Performance of Missing Transverse Momentum (MET) reconstruction in High Pile-Up

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Outline

1. **Introduction and Baseline MET performance**
2. **Recent developments**
3. **MET towards HL-LHC**
4. **Summary**

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Introduction (1)

What is MET and why is that important?

What is Missing Transverse Momentum (MET)?

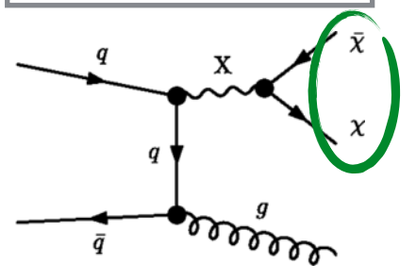
$$E_T^{\text{miss}} \equiv \sum_{\substack{\text{invisible} \\ \text{particles}}} \vec{p}_{T,i} = - \sum_{\substack{\text{visible} \\ \text{particles}}} \vec{p}_{T,i}$$

We can distinguish two types of MET:

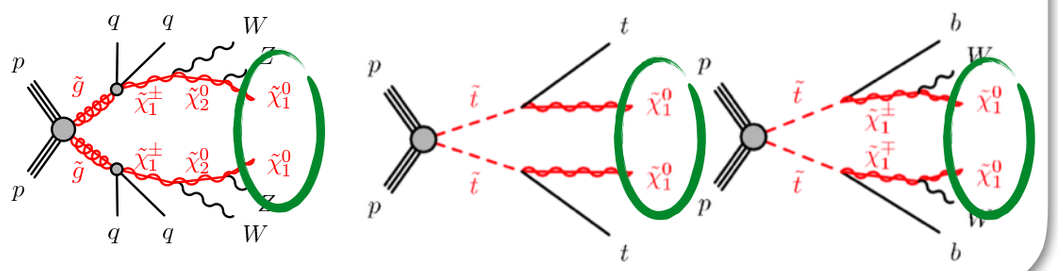
- **True MET:** non-zero MET due to real invisible particles.
- **Fake MET:** non-zero MET values are purely due to mis-detection and mis-reconstruction effects.

The distinction between Fake and True MET events is fundamental for many ATLAS analyses!

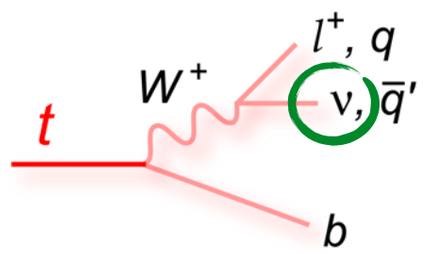
Dark Matter



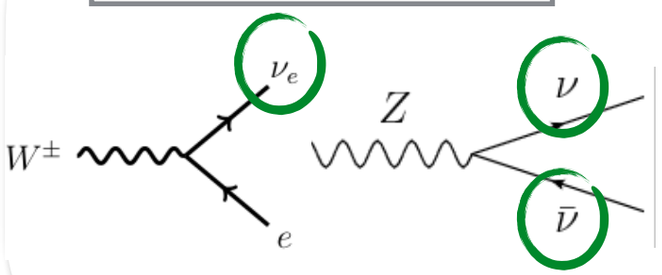
Supersymmetry (RPC)



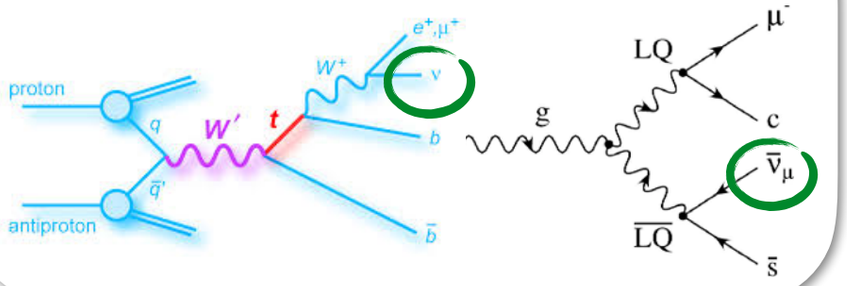
Top physics



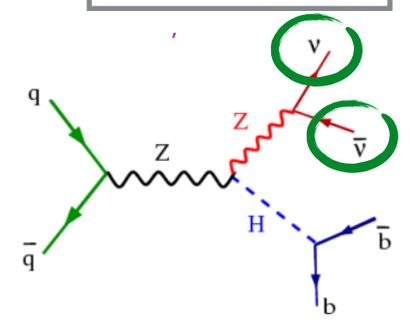
Standard Model



Exotics



Higgs



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Introduction (2)

ATLAS MET reconstruction overview and pileup

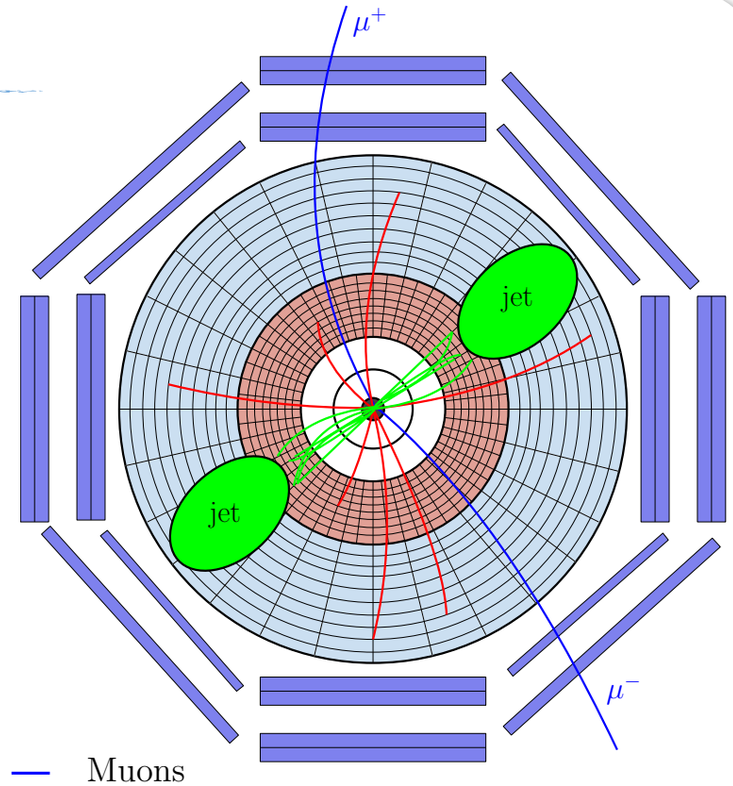
MET reconstruction and Track-based Soft Term (TST)

Negative vectorial sum of well identified physics objects (hard term) plus a soft term :

$$\vec{E}_T^{\text{miss}} = -\Big(\underbrace{\vec{p}_T^{\,\text{muons}} + \vec{p}_T^{\,\text{electrons}} + \vec{p}_T^{\,\text{photons}} + \vec{p}_T^{\,\text{taus}} + \vec{p}_T^{\,\text{jets}}}_{\text{hard term}} + \underbrace{\vec{p}_T^{\,\text{soft term}}}_{\text{soft term}}\Big)$$

Objects:

- **Track-based Soft Term (TST):** tracks unassociated to any well-identified physics object (track p_T> 500 MeV) and matched to primary vertex.
- **Jets:** calibrated, made of anti-kt R=0.4 topoclusters, pile-up suppression with JVT.



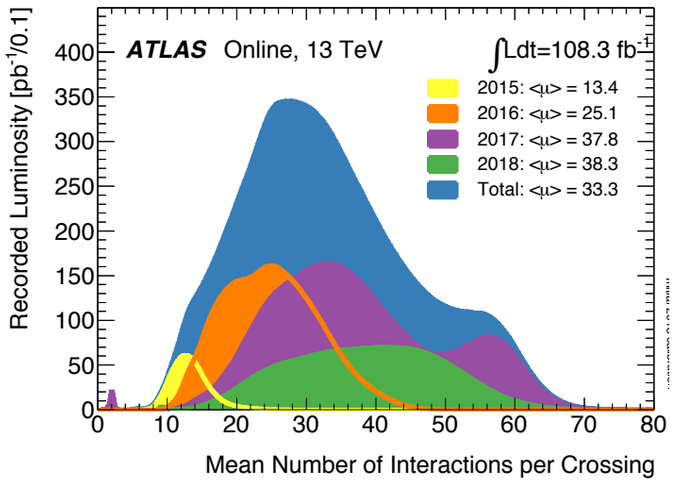
Pileup and MET

Pileup = multiple p-p interactions in the same (or close-by) LHC bunch crossing.

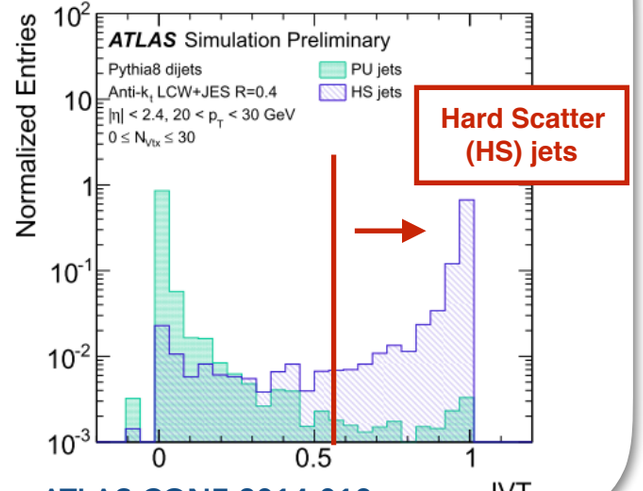
This contamination particularly affects the MET reconstruction.

Robust pileup suppression in MET is fundamental for the current and future ATLAS physics program.

ATLAS-PUBLIC-Lumi



Jet Vertex Tagger (JVT)



ATLAS-CONF-2014-018

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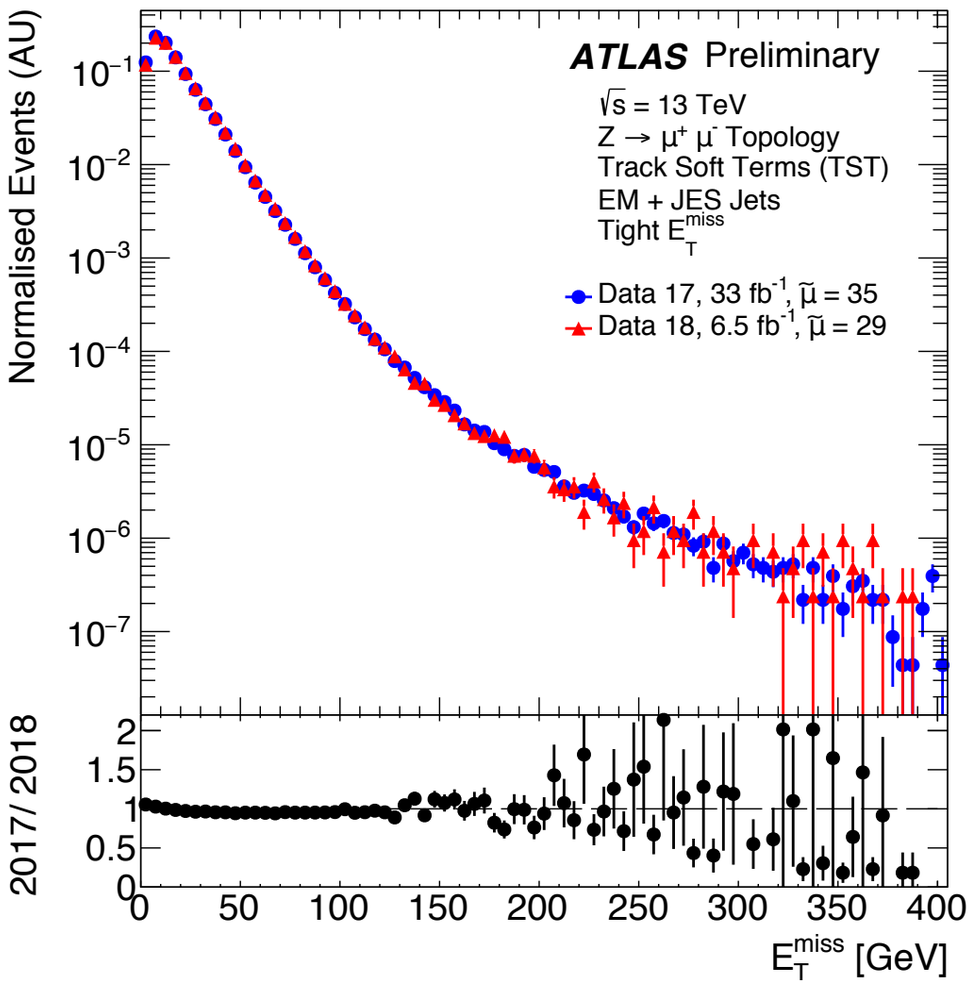
Baseline MET reconstruction performance

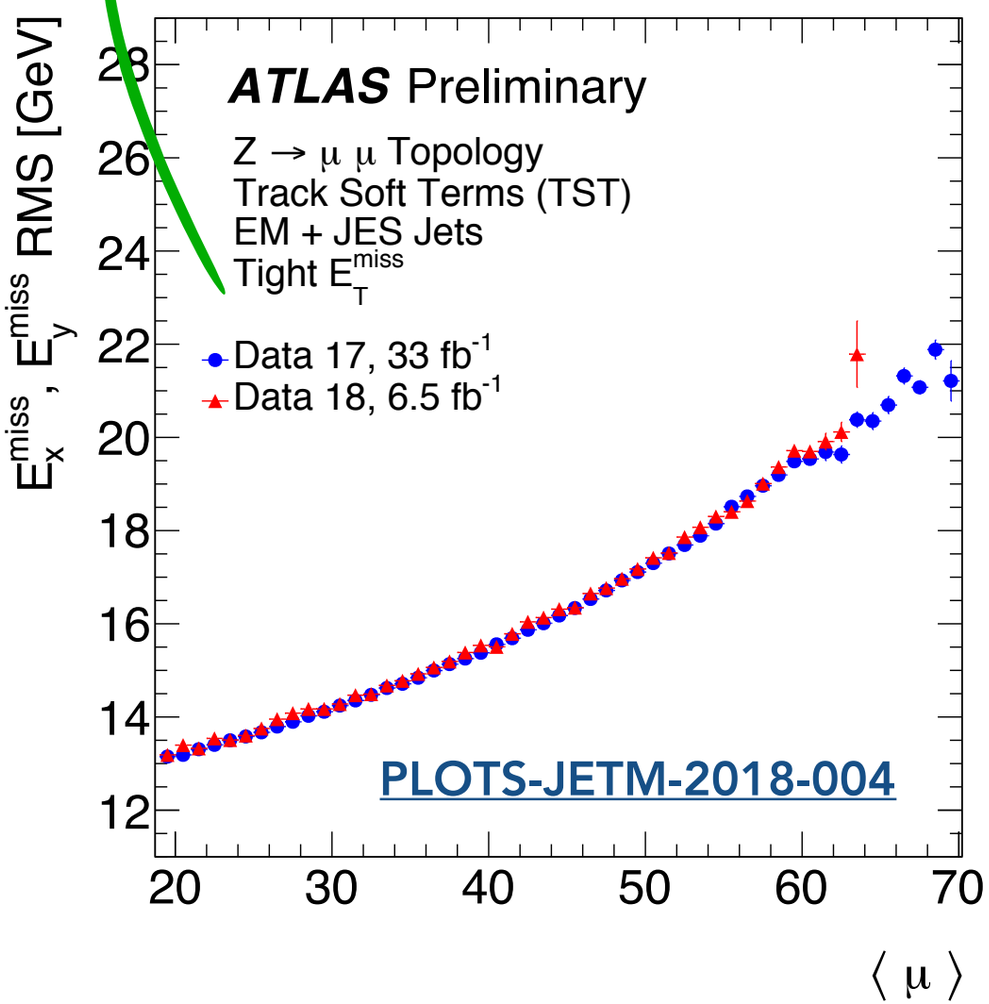
ATLAS MET performance in recent data (2017-2018)

- Performance of MET reconstruction has been recently evaluated using the new data provided by the LHC.
- MET tails and resolution are the same between the 2017 and 2018 data periods.

MET working points (WPs)

Working Point	*Central jets (|η|<2.5)*	*Forward jets (|η|>2.5)*
Loose	p_T > 20 GeV	p_T > 20 GeV
Tight	p_T > 20 GeV	**p_T > 30 GeV**
fJVT	p_T > 20 GeV	p_T > 20 GeV **+ fJVT cut**





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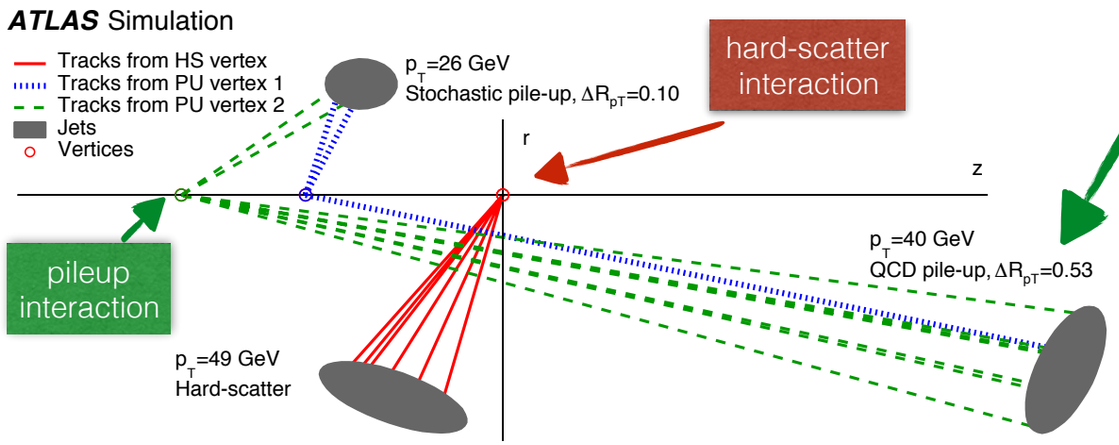

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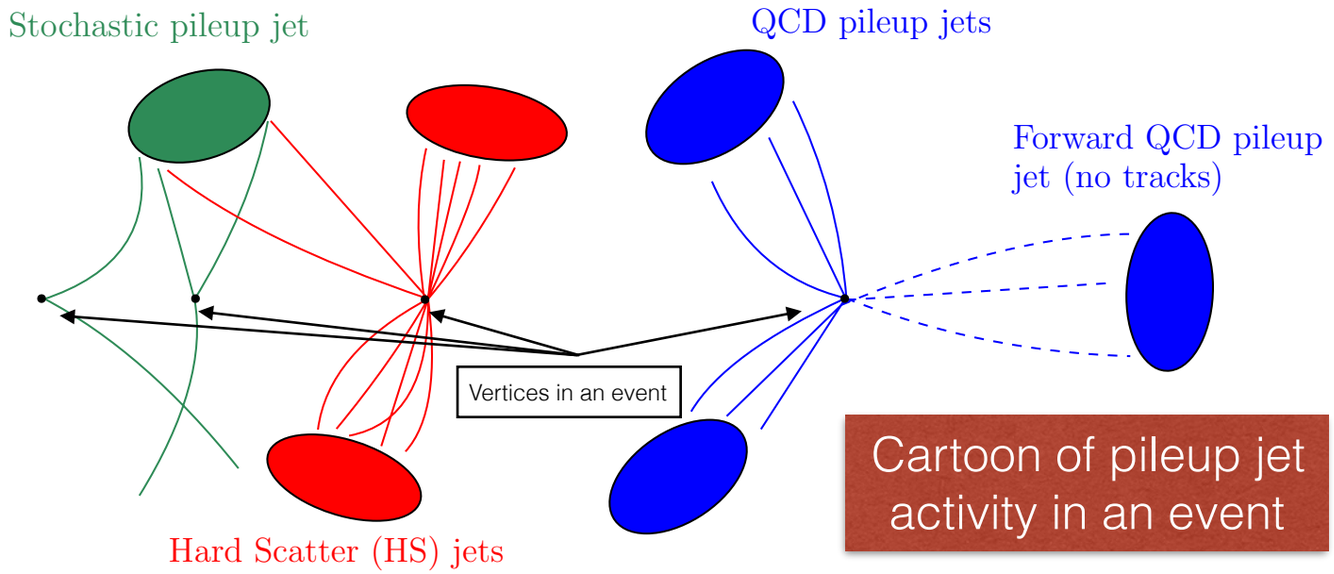
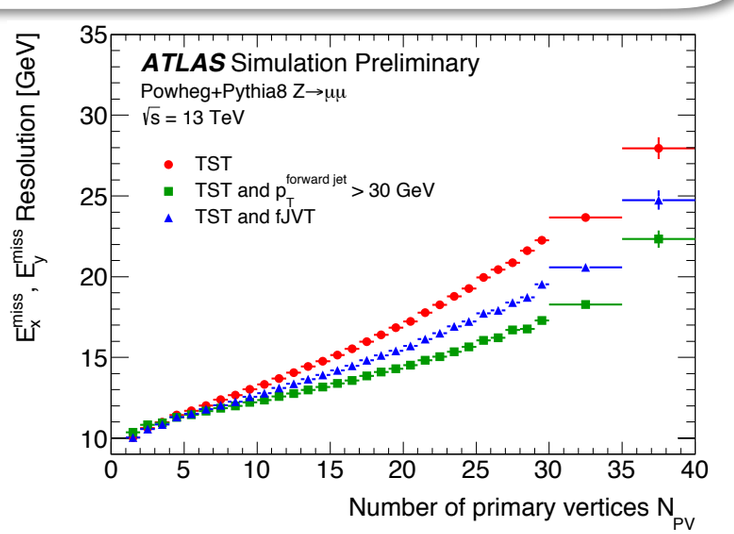
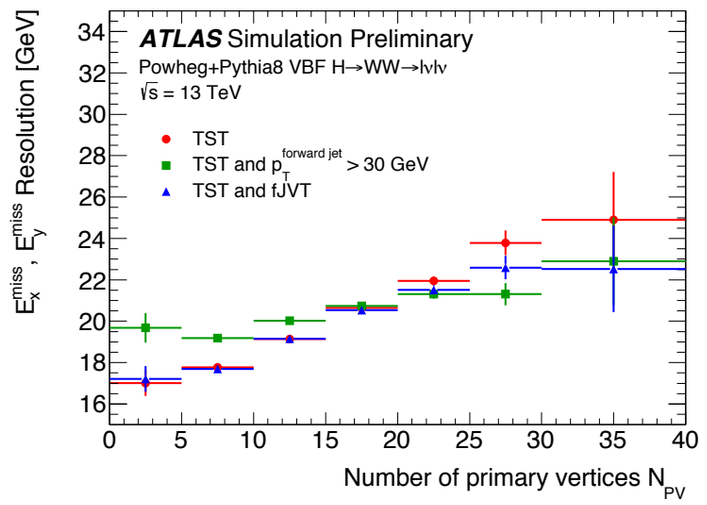


Cartoon of pileup jet activity in an event





arxiv:1705.02211

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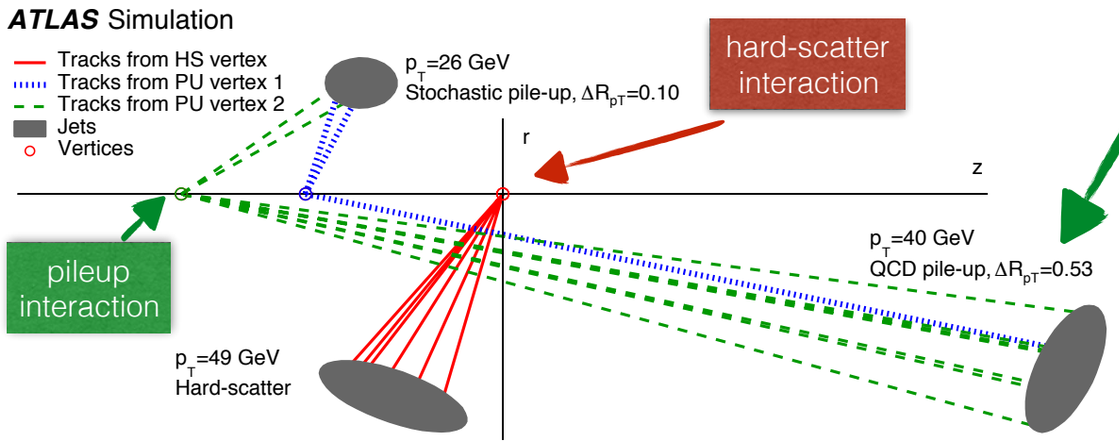

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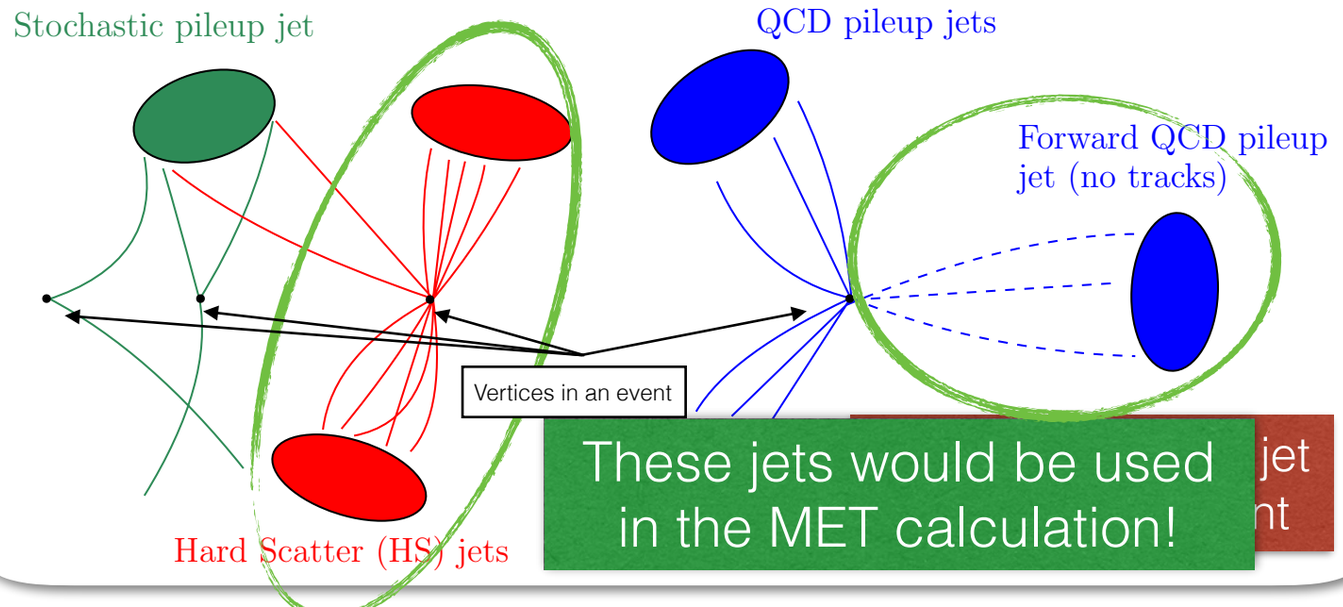

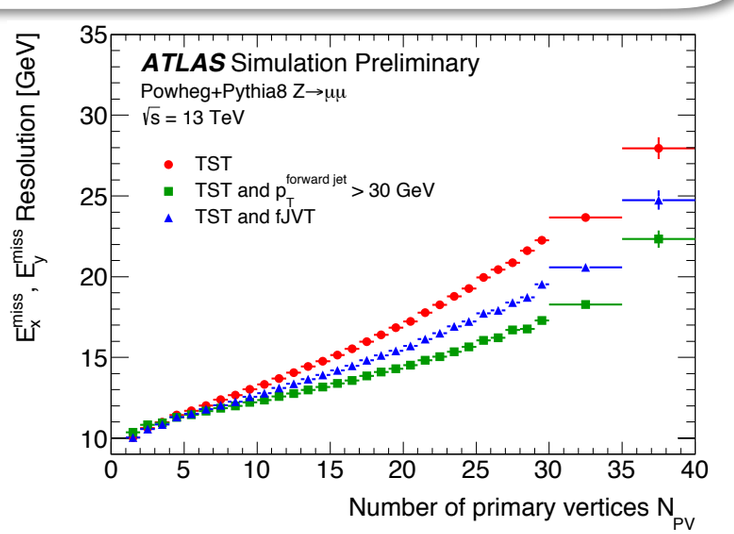

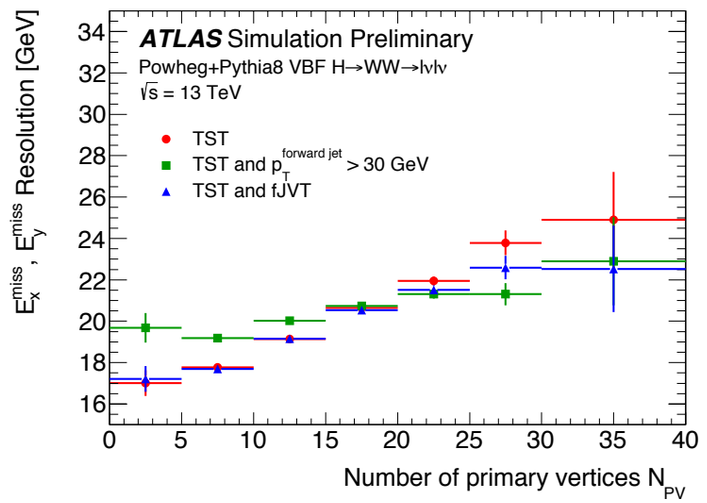

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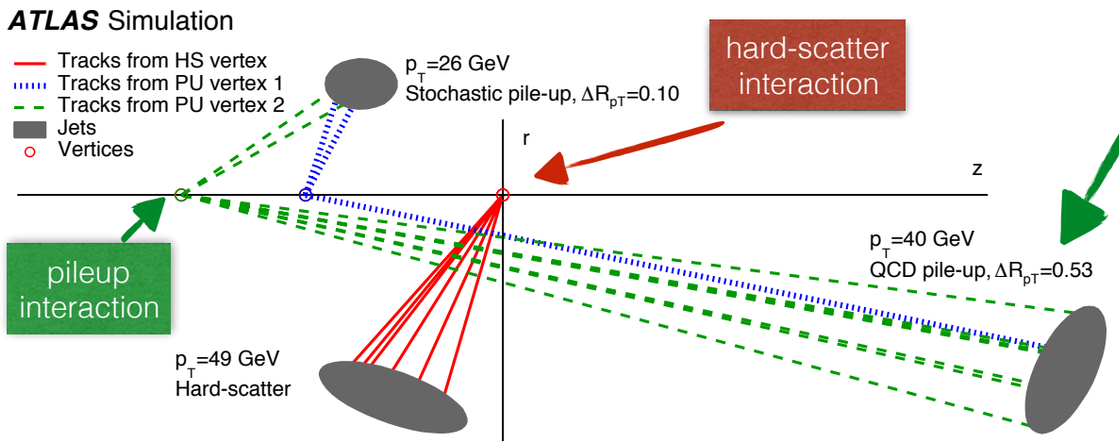

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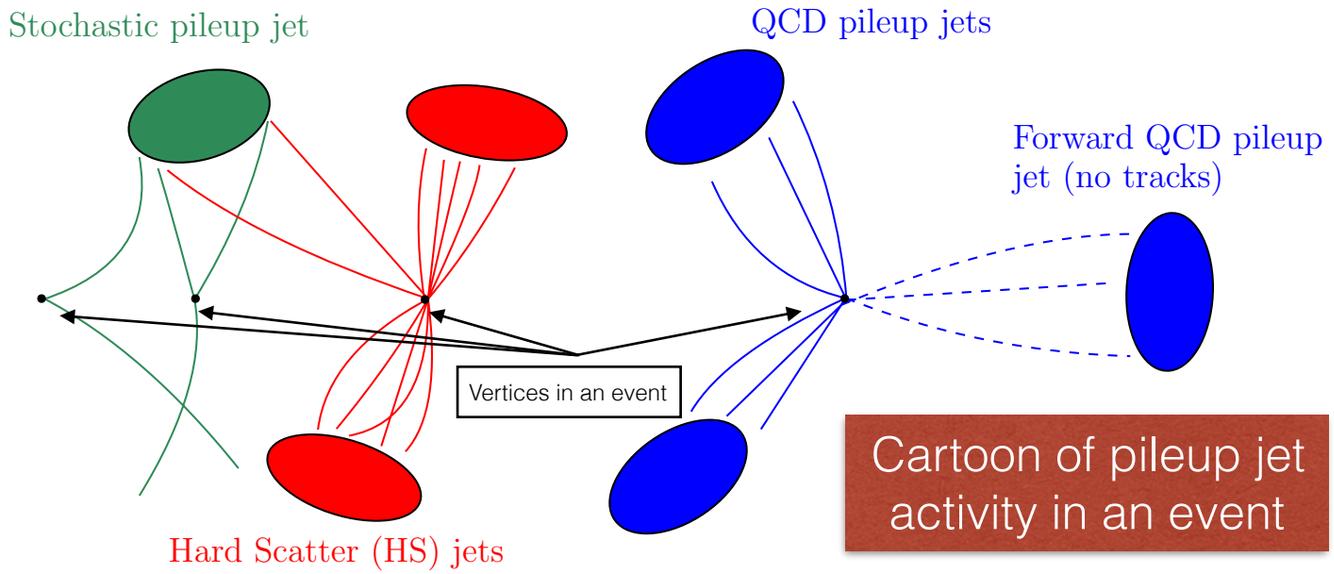

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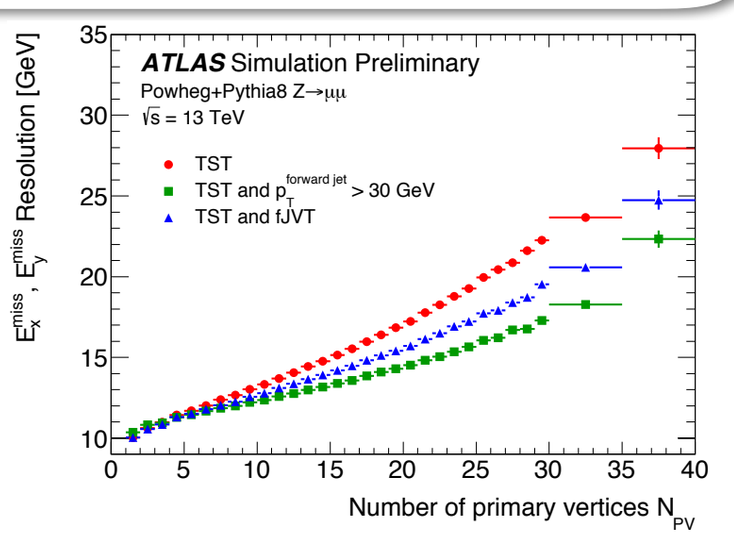

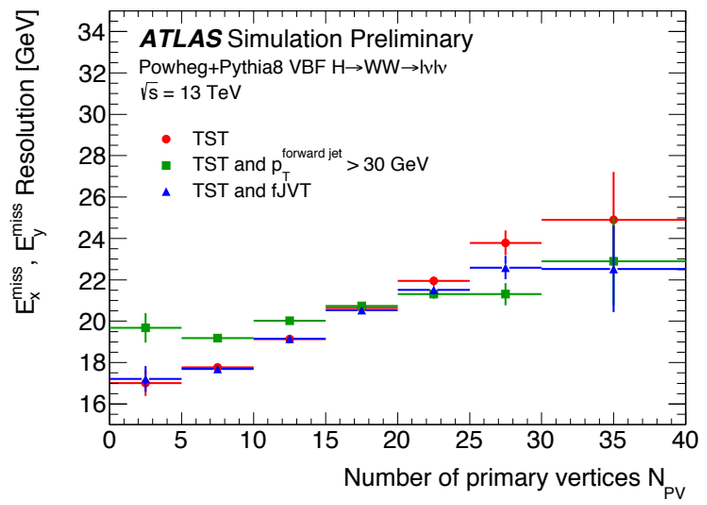

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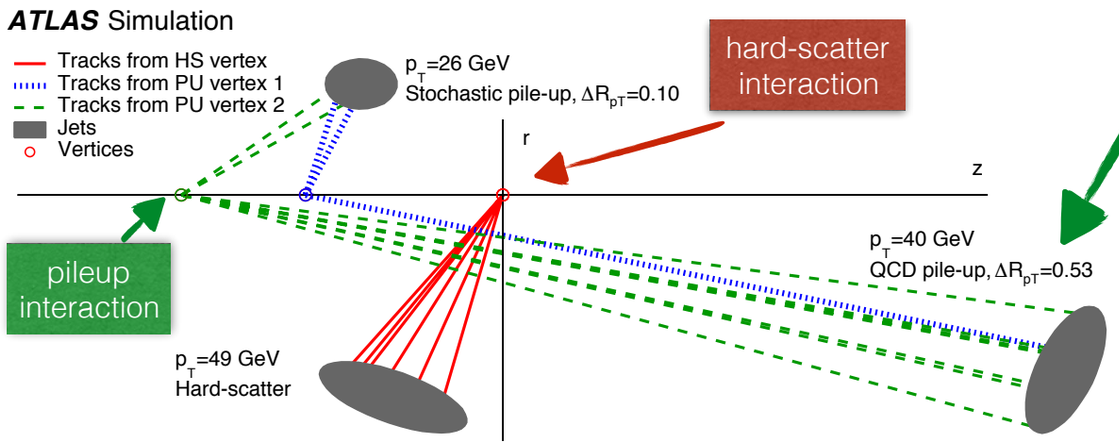

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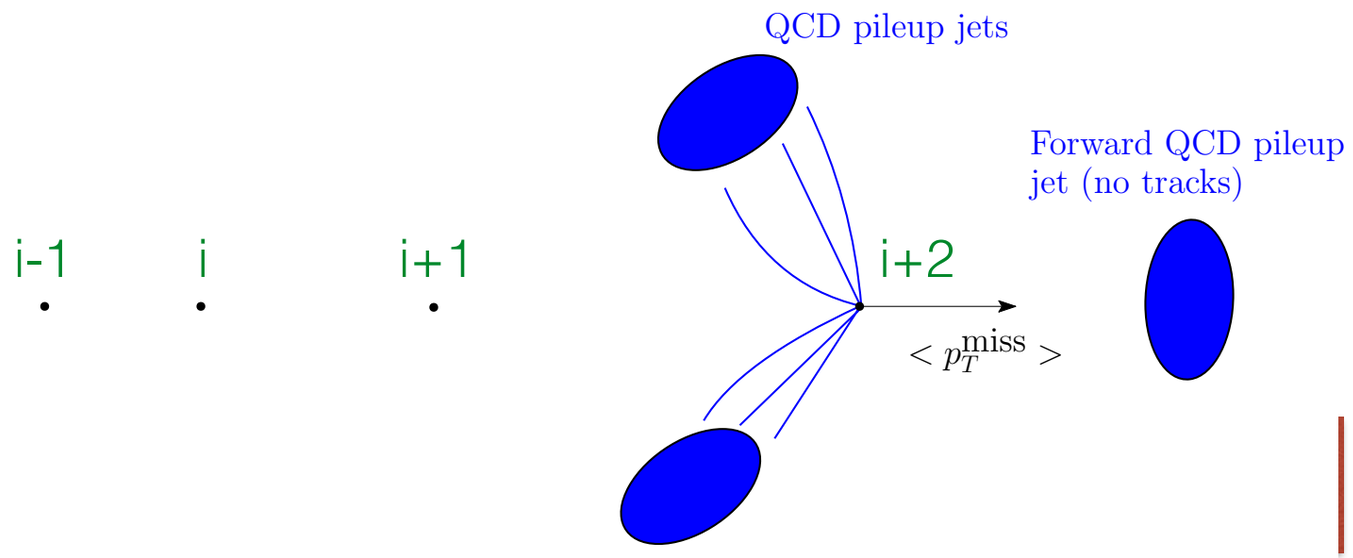

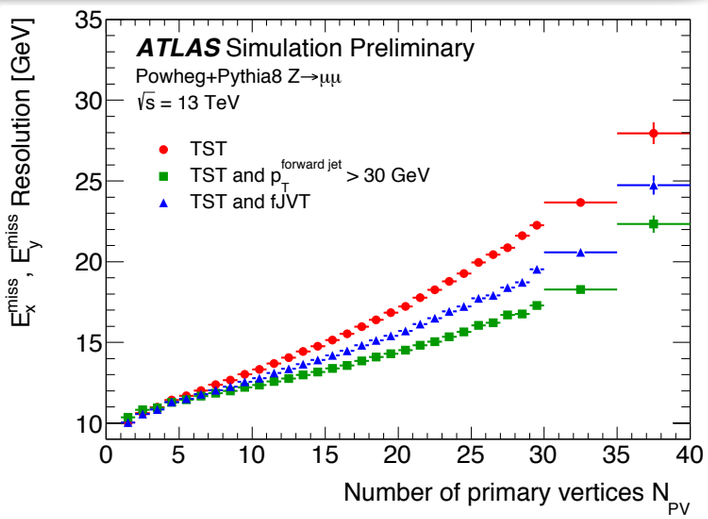

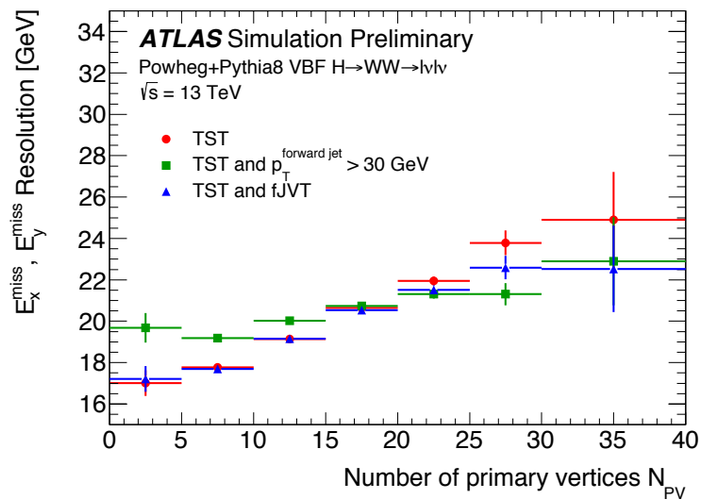

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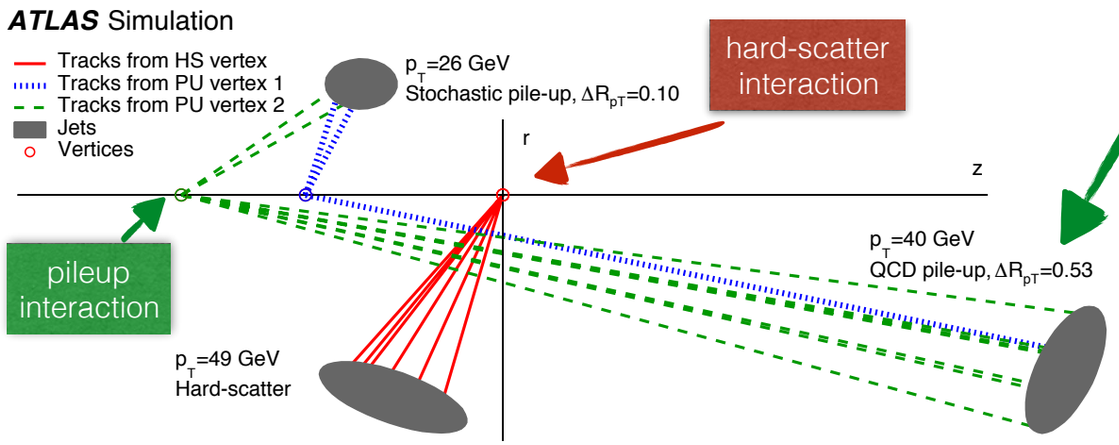

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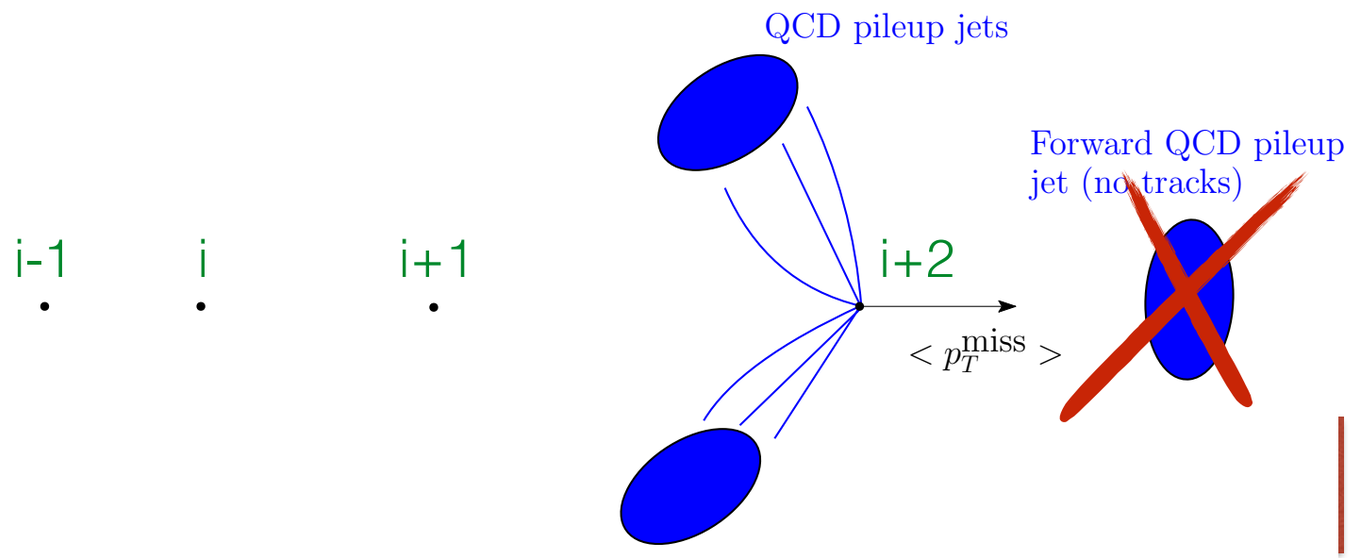

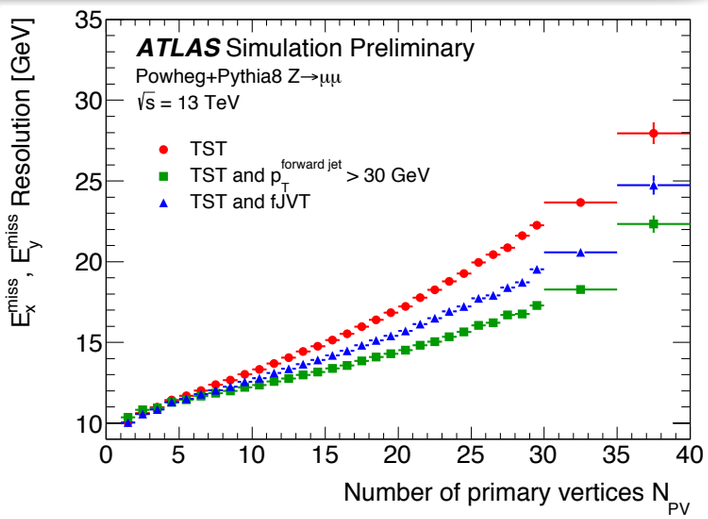

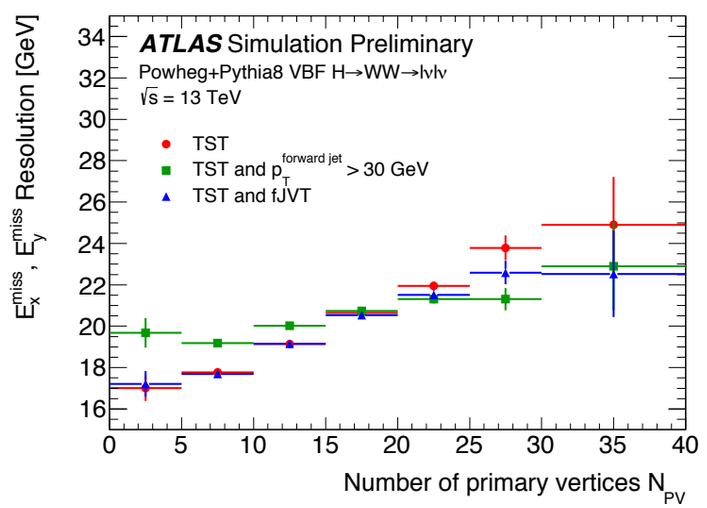

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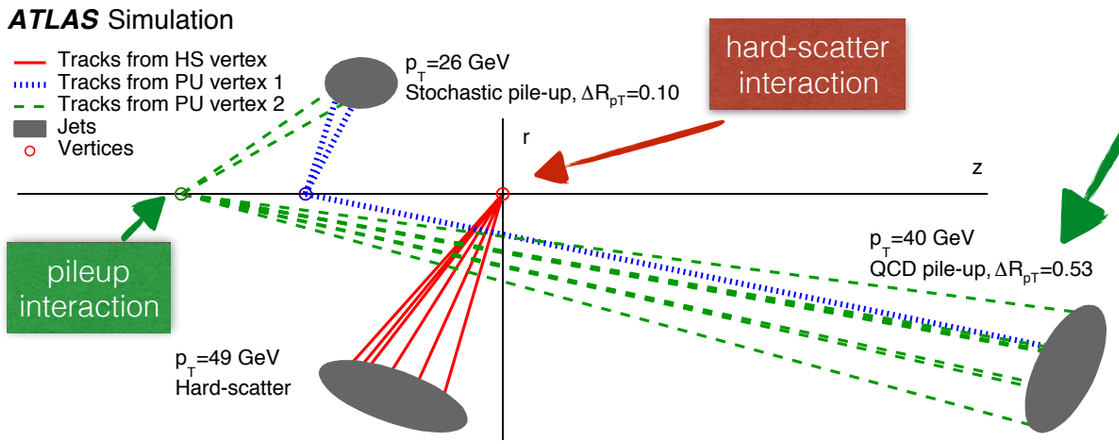

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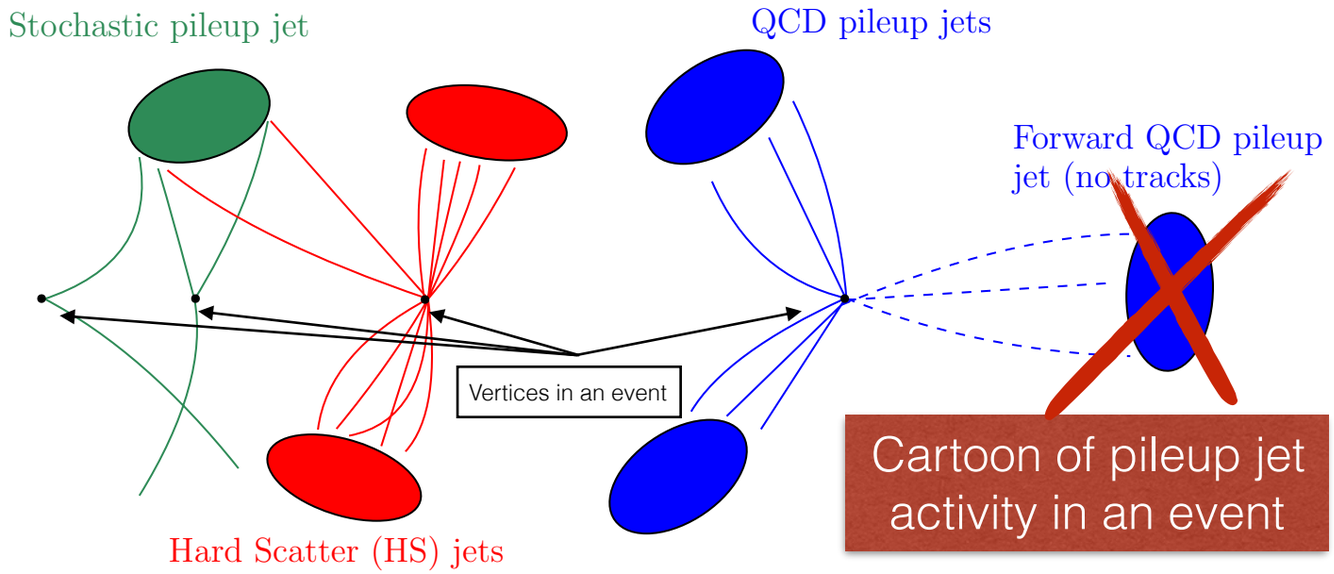

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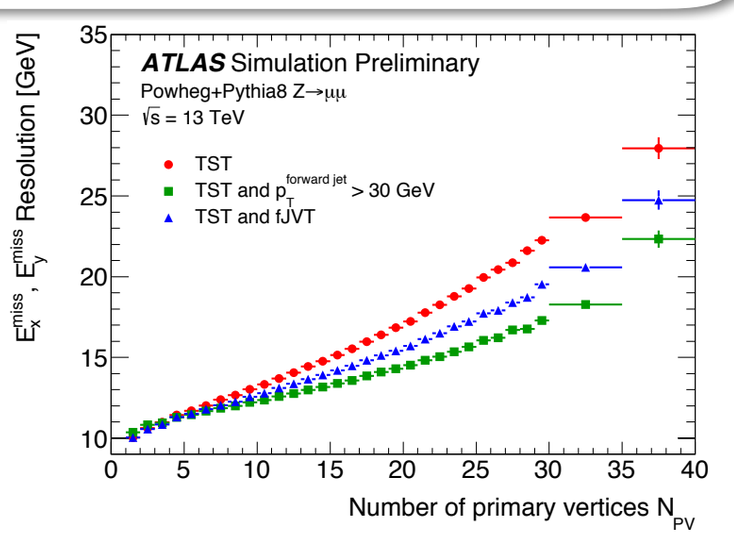

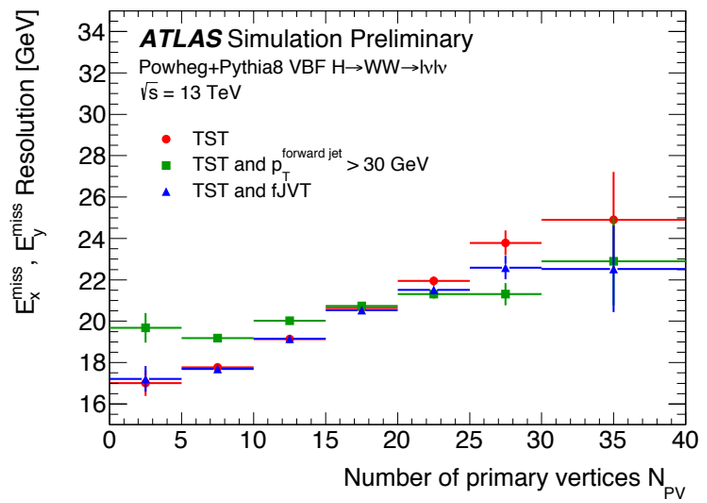

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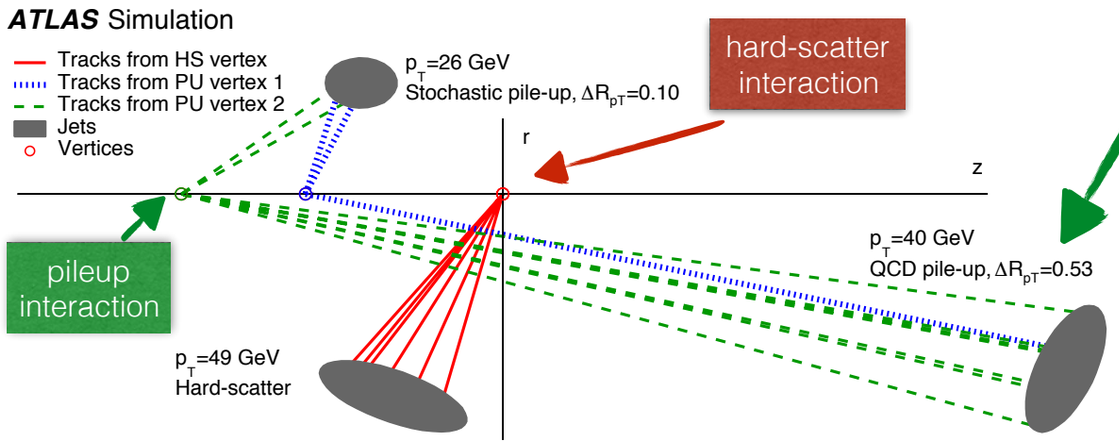

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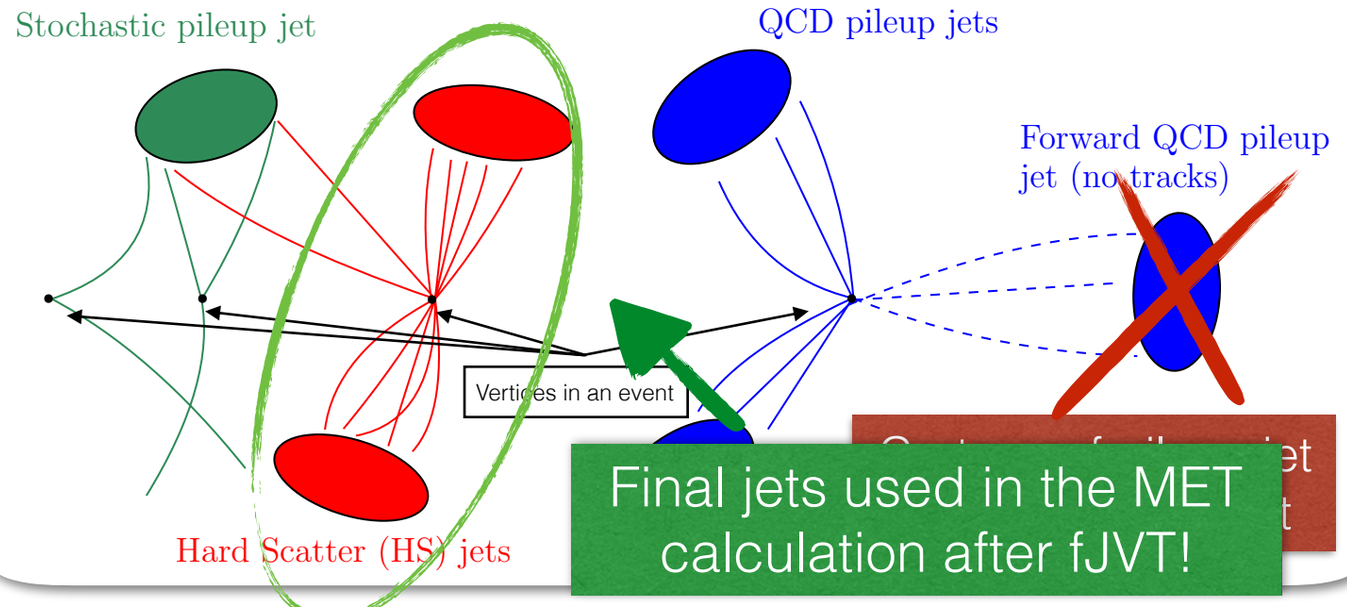
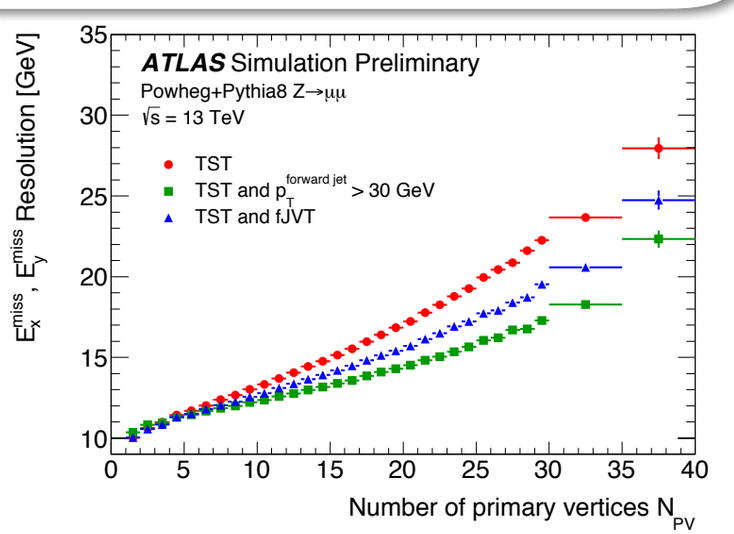
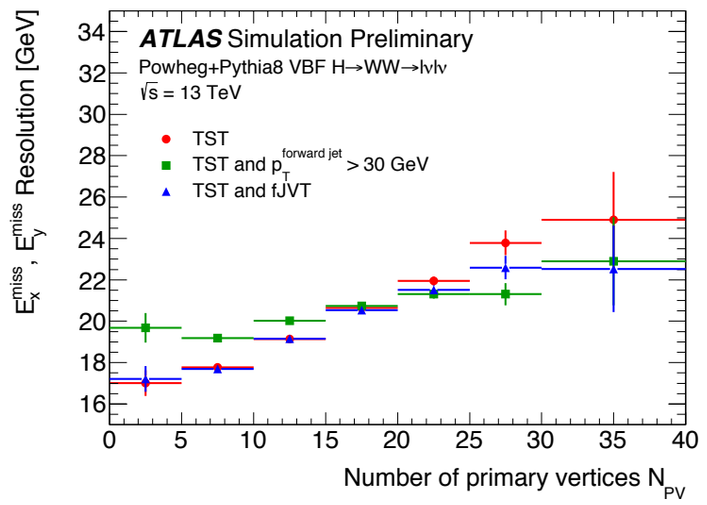


Final jets used in the MET calculation after fJVT!





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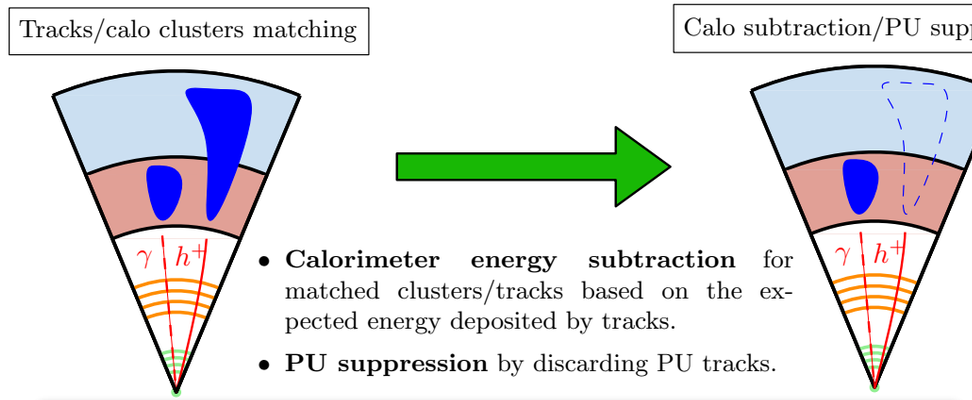
Recent developments (2)

Particle Flow and jet/MET reconstruction performance

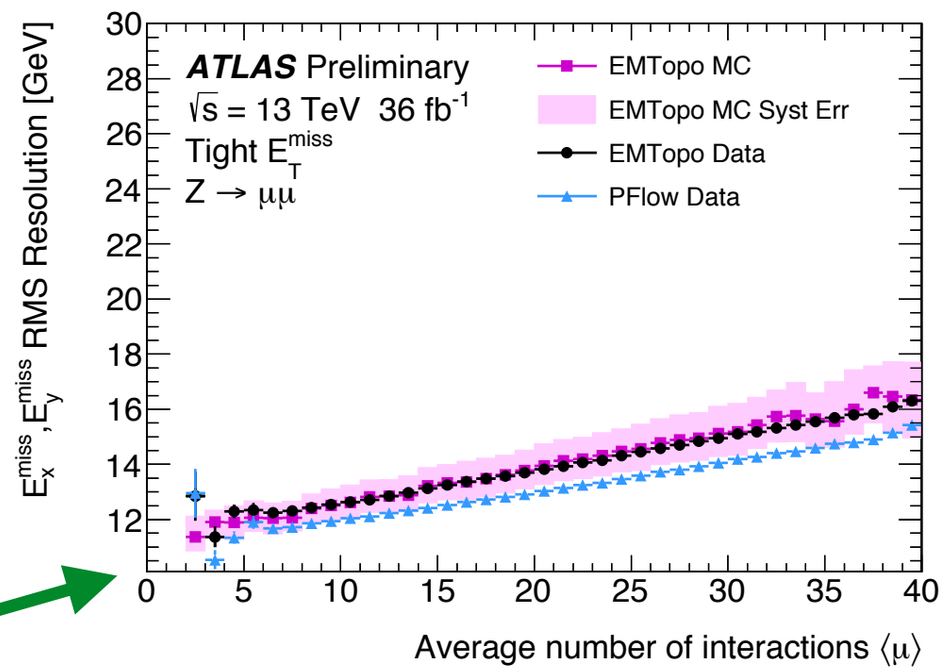
The (ATLAS) Particle Flow algorithm

- **Combine the optimal resolution of the tracker and calorimeter information** in the low and high p_T regimes respectively.
- These techniques have already been implemented in other experiments (CMS, ALEPH).



- **Calorimeter energy subtraction** for matched clusters/tracks based on the expected energy deposited by tracks.
- **PU suppression** by discarding PU tracks.

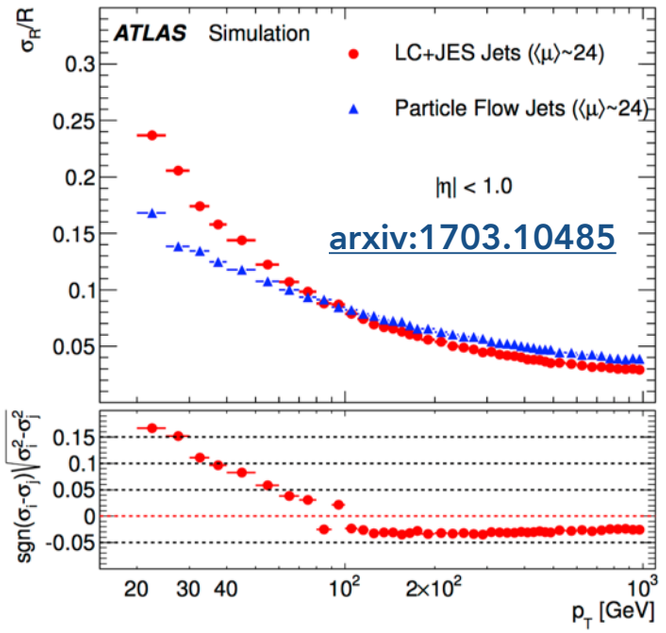
Resolution of MET significantly improved!

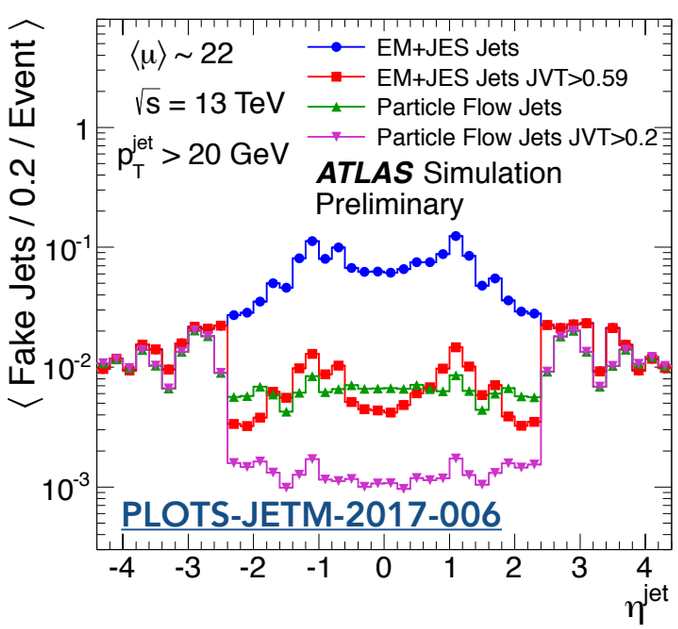


Particle Flow jet and pileup rejection improvements

Improvements from Particle Flow to MET are due to:

- **Improvements to the jet energy resolution at low p_T.**
- **Larger rejection of pileup jets** (lower amount of fake jets).





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Recent developments (3)

Electromagnetic end-cap calorimeter (EMEC) cleaning

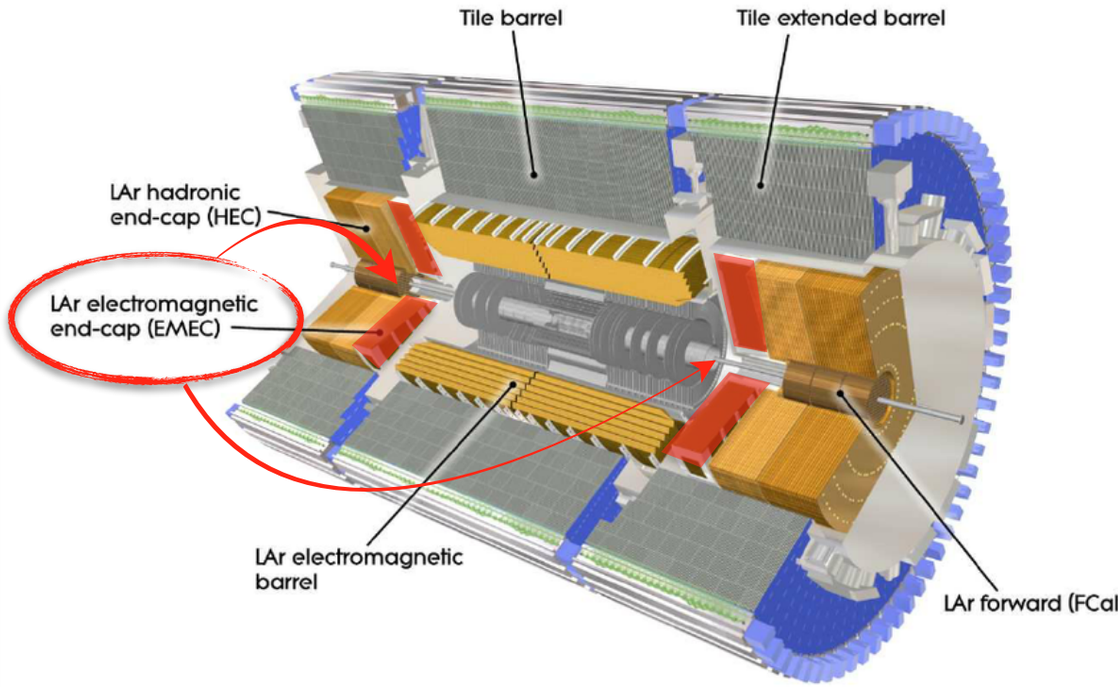
EM calorimeter end-cap saturation

Some bunch filling schemes of the LHC in high pileup data led to a **saturation of the ATLAS Electromagnetic end-cap calorimeter** (EMEC).

Large electronic noise fluctuations

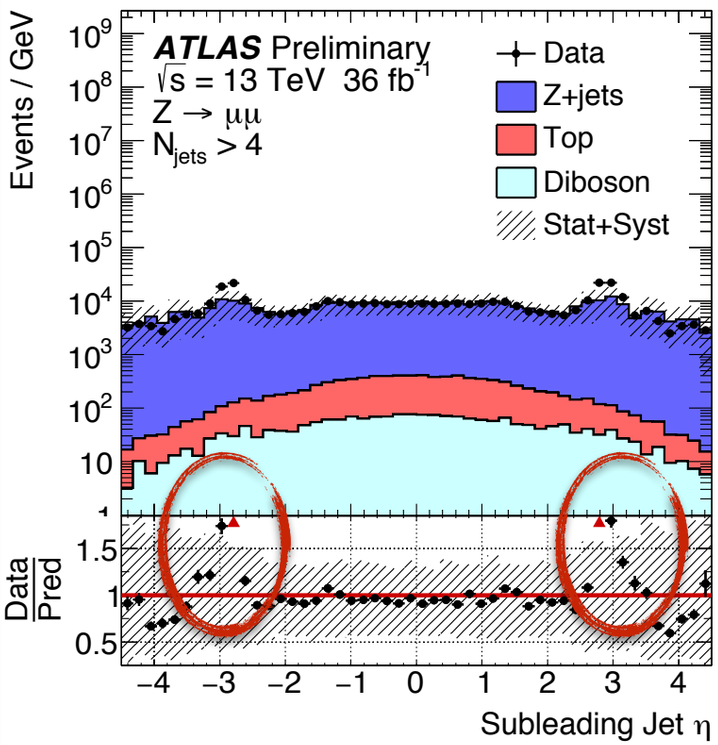
↓

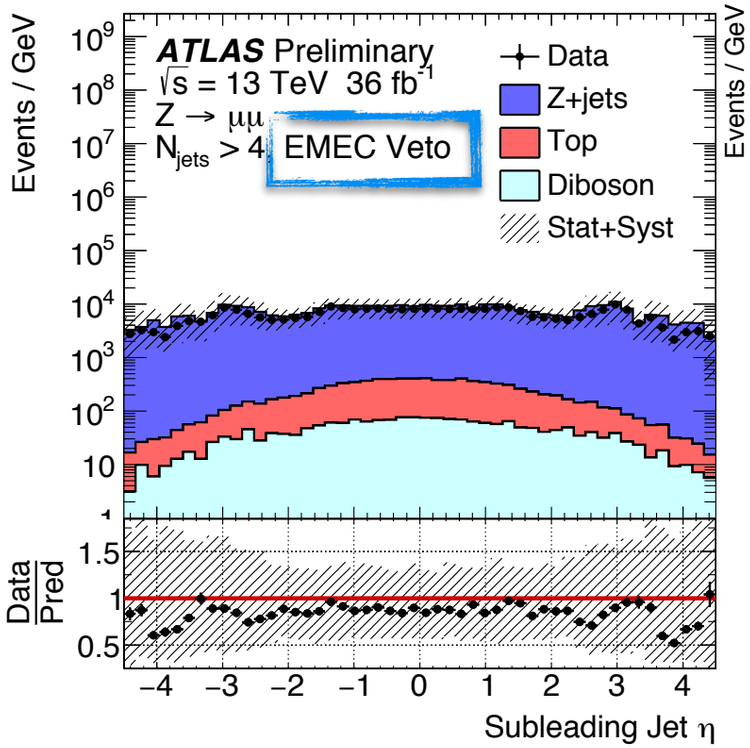
Large fraction of fake jets within $2.5<|\eta|<3.2$

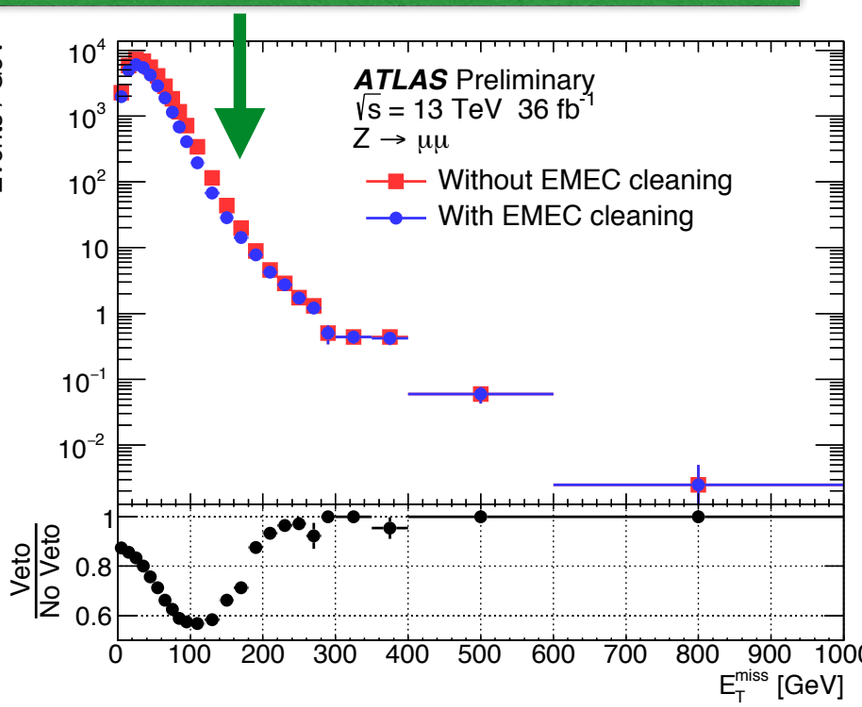


Large improvement to the core of the MET distribution!

Cleaning applied to data only!







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Recent developments (4)

Object-based MET significance

MET significance definition

MET significance: is the measured MET compatible with the 0 MET hypothesis when we consider object resolutions?

$$\mathcal{S} = \frac{E_T^{\text{miss}}}{\sigma(E_T^{\text{miss}})} \approx \frac{E_T^{\text{miss}}}{\sqrt{\sum E_T}}$$

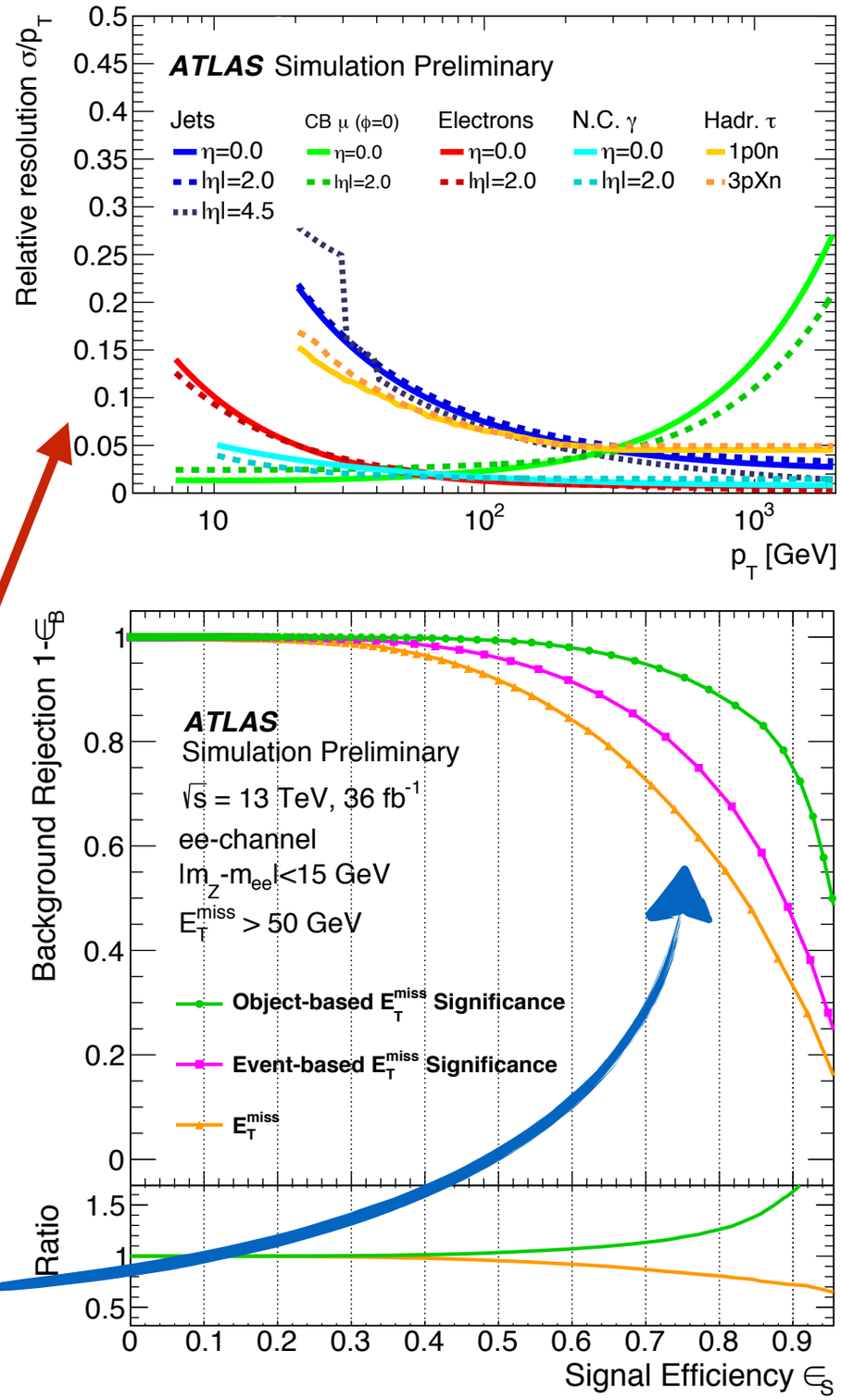
Event-based MET significance
used by many ATLAS analyses

Event-based MET significance is just an approximation **made assuming** $\sigma(E_T^{\text{miss}}) \approx \sqrt{\sum E_T}$

This approximation is not always good
and a MET significance estimation based on individual object resolution might be better!

Many CMS analyses are already using a similar observable!

The object based MET significance provides better separation for events with true and fake MET (ZZ→ee$\nu\nu$ and Z→ee).



First ATLAS analysis application can be found in Christian Lüdtke talk (link).

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Recent developments (5)

MET triggers

ATLAS-MissingEtTriggerPublicResults

MET triggers and pileup mitigation

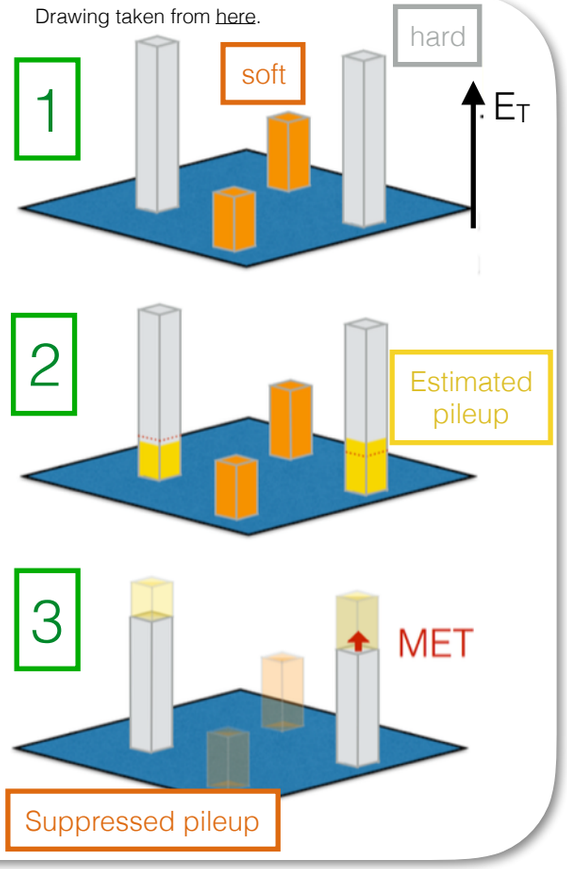
The large amount of collisions from the LHC can produce additional objects that could fire triggers without a proper online pileup mitigation.

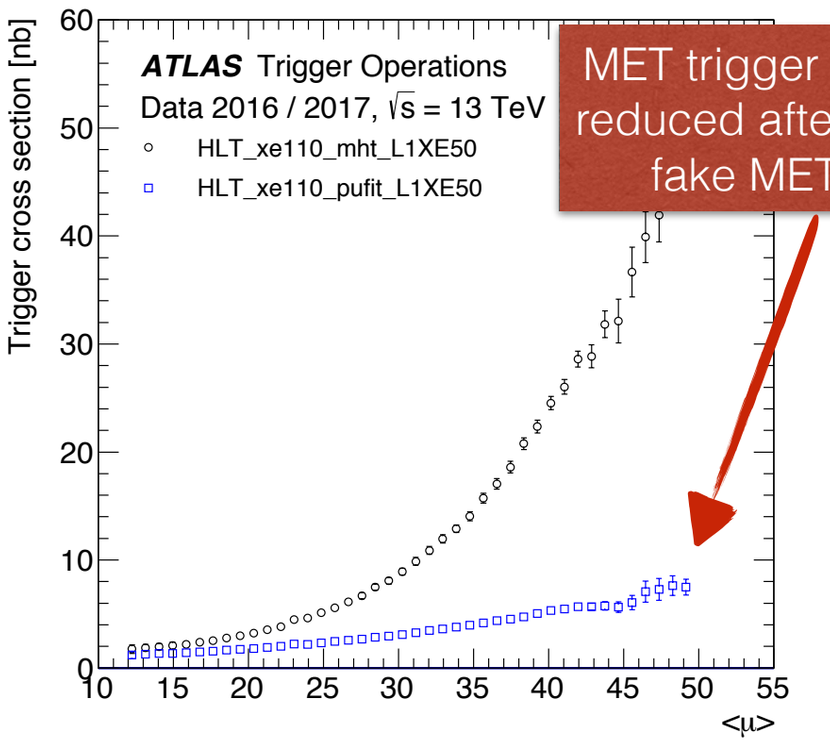
Pileup degradation is particularly large in MET triggers (no sufficient tracking information available).

Pileup fit (or pufit) procedure:

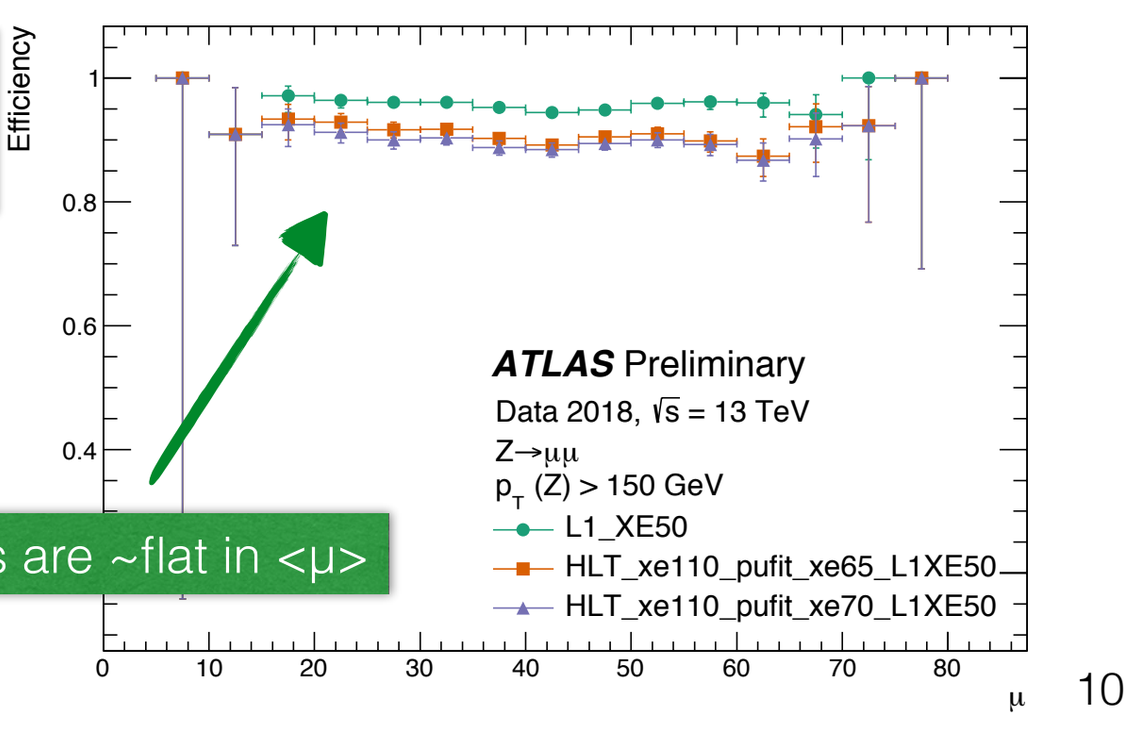
1. **Categorisation** of calorimeter towers as soft/hard using tower E_T.
2. **Fit** of estimated soft pileup contributions (total MET = 0 for pileup).
3. **Calculation** of final MET after removal of soft pileup contributions.

Drawing taken from here.





MET trigger rates largely reduced after pufit (fewer fake MET events)!



Efficiencies are ~flat in <μ>

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MET towards HL-LHC

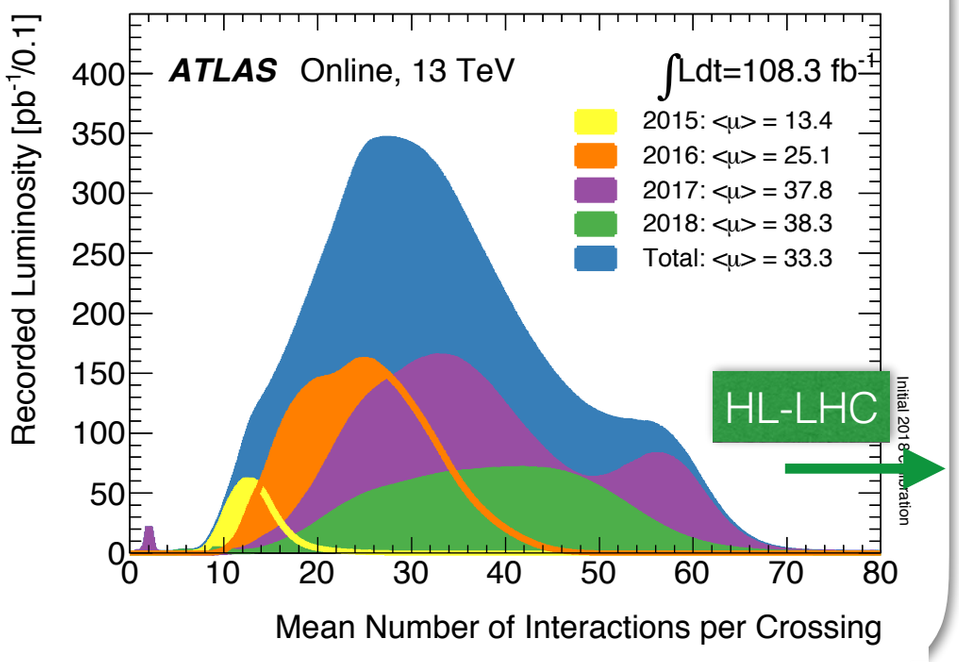
Pileup conditions at the HL-LHC

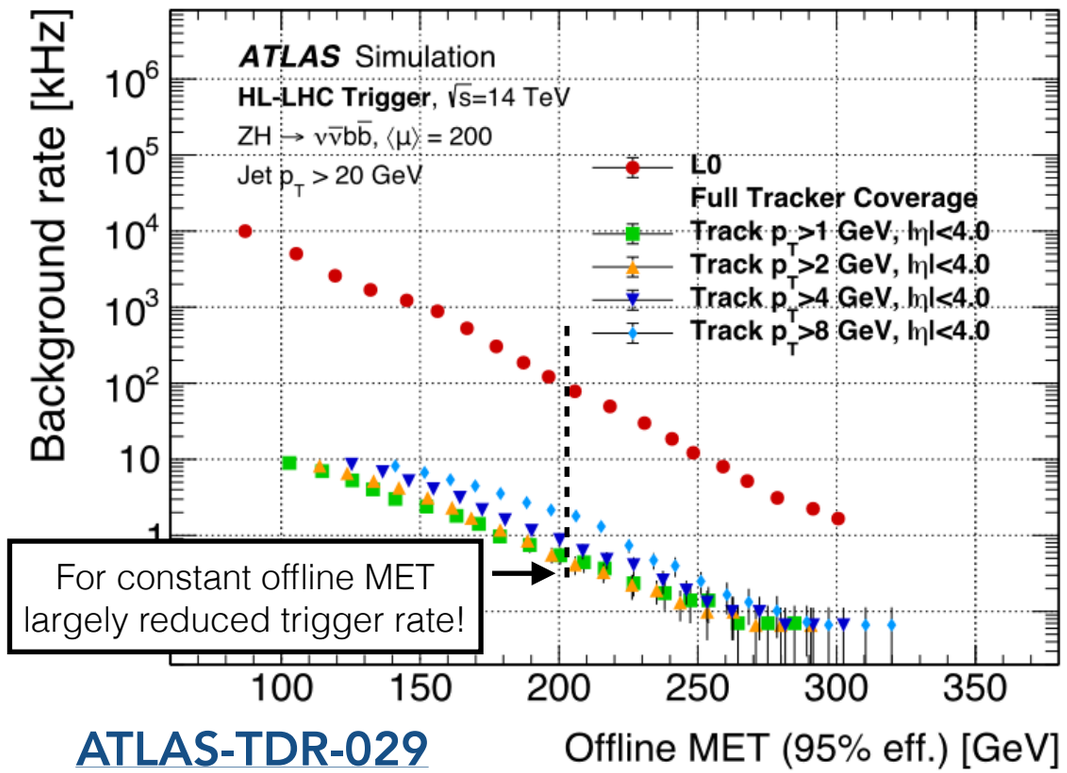
Today, the average number of interactions per bunch crossing is <μ> ≅ 40. **For the HL-LHC program, the <μ> value is estimated to be around 200.**

~5 times more pileup compared to now!

Reconstruction of MET (online and offline) will become more challenging at the HL-LHC.

ATLAS-PUBLIC-Lumi





ATLAS-TDR-029

E.g. Tracking impact on MET triggers

- The upgrades to the ATLAS TDAQ system for the HL-LHC will provide **tracks for MET trigger chains**.
- Offline pileup mitigation techniques can be applied also online.
- Lowest track p_T and larger η acceptance provides the best MET trigger performance.

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Summary

1. The **large pileup conditions of the LHC represent today a major challenge for the ATLAS detector**.
2. A precise and **robust MET reconstruction (offline and online) against pileup will play a fundamental role**, already for analyses using the full Run 2 dataset.
3. **Large improvements to offline MET reconstruction have been recently achieved**, in particular related to forward Jet cleaning, Particle Flow.
4. **Object-based MET significance definition has also been recently developed**, allowing analyses to exploit better signal/background separation.
5. **Pileup suppression will play a fundamental role for offline and online MET in Run 3 and beyond (HL-LHC)**.

Backup

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MET reconstruction

Missing Transverse MomEntum (MET) reconstruction

Negative vectorial sum of well identified physics object (hard term) plus a soft term :

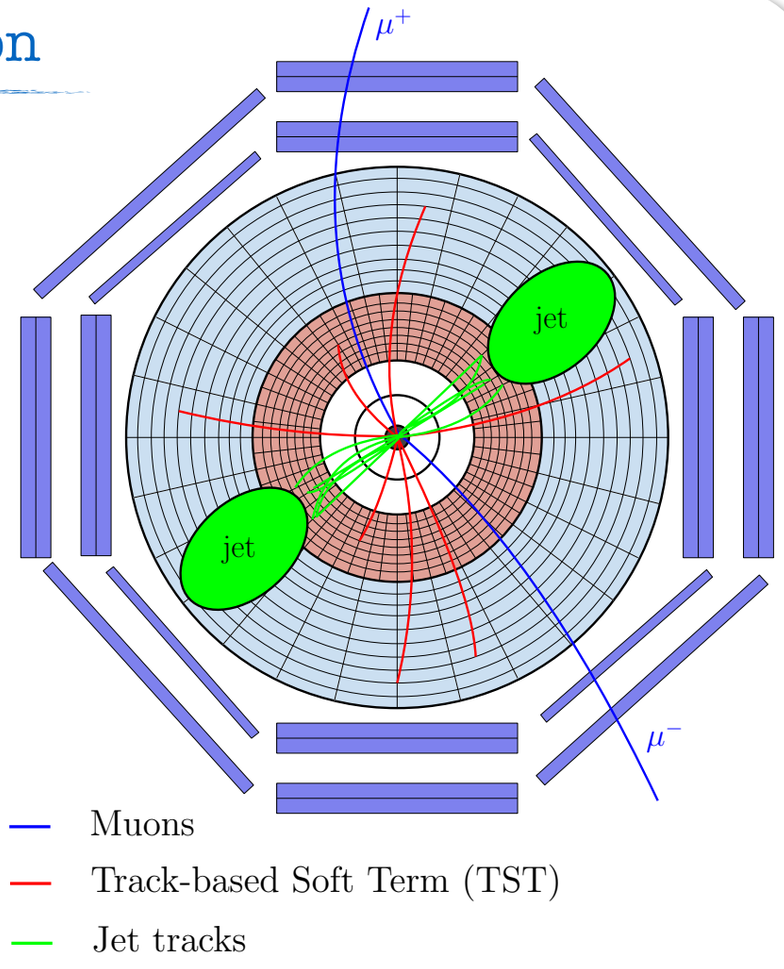
$$\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}} = -\left(\sum_{i \in \mathrm{muons}} \boldsymbol{p}_{\mathrm{T},i} + \sum_{i \in \mathrm{electrons}} \boldsymbol{p}_{\mathrm{T},i} + \sum_{i \in \mathrm{photons}} \boldsymbol{p}_{\mathrm{T},i} + \sum_{i \in \mathrm{hadronic}\ \tau} \boldsymbol{p}_{\mathrm{T},i} + \sum_{i \in \mathrm{jets}} \boldsymbol{p}_{\mathrm{T},i} + \sum_{i \in \mathrm{Soft\ Term}} \boldsymbol{p}_{\mathrm{T},i} \right)$$

hard term — soft term

Object selection:

- **Electrons, Muons, Taus, Photons:** analysis dependent.
- **Jets:** anti-kt topoclusters (R=0.4), pT > 20 GeV, pile-up suppression + EM+JES calibration.
- **Track-based soft term (TST):** tracks unassociated to any well-identified physics object with pT> 500 MeV, $|\eta| < 2.4$ (ATLAS tracker acceptance), $|d_0| < 2$ mm, $|z_0 \sin\theta| < 3$ mm.

TST advantages	TST disadvantages
Small pileup dependence (PV association)	Missing soft neutral particles.



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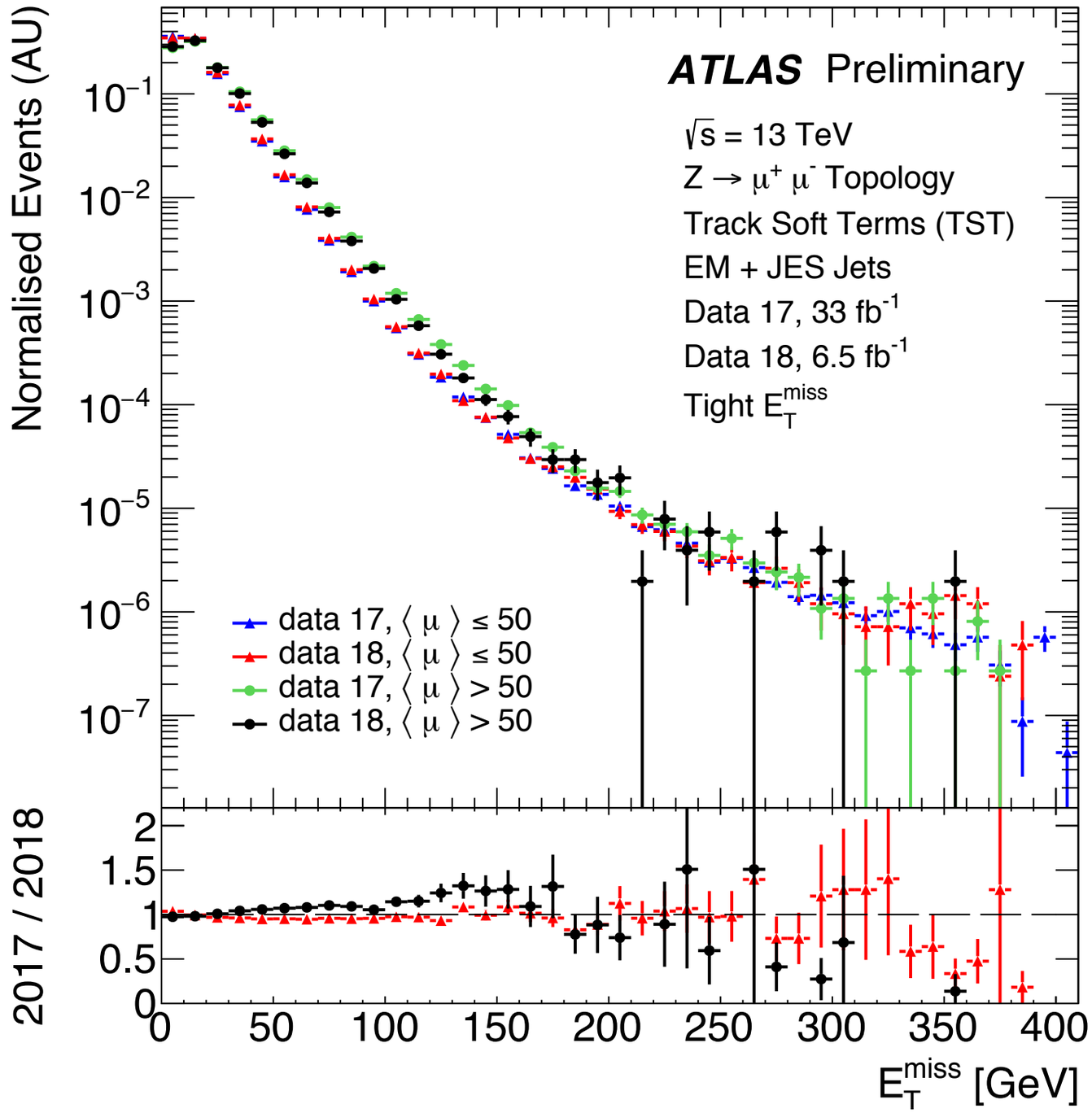
MET pileup dependency



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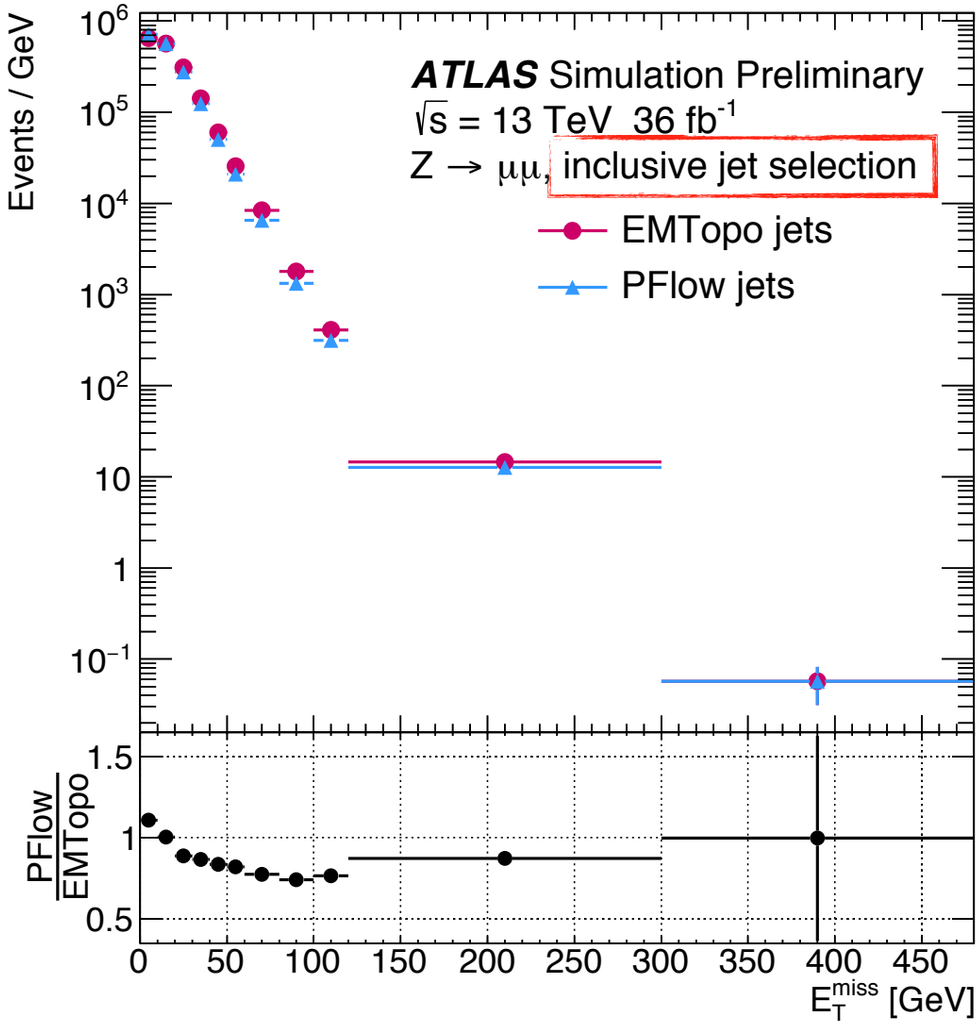
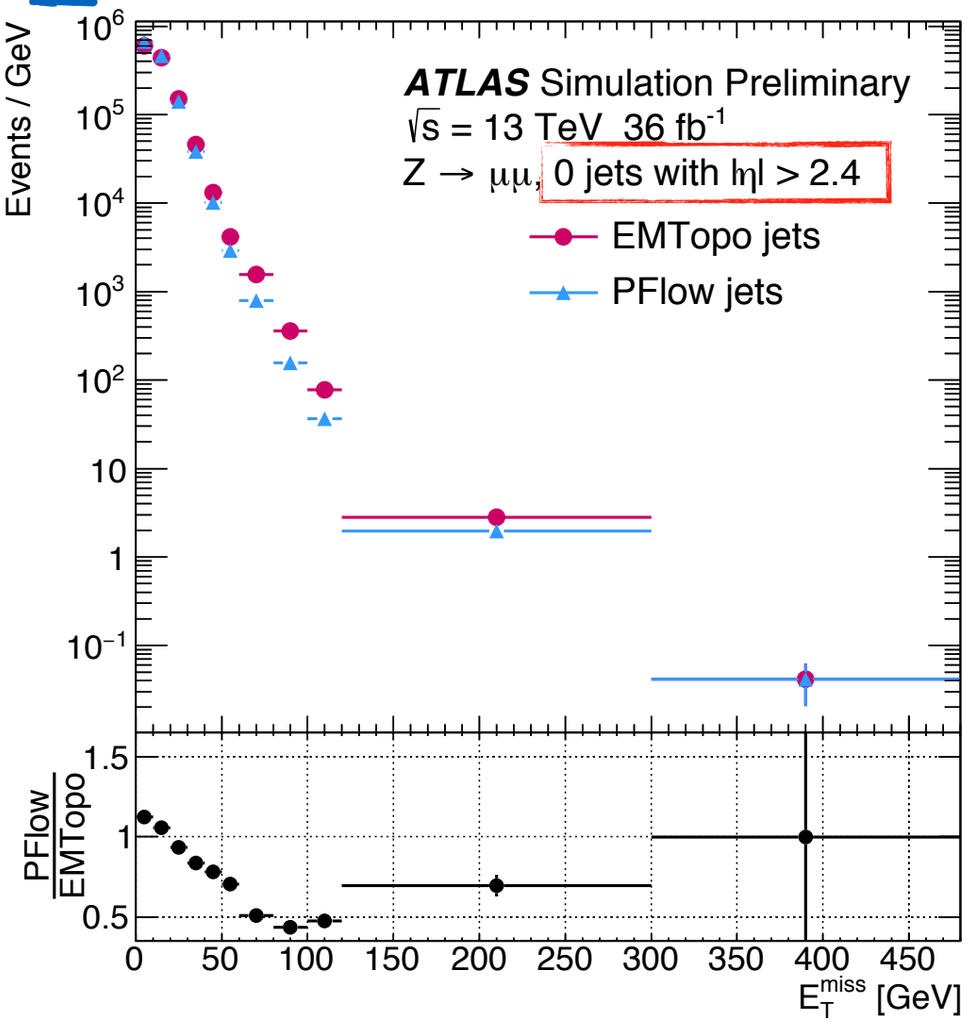
Particle Flow MET

Particle Flow vs topocluster reconstruction

Most of PFlow effects observed in the central part of the detector.

ATLAS-CONF-2018-023





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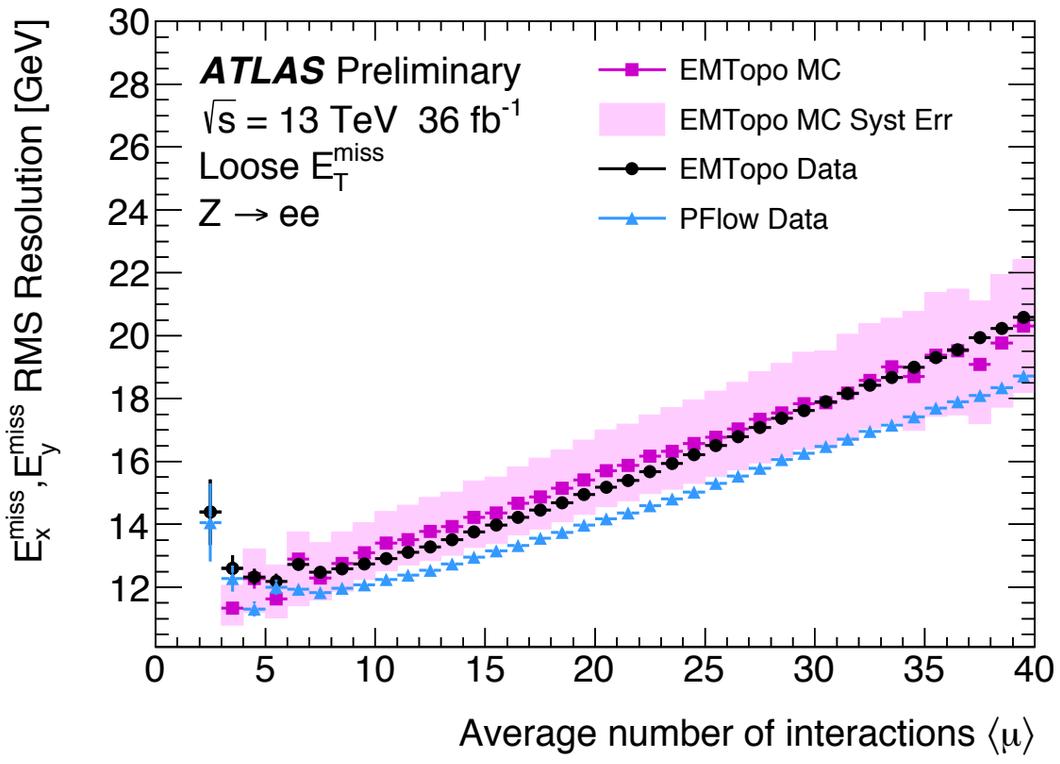
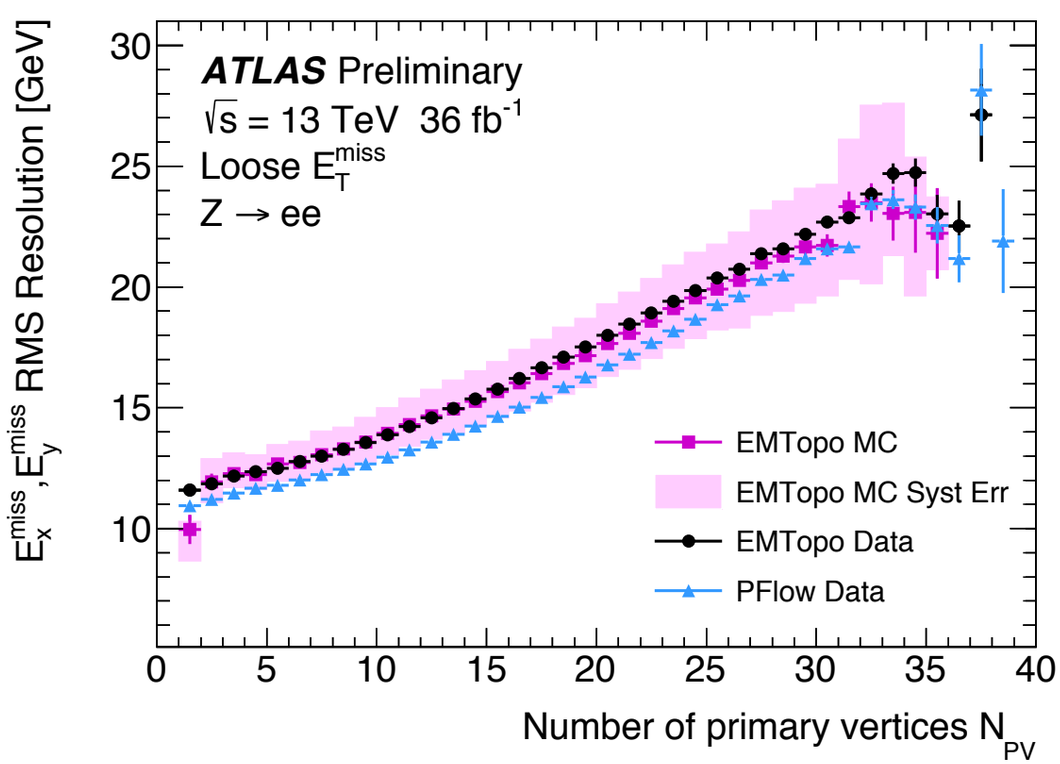
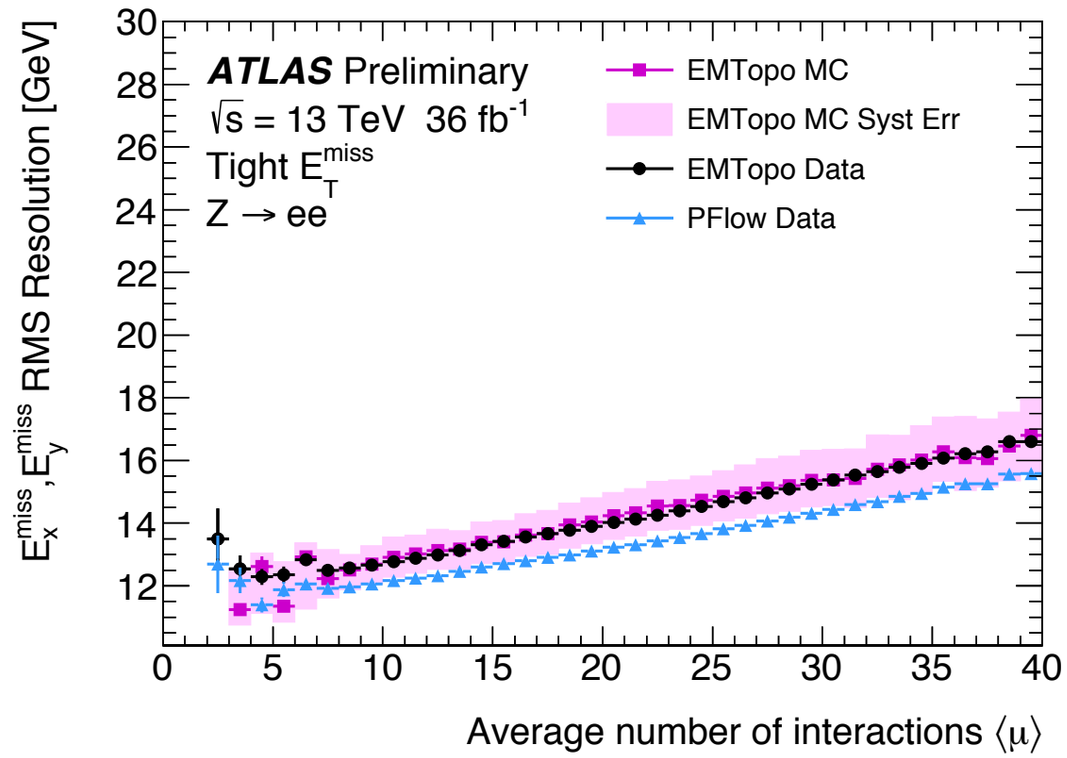
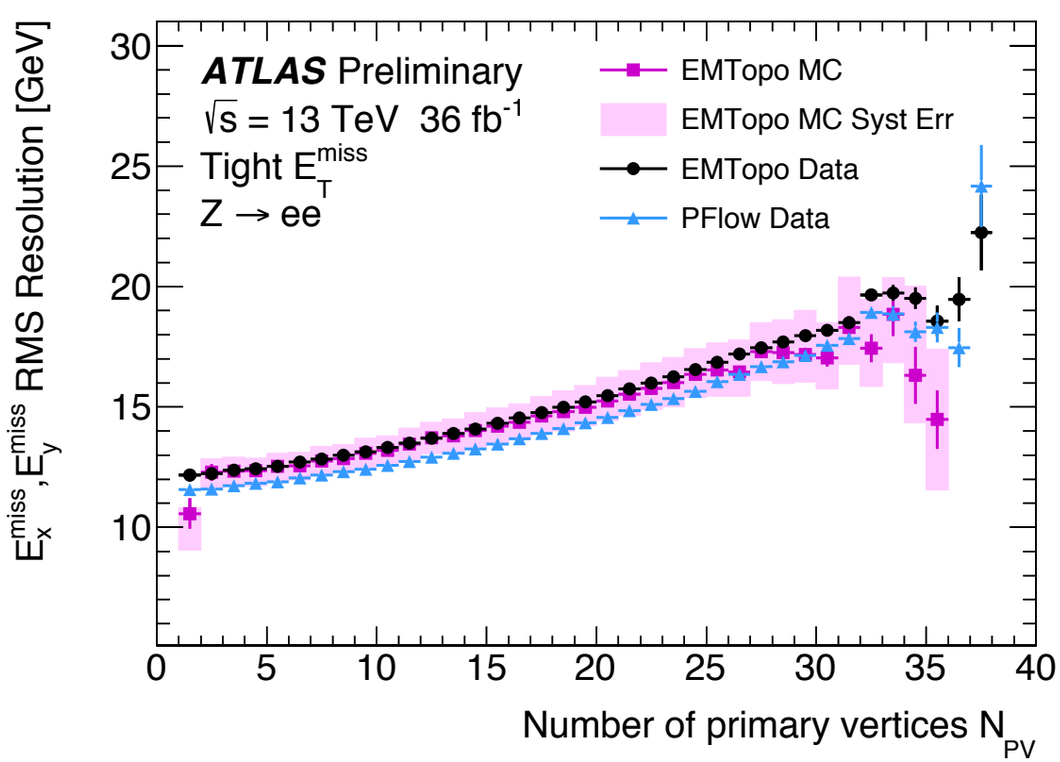
Particle Flow MET

Resolutions for Tight and Loose Working Points









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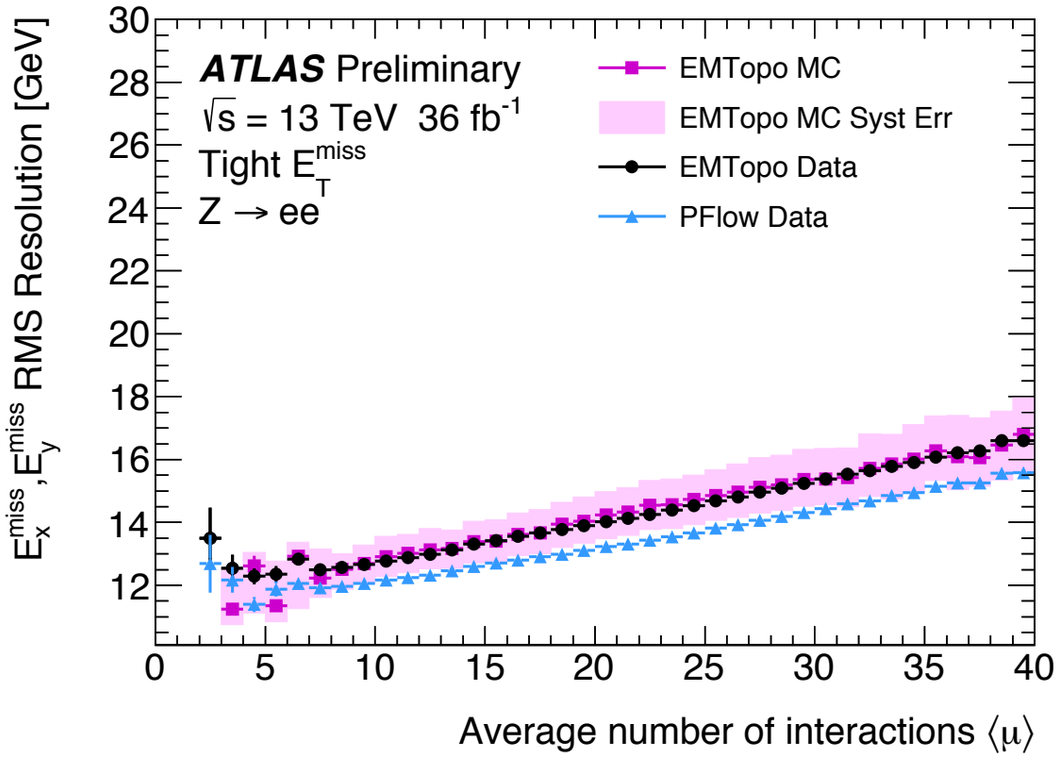
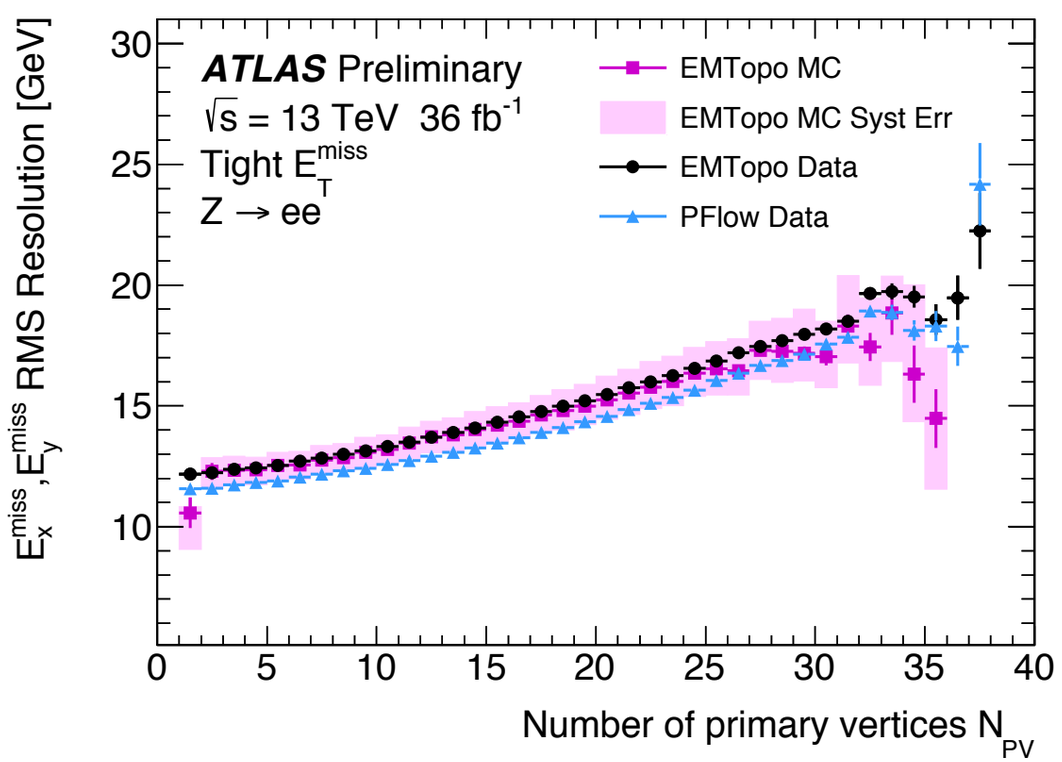
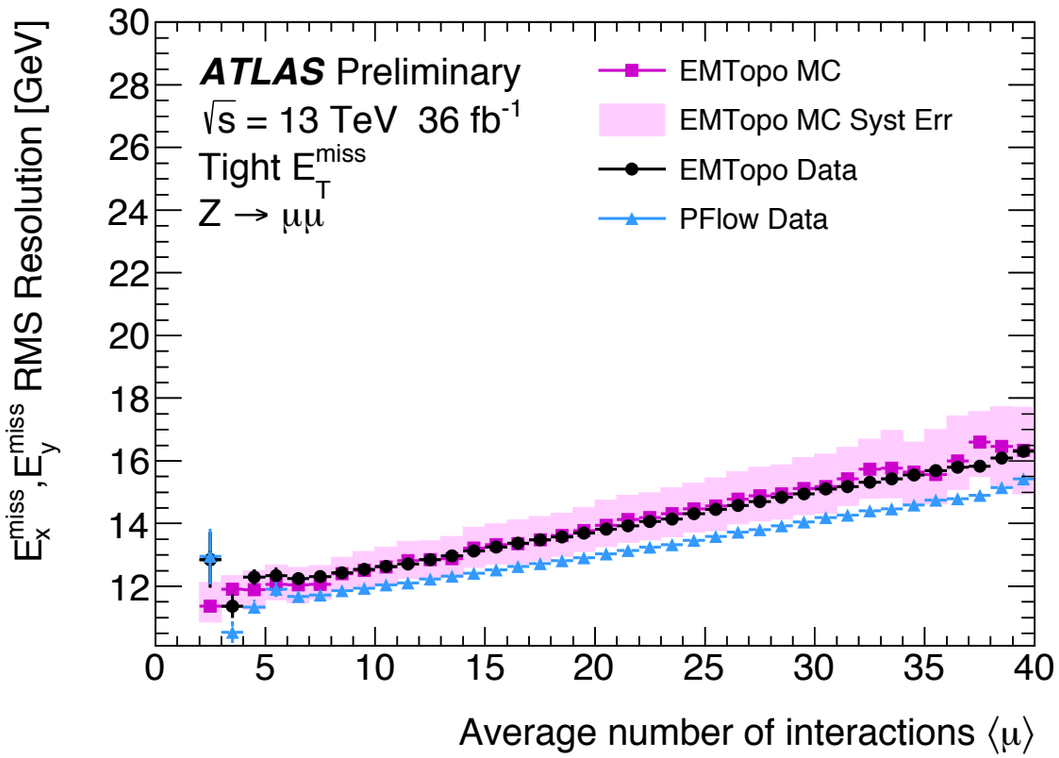
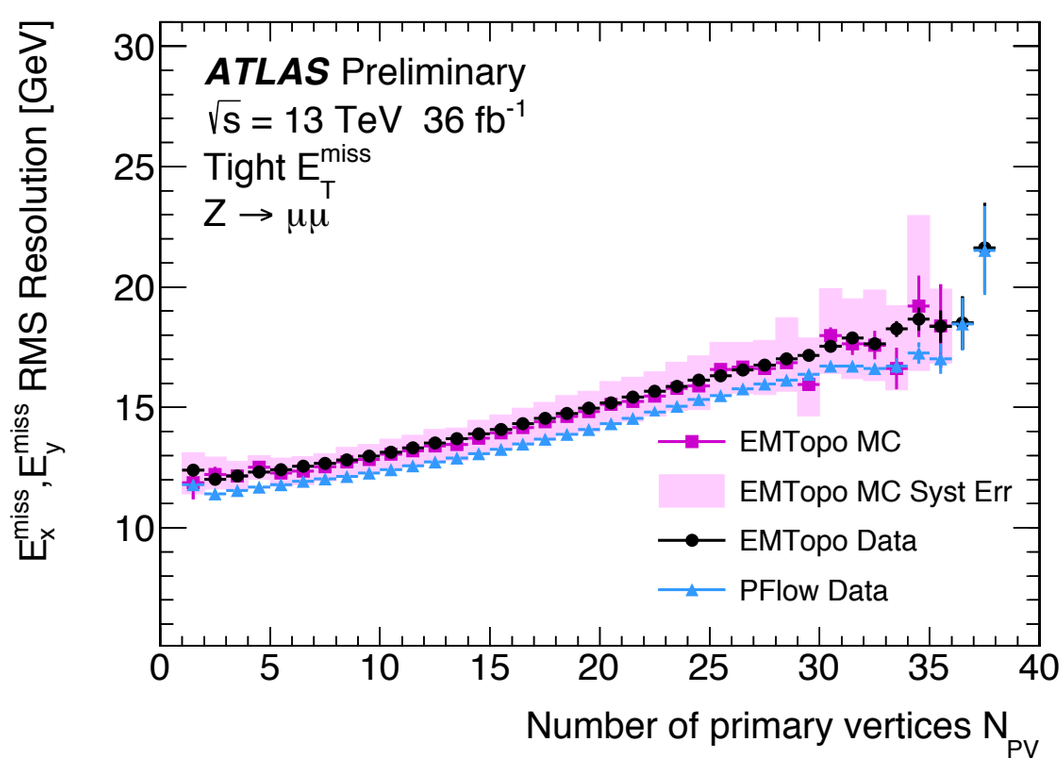
Particle Flow MET

Resolutions for Z→ee and Z→μμ









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Recent developments (5)

Object-based MET significance

ATLAS-CONF-2018-038

MET significance definition

MET significance = is the measured MET compatible with the 0 MET hypothesis when we consider object resolutions?

In general, the **squared MET significance** can be defined as:

$$\mathcal{S}^2 = \frac{\left|\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}{\sigma_{\mathrm{L}}^2\left(1-\rho_{\mathrm{LT}}^2\right)}.$$

σ_L^2 = total longitudinal variance of E_T^{miss}

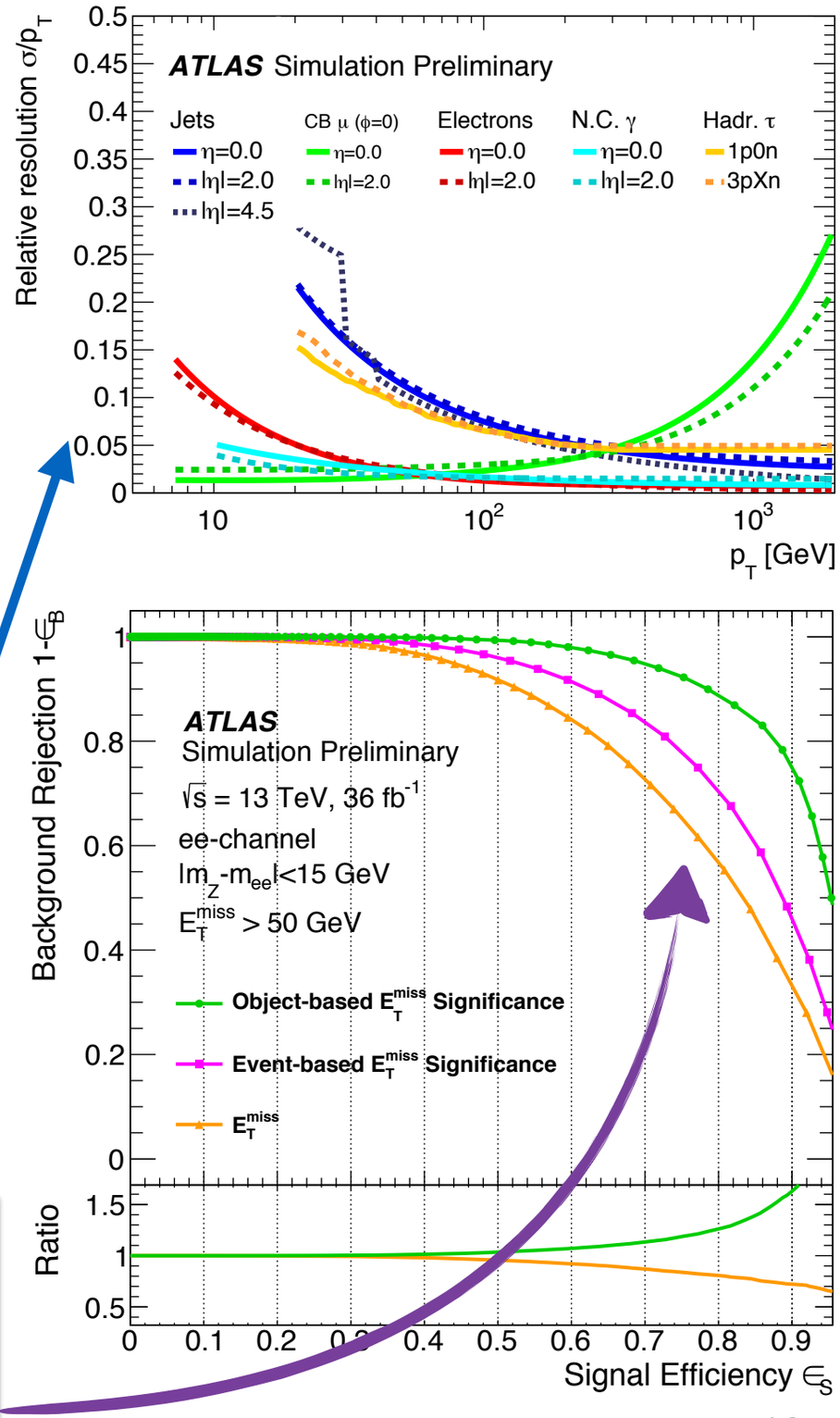
ρ_{LT} = longitudinal and transverse E_T^{miss} correlation

$$\mathcal{S} = \frac{E_T^{\mathrm{miss}}}{\sqrt{\sum E_T}}$$

Event-based MET significance
used by many ATLAS analyses

Event-based MET significance is just an approximation **made assuming** $\sigma_L^2 \propto \sum E_T$ and $\rho_{LT}^2 \approx 0$.

This approximation is not always good and a MET significance estimation based on single object resolution might be better!



The object based MET significance provides better separation for events with true and fake MET (Z→ee$\nu\nu$ and Z→ee).

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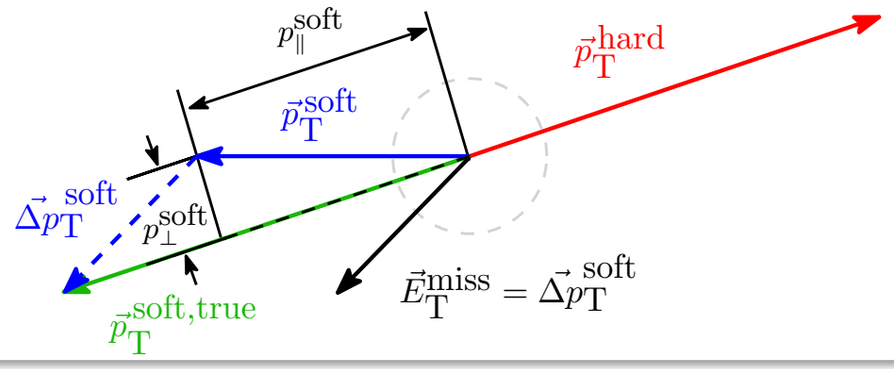
Systematic uncertainties

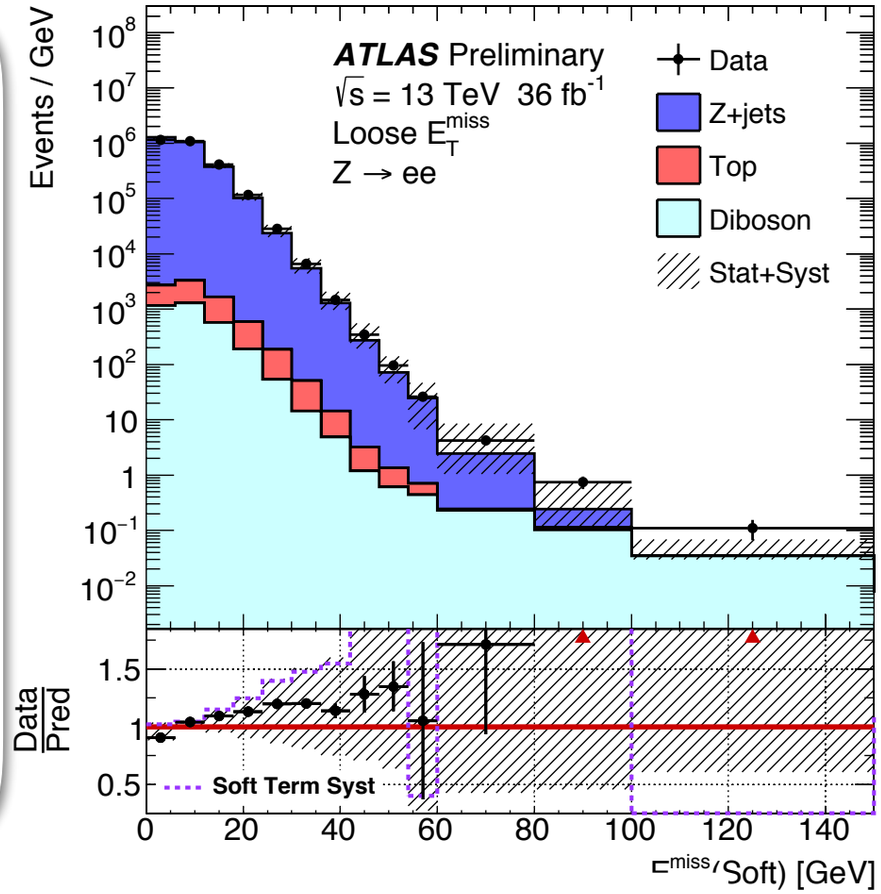
ATLAS-CONF-2018-023

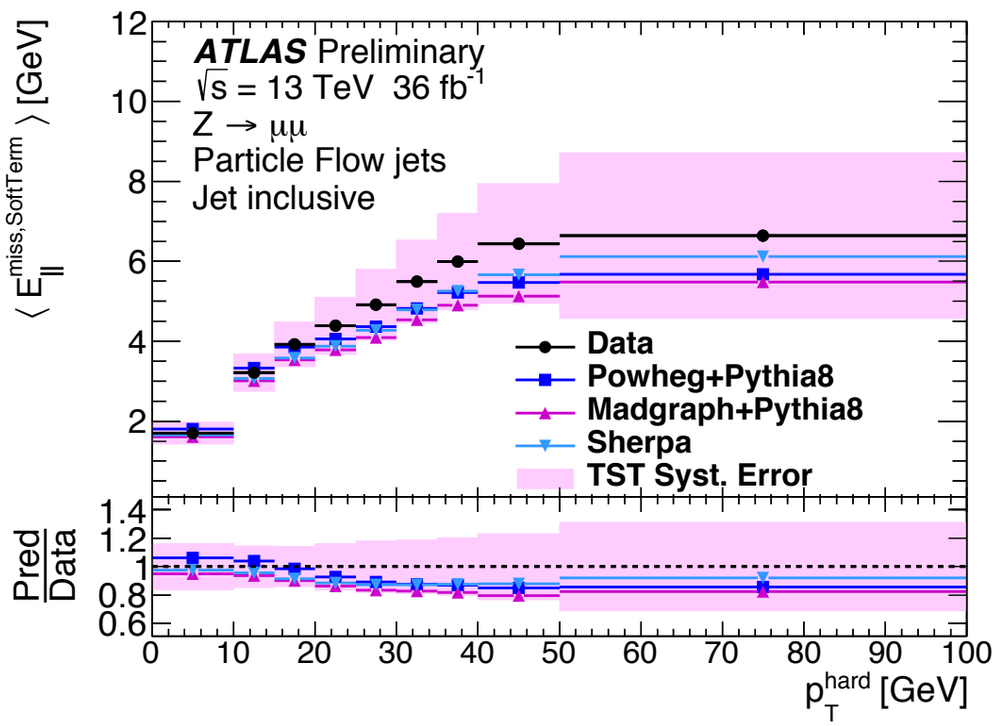
TST systematic uncertainties

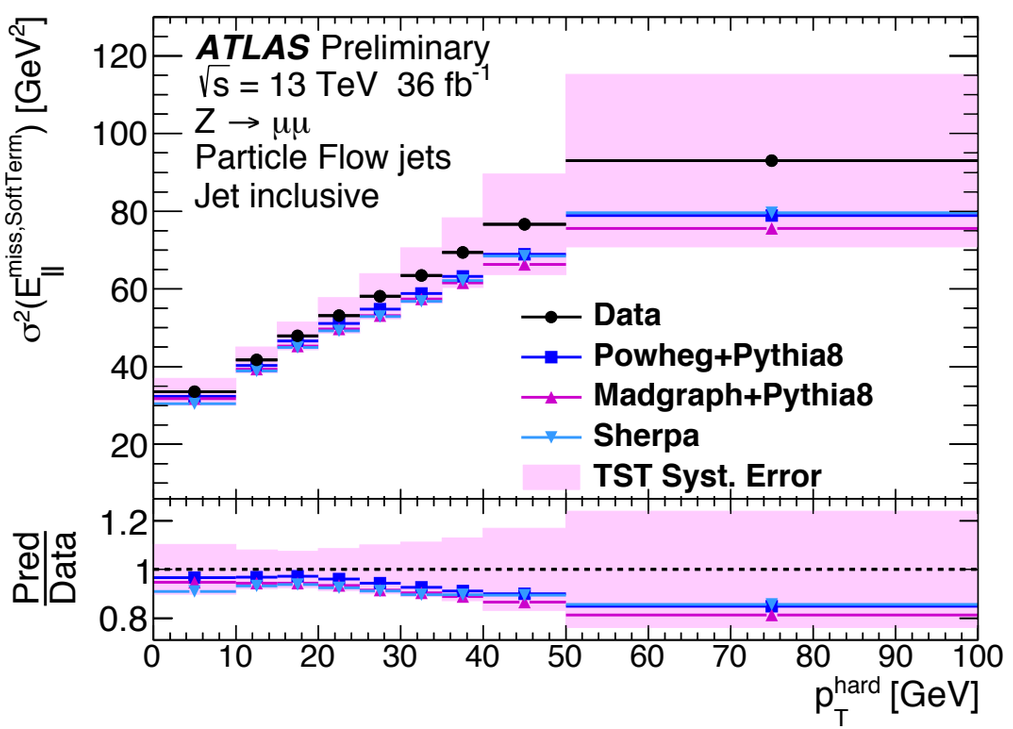
The systematics uncertainties specifically derived for MET are the **TST systematics**. These are evaluated by computing the maximal data/MC discrepancies of three projected quantities:

- Parallel scale: average value of p_T^{soft} projection parallel to p_T^{hard}.
- Parallel resolution: RMS value of p_T^{soft} projection parallel to p_T^{hard}.
- Perpendicular resolution: RMS value of p_T^{soft} projection perpendicular to p_T^{hard}.









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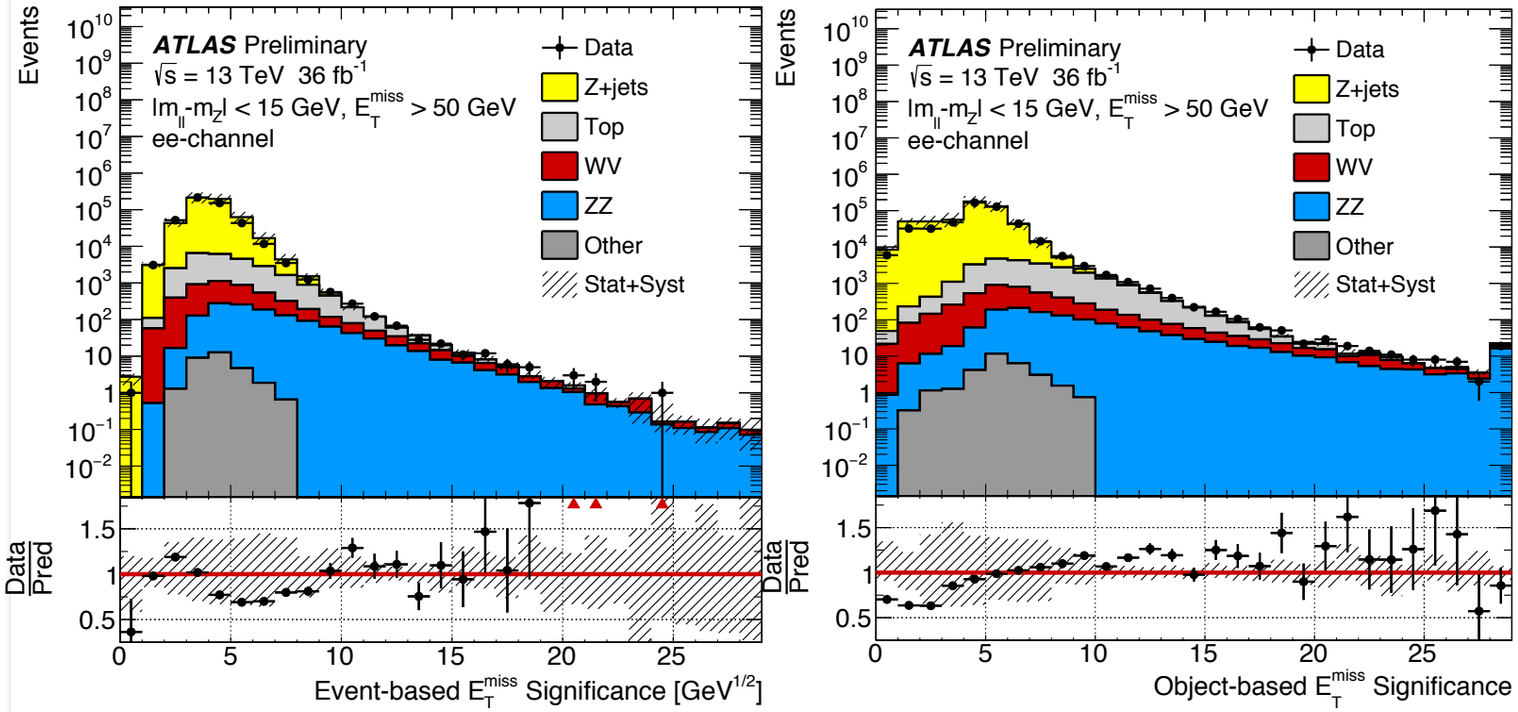
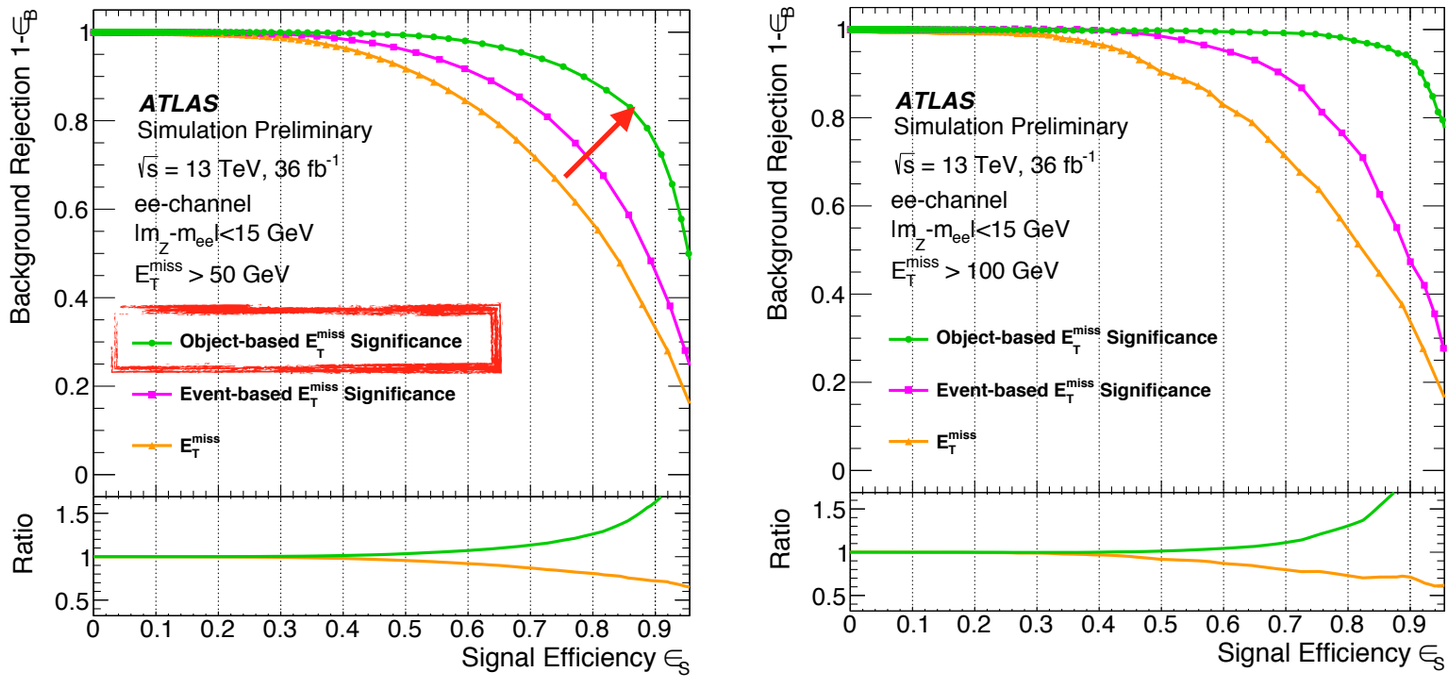
Recent developments

Object-based MET significance

ATLAS object-based MET significance





Fake MET events (Z→ee) has better separation from the ones with True MET.

ROC curves made using Z→ee and Z→ee$\nu\nu$ as background and signal samples show clearly that **the object based MET significance provides better separation for events with true and fake MET**.

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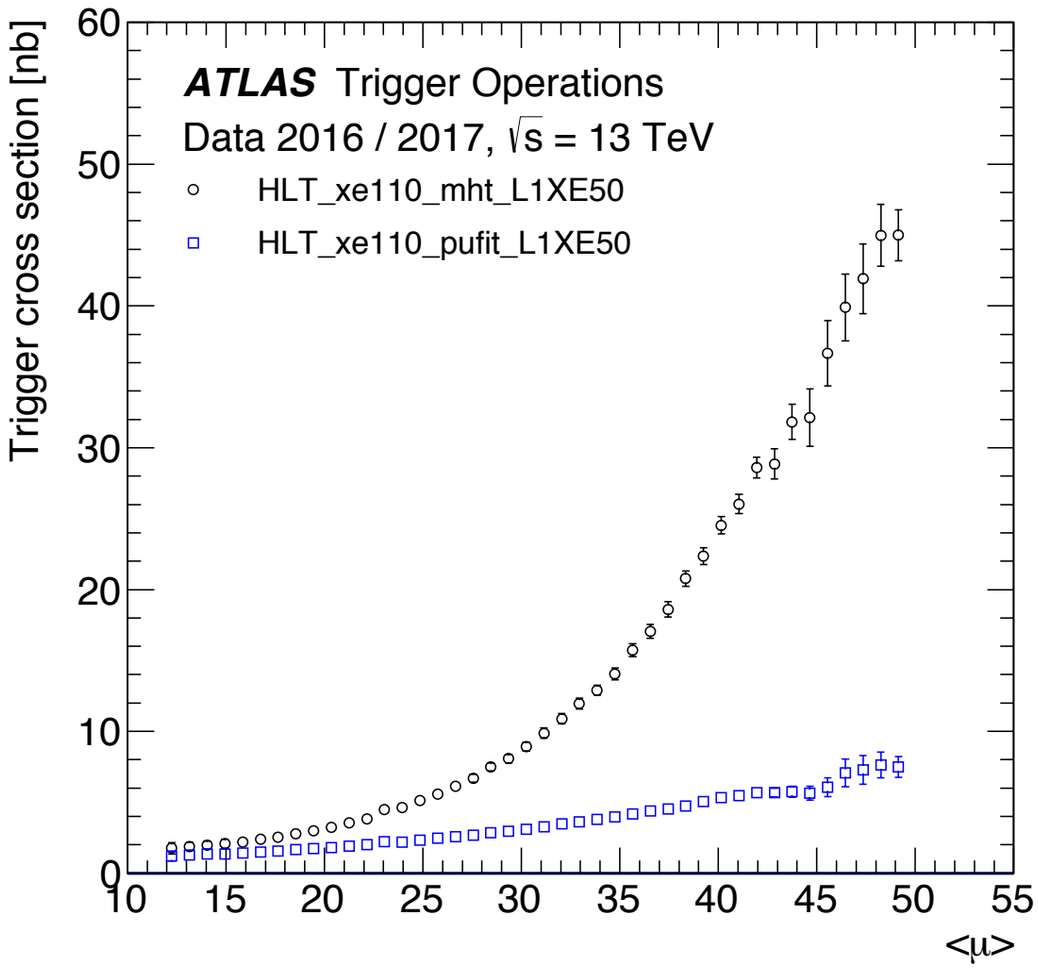
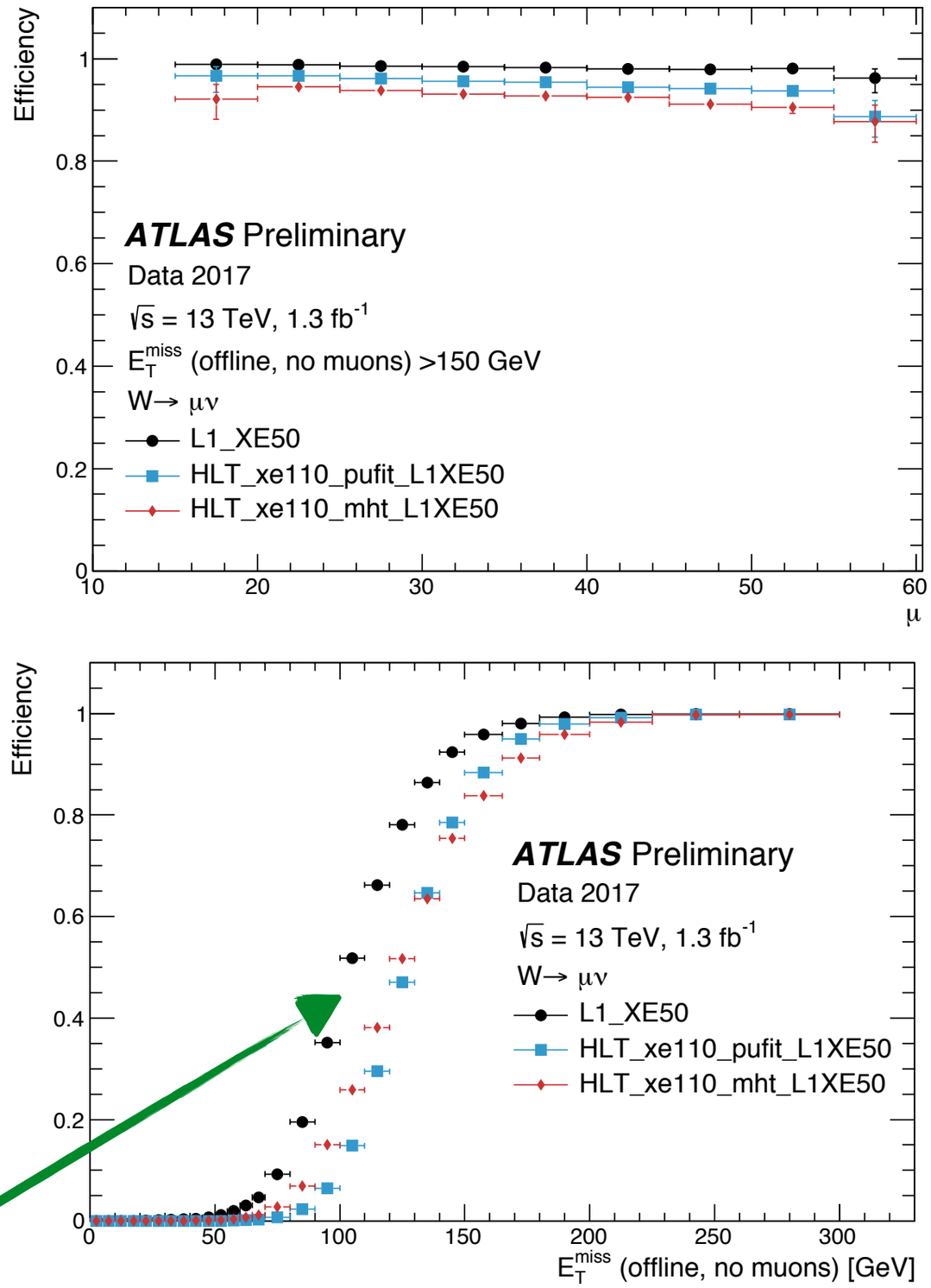
MET triggers

Pufit rate and efficiencies

[ATLAS-MissingEtTriggerPublicResults]





Efficiency improved with pufit

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MET triggers at HL-LHC