Performance of Jet and Missing Transverse Energy Reconstruction with CMS in pp Collisions at $\sqrt{s}=7$ TeV

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On behalf of the CMS collaboration

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Motivation

Jets and MET crucial for many measurements and also important for searches

From “Hadronic Event Shapes in pp Collisions at $\sqrt{s}=7$TeV”, CMS PAS QCD-10-013

From “Search for Dijet Resonances in the Dijet Mass Distribution in pp Collisions at $\sqrt{s}=7$TeV”, CMS PAS EXO-10-001
The CMS Detector
Jet/MET Types in CMS

**Default Jet Clustering Algorithm**: Anti $K_T$ with $R=0.5$

**Calorimeter Jets**
Jets clustered from ECAL and HCAL deposits (Calo Towers)
Accordingly:
**Calo MET**

**Jet-Plus-Track Jets (JPT)**
Subtract average calorimeter response from CaloJet and replace it with the track measurement
Accordingly:
**Tc MET**

**Particle Flow Jets (PF)**
Cluster Particle Flow objects: Unique list of calibrated particles “a la Generator Level”
Accordingly:
**PF MET**

**Track Jets**
Reconstructed from tracks of charged particles, independent from calorimetric jet measurements

=> Using different inputs allows CMS to study and constrain experimental systematics
Jet results @ 7 TeV

How well do we understand Jet Energy Scale and Jet Resolution?
Example: Dijets $\Delta \phi$ in Data/MC

Important variable to select a clean dijet sample

$\Delta \phi$

* => Good agreement for all jet types between data and MC
Two Strategies:
**MC-truth JEC and In-situ JEC**
- Majority of CMS physics analyses currently use **MC-truth JEC**
- MC corrections are derived from PYTHIA QCD dijet MC events
- **In-situ JEC** sub-corrections will replace **MC-truth** corrections when available

Factorized approach:
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**Factorized approach:**

- **Reconstructed Jets**
  - **Offset**
  - **Rel: \( \eta \)**
  - **Abs: \( p_T \)**

**Relative:** Correct to make calorimeter response uniform in \( \eta \)
**In-situ method:** Dijet \( p_T \) balance

**Absolute:** Correct absolut energy scale
**In-situ method:** Photon+jet \( p_T \) balance
**MPF method**
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**In-situ method:**
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Absolute: Correct absolut energy scale

**In-situ method:**
- Photon+jet $p_T$ balance
- MPF method
Relative JEC: dijet $p_T$ balance

Relative JEC removes jet response variation in $\eta$
A priori estimate of uncertainty: $\pm 2\% \times |\eta|$

Barrel Jet

- Require at least 2 jets, one jet in the barrel region $|\eta|<1.3$
- Azimuthal separation $\Delta \Phi > 2.7$
- Third jet veto $p_T^{3rd}/p_T^{dijet} < 0.2$

$\Rightarrow$ Measure distributions of balance variable $B$ in representative $(p_T^{dijet}, |\eta|)$ bins for all jet types

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

$\begin{align*}
    r &= \frac{2+ < B >}{2- < B >} \\
    p_T^{dijet} &= \frac{p_T^{probe} + p_T^{barrel}}{2}
\end{align*}$

$r$ := relative response in a given $(p_T^{dijet}, |\eta|)$ bin
Relative JEC: Data/MC

- Good agreement up to $|\eta| = 2$
- Relative response in data ~10% higher compared to simulation for $|\eta| > 2$

=> Data/MC close to unity after the residual correction
=> Data/MC deviations are covered by conservative $\eta$-dependent systematic uncertainty of $\pm 2\% \times |\eta|$
Mean response in Data and MC agrees within 2-3 % in **barrel region**

In **endcap**, the simulated response is systematically lower than data (~4%)
Absolute JEC: photon+jet balance

A-priori estimate of JEC uncertainty in barrel 5% for tracking-based jets (JPT, PFJets, track jets), 10% for CaloJets

- Method employs $p_T$ balance in back-to-back photon+jet events (well measured photon as a reference object)
- Use photon trigger and isolated photons $p_T>15$ GeV and $|\eta|<1.3$
Absolute JEC: photon+jet balance

Photon+jet balance: Bias due to soft veto on second jet

Miss-E<sub>T</sub> projection fraction method (MPF, from D0) uses MET to measure the balance and is less sensitive to QCD radiation.

Distributions of "response sensitive" variable R<sub>MPF</sub> vs p<sub>T</sub><sup>γ</sup>

=> Mostly good agreement when same method applied to MC and Data
=> Direct evidence from MPF supports 5%/10% JEC uncertainty as conservative

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Jet $p_T$ resolutions

- Define $p_T$ asymmetry of the two leading jets in back-to-back dijet events:
  \[ A = \frac{p_T^{jet_1} - p_T^{jet_2}}{p_T^{jet_1} + p_T^{jet_2}} \]

- For approximately equal value of the jet $p_T$'s:
  \[ \frac{\sigma(p_T)}{p_T} = \sqrt{2} \sigma_A \]

- Full chain of Dijet Asymmetry method applied to data and MC to extract jet $p_T$ resolutions

=> Observed data/MC agreement within a priori $\sim 10\%$ uncertainty
MET results @ 7 TeV

How well do we model our MET and control MET tails?
Cleaning of MET Tails

Basic cleaning strategy:
identify anomalous signals based on:

- Unphysical charge sharing of neighboring channels
- Timing/pulse shape information

=> Cleaning is very effective
=> After cleaning, MET tail is no longer dominated by anomalous signals
MET in Data /MC

Minimum Bias: Calo MET

11.7 nb⁻¹.

Dijet events with corr. $p_T^{1,2} > 25$ GeV, $|\eta_{1,2}| < 3$:

=> General Agreement between Data and MC
Study of MET distribution in 1-and 2-vertex events in minimum-bias

- MET distributions wider in 2-vertex events
- Reweight 2-vertex events so that the SumE_T distribution matches that of the 1-vertex events
- After reweighting, MET distribution agrees between 1-vertex and 2-vertex events

=> Widening of MET distribution in 2-vertex events due to transverse energy increase in events
MET Resolution vs SumE$_T$

Compare the resolution of different MET types at the same PF SumE$_T$ (closest to real sumE$_T$)

- PF SumE$_T$ is calibrated to generator level Sum E$_T$
- Observed MET sigma is calibrated using photon+jets MC events:

=> PF MET has the best resolution.
=> Tc MET also shows significant improvement w.r.t. Calo MET
First results of the Jet and Missing Transverse Energy performance were presented

**Jets:**
- General data/MC agreement for jet response and $p_T$ resolutions
- Observations from current data support a priori estimates:
  - $10\%$ ($5\%$) JEC uncertainty for calorimeter jets (jets using tracking)
  - Additional $2\%$ uncertainty per unit rapidity
  - $10\%$ $p_T$ resolution uncertainties for all three jet types

**MET:**
- Acceptable data/MC agreement
- Improved cleaning, tails are under control
- Tackling the challenge of MET commissioning with large pile up
- Tc MET, and especially PF MET, improve resolution **significantly**

Impressive Jet and MET understanding already after just 3 months of data taking at $\sqrt{s}=7$TeV!
References

- CMS DP-2010/014 -- Jet and MET Commissioning Results from 7 TeV Collision Data
- JME-10-006 -- Commissioning of Track Jets in pp Collisions at $\sqrt{s}=7$TeV
- JME-10-008 -- Single Particle Response in the CMS Calorimeters
- JME-10-003 -- CMS Jet Performance in pp Collisions at $\sqrt{s}=7$TeV
- JME-10-004 -- Missing Transverse Energy Performance in Minimum-Bias and Jet Events from Proton-Proton Collisions at $\sqrt{s}=7$TeV
- ME-10-006 -- Commissioning of Track Jets in pp Collisions at $\sqrt{s}=7$TeV
- JME-10-008 -- Single Particle Response in the CMS Calorimeters
- PFT-10-001 -- Commissioning of the Particle-flow Event Reconstruction with the first LHC Collisions recorded in the CMS detector
- PFT-10-002 -- Commissioning of the Particle-Flow reconstruction in Minimum-Bias and Jet Events from pp Collisions at $\sqrt{s}=7$TeV
- QCD-10-013 -- Hadronic Event Shapes in pp Collisions at $\sqrt{s}=7$TeV
- EXO-10-001 -- Measurement of the Dijet Mass Spectra in pp Collisions at $\sqrt{s}=7$TeV
Backup: CMS Parameters

Tracker: 66M pixel channels, ~10M Si microstrip channels,

Calorimetry: ~75k crystals, ~15k HCAL channels,

Muon System: 250 DT chambers (170k wires), 450 CSC chambers (~200k wires), ~ 500 Barrel RPCs ~ 400 endcap RPCs,

Trigger System: muon and calorimeter trigger system, 40 kHz DAQ system (~ 10k CPU cores),

Grid Computing (~ 50 k cores), Offline (> 2M lines of source code).
Backup : Anti $K_T$

\[ d_{i,j} = \min \left( k_{T,i}^{-2}, k_{T,j}^{-2} \right) \frac{\Delta R_{i,j}^2}{R^2} \]

\[ \Delta R_{i,j}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \]

- New development in the jet clustering theory.
- Tends to cluster the energy around the hardest particles.
  - essentially behaves like a cone algorithm giving perfectly round jet areas
- Belongs to the “$k_T$” family.
  - merging of 4-vector pairs based on transverse momentum weighted distance in $y$-$\varphi$ plane.
  - the clustering terminates when the weighted distance between particles is greater than a specific value $R$ (resolution parameter).
  - the quantity $R$ is of the order of unity.
- infrared and collinear safe (suitable for theory calculations).
Backup: Offset correction

- **Offset from noise:**
  - Is below 400 (300) MeV in energy ($p_T$).
  - Simulation gives good description of noise in data.

- **Offset from one pile-up event:**
  - Up to 7 GeV in energy, but stays below 350 MeV in $p_T$.
  - Pythia Minimum Bias (D6T tune) gives decent description of PU.

- **Probability of pile-up in 2010 data typically ~50% (was ~10% in earlier plots)**

=> Total average offset contribution to jet $p_T$ is small in the current data.

=> No offset correction is applied in the standard JEC chain.
Backup : Absolute JES

- A-priori estimate of JEC uncertainty in barrel 5% for tracking-based jets (JPT, PFJets, track jets), 10% for CaloJets

- Constraints from test beam, jet composition studies and “first principles” (single pion response, $\pi^0$ mass peak, tracker resonances)

- Direct evidence from Missing-ET projection fraction method (MPF) supports 5%/10% JEC uncertainty as conservative
Backup: Absolute JES

**Photon**

\[ \rho_T = 76.1 \text{ GeV/c} \]
\[ \eta = 0.0 \]
\[ \phi = 1.9 \text{ rad} \]

**Photon is looking even better:**

<table>
<thead>
<tr>
<th></th>
<th>VALUE</th>
<th>ALLOWED RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster Minor Axis</td>
<td>0.22</td>
<td>0.15 ÷ 0.3</td>
</tr>
<tr>
<td>Cluster Major Axis</td>
<td>0.29</td>
<td>0.15 ÷ 0.35</td>
</tr>
<tr>
<td>ECAL GT Isolation (\Delta R&lt;0.4)</td>
<td>1.7% (E_Y)</td>
<td>&lt; 5% (E_Y)</td>
</tr>
<tr>
<td>HCAL Isolation (\Delta R&lt;0.4)</td>
<td>0.4% (E_Y)</td>
<td>&lt; 5% (E_Y)</td>
</tr>
<tr>
<td>Sum (\rho_T) Tracks (\Delta R&lt;0.35)</td>
<td>0</td>
<td>&lt; 10% (\rho_{T,Y})</td>
</tr>
<tr>
<td>Number of Tracks (\Delta R&lt;0.35)</td>
<td>0</td>
<td>&lt; 3</td>
</tr>
</tbody>
</table>

**Anti-\(k_T\) 0.5 PFJet**

\[ \rho_T = 72.0 \text{ GeV/c} \]
\[ \eta = 0.0 \]
\[ \phi = -1.2 \text{ rad} \]
Backup: Absolute JEC

Balance "Response" versus $p_T^\gamma$

- Measured "response" is lower than MC-truth response
  - Loose second jet veto ($p_T^{2nd} < 0.5 p_T^\gamma$) violates photon-jet $p_T$ balancing and produces downward bias in the measurement.
- Reasonable data/MC agreement when the same $p_T$ balance method is applied to data and simulation
- Pileup test in backups: ~no change with PV=1 cut
Backup: MPF

- Basics of MPF (Missing Momentum Fraction; AN-2010/218)
  - Ideally: \[ \vec{p}_T^\gamma + \vec{p}_T^{\text{recoil}} = \vec{0} \]
  - Add in the detector: \[ R_\gamma \vec{p}_T^\gamma + R_{\text{recoil}} \vec{p}_T^{\text{recoil}} = -\vec{E}_T^{\text{miss}} \]
  - Solving: \[ R_{\text{recoil}}/R_\gamma = 1 + \frac{\vec{E}_T^{\text{miss}} \cdot \vec{p}_T^\gamma}{|\vec{p}_T^\gamma|^2} \equiv R_{\text{MPF}} \]

- \( R_{\text{MPF}} \) is assigned as the response of the recoil jet

- Advantage of MPF: Low sensitivity to extra radiation
  - Smaller error bars: Widths of distributions are narrower thanks to less fluctuations from the impact of extra radiation
  - Smaller bias wrt MC-truth than \( p_T^{\text{jet}}/p_T^\gamma \) for current very loose cuts on extra radiation
  - Helps to fully exploit the accuracy of PF method

- MPF method demonstrates the accuracy of JES for different types of jets more clearly than \( \gamma \)-jet balancing method does
Backup: Absolute MPF

MPF “Response” versus $p_T^Y$

- Measured “response” is closer to MC-truth response than for $p_T$ balance
- Good data/MC agreement when the same MPF method is applied to data and simulation.
Well measured tracks which do not interact in tracker material are used for measuring response of calorimeter.

- Tracks reconstructed with High Purity quality
- Track Pt > 1.0 GeV/c
- Atleast 8 tracker layers crossed
- No missing hits in the innermost or outermost tracker layers
- Track \((\text{dxy}) < 0.2 \text{ mm}\)  
  \( |\text{Track dz}| < 0.2 \text{ mm} \)
  \( \chi^2/\text{ndof} < 5.0 \)
ECAL spikes
- Remove rechits with ET>5 GeV and “1-E4/E1<0.95“
- Remove out-of-time rechits (kOutOfTime and E>2GeV)

HF anomalous signals
- Cut on (L-S)/(L+S) for short fibers (PET algorithm)
- Topological isolation cut for long fibers based on S9/S1 isolation
- Remove rechits with “faulty” pulse shape

HBHE noise in RBX/HPD
- Rejects events with high energy/high hit multiplicity anomalous noise
Backup: Beam Halo

CMS preliminary 2010
\[ \sqrt{s} = 7 \text{ TeV} \]

CaloMET for events before the beam-halo filter is applied and for beam-halo tagged events in minimum-bias or jet 15 trigger events

Beam-halo tagged events with highest CaloMET (224 GeV)

Beam halo does not significantly affect MET generally; however, it can cause high MET in an event.
Backup: MET in MinBias Events

- Calorimeter only MET and SumET distributions in minimum-bias events
- Minimum-bias events allow a study of MET tail in least-biased way
- Generator description of minbias events not as reliable as high Pt events

- General agreement between data and MC in both distributions
- MET tail under control after anomalous signal cleaning procedure
  - Slight excess in data attributed to residual noise in HF
- MET distribution slightly wider in data
  - Attributed mainly to imperfect modeling of the HB & HE response
Backup: MET in Multijets

Does MET depend on the jet multiplicity?

- Uncorrected Calo MET in jet events for different SumE_T ranges
- Different jet multiplicity bins (jets w/ p_T > 20 GeV, |η| < 3)

=> MET distribution "primarily" controlled by SumE_T, and not jet multiplicities
Backup: $H_T$ and $MH_T$

$H_T$ & $MH_T$ explored in various new physics searches

$H_T = \sum p_{T_{jets}}$ and $MH_T = |\vec{H}_T|$ ($\vec{H}_T = -\sum \vec{p}_{T_{jets}}$).

$H_T$ and $MH_T$ studies with Calo, JPT and PF jets
Calculation relies purely on clustered energy
-> more robust alternative, less sensitive to pile-up

(leading jet with $p_T > 40$ GeV, other ets w/$p_T > 20$ GeV, $|\eta| < 5$)

=> Good Agreement between data and MC