Jets and Missing ET at ATLAS

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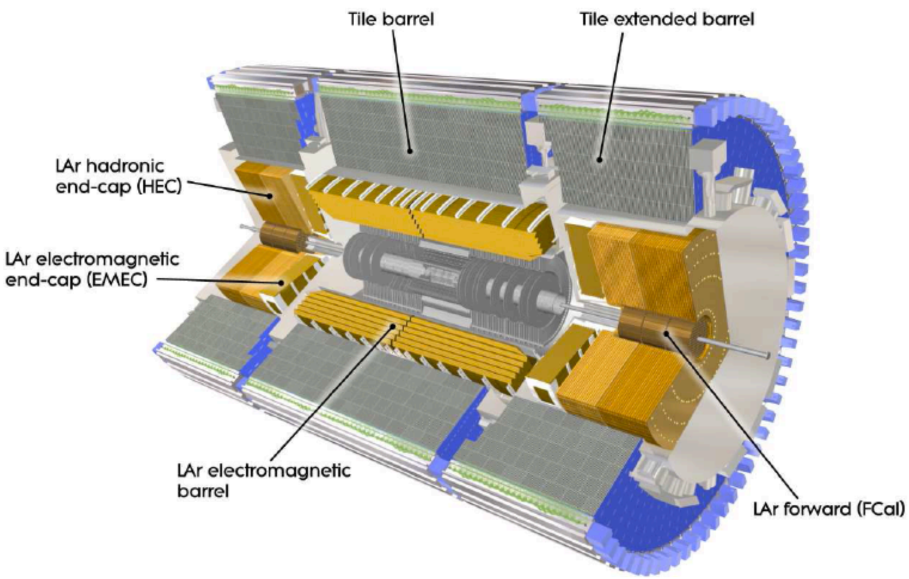
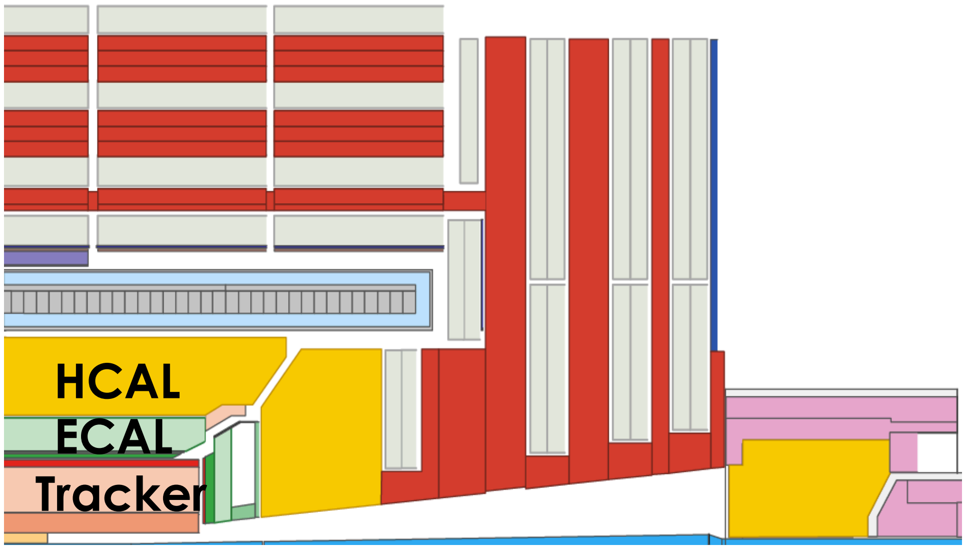
JetMET @ High Pileup, Fermilab, 27-Jan-2014

Outline

- **ATLAS Calorimeter and signal formation**
  - Topoclustering
- **Jet calibration and uncertainty**
  - Pileup subtraction and suppression
  - Use of tracks
- **Jet substructure**
  - Track-based grooming
- **Jet-by-jet tagging**
- **Missing ET**
- **Jet and missing ET reconstruction and performance under HL-LHC conditions**
  - ATLAS Full simulation results

ATLAS and CMS





Tracking detector within 2T magnetic field

Excellent hadronic calorimeter resolution

Fine longitudinal segmentation

- 3 to 7 layers

Long integration time:

- ~20 bunch crossings

Tracking and calorimeters inside **strong 3.8 T superconducting magnet**

- Reduced inactive material in front of calorimeters
- **Greater separation between particle showers**
- Low p_T charged particles not reaching calorimeter and increased out-of-cone

High transverse granularity and high resolution crystal ECAL

Fast integration time (~2 bunch crossings)

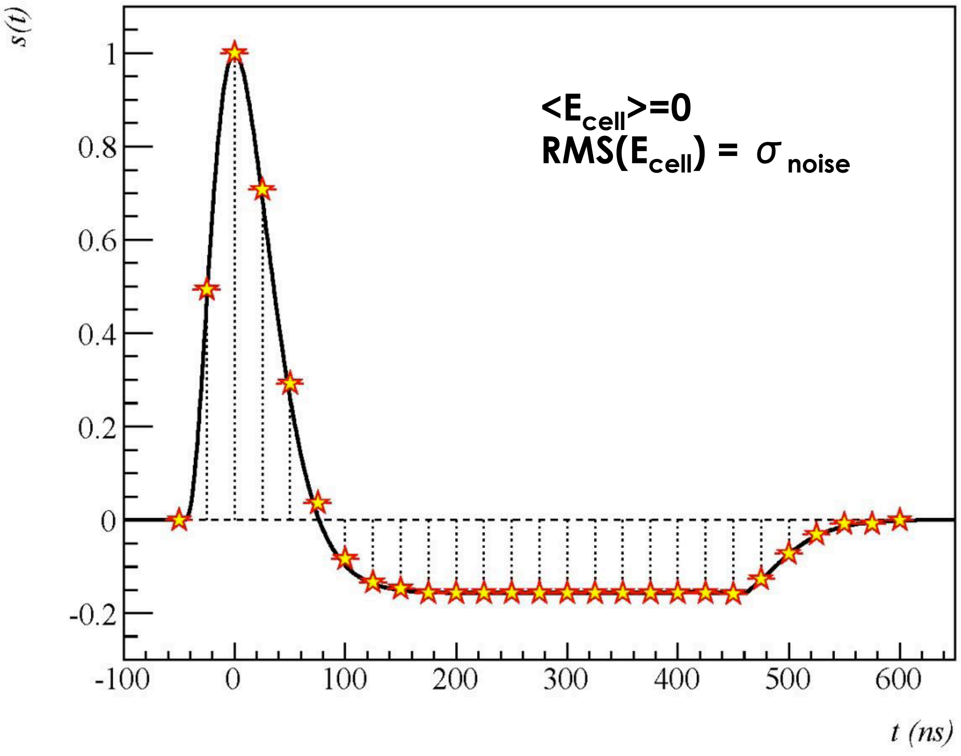
- no out-of-time pileup

No longitudinal segmentation in ECAL/HCAL

Calorimeter signal reconstruction

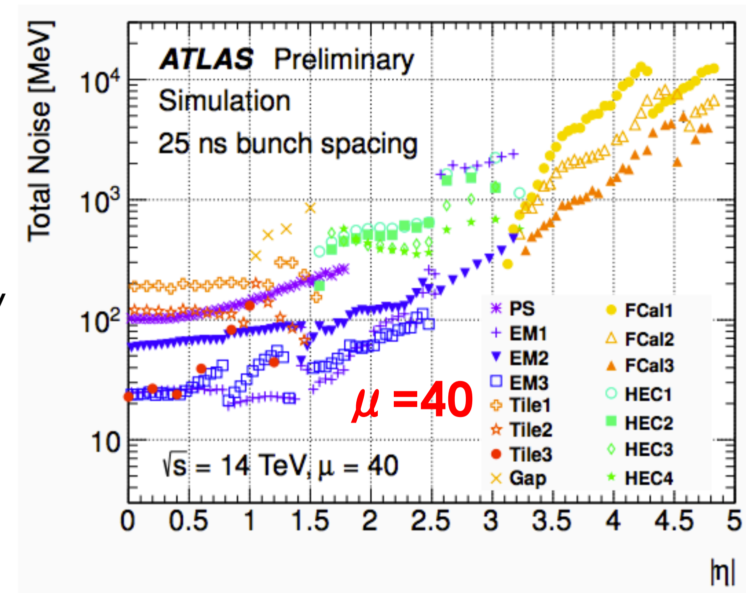
- **Slow signal collection in liquid argon calorimeters**
  - Out-of-time pileup
- **Use of fast bipolar signal shaping to cancel pileup on <u>average</u>**
  - Shape pulse integral = 0 leads to an average cancelation of pileup
  - Signals from pileup history suppresses in-time pileup contributions
- **Residual pileup effects:**
  - Bunch structure, fluctuations

Online pileup suppression

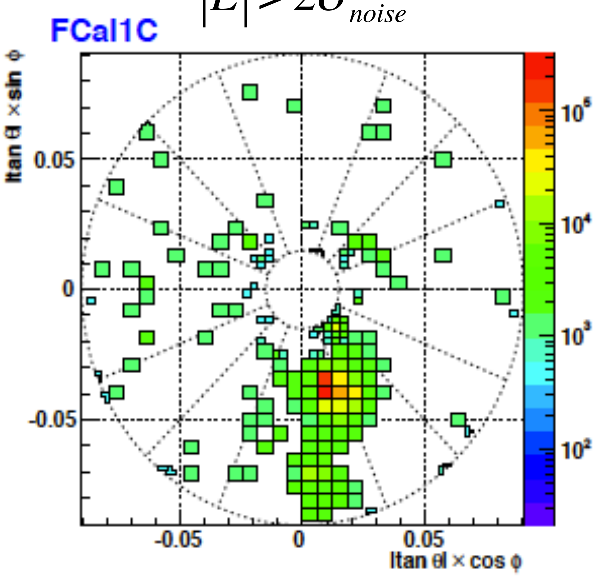


Topoclustering

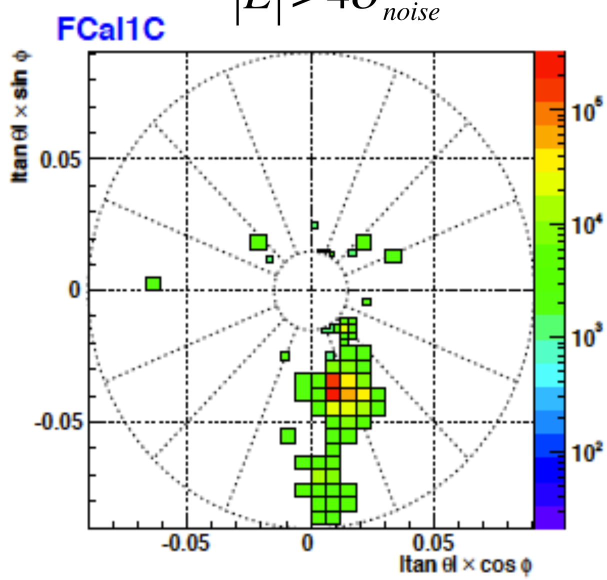
- **Topological clusters:**
  - 3D nearest-neighbor algorithm that clusters calorimeter cells with energy significance ($|E_{cell}|/\sigma$) >**4** for the seed, >**2** for neighbors, and >**0** at the boundary
- **Sigma noise**: electronic + pileup noise
  - Adjusted with μ for **pileup noise suppression**



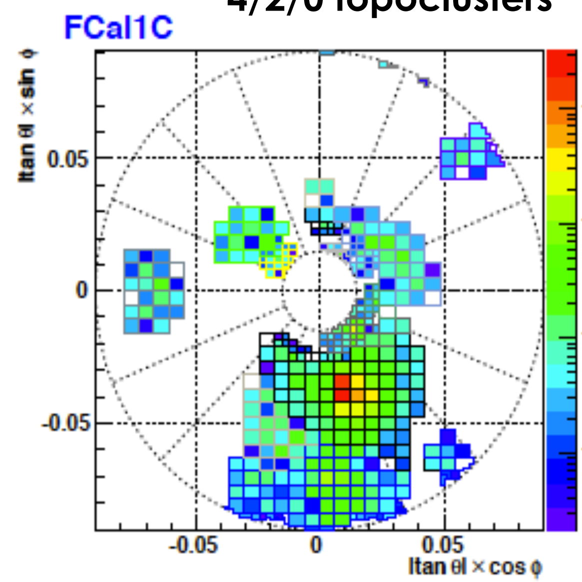
$|E| > 2\sigma_{noise}$



$|E| > 4\sigma_{noise}$



4/2/0 topoclusters



Jet calibration

Jet energy scale

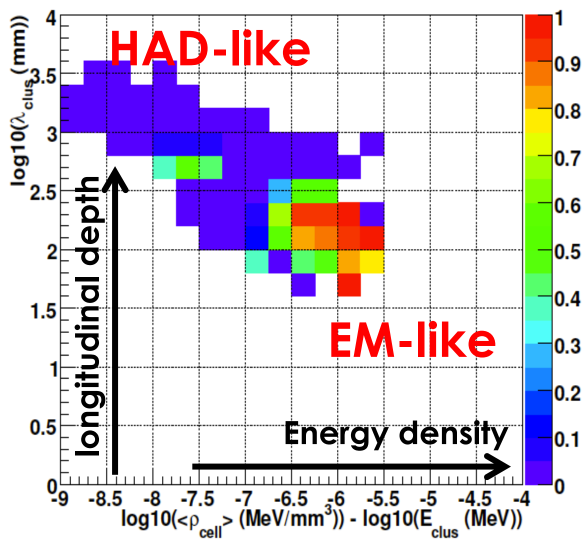
inputs

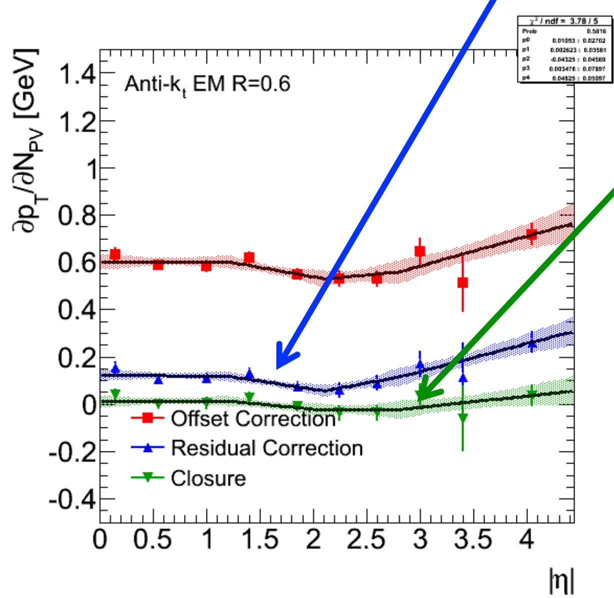
Topo-clusters (pileup noise threshold) → Local cluster weighting (LCW) → Event-by-event pileup subtraction → Residual offset (out-of-time, occupancy) → Jet Energy Scale

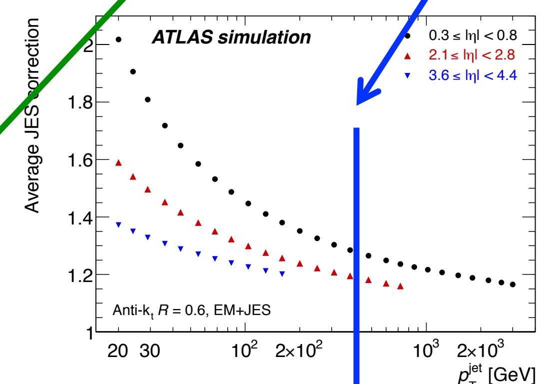
Pileup noise:
σ(μ)

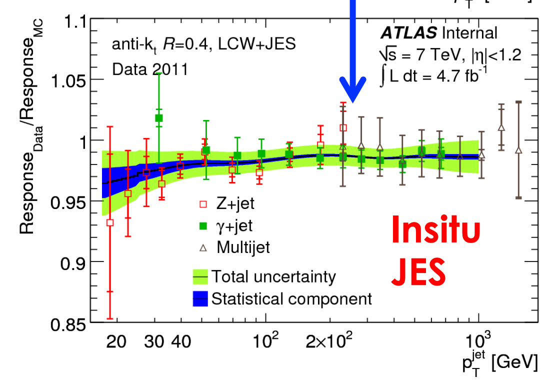
EM/HAD classification

$$p_T^{calib} = \left(p_T - \rho A - \alpha (N_{PV} - 1) - \beta \langle \mu \rangle \right) \times JES$$









Pileup subtraction (I)

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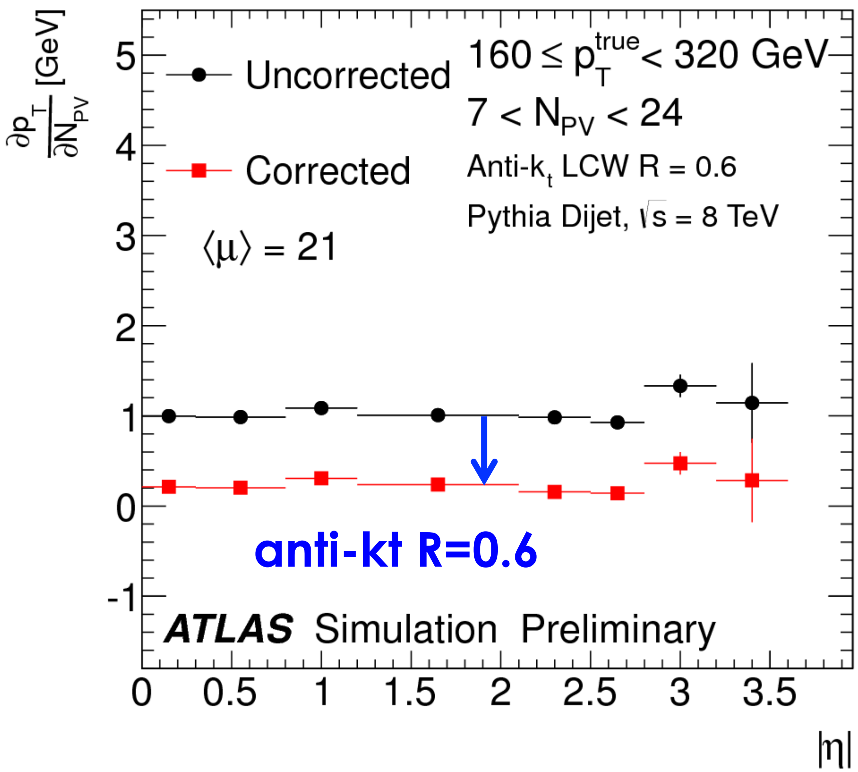
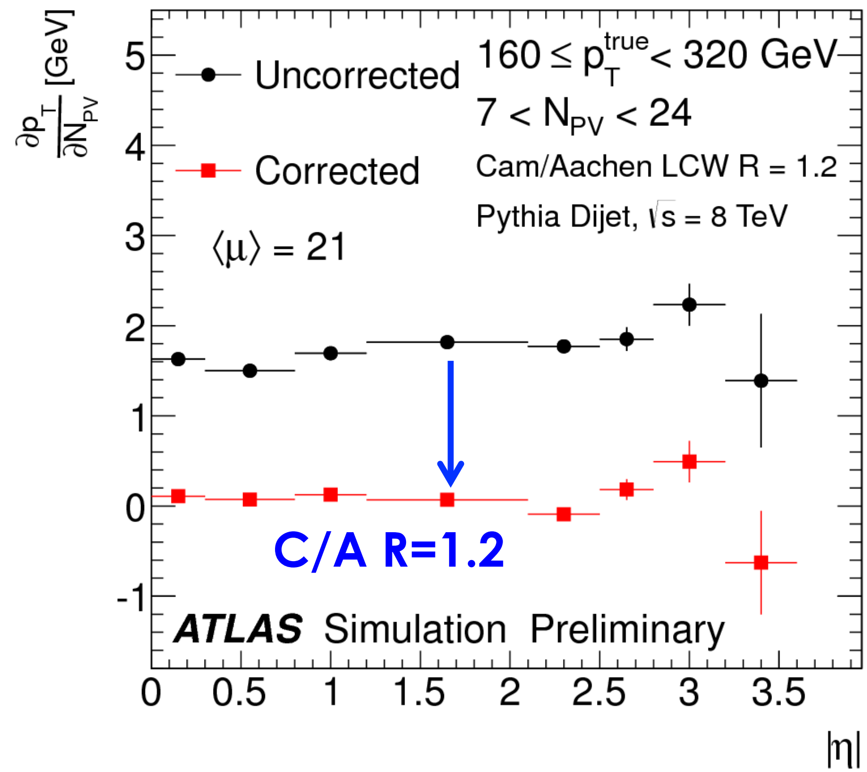


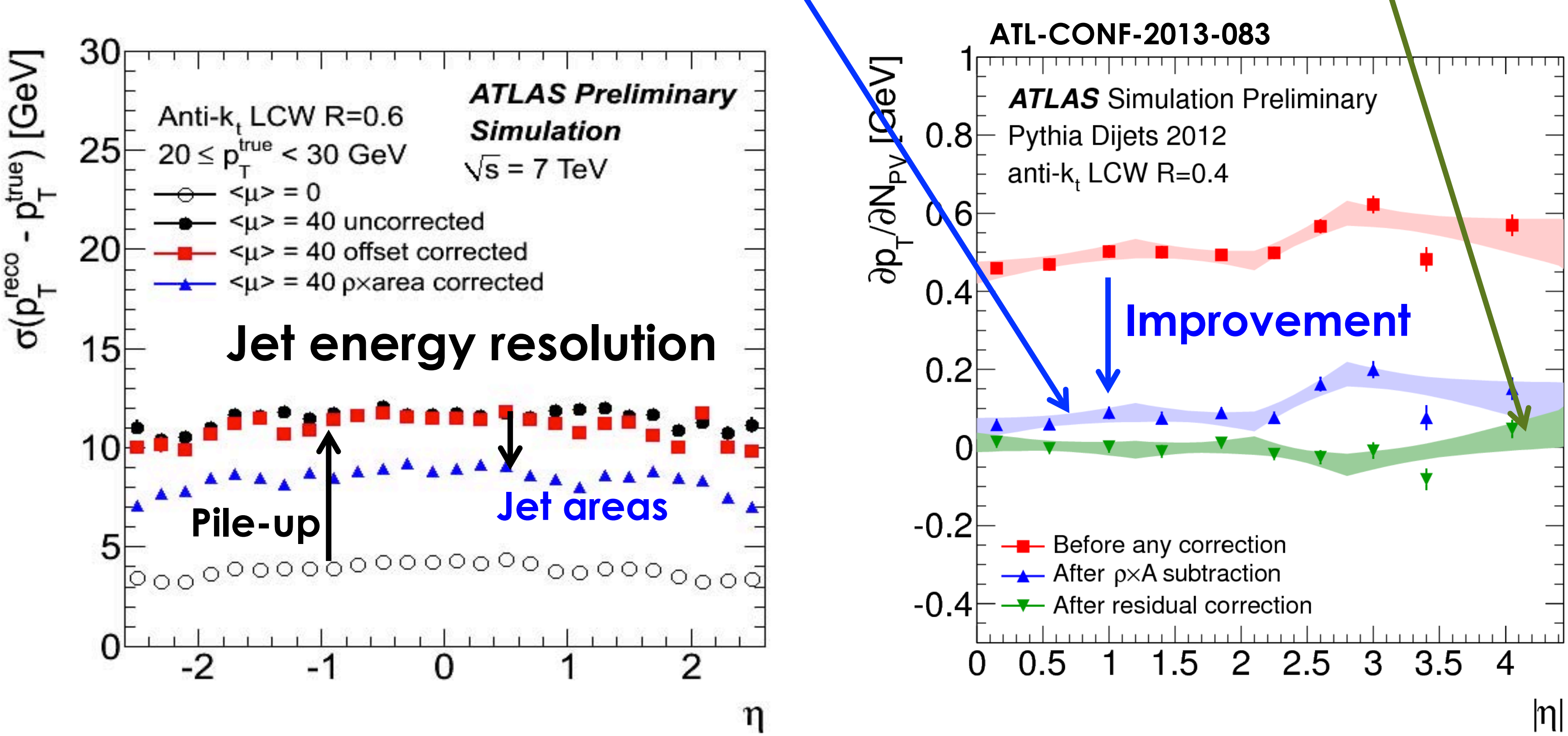


- Estimate, **event-by-event**, the pile-up p_T density
- Subtract pileup contribution based on **jet area**
- **Residual correction** to compensate for noise thresholds, occupancy, and out-of-time pileup

Pileup subtraction (II)

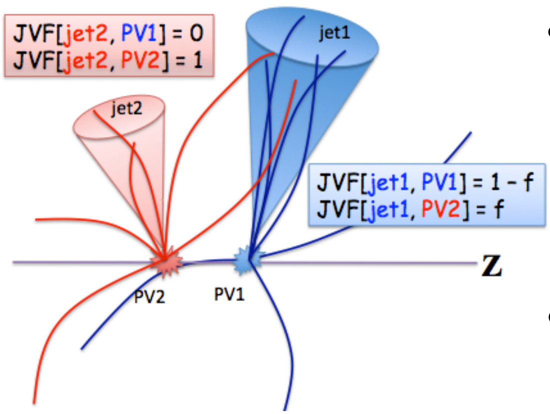
Residual correction (MC-based)

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



- Reduced event-by-event pile-up fluctuations: **improved resolution**
- Reduced reliance on Monte Carlo to correct for pileup offset: **smaller systematic uncertainty**

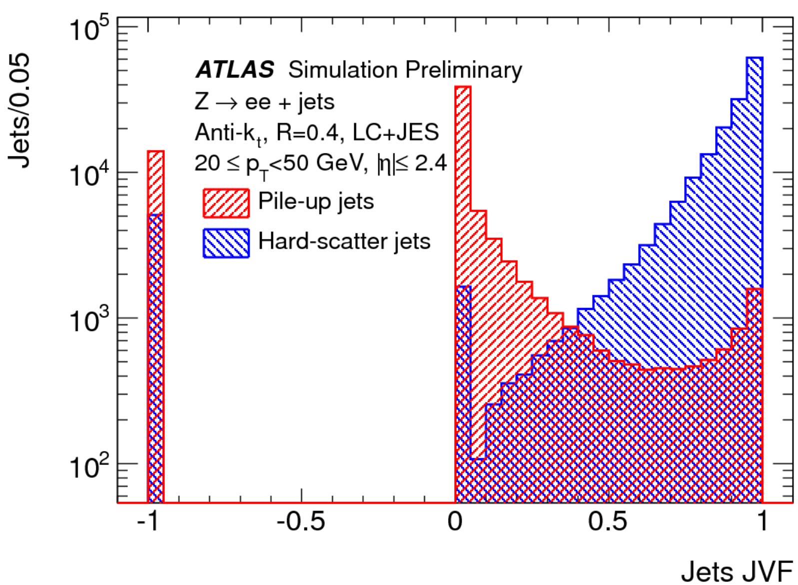
Pileup jet suppression



Jet Vertex Fraction (JVF)

- **Pileup local fluctuations within a same event can lead to pileup jets:**
  - Mix of QCD jets from additional interactions and random combination of particles from pileup interactions
- **Jet vertex fraction algorithm**
  - Tag and reject pileup jets using tracking and vertexing information

$$\mathrm{JVF} = \frac{\sum_k p_T^{\mathrm{trk}_k}(\mathrm{PV}_0)}{\sum_l p_T^{\mathrm{trk}_l}(\mathrm{PV}_0) + \sum_{n\geq 1} \sum_l p_T^{\mathrm{trk}_l}(\mathrm{PV}_n)}$$



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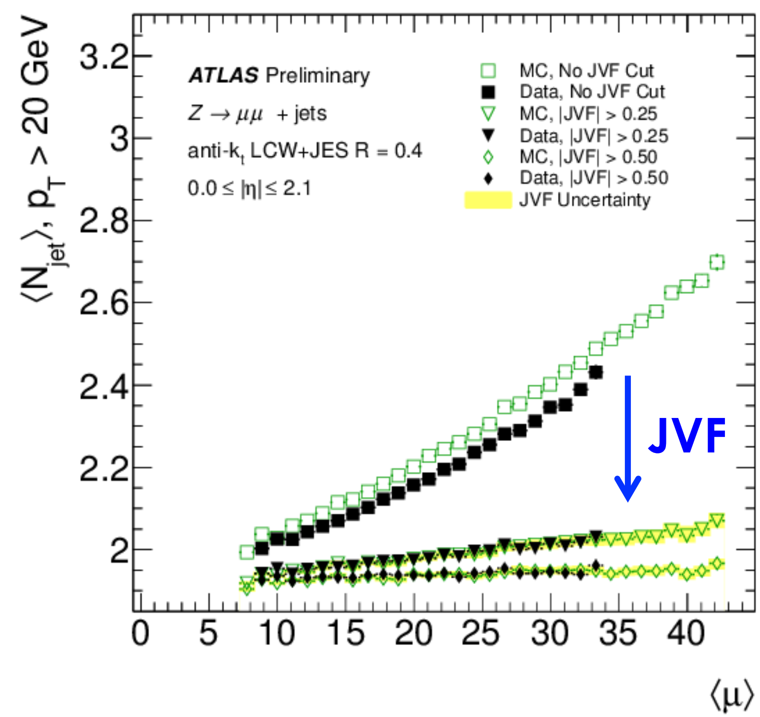

JVF pileup suppression

- JVF measures the fraction of track p_T from the hard-scatter vertex:

$$\mathrm{JVF} = \frac{\sum_k p_T^{\mathrm{trk}_k}(\mathrm{PV}_0)}{\sum_l p_T^{\mathrm{trk}_l}(\mathrm{PV}_0) + \sum_{n\geq 1}\sum_l p_T^{\mathrm{trk}_l}(\mathrm{PV}_n)}$$

- JVF decreases with increasing luminosity:
  - **Pileup-dependent jet selection efficiency**

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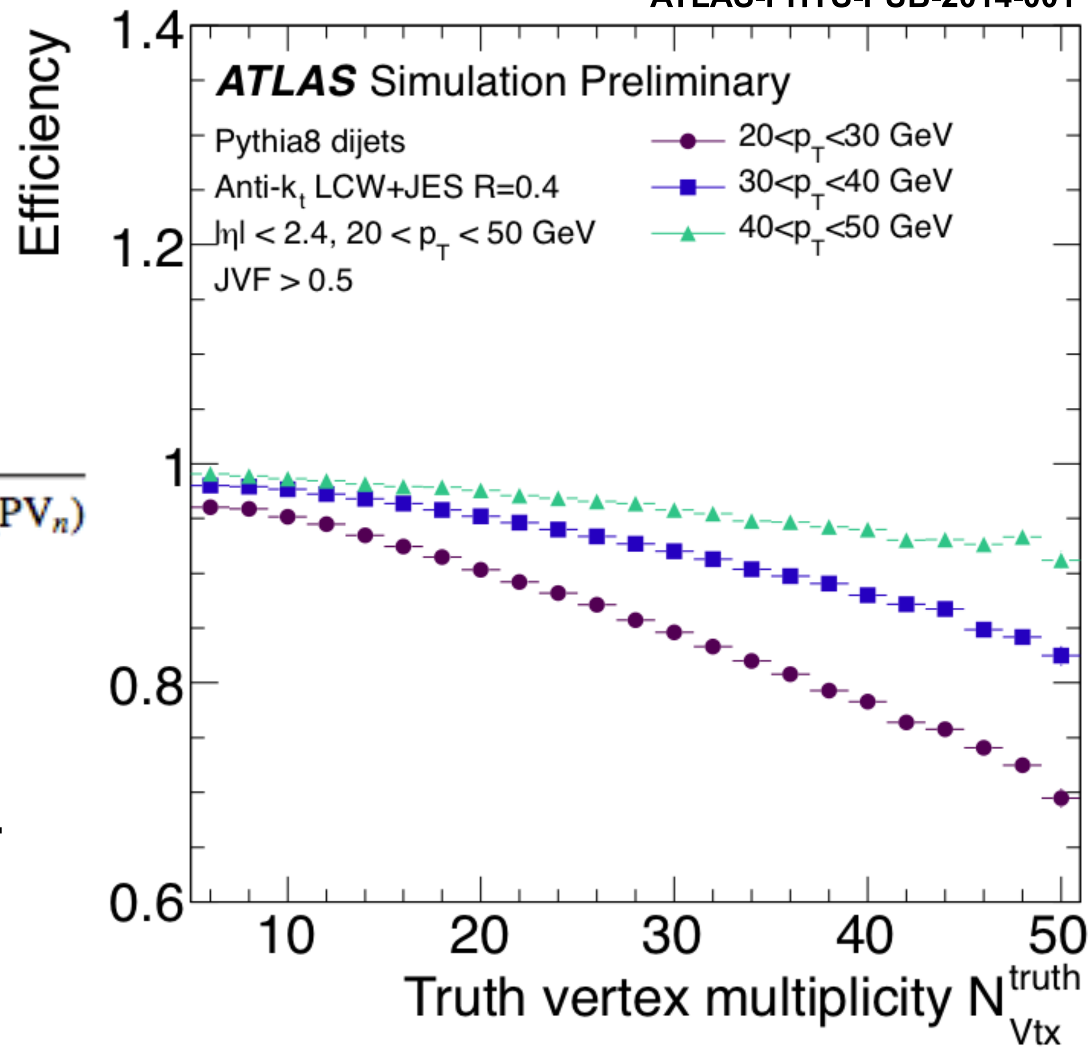
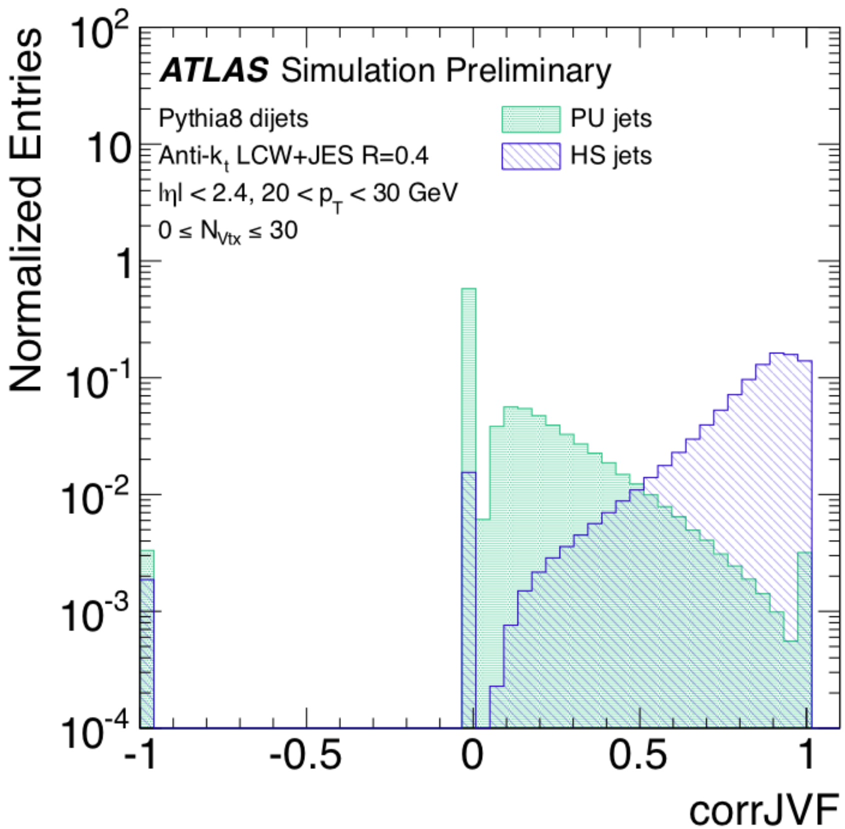


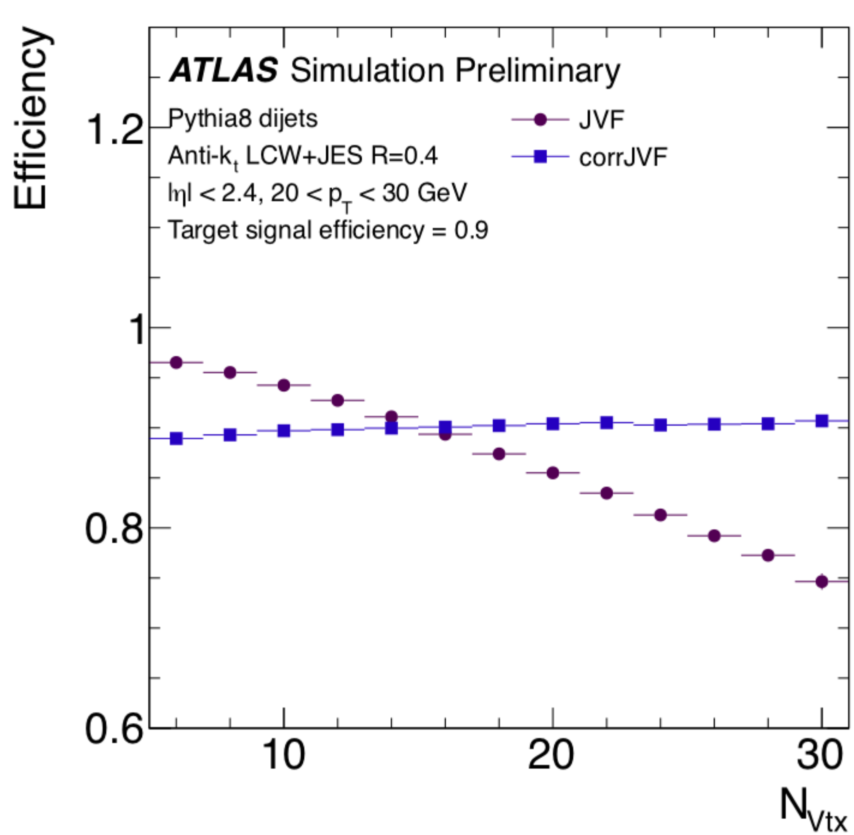
→ **Find new variables for jet vertex tagging**

CorrJVF

- Correct JVF for the pileup dependence
- <u>**CorrJVF efficiency stable within 1%**</u>
- Similar discrimination power than JVF

$$\text{corrJVF} = \frac{\sum_k p_T^{\text{trk}_k}(\text{PV}_0)}{\sum_l p_T^{\text{trk}_l}(\text{PV}_0) + \frac{\sum_{n\geq 1}\sum_l p_T^{\text{trk}_l}(\text{PV}_n)}{(k * n_{\text{trk}}^{\text{PU}})}}$$





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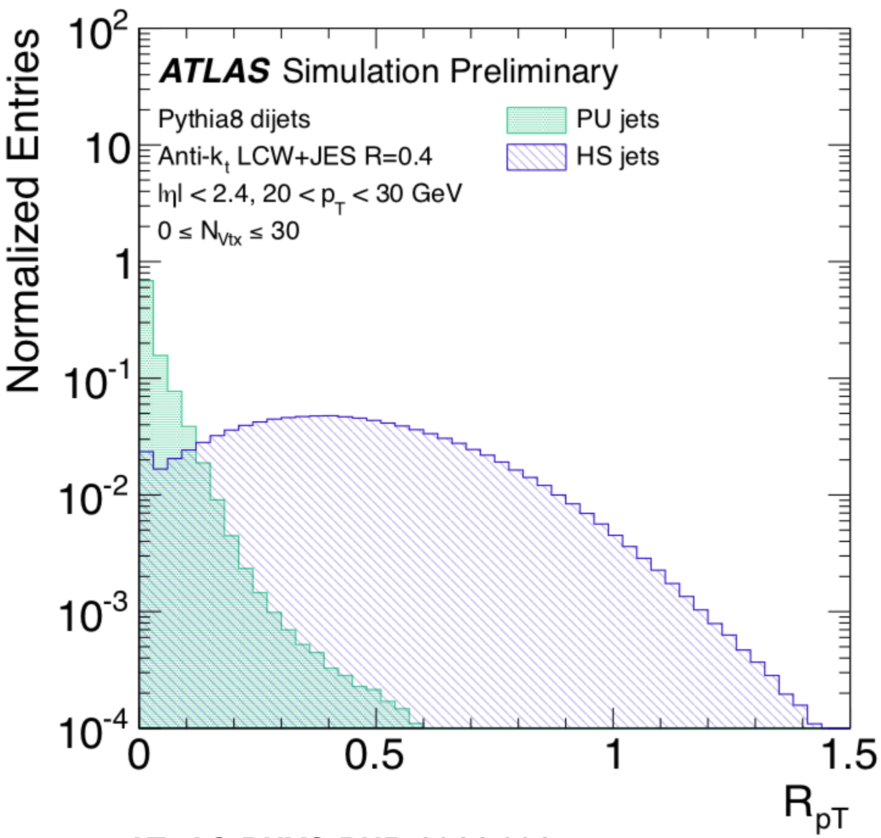
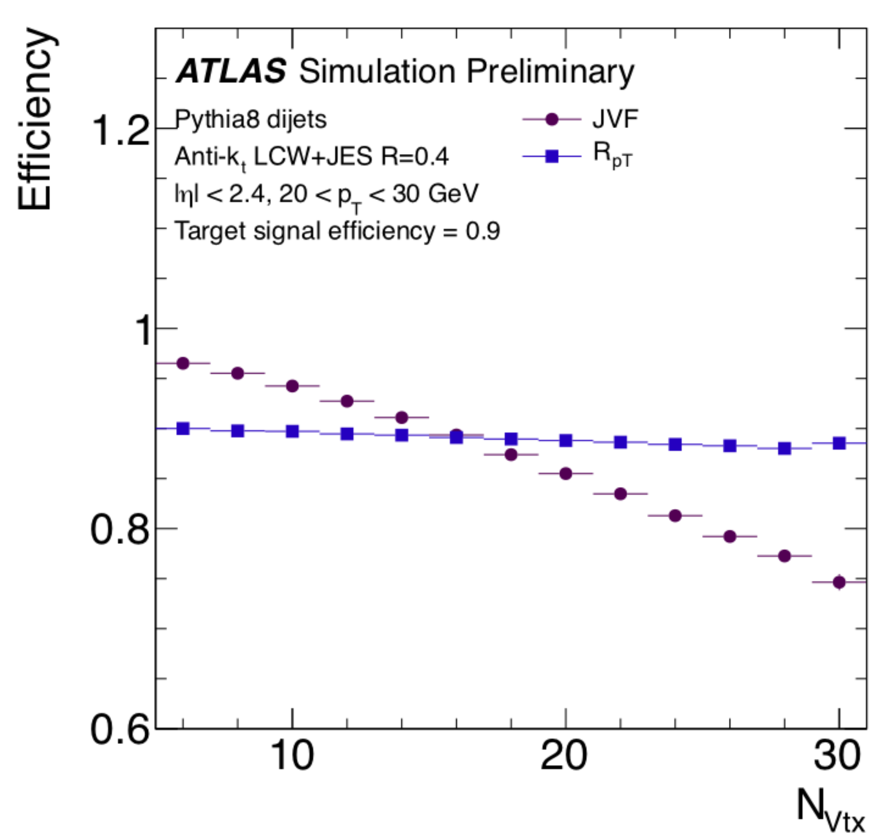
R_{pT}

- **Defined only using pileup-corrected variables:**
  - Tracks from the hard-scatter vertex
  - Pileup subtracted calorimeter jet p_T

$$R_{\mathrm{pT}} = \frac{\sum_k p_{\mathrm{T}}^{\mathrm{trk}_k}(\mathrm{PV}_0)}{p_{\mathrm{T}}^{jet}}$$





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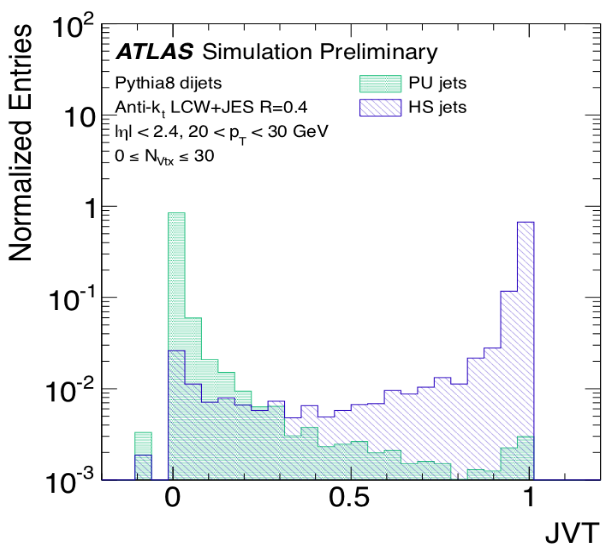
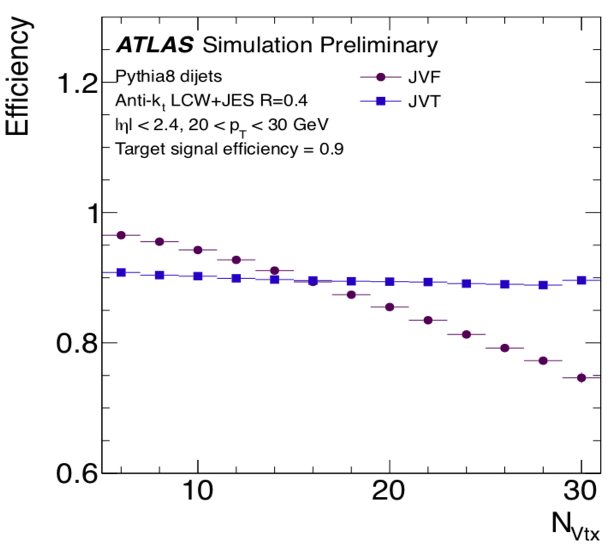
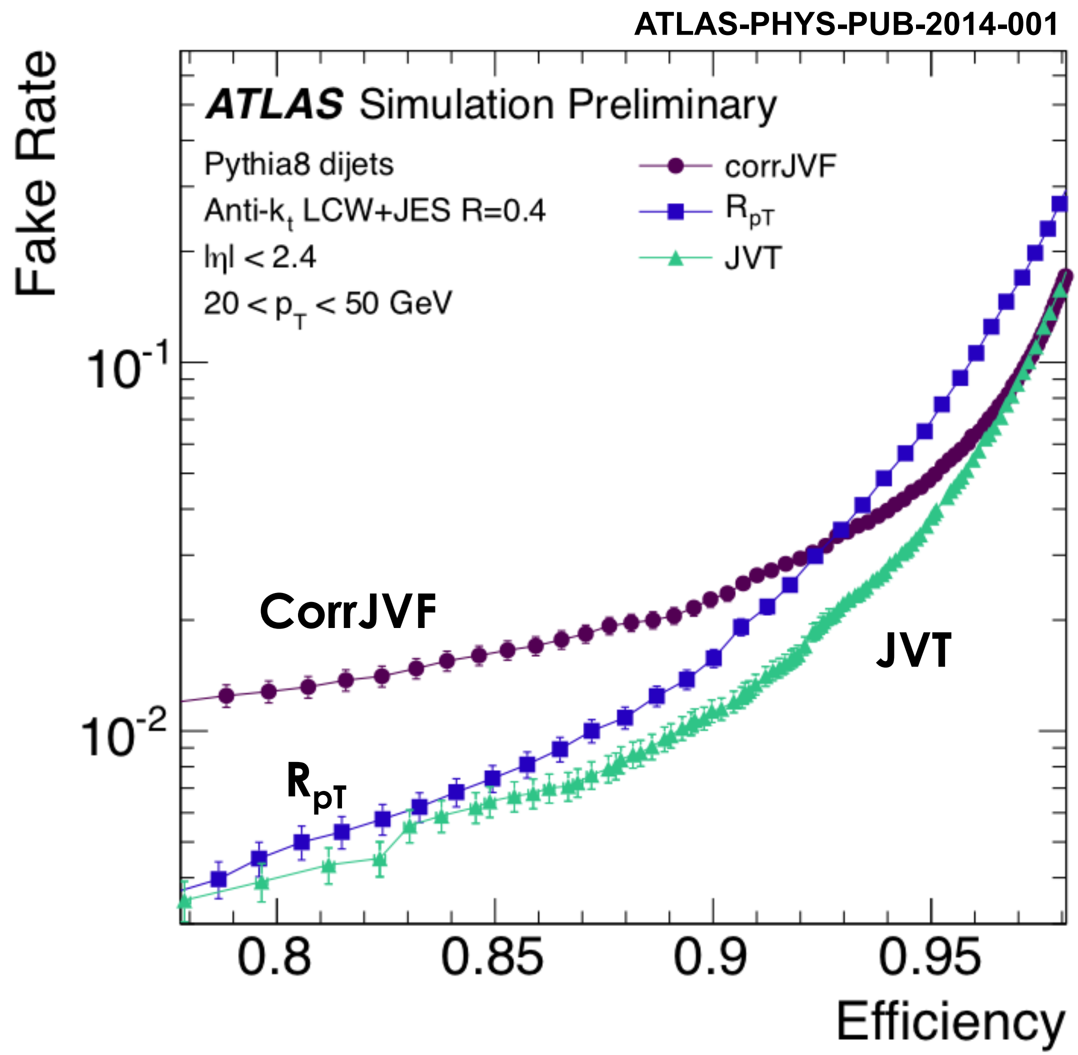
Jet Vertex Tagger (JVF)

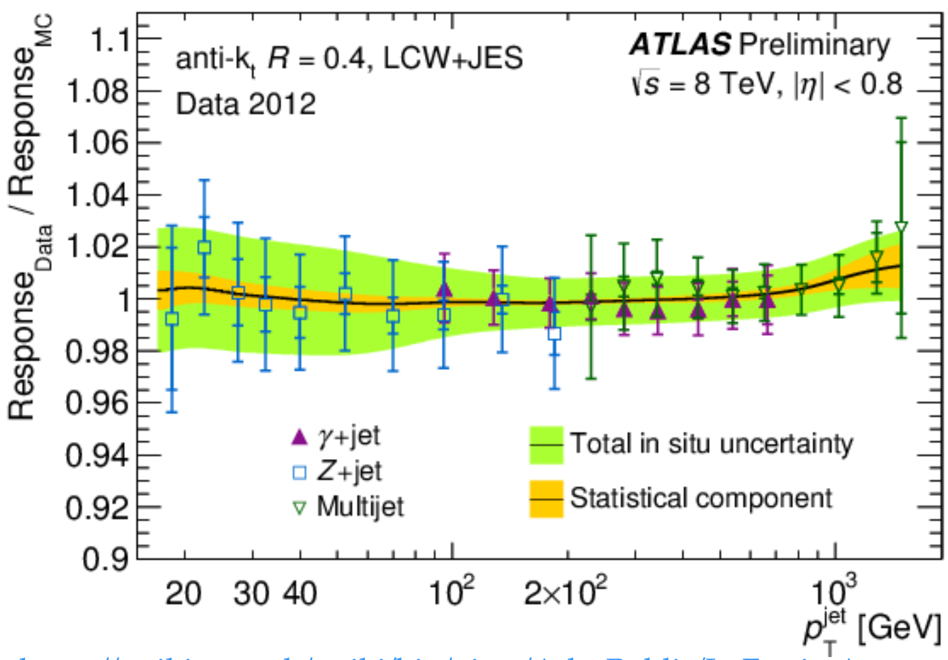


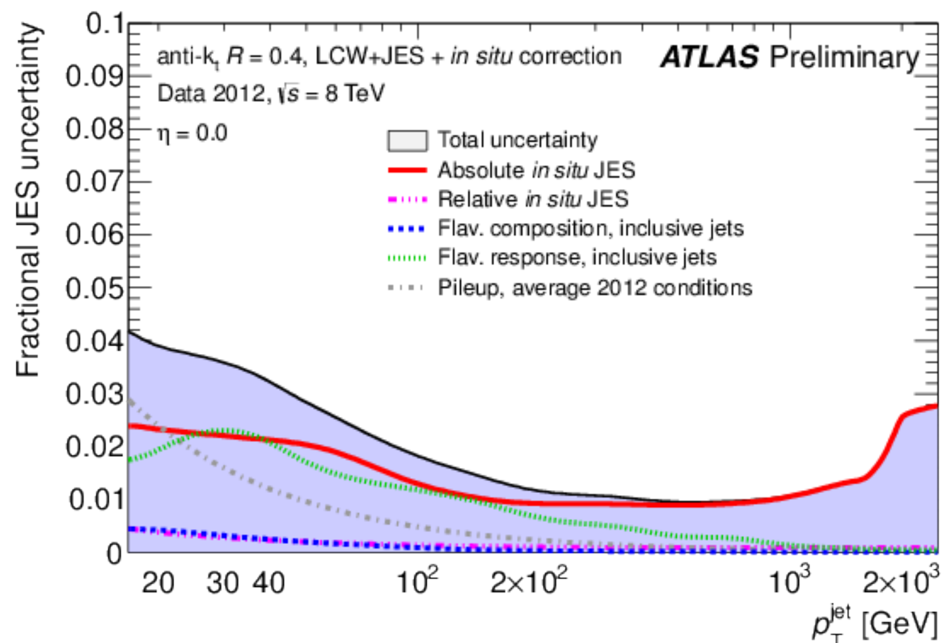




Jet energy scale uncertainty

- **Determined insitu**
  - Pileup: using track-jets in Z+jets (p_T-dependence, topology, data/MC)
  - Relative eta inter-calibtration: dijets
  - Absolute response: Z+jets, γ+jets, multijets
- **Additional flavor uncertainties**
  - Flavor composition and response
- **High p_T extrapolation from single pions**
  - test beam and insitu single pion response measurements

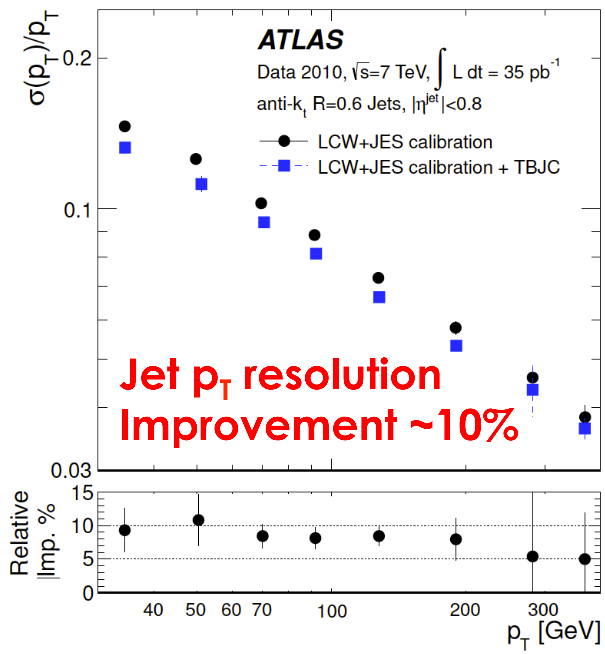


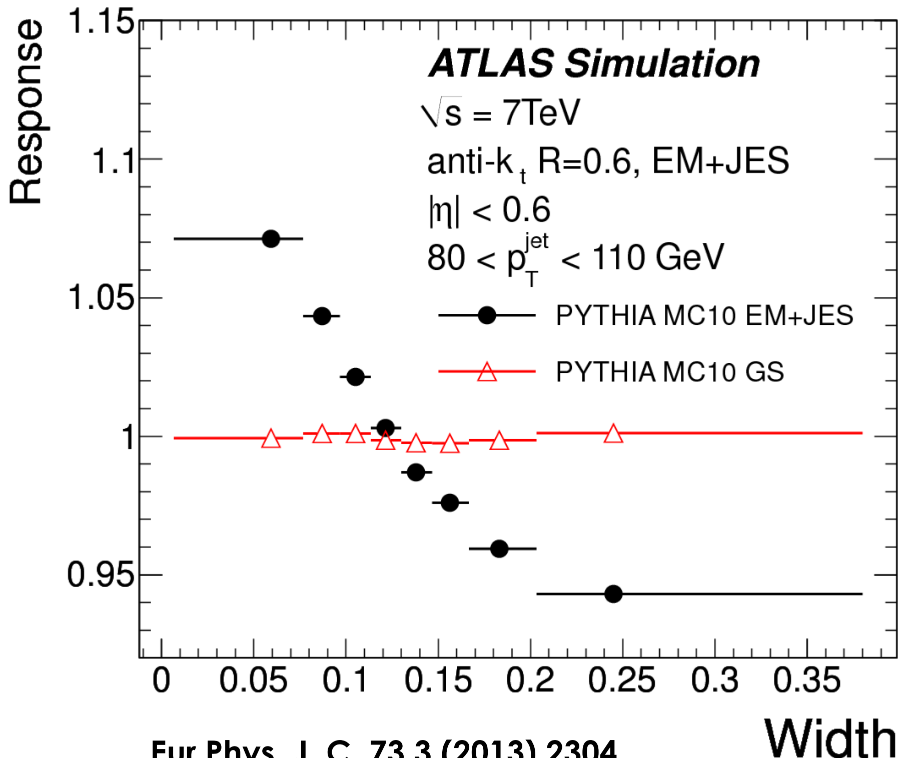


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013JESUncertainty

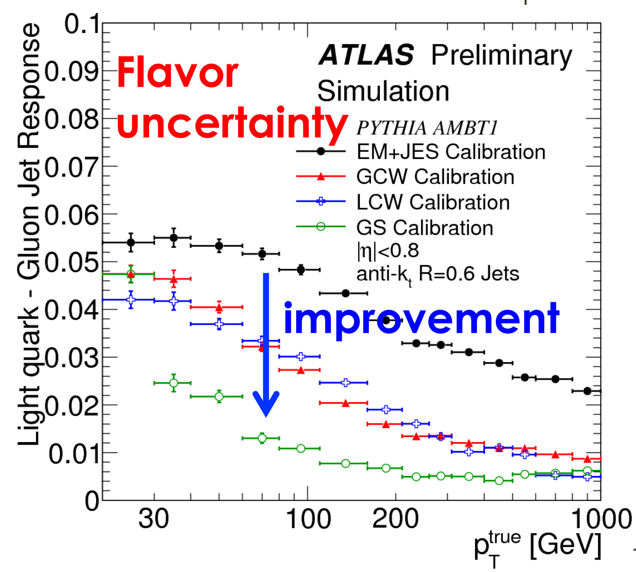
Use of tracks

- Use jet-by-jet information to correct the response of each jet individually
- **<u>Global Sequential Calibration:</u>**
  - Track multiplicity, Jet width, Longitudinal p_T fractions
  - **Improved resolution and reduced flavor dependence**



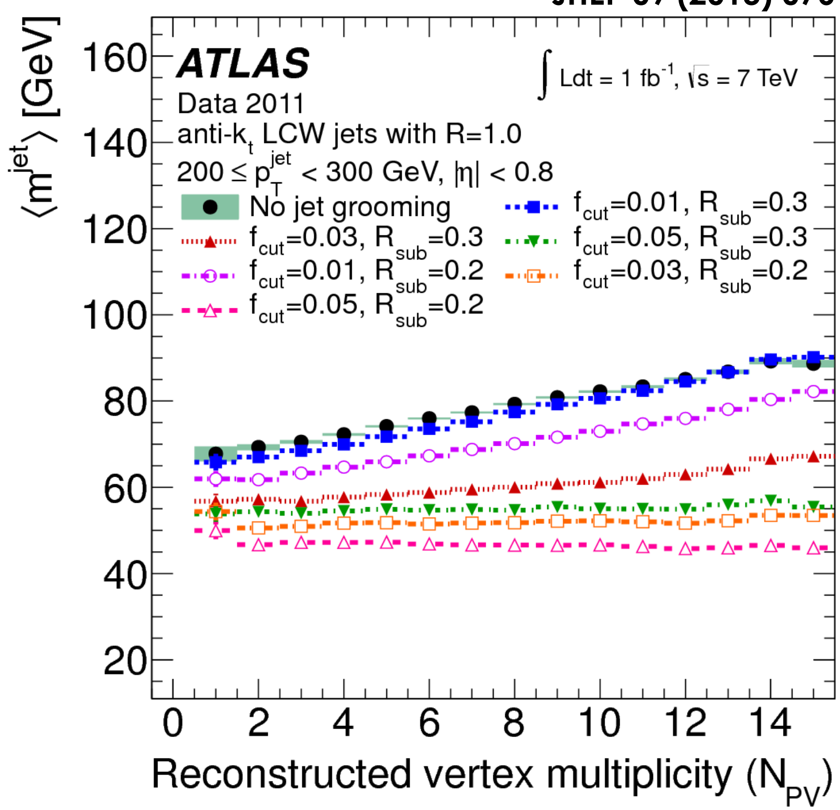


Eur.Phys. J. C. 73 3 (2013) 2304



Jet substructure

JHEP 09 (2013) 076



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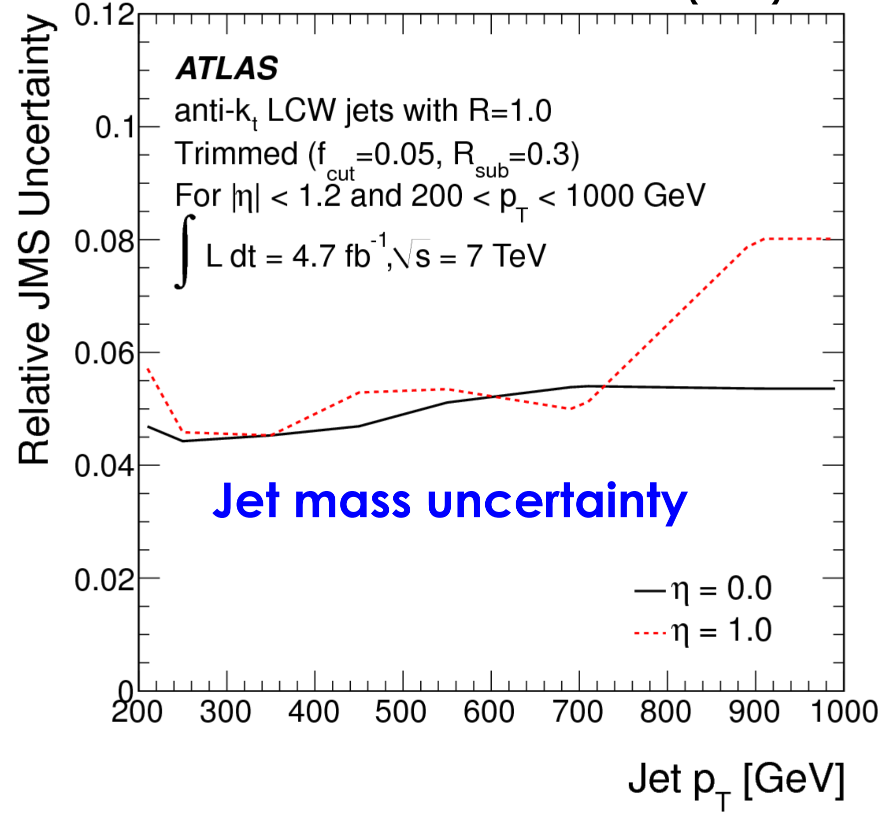
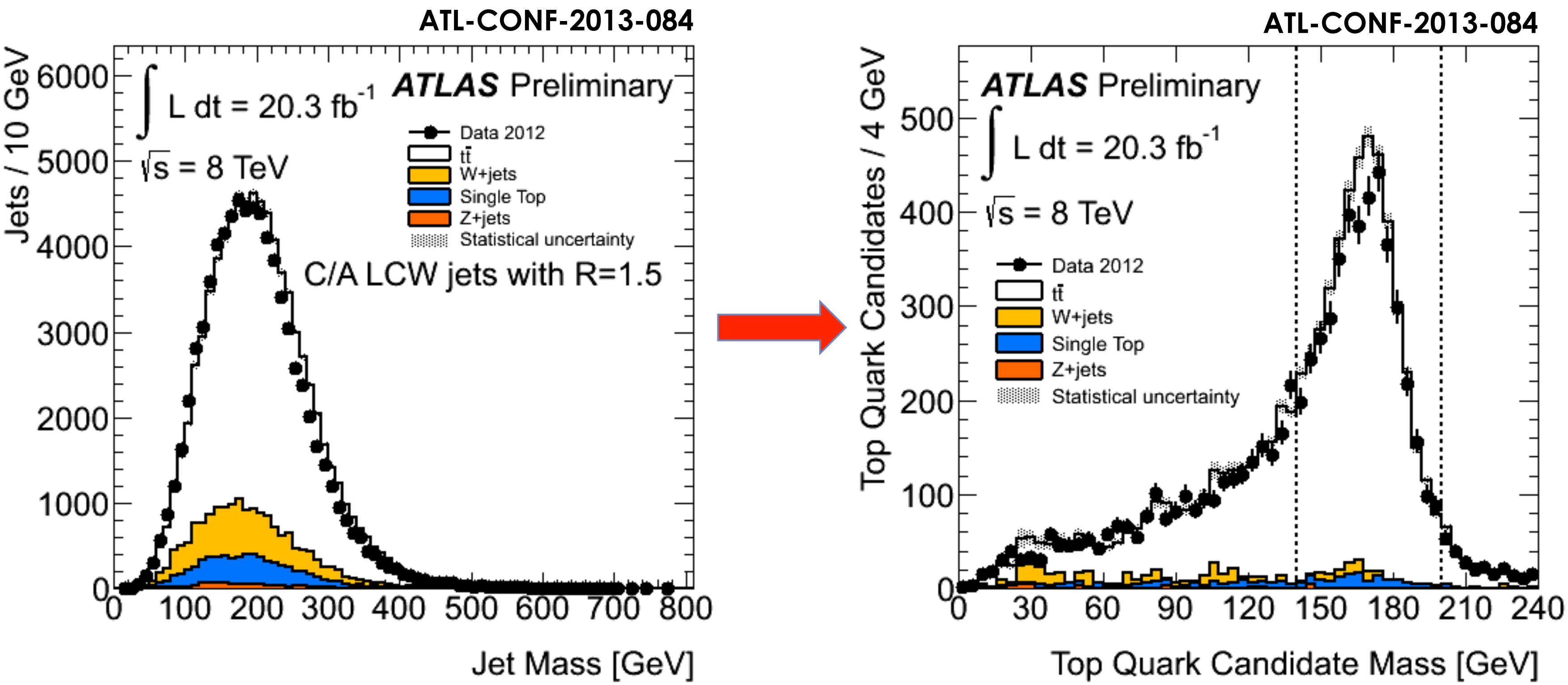


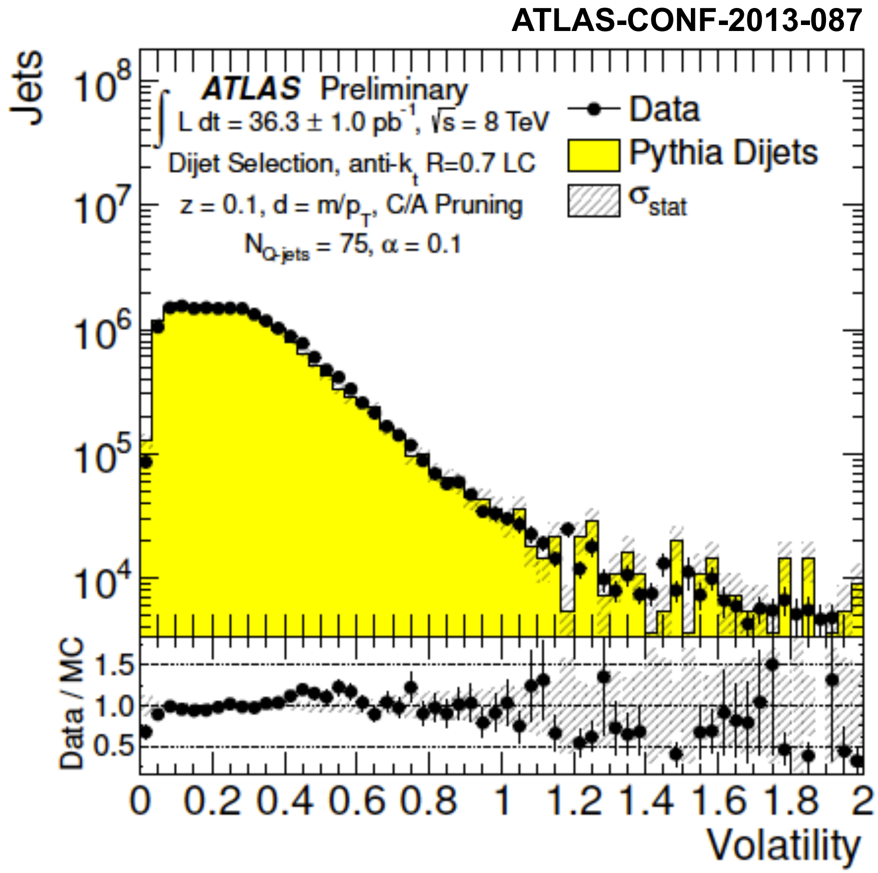
- **Commissioned a large number of large-R jet algorithms and grooming configurations**
  - Detailed performance understanding: **mass calibration**, **uncertainties**, pileup sensitivity and corrections, subjets and **subjet calibration**

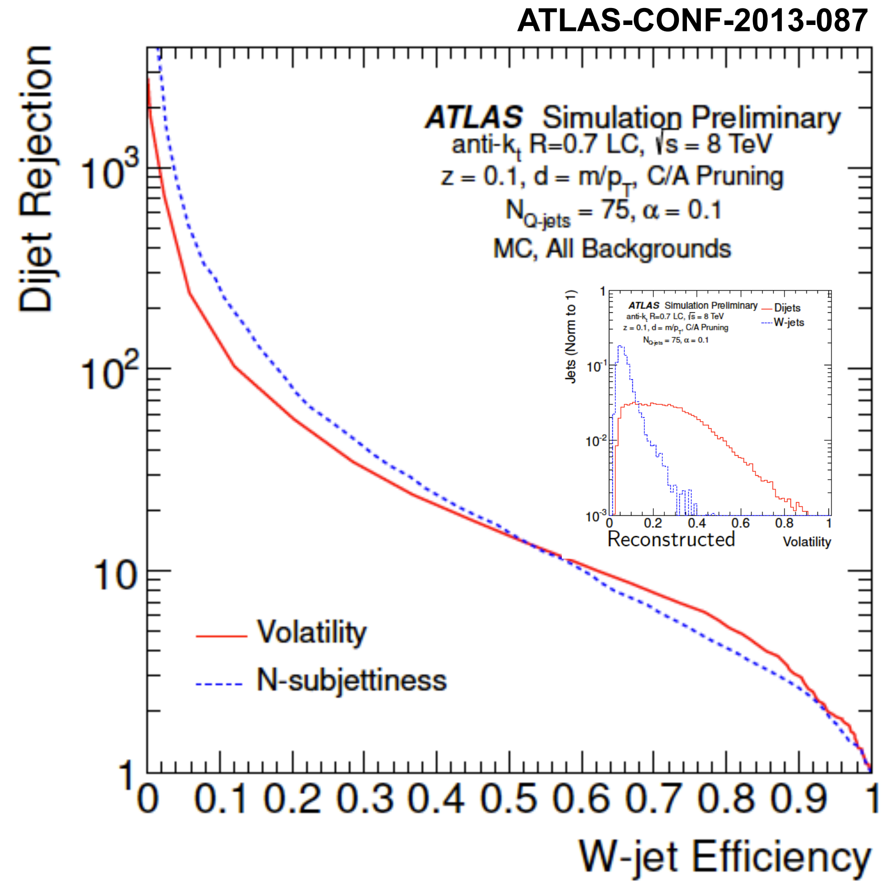
HEPTopTagger

- **Reconstruct top quark mass from C/A subjets**
- Kinematic cuts on invariant mass ratios of subjet combinations require **subjet calibration** for optimal performance
- **C/A subjets with R=0.2-0.5 in 0.05 steps, p_T>20 GeV**
  - Jet areas and MC-based JES response correction



Q-Jets





- **New paradigm to interpret jets and hadronic final states**
- Good data/MC agreement in dijets and W jets in ttbar events
- Comparable performance to n-subjettiness, not fully correlated

Top tagging performance

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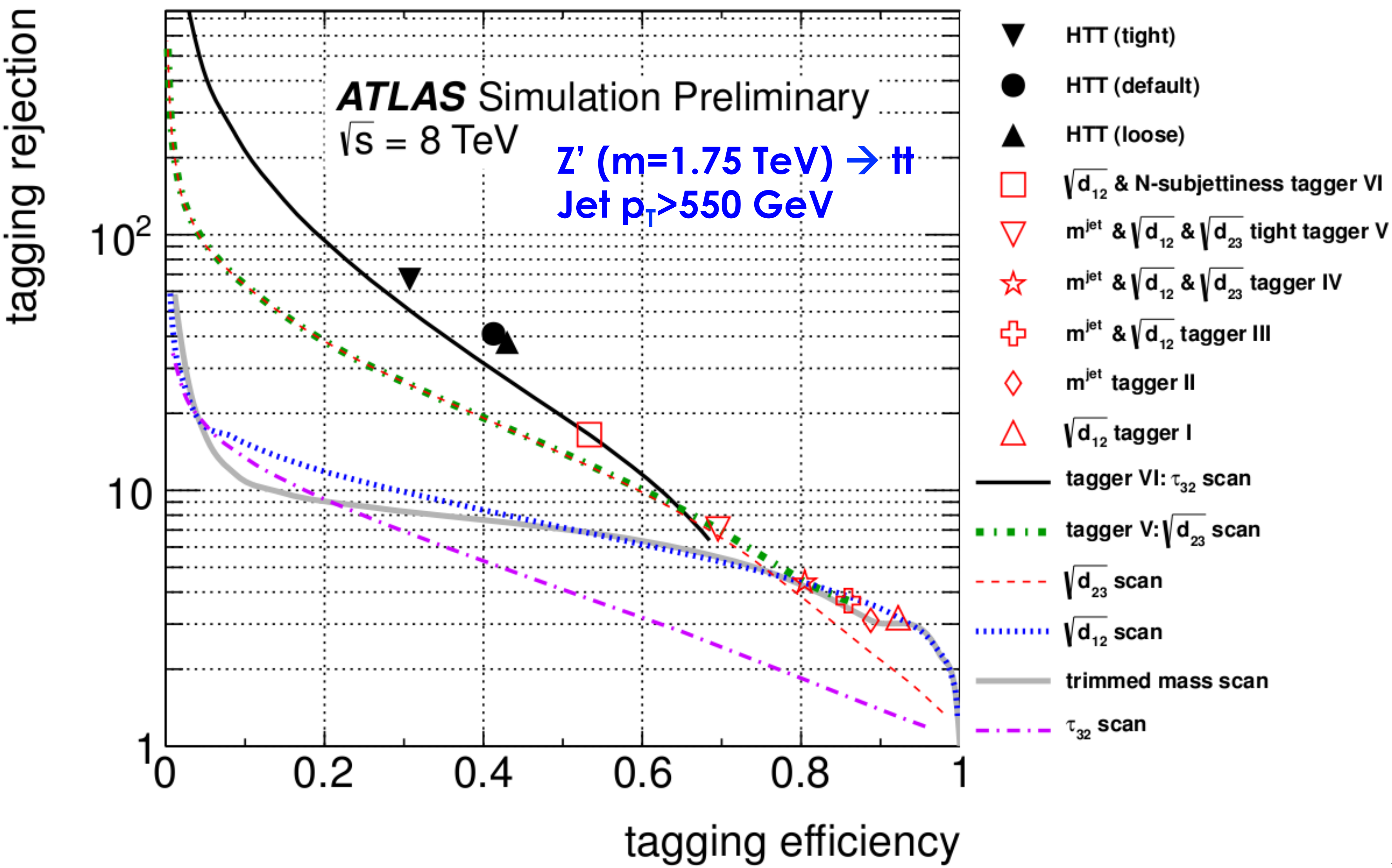
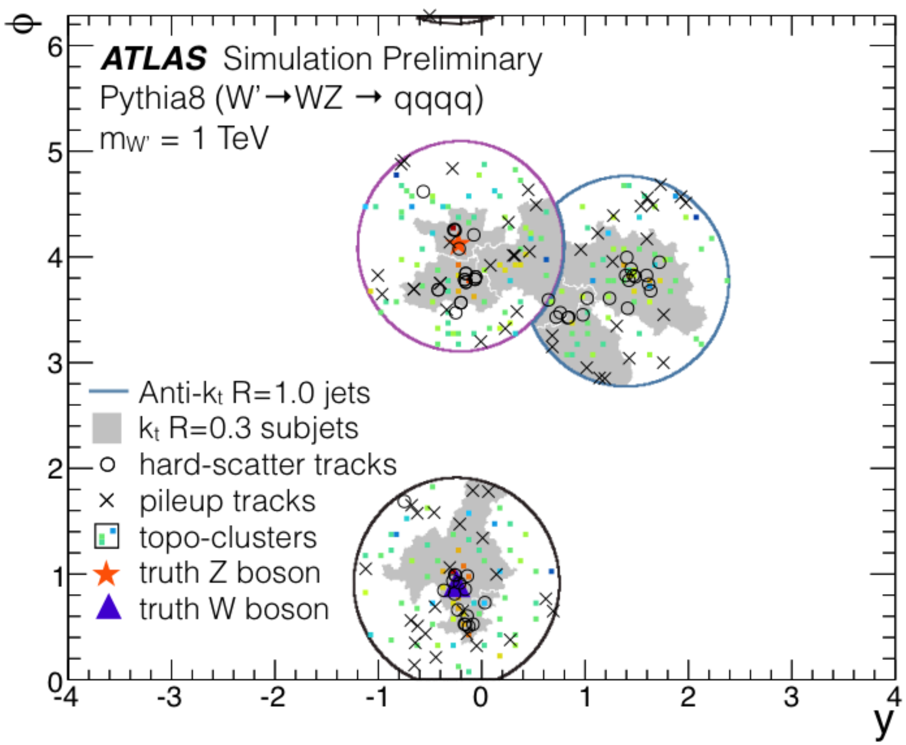
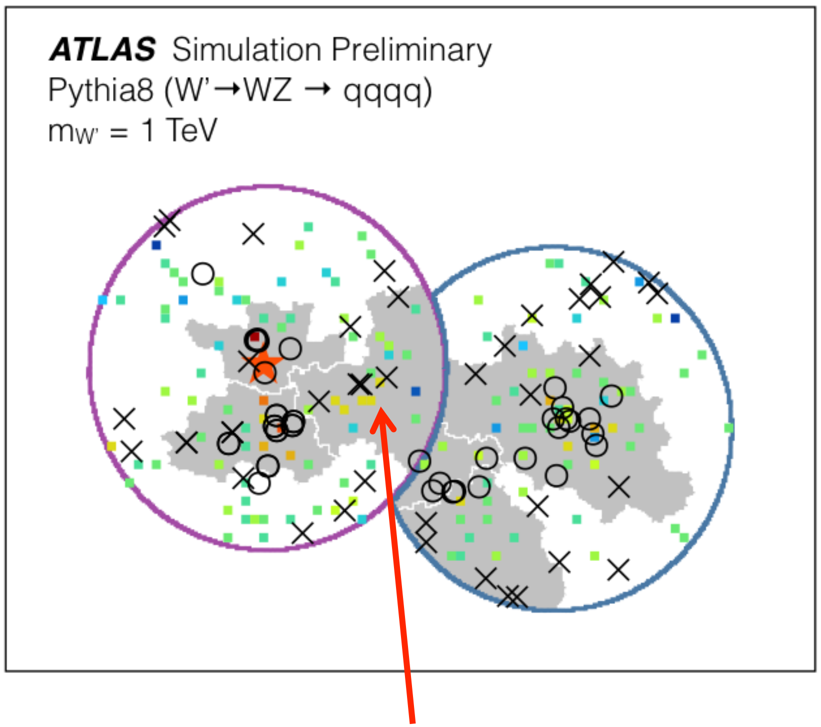


Track-based grooming

- **Improve grooming techniques by extending JVF concept to large-R jets**
  - Remove subjets based on track-vertex information





Subjet entirely composed of pileup tracks (no PV tracks)

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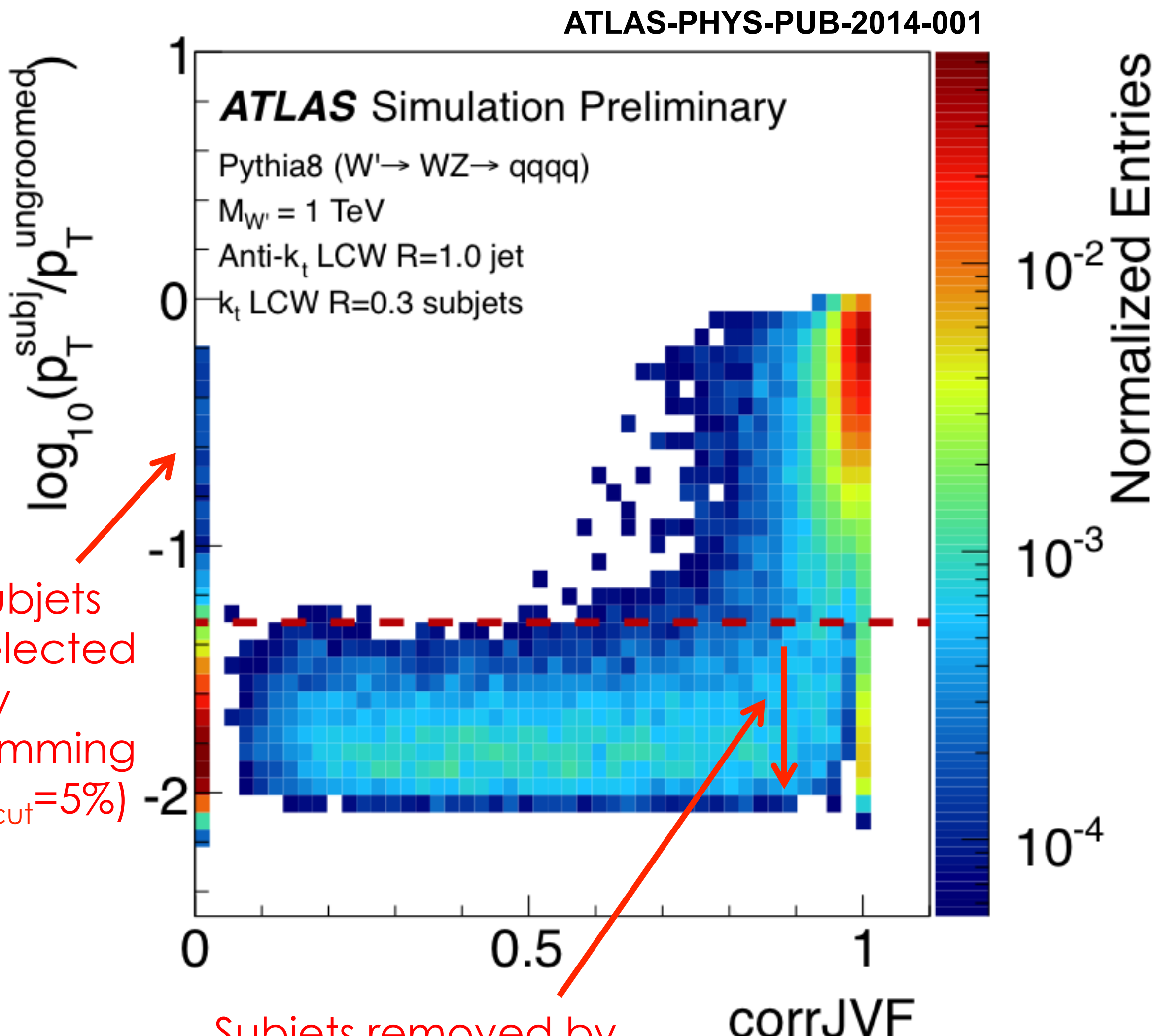
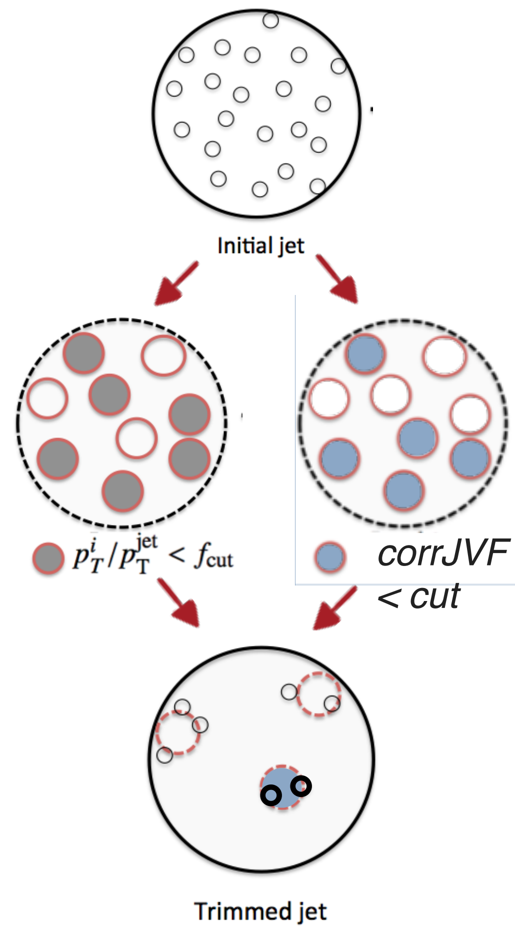
CorrJVF Trimming



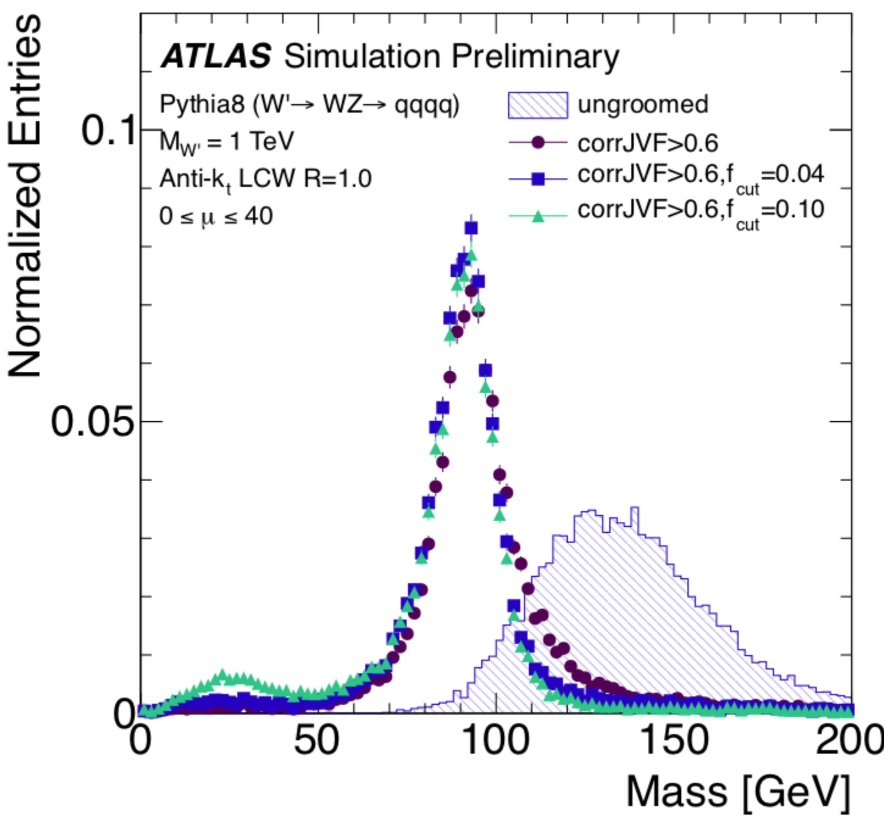
Subjets selected by trimming (f_{cut}=5%)

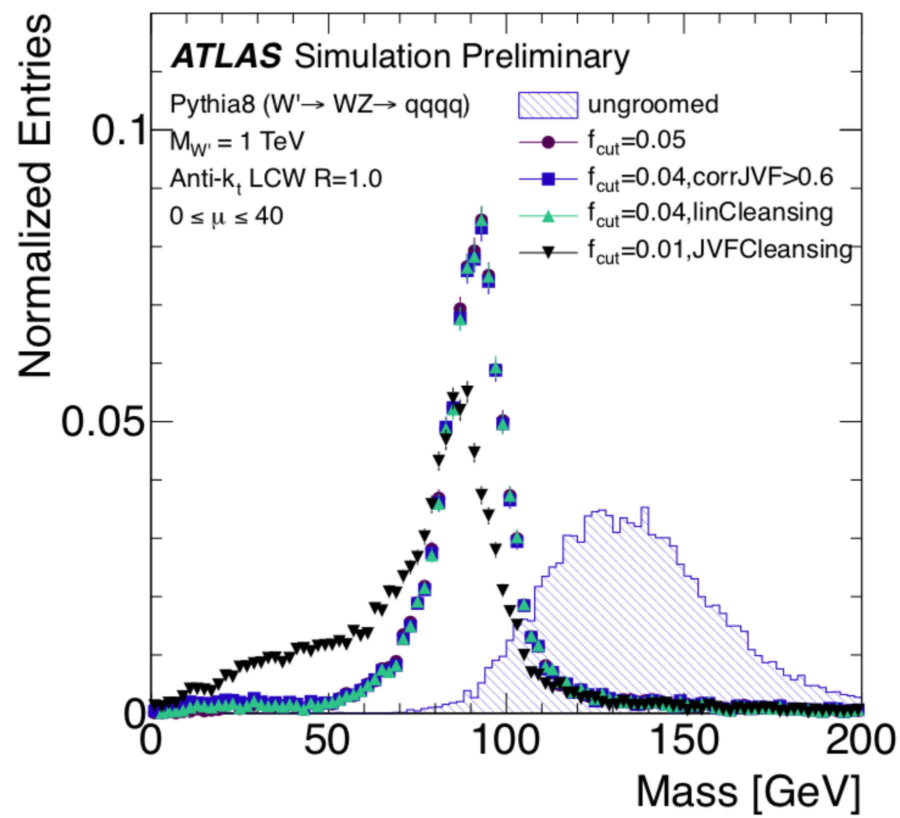
Subjets removed by trimming (f_{cut}=5%)



Track grooming performance

- **Best performance for corrJVF>0.6 and f_{cut}=4%**
  - **Similar performance than calorimeter-only trimming (f_{cut}=5%)**
  - Linear jet cleansing has the same performance as corrJVF





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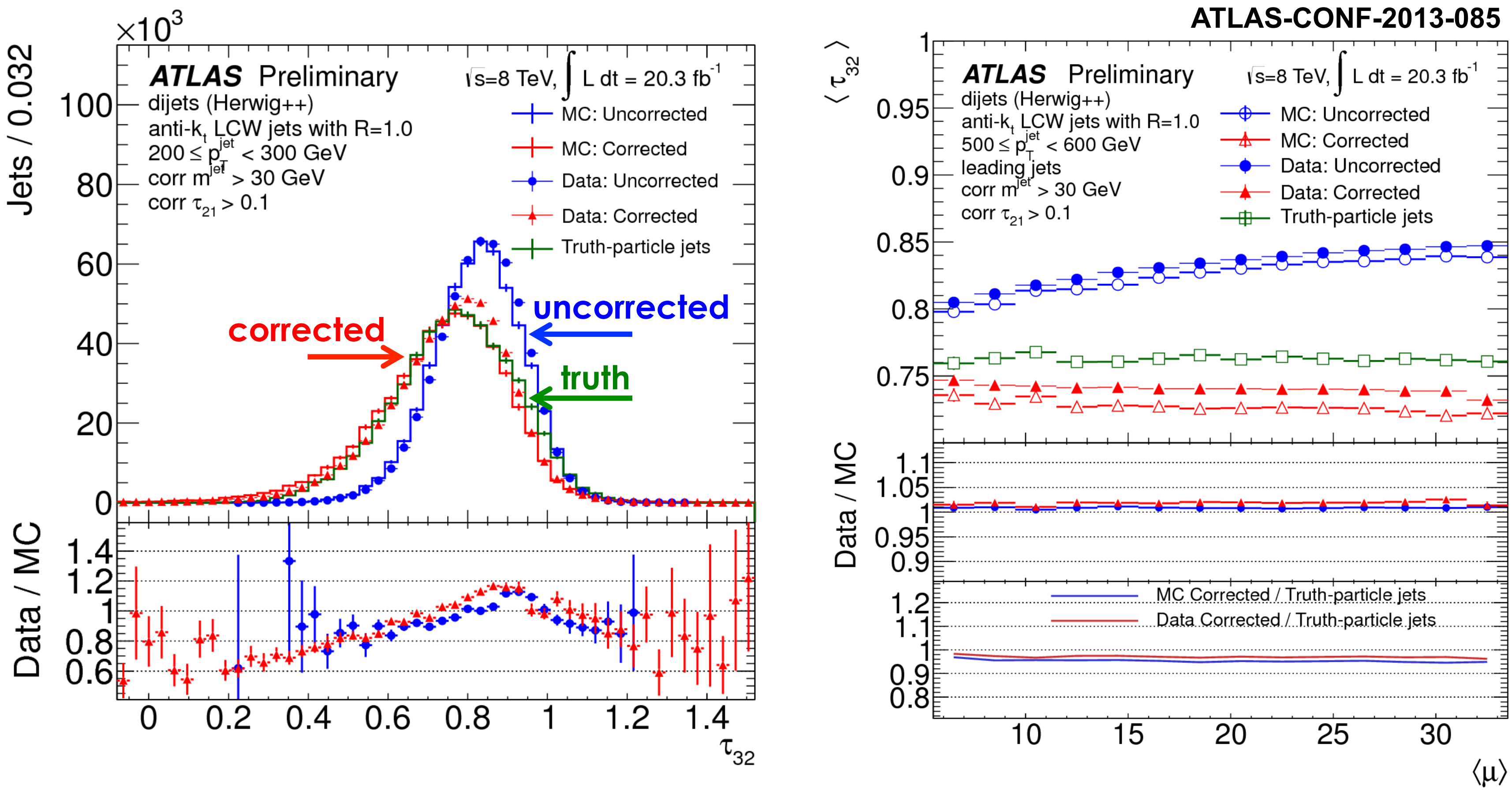
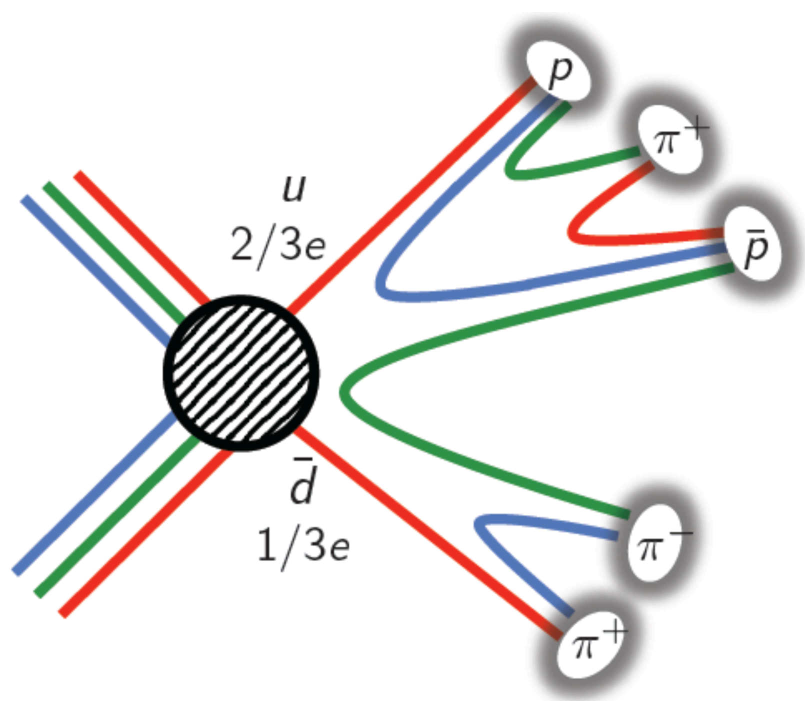
Jet shapes subtraction



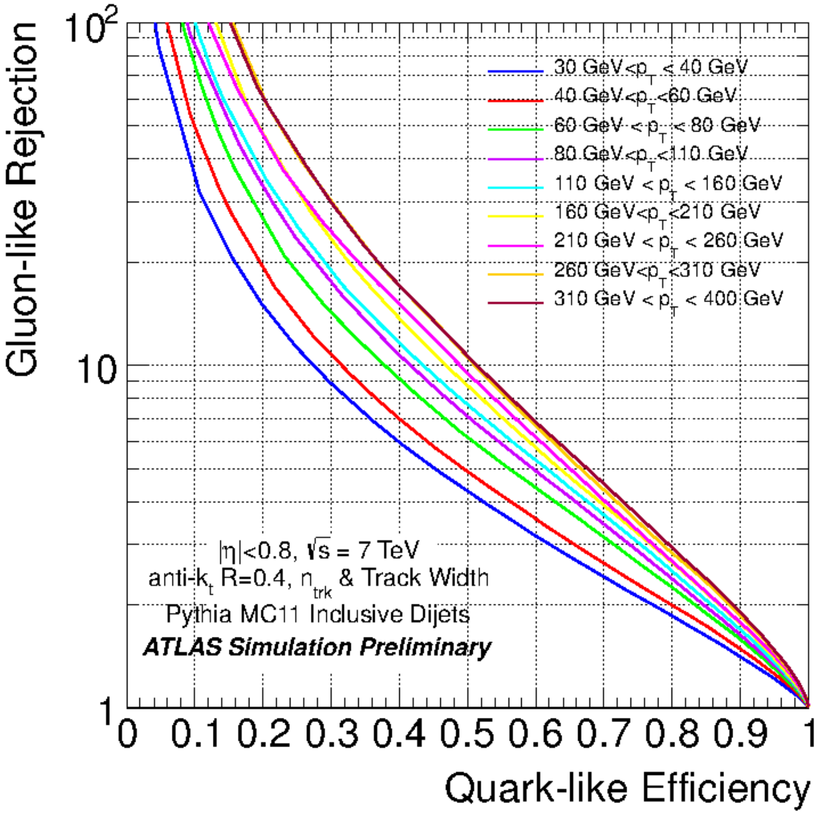
- Extension of jet areas subtraction to correct for any jet shape
- **Key technique to enable the use of jet-based kinematic variables that are pileup resilient**

Jet-by-jet tagging

- **Characterization of new physics and understanding QCD**
  - **Quark/gluon tagging**
  - **Double B-hadron tagging:**
    - Gluon splitting to bb
  - **Jet charge**
    - Distinguish up squarks from do squarks
    - W' vs Z'
    - Jet charge evolution
  - Color flow
    - Jet pull
      - https://indico.cern.ch/getFile.py/access?contribId=22&resId=0&materialId=slides&confId=274902



Quark-Gluon tagging



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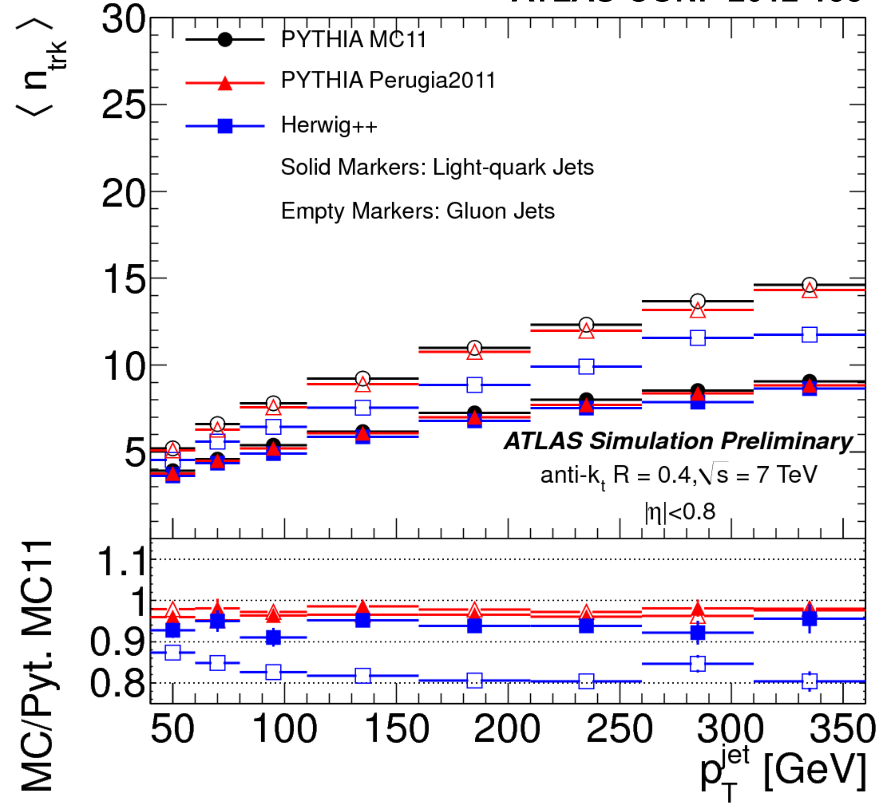
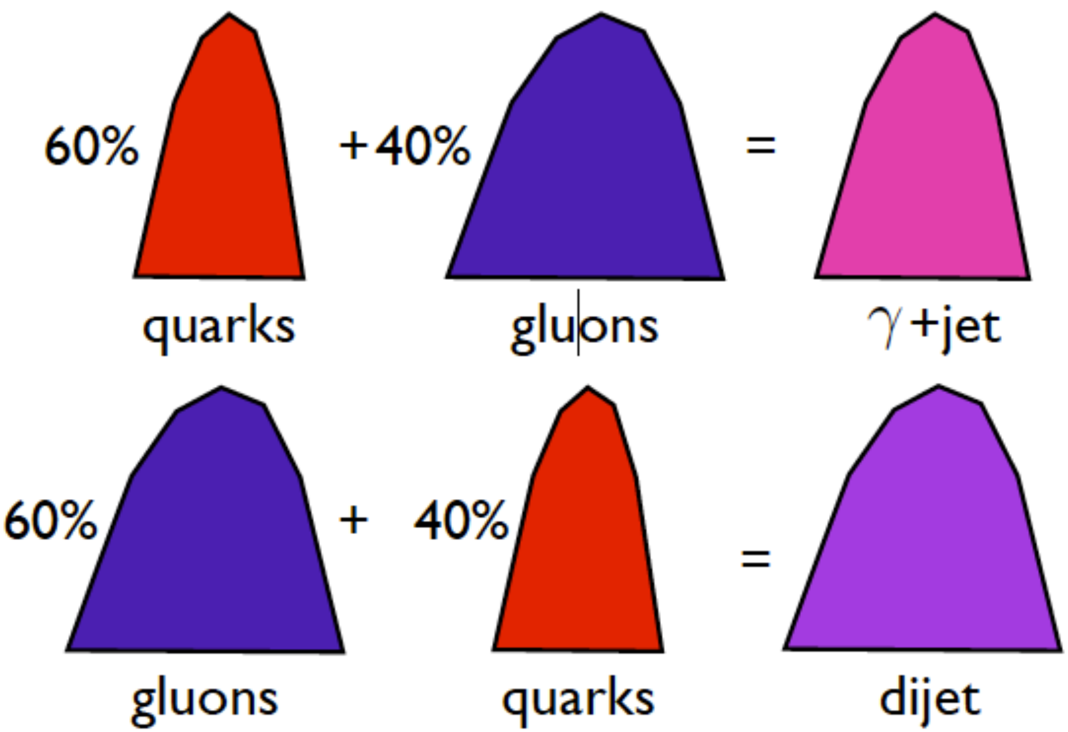


- Likelihood discriminant using track multiplicity and (track) jet width
- Large differences observed between different generators and data
- **Data-driven determination of discriminant using dijet and γ +jet data**

Quark-Gluon discriminant

- **Build a discriminant using a data-driven template technique**
  - Take q/g fractions from MC and determine the shape of n_{trk} and jet width bin-by-bin



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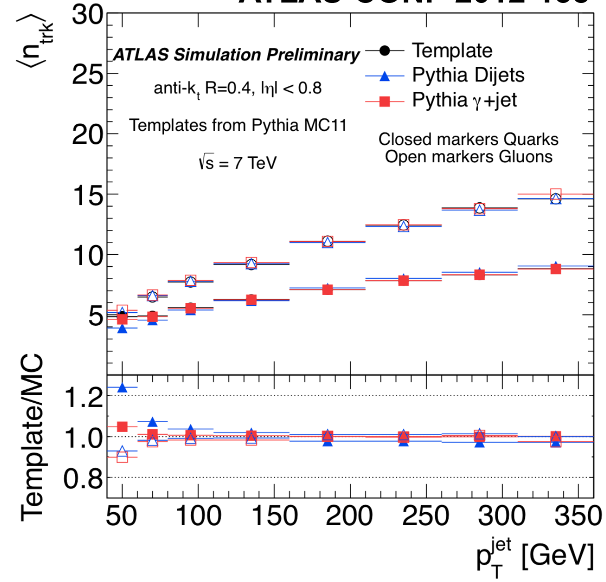

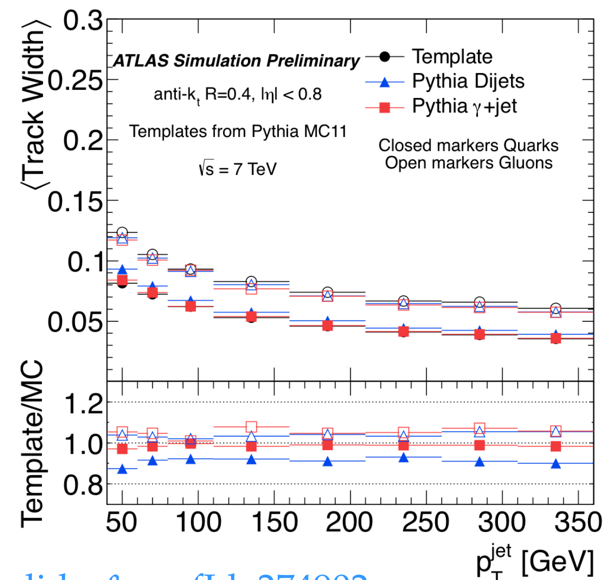

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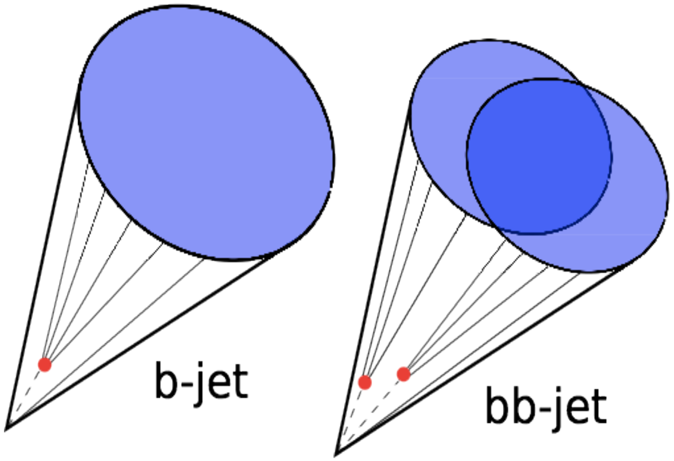
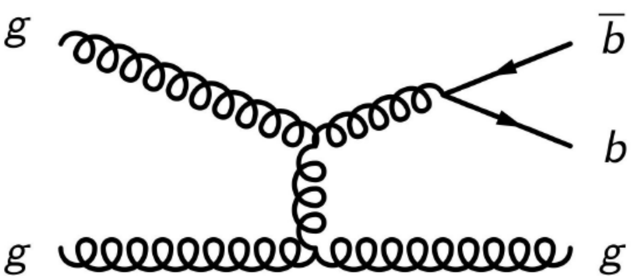
B-hadron structure of jets

- **Gluons can split to 2 b-quarks at small angles, which can be reconstructed as one single (merged) b-jet**
  - b-tagging algorithms do not provide information on the number of B-hadrons within jets, or on the **net heavy flavor content**
- Tagging and removing these jets can **suppress SM backgrounds to physics searches** (*W(bb)j*)
- **Identify b-tagged jets containing two B-hadrons** exploiting the distinct b-jet substructure between single and double b-hadron b-jets





Gluon splitting

Double B-hadron tagging

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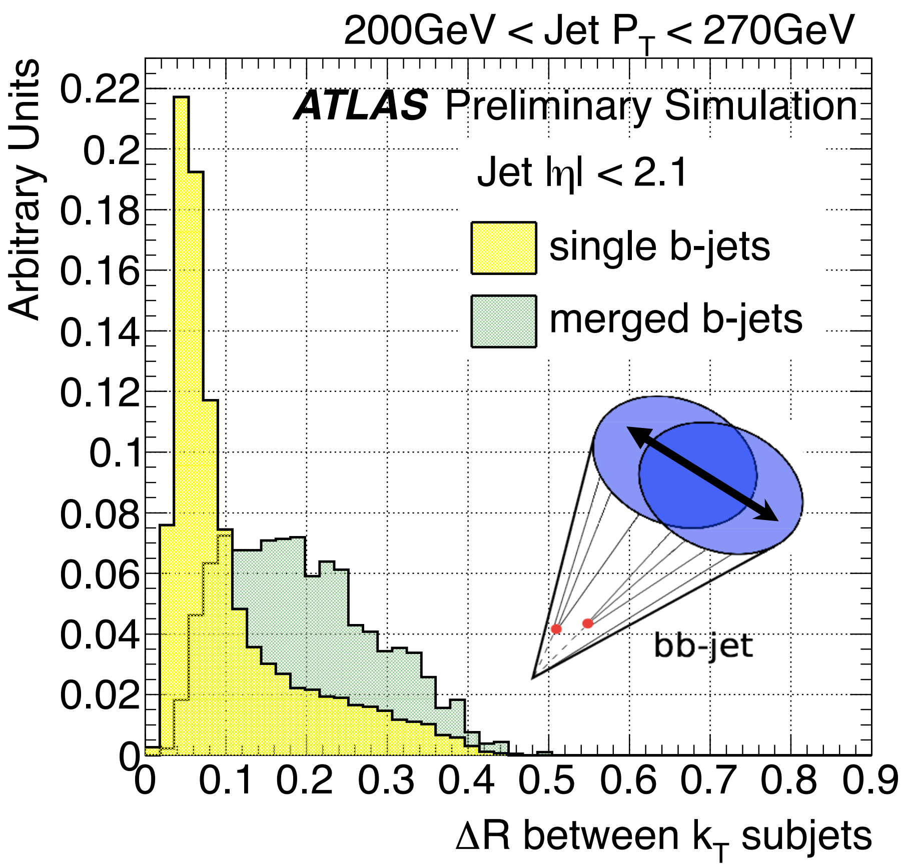
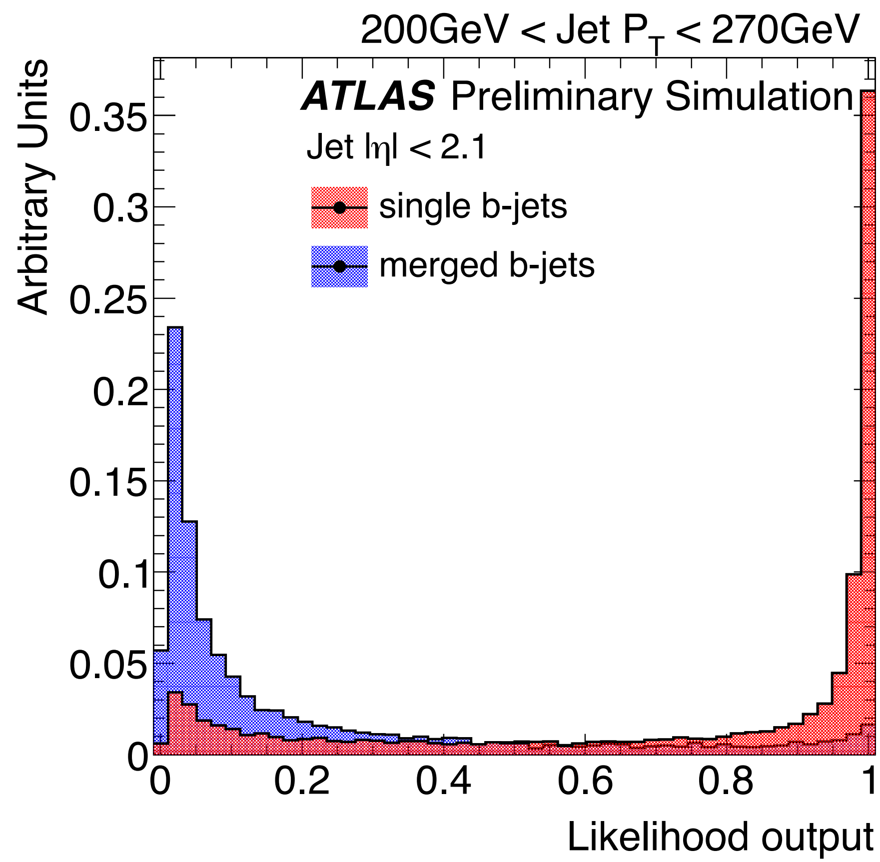
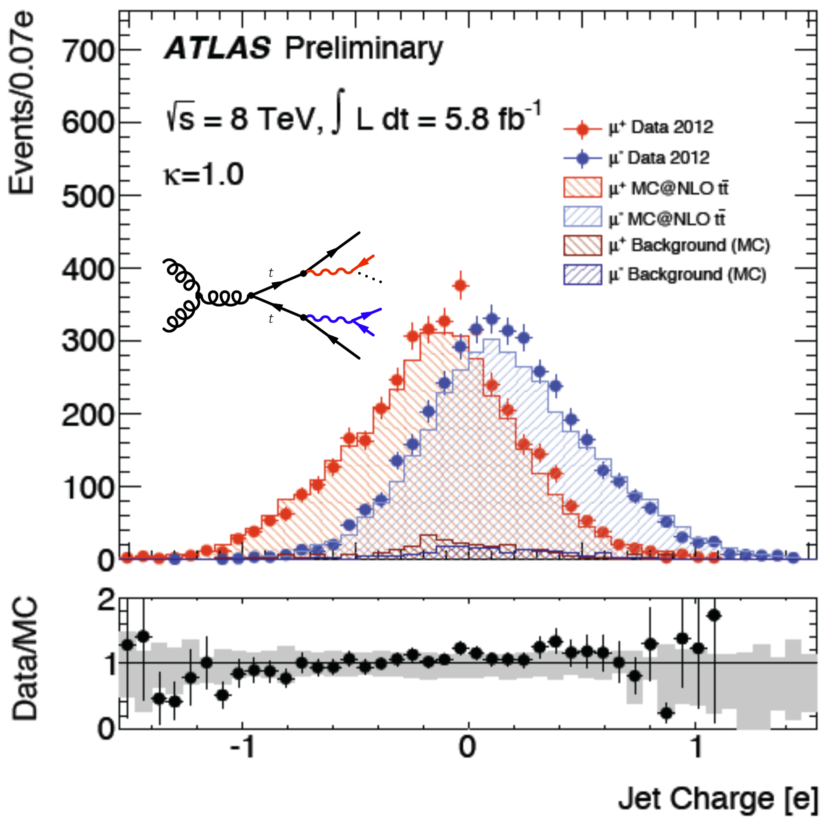




- **Rejection of merged b-jets @ 50% b-jet efficiency:**
  - 8x (30x) for jet p_T > 40 (200) GeV
- Combine with multi-vertex techniques for higher purity

Jet charge



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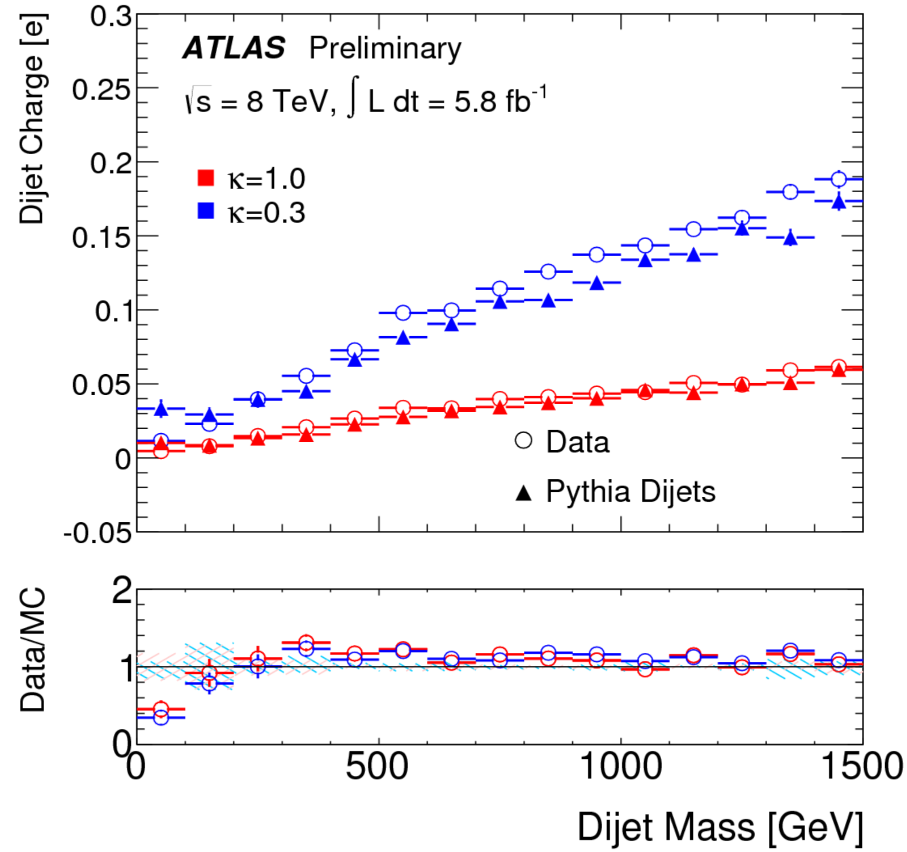

$$Q_j = \frac{1}{(p_{T_j})^{\kappa}} \sum_{i \in \mathrm{Tr}} q_i \times (p_T^i)^{\kappa}$$

- **Dijet charge** from hadronic W decays in ttbar semileptonic decays

arXiv:1209.2421

Jet charge optimization

- **Optimal momentum weighting factor (κ)**
  - For fixed positive charge, the optimal value for κ is ~0.4, independently of jet p_T

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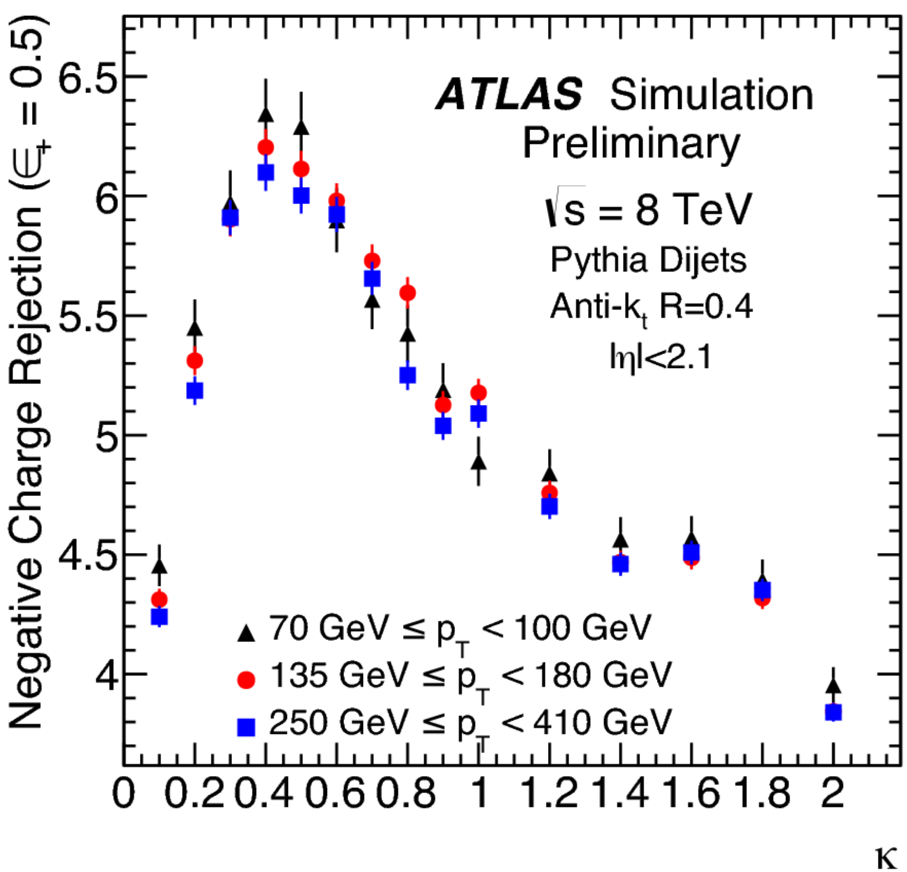

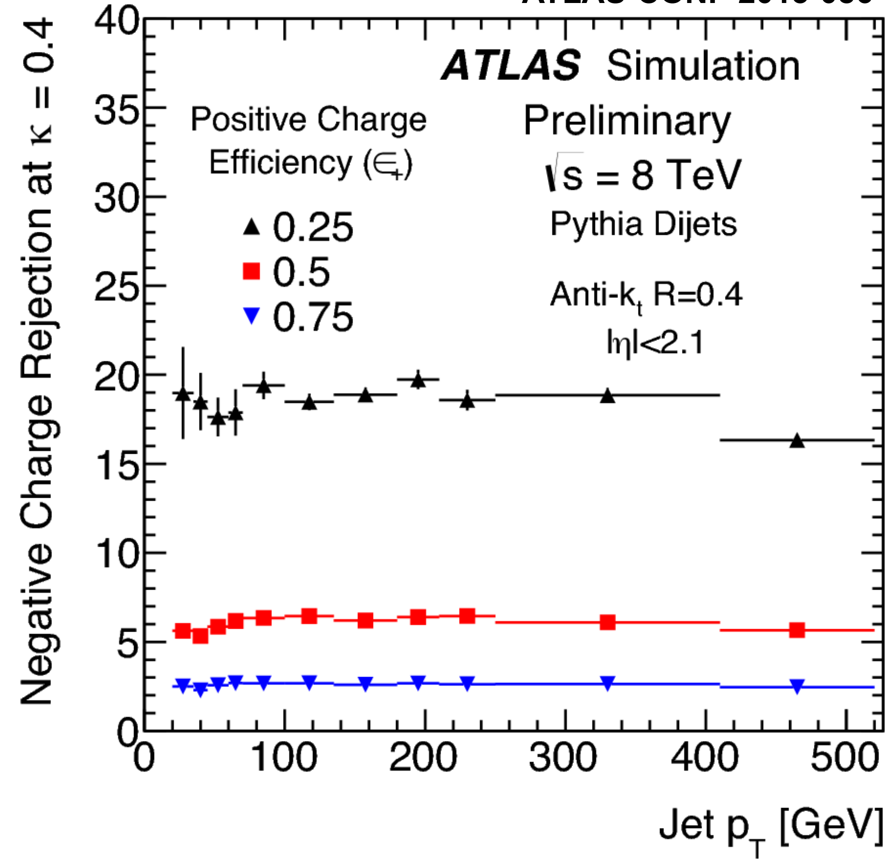

Jet charge in boosted W jets

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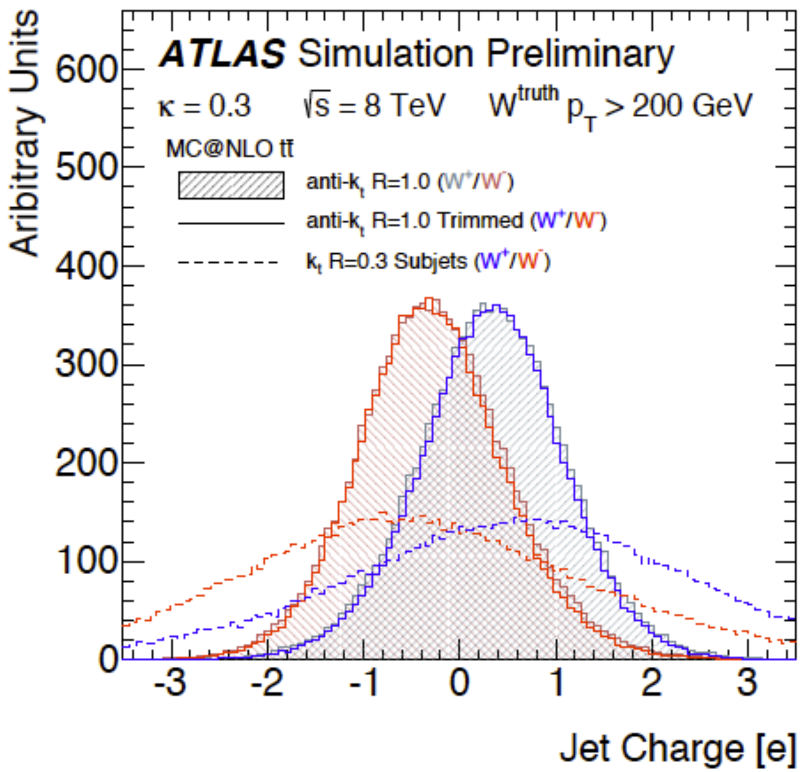
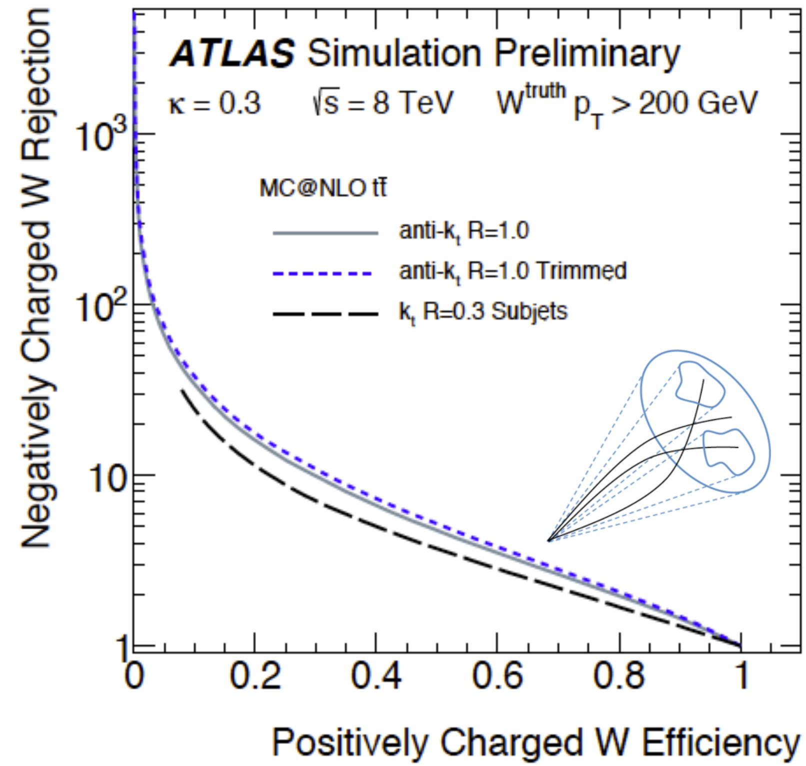


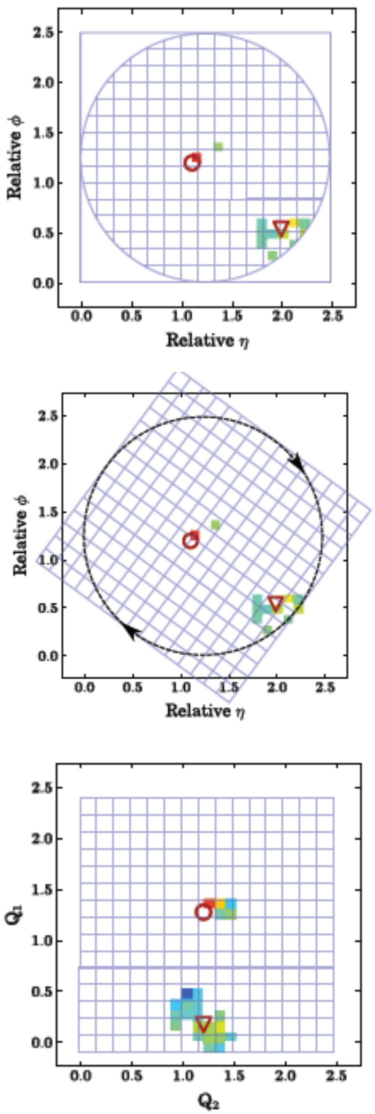


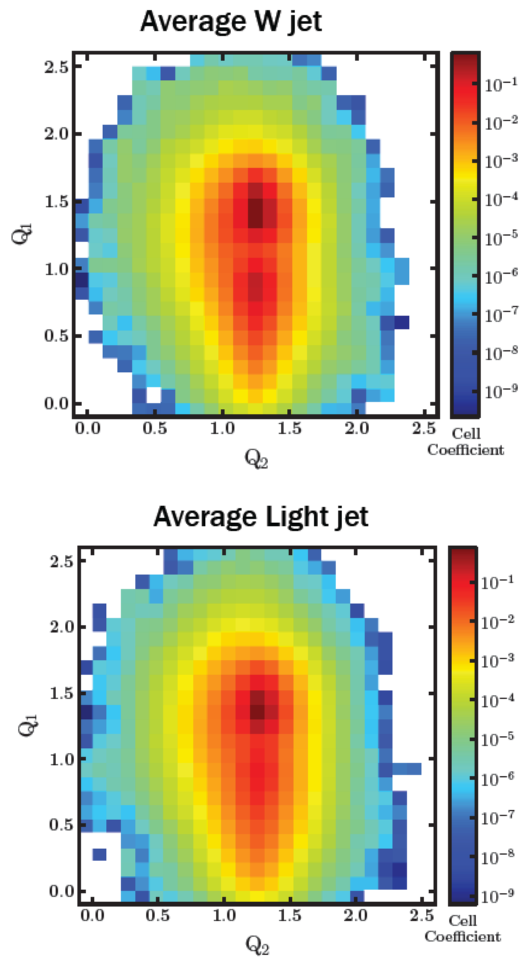
- **Different ways to define jet charge in a boosted W jet**
  - Using the sum of leading subjet charges leads to worse separation
- **Optimal definition makes use of all associated tracks**
  - Grooming has not impact

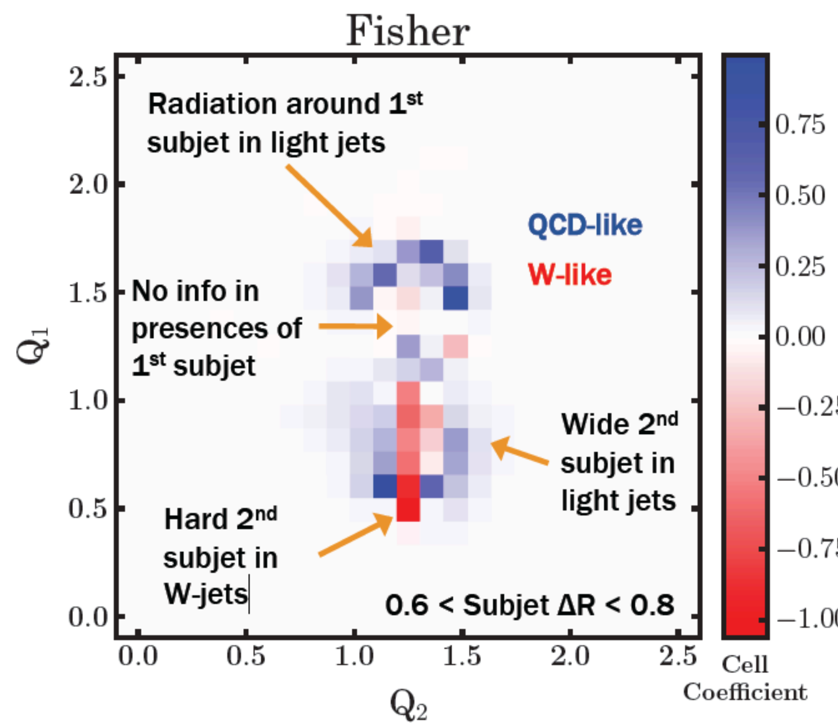
New idea: computer vision

From BOOST13, not an ATLAS result

J. Cogan, M. Kagan, M. Strauss, A. S.
(paper in preparation)





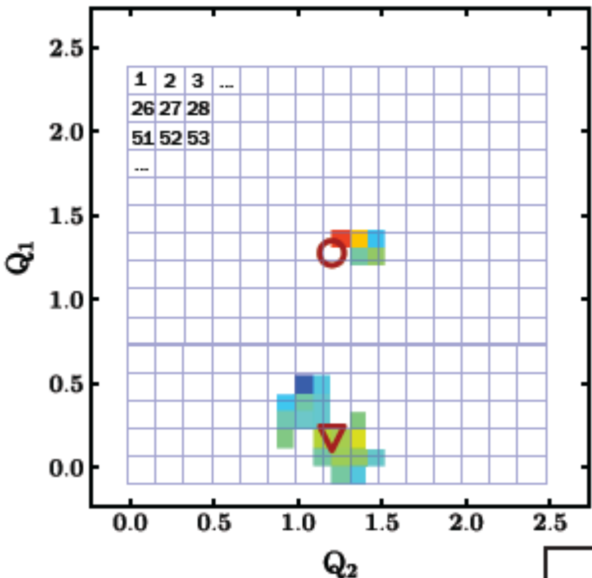


Fisher discriminant

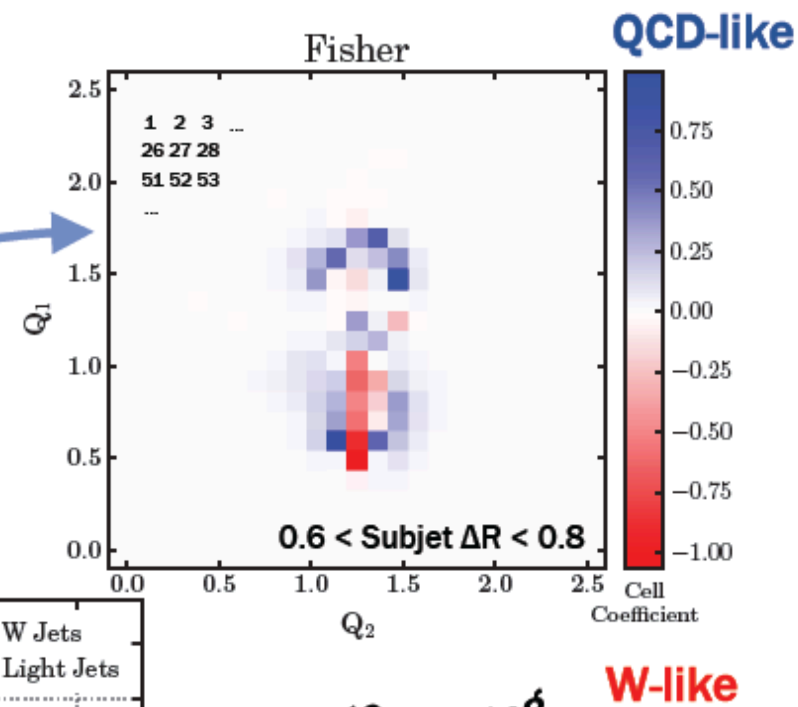
Computer vision (II)

Dot product of two jets-images!

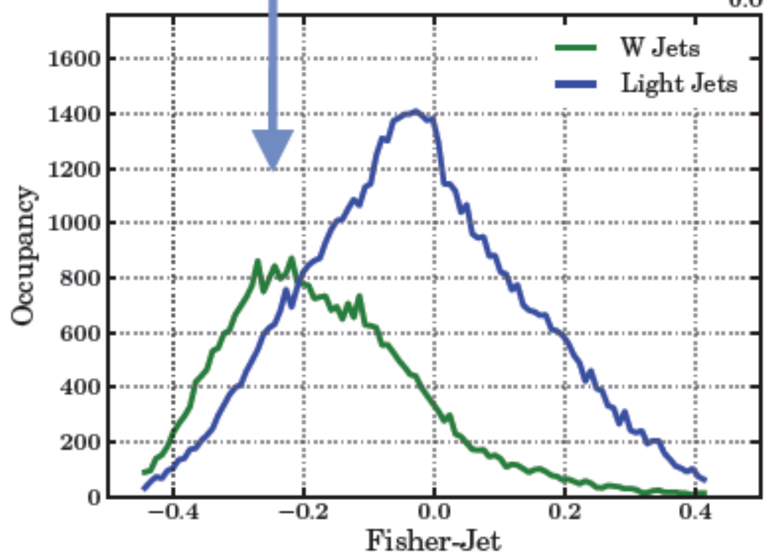
$$D = \sum p^T_i \lambda_i$$



Jet-image being tested

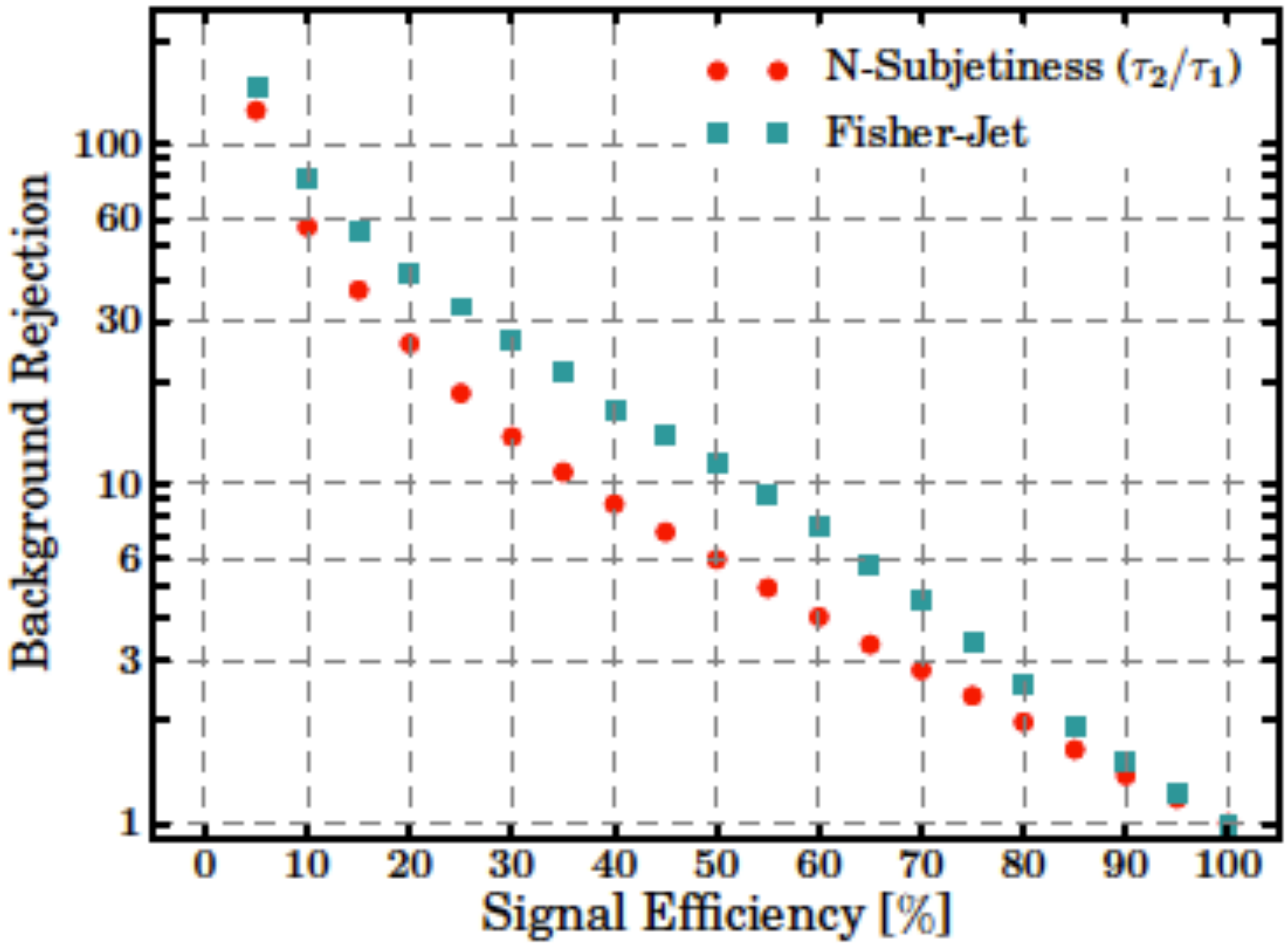


Jet-image doing the testing



Computer vision performance

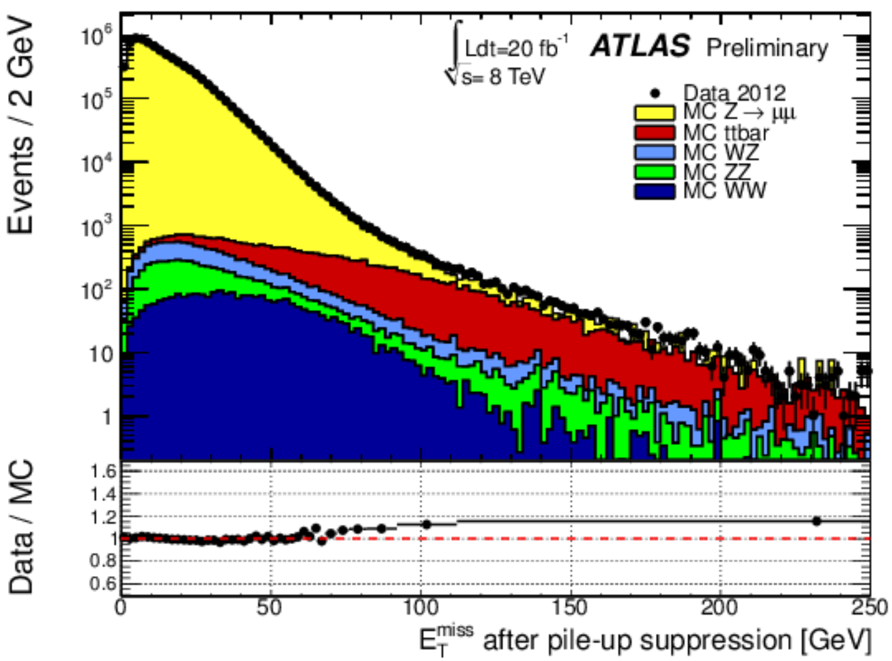
- **W tagging performance with mu=30, p_T=250 GeV**



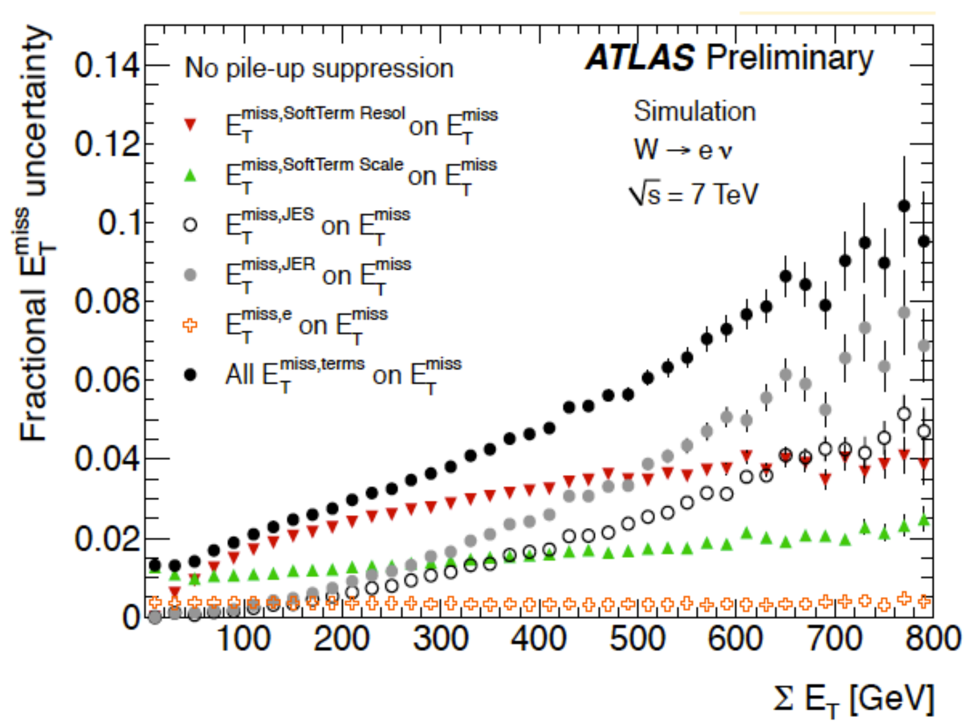
Missing ET

- Based on calibrated physics objects plus clusters and tracks not associated to physics objects

E_T(jets) + $E_T(\gamma/e/\mu/\tau)$ + Soft term



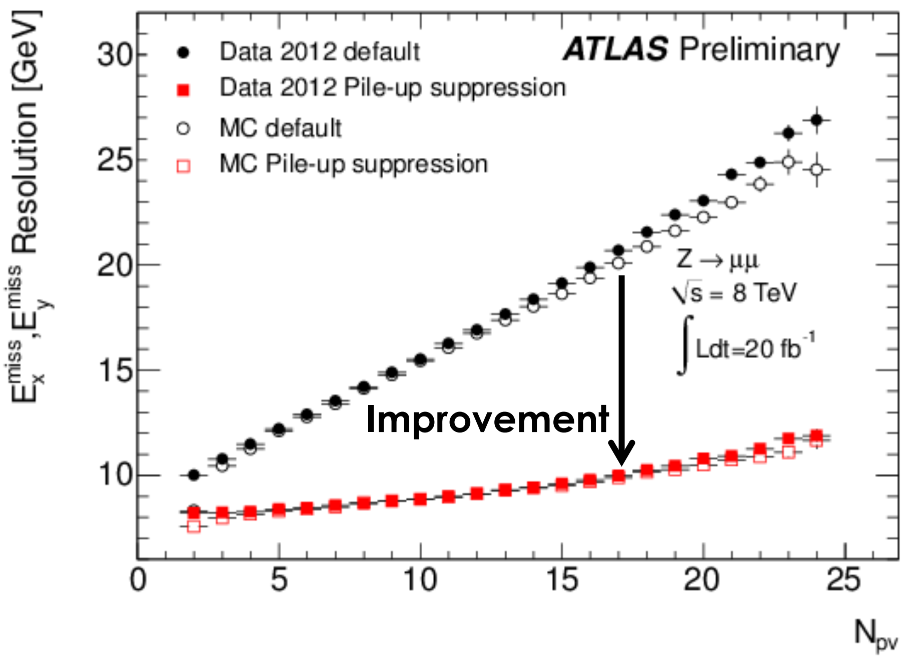
ATLAS-CONF-2013-082

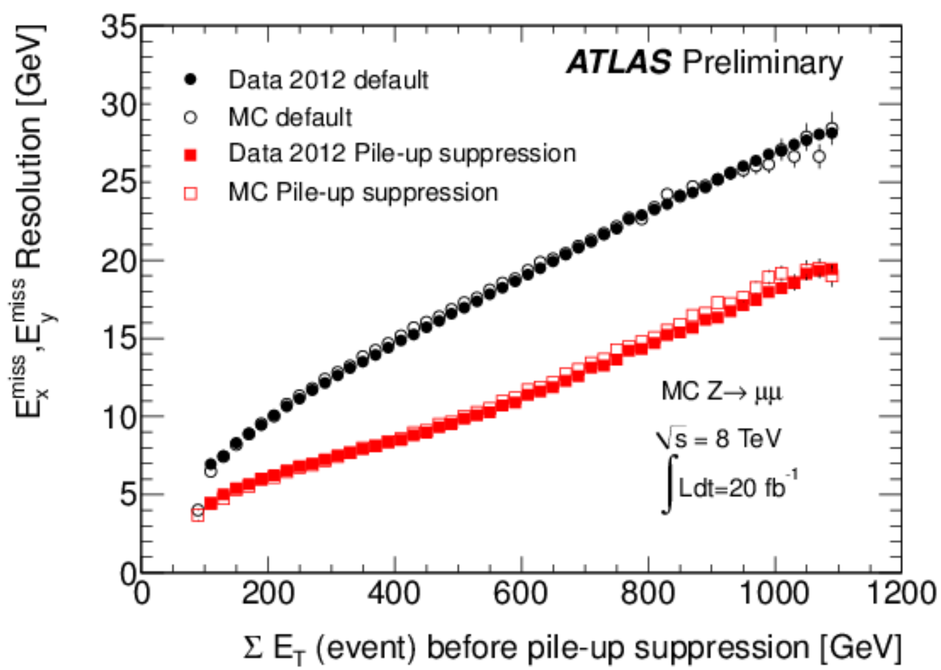


Missing ET: pileup

- **Pile-up suppression using tracks: Soft Term Vertex Fraction (STVF)**
  - Extension of the JVF concept to the soft component of the missing ET

$$STVF = \left(\sum p_{\mathrm{T}}^{track,PV} \Big/ \sum p_{\mathrm{T}}^{track}\right)_{\substack{unmatched\\objects}}$$





ATLAS-CONF-2013-082

ATLAS jet reconstruction under HL-LHC conditions

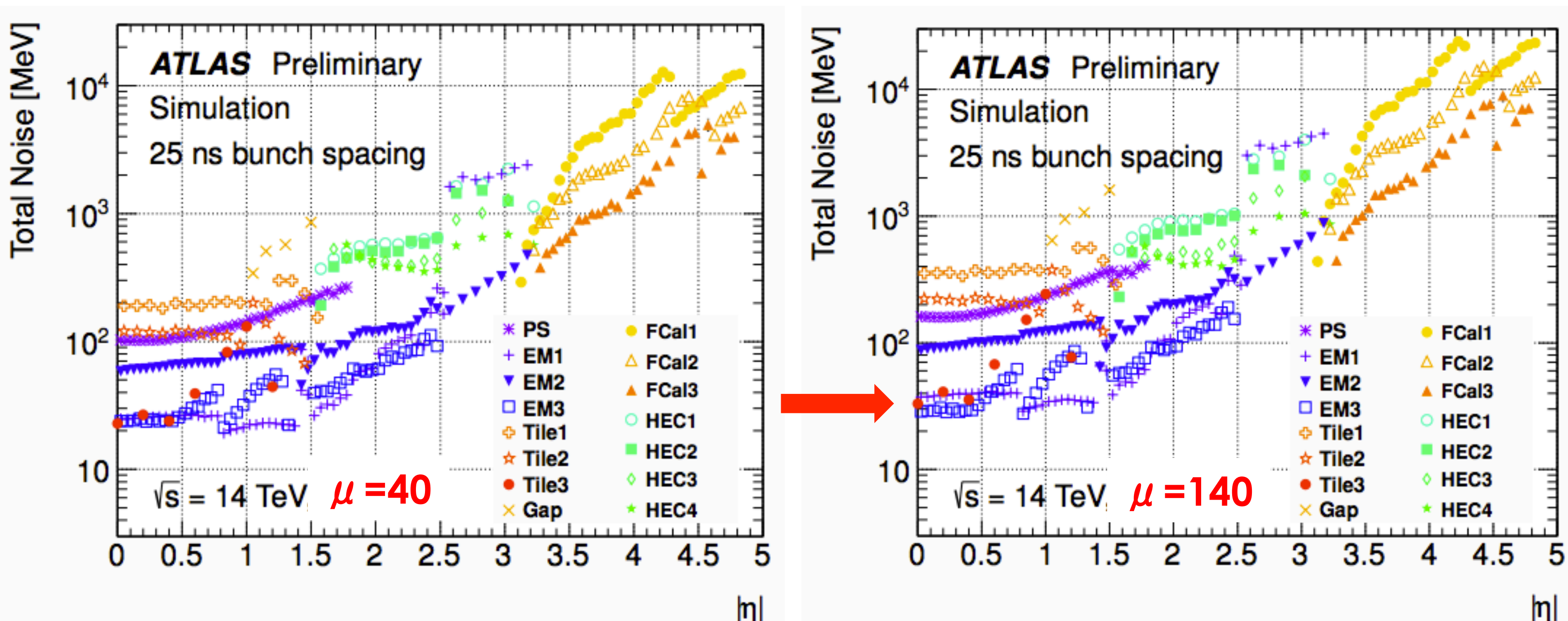
- **Broad program to optimize jet reconstruction and calibration techniques at very high luminosity**
  - Topoclustering and cluster calibration (pileup sigma noise)
  - Pileup subtraction, residual offset, and jet energy scale
  - Pileup suppression
  - Jet substructure and grooming

μ\σ	30	40	60	80	100	140	200
0	**X**	x	x	x	x	x	x
40	x	**X**	x	x			
60	x	x	**X**	x	x		
80			x	**X**	x		
140					x	**X**	x
200						x	**X**

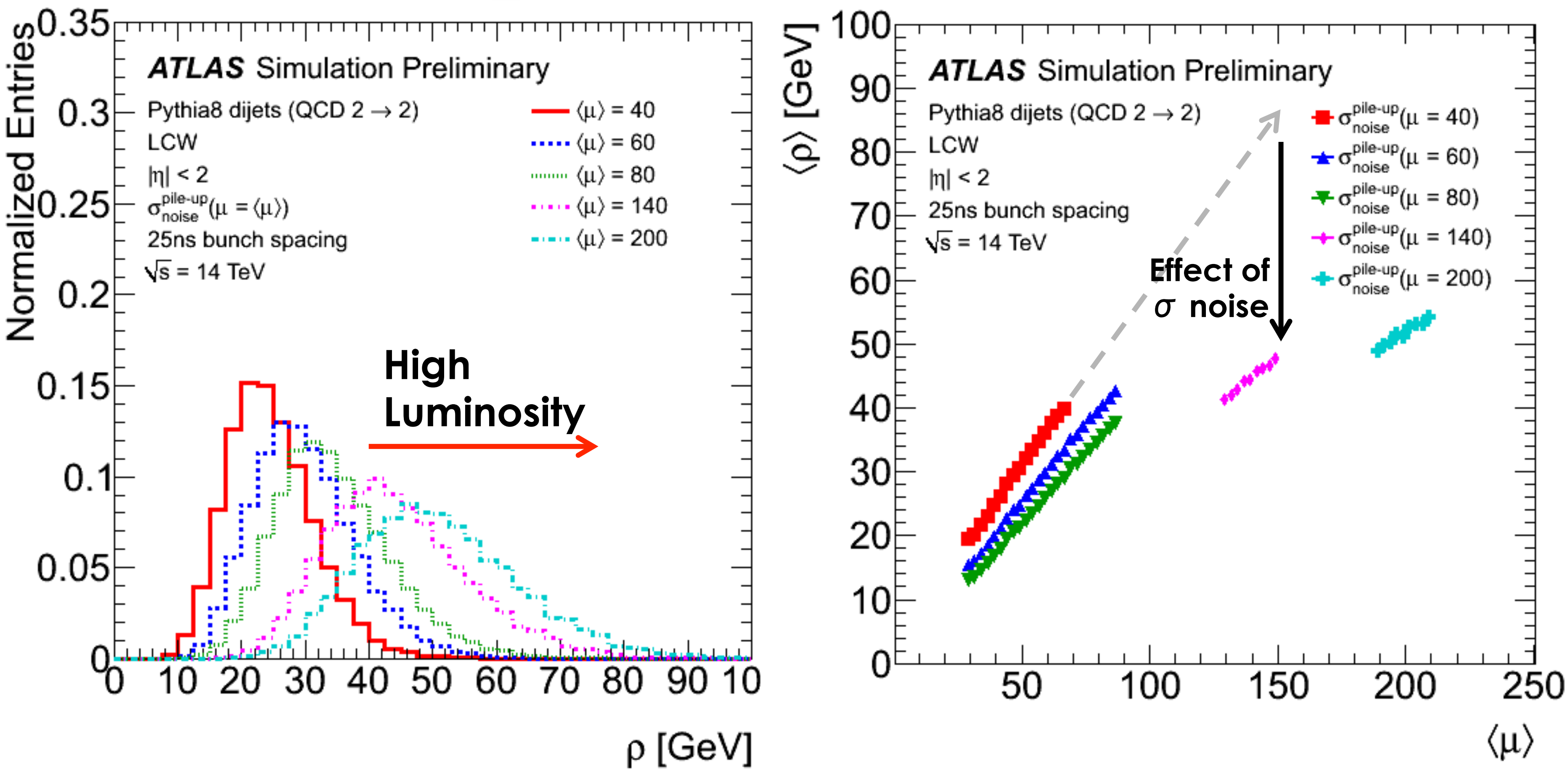
- Production of dedicated datasets at several μ and pileup noise values (σ)
- **Calorimeter-only simulation:**
  - **No tracks available in this analysis**
  - Focus on optimization of calorimeter level reconstruction
- **Ongoing work using phase 2 tracking layout**

Topoclustering at high luminosity

- **Adjust σ pileup noise for each μ configuration**
- Optimization of local calibration for EM/HAD cluster classification for each pileup noise value



Pileup subtraction (I)

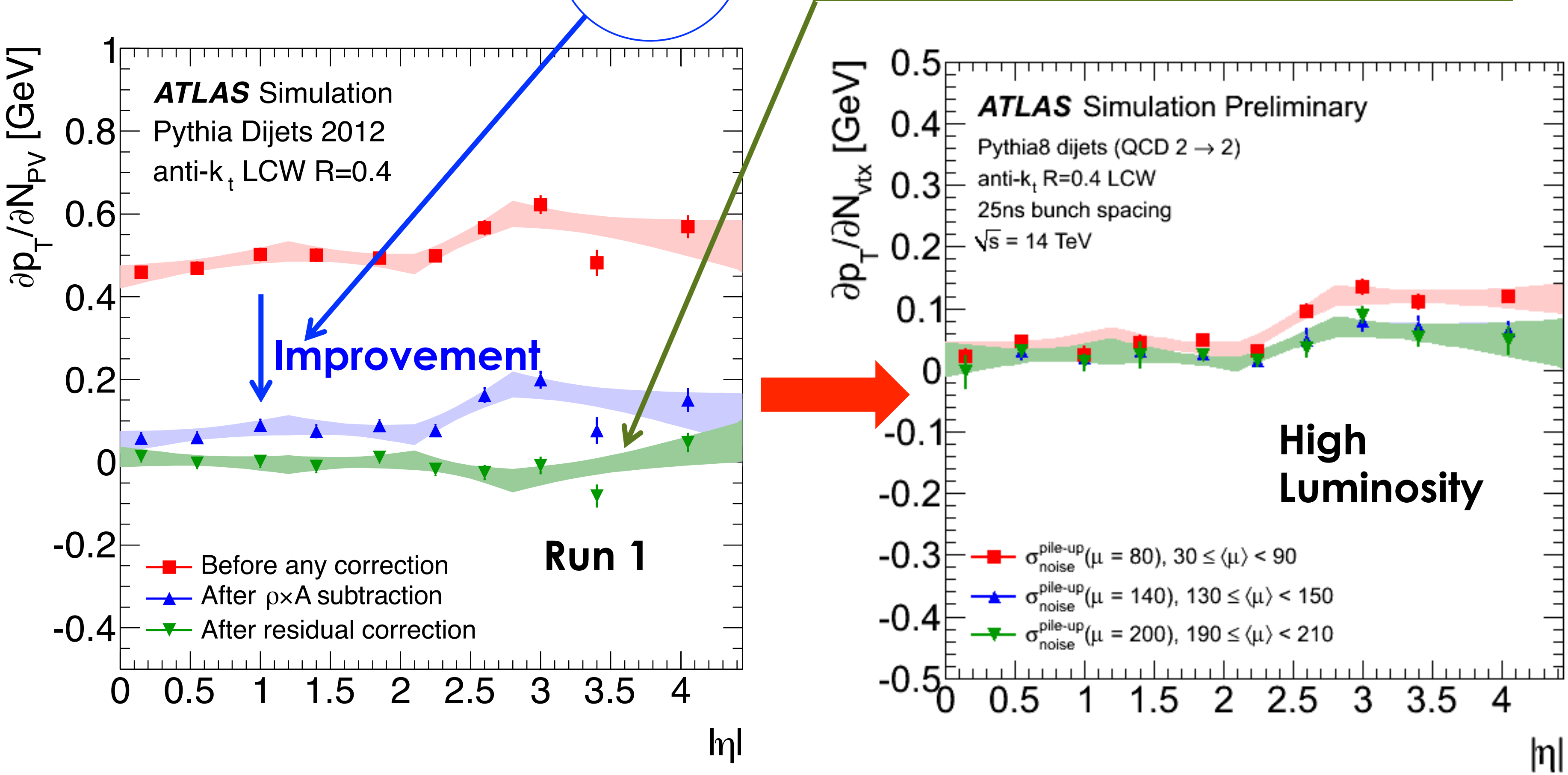


- **Linear behavior of rho up to high mu for fixed pileup noise values**
- **The use of higher pileup noise values leads to a partial suppression of pile-up**
- Optimization of noise in topoclustering is key to reconstruct jets at high luminosity

Pileup subtraction (II)

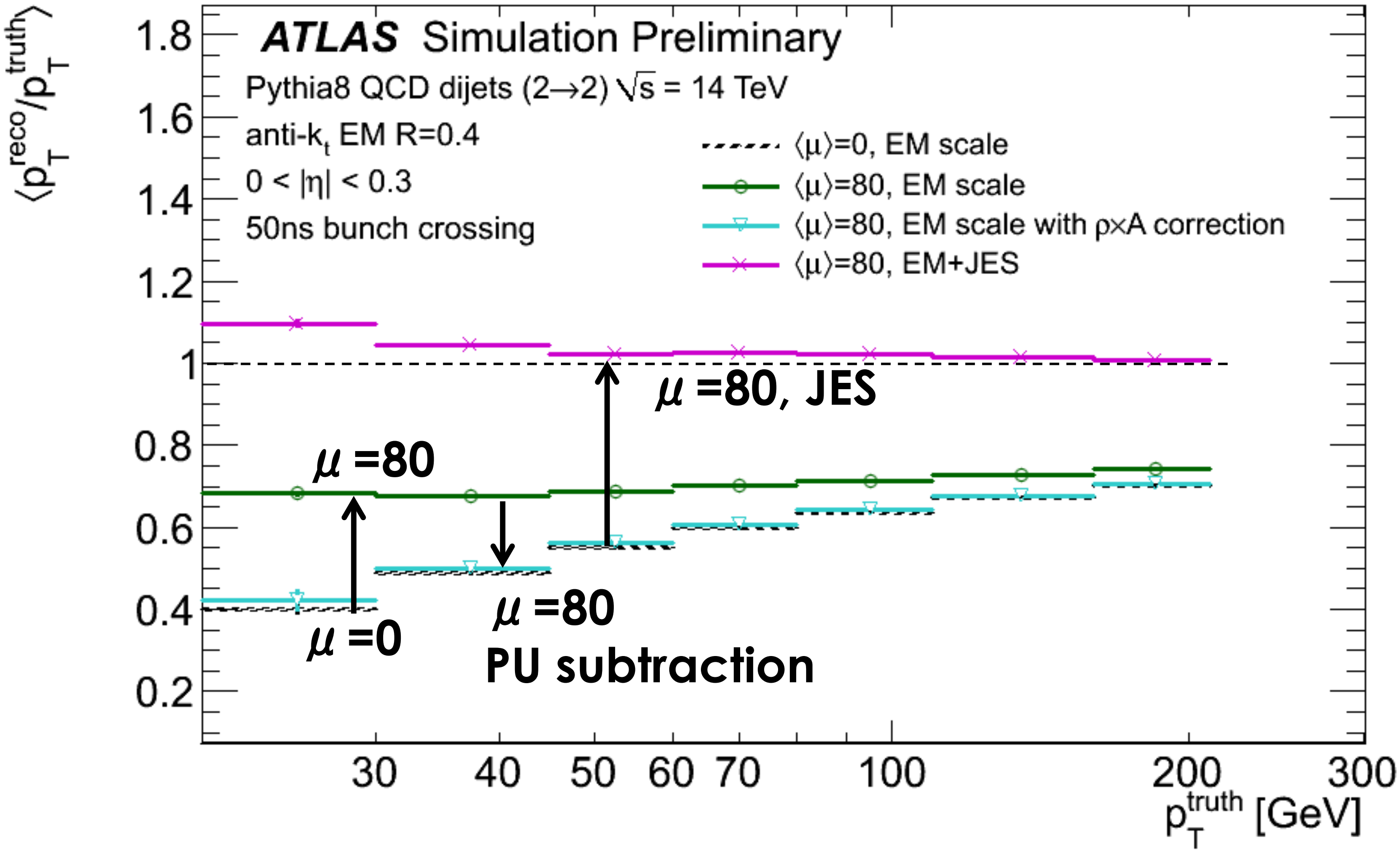
Residual correction

$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - \rho A_{\mathrm{T}} - \alpha(N_{\mathrm{PV}} - 1) - \beta\langle\mu\rangle$$



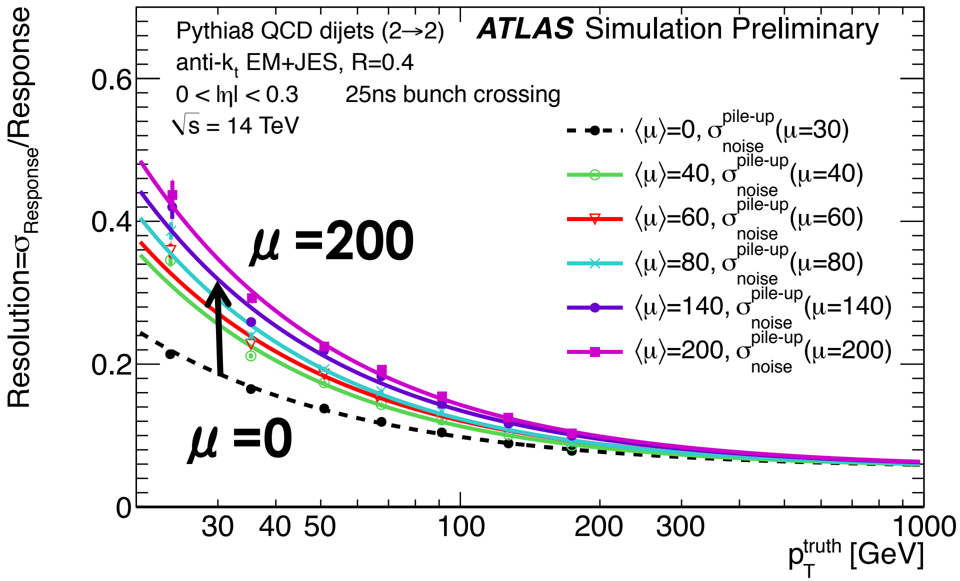
- Residual offset is mostly pileup independent after adjusting sigma noise
- **Jet areas subtraction, topoclustering, and local cluster weighting work well at high luminosity**

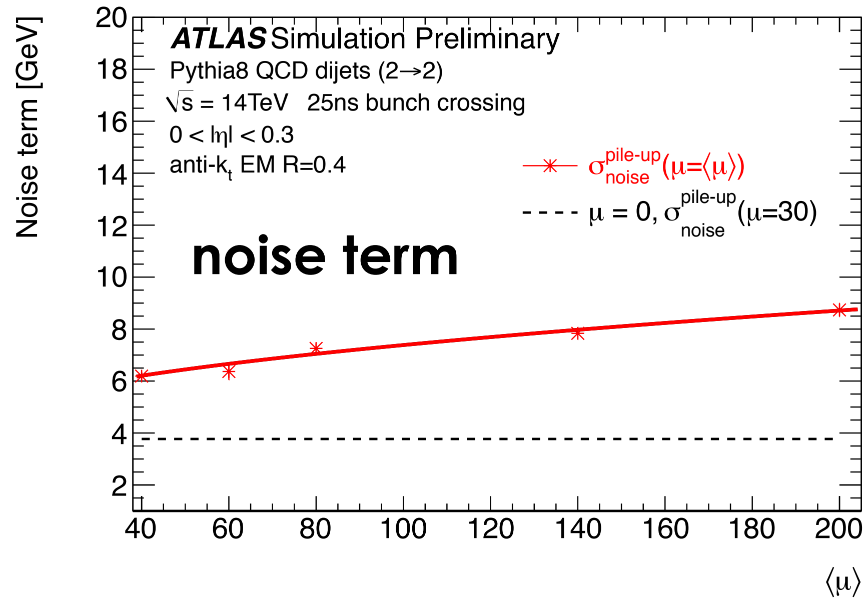
Jet energy scale



- Pileup subtraction restores the jet response to that of the jets with mu=0
- Jet energy scale restores the response to unity
- **Jet calibration scheme continues to work at high luminosity**

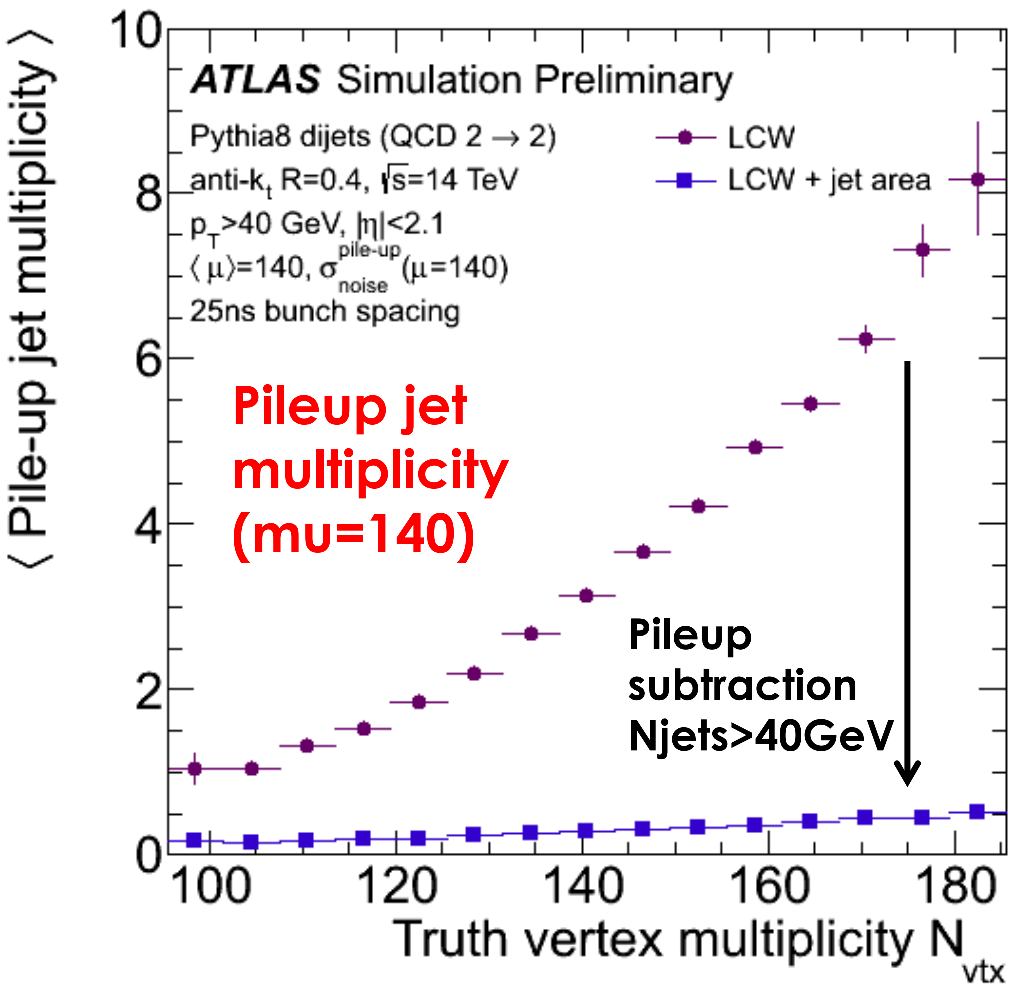
Jet energy resolution





- **Fractional jet energy resolution degrades at low p_T due to increased (pileup) noise term:**
  - Local pileup fluctuations within events
- **Noise term increases as sqrt(mu)**
- **Expect improvements using tracks**
  - Reduce local pileup fluctuations

Pileup jets

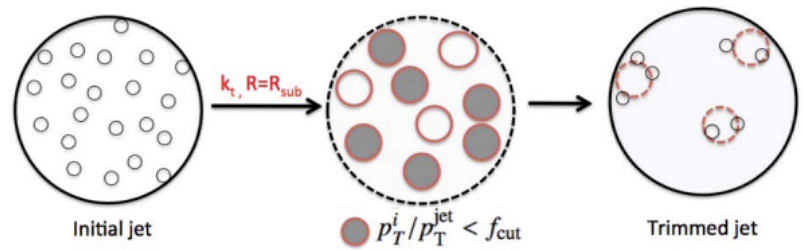


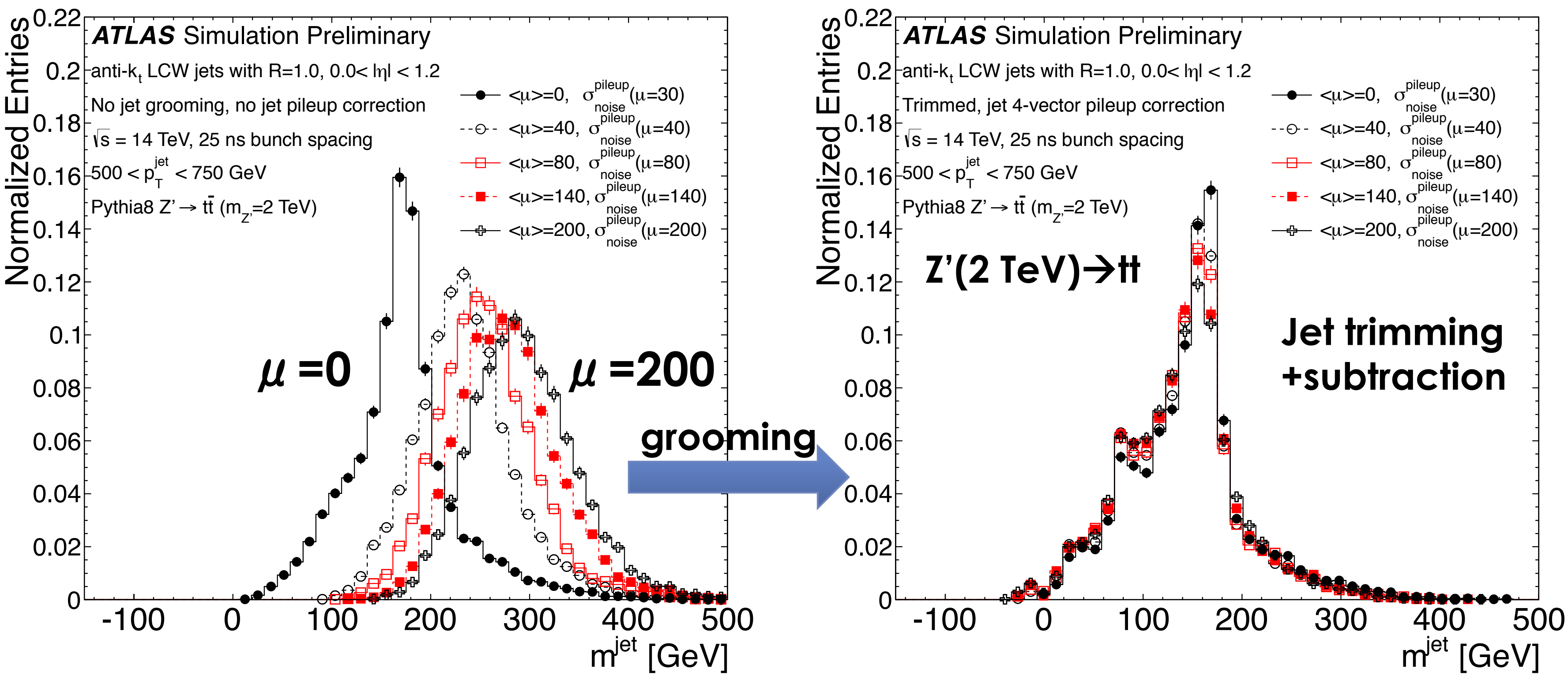
- **Pileup subtraction significantly reduces the mean number of pileup jets per event**
  - About 3 (0.5) pileup jets with p_T>20 (40) GeV per event at N_{PV} = 140
- **Further improvements expected using tracking and vertexing information**

Jet substructure

- **Test performance of grooming algorithms using 2012 based optimization:**
  - Trimming R_{kt}=0.3, f=5%

Jet trimming

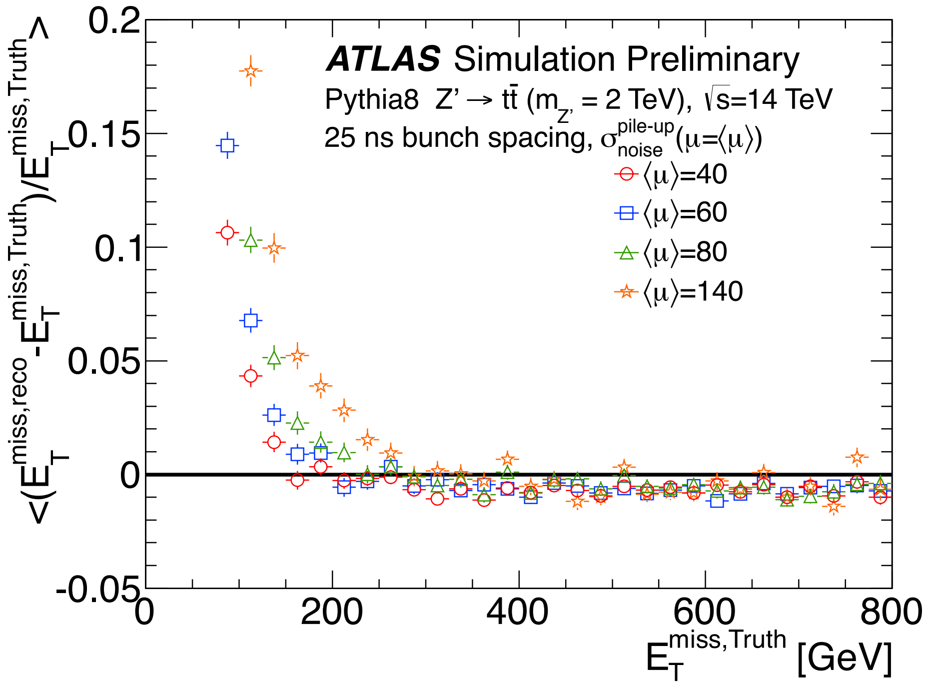


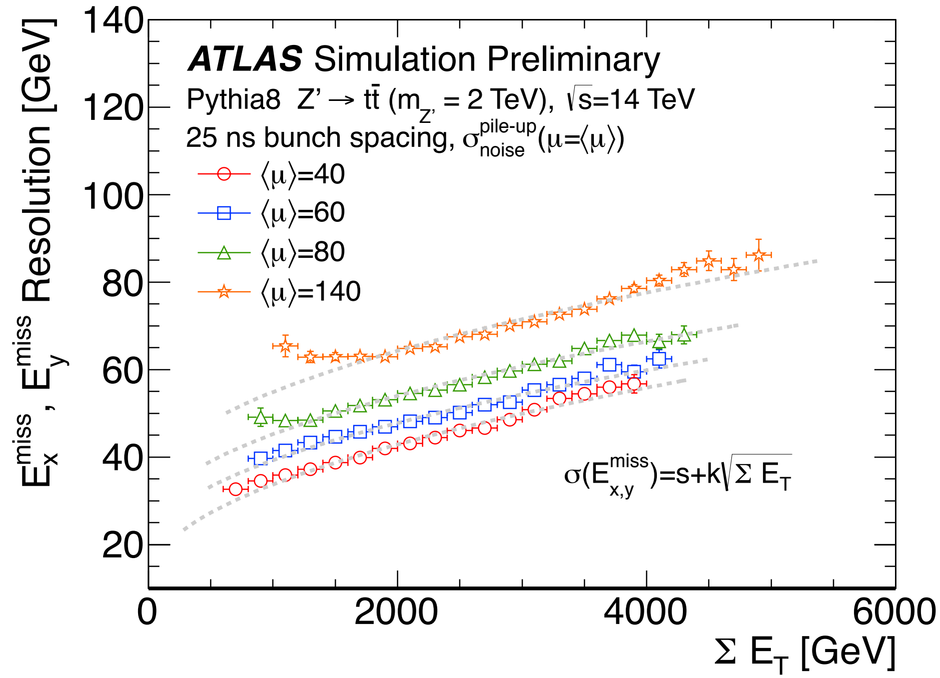


- **Trimming with 2012 parameter optimization works at μ =200**
  - Jet mass distribution stable with μ up to very high luminosity

Missing ET @ high luminosity

- **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 noise (s) term of the resolution, but the stochastic (k) term remains approximately constant



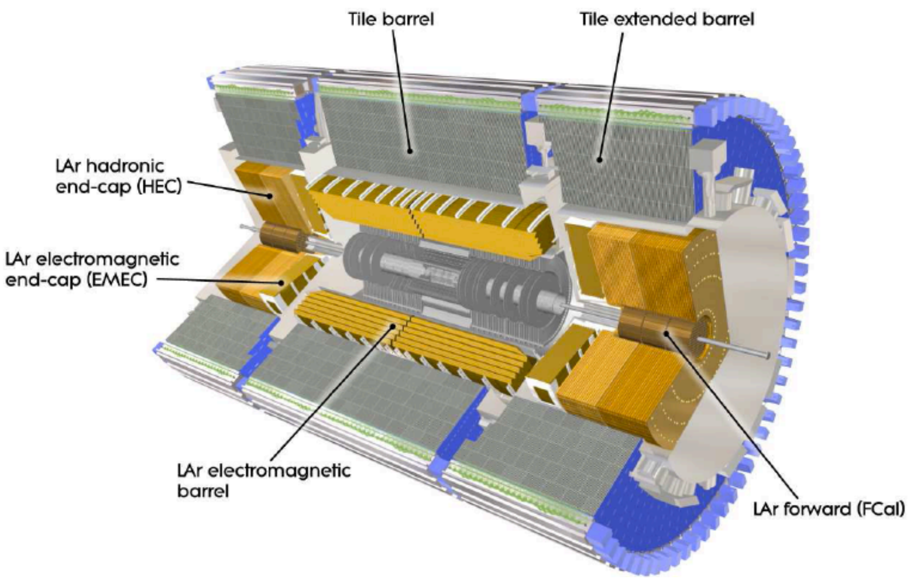


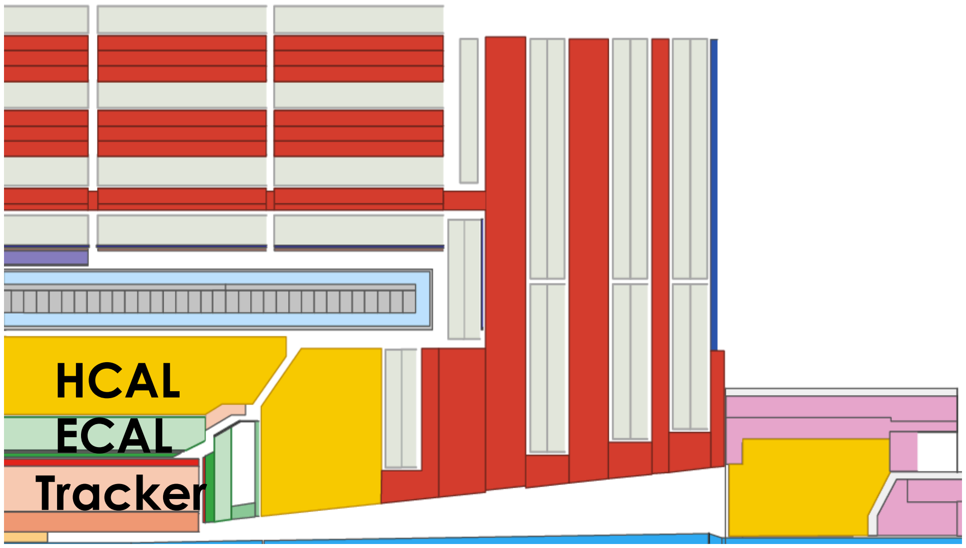
Summary

- **ATLAS has achieved a very high precision in jet energy and missing ET scale uncertainty and resolution**
  - Topoclustering and local hadron calibration
  - Event-by-event pile-up subtraction and suppression techniques
  - Insitu jet energy calibration
  - Post-calibration (jet-by-jet) corrections to improve the jet energy resolution
- **Many new jet algorithms, jet substructure, and jet-by-jet tagging techniques**
  - New ideas continue to emerge: telescoping jets, track-based grooming, computer vision tagging, jets without jets, …
- **Jet reconstruction and calibration continues to work under HL-LHC conditions**
  - Relies on optimization of topoclustering pileup suppression
  - Resolution degrades at low p_T due to increased pileup fluctuations: room for improvements using tracking information

Backup slides

ATLAS and CMS





- Calorimeter transverse granularity($\eta \times \phi$):
  - EM: (0.025 x 0.025)
  - HAD: (0.1x0.1) – (0.2x0.2)
- Resolution (stochastic term)
  - EM ~ 10%/√E
  - HAD ~ 60%/√E

e/h>1

- Calorimeter transverse granularity($\eta \times \phi$):
  - ECAL: (0.0174 x 0.0174)
  - HCAL: (0.087x0.087) --5 times coarser
- Resolution (stochastic term)
  - ECAL ~ 3%/√E
  - HCAL ~ 120%/√E

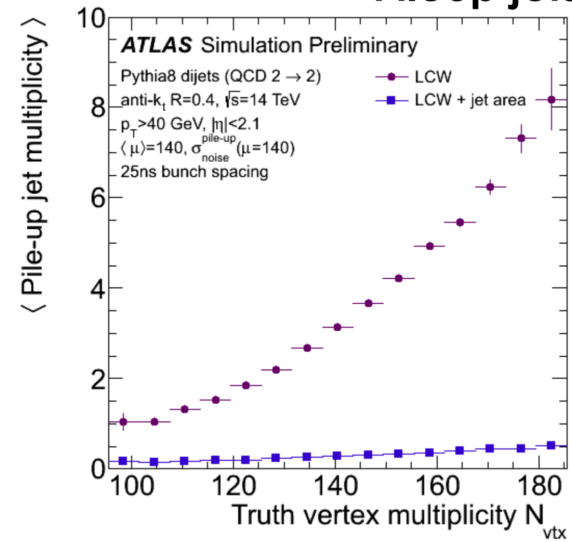
e/h>1

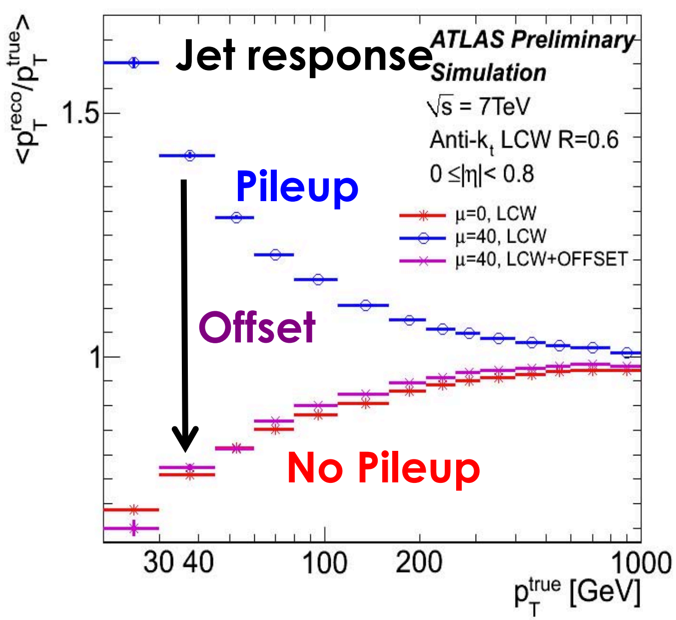
Pileup

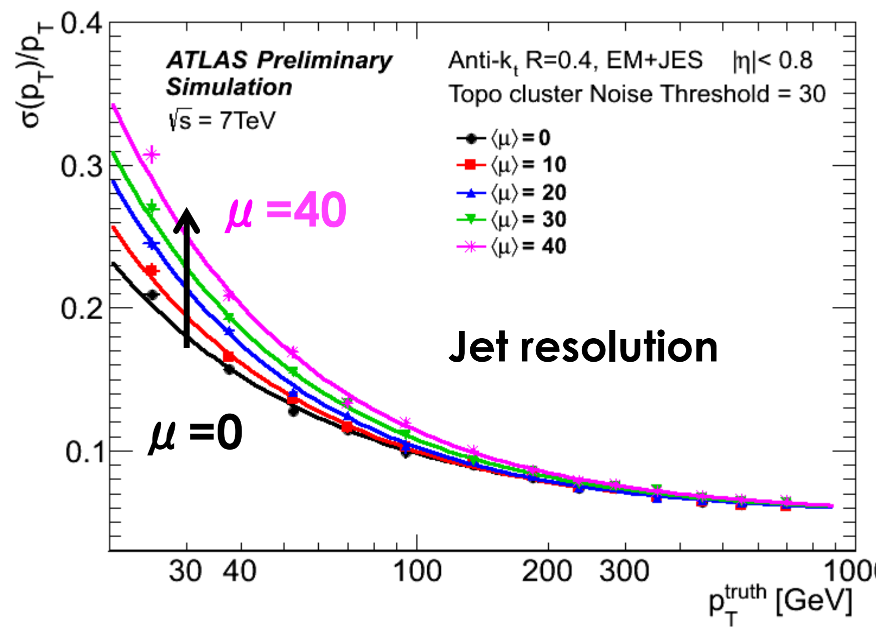
Pileup is one of the main challenges for jets and missing ET at the LHC:

- **Additional energy ([offset]())**
- **Pileup fluctuations:**
  - increase the noise term of the jet **[energy resolution]()** (event-by-event fluctuations)
  - additional **fake jets** (local fluctuations)

Pileup jets







Flavor uncertainty

$$\Delta\mathfrak{R}_s = \Delta f_g \times (\mathfrak{R}_q - \mathfrak{R}_g) \oplus f_g \times \Delta\mathfrak{R}_g,$$

- **Accounts for the application of the JES to final states with different flavor composition than the one used to derive it**
- Two components:
  - **Flavor response**
    - Difference in response between Pythia and Herwig++
  - **Flavor composition**
    - Different flavor composition in data and MC

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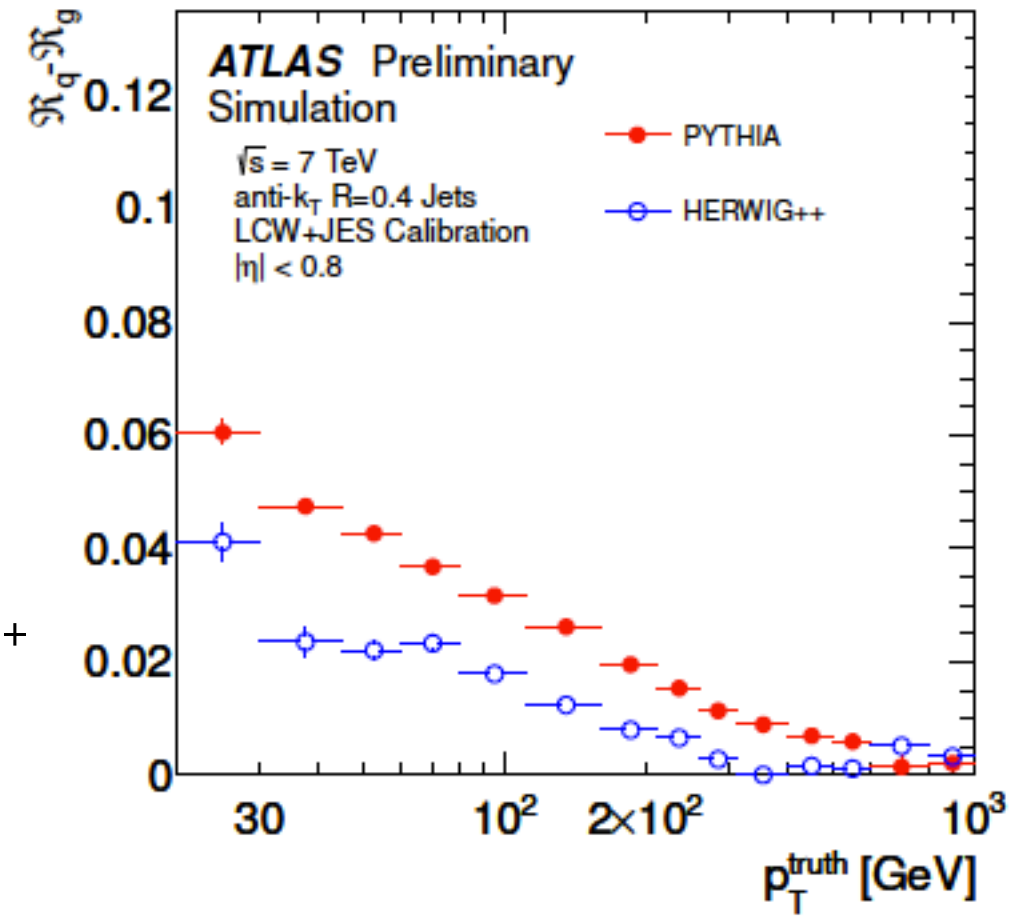
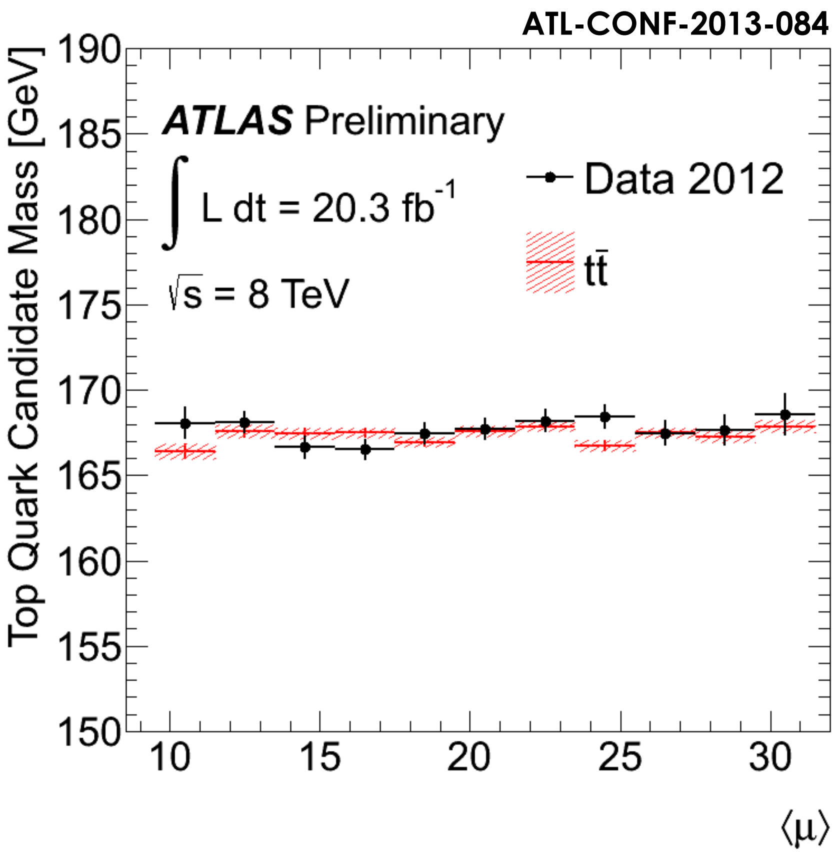
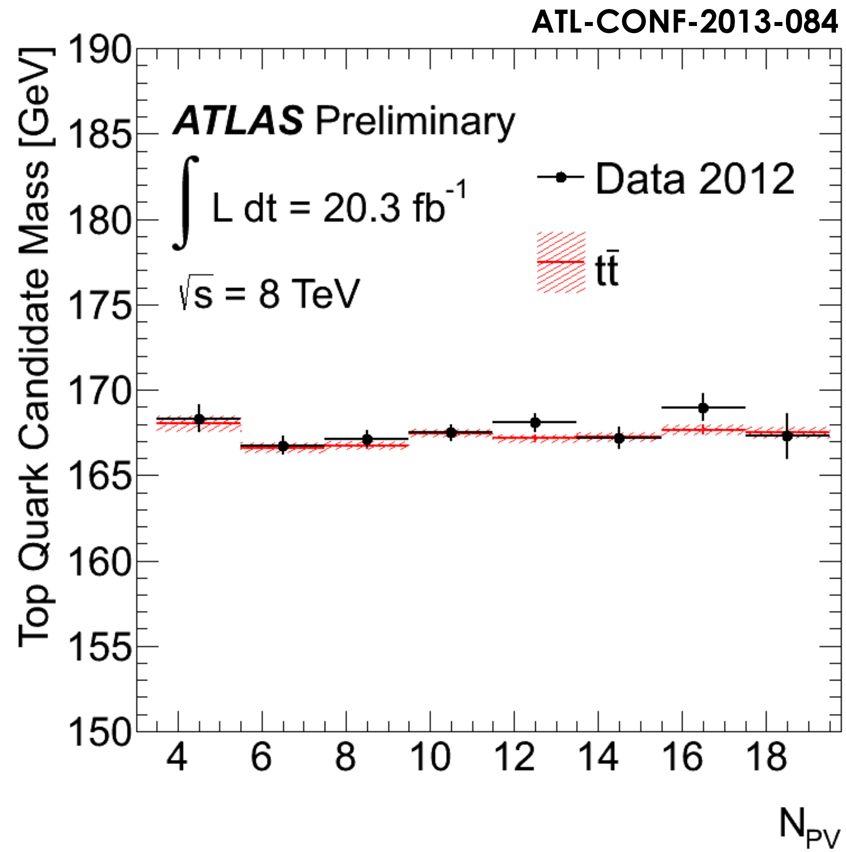


HEPTopTagger (II)

- **Stability of the reconstructed top mass with pileup**
  - Test of subjet calibration and pileup subtraction, and filtering

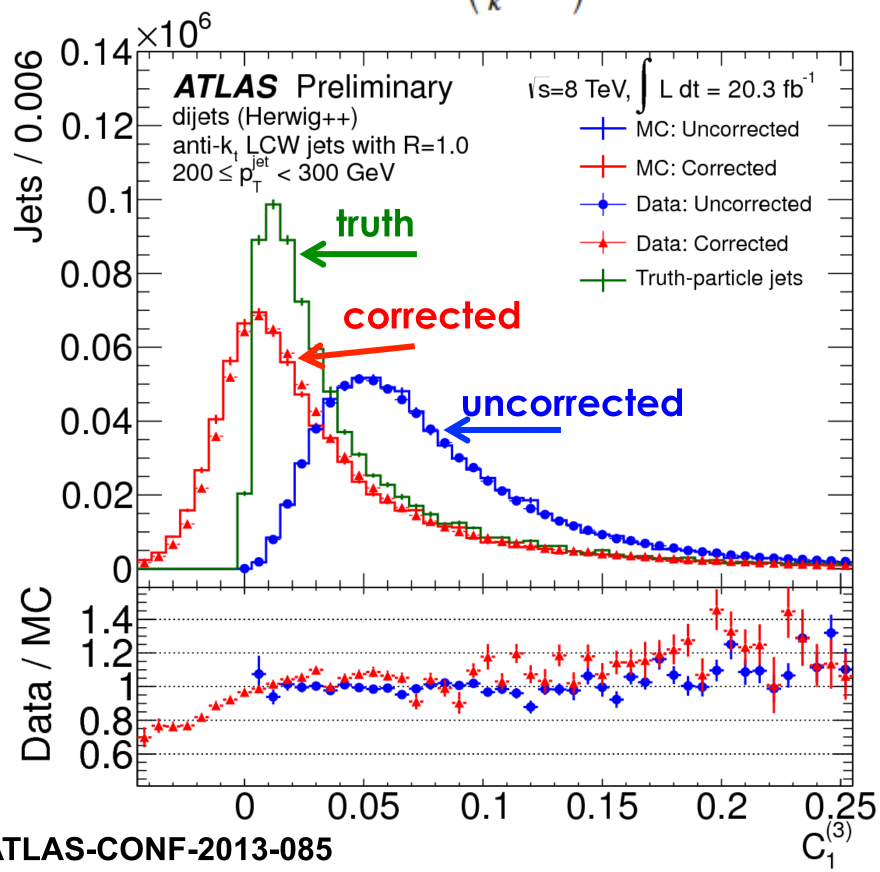




Jet shapes subtraction (II)

Energy-Energy Correlation:

$$C_1^{(\beta)} = \frac{\sum_{i<j} p_{\mathrm{T}i} p_{\mathrm{T}j} \left(\delta R_{ij}\right)^{\beta}}{\left(\sum_k p_{\mathrm{T}k}\right)^2},$$

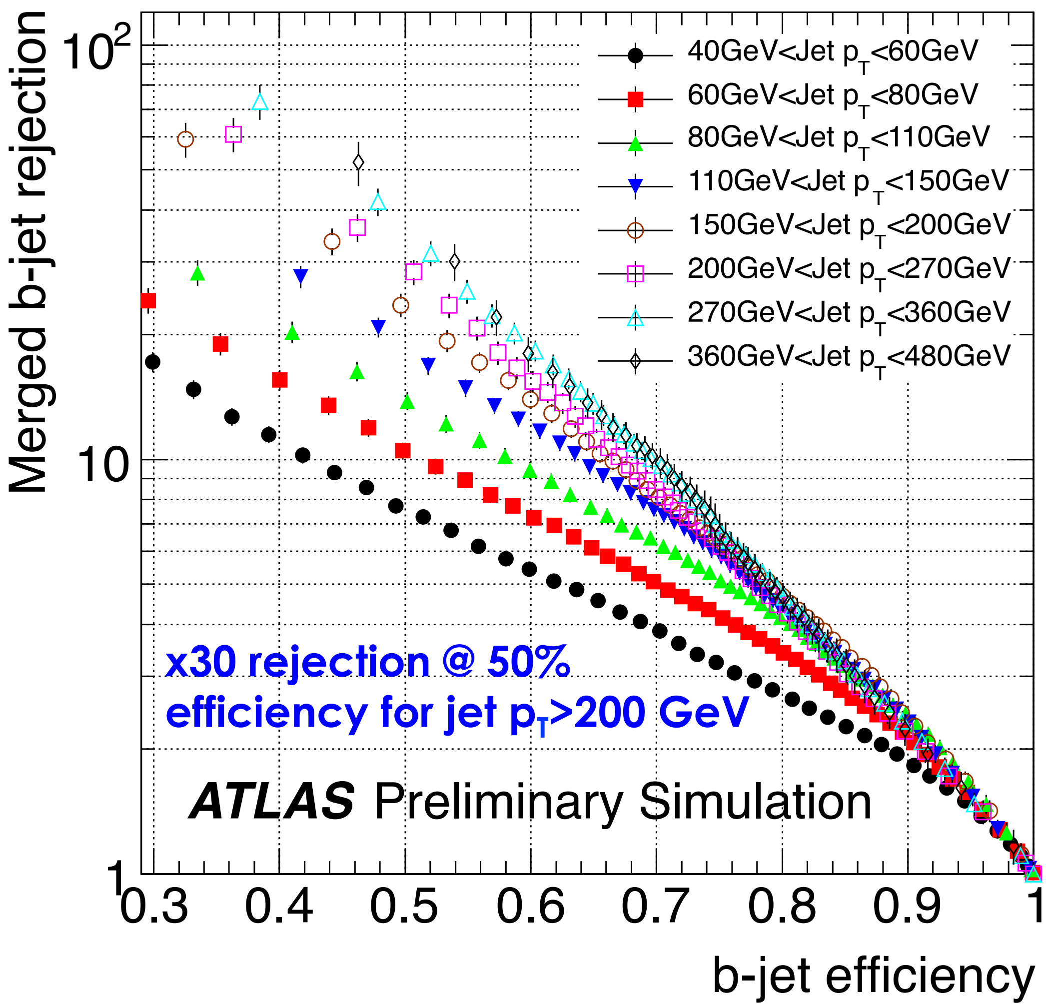


ATLAS-CONF-2013-085

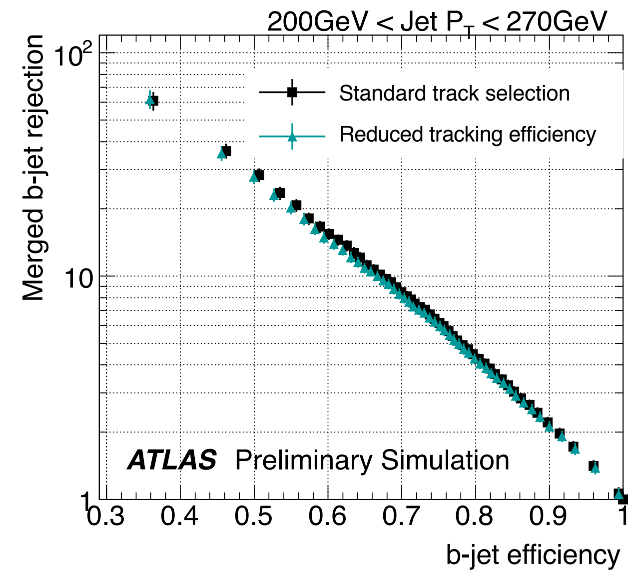
- **Over subtraction at low p_T leads to negative values for C_1**
- Feature modeled by the simulation (caused by the subtraction procedure)
- May be problematic for the use of this variable in the context of quark/gluon tagging
- Some variables more affected than others:

shape	p_T range [GeV]					
	200-300	300-400	500-600	600-800	800-1100	1100-1500
$C_1^{(3)}$	21.1 (24.7)	15.6 (18.5)	15.0 (16.3)	14.2 (15.7)	13.5 (14.6)	12.6 (13.5)
M	2.4 (3.2)	1.2 (1.8)	0.8 (1.0)	0.7 (0.8)	0.6 (0.7)	0.5 (0.6)
$\sqrt{d_{12}}$	0.5 (0.7)	0.2 (0.4)	0.1 (0.2)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)
τ_1	0.9 (1.4)	0.4 (0.8)	0.3 (0.5)	0.3 (0.4)	0.3 (0.3)	0.3 (0.3)
τ_2	3.0 (4.5)	1.9 (3.0)	1.7 (2.3)	1.6 (2.1)	1.6 (2.0)	1.9 (2.0)
τ_3	5.7 (8.1)	3.9 (5.9)	3.9 (5.0)	3.8 (4.8)	3.9 (4.7)	4.5 (4.9)
τ_{32}	0.3 (0.4)	0.3 (0.5)	0.5 (0.6)	0.6 (0.7)	0.8 (0.8)	1.3 (1.0)

Double B-hadron performance

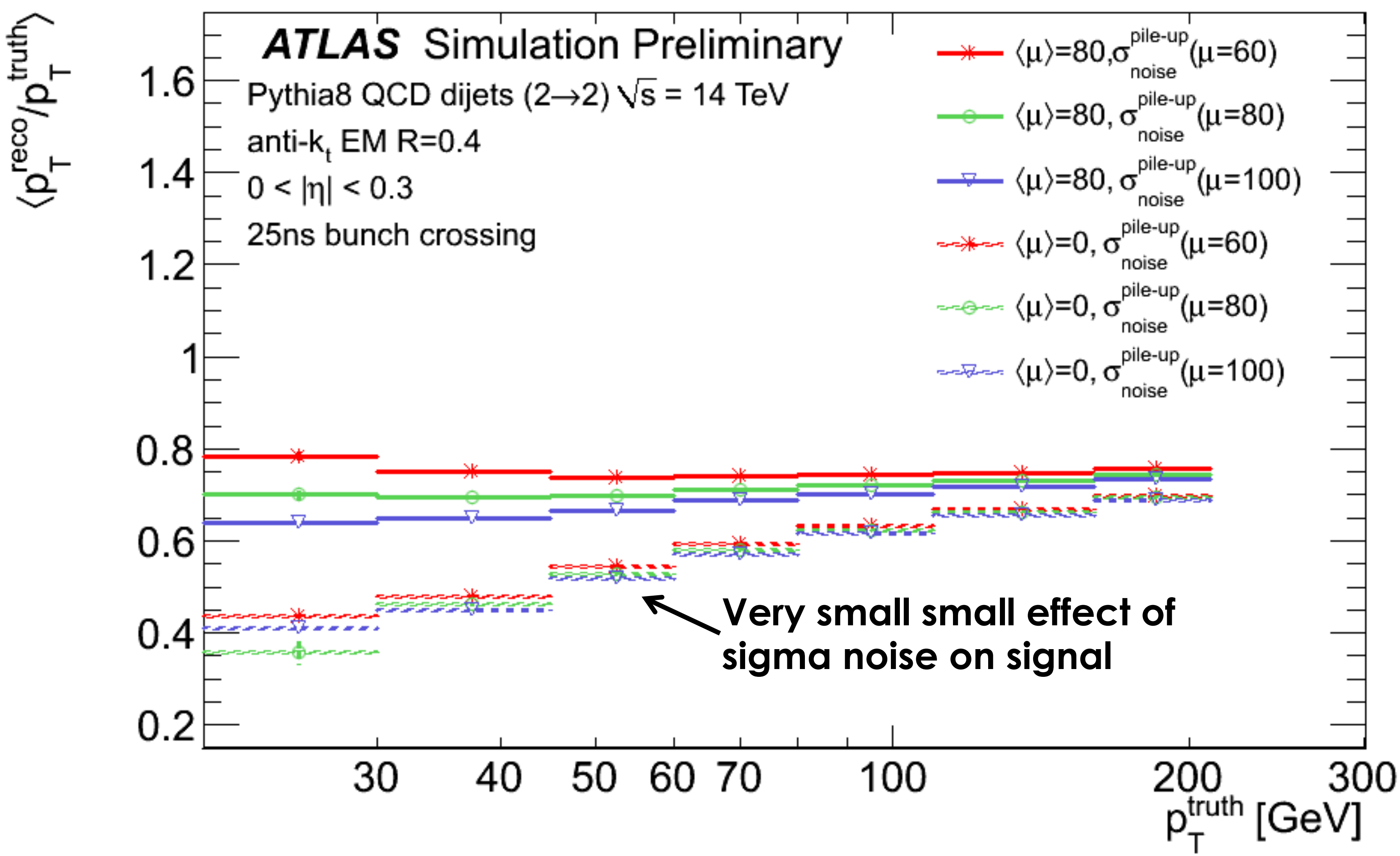


ATLAS-CONF-2012-100

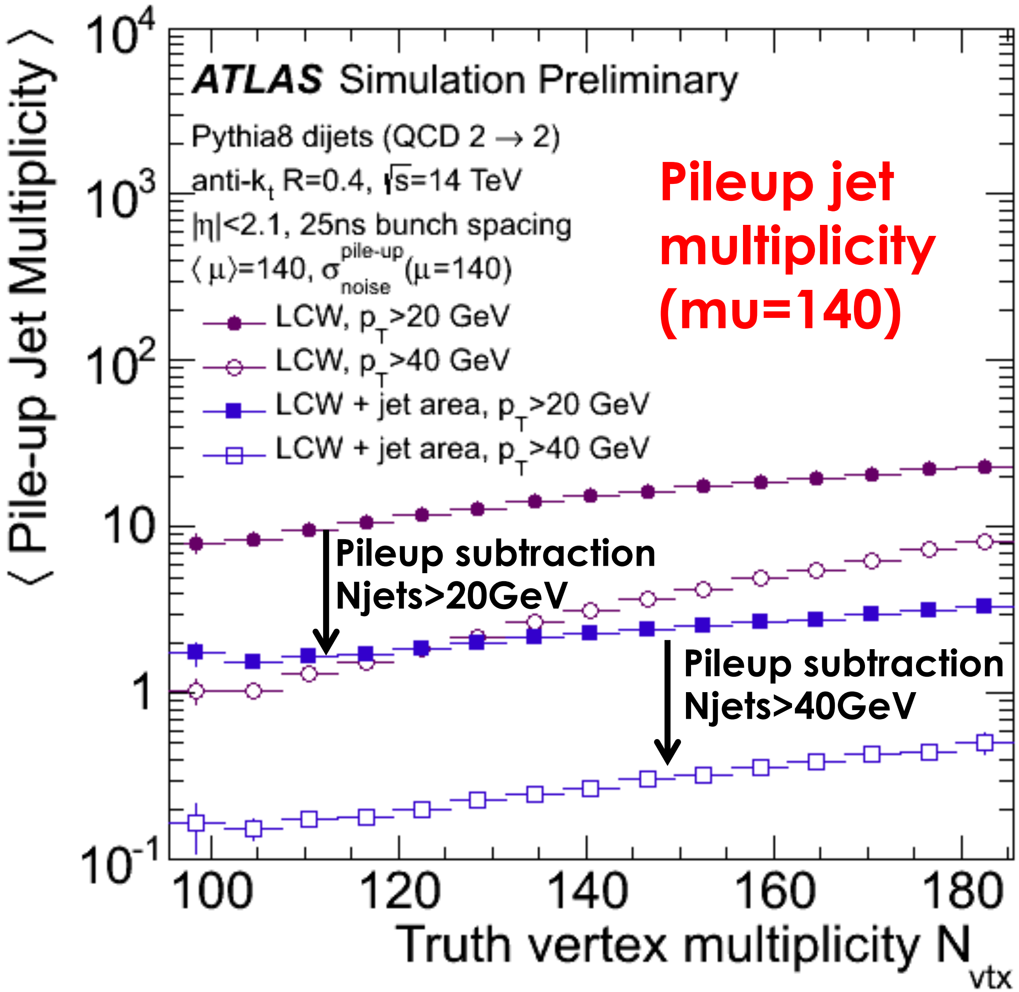


Systematic source	Uncertainty
pile-up	neglible
b-tagging efficiency	neglible
track reconstruction efficiency	4%
track p_T resolution	neglible
jet p_T resolution	6%
jet energy scale	5%

Jet response



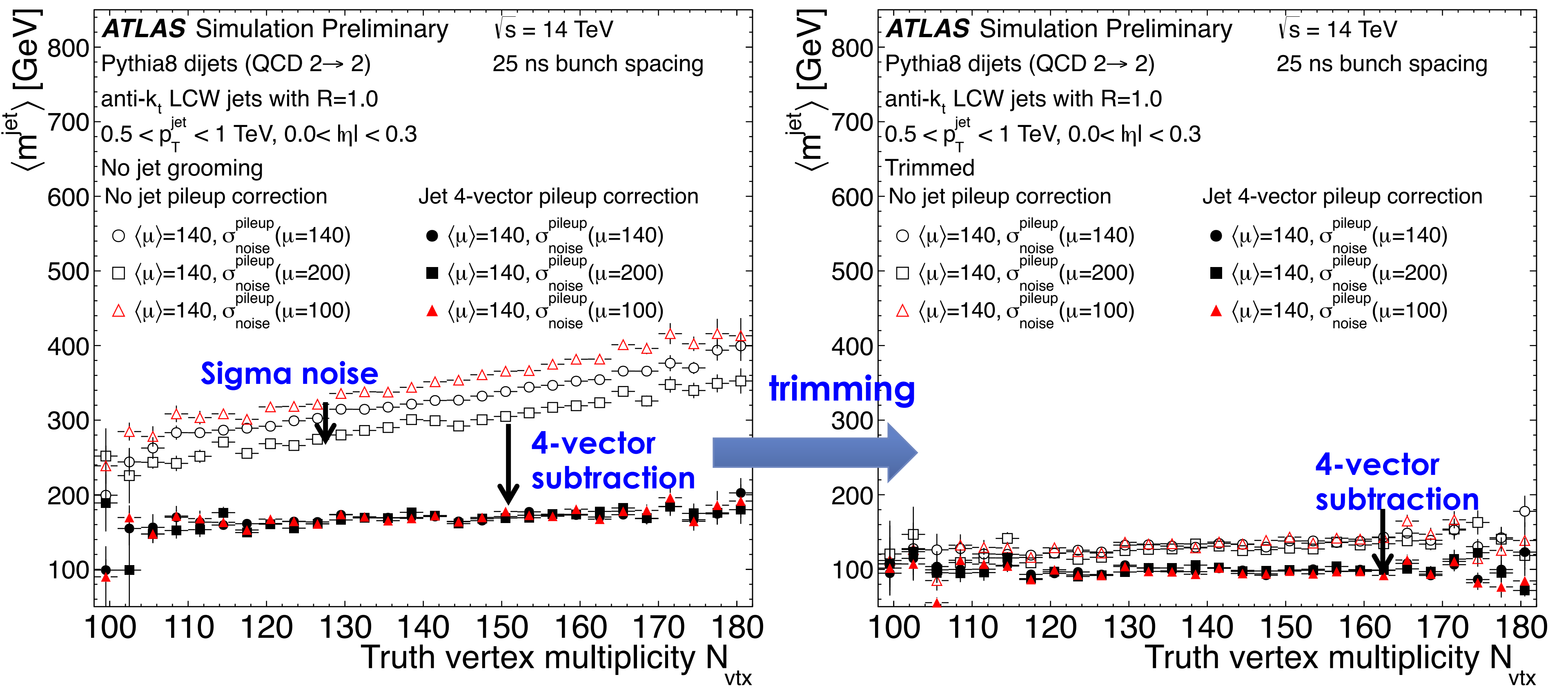
Pileup jets



- **Pileup subtraction significantly reduces the mean number of pileup jets per event**
  - About 3 (0.5) pileup jets with p_T>20 (40) GeV per event at N_{PV} = 140
- **Further improvements expected using tracking and vertexing information**

Jet grooming performance

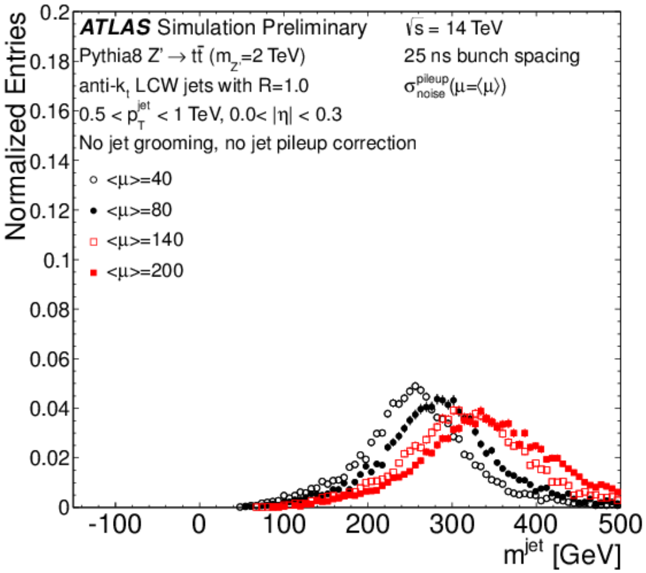
Dijet events



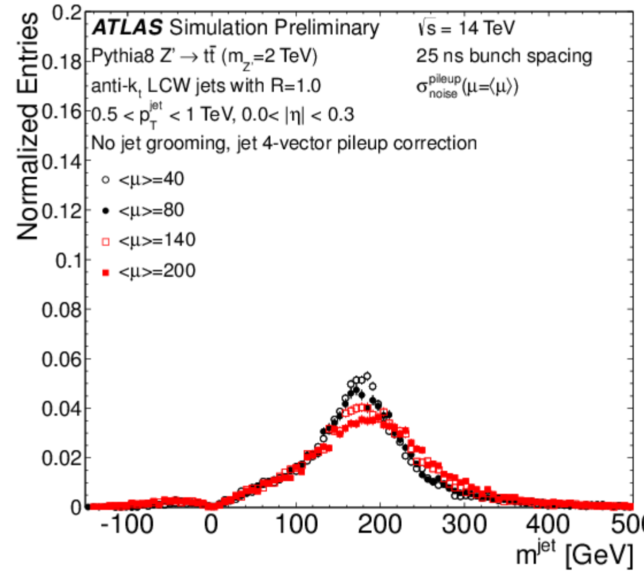
- Raising pileup noise values reduces the mean mass, but does not affect the dependence on pileup
- 4-vector subtraction successfully suppresses pileup, even without grooming
- **Trimming with subtraction further reduces pileup contributions to the jet mass**

Jet grooming performance

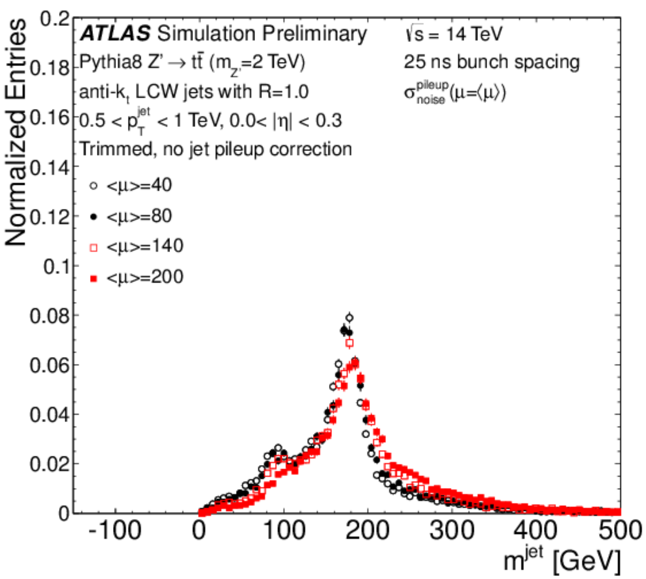
Top jets

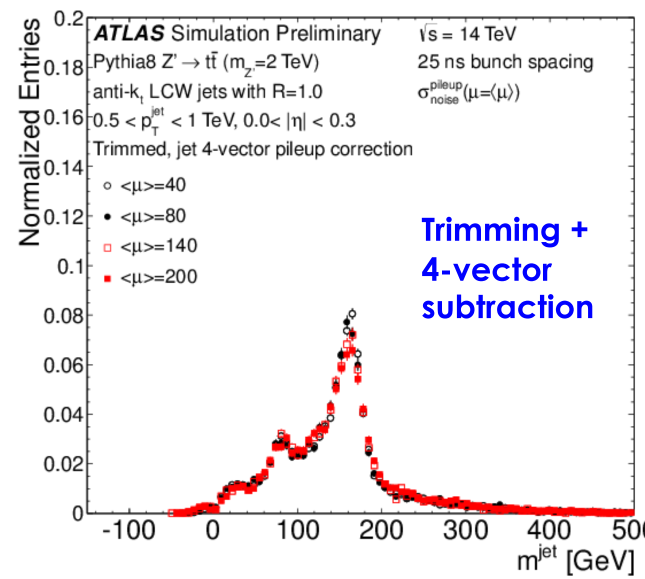


4-vector subtraction



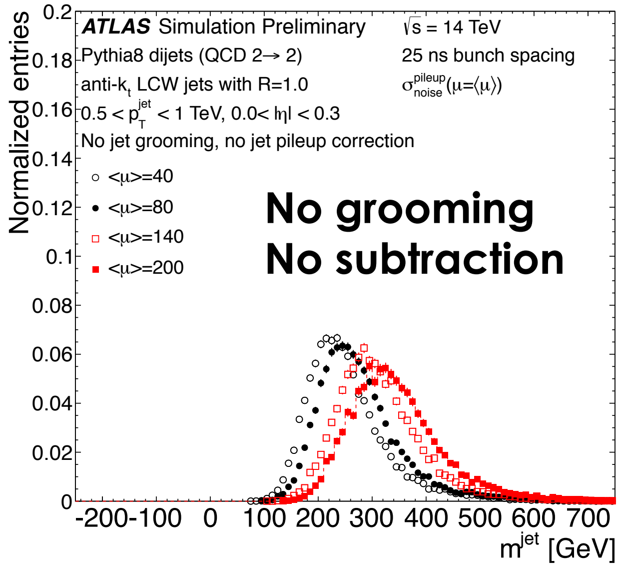
trimming



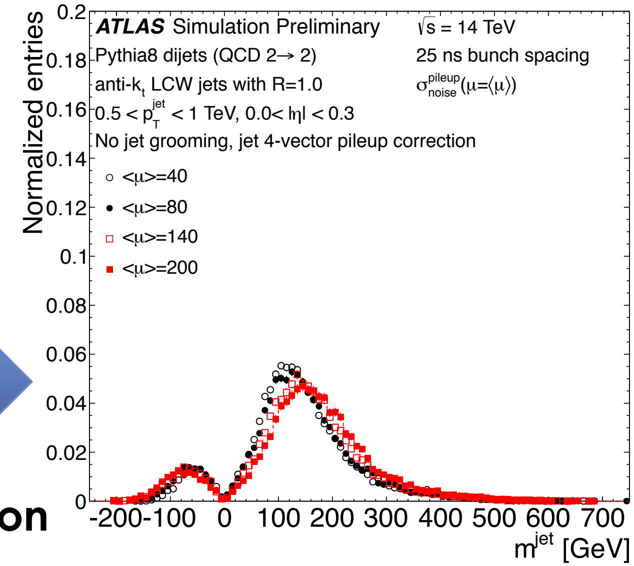


Jet grooming performance

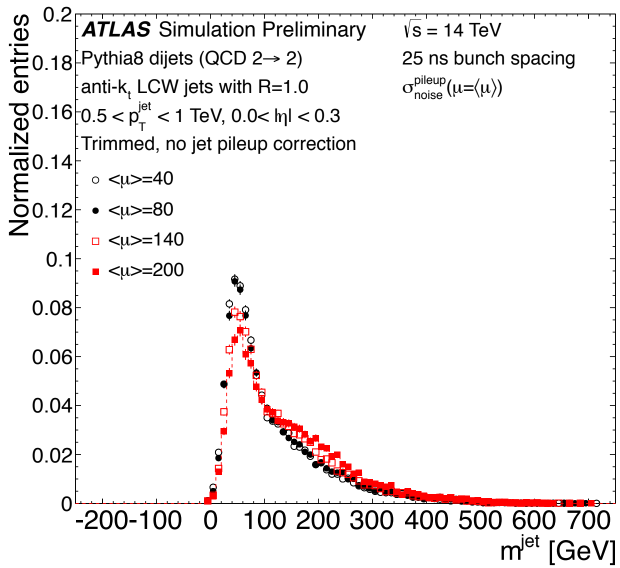
Dijet events

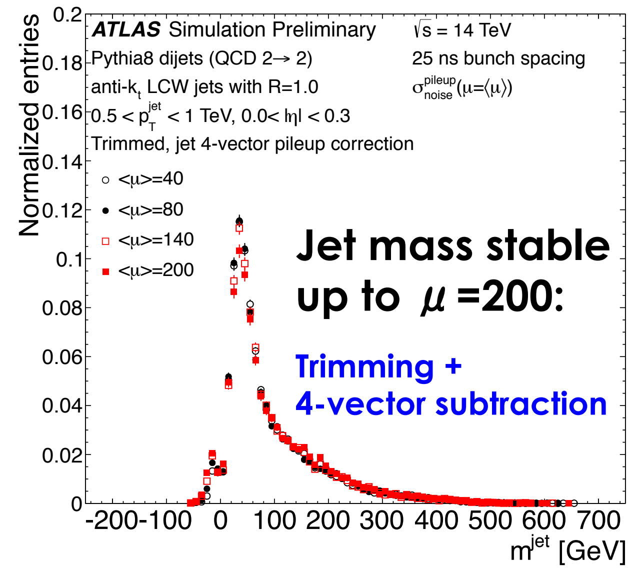


4-vector subtraction

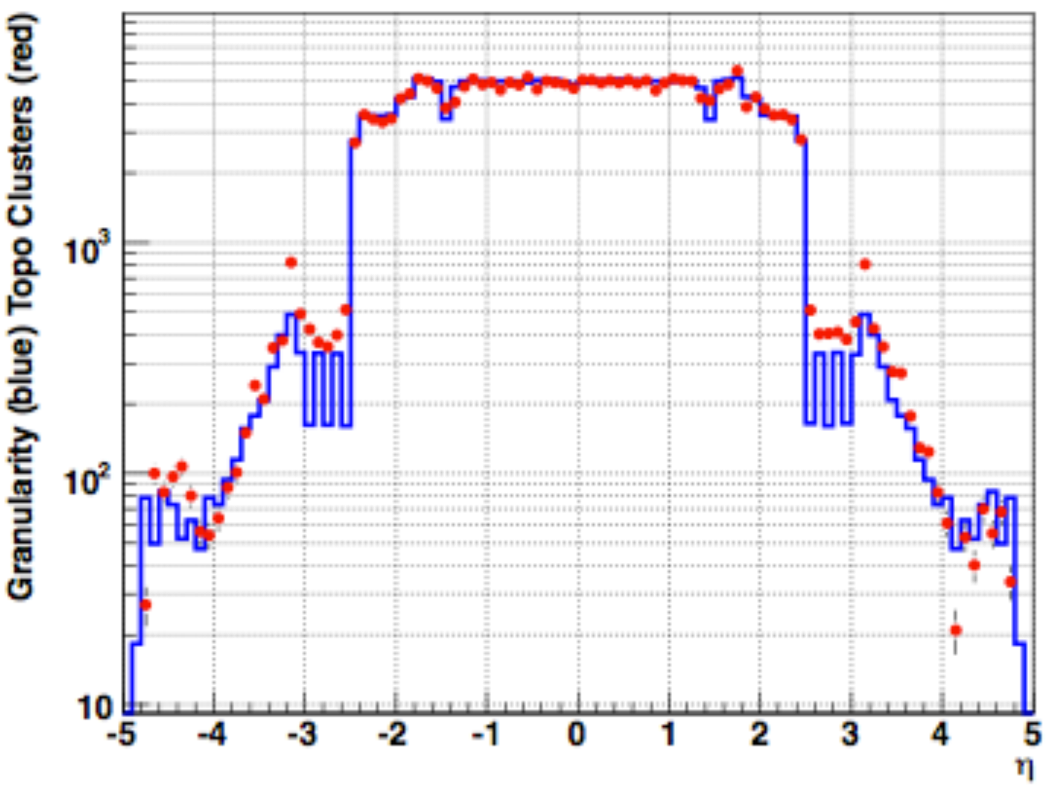


trimming





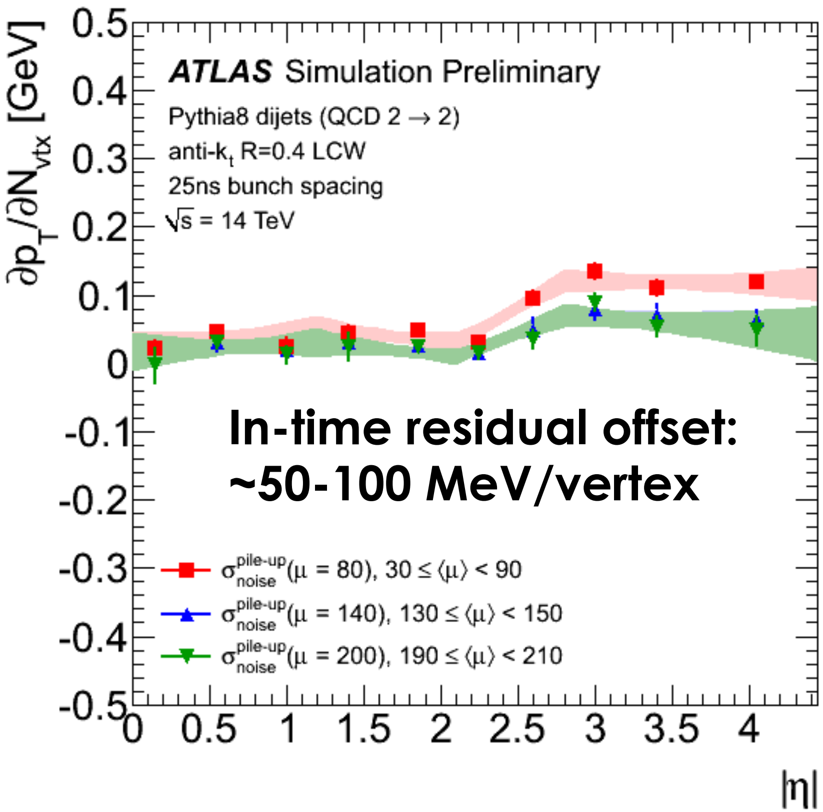
Experimental issues

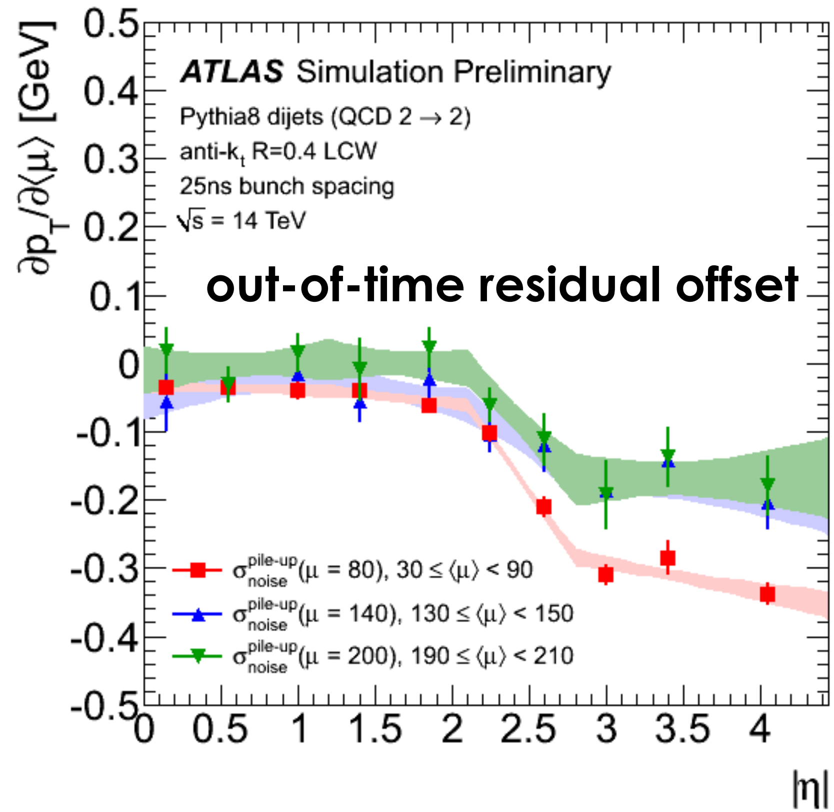


- **Noise thresholds** (topoclusters) **have a different effect inside and outside the core of jets** (pileup particles outside jets are more suppressed than inside jets, where signals are more likely to be above threshold)
- **Coarser calorimeter granularity above |eta|>2:**
  - Few clusters from pileup (noise) only above threshold
  - Need to restrict the calculation of rho to the central eta region
  - Leads to a reduction in the power of the jet areas technique to correct for pile-up effects in the forward region

Pileup subtraction (HL)

- Residual offset after subtraction is mostly pileup independent
- **Jet areas subtraction, topo-clustering, and local cluster weighting work well at high luminosity**





Double B-Hadron Data/MC