ATLAS jet and missing E_T reconstruction, calibration, and performance

Mireia Crispin-Ortuzar
On behalf of the ATLAS Collaboration

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Summary

Jets and missing energy are key in many new physics searches and standard model measurements.

- **Jet reconstruction and calibration**
  - Key physics objects.
  - Jet energy scale uncertainty - main contribution to the systematic uncertainty of many physics results.
  - Input to missing transverse energy.

- **Missing transverse energy (E_T^{miss})**
  - Signature of many physics processes (including new physics).

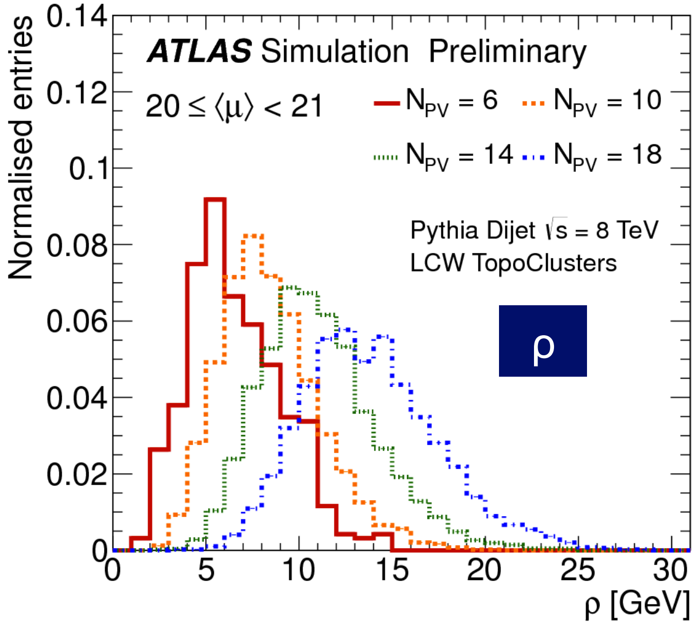
- **Jet substructure and tagging**
  - Top tagging.
  - Quark- and gluon-initiated jet discrimination.

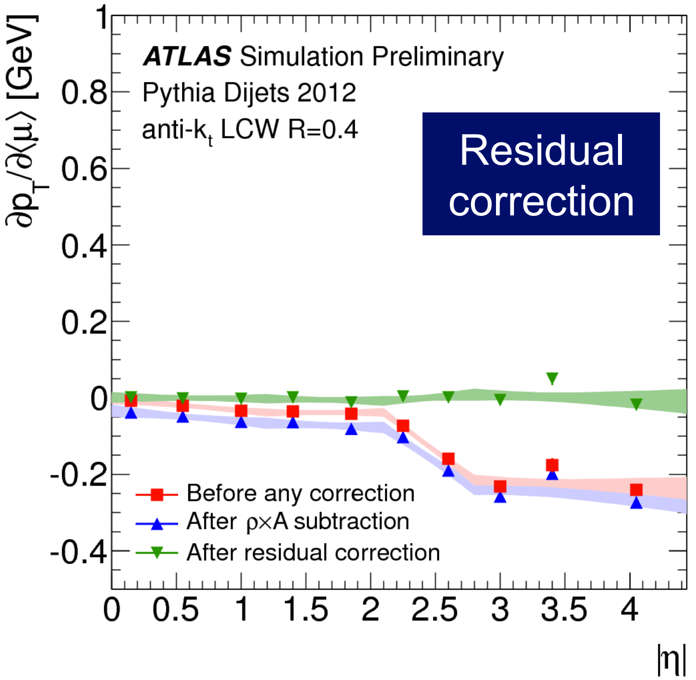
- **High luminosity studies**

Jets: Reconstruction and calibration

Jet calibration (I)

ATLAS-CONF-2013-083, arXiv:1406.0076





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- **Topo-cluster**: group of calorimeter cells topologically connected (3D). Clustering algorithm optimised for pile-up and electronic noise suppression.

2

- Topo-clusters used as inputs for **anti-k_t R=0.4 or 0.6** jets

3

- **Pile-up correction**
- 2011: **Offset correction**. Average correction parametrised by N_{PV} and <μ>.

$$p_T^{corr} = p_T - \alpha \cdot (N_{PV} - 1) - \beta \cdot \mu$$

- 2012: **Jet-areas correction** + residual offset correction.
  - Event-by-event fluctuations
  - Same for all jet definitions (modulo residual correction)
  - ~insensitive to vertex reconstruction

$$p_T^{corr} = p_T - A \cdot \rho$$

Median p_T density

Jet calibration (II)

4

- **JES calibration.**
- **Energy** calibration: multiplicative factor based on jet response,

$$R^{\mathrm{EM(LCW)}} = \left\langle \frac{E_{\mathrm{jet}}^{\mathrm{EM(LCW)}}}{E_{\mathrm{jet}}^{\mathrm{truth}}} \right\rangle$$

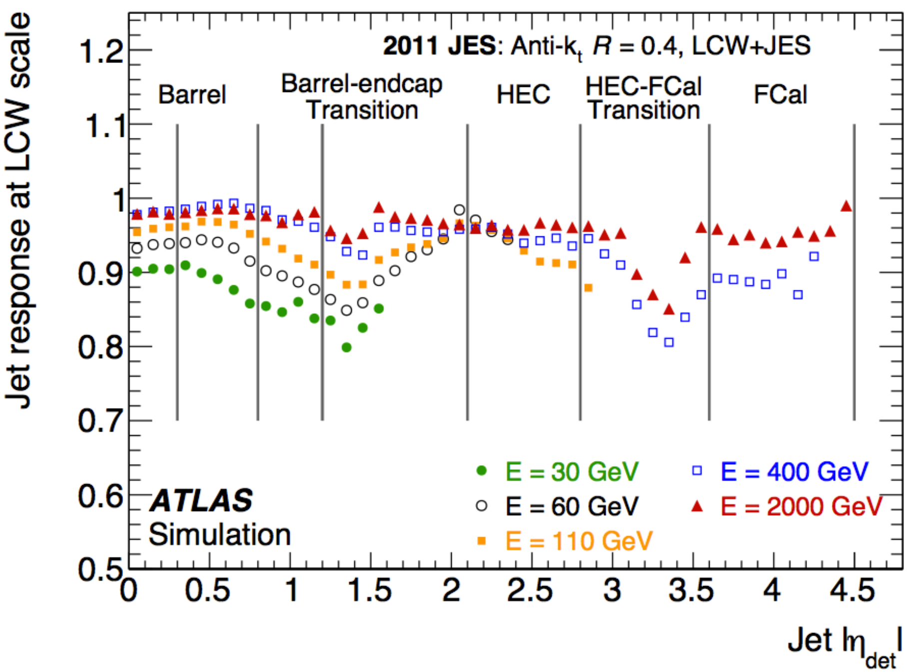
- **η** calibration.

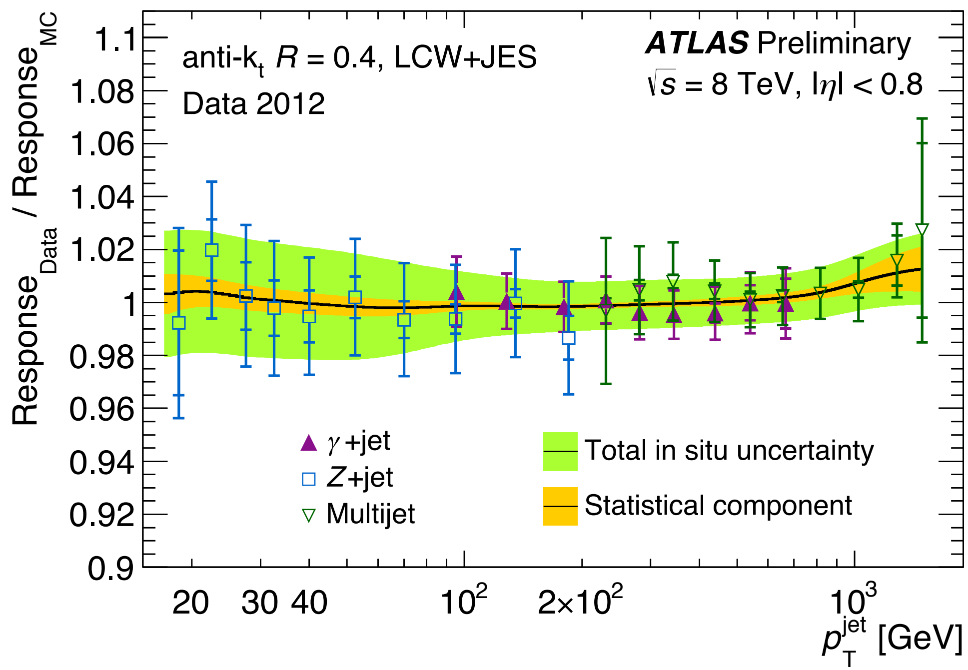
5

- **Residual in-situ calibration.**
- Applied to data only.
- Based on correction factor:

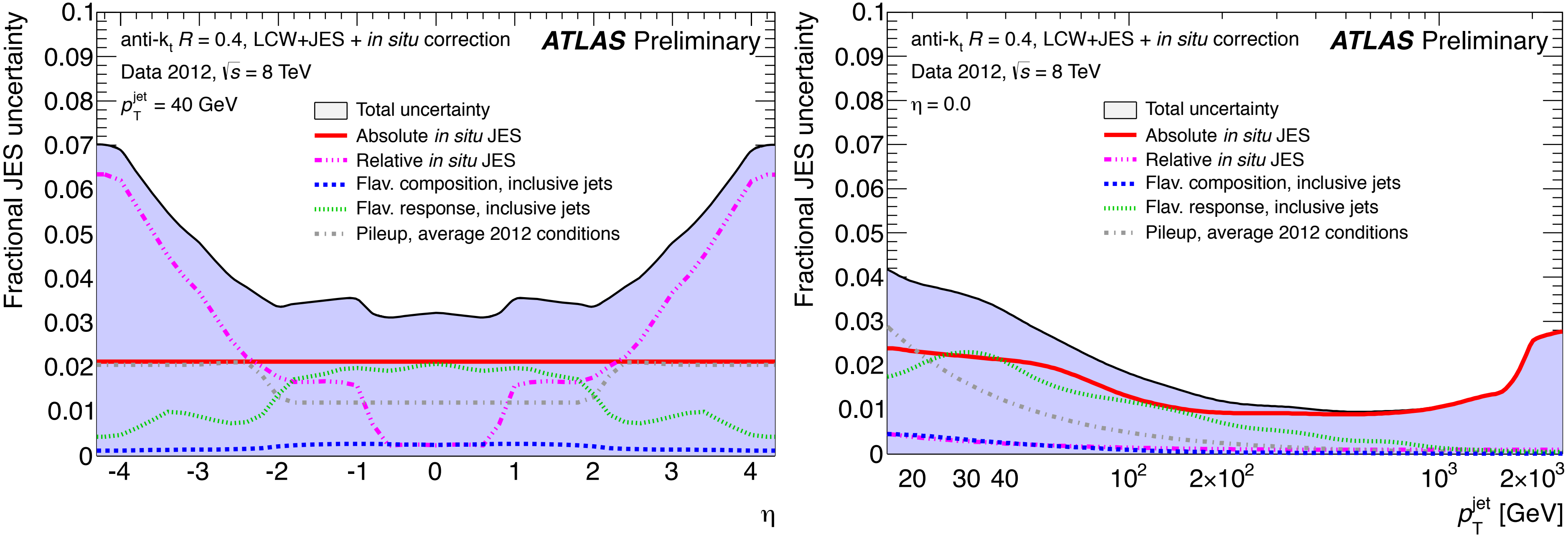
$$\frac{\mathrm{Response}_{\mathrm{MC}}}{\mathrm{Response}_{\mathrm{Data}}} = \frac{\left\langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{ref}} \right\rangle_{\mathrm{MC}}}{\left\langle p_{\mathrm{T}}^{\mathrm{jet}} / p_{\mathrm{T}}^{\mathrm{ref}} \right\rangle_{\mathrm{Data}}}$$

- Exploit p_T balance between jet and reference object.





Jet energy scale uncertainty



- Components:
  - In-situ calibration uncertainties
  - Pile-up uncertainty
  - Flavour composition and response uncertainty
- All components are summed in quadrature.
- For central jets: <4% for p_T>20 GeV, <2% for 100<p_T<1000 GeV.

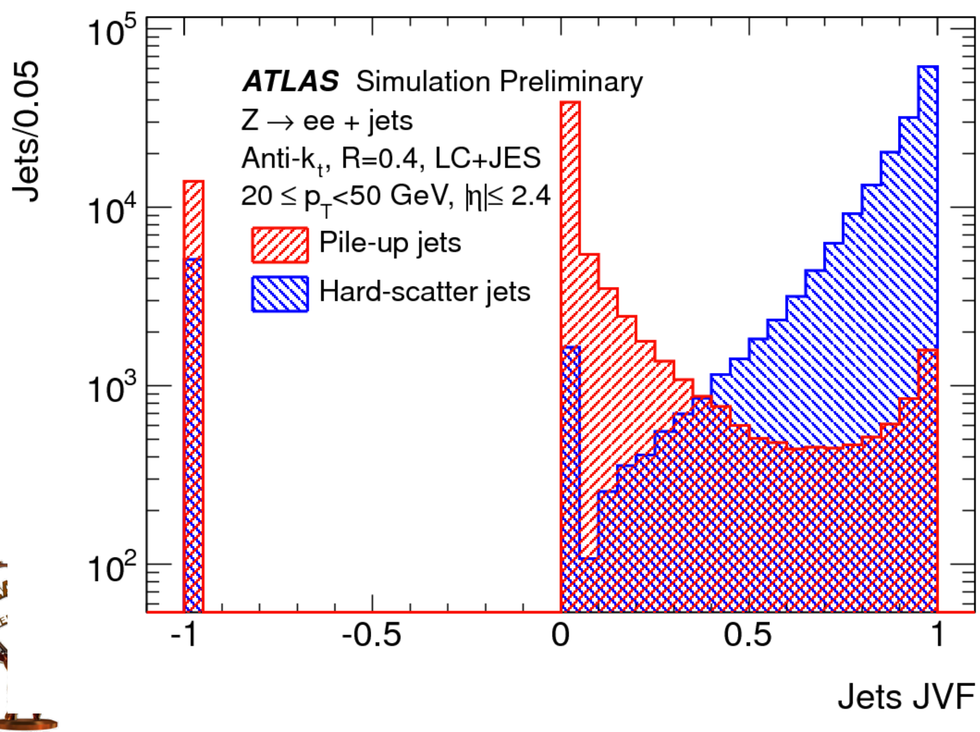
Track-based pile-up jet suppression

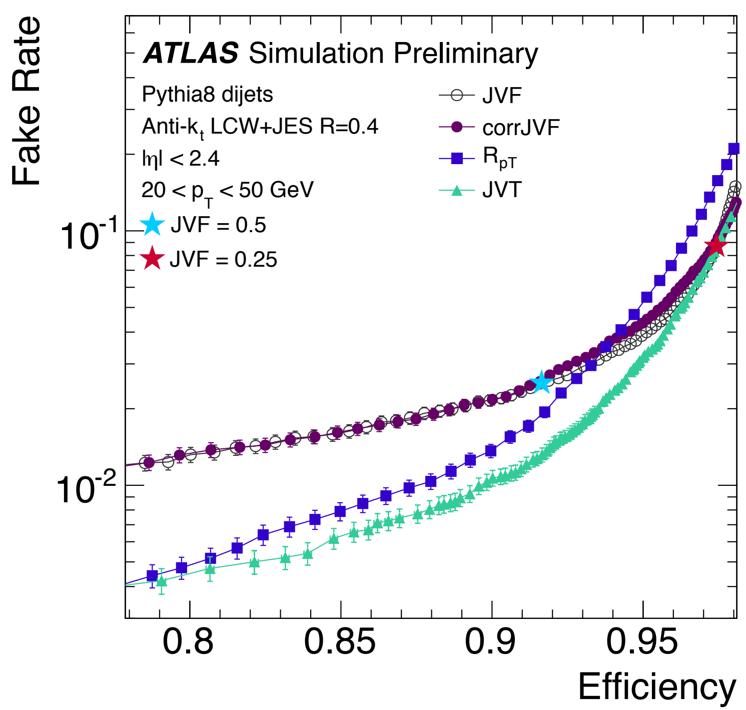
ATLAS-CONF-2014-018

- Local fluctuations in the pileup activity may result in spurious pile-up jets.
- **Jet Vertex Fraction (JVF)**
  - Fractional p_T from tracks associated with the hard-scatter vertex.
  - Dependent on N_{vtx} and $<\mu>$.

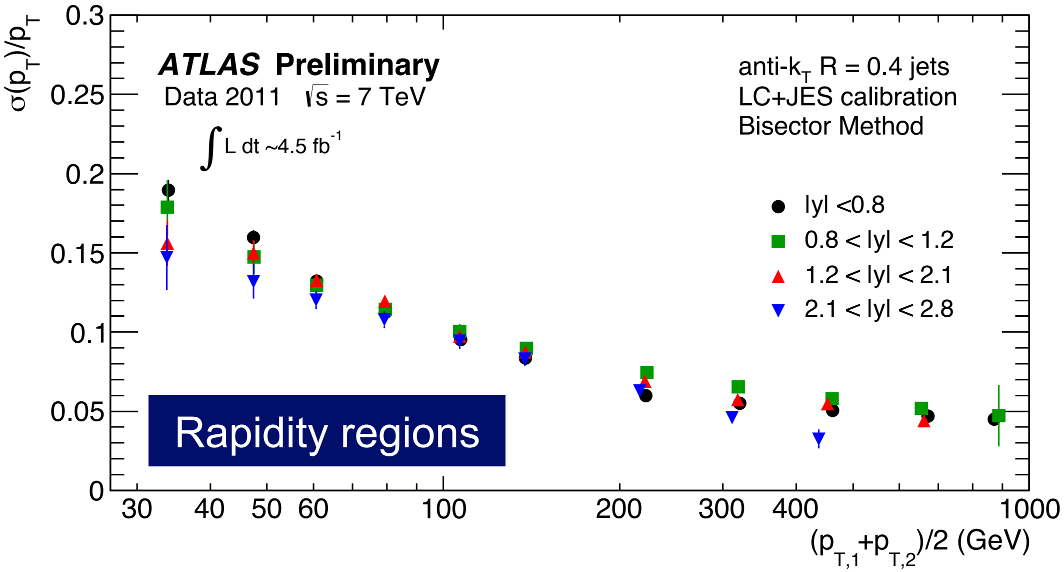
$$\mathrm{JVF} = \frac{\sum_{i \in \mathrm{PV0}} p_T^{\mathrm{track}\ i}}{\sum_j p_T^{\mathrm{track}\ j}}$$

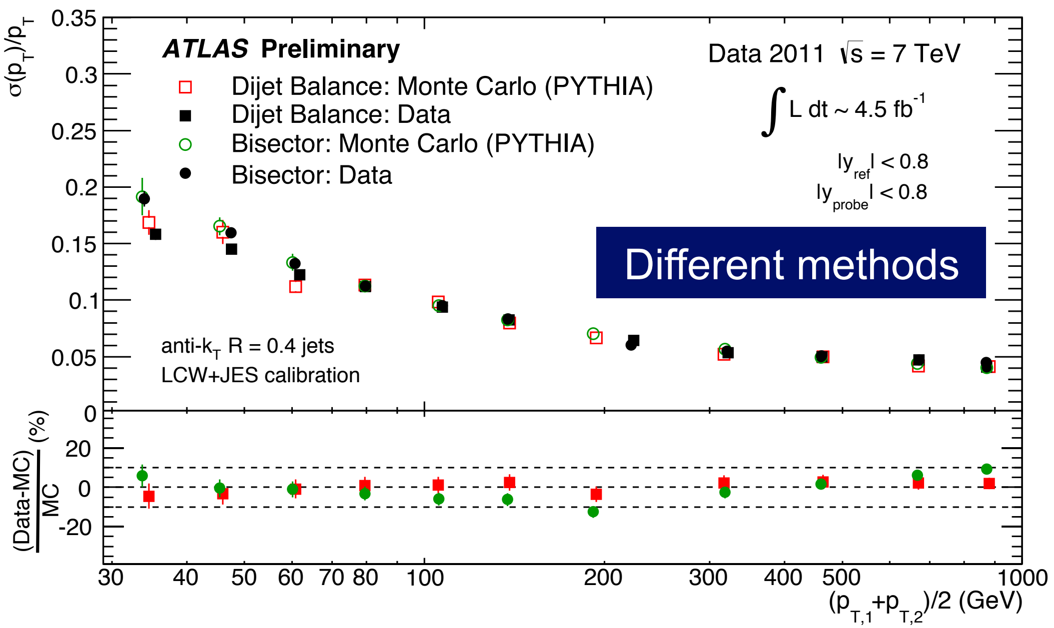
- **Jet-Vertex-Tagger (JVT)**
  - 2D likelihood of two track-based variables, similar to JVF but pile-up corrected.
  - Performance improvement.





Jet Energy Resolution





- Important for
  - cross-section measurements of processes with jets,
  - searches for jet resonances,
  - missing energy…
- Determined in-situ from transverse momentum balance in dijet events
  - **Dijet balance method**: measure asymmetry of two leading jets.
  - **Bisector method**: project over bisector angles (no balance assumption).

E_T^{miss} (missing transverse energy)

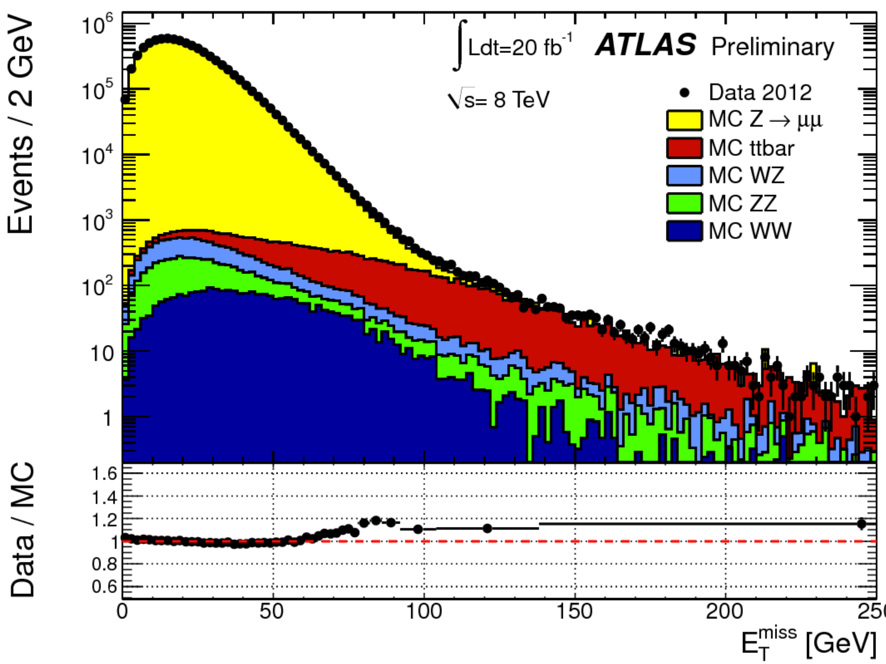
E_T^{miss} performance in 2012 data

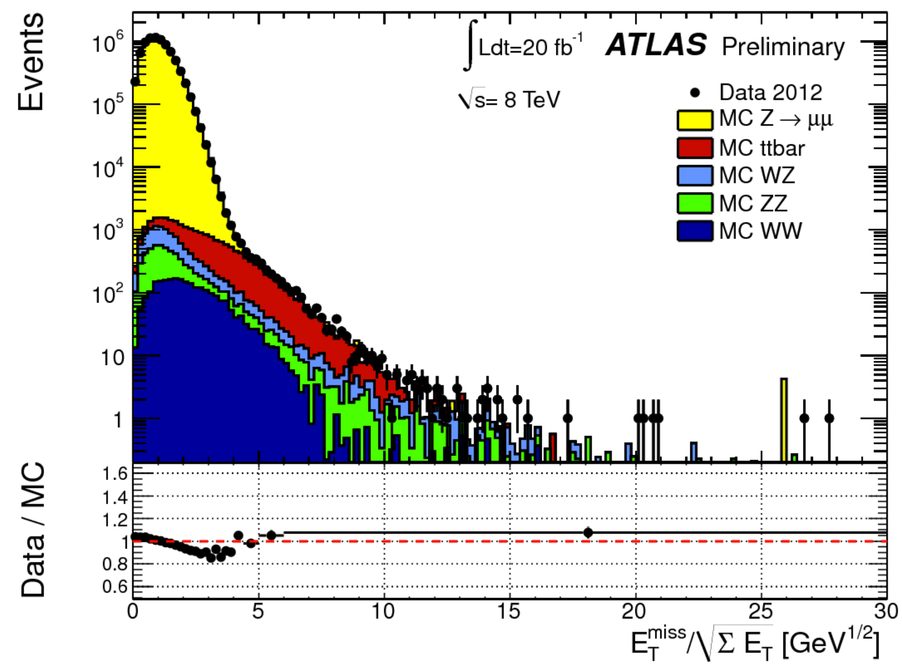
ATLAS-CONF-2013-082, ATLAS-CONF-2014-019

- E_T^{miss} is defined as: $E_T^{miss} = -\sum_i \vec{p}_{T,i}$
- The « refined » version used by ATLAS uses all the object-specific calibrations:

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,\tau} + E_{x(y)}^{miss,jets} + E_{x(y)}^{miss,SoftTerm} + E_{x(y)}^{miss,\mu}$$

  - All objects are calibrated and corrected for pile-up.
  - Overlap removal.
  - Soft term includes jets with p_T<20 GeV and soft tracks/clusters not associated with fully reconstructed objects → sensitive to pile-up.



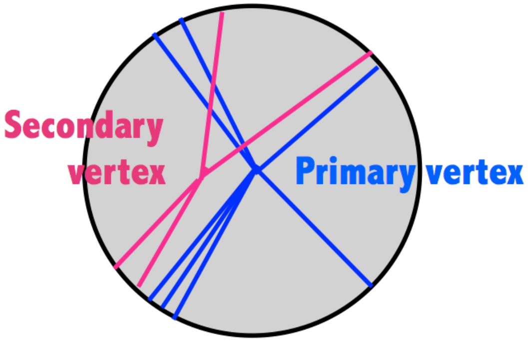


Pile-up suppression for E_T^{miss}

- Applied to the soft term.
- Overlap between tracks and clusters: preference given to tracks for $p_T^{cluster}<100$ GeV.

- **Tracking-based corrections:**
  - Soft term E_T^{miss} and ΣE_T scaled by soft-term vertex fraction (STVF):

$$STVF = \frac{\sum_{Soft\ term\ tracks,\ PV} p_T}{\sum_{All\ soft\ term\ tracks} p_T}$$



$$E_{T,\ corrected}^{miss,\ SoftTerm} = E_T^{miss,\ SoftTerm} \times STVF$$

  - Jet vertex fraction (JVF) filtering: JVF calculated for each jet in the *hard term*. Jets are only accepted if $JVF_{jet} \neq 0$.

Pile-up suppression for E_T^{miss}

- Applied to the soft term.
- Overlap between tracks and clusters: preference given to tracks for $p_T^{cluster}$<100 GeV.

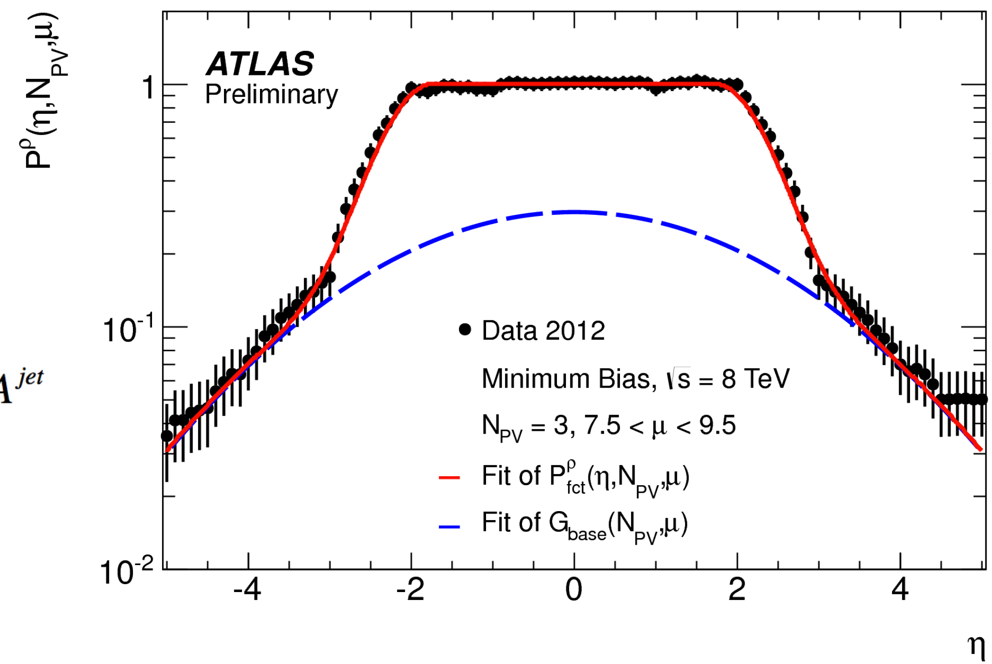
- **Jet-area-based corrections:**
  - Based on event-by-event transverse momentum density of the *soft* event (ρ).

1. Build jets from topoclusters and tracks in the soft term.

2. Calculate ρ as a function of η.

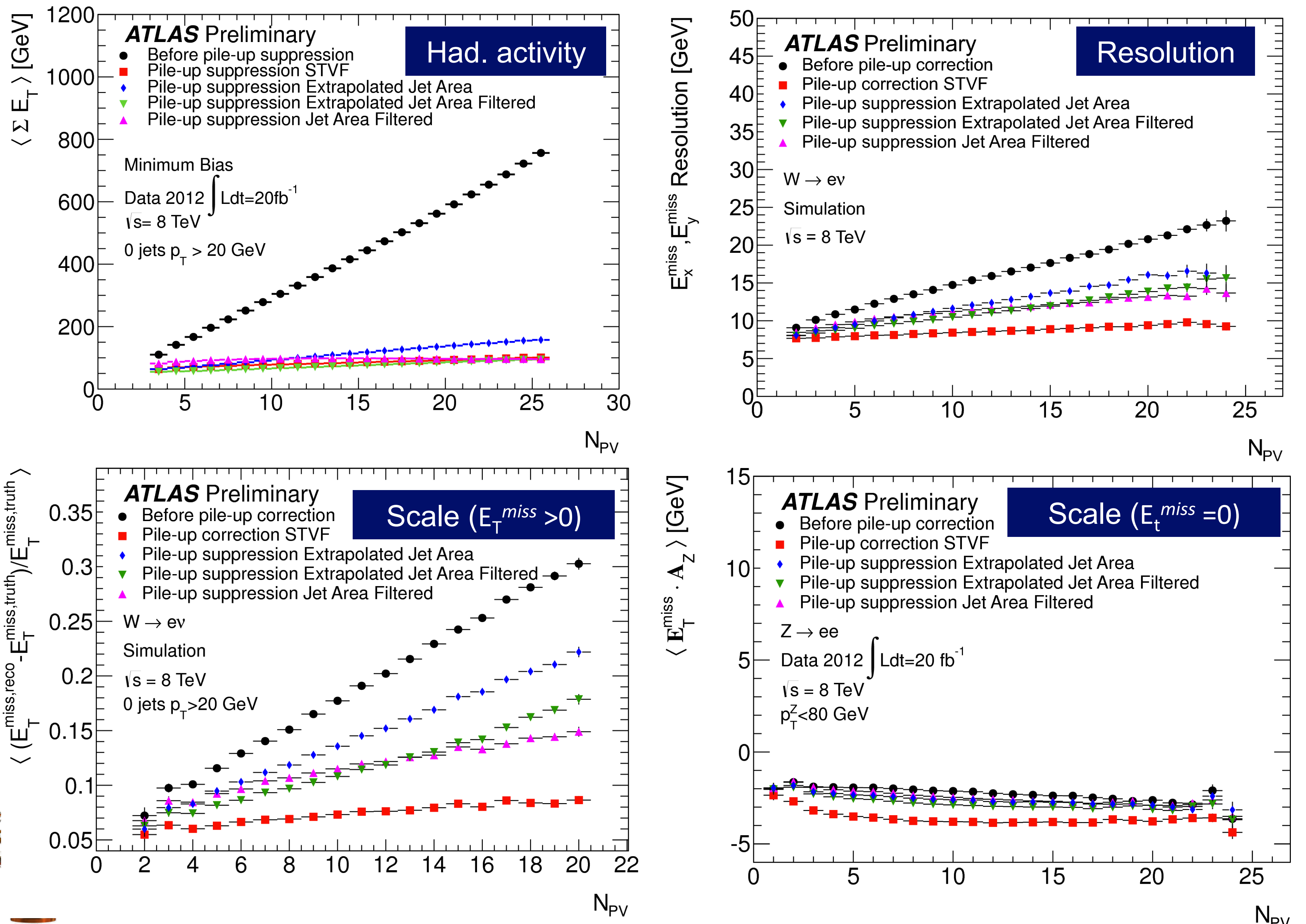
2. Recalculate soft term:

$$p_T^{PU\ corr} = \begin{cases} 0 & p_T^{jet} < \rho(\eta) \times A^{jet} \\ p_T^{jet} - \rho(\eta) \times A^{jet} & otherwise \end{cases}$$



  - ρ obtained either from data or by extrapolating between detector regions.
  - Re-clustered soft jets may or may not be applied a JVF cut (« filtered »).

Pile-up suppression for E_T^{miss}

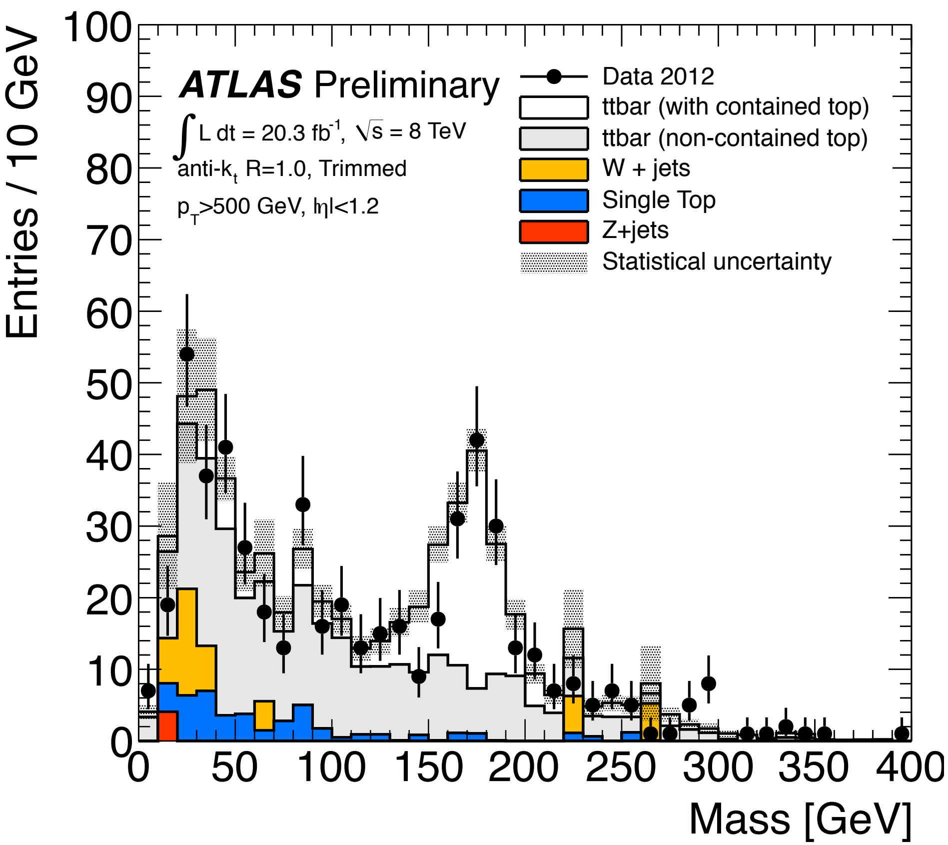


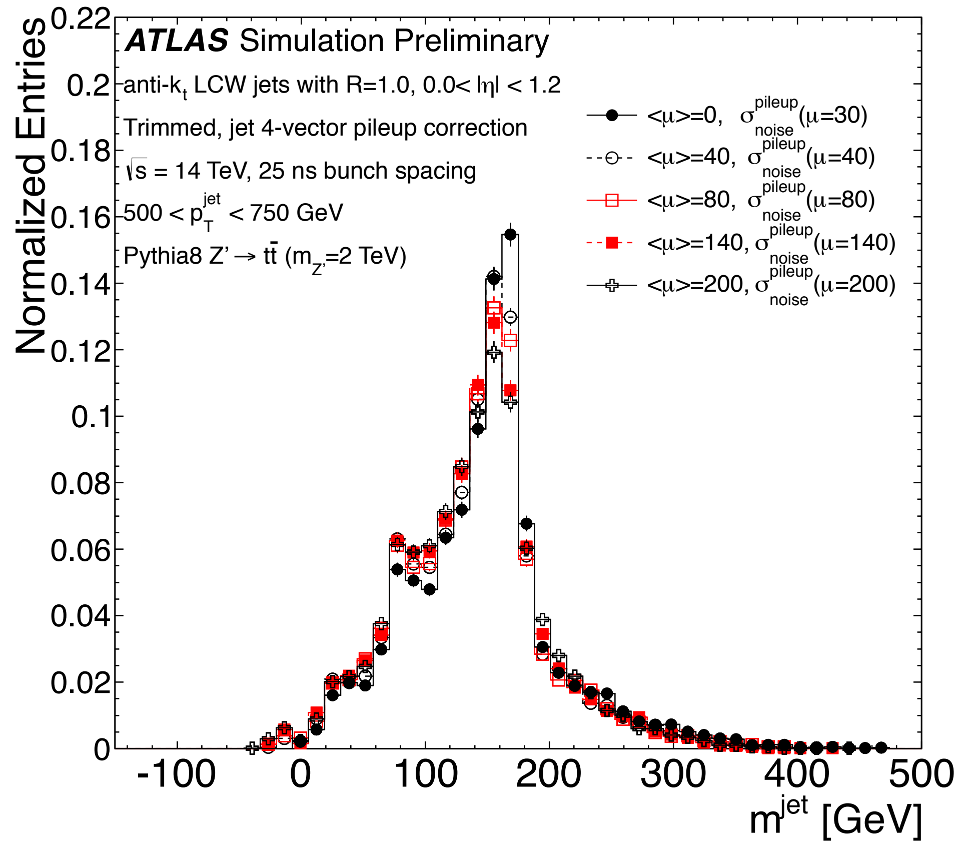
Jets: substructure and tagging

Jet substructure

JHEP09 (2013) 076

- Identification of hadronically decaying boosted objects (W, Z, H, top)
- Extensive studies on large-radius jets (anti-k_T with R = 1.0 and C/A with R = 1.2) and substructure techniques.
- Jet *grooming* techiques provide better energy and mass resolution.





Jet taggers

- **Quark-gluon tagger**
- Likelihood-based discriminant.
- Based on track width and track multiplicity.
- Light jets with p_T 40-360 GeV tagged with e≈50% (mistag rate 25%).

ATLAS-CONF-2013-087

- **Shower deconstruction**
- Exploits shower history for top tagging.
- Consider the probability that the sub-jets appear in a certain configuration inside a *fat* jet – calculate using approximate parton shower model.
- Discriminant: ratio of such probabilities for signal and background.

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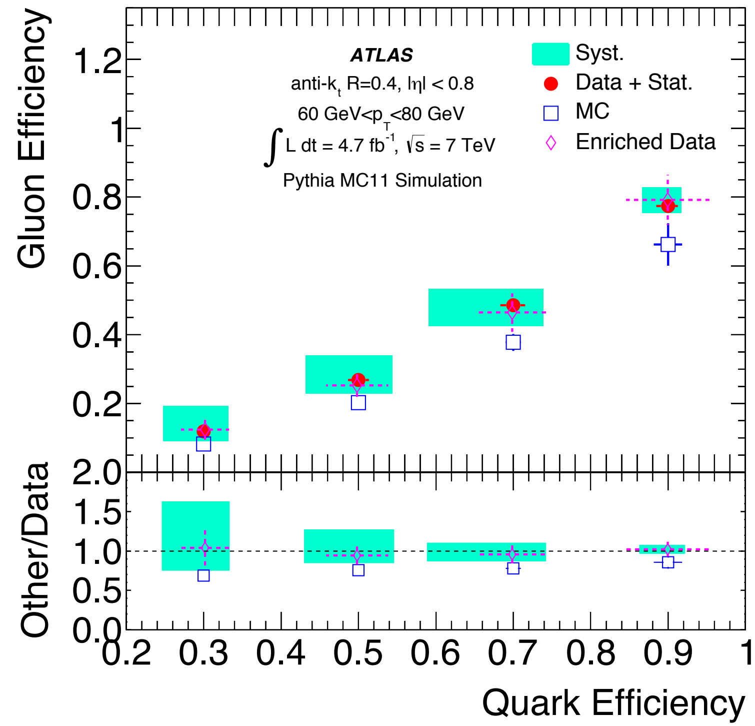
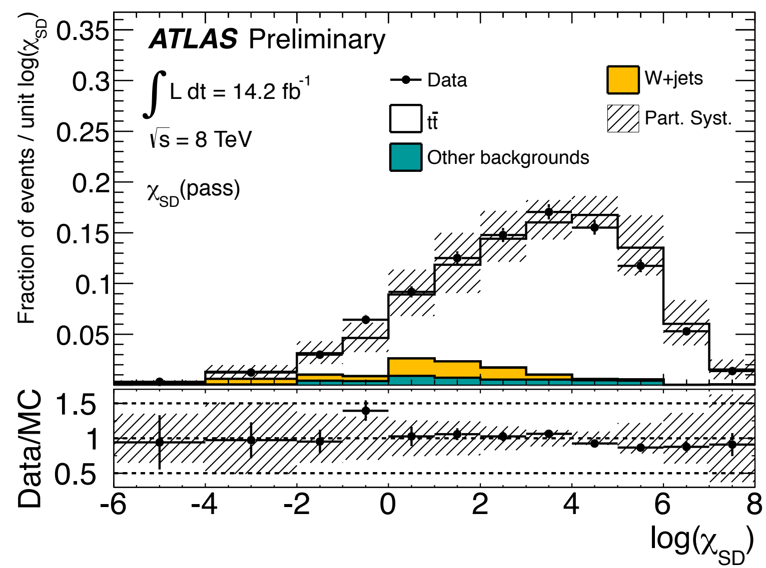
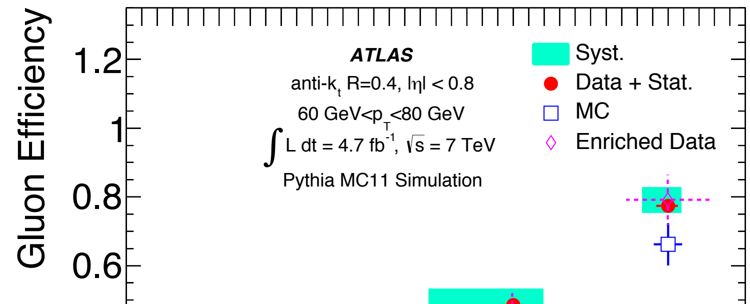


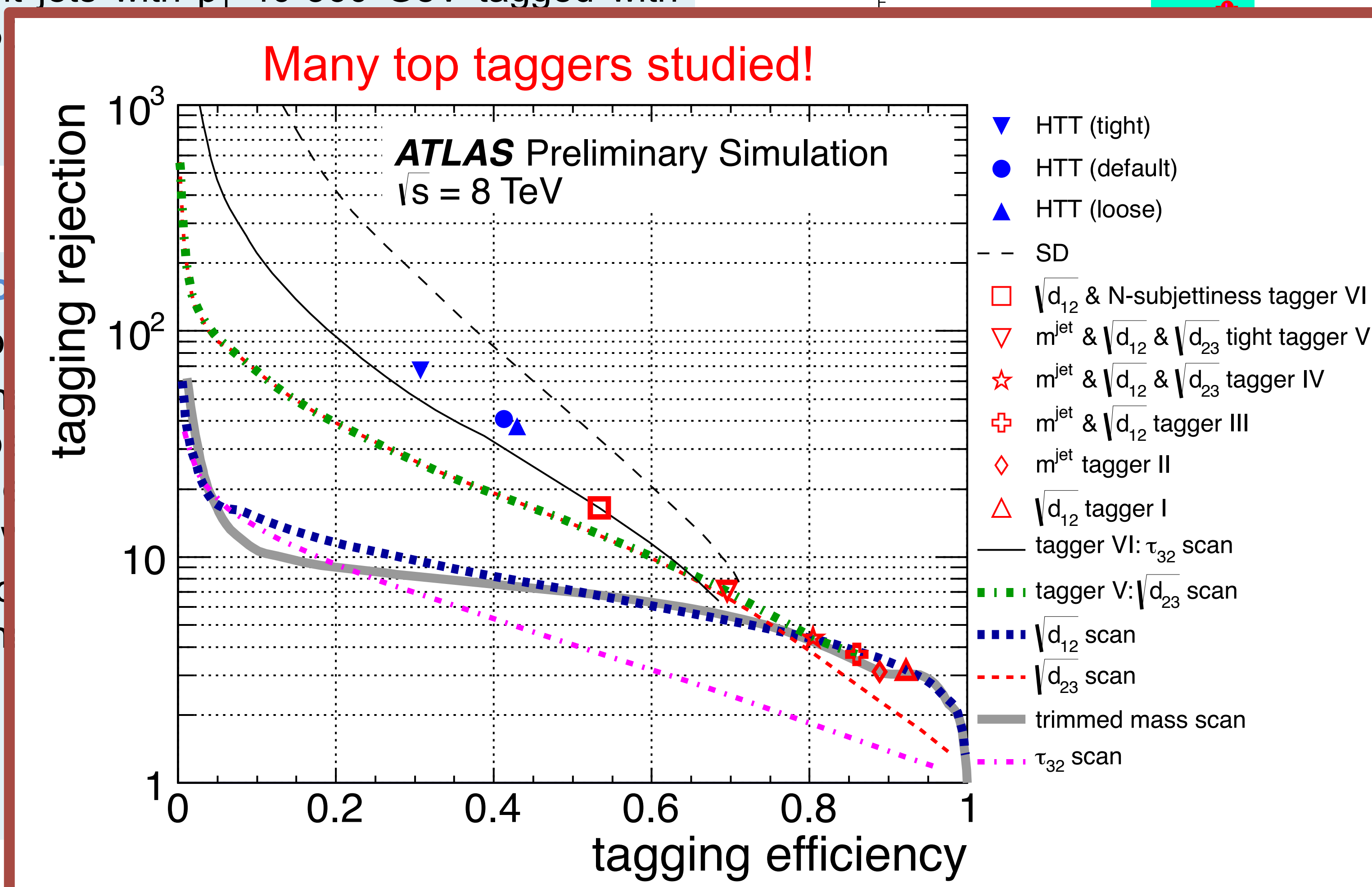


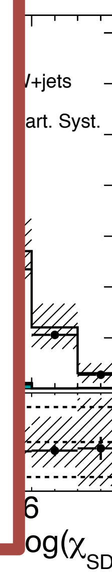
Jet taggers

- **Quark-gluon tagger**
- Likelihood-based discriminant.
- Based on track width and track multiplicity.
- Light jets with p_T 40-360 GeV tagged with e≈5



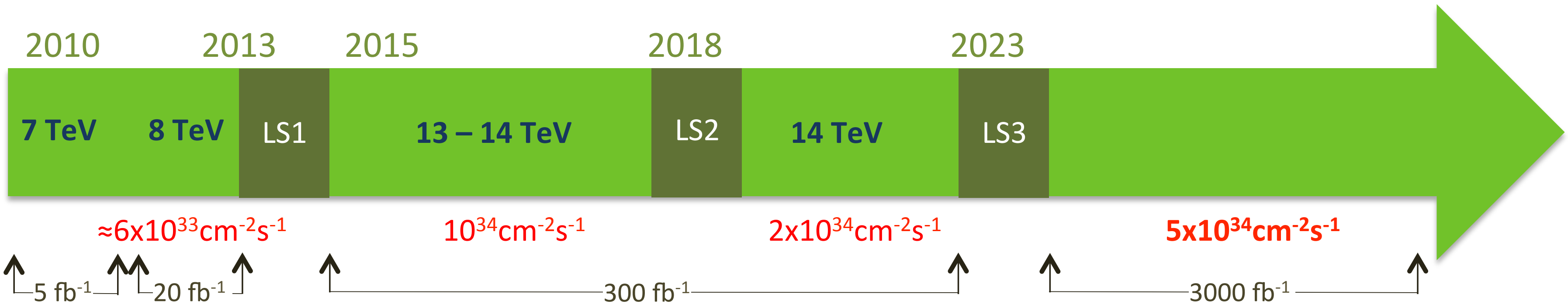
- **Sho**
- Exp
- Con app *fat j* sho
- Disc sign



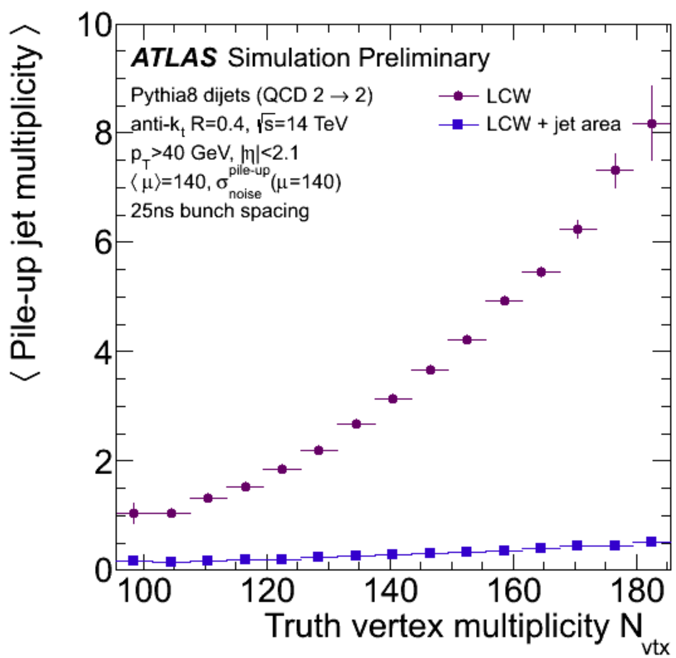


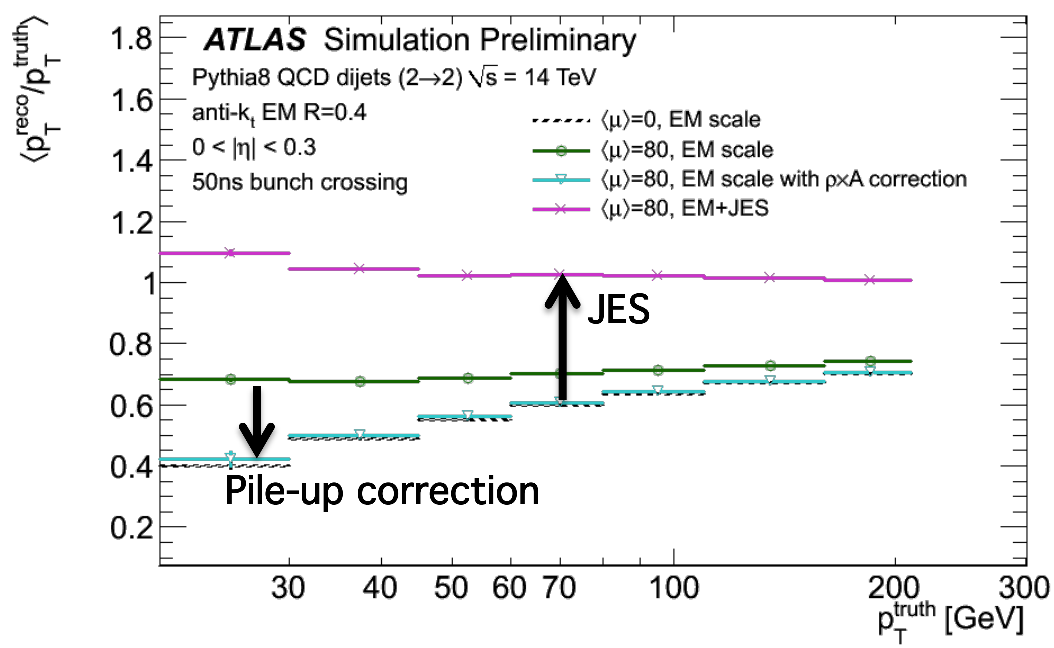
High luminosity

HL-LHC jet performance

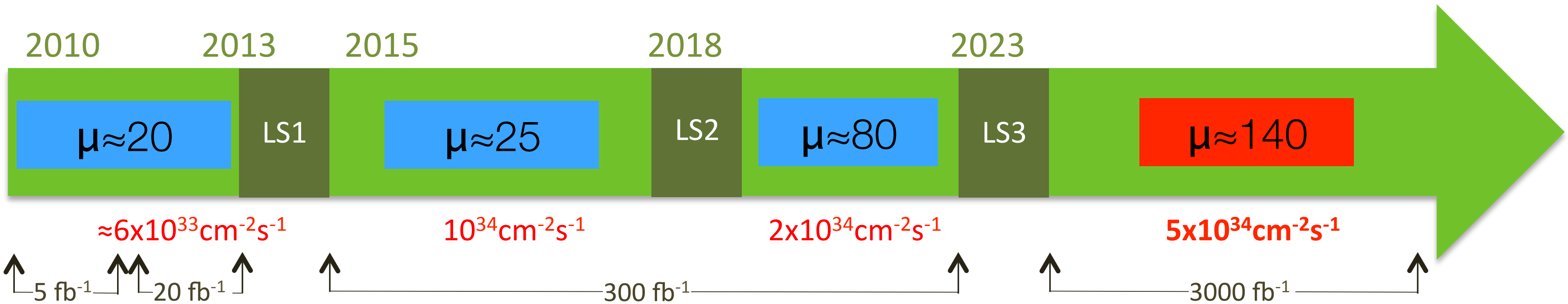


- Samples without tracking: focus on optimisation of calorimeter-level reconstruction.
- Grid of samples generated for different values of μ and pile-up noise threshold.
- Full jet calibration and pile-up subtraction derived.





HL-LHC jet performance



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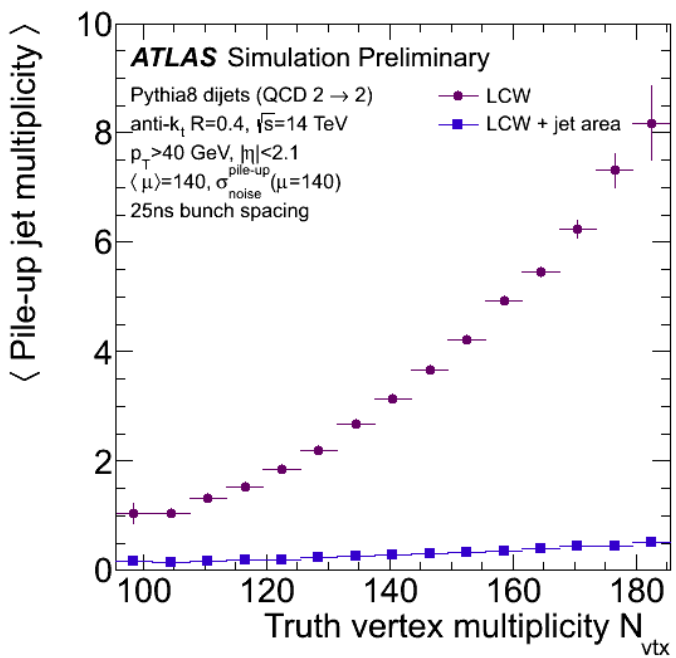
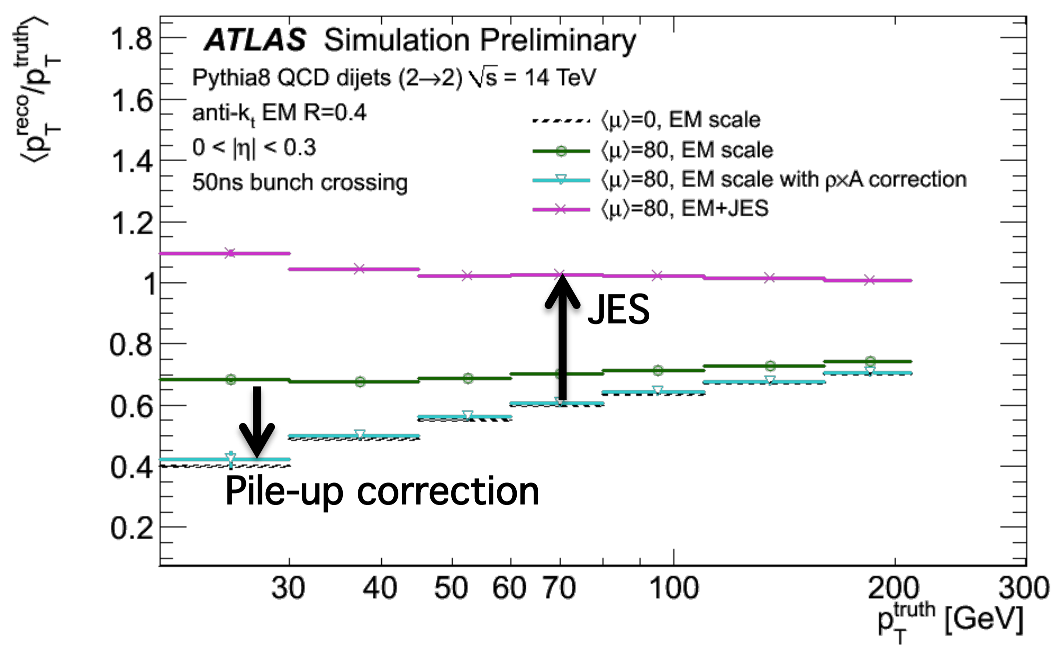
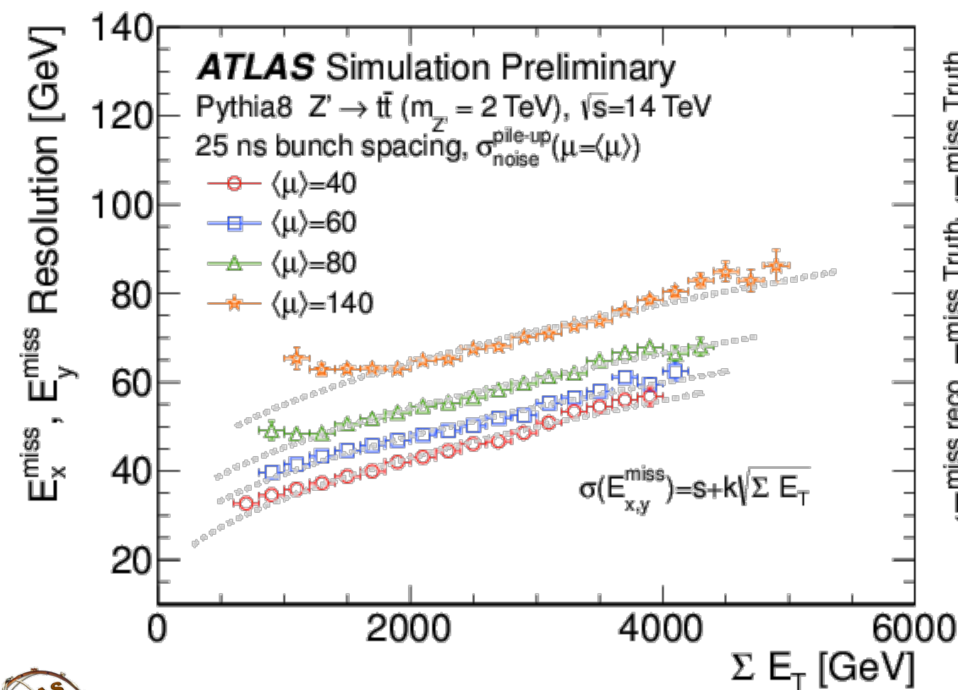
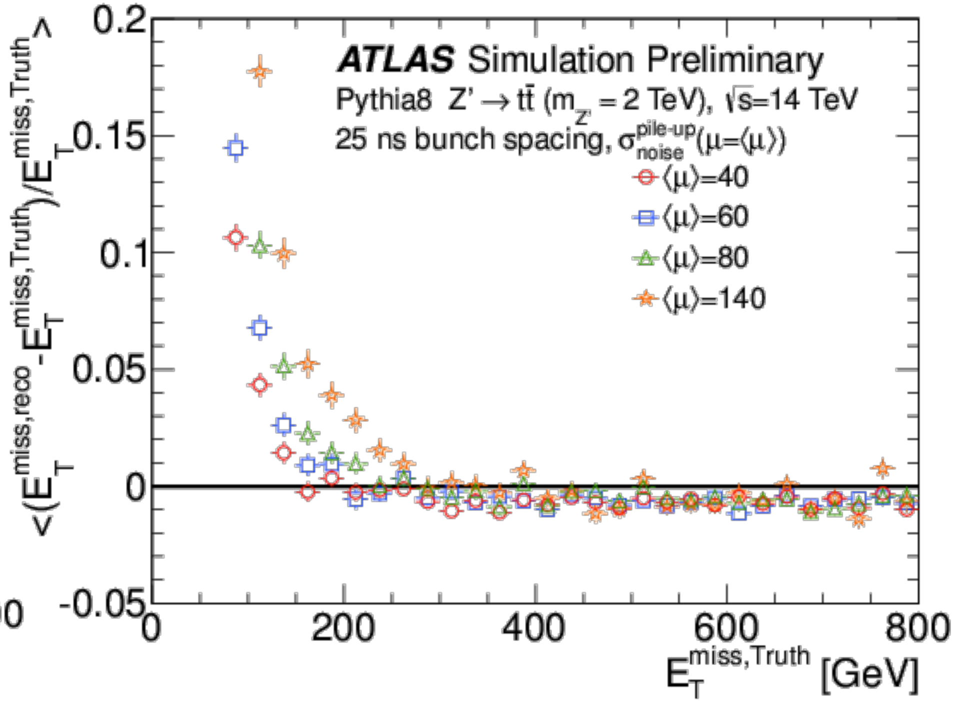




HL-LHC E_T^{miss} performance

- Simple definition of E_T^{miss} using just the calorimeter (jet calibration only).
- Pile-up degrades the E_T^{miss} resolution and scale.
- Hadronic activity significantly higher: $<\Sigma E_T^{PU}>=<\Sigma E_T - \Sigma E_T^{Truth}>$ ~ 1.3 TeV for μ~140.
- Positive bias in E_T^{miss} scale due to
  - Event topology
  - High average ΣE_T





Conclusions

- **Jet reconstruction and calibration**
  - Pile-up subtraction methods suppress event-by-event and local effects.
  - Jet energy scale determined with high precision.
  - JES uncertainty below 4% in central region.
  - Good data/MC agreement.

- **Missing transverse energy**
  - E_T^{miss} uses object-specific calibrations and pile-up suppression techniques.
  - Pile-up suppression in soft term studied thoroughly – jet areas subtraction and JVF-like methods studied.

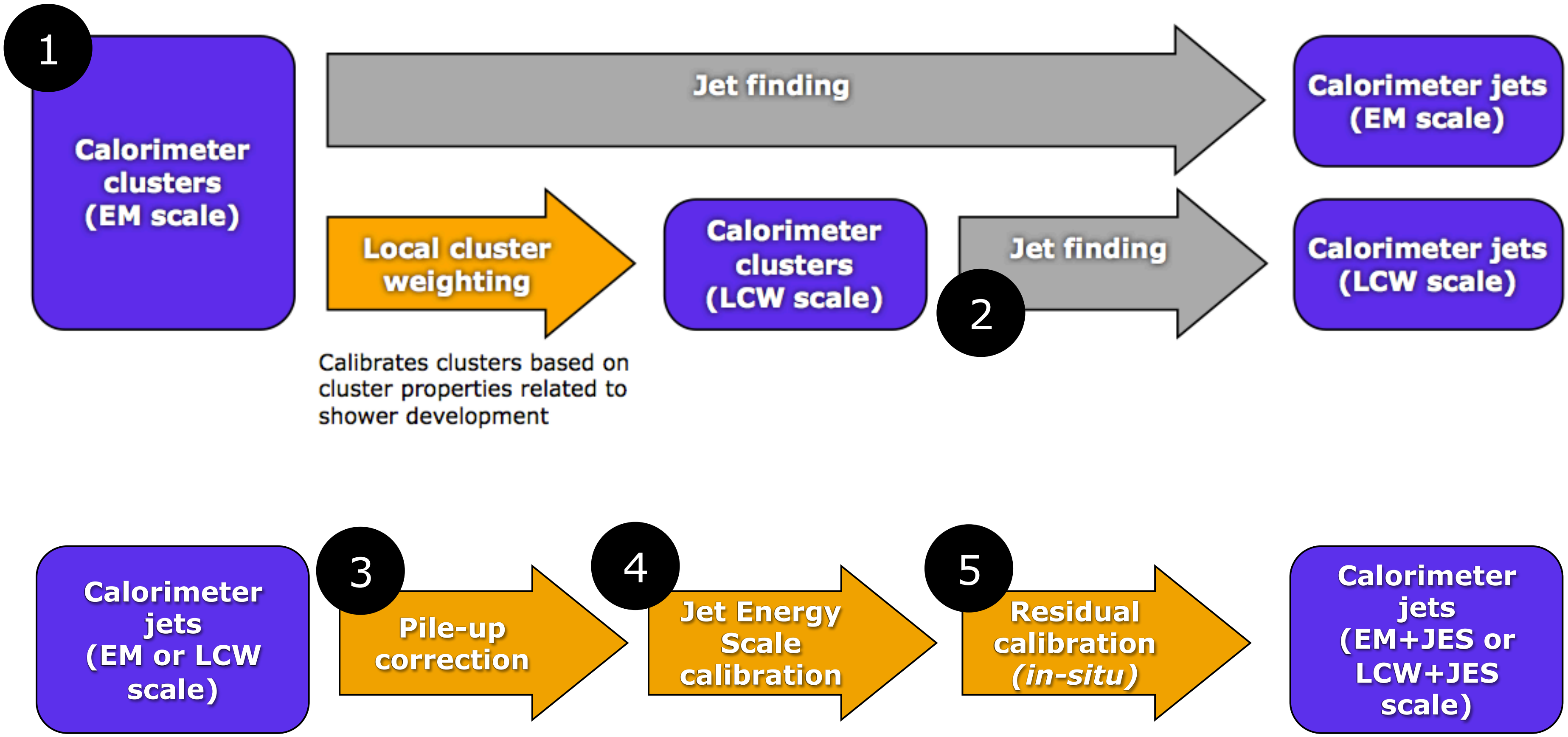
- **Jet substructure and jet tagging**
  - Large-radius jets energy and mass calibrated – identification of boosted hadronically-decaying objects.
  - Quark/gluon jet discrimination.

- **High luminosity scenario**
  - Pile-up suppression still possible with current techniques.

BACKUP

Jet reconstruction chain

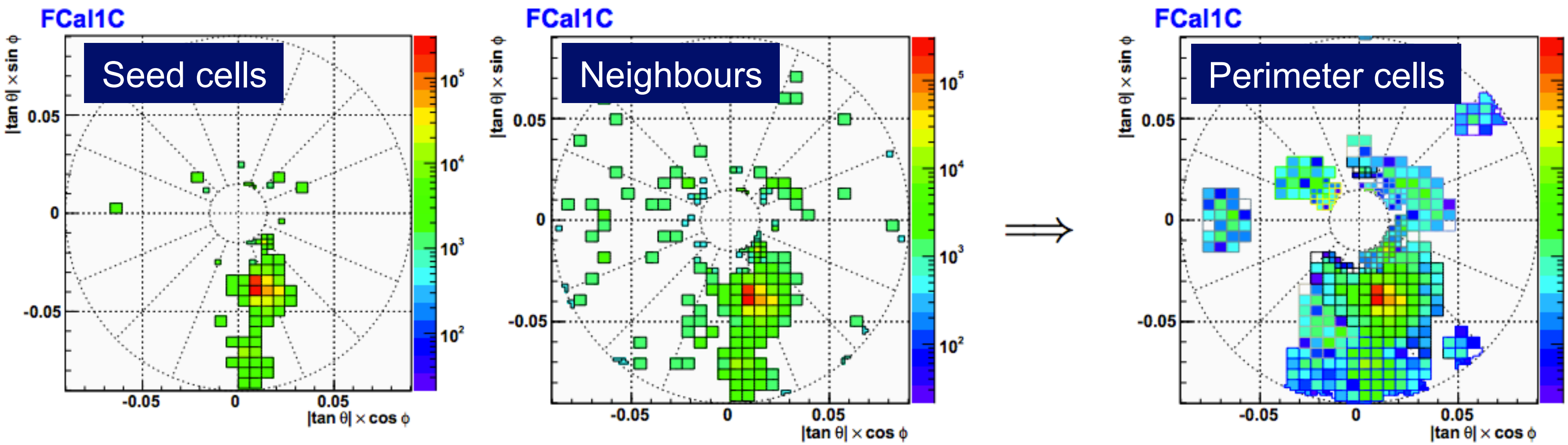
ATLAS-CONF-2013-083,   arXiv:1406.0076



Jet reconstruction (II)

1

- **Topo-cluster**: group of calorimeter cells topologically connected.
- σ_{noise} optimised for pile-up and electronic noise suppression.



$E > 4\sigma_{\text{noise}}$ $E > 2\sigma_{\text{noise}}$ $\Longrightarrow$ topo-clusters (one layer)

- **Electromagnetic calibration:**
  - All topo-clusters calibrated to the response for electrons
- **Local Calibration Weighting:**
  - Topo-cluster: electromagnetic or hadronic (energy density and depth)
  - Weighting scheme to correct for different e/π response
  - Out-of-cluster & dead material corrections

Pile-up suppression for E_T^{miss}

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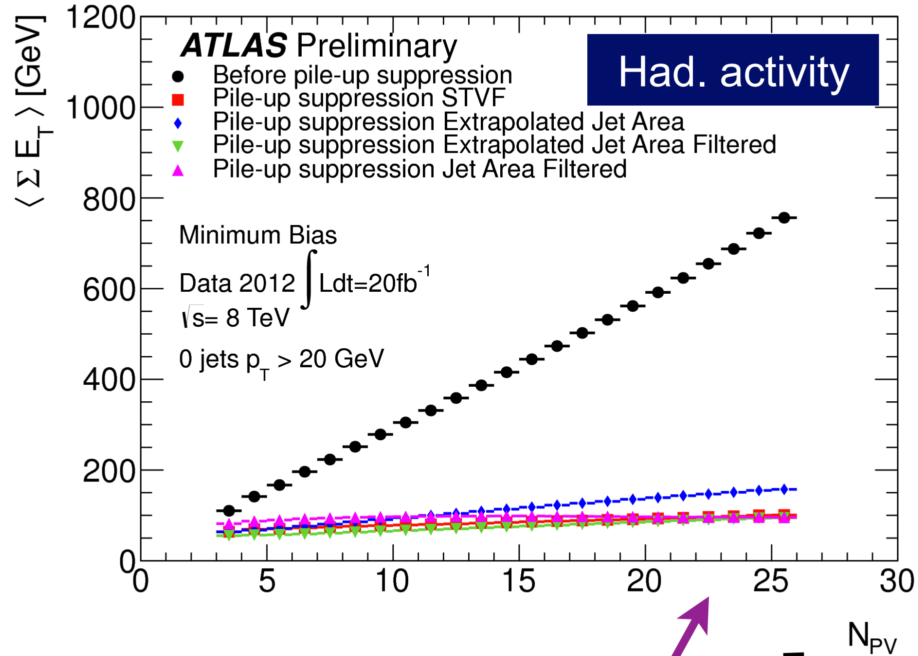

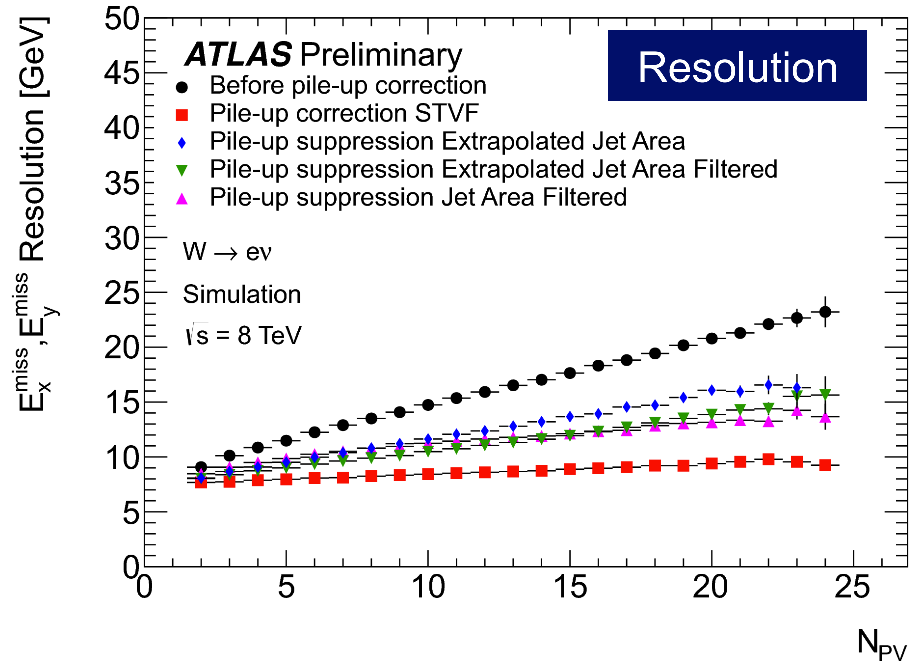

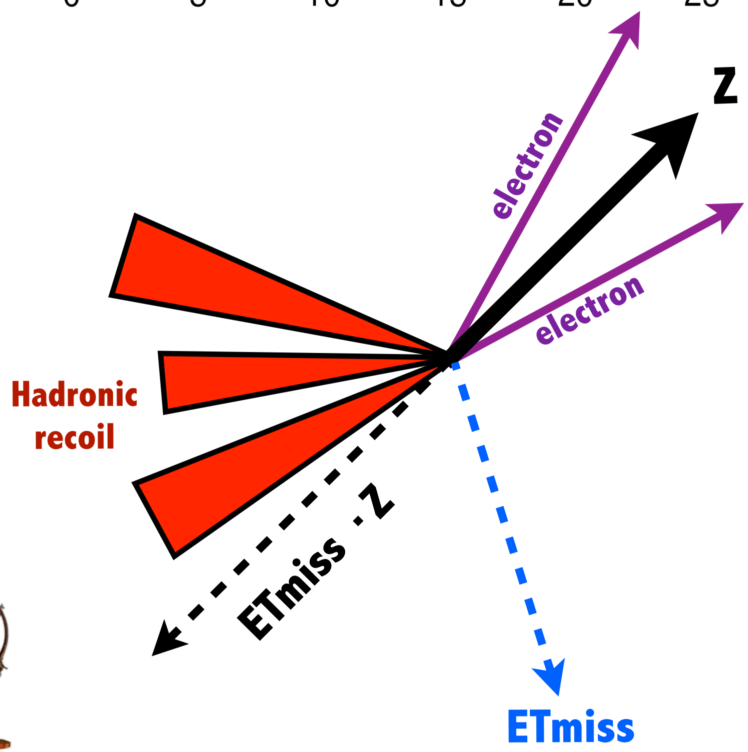

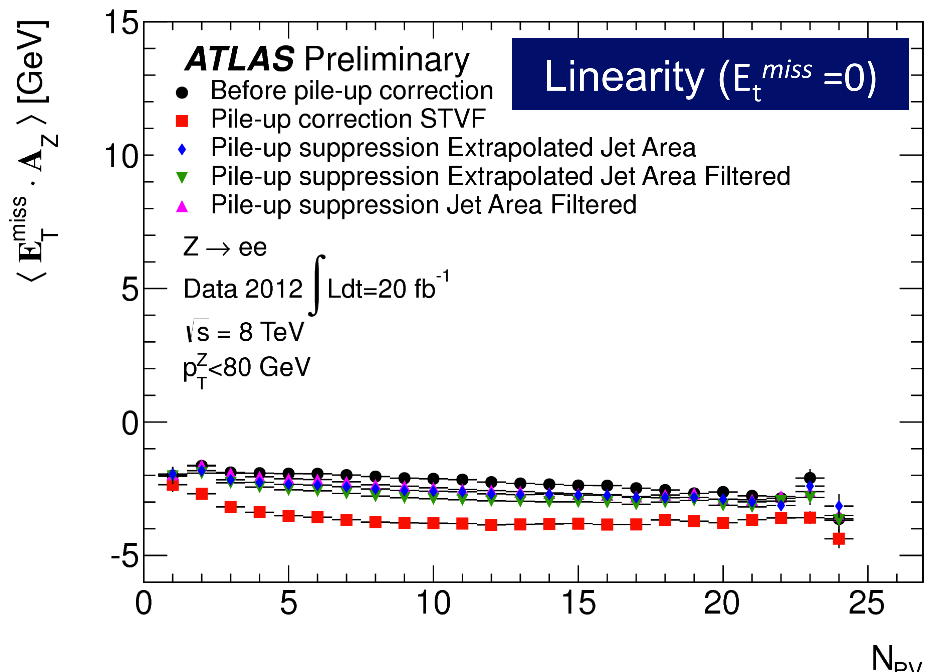

Learning from the shower history

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- **Q-jets**
- Parton shower history is not unique.
- Re-cluster each jet N times using random weights when choosing constituent pairs.
- Jet observables → distributions – provide discrimination of boosted particles vs light q/g background.
  - E.g. *Volatility*

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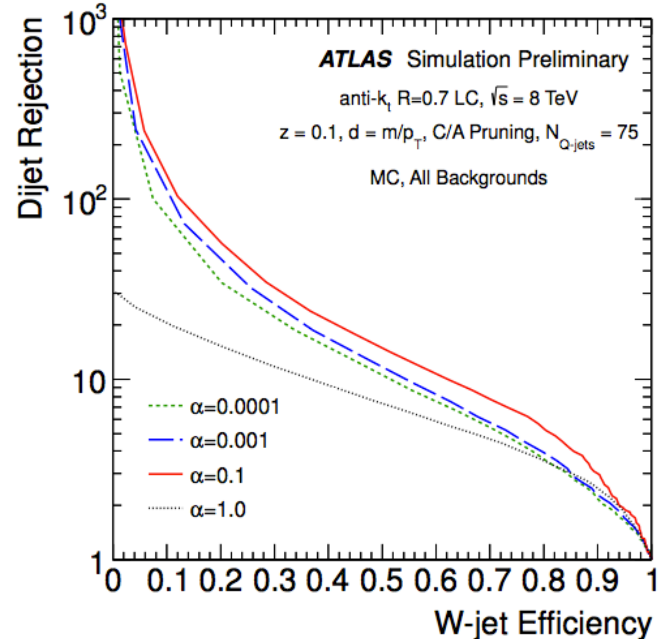

- **Jet charge**
- Momentum-weighted sum of the charges of tracks
- Constrains hadronization models.
- Useful for measurements and searches.

ATLAS-CONF-2013-086