Pileup Mitigation Techniques in CMS

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on behalf of the CMS Collaboration
Pileup Profile of Run 2

Analysing 2016 data which is limited to ~50 PU

But most of Run 2 is up to 50 PU
CMS Preliminary

Analysing 2016 data which is limited to ~50 PU

But most of Run 2 is up to 50 PU
Pileup in LHC Run 2

PU affects jet substructure, jet counting, lepton isolation…
Pileup Mitigation Techniques

Charged Hadron Subtraction (CHS)

PileUp Per Particle Identification (PUPPI)

Pileup Jet ID

δβ—corrected Isolation
Pileup Mitigation Techniques

Charged Hadron Subtraction (CHS)

Pileup Per Particle Identification (PUPPI)

Pileup Jet ID

$\delta \beta$—corrected Isolation
Pileup Mitigation Techniques

Charged Hadron Subtraction (CHS)

PileUp Per Particle Identification (PUPPI)

Pileup Jet ID

$\delta \beta$—corrected Isolation
Performance Studies

1. PUPPI in Detail
   • Performance of PUPPI variables

2. Jet Reconstruction
   • Noise Rejection
   • Jet Energy Resolution
   • Pileup Jet Rejection

3. Tagging Performance

4. Muon Isolation

part of the 2016 data
($\mathcal{L} = 0.36$ fb$^{-1}$)

All new results!
Based on
CMS-PAS-JME-18-001!
1. Define variable $\alpha$ to discriminate pileup from leading vertex

2. Assume charged pileup has the same shape as neutral pileup

3. Use $\alpha$ on an event-by-event basis to calculate a per-particle weight
1. Define variable $\alpha$ to discriminate pileup from leading vertex

$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left( \frac{p_{Tj}}{\Delta R_{ij}} \right)^2$$

for $|\eta_i| < 2.5$, $j$ are charged particles from leading vertex

for $|\eta_i| > 2.5$, $j$ are all kinds of reconstructed particles

PUPPI variable $\alpha$ reasonable described by Pythia MC.

Charged PU distribution has peak at low $\alpha$ and only a low misidentification rate at high $\alpha$.

Charge LV has double peak structure from particles not part of hadronic showers.

Peak at 0 is for particles that do not have neighbour particles in the cone.
2. Assume charged pileup has the same shape as neutral pileup

\[ \alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left( \frac{p_{Tj}}{\Delta R_{ij}} \right)^2 \]

\[ \begin{array}{ll}
\text{for } |\eta_i| < 2.5, & j \text{ are charged particles from leading vertex} \\
\text{for } |\eta_i| > 2.5, & j \text{ are all kinds of reconstructed particles}
\end{array} \]
3. Use $\alpha$ on an event-by-event basis to calculate a per-particle weight

1. Calculate Median and RMS of charged PU shape (blue)

$$\bar{\alpha}_{PU}, \ RMS_{PU}$$
3. Use $\alpha$ on an event-by-event basis to calculate a per-particle weight

1. Calculate Median and RMS of charged PU shape (blue) $\bar{\alpha}_{PU}$, $RMS_{PU}$

2. For each particle calculate

$$\chi_i^2 = \frac{(\alpha_i - \bar{\alpha}_{PU}) | \alpha_i - \bar{\alpha}_{PU} |}{RMS_{PU}^2}$$
3. Use $\alpha$ on an event-by-event basis to calculate a per-particle weight

1. Calculate Median and RMS of charged PU shape (blue) $\bar{\alpha}_{PU}$, $RMS_{PU}$

2. For each particle calculate

$$\chi_i^2 = \frac{(\alpha_i - \bar{\alpha}_{PU}) | \alpha_i - \bar{\alpha}_{PU} |}{RMS_{PU}^2}$$

3. Assign a weight to each particle

$$w_i = F_{\chi^2,NDF=1}(\chi_i^2)$$
Performance Studies

1. PUPPI in Detail
   • Performance of PUPPI variables

2. Jet Reconstruction
   • Noise Rejection
   • Jet Energy Resolution
   • Pileup Jet Rejection

Dijet data + MinBias data (2017)

QCD multijet MC sample

DoubleMuon data + DY MC sample

3. Tagging Performance

4. Muon Isolation
Noise Jet ID

Purpose: remove noise from HCAL & ECAL by retaining ~98% of the real jets

Definition of the JetID in backup
Jet Energy Resolution

Antik T, R=0.4

central region (left): PUPPI outperforms CHS at low pT (circle) but other way around at high pT (triangle)

Antik T, R=0.8

central region (bottom): PUPPI outperforms CHS at low pT (circle) but other way around at high pT (triangle)

missing ET resolution in backup
Pileup Jet Id Definition

12 different variables (list in the backup)

- vertex association of charged particles
- jet shape information
- $p_T$ ratio variables

→ trained in $\eta$ & $p_T$ bins
Pileup Jet Id Discriminator

BDT output in agreement with Herwig/Pythia and PU uncertainty.

Central region (left) shows good discrimination power.

Forward region (right) has less discrimination power than central region.
Z Boson
2 Muons $p_T > 20$ GeV,
70 GeV $< M_{\mu\mu} < 110$ GeV

Jets overlapping with muons ($\Delta R < 0.4$) are removed

Only AK4 jets with $p_T > 20$ GeV are considered

Efficiency & Purity in Z+Jets

MC studies
Efficiency & Purity in Z+jets

generator jets

Efficiency

MC studies
Efficiency & Purity in Z+jets

Either not reconstructed or rejected:
• Pileup Jet ID
• down weighted particles from PUPPI

Efficiency

MC studies
Efficiency & Purity in Z+jets

reconstructed jets

MC studies  Purity
Efficiency & Purity in Z+jets

Most likely PU Jets did not get rejected:
• CHS does not remove enough jets
• PUPPI does not remove enough particles
• …

reconstructed jets

generator jets

Purity

MC studies
Efficiency & Purity in Z+Jets

CMS Simulation Preliminary

Efficiency

CHS
CHS + tight PU jet ID
CHS + medium PU jet ID
CHS + loose PU jet ID
PUPPI

Purity

CHS
CHS + tight PU jet ID
CHS + medium PU jet ID
CHS + loose PU jet ID
PUPPI

PUPPI better than CHS+loose/medium pileup jet ID

Quark-Gluon comparison in backup
Efficiency & Purity in Z+Jets

**CMS Simulation Preliminary**

Anti-\(k_T\), \(R=0.4\), \(3 < \eta l < 5\)

\(p^\text{gen}_{T} > 30\) GeV, \(p^\text{reco}_{T} > 20\) GeV

Efficiency

0

0.1

0.2

0.3

0.4

0.5

0.6

0.7

0.8

0.9

1

Efficiency

0

5

10

15

20

25

30

35

40

45

50

Number of pileup interactions

**CMS Simulation Preliminary**

Anti-\(k_T\), \(R=0.4\), \(3 < \eta l < 5\)

\(p^\text{gen}_{T} > 20\) GeV, \(p^\text{reco}_{T} > 30\) GeV

Purity

0

0.1

0.2

0.3

0.4

0.5

0.6

0.7

0.8

0.9

1

Purity

0

5

10

15

20

25

30

35

40

45

50

Number of pileup interactions

**PUPPI** is compatible with **CHS+loose pileup jet ID**

**Quark-Gluon comparison in backup**
AK4 jets most likely from PU

Z Boson of two muons

AK4 jets recoiling the Z Boson most likely from LV

\[ \Delta \phi(Z, jet) < 1.5 \quad \text{and} \quad \Delta \phi(Z, jet) > 2.5 \]

Data / MC

\[ \begin{array}{c|c|c|c|c|c|c}
\hline
\Delta N / N & 0 & 0.05 & 0.1 & 0.15 & 0.2 & 0.25 & 0.3 & 0.35 & 0.4 & 0.45 & 0.5 \\
\hline
\hline
\end{array} \]
Central region (left): **CHS** shows a strong PU dependence. **PUPPI** and **PU Jet ID** mitigate the effect.

Forward region (right): All shows a PU dependence, but **PUPPI** and **PU Jet ID** show improved behaviour.
Central region (left): CHS shows a strong PU dependence. PUPPI and PU Jet ID mitigate the effect.

Forward region (right): All shows a PU dependence, but PUPPI and PU Jet ID show improved behaviour.
Performance Studies of the Paper

1. PUPPI in Detail
   • Performance of PUPPI variables

2. Jet Reconstruction
   • Noise Rejection
   • Jet Energy Resolution
   • Pileup Jet Rejection

3. Tagging Performance
   • BulkGraviton Signal + QCD multijet

4. Muon Isolation
W Boson Identification Variables

stable jet mass resolution for **PUPPI** while an increase for **CHS**

**PUPPI** shows a stable behaviour while **CHS** increase both for signal and for background
W Boson Identification Variables

**W mass window cut applied:** $65 \text{ GeV} < M_{M_{SD}}^{AK8} < 105 \text{ GeV}$

**PUPPI** shows a stable performance for W-tagging, while **CHS** drops in performance with increasing PU.
Performance Studies of the Paper

1. PUPPI in Detail
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4. Muon Isolation

SingleMuon data + Z+jets MC sample
Muon with $p_T > 20 \text{ GeV}$


Muon Isolation Definition

**$\delta\beta$—corrected Isolation**

\[
\text{Iso}^\mu_i = \sum_{\Delta R(i,j)<0.4} \text{p}_T^j + \text{max}(0, \sum_{\Delta R(i,j)<0.4} \text{p}_T^j + \sum_{\Delta R(i,j)<0.4} \text{p}_T^j - \frac{1}{2} \sum_{\Delta R(i,j)<0.4} \text{p}_T^j)
\]

Assumes Charged PU = 2 x Neutral PU
Muon Isolation Definition

**PUPPI with lepton**

assumes all muons are non-prompt

→ prompt muons get higher isolation (PU dependent)

→ non-prompt muons get reasonable isolation (lower misidentification rate)
Muon Isolation Definition

PUPPI with lepton

assumes all muons are non-prompt

→ prompt muons get higher isolation (PU dependent)

→ non-prompt muons get reasonable isolation (lower misidentification rate)
Muon Isolation Definition

**PUPPI no lepton**

assumes all muons are prompt

→ prompt muons get a reasonable isolation (less PU dependent)

→ non-prompt muons get a lower isolation (higher misidentification rate)
Muon Isolation Definition

PUPPI no lepton

assumes all muons are prompt

→ prompt muons get a reasonable isolation (less PU dependent)

→ non-prompt muons get a lower isolation (higher misidentification rate)
Muon Isolation Definition

\[
PUPPI\text{-combined} = \frac{PUPPI\text{-no-lepton} + PUPPI\text{-with-lepton}}{2}
\]

![Graph showing efficiency vs. misidentification rate for CMS Simulation Preliminary with PUPPI combined approach compared to individual components.](image-url)
Summary

- Full validation of PUPPI shows a good performance especially at high PU
- PUPPI to become the standard pileup mitigation technique for CMS in Run 3

Outlook

- Pileup mitigation absolutely necessary for jet and MET performance at the HL-LHC. PUPPI shown to perform very well

Figure 25: The corrected jet response resolution for $|\eta| < 1.3$ (left), $1.3 < |\eta| < 1.7$ (middle), and $1.7 < |\eta| < 2.8$ (right) as a function of $p_T^{\text{Gen}}$ for PF+PUPPI jets with 200 PU. Taken from Ref. [8].
Backup
PUPPI algorithm
1. Particles with weight < 0.01 are removed to mitigate noise

2. weighted $p_T$ cut

$$\omega_i p_{T,i} < A + B \ast N_{PV}$$

Table 1: The tunable parameters of PUPPI optimized for application of 2016 data analyses.

| $|\eta|$ of particle | A (GeV) | B (GeV) | TF $\tilde{\alpha}_{PU}$ | TF $\alpha_{RMS}$ |
|--------------------|---------|---------|---------------------------|------------------|
| [0.0, 2.5]         | 0.2     | 0.015   | 1                         | 1                |
| [2.5, 3.0]         | 2.0     | 0.13    | 0.9                       | 1.2              |
| [3.0, 5.0]         | 2.0     | 0.13    | 0.75                      | 0.95             |
PUPPI Variables

\[ \Delta N/N \]

CMS Preliminary

Data, neutral \( 2.5 < \mid \eta \mid < 3.0 \)

MC, neutral \( 2.5 < \mid \eta \mid < 3.0 \)

Data, neutral \( 3.0 < \mid \eta \mid < 5.0 \)

MC, neutral \( 3.0 < \mid \eta \mid < 5.0 \)

\[ \text{RMS}_{\text{PU}} \]

CMS Preliminary

Neutral Particles

- Data
- MC

\[ 0.36 \text{ fb}^{-1} (13 \text{ TeV}) \]

Data/MC

\[ 0.95, 1.05 \]

\[ (13 \text{ TeV})^{-1} \]

\[ 0.36 \text{ fb} \]

CMS Preliminary

Anna Benecke
Alternative Generators for PUPPI Variables

1. Charged PV: small differences between all generators
2. Charged PU / Neutrals: nearly no differences between Herwig+Pythia and Pythia only
3. Charged PU / Neutrals: visible difference between Madgraph and other two
PUPPI Variables

**Charged Particles**

- Data, associated with PV
- MC, associated with PV

**Neutral Particles**

- Data
- MC

**Preliminary Results**

- CMS

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Charged Particles

- $|\eta| < 2.5$

**Neutral Particles**

| $|\eta| < 2.5$ | $2.5 < |\eta| < 3.0$ | $3.0 < |\eta| < 5.0$ |
|--------------|----------------|----------------|
| Data, associated with PV | Data | Data |
| MC, associated with PV | MC | MC |
Noise Jet ID
Noise Jet Id criteria

"Tight PFJetID" for $|\eta| < 2.7$ for both AK4CHS and PUPPI jets
- Charged Hadron Fraction > 0.0
- Neutral Hadron Fraction < 0.9
- Number of Constituents > 1
- Charged Multiplicity > 0.0
- Charged EM Fraction < 0.8
- Neutral EM Fraction < 0.9
- Muon Fraction < 0.8

For the "charged" variables: $|\eta| < 2.4$ since there is no tracker coverage outside of this region, whereas the "neutral" variables extend to the whole $\eta$ region.

"Tight PFJetID" for $|\eta|: 2.7 - 3.0$ for AK4CHS jets
- Neutral Electromagnetic Fraction > 0.02 AND < 0.99
- Neutral Multiplicity > 2

"Tight PFJetID" for $|\eta|: 2.7 - 3.0$ for PUPPY jets
- Neutral Hadron Fraction < 0.99

"Tight PFJetID" for $|\eta|: 3.0 - 5.0$ for AK4CHS jets
- Neutral Hadron Fraction > 0.02
- Neutral Electromagnetic Fraction < 0.9
- Neutral Multiplicity > 10

"Tight PFJetID" for $|\eta|: 3.0 - 5.0$ for PUPPY jets
- Neutral Hadron Fraction > 0.02
- Neutral Electromagnetic Fraction < 0.9
- Neutral Multiplicity > 2 AND <15
Noise Jet ID

Purpose: remove noise from HCAL & ECAL by retaining ~98% of the real jets

Measure in dijet and minbias data:

Noise enriched region = MinBias Data

Real jet enriched region = Back-to-Back data
Pileup Jet ID
Pileup Jet Id Criteria

Working points for the 81X training (completed in 80X with variable fixes)

```
full_80x_chs_wp = cms.PSet(
    #4 Eta Categories 0-2.5 2.5-2.75 2.75-3.0 3.0-5.0

    #Tight Id
    Pt010_Tight = cms.vdouble( 0.69, -0.35, -0.26, -0.21),
    Pt1020_Tight = cms.vdouble( 0.69, -0.35, -0.26, -0.21),
    Pt2030_Tight = cms.vdouble( 0.69, -0.35, -0.26, -0.21),
    Pt3050_Tight = cms.vdouble( 0.86, -0.10, -0.05, -0.01),

    #Medium Id
    Pt010_Medium = cms.vdouble( 0.18, -0.55, -0.42, -0.36),
    Pt1020_Medium = cms.vdouble( 0.18, -0.55, -0.42, -0.36),
    Pt2030_Medium = cms.vdouble( 0.18, -0.55, -0.42, -0.36),
    Pt3050_Medium = cms.vdouble( 0.61, -0.35, -0.23, -0.17),

    #Loose Id
    Pt010_Loose = cms.vdouble(-0.97, -0.68, -0.53, -0.47),
    Pt1020_Loose = cms.vdouble(-0.97, -0.68, -0.53, -0.47),
    Pt2030_Loose = cms.vdouble(-0.97, -0.68, -0.53, -0.47),
    Pt3050_Loose = cms.vdouble(-0.89, -0.52, -0.38, -0.30)
)
```
**PU Jet ID variables**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>fraction of transverse momentum of charged particles associated to the primary vertex, defined as $\frac{\sum_{i\in PV} p_{Ti}}{\sum_i p_{Ti}}$</td>
</tr>
<tr>
<td>$n_{PV}$</td>
<td>number of reconstructed vertices in the event.</td>
</tr>
<tr>
<td>$\langle \Delta R^2 \rangle$</td>
<td>$p_T^2$ average weighted by square distance of jet constituents from the jet axis: $\frac{\sum_i \Delta R^2 p_{Ti}^2}{\sum_i p_{Ti}^2}$</td>
</tr>
<tr>
<td>$f_{ringX \text{, } X = 01, 02, 03, \text{ and } 04}$</td>
<td>fraction of $p_T$ of the constituents ($\sum p_{Ti} / p_{T\text{jet}}$) in the region $R_i &lt; \Delta R &lt; R_{i+1}$ around the jet axis, where $R_i = 0, 0.1, 0.2, \text{ and } 0.3$ for $X=01, 02, 03 \text{ and } 04$.</td>
</tr>
<tr>
<td>$p_{T\text{lead} \text{ / } p_{T\text{jet}}}$</td>
<td>transverse momentum fraction carried by the leading PF candidate.</td>
</tr>
<tr>
<td>$p_{T\text{charged} \text{ / } p_{T\text{jet}}}$</td>
<td>transverse momentum fraction carried by the leading charged PF candidate.</td>
</tr>
<tr>
<td>$</td>
<td>\vec{m}</td>
</tr>
<tr>
<td>$N_{\text{total}}$</td>
<td>number of PF candidates.</td>
</tr>
<tr>
<td>$N_{\text{charged}}$</td>
<td>number of charged PF candidates.</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>major axis of the jet ellipsoid in the $\eta - \phi$ space.</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>minor axis of the jet ellipsoid in the $\eta - \phi$ space.</td>
</tr>
<tr>
<td>$p_{T\text{D}}$</td>
<td>jet fragmentation distribution, defined as $\sqrt{\frac{\sum_i p_{Ti}^2}{\sum_i p_{Ti}}}$ where $i$ sums over all the PF particles in the jet, and it takes values between zero and one.</td>
</tr>
</tbody>
</table>

Table 2: List of variables used for pileup jet ID for CHS jets.
**PU Jet ID**

[CMS Preliminary plots showing data, quark, gluon, pileup, unassigned distributions, and Herwig predictions for Anti-$k_T$, R=0.4, 2.5 < $|\eta|$ < 2.75 and 2.75 < $|\eta|$ < 3 with data/MC ratios and BDT output.]

35.9 fb$^{-1}$ (13 TeV)
PU Jet Rate
The $\Delta \phi$ distribution in the different $|\eta|$ regions. The fraction of PU jets in the PU enriched region ($\Delta \phi < 1.5$) and the real jet enriched region ($\Delta \phi > 2.5$) are shown.
Efficiency and Purity in Z+Jets

**Efficiency**

- CMS Simulation Preliminary
- Anti-$k_T$, $R=0.4$, $2.5 < |\eta| < 3$
- $p_T^{\text{gen}} > 30 \text{ GeV}$, $p_T^{\text{reco}} > 20 \text{ GeV}$

**Purity**

- CMS Simulation Preliminary
- Anti-$k_T$, $R=0.4$, $2.5 < |\eta| < 3$
- $p_T^{\text{gen}} > 20 \text{ GeV}$, $p_T^{\text{reco}} > 30 \text{ GeV}$

- CHS
- CHS + tight PU jet Id
- CHS + medium PU jet Id
- CHS + loose PU jet Id
- PUPPI

Number of pileup interaction
Quark-Gluon Efficiency

CMS Simulation Preliminary

Number of Pileup Interaction vs Efficiency

- (13 TeV)
- Anti-$k_T$, $R=0.4$, $|\eta| < 2.5$
- $p_T^{gen} > 30$ GeV, $p_T^{reco} > 20$ GeV

- PUPPI
- PUPPI Quarks
- PUPPI Gluons

- CHS + tight pileup jet ID
- CHS + tight pileup jet ID Quarks
- CHS + tight pileup jet ID Gluons

CMS Simulation Preliminary

Number of Pileup Interaction vs Efficiency

- (13 TeV)
- Anti-$k_T$, $R=0.4$, 2.5 < $|\eta| < 3$
- $p_T^{gen} > 30$ GeV, $p_T^{reco} > 20$ GeV

- PUPPI
- PUPPI Quarks
- PUPPI Gluons

- CHS + tight pileup jet ID
- CHS + tight pileup jet ID Quarks
- CHS + tight pileup jet ID Gluons

CMS Simulation Preliminary

Number of Pileup Interaction vs Efficiency

- (13 TeV)
- Anti-$k_T$, $R=0.4$, 3 < $|\eta| < 5$
- $p_T^{gen} > 30$ GeV, $p_T^{reco} > 20$ GeV

- PUPPI
- PUPPI Quarks
- PUPPI Gluons

- CHS + tight pileup jet ID
- CHS + tight pileup jet ID Quarks
- CHS + tight pileup jet ID Gluons
Jet Reconstruction
Jet Energy Resolution

**AK4**
- Central region (left): CHS and PUPPI similar
- Forward region (right): PUPPI comparable with CHS

**AK8**
- Central region (bottom): PUPPI outperforms CHS at low pT
Jet Eta Resolution

Jet eta resolution is representative for all angular resolution since the detector has similar eta/phi segmentation.
W Tagging
## W-Tagging Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data/Simulation</th>
<th>CHS</th>
<th>PUPPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass scale</td>
<td></td>
<td>$1.007 \pm 0.009$ (stat) $\pm 0.005$ (sys)</td>
<td>$0.998 \pm 0.007$ (stat) $\pm 0.006$ (sys)</td>
</tr>
<tr>
<td>mass resolution</td>
<td></td>
<td>$1.15 \pm 0.04$ (stat) $\pm 0.04$ (sys)</td>
<td>$1.08 \pm 0.02$ (stat) $\pm 0.09$ (sys)</td>
</tr>
<tr>
<td>$\tau_{21} &lt; 0.45$</td>
<td></td>
<td>$1.00 \pm 0.06$ (stat) $\pm 0.07$ (sys)</td>
<td>-</td>
</tr>
<tr>
<td>$\tau_{21} &lt; 0.4$</td>
<td></td>
<td>-</td>
<td>$1.01 \pm 0.06$ (stat) $\pm 0.05$ (sys)</td>
</tr>
</tbody>
</table>

Table 3: Data to simulation scale factors for the jet mass scale, jet mass resolution and the $\tau_{21}$ selection efficiency for CHS and PUPPI.
Median Jet Mass

CMS Simulation Preliminary

Bulk graviton Anti-\( k_T \), R=0.8

CHS W boson jets

PUPPI W boson jets

400 GeV < \( p_T \) < 600 GeV
Top-Tagging Performance

CMS Simulation Preliminary

Top quark identification efficiency vs. number of vertices for different tagging scenarios.

CMS Simulation Preliminary

Top quark misidentification rate vs. number of vertices for different tagging scenarios.
Muon Isolation
Muon Isolation in Data

AK4 jets most likely from PU

AK4 jets recoiling the Z Boson most likely from LV

Z Boson
2 Muons $p_T > 15$ GeV,
$80$ GeV $< M_{\mu\mu} < 100$GeV

Technical Details:

Data: SingleMuon
Trigger: HLT_IsoMu24_v ||HLT_IsoTkMu24_v
MC: Z+Jet

Tag-and-Probe Method:

Tag Muon:

$p_T > 26$ GeV
delta-beta isolation $< 0.15$
$\Delta R$(tag muon, trigger muon)$<0.1$
Muon Isolation Performance

PUPPI has a lower efficiency since it reweights more particles.

PUPPI has a lower fake rate.
Muon Isolation

PUPPI with lepton (left) shows a higher dependence on PU for neutrals → higher isolation in general.

PUPPI no lepton (right) has a lower isolation in general, also for non-prompt muons.
MET Performance
$E_T^{\text{miss}}$ Performance

AK4 jets most likely from PU

$Z$ Boson

2 Electrons $p_T > 20$ GeV, $80$ GeV < $M_{\mu\mu}$ < $100$ GeV

Response:

\[ \frac{u_\parallel}{q_T(Z)} \]

Resolution:

\[ \sigma(u_\parallel) \quad \sigma(u_\perp) \]

Methode also described in arXiv 1903.06078

Leonora Vesterbacka
MET Performance

CMS Preliminary

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

Response-corrected
PF \(p_T^{\text{miss}} \rightarrow \text{ee}\)
PUPPI \(p_T^{\text{miss}} \rightarrow \text{ee}\)

Uncertainty

Data / MC

Number of vertices

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

Response-corrected
PF \(p_T^{\text{miss}} \rightarrow \text{ee}\)
PUPPI \(p_T^{\text{miss}} \rightarrow \text{ee}\)

Uncertainty

Number of vertices
MET Performance

CMS Preliminary

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

$\langle u \rangle / \langle q \rangle$

$|q_T|$ [GeV]

Data / MC

$0.85 < p_T^\text{miss} Z \rightarrow ee < 1.15$

$0 < q_T < 500$

Uncertainty
Pileup Mitigation Techniques

Charged Hadron Subtraction (CHS)
• Removes charged particles associated to PU vertex, but no neutral particles
• Correct jet quantities for neutral PU

Pileup Jet ID
• Problem: pileup can generate additional “PU” jets
• Solution: Multi-variant technique to reject PU jets applied on CHS

PileUp Per Particle Identification (PUPPI)
• Calculate weight for each particle based on the shape of charged PU
• Reweights particles rather than correct jet quantities for consistent event interpretation

Delta-Beta corrected Isolation
• Corrects the neutral amount of PU from lepton isolation by subtracting 1/2 of charged PU from neutral component