ATLAS Measurements of Jets in Heavy-Ion Collisions

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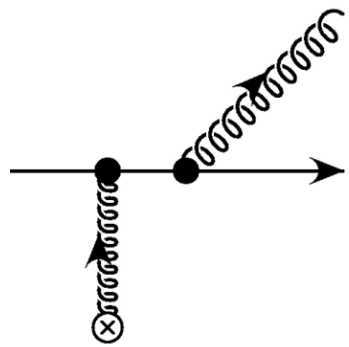
PANIC 2011
Cambridge, Massachusetts
7/28/11

Jets in Heavy Ion Collisions

- Jets provide a powerful tool for determining the degrees of freedom and their effective scales in heavy ion collisions
- Results from the RHIC program show that high p_T particle production is suppressed and that usual factorization of hard processes is broken in nuclear collisions
    - q^2 not dominant scale
    - new relevant scales: temperature, system size ?
- Single particle suppression doesn't tell us:
    - Does energy remain in jet but redistributed among fragments?
    - Or is the jet energy being transferred to the medium?
- Need to go beyond single particles, look at **full jets**

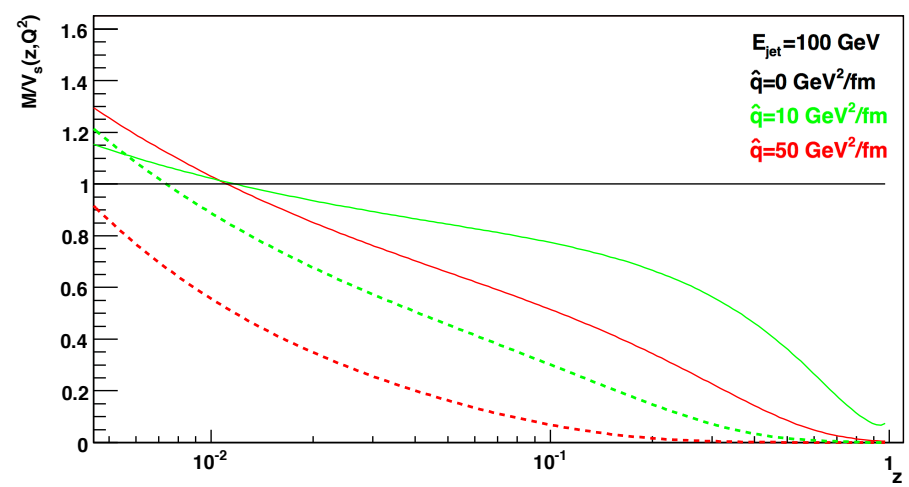
Radiative Energy Loss

Medium interactions induce additional radiation modifying usual vacuum fragmentation



high z region of fragmentation function sensitive to medium induced radiation

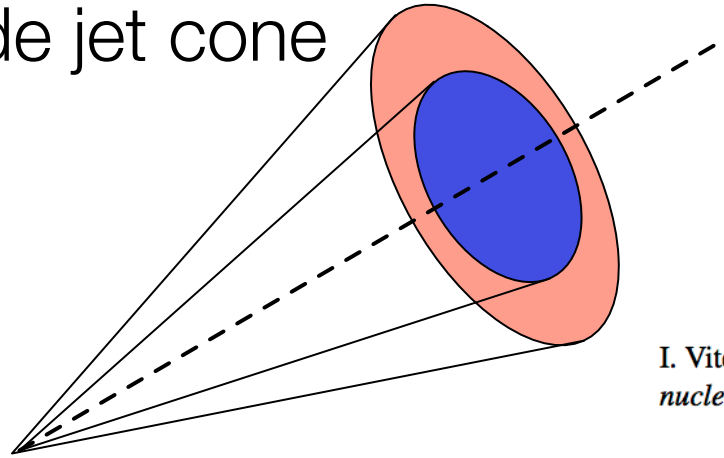
Ratio of modified fragmentation functions to vacuum



N. Armesto, L. Cunqueiro, C. A. Salgado, and W.-C. Xiang, *Medium-evolved fragmentation functions*, JHEP **0802** (2008) 048, arXiv:0710.3073 [hep-ph].

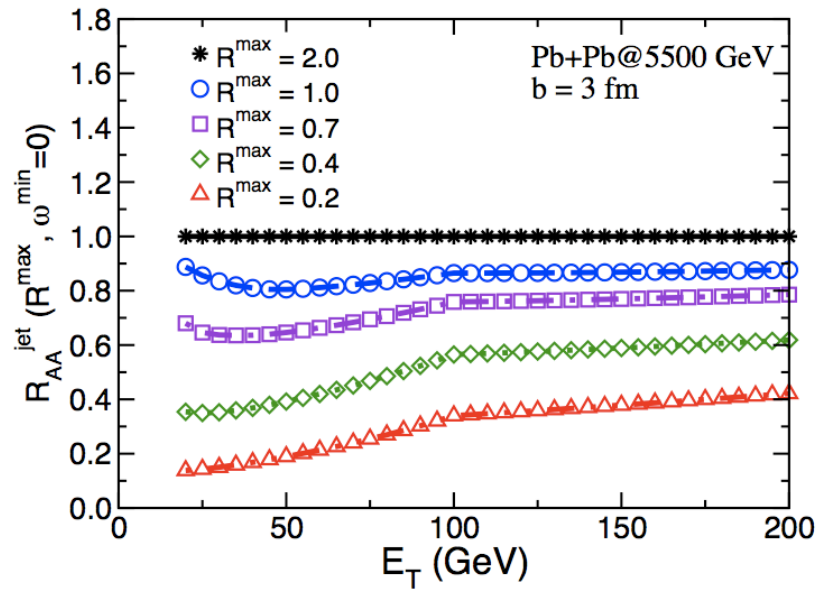
Radiative Energy Loss

Broadening of radiation may cause energy deposition outside jet cone

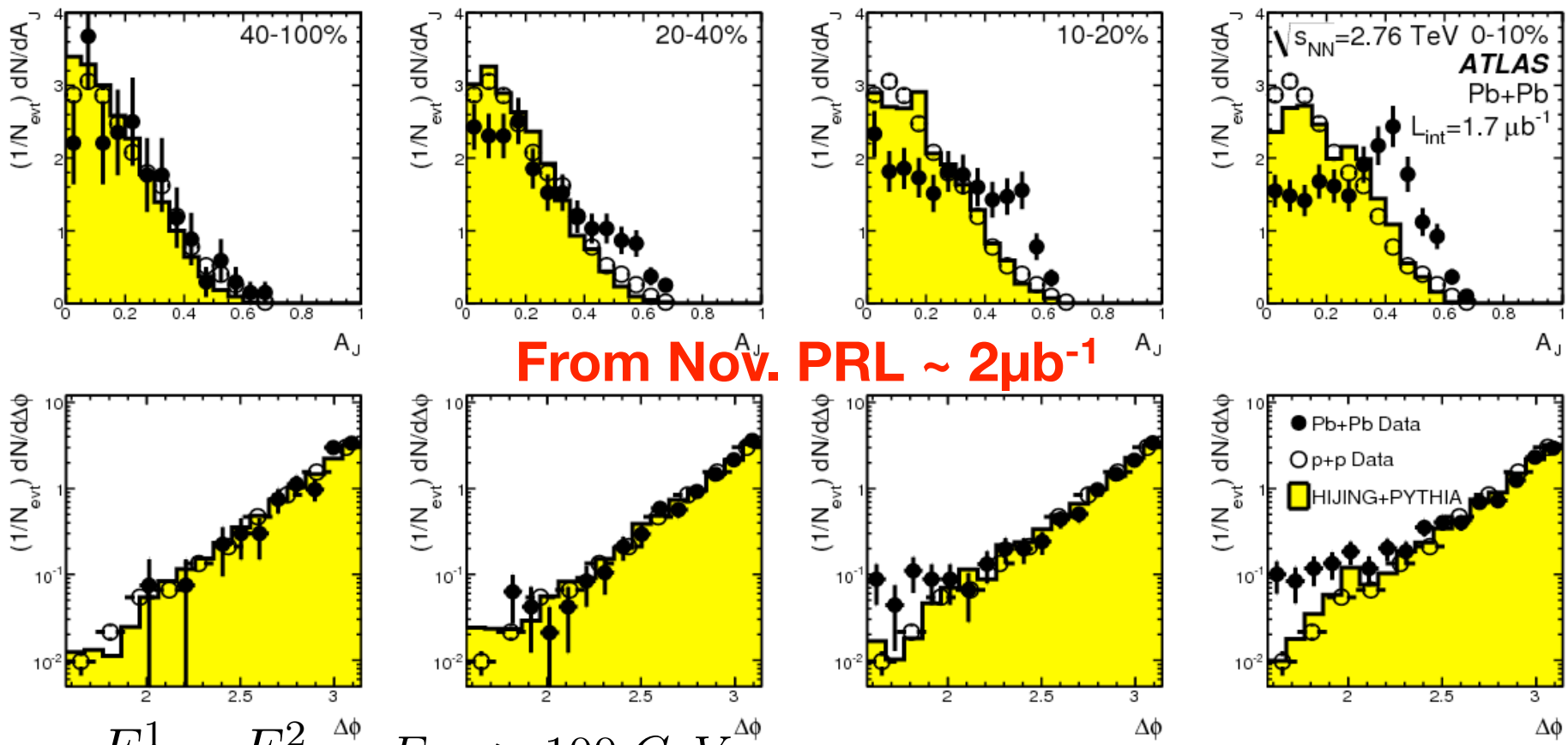


I. Vitev, S. Wicks, and B.-W. Zhang, *A theory of jet shapes and cross sections: from hadrons to nuclei*, JHEP **11** (2008) 093, `arXiv:0810.2807 [hep-ph]`.

Predictions of radiative energy loss suggest energy can be recovered by expanding jet cone



Di-jet Asymmetry: Original Result



From Nov. PRL ~ 2μb^{-1}

$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

$$E_{T1} > 100\ GeV$$

$$E_{T2} > 25\ GeV$$

Atlas Collaboration Collaboration, G. Aad et al., *Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at sqrt(S(NN))= 2.76 TeV with the ATLAS Detector at the LHC*, Phys.Rev.Lett. **105** (2010) 252303, arXiv:1011.6182 [hep-ex].

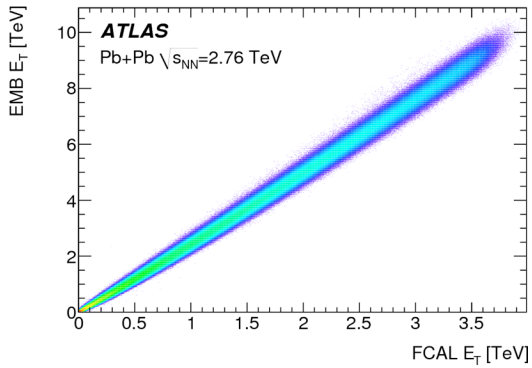
First indication of suppression of full jets

Momentum balance from hard process not contained in jets

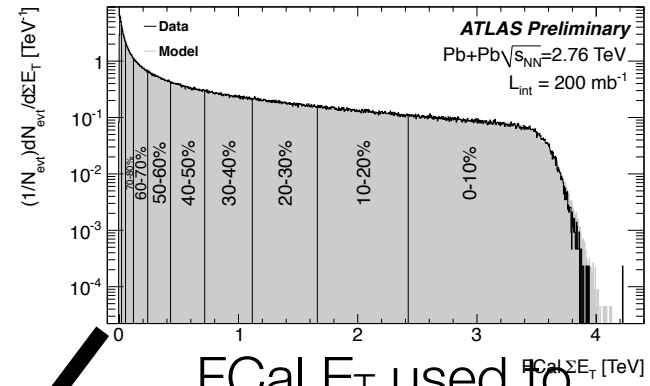
Understanding Asymmetry

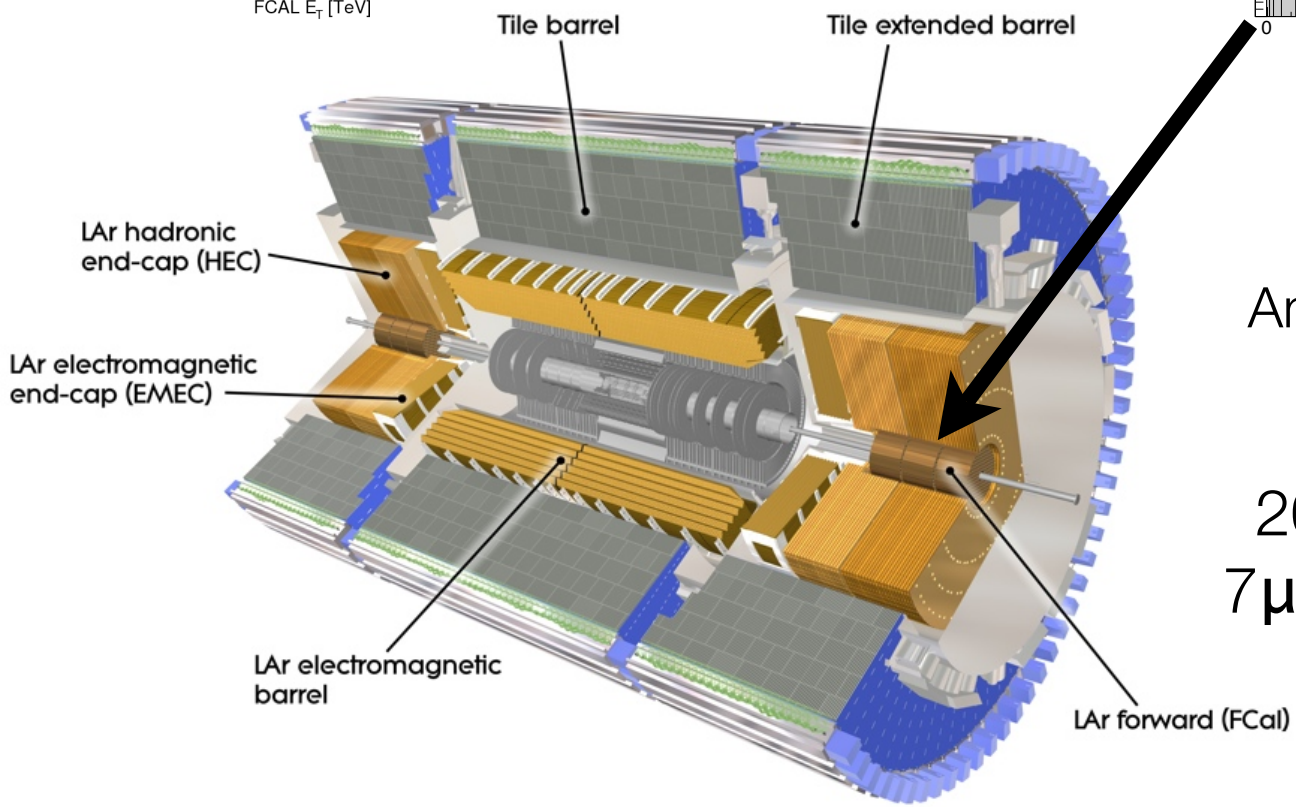
- Asymmetry results are startling, does this constrain energy loss picture?
- Difficult with a two-jet observable by itself. Supplement with single jet observables:
  - Jet spectra/central to peripheral ratio (R_{CP})
  - Longitudinal and transverse fragment distributions (z and j_T)
- Known to be sensitive to quantitative details of energy loss
- Less sensitive to global event features, hopefully can disentangle potentially complicated medium effects

ATLAS Detector: Calorimeter



E_T in barrel strongly correlated with FCal





FCal E_T used to determine centrality
$3.2 < |\eta| < 4.9$

Analysis uses jets in barrel: $|\eta| < 2.8$

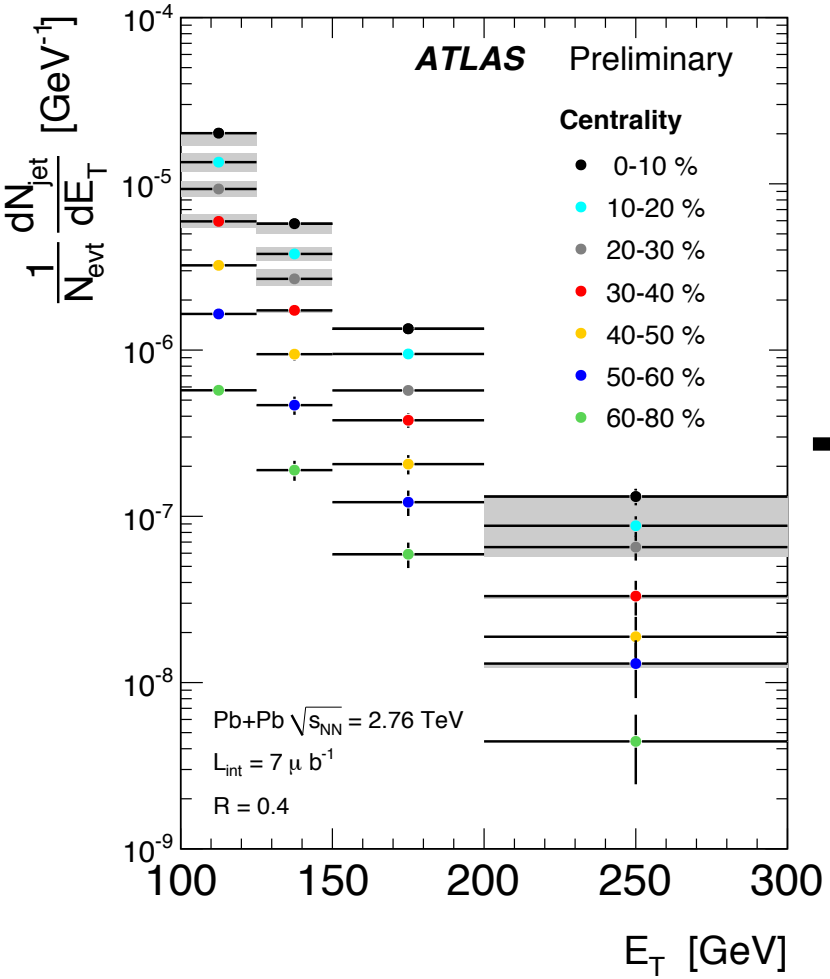
2010 Pb Ion run:
$7\mu b^{-1}$, 50 M events

Jet Reconstruction

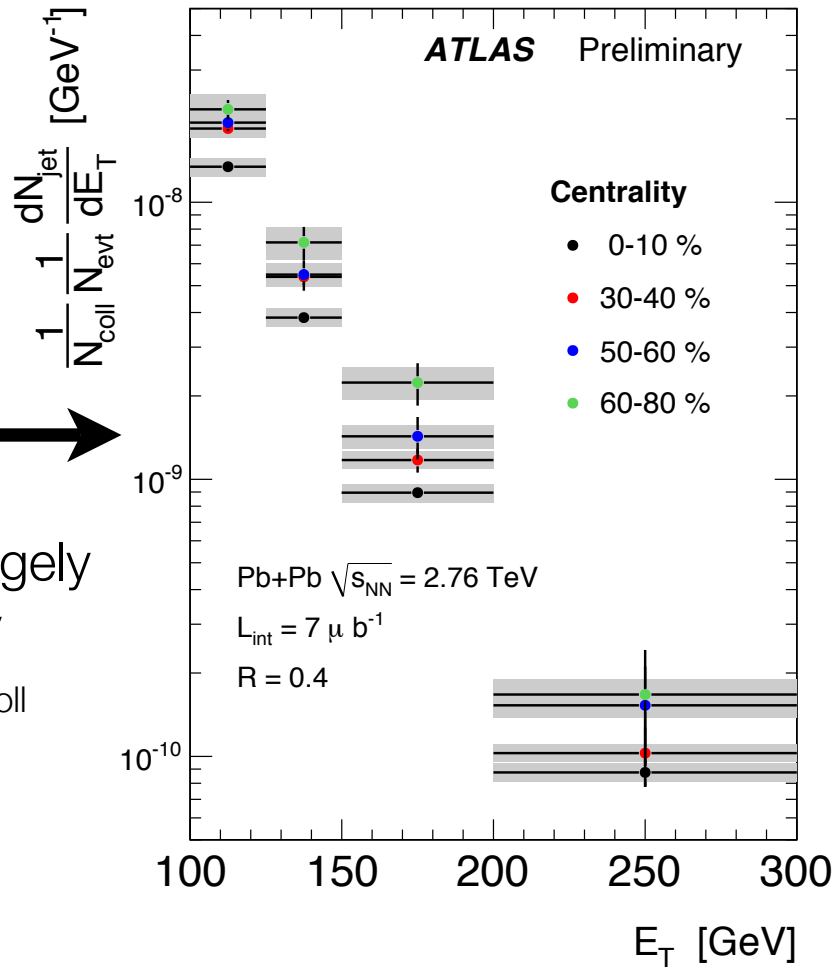
- Jets reconstructed using anti-k_t algorithm with two choices of R parameter (R=0.4 and R=0.2)
- Inputs are 0.1x0.1 ($\Delta\eta$x$\Delta\phi$) calorimeter towers
- Average background computed per calorimeter sampling layer per 0.1 η strip for each event
- Potential jets excluded from averaging to prevent bias

R=0.4 jets
- utilize an iterative procedure to determine background
- background modulated by elliptic flow before subtraction

Jet Spectra R=0.4

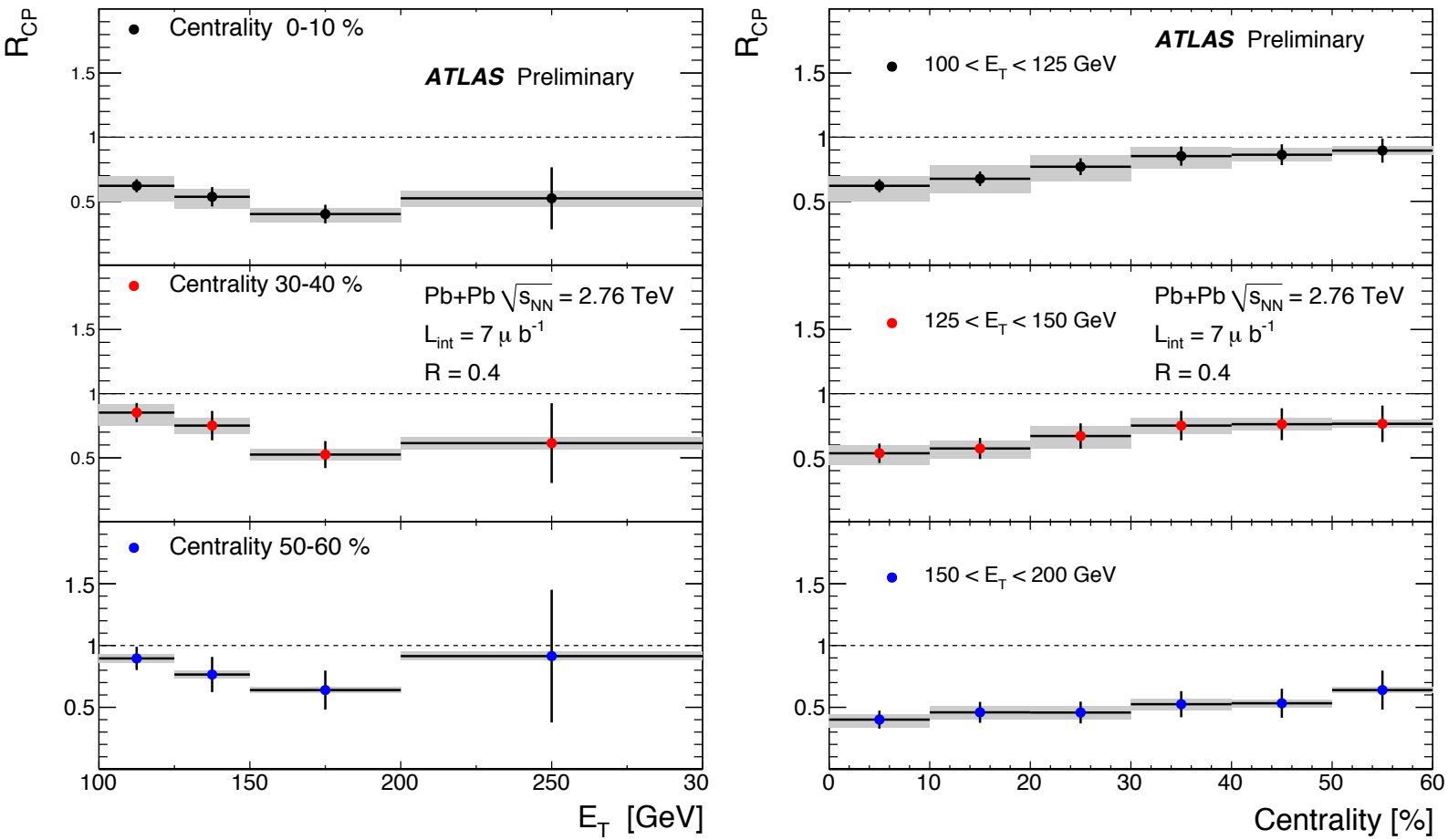


Centrality dependence largely removed by geometry N_{coll}



Raw spectra with bin-by-bin unfolding, additional 22% systematic uncertainty from jet energy scale

R_{CP} R=0.4 Jets

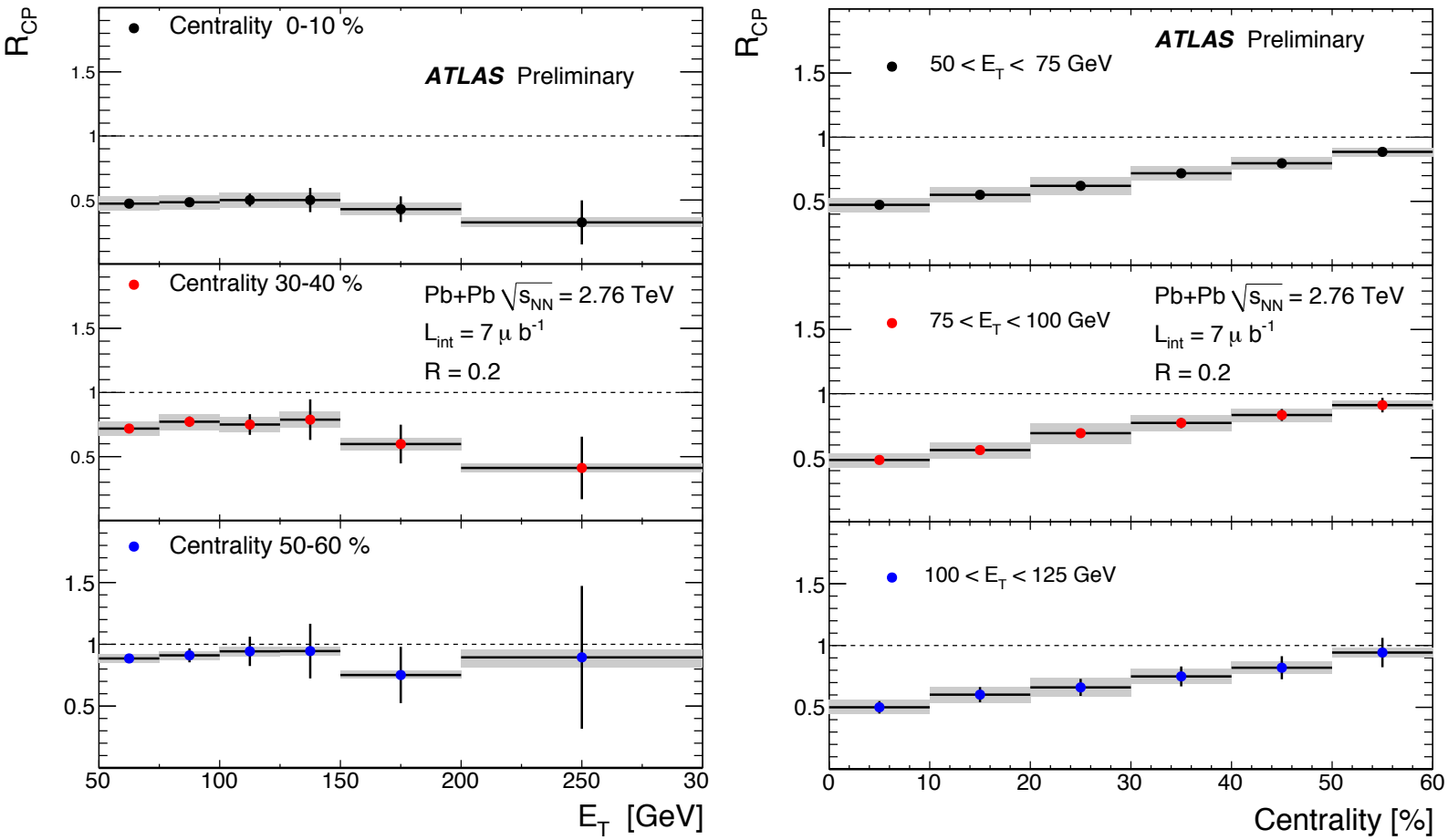


Gradual turn on of medium effects with increasing centrality

Clear **factor of ~2 suppression** indicated in most central collisions

Entire jet, not just leading fragment

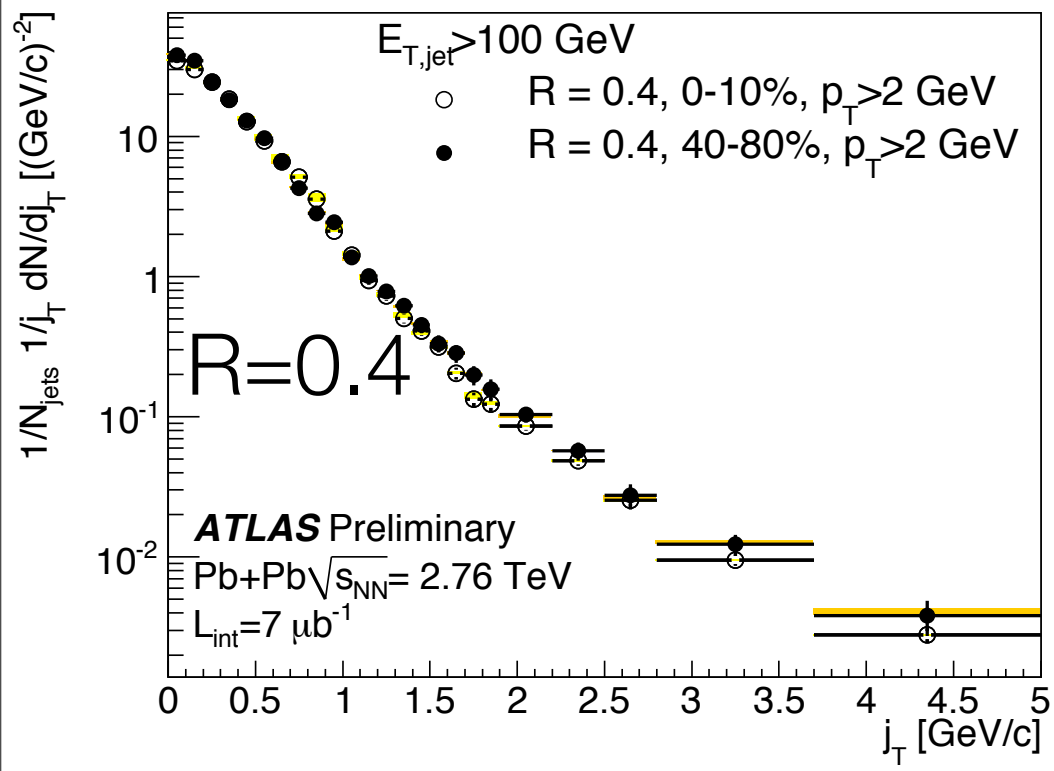
R_{CP} R=0.2 Jets

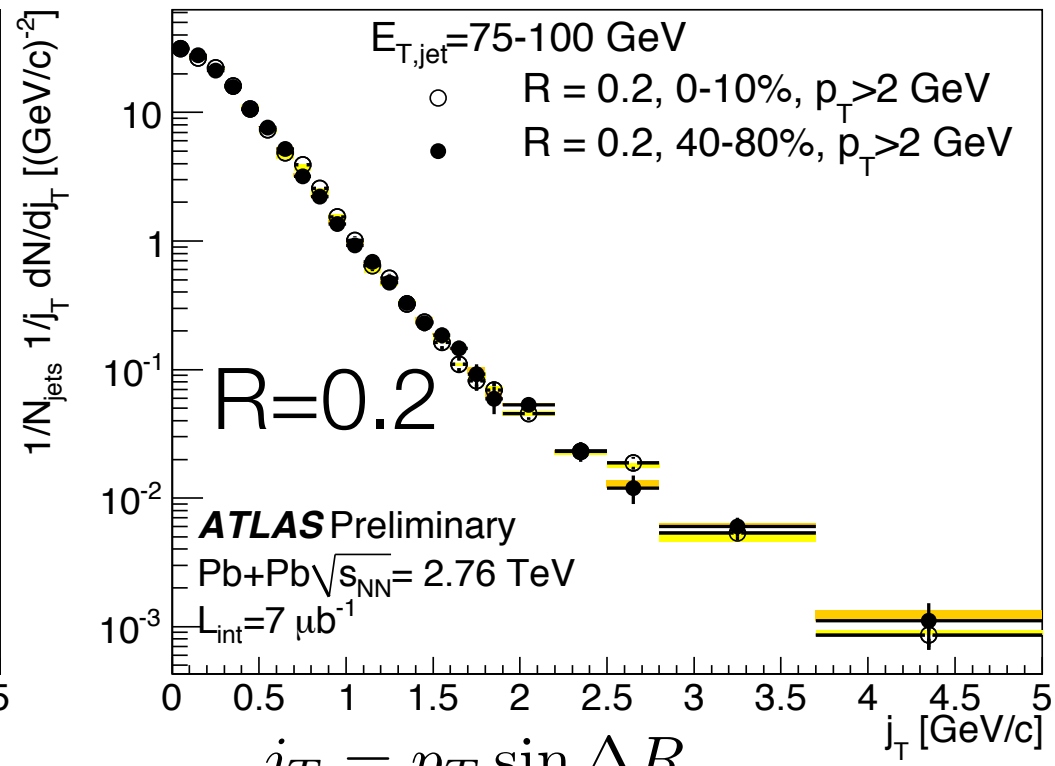


Slightly more suppression observed

Not much energy recovered by larger cone size: 0.2 ⇒ 0.4

Jet Fragments: Transverse Structure





All charged particles with $p_T > 2$ GeV and within jet radius

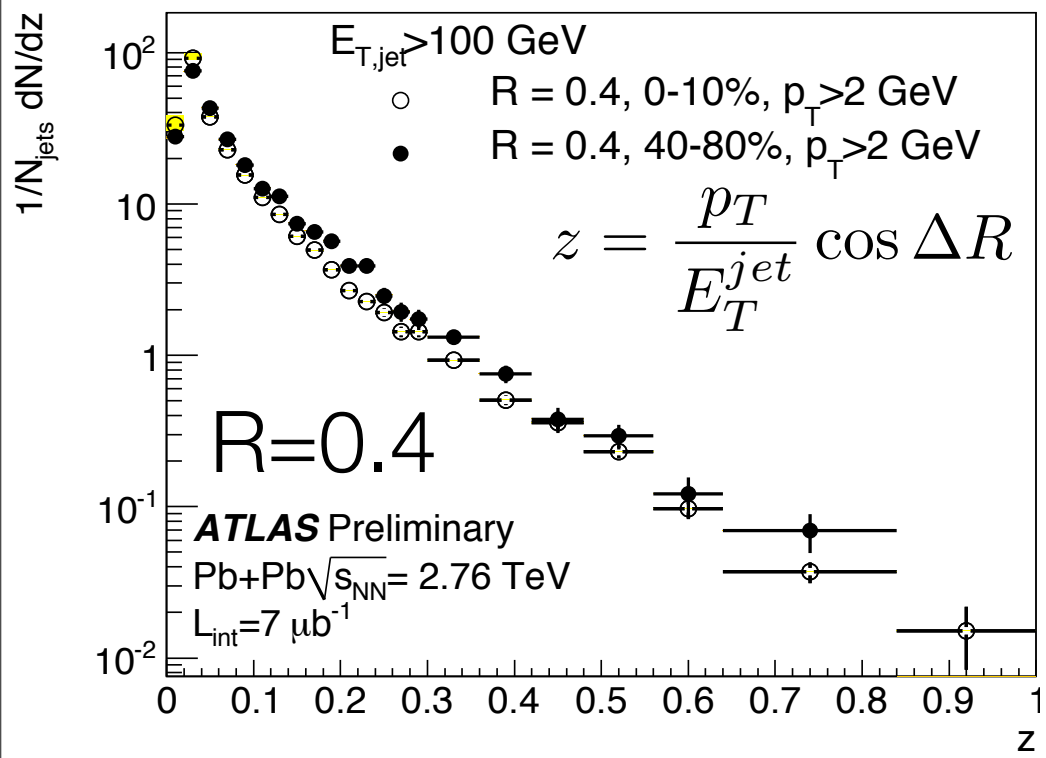
$$j_T = p_T \sin \Delta R$$

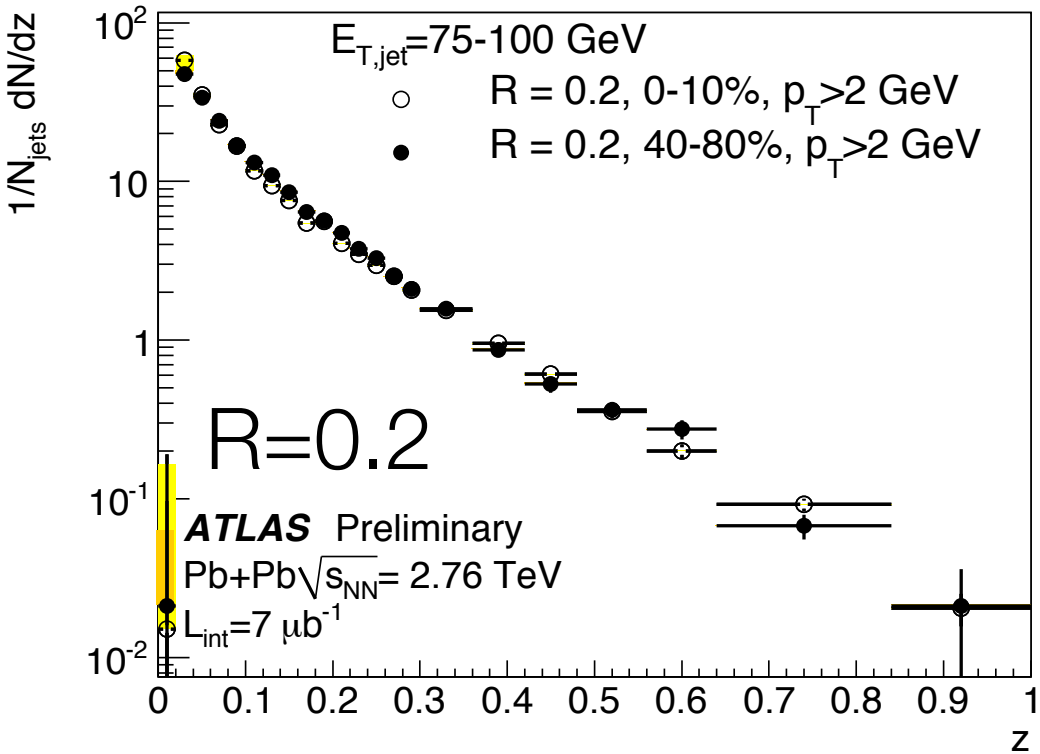
$$\Delta R = \sqrt{(\eta - \eta^{jet})^2 + (\phi - \phi^{jet})^2}$$

Lack of broadening consistent with R_{CP} measurement

Some change in shape with centrality, not enough to indicate a strong effect

Jet Fragments: Longitudinal Structure





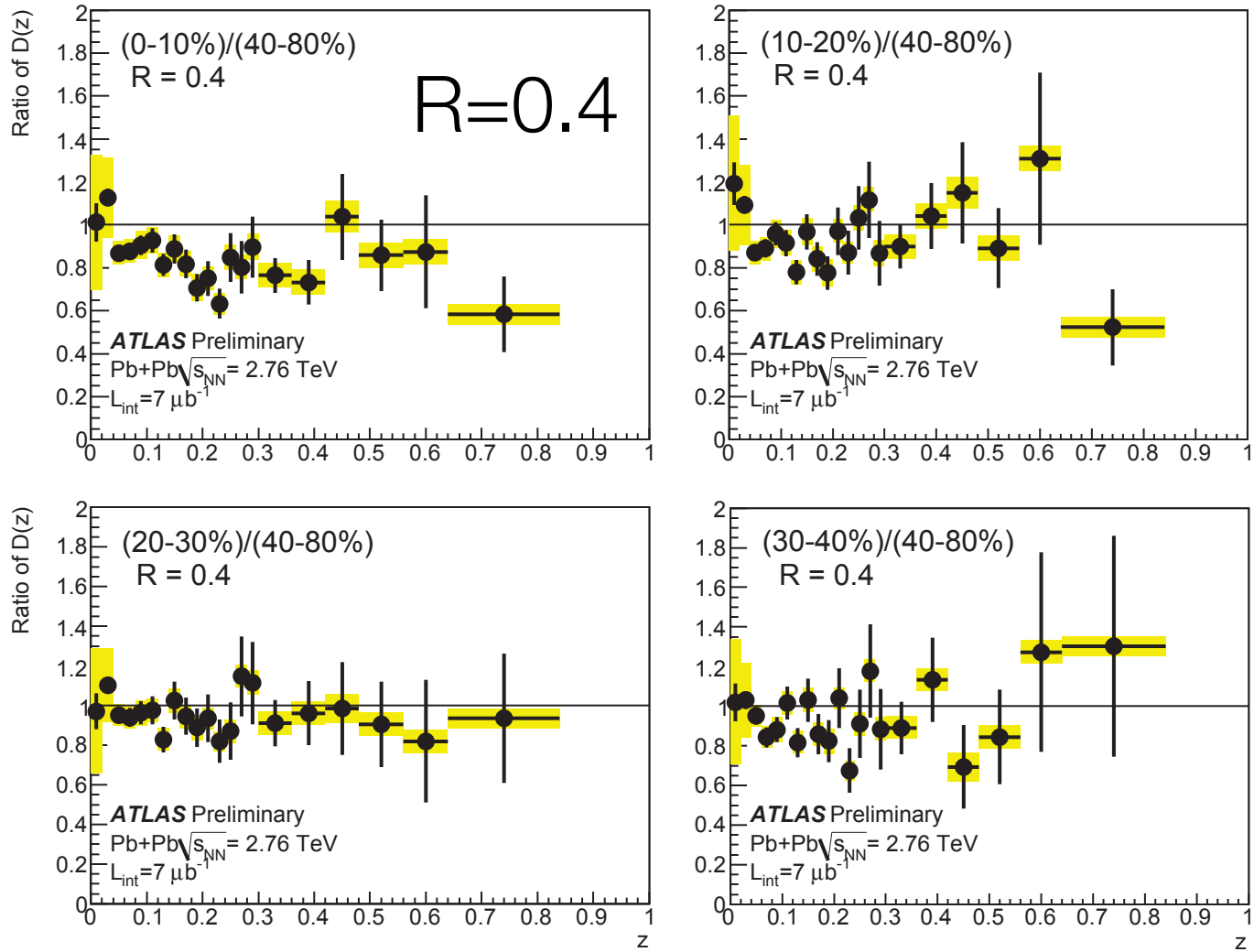
Large modification at high z not indicated

Slight redistribution of jet's energy among fragments seen at mid-low z (0.2)

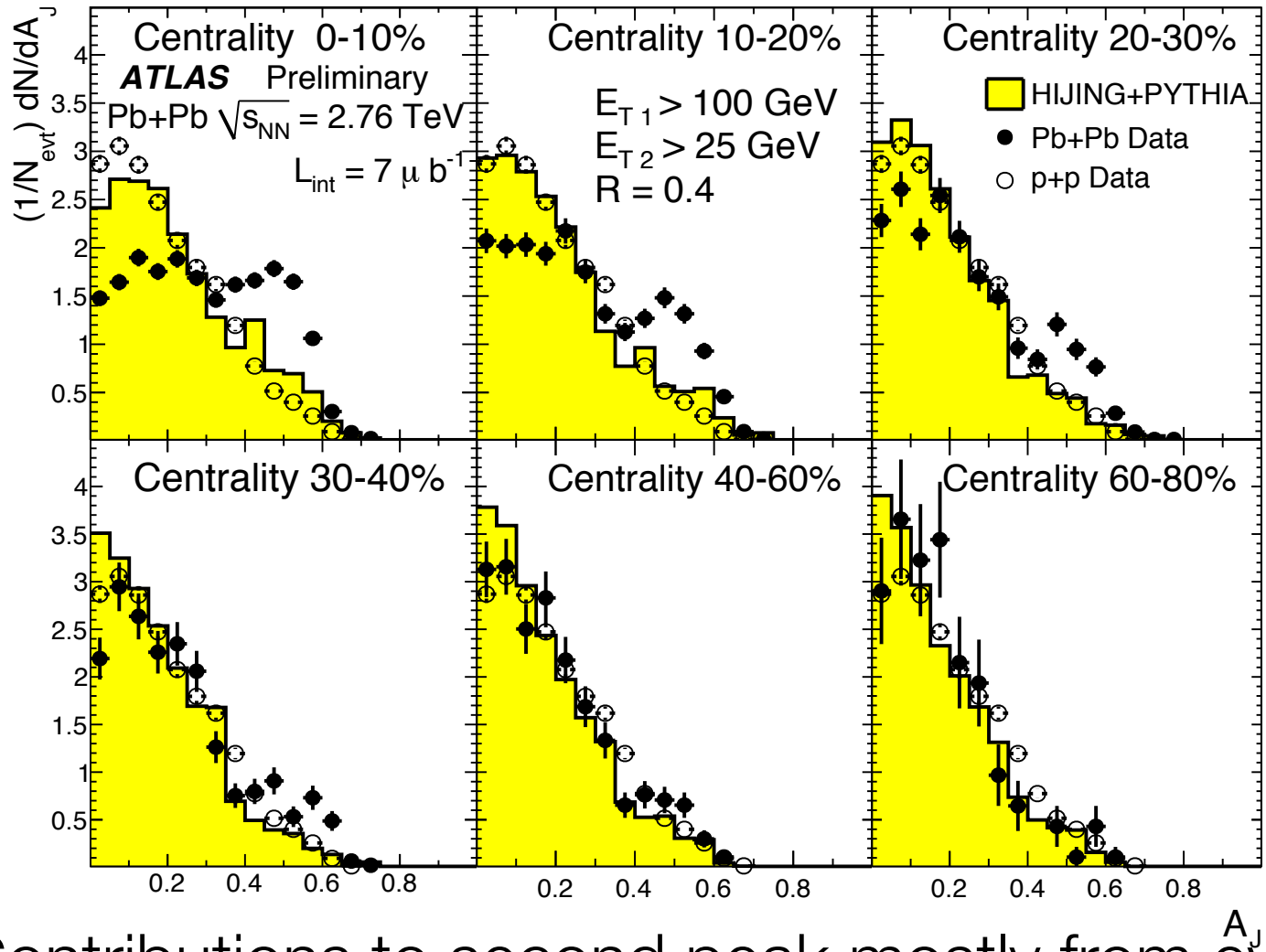
Jet Fragments: Longitudinal Structure

Modest modification at mid-low z

High z behavior unlike prediction



Two-Jet Observables: Di-jet Asymmetry



$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

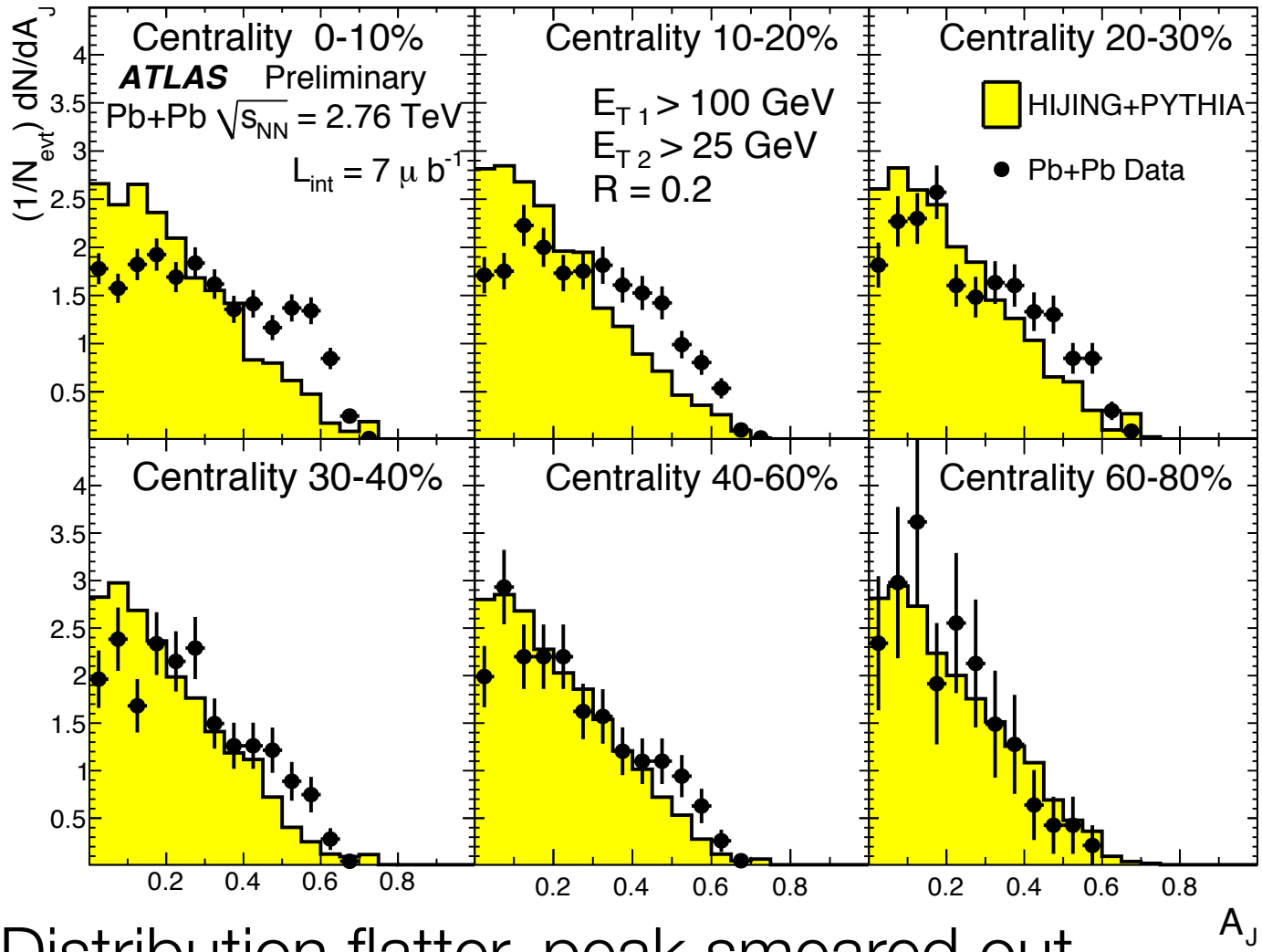
$$E_{T1} > 100\ GeV$$

$$E_{T2} > 25\ GeV$$

Updated from published result

Contributions to second peak mostly from events where second jet consistent with background level

Di-jet Asymmetry: R=0.2



$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

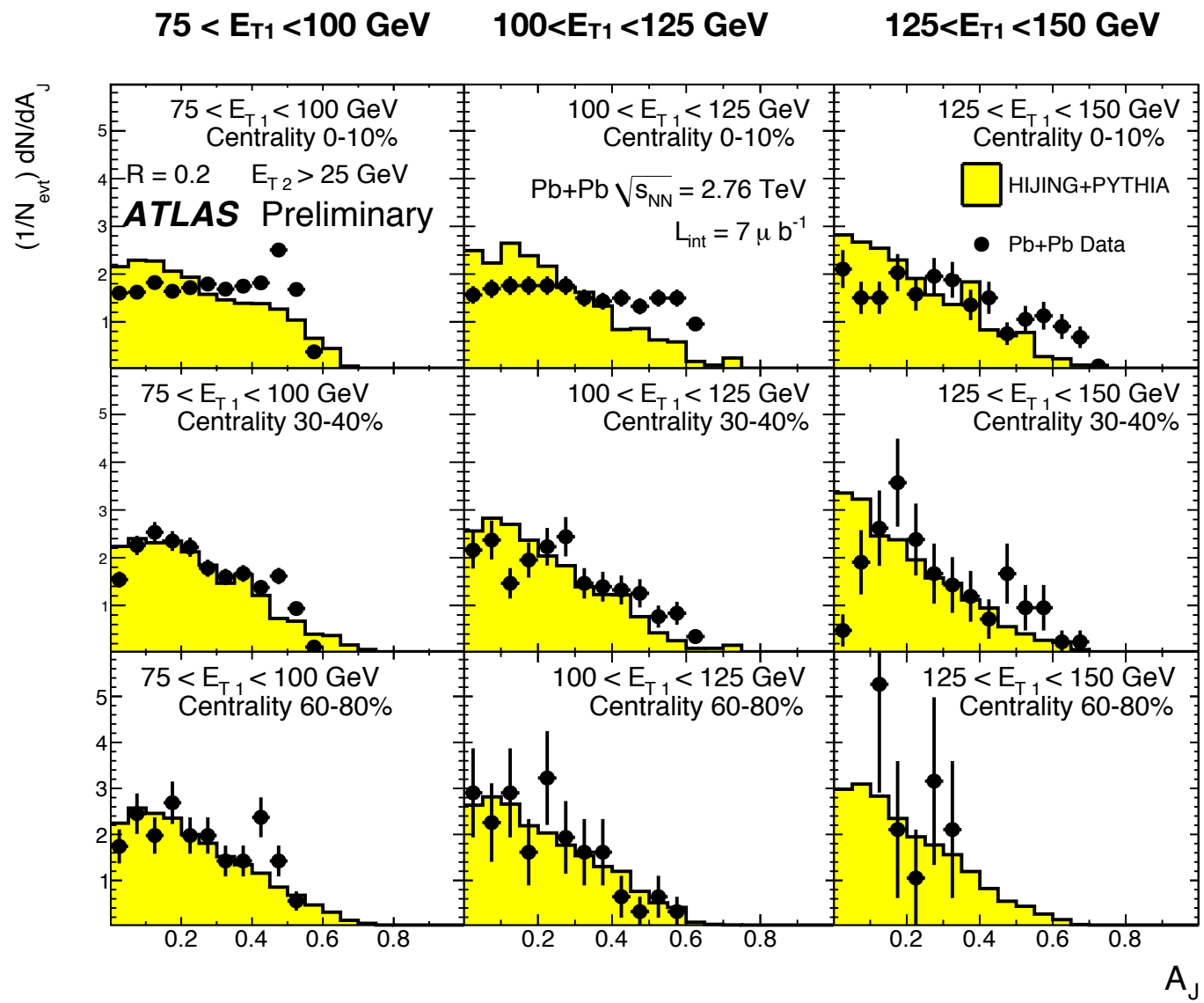
$$E_{T1} > 100\ GeV$$

$$E_{T2} > 25\ GeV$$

Distribution flatter, peak smeared out

Less sensitive to background fluctuations

Asymmetry: Energy Dependence, R=0.2



Increasing jet energy stretches peak out

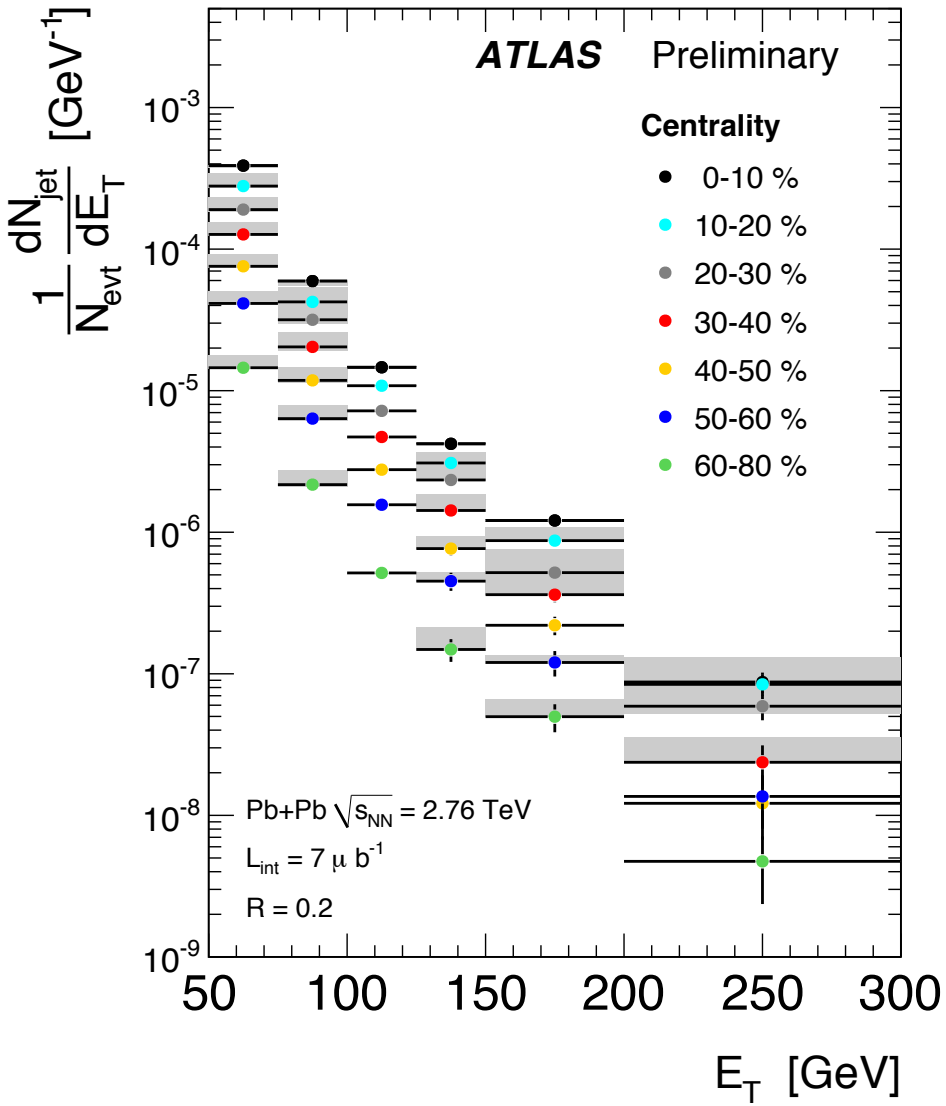
Peak at low values of A_J restored in peripheral collisions

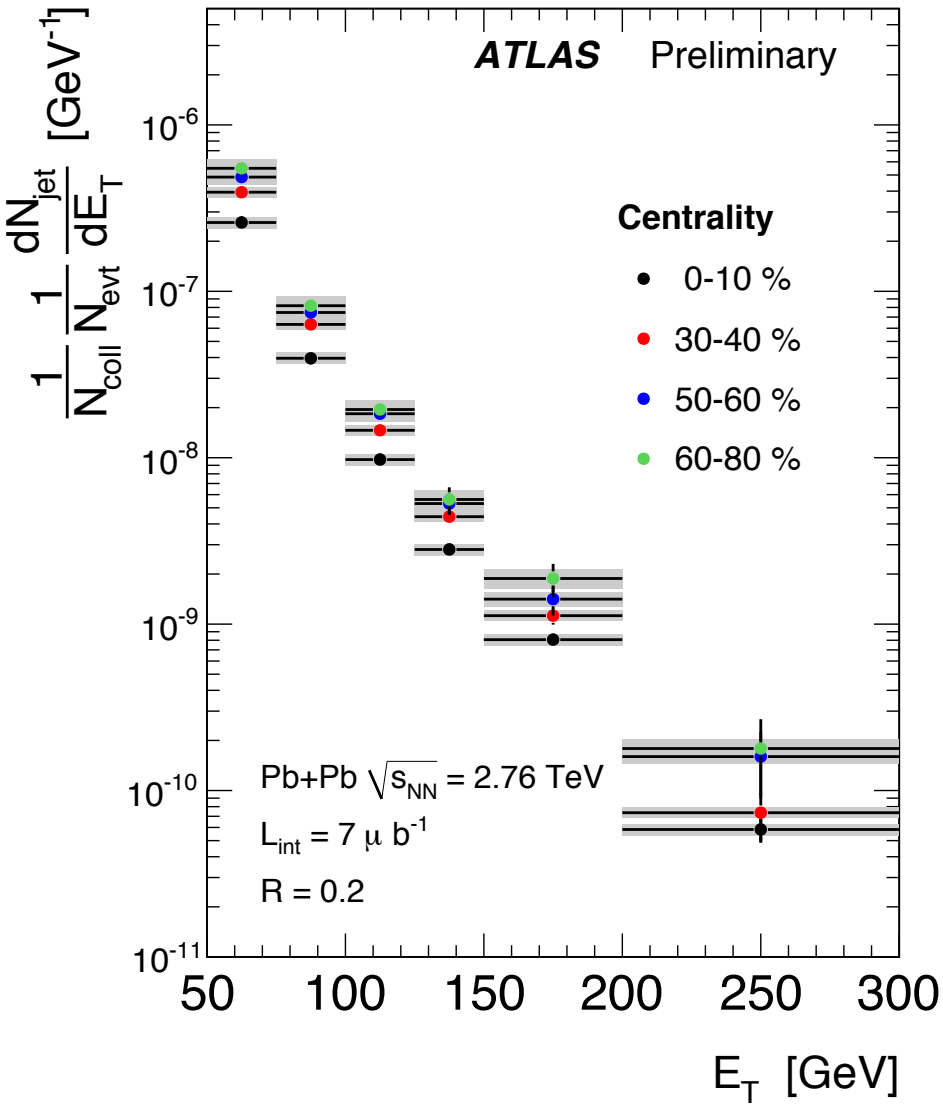
Summary

- Di-jet asymmetry indicates significant distortion in momentum balance contained in jets that increases with centrality, nearly flat away from peak
- R_{CP} measurements support the interpretation that asymmetry is caused by significant suppression of high energy jets
- Small variation between results of different cone sizes shows little room for suppression coming from out-of-cone energy loss
- j_T and z distributions provide complementary result indicating that the suppression mechanism does not modify longitudinal or transverse distributions of charged particle jet fragments as would be expected with radiation-dominated energy loss scenario
- Results not obviously consistent with radiation-dominated energy loss except possibly at large angles

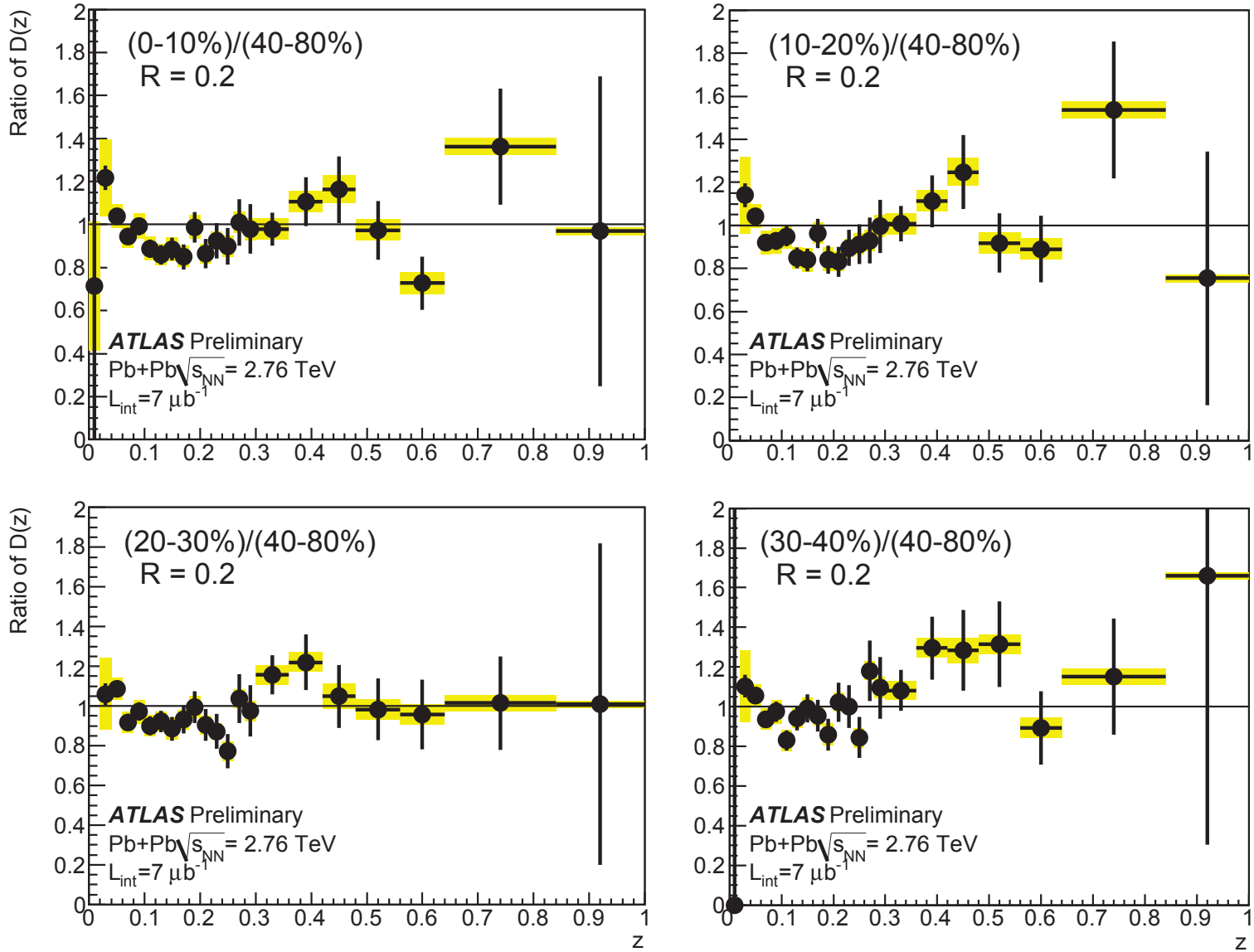
Supporting Slides

Jet Spectra R=0.2



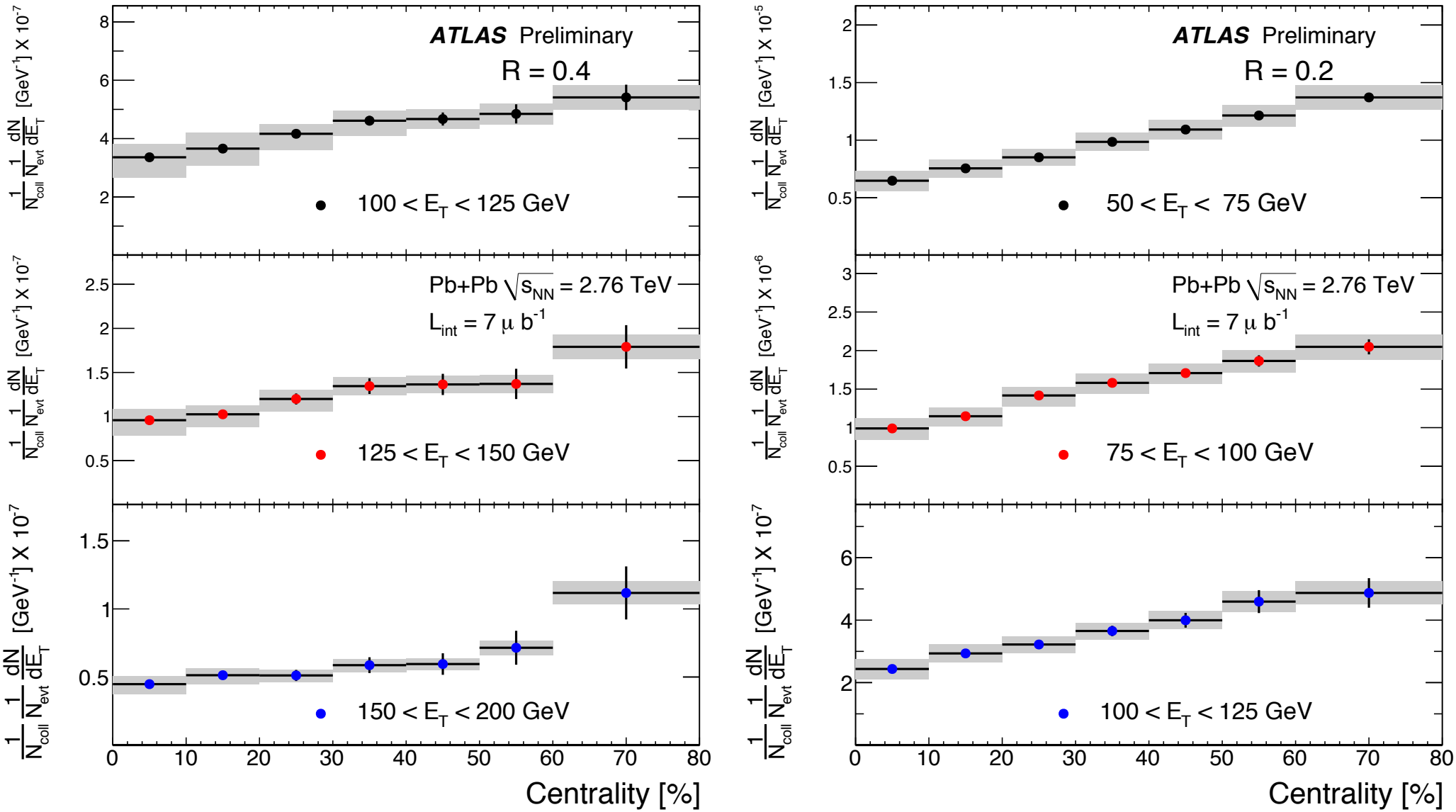


Jet Fragments: Longitudinal Structure

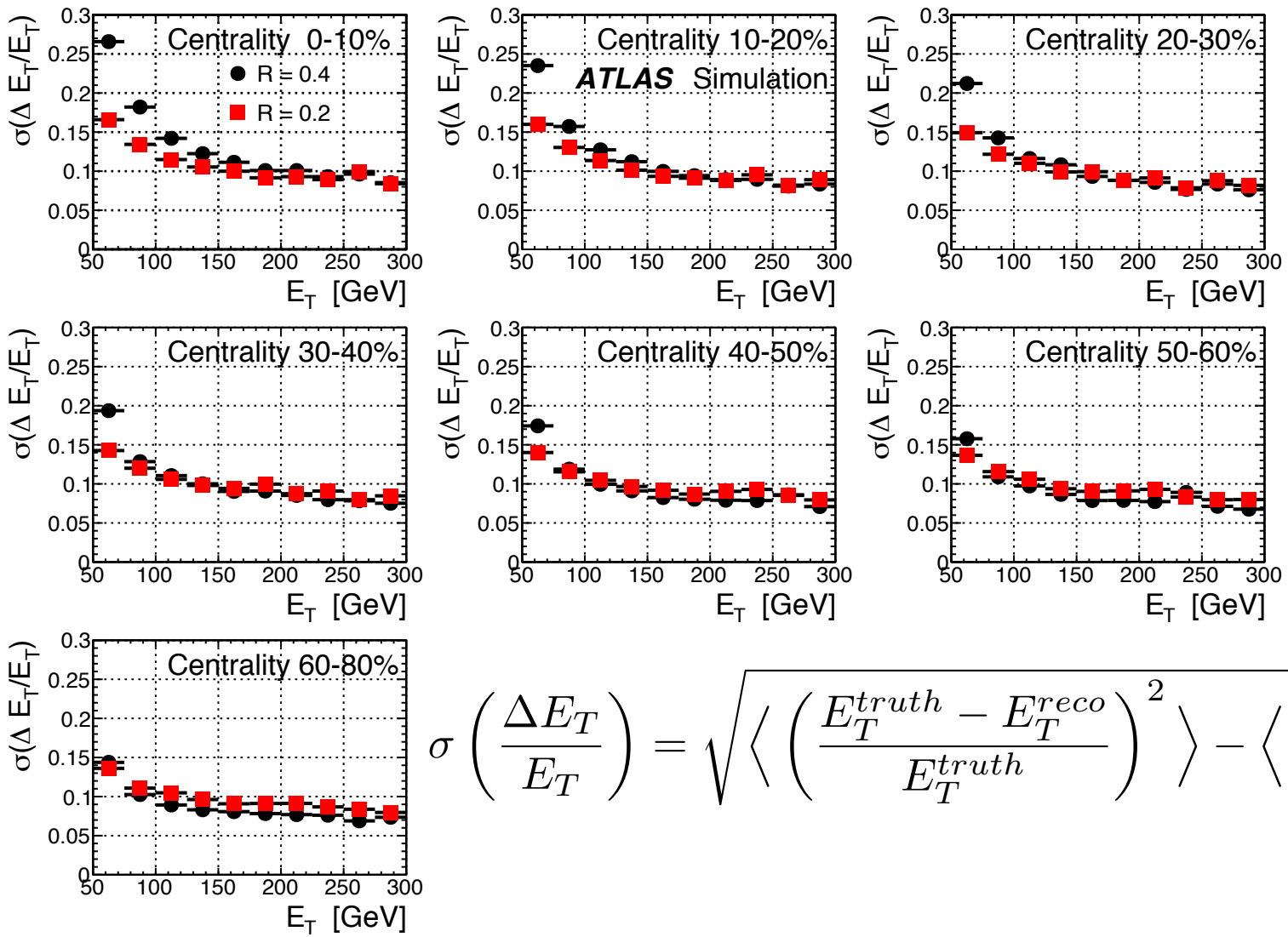


R=0.2

Yields vs Centrality

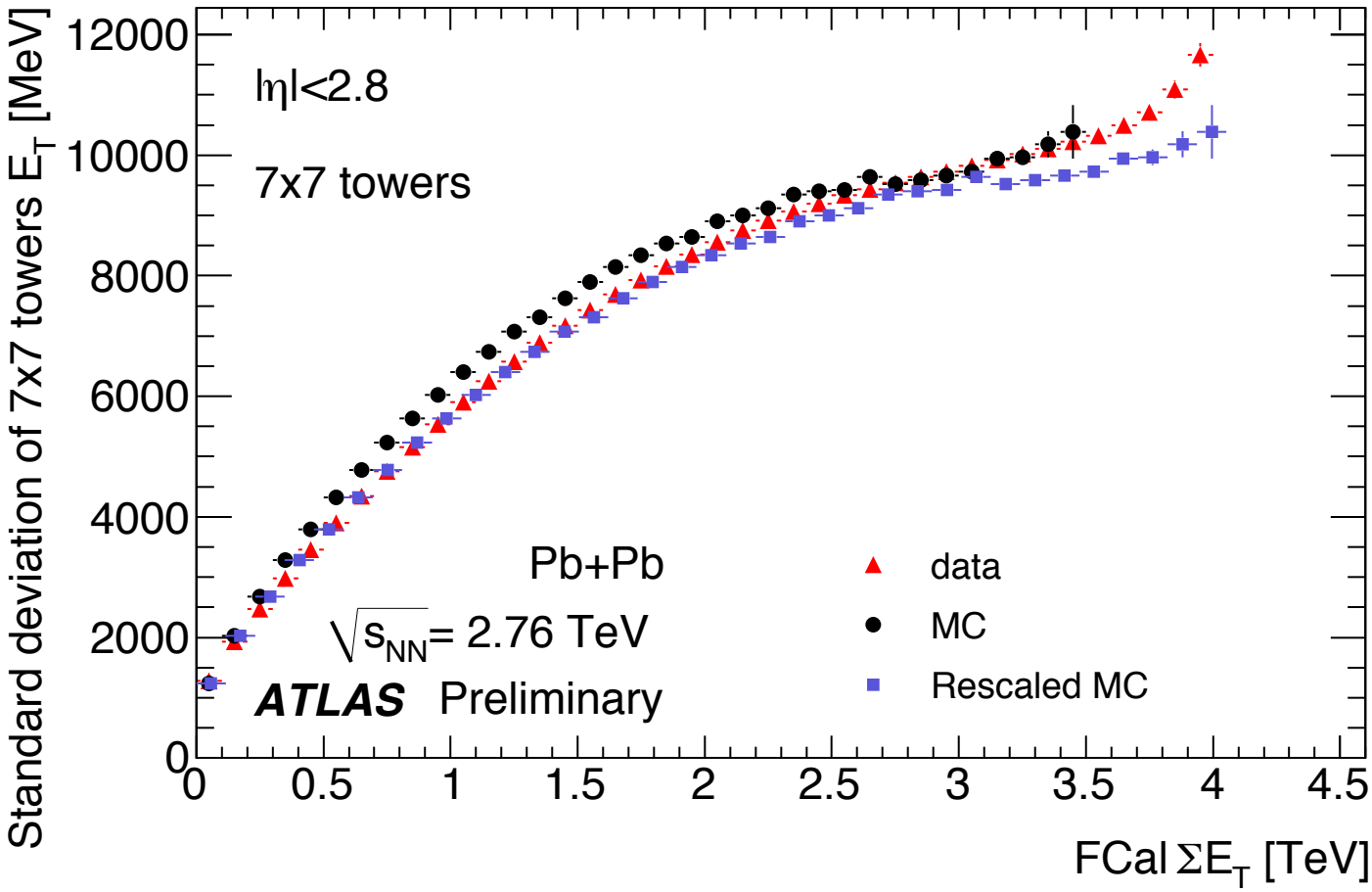


Jet Performance: Resolution from MC



$$\sigma\left(\frac{\Delta E_T}{E_T}\right) = \sqrt{\left\langle \left(\frac{E_T^{truth} - E_T^{reco}}{E_T^{truth}}\right)^2 \right\rangle - \left\langle \frac{E_T^{truth} - E_T^{reco}}{E_T^{truth}} \right\rangle^2}$$

Jet Resolution: Background Fluctuations



ATLAS Detector: Inner Detector

Jets in heavy ion collisions