Jet Probes of $\sqrt{s_{NN}}$ = 2.76 TeV Pb+Pb Collisions with the ATLAS Detector

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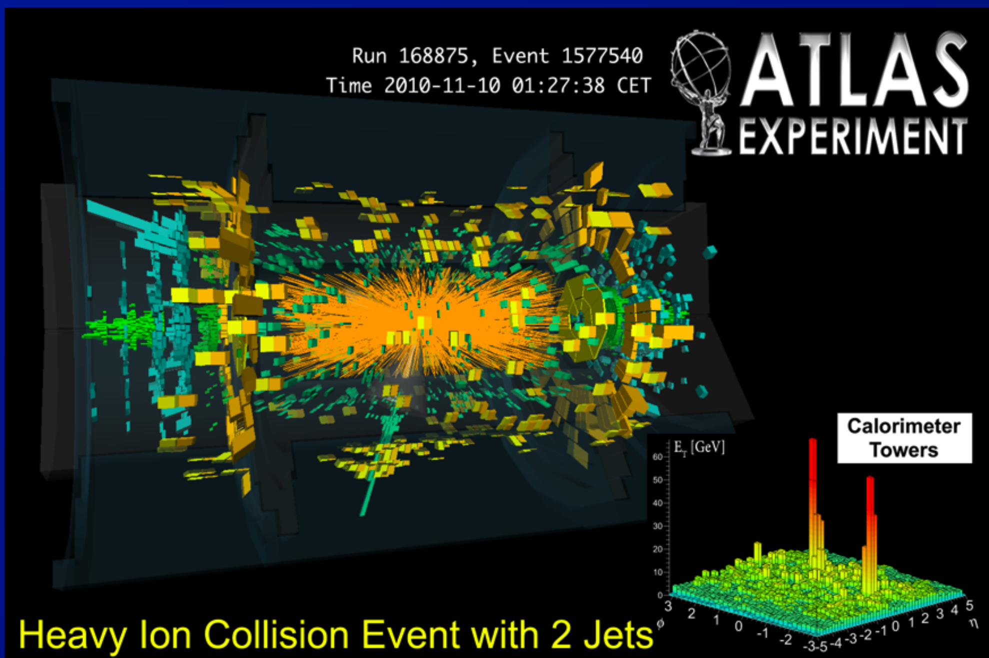
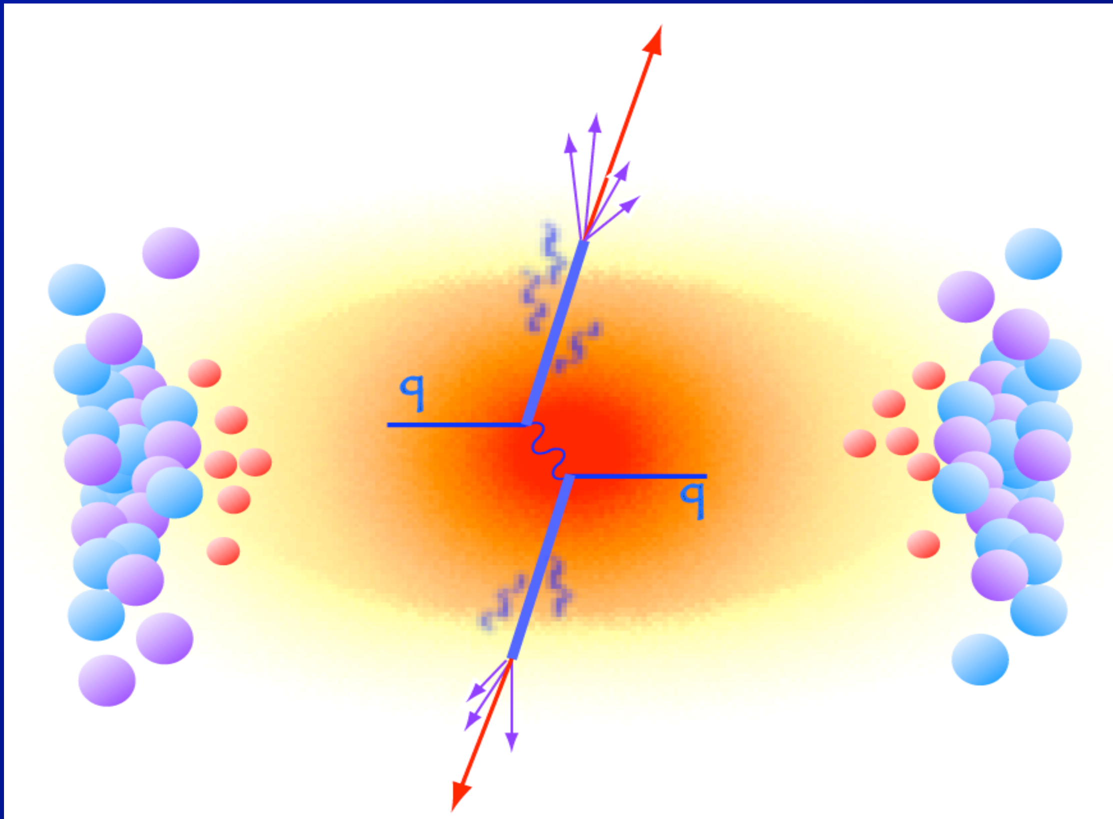
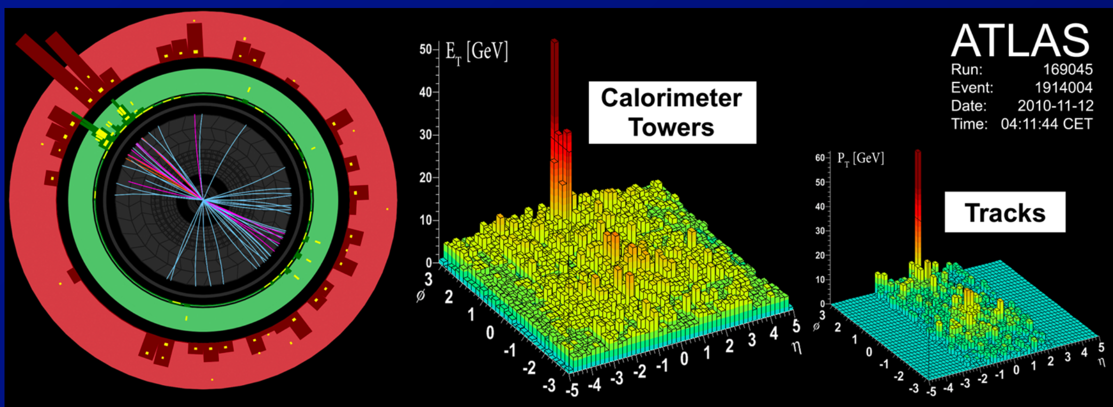
Columbia University
on behalf of the ATLAS Collaboration



Quark Matter Annecy 2011

Jet Quenching



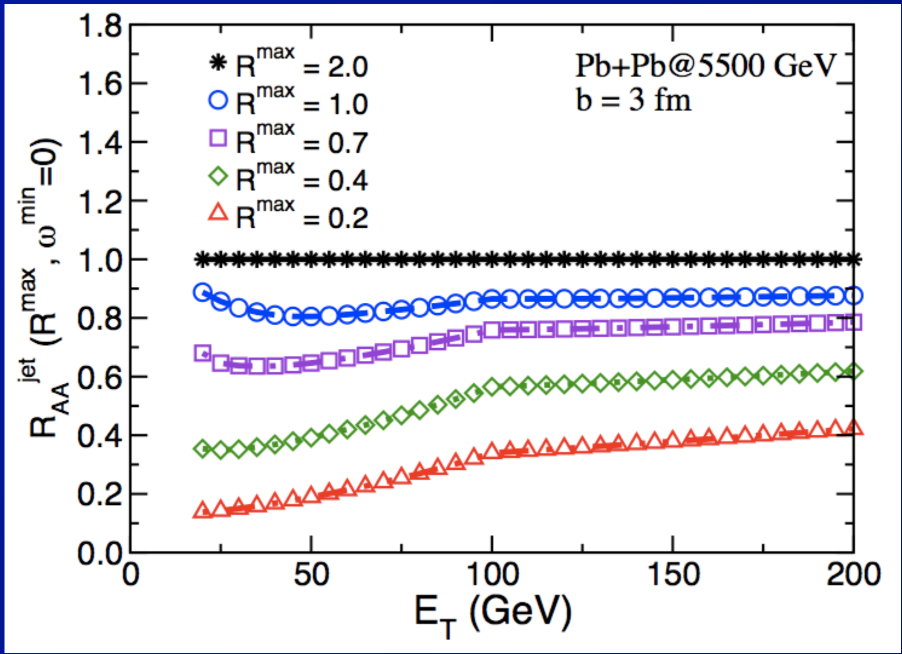


- **Key question:**
  - How do parton showers in hot medium (quark gluon plasma) differ from those in vacuum?
- **1st ATLAS result:**
  - Insight on differential quenching

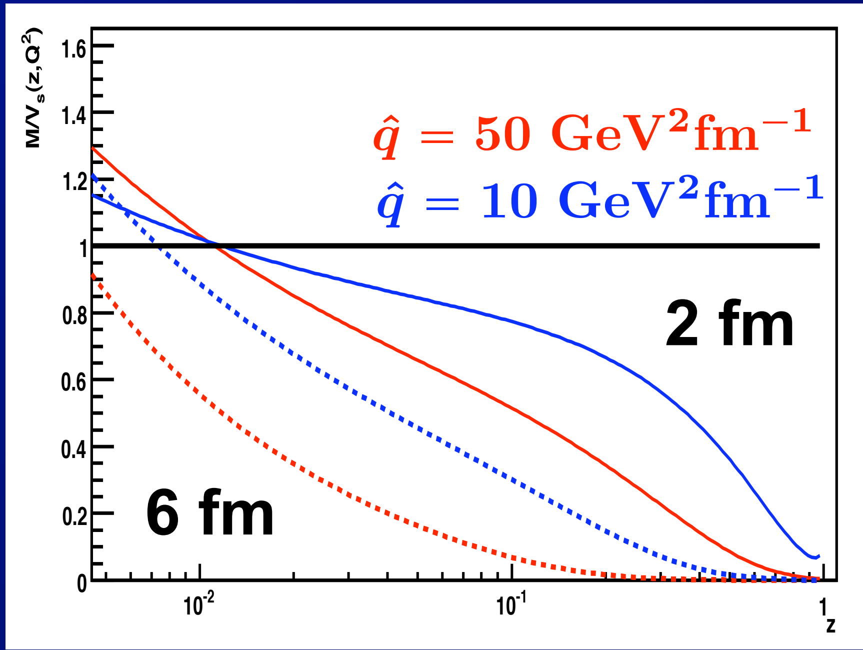
⇒ Next: probe “inclusive” quenching

Jet Quenching: Inclusive Observables

Vitev, Wicks, Zhang, JHEP 0811 (2008) 093

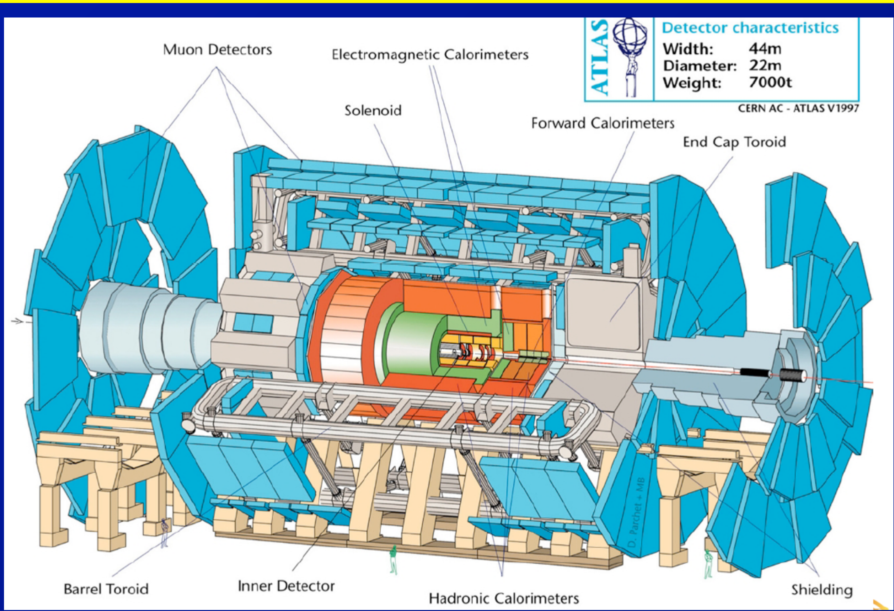


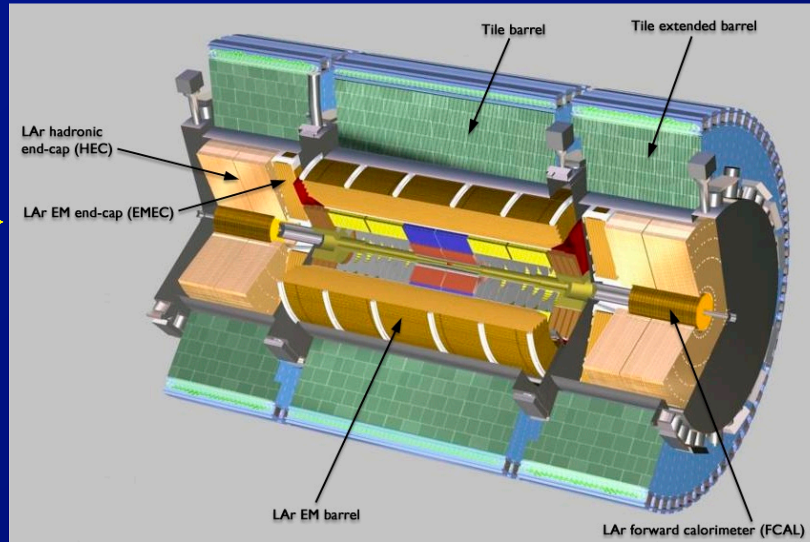
Armesto, Salgado, *et al*, JHEP 0802 (2008) 048

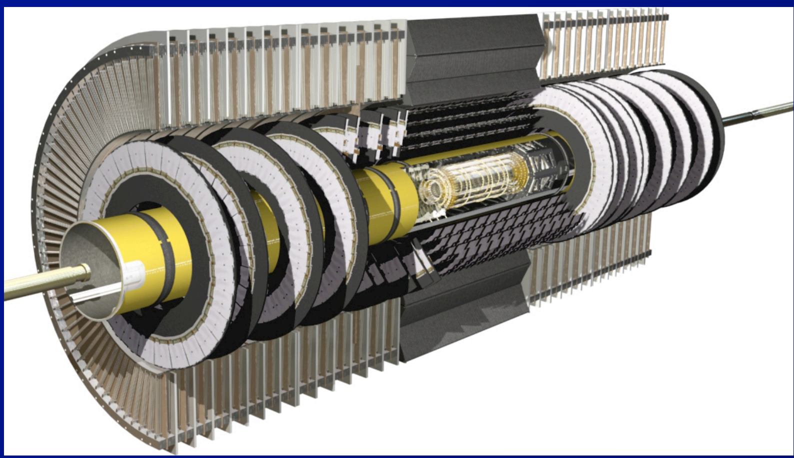


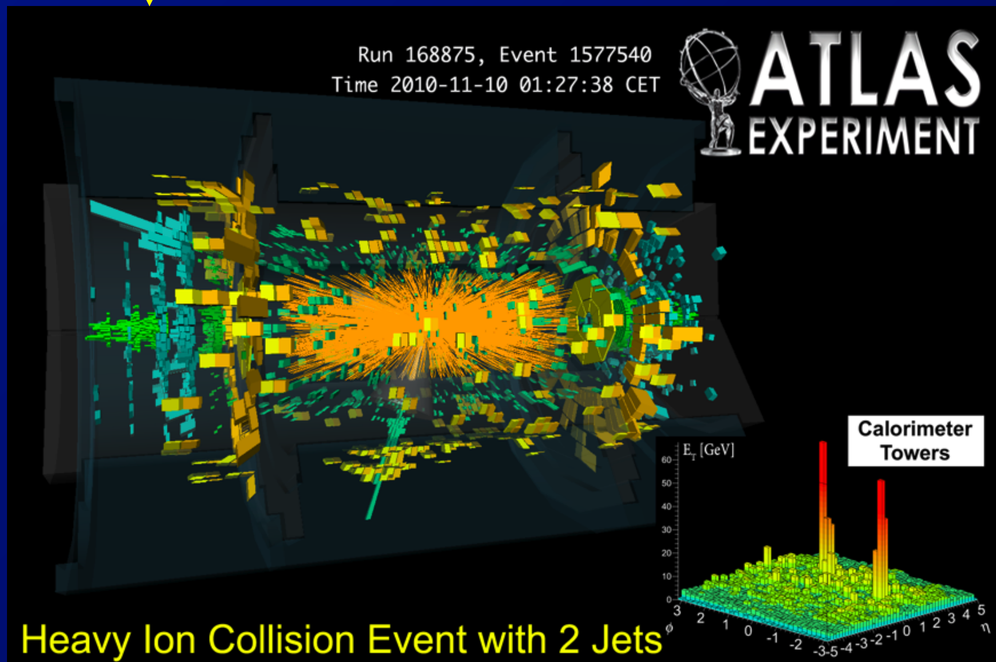
- **Key questions:**
  - ⇒ (How much) Is the jet yield suppressed?
  - ⇒ How does suppression depend on jet radius?
  - ⇒ Is the fragmentation function D(z) modified?
  - ⇒ Is the hadron angular distribution broadened?

Pb+Pb Measurements in ATLAS

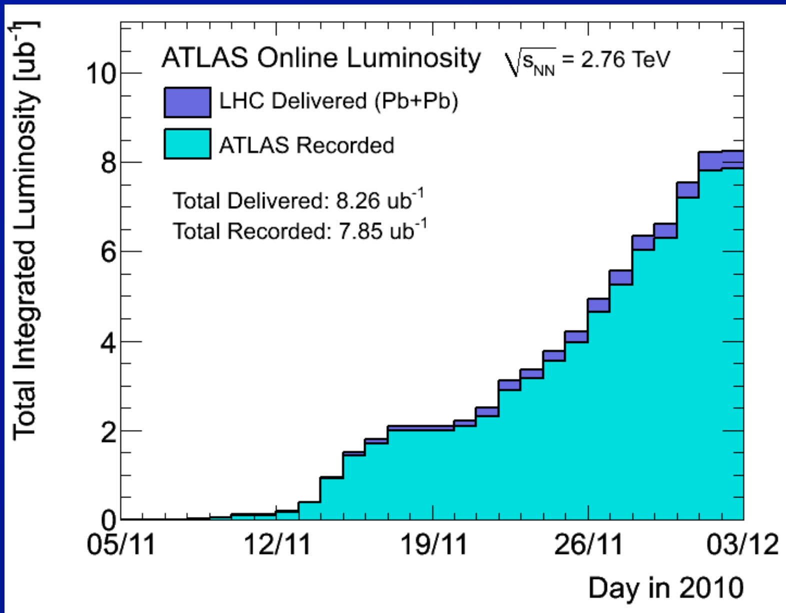








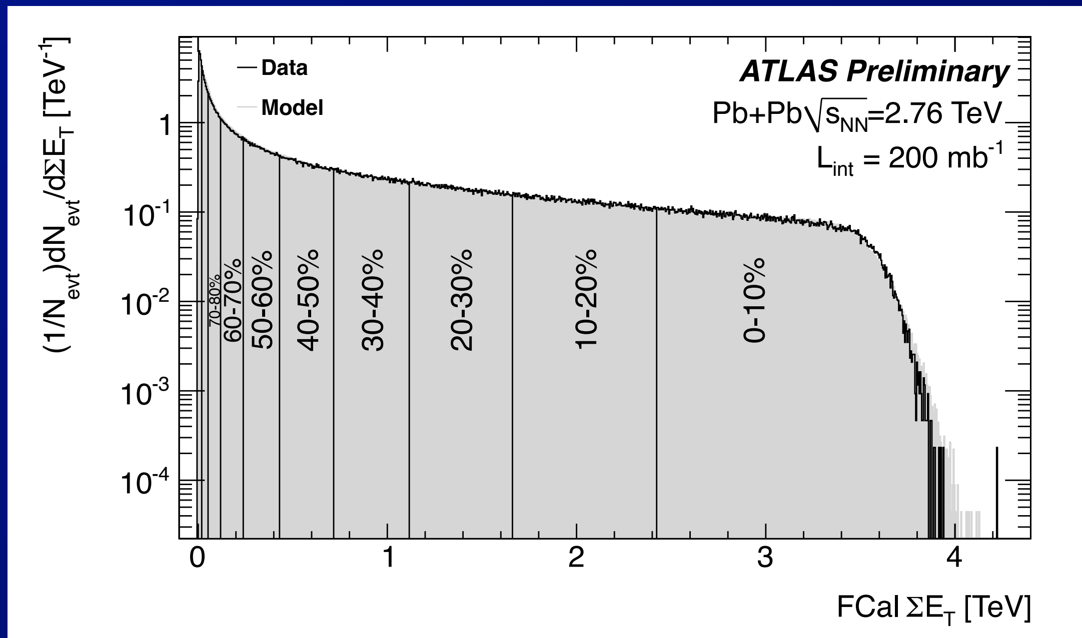
ATLAS: Fall 2010 Pb+Pb Data set



For QM 2011 analyses

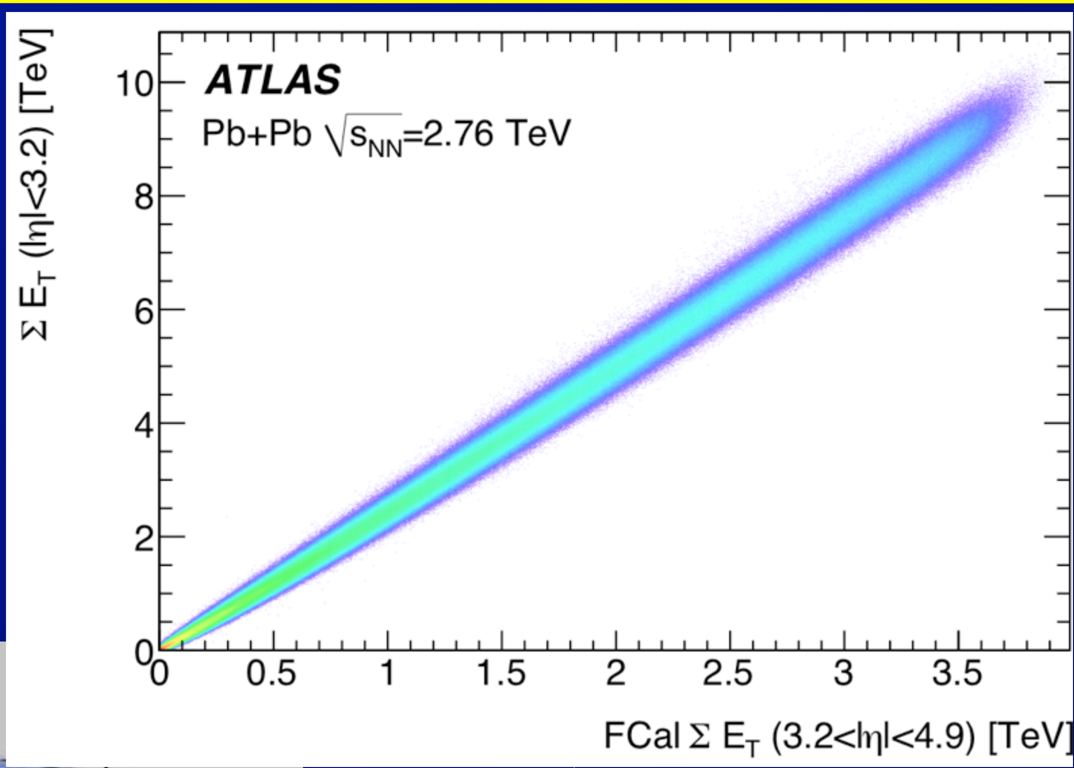
- Using solenoid on, good runs: 47 million events

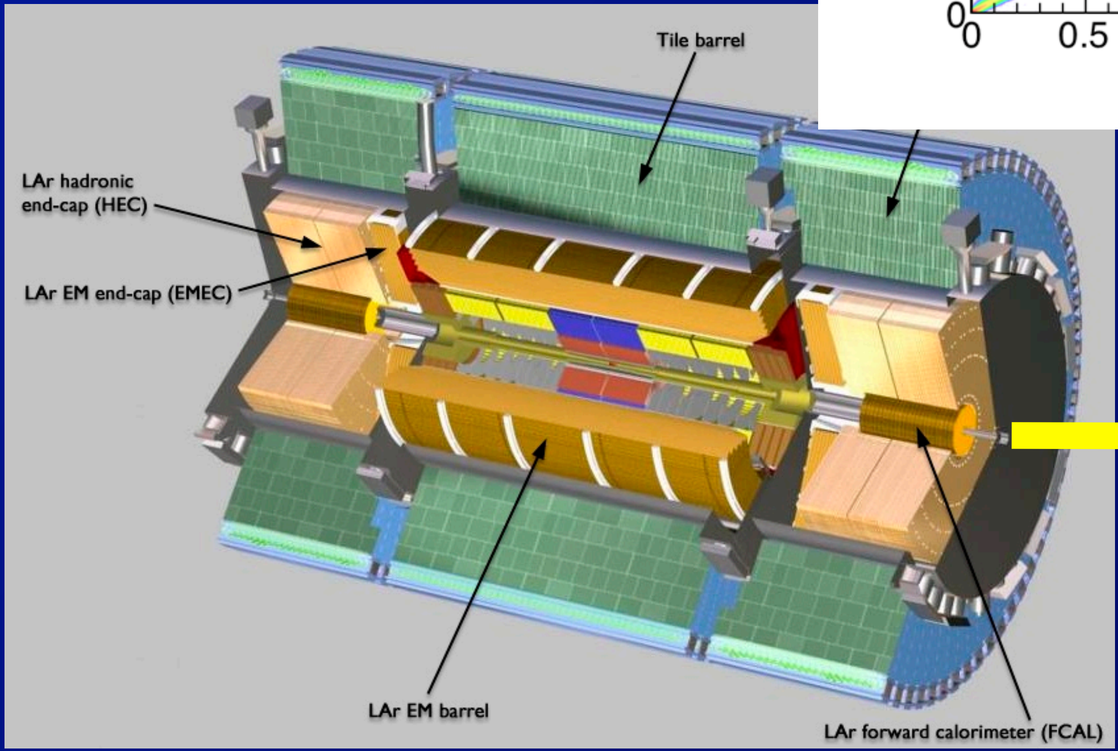
- Centrality measured by FCal ΣE_T
- N_{coll} from Glauber Monte Carlo analysis



Centrality bin	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%
$N_{coll}^{cent}/N_{coll}^{60-80\%}$	56.7	34.9	21.1	12.2	6.5	3.2
Relative error (%)	11.4	10.5	11.3	7.9	6.1	3.8

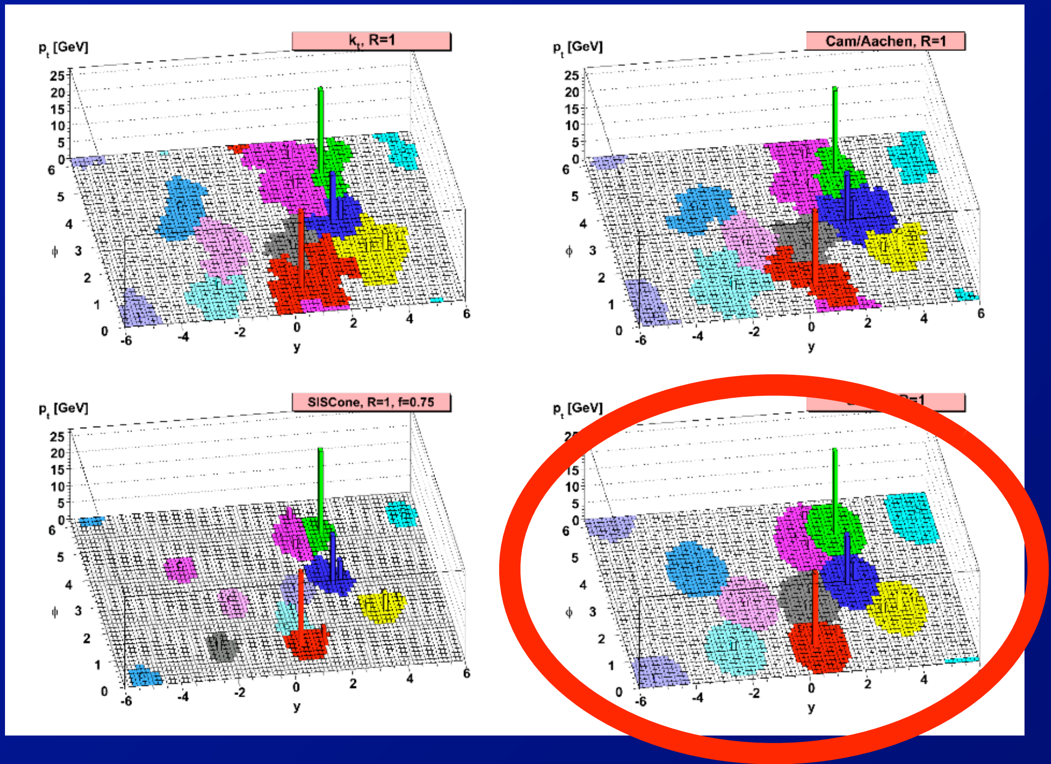
Calorimetry over Δη = 9.8





Jet reconstruction (1)

Cacciari, M., Salam, G. P. and Soyez, G., *The anti-kt jet clustering algorithm*, Journal of High Energy Physics, 2008, 063



Use anti-k_t clustering algorithm

cone-like but infrared and collinear safe

- Perform anti-k_t reconstruction prior to any background subtraction
  - R = 0.4 and R = 0.2
  - Input: $\Delta\eta \times \Delta\varphi$ = 0.1 x 0.1 towers

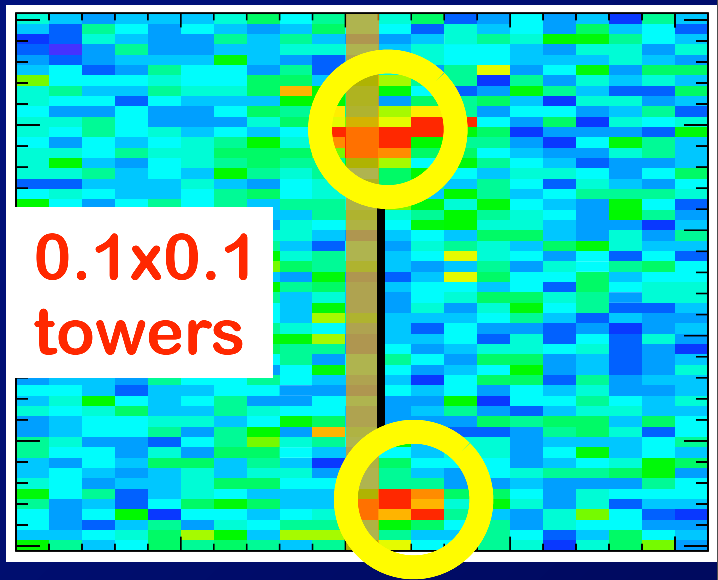
Jet reconstruction (2)

- Take maximum advantage of ATLAS segmentation
  - Underlying event estimated and subtracted for each longitudinal layer and for 100 slices of $\Delta\eta = 0.1$

    $$\Rightarrow \quad E_T{}^{cell}_{sub} = E_T^{cell} - \rho^{layer}(\eta) \times A^{cell}$$

  - ρ is energy density estimated event-by-event

    ⇒ From average over $0 < \varphi < 2\pi$



- Avoid biasing ρ due to jets
  - Two methods:

    ⇒ Sliding window exclusion

    ⇒ Exclude cells in jets satisfying

    $$D = E_T{}^{tower}_{max} / \langle E_T^{tower} \rangle > 5$$

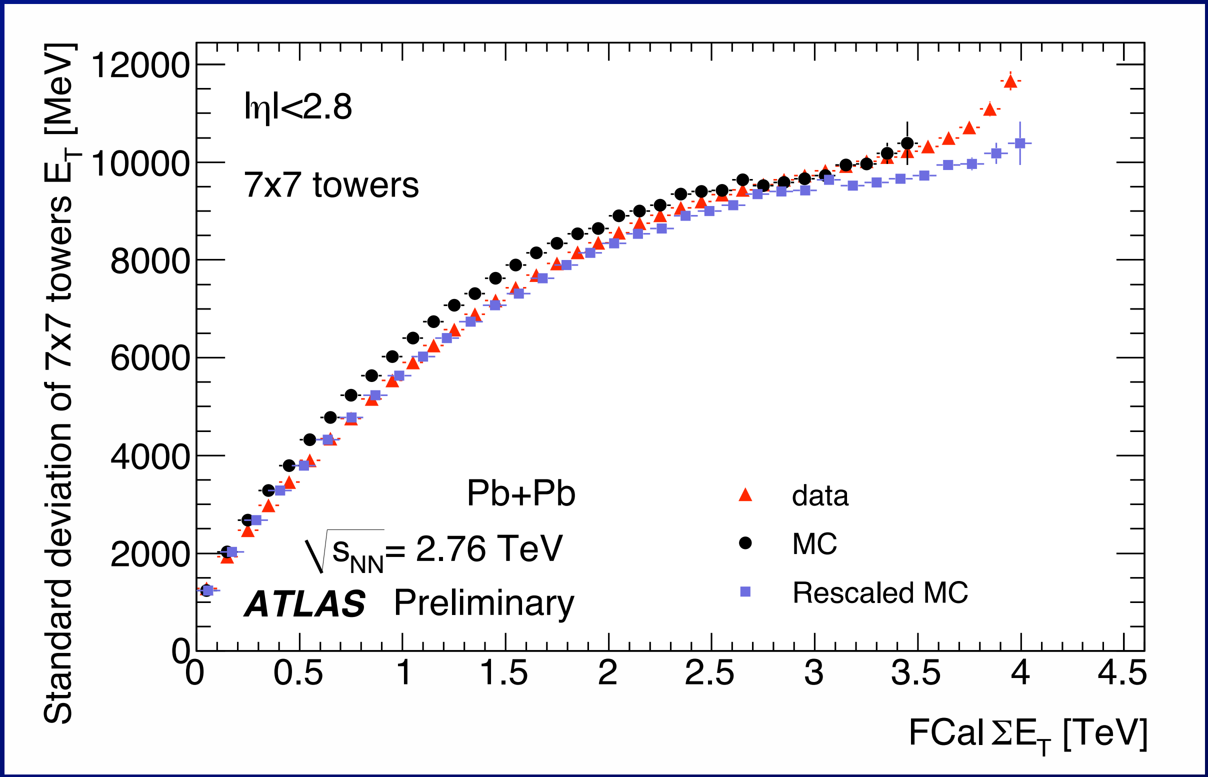
  - For R = 0.4, add an iteration step to ensure jets with $E_T >$ 50 GeV are always excluded from ρ
  - Correct for underlying event v_2

Monte Carlo

- **Monte Carlo: GEANT PYTHIA + GEANT HIJING**
  - ⇒ Bin-by-bin unfolding corrections to jet spectra for detector ⊕ underlying event ⊕ analysis
  - ⇒ Asymmetry w/ detector ⊕ underlying event ⊕ analysis ⊕ combinatoric 2nd jet

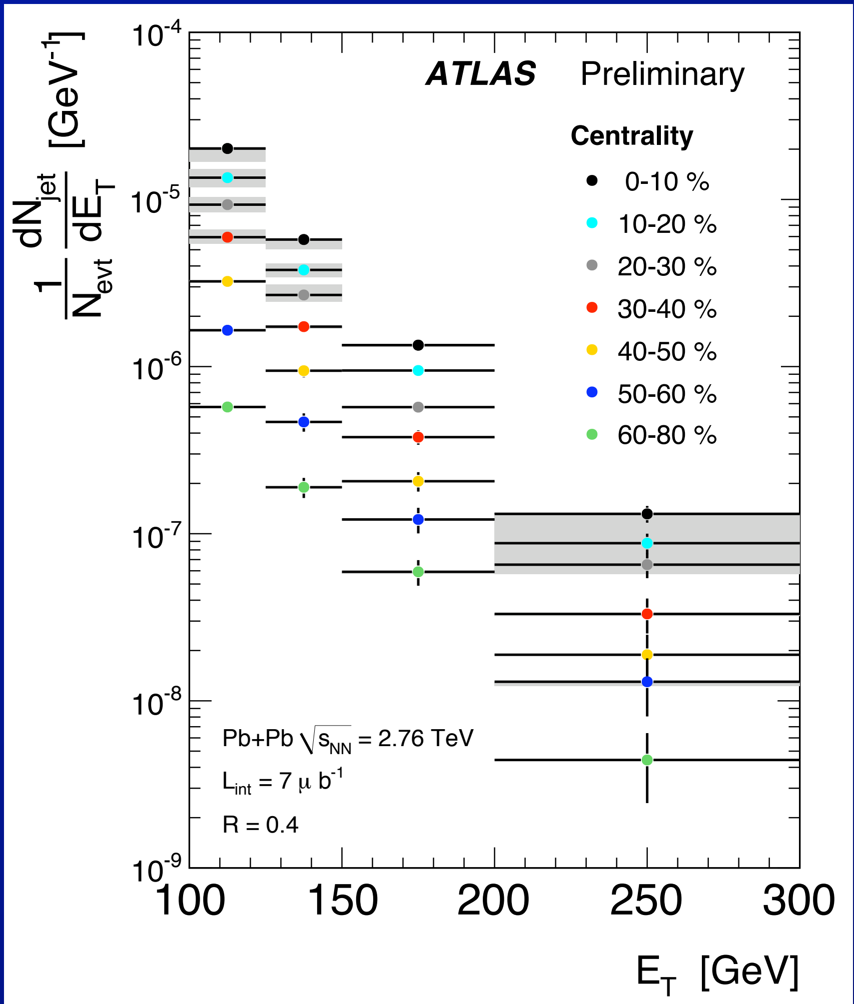
Compare data, Monte Carlo:

- Event-by-event Std Dev of ΣE_T in 7x7 groups of towers
  - ➡ ~ R = 0.4
  - ➡ (@ EM scale)

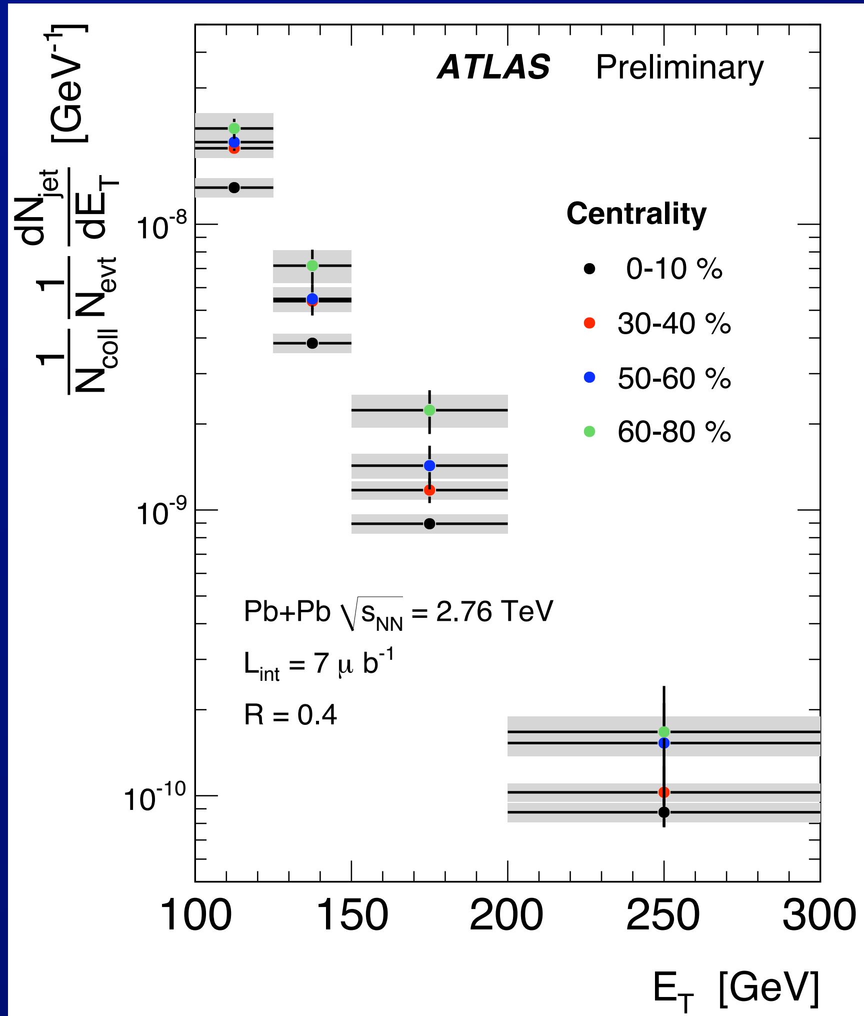


Single Jet Rates, R = 0.4

Single jet spectra



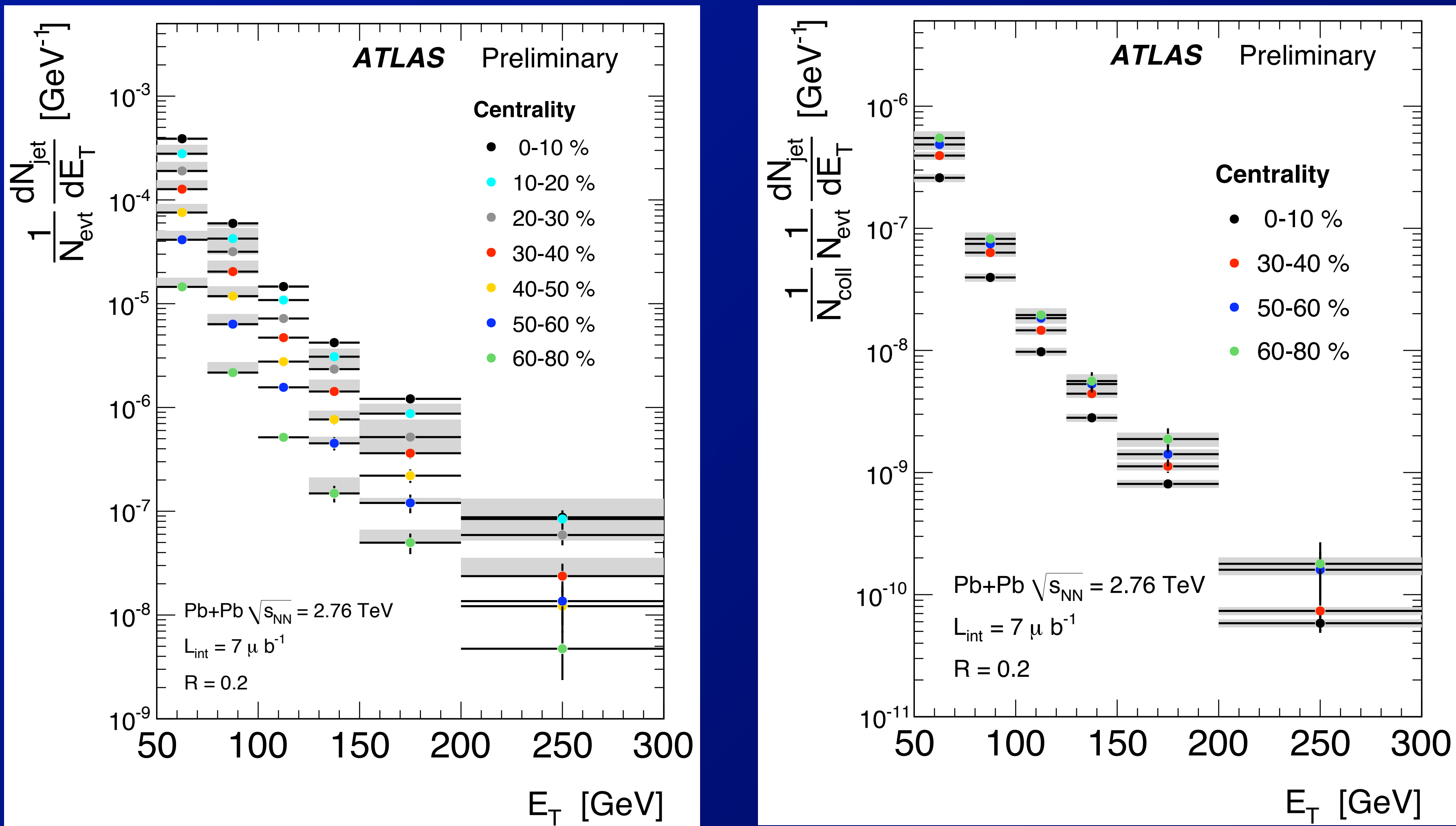
Single jet spectra/N_{coll}



- For single jet spectra
  - Centrality independent 22% systematic error on normalization due to 4% jet energy scale uncertainty.

Single Jet Rates, R = 0.2

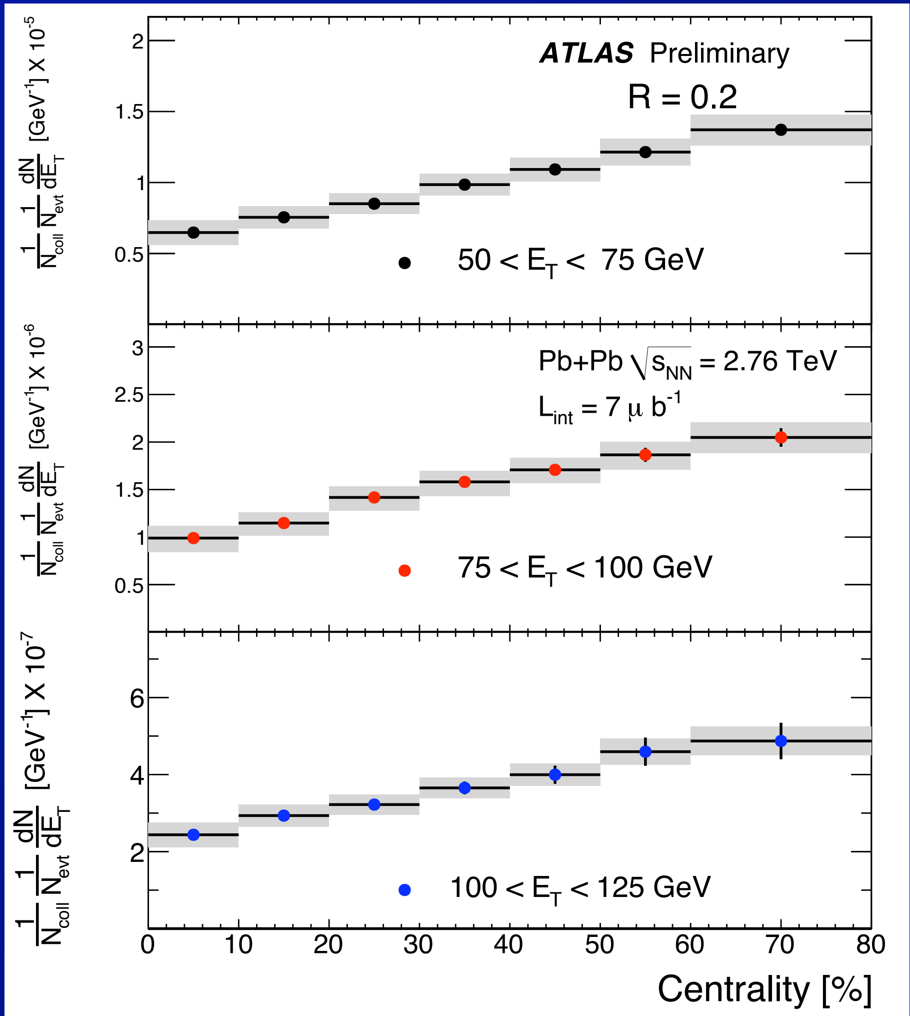
Single jet spectra / Single jet spectra/N_{coll}



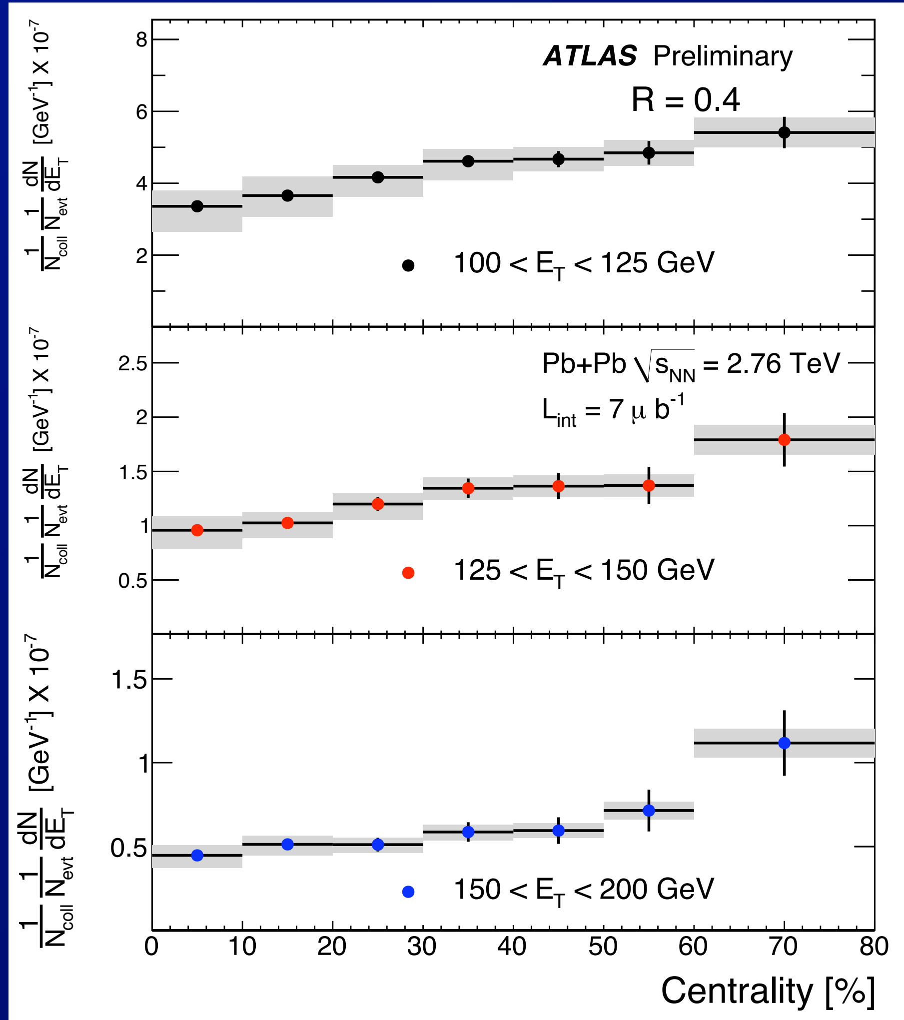
- **For single jet spectra**
  - Centrality independent 22% systematic error on normalization due to 4% jet energy scale uncertainty.

Jet Yield/N_{coll} vs centrality

R = 0.2



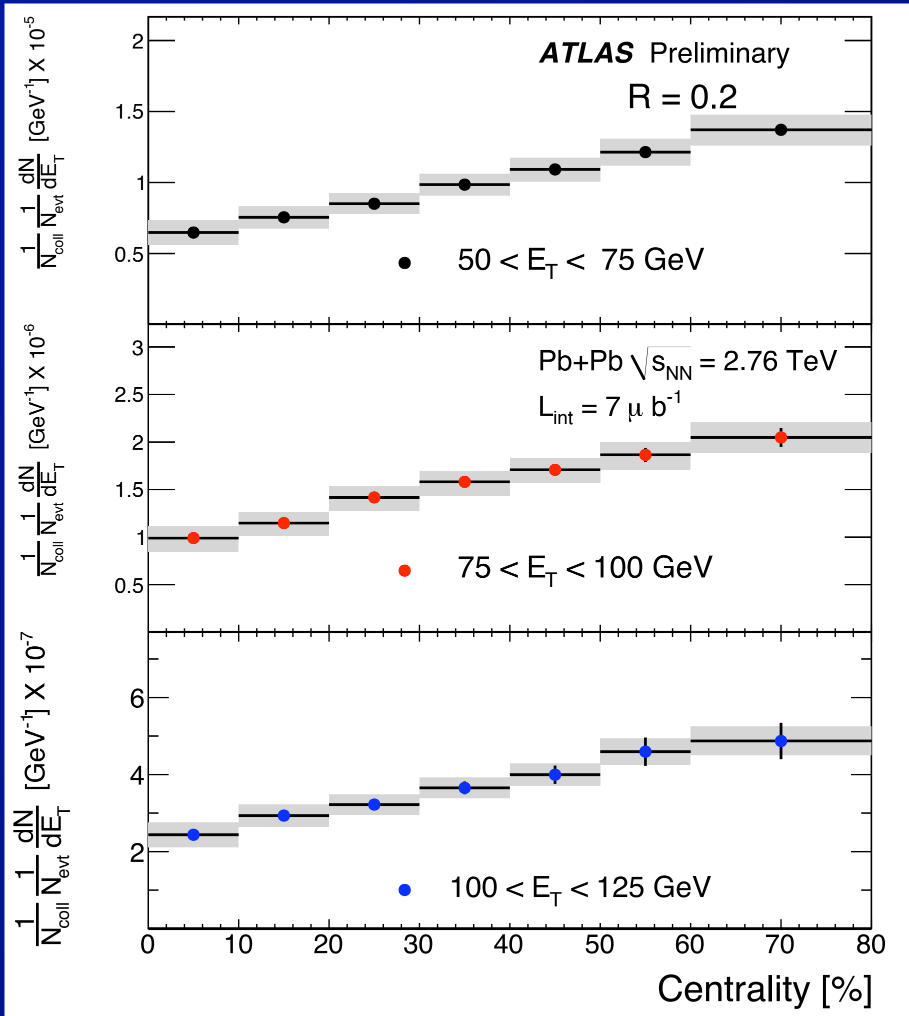
R = 0.4



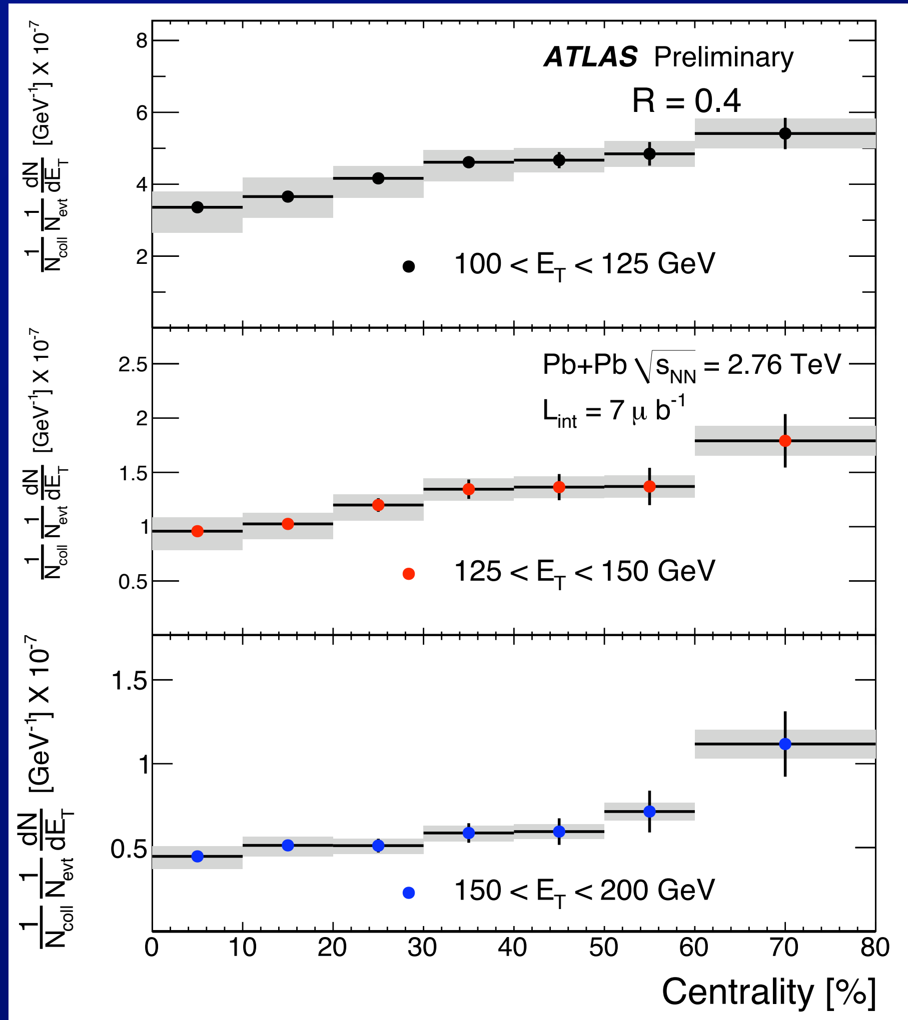
- Systematic errors account for:
  - Centrality dependence of jet energy resolution and jet energy scale and N_{coll} uncertainties

Jet Yield/N_{coll} vs centrality

R = 0.2



R = 0.4

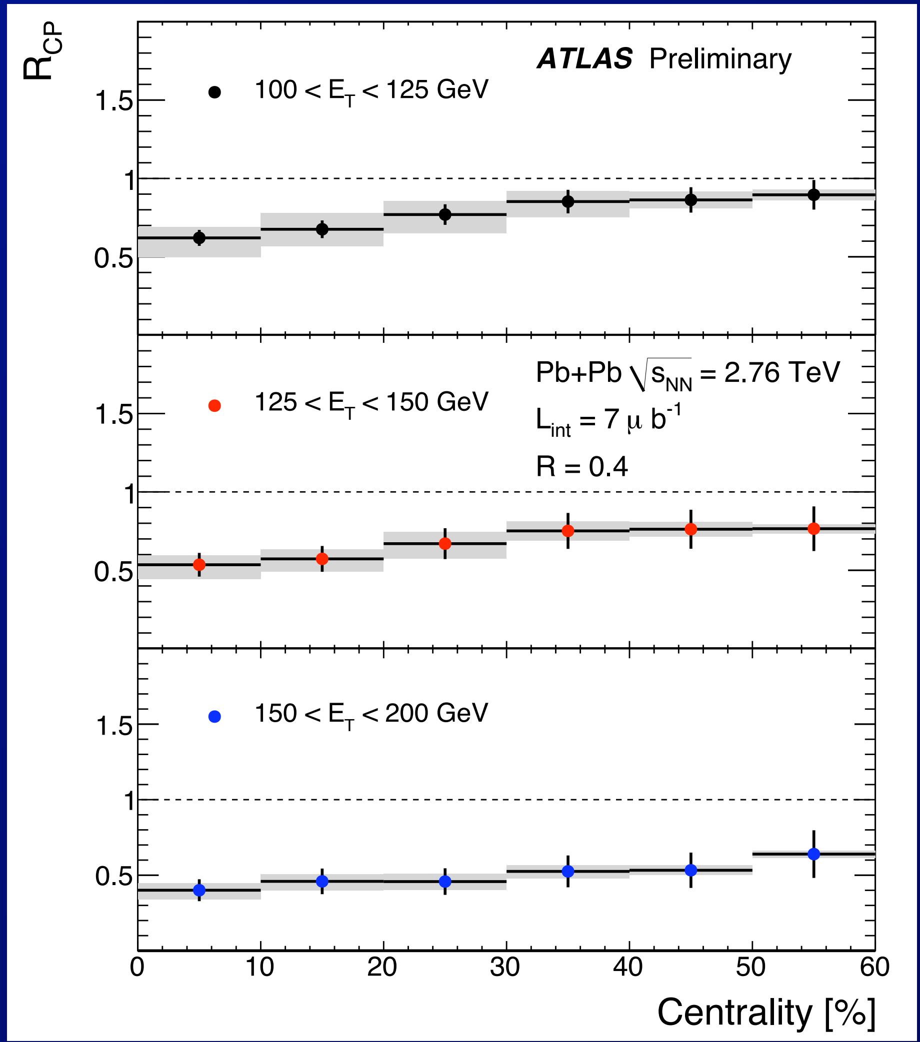


- **For both R = 0.2 and R = 0.4**

  ⇒**Observe a monotonic decrease in jet yield/N_{coll} from peripheral to central collisions.**

Single Jet central to peripheral ratio: R_{cp}

R = 0.4



Use 60-80% centrality as peripheral reference for R_{cp}

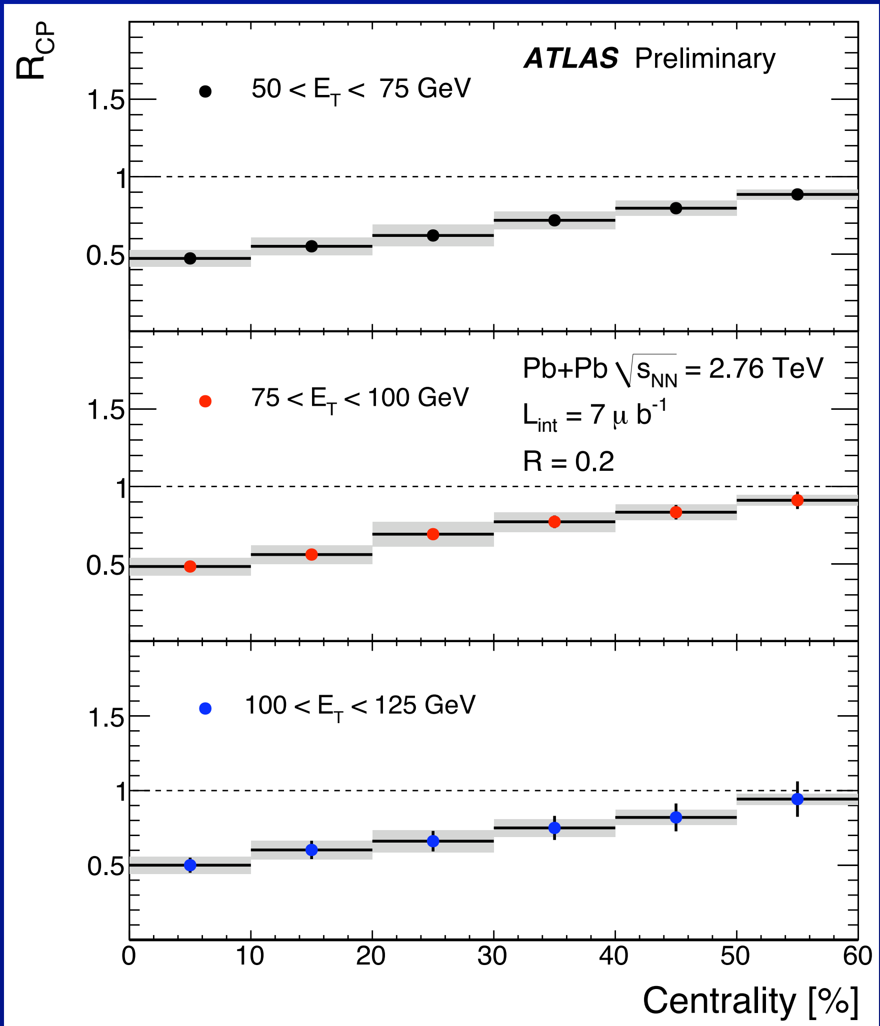
$$Rcp = \frac{\frac{1}{N_{coll}^{cent}} \frac{1}{N_{evt}^{cent}} \frac{dN_{jet}^{cent}}{dE_T}}{\frac{1}{N_{coll}^{60-80}} \frac{1}{N_{evt}^{60-80}} \frac{dN_{jet}^{60-80}}{dE_T}}$$

- **Observe:**

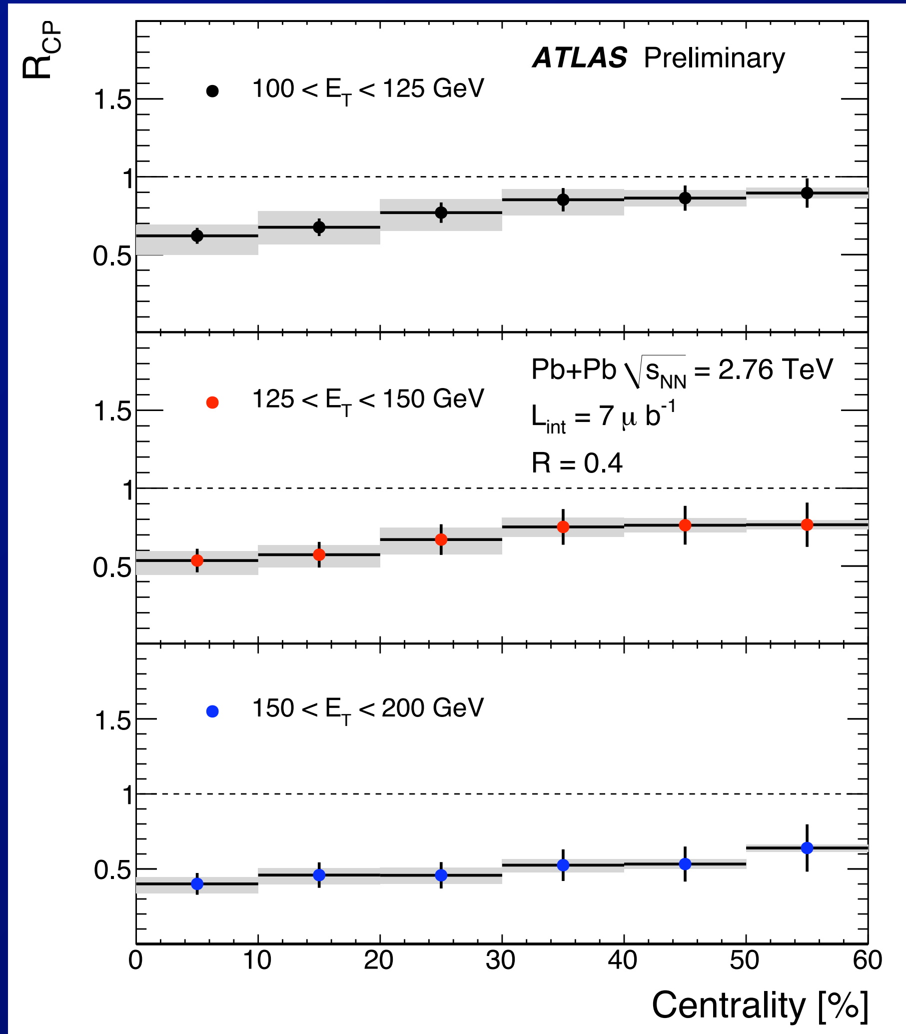
⇒Factor of ≈ 2 suppression of jet yield/N_{coll} in central (0-10%) collisions relative to 60-80% collisions.

Single Jet central to peripheral ratio: R_{cp}

R = 0.2



R = 0.4

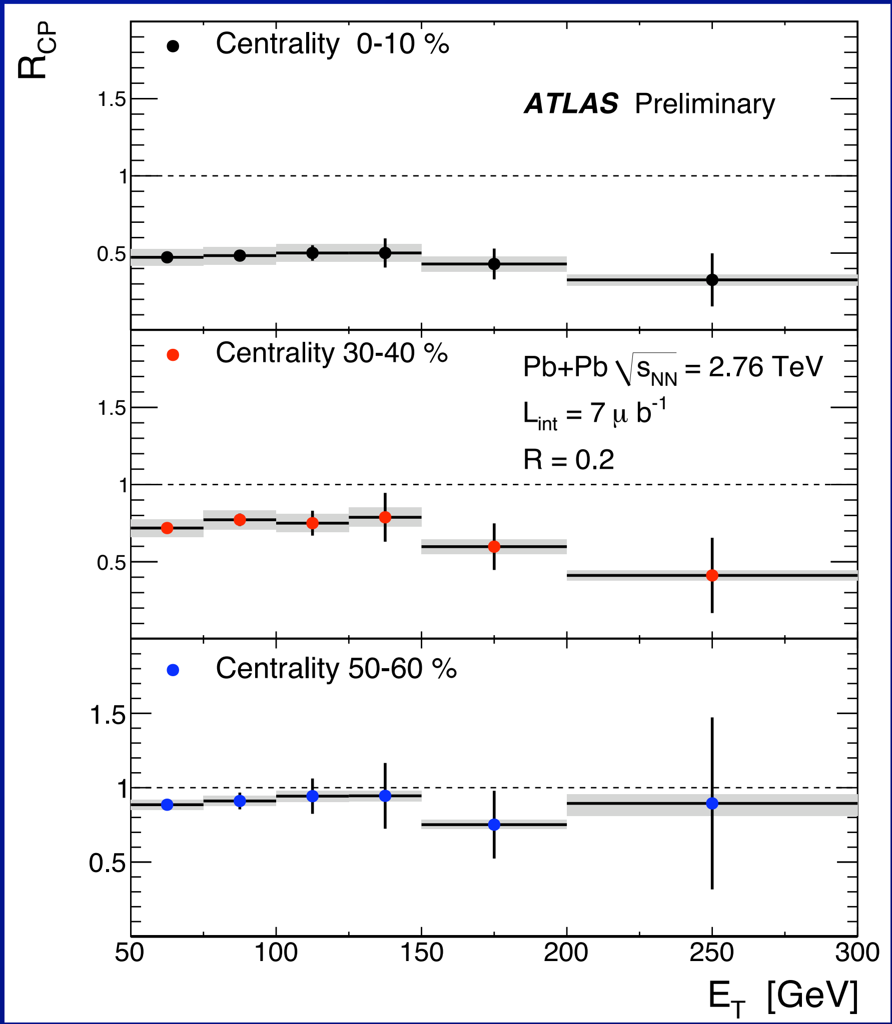


- **Observe:**

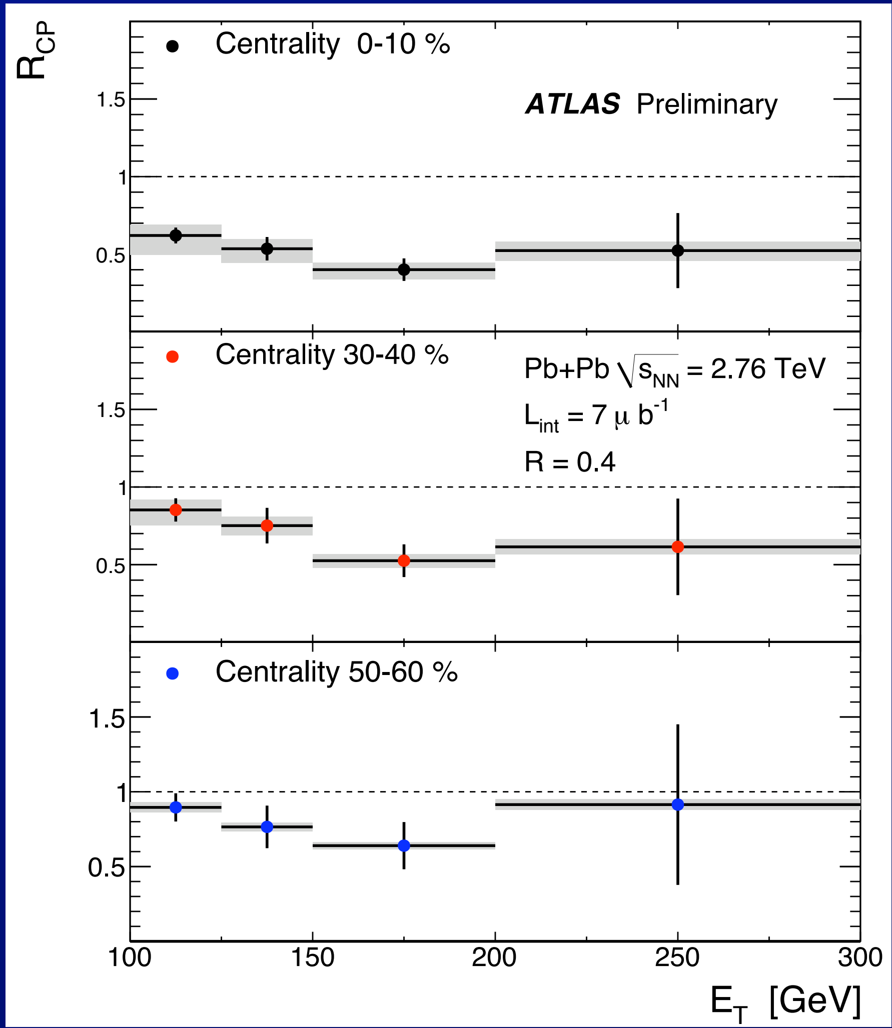
⇒Comparable suppression in R = 0.2 and R = 0.4 jet yields/N_{coll} over full range of reported E_T

Single Jet central to peripheral ratio: R_{cp}

R = 0.2

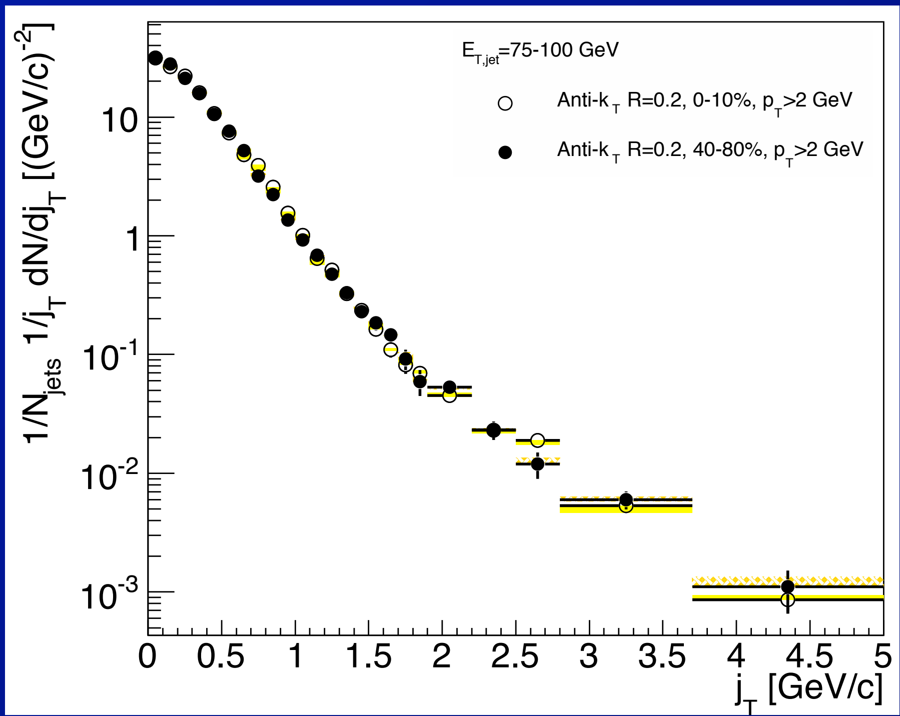


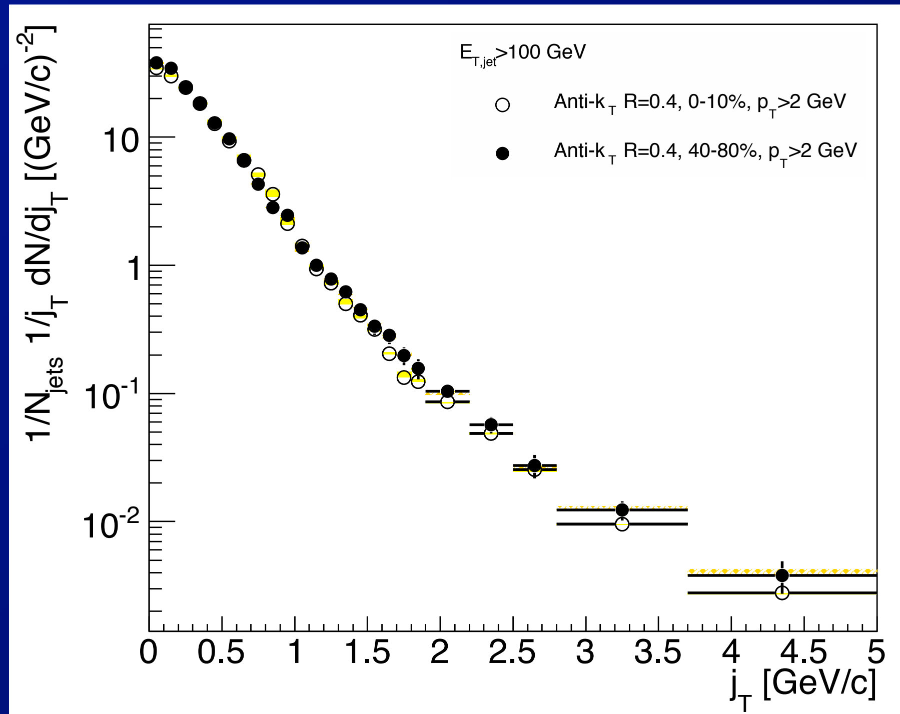
R = 0.4



- **Observe:**
  - ⇒ Suppression independent of jet E_T within statistical ⊕ systematic errors

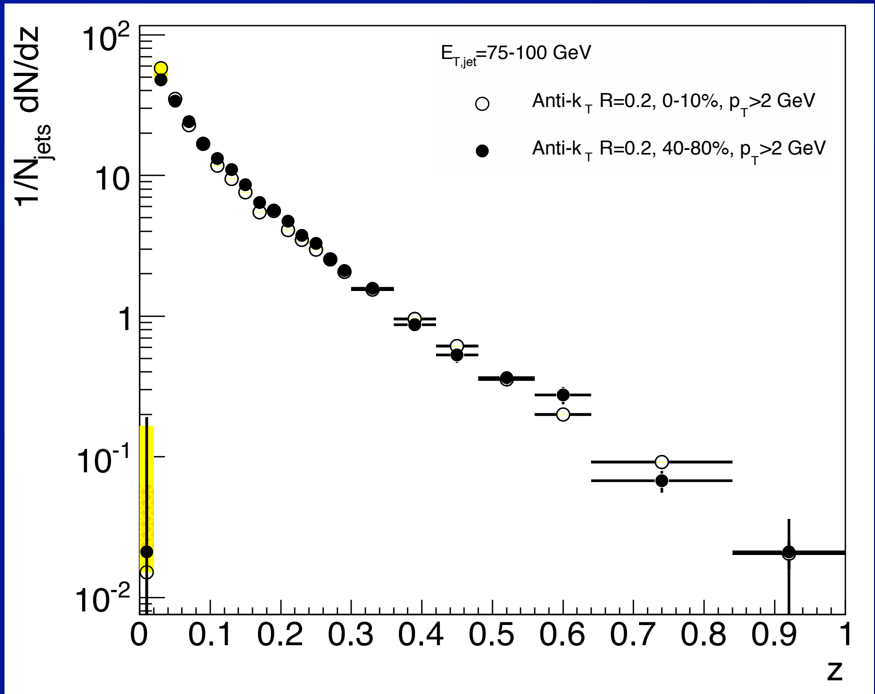
Jet Fragmentation (Transverse)

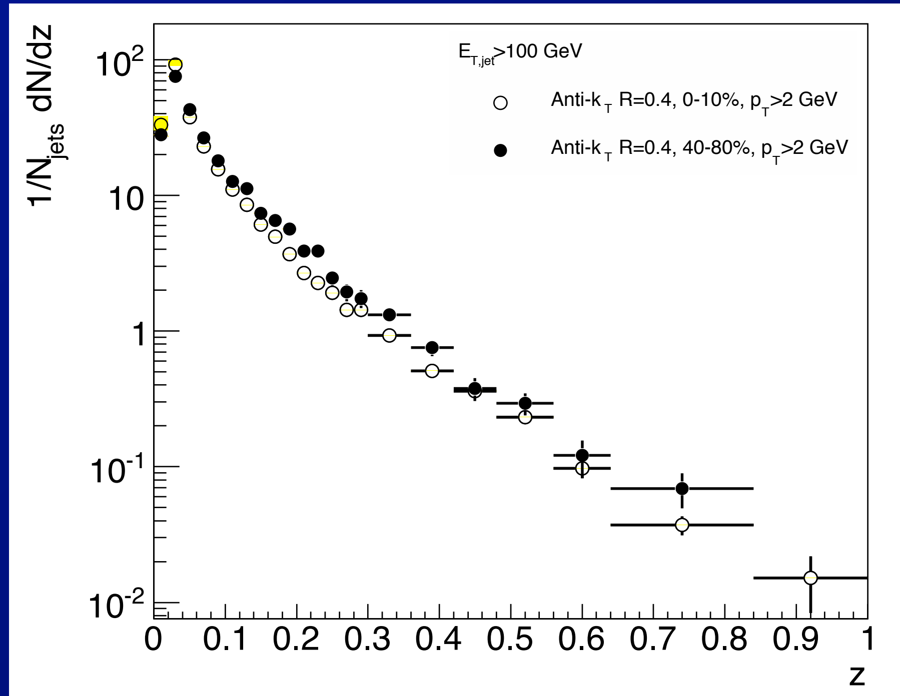




- Measure distribution of fragment p_T normal to jet axis: $j_T \equiv p_T^{\rm had} \sin \Delta R = p_T^{\rm had} \sin \left(\sqrt{\Delta\eta^2 + \Delta\phi^2}\right)$
  - For both R = 0.2 and R = 0.4 jets
  - Not unfolded for angular resolution
- Compare central (0-10%) to peripheral (60-80%)
  - No substantial broadening observed.

Jet Fragmentation (Longitudinal)

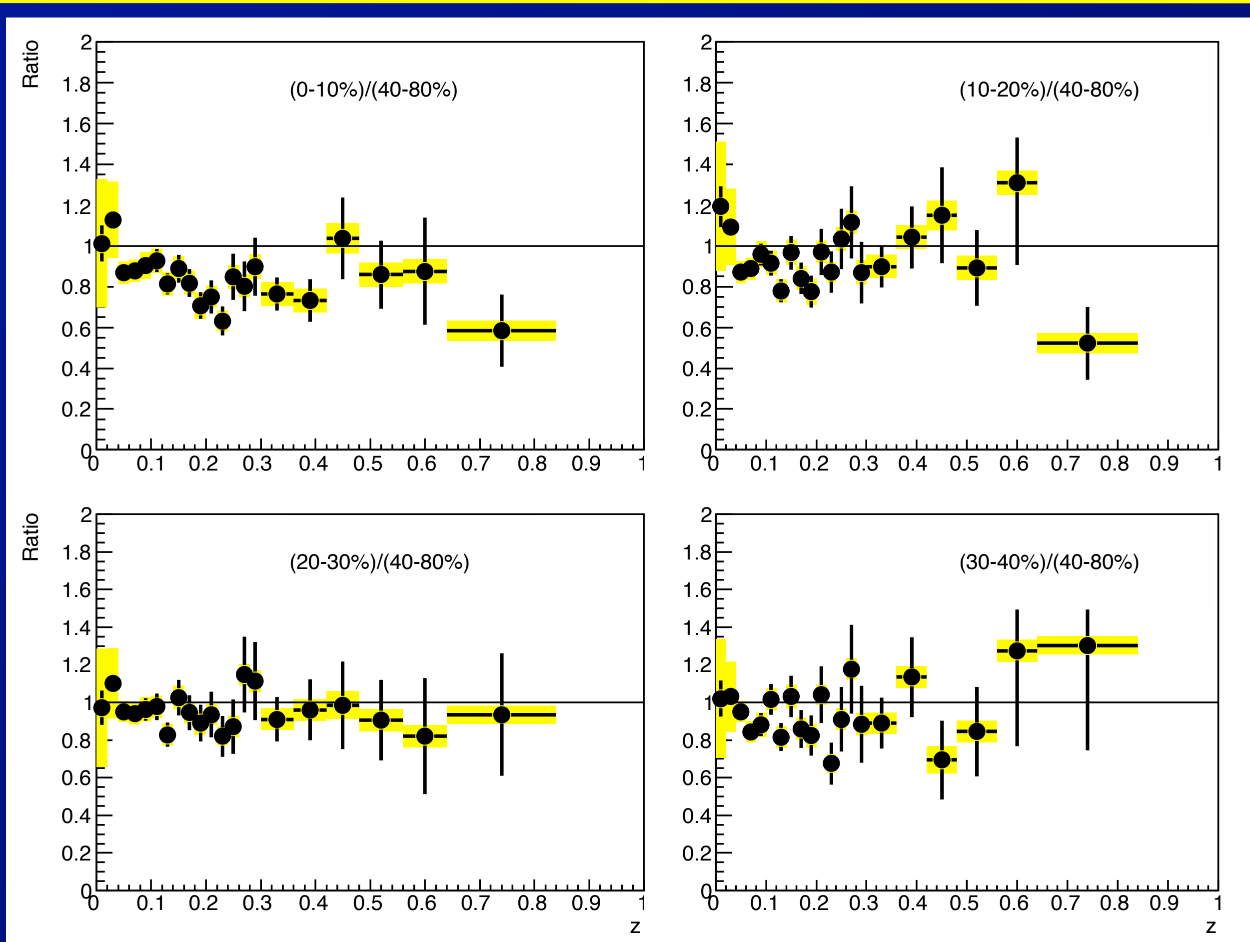




- Measure distribution of fragment p_T along jet axis: $z \equiv \left(\frac{p_T^{had}}{E_T}\right) \cos \Delta R$
  - For both R = 0.2 and R = 0.4 jets
  - Systematic uncertainties from jet energy resolution, centrality dependence of jet energy scale.
- Compare central (0-10%) to peripheral (60-80%)

Jet Fragmentation Ratios (Longitudinal)

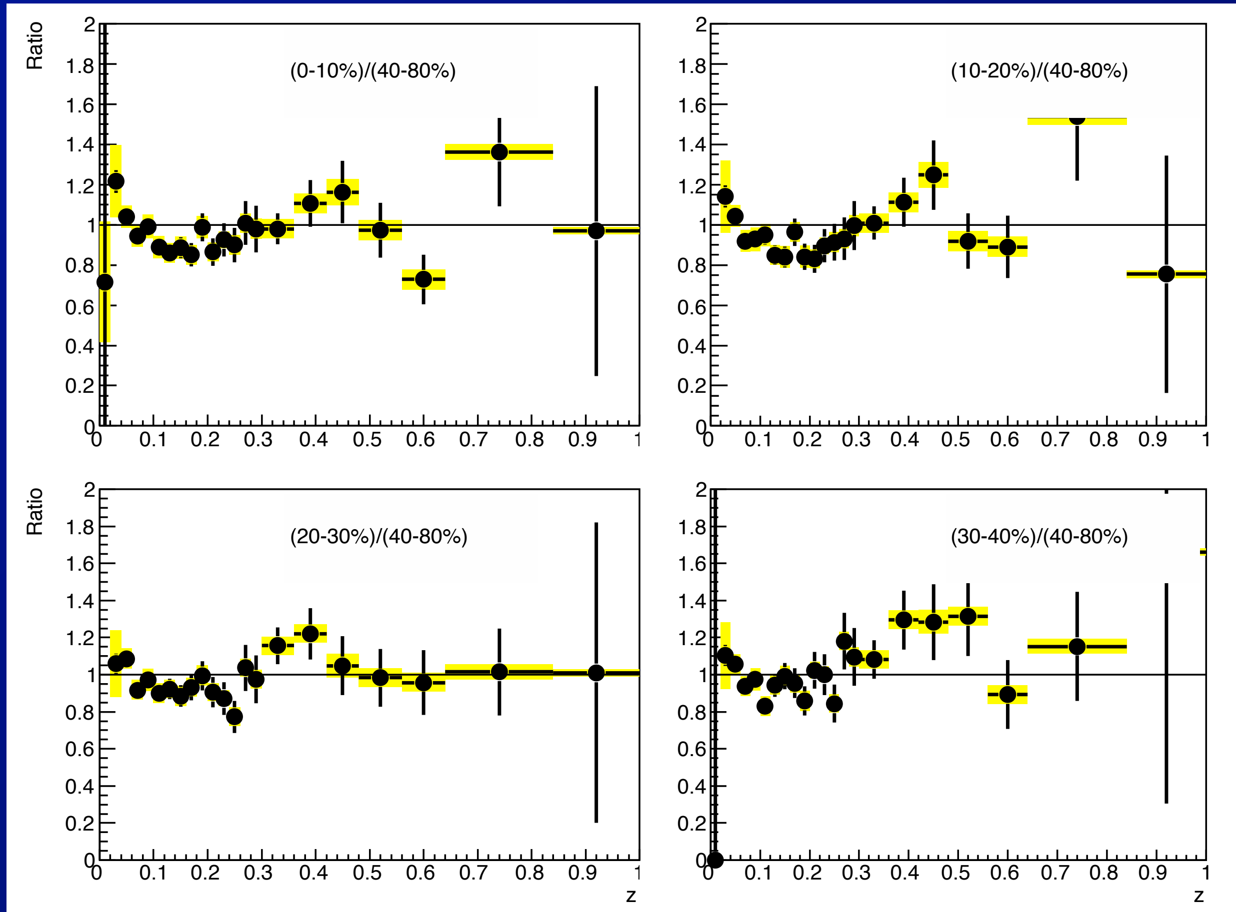
R = 0.4
E_T > 100 GeV



- **Evaluate ratio of $1/N_{\rm jet}\; dN/dz$ in different centrality bins to peripheral (40-80%)**
  - ⇒**At most, small (~ 20%) weakly z-dependent suppression in central (0-10%) collisions.**

Jet Fragmentation Ratios (Longitudinal)

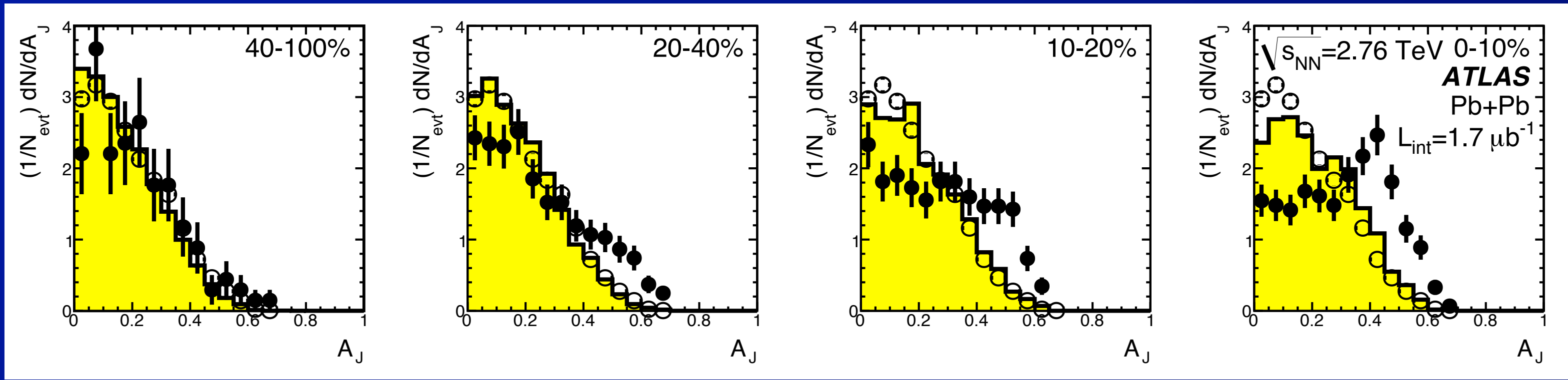
R = 0.2
75 < E_T < 100 GeV



- Evaluate ratio of $1/N_{\text{jet}}\ dN/dz$, different centrality bins to peripheral (40-80%)

  ⇒ ~ 20% Suppression in central (0-10%, 10-20%) collisions for 0.05 < z < 0.3

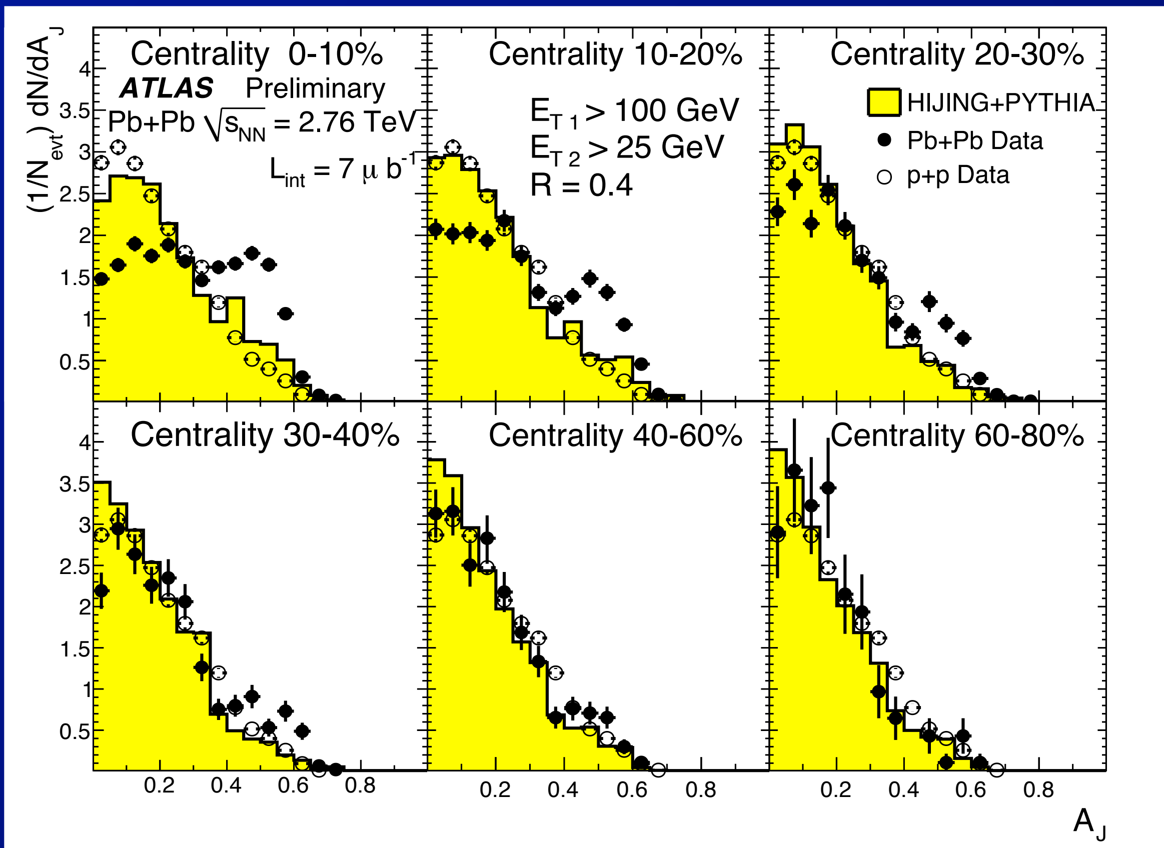
Di-jet Asymmetry



2010 PRL results

R = 0.4, E_{T1} > 100 GeV, E_{T2} > 25 GeV

$$A_J \equiv \frac{E_{T\,1} - E_{T\,2}}{E_{T\,2} + E_{T\,1}}$$



- **Update:**
  - Full statistics
  - Iteration step in background estimation
  - Correction for flow in underlying event
  - MC down to 35 GeV

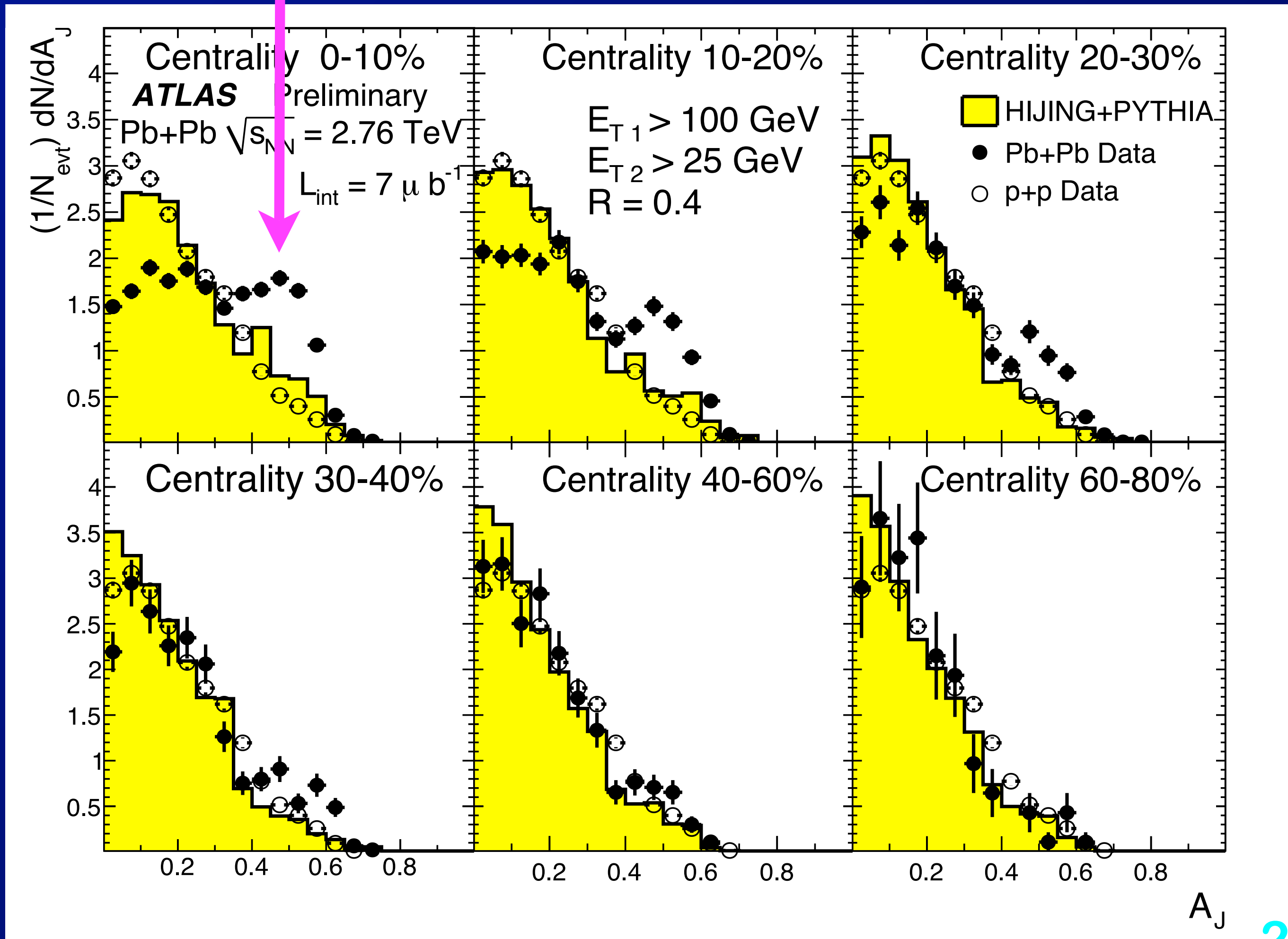
Di-jet Asymmetry, R = 0.4

30 Gev

R = 0.4

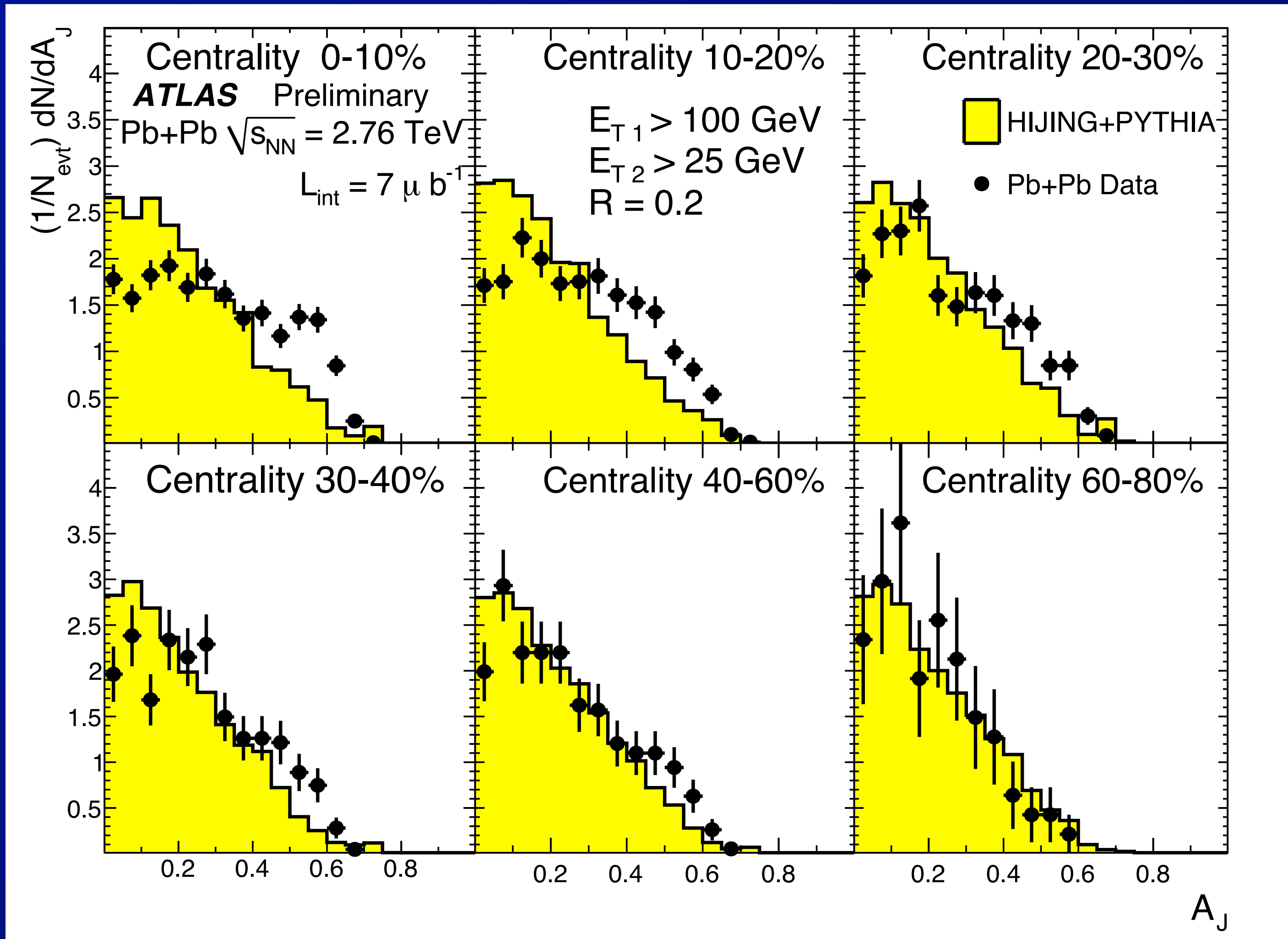
E_{T1} > 100 GeV

E_{T2} > 25 GeV



Di-jet Asymmetry, R = 0.2

- R = 0.2
- E_{T1} > 100 GeV
- E_{T2} > 25 GeV

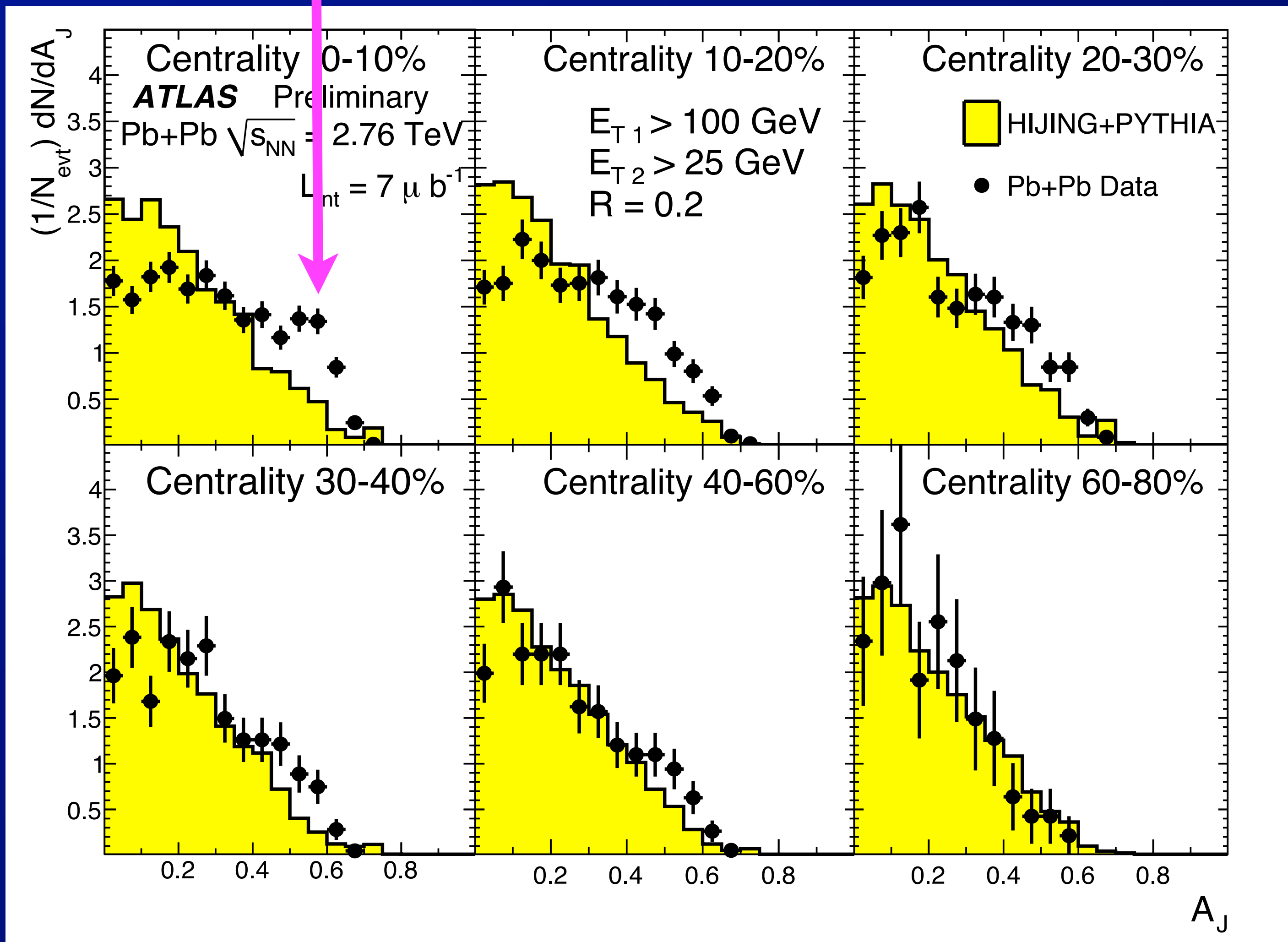


NB: underlying event fluctuations in R = 0.2 ~ 1/2 of R = 0.4

Di-jet Asymmetry, R = 0.2

25 Gev

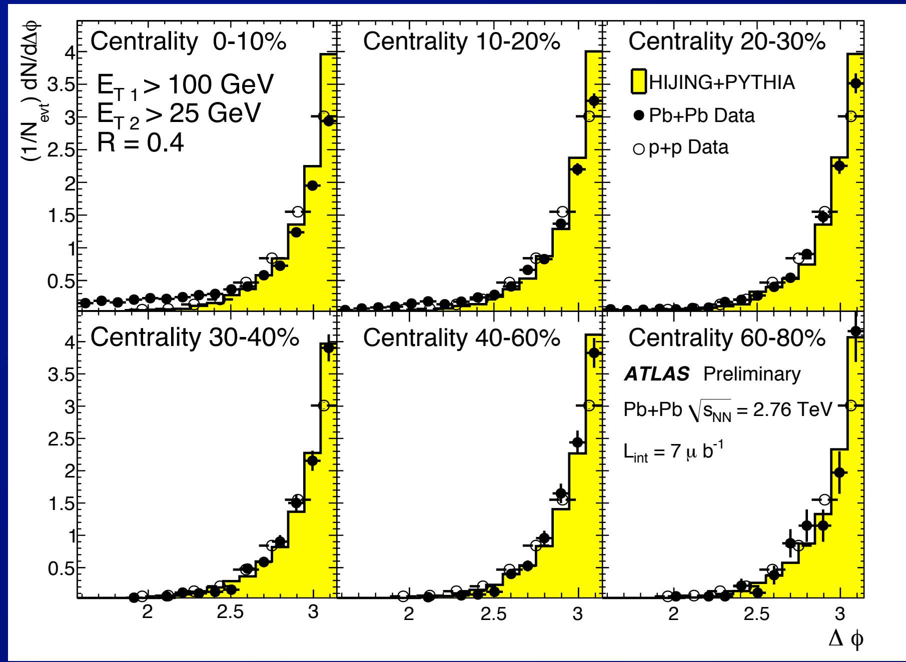
- R = 0.2
- E_{T1} > 100 GeV
- E_{T2} > 25 GeV



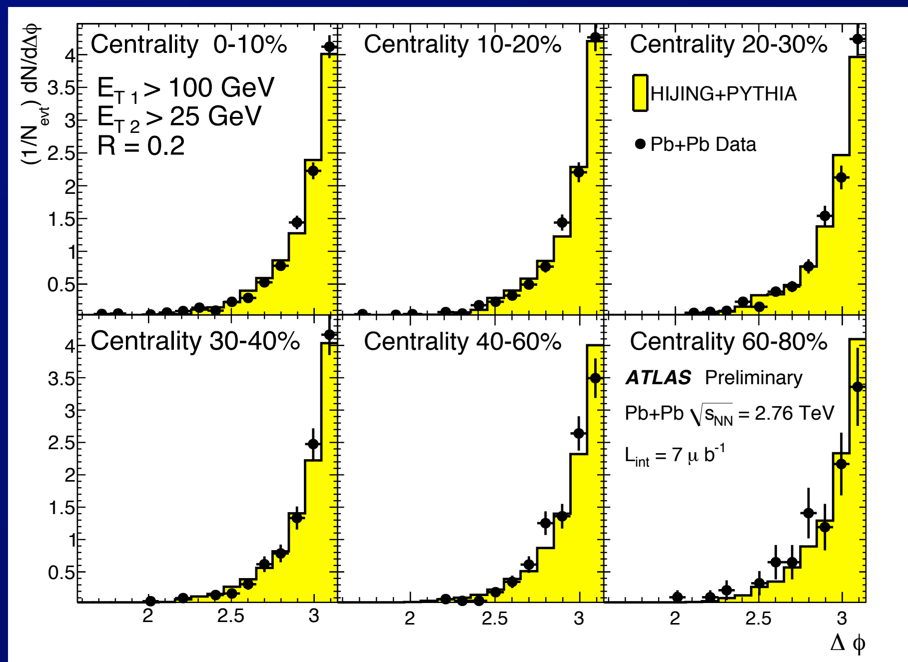
NB: underlying event fluctuations in R = 0.2 ~ 1/2 of R = 0.4

Di-jet Δφ Distributions

- This is clearly a combinatoric contribution to R = 0.4 di-jet Δφ distribution
  - 2^{nd} jet "missing" and uncorrelated jet used

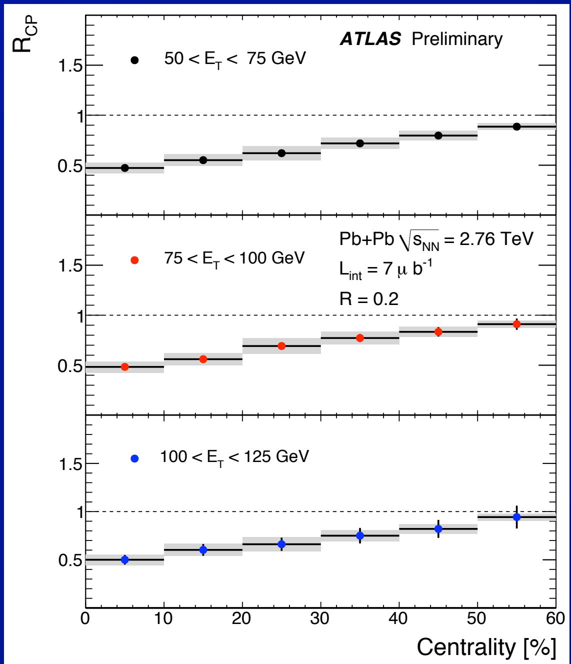


- But, combinatoric contribution much smaller for R = 0.2.
  - Yet, equally strong asymmetry modification.

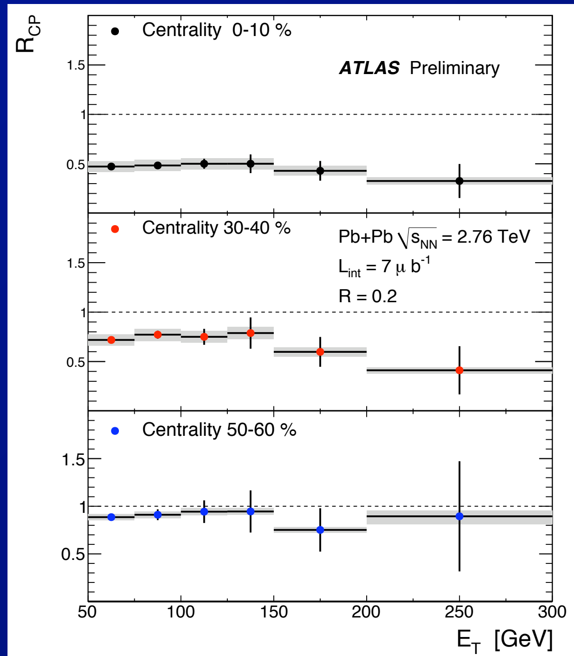


Summary (1)

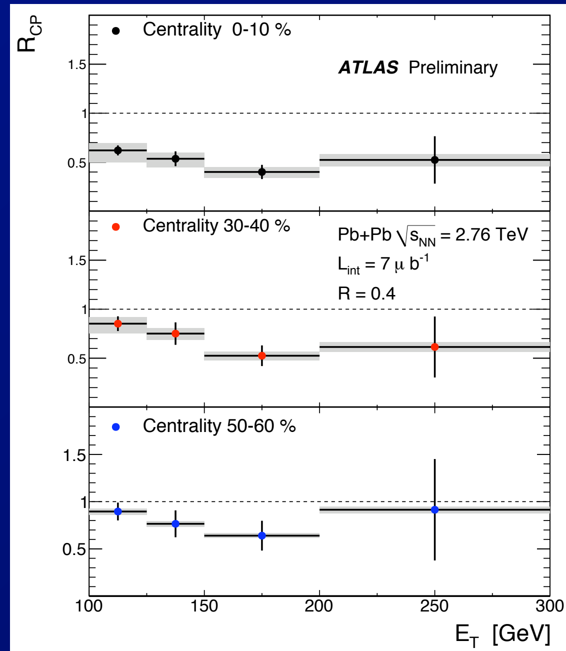
R = 0.2 R_{cp}(cent)



R = 0.2 $R_{cp}(E_T)$

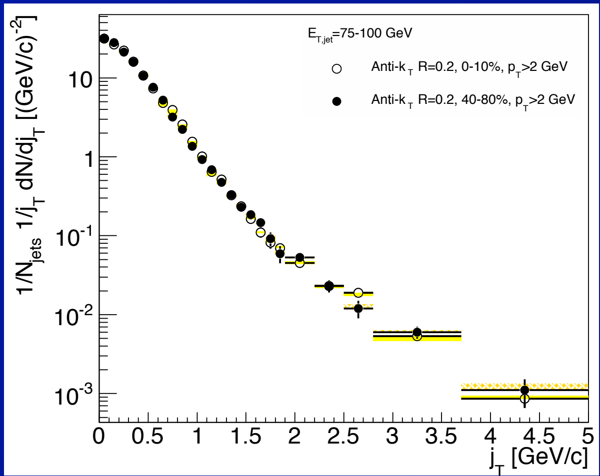


R = 0.4 $R_{cp}(E_T)$



- We observe a factor of ~ 2 suppression in jet yield at high E_T in central collisions
  - ⇒Gradual turn-on of suppression with centrality
  - ⇒R = 0.2 and R = 0.4 results quantitatively similar
  - ⇒No significant (yet) E_T dependence of suppression

Summary (2)

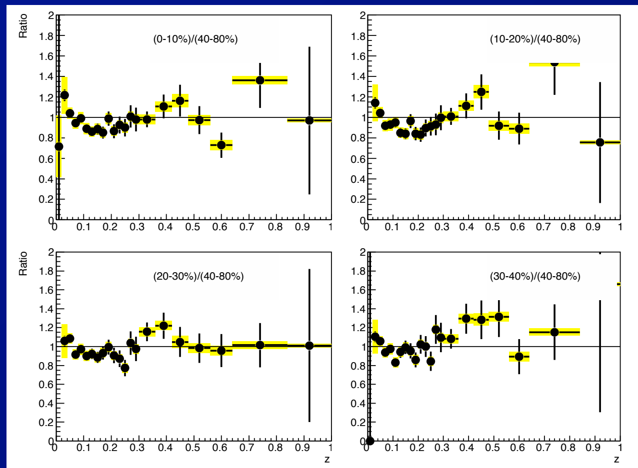


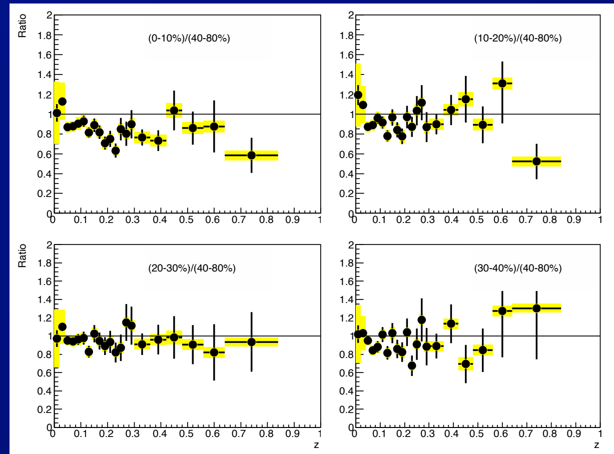
R = 0.2 J_T

R = 0.2

$1/N_{\rm jet}\ dN/dz$

Ratio





R = 0.4

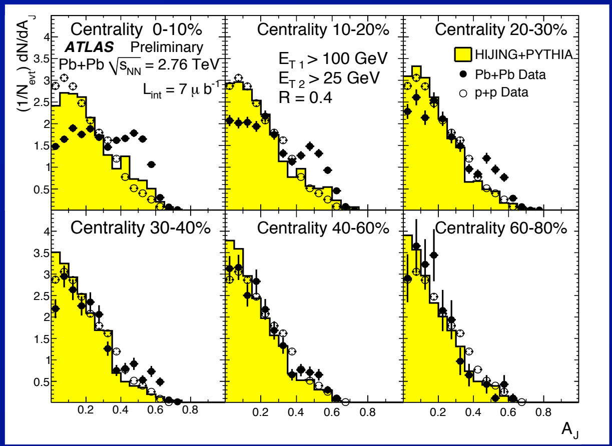
$1/N_{\rm jet}\ dN/dz$

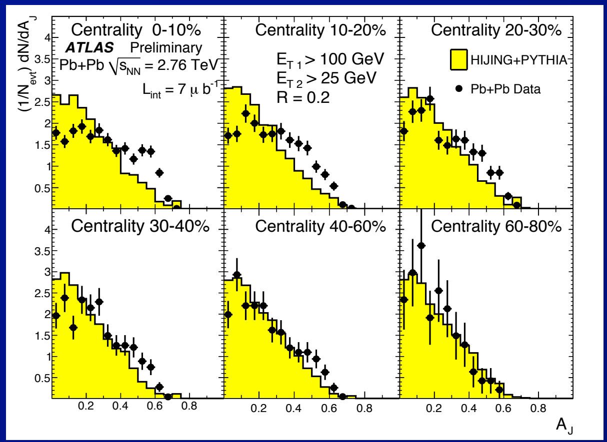
Ratio

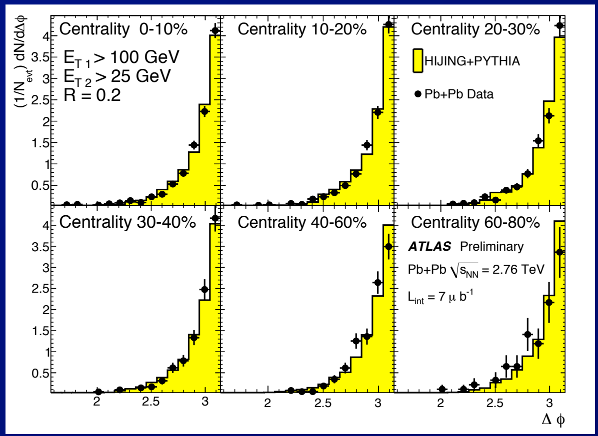
- We observe no significant broadening of fragment J_T distribution
  - ⇒Remains to be quantified.
- We observe, at most, weak modification of fragment z distributions
  - ⇒ Restricted to intermediate z?

Summary (3)

R = 0.4 A_J | R = 0.2 A_J | R = 0.2 $\Delta\varphi$



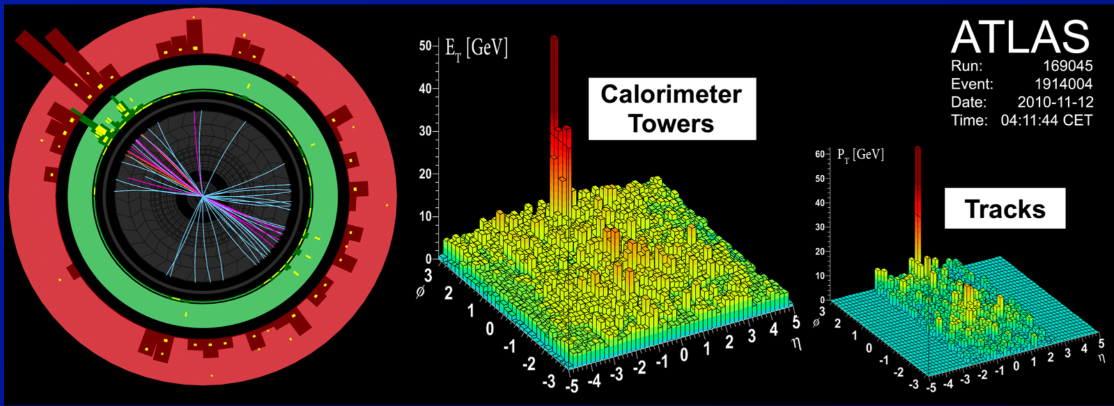


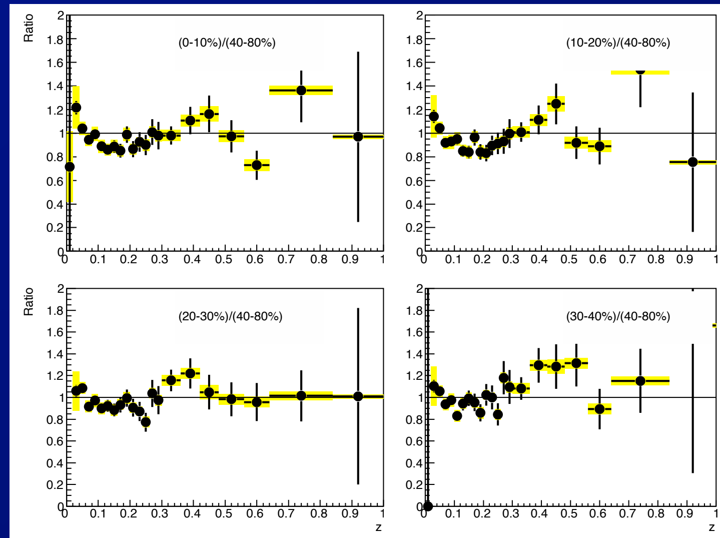


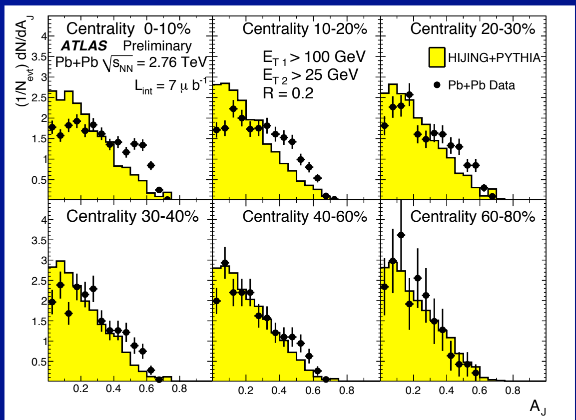
- With improvements in underlying jet analysis (background, flow correction) since 2010 PRL
  - ⇒Conclusions re: modifications of di-jet asymmetry & no broadening in $\Delta\varphi$ only strengthened.
  - ⇒Not a result of UE fluctuations
- A_J distributions sensitive to E_{T2}, $\Delta\varphi$ cuts
  – Events with 2nd jet "missing" appear @ end-point of A_J
  – Important physics in events that fail E_{T2}, $\Delta\varphi$ cuts

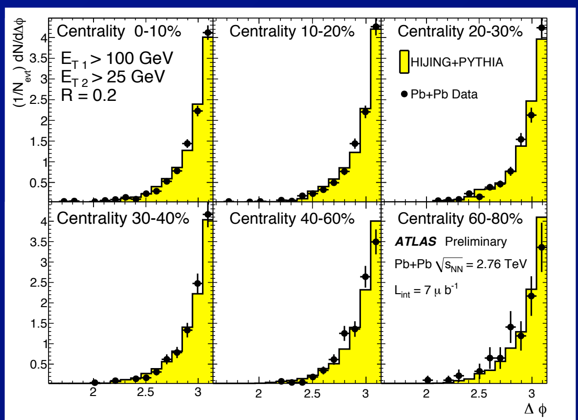
Summary (4)

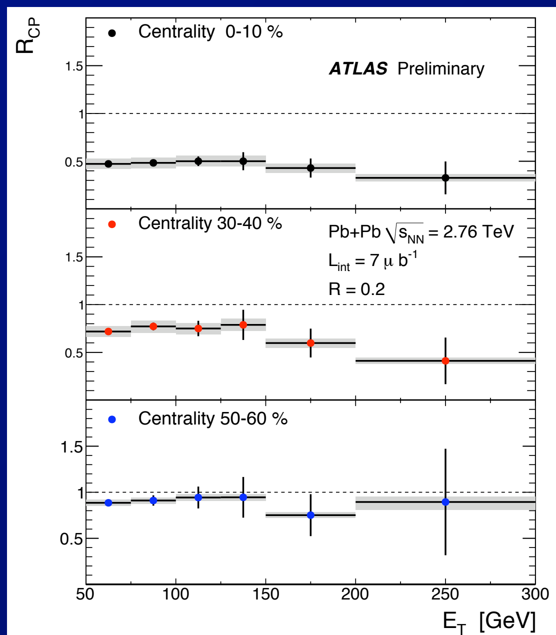
Many thanks to the LHC for outstanding 2010 run !

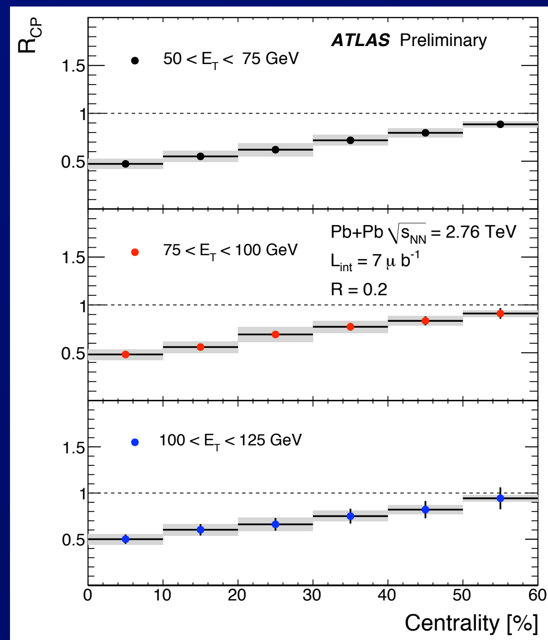












Backup Material

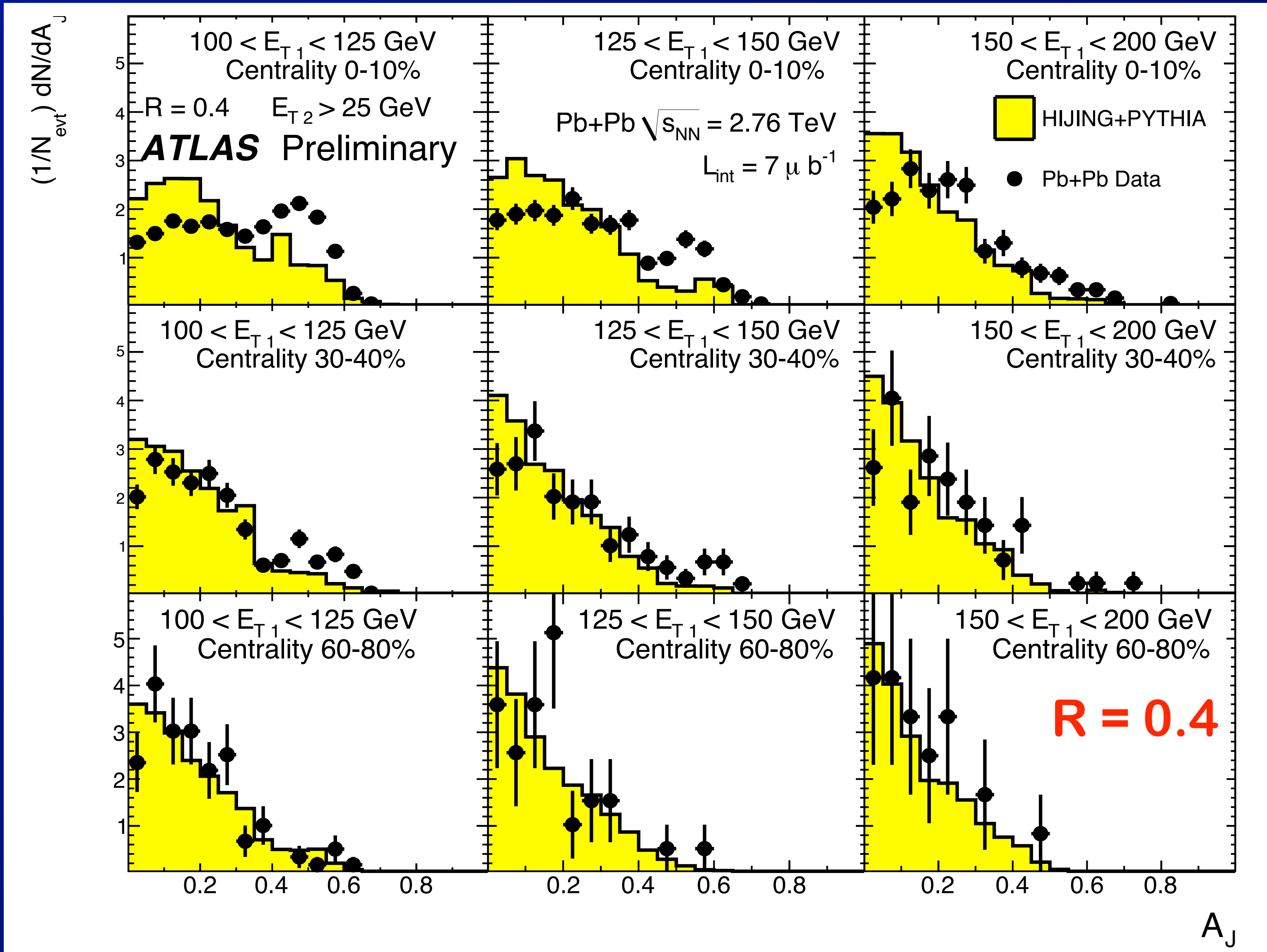
Di-jet Asymmetry, E_{T1} Dependence

$100 < E_{T1} < 125$ $125 < E_{T1} < 150$ $150 < E_{T1} < 200$ GeV

0-10%

30-40%

60-80%



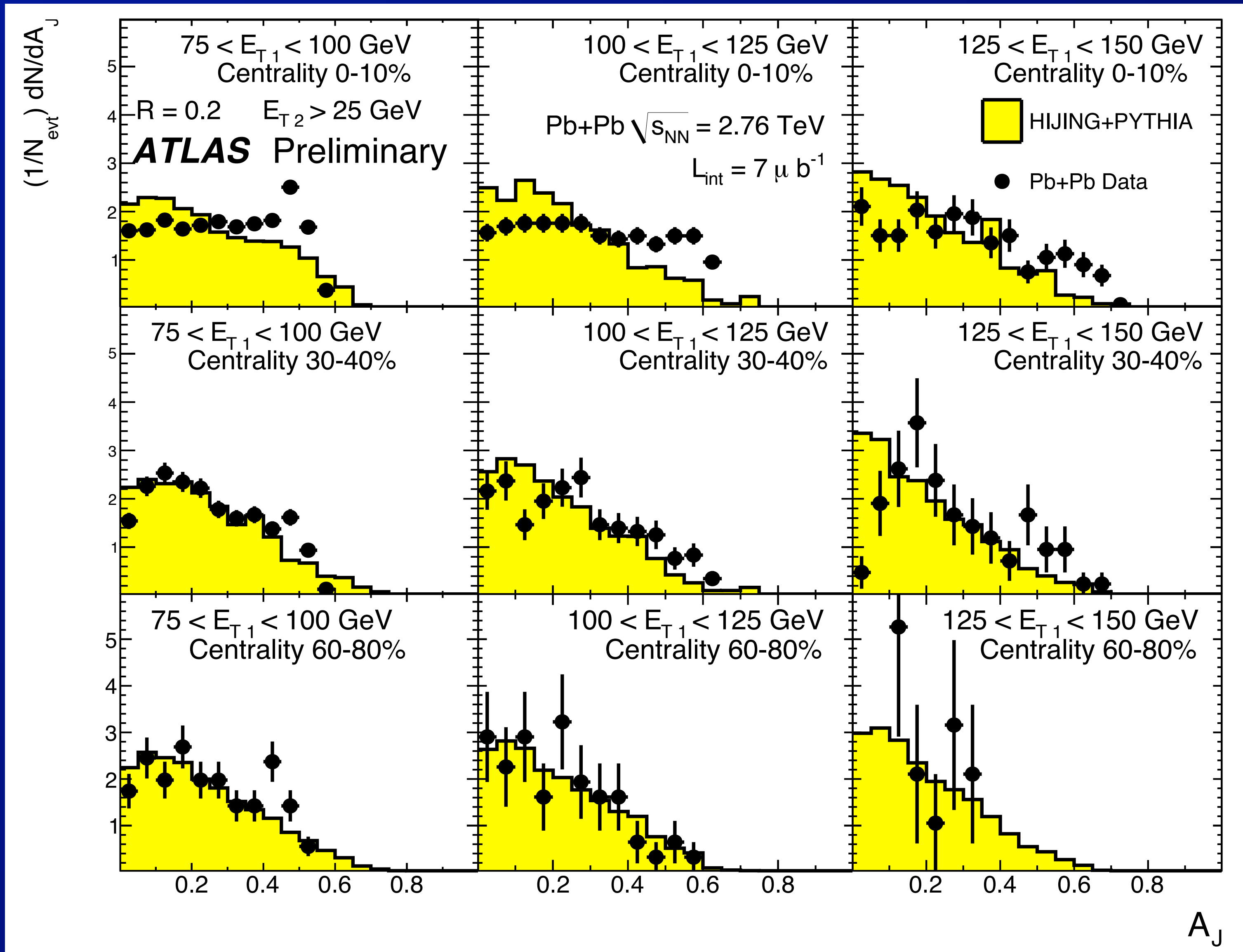
Di-jet Asymmetry, E_{T1} Dependence

$75 < E_{T1} < 100$ | $100 < E_{T1} < 125$ | $125 < E_{T1} < 150$ GeV

0-10%

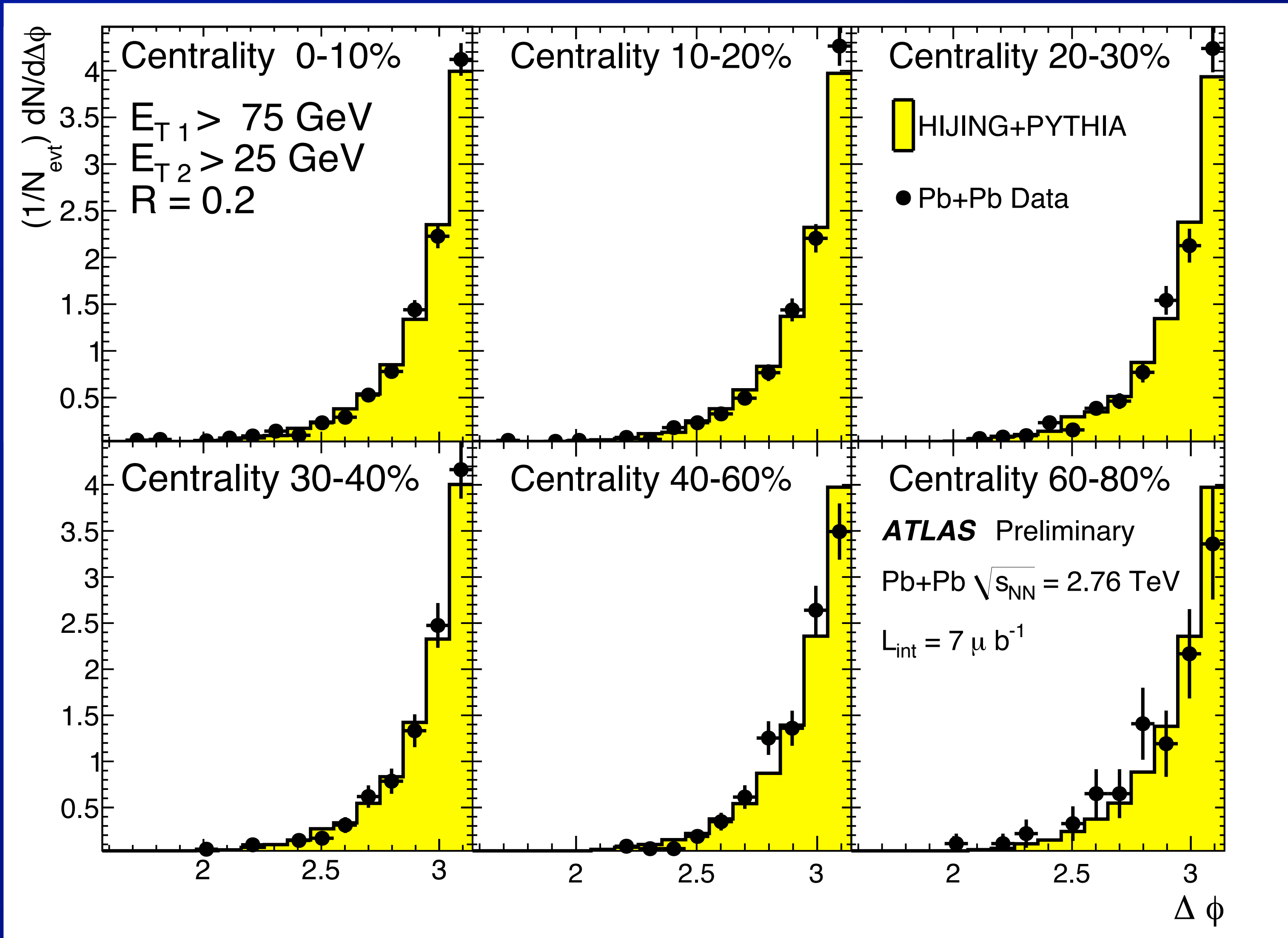
30-40%

60-80%



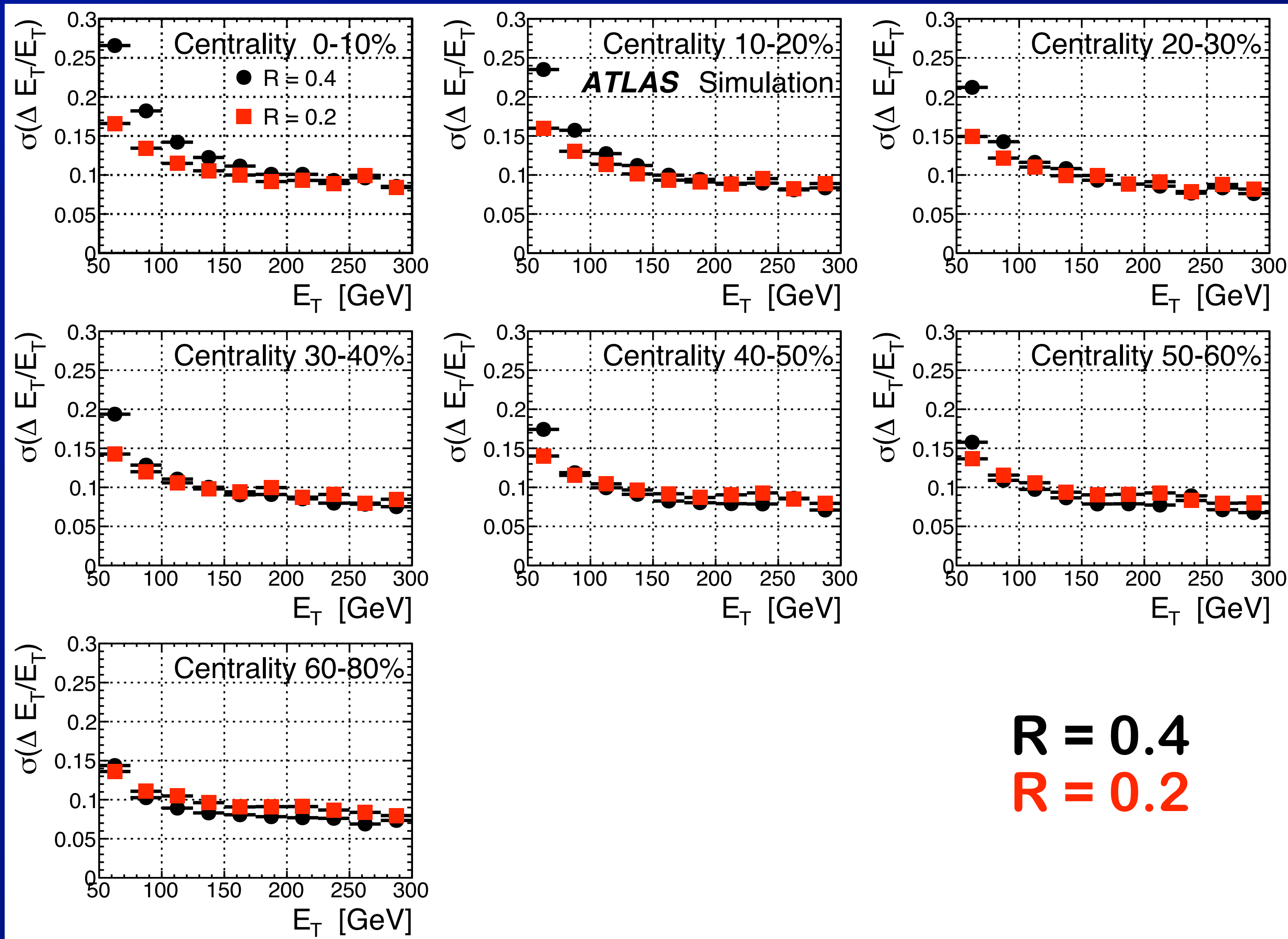
R = 0.2 Di-jet Δφ Distributions

R = 0.2, E_{T1} > 75 GeV, E_{T2} > 25 GeV



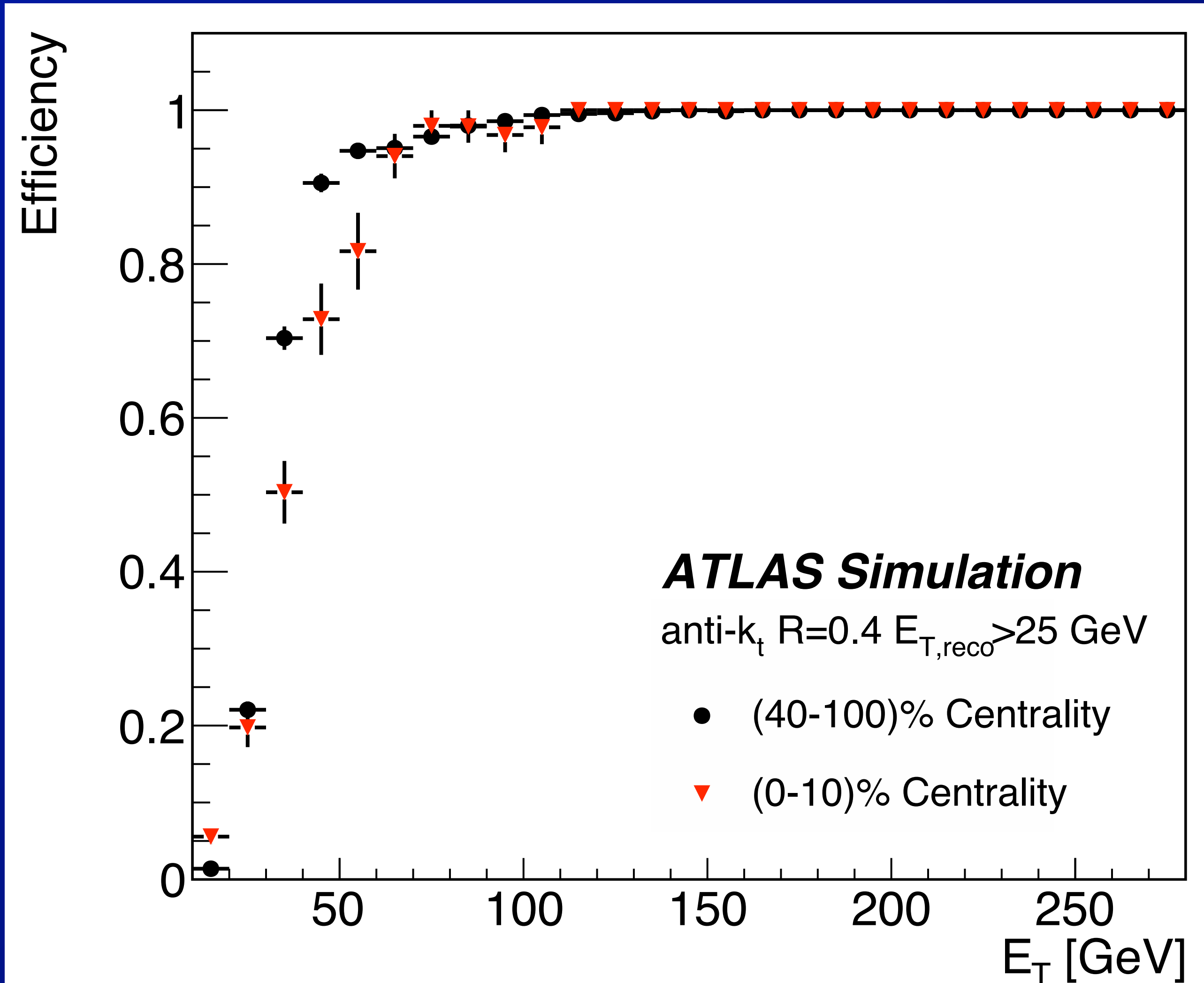
Pb+Pb Jet Energy Resolution (JER)

$\sigma(\Delta E_T / E_T)$



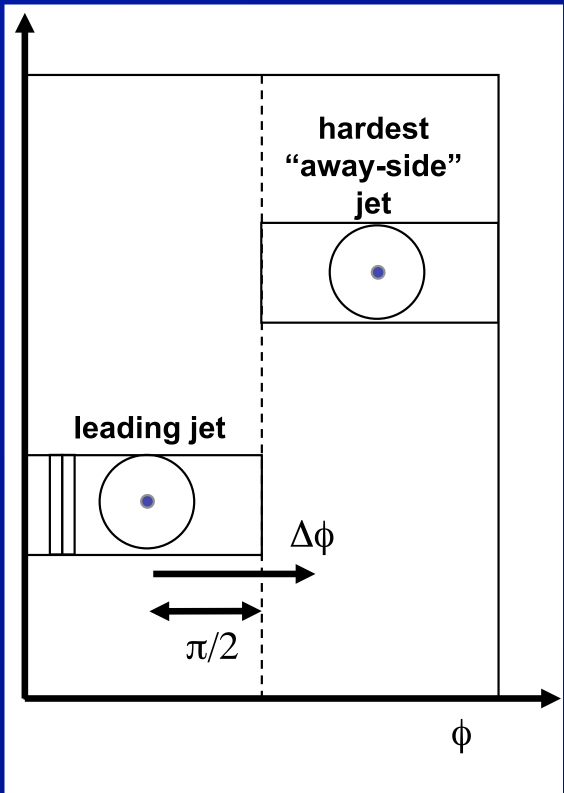
- From HIJING + PYTHIA GEANT Monte Carlo
  - PYTHIA samples with $35 < \hat{p}_T < 280$ GeV

Jet Reconstruction Efficiency

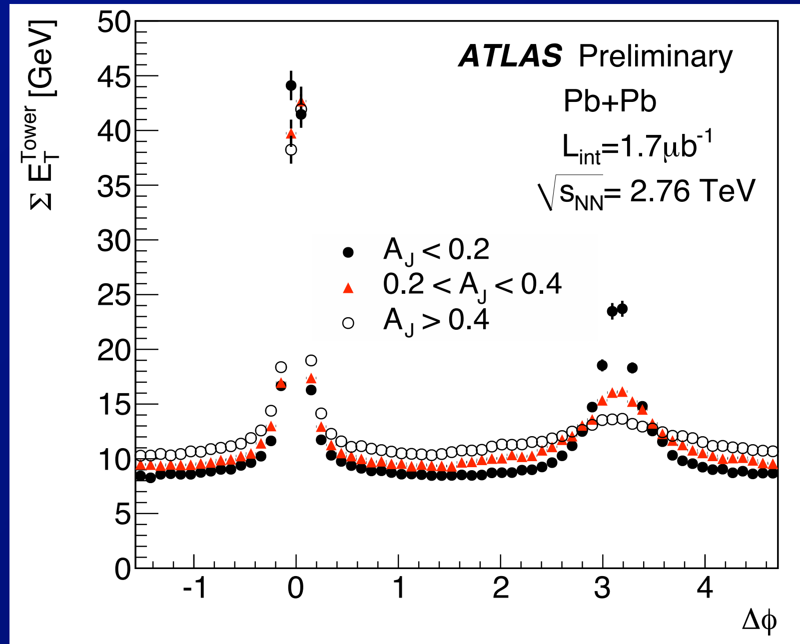


- Anti-k_t R = 0.4, jet reconstruction efficiency
  - truth match $\Delta R < 0.2$

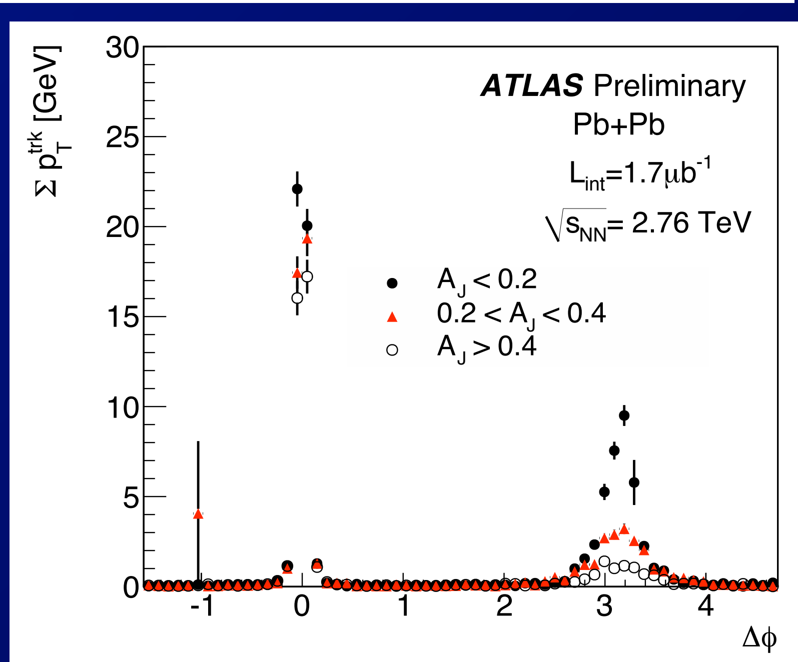
Energy, p_T flow analysis



Calorimeter E_T with no subtraction

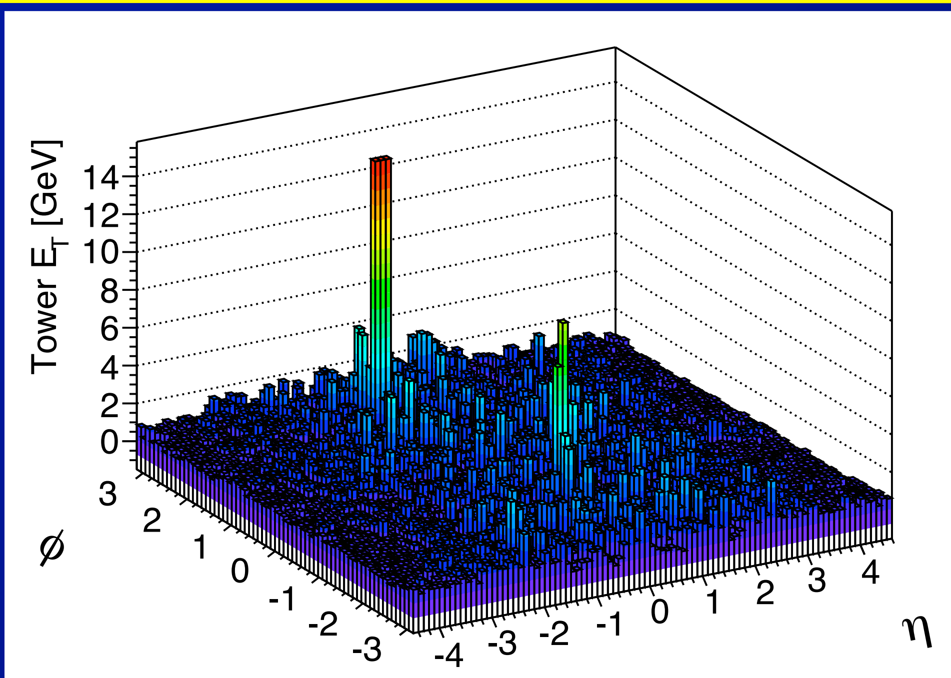


Tracks, p_T > 4 GeV



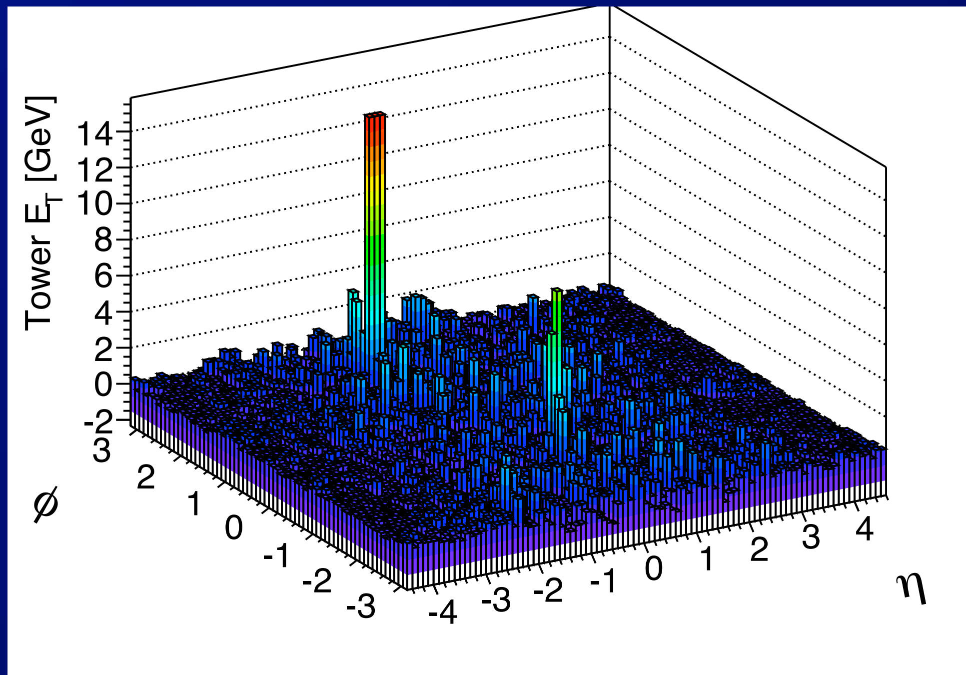
- Independent check without jet algorithm and no subtraction
  - Asymmetry seen in calorimeter data
  - And also in tracks

Dijet event before & after

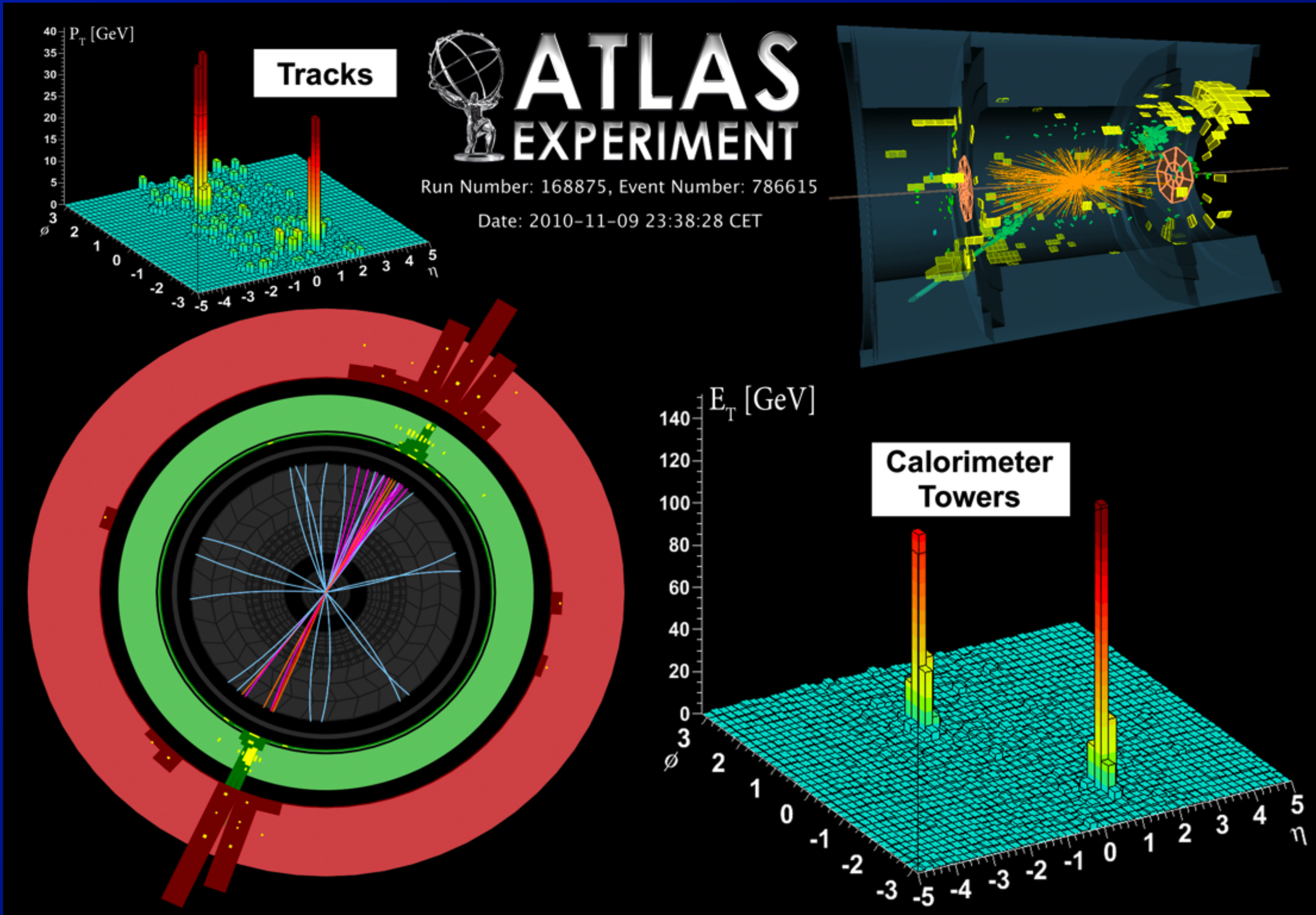


- Before subtraction
  - ΣE_T in $\Delta\eta x \Delta\varphi$ = 0.1x0.1 towers

- After subtraction, underlying event at zero
- Event topology unchanged by subtraction.

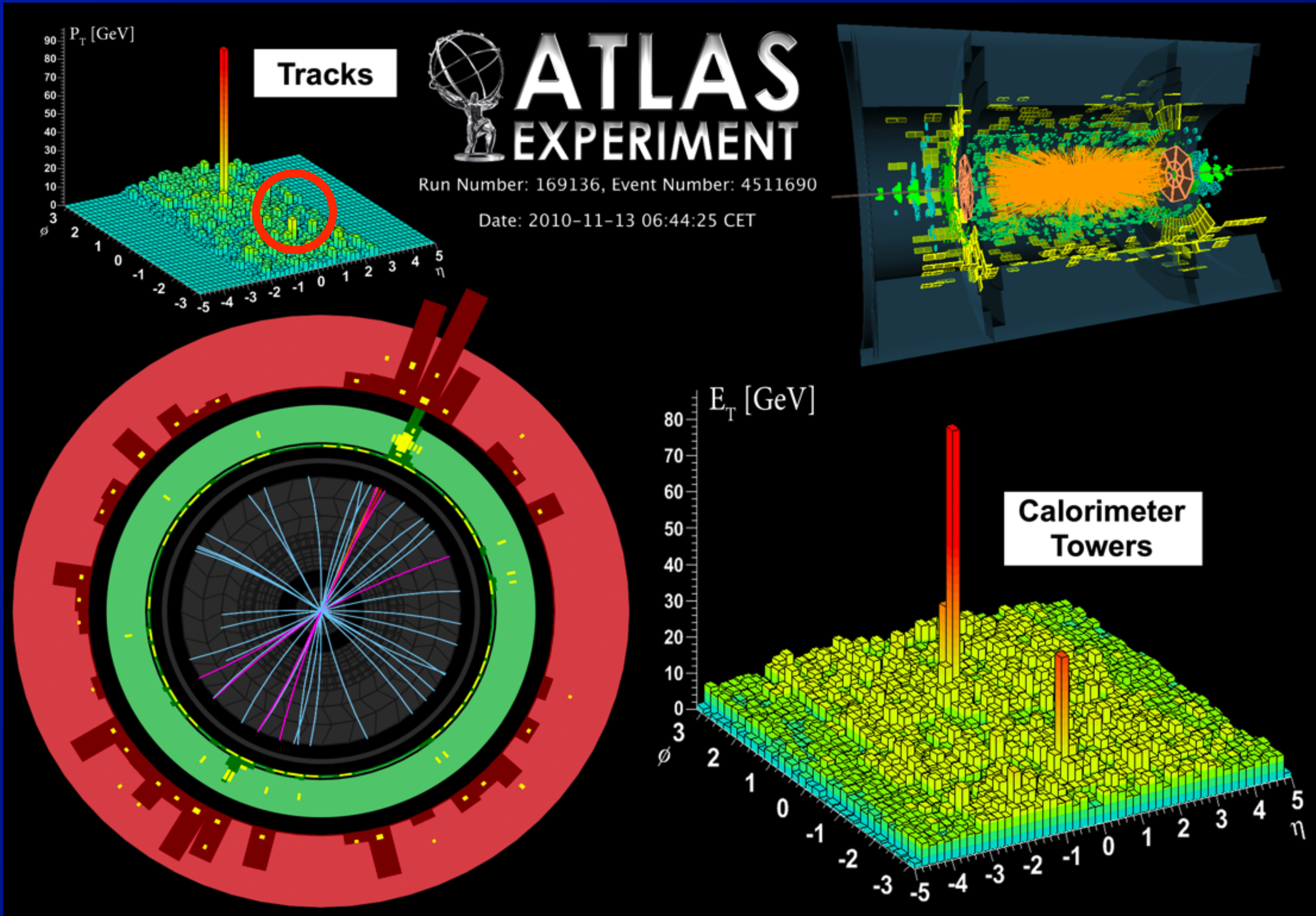


A (more) symmetric dijet event



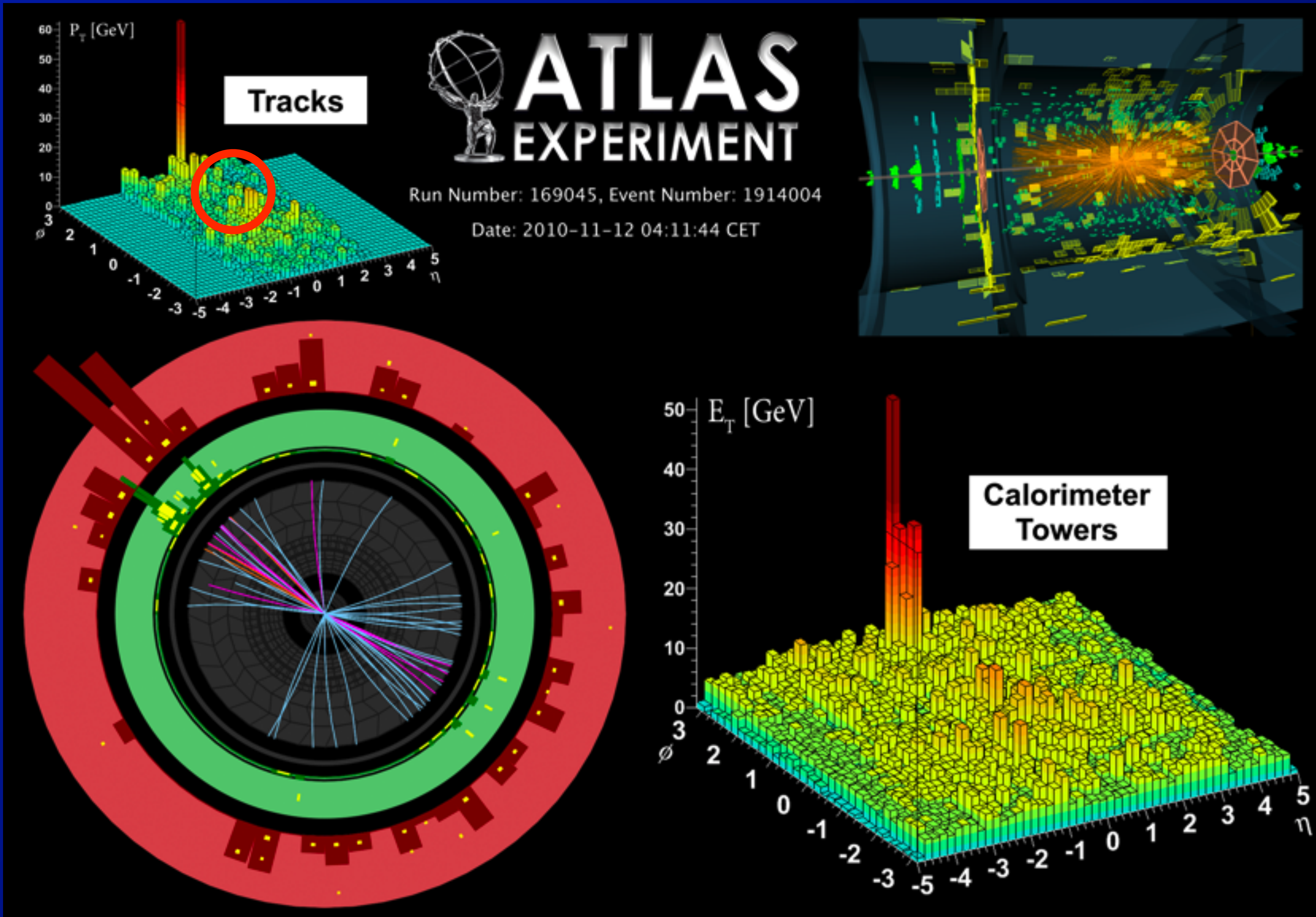
Peripheral, symmetric dijet event

An asymmetric event



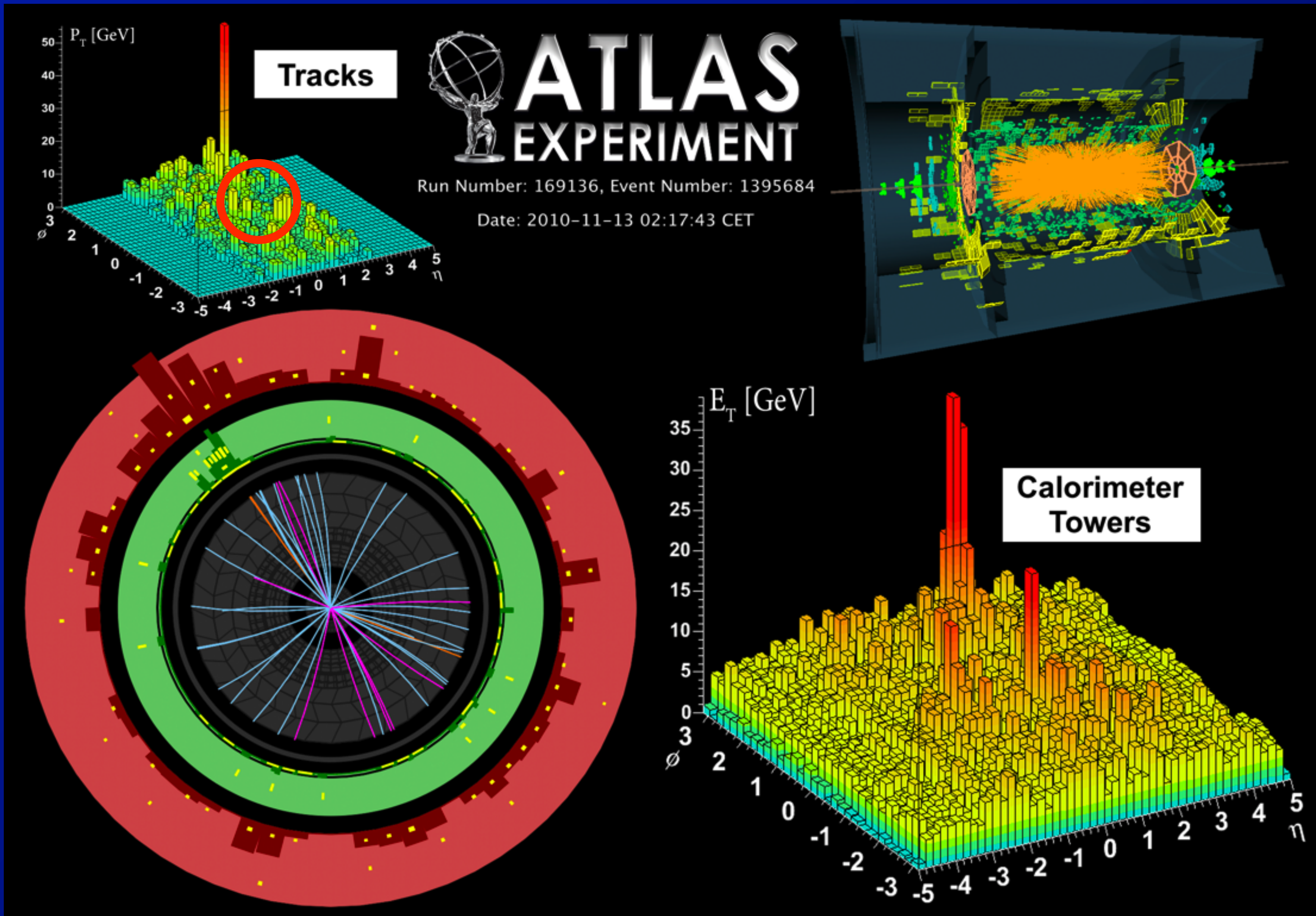
More central, asymmetric dijet event

Another asymmetric event



Even more central collision, more asymmetric dijet

Yet another asymmetric event



Central event, with split dijet + additional activity