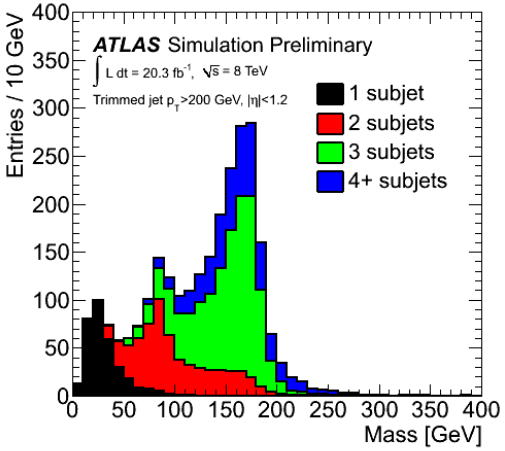
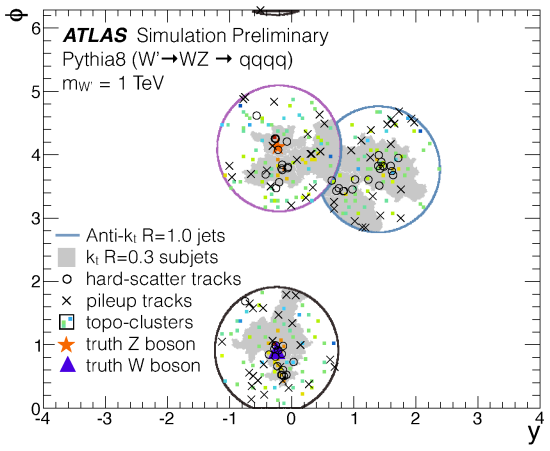
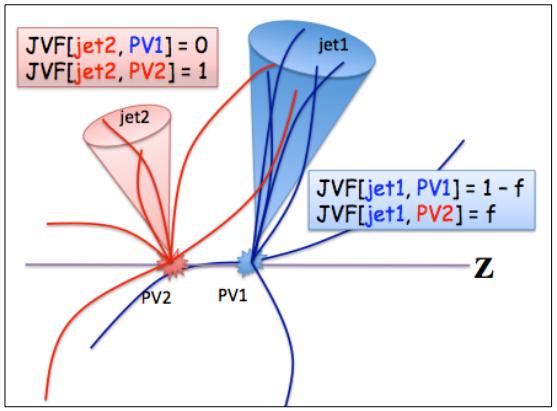
Jets, Subjets, and Particles







Ariel Schwartzman

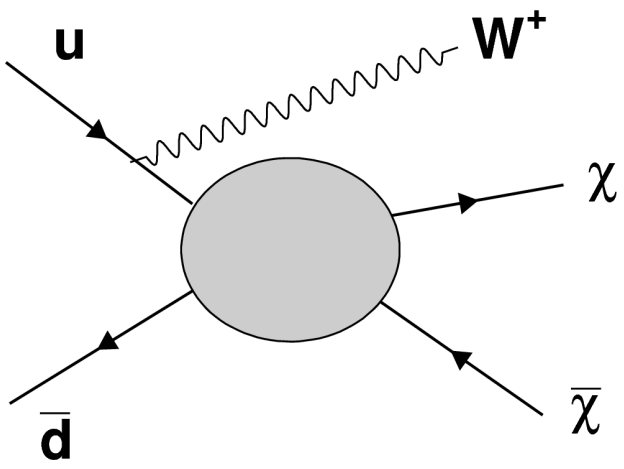
(SLAC)

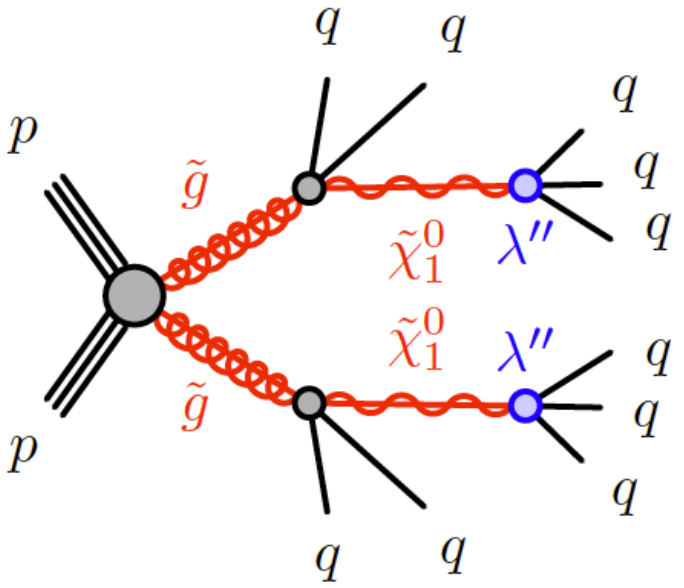
Boston Jets Workshop, 21-Jan-2014

MIT

Jets, subjets, particles

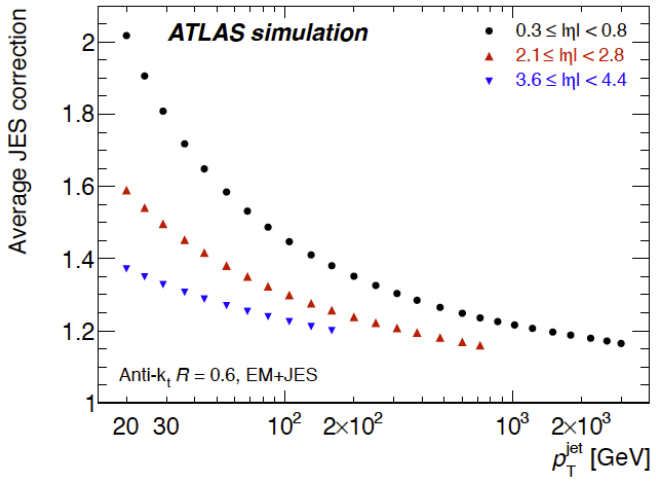
- **Jets and jet substructure have enabled new ways to interpret hadronic events**
  - Detailed understanding of the internal structure of jets
- **Interplay between jets, subjets, and particles**
  - **Jet** reconstruction, calibration and resolution
  - **Subjet** reconstruction and calibration (HEPTopTagger, Shower Deconstruction)
  - **(charged) particle** reconstruction (quark/gluon tagging, jet charge, pileup tagging)
  - **B-hadron** structure



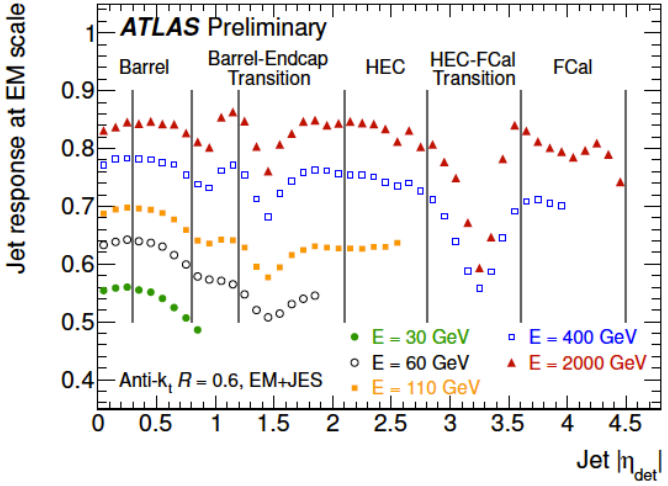


Experimental challenges

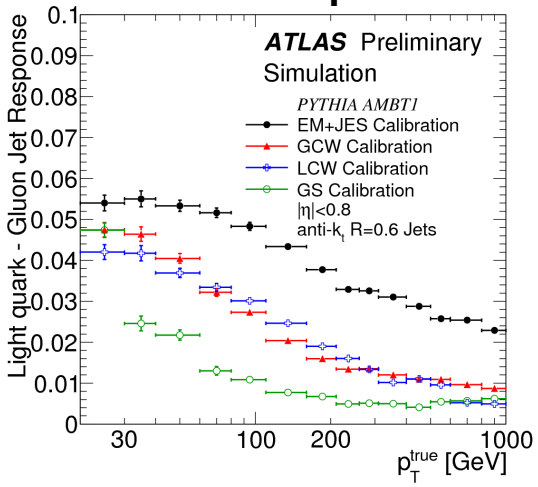
Non-linear jet response



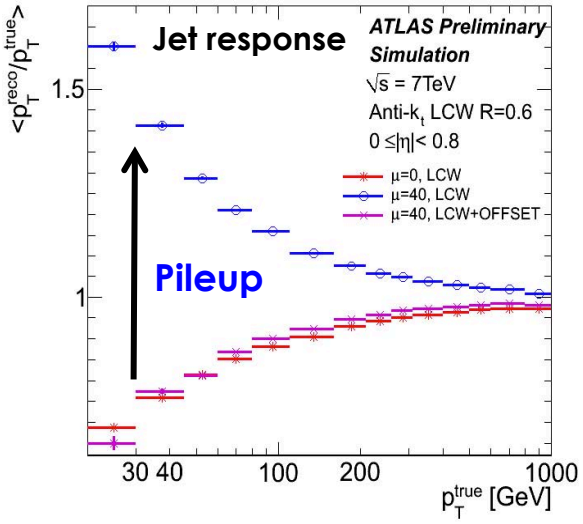
Eta-dependent response



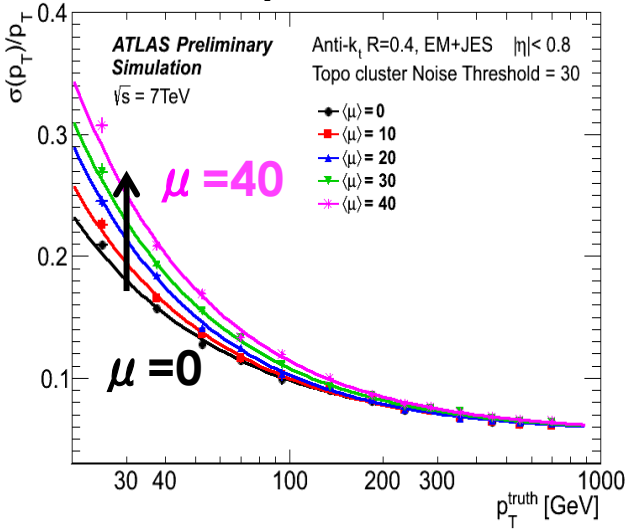
Flavor response



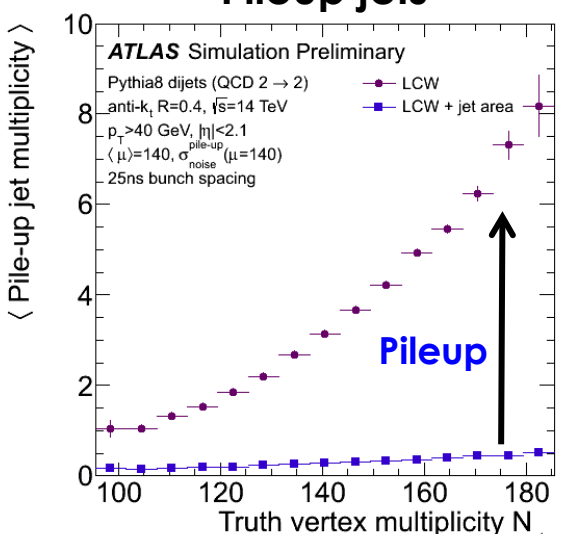
Pileup: response



Pileup: resolution



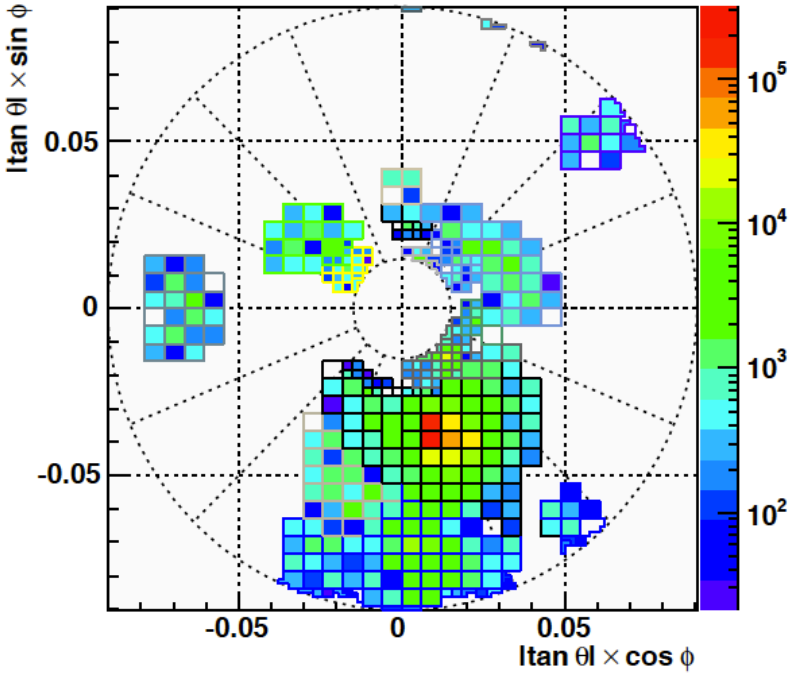
Pileup jets

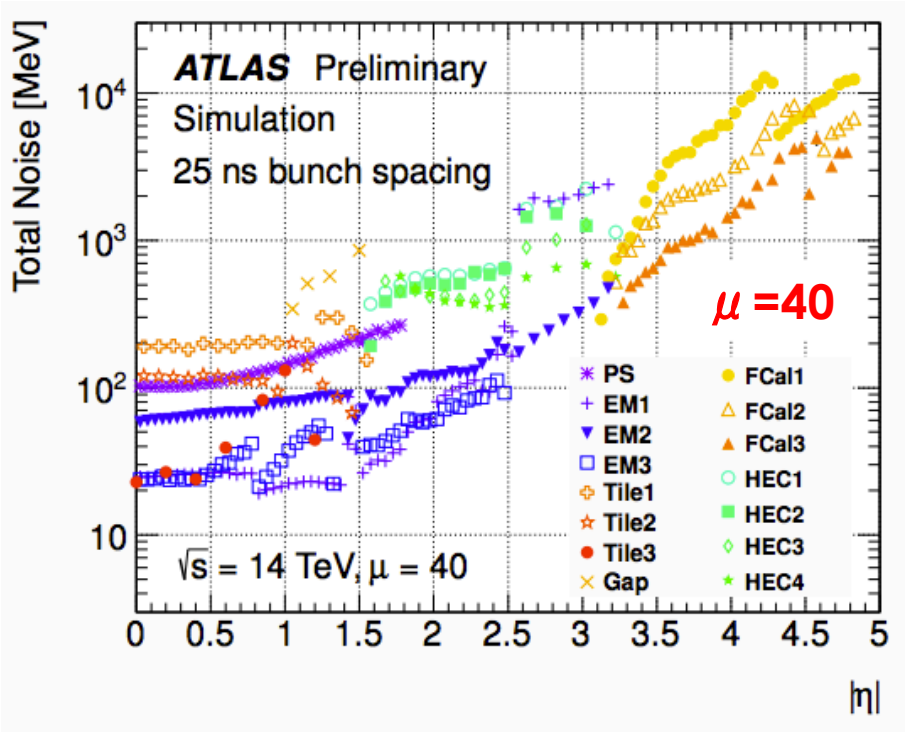


Jet reconstruction at ATLAS

- **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 (σ)**: electronic + pileup noise
  - Adjusted with μ for **pileup noise suppression**

2010: $\sigma(\mu=0)$
2011: $\sigma(\mu=8)$
2012: $\sigma(\mu=30)$





Jet calibration

Jet energy scale

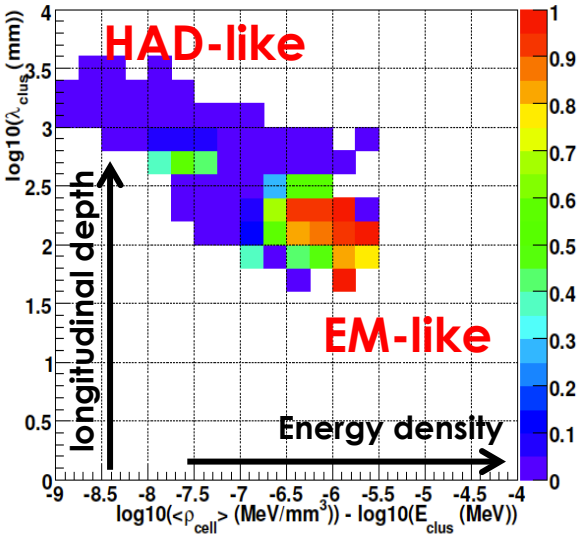
inputs

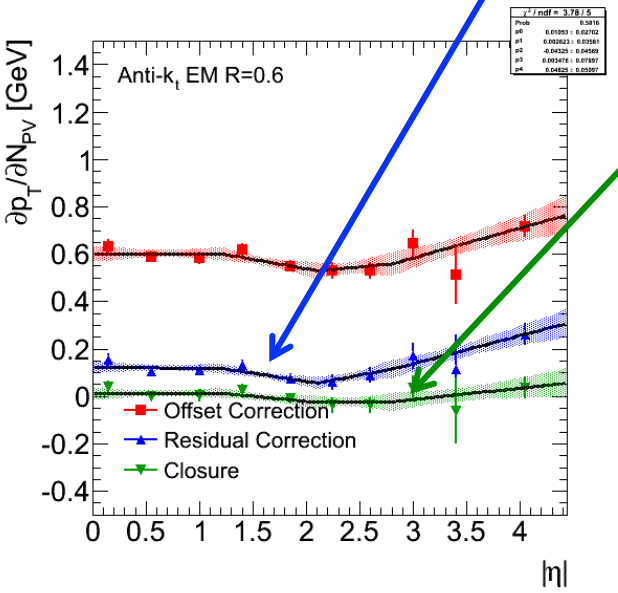
Topo-clusters (pileup noise threshold) → Local cluster weighting (LCW) → Event-by-event pileup subtraction → Residual offset (out-of-time, occupancy) → Jet Energy Scale

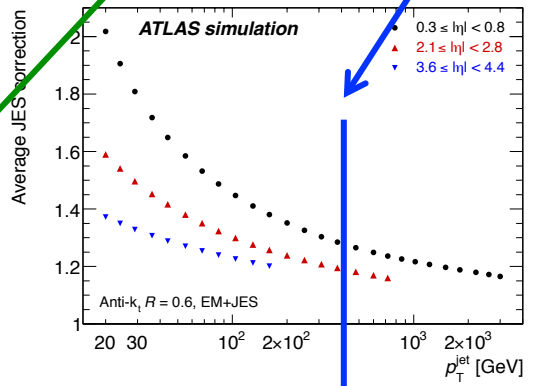
Pileup noise: $\sigma(\mu)$

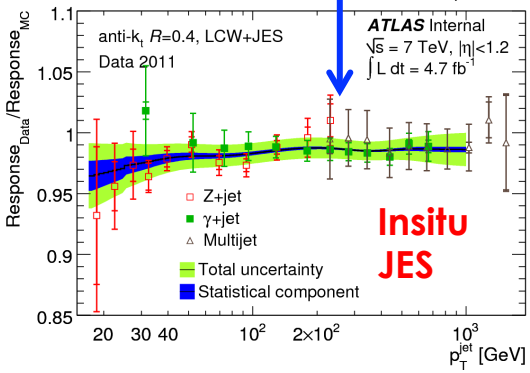
EM/HAD classification

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









Jet calibration

Correct jets to particle level on *average*

- **Two main goals:**

1. **Reduce fluctuations (improve resolution)**
   - Event-by-event pileup subtraction
   - EM/HAD cluster classification/calibration
   - Jet-by-jet corrections
2. **Reduce data/MC differences (improve uncertainty)**
   - Insitu corrections determined from data (insitu JES)
   - Jet-by-jet techniques to reduce effects not well modeled (Jet Vertex Fraction, p_T density)

1. Fluctuations

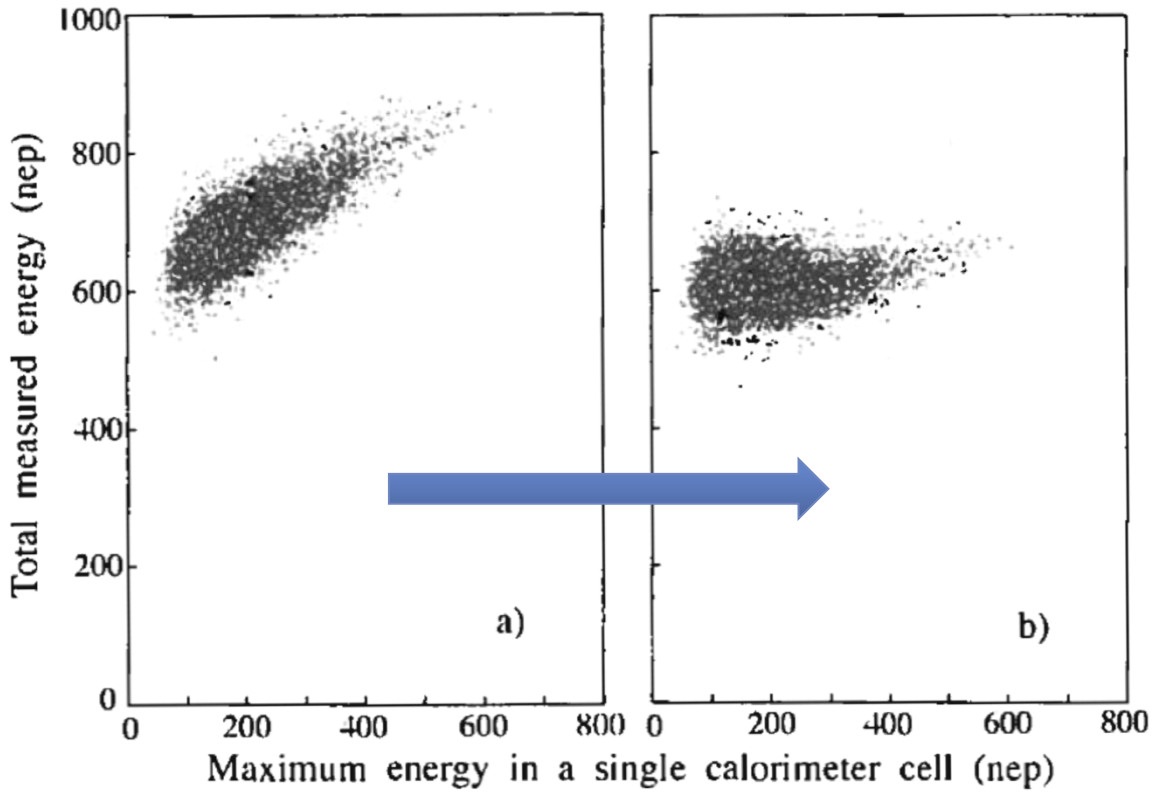
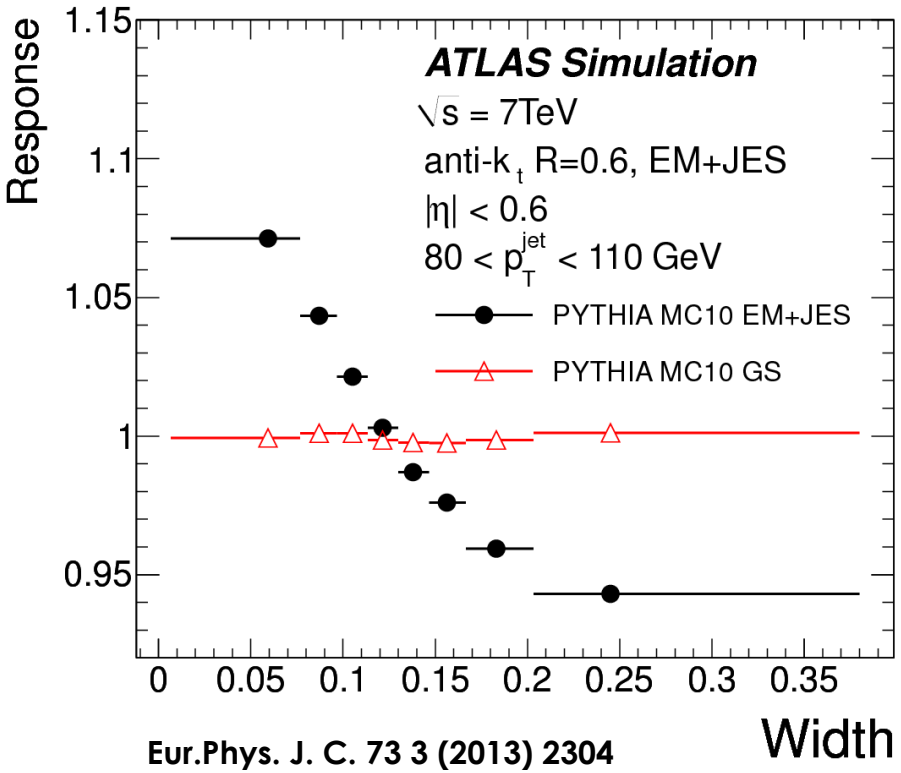


FIG. 4.60. WA1 results on off-line compensation, showing the correlation between the total measured signal and the maximum signal observed in one individual calorimeter segment. Results are given for 140 GeV pions before (*a*) and after (*b*) applying a weighting factor, based on the signals observed in the individual calorimeter segments [Abr 81].

Reducing fluctuations

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



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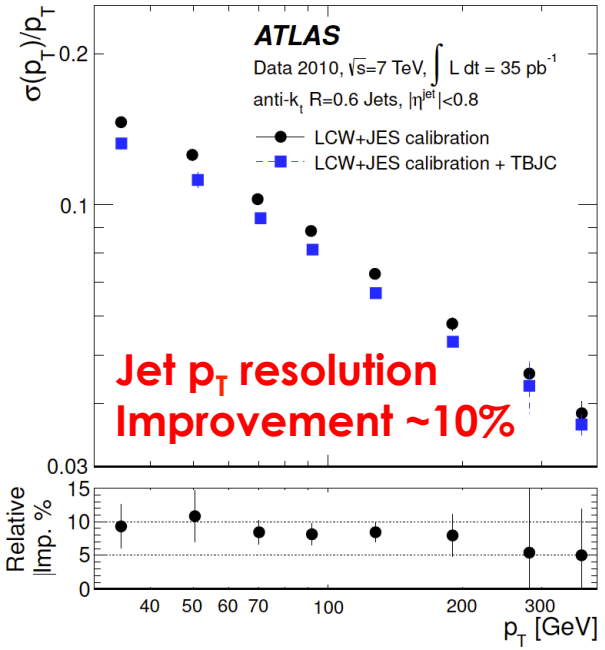
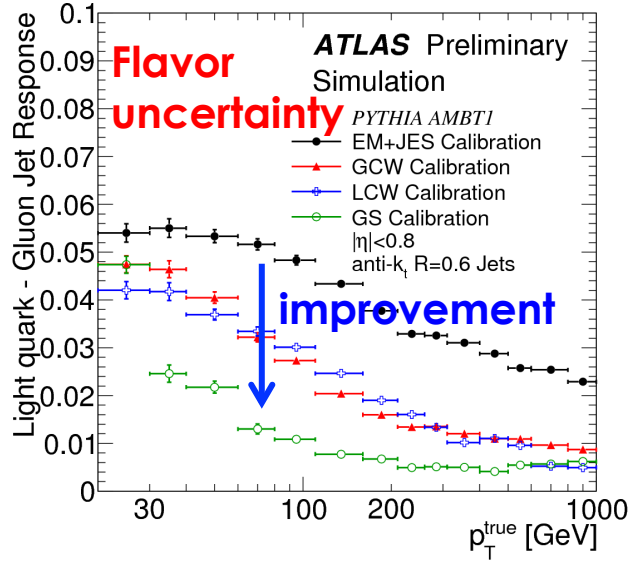


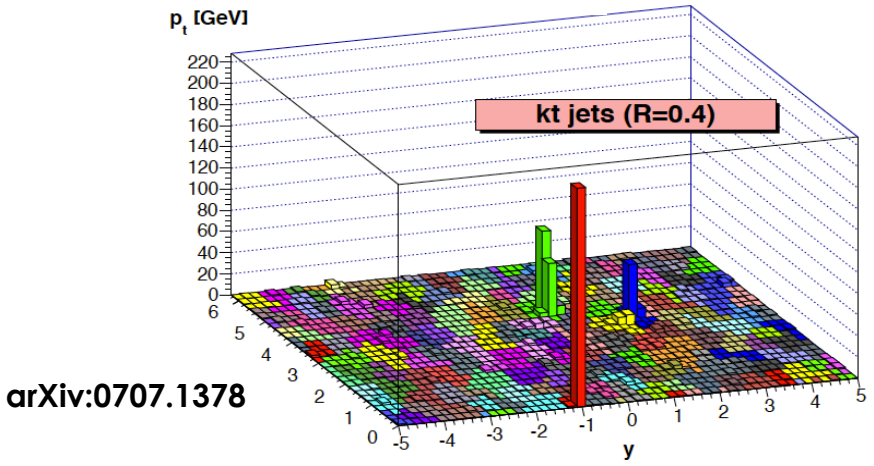


2. Reducing data/MC differences

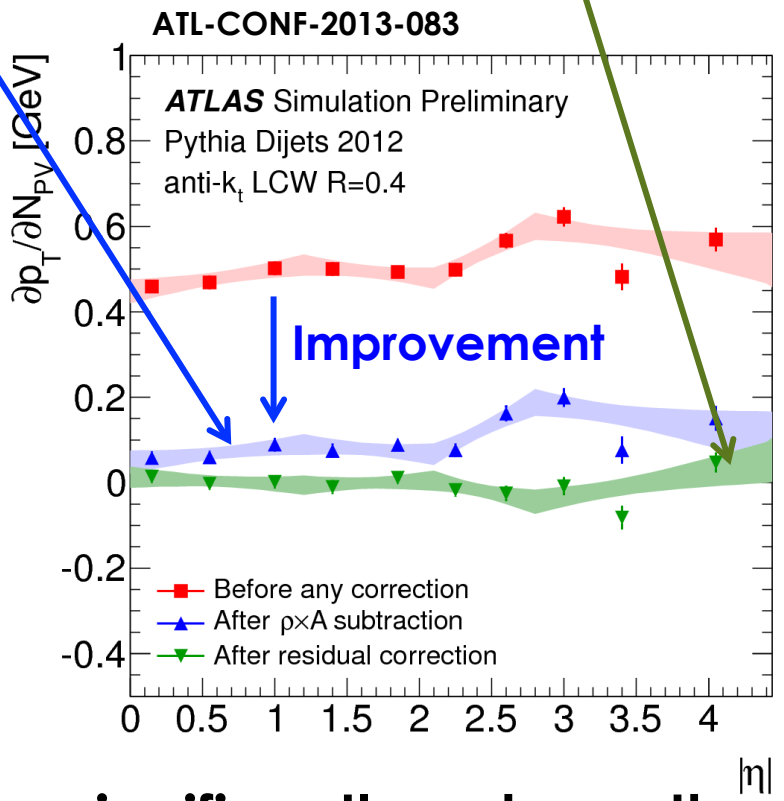
$$p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - \rho A_{\mathrm{T}} - \alpha(N_{\mathrm{PV}} - 1) - \beta\langle\mu\rangle$$

Residual correction (MC-based)

Event-by-event p_T density (no MC assumptions)



arXiv:0707.1378



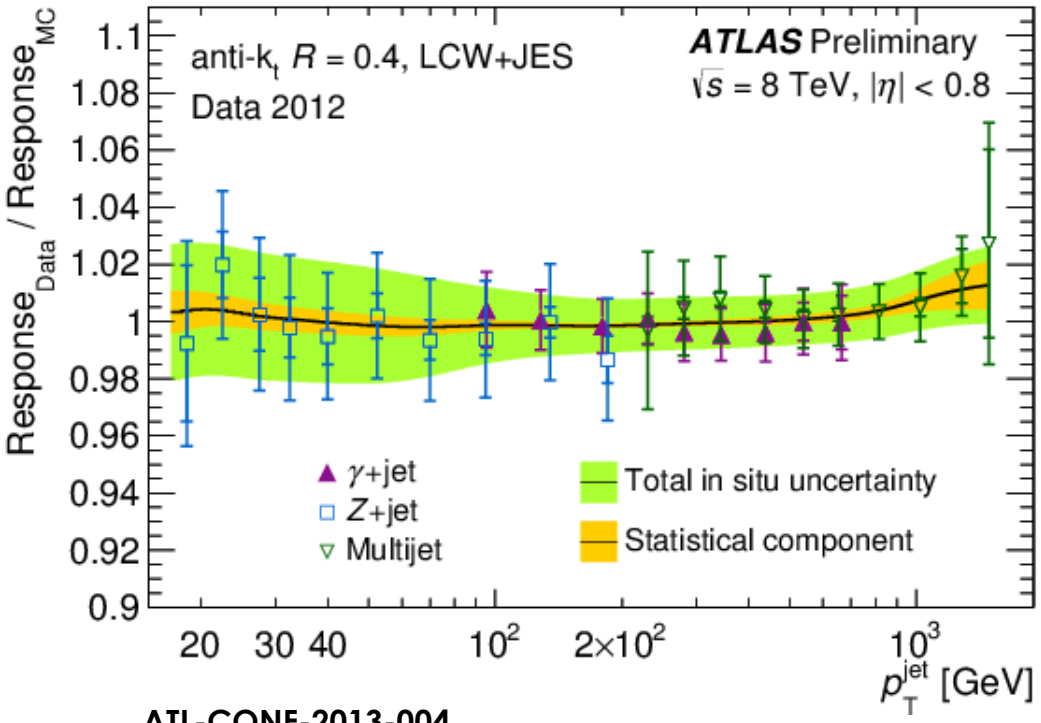
$$p_T^{jet,corr} = p_T^{jet} - \rho \times A_T^{jet}$$

- **Event-by-event pile-up estimation significantly reduces the reliance on Monte Carlo to derive the offset correction:**
  - Reduced systematic uncertainty

2. Reducing data/MC differences

- **Insitu jet energy scale correction**
  - Correct jets in data only, with the data/MC response difference
  - **Enables a significant reduction of the JES uncertainty**
  - JES uncertainty limited by the precision of the jet response ***measurement***

- **Jet Vertex Fraction:**
  - Reject pile-up jets using track and vertex information
  - **Improve the Data/MC agreement by removing pileup jets not well modeled by the simulation**



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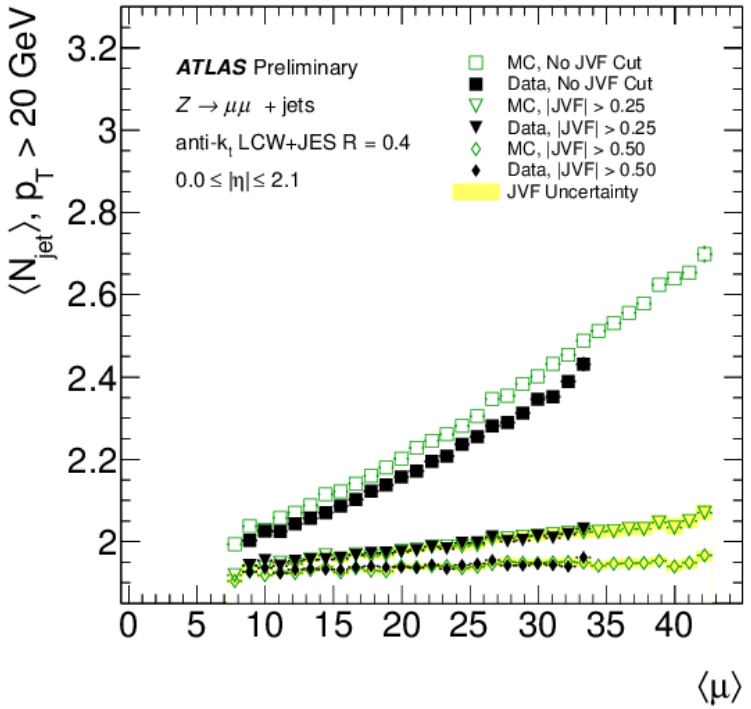

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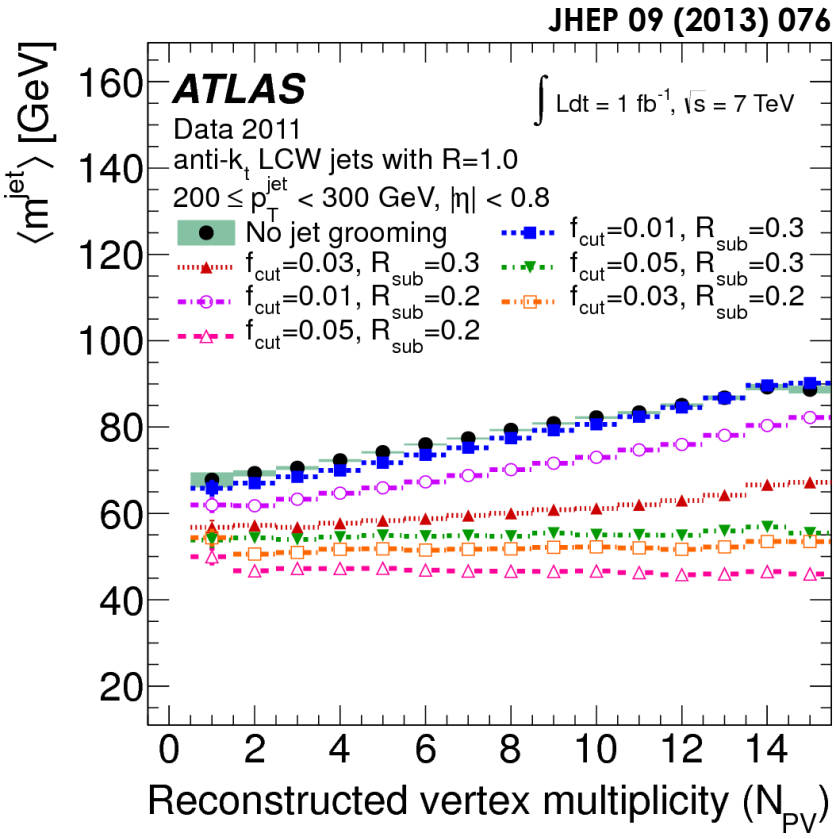
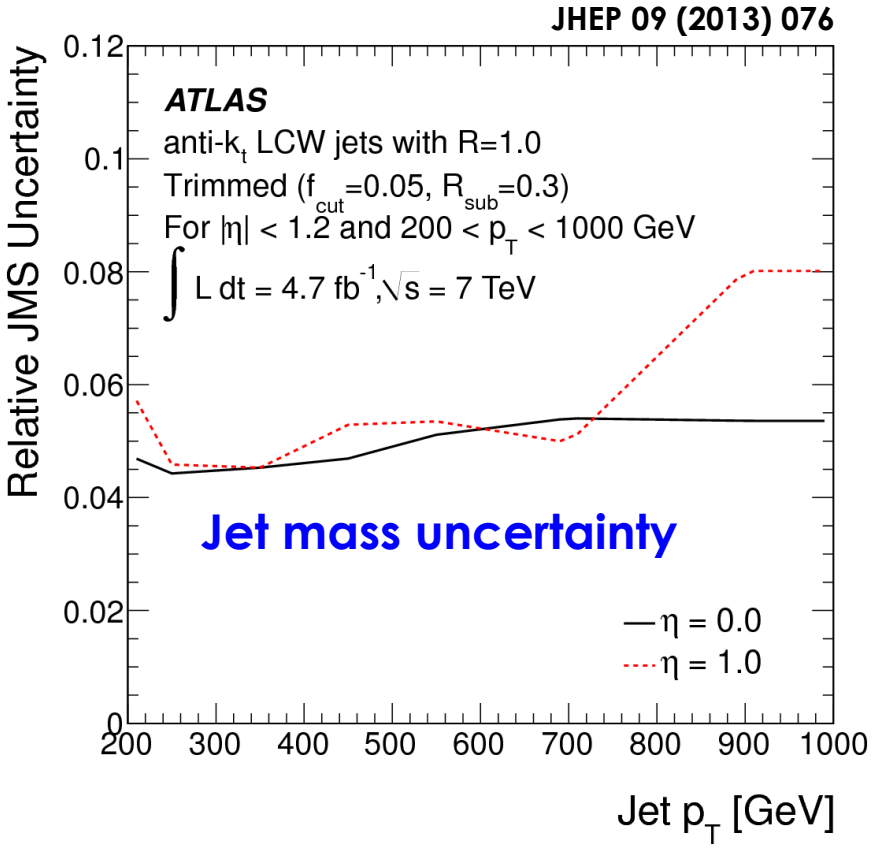
Jet substructure

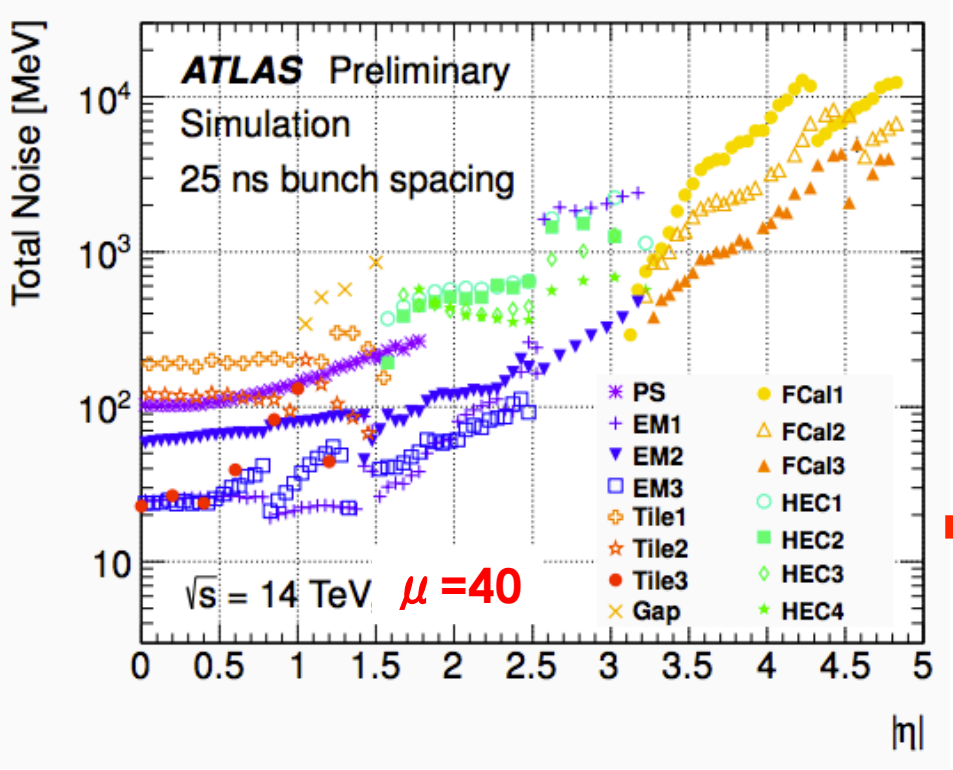


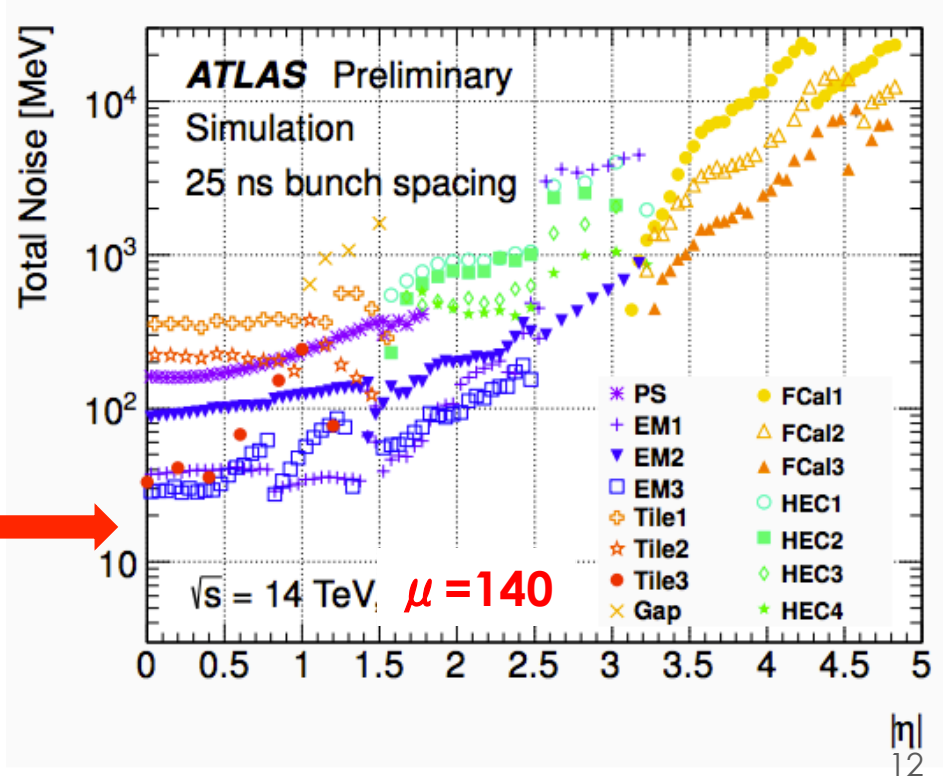


- **Commissioned a large number of large-R jet algorithms and grooming configurations**
  - Detailed performance understanding: mass calibration, uncertainties, pileup sensitivity and corrections, subjets and **subjet calibration** (HepTopTagger and Shower Deconstruction), Q-jets

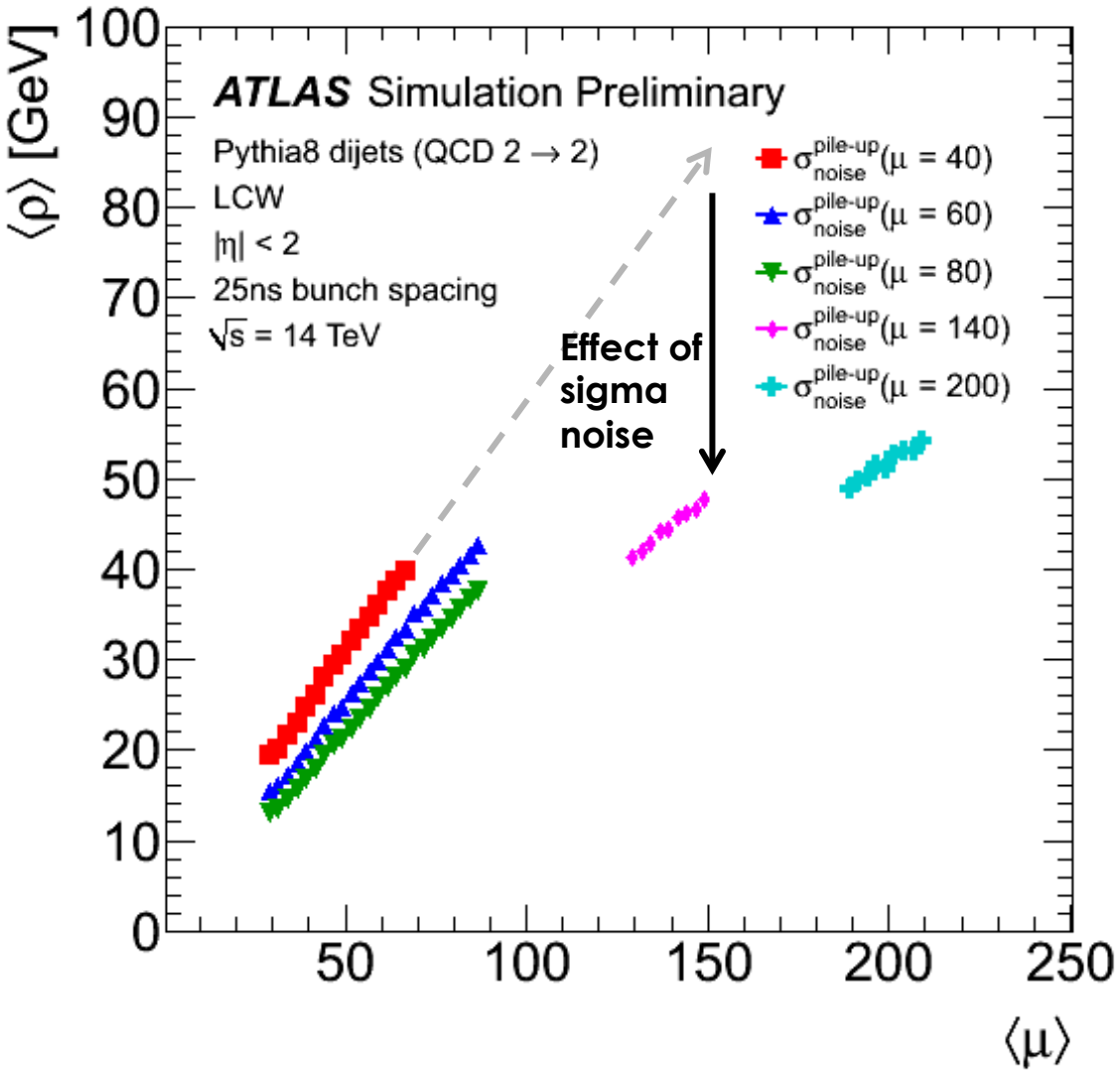
Jet substructure @ high luminosity

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



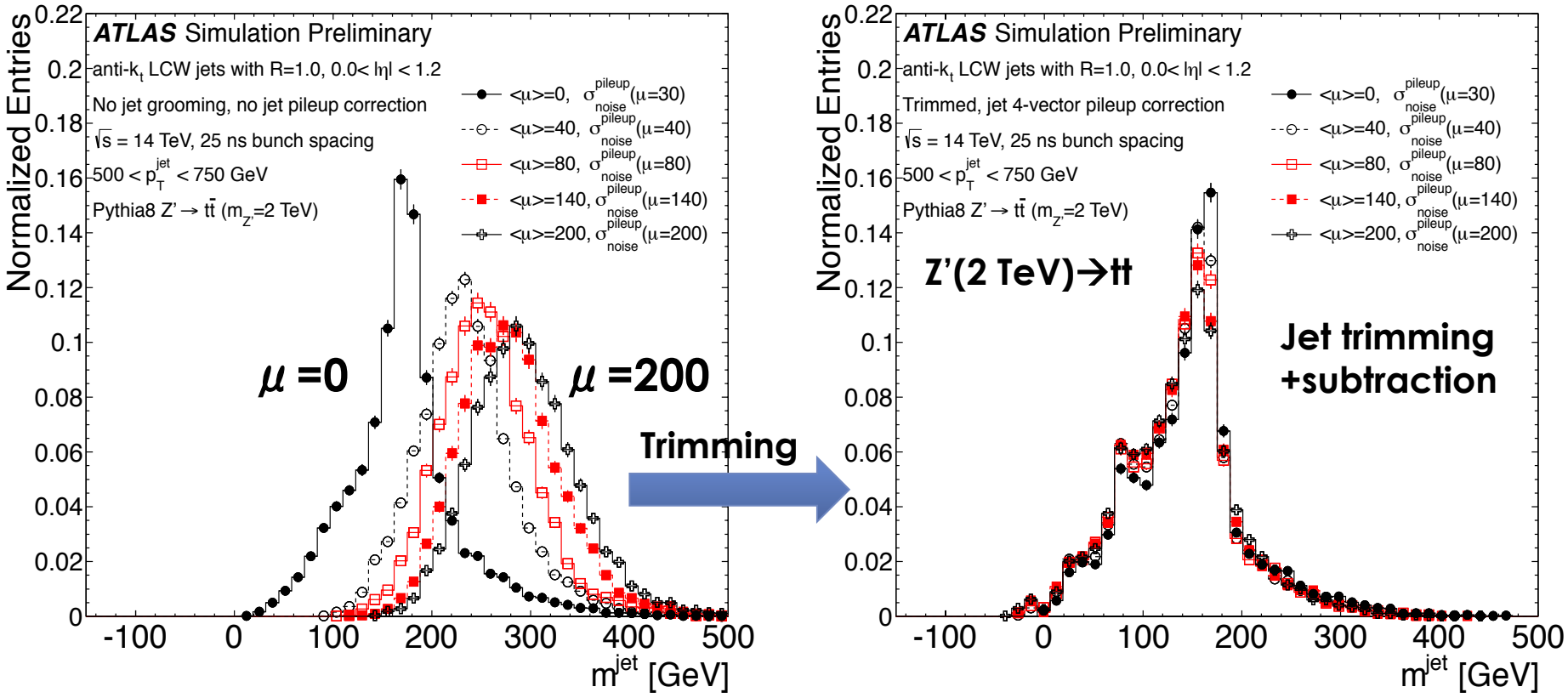


Pileup subtraction (II)



- Linear behavior of rho up to high mu for fixed pileup noise values
- Higher pileup noise values lead to partial suppression of pile-up
- **Optimization of sigma noise in topoclustering is key to reconstruct jets at high luminosity**

Jet grooming performance



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

Subjets

- Exploit additional features of the internal structure of jets
- Top tagging (HepTopTagger, Shower Deconstruction)
- Key element in many new physics searches
- **Require small-R subjet reconstruction and calibration**

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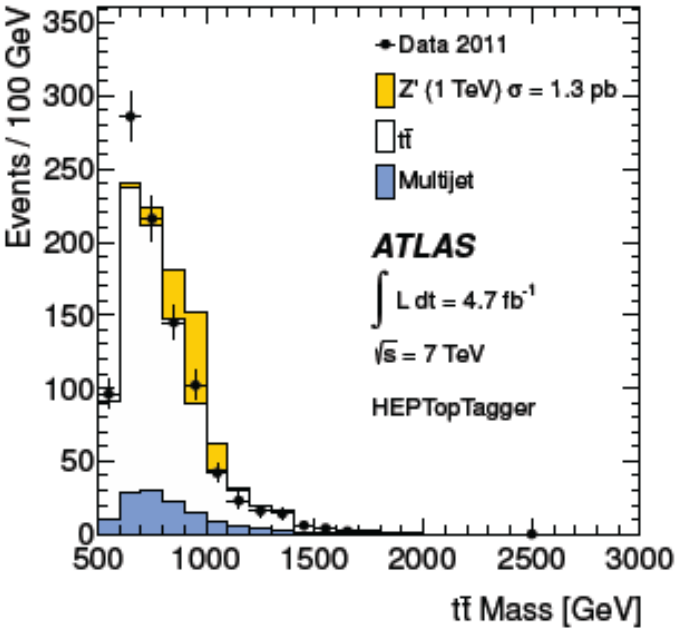
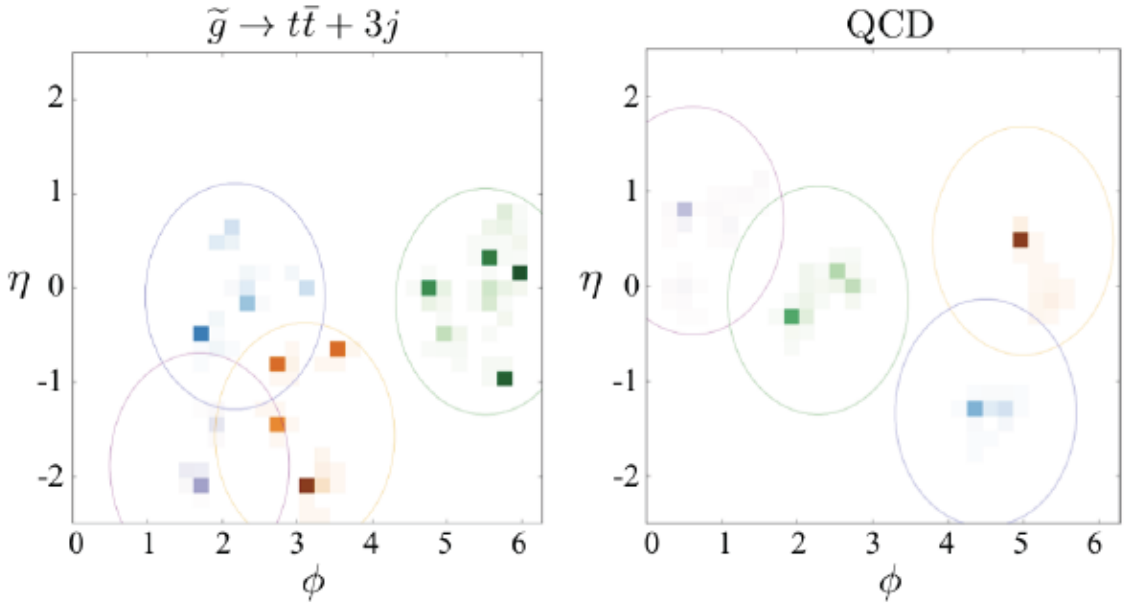
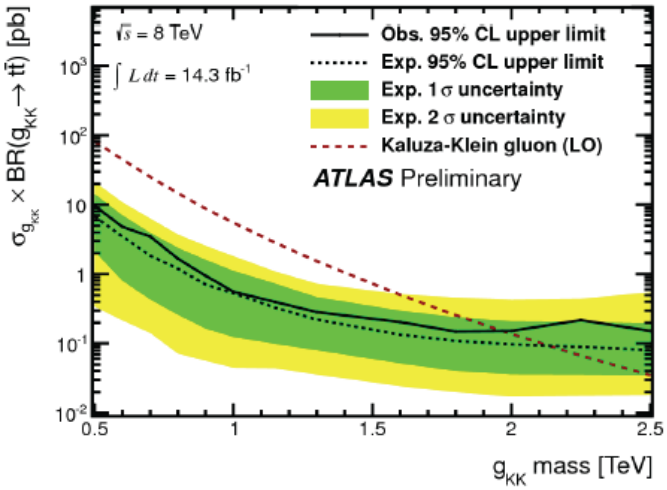




arXiv:1212.1456



See P-H Beauchemin's talk

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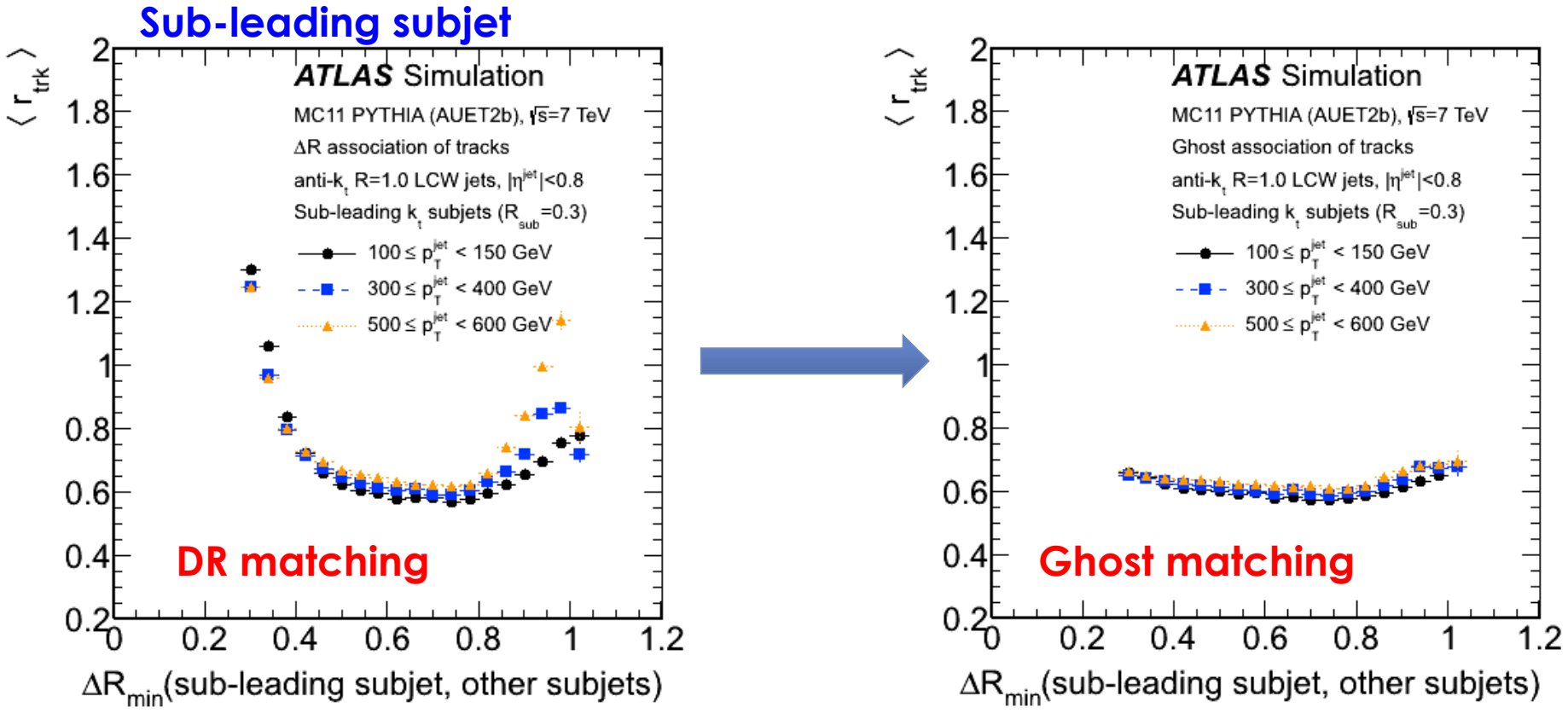
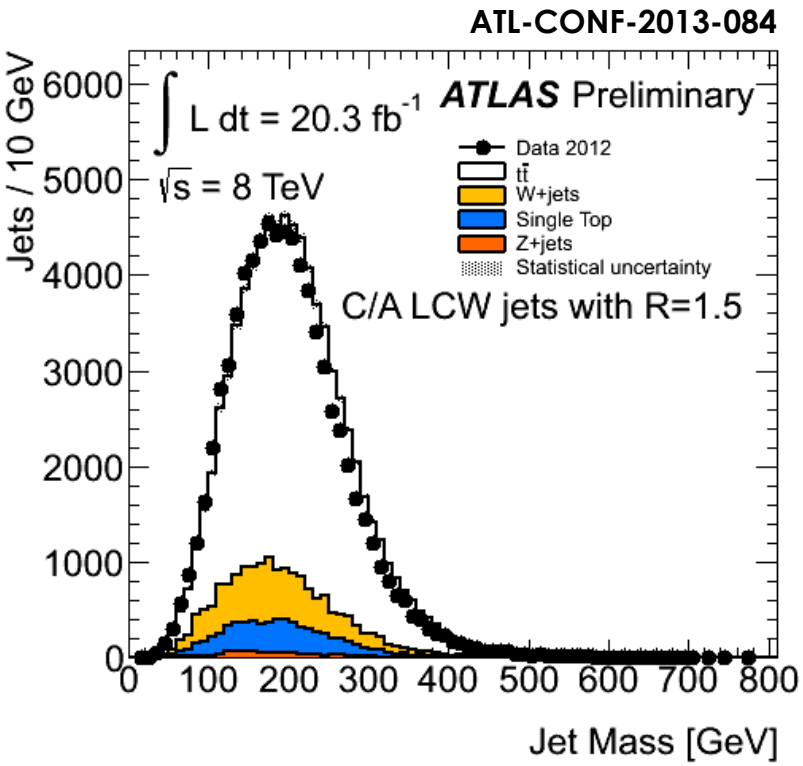
Subjet calibration using tracks

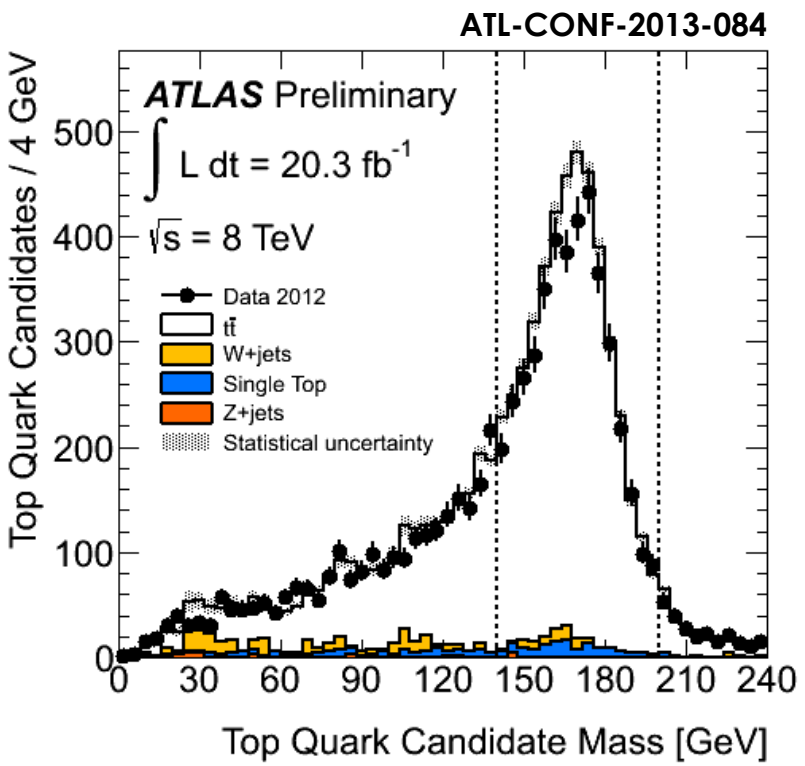


- Track/Calorimeter jet p_T ratio
- DR matching leads to large energy scale dependence from incorrect geometrical matching → **ghost-track association**

HEPTopTagger (I)

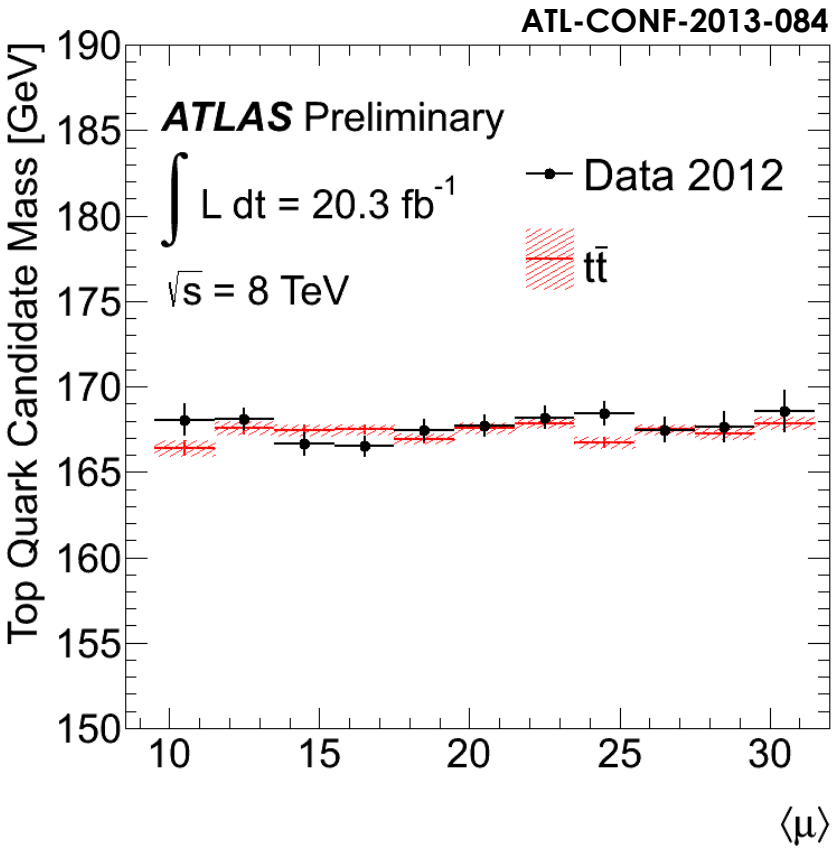
- **Reconstruct top quark mass from C/A subjets**
- Kinematic cuts on invariant mass ratios of subjet combinations require **subjet calibration** for optimal performance
- **C/A subjets with R=0.2-0.5 in 0.05 steps, p_T>20 GeV**
  - Jet areas and MC-based JES response correction

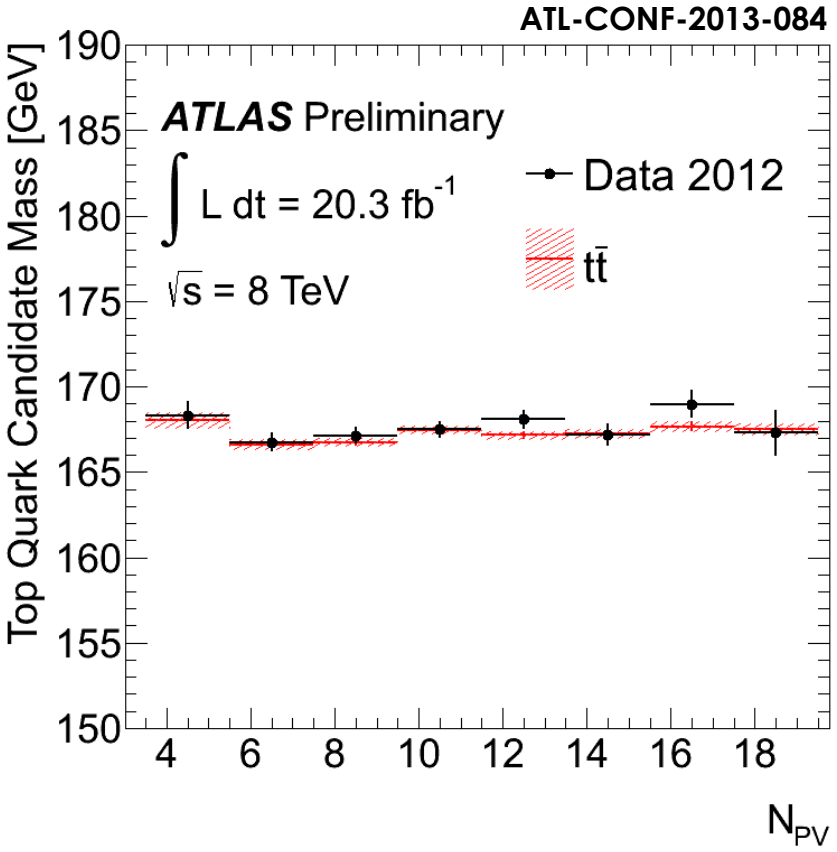




HEPTopTagger (II)

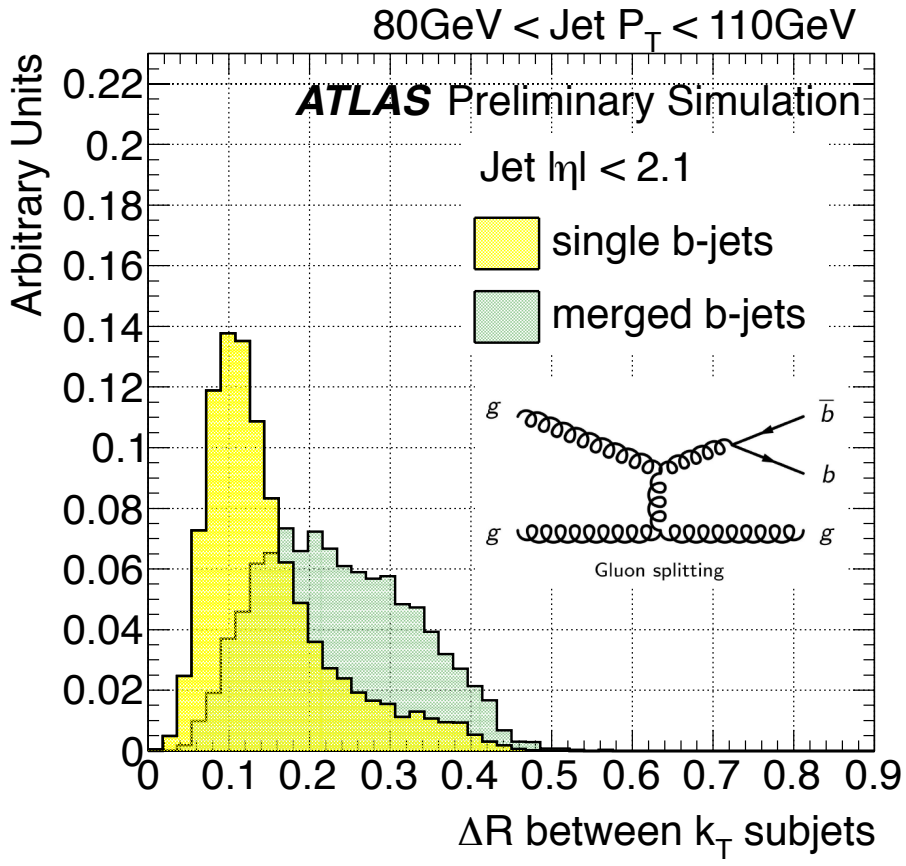
- **Stability of the reconstructed top mass with pileup**
  - Test of subjet calibration and pileup subtraction, and filtering





Double b-Hadron tagging

- **Tag b-jets containing two B hadrons from gluon splitting**
  - Handle on the **net heavy flavor content of jets**



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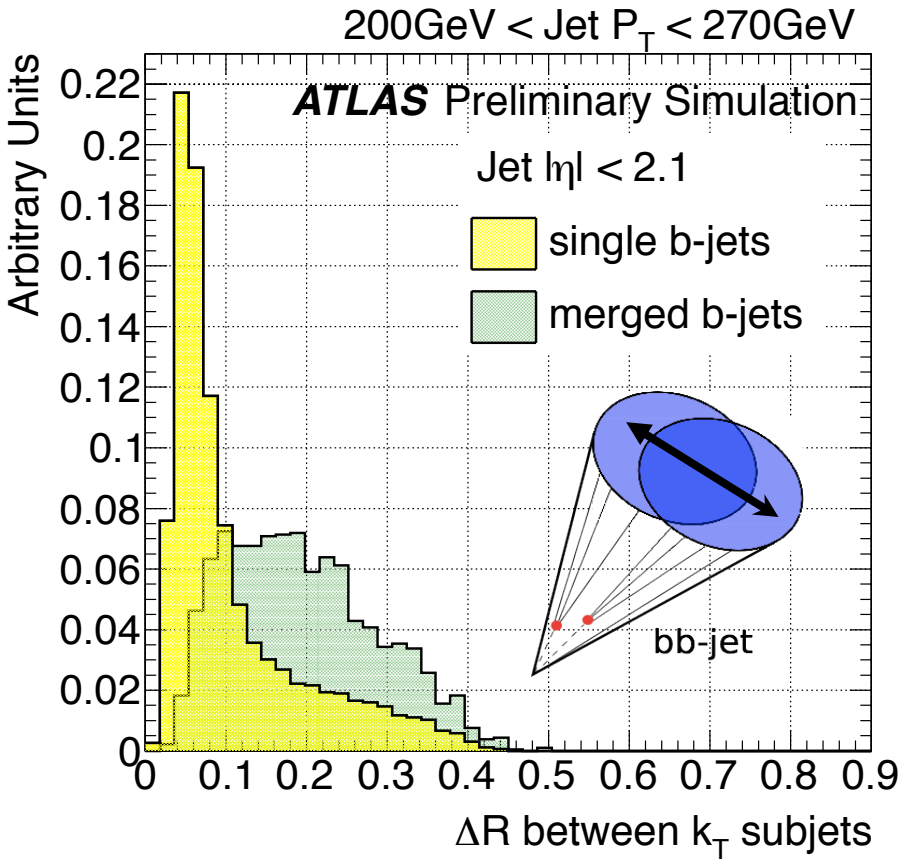
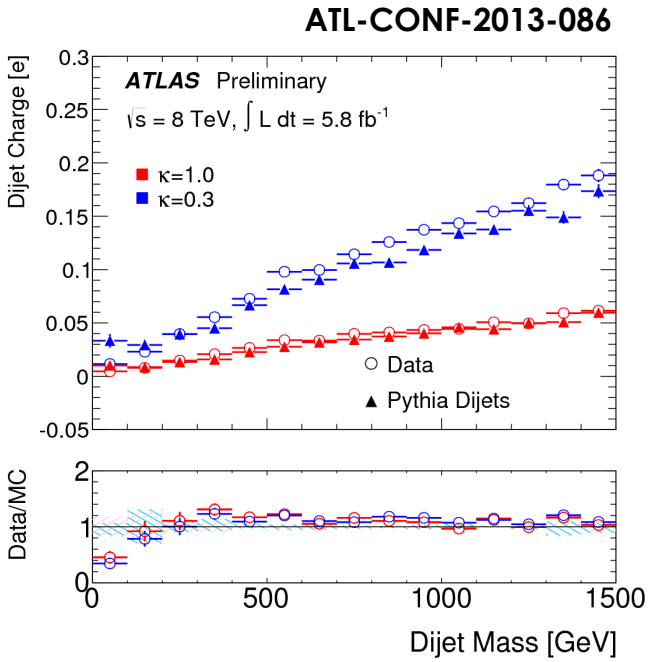
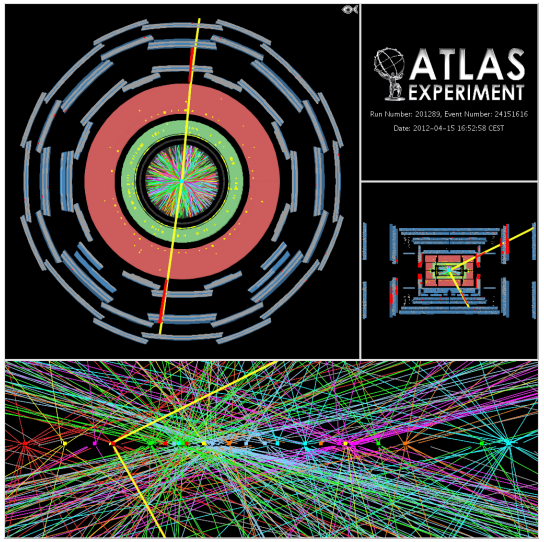


ATL-CONF-2012-100

Particles

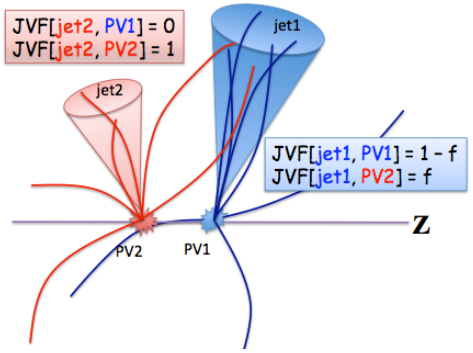
- **Charged particles:**
  - Observables:
    - multiplicity, charge, calculable track-based observables based on track functions –**arXiv:1303.6637**)
  - Vertex-z position: pileup rejection
  - Excellent angular resolution: jet substructure
- **Particle reconstruction:**
  - Combining tracking with calorimeter information (CMS particle flow)
- **B-hadrons:**
  - B-hadron substructure of large-R jets



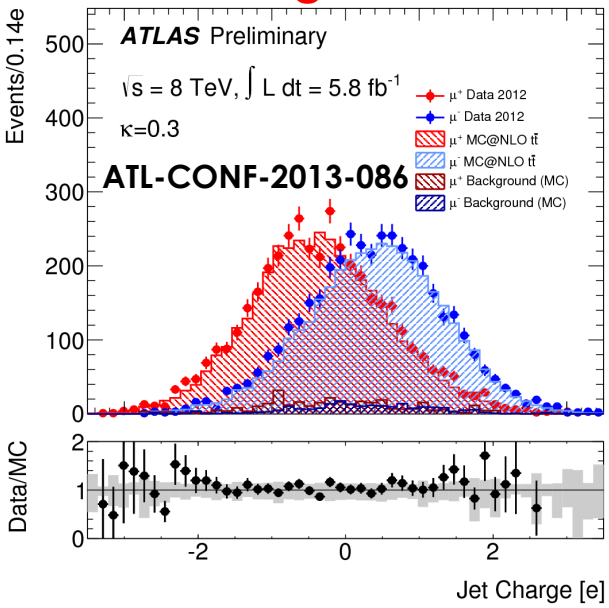


Charged particles

- **Multiple applications of charged particle tracks as jet jet-by-jet tagging algorithms:**
  - **Track charge** for jet charge tagging
  - **Track multiplicity** for quark/gluon separation
  - **Track-vertex-information** for pileup jet tagging

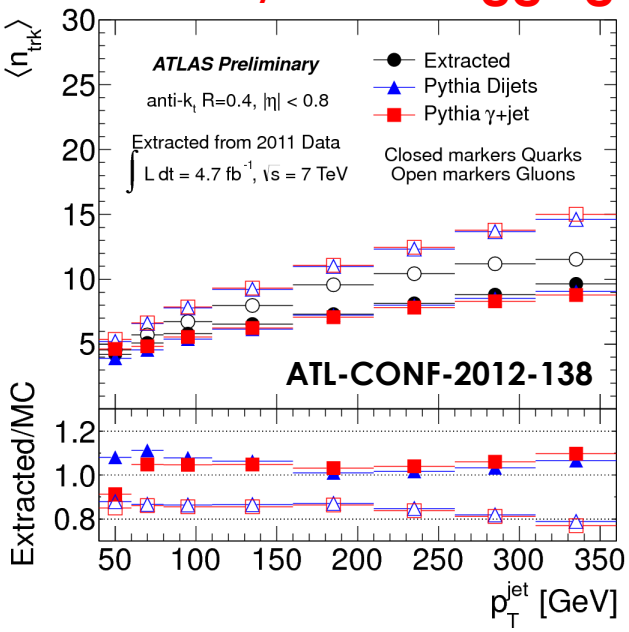


Jet charge



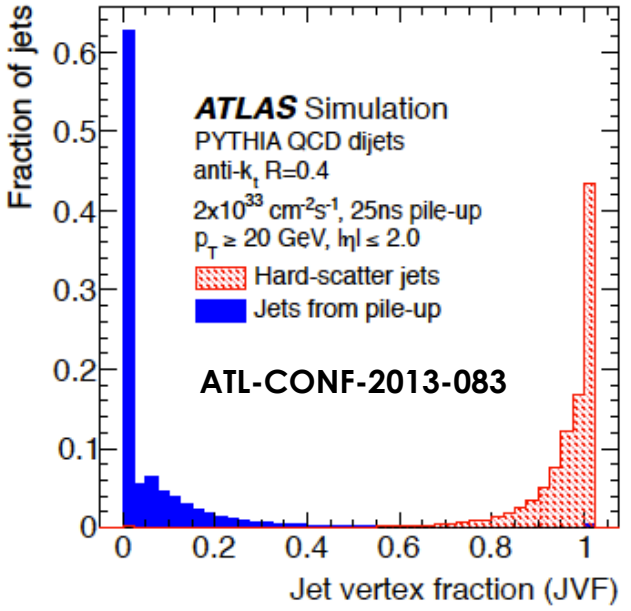
See B. Nachman's talk

Quark/Gluon tagging



See M. Swiatlowski's talk

Jet Vertex Fraction (JVF)

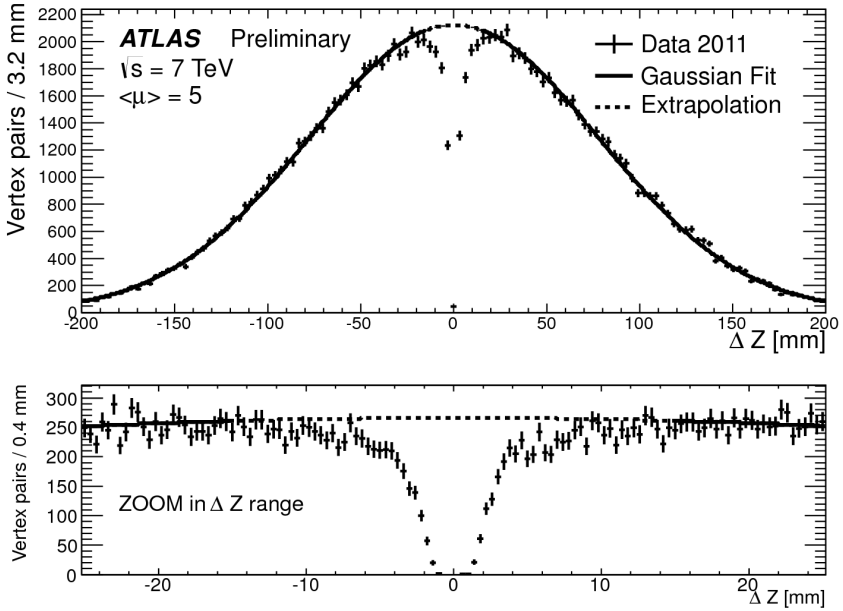


See P. Nef's talk

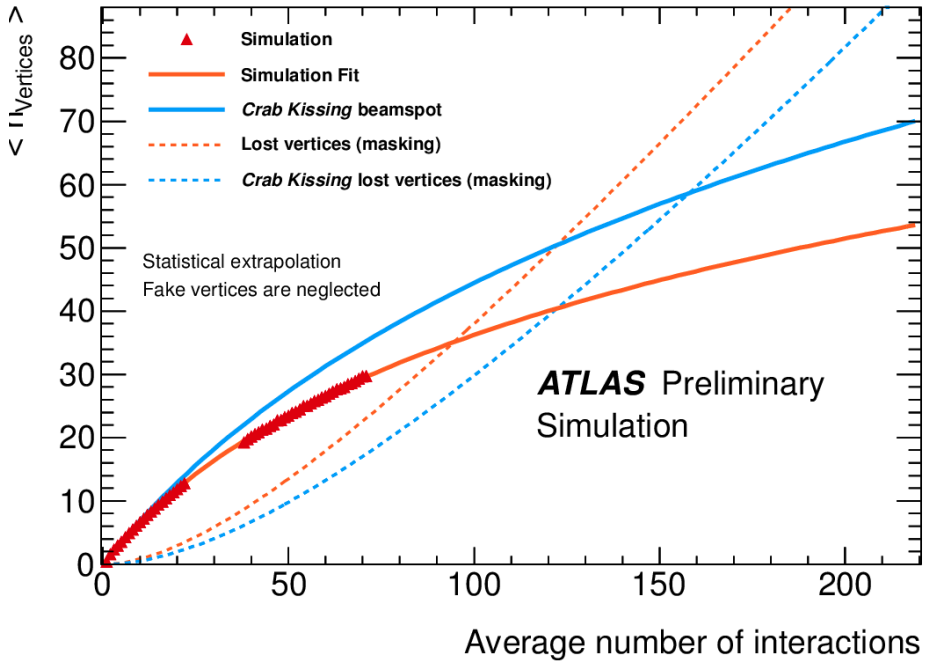
Experimental challenges

- **Vertex shadowing at high luminosity can limit the ability to separate pileup particles close to the hard-scatter vertex:**
  - Limited by detector resolution, vertex reconstruction algorithm, and density of interactions (beam spot longitudinal profile)

Merging of close-by primary vertices

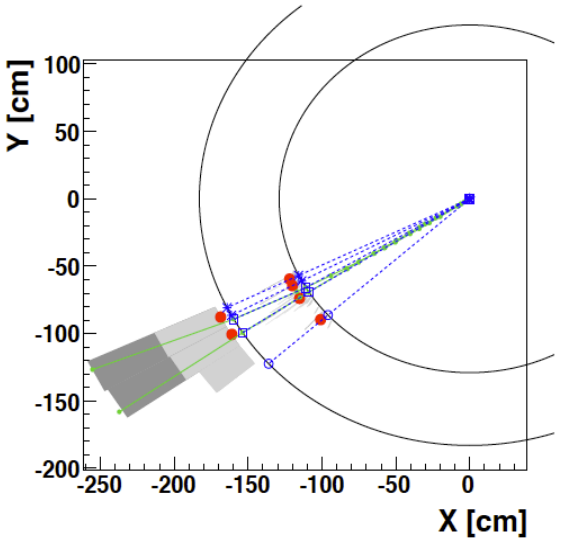


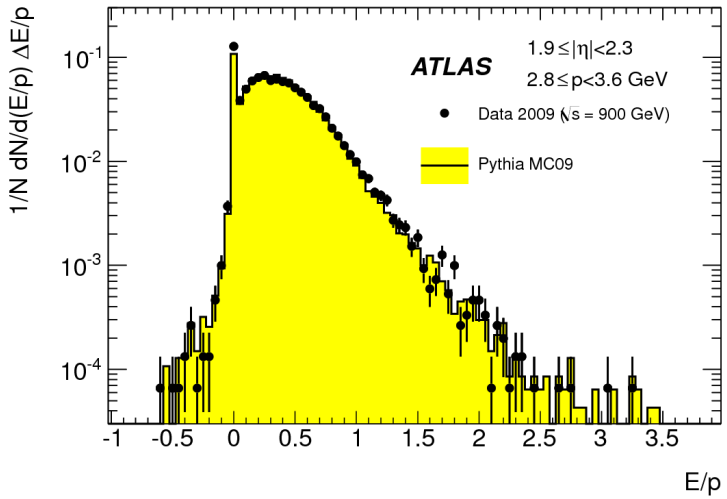
Vertex masking at high luminosity

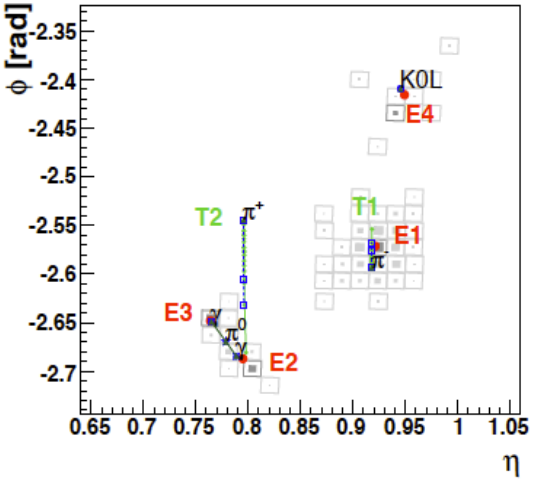


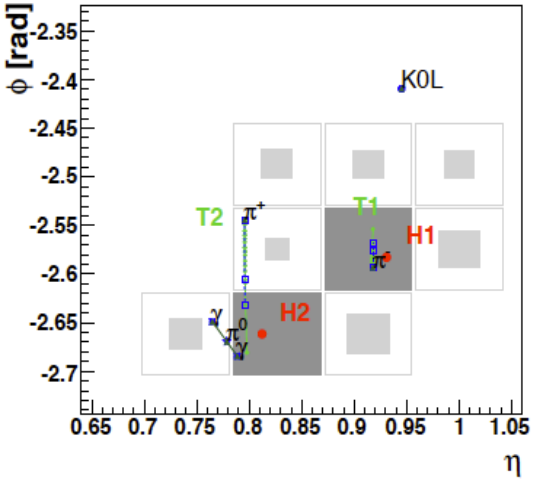
Particle reconstruction

- **CMS particle flow paradigm attempts to reconstruct individual particles:**
  - Reduce large fluctuations in the energy response of low p_T particles
  - Successfully used in jet substructure and charged hadron subtraction
- **Challenges**:
  - Very high p_T, and very high pileup
  - ATLAS track-based corrections: calorimeter energy fluctuations









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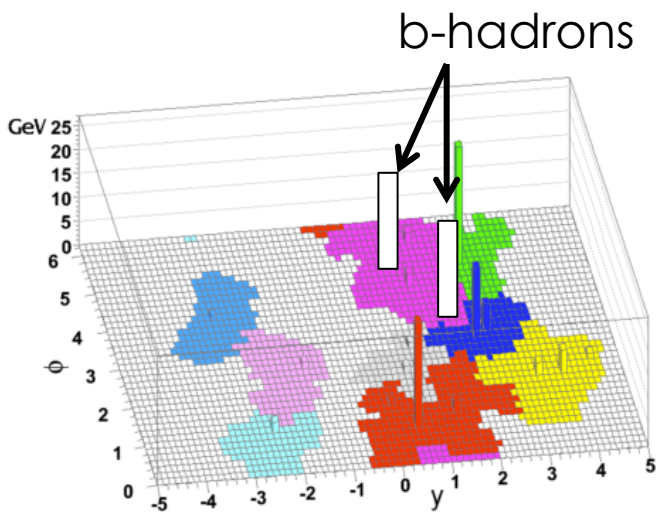
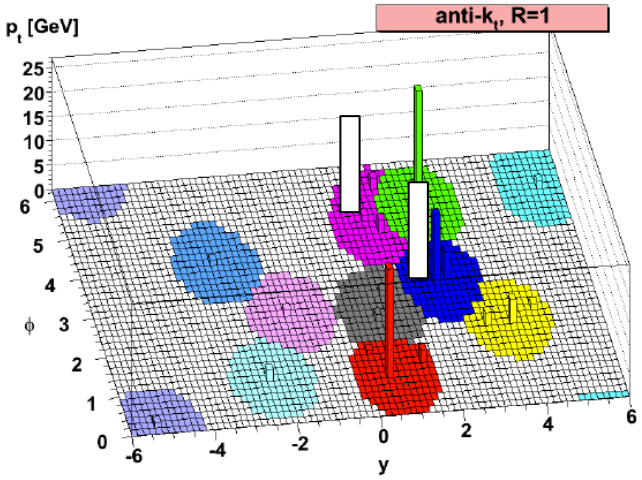
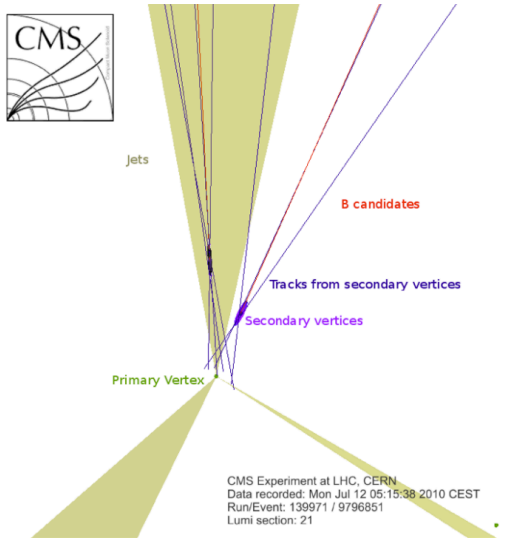
B-hadrons (I)





- Traditional B-tagging is not adequate for jet algorithms and subjets of irregular shape
- **Both ATLAS and CMS are developing more flexible b-tagging algorithms that can be more broadly applicable to different jet and subjet algorithms, and final state topologies**



CMS Inclusive vertex reconstruction seeded from tracks (no jets)

JHEP 03 (2011) 136

B-hadrons (II)

- **SLD Topological vertex reconstruction**
  - Associate tracks to 3D spatial regions
  - Construct a **vertex probability map** V(**r**)
  - Resolve vertices based on maxima of V(**r**)

Very interesting idea to apply to the the analysis of LHC events: "vertex substructure"

D.J. Jackson / Nucl. Instr. and Meth. in Phys. Res. A 388 (1997) 247–253

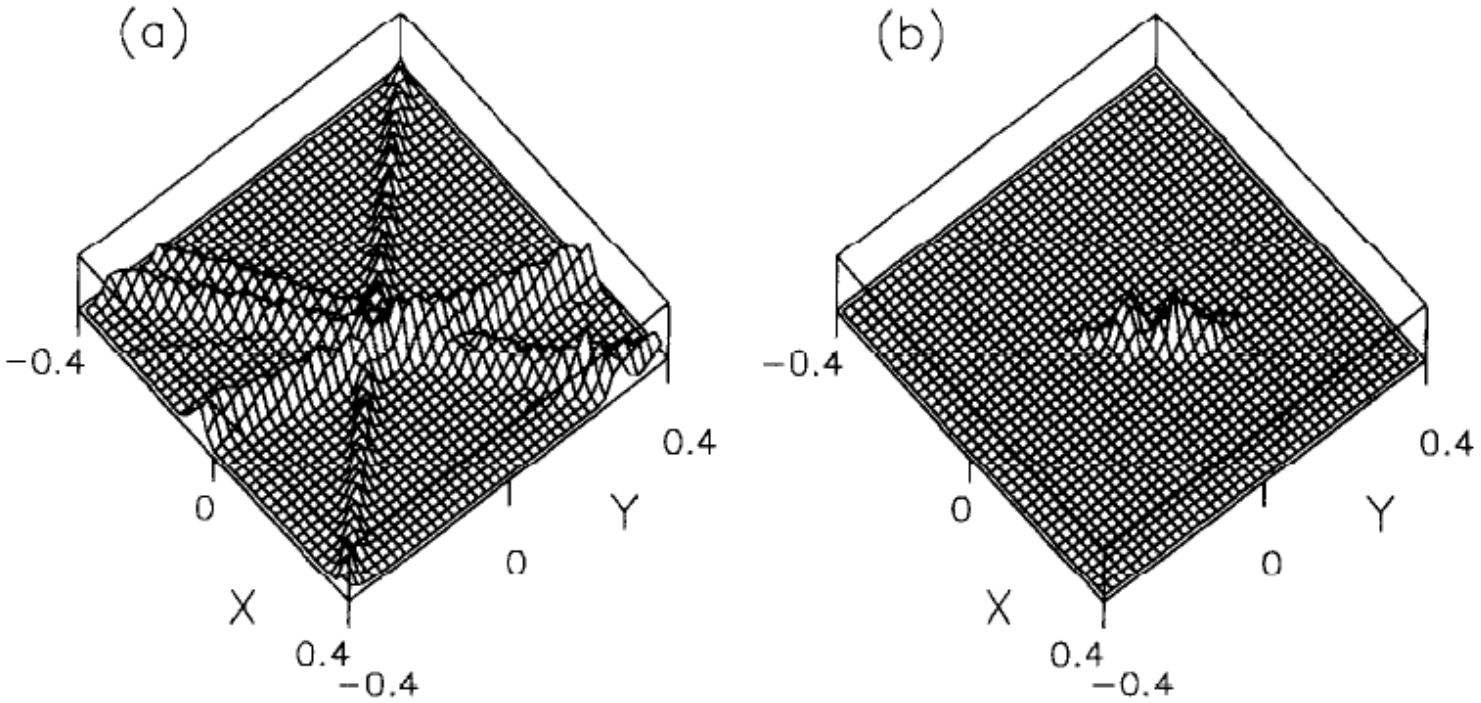
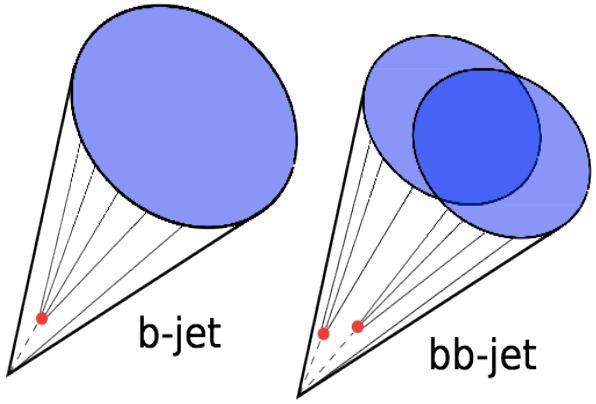
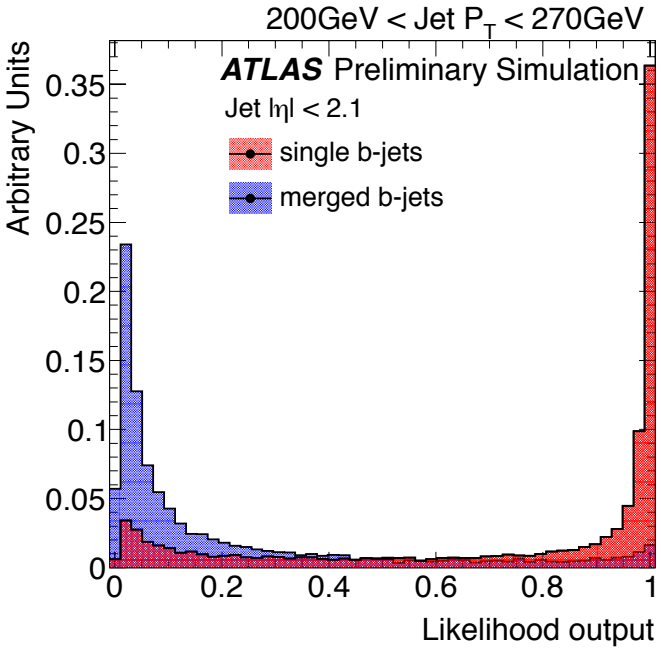


Fig. 3. The track (a) and vertex (b) functions projected onto the xy plane (cm).

B-hadron structure of jets

- **Jets, subjets, particles, and vertices:**
  - **Direct reconstruction of two secondary vertices within jets:**
    - Used by CDF [PRD 71 (2005) 092001] and CMS [JHEP 03 (2011) 136]
  - **Exploit the jet substructure differences between single and double b-hadron jets:**
    - One-prong versus two-prong structure using **tracks and subjets**
    - x30 rejection @ 50% efficiency for p_T>200 GeV





ATL-CONF-2012-100

Summary

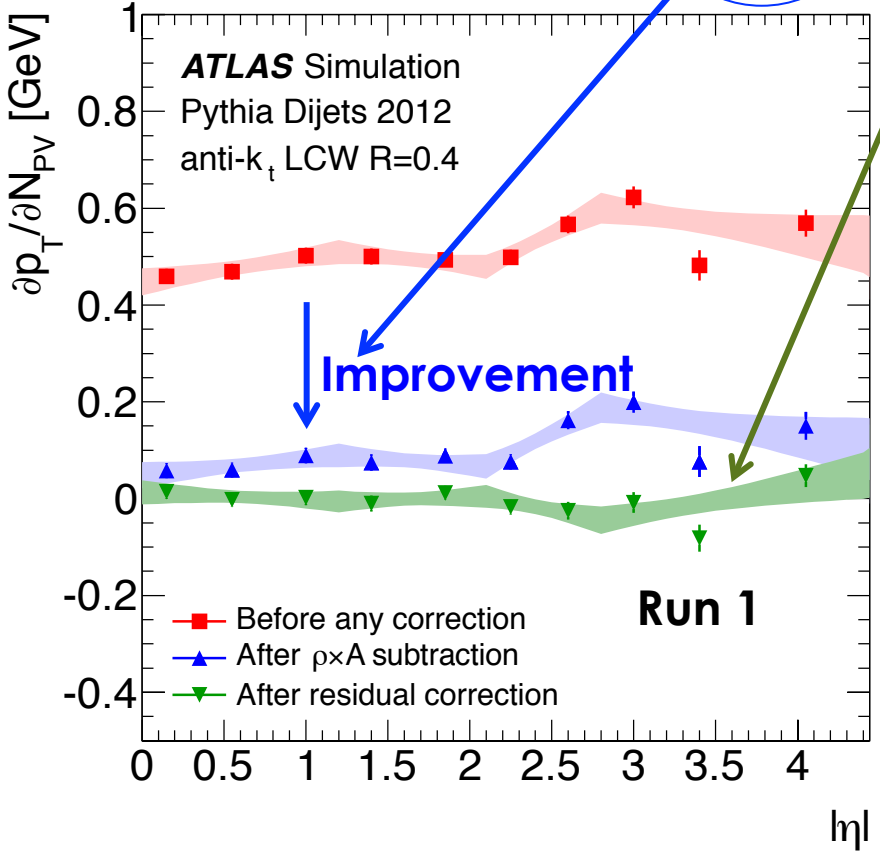
- **The analysis of LHC hadronic events relies on a detailed understanding of jets, subjets, and particles**
  - Different, interrelated, handles on the internal structure of jets
- **LHC experiments have commissioned these techniques and continue to improve their understanding, as new ideas continue to emerge**
- **Improvements in jet, subjet, and particle reconstruction will directly enhance the power of LHC experiments to discover new physics and to perform precision measurements**

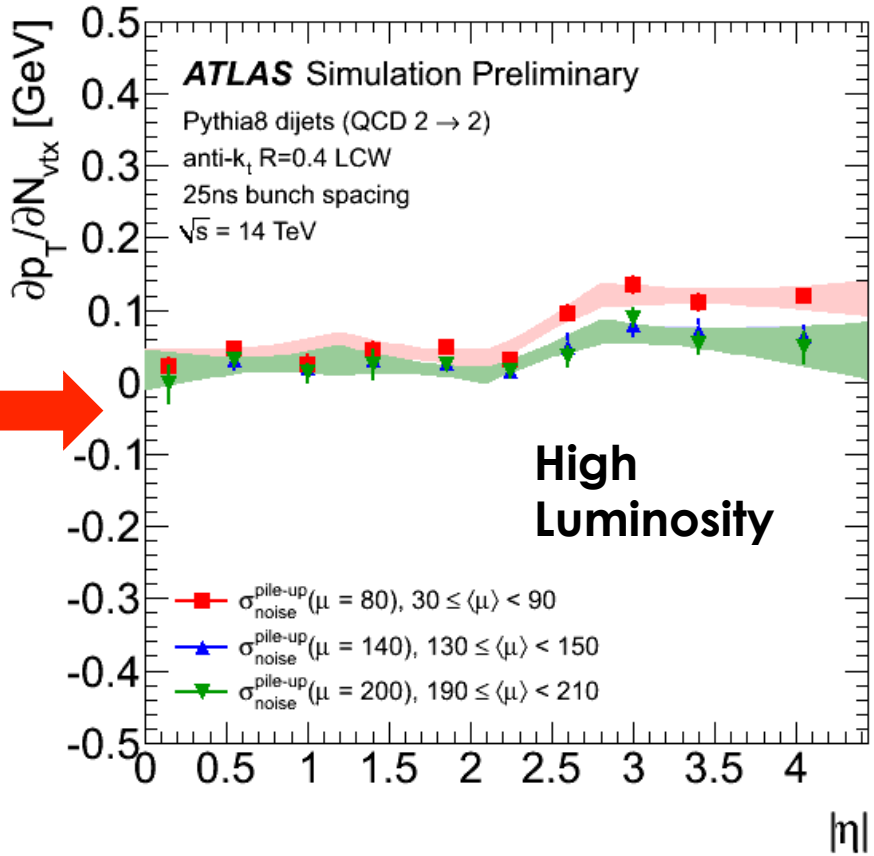
Backup

Pileup subtraction

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, topo-clustering, and local cluster weighting work well at high luminosity**