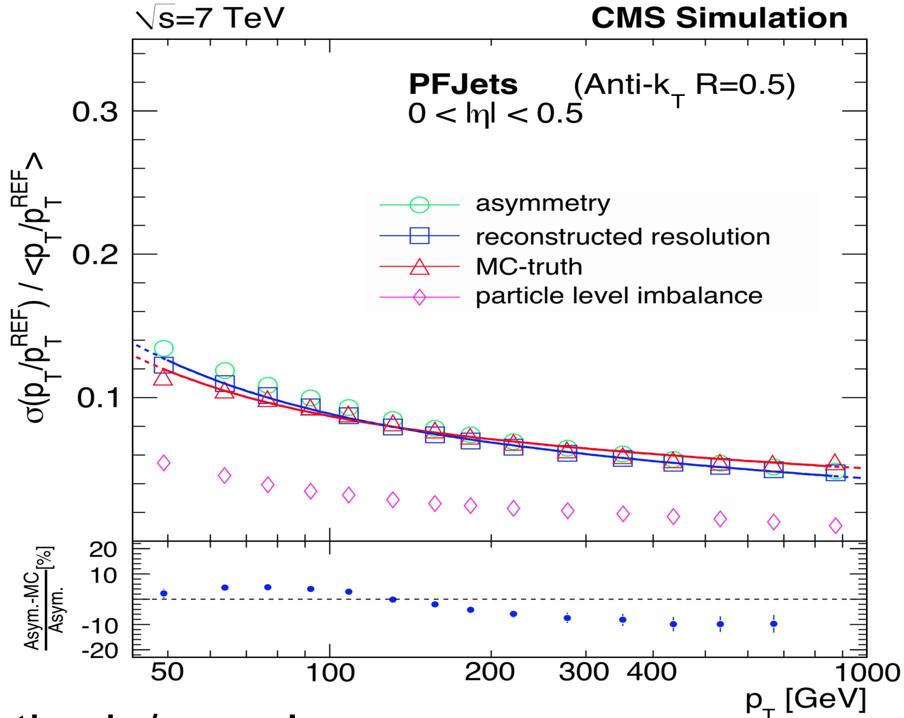
- P_T asymmetry method applied in dijet sample

$$A = \frac{p_T^1 - p_T^2}{p_T^1 + p_T^2}, \qquad \frac{\sigma(p_T)}{p_T} = \sqrt{2}A$$

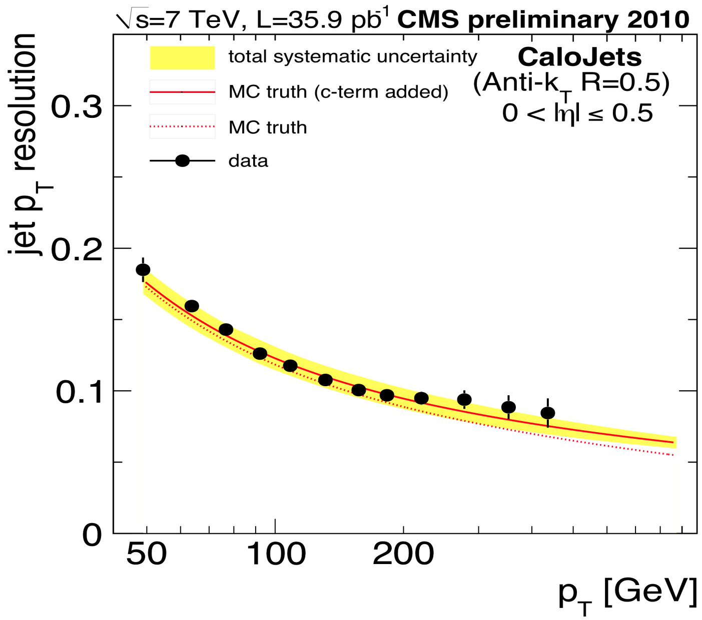
- P_T balancing method applied in γ+jet sample

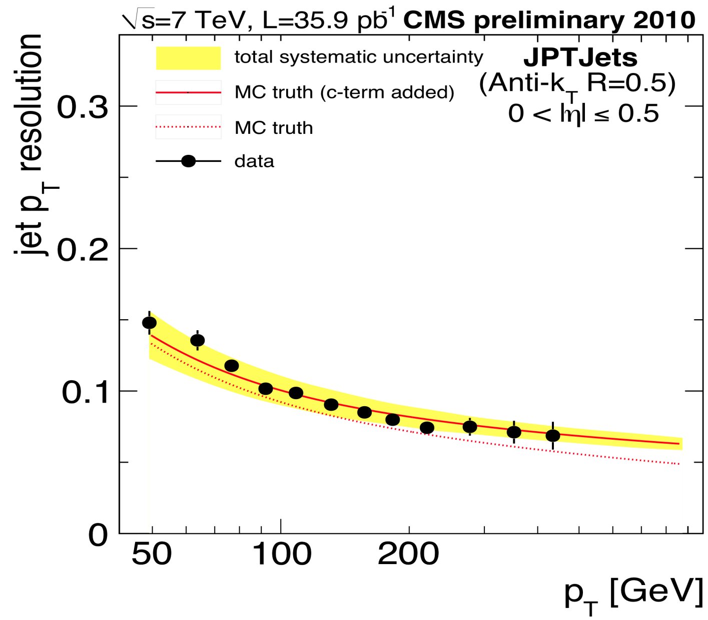
$$\sigma\left(\frac{p_T^{jet}}{p_T^{\gamma}}\right) = \sigma\left(\frac{p_T^{jet}}{p_T^{Genjet}}\right) \oplus \sigma\left(\frac{p_T^{Genjet}}{p_T^{\gamma}}\right)$$

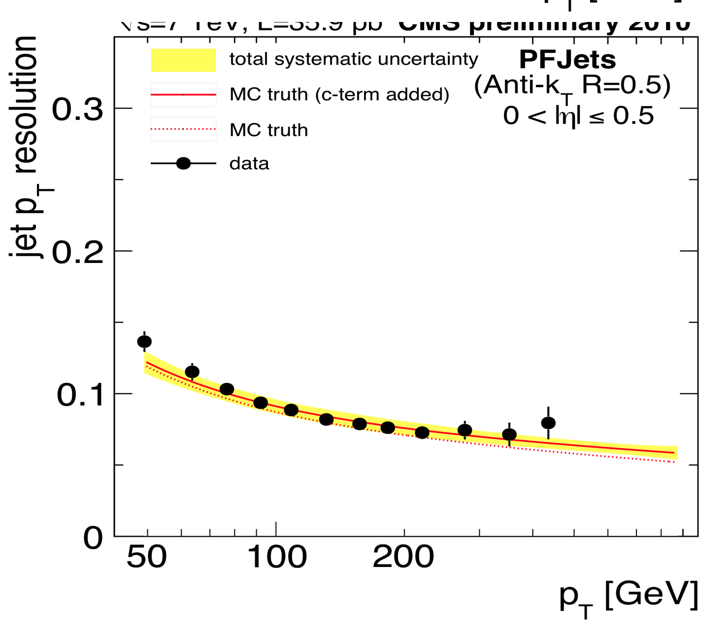
- Bias corrections
  - soft-radiation correction for both methods/samples
  - Particle level imbalance correction in p_T asymmetry method
  - Genjet-γ imbalance correction in p_T balancing method
- Measurement systematics
  - the bias corrections
  - MC closure
  - data/MC scaling

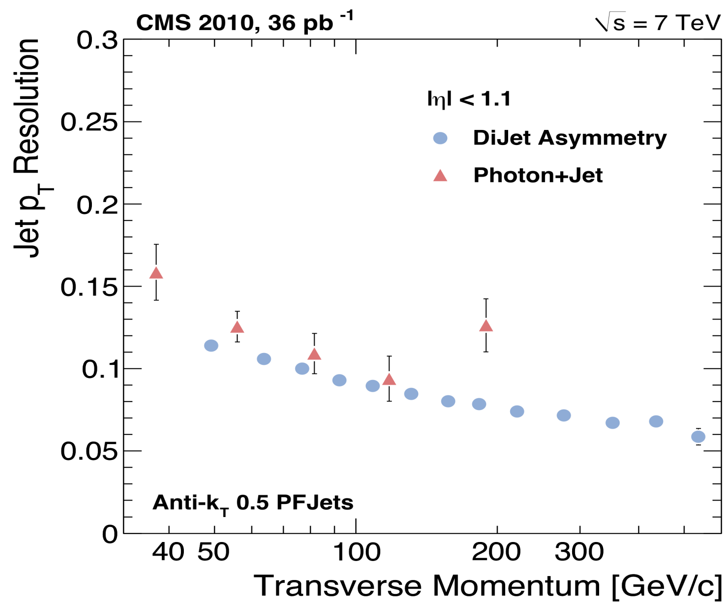


Jet Energy Resolutions – Core Measurements







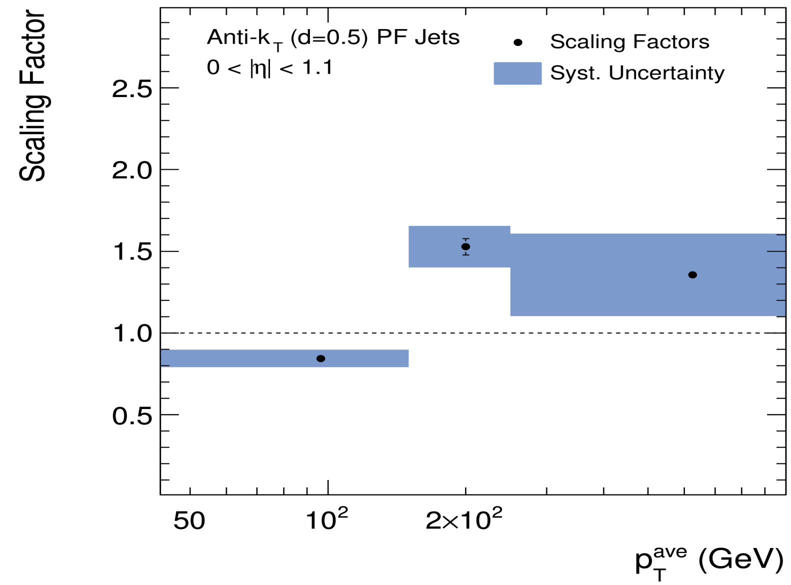


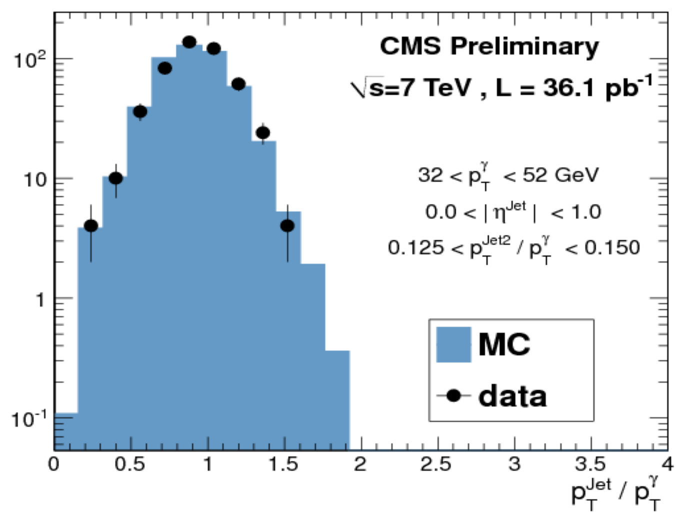
Jet Energy Resolutions – Tail Measurement

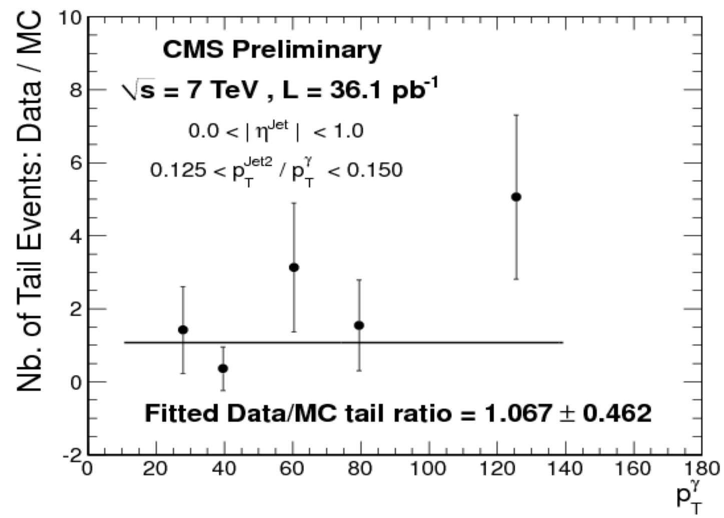
- Resolution tails measured from both dijet and γ+jet events.
  - Counting events in tail regions of asymmetry/p_T balancing distributions

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

- 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 γ+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