Performance of missing transverse momentum reconstruction at the CMS detector in 13 TeV data

Leonora Vesterbacka on behalf of the CMS collaboration
introduction: $p_T^{\text{miss}}$

neutrinos and other weakly interacting particles leave no signal in the detector

- momentum imbalance in the transverse plane
- crucial in SM, Higgs and BSM physics

\[
\begin{align*}
P_T^{\text{miss}} &= \begin{cases} 
  \text{PF} & - \sum_{i \in \text{PF}} p_T^i \\
  \text{PF + Puppi} & - \sum_{i \in \text{PF}} w^i p_T^i 
\end{cases}
\end{align*}
\]

Particle Flow $p_T^{\text{miss}}$ (PF):
- used in majority of CMS analyses

PUPPI $p_T^{\text{miss}}$:
- developed to provide a $p_T^{\text{miss}}$ calculation that is robust against pileup

---

all results presented are from JME-17-001
introduction: $p_T^{\text{miss}}$ calibration

improve $p_T^{\text{miss}}$ performance by propagating the JECs to the $p_T^{\text{miss}}$: Type 1 corrections

- correct jets if
  - $p_T > 15$ GeV
  - EM fraction < 0.9
  - no muon overlapping
- Type 1 corrected $p_T^{\text{miss}}$ is used throughout this talk

$$\text{Type 1 } p_T^{\text{miss}} = p_T^{\text{miss}} - \sum_{\text{jets}} (\vec{p}_{T,\text{jet}} - \vec{p}_{T,\text{jet}}).$$

uncertainties:

- jet energy scale: $\sim 3\%$ (1-12\%) inside (outside) tracker acceptance *
- unclustered energy: depends on the class of the objects
- muons, electrons, photons and taus scale: negligible compared to jets and unclustered energy.

the uncertainties are represented by a grey band and contain jet energy scale/resolution, unclustered energy up/down variations and MC statistics

*Jet energy scale and resolution performance
anomalous $p_T^{\text{miss}}$

event cleaning algorithms and $p_T^{\text{miss}}$ filters

- $p_T^{\text{miss}}$ distribution in di-jet events
- leading jet $\phi$ in mono-jet events
- cleaning and jet-id applied

CMS Experiment at LHC, CERN
Data recorded: Thu May 12 03:24:00 2016 CEST
Run/Event: 273158 / 10369617920
Lumi section: 725
PF $p_T^{\text{miss}}$ performance in 2016 data
PF performance in events with no intrinsic $p_T^{\text{miss}}$

$Z \to \ell\ell/\gamma + \text{jets}$ events used to study the detector response
PF performance in events with no intrinsic $p_T^{\text{miss}}$

$Z\rightarrow \ell\ell/\gamma + \text{jets}$ events used to study the detector response

$$\vec{q}_T + \vec{u}_T + \vec{E}_T = 0$$

Parallel component $u_\parallel + q_T$

Perpendicular component $u_\perp$

Data / MC
Z→ℓℓ/γ+jets events used to study the detector response

PF performance in events with no intrinsic p_{T}^{miss}

response:
−<u_||> / <q_T>

parallel component u_|| + q_T
perpendicular component u_⊥
PF performance in events with no intrinsic $p_T^{\text{miss}}$

$Z\rightarrow\ell\ell/\gamma+\text{jets}$ events used to study the detector response

- **Resolution:** RMS of $u_\parallel + q_T$

- Parallel component $u_\parallel + q_T$
- Perpendicular component $u_\perp$

![Graphs showing $Z\rightarrow\ell\ell/\gamma+\text{jets}$ events used to study the detector response.](image-url)
PF performance in events with no intrinsic $p_T^{\text{miss}}$

$Z\rightarrow\ell\ell/\gamma+\text{jets}$ events used to study the detector response

**Resolution:**
RMS of $u_\perp$

- Parallel component $u_\parallel + q_T$
- Perpendicular component $u_\perp$

![Graphs showing resolution and parallel/perpendicular components](image-url)
PF performance in events with no intrinsic $p_T^{miss}$

response: $-<u_\parallel>/<q_T>$

resolution as a function of $q_T$
PF performance in events with no intrinsic $p_T^{\text{miss}}$

resolution as a function of number of vertices:

$$f(N_{\text{vtx}}) = \sqrt{\sigma_c^2 + \frac{N_{\text{vtx}}}{0.7} \sigma_{\text{PU}}^2}$$

- $\sigma_c$: resolution of hard scattering
- $\sigma_{\text{PU}}$: resolution degrades with 4 GeV per additional PU interaction
- 0.7 coefficient: accounts for the 2016 vertex reconstruction efficiency
PF performance in events with no intrinsic $p_T^{miss}$ resolution as a function of $\sum E_T$:
PUPPI $p_T^{\text{miss}}$ performance in 2016 data
PUPPI algorithm

- A typical event. Particle Flow algorithm can provide (within tracker volume) the following candidates:

  - PU track
  - Good track
  - PU neutral
  - Good neutral
PUPPI algorithm

1. tracks can point to PU vertices, only keep charged tracks that come from the primary vertex
PUPPI algorithm

2. draw a cone around each neutral PF candidate
PUPPI algorithm

3. remove 0 weight contributions

$w(a_{PU}) \times \Box = \Box$

PU track
Good track
PU neutral
Good neutral

1407.6013
PUPPI algorithm

1. 4. reweight neutrals

$w(\alpha_1) \times \text{PU track} = \text{Good track}$

$w(\alpha_2) \times \text{PU track} = \text{Good track}$

$1407.6013$
PUPPI algorithm

1. 5. reinterpret the event
PUPPI performance in events with no intrinsic $p_T^{\text{miss}}$

$Z \rightarrow \ell\ell/\gamma+\text{jets}$ events used to study the detector response

$$ p_T^{\text{miss}} = - \sum_{i \in \text{PF}} p_T^{i} - \sum_{i \in \text{PF}} w^i p_T^{i} $$

<table>
<thead>
<tr>
<th>Process</th>
<th>$c$(data)[GeV]</th>
<th>$c$(MC)[GeV]</th>
<th>$PU$(data)[GeV]</th>
<th>$R_{PU} = PU$(data) / $PU$(MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>17.9 ± 0.98 16.3 ± 1.31 1.75 ± 0.42 0.78 ± 0.22</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>17.9 ± 1.25 16.7 ± 1.02 1.82 ± 0.52 0.82 ± 0.25</td>
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</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>12.6 ± 0.56 13.0 ± 0.87 1.95 ± 0.16 0.98 ± 0.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>12.7 ± 0.74 13.1 ± 1.01 1.97 ± 0.21 0.98 ± 0.16</td>
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</tr>
</tbody>
</table>
PUPPI performance in events with no intrinsic $p_T^{miss}$ resolution as a function of number of vertices:

### PF $p_T^{miss}$

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_c$(data)[GeV]</th>
<th>$\sigma_c$(MC)[GeV]</th>
<th>$\sigma_{PU}$(data)[GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z\rightarrow \mu\mu$</td>
<td>$13.9 \pm 0.07$</td>
<td>$11.9 \pm 1.53$</td>
<td>$3.82 \pm 0.01$</td>
</tr>
<tr>
<td>$Z\rightarrow ee$</td>
<td>$14.6 \pm 0.09$</td>
<td>$12.0 \pm 1.09$</td>
<td>$3.80 \pm 0.02$</td>
</tr>
<tr>
<td>$\gamma$+jets</td>
<td>$12.2 \pm 0.10$</td>
<td>$10.2 \pm 1.98$</td>
<td>$3.97 \pm 0.02$</td>
</tr>
</tbody>
</table>

### PUPPI $p_T^{miss}$

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<thead>
<tr>
<th>Process</th>
<th>$\sigma_c$(data)[GeV]</th>
<th>$\sigma_c$(MC)[GeV]</th>
<th>$\sigma_{PU}$(data)[GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z\rightarrow \mu\mu$</td>
<td>$18.9 \pm 0.05$</td>
<td>$17.5 \pm 0.74$</td>
<td>$1.93 \pm 0.02$</td>
</tr>
<tr>
<td>$Z\rightarrow ee$</td>
<td>$18.9 \pm 0.06$</td>
<td>$17.4 \pm 0.79$</td>
<td>$1.94 \pm 0.02$</td>
</tr>
</tbody>
</table>

### MET performance in CMS, July 6th 2018, ICHEP Seoul

Leonora Vesterbacka
performance of PF and Puppi in genuine $p_T^{miss}$ events

$$M_T = \sqrt{2p_T^{miss}p_T^{lepton}(1 - \cos\Delta\phi)}$$

### Process

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>1.41 ± 0.28</td>
<td>0.77 ± 2.42</td>
<td>0.01 ± 0.10</td>
<td>1.00 ± 0.05</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>3.53 ± 0.20</td>
<td>0.37 ± 2.55</td>
<td>0.01 ± 0.09</td>
<td>1.03 ± 0.06</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>1.67 ± 0.05</td>
<td>1.08 ± 1.89</td>
<td>0.01 ± 0.01</td>
<td>1.02 ± 0.03</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>-2.29 ± 0.21</td>
<td>-2.05 ± 2.57</td>
<td>0.01 ± 0.11</td>
<td>1.01 ± 0.05</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>-2.36 ± 0.26</td>
<td>-2.03 ± 2.71</td>
<td>0.01 ± 0.11</td>
<td>1.01 ± 0.05</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>-1.19 ± 0.05</td>
<td>-1.32 ± 2.52</td>
<td>0.01 ± 0.10</td>
<td>1.02 ± 0.06</td>
</tr>
</tbody>
</table>

### Process

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>11.9 ± 0.40</td>
<td>10.2 ± 3.26</td>
<td>0.97 ± 0.03</td>
<td>0.97 ± 0.06</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>12.6 ± 0.50</td>
<td>11.3 ± 3.26</td>
<td>0.97 ± 0.05</td>
<td>0.97 ± 0.07</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>12.1 ± 0.08</td>
<td>9.61 ± 3.04</td>
<td>0.97 ± 0.01</td>
<td>0.97 ± 0.06</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>8.51 ± 0.32</td>
<td>7.3 ± 2.57</td>
<td>0.98 ± 0.02</td>
<td>0.98 ± 0.05</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>9.03 ± 0.43</td>
<td>5.9 ± 7.42</td>
<td>0.96 ± 0.03</td>
<td>0.96 ± 0.10</td>
</tr>
<tr>
<td>$Z\rightarrow\mu\mu$</td>
<td>9.22 ± 0.08</td>
<td>6.5 ± 4.62</td>
<td>0.96 ± 0.01</td>
<td>0.96 ± 0.06</td>
</tr>
</tbody>
</table>
$p_T^{\text{miss}}$ significance in 2016 data
**$p_T^{\text{miss}}$ significance**

- quantifies the degree of compatibility of the $p_T^{\text{miss}}$ with 0
- the significance is defined as a log-likelihood ratio

\[
S = 2 \ln \left( \frac{\mathcal{L}(\bar{\epsilon}' = \sum \bar{\epsilon}_i)}{\mathcal{L}(\bar{\epsilon}' = 0)} \right)
\]

null hypothesis: true $p_T^{\text{miss}} = 0$
performance of $p_T^{miss}$ significance in $Z\rightarrow \mu\mu/W\rightarrow \mu\nu$ and no jets events

- $\chi^2$ with 2 degrees of freedom follow the distribution with no genuine $p_T^{miss}$
performance of missing transverse momentum at the CMS detector in 13 TeV data

- two algorithms used in CMS studied: PF and Puppi $p_T^{\text{miss}}$
  - the response and resolution of both algorithms is studied in $Z\rightarrow\ell\ell/\gamma+jets$ events.
  - good agreement is found between the different samples and between data and simulation.
  - Puppi $p_T^{\text{miss}}$ is more stable than PF $p_T^{\text{miss}}$ vs pileup
**datasets**

<table>
<thead>
<tr>
<th>di-jet and mono-jet samples</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>for $p_T^{\text{miss}}$ filter studies</td>
<td></td>
</tr>
<tr>
<td>collected using triggers on both $p_{T,\text{trig}}^{\text{miss}}$ and $H_{T,\text{trig}}^{\text{miss}}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>di-lepton and single photon samples</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>used for PF and Puppi $p_T^{\text{miss}}$ performance studies in fake $p_T^{\text{miss}}$ events</td>
<td></td>
</tr>
<tr>
<td>collected using triggers on leading and subleading muon/electron $p_T$, or using a set of isolated single photon triggers</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>single lepton samples</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>used for PF and Puppi $p_T^{\text{miss}}$ performance studies in genuine $p_T^{\text{miss}}$ events</td>
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</tr>
<tr>
<td>collected using triggers on $p_T$ and isolation on the electron/muon</td>
<td></td>
</tr>
</tbody>
</table>

**03Feb2017 re-reco of 2016 data**

<table>
<thead>
<tr>
<th>JEC Summer16_23Sep2016V4</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MC reweighted to match data in number of vertices</td>
<td></td>
</tr>
</tbody>
</table>
$Z \rightarrow \mu\mu$ for fake $p_T^{\text{miss}}$ studies
- muons: medium ID, $p_T > 25, 20$ GeV
- electrons: tight ID, $p_T > 25, 20$ GeV
- compatible with $Z$ boson mass ($80 < m_{ll} < 100$ GeV)
- additional leptons ($p_T > 20$ GeV) vetoed

$Z \rightarrow ee$ for fake $p_T^{\text{miss}}$ studies
- photons: tight ID, $p_T > 50$ GeV
- at least 1 AK4 jet with $p_T > 40$ GeV
- leptons ($p_T > 20$ GeV) vetoed

**selections**

- $Z \rightarrow \mu\mu$
- $Z \rightarrow ee$
- $\gamma + \text{jets}$

**Plots**

- Plots showing $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$
- Plot showing $\gamma + \text{jets}$

**Invisible Mass Peaks**

- Invisible mass peaks for $Z \rightarrow ll$ and $\gamma + \text{jets}$

**CMS Preliminary**

- Data, Top quark, Diboson, $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, Uncertainty

**35.9 fb^{-1} (13 TeV)**

- Plot scale: Events / GeV

**q_T [GeV]**

- q_T range: 0 to 450 GeV

**Data/MC**

- Data/MC ratio: 0.5 to 2.0

**Legends**

- Data, Top quark, Diboson, $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, Uncertainty, $V\gamma$+top quark, QCD multijet, $\gamma + \text{jets}$, Uncertainty

**Graphs**

- Graphs showing event distributions for $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, and $\gamma + \text{jets}$
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**selections**

- **$W \rightarrow l\nu$ for genuine $p_T^{\text{miss}}$ studies**
  - single muons: tight ID, $p_T > 25$ GeV
  - single electrons: tight ID, $p_T > 26$ GeV
  - events with b-tagged jets or additional leptons ($p_T > 10$ GeV) rejected

- **mono-jet for $p_T^{\text{miss}}$ filter studies**
  - leading AK4 jet $p_T > 100$ GeV
  - $p_T^{\text{miss}} > 250$ GeV
  - veto events with
    - electrons/muons with $p_T > 10$ GeV
    - taus with $p_T > 18$ GeV
    - photon with $p_T > 15$ GeV
    - b-tagged jet with $p_T > 20$ GeV

- **di-jet for $p_T^{\text{miss}}$ filter studies**
  - leading AK4 jet $p_T > 500$ GeV
  - trailing AK4 jet $p_T > 200$ GeV
  - $p_T^{\text{miss}} > 250$ GeV
  - same veto as mono-jet selection
Projections of the hadronic recoil
- PF $u_l + q_T$ (top row)
- PF $u_\perp$ (bottom row)
- good data-simulation agreement

Performance of PF $p_T^{miss}$ algorithm
resolution as a function of number of vertices:

○ FWHM vs. RMS: similar performance

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_r$(data)[GeV]</th>
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<th>$\sigma_{PF}$(data)[GeV]</th>
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<td>$0.97 \pm 0.05$</td>
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</table>

Voigtian FWHM

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Robustness against pileup evaluated

- di-muon
- single electron

**p_T^{miss} significance**

<table>
<thead>
<tr>
<th>Number of vertices</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
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<tbody>
<tr>
<td>CMS</td>
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<td>2</td>
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<td></td>
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<tr>
<td>Simulation</td>
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<td>2</td>
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<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Data (μμ)</td>
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<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td>2</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

**Number of vertices**

- 35.9 fb⁻¹ (13 TeV)

**Significance**

- CMS

- Simulation
- Data (μμ)

**Number of vertices**

- 35.9 fb⁻¹ (13 TeV)

**Significance**

- CMS

- Simulation
- Data (e)
**anomalous $p_T^{\text{miss}}$ arise from many sources**

- Beam-halo
  - Real showers with non collision origins
  - Identified by matching hits in CSC and deposits in the calorimeters
- Noise in calorimeters
  - Noise in the hybrid photodiode and readout box of the HCAL
  - Direct particle interactions with the light guides and photomultipliers tubes of the forward calorimeter
  - ECAL super crystals producing anomalous pulses
  - Absence of crystal level information in few ECAL towers
- Dead parts in the detector
- Object misreconstruction
  - In 2016, high $p_T$ tracks misreconstructed as PF muons

Strategies to reject these events: cleaning at reconstruction level and filters at analysis level

- primary vertex filter
- beam halo filter
- HBHE noise filter
- HBHEiso noise filter
- ECAL TP filter
- ee badSC noise filter
- bad muon filter
- bad charged hadron filter
- twiki
How to get the weight factor for $\alpha_i^C$ for a particle $i$ with nearby particles $j$

1. define a local metric, $\alpha$, that differs between pileup (PU) and leading vertex (LV)

2. using tracking information, define unique distributions of $\alpha$ for PU and LV

3. for the neutrals, ask “how PU-like is $\alpha$ for this particle?”, compute a weight for how LV-like it is

4. reweight the four-vector of the particle by this weight

$$\alpha_i^C = \log \left[ \sum_{j \in \text{Ch, LV}} \frac{p_T,j}{\Delta R_{ij}} \Theta(R_0 - \Delta R_{ij}) \right]$$
**p_\text{miss}** significance

- quantifies the degree of compatibility of the \(p_\text{miss}\) with 0
- the significance is defined as a log-likelihood ratio
- a high value of \(S\) is an indication that the
  - \(p_\text{miss}\) observed in the event is not well explained by resolution smearing alone
  - suggesting that the event may contain unseen objects such as neutrinos or more exotic weakly interacting particles.
- to a good approximation, \(L(\vec{\epsilon})\) has the form of a Gaussian distribution
  - significance can be expressed in terms of a covariance matrix
    \[ S = \left( \sum \vec{\epsilon}_i \right)^T V^{-1} \left( \sum \vec{\epsilon}_i \right) \]

null hypothesis: true \(p_\text{miss} = 0\)

\[ S = 2 \ln \left( \frac{L(\vec{\epsilon} = \sum \vec{\epsilon}_i)}{L(\vec{\epsilon}' = 0)} \right) \]
p_T^{miss} significance

standard technique
- assuming resolution of unclustered PF candidates is isotropic in transverse plane

jackknife technique
- does not assume an isotropic covariance matrix including off-diagonal elements
- calculated using “delete-1” technique

both techniques compared to p_T^{miss}
- background: processes with no intrinsic p_T^{miss}
- signal: processes with intrinsic p_T^{miss}
- similar performance
- improvement with respect to regular p_T^{miss}
performance of $p_T^{miss}$ significance in instrumental $p_T^{miss}$ events

- using standard method
- in $Z\rightarrow ll$ events, with no jets or $\geq 1$ jets
  - 0 jet requirement to further enhance the fake $p_T^{miss}$ contribution
  - chi2 with 2 dof follow the distribution with no genuine $p_T^{miss}$
performance of $p_T^{\text{miss}}$ significance in genuine $p_T^{\text{miss}}$ events

- using standard covariance matrix estimation
- in $W\to lv$ events, with no jets or $\geq 1$ jets
  - 0 jet requirement to enhance fake $p_T^{\text{miss}}$ contribution
- chi2 with 2 dof follow the distribution with no genuine $p_T^{\text{miss}}$