ATLAS TopoClusters and Pile-up Suppression

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with lots of material collected by Ariel Schwartzman (SLAC)

ATLAS Topological Cell Clustering

Cluster seeding

- Defined by signal significance above primary threshold
  - Cells above this threshold can seed cluster

Cluster growth control

- Defined by signal significance above secondary threshold
  - Cells neighbouring seeds with significance above this threshold drive cluster growths

Cluster signal

- Defined by cells with significance above basic threshold
  - Cells to be considered in cluster energy sums

Use of negative signal cells

- Thresholds are considered for the absolute (unsigned) signal magnitude
  - Large negative signals can seed and grow clusters

Parameters for each stage optimized with testbeam data

- Experimental single pion shower shapes guide cluster algorithm development
  - Clean tuning reference!

Primary threshold

$$\left|\frac{E_{\text{cell}}}{\sigma_{\text{cell}}}\right| > S, \text{ default } S = 4$$

Secondary threshold

$$\left|\frac{E_{\text{cell}}}{\sigma_{\text{cell}}}\right| > N, \text{ default } N = 2$$

Collecting

$$\left|\frac{E_{\text{cell}}}{\sigma_{\text{cell}}}\right| > P, \text{ default } P = 0$$

(note $S \geq N \geq P$)

Famous "4/2/0" clustering in ATLAS

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ATLAS Topological Cell Clustering

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May 17, 2014

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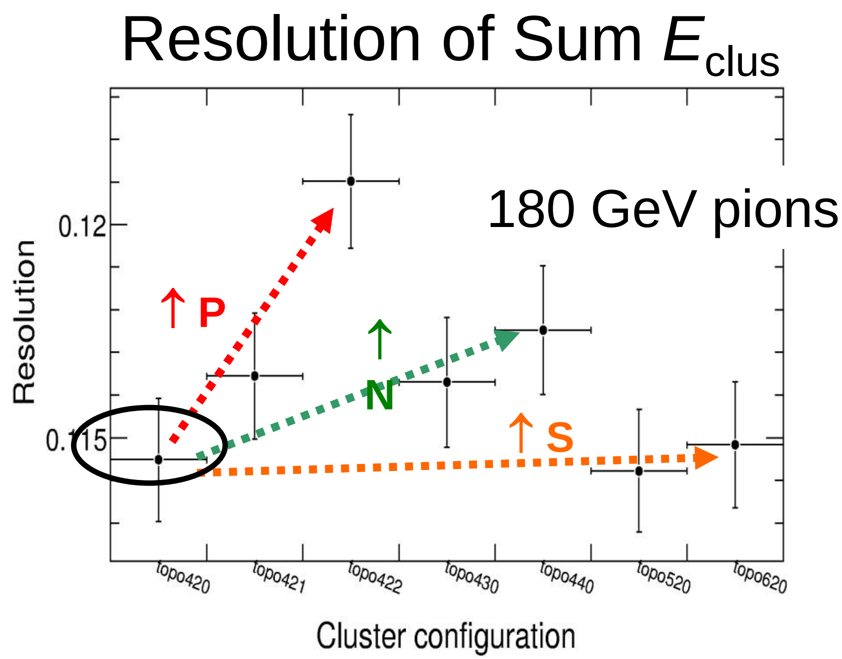
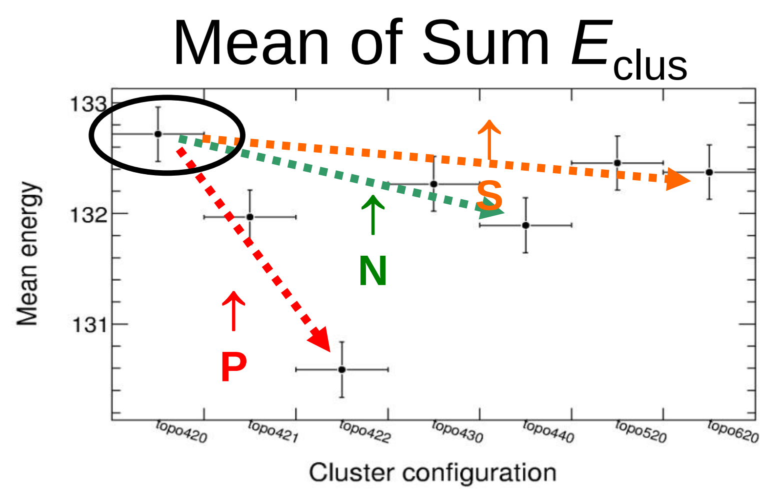
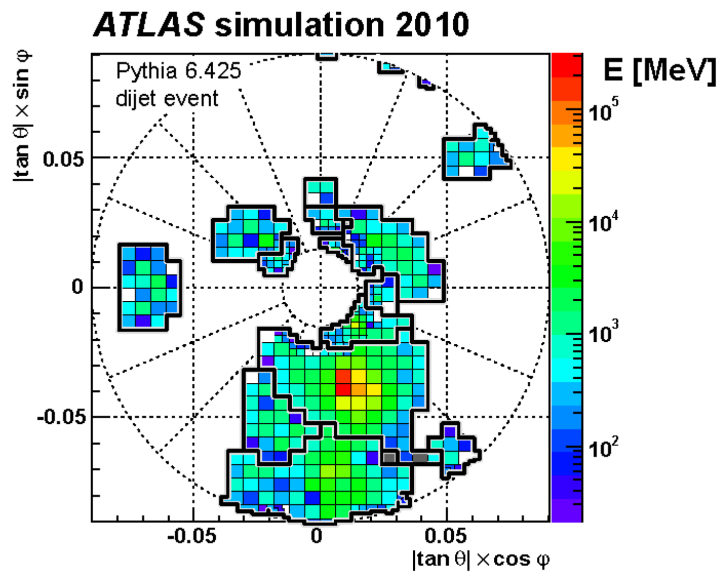




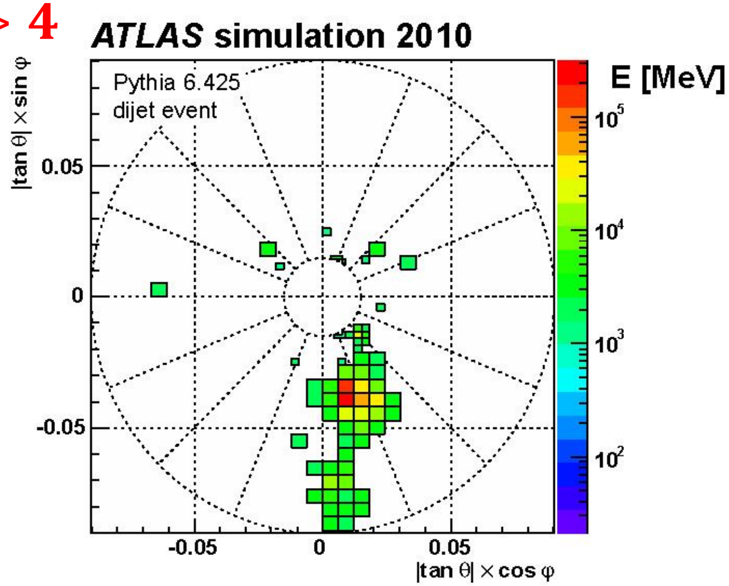
TopoClusters in the Detector

Basic ideas and features

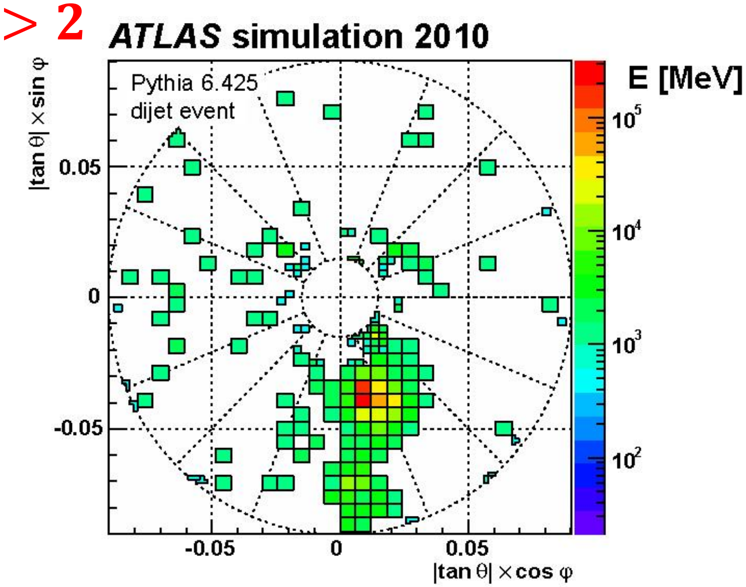
- Suppresses insignificant calorimeter signals
  - Pile-up and pile-up fluctuations
- Provide locally calibrated signal
  - Equalize relative inter-cluster response – 5-10% after local calibration, O(60%) before
  - Improves jet energy resolution
  - Reduces response dependence on jet flavor
  - Improves MET performance
- Reconstruct particle energy flow
  - Inside and out side of jet
    - But does not necessarily represent one particle!



$$\left|\frac{E}{\sigma}\right| > 4$$



$$\left|\frac{E}{\sigma}\right| > 2$$



TopoCluster Performance in Pile-up

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Performance in the presence of pile-up

Sensitivity to pile-up

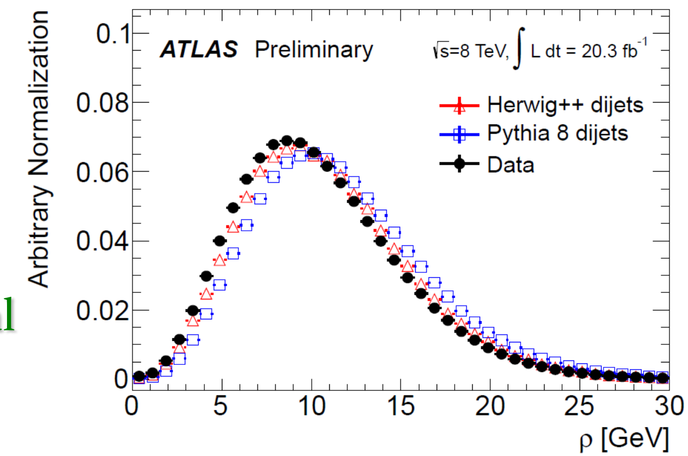
Residual effects due to non-Gaussian pile-up noise and cluster signal extraction

No straight forward association of clusters to signal or pile-up – no significant experimental handles from calorimeter signal

Physics message

Principal energy flow pattern preserved

JES mitigation using jet-area subtraction



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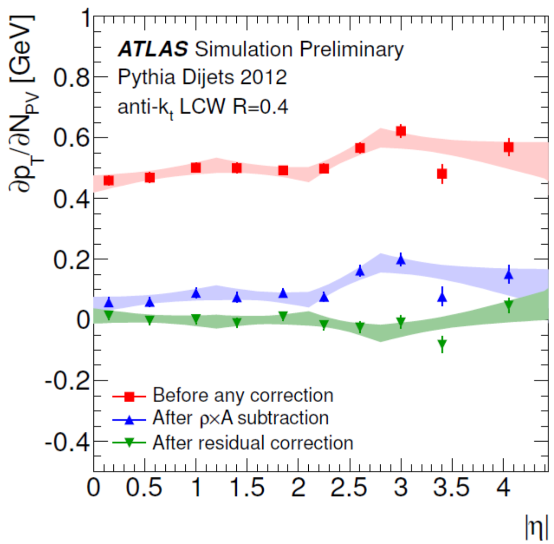

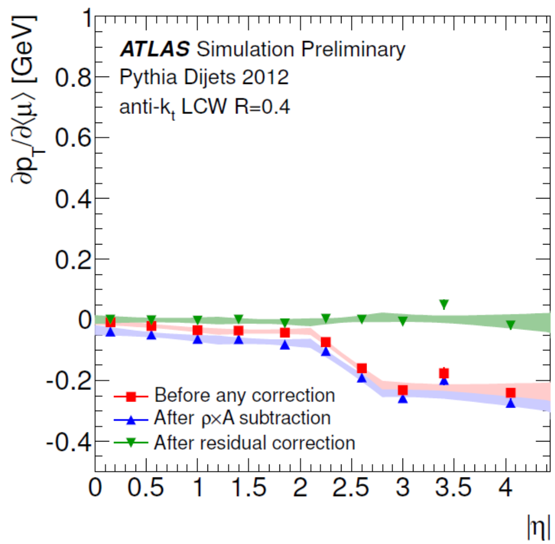

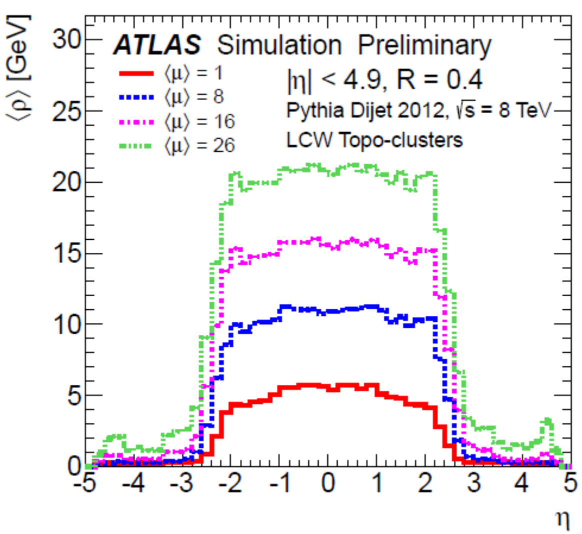

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Performance in the Presence of Pile-up

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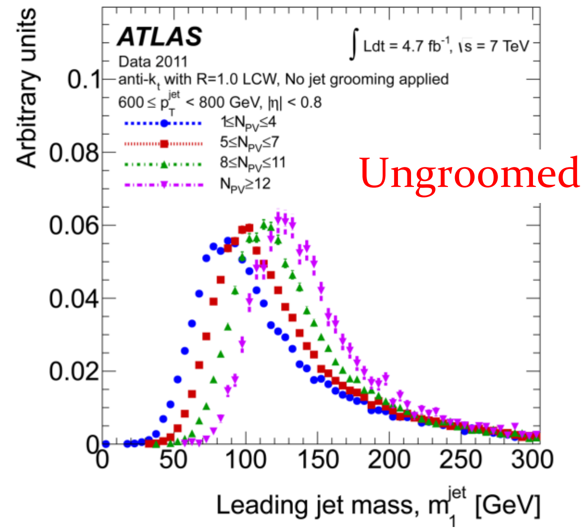
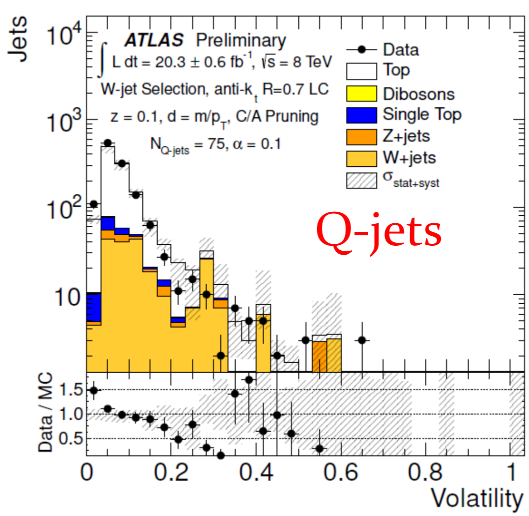
Jet substructure

- Highly granular calorimeters allow substructure analysis at small scales
  - TopoClusters are good representation of energy flow
  - Application of all recent jet grooming techniques is now part of many standard analyses
- Pile-up is controlled
  - Modelled well enough & focus on observables little affected anyway
  - But details of pile-up are often not modeled well especially outside of jets (like for missing transverse momentum)
  - Application of mitigation techniques possible within few % uncertainties



(ATLAS Coll., JHEP 1309 (2013) 076)



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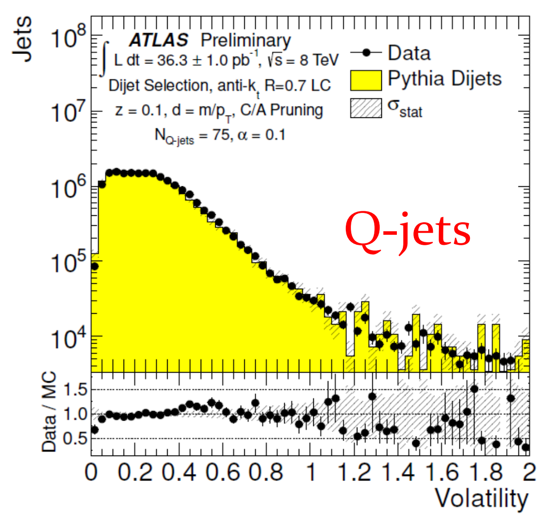

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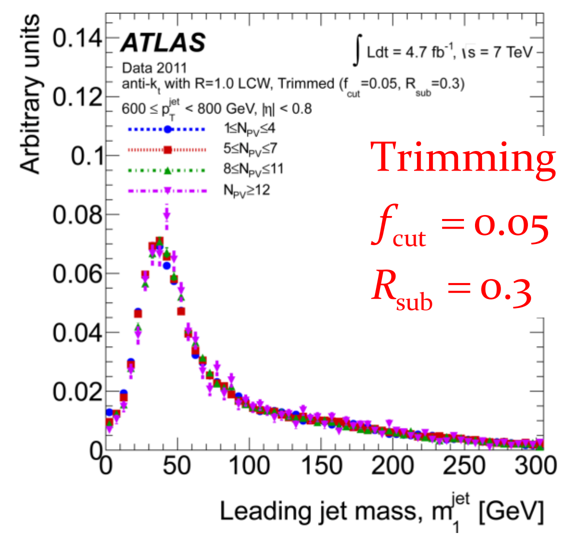

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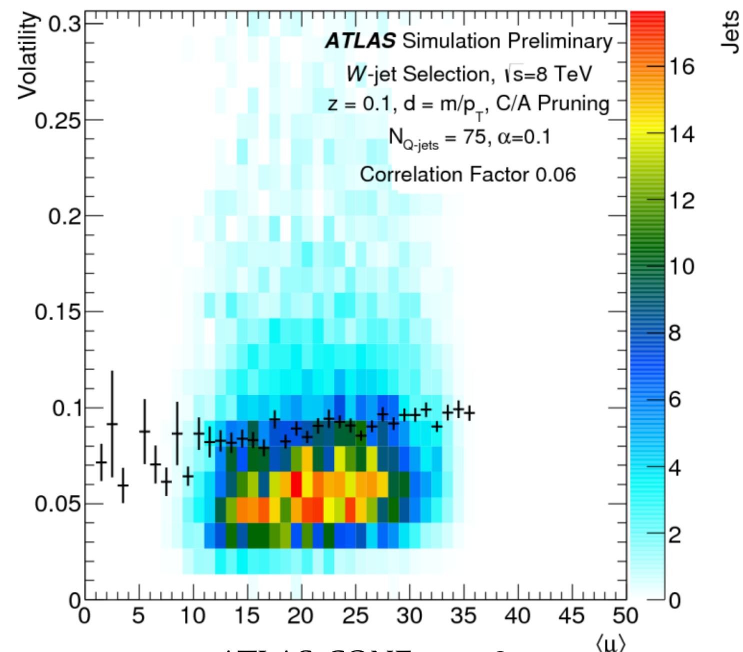
Q-jets with Pile-up

Volatility shows little dependence on pile-up

- Not too surprising as Q-jets are based on pruning – originally designed to suppress soft contributions to jets
  - Includes the diffuse scattering of energy into the jet from pile-up
- Very small effect on jets from *W* decays
  - Small volatility indicates small contribution of recombination to jet mass measurement – expected for 2-prong decay
  - Pile-up introduces more significant fluctuations on this scale than in di-jets where volatility is large to begin with…

Anti-k_T jets, $R = 0.7$



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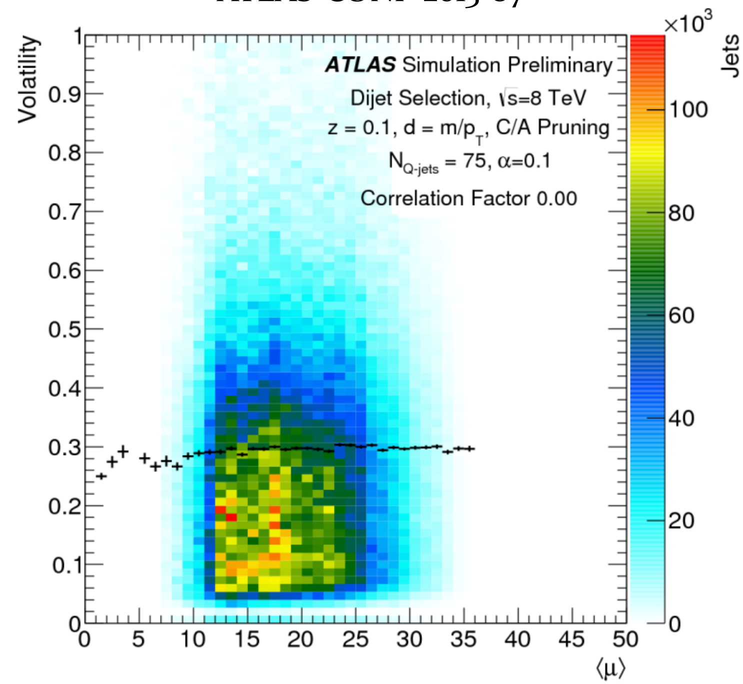

Splitting Scales & *N*-subjettiness with Pile-up

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Average effect of jet trimming on the pile-up dependence of the k_T splitting scales

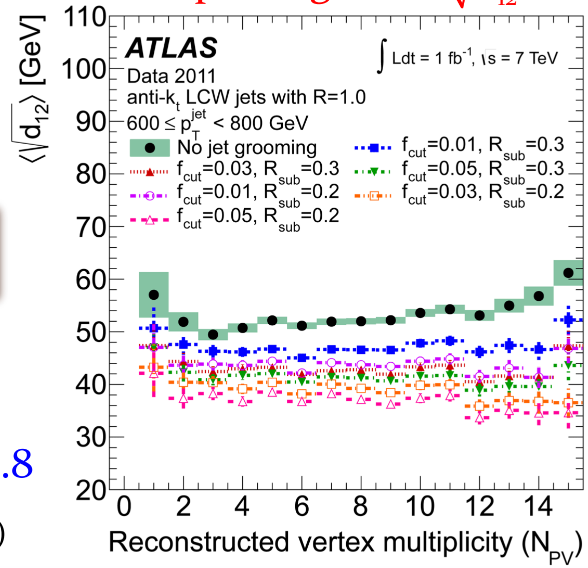
Anti-k_T jets, $R = 1.0$

inclusive jet sample:

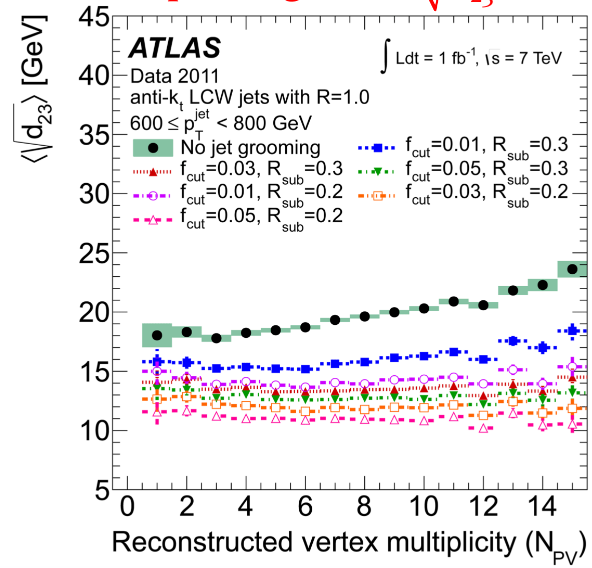
$600 < p_T^{jet} < 800$ GeV, $|\eta| < 0.8$

(ATLAS Coll., JHEP 1309 (2013) 076)

Splitting scale $\sqrt{d_{12}}$



Splitting scale $\sqrt{d_{23}}$



Effect of jet trimming on *N*-subjettiness ratios

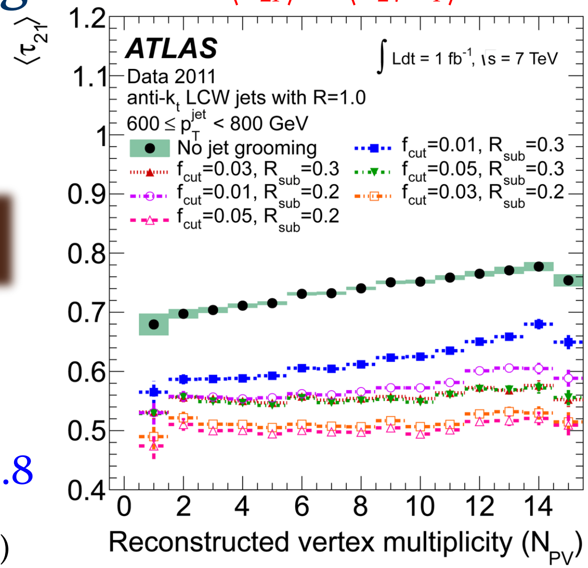
Anti-k_T jets, $R = 1.0$

inclusive jet sample:

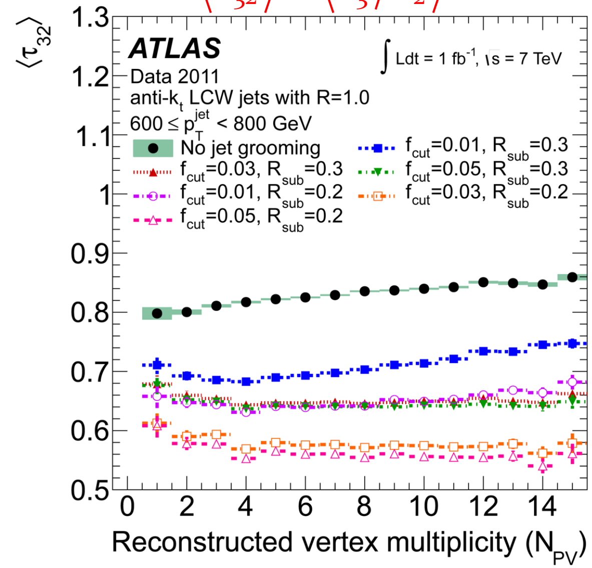
$600 < p_T^{jet} < 800$ GeV, $|\eta| < 0.8$

(ATLAS Coll., JHEP 1309 (2013) 076)

$\langle \tau_{21} \rangle = \langle \tau_2 / \tau_1 \rangle$



$\langle \tau_{32} \rangle = \langle \tau_3 / \tau_2 \rangle$



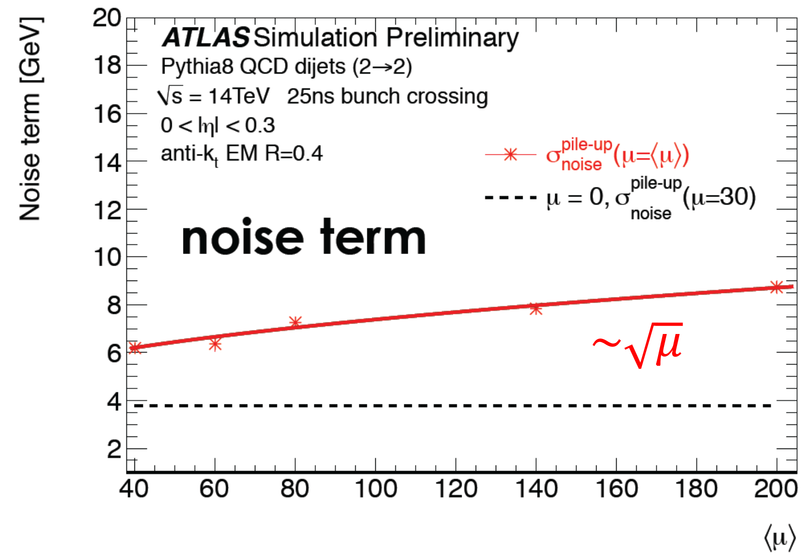
The following plots are from Ariel Schwatzman's Talk at BOOST2013

Noise increases

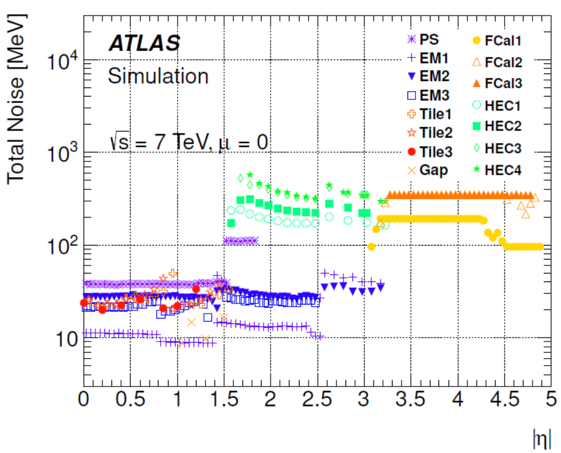
Minimum measureable energy increases

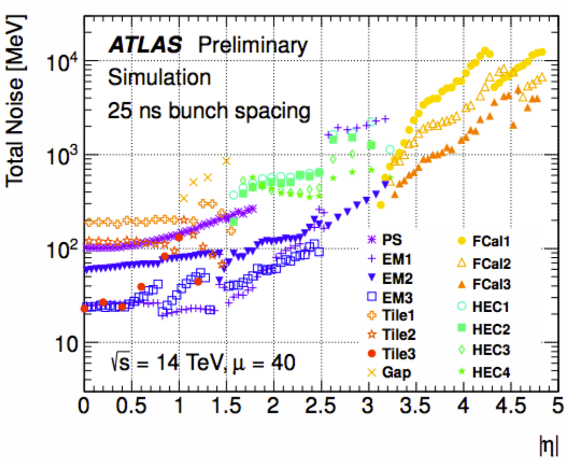
TopoCluster provide ~ fixed signal fixed significance/region

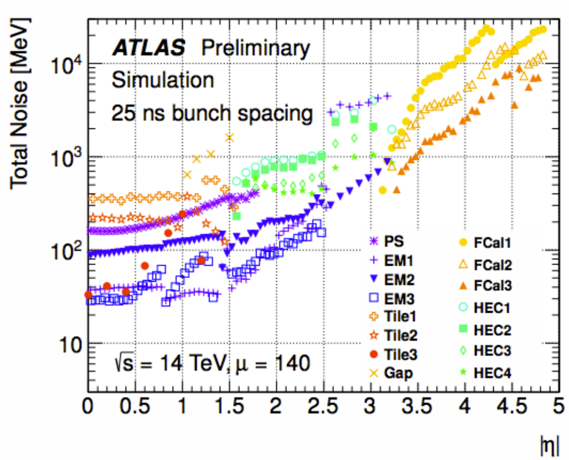
Changing noise changes regional acceptance



$$\sigma_{\text{noise}} = \begin{cases} \sigma_{\text{noise}}^{\text{electronic}} & \text{2010 running} \\ \sqrt{\left(\sigma_{\text{noise}}^{\text{electronic}}\right)^2 + \left(\sigma_{\text{noise}}^{\text{pile-up}}\right)^2} & \text{2011 / 2012 \& LHC Run II} \end{cases}$$







Pile-up Suppression at High Intensity

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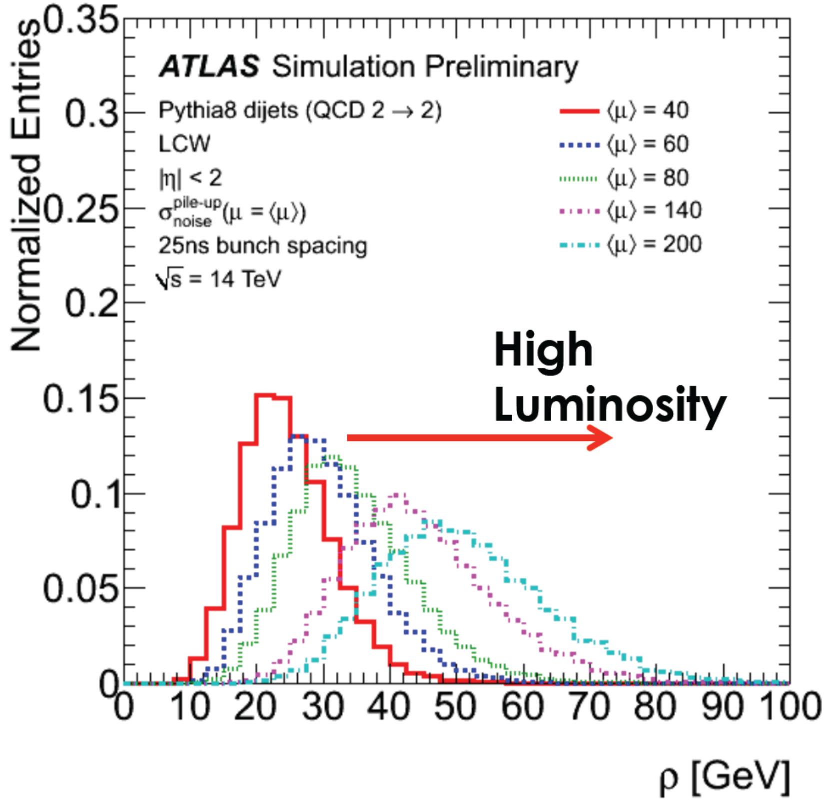
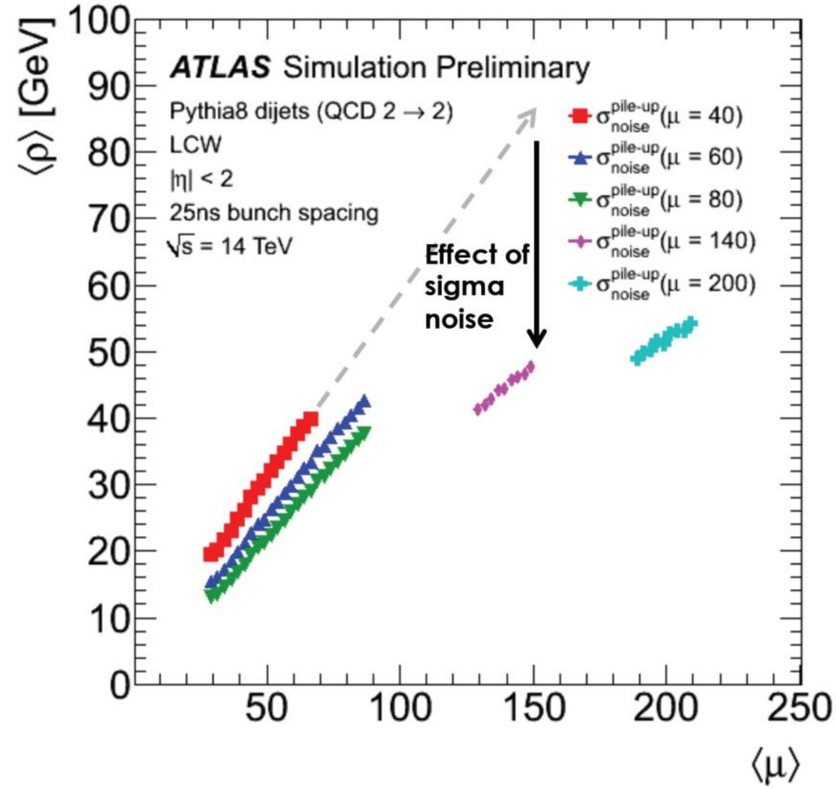
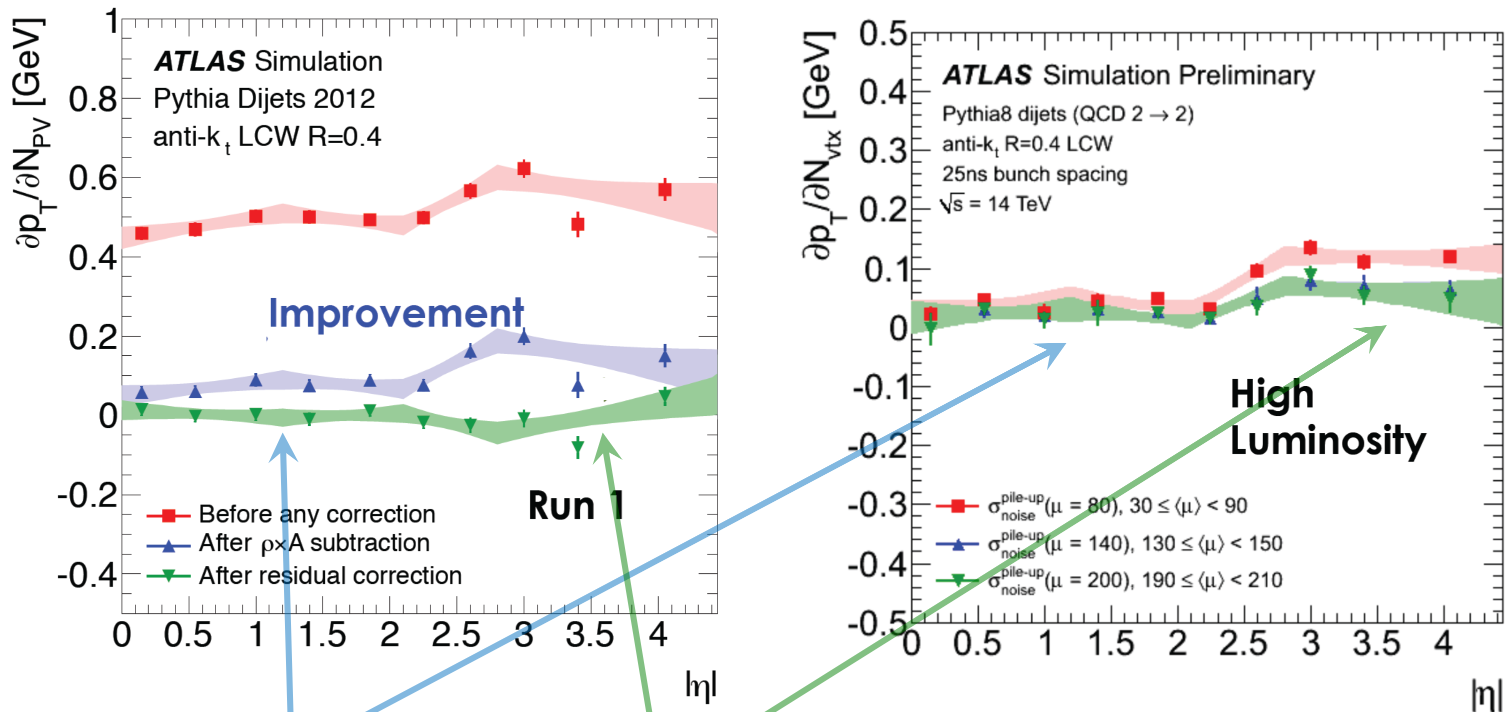




Jet-area based pile-up correction

- ρ-based mitigation technique (like for 2012 data)
  - Reconstructed from TopoClusters in $|\eta| \leq 2$
- $\sqrt{s} = 14$ TeV, 25 ns bunch spacing
  - "Correct" adjustment of σ_{noise} suppresses pile-up

Pile-up Suppression at High Intensity



$$p_T^{corr} = p_T - \rho A - \alpha(N_{PV} - 1) - \beta\langle\mu\rangle$$

- Residual offset mostly pile-up independent
  - After adjusting σ_{noise}
- Jet area subtraction, topological clustering, and local cluster calibration work well at high luminosity
  - All studies “out-of-the-box”

Jet Energy Scale & Resolution

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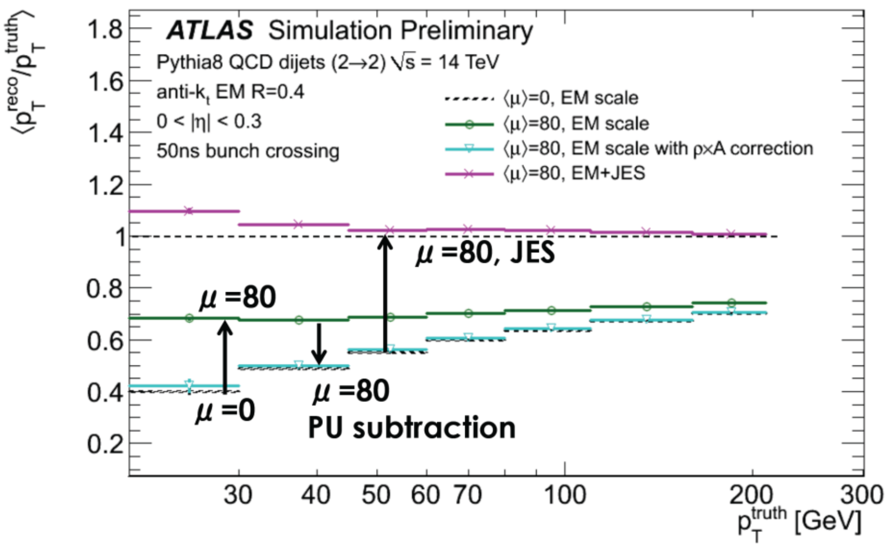

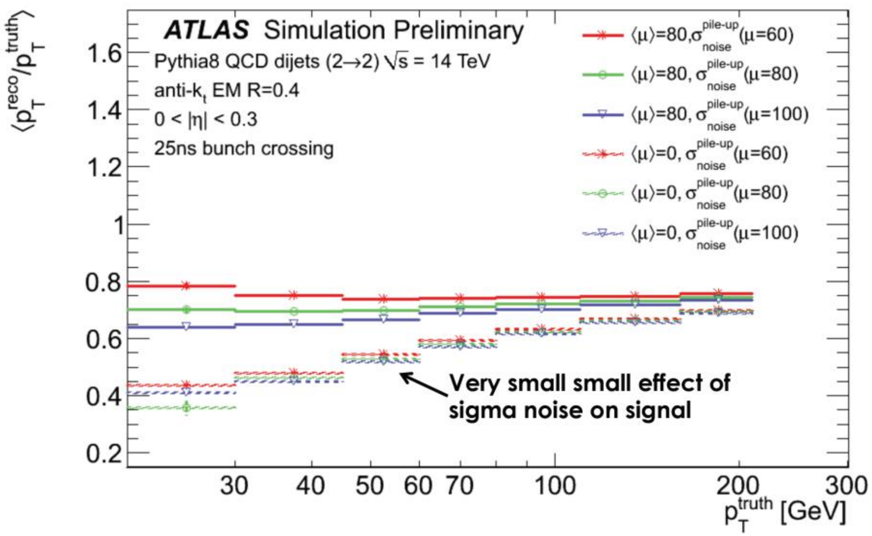

Jet response

- Effect of non-perfect noise thresholds on jets relatively small
  - Best linearity for correctly adjusted noise thresholds
  - Applying high noise thresholds in the absence of pile-up introduces significant non-linearity but small variations for $\sigma(\mu = 60) \rightarrow \sigma(\mu = 100)$

Jet energy scale

- Pile-up subtraction restores jet response to $\langle\mu\rangle$=0 performance
  - JES calibration restores the jet response to unity
- Jet Calibration Scheme works well up to very high luminosity

Jet Energy Scale & Resolution

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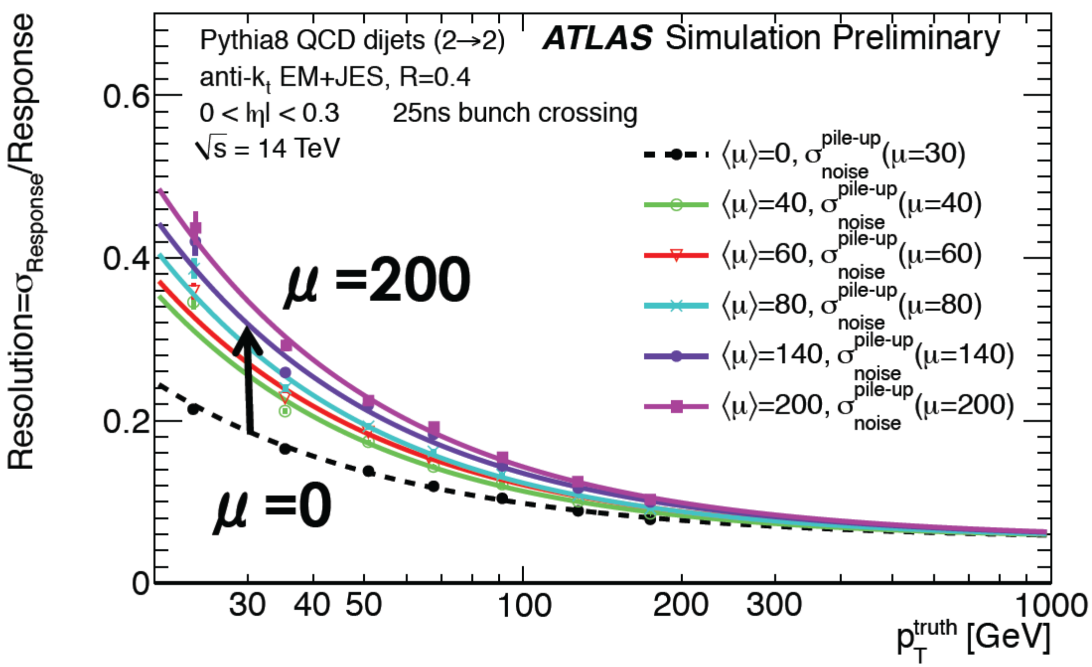
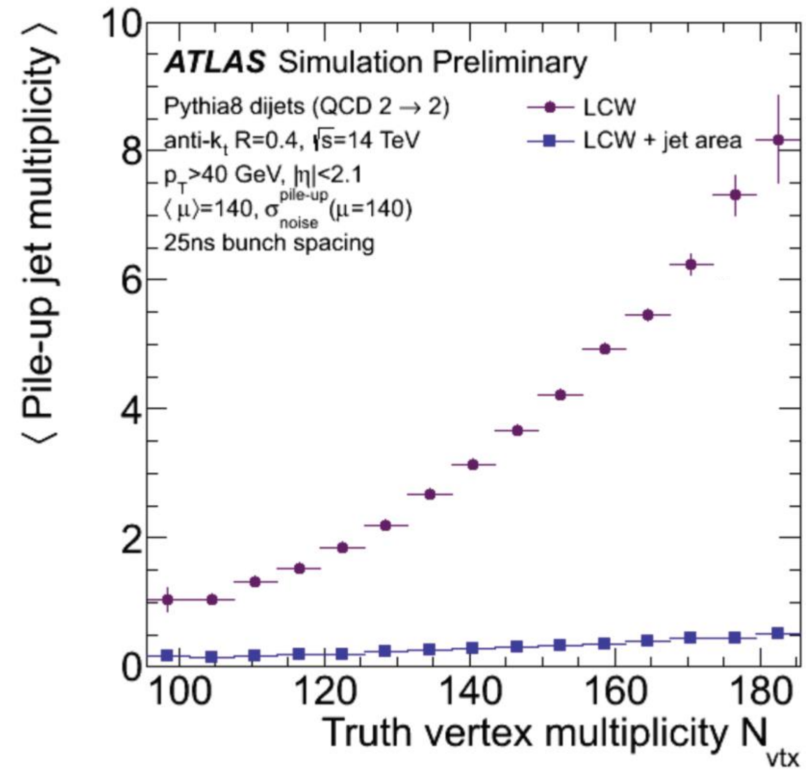
Fraction jet energy resolution

- Degraded at low p_{T} due to increased (pile-up) noise term
  - Local pile-up fluctuations within the event – not captured by global event-by-event ρ-based correction
- Noise term increases as $\sqrt{\mu}$
  - Linear behavior of topo-clustering, pile-up subtraction, and jet calibration up to very high luminosity
- No use of tracks here
  - Can help reduce local fluctuations



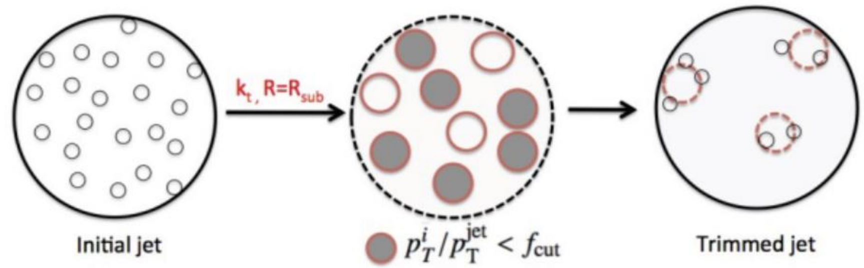
Pile-up subtraction reduces number of pile-up jets

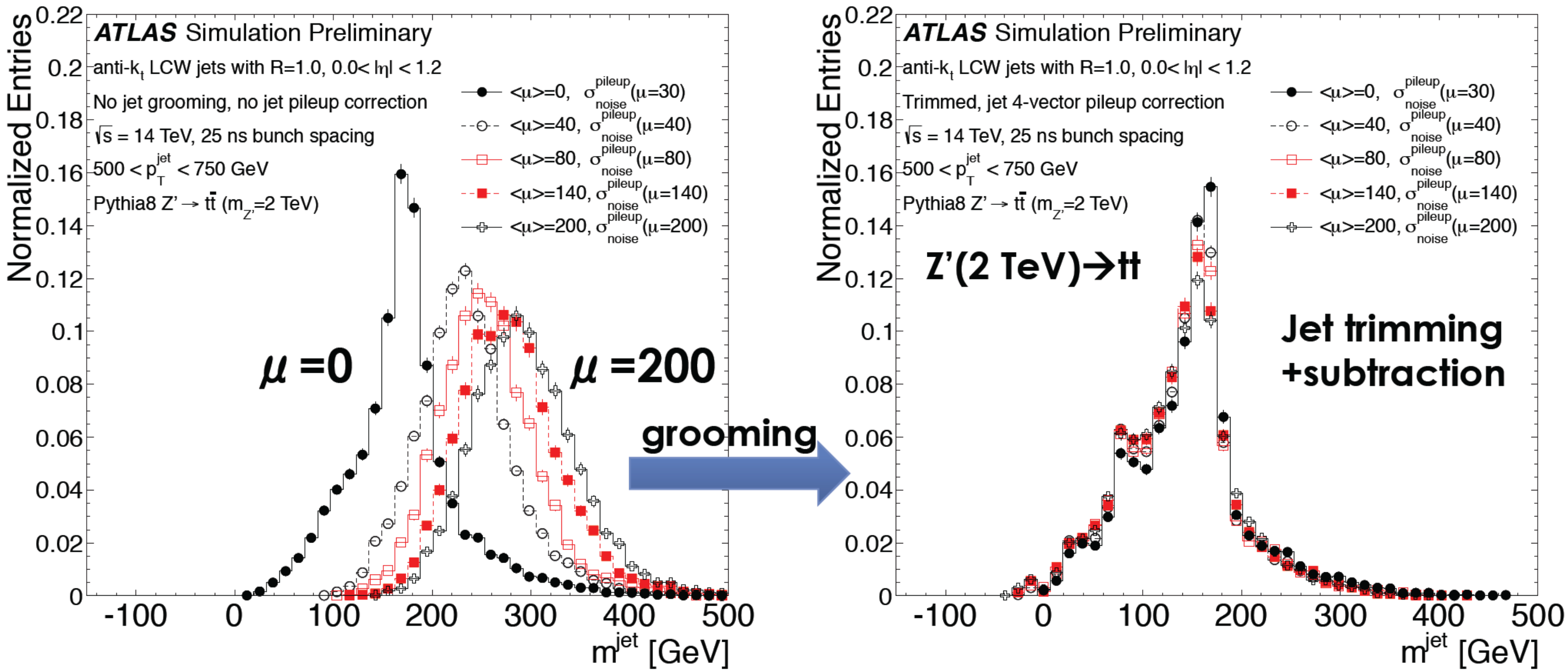
- Significant reduction
  - About 3 pile-up jets per event with $p_T > 40$ GeV at $N_{PV} = 140$ before correction → less than 0.5 after correction
- No tracking or vertexing information used
  - Expect even better rejection with track- and vertex-based filters (see Pascal Nef's talk May 16, 2014)



Jet substructure reconstruction

- Test performance with 2012 based optimization
  - Trimming, $R_{sub} = 0.3$, $f = 5\%$
- Works at $\mu = 200$
  - Stable jet mass reconstruction at very high intensities





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Jet Grooming Performance (2)

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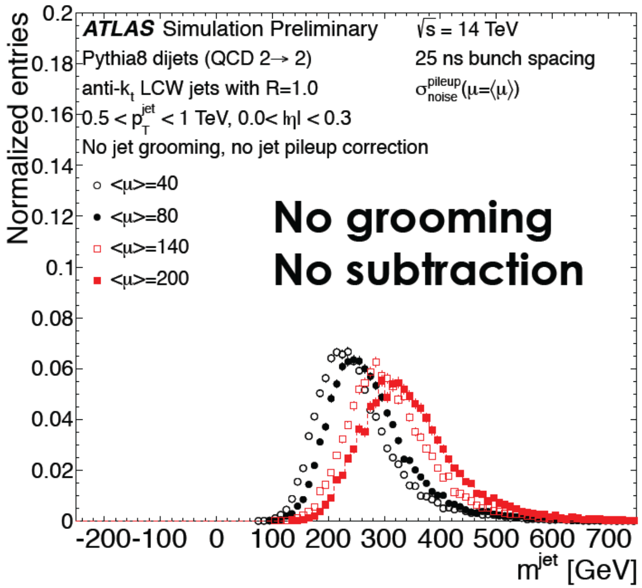
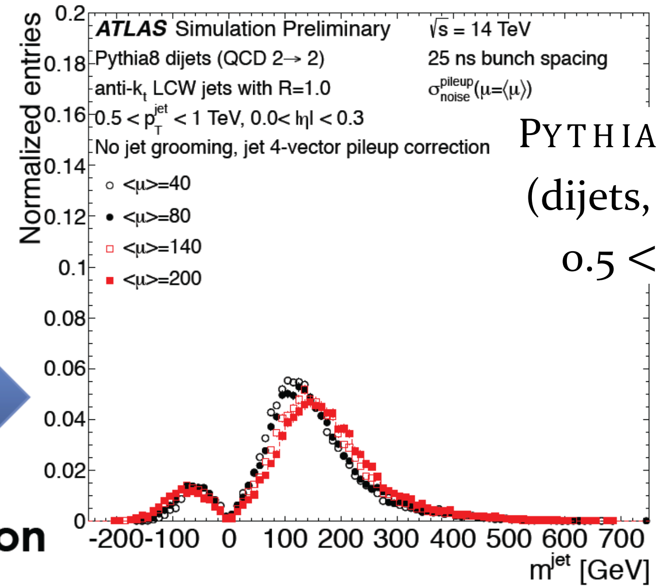


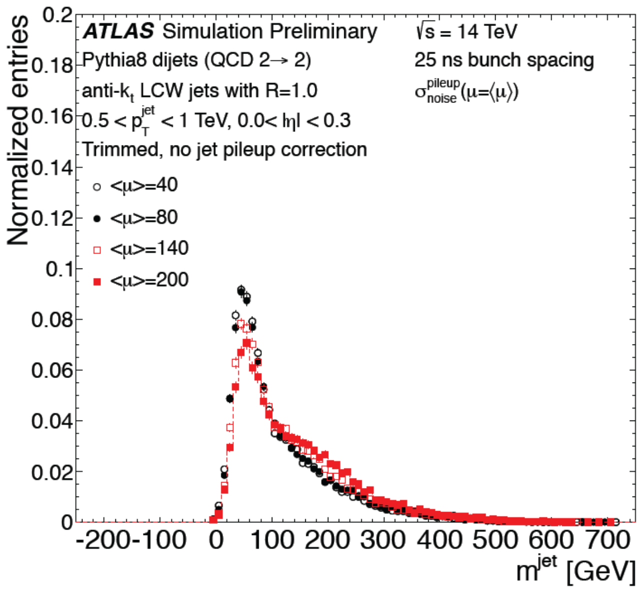
No grooming
No subtraction

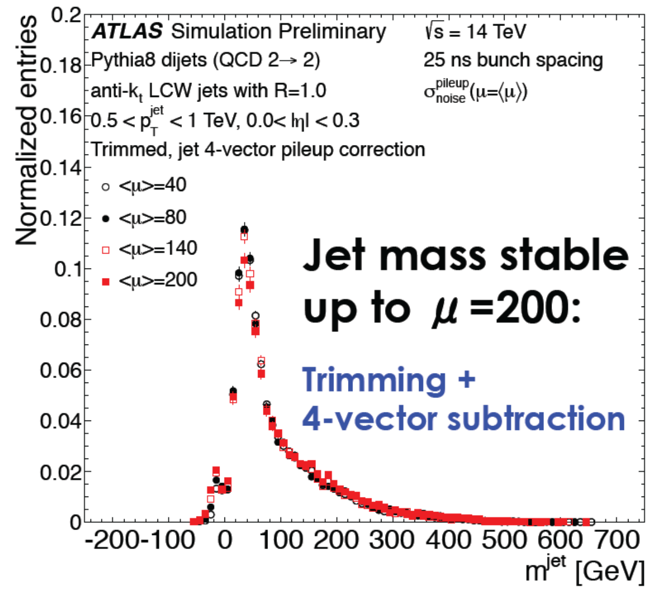
4-vector subtraction



PYTHIA8 QCD $2 \rightarrow 2$
(dijets, $\sqrt{s} = 14$ TeV)
$0.5 < p_T < 1$ TeV

trimming





Jet mass stable up to μ =200:

Trimming + 4-vector subtraction

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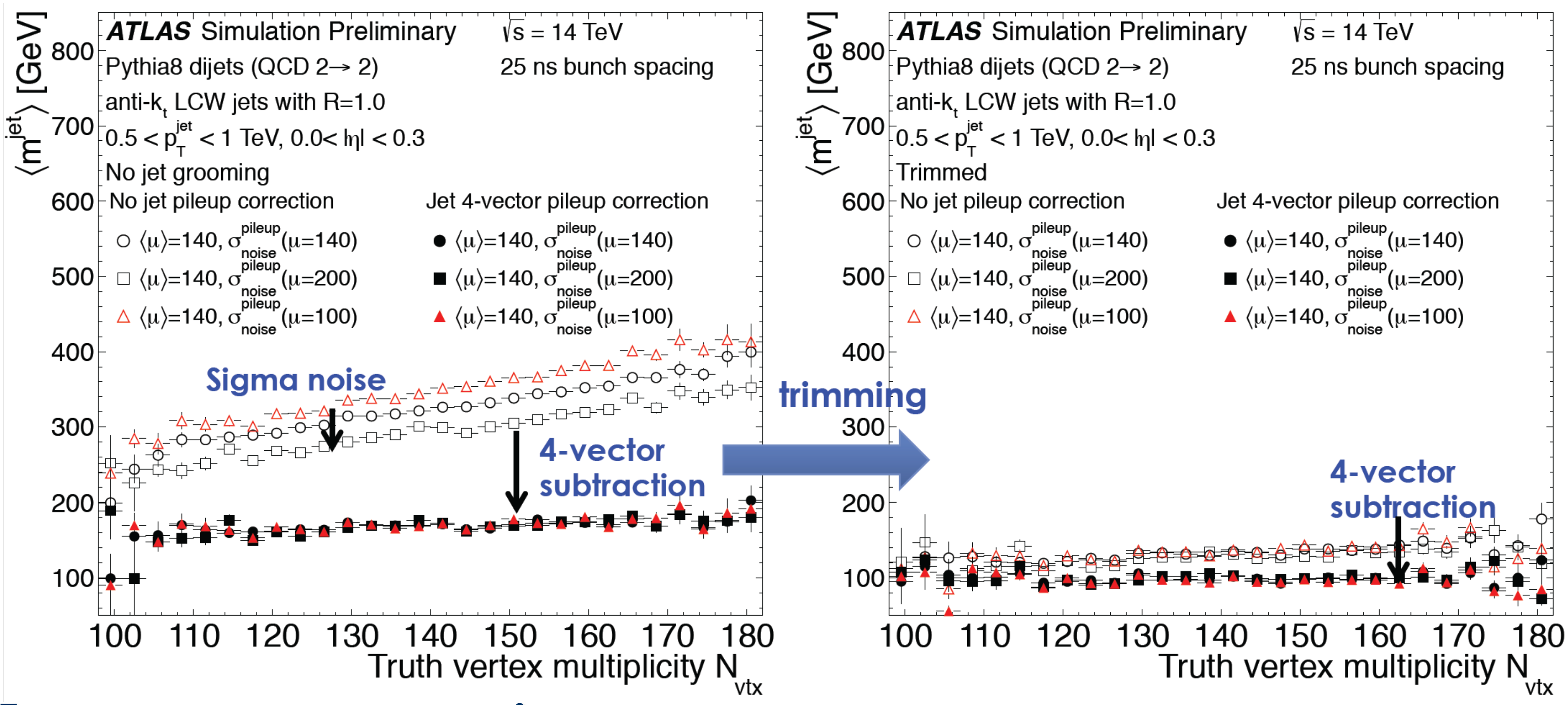
Jet Mass Reconstruction at high Intensity



Jet mass reconstruction

- Raising noise thresholds
  - Reduces mass but does not affect pile-up dependence
- 4-vector jet area subtraction suppresses pile-up
  - Even without further grooming
- Trimming with subtraction mitigates pile-up effect best
  - Pile-up independent jet mass response – but need to address p_T-response

Conclusions

TopoCluster signal definition at high intensity

- Stable signal definition with predictable features
  - If noise thresholds are adapted to pile-up fluctuations – no precise adjustment needed (not really possible…)
- Global jet kinematics can be corrected
  - Relative jet energy resolution at low transverse momentum can be recovered using p-flow and CHS – under investigation in ATLAS
  - High energy limit comparable to 2010 – 2012 performance
- Some concern for MET reconstruction
  - Rising pile-up noise shifts minimum measureable energy up – loss of small energy acceptance
  - Can affect final states with low multiplicity hard interactions (e.g., $H \to WW$) – soft term may have to be recovered (more tomorrow!)

Pile-up is a major challenge

- 25 ns running should help ATLAS
  - Better in-time/out-of-time online pile-up cancellation by shaping function
  - But slightly larger fluctuations
- Radiation, trigger, object reconstruction quality also for leptons, computing effort…
  - No need to panic, though!