Measurements of the CMS jet energy scale and resolution at 13 TeV

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Motivation

- **Jets** are the **experimental signatures of quarks and gluons** produced in high-energy processes such as proton-proton collisions at the LHC.

- Jet production cross-sections are several orders of magnitude higher than other processes.

- Besides being the signal, jets can fake particles like $\gamma,e,\mu,\tau$.

- High event pileup presents a challenge to reconstruct and calibrate jets in $p$-$p$ collisions.
Jet Reconstruction at CMS

- Jets at CMS experiment are clustered using the anti-$k_T$ algorithm ($R = 0.4, 0.8$ etc.)

- Particle level jets: all stable and visible particles in gen. event

- Calorimeter jets: from energy deposits in calorimeter towers

- Particle Flow jets: reconstructed by clustering PF candidates

- Charged hadron subtraction algorithm for pileup removal

- PFCHS: main algorithm used at CMS
  - results in this talk based entirely on PF+CHS

- Pile Up Per Particle Id (PUPPI) algorithm: weights to particles based on probability to come from PU
Jet Particle Flow composition

- Jet PF composition from dijet events (jets w/ JEC)
- Data compared to the multijet Pythia 8 QCD
- Photons, leptons, charged & neutral hadrons (pileup refers to energy fraction that was removed by CHS)

- Improved tracking efficiency towards the end of the data taking in 2016:
  - better agreement between the data and MC for the PF composition
Jet Calibration at CMS

- **Jet Energy Corrections (JEC)** procedure using **factorized approach** in order to correct the reconstructed jets (on average) back to the particle jet level

  - Pileup correction in order to account for the offset energy
  - Correction to particle level jet vs $p_T$ and $\eta$ (from simulation)
  - Small residual corrections to data for pileup, relative vs $\eta$, absolute vs $p_T$; **full physics analysis** to derive the residuals
  - **Jet Energy Resolutions (JER)** measured in MC events vs $p_T^{ptcl}$, $\eta$ and $\mu$ and data to MC scale factors derived from dijet events are applied in addition

\[
\frac{<p_T^{RECO}>}{<p_T^{ptcl}>} (p_T, \eta, \mu) = 1
\]
Jet Energy Offset correction

- Charged hadrons associated to the pileup vertices removed using the CHS algorithm
- Residual pileup offset contribution can be estimated using Random Cone method for ZeroBias data & Single Neutrino MC sample

Data to MC scale factor vs $\eta$ during the different periods of the CMS data taking

- Time dependence of the scale factors in EB after fix of track dynamic inefficiency
Jet Energy Scale in simulation

- Jet response, $<p_T^{RECO}>/ <p_T^{ptcl}>$, particle jets from stable & visible particles

- Stable response in the barrel region:
  - neutral hadron response of 0.6 (15% of $p_T^{ptcl}$) => 0.95 response
  - response drops for $p_T < 30$ GeV due to limited HCAL acceptance

- Stronger $p_T$ dependence in EC & HF

- Response drop: $3.0 < |\eta| < 3.2$ due to transition & $|\eta| > 4.5$ for acceptance

- Correction performed for $p_T$ and $\eta$ dependence, determined in bins of $\eta$
Jet Energy Scale: relative $\eta$ residual corrections

- Relative residual correction derived as a function of $p_T$ and $\eta$, relative to the well calibrated detector region with $|\eta| < 1.3$
- The missing transverse energy projection fraction (MPF) method with di-jet events

**Data** compared to Pythia8 QCD simulation

- Relative res. correction as a function of jet $p_T$
- Correction value at average $p_T$ in each $\eta$ bin shown for various data taking periods
Jet Energy Scale: absolute scale corrections

- Response dependence on $p_T^Z$ in $Z(\mu\mu)$+jets events, before absolute residual correction
- Response is calculated with events where the additional jet activity $\alpha = p_T^2/p_T^{\text{ref}} < 0.3$

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$\gamma$ + jets Run2016 36.5 fb$^{-1}$ (13 TeV)

- Madgraph_aMC@NLO ($Z$+jets), PYTHIA8 ($\gamma$+jets)
- $p_T$ balance response < 1 due to FSR + ISR effects
Jet Energy Scale: multijet balance method

- Extrapolation of JEC to high $p_T$ constrained using multijet balance method:
  - evt. with high $p_T$ barrel jet balanced by recoil system of 2 or more jets
- The $p_T$ balance and MPF response are defined using the following expressions:
  \[
  MJB = \frac{|\vec{p}_T^{\text{Leading jet}}|}{|\vec{p}_T^{\text{Recoil}}|}
  \]
  \[
  R_{\text{MPF}} = 1 + \frac{E_t \cdot \vec{p}_T^{\text{Recoil}}}{(\vec{p}_T^{\text{Recoil}})^2}
  \]
- Multijet analysis can only constrain the jet energy scale $p_T$ dependence
Jet Energy Scale: absolute residual corrections

- The data to MC comparison for the dependence of jet response on jet $p_T$
- Combination of four samples: $\gamma +$ jets, $Z(\mu\mu) +$ jets, $Z(ee) +$ jets & multijet

- Scale uncertainties of the reference objects taken as nuisance parameters
- Reduced correction@end of data taking (fixed strip tracker dynamic ineff.)
Jet Energy Resolution

- Resolution stable against pileup above jet $p_T > 100$ GeV

$$JER = \sigma \left( \frac{<p_T>}{<p_T^{ptcl}>} \right)$$

- Resolution better than 10% (5%) above $p_T$ of 100 GeV (1 TeV), degradation of 50 % at $p_T$ of 20 GeV for very high pileup scenario (up to the value $\mu=75$)
Jet Energy Scale Uncertainties

- Flat absolute scale uncertainties -> combined $\gamma$, $Z(\text{ee})$ and $Z(\mu\mu)$ reference scale and FSR + ISR
- Relative scale -> di-jet uncertainties for JER (SF variation); FSR+ISR from Pythia8 vs Herwig diff.
- Pileup->5% uncertainty of data/MC scale factor for offset correction & offset jet $p_T$ dependence

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- Time stability: different corrections per epoch
- Method & sample: MPF vs $p_T$ balance; $Z/\gamma$+jets vs dijet difference outside (inside) the tracking
Conclusions

• Precise reconstruction and calibration of hadronic jets is crucial for the large majority of the physics analysis of the CMS collaboration.

• Various data and MC samples used to derive corrections, applying factorized approach to cover wide range of $p_T$ with full $\eta$ coverage.

• Zero Bias (data) events, then QCD dijet, $Z(\text{ee, } \mu\mu) + \text{jets}$, $\gamma + \text{jets}$ and multi-jet (MC) events used for the in-situ calibration of jets.

• High precision of the jet energy calibrations (1% in central region).

• The CHS algorithm strongly reduces the impact of pileup on the jet energy resolution; PUPPI expected to improve on this even further.
BACKUP
The CMS detector at CERN

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
Particles in the CMS detector

Key:
- Muon
- Electron
- Charged Hadron (e.g., Pion)
- Neutral Hadron (e.g., Neutron)
- Photon

Transverse slice through CMS

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

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The CMS Particle Flow Algorithm

- Global event reconstruction: correlation of the basic elements (tracks & clusters) from all detectors for particle reco & ID
- Higher efficiency and purity, better energy resolution
- Iterative tracking algo
- Higher eff. & same FR
- Modified (faster) PF algorithm in the HLT system
- Increased HLT efficiency for the jets and τ leptons
Charged Hadron Subtraction at CMS

- **Pileup** leads to additional charged hadrons, thus affecting the jet reconstruction, missing transverse energy, the $\tau$ isolation and ID

- Charged hadron subtraction (CHS) algorithm used for identification and also removal of PF candidates corresponding to pileup vertices

- Improved the JER w/ CHS algorithm

- The CHS removes about 85% PU jets
Improvement of JER with PUPPI at high PU

- Mass response and mass resolution for W+jets as function of # prim. vertices

- PUPPI shows the best mass resolution along with an improved stability against the pileup
Strip Tracker Dynamic Inefficiency

- Decrease of signal over noise ratio associated to loss of tracking hits observed in late 2015 and part of 2016
  - Increasing with the Instantaneous Luminosity and occupancy
  - Initially believed to be due to heavily ionizing particles (HIPs)
  - Finally traced to saturation effects in the APV chip preamplifier
- Fixed in mid August changing the APV chip settings to increase drain speed
  - About 20/fb of data affected -> problem mitigated in data reprocessing