Improvement of missing transverse momentum reconstruction for ATLAS experiment at LHC

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Outline

Missing Transverse Momentum (MET)
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  Measuring MET

New algorithm for MET determination
  Physics constraints
  Input parameters

Performance Evaluation
  Comparison on data and MC samples of $pp \rightarrow Z^0 + \text{jets}$ with $Z^0 \rightarrow \mu^+ \mu^-$
  Comparison on $pp \rightarrow t\bar{t}$ sample
  Conclusion
Many interesting physics processes involve elusive particles that escape detection: Neutrino, SUSY particles, dark matter candidates, etc.

The missing transverse energy (MET or $\vec{E}_{T}^{\text{miss}}$) measures the imbalance of momentum in the transverse plane, which is sensitive to non-interacting particles.

The transverse plane is defined to be the plane perpendicular to the beam line. The azimuthal angle in the transverse plane is $\phi$ and the polar angle from the beam axis is $\theta$. In practice the pseudorapidity $\eta = -\ln \tan(\frac{\theta}{2})$ is used, since particle production is nearly uniform in eta
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Comparison on \( pp \to t\bar{t} \) sample

Conclusion

MET

- The LHC collides bunches of protons. Each bunch crossing produces many pp collisions. The hardest collision is called hard scatter, and others are referred to as pile-up interactions.
- Each collision location is called a primary vertex. The number of primary vertices \( (N_{pv}) \) measures the pile-up activities.
- Charged particles can be associated with their vertices using their tracks.
MET measures the imbalance of the hard scatter with two inputs:

- **hard term**: Made of high $p_T$ reconstructed objects that passed selections. (Jets, $e^\pm$, $\mu^\pm$ and etc) These are carefully calibrated objects used by all MET algorithms.

- **soft term**: Low $p_T$ hard scatter signals then contribute to the soft term.

\[
\vec{E}_T^{\text{miss}} = - \sum_{j \in \{\text{hard objects}\}} \vec{p}_T^{\text{miss},j} - \sum_{i \in \{\text{soft signals}\}} \vec{p}_T^{\text{miss},i}
\] (1)
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The two soft term options for MET calculation

Track Soft Term (TST):

- Using only hard scatter tracks.
- **Pro:** Insensitive to pile-up; only hard scatter tracks are used.
- **Con:** Ignores neutral particles and charged particles with $|\eta| > 2.4$

Cluster Soft Term (CST):

- Summing over all calorimeter energy deposited outside hard objects.
- **Pro:** Includes charged and neutral particles. Covers $|\eta| > 2.4$
- **Con:** Includes pile-up particles $\rightarrow$ Sensitive to pile-up.
PUfit aims to add neutral particles to TST along with physics constraints to reduce pileup dependence.

PUfit is adapted from a similar algorithm used in the ATLAS trigger.

There are two parts in the PUfit soft term $\vec{E}_T^{PST}$:

$$\vec{E}_T^{PST} = \vec{E}_T^{TST} + \vec{E}_T^{PAT}$$

$\vec{E}_T^{TST}$ is the Track Soft Term and $\vec{E}_T^{PAT}$ is the Pileup-imbalance Adjustment Term.

The PAT term is determined by a $\chi^2$ fit using the following two constraints:

1. Pileup vertices should not produce any invisible particles

2. The pile-up energy density is nearly uniform in the $\eta - \phi$ plane.
Pileup-imbalance Adjustment Term $\vec{E}_{PAT}$

PAT measures the Pileup imbalance in the PU distribution.

- First, determine the average energy density $\langle \rho \rangle$ outside hard objects in the calorimeter.

- Parameters $\mathcal{E}_k$ are introduced to represent the PU energy under HS jets. They are determined by the fit.

- The Pileup-imbalance Adjustment Term is:

\[
\vec{E}^{PAT}_T = \sum_{k=1}^{J} (\mathcal{E}_k - \langle \rho \rangle A_k) \frac{\vec{p}_{T_k}^{jet}}{p_{T_k}^{jet}}
\]

where $A_k$ is the area of the k-th jet.
Performance on pp → Z⁰ + jets

- Data used from 2017 ATLAS run at 13TeV. Fully simulated MC events are also used.
- Z → μ⁺μ⁻ decays are selected based on muon trigger, muon ID and also the invariant mass of μ⁺μ⁻.
- Muons leave negligible energy in the calorimeter, resulting in an imbalance. The imbalance should mirror the Zp_T measured using muon tracks.
- MET resolution and scale are tested in both data and MC.
pp → Z⁰ + jets sample

- Zero jet events are not used since PST and TST soft terms are equivalent in these events.
We are making a correction (PAT) that is of comparable magnitude to TST.

- **TST**: track soft term; **CST**: cluster soft term
- **PAT**: The correction; **PST**: PUfit soft term (TST+PAT)

![Graph showing MET distributions](image)

- mean=16.9; σ=14.3
- mean=13.0; σ=14.0
- mean=9.50; σ=5.99
- mean=22.6; σ=13.8

« ATLAS work in progress »

Z+jets (data17;13 TeV)
MET resolution from $pp \rightarrow Z^0 + \text{jets}$

- Ex and Ey are independent. So $\sigma_{\text{MET}} = \sigma_{Ex} = \sigma_{Ey}$
- Resolutions of PST MET and TST MET are similar. Both better than the CST MET.

![Graph showing MET resolution for different MET types (PST, TST, CST) with data from 2017-13 TeV Z+jets.](chart.png)
MET scale from $pp \rightarrow Z^0 + \text{jets}$

- The magnitude of the measured MET should on average correspond to that of the true MET.
- The parallel scale difference (PSD) should ideally be 0.

$$\text{PSD} = \vec{E}_{\text{miss}} \cdot \vec{E}_Z - |\vec{E}_Z|$$

- The errorbar is the RMS width in each bin.
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MET resolution on $pp \rightarrow t\bar{t}$ Monte Carlo

- $t\bar{t}$ has a higher jet multiplicity.
- PST MET and CST MET are similar. Get worse than TST MET at large $N_{pv}$.
- Still under investigation.

Resolution against $N_{pv}$

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ttbar; MC16; 13 TeV
Conclusion

- PUfit uses both charged and neutral signals to determine the soft term, and it was tested in both Z+jets and ttbar eventys.
- It achieves similar resolution compared to the TST MET and much better than the CST MET in Z+jets events.
- More investigations needed for the $t\bar{t}$ sample.
- Further analysis is needed with high pile-up MC samples.
MET resolution on pp → \(Z^0 +\) jets Monte Carlo

- The resolution is based on measured versus true MET.
- Similar to results on data: PST similar to TST, better than CST. A consistent improvement of 1 GeV between 15 < \(N_{pv}\) < 35.
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Backup slides
Z + jets Monte Carlo
$t\bar{t}$ multiplicities
PUfit constraints
The fit

$pp \rightarrow t\bar{t}$ sample

Hard objects distribution

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Ttbar; MC16; 13 TeV
PUfit determines $\mathcal{E}$ by two constraints:

- Pileup vertices should not produce any real $\vec{E}_{T}^{\text{miss}}$.
- Pileup energies under HS jets ($\mathcal{E}_k$) are close to the average pileup ($<\rho> A_k$)

For example, we can formulate the first constraint by:

$$\sum_{\text{clus}} \vec{E}_{Tj} - \sum_{j} \vec{p}_{Tj}^{\text{HS}} + \sum_{k} \vec{E}_{Tk} = 0$$

where the first term sums over all clusters outside HS jet and $\vec{p}_{Tj}^{\text{HS}}$ are momentum vectors of HS tracks.
The final version of PUfit only involve one more change: adopting PFlow. Instead of subtracting HS track Pt manually, PFlow objects were use instead since they offer better energy subtraction precision.

Previously we had:

\[ \sum_{j} \vec{E}_{Tj} - \sum_{j} \vec{p}_{Tj}^{HS} + \sum_{k} \vec{E}_{Tk} = 0 \]

Now it becomes:

\[ \sum_{j} \vec{E}_{Tj} + \sum_{j} \vec{E}_{Tj} + \sum_{k} \vec{E}_{Tk} = 0 \]

where \( PFO_N \) is neutral PFlow objects outside HS jets, \( PFO_{C,PU} \) are non-HS charged PFlow objects outside HS jets.
Formulating the constraint

So we can encode this constraint in a $\chi^2$ function:

$$\chi^2(\mathcal{E}_T^1, ..., \mathcal{E}_T^m) = \Delta^T V^{-1} \Delta$$

$\Delta$ is defined as:

$$\Delta = \left( \begin{array}{c}
\sum_{j} PFO_N \vec{E}_T^j \cos \phi_k + \sum_{j} PFO_{C,PU} \vec{E}_T^j \cos \phi_k + \sum_{k=1}^{n_J} \mathcal{E}_T^k \cos \phi_k \\
\sum_{j} PFO_N \vec{E}_T^j \sin \phi_k + \sum_{j} PFO_{C,PU} \vec{E}_T^j \sin \phi_k + \sum_{k=1}^{n_J} \mathcal{E}_T^k \sin \phi_k \\
\mathcal{E}_T^1 - \langle \rho \rangle A_1 \\
\vdots \\
\mathcal{E}_T^{n_J} - \langle \rho \rangle A_{n_J} \end{array} \right)$$

(3)
Fit

The covariance matrix is given by:

\[
V = \begin{pmatrix}
V_{11} & V_{12} & 0 & 0 & \ldots & 0 \\
V_{21} & V_{22} & 0 & 0 & \ldots & 0 \\
0 & 0 & V^J & 0 & \ldots & 0 \\
0 & 0 & 0 & V^J & \ldots & 0 \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & 0 & \ldots & V^J
\end{pmatrix}
\]

where \( V^J \) is defined as the variance of the PU under jets and the upper 2 \( \times \) 2 submatrix is given by

\[
\begin{pmatrix}
V_{11} & V_{12} \\
V_{21} & V_{22}
\end{pmatrix}
= \begin{pmatrix}
\sum_{j=1}^{O} \sigma_j^2 \cos^2 \phi_j & \sum_{j=1}^{O} \sigma_j^2 \cos \phi_j \sin \phi_j \\
\sum_{j=1}^{O} \sigma_j^2 \cos \phi_j \sin \phi_j & \sum_{j=1}^{O} \sigma_j^2 \sin^2 \phi_j
\end{pmatrix}
\]

where \( \sum_{j}^{O} = \sum_{j}^{\text{PFO}_N} + \sum_{j}^{\text{PFO}_{C,PU}} \)