Pile-up Suppression in Missing Transverse Momentum Reconstruction in ATLAS

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(All results from ATLAS-CONF-2014-019)

Mitigation of pileup effects at the LHC

Contributions

Hard objects – $E_{\mathrm{T}}^{\mathrm{miss,HardTerm}}$

Identified and fully calibrated particles like leptons and photons

Fully calibrated Anti-k_{T} $R = 0.4$ jets – including pile-up corrections

Soft signals – $E_{\mathrm{T}}^{\mathrm{miss,SoftTerm}}$

TopoCluster and tracks not used in hard object reconstruction

Composition

Reconstruction sequence

Reflects reconstruction quality – default: (1) electrons, (2) photons, (3) taus, (4) jets, (5) muons, (6) soft signals

Object filters

Kinematics (p_T thesholds and η selections)

Reconstruction quality

Event signal ambiguity resolution

Based on accepted objects from reconstruction sequence

Vetoes use of lower priority distribution if signal is shared with accepted object – object based, no geometrical assumptions

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MET in ATLAS (reconstructed in $|\eta| < 4.9$)

Missing transverse momentum components

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss,HardTerm}} + E_{x(y)}^{\text{miss,SoftTerm}} = -\sum_{\text{hard objects}} p_{x(y)} - \sum_{\text{soft signals}} p_{x(y)} \,,$$

$$\mathbf{E}_{\mathrm{T}}^{\text{miss}} = \left(E_x^{\text{miss}}, E_y^{\text{miss}}\right) \,,$$

Missing transverse momentum vector

$$E_{\mathrm{T}}^{\text{miss}} = \left|\mathbf{E}_{\mathrm{T}}^{\text{miss}}\right| = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \,,$$

Missing transverse momentum (MET)

$$\Sigma E_{\mathrm{T}} = \Sigma E_{\mathrm{T}}^{\text{HardTerm}} + \Sigma E_{\mathrm{T}}^{\text{SoftTerm}} = \sum_{\text{hard objects}} p_{\mathrm{T}} + \sum_{\text{soft signals}} p_{\mathrm{T}} \,.$$

Scalar transverse momentum sum (SumET)

Effect of Pile-up on MET and SumET

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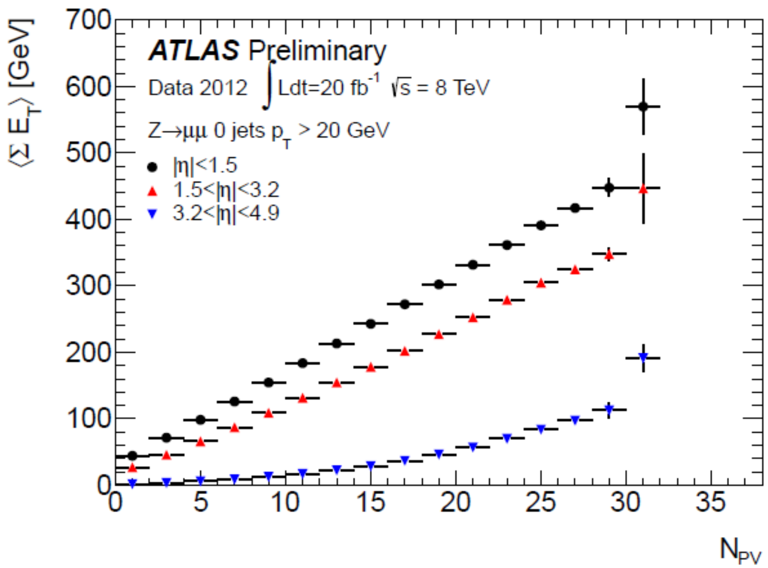
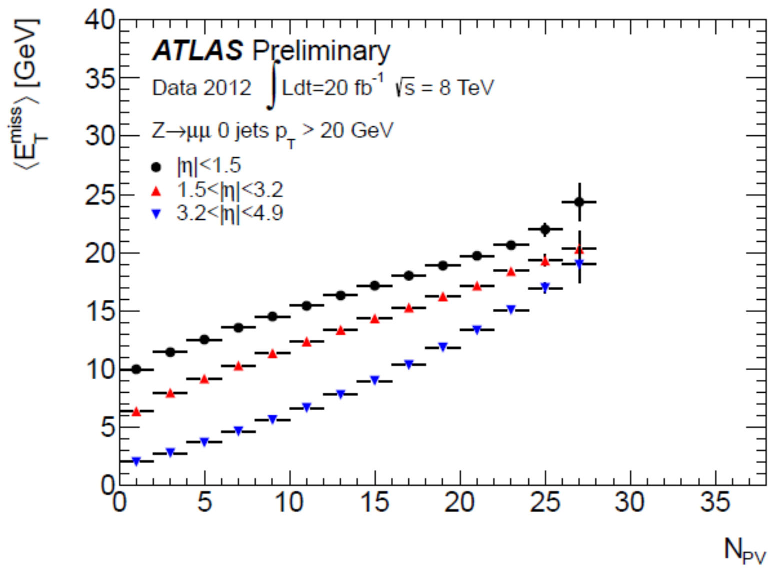
Calorimeter region dependence

- Different signal shapes in the LAr calorimeters
  - Different out-of-time/in-time pile-up cancellations due to sensitivity to bunch spacing (50 ns in 2012 not ideal, 25 ns better)
- Different acceptances
  - Dead materials, signal formation, cluster corrections, …





$Z \to \mu\mu$, no jets with $p_T > 20$ GeV ⇒ only muon and soft term contributions to MET

MET pile-up corrections

- Hard term contributions are expected to be corrected for pile-up
  - Only jet contribution to MET is filtered by JVF cut (JVF > 0 for jets $|\eta| < 2.4$ – at least weak association with hard-scatter vertex for central jets)
- SoftTerm is not corrected a priori
  - Observables with large dependence on final state reconstruction selections – inhomogeneous signal with contributions from e.g. jetty structures below threshold, single soft particles, residual pile-up fluctuations…
  - No universal calibration reference (“truth”) available a priori – needs pile-up corrections
- Challenges for SoftTerm pile-up corrections
  - Transverse momentum flow pattern from UE belonging to hard scatter very similar to pile-up induced signal structures
  - Pile-up can “hide” even relatively significant local hadronic activity like the hadronic recoil in *Z* or *W* production

MET Pile-up Corrections (2)

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Track-based corrections

Soft Term Vertex Fraction

Use ratio of summed p_T from SoftTerm tracks coming from the hard scatter vertex V_{HS} to the p_T sum of all tracks contributing to the SoftTerm (one factor per event)

Applied to SoftTerm signals everywhere – underlying idea is that central PU activity has some correlation with forward activity

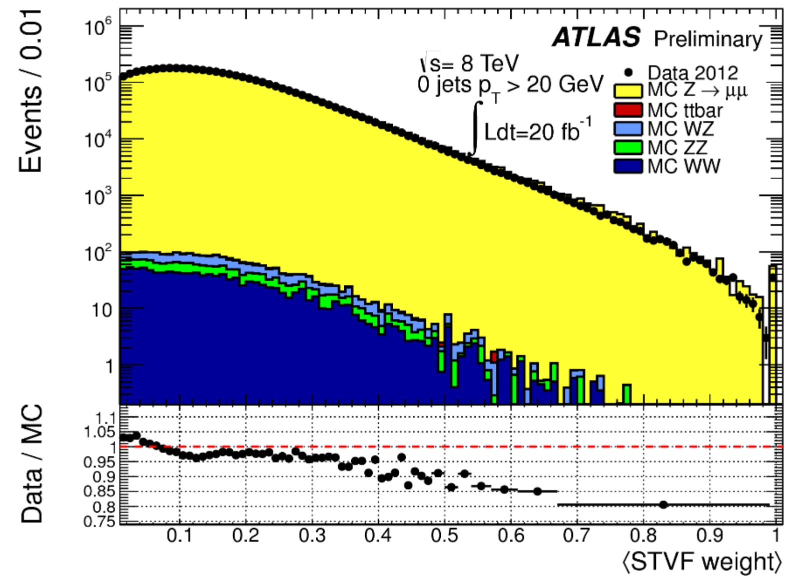
Sensitive to (hard scatter and pile-up) vertex reconstruction efficiency

$$\text{STVF} = \frac{\sum_{i=1}^{N_{\rm trk}(V_{\rm HS})} p_{{\rm T},i}^{\rm trk}(V_{\rm HS})}{\sum_{k=1}^{N_{\rm PV}} \sum_{i=1}^{N_{\rm trk}(V_k)} p_{{\rm T},i}^{\rm trk}(V_k)}$$

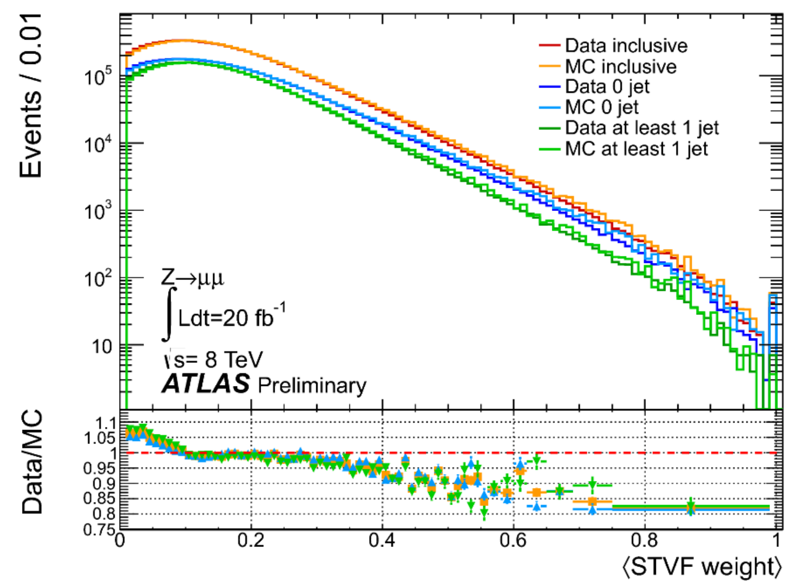
$$E_{x(y),{\rm corr}}^{\rm miss,SoftTerm} = \text{STVF} \cdot E_{x(y)}^{\rm miss,SoftTerm}$$

$$E_{\rm T,corr}^{\rm miss,SoftTerm} = \text{STVF} \cdot E_{\rm T}^{\rm miss,SoftTerm}$$

$$\Sigma E_{\rm T,corr}^{\rm SoftTerm} = \text{STVF} \cdot \Sigma E_{\rm T}^{\rm SoftTerm}$$



more ← pile-up → less



MET Pile-up Corrections (3)

Jet-area-based suppression

Strategy

- Use correction similar to (hard) jet ($p_{\mathrm{T}} > 20$ GeV)
- Requires signals with catchment area – cluster SoftTerm signals into jets with $p_{\mathrm{T}} \geq 0$ (*filter-jets*)
- Calculate ρ from SoftTerm signals only and filter jets

$$p_{\mathrm{T},i}^{\mathrm{jet}} = \begin{cases} 0 & p_{\mathrm{T},i}^{\text{filter-jet}} < \rho_{\mathrm{evt}}^{\mathrm{med}}(\eta_i^{\text{filter-jet}}) \cdot A_i^{\text{filter-jet}} \\ p_{\mathrm{T},i}^{\text{filter-jet}} - \rho_{\mathrm{evt}}^{\mathrm{med}}(\eta_i^{\text{filter-jet}}) \cdot A_i^{\text{filter-jet}} & p_{\mathrm{T},i}^{\text{filter-jet}} \geq \rho_{\mathrm{evt}}^{\mathrm{med}}(\eta_i^{\text{filter-jet}}) \cdot A_i^{\text{filter-jet}} \end{cases}$$

- Like soft event trimming with sub-jet p_{T}-threshold defined by ρ

ρ calculation (FastJet 2.4.x)

- Cluster SoftTerm into jets with $p_T \geq 0$ (ρ-*jets*) – can be the same as filter-jets (see configurations later)
- Calculate median transverse momentum density from ρ-jets

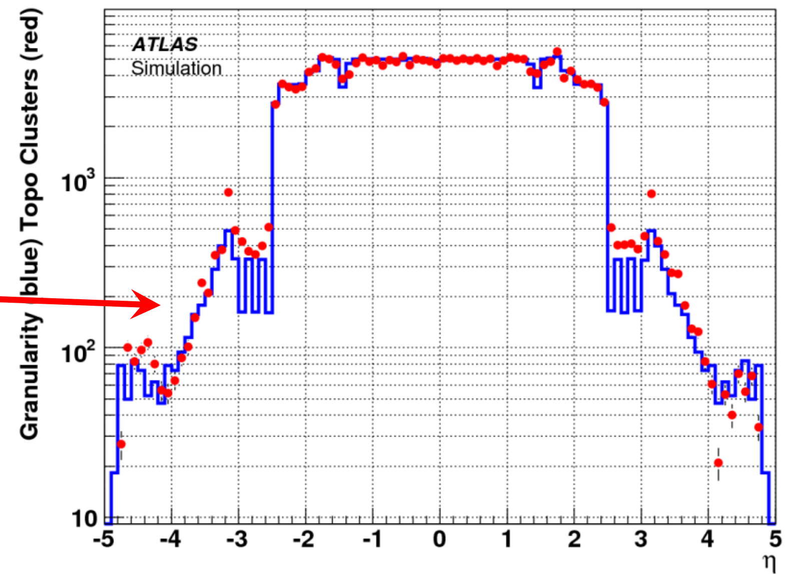
Challenges

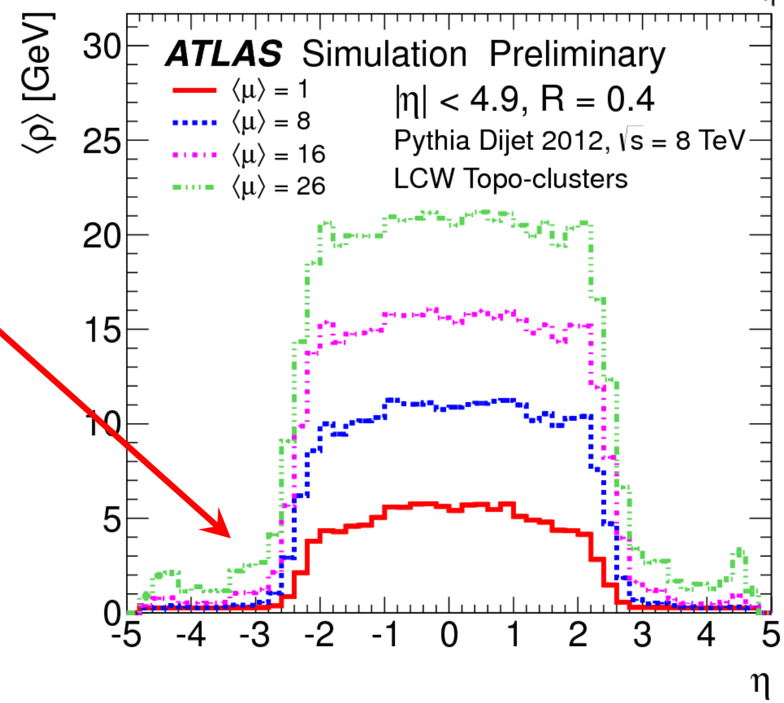
- Need to provide $\rho(\eta)$ for $|\eta| < 4.9$ – forward calorimeter response to soft activity

ρ-measurement with ATLAS Calorimeters

Effect from calorimeter granularity

- TopoCluster density drops sharply when granularity decreases in forward direction
  - Region sparsely populated with TopoClusters = 4-vectors
  - Biases ρ reconstruction towards smaller values – even 0 (median!)
- Drop severely steeper than expected from physics!





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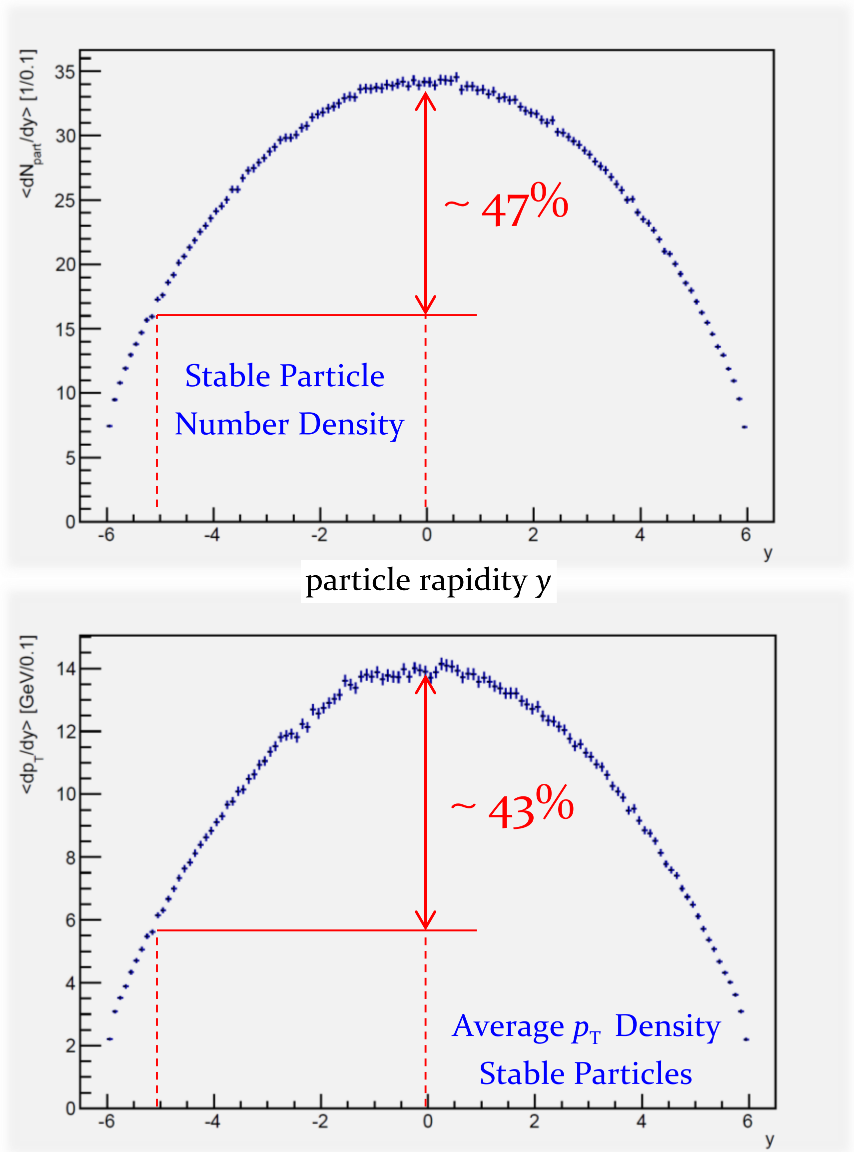

Pythia 8 MB (Tune 4C)
All stable particles
(no p_T cut)
$\langle\mu\rangle = 30, \sqrt{s} = 8$ TeV

Forward region ρ determination

- Determine $\boldsymbol{\rho}$ with $\boldsymbol{\rho}$-jets in central region $|\eta| < 2$...
  - Flat p_{T} density
- ... and extrapolate to forward region $|\eta| > 2$
  - Average relative extrapolation shapes determined with **average** p_{T} collected in sliding η-windows
    - $[\eta - \Delta\eta/2, \eta + \Delta\eta/2]$
    - $\Delta\eta = 1.6,\ \delta\eta = 0.1$
  - in MB events in data
  - Shapes are dependent on the pile-up condition (N_{PV}, μ) - shape functions fully parameterized for all conditions
- Shapes found to be universal in data and MC
  - p_{T} density drop dominated by well simulated detector effects – not "hard to model right" soft physics

ρ-measurement with ATLAS Calorimeters

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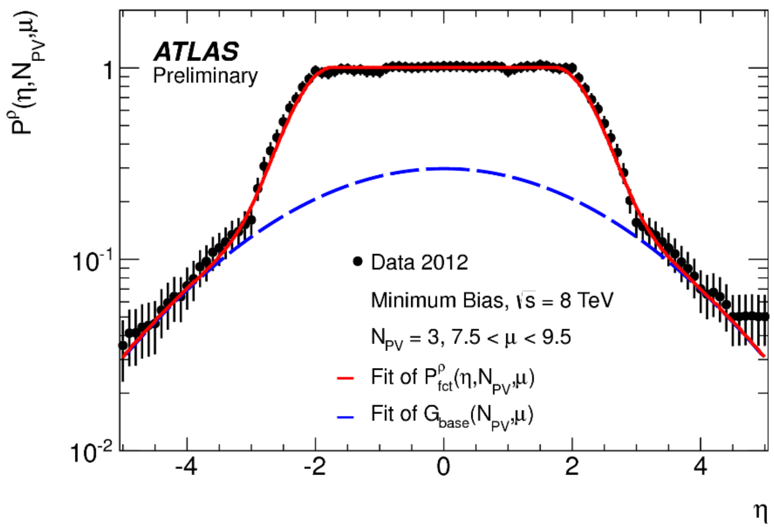
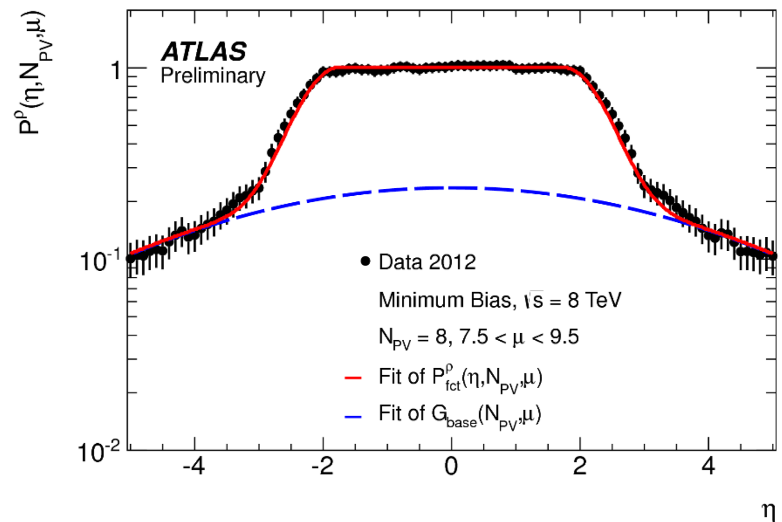
Same μ, different N_{PV}

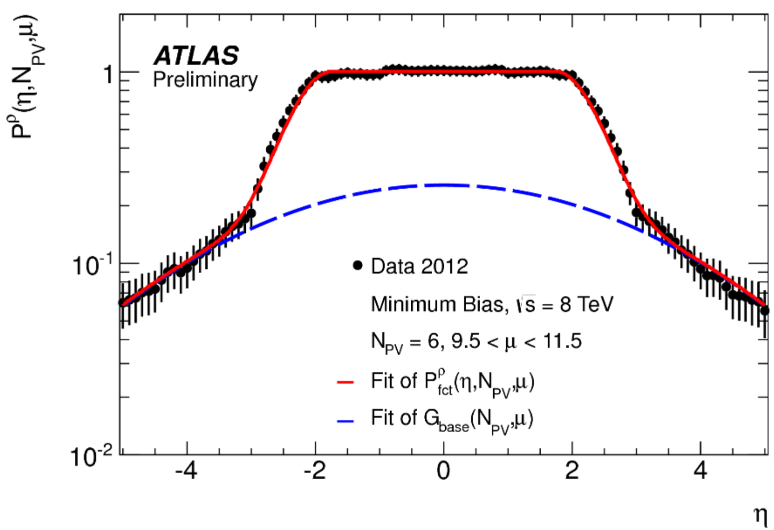
N_{PV} increasing ⟶

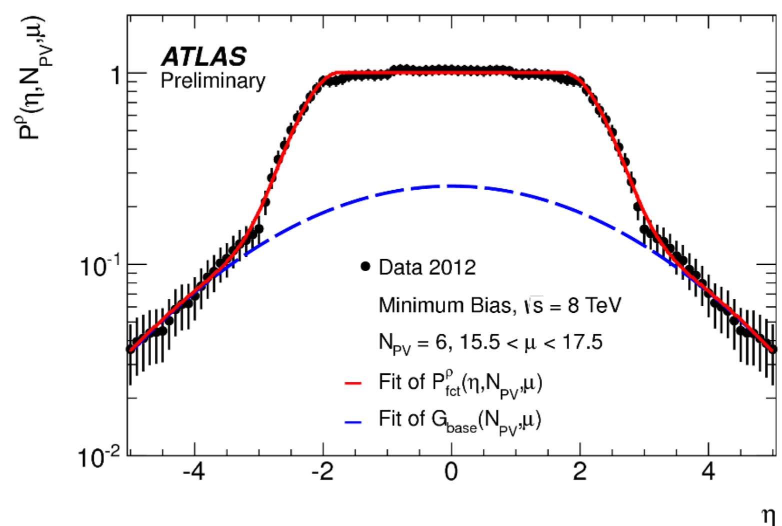




Same N_{PV}, different μ

μ increasing ⟶





Jet-area Based Pile-up Suppression

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Extrapolated Jet Area EJA

- Calorimeter-only jet-area based correction with the same jets for ρ-reconstruction and filtering
- ρ is measured in central region and extrapolated to forward

Extrapolated Jet Area Filter EJAF

- Jet-area based correction with same (larger) jets or ρ-reconstruction and filtering
- ρ is measured in central region and extrapolated to forward
- Selected SoftTerm jets are filtered in addition using tracks

Jet Area Filter JAF

- Jet-area based correction with two different jets for ρ-reconstruction and filtering
- ρ is measured including the forward region – no extrapolation
- Selected SoftTerm jets are filtered in addition using tracks

Name	Jet Algorithm	R	Filters
EJA	ρ-jets: k_T	0.4	
	filter-jets: k_T	0.4	
EJAF	ρ-jets: k_T	0.6	JVF > 0.25
	filter-jets: k_T	0.6	
JAF	ρ-jets: k_T	0.8	JVF > 0.25
	filter-jets: k_T	0.4	

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Final States Without Genuine MET

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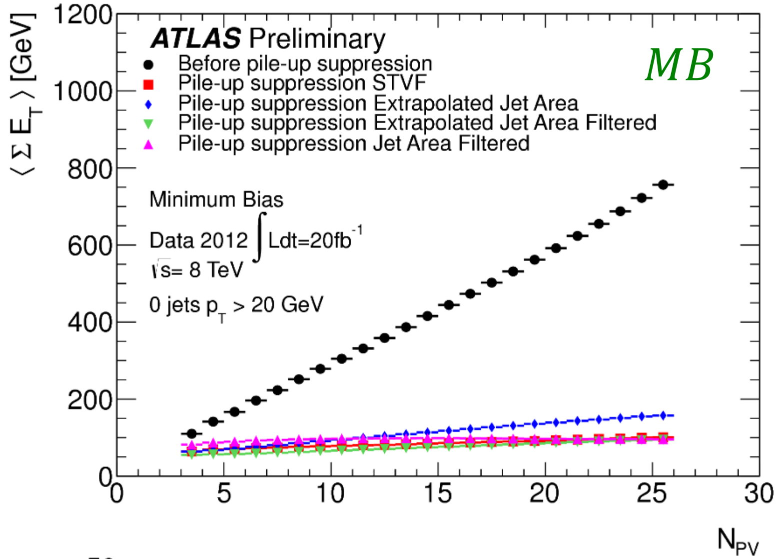
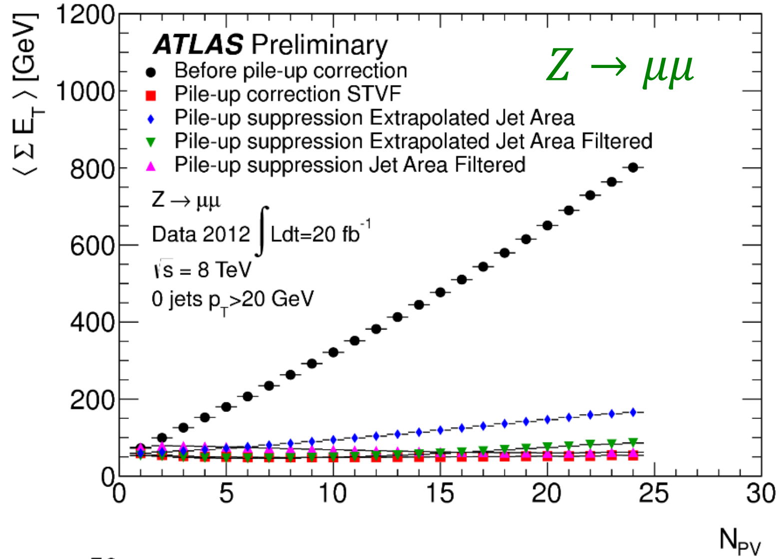
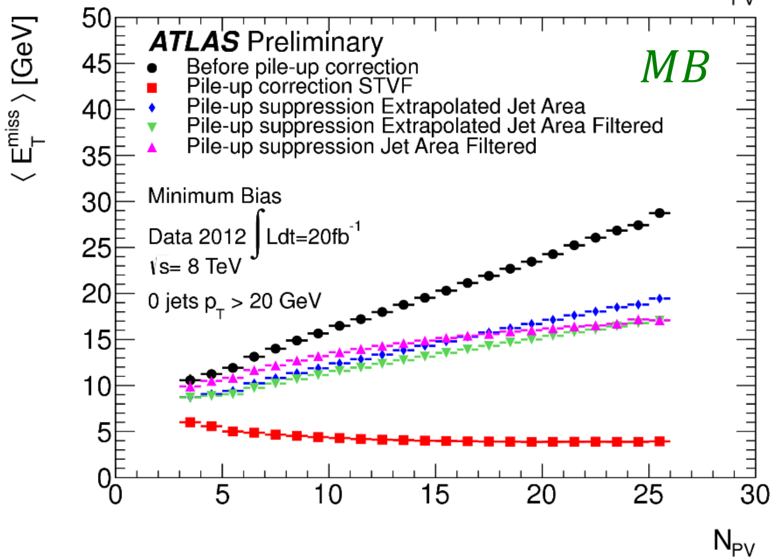
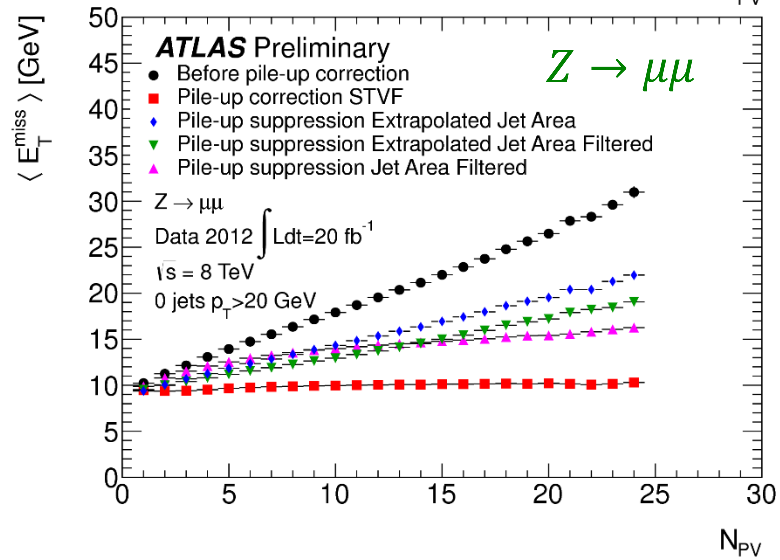
No genuine MET, no jets $p_T > 20$ GeV, versus N_{PV}









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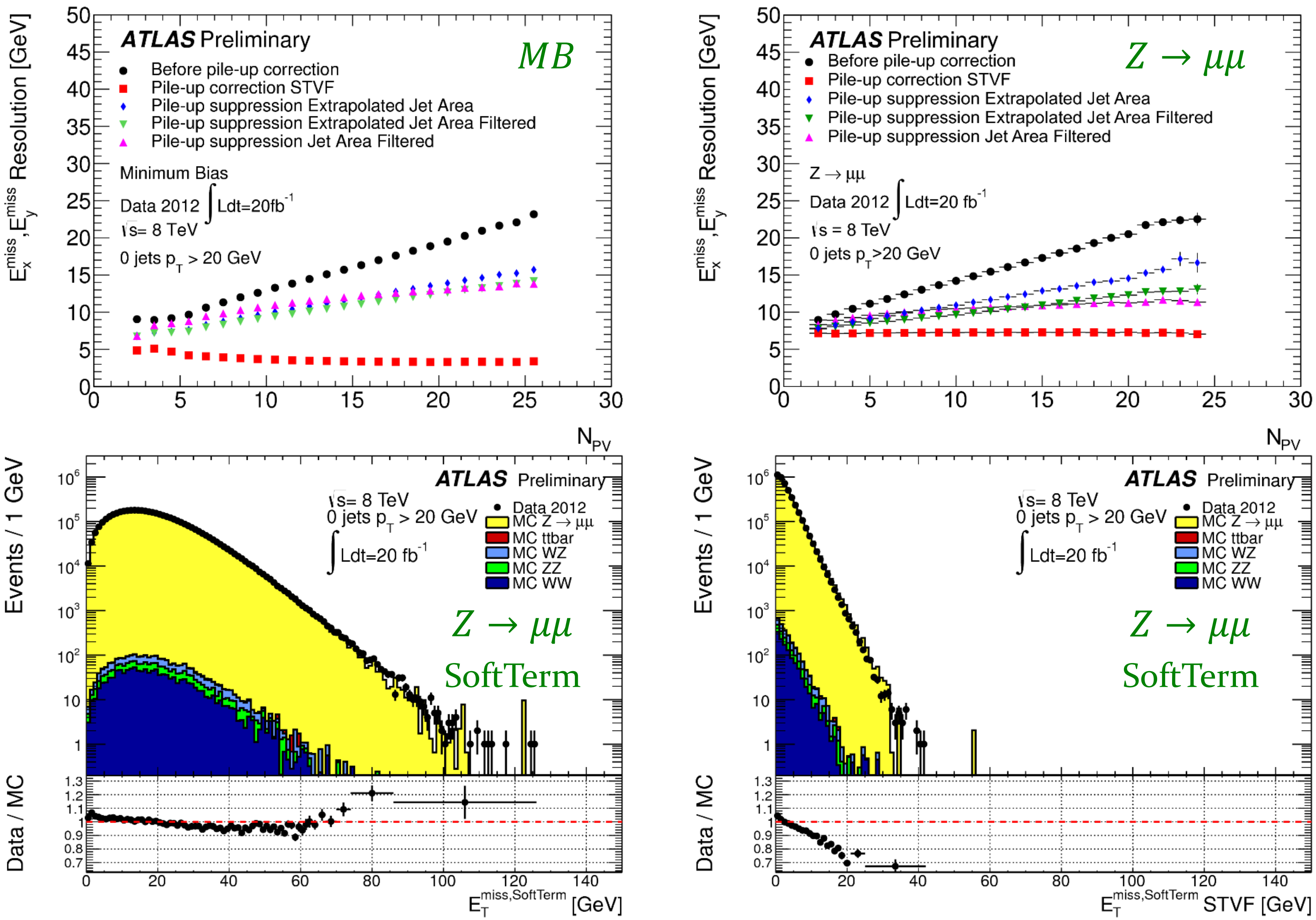
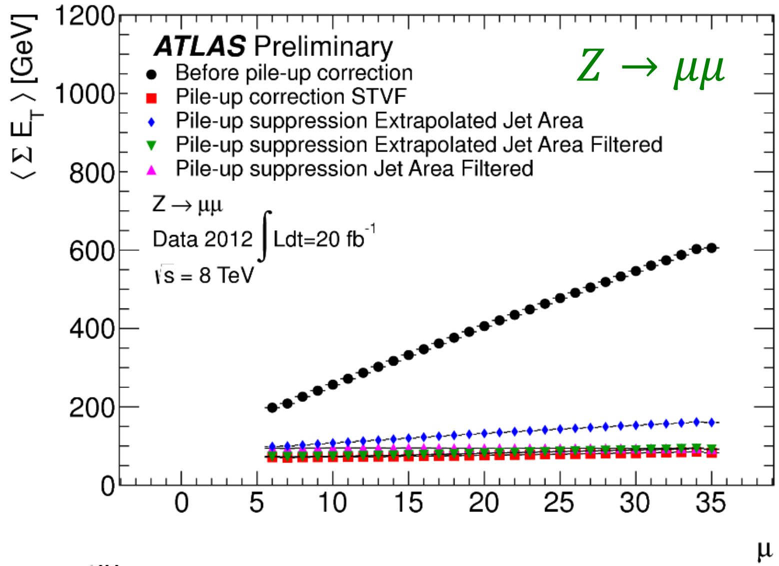
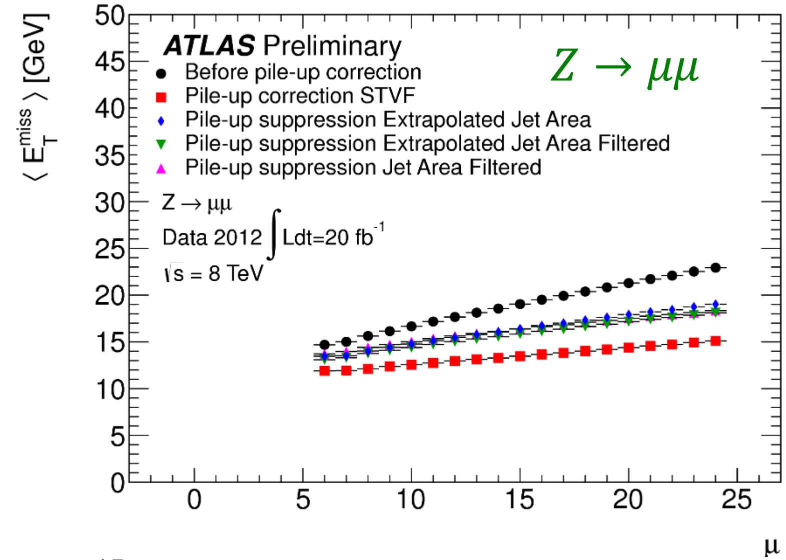
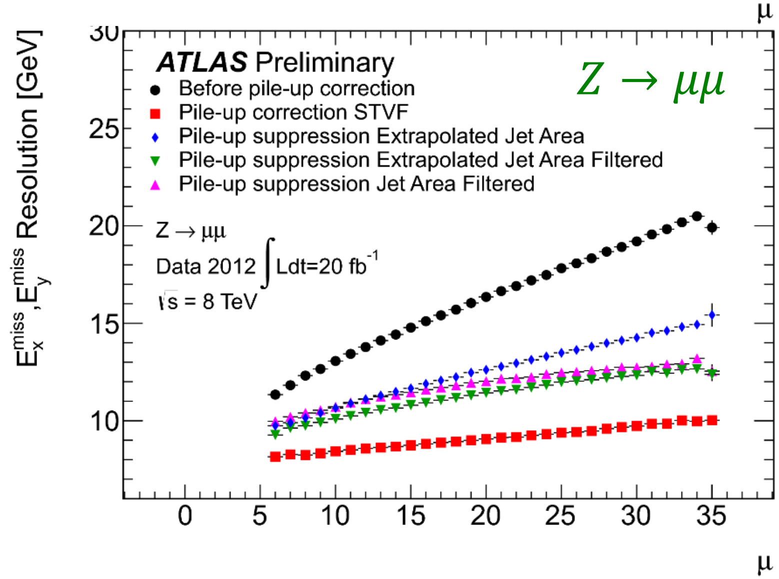


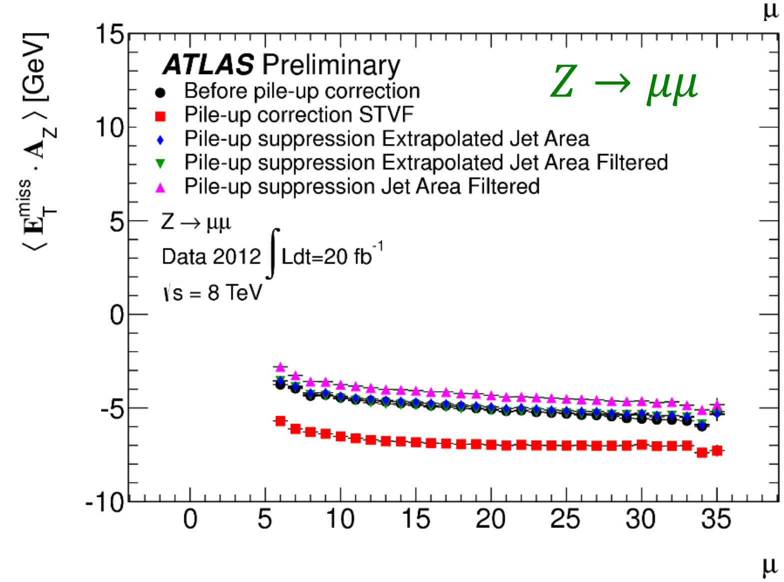
Final States Without Genuine MET

No genuine MET, versus μ









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MET Scale

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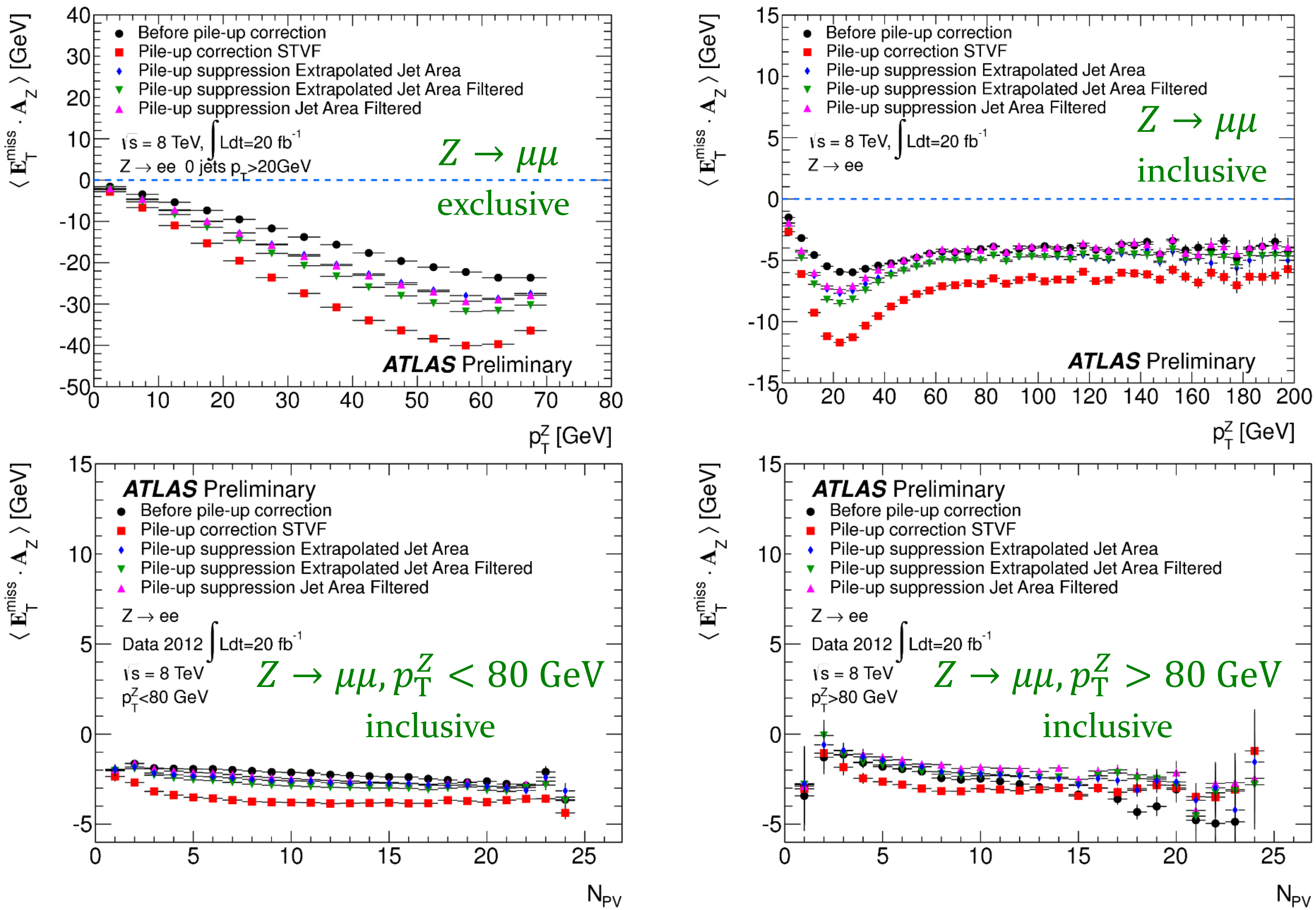
No genuine MET



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MET SoftTerm

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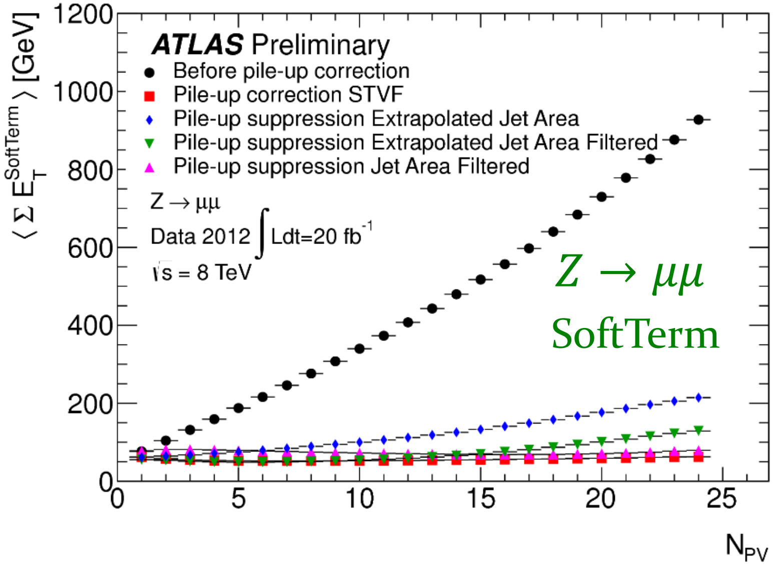
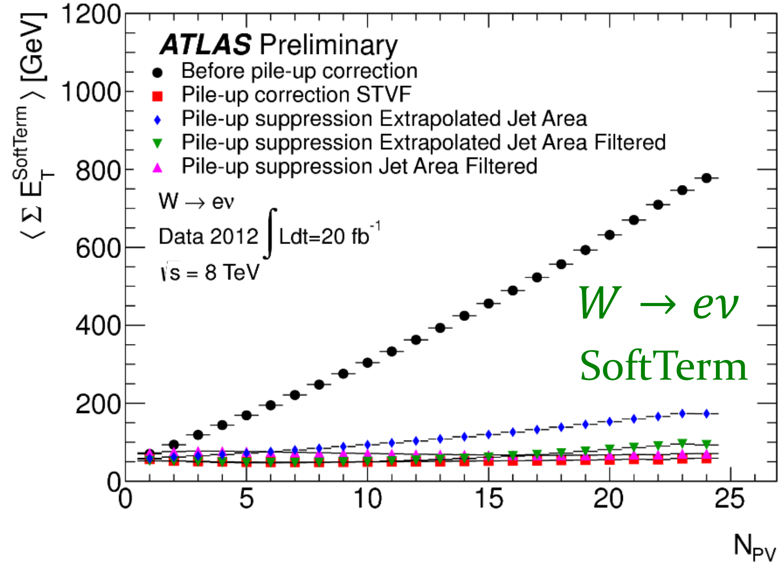
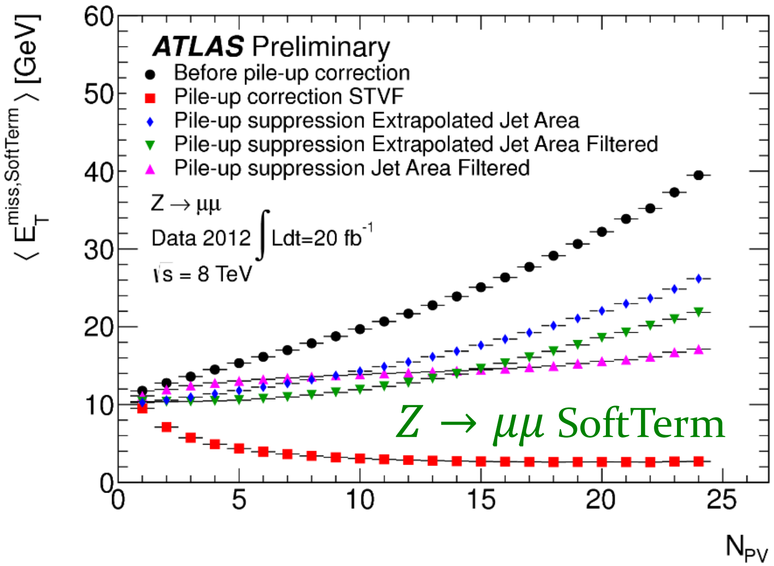
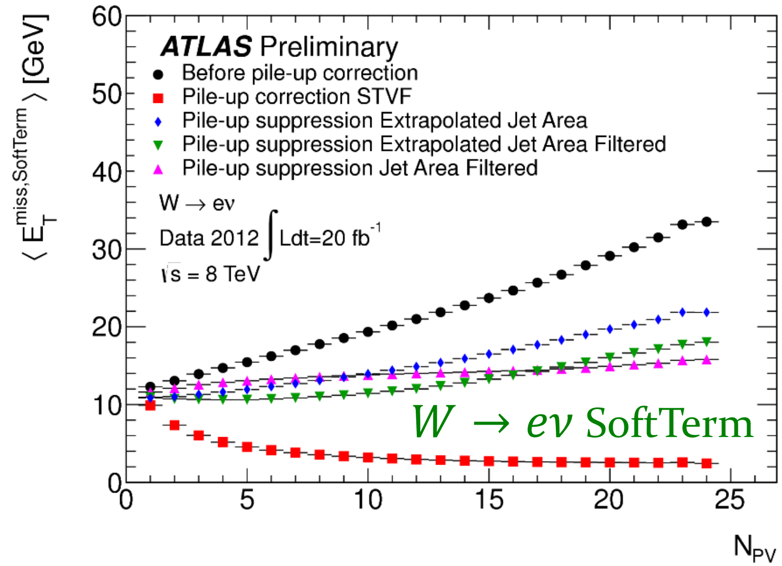
Inclusive Samples









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Final State With Genuine MET

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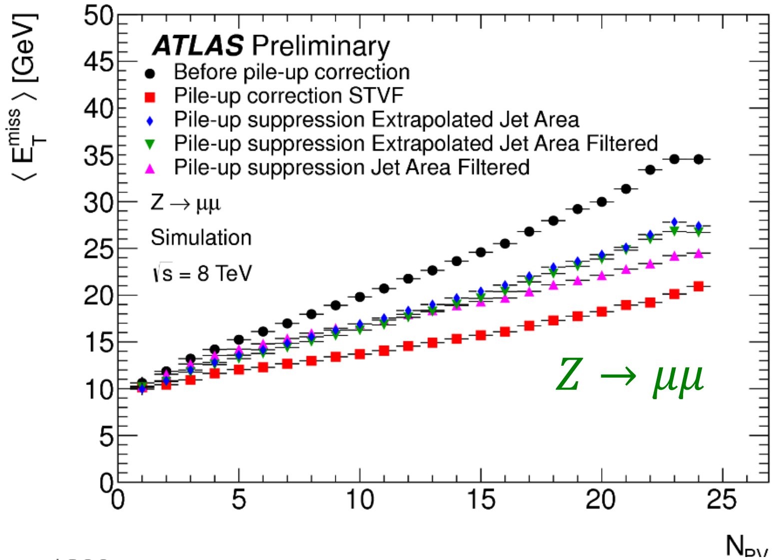

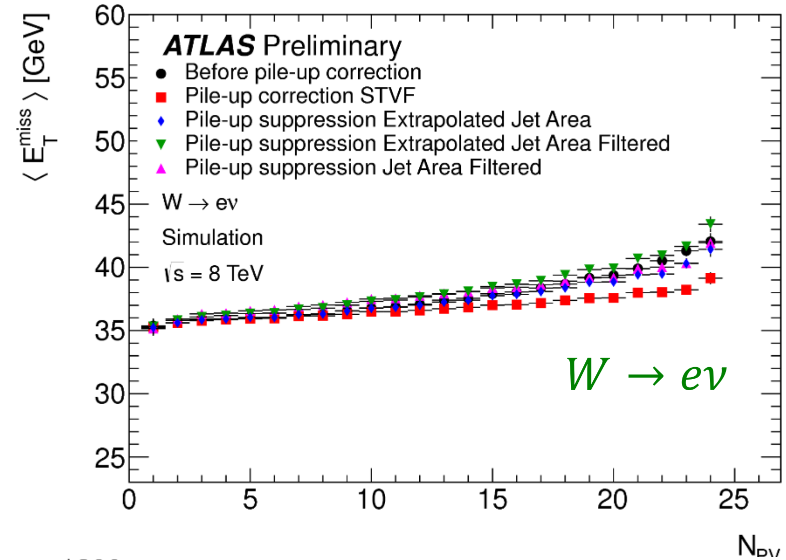

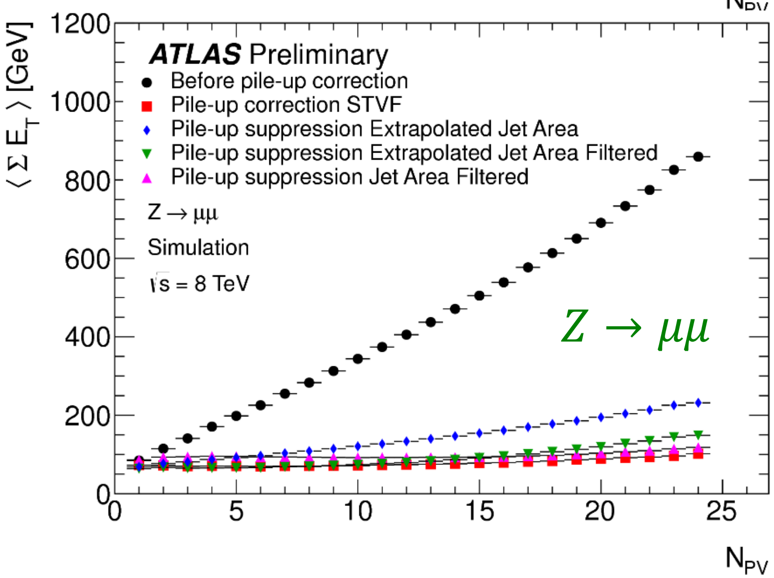

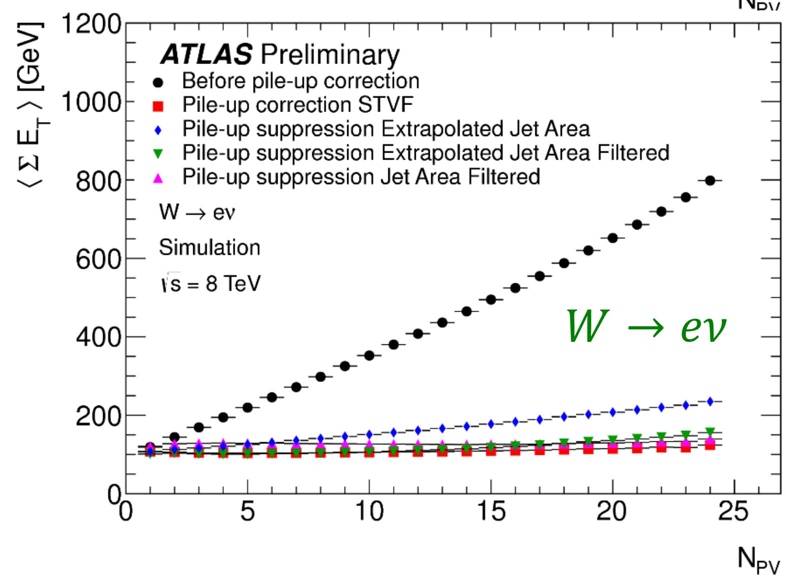

MET Resolutions

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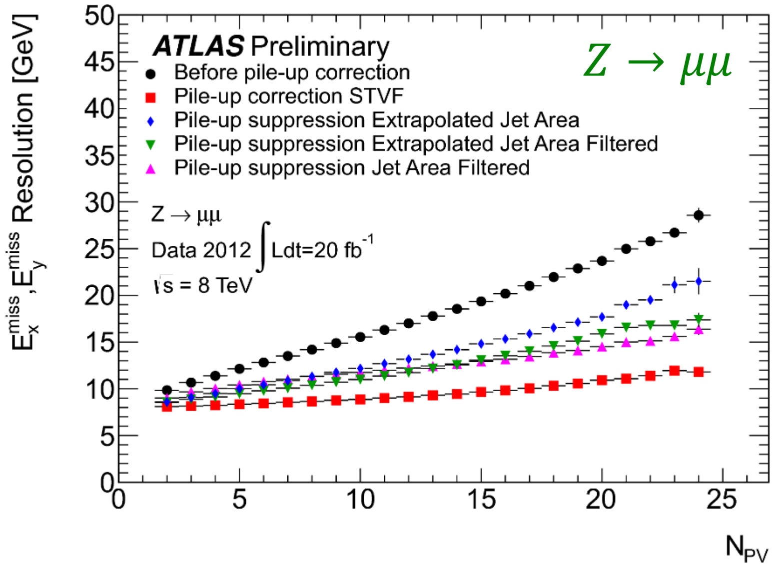
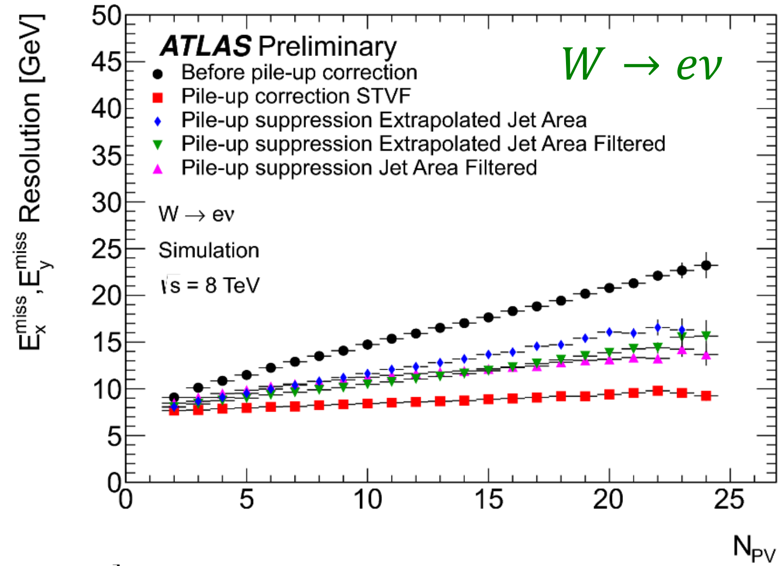




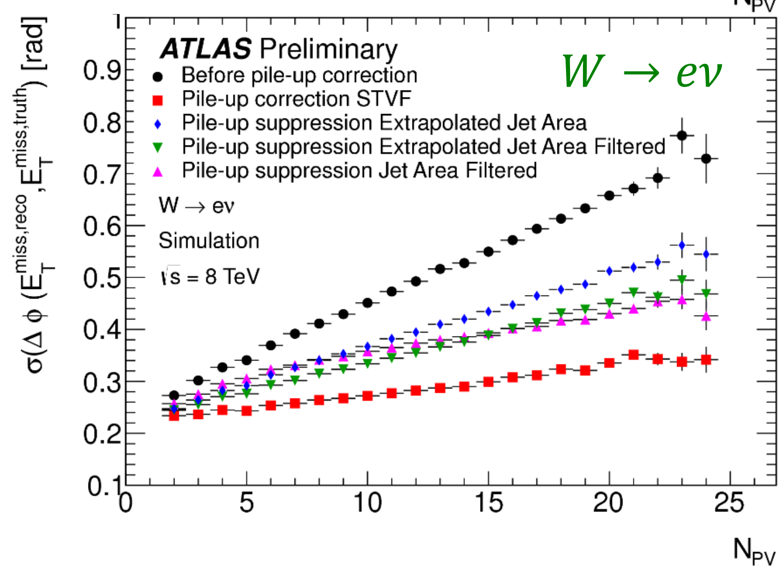
MET resolution

Component resolution

Well controlled by pile-up mitigation techniques – best if tracking is used as well

Angular resolution

Tracking-based mitigation techniques perform best



Conclusion

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First attempt for MET SoftTerm pile-up suppression

- Purely track-based (STVF), jet-area based (EJA) and combinations (EJAF, JAF)
  - Calorimetric jet-area based EJA alone does not perform that well – purely stochastic subtraction cannot reinstate performance w/o pile-up
  - Additional use of JVF improves performance (EJAF/JAF)
  - STVF performs best for MET resolution but suppresses MET scale – and suffers from the same problems as JVF at high pile-up (Pascal Nef's talk)
  - Calorimeter based methods do very well for SumET pile-up mitigation – important for analyses using MET significance
- Particular choice is final state dependent
  - No universal recommendation – mostly hangs on importance of soft term and topology of energy flow
  - Jet-area based methods clearly an alternative for final states with track-starved hard-scatter vertex and genuine MET

Further development

- Use of GridMedianEstimator – moderates forward flow reconstruction problem
  - Replace extrapolation?
- More dissection of MET soft term
  - Conglomerate of jetty and diffuse transverse momentum flow – better flow analysis at least in final states with considerable SoftTerm

Missing ET

- **Linearity of the response is within 1% up to mu=140**
  - Achieve a correct missing ET scale
  - Positive bias at low missing ET is due to the finite resolution of the missing ET, and is highly dependent on the event topology
- **Missing ET resolution shifts upwards with pileup, but it does not change the slope with mu**
  - Pileup affects the s-term of the resolution, but the k-term remains approximately constant
- **Large room for improvements using tracks to suppress pileup**