

Measurements of Jets and Jet Quenching in $\sqrt{s_{NN}}=2.76$ TeV Pb+Pb Collisions with the ATLAS Detector at the LHC

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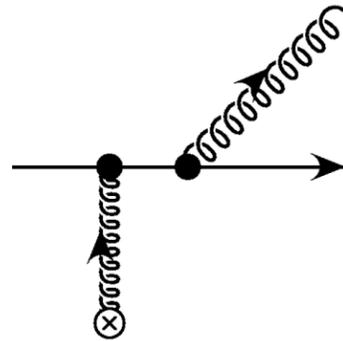
Jets in Heavy Ion Collisions

- 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: intensive (T) extensive (L) ?
- 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**



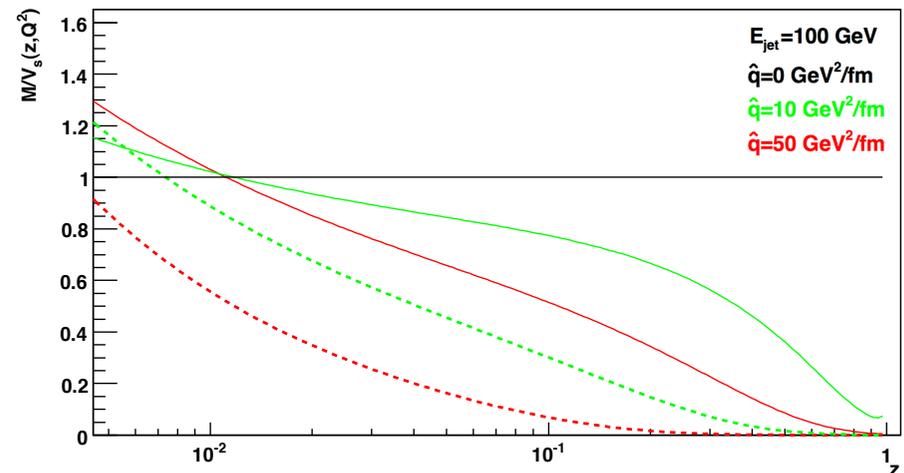
Radiative Energy Loss

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

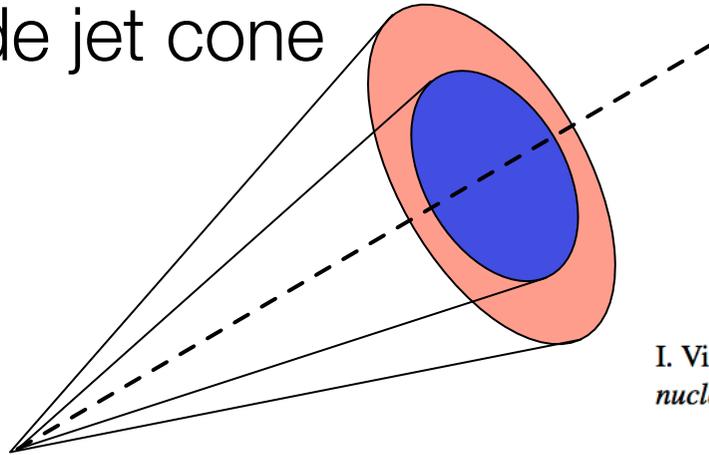


N. Armesto, L. Cunqueiro, C. A. Salgado, and W.-C. Xiang, *Medium-evolved fragmentation functions*, JHEP **0802** (2008) 048, arXiv:0710.3073 [hep-ph].



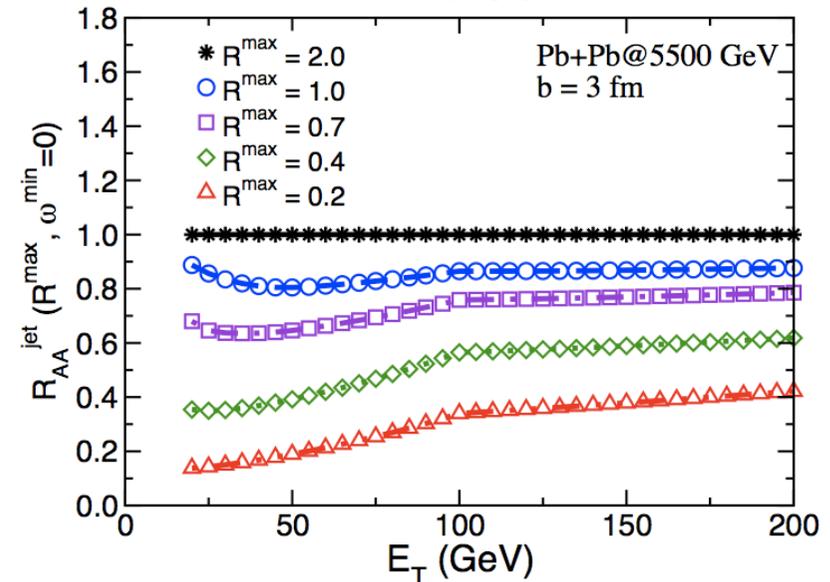
Radiative Energy Loss

Broadening of radiation may cause energy deposition outside jet cone



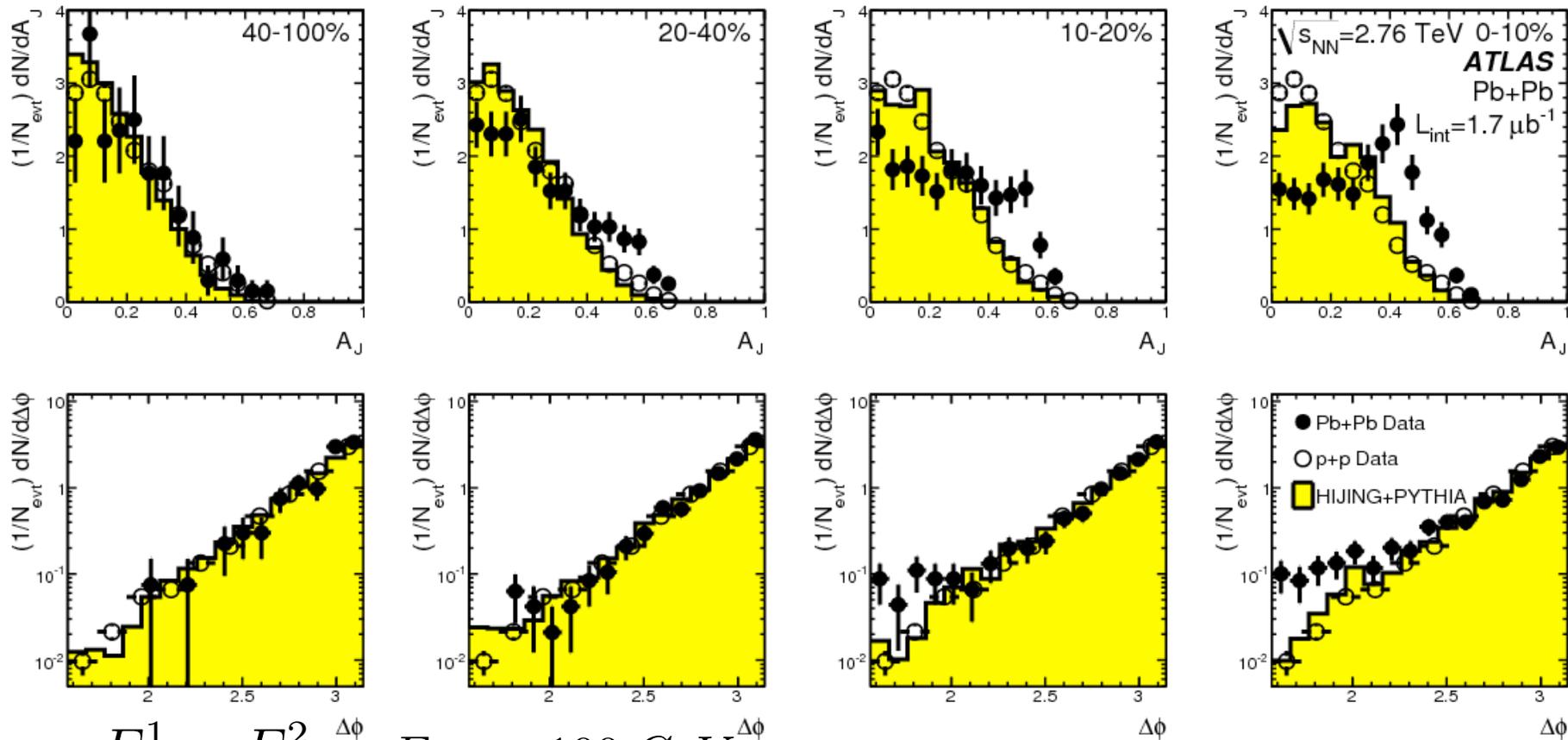
I. Vitev, S. Wicks, and B.-W. Zhang, *A theory of jet shapes and cross sections: from hadrons to nuclei*, JHEP 11 (2008) 093, arXiv:0810.2807 [hep-ph].

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





Di-jet Asymmetry: Original Result



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

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

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

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

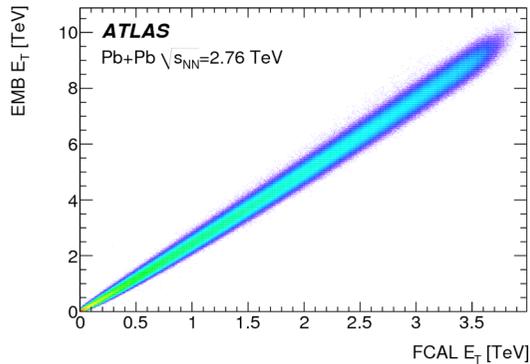


Understanding Asymmetry

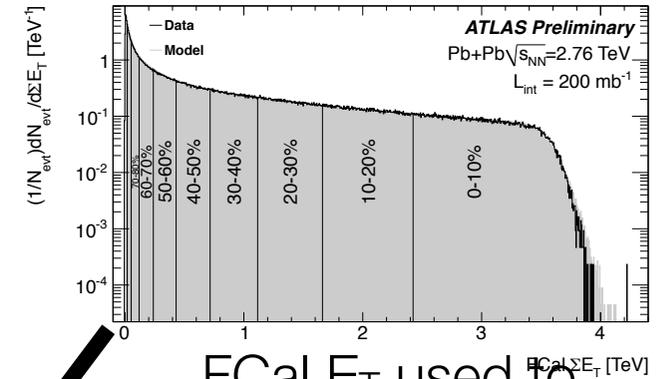
- Asymmetry results are startling, does this constrain energy loss picture?
- Difficult with a two-jet observable by itself. Supplement with single jet observables:
 - Jet spectra/ R_{CP}
 - Longitudinal and transverse fragment distributions (z and j_T)
- Known to be sensitive to quantitative details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



ATLAS Detector: Calorimeter

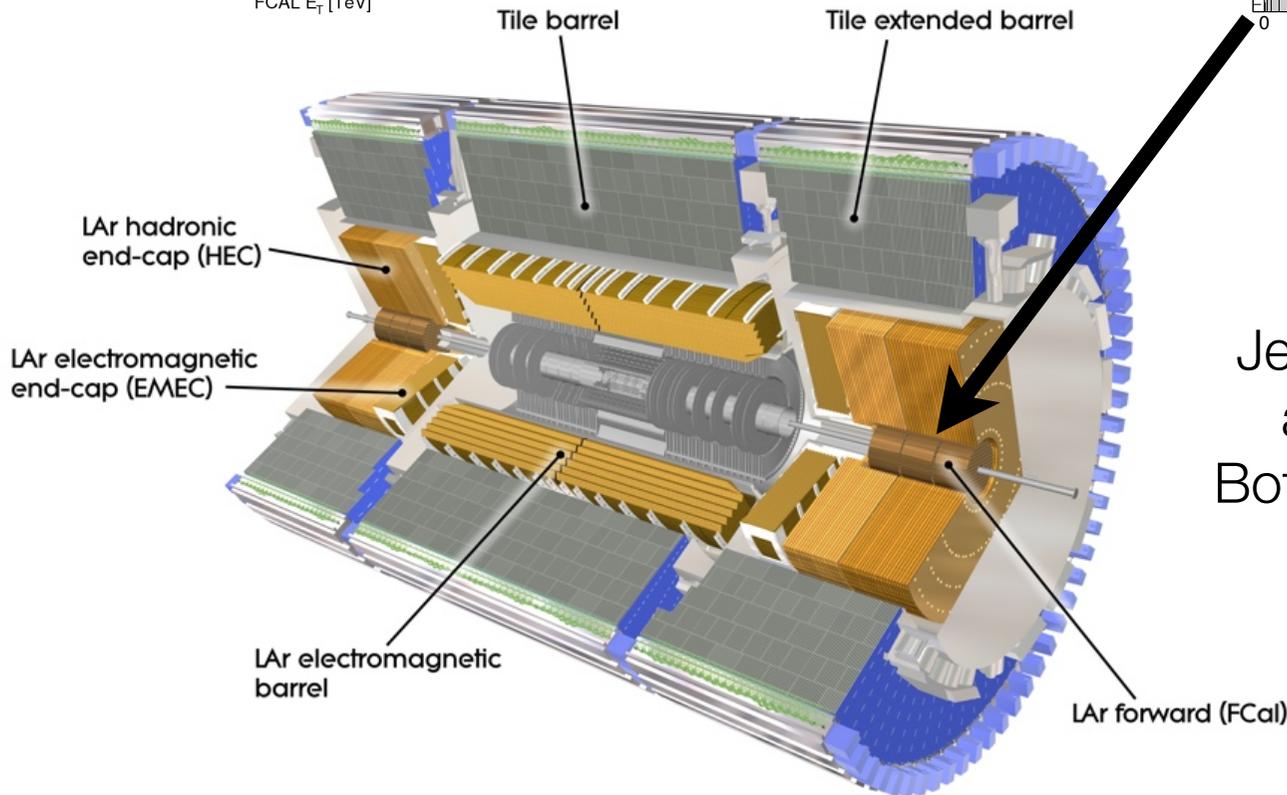


← E_T in barrel strongly correlated with FCal →



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

Jets in barrel used in analysis $|\eta| < 2.8$
Both EM and hadronic calorimetry





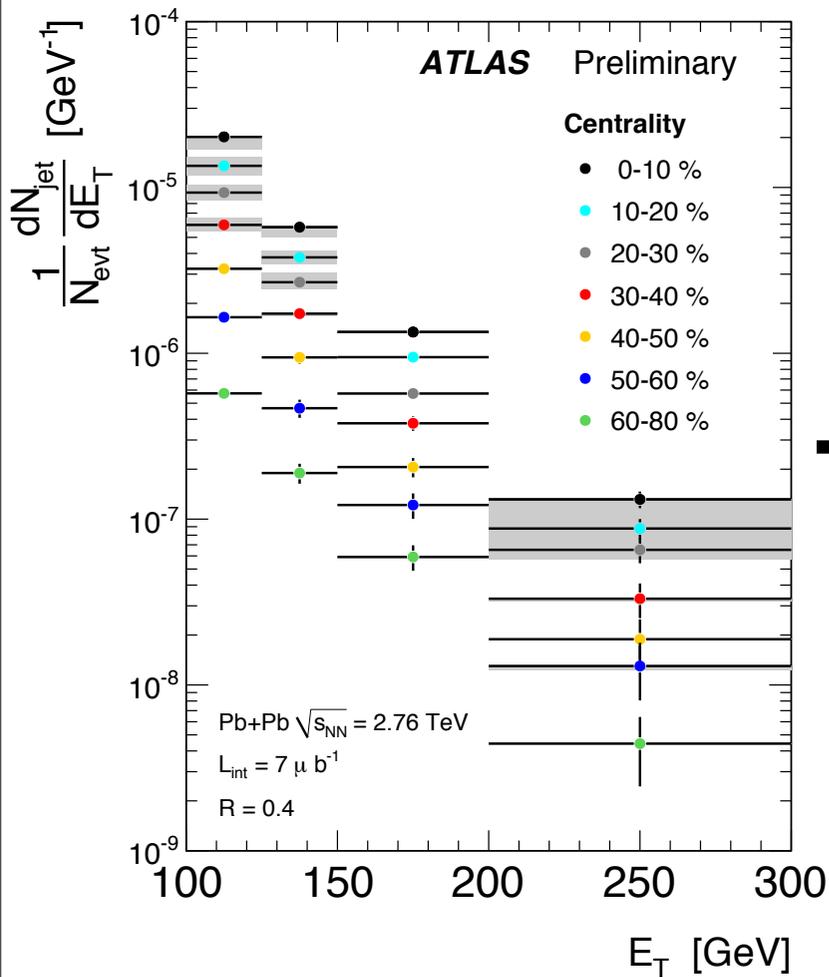
Jet Reconstruction

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

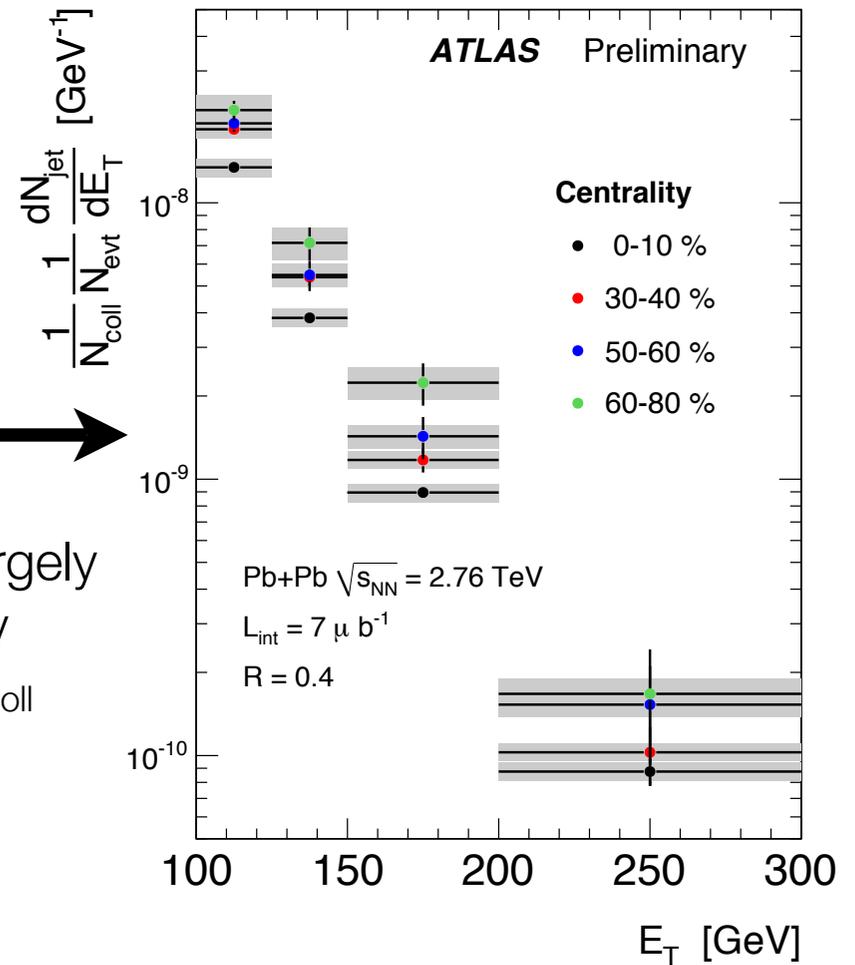
- $R=0.4$ jets
- utilize an iterative procedure to determine background
 - background modulated by elliptic flow before subtraction



Jet Spectra R=0.4



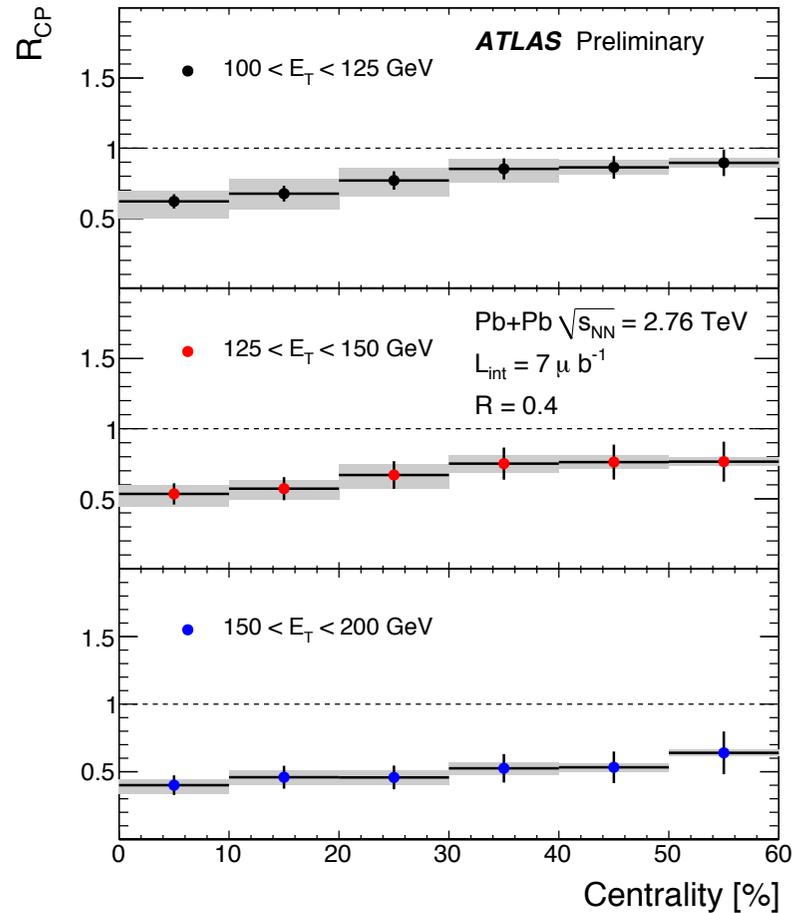
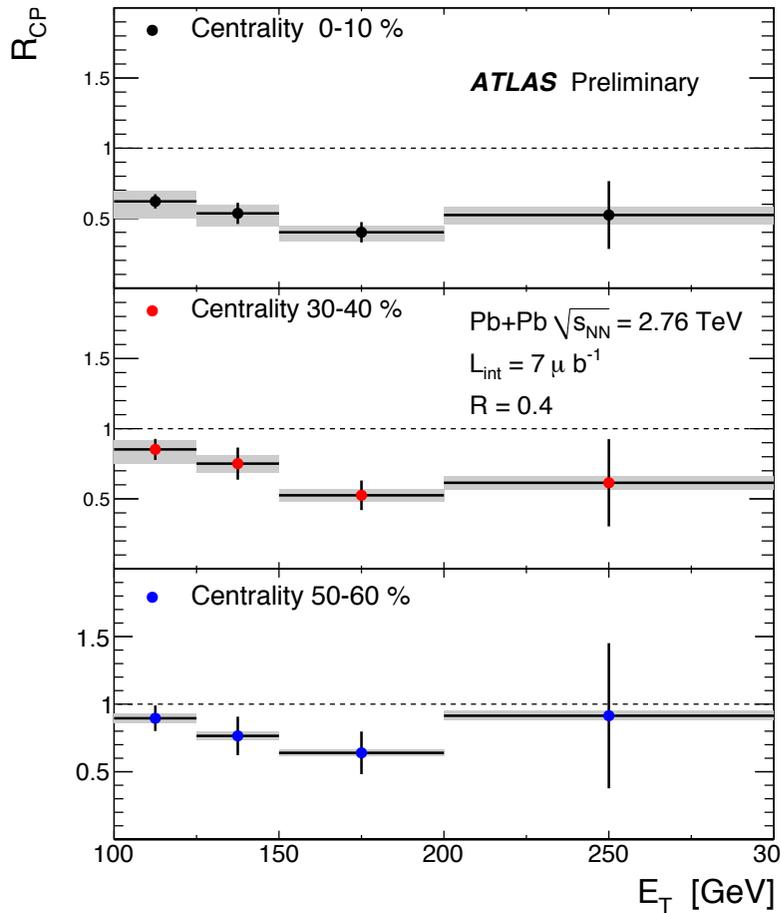
Centrality
dependence largely
removed by
geometry N_{coll}



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



R_{CP} $R=0.4$ Jets

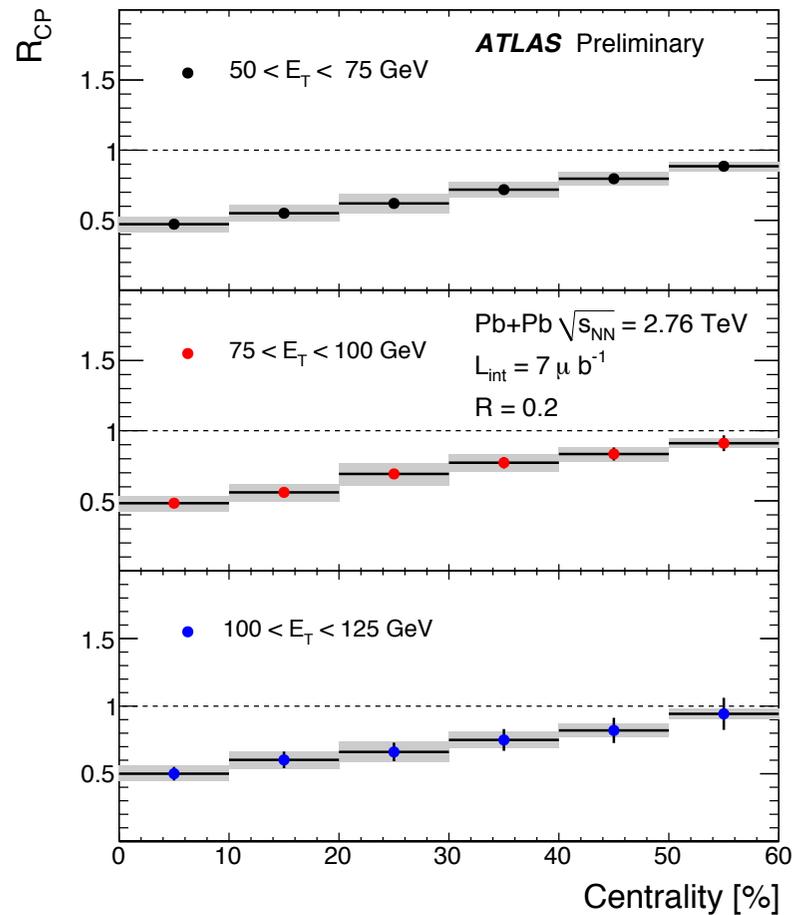
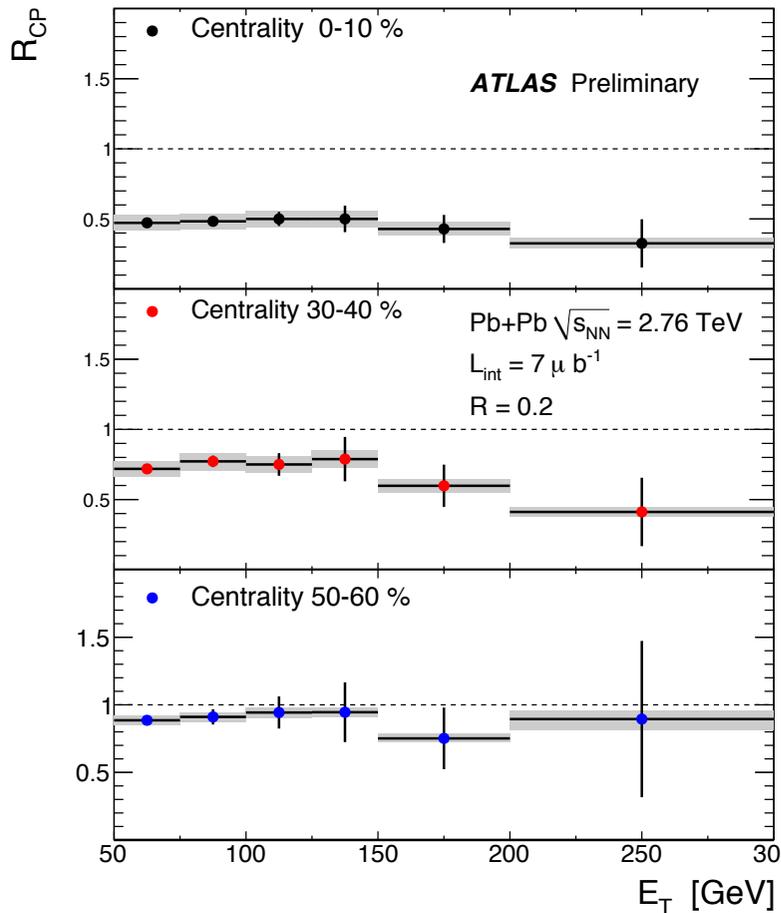


Gradual turn on of medium effects with increasing centrality

Clear **factor of ~2 suppression** indicated in most central collisions
Entire jet, not just leading fragment



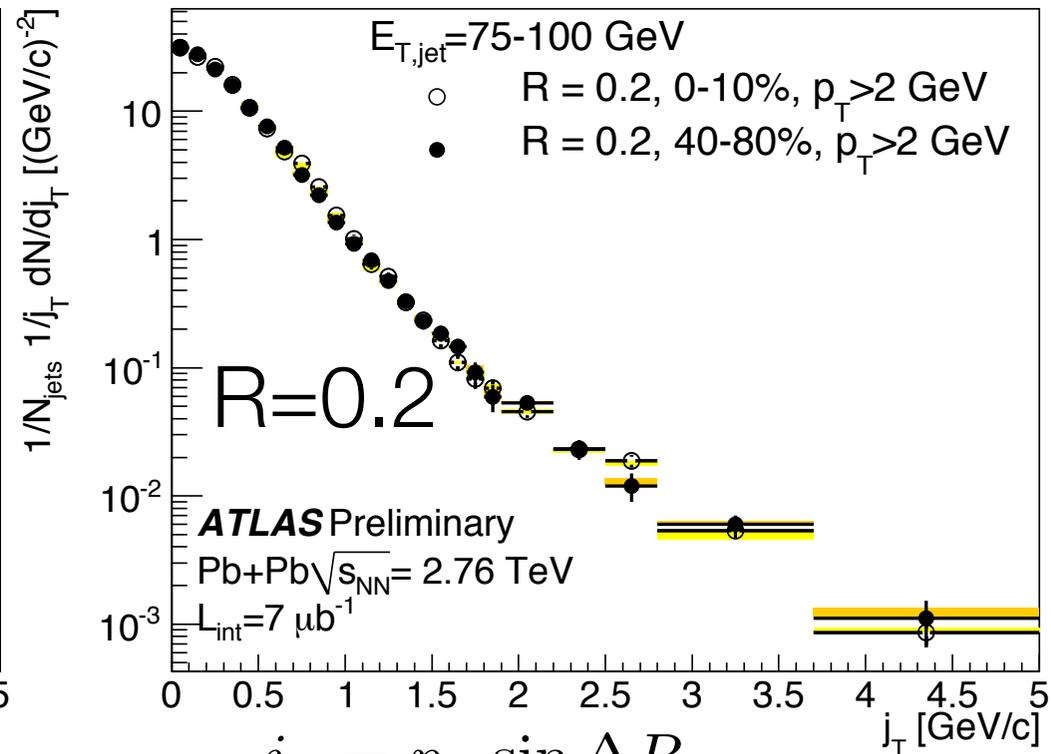
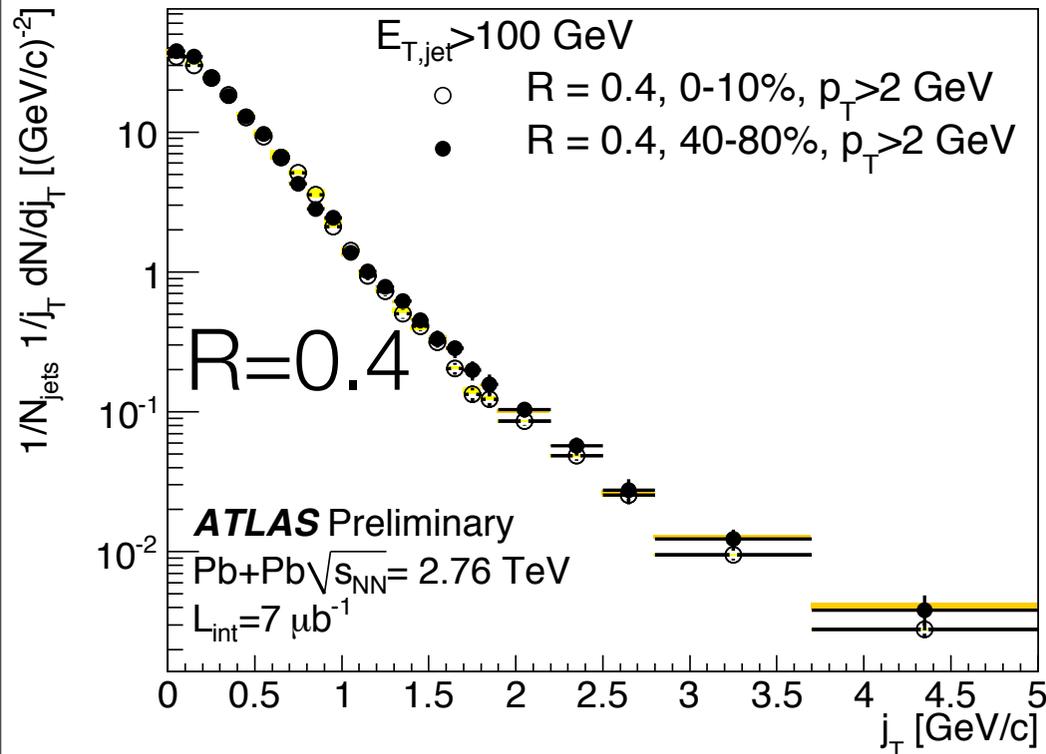
R_{CP} $R=0.2$ Jets



Slightly more suppression observed
Not much energy recovered by larger cone size



Jet Fragments: Transverse Structure



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

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

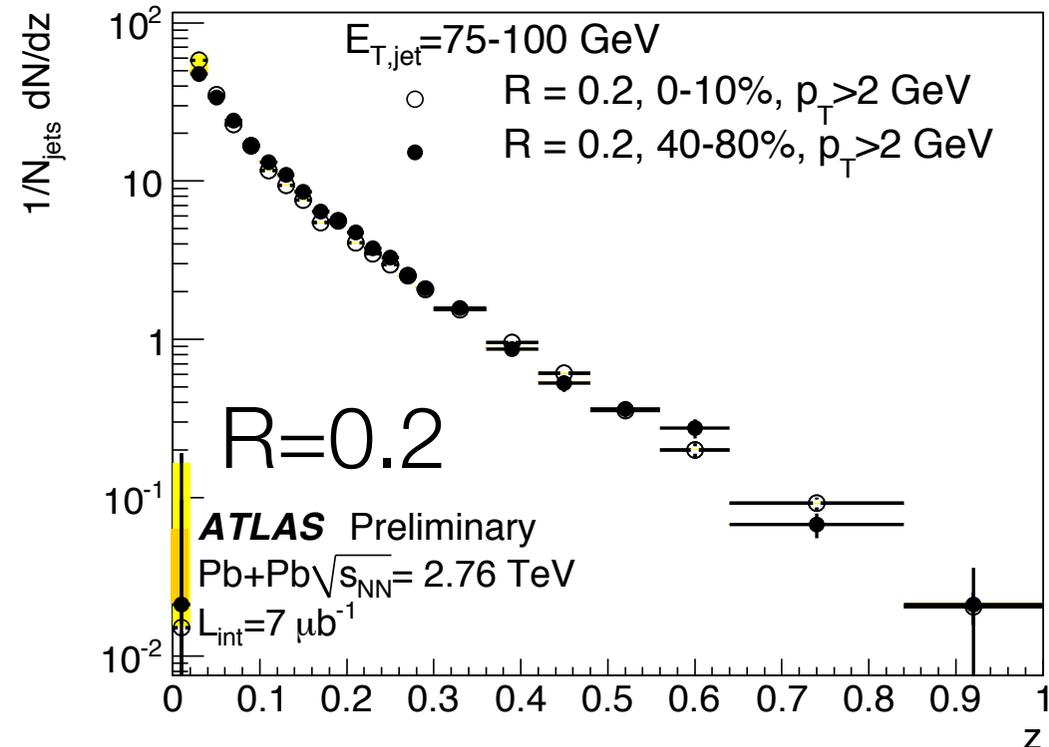
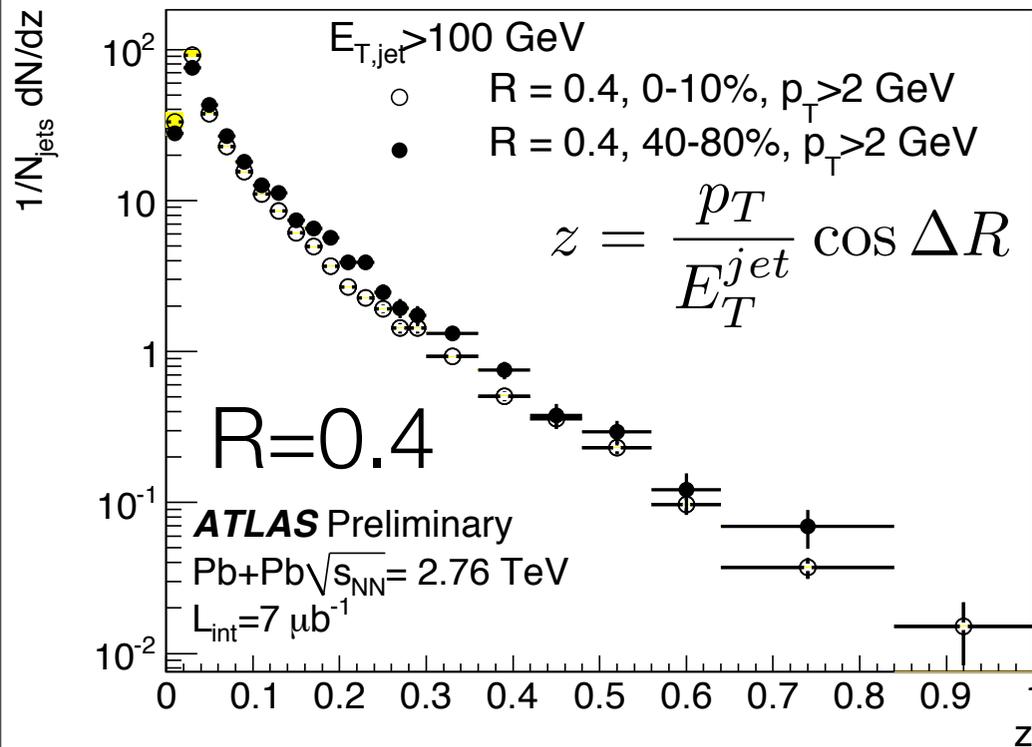
$$\Delta R = \sqrt{(\eta - \eta^{jet})^2 + (\phi - \phi^{jet})^2}$$

Lack of broadening consistent with Rcp 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

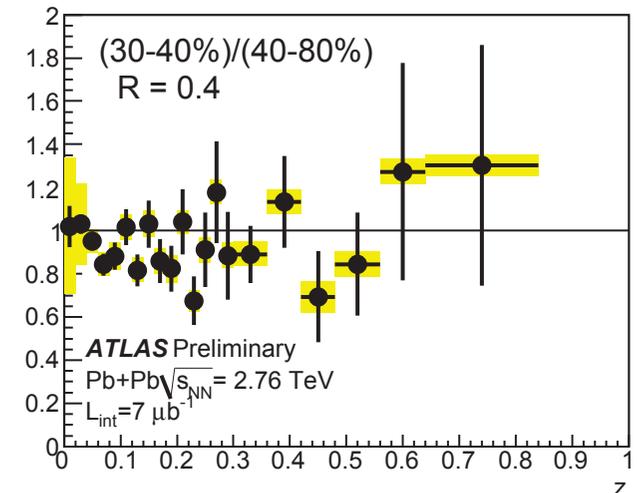
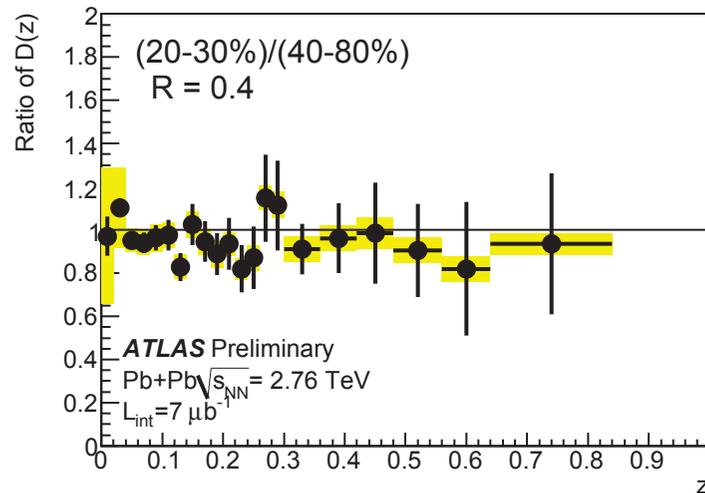
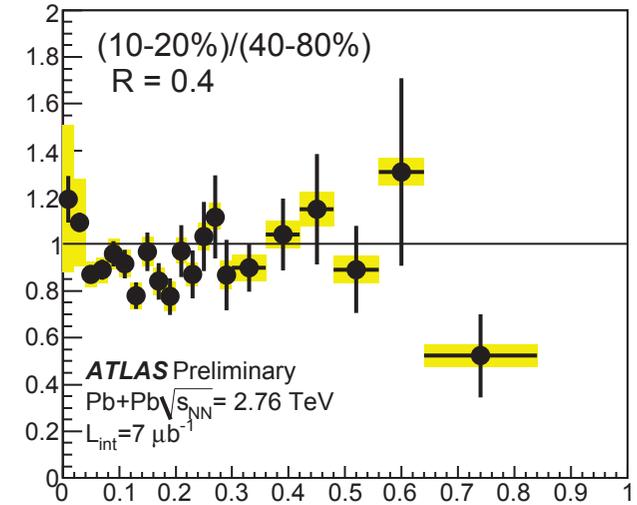
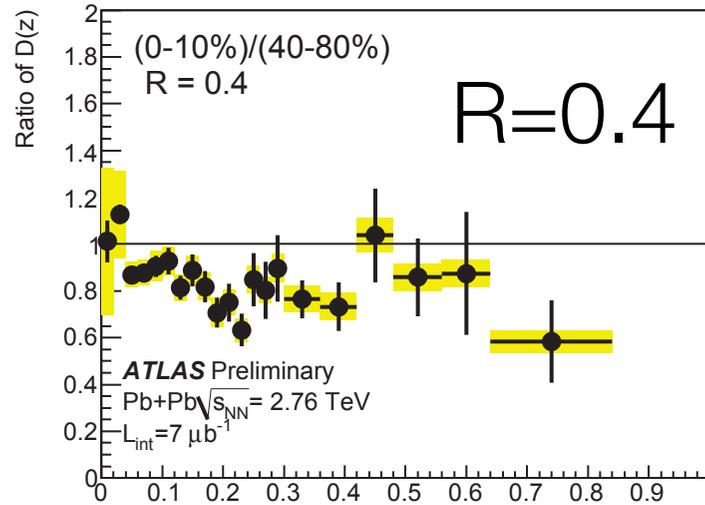
Slight redistribution of jet's energy among fragments seen at mid-low z (0.2)



Jet Fragments: Longitudinal Structure

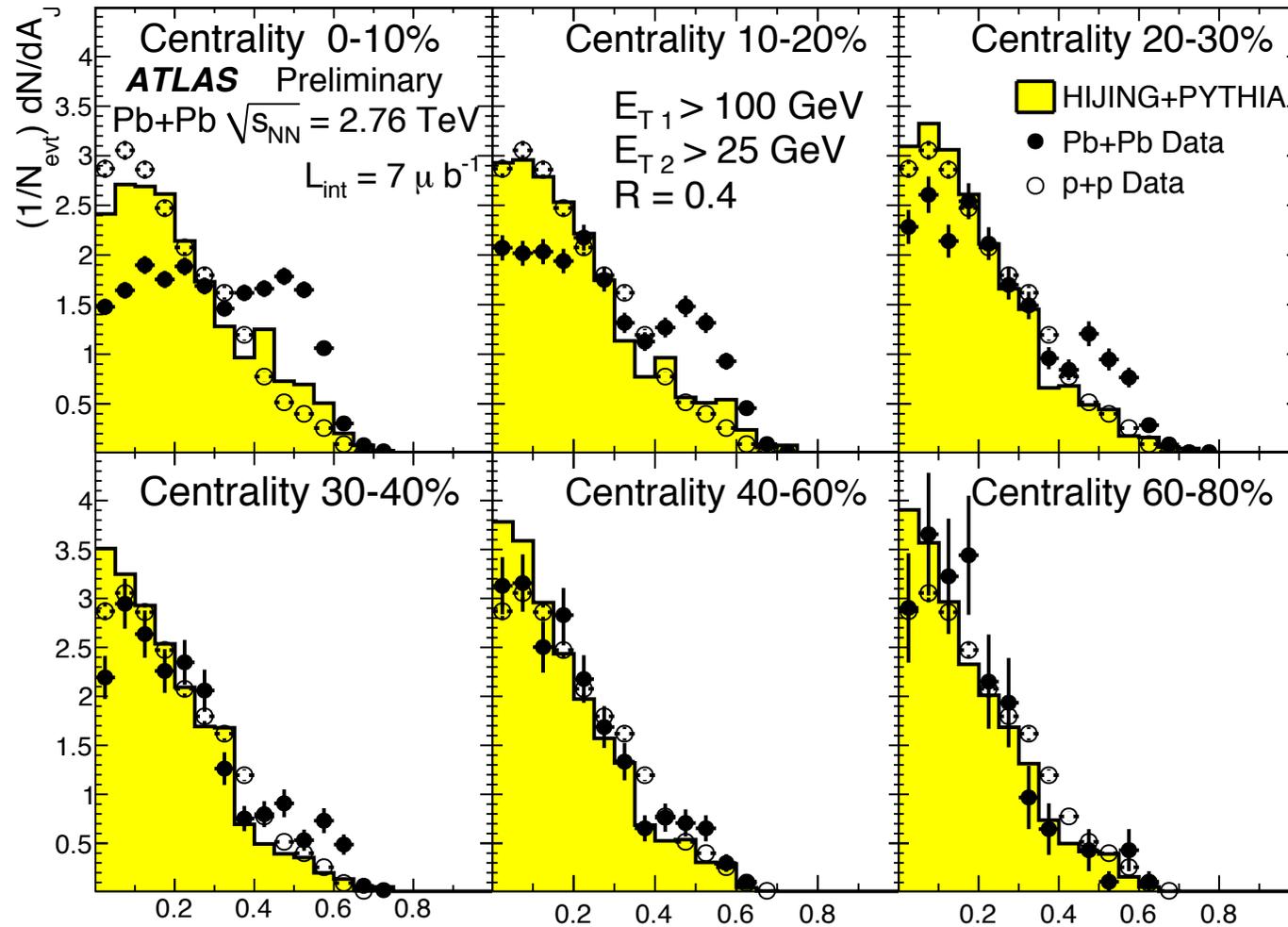
Modest
modification at
mid-low z

But high z
behavior unlike
prediction





Two-Jet Observables: Di-jet Asymmetry



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

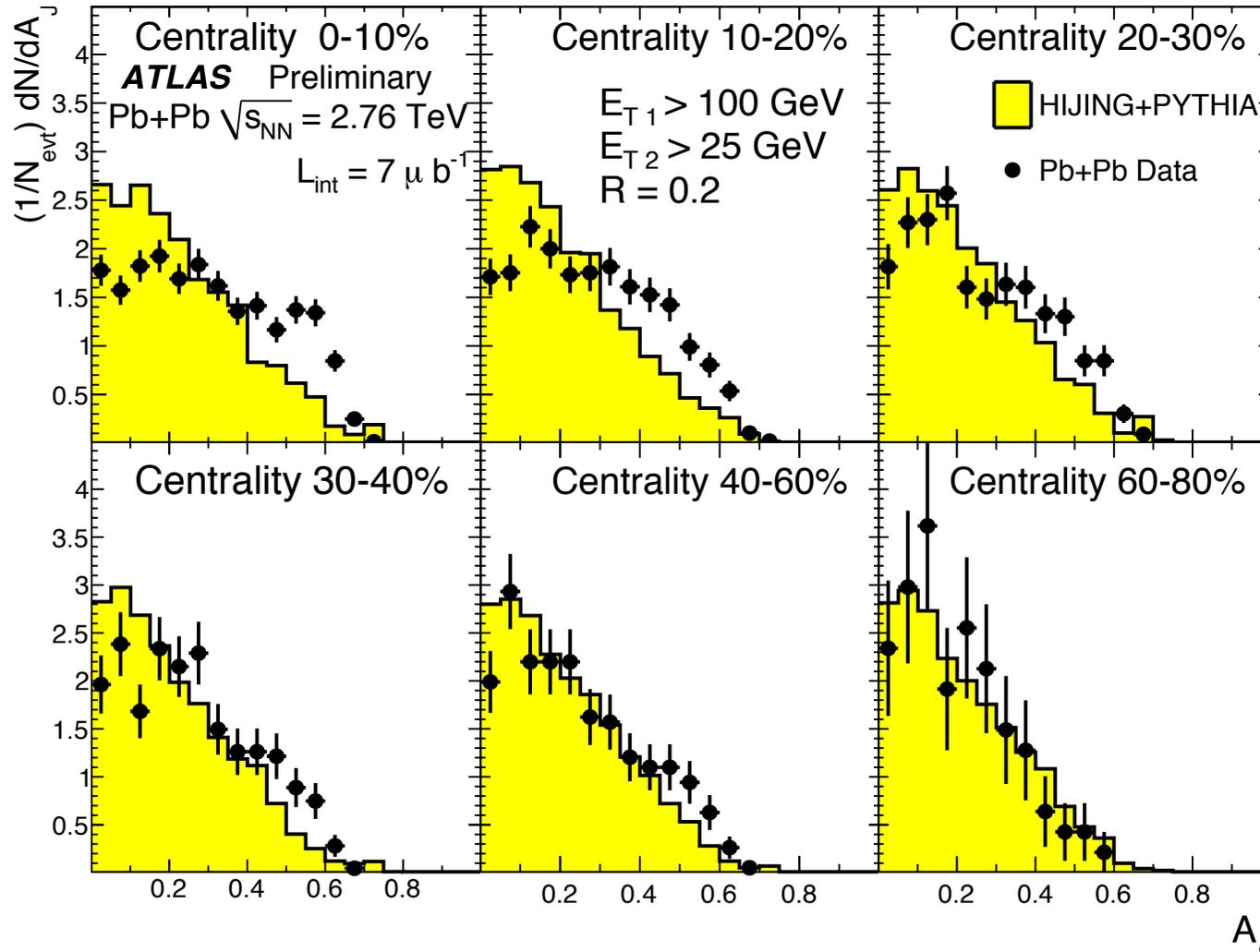
$$E_{T1} > 100 \text{ GeV}$$

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

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



Di-jet Asymmetry: $R=0.2$



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

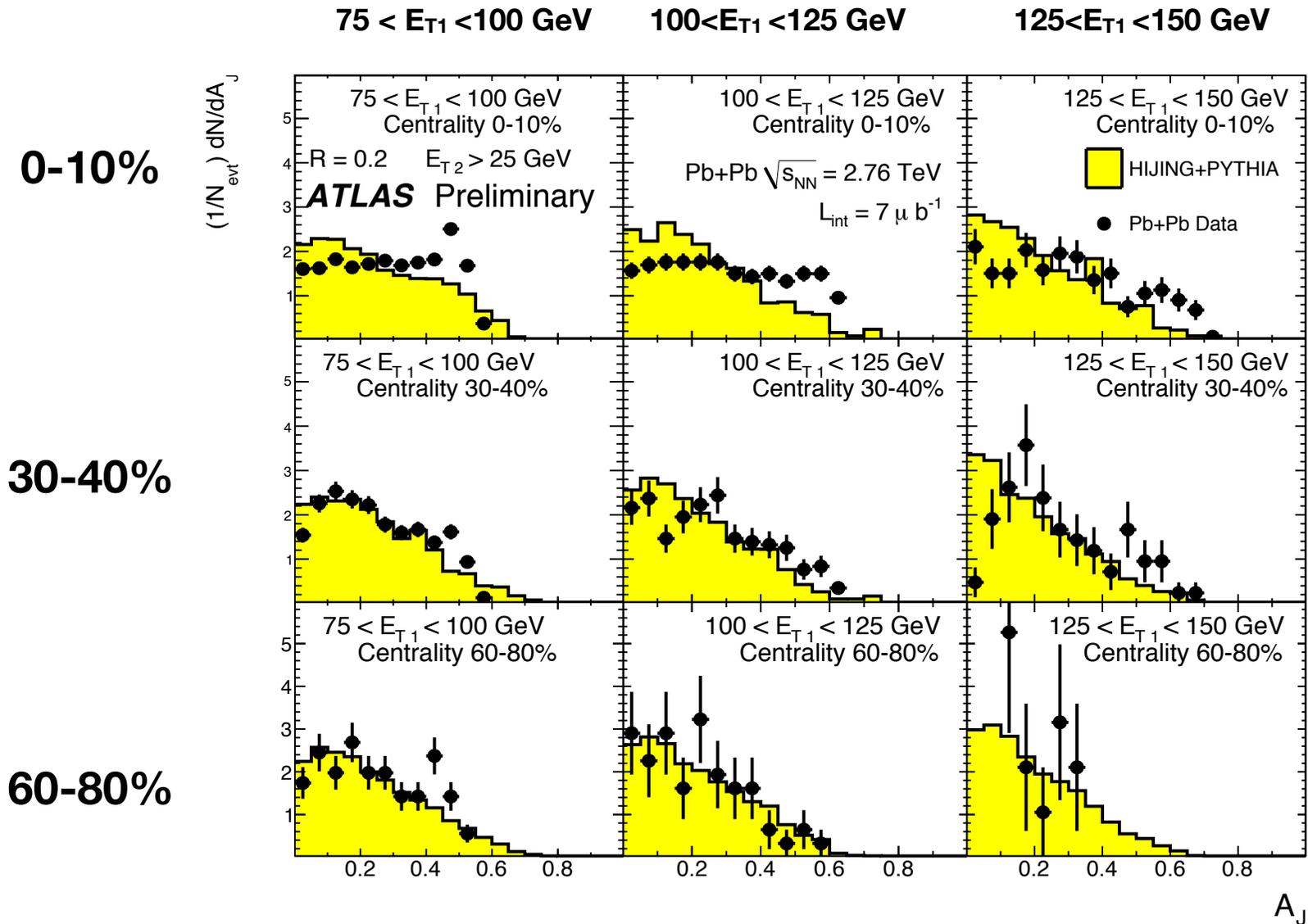
$$E_{T1} > 100 \text{ GeV}$$

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

Distribution flatter, peak smeared out



Asymmetry: Energy Dependence, $R=0.2$



Increasing jet energy stretches peak out

More peripheral restores peaking at low values of A_J



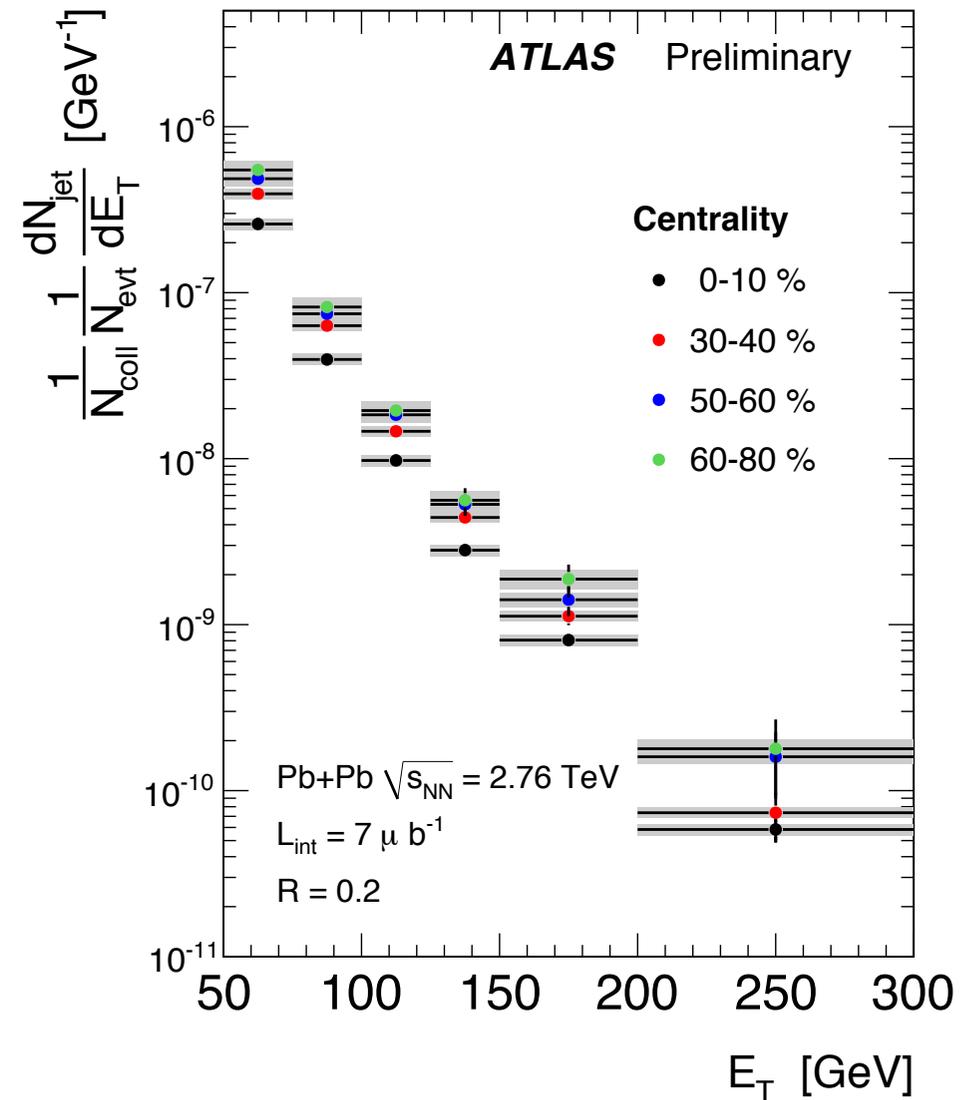
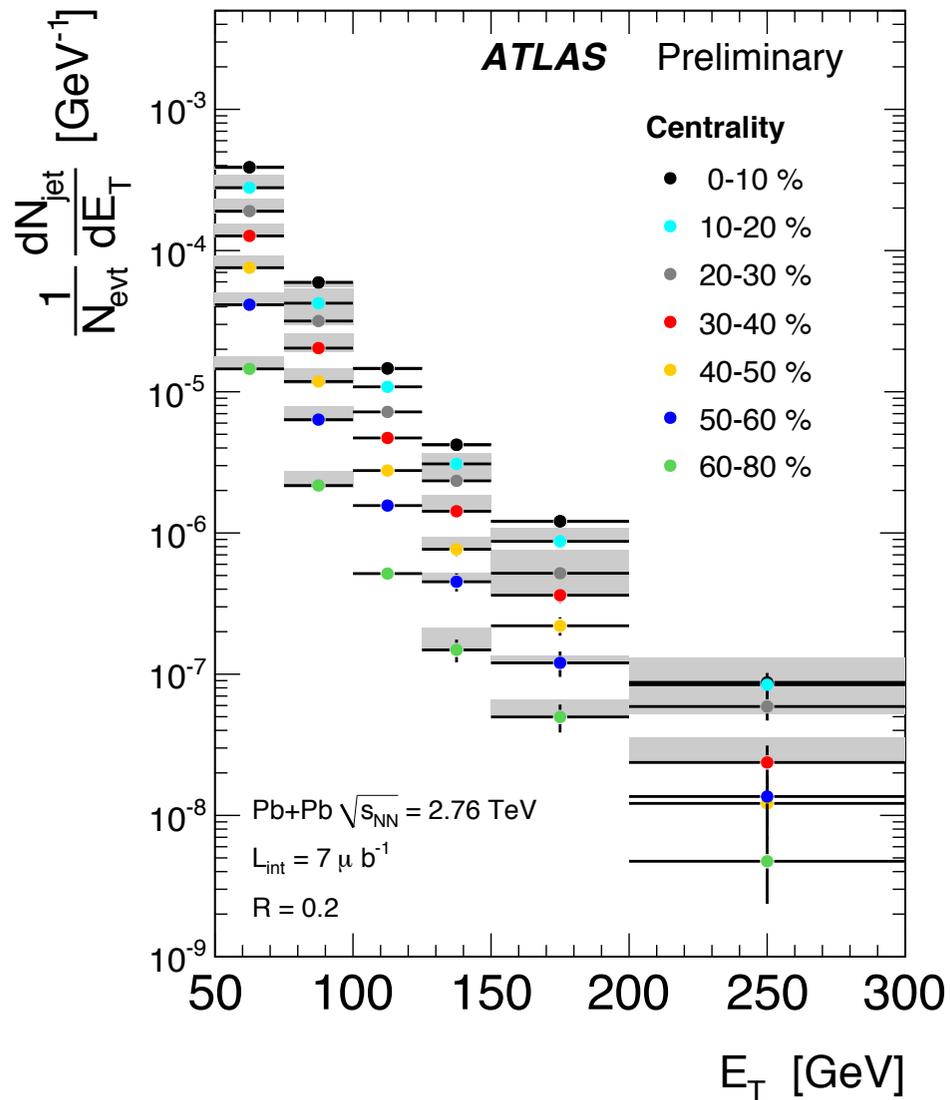
Summary

- 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
- Convincing picture that energy loss is not radiation-dominated and mechanism involves complicated interplay with collisional effects

Supporting Slides

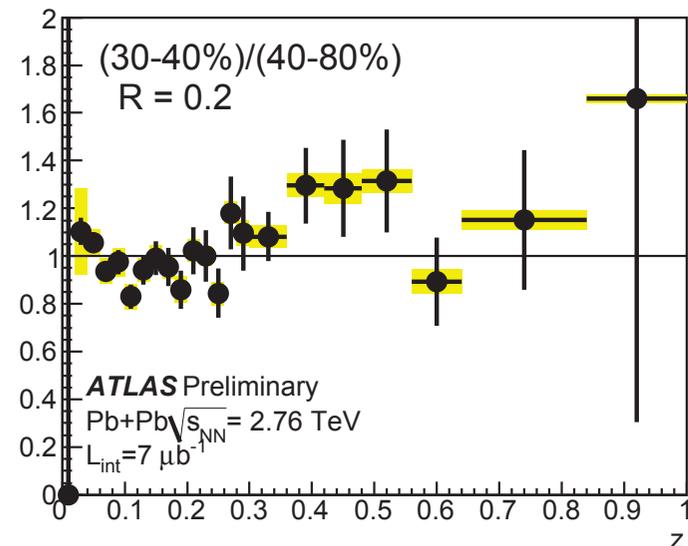
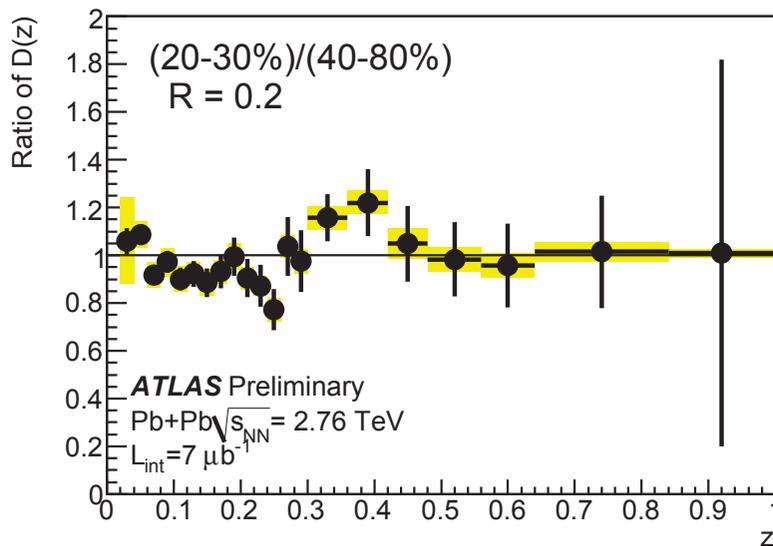
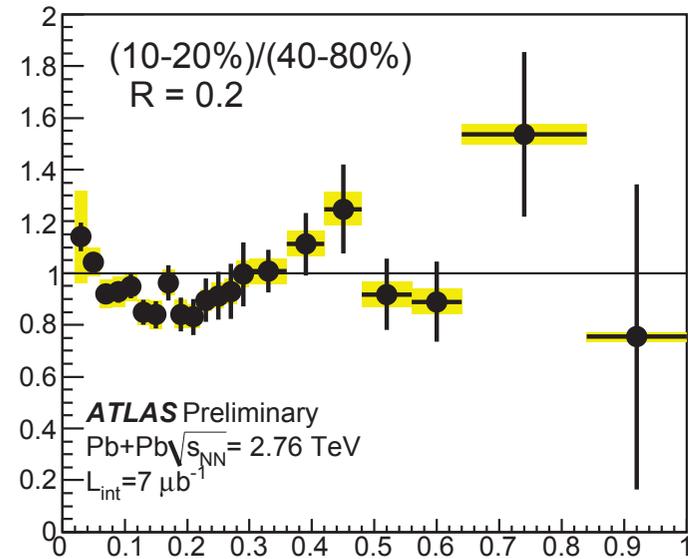
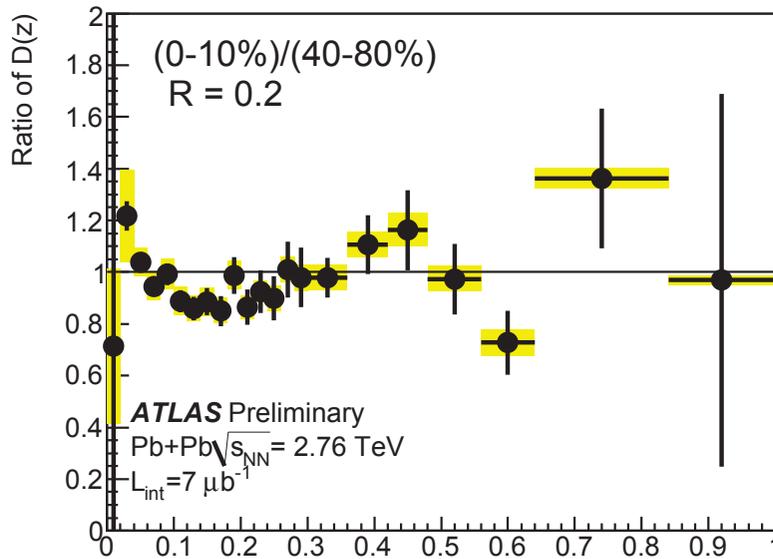


Jet Spectra R=0.2





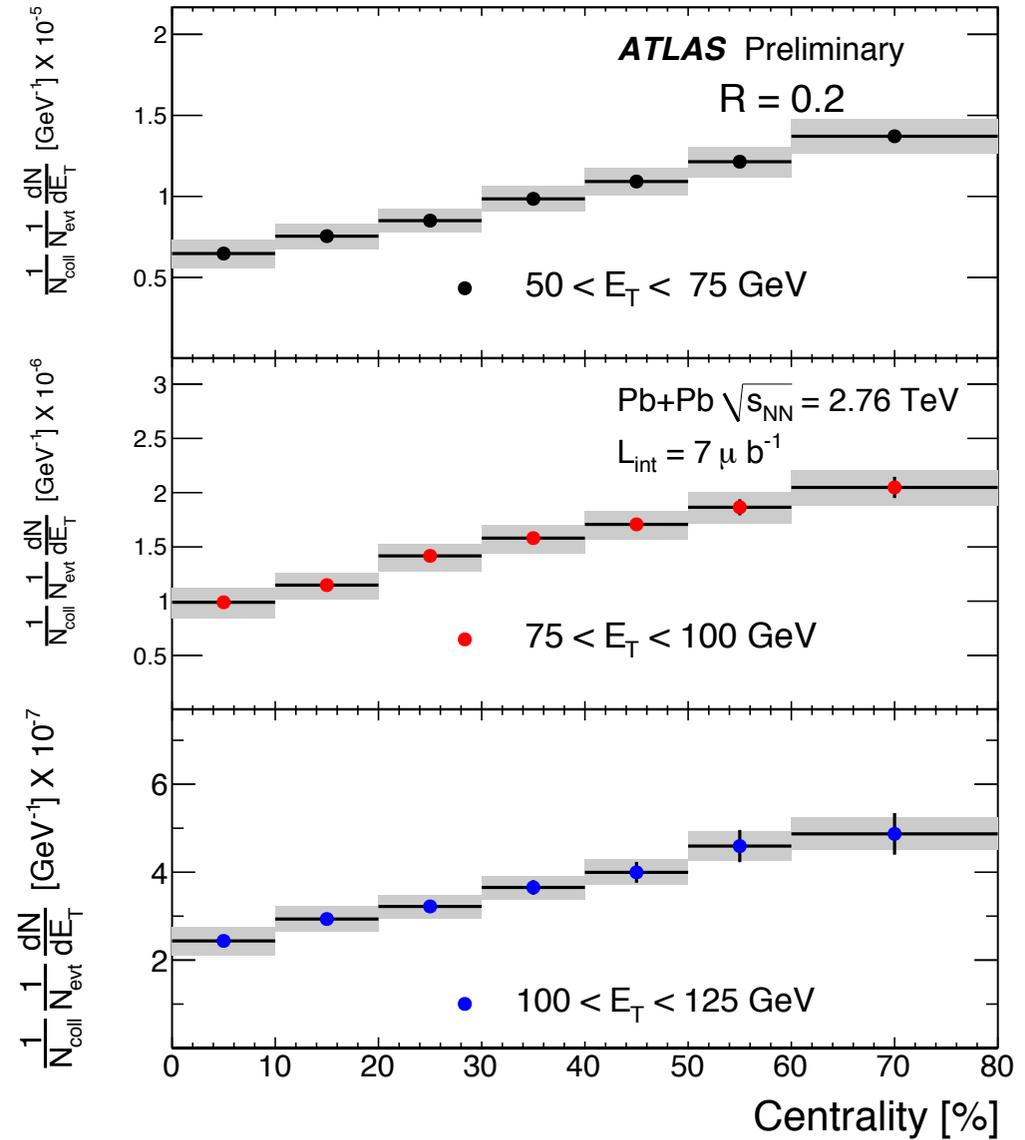
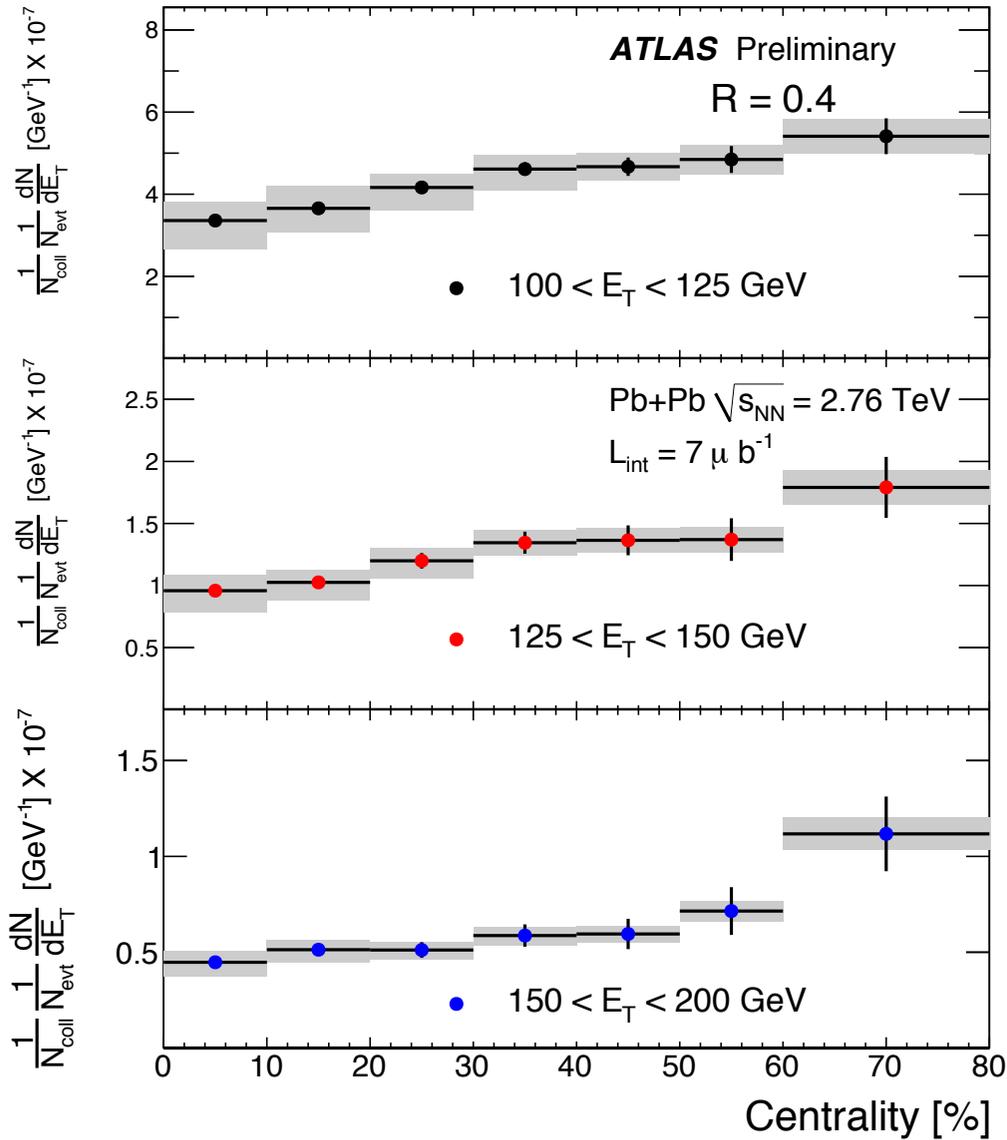
Jet Fragments: Longitudinal Structure



$R=0.2$

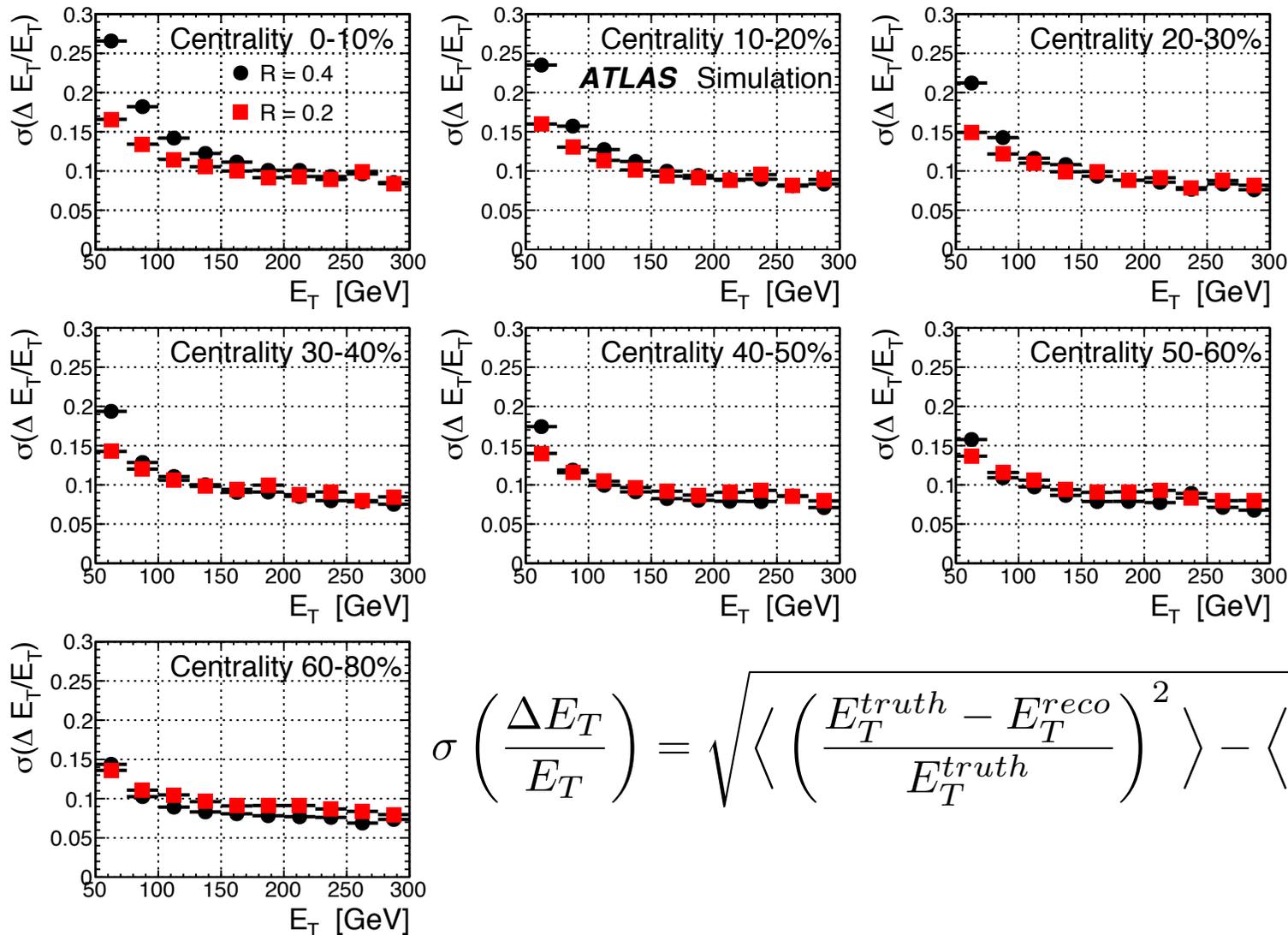


Yields vs Centrality





Jet Performance: Resolution from MC



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



ATLAS Detector: Inner Detector

Jets in heavy ion collisions

