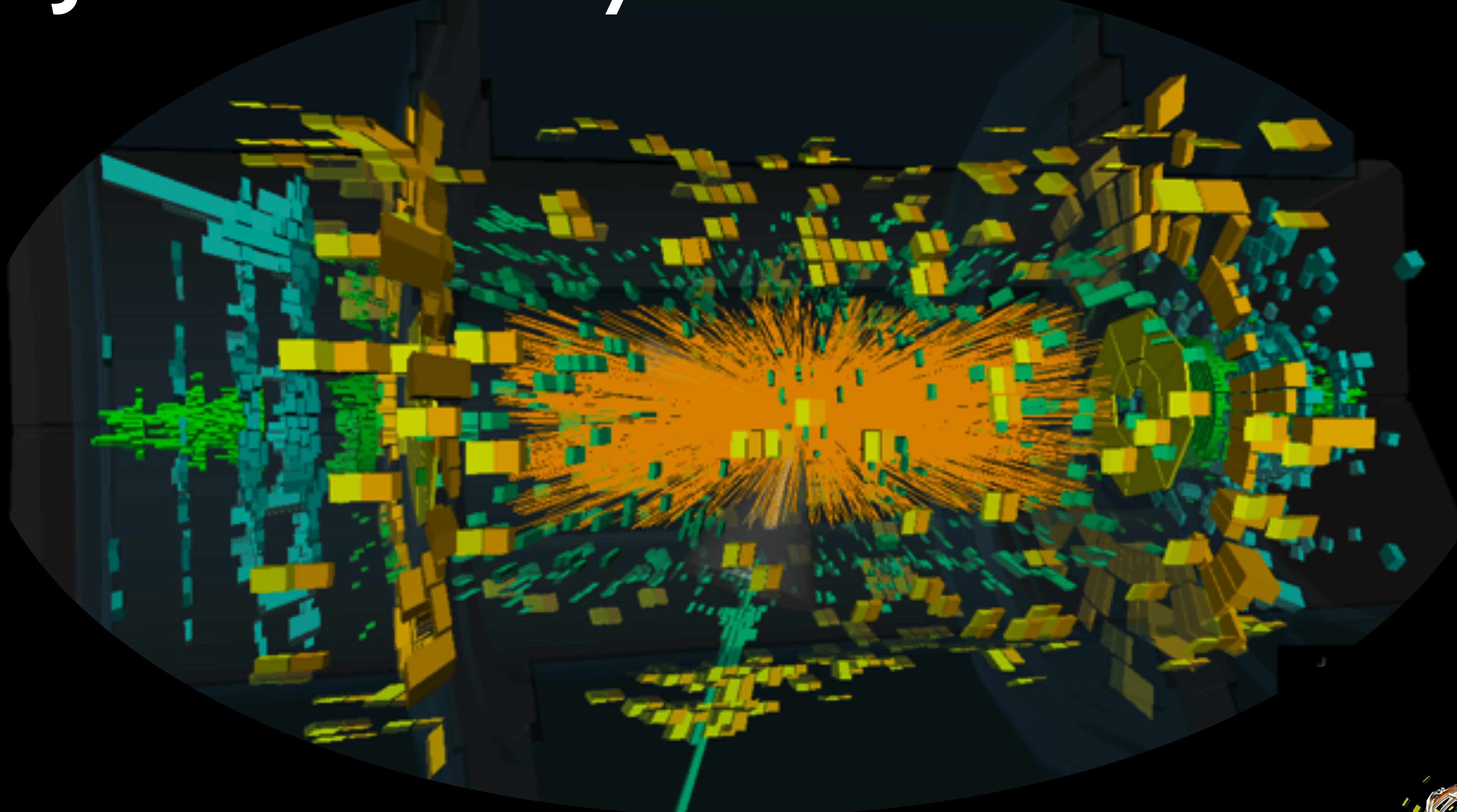
Jets in Heavy Ions with ATLAS



Will Brooks
USM, Valparaíso, Chile
For the ATLAS Collaboration

High-energy jets in heavy ion collisions

ATLAS-CONF-2011-075

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  - radial profile
  - fragmentation functions
  - internal distribution of momenta
- What we have found is surprising, intriguing, unexpected

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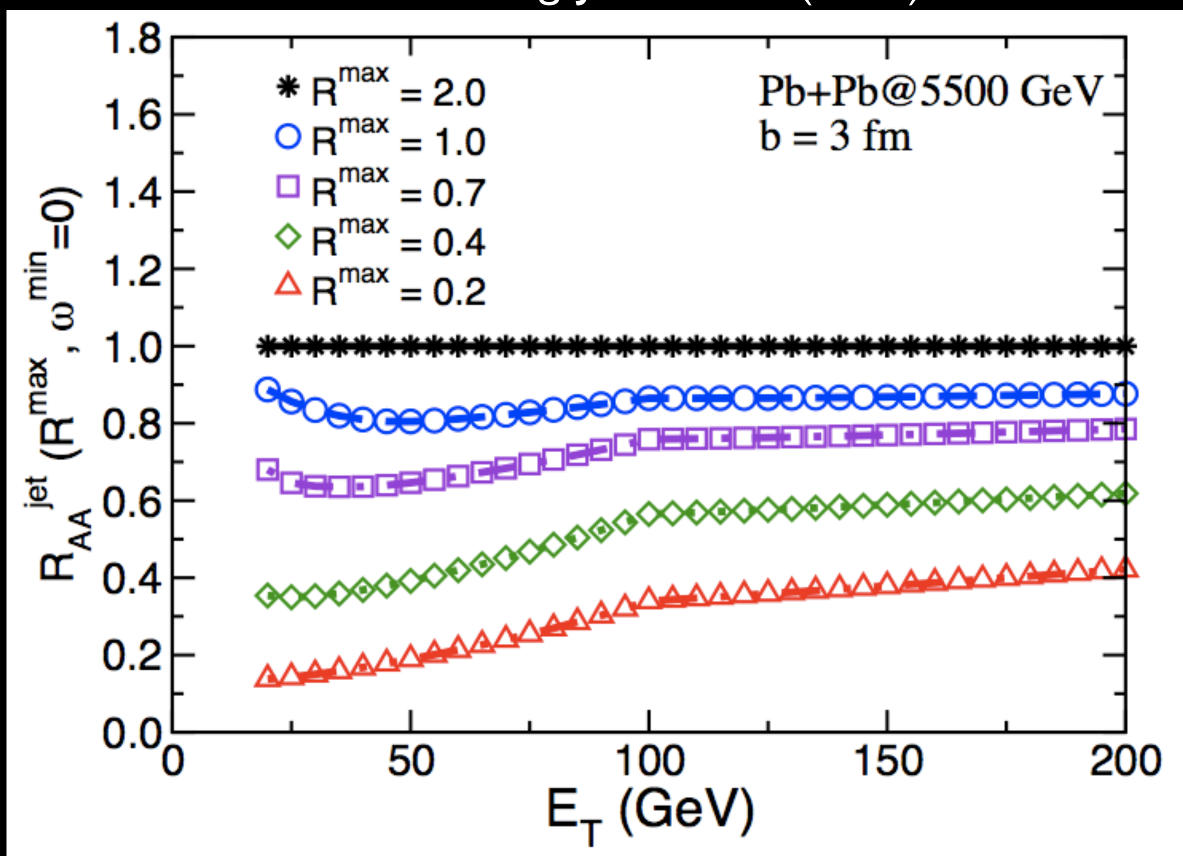
Theoretical expectations prior to LHC HI data: *modified jet shape*

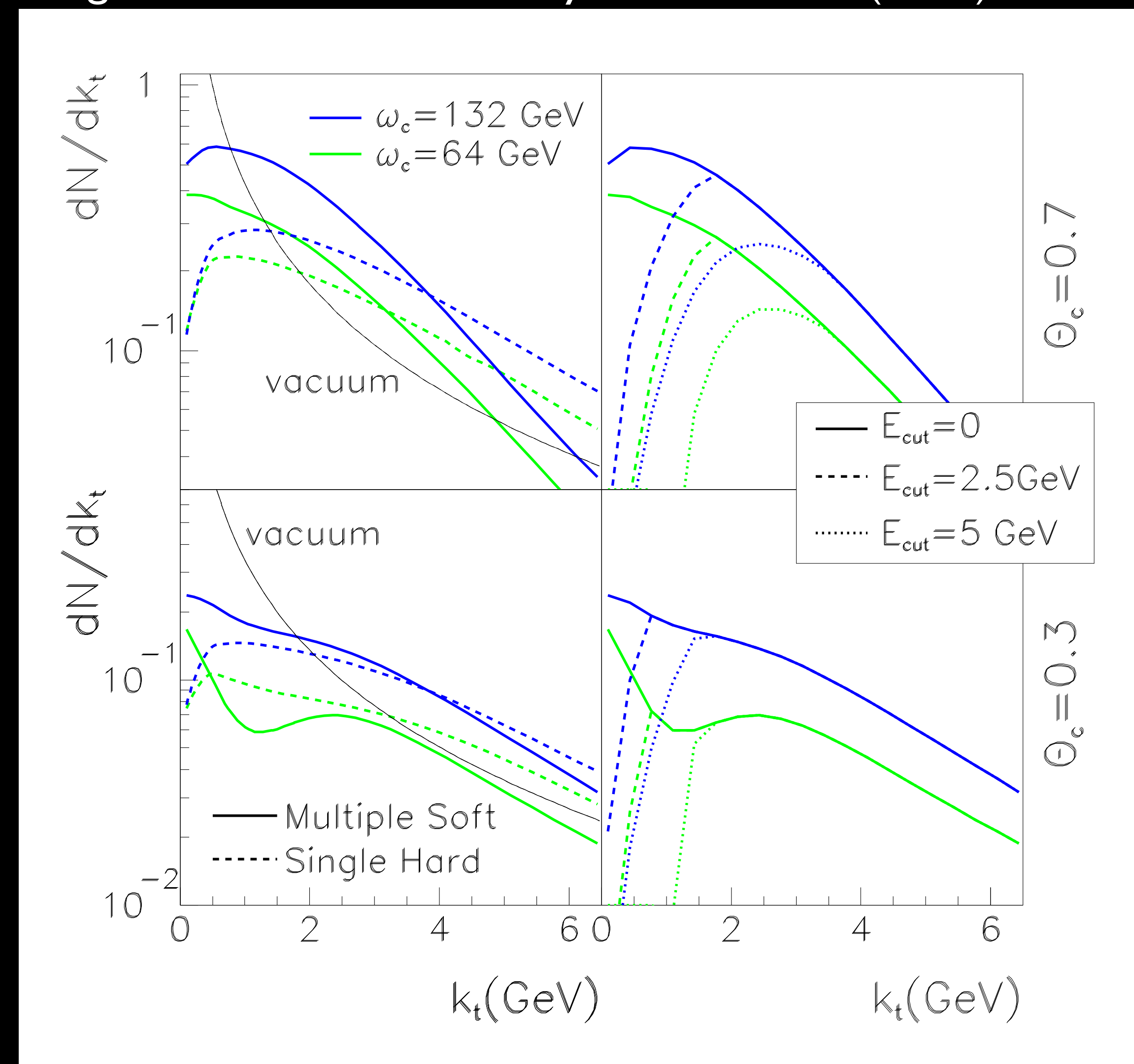
Vitev, Wicks, Zhang, JHEP 0811 (2008) 093



Substantially expanded jet cone with diffuse edge

Jet suppression depends critically on cone size

Salgado and Wiedemann, Phys. Rev. Lett. 93 (2004) 042301

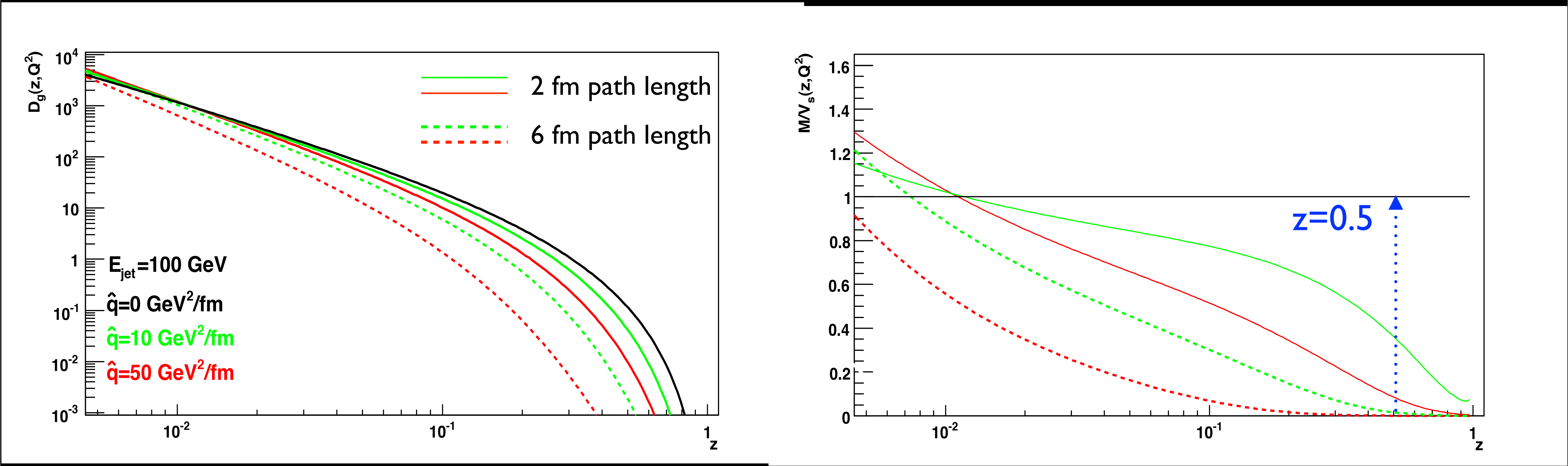


Broadened distribution of transverse momentum within jet

(however, note Zapp et al., arXiv:0805.4759v2 [hep-ph])

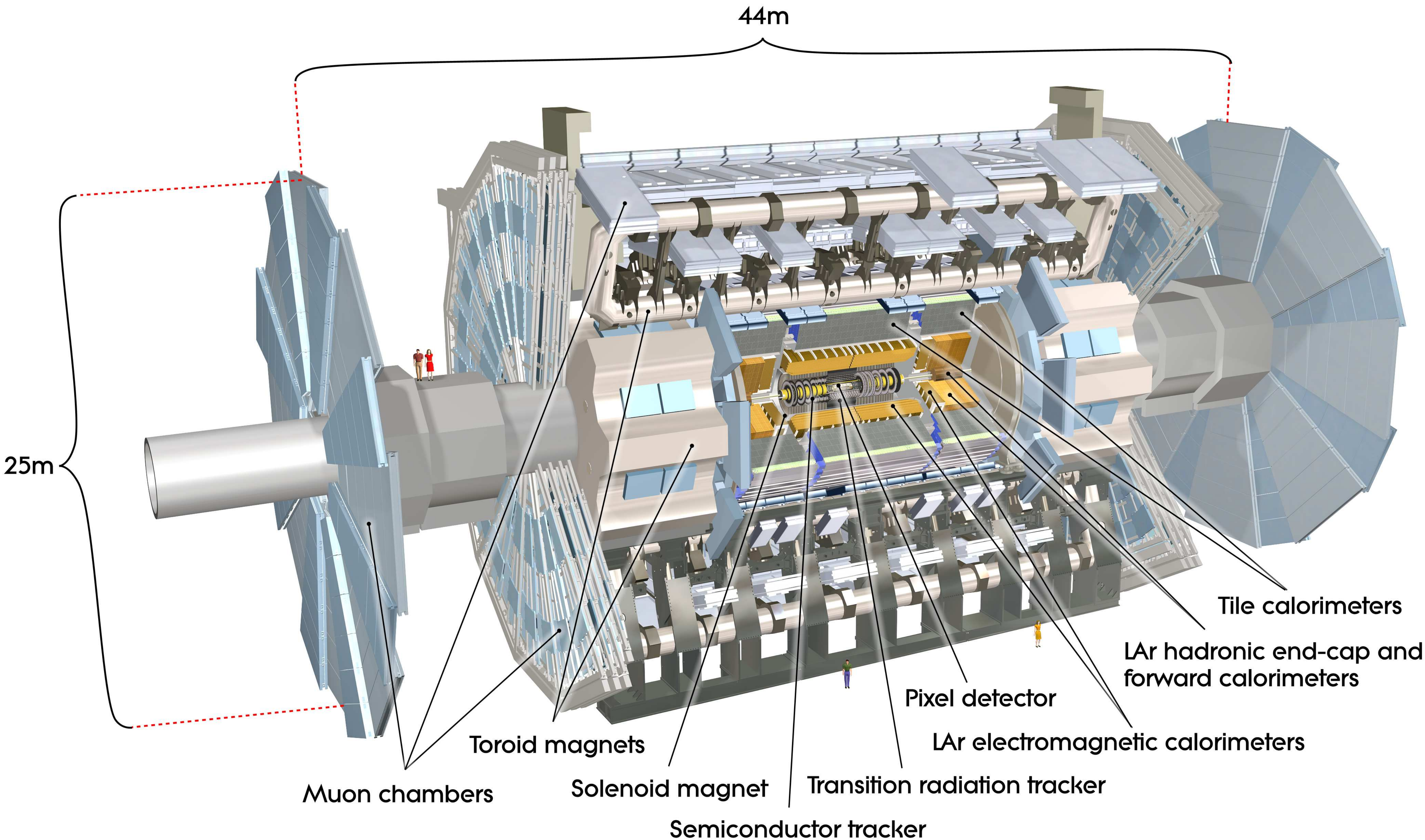
Theoretical expectations prior to LHC HI data: *modified jet fragmentation function*

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



- Redistribution of high-z component to low z
- Results in strong depletion of higher-z component, e.g., factor >2 at z=0.5 for $\hat{q} = 10\ GeV^2/fm$

ATLAS Instrumentation



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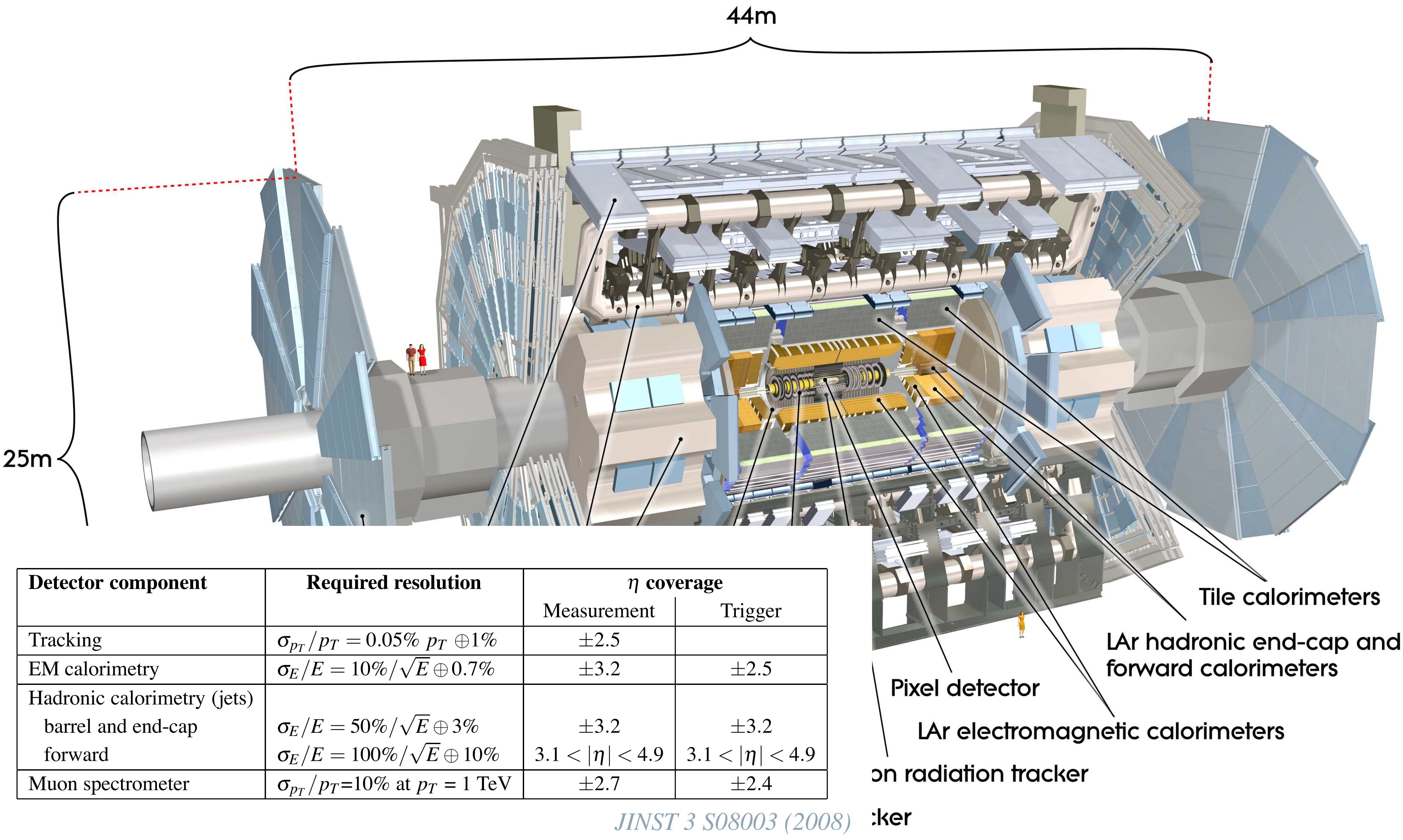
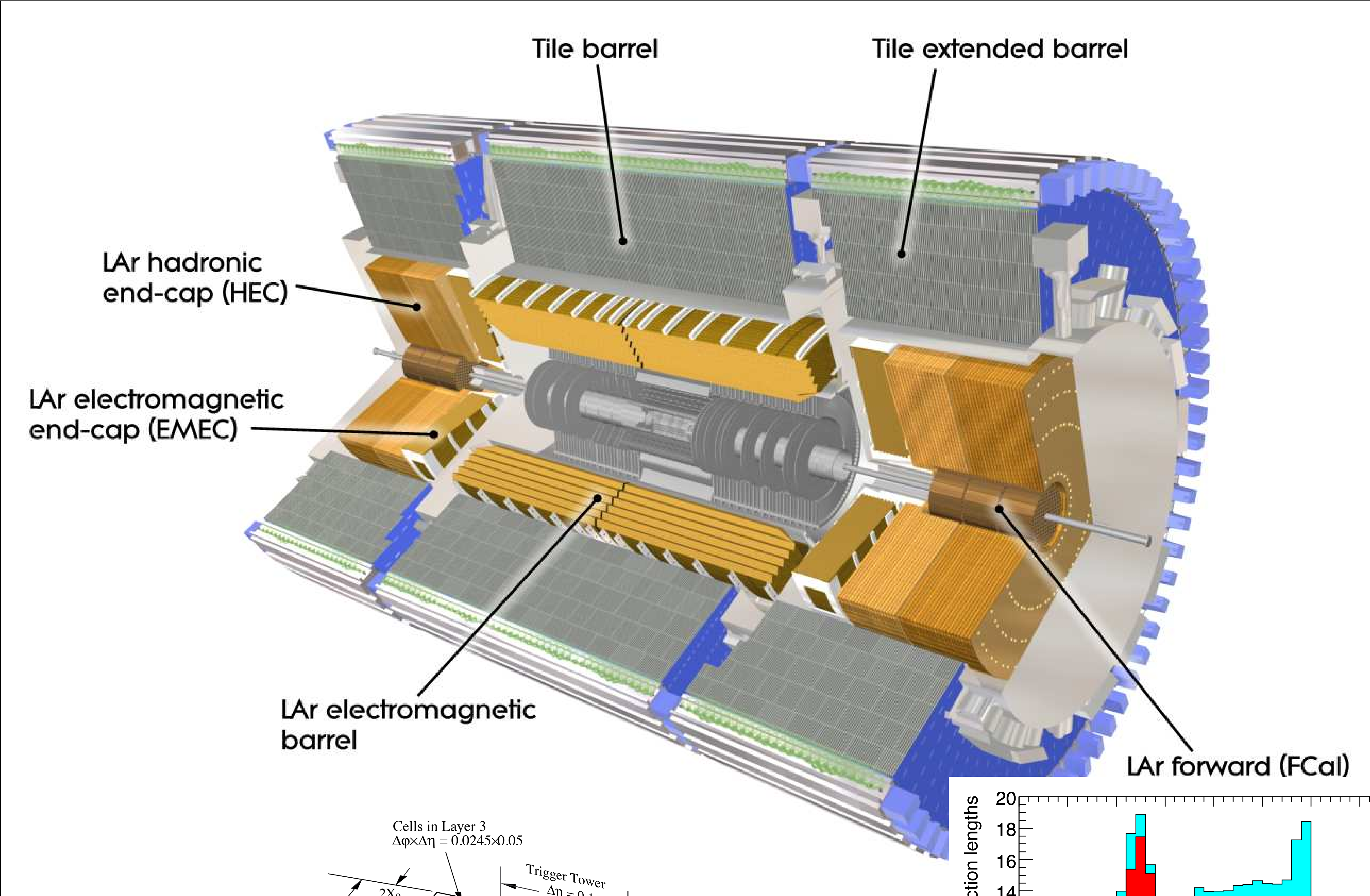
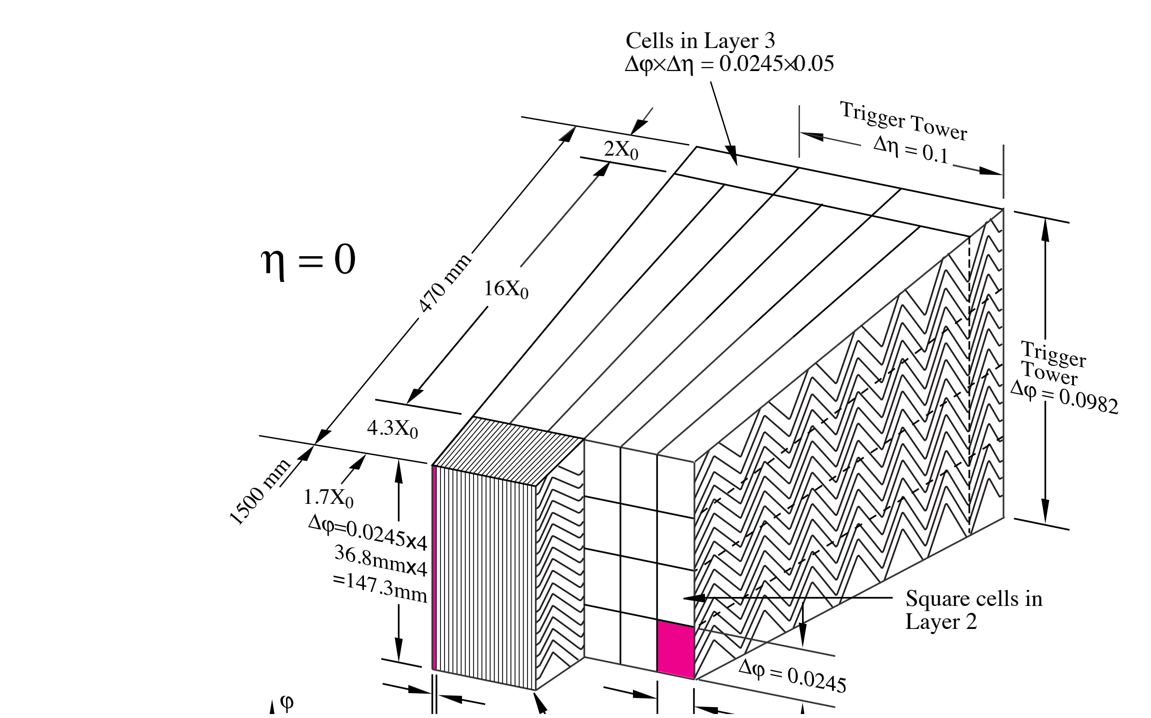
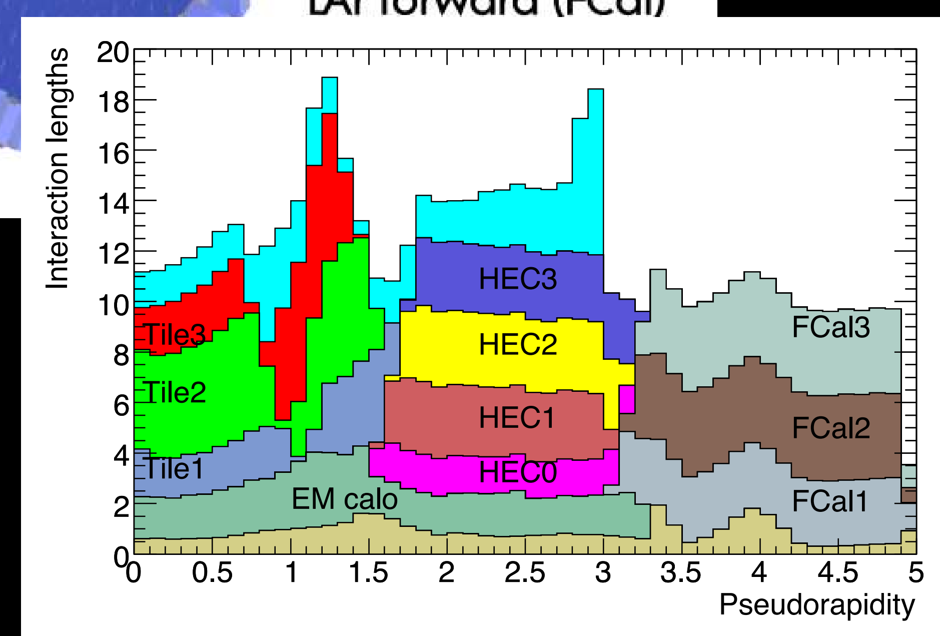


Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	± 2.7	± 2.4

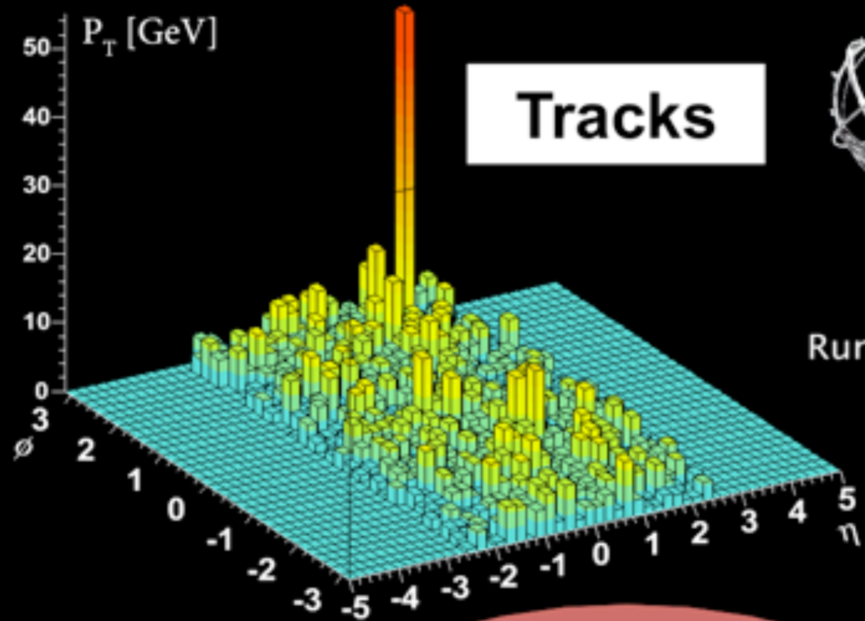
JINST 3 S08003 (2008)







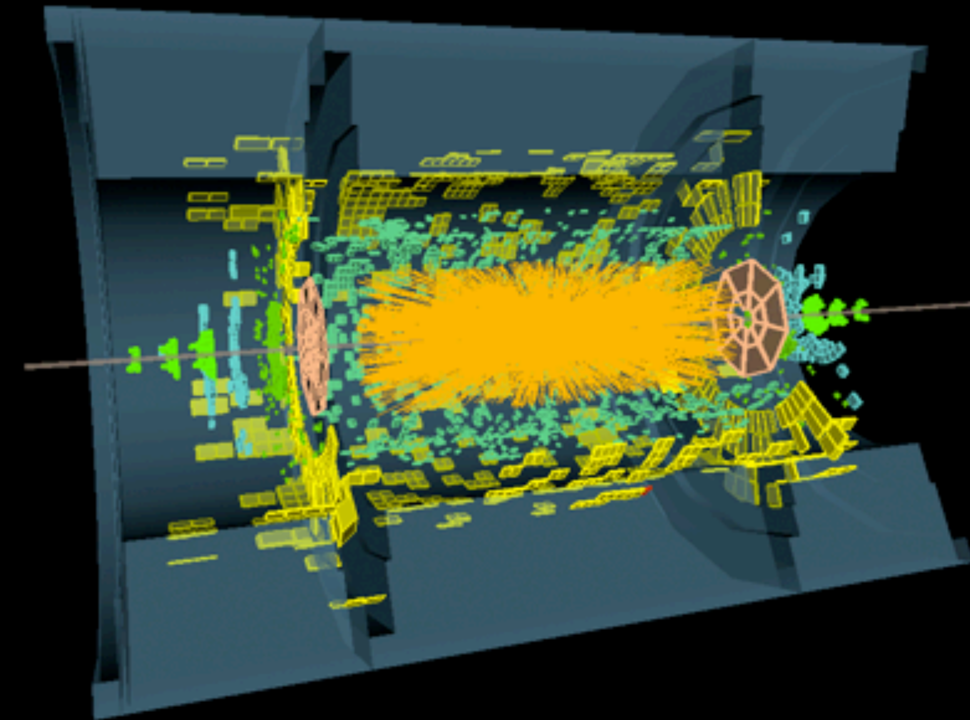
ATLAS Calorimeters

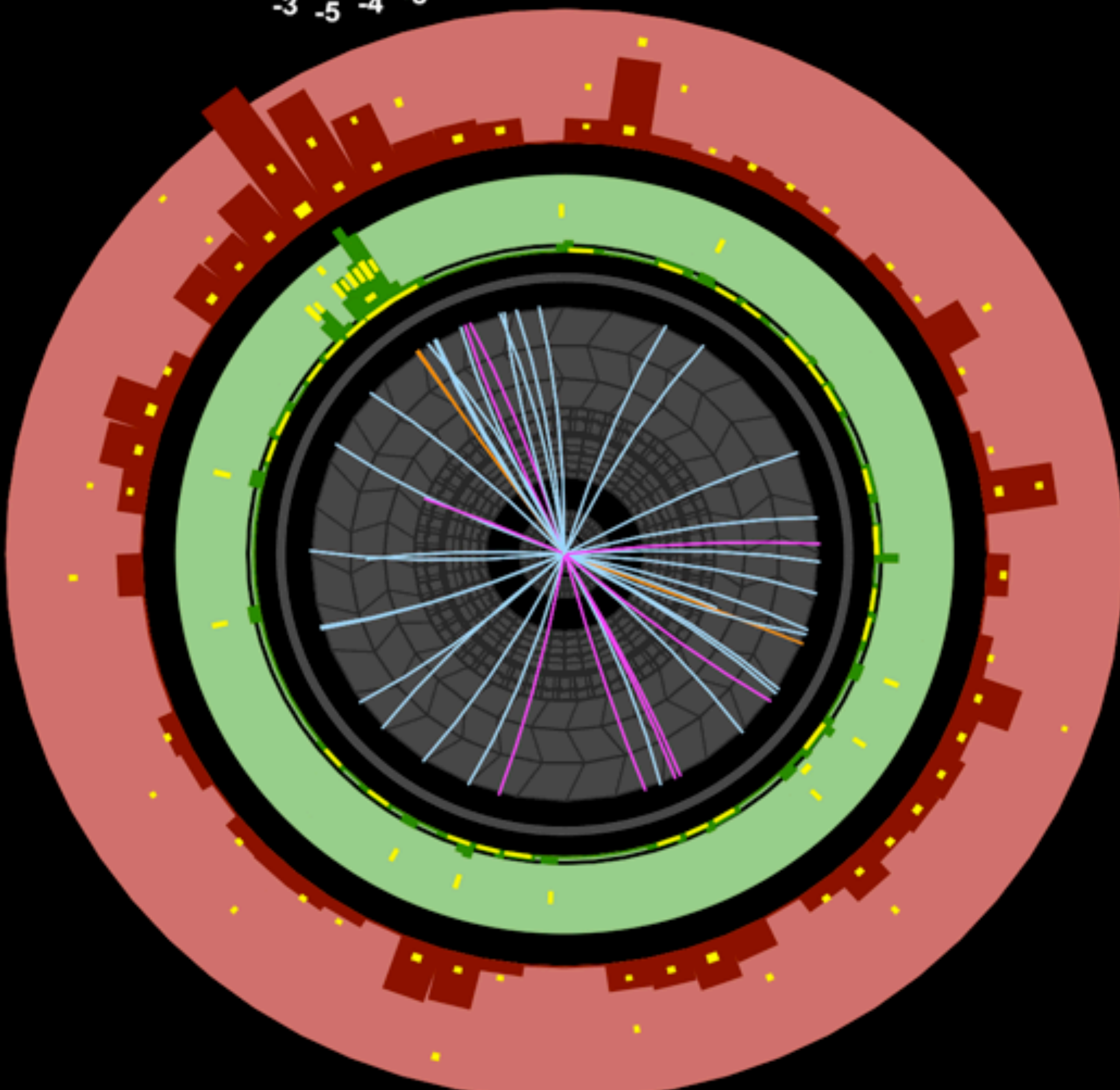


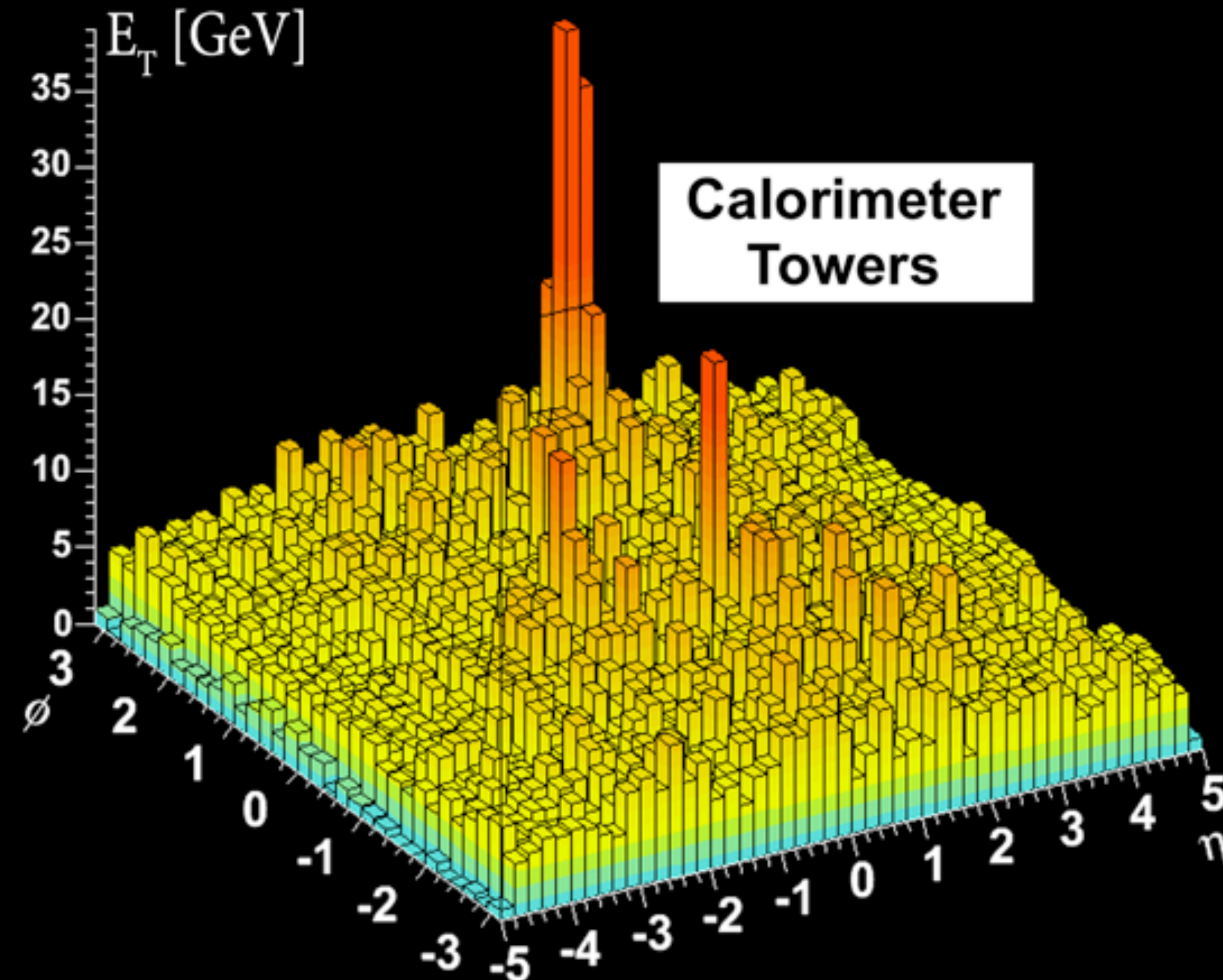
ATLAS EXPERIMENT

Run Number: 169136, Event Number: 1395684

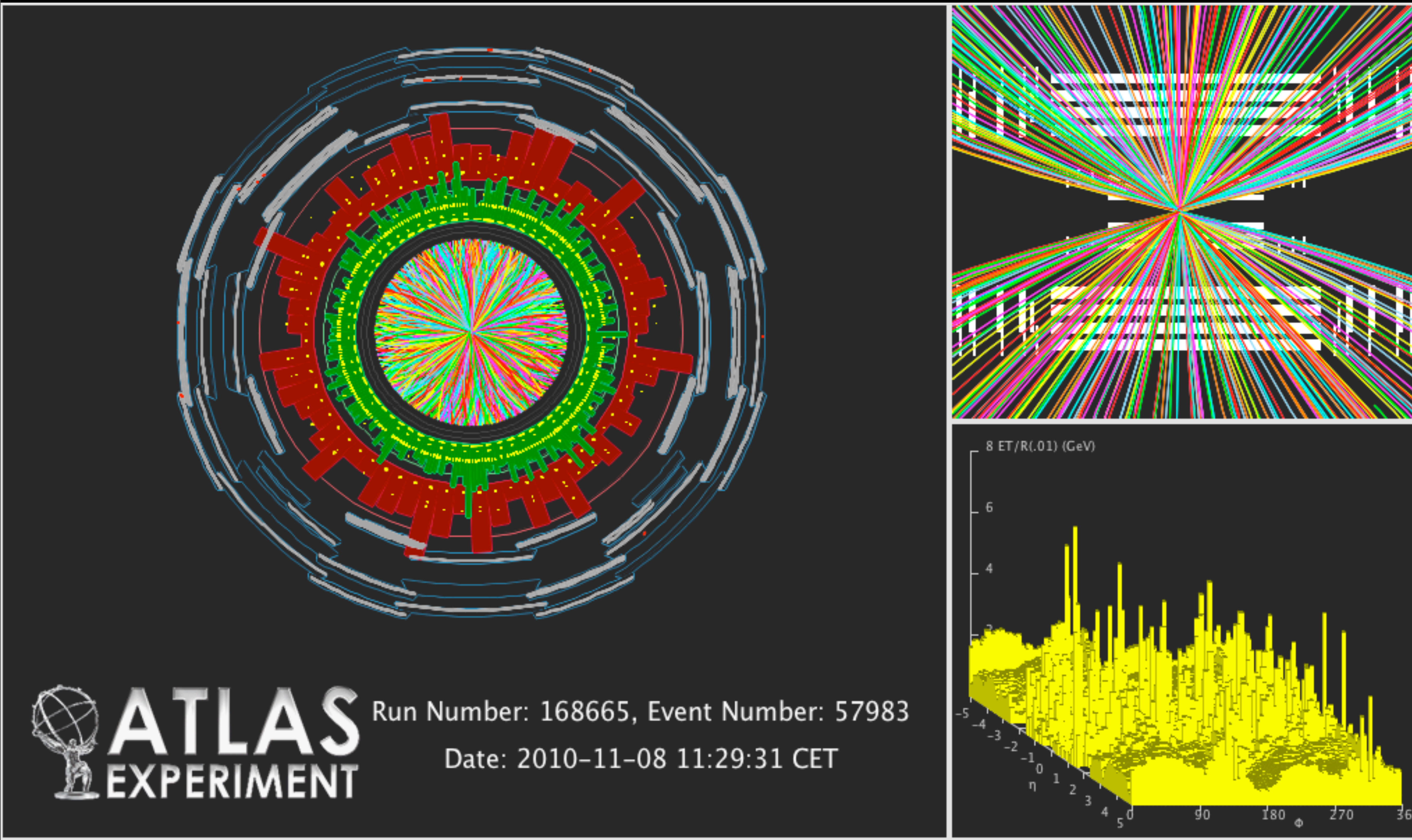
Date: 2010-11-13 02:17:43 CET

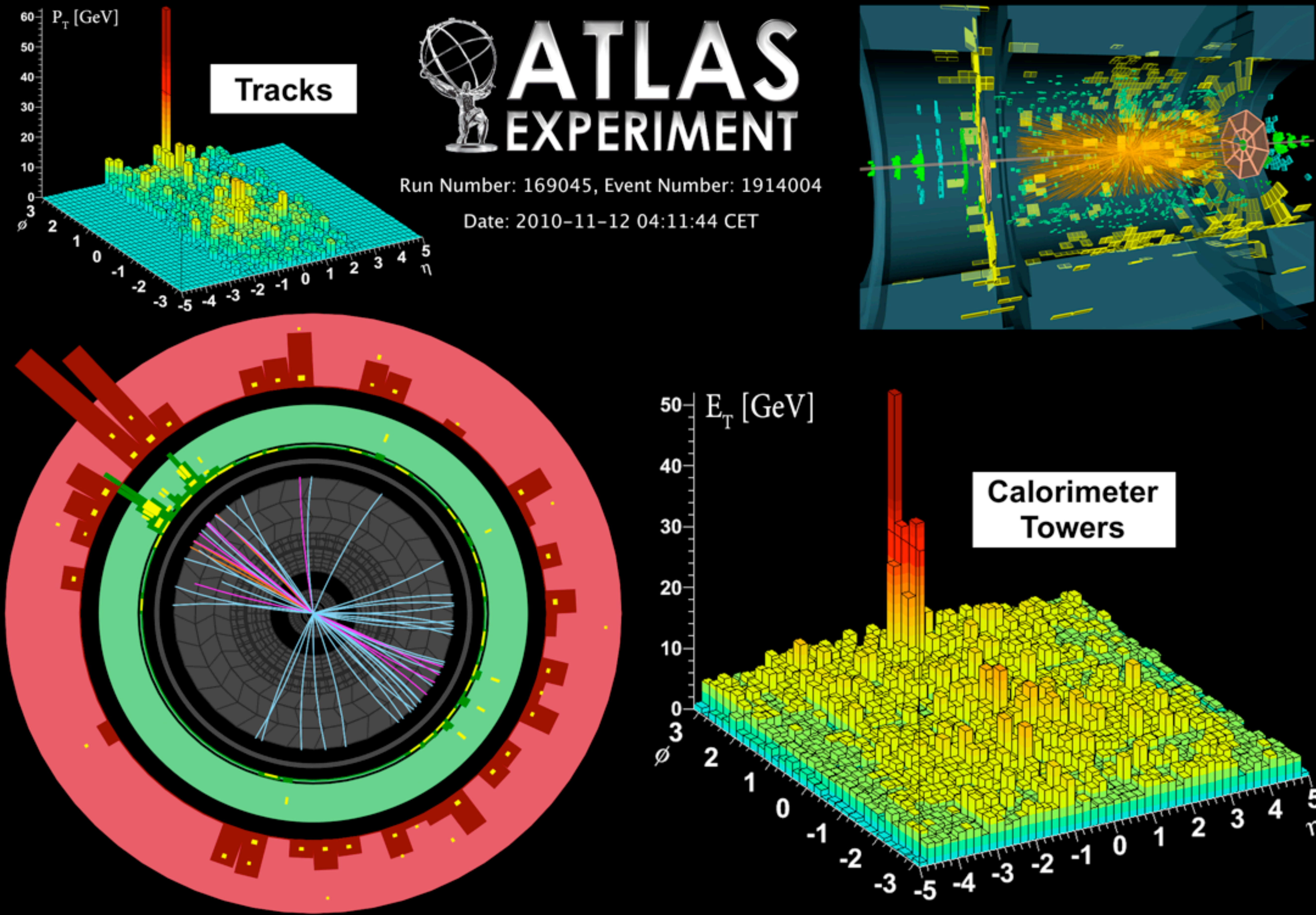


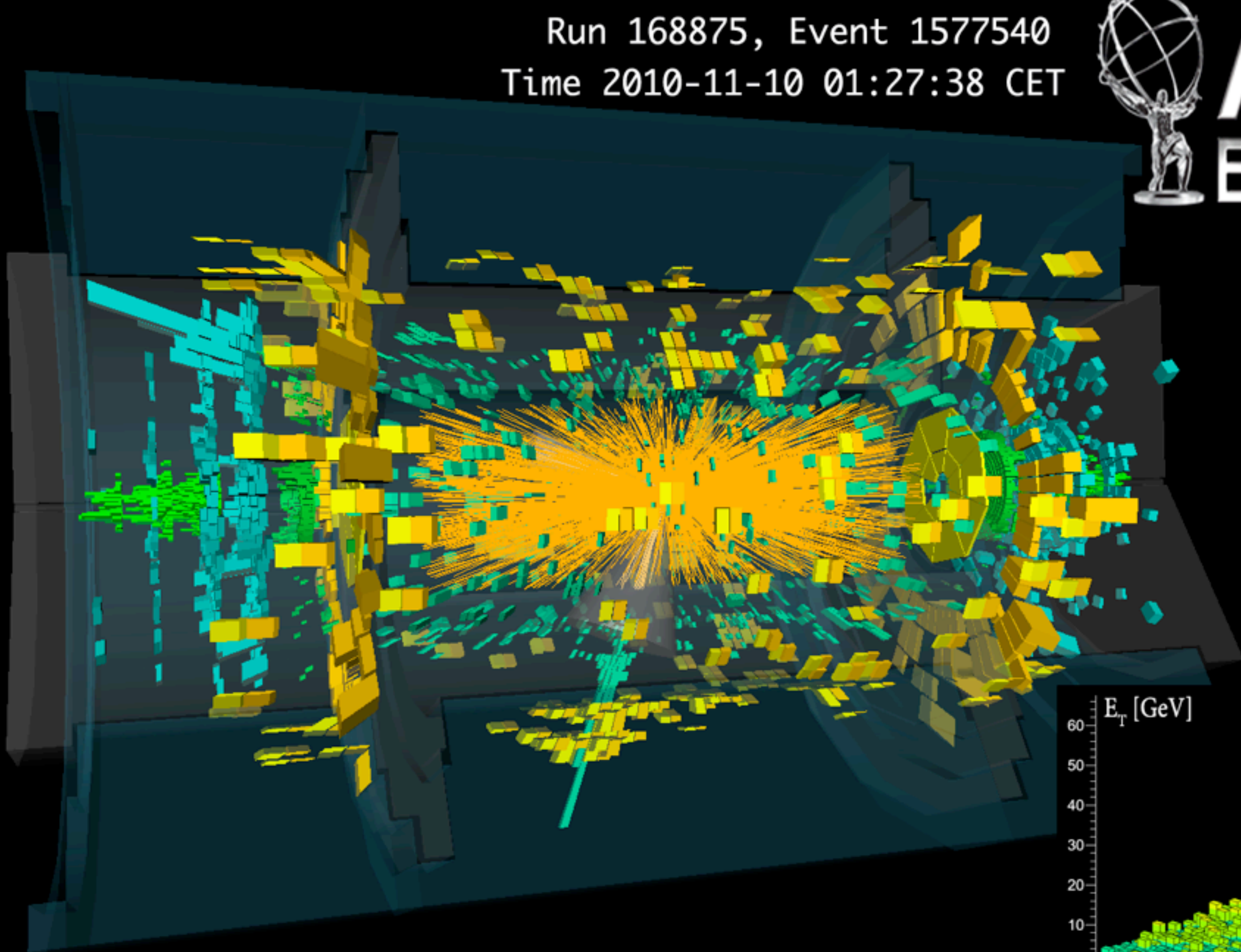


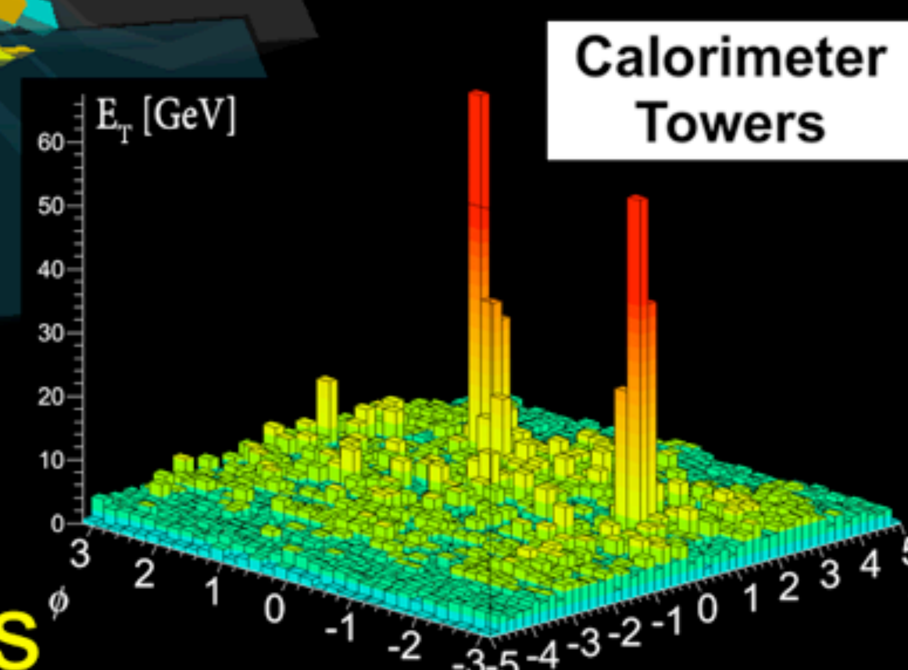


Pb+Pb data in ATLAS



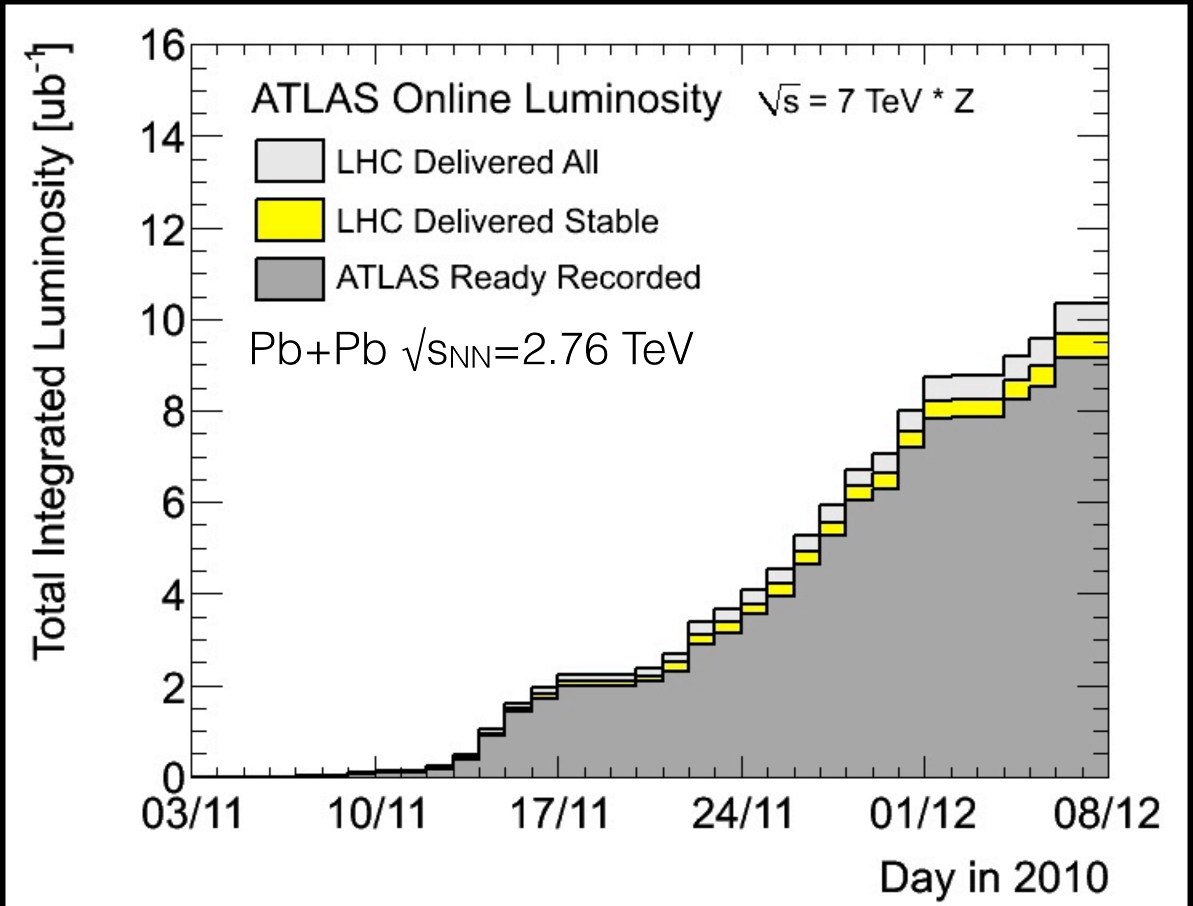

ATLAS EXPERIMENT
Run Number: 169045, Event Number: 1914004
Date: 2010-11-12 04:11:44 CET
Tracks
P_T [GeV]
Calorimeter Towers
E_T [GeV]
ø
η

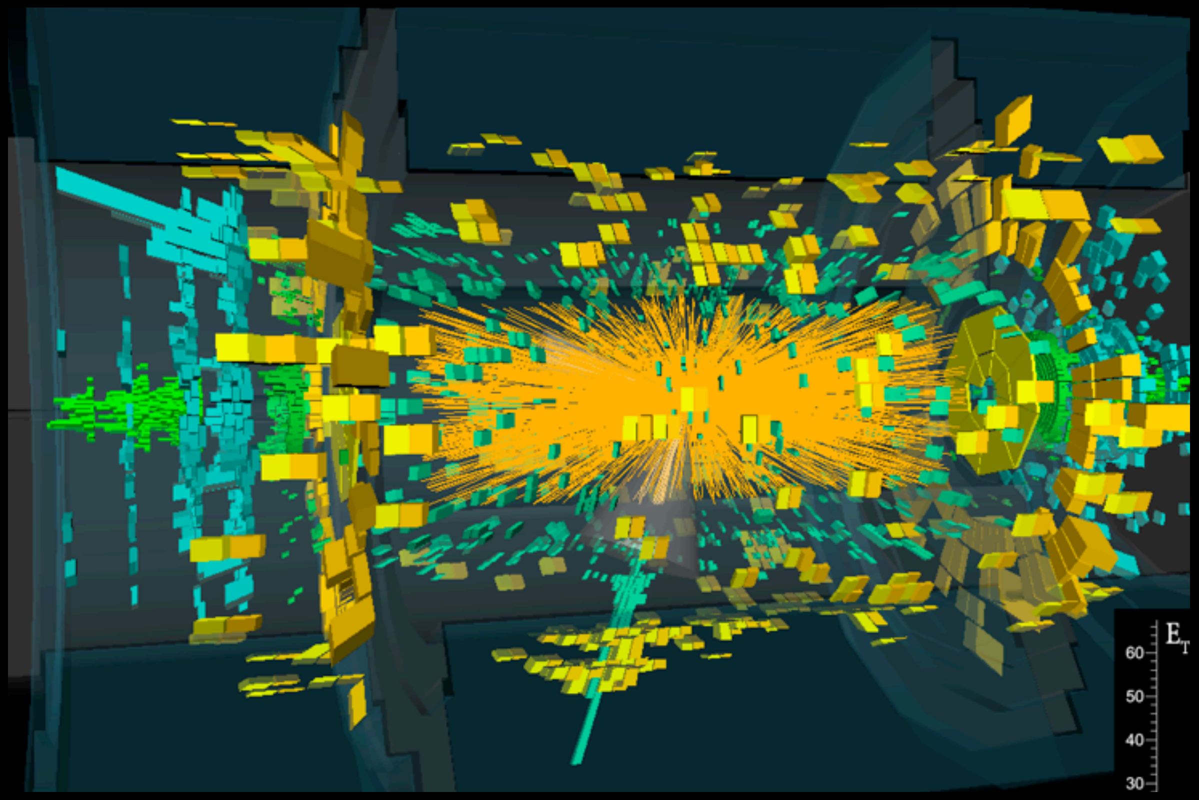




Heavy Ion Collision Event with 2 Jets

Pb+Pb data in ATLAS





- Trigger:
  - minimum bias scintillators, both sides firing within 3 ns
  - zero degree calorimeter coincidence
- Using good runs with solenoid field on, have 47 million events

Jet reconstruction

- Used anti-k_T clustering algorithm (Cacciari, M., Salam, G. P. and Soyez, G., The anti-kt jet clustering algorithm, Journal of High Energy Physics, 2008, 063)
  - 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: $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ towers
- Underlying event estimated and subtracted for each longitudinal layer and for 100 slices of $\Delta\eta = 0.1$

$$E_{T\,sub}^{\,cell} = E_T^{cell} - \rho^{layer}(\eta) \cdot A^{cell}$$

- ρ is energy density estimated event-by-event, from average over $0 < \varphi < 2\pi$

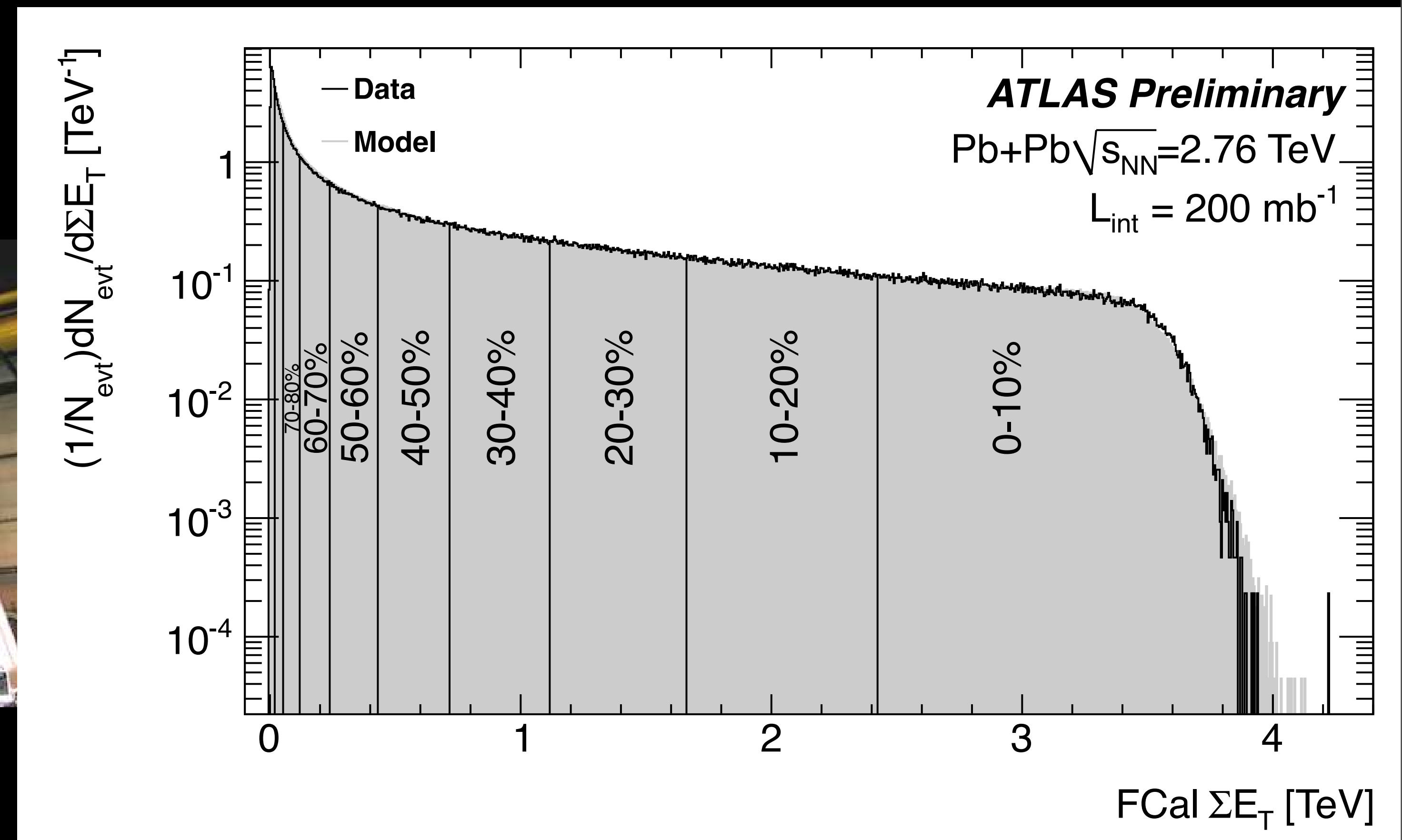
Jet reconstruction bias

- Avoid biasing ρ due to jets – two methods:
  - Sliding window exclusion
  - Exclude cells in jets satisfying:

$$D = \frac{{E_T}^{tower}_{max}}{< {E_T}^{tower} >} > 4$$

- 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 v2

Centrality measurement using FCAL



- Jets measured $|\eta|<2.8$, no interference: $|\eta_{FCAL}|>3.1$
- Correlation between ΣE_T of FCAL and other calorimeters
- Centrality translated into $\langle N_{coll} \rangle$ via Glauber model

Ann.Rev.Nucl.Part.Sci.57:205-243,2007, http://arxiv.org/abs/0805.4411

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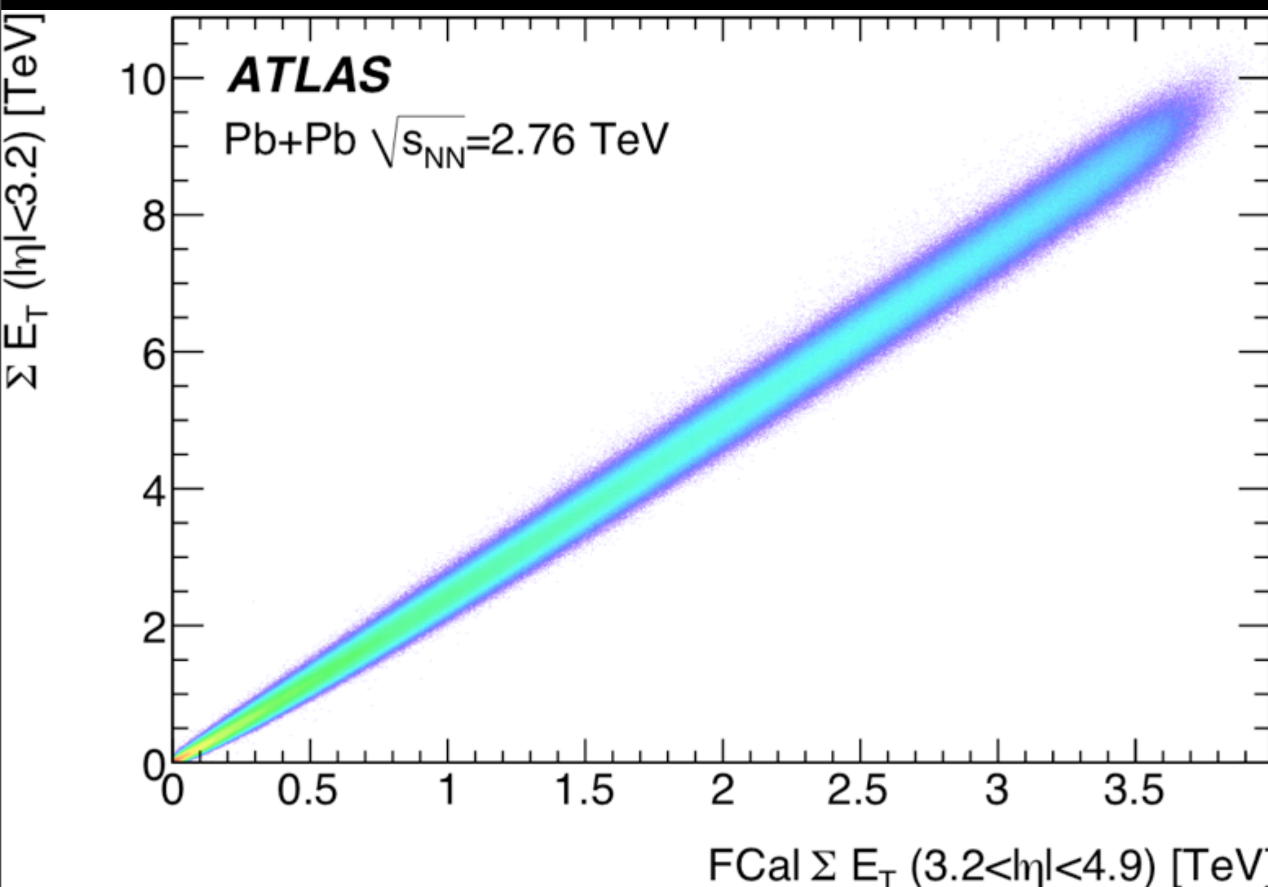

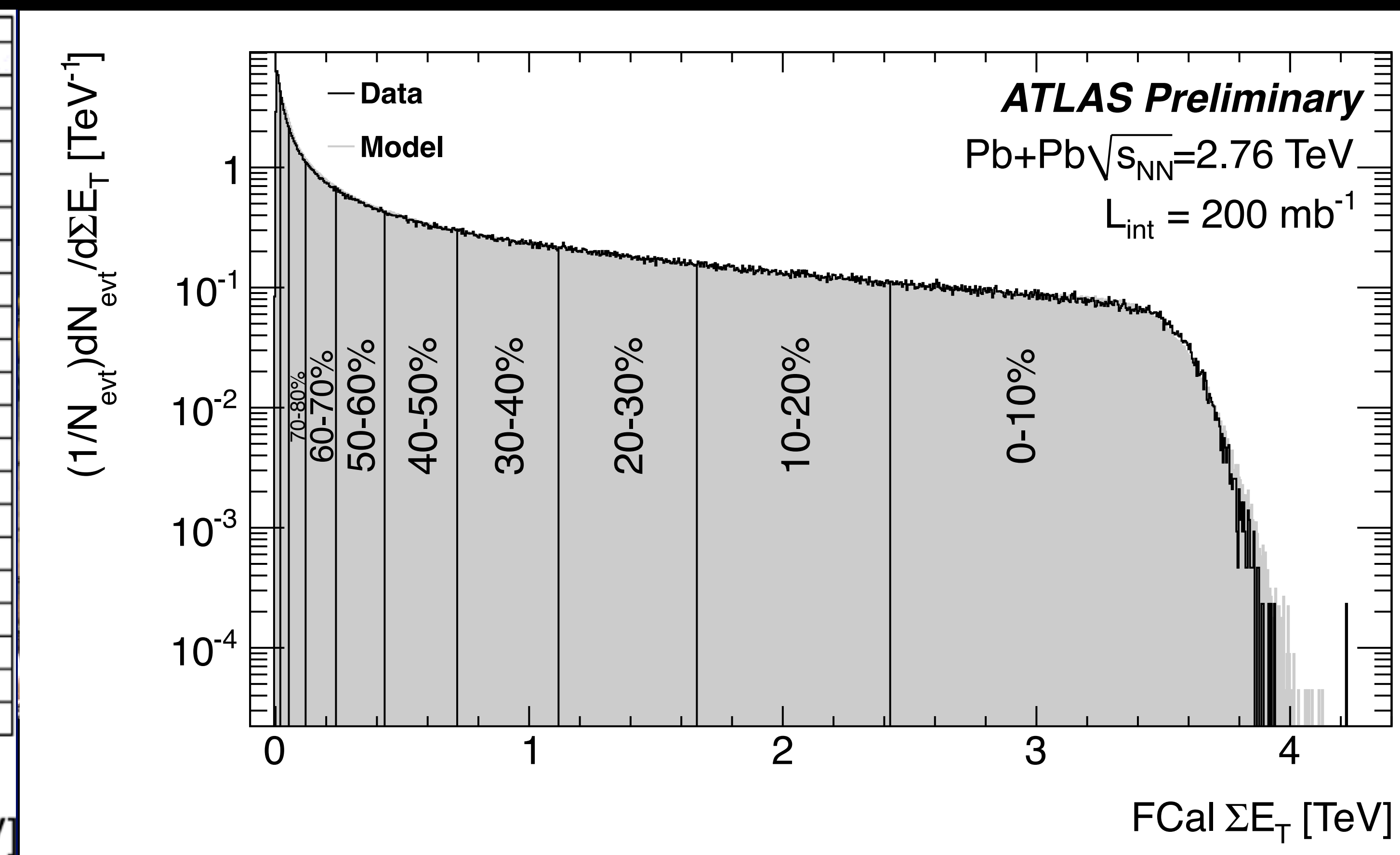

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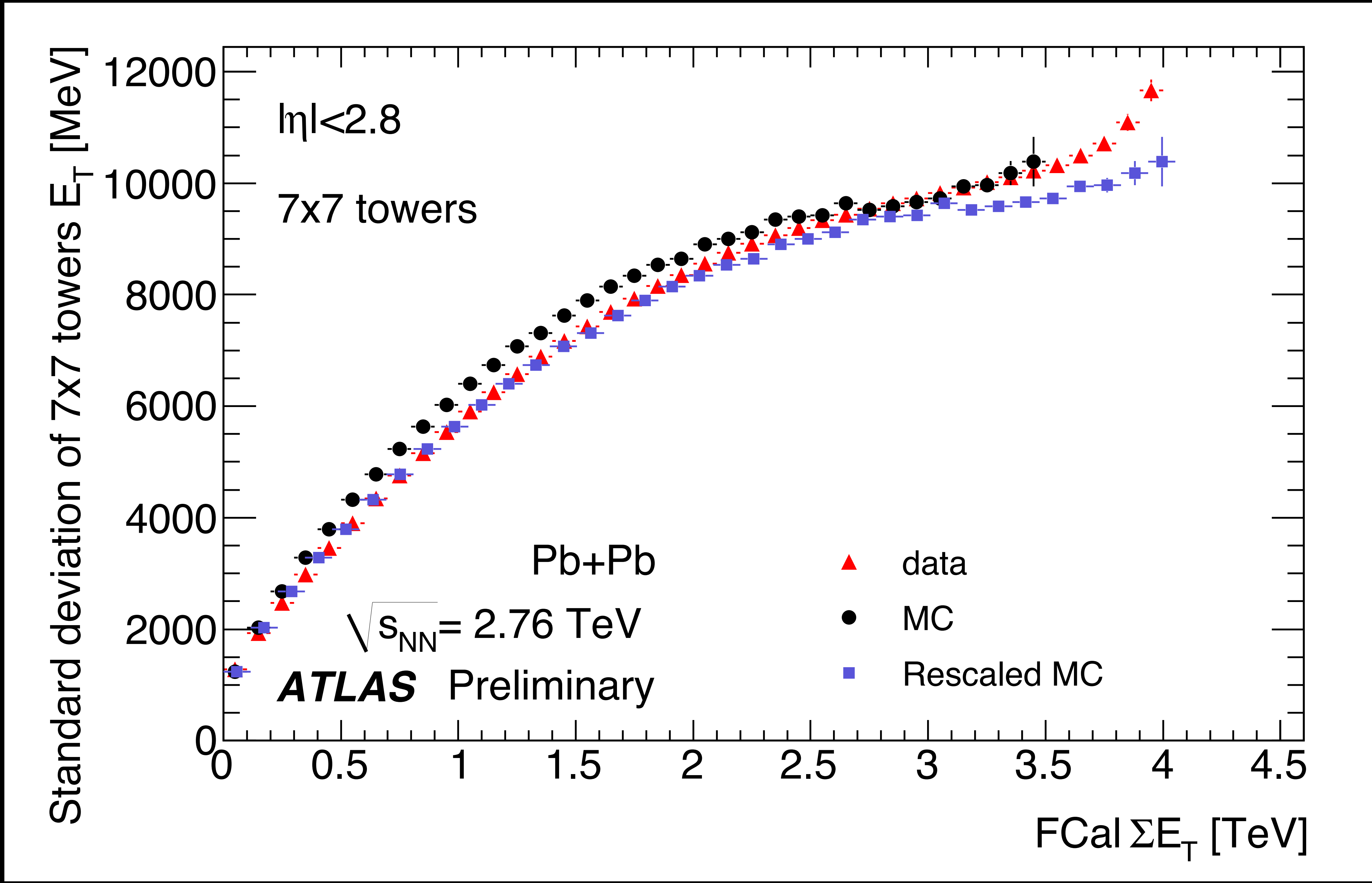
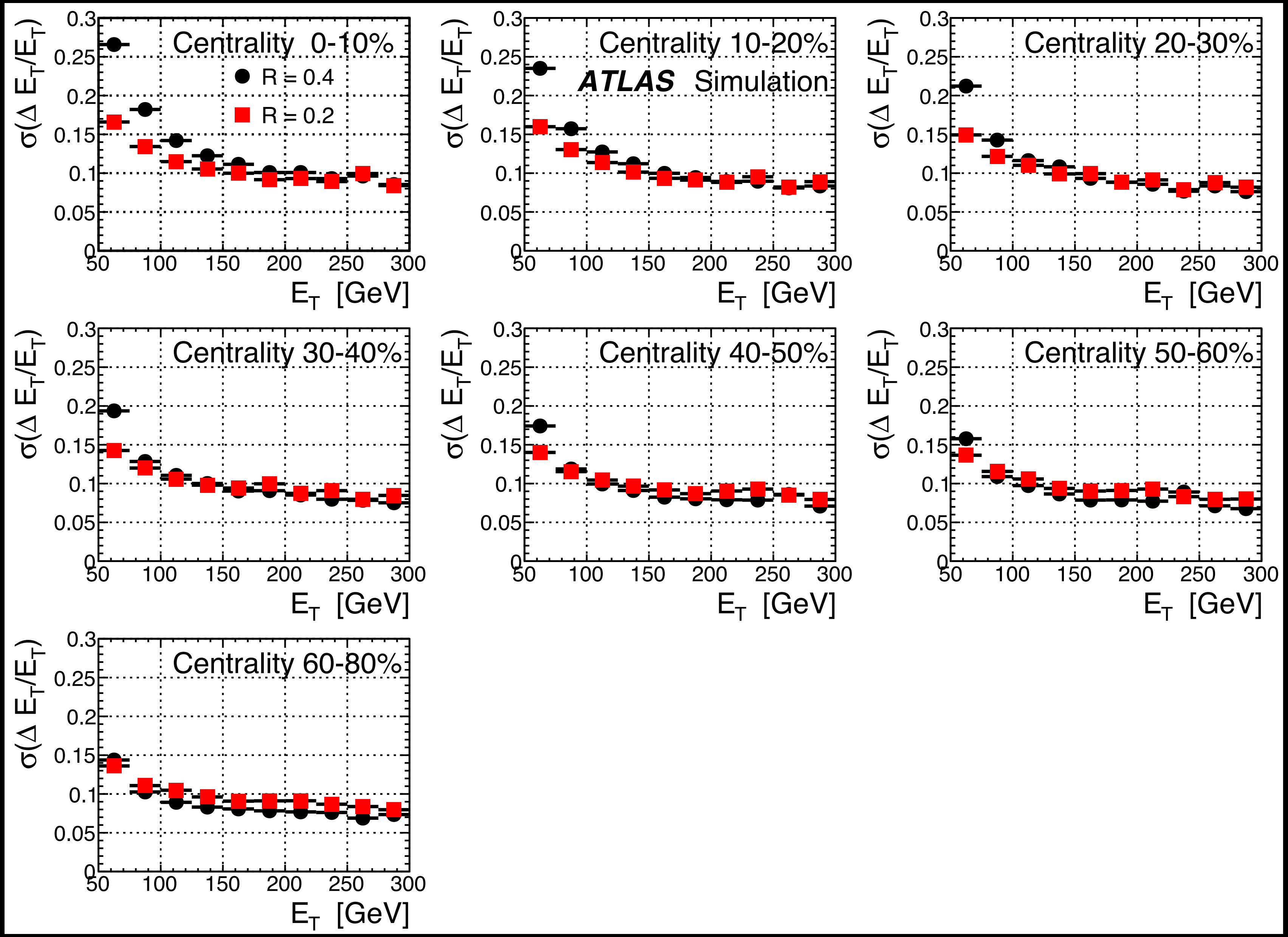
Fluctuations in ΣE_T, Data and MC



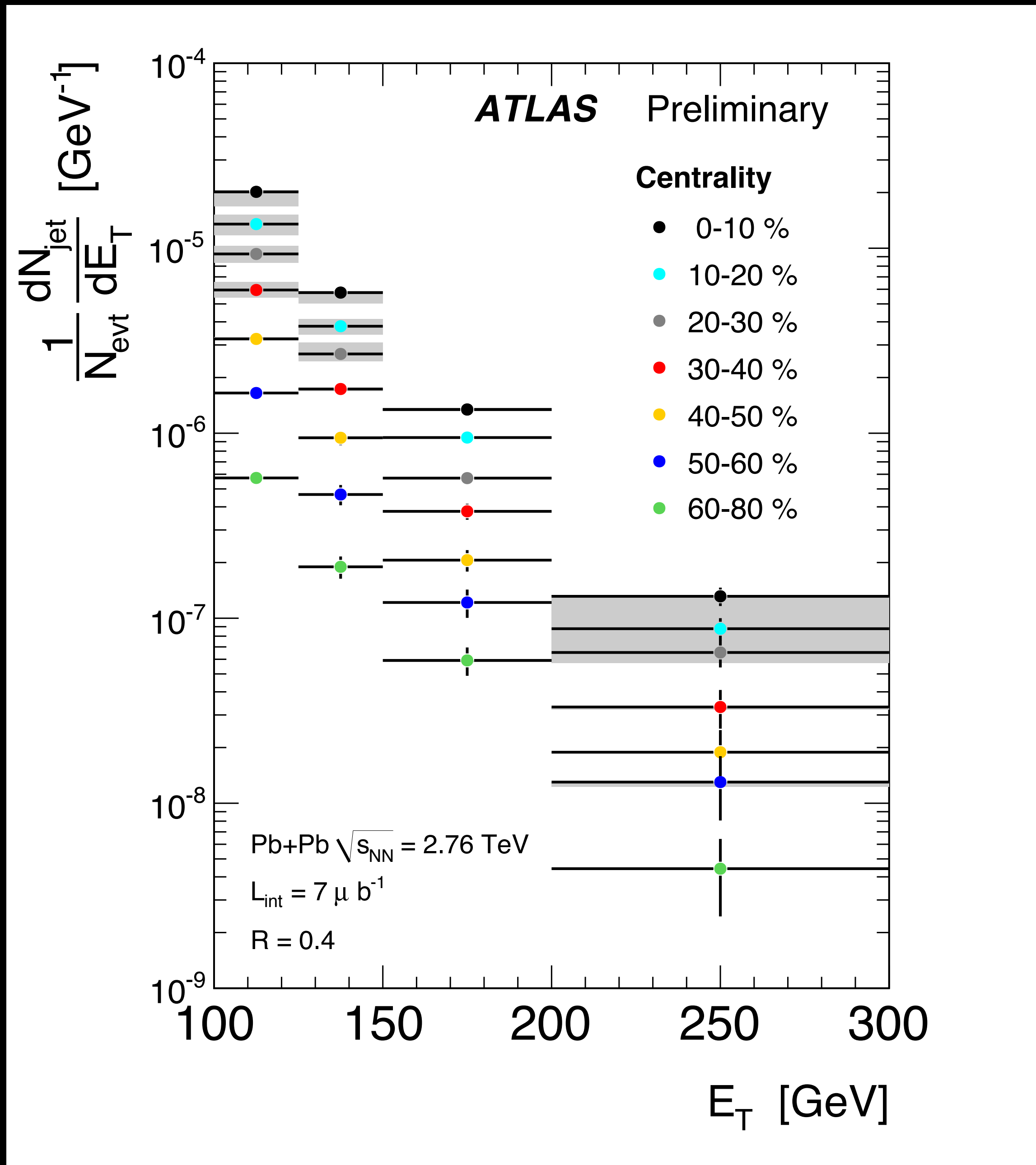
- Agreement in fluctuations between MC and data at the 10% level

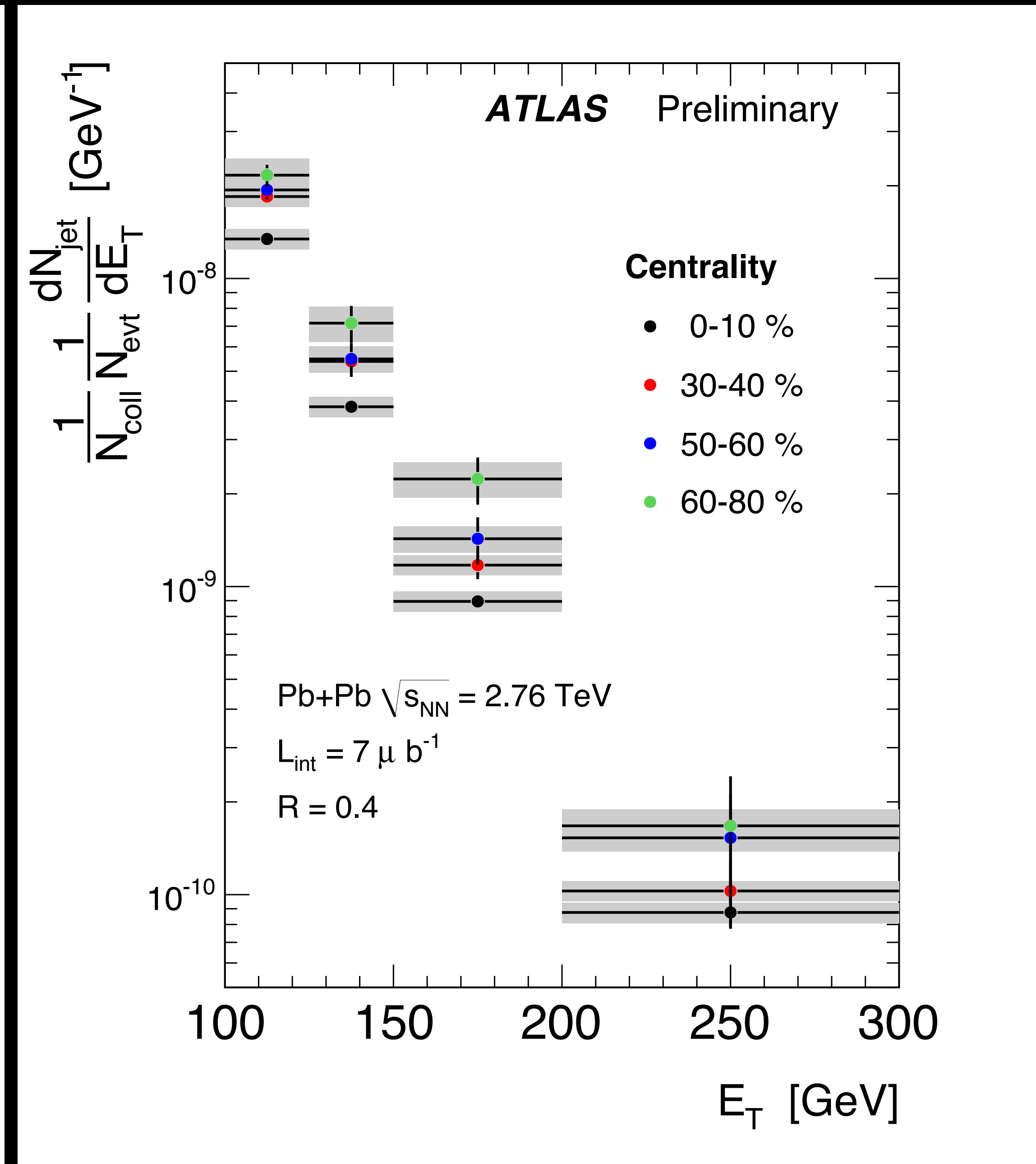
Jet Energy Resolution



- Jet energy resolution for R=0.4 and R=0.2 jets for 7 centrality bins
- Typical range is 10-15%; mild centrality dependence

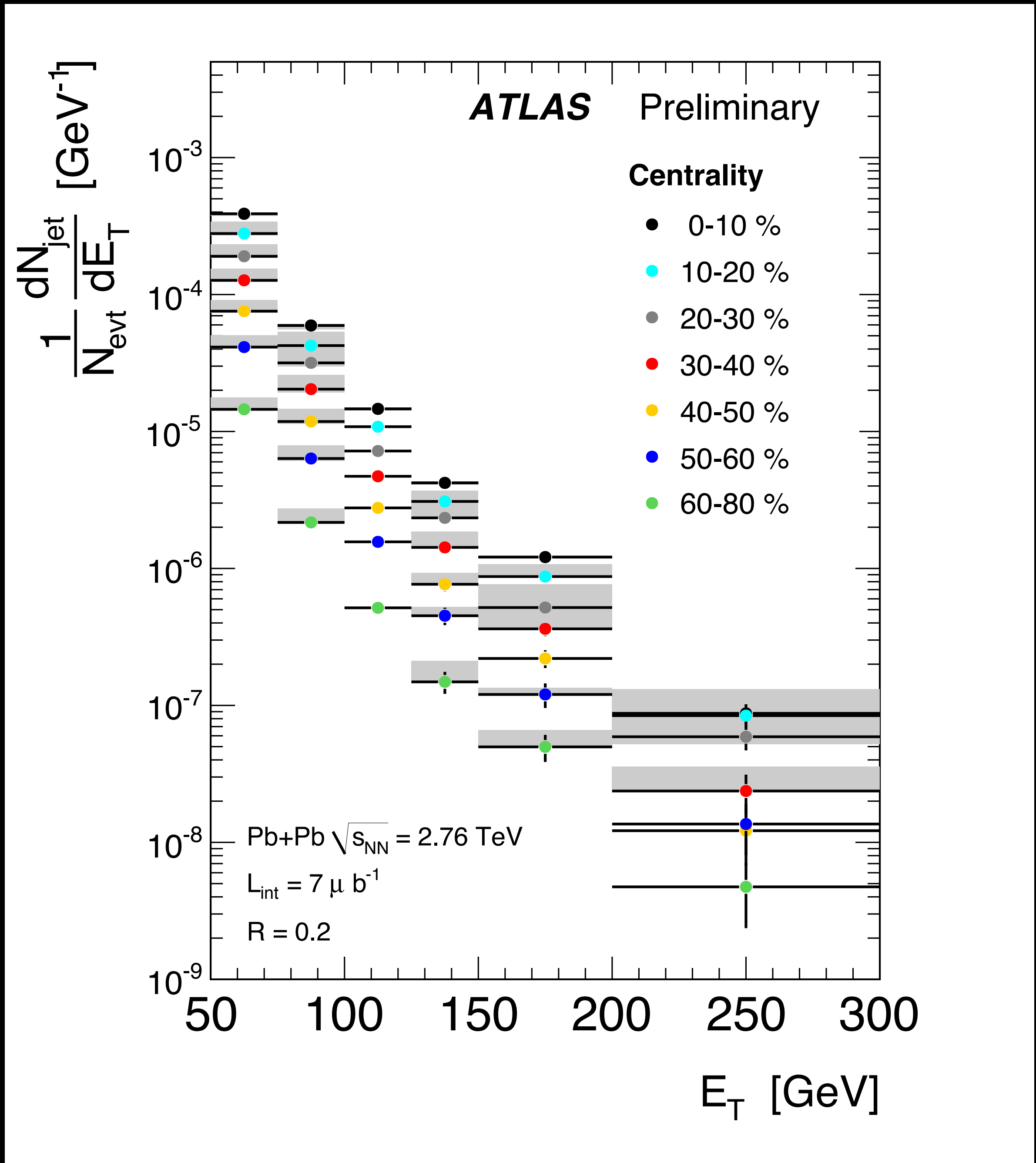
Single jet spectrum, R=0.4

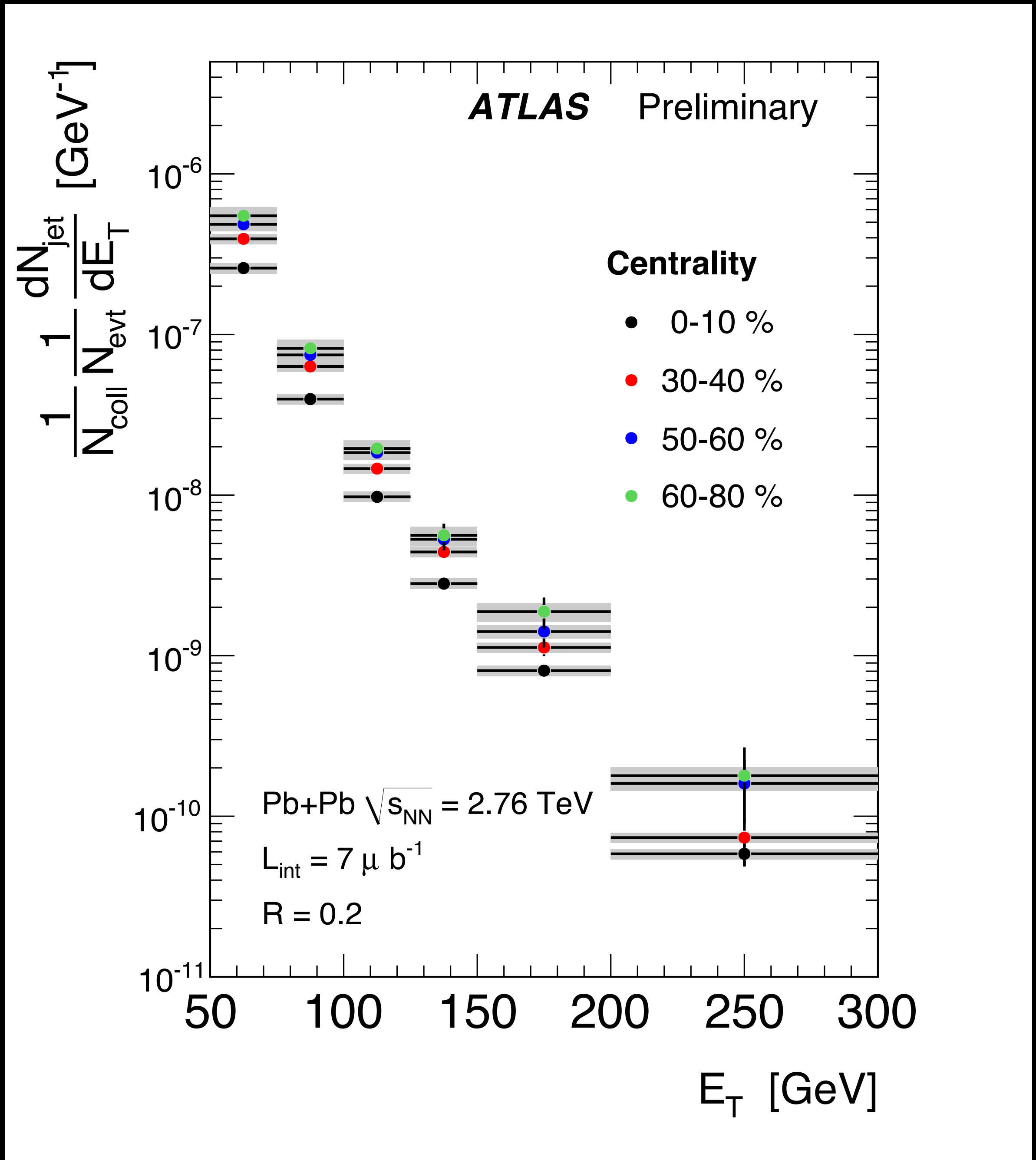




- Jet spectrum per event, R=0.4 jets, unnormalized (left) and normalized to N_{coll} (right), for various centralities
- Additional scale uncertainty of 22% due to global JES

Single jet spectrum, R=0.2





- Jet spectrum per event, R=0.2 jets, unnormalized (left) and normalized to N_{coll} (right), for various centralities
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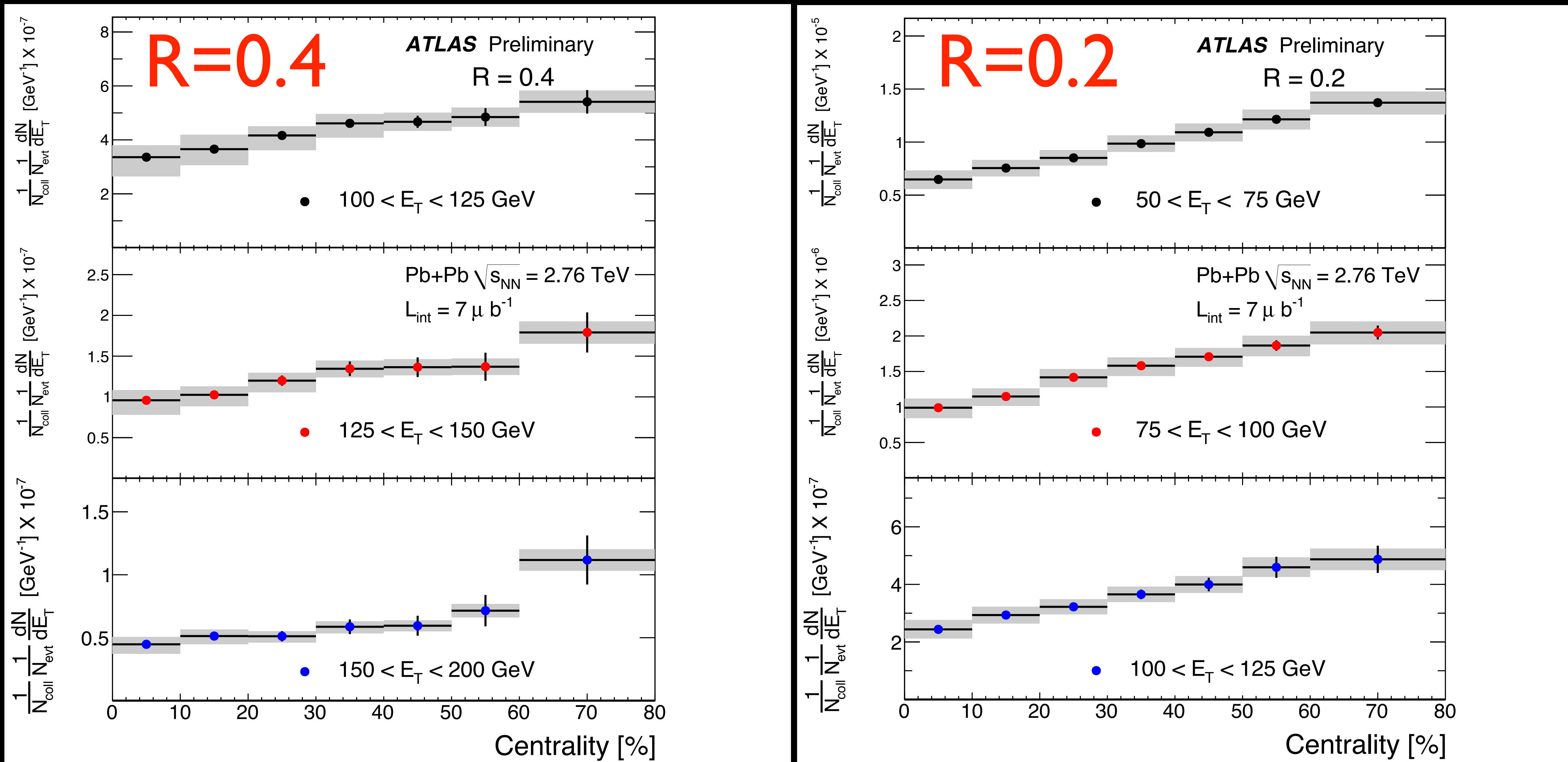
Centrality Dependence for 3 Jet Energies



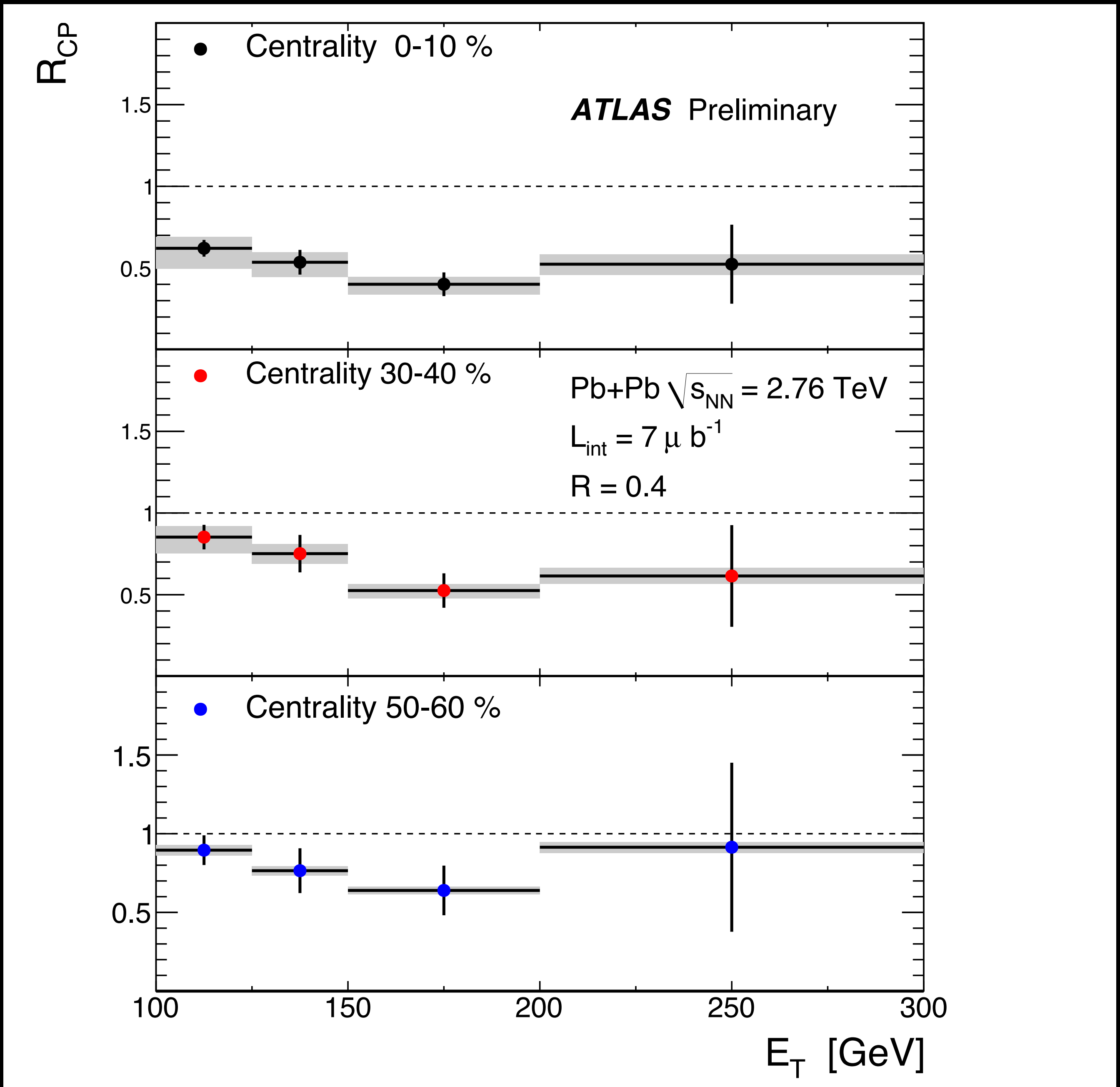
- Normalized to N_{coll} and N_{event}, three different energy ranges
- Slow, monotonic dependence on centrality
- Systematic uncertainties: centrality dependence of jet energy resolution, and jet energy scale and N_{coll} uncertainties

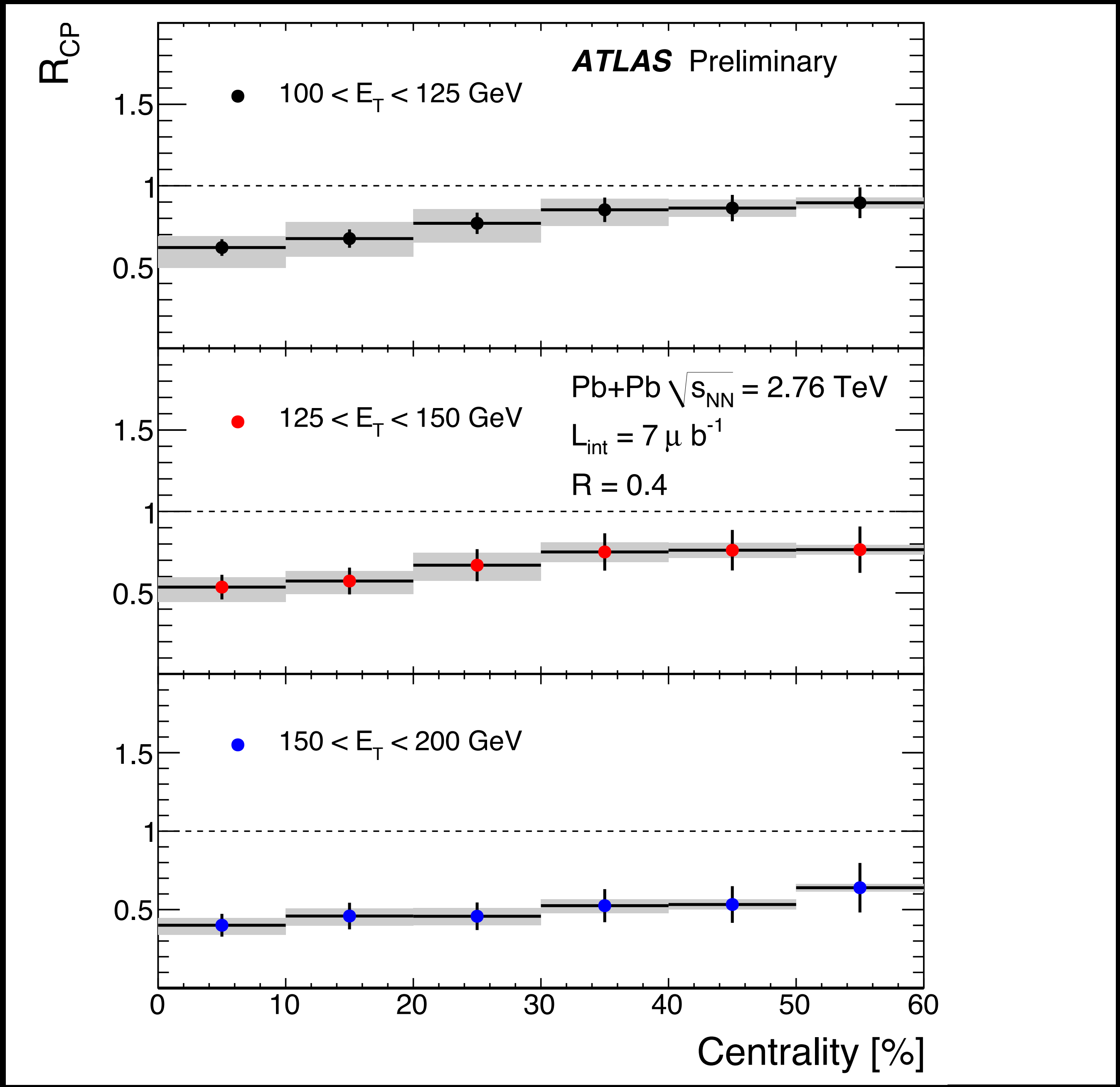
Single jet central to peripheral ratio: R_{cp}

Use 60-80% centrality as peripheral reference for Rcp

$$R_{cp} \equiv \frac{\frac{1}{N_{coll}^{centrality}} \frac{1}{N_{evt}^{centrality}} \frac{dN_{jet}^{centrality}}{dE_T}}{\frac{1}{N_{coll}^{60-80}} \frac{1}{N_{evt}^{60-80}} \frac{dN_{jet}^{60-80}}{dE_T}}$$

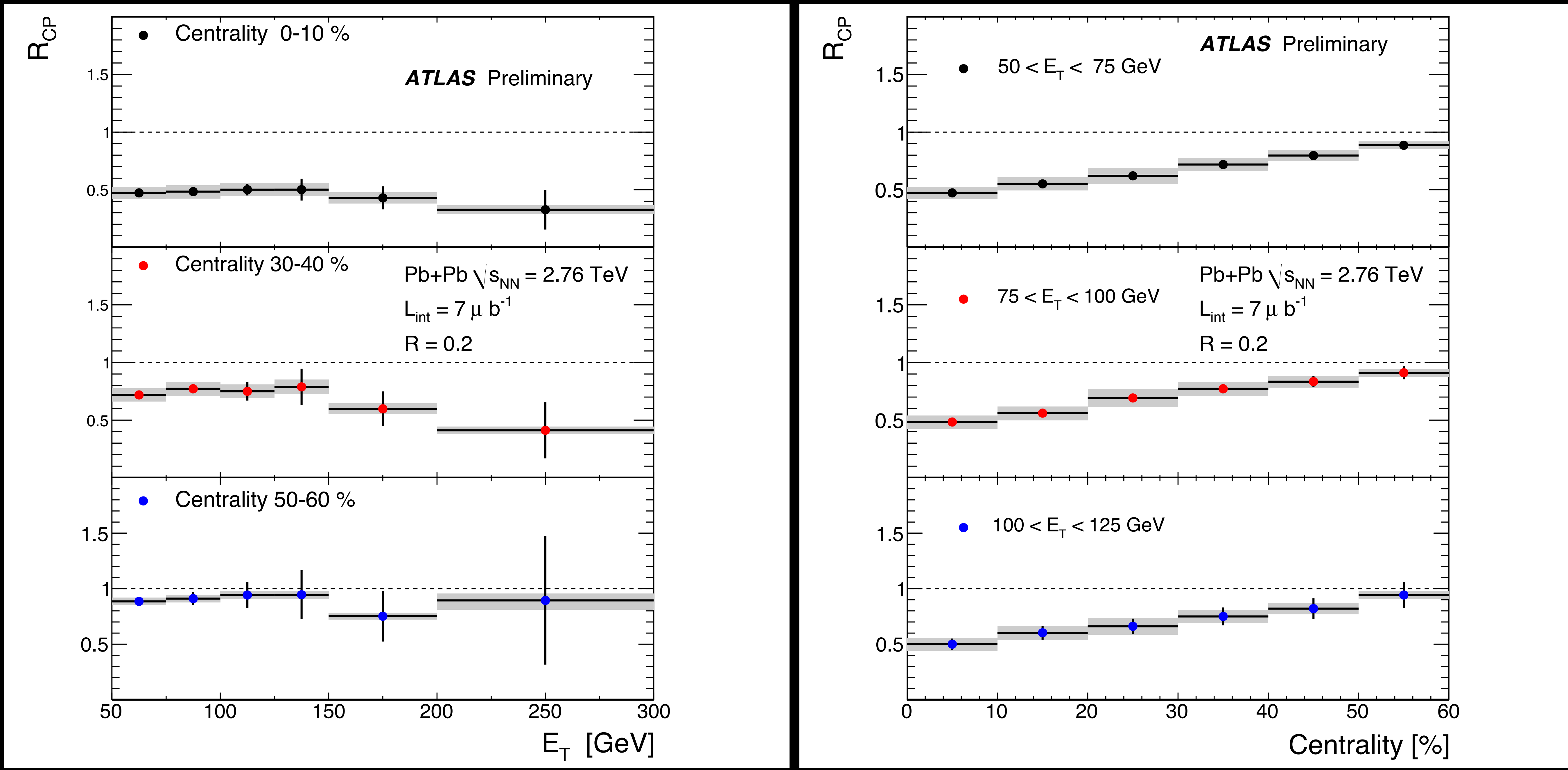
R_{CP} vs. E_T and Centrality, R=0.4 Jets





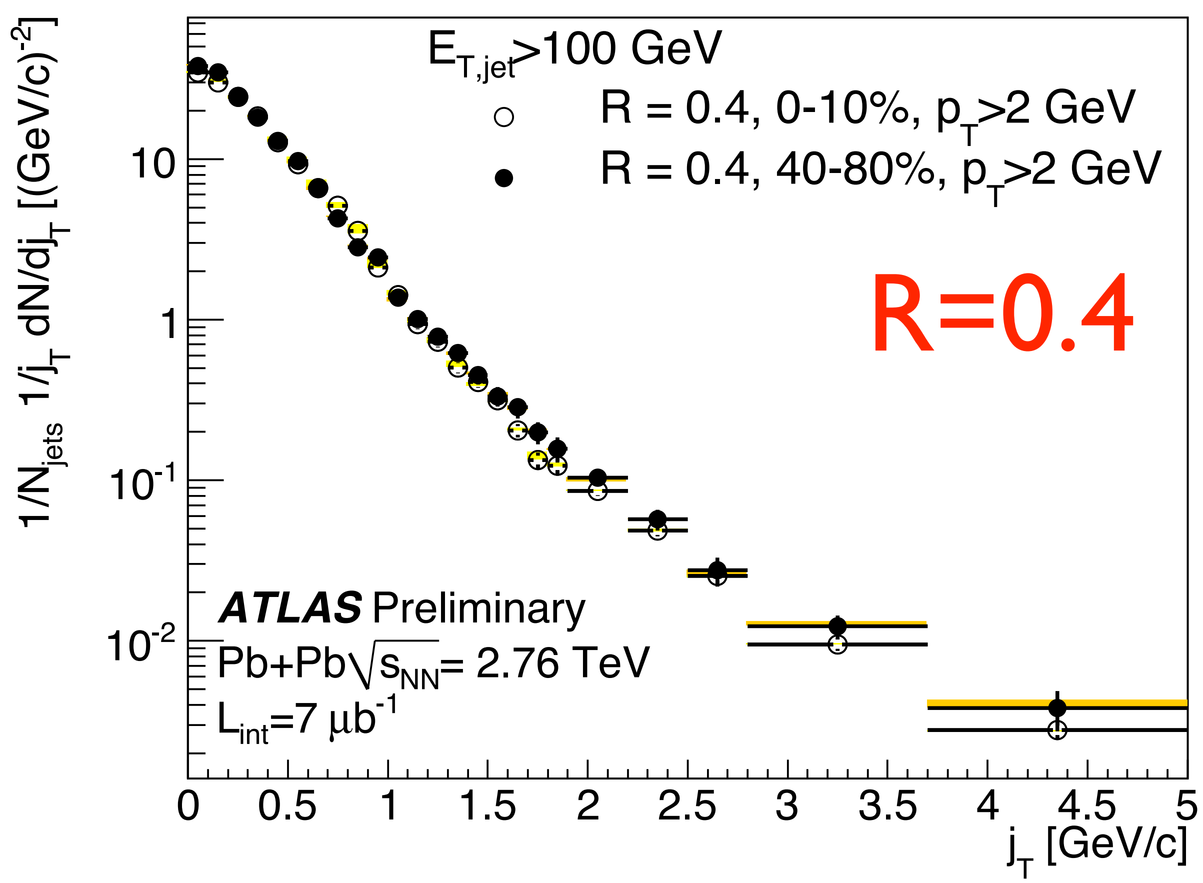
- Limited E_T dependence
- Monotonic centrality dependence, suppression ~factor 2

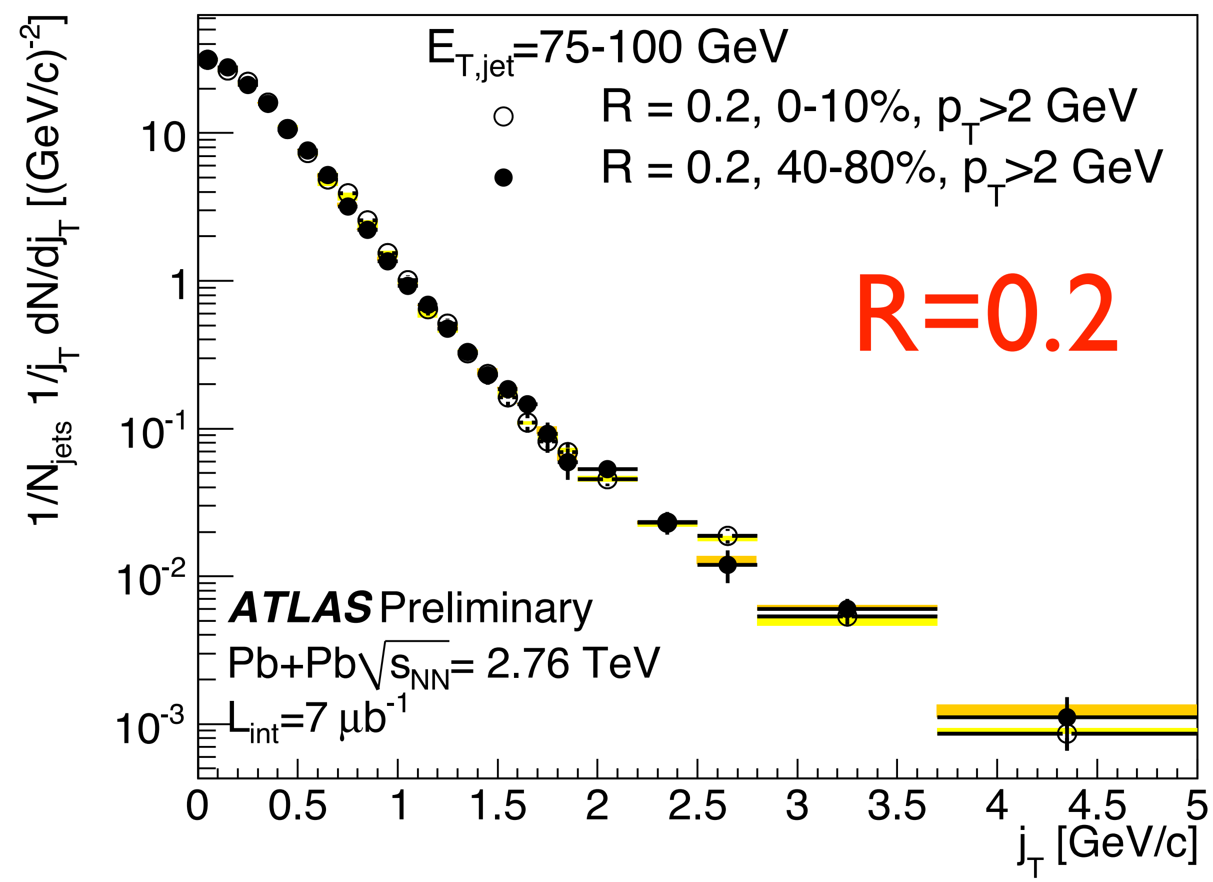
R_{CP} vs. E_T and Centrality, R=0.2 Jets



- Limited ET dependence
- Monotonic centrality dependence, up to 50% suppression

Transverse Momentum within Jet

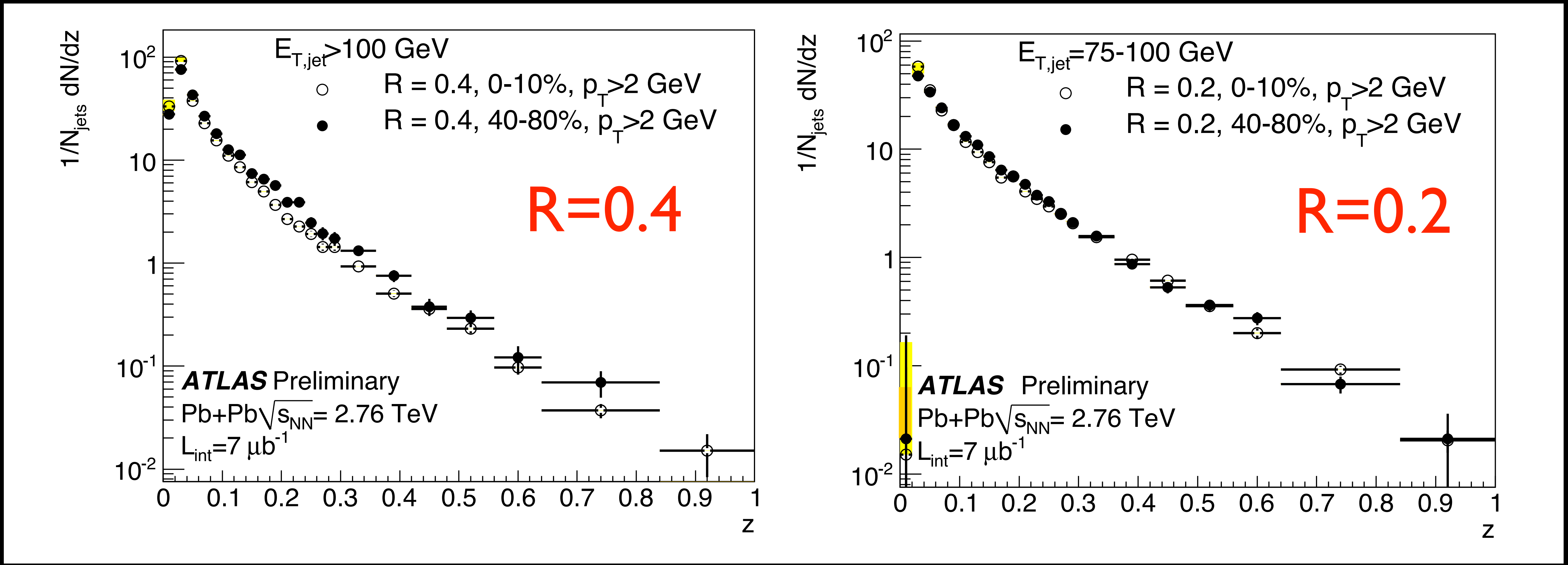




$$j_T \equiv p_T^{had} sin \Delta R = p_T^{had} sin(\sqrt{\Delta\eta^2 + \Delta\phi^2})$$

- Not yet unfolded for angular resolution
- Little systematic dependence seen on centrality
- Little difference between R=0.4 and R=0.2 jets

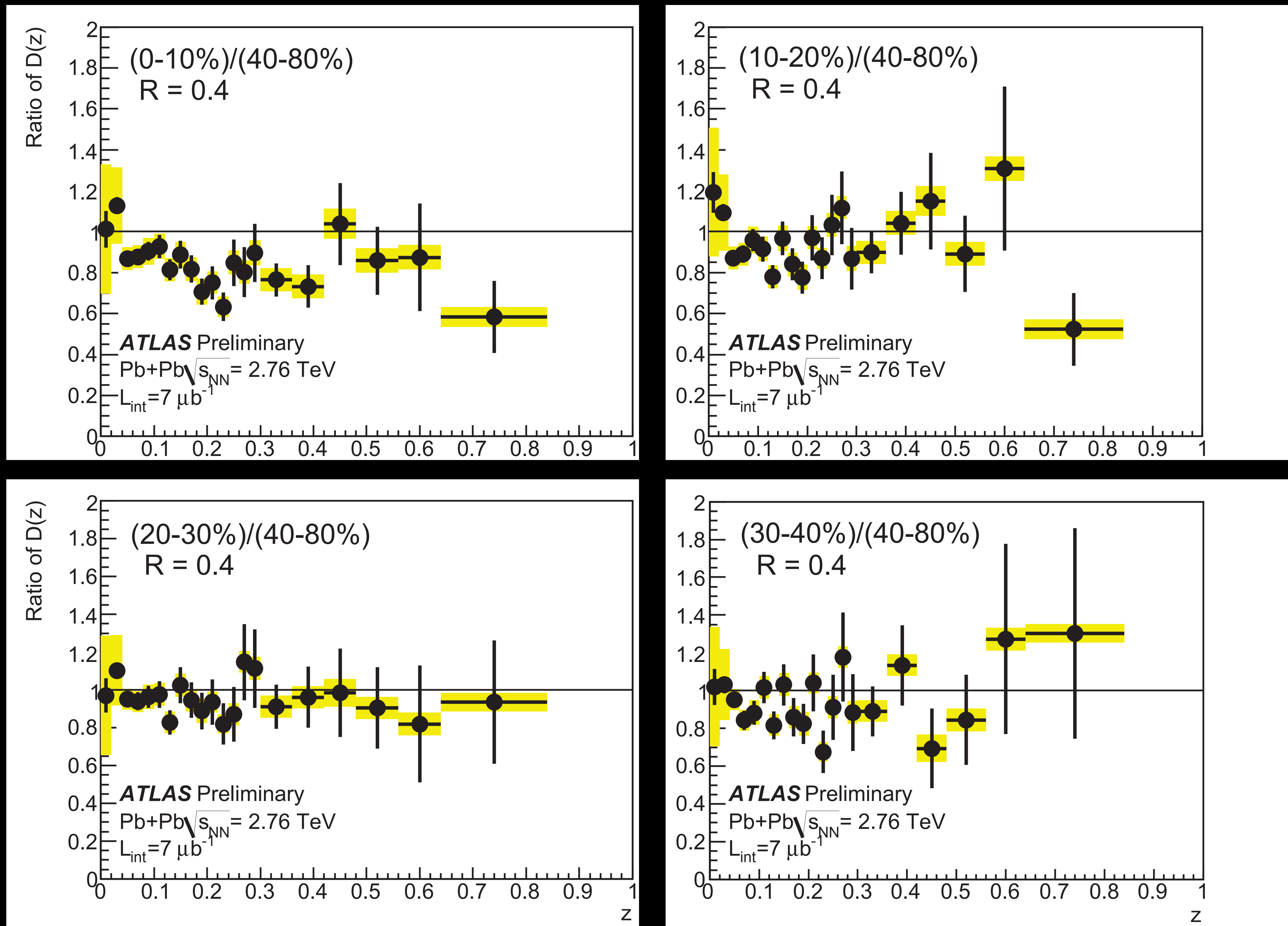
Fragmentation Function Dependencies



$$z \equiv (\frac{p_T^{had}}{E_T}) cos \Delta R$$

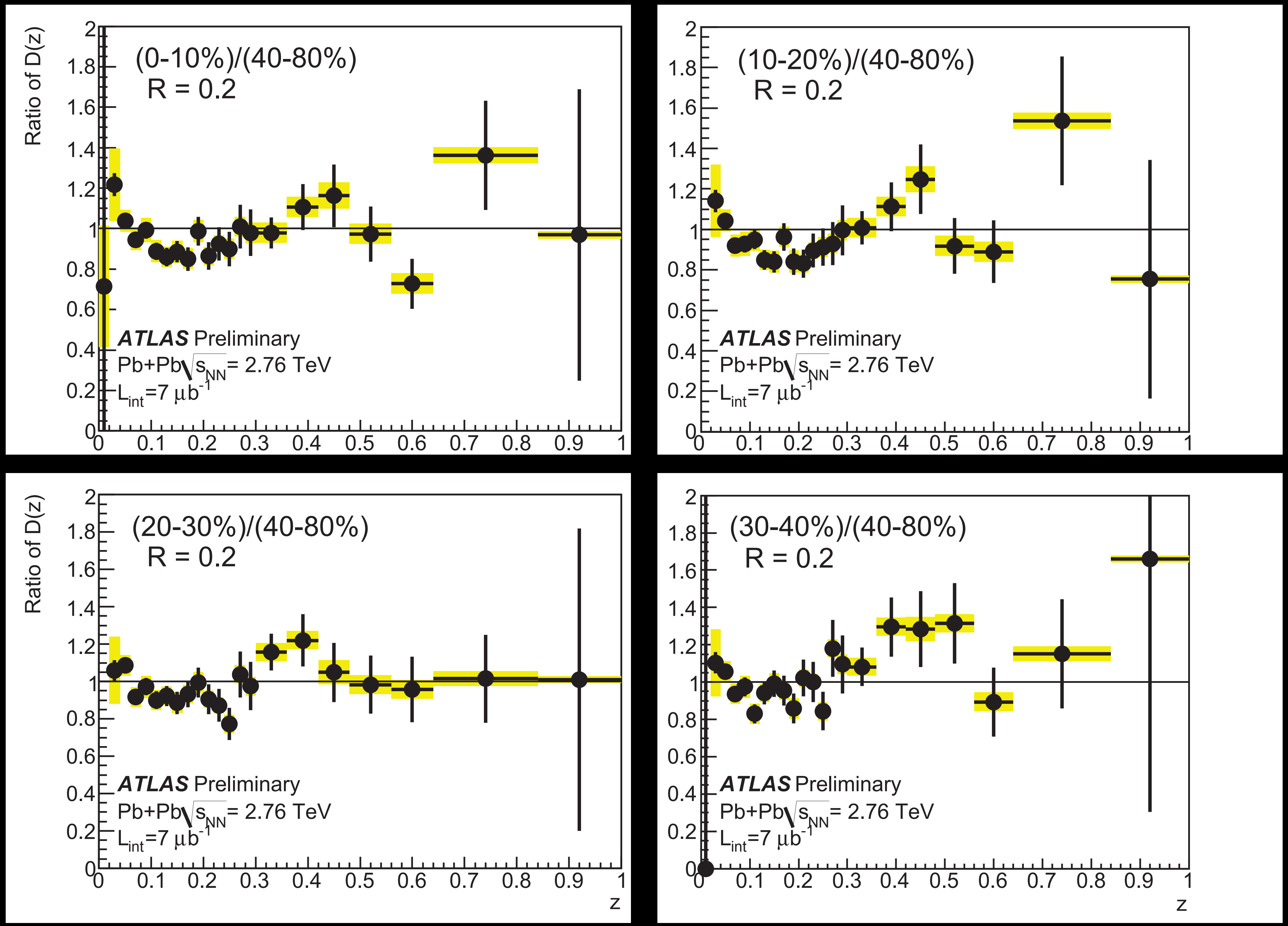
- Systematic uncertainties from jet energy resolution, centrality dependence of jet energy scale.
- Compare central (0-10%) to peripheral (40-80%)
- See: limited FF centrality dependence for R=0.4, less for R=0.2

Fragmentation Function Ratios, R=0.4 Jets



- Visible small effect for 0-10% and 10-20% centralities
- Suppression concentrated at high z is not evident

Fragmentation Function Ratios, R=0.2 Jets



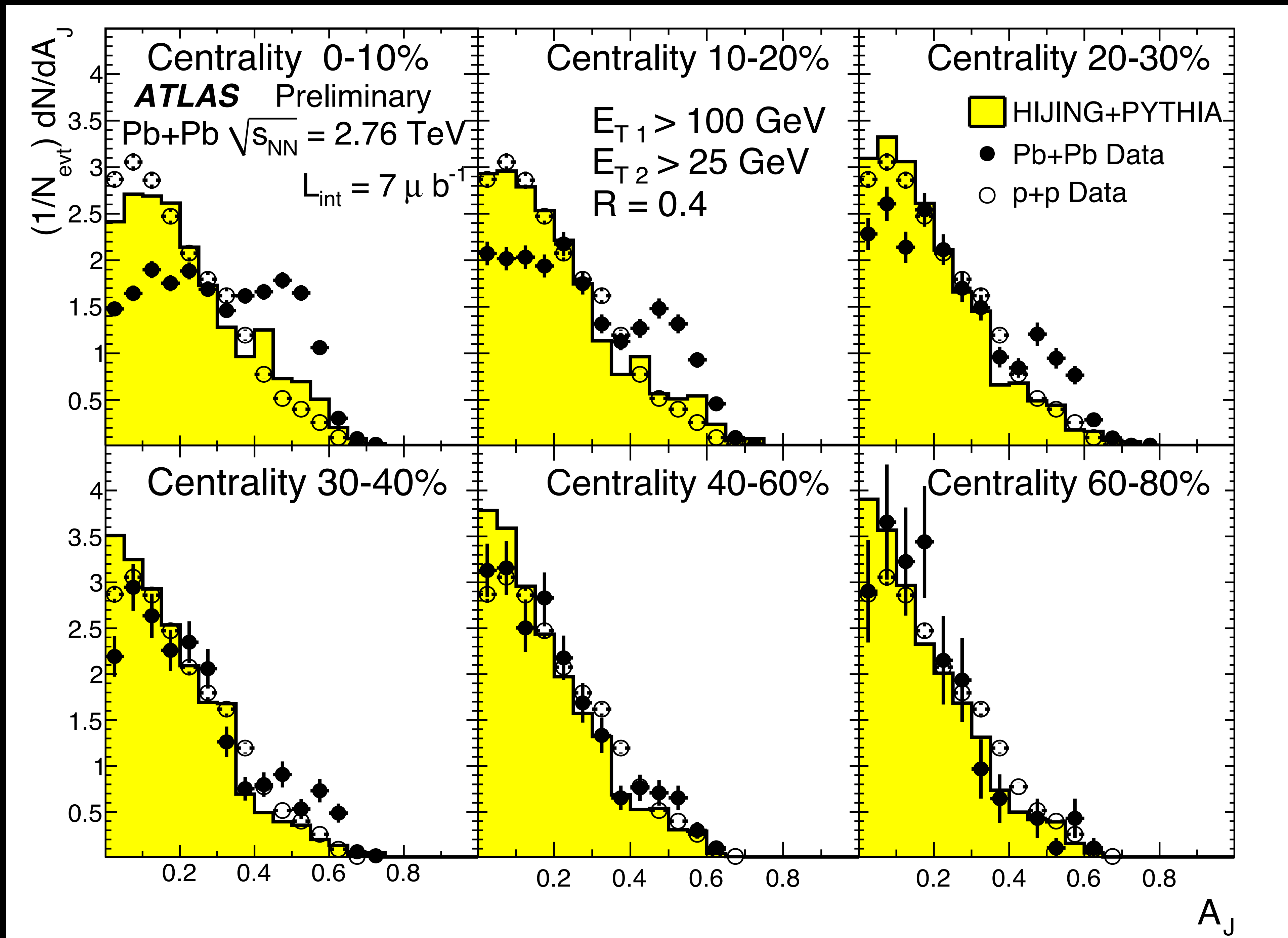
- Even smaller effect than in R=0.4 jets
- Suppression concentrated at high z is not evident

Update on di-jet asymmetry

$$A_J \equiv \frac{E_T^{jet1} - E_T^{jet2}}{E_T^{jet1} + E_T^{jet2}}$$

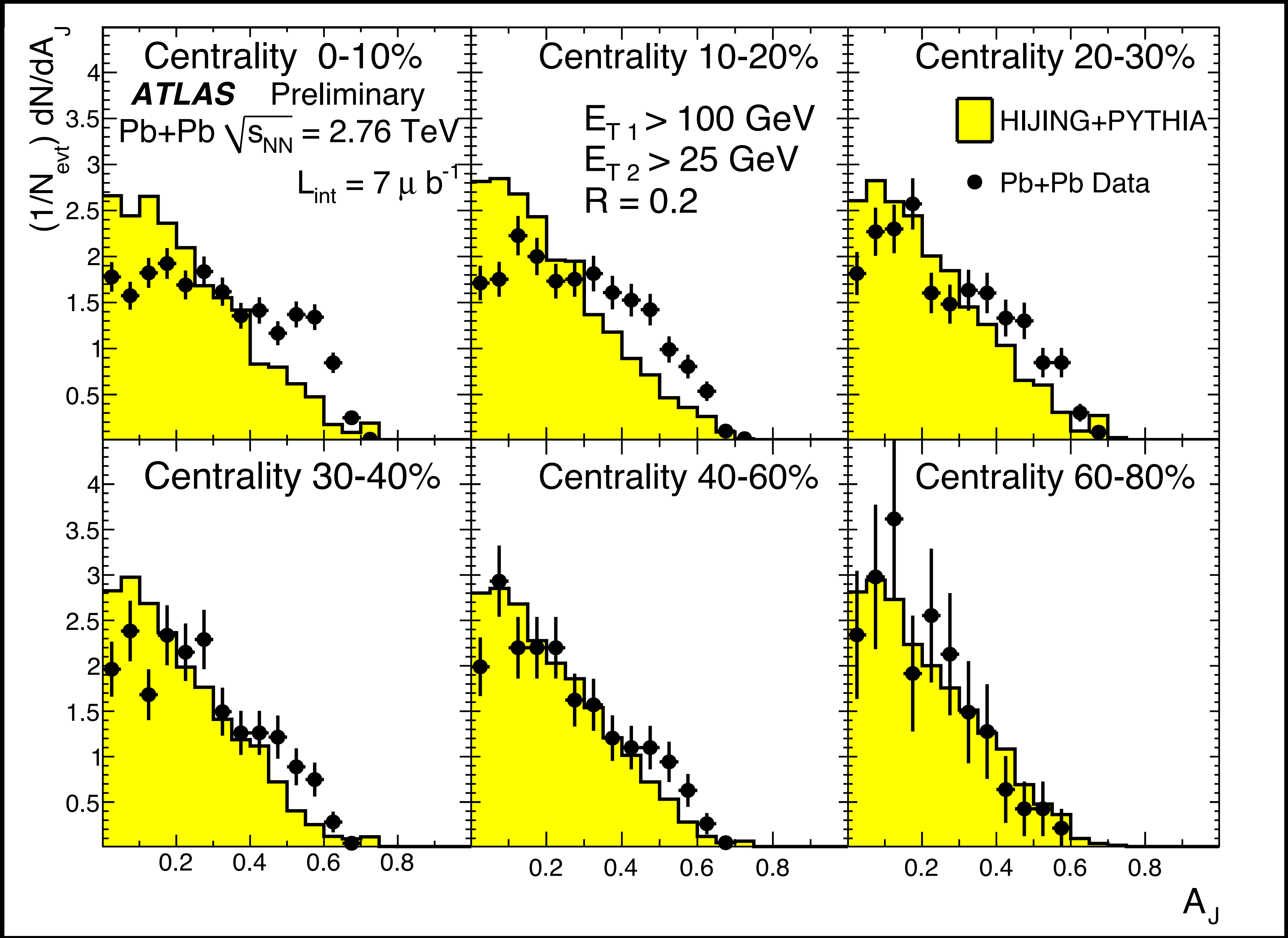
- R = 0.4, E_T(jet 1) > 100 GeV, E_T(jet 2) > 25 GeV
- Correction for flow in underlying event
- Iterative step in background estimation
- Integrated luminosity 7 μb^{-1} (PRL had 1.7 μb^{-1})

Di-Jet Asymmetry, R=0.4 Jets



- Updated from ATLAS 2010 Phys. Rev. Lett. with full luminosity

Di-Jet Asymmetry, R=0.2 Jets



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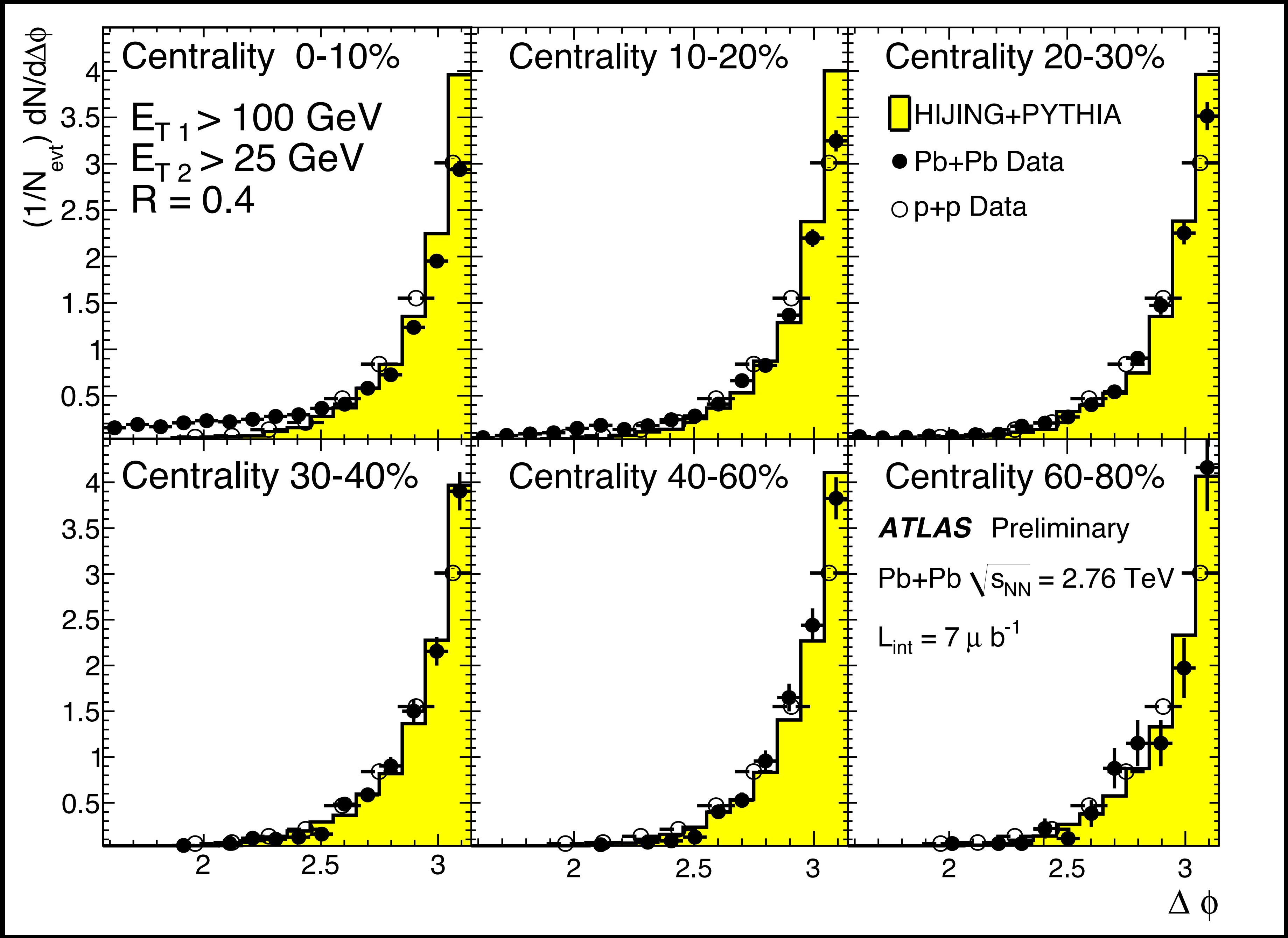
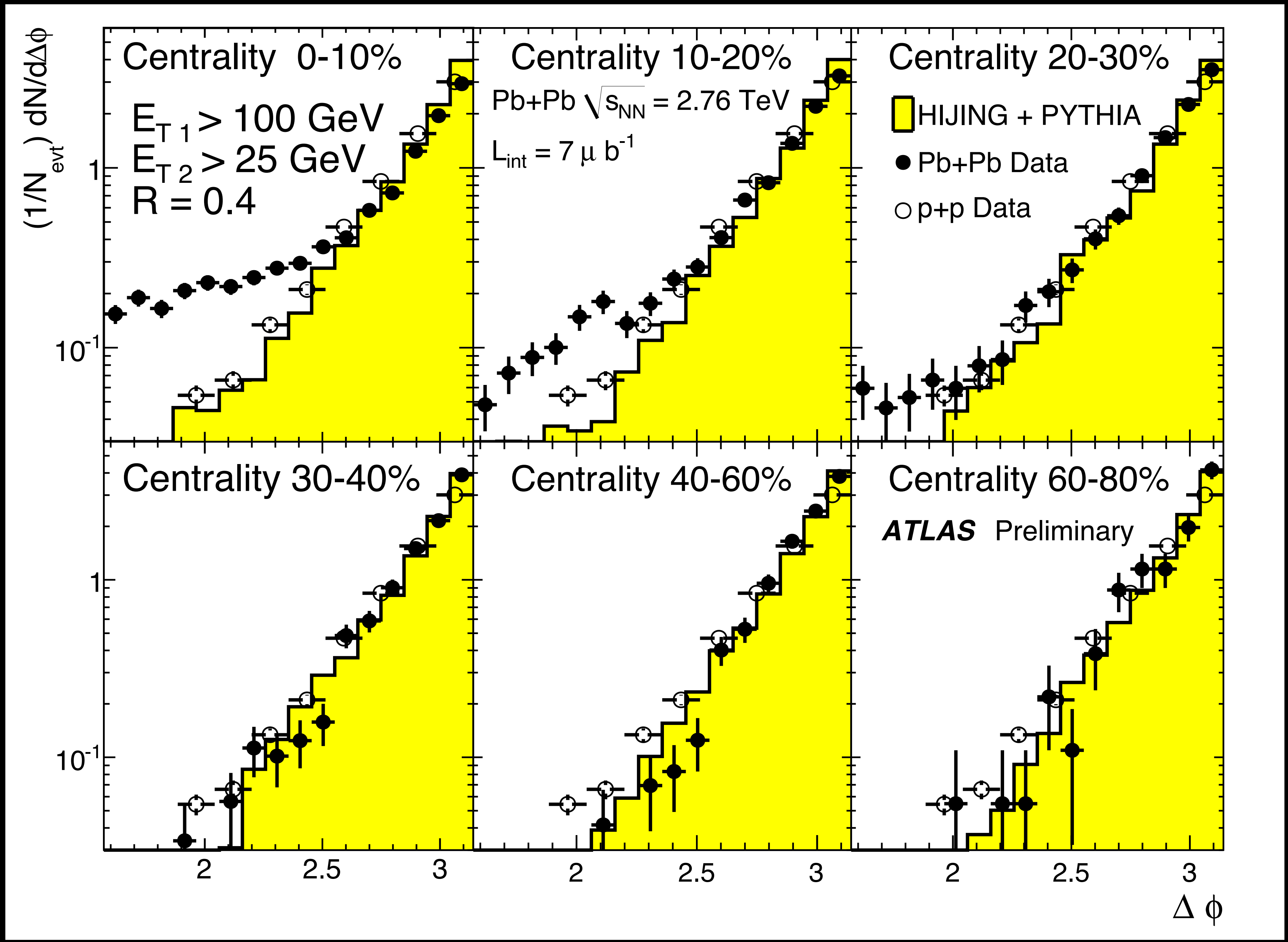
Di-Jet Angular Distribution, R=0.4 Jets



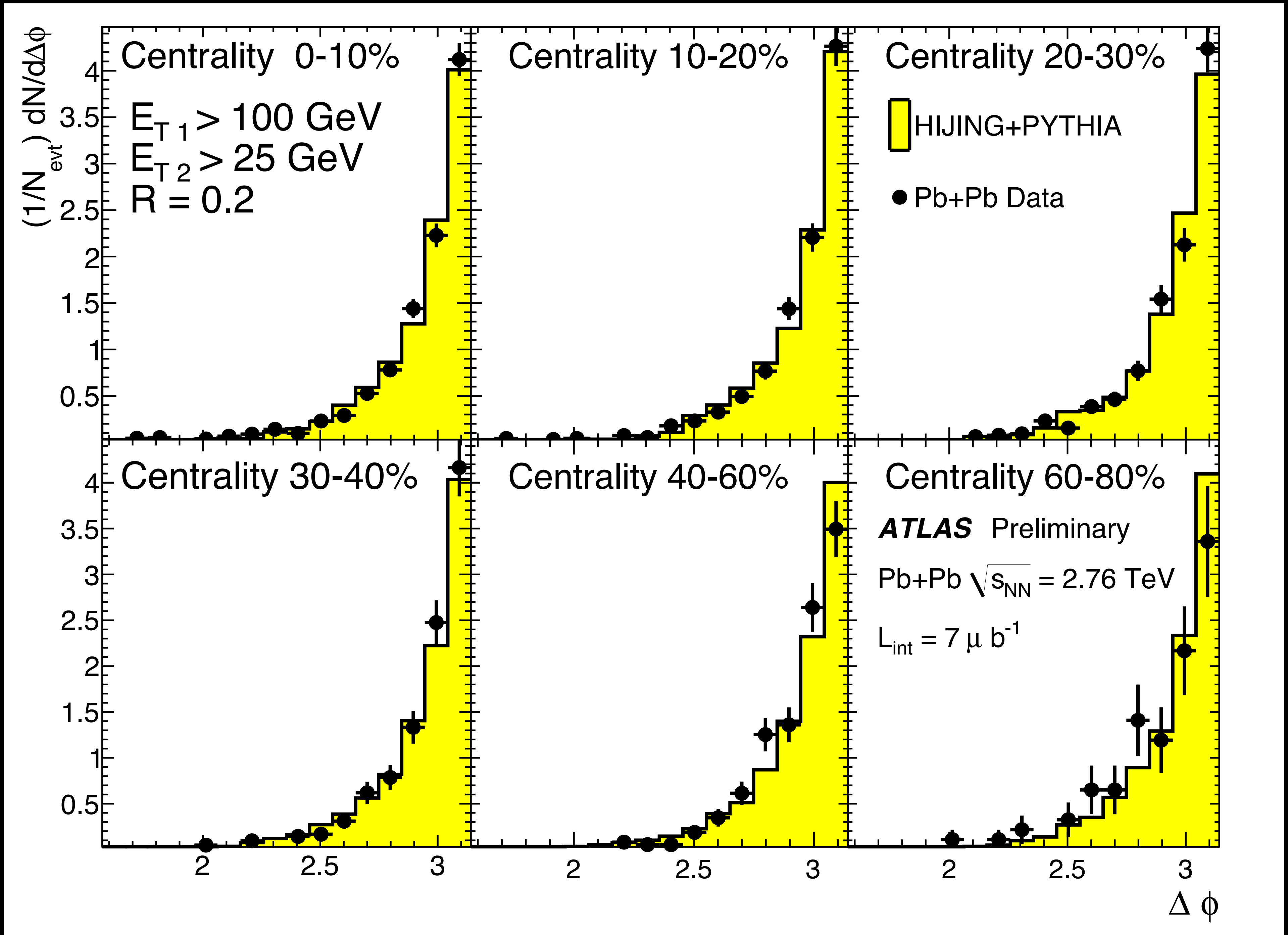
- Limited angular broadening of the di-jet pair

Di-Jet Angular Distribution, R=0.4 Jets



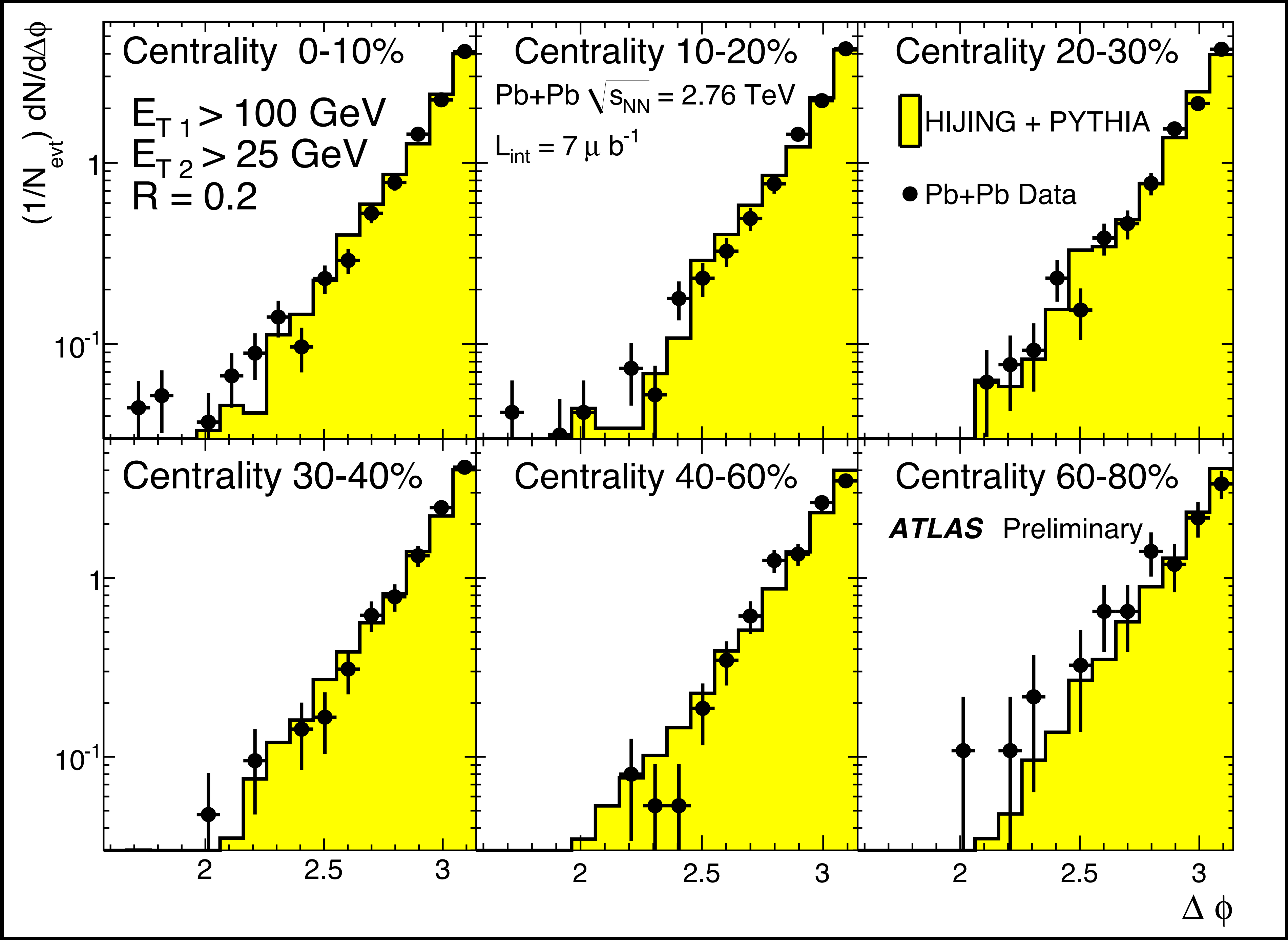
- Log scale version of previous plot
- Limited angular broadening of the di-jet pair

Di-Jet Angular Distribution, R=0.2 Jets



- Even less angular broadening of the di-jet pair than for R=0.4 jets

Di-Jet Angular Distribution, R=0.2 Jets



- Log scale version of previous plot

Conclusions

- 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 E_T dependence of suppression
- No significant broadening of fragment j_T distribution
- Weak modification of fragment z distributions
- Di-jet asymmetry analysis improved (background, flow correction), still see strong modification and no $\Delta\phi$ broadening

BACKUP SLIDES

	Barrel		End-cap	
EM calorimeter				
Number of layers and $\|\eta\|$ coverage				
Presampler	1	$\|\eta\| < 1.52$	1	$1.5 < \|\eta\| < 1.8$
Calorimeter	3	$\|\eta\| < 1.35$	2	$1.375 < \|\eta\| < 1.5$
	2	$1.35 < \|\eta\| < 1.475$	3	$1.5 < \|\eta\| < 2.5$
			2	$2.5 < \|\eta\| < 3.2$
Granularity $\Delta\eta \times \Delta\phi$ versus $\|\eta\|$				
Presampler	0.025×0.1	$\|\eta\| < 1.52$	0.025×0.1	$1.5 < \|\eta\| < 1.8$
Calorimeter 1st layer	$0.025/8 \times 0.1$	$\|\eta\| < 1.40$	0.050×0.1	$1.375 < \|\eta\| < 1.425$
	0.025×0.025	$1.40 < \|\eta\| < 1.475$	0.025×0.1	$1.425 < \|\eta\| < 1.5$
			$0.025/8 \times 0.1$	$1.5 < \|\eta\| < 1.8$
			$0.025/6 \times 0.1$	$1.8 < \|\eta\| < 2.0$
			$0.025/4 \times 0.1$	$2.0 < \|\eta\| < 2.4$
			0.025×0.1	$2.4 < \|\eta\| < 2.5$
			0.1×0.1	$2.5 < \|\eta\| < 3.2$
Calorimeter 2nd layer	0.025×0.025	$\|\eta\| < 1.40$	0.050×0.025	$1.375 < \|\eta\| < 1.425$
	0.075×0.025	$1.40 < \|\eta\| < 1.475$	0.025×0.025	$1.425 < \|\eta\| < 2.5$
			0.1×0.1	$2.5 < \|\eta\| < 3.2$
Calorimeter 3rd layer	0.050×0.025	$\|\eta\| < 1.35$	0.050×0.025	$1.5 < \|\eta\| < 2.5$
Number of readout channels				
Presampler	7808		1536 (both sides)	
Calorimeter	101760		62208 (both sides)	
LAr hadronic end-cap				
$\|\eta\|$ coverage			$1.5 < \|\eta\| < 3.2$	
Number of layers			4	
Granularity $\Delta\eta \times \Delta\phi$			0.1×0.1	$1.5 < \|\eta\| < 2.5$
			0.2×0.2	$2.5 < \|\eta\| < 3.2$
Readout channels			5632 (both sides)	
LAr forward calorimeter				
$\|\eta\|$ coverage			$3.1 < \|\eta\| < 4.9$	
Number of layers			3	
Granularity $\Delta x \times \Delta y$ (cm)			FCal1: 3.0×2.6	$3.15 < \|\eta\| < 4.30$
			FCal1: $\sim$ four times finer	$3.10 < \|\eta\| < 3.15$,
				$4.30 < \|\eta\| < 4.83$
			FCal2: 3.3×4.2	$3.24 < \|\eta\| < 4.50$
			FCal2: $\sim$ four times finer	$3.20 < \|\eta\| < 3.24$,
				$4.50 < \|\eta\| < 4.81$
			FCal3: 5.4×4.7	$3.32 < \|\eta\| < 4.60$
			FCal3: $\sim$ four times finer	$3.29 < \|\eta\| < 3.32$,
				$4.60 < \|\eta\| < 4.75$
Readout channels			3524 (both sides)	
Scintillator tile calorimeter				
	Barrel		Extended barrel	
$\|\eta\|$ coverage	$\|\eta\| < 1.0$		$0.8 < \|\eta\| < 1.7$	
Number of layers	3		3	
Granularity $\Delta\eta \times \Delta\phi$	0.1×0.1		0.1×0.1	
Last layer	0.2×0.1		0.2×0.1	
Readout channels	5760		4092 (both sides)	

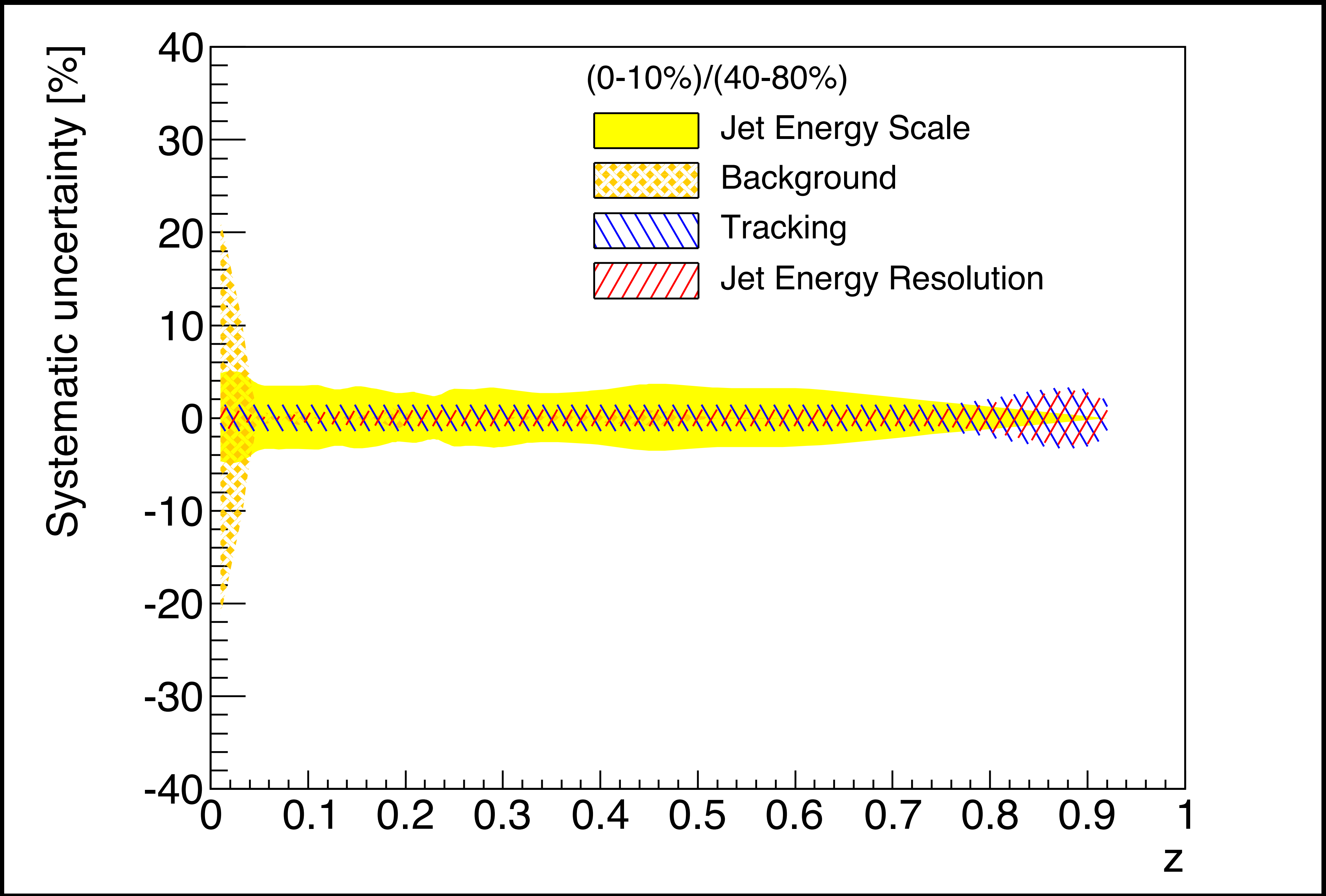
Table 3. Main parameters of the calorimeter system.

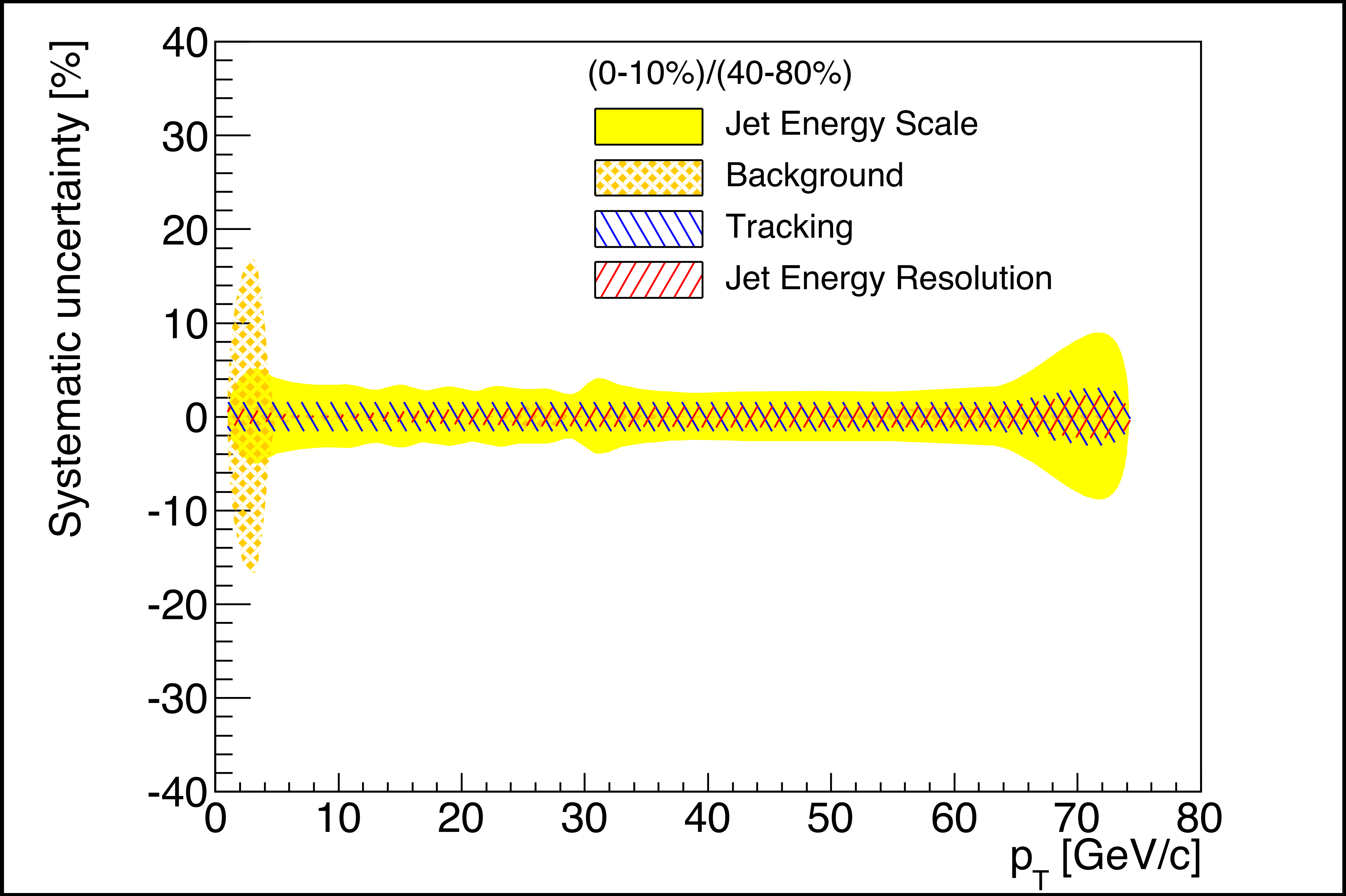
Jet Calibration

Several Jet Calibration Schemes in ATLAS:

- Simple pT- and η-dependent calibration scheme (EM+JES)
- Global Sequential calibration scheme (GS)
- Global Cell-energy-density Weighting calibration scheme (GCW)
- Local Cluster Weighting calibration scheme (LCW)

- We are using GCW because we want to calibrate the entire detector including the hadronic response before doing the subtraction.


(0-10%)/(40-80%)
Jet Energy Scale
Background
Tracking
Jet Energy Resolution
Systematic uncertainty [%]
40
30
20
10
0
-10
-20
-30
-40
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z


(0-10%)/(40-80%)
Jet Energy Scale
Background
Tracking
Jet Energy Resolution
Systematic uncertainty [%]
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
70
80
p_T [GeV/c]

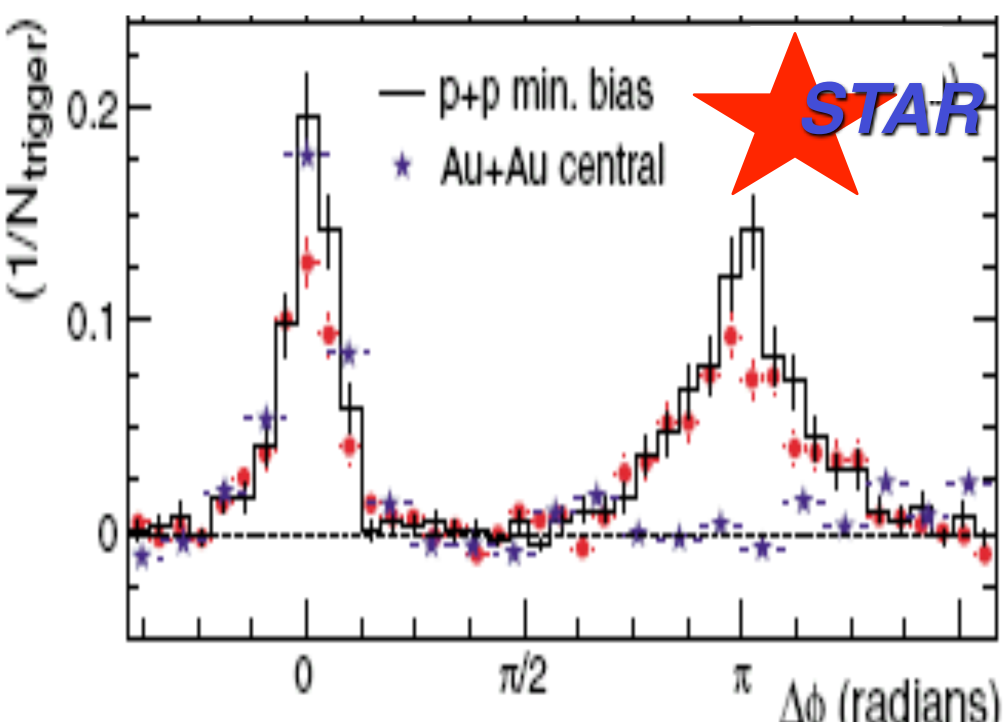
arXiv:1011.6182

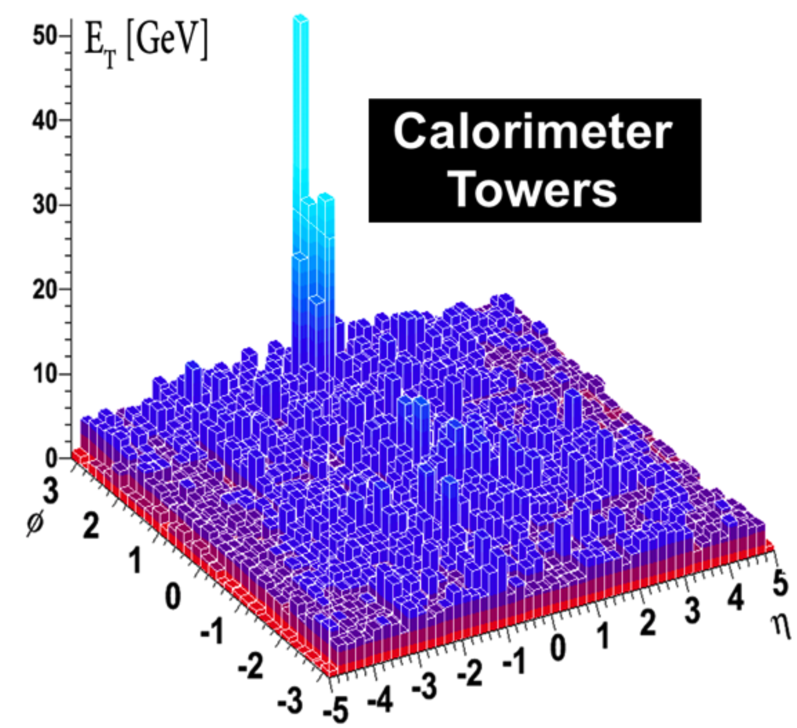
Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

G. Aad *et al.* (The ATLAS Collaboration)*

Using the ATLAS detector, observations have been made of a centrality-dependent dijet asymmetry in the collisions of lead ions at the Large Hadron Collider. In a sample of lead-lead events with a per-nucleon center of mass energy of 2.76 TeV, selected with a minimum bias trigger, jets are reconstructed in fine-grained, longitudinally-segmented electromagnetic and hadronic calorimeters. The underlying event is measured and subtracted event-by-event, giving estimates of jet transverse energy above the ambient background. The transverse energies of dijets in opposite hemispheres is observed to become systematically more unbalanced with increasing event centrality leading to a large number of events which contain highly asymmetric dijets. This is the first observation of an enhancement of events with such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

- Paper submitted on Nov 25, accepted by PRL

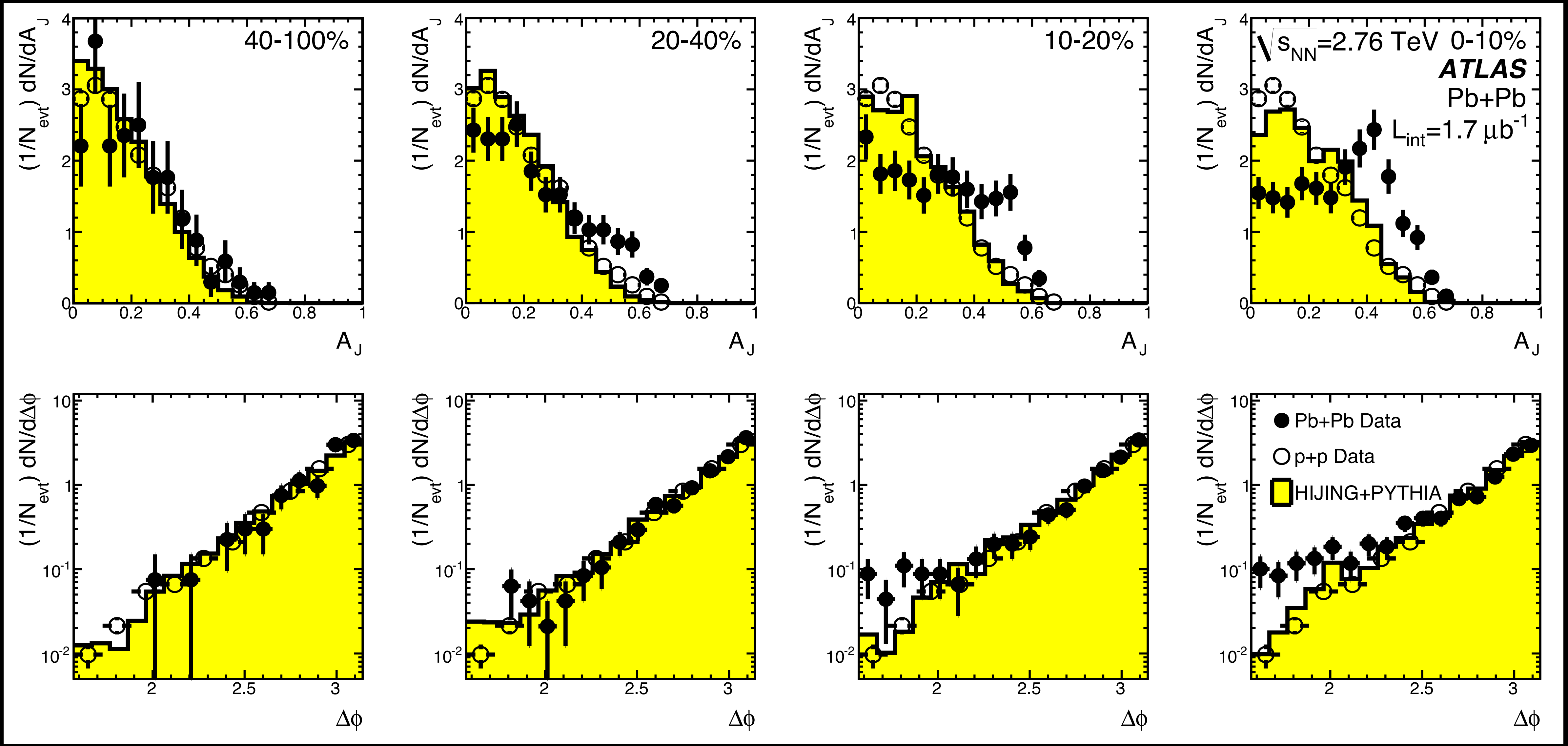




Indirect jet quenching @ RHIC

Direct quenching @ LHC?

From 2010 PRL

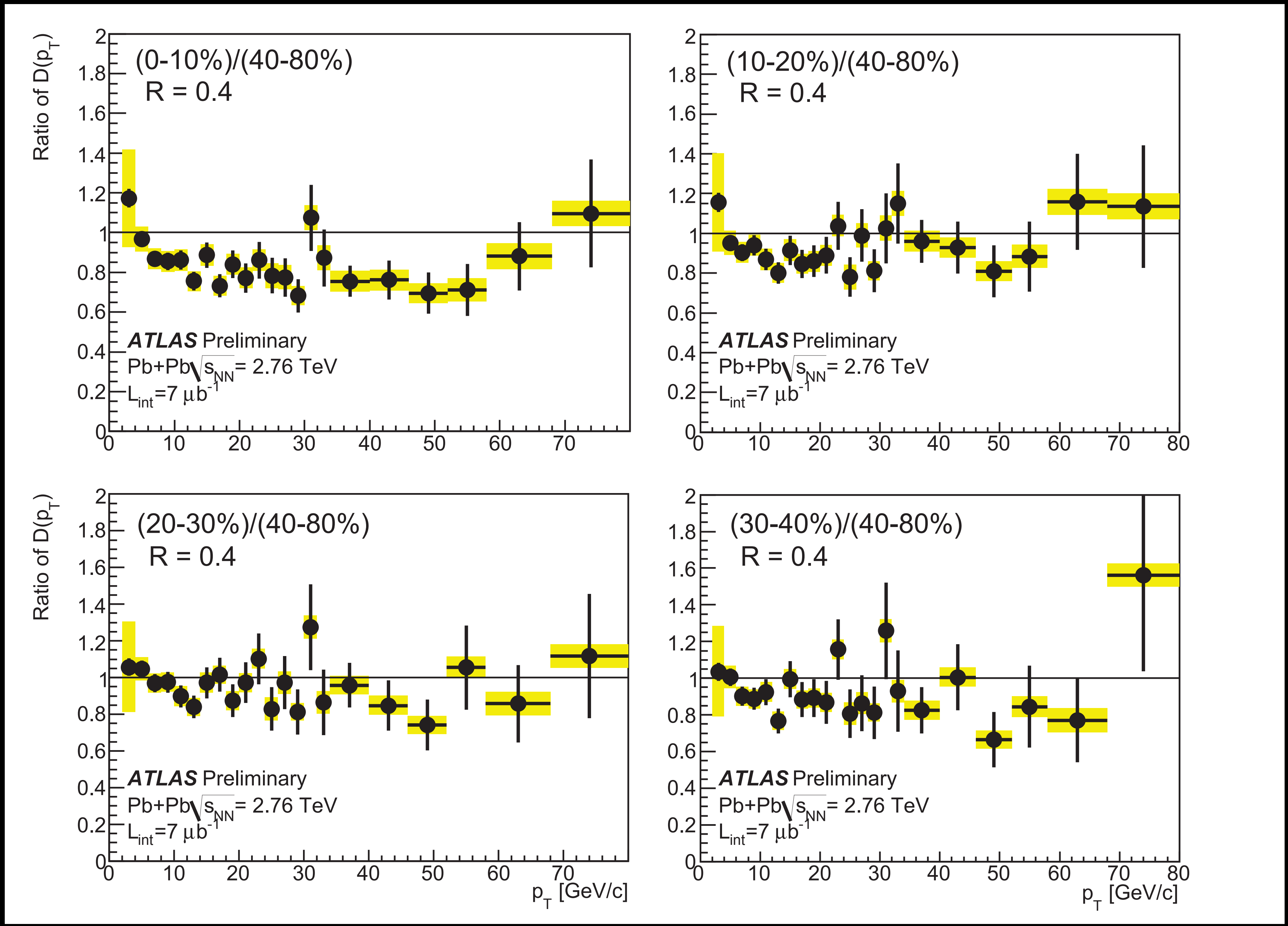


Phys. Rev. Lett. 105, 252303 (2010))

Uncertainties from centrality assignment

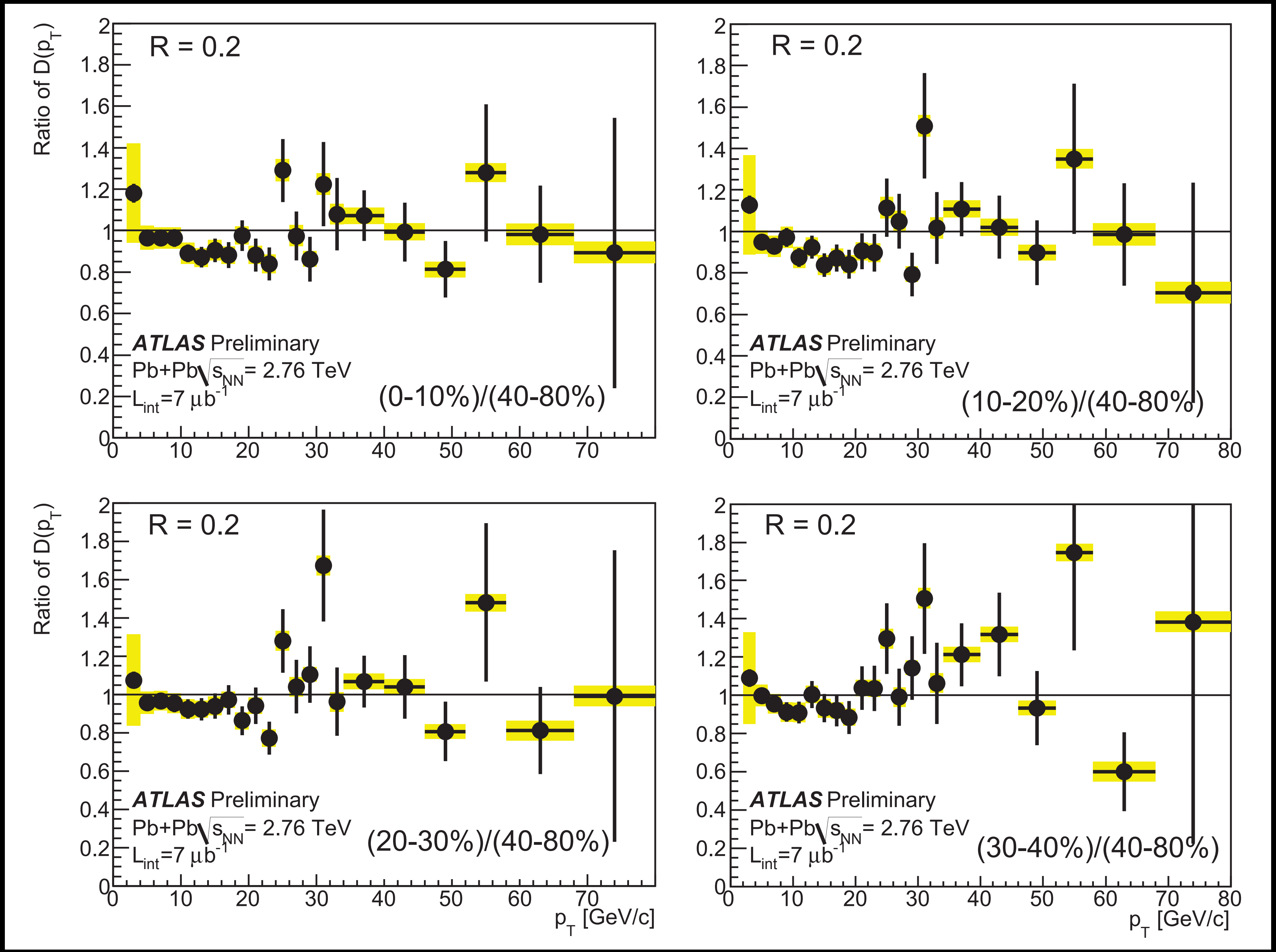
Centrality bin	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%
${N_{coll}}^{cent}/{N_{coll}}^{60-80\%}$	56.7	34.9	21.1	12.2	6.5	3.2
Relative error (%)	11.4	10.5	11.3	7.9	6.1	3.8

Ratios vs. p_T, R=0.4 Jets



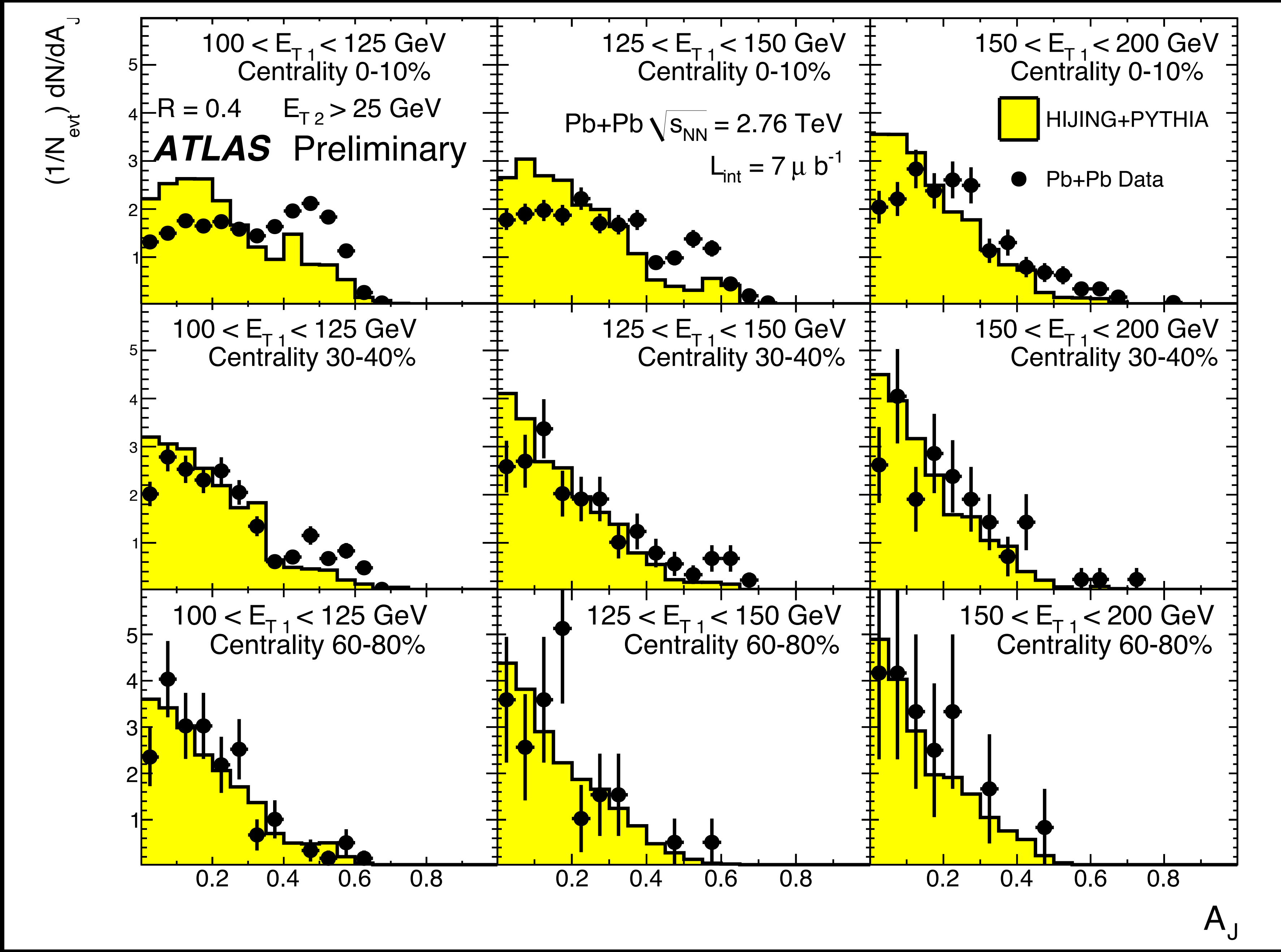
- Visible effect for 0-10% and 10-20% centralities

Ratios vs. p_T, R=0.2 Jets



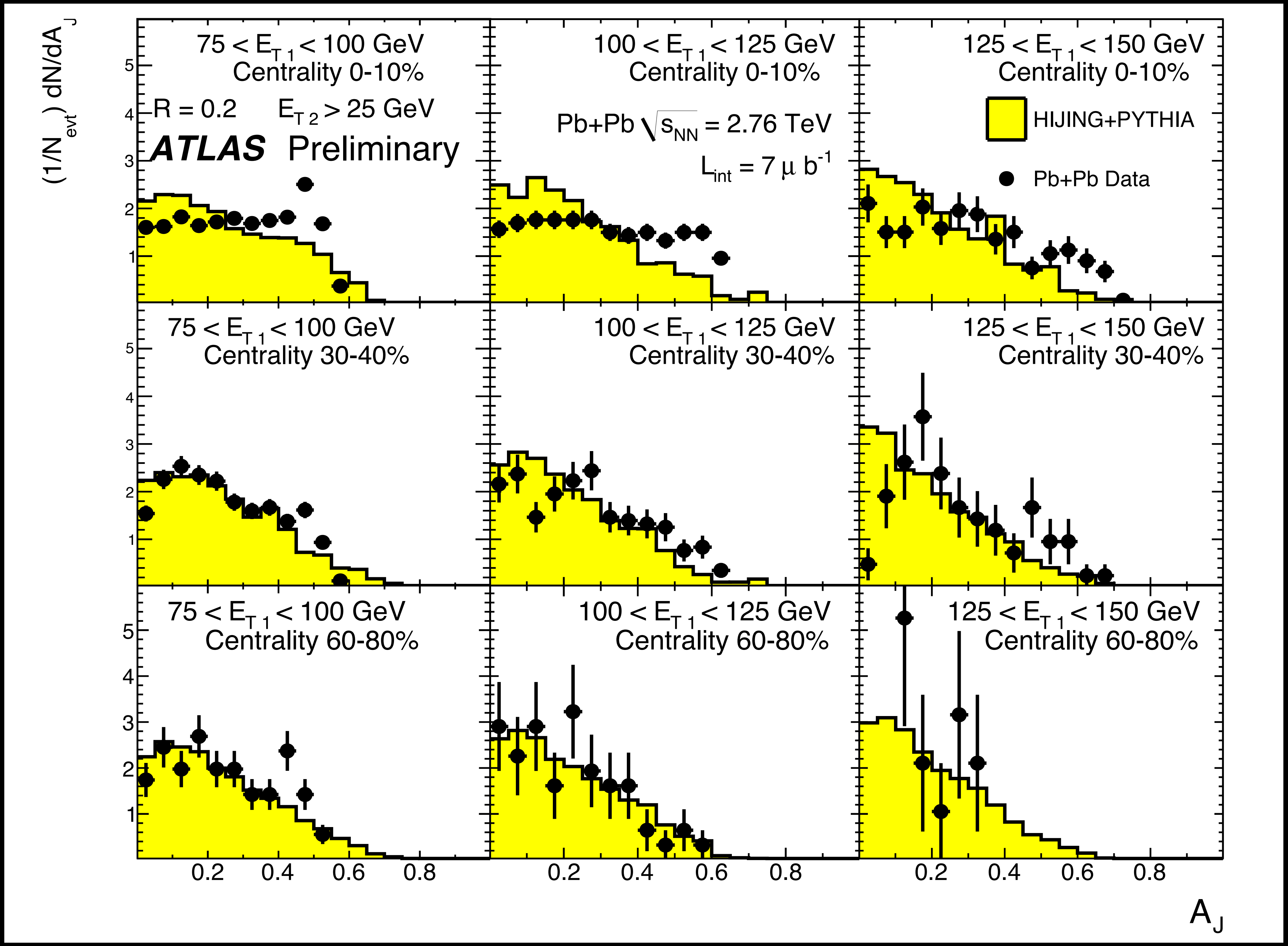
- Little visible effect at any centrality

E_{T1} dependence, Di-Jet Asymmetry, R=0.4 Jets



Monday, May 30, 2011

E_{T1} dependence, Di-Jet Asymmetry, R=0.2 Jets



Di-Jet Asymmetry, E_{T1}=75 GeV, R=0.2 Jets