



# Jet Energy Scale and Resolution Measurements at CMS

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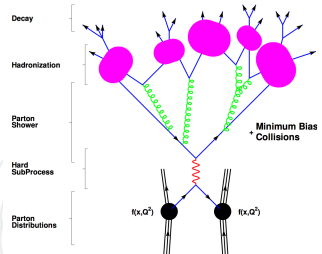
CMS Collaboration

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- ▶ At the LHC, quarks and gluons are abundantly produced in proton-proton collisions at  $\sqrt{s} = 13$  TeV.
- ▶ Jets are signatures of quarks and gluons.
- ▶ The production cross section of jets (QCD) is orders of magnitude higher compared to any other processes.
- ▶ Depending on the physics process, jets can either be the **signal or background**  $\implies$  **measurement of jet 4-momentum is essential for most analyses.**
- ▶ Jet reconstruction and calibration is challenging in busy LHC environment. **Additional pp interactions (event pileup) produce extra unwanted energy underneath a jet, smearing its 4-momentum.**

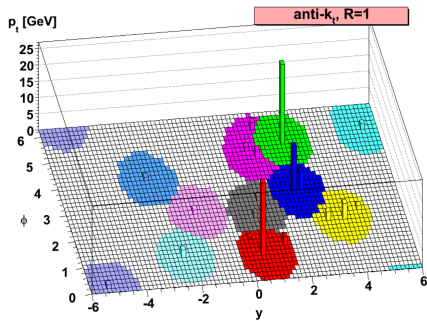


- ▶ We use **infrared and collinear safe Anti- $k_T$**  recombination algorithm to cluster jets.
- ▶ PF particle list used as input. **PF algorithm combines information from all CMS sub-detectors** (Tracker, ECAL, HCAL, Preshower and Muon System) to precisely reconstruct produced particles.
- ▶ **PFchs Jets:** Clustered from identified PF particles. Charged PF particles associated to pileup vertices are removed.
- ▶ **PUPPI Jets:** Clustered from weighted (for pileup probability) PF particles.

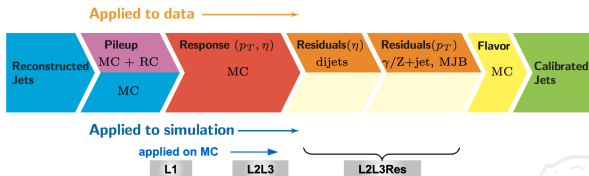
- ▶ **Anti- $k_T$  Clustering:**

$$d_{ij} = p_{T,i}^{2x} \quad d_{ij} = \min(p_{T,i}^{2x}, p_{T,j}^{2x}) \frac{\Delta_{ij}^2}{R^2}$$

- ▶ We use Anti- $k_T$  with distance parameter  $R = 0.4$  and  $0.8$ .



- ▶ Aim: correct Reconstructed jets to Particle Level jets.



- ▶ **MC truth based calibration:**

$$\langle p_T^{reco} \rangle / \langle p_T^{particle} \rangle = 1$$

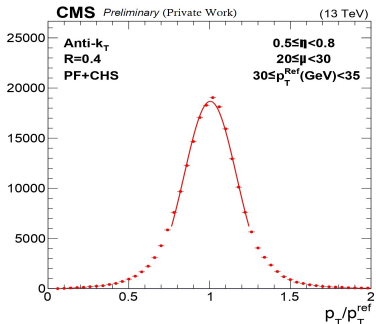
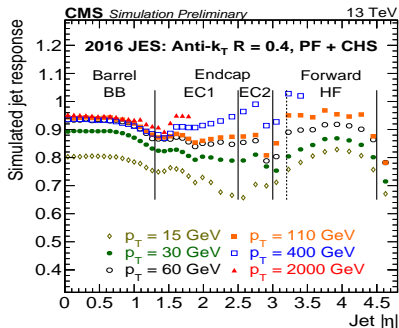
- ▶ **L1 Offset corrections:** removes pileup energy. Extracted from QCD samples with and without pileup.
- ▶ **L2L3Response:** corrects for detector non-uniformity and response.

- ▶ **Residual Data/MC correction:**

$$\langle p_T^{reco} \rangle / \langle p_T^{ref} \rangle = 1$$

- ▶ **L1Res:** Pileup residuals from Zero Bias data and MC.
- ▶ **L2Res:**  $\eta$ -dependent and coarse  $p_T$ -dependent residuals from QCD dijet.
- ▶ **L3Res:** Finely  $p_T$  dependent residuals from  $Z(\rightarrow ee, \mu\mu)$ +jet,  $\gamma$ +jet and multijet.

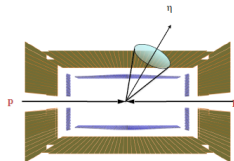
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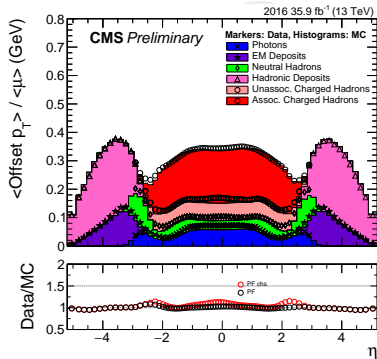
- ▶ Jet Response (Scale) =  $\frac{\langle p_T^{reco} \rangle}{\langle p_T^{particle} \rangle}$
- ▶ Less than 1 response at low  $p_T$  due to neutral hadrons which have response  $\sim 0.6$
- ▶ Jet Response is stable in the Barrel region.
- ▶ Drops in Response at low  $p_T$  in:
  - $|\eta| = [3 - 3.2]$  due to calorimeter gaps.
  - $|\eta| > 4.7$  due to acceptance.

- ▶ Jet Energy Correction = reciprocal of Jet Energy Response.
- ▶ After jets are corrected by multiplicative JEC factor, Response is centered at unity.

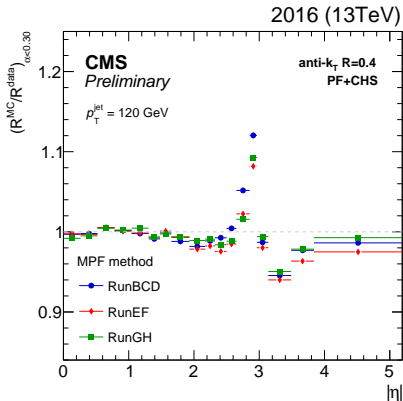
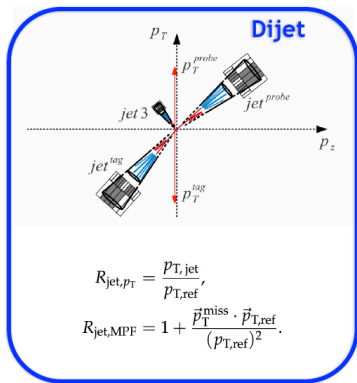
- ▶ Pileup Offset: Extra unwanted energy due to multiple pp interactions.
- ▶ Charged Hadron Subtraction: Hadrons associated with PU vertices are removed with CHS algorithm.
- ▶ Remaining contributions are subtracted in L1 Offset Correction.
- ▶ L1 Residual Offset is measured with Zero Bias data and MC.
- ▶ Use "Random Cone" method to derive L1 Residual.



Random cone centered at  $\eta$

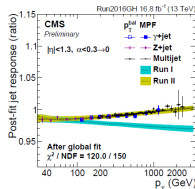
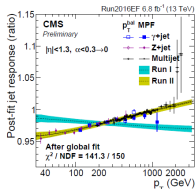
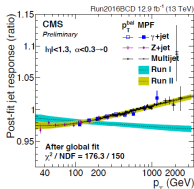
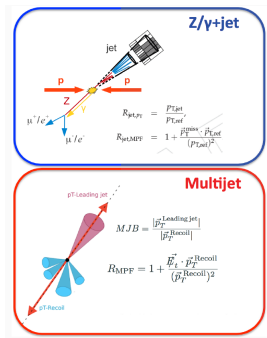


- ▶ Goal: make Data/MC jet response ratio uniform in  $\eta$ .

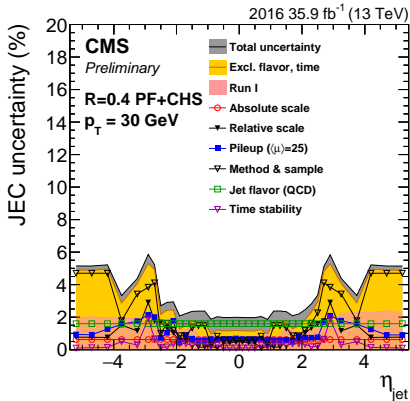
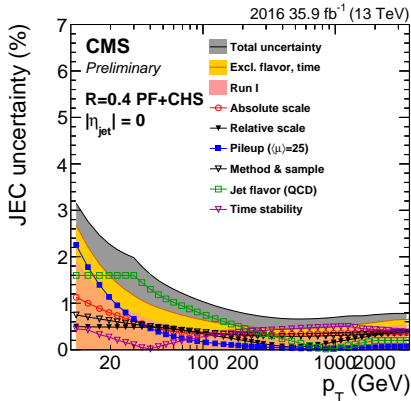


- ▶ Uses back-to-back dijet events.
- ▶ Balance Probe Jet with reference jet at central eta region ( $|\eta| < 1.3$ ).
- ▶ Employ two complementary methods:
  - ▶  $p_T$  balance.
  - ▶ Missing  $E_T$  projection fraction (MPF).

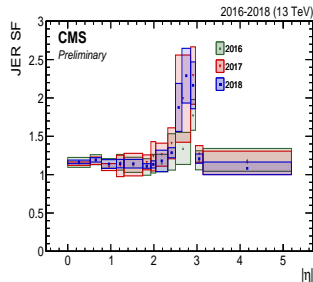
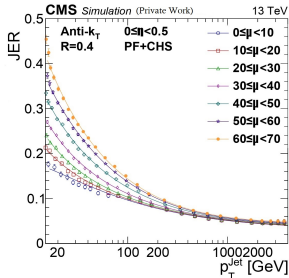
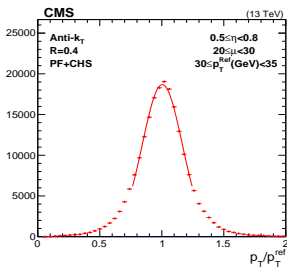
- ▶ Goal: Make residual Data/MC jet response uniform in  $p_T$  and equal to 1.



- ▶ We use several channels to cover a wide  $p_T$  range: Z( $\rightarrow ee, \mu\mu$ )+jet,  $\gamma$ + jet and multijet samples.
- ▶ Relative scale obtained by global fit taking into account individual scales and uncertainties of reference objects.
- ▶ Both, direct  $p_T$  balance and MPF methods are employed.



- ▶ In the Barrel, the JEC performance is close to Run I.
- ▶ Main uncertainty at low  $p_T$  is the pileup offset.
- ▶ Higher pileup in Run II leads to increased uncertainties in  $|\eta| > 2.5$  compared to Run I.



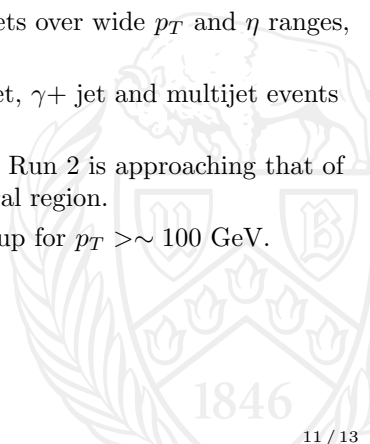
- ▶ Use fits of response distributions from MC truth.
- ▶ Resolution =  $\sigma_{fit}/\mu_{fit}$ .

- ▶ Resolutions are stable against pileup above jet  $p_T \sim 100$  GeV for all  $\eta$ .

- ▶ Data/MC resolution scale factors derived using dijet events.
- ▶ Scale factors  $\sim 1.2$  except for the Endcap-Forward transition region around  $|\eta| = 3$ .



- ▶ Hadronic jets are abundantly produced in pp collisions at the LHC.
- ▶ Precise calibration of jets is of the utmost importance for the majority of physics analyses at CMS.
- ▶ CMS uses simulation and data to calibrate jets over wide  $p_T$  and  $\eta$  ranges, and under increased pileup conditions.
- ▶ Zero Bias events, QCD dijet,  $Z(\rightarrow ee, \mu\mu)+\text{jet}$ ,  $\gamma+\text{jet}$  and multijet events are used for in-situ calibration.
- ▶ The precision of the jet energy calibration in Run 2 is approaching that of Run 1: better than 1% precision in the central region.
- ▶ Jet energy resolutions are stable against pileup for  $p_T > \sim 100$  GeV.



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- [1] <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsDP20019>.
- [2] <https://cms.cern.ch/iCMS/user/noteinfo?cmsnoteid=CMS%20DP-2018/028>

