Improvement of missing transverse momentum reconstruction for ATLAS experiment at LHC

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Outline

Missing Transverse Momentum (MET)

The importance of MET

Measuring MET

New algorithm for MET determination

Physics constraints

Input parameters

Performance Evaluation

Comparison on data and MC samples of pp $\rightarrow Z^0 +$ jets with $Z^0 \rightarrow \mu^+\mu^-$

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

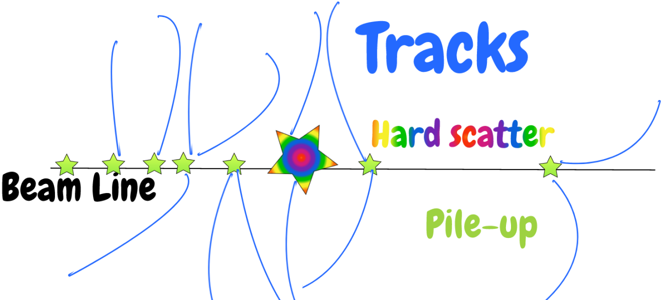
Conclusion

MET

- Many interesting physics processes involve elusive particles that escape detection: Neutrino, SUSY particles, dark matter candidates, etc.
- The missing transverse energy (MET or $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$) 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 ϕ and the polar angle from the beam axis is θ. In practice the pseudorapidity $\eta = -\ln\tan(\frac{\theta}{2})$ is used, since particle production is nearly uniform in eta

MET

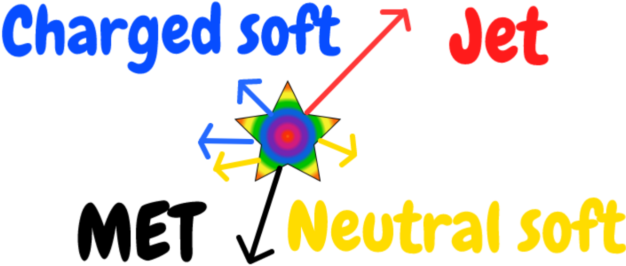
- The LHC collides bunches of protons. Each bunch crossing produces many pp collisions. The hardest collision is called **hard scatter**, and others are referred to as **pile-up** interactions.
- Each collision location is called a **primary vertex**. The number of primary vertices (N_{pv}) measures 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.

$$\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = -\sum_{j\in\{\text{hard objects}\}} \vec{p}_{\mathrm{T,j}}^{\mathrm{miss}} - \sum_{i\in\{\text{soft signals}\}} \vec{p}_{\mathrm{T,i}}^{\mathrm{miss}} \tag{1}$$



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 → 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 χ^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:

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

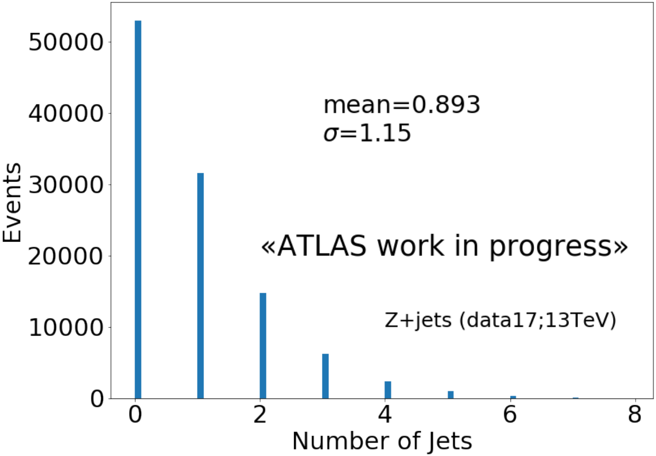
where A_k is the area of the k-th jet.

Performance on pp $\rightarrow Z^0 +$ jets

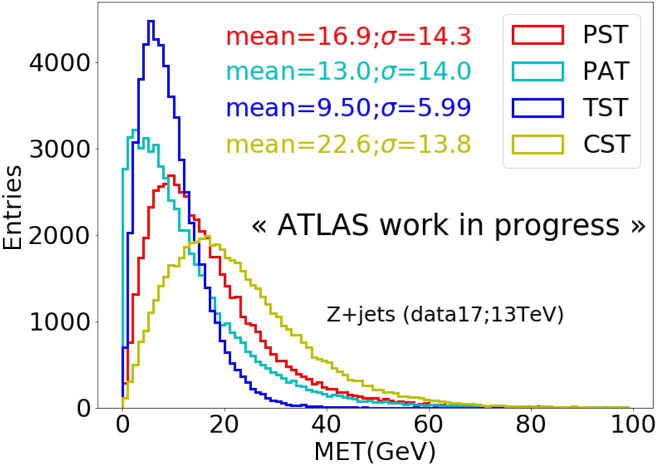
- Data used from 2017 ATLAS run at 13TeV. Fully simulated MC events are also used.
- $Z \rightarrow \mu^+\mu^-$ decays are selected based on muon trigger, muon ID and also the invariant mass of $\mu^+\mu^-$.
- Muons leave negligible energy in the calorimeter, resulting in an imbalance. The imbalance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

pp $\rightarrow Z^0 +$ jets sample

- Zero jet events are not used since PST and TST soft terms are equivalent in these events.

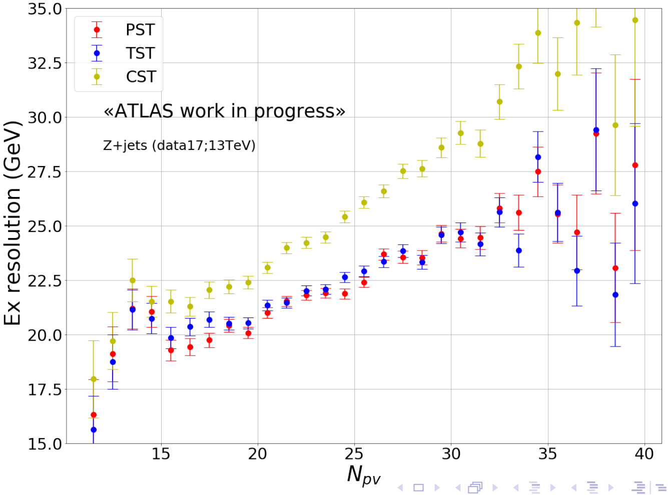


- We are making a correction (PAT) that is of comparable magnitude to TST.
- TST: track soft term; CST: cluster soft term
  PAT: The correction; PST: PUfit soft term (TST+PAT)



MET resolution from pp $\rightarrow Z^0+$ jets

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

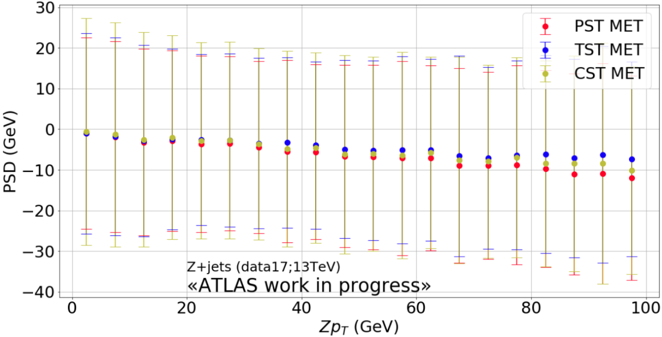


MET scale from pp $\rightarrow Z^0 +$ jets

- 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.

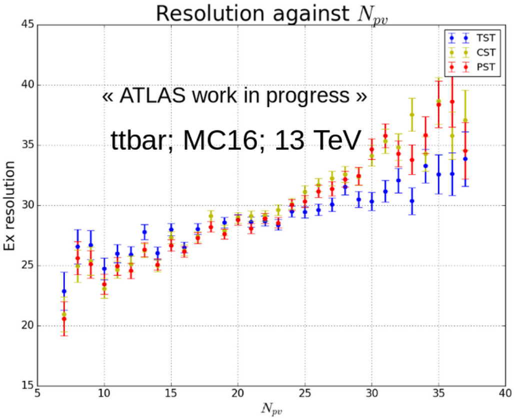
$$\text{PSD} = \vec{E}_\text{T}^\text{miss} \cdot \hat{E}_T^Z - |\vec{E}_T^Z| \tag{2}$$

- The errorbar is the RMS width in each bin.



MET resolution on $pp \to t\bar{t}$ 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.

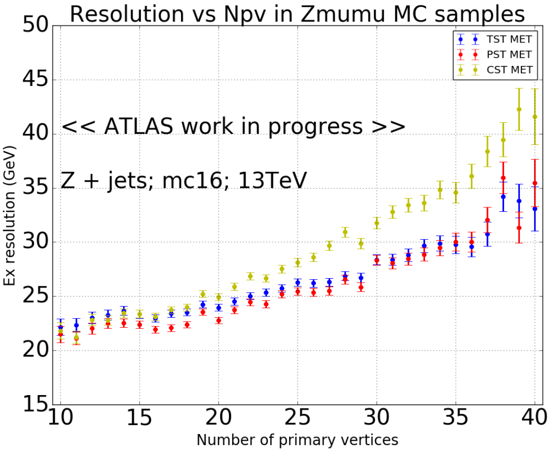


Conclusion

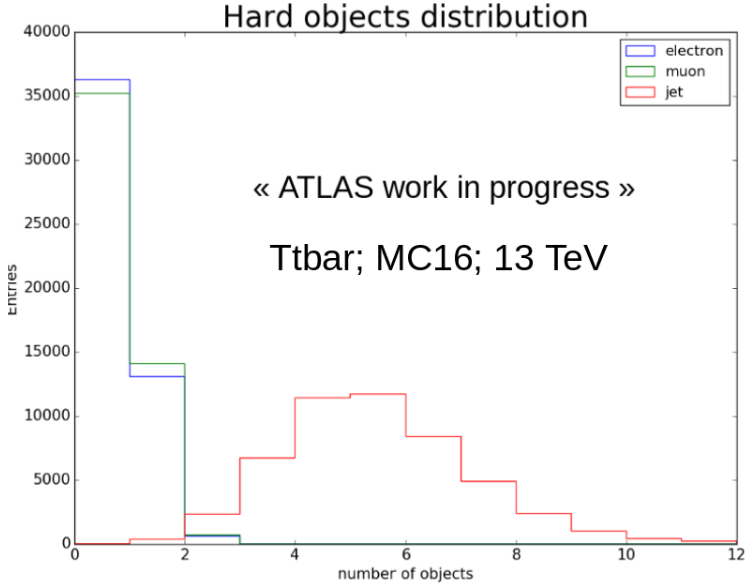
- PUfit uses both charged and neutral signals to determine the soft term, and it was tested in both Z+jets and ttbar eventys.
- It achieves similar resolution compared to the TST MET and much better than the CST MET in Z+jets events.
- More investigations needed for the $t\bar{t}$ sample.
- Further analysis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

MET resolution on pp $\rightarrow Z^0+$ 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 $15 < N_{pv} < 35$.



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



PUfit determines $\mathcal{E}$ by two constraints:

- Pileup vertices should not produce any real $\vec{E}_T^{miss}$.
- 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:

$$\sum_j^{\text{clus}} \vec{E}_{T_j} - \sum_j^{C} \vec{p}_{T_j}^{\text{HS}} + \sum_k^{J} \vec{\mathcal{E}}_{T_k} = 0$$

where the first term sums over all clusters outside HS jet and $\vec{p}_{T_j}^{HS}$ 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:

$$\sum_{j}^{\mathrm{clus}} \vec{E}_{T_j} - \sum_{j}^{C} \vec{p}_{T_j}^{\mathrm{HS}} + \sum_{k}^{j} \vec{\mathcal{E}}_{T_k} = 0$$

Now it becomes:

$$\sum_{j}^{\mathrm{PFO_N}} \vec{E}_{T_j} + \sum_{j}^{\mathrm{PFO_{C,PU}}} \vec{E}_{T_j} + \sum_{k}^{j} \vec{\mathcal{E}}_{T_k} = 0$$

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 χ^2 function:

$$\chi^2(\mathcal{E}_{T_1}, ..., \mathcal{E}_{T_m}) = \Delta^T V^{-1} \Delta$$

Δ is defined as:

$$\Delta = \begin{pmatrix} \sum_j^{\mathrm{PFO_N}} \vec{E}_{T_j} \cos\phi_k + \sum_j^{\mathrm{PFO_{C,PU}}} \vec{E}_{T_j} \cos\phi_k + \sum_{k=1}^{n_J} \mathcal{E}_{T_k} \cos\phi_k \\ \sum_j^{\mathrm{PFO_N}} \vec{E}_{T_j} \sin\phi_k + \sum_j^{\mathrm{PFO_{C,PU}}} \vec{E}_{T_j} \sin\phi_k + \sum_{k=1}^{n_J} \mathcal{E}_{T_k} \sin\phi_k \\ \mathcal{E}_{T_1} - \langle\rho\rangle A_1 \\ \vdots \\ \mathcal{E}_{T_{n_J}} - \langle\rho\rangle A_{n_J} \end{pmatrix} \tag{3}$$

Fit

The covariance matrix is given by:

$$V = \begin{pmatrix} V_{11} & V_{12} & 0 & 0 & \dots & 0 \\ V_{21} & V_{22} & 0 & 0 & \dots & 0 \\ 0 & 0 & V^{\mathrm{J}} & 0 & \dots & 0 \\ 0 & 0 & 0 & V^{\mathrm{J}} & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \dots & V^{\mathrm{J}} \end{pmatrix} \tag{4}$$

where V^{J} is defined the variance of the PU under jets and the upper 2×2 submatrix is given by

$$\begin{pmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{pmatrix} = \begin{pmatrix} \sum_{j=1}^{O} \sigma_j^2 \cos^2 \phi_j & \sum_{j=1}^{O} \sigma_j^2 \cos \phi_j \sin \phi_j \\ \sum_{j=1}^{O} \sigma_j^2 \cos \phi_j \sin \phi_j & \sum_{j=1}^{O} \sigma_j^2 \sin^2 \phi_j \end{pmatrix} \tag{5}$$

where $\sum_j^O = \sum_j^{\mathrm{PFO_N}} + \sum_j^{\mathrm{PFO_{C,PU}}}$