Jet suppression in Pb+Pb collisions with the ATLAS detector

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IPNP
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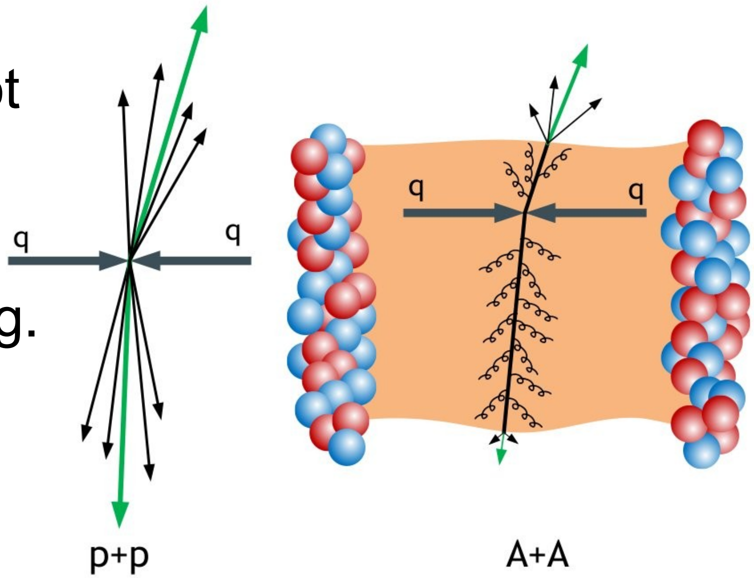
Jets in Heavy Ion Collisions

- Jets provide a powerful tool to probe the hot and dense medium created in HI collisions.
- RHIC's measurements of single high p_T particles: the first evidence for jet quenching.
- Need to do the full jet reconstruction to understand the quenching in more details.



- The first ATLAS Pb+Pb paper: significant increase of the number of collisions with a large di-jet asymmetry with increasing collision centrality: *arXiv:1011.6182, Phys. Rev. Let. 105, 252303*
- How do partons loose energy in QGP?

➡ Better understanding of QCD in the limit of high densities and temperatures.

- How does the medium modify the parton showers?

Jets in Heavy Ion Collisions

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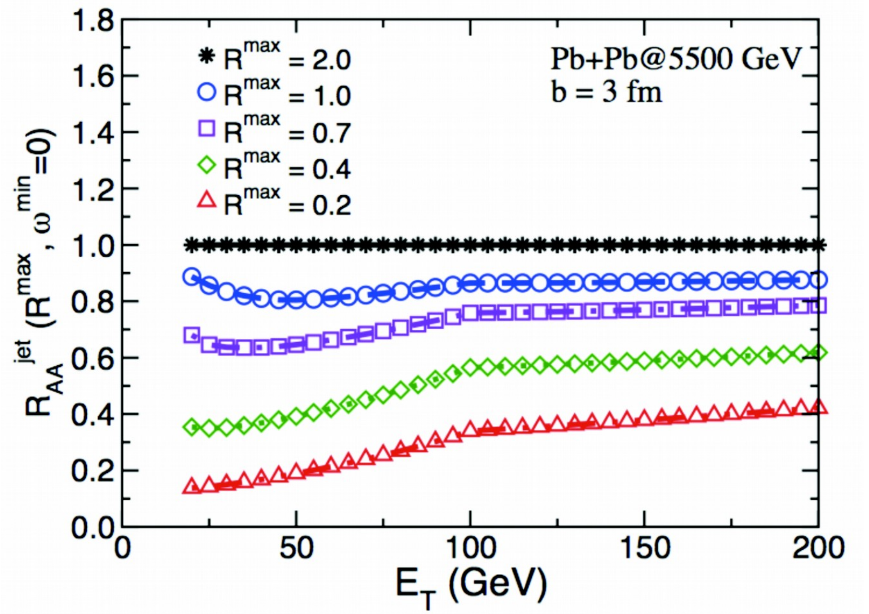
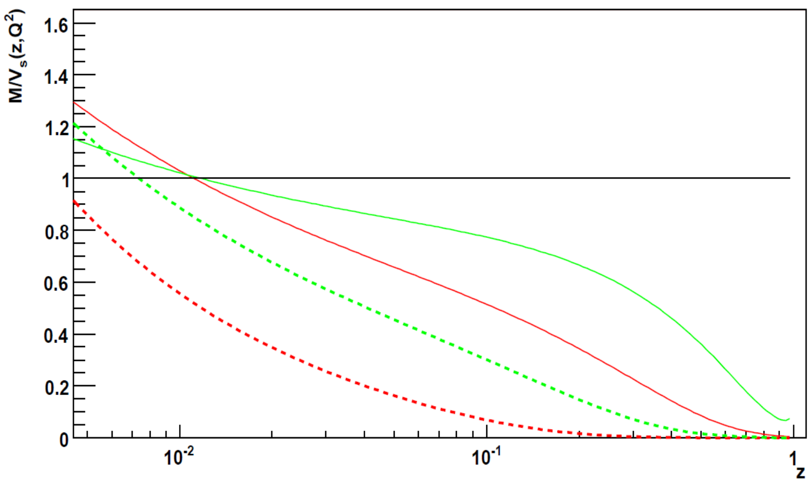


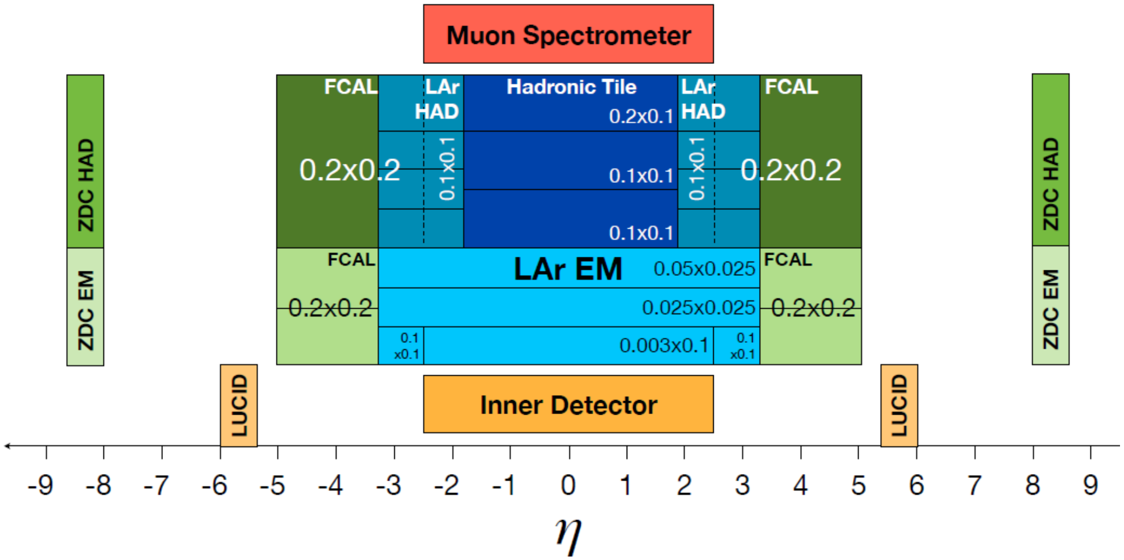
I.Vitev et al., JHEP11 (2008) 093

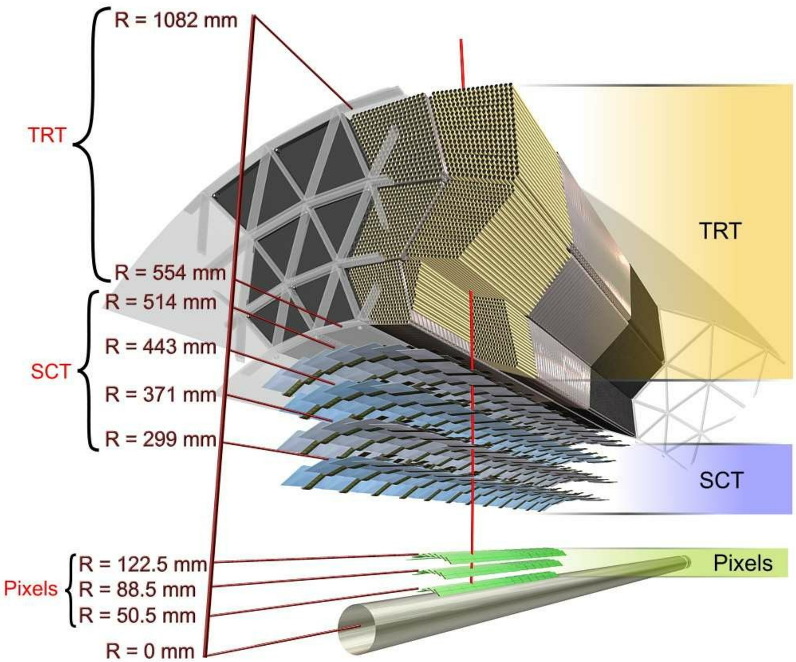


N.Armesto et al., JHEP0802 (2008) 048:

The ATLAS Detector

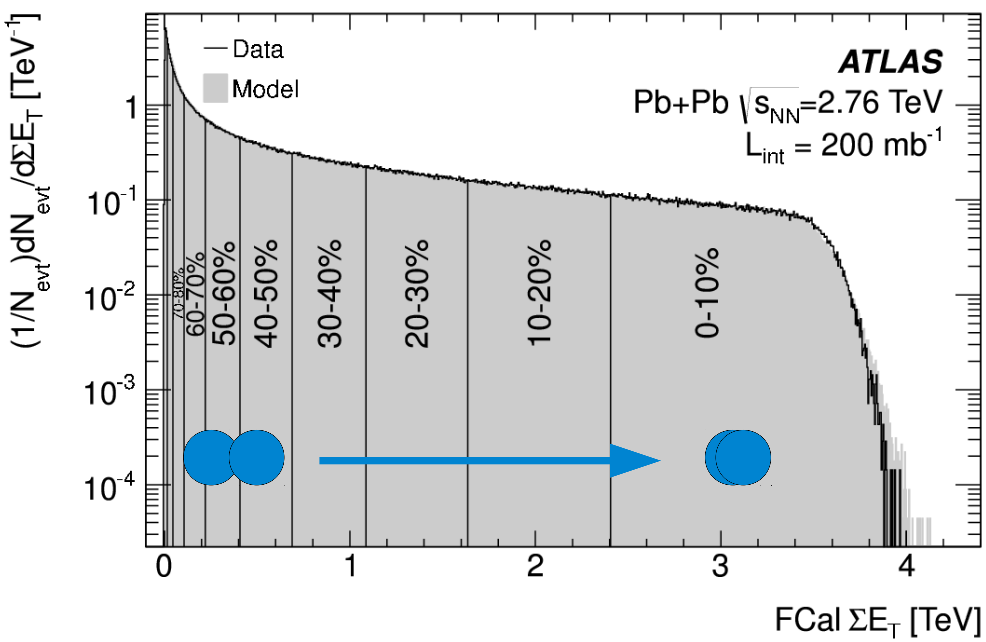
- ATLAS, a general-purpose p-p experiment, is also an excellent detector for heavy ion physics!
- Large pseudorapidity coverage and full azimuthal acceptance.
- Fine granularity and longitudinal segmentation.
- Precise inner detector in a 2T solenoid field.
- Extensive system of muon chambers placed inside a 1T toroid field.

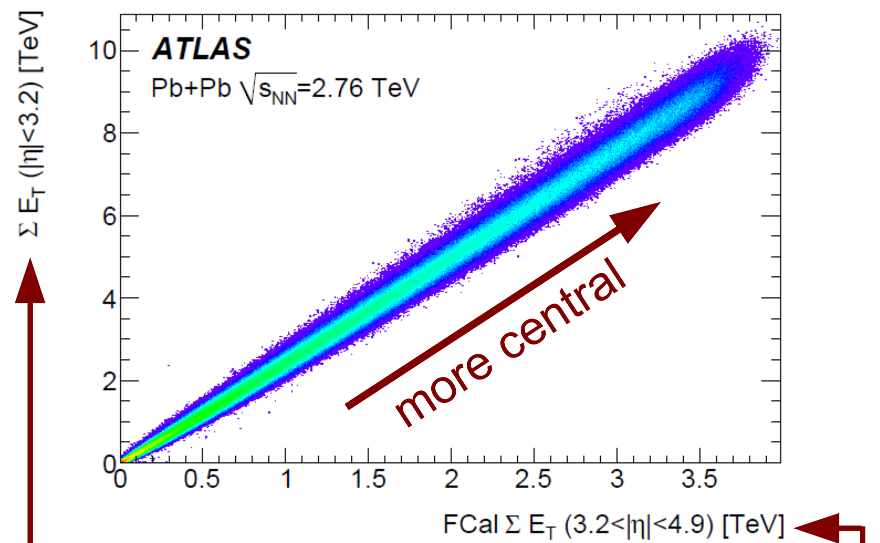


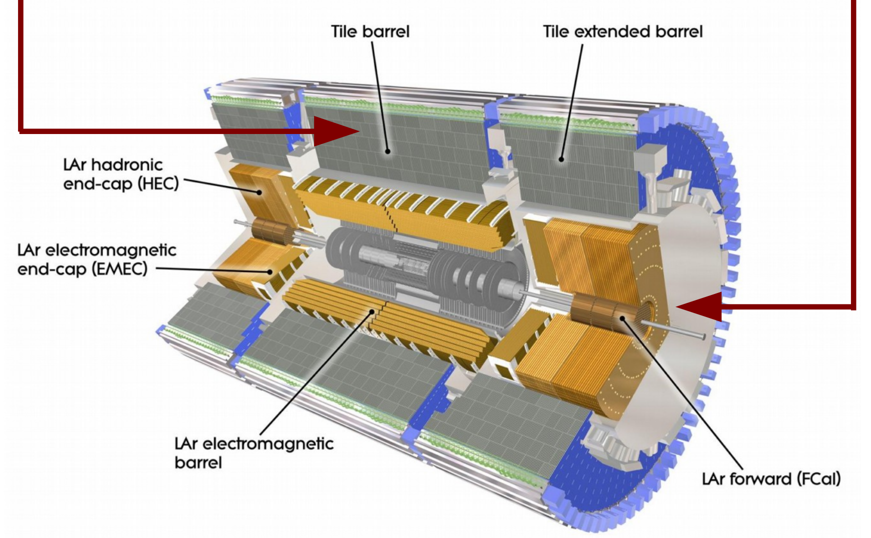


Centrality

- Characterize centrality by percentile of total cross-section using total E_T.
- Measured in Forward Calorimeter ($3.2<|\eta|<4.9$).
- Centrality → number of participants N_{part} and binary collisions N_{coll}.







ATLAS calorimeter

Jet Reconstruction at ATLAS

- Reconstruction algorithm: anti-k_t with R=0.2, 0.3 and 0.4.
- Input: calorimeter towers 0.1 x 0.1 ($\Delta\eta$ x $\Delta\varphi$).
- Event-by-event background subtraction:

$$E_{\mathrm{T}\,j}^{\mathrm{sub}} = E_{\mathrm{T}\,j} - A_j \; \rho_i(\eta_j) \left(1 + 2v_{2\,i} \cos\left[2\left(\phi_j - \Psi_2\right)\right]\right)$$

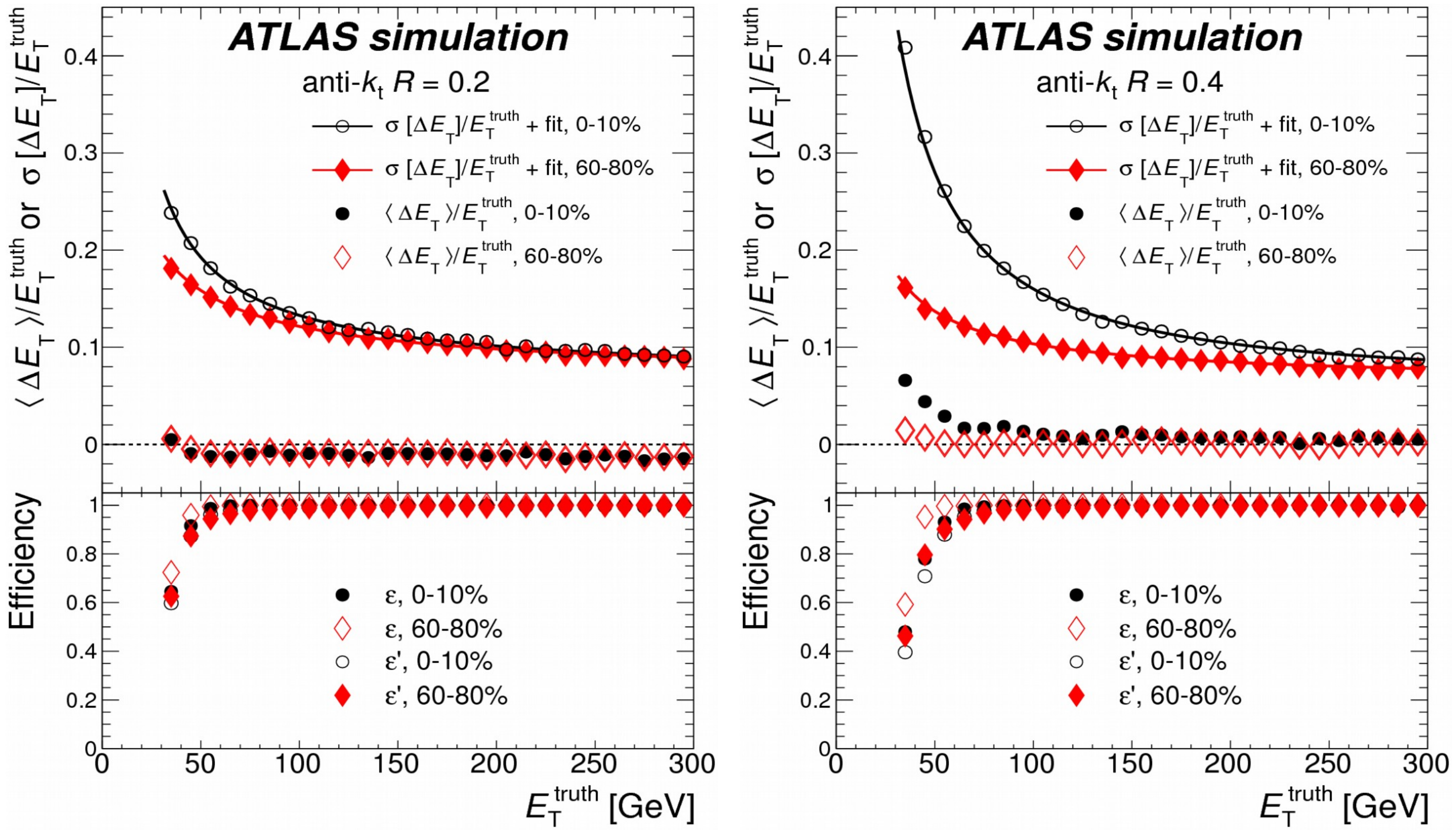
➡ Anti-k_t reconstruction prior to a background subtraction.

➡ Underlying event estimated for each longitudinal layer and η slice separately.

- We exclude jet candidates with $D = E_{T\,tower}^{max} / \langle E_{T\,tower} \rangle > 4$ to avoid biasing subtraction from jets but no jet rejection based on *D.*
- Additional iteration step to remove residual effect of the jets on the background estimation.
- Jets corrected for flow contribution.

Performance of the Jet Reconstruction

- Performance is evaluated using pp hard scattering events from Pythia overlying on top of HIJING MB events without quenching.

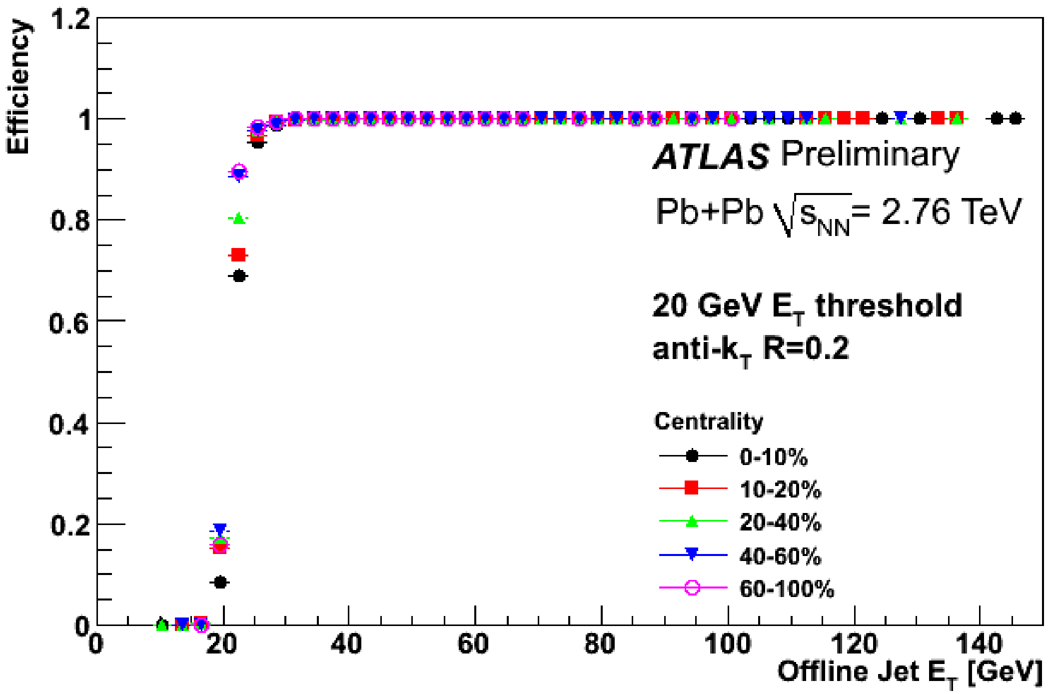


- JER is well described by $\sigma(\Delta E_T)/E_T = 1/E_T(a.\sqrt{E_T} + b + c.E_T)$ where parameter *b* is consistent with the result from the fluctuation analysis.
- The performance have been also verified using data overlay with similar results.

Data and MC

- Three data sets were used:
- Pb+Pb data recorded in 2011 with integrated luminosity of 0.14 nb^{-1}.
- Pb+Pb data recorded in 2010 with integrated luminosity of 7 μb^{-1}.
- High level jet triggers (HLT) seeded by L1 minimum bias (MB) triggers were used to select events in 2011 and only MB triggers for 2010 data.

- Jet trigger algorithm required a R=0.2 jet with E_T > 20 GeV.
- All events were required to satisfy MB events selection: good timing and vertex.
- MC Pythia di-jet events embedded into MC HIJING and data overlay were used for performance evaluation.

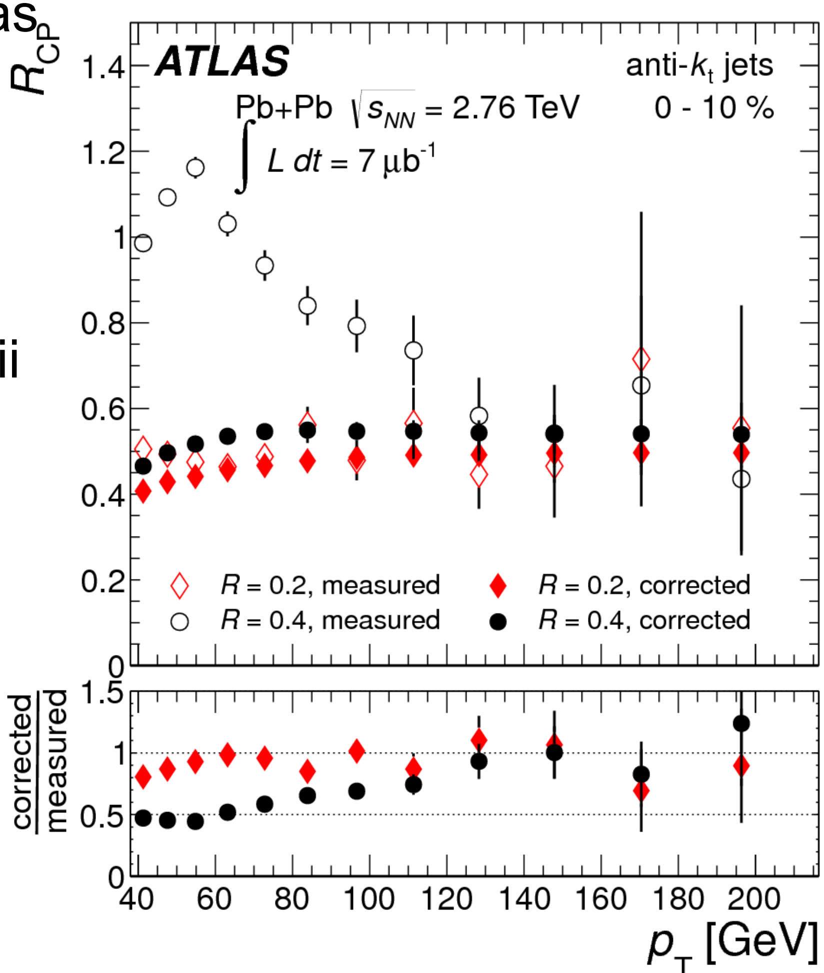


Inclusive jet production

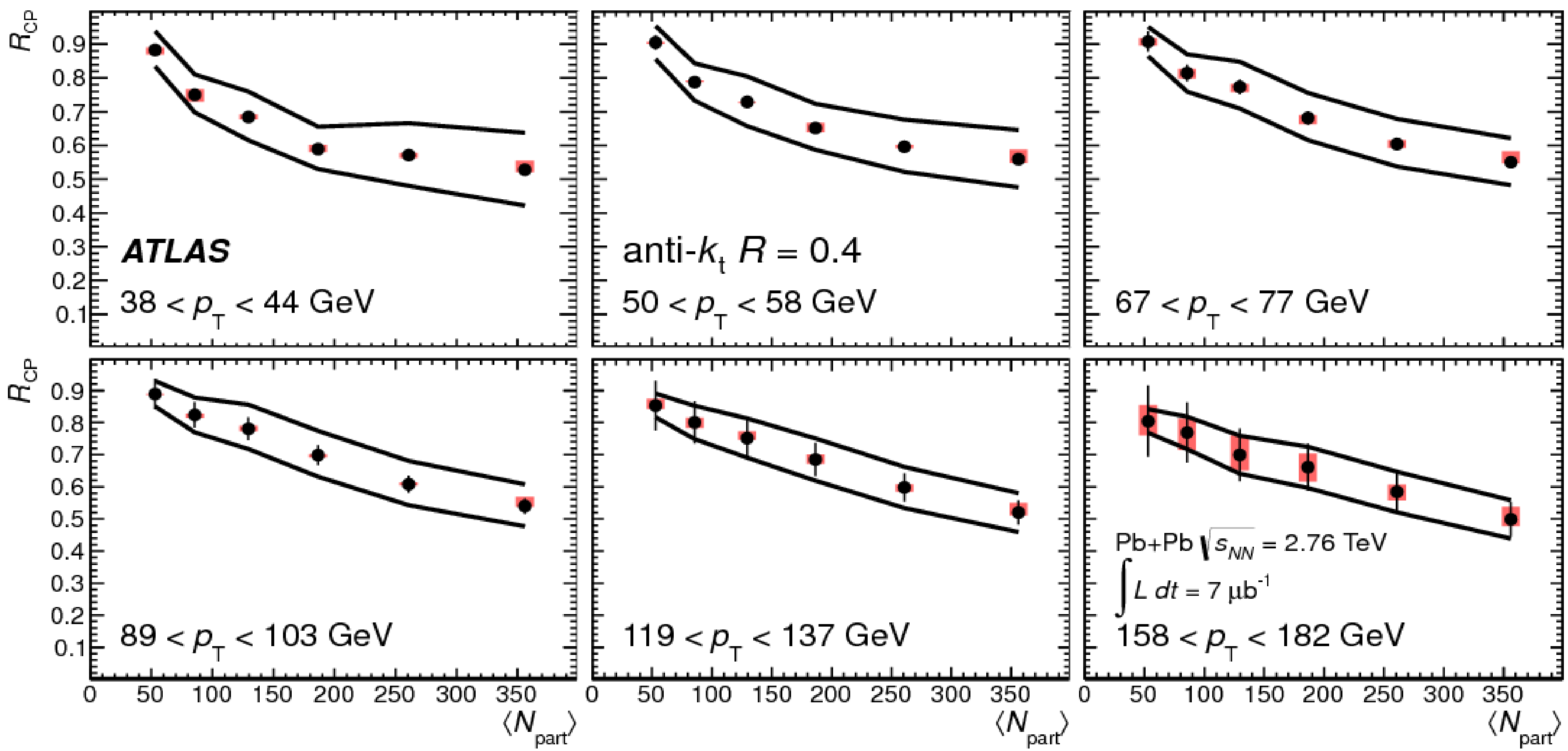
- Measurement of an inclusive jet production is the important probe of jet quenching.
- The jet suppression was quantified by to different variables:
- R_{CP} – central to peripheral ratio, defined as

$$R_{CP} = \frac{1/N_{coll}^{cent}}{1/N_{coll}^{periph}} \frac{1/N_{evnt}^{cent}\, dN/dE_T}{1/N_{evnt}^{periph}\, dN/dE_T}$$

- We measured the R_{CP} for different jet radii to study the role of radiative energy loss.
- SVD unfolding was used to account effect of bin migration caused by detector and UE effects.
  - Small effect on R=0.2 jets.
  - R_{CP} is reduced for R=0.4 by factor of two for low E_T jets.

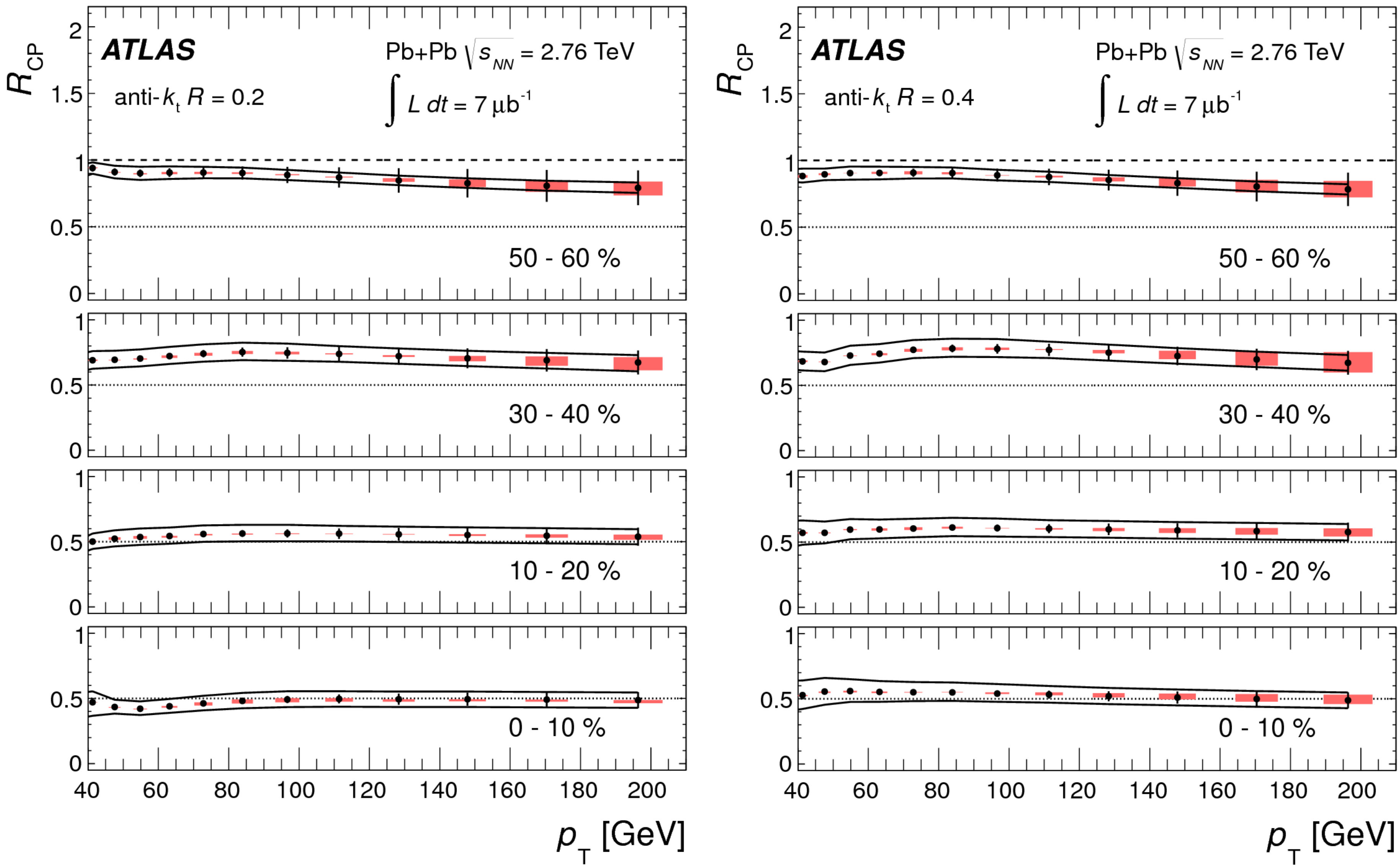


Centrality Dependence of Jet R_{CP}



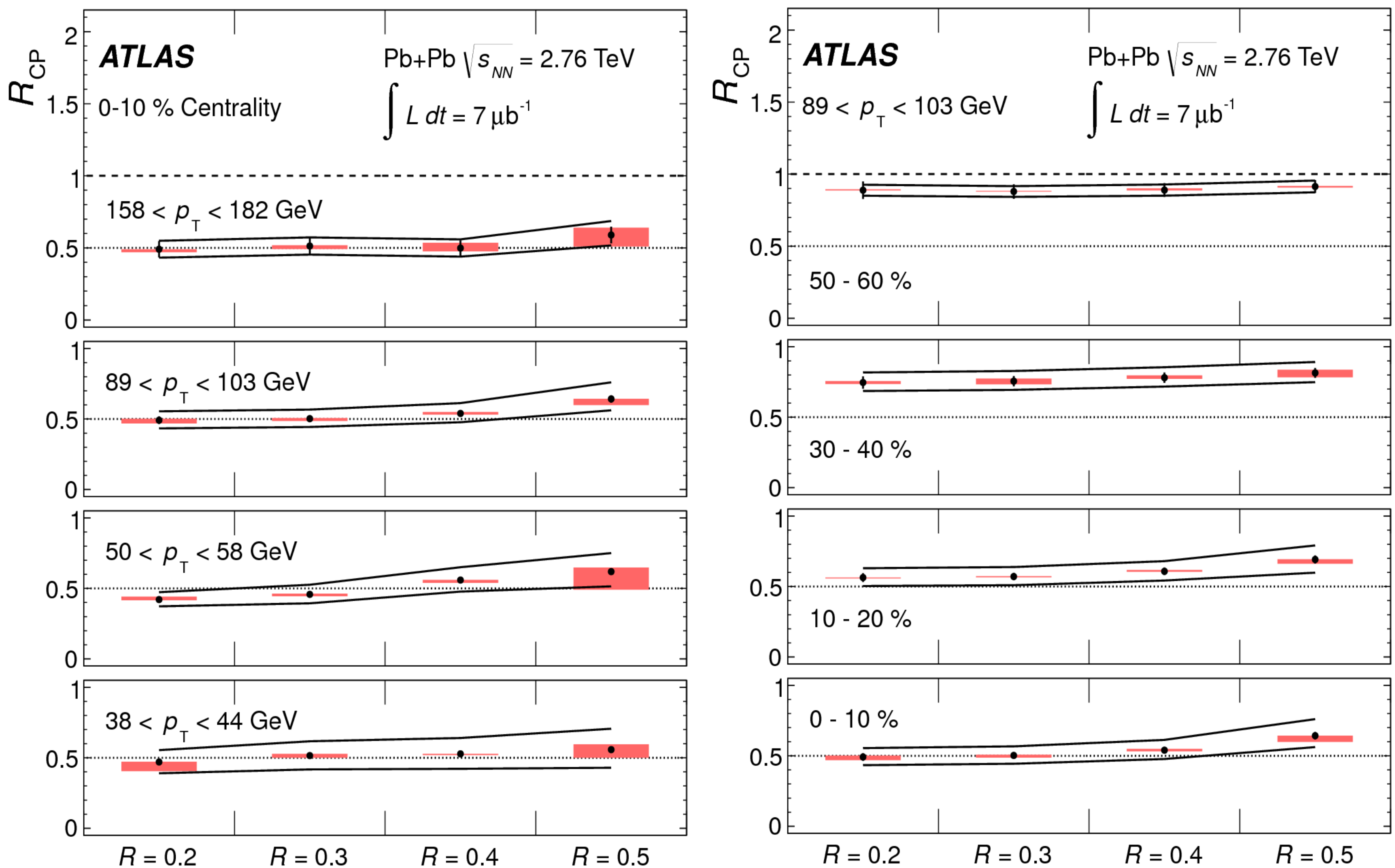
- Factor of 2 suppression in central with respect to peripheral collisions.
- Increasing suppression with increasing centrality.
  - The increase is linear for high p_T, quick turns on at low p_T.
  - Similar result is observed also for other jet radii.

Jet R_{CP} as a Function of Jet p_T



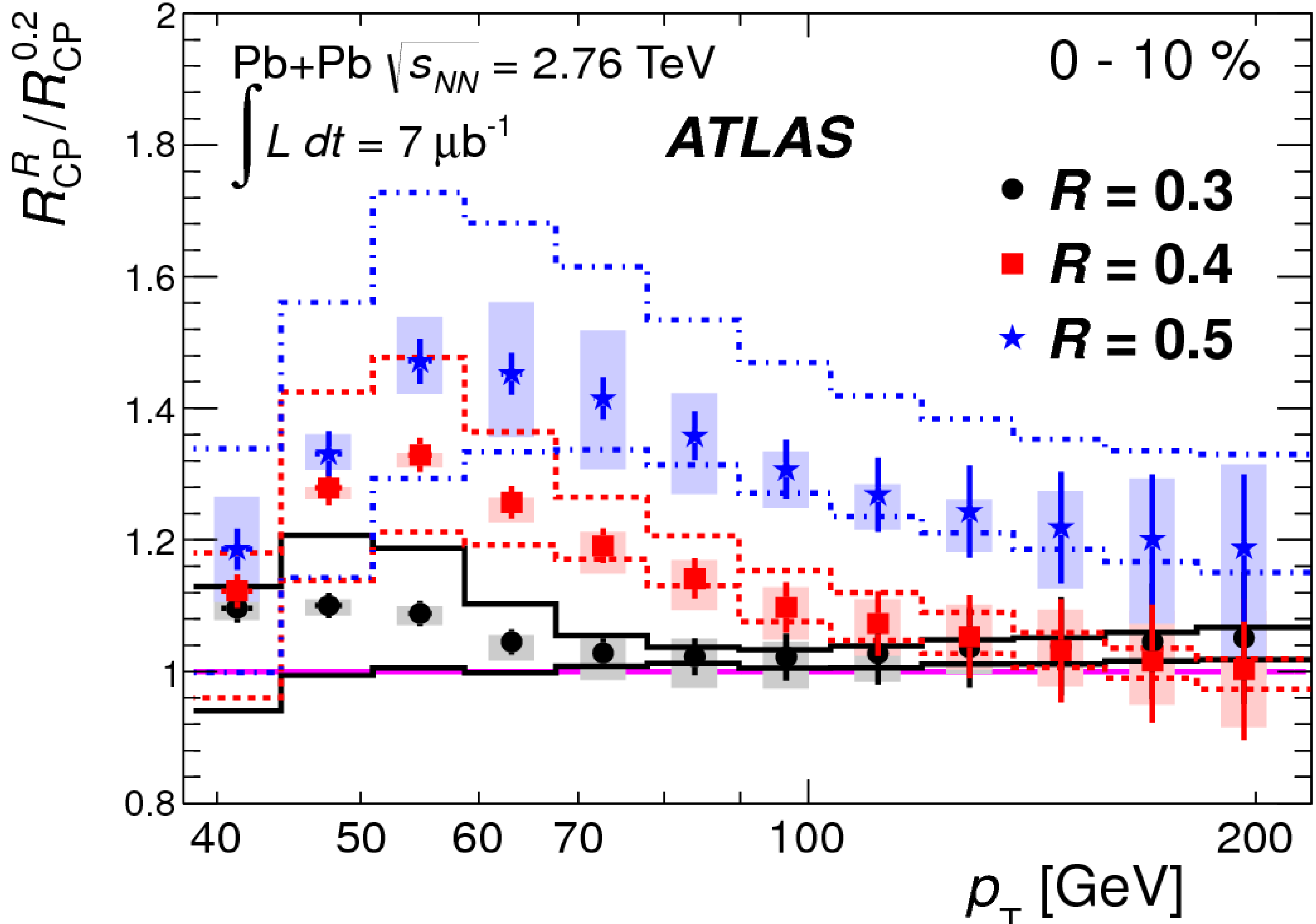
➡ The jet suppression factor shows small variation with the jet p_T.

Jet R_{CP} as a Function of Jet Radius



- Weak dependence on jet radius is observed.
- A small difference is present only at very low p_T.

R_{CP} – R dependence

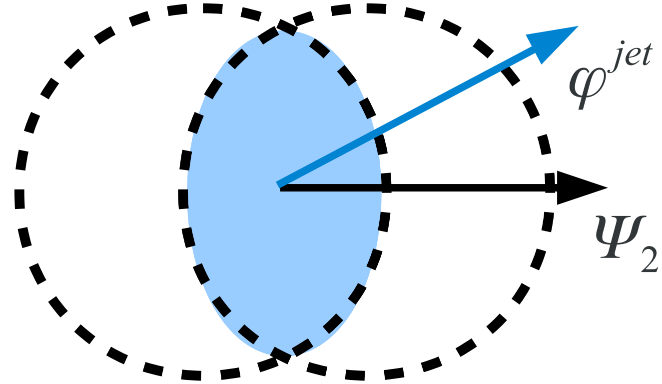


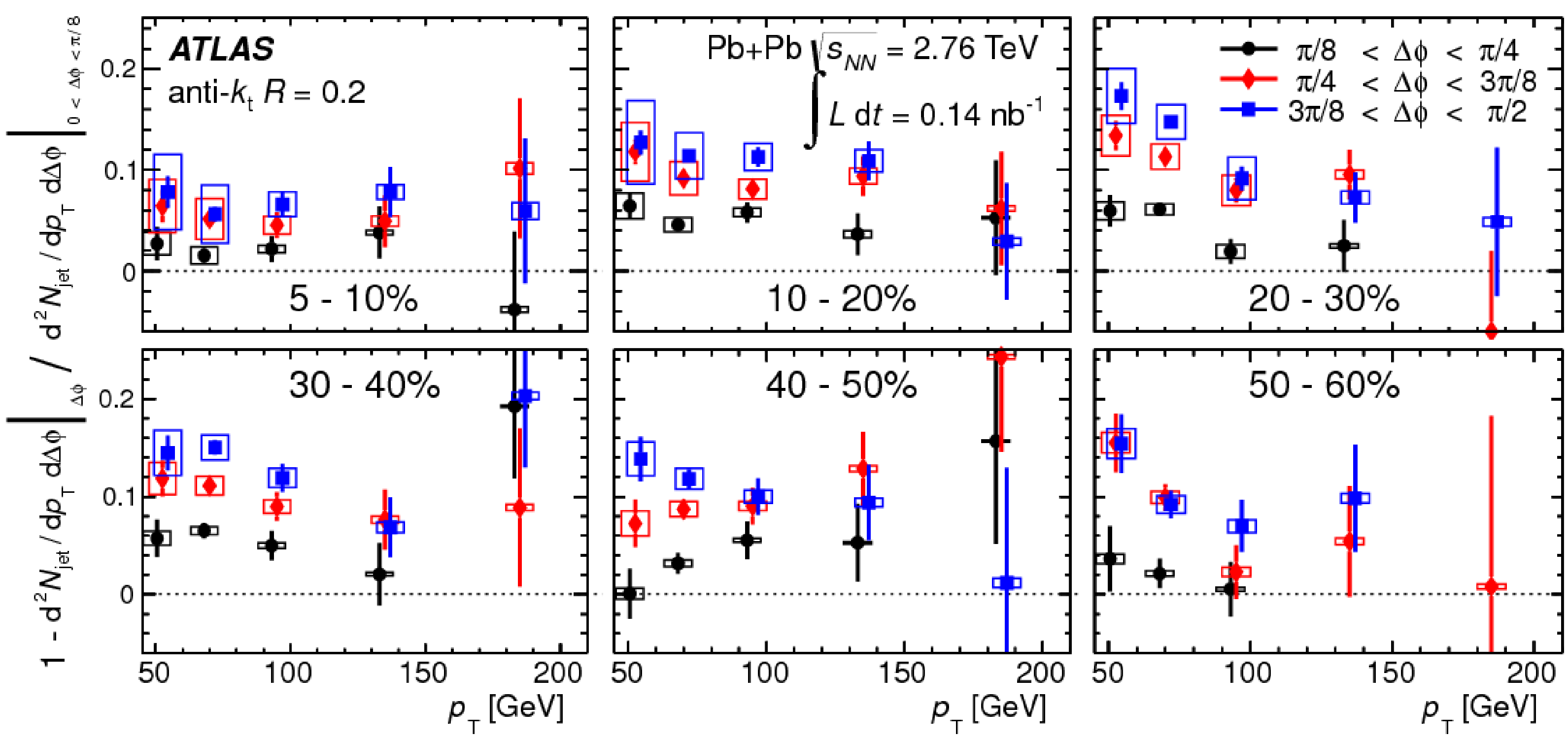
➡ Less suppression for jets with larger R.

Azimuthal dependence of jet yields

- Path length dependence of jet suppression
- Ratios of yields in different slices of

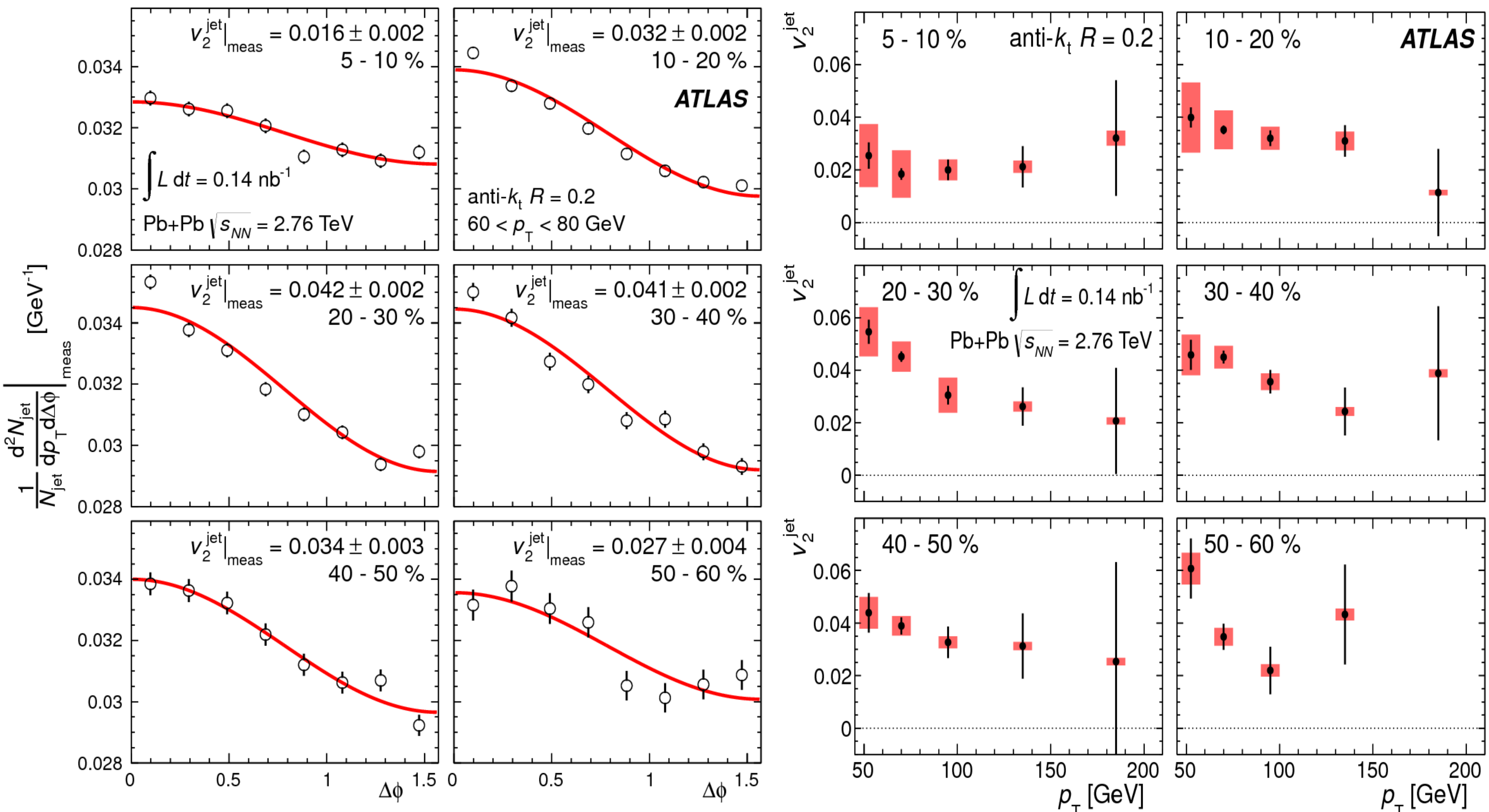
$\Delta\varphi = \varphi^{jet} - \Psi_2$ with respect to $\Delta\varphi = 0 - \pi/8$





➡ ~15% reduction in plane yields with respect to out of plane yields.

Jet v_2



➡ Weak p_T dependence

- Consistent result with the measurement using single high-p_T particles

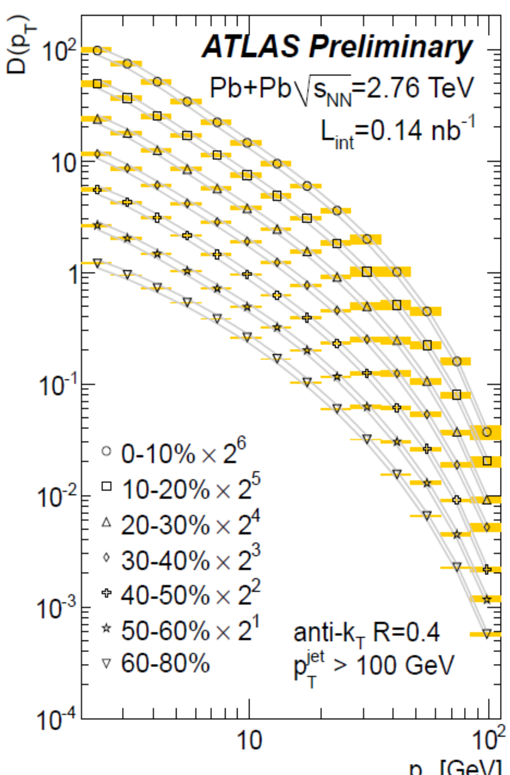
Jet Structure

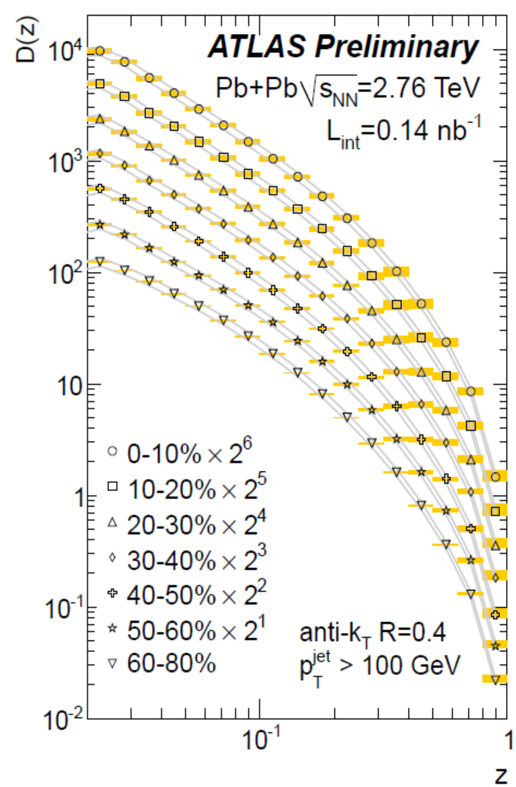
- We measured two sets of fragmentation distributions describing the jet structure:

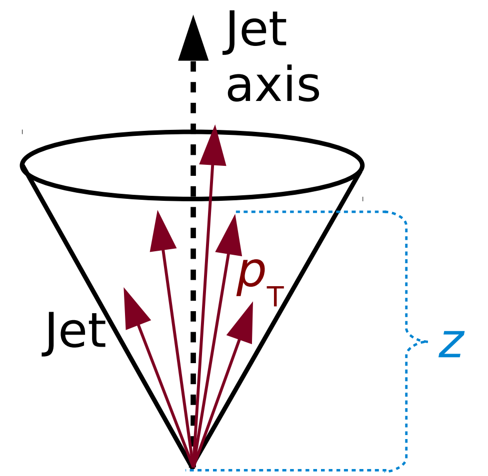
$$D(p_{\mathrm{T}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{1}{\varepsilon} \frac{\Delta N_{\mathrm{ch}}(p_{\mathrm{T}})}{\Delta p_{\mathrm{T}}} \qquad D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{1}{\varepsilon} \frac{\Delta N_{\mathrm{ch}}(z)}{\Delta z} \qquad z = p_{\mathrm{T}}^{\mathrm{ch}} / p_{\mathrm{T}}^{\mathrm{jet}} \cos \Delta R$$

Spectra of charged particles in jets

Fragmentation function



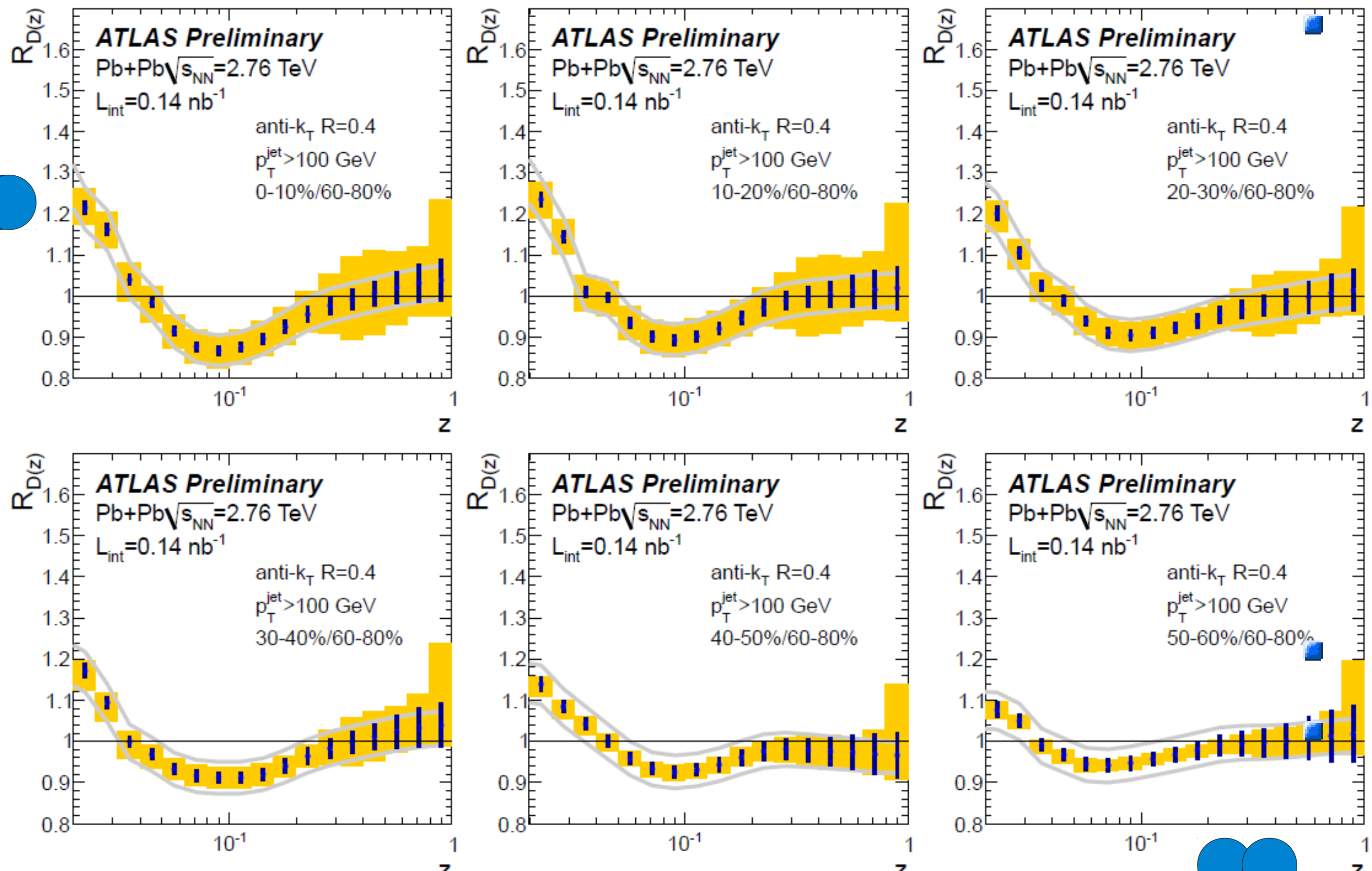




- D(z) and D(p_T) distributions have similar shape in all centrality bin.

➡ ratios are needed to study centrality dependence.

D(z) centrality dependence

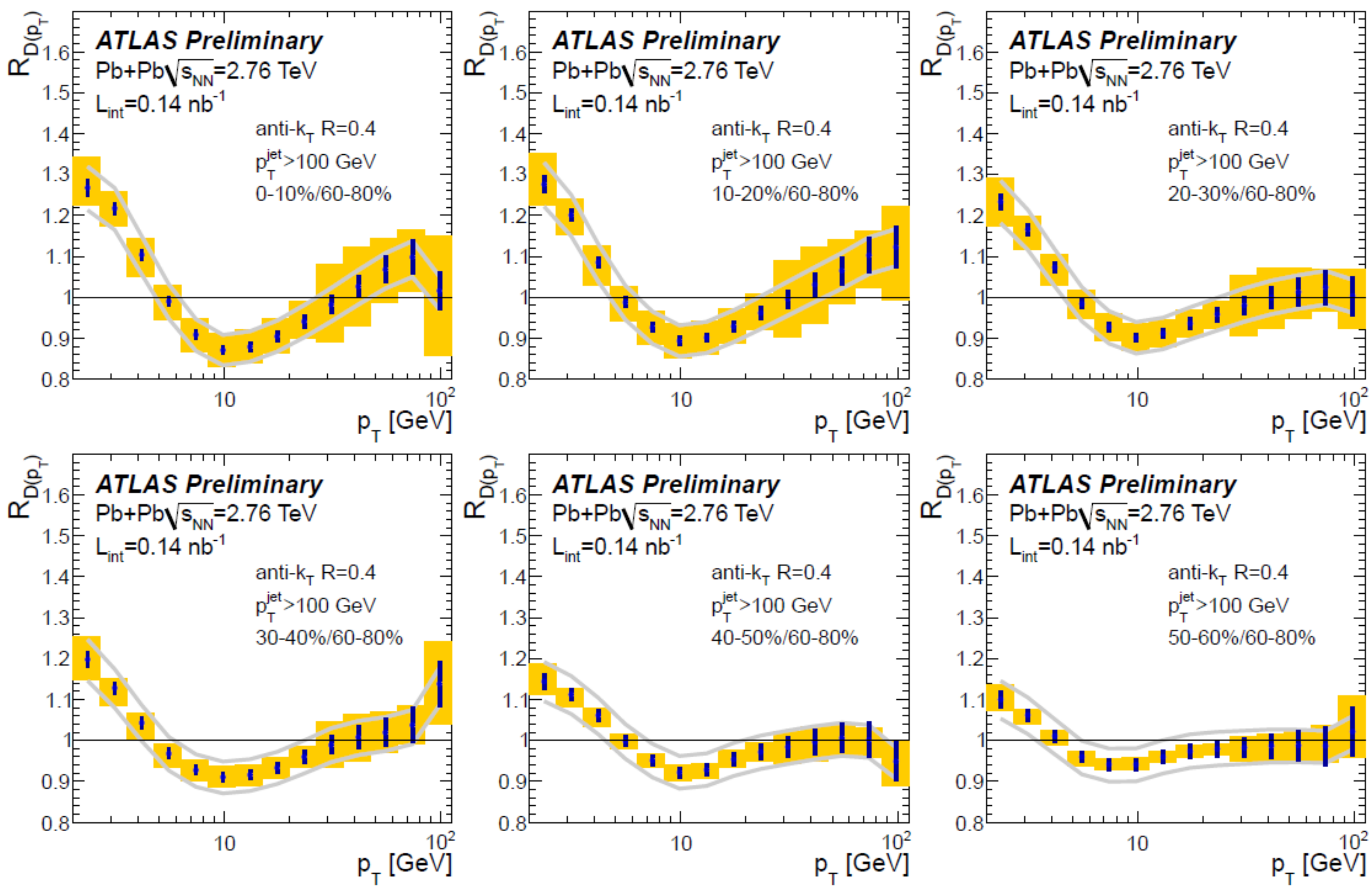


Shaded bands uncorrelated or partially correlated systematic errors: regularization, JES, JER, tracking efficiency, non-zero central to peripheral ration of D(z) and D(p_T) in MC.

Solid lines 100% correlated systematic errors: tracking efficiency.

- ~15% suppression at intermediate z (~0.1) and 25% enhancement at very low z (~0.02).
- No strong modification at large z (↔ leading parton) in central collisions with respect to peripheral ones.

D(p_T) centrality dependence



Shaded bands: uncorrelated or partially correlated systematic errors

Solid lines: 100% correlated systematic errors

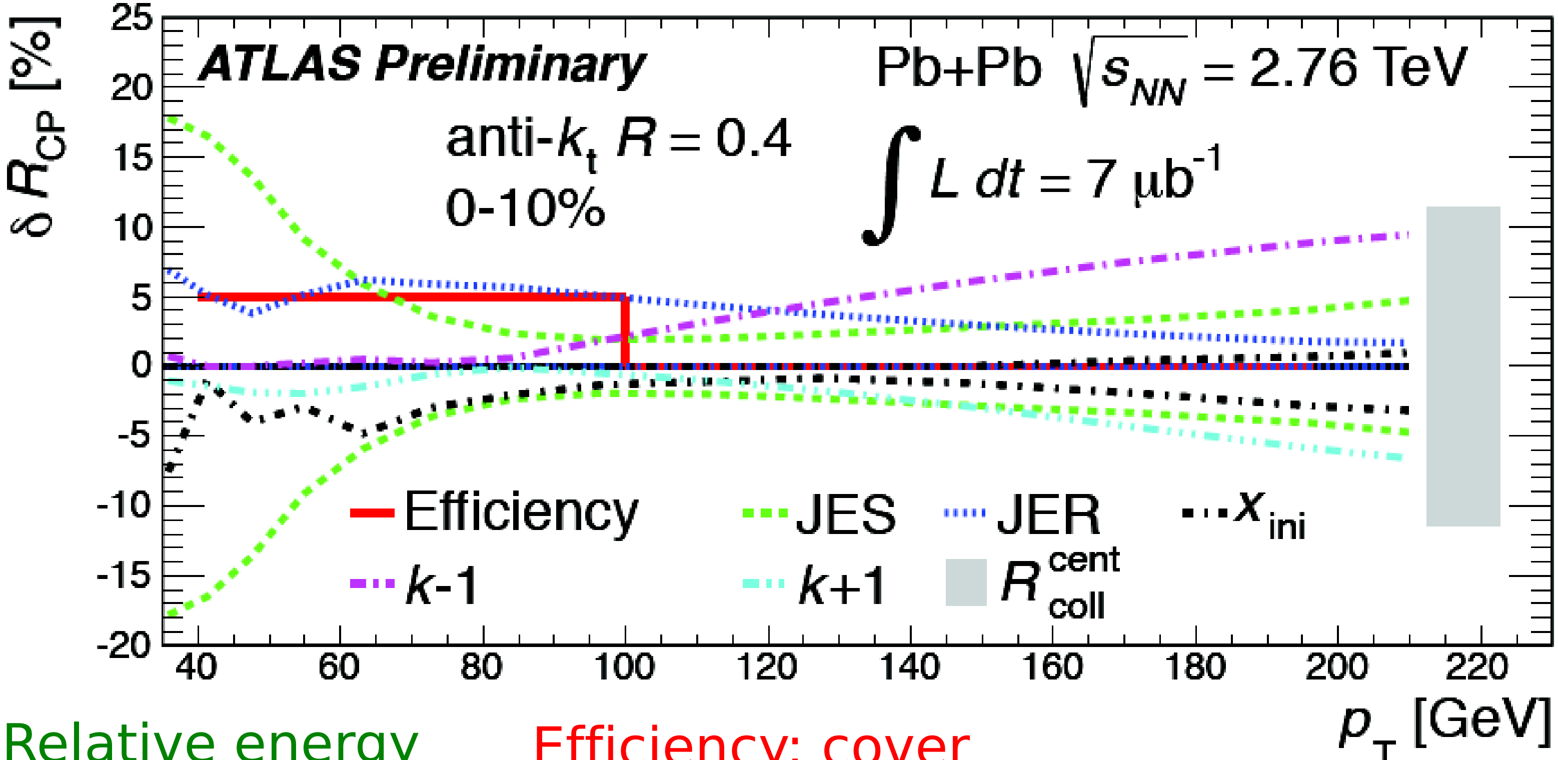
➡ Similar behaviour as for D(z) distribution.

Conclusions

- Energy imbalance in the di-jet system is strongly increasing with increasing centrality.
- Suppression by a factor of 2 is observed in jet yield in central with respect to peripheral collisions.
- The dependence of the R_{CP} is very weak on jet p_T
- Less suppression is observed for jets with larger R parameters.
- Azimuthal dependence of jet yields exhibits a clear path length dependence.
- Study of jet internal structure shows increasing size of modifications of fragmentation functions with increasing centrality.

Backup

R_{CP} – Systematics



JES: Relative energy scale differences central and peripheral

JER: Possible disagreement between data and MC in UE fluctuations

Efficiency: cover possible MC/data differences, 5% for pT < 100 GeV

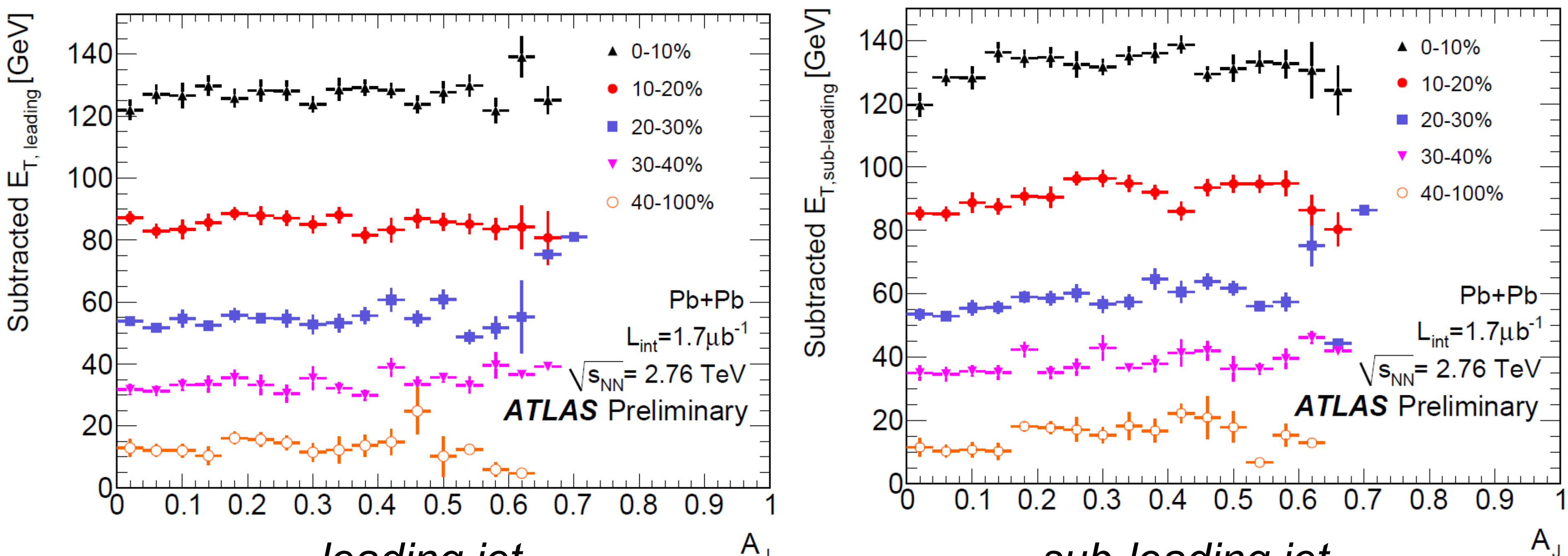
Xini: Sensitivity to power in power law: +0.5, -0.5

R_{coll}: sensitive to centrality determination, σ_{NN}

Regularization: Sensitivity to choice of k:+/-1

Subtracted E_T

- Mean subtracted energy as a function of asymmetry



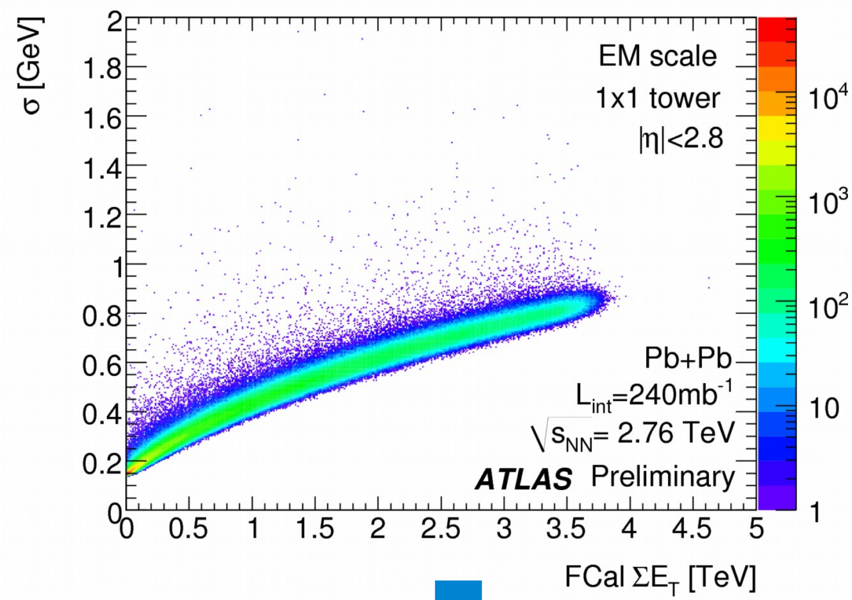
leading jet *sub-leading jet*

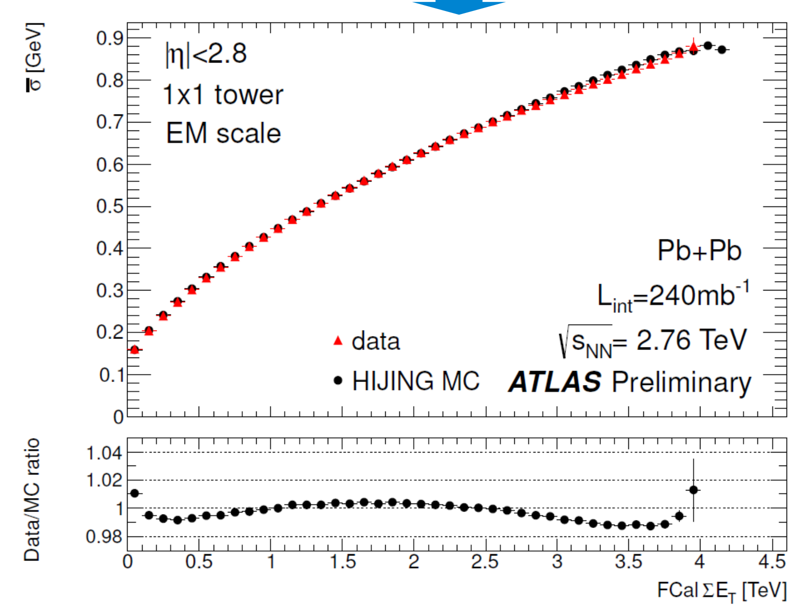
➡ no asymmetry dependence

➡ amount of subtracted energy for leading and sub-leading jet is comparable

Study of Background Fluctuations

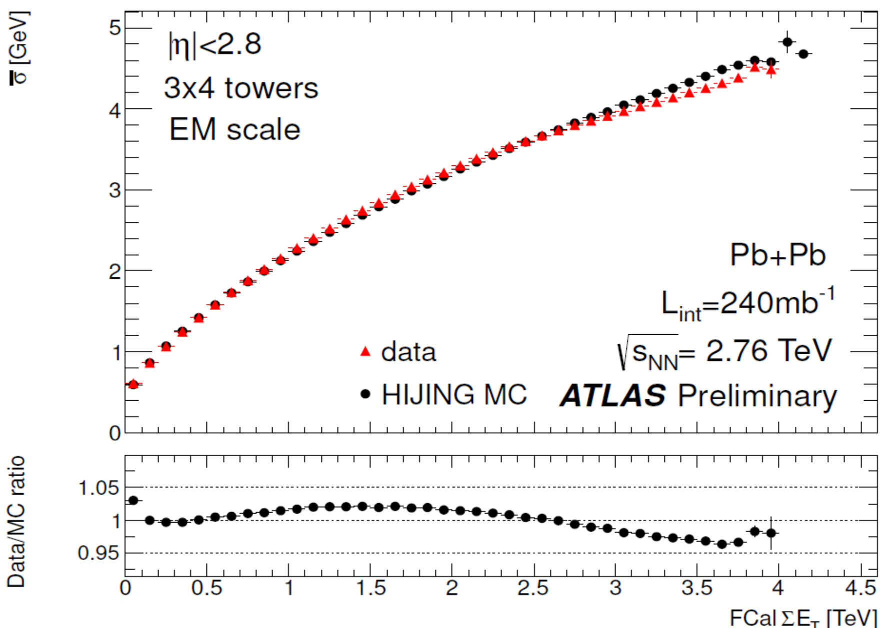
- Study physics of underlying event fluctuations → it can provide a basic information about correlations in the underlying event.
- Independent validation of JER.
- The size of fluctuations is characterized by standard deviation $\sigma = \sqrt{\langle E_T^2 \rangle - \langle E_T \rangle^2}$ and plotted as a function of FCal ΣE_T.
- A very good agreement between data and MC.



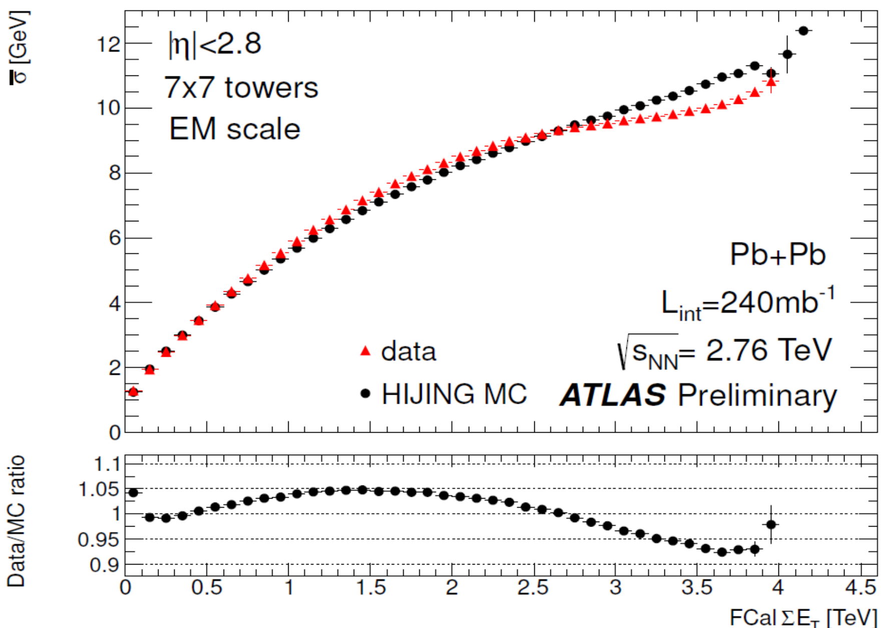


Background Fluctuations

- Fluctuations are measured in single towers and also in larger windows comparable to the area of jet:
  - 7x7 towers ~ R = 0.4 jets.
  - 4x3 towers ~ R = 0.2 jets.



R=0.2 jets

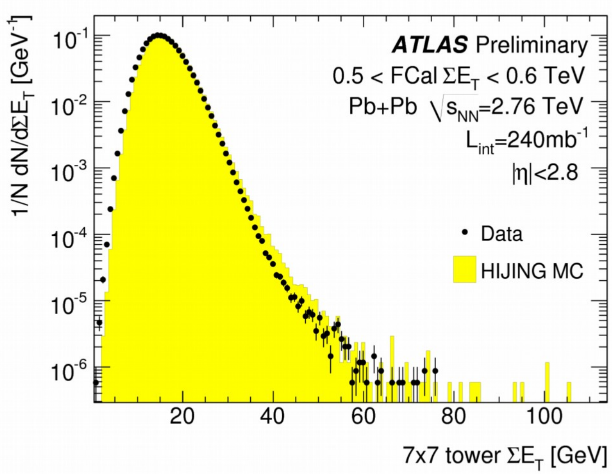


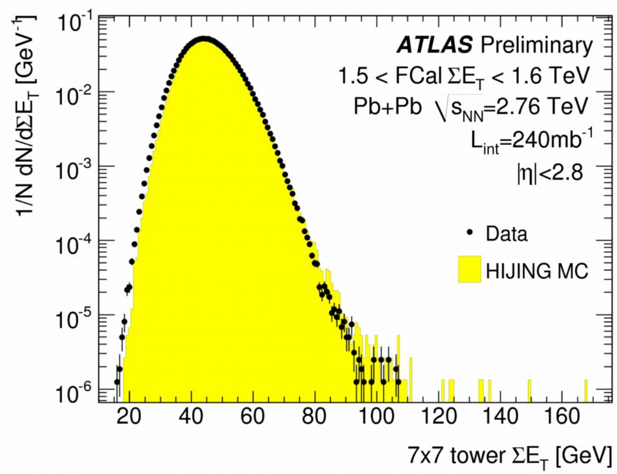
R=0.4 jets

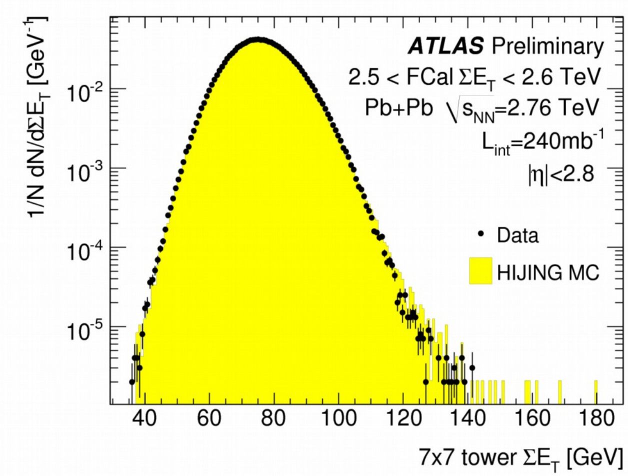
- An agreement between data and MC is better than 5% for R=0.2 jets.
- Fluctuations in data are at most 5% higher than in MC for R=0.4 jets.
- Fluctuations are higher in MC in the most central events.

Detail study of Underlying Event

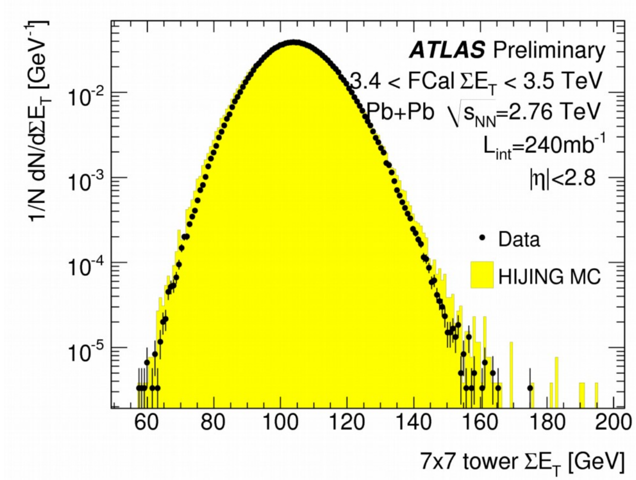
- Data and MC are compared in a narrow bin of FCal ΣE_T:



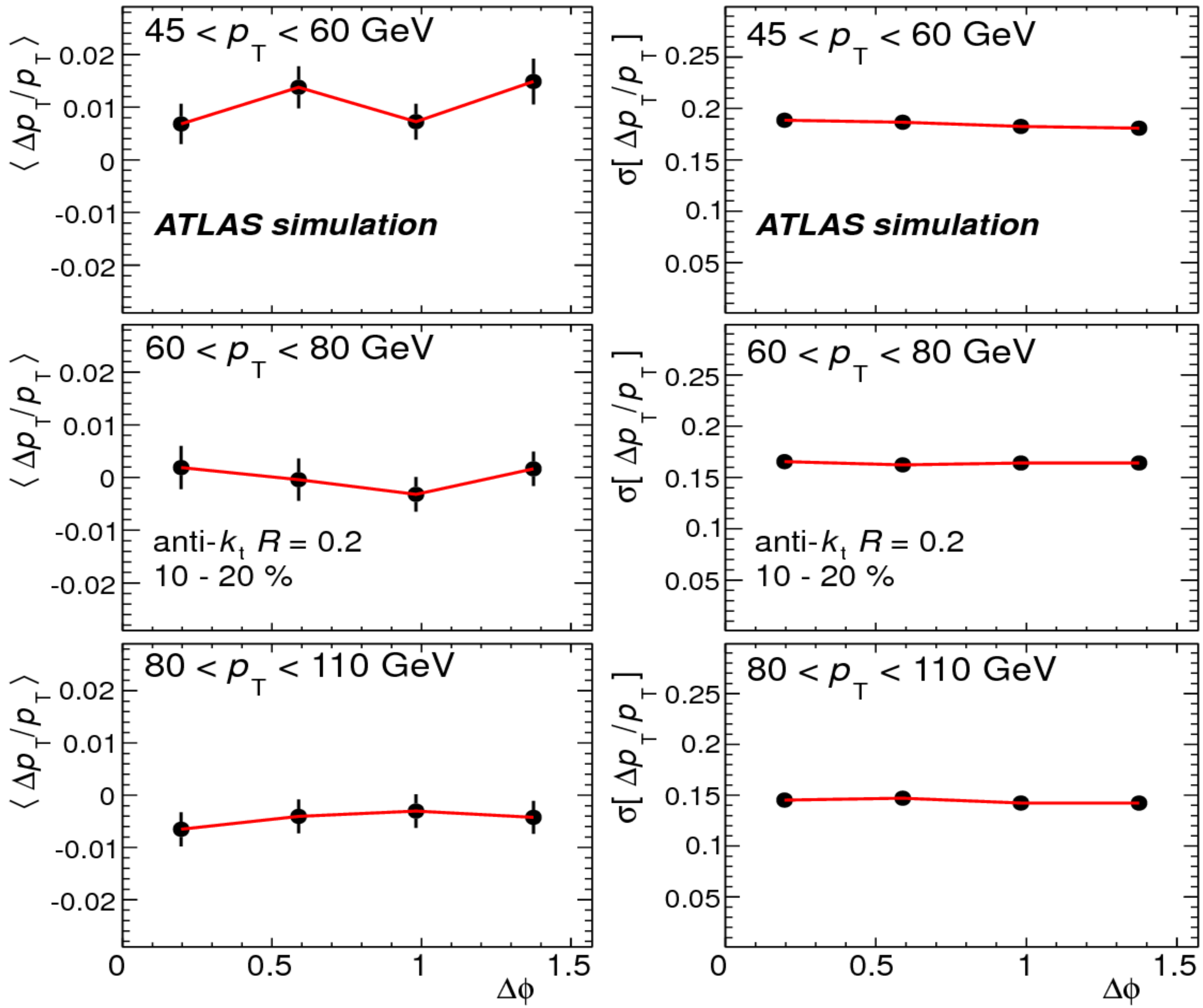




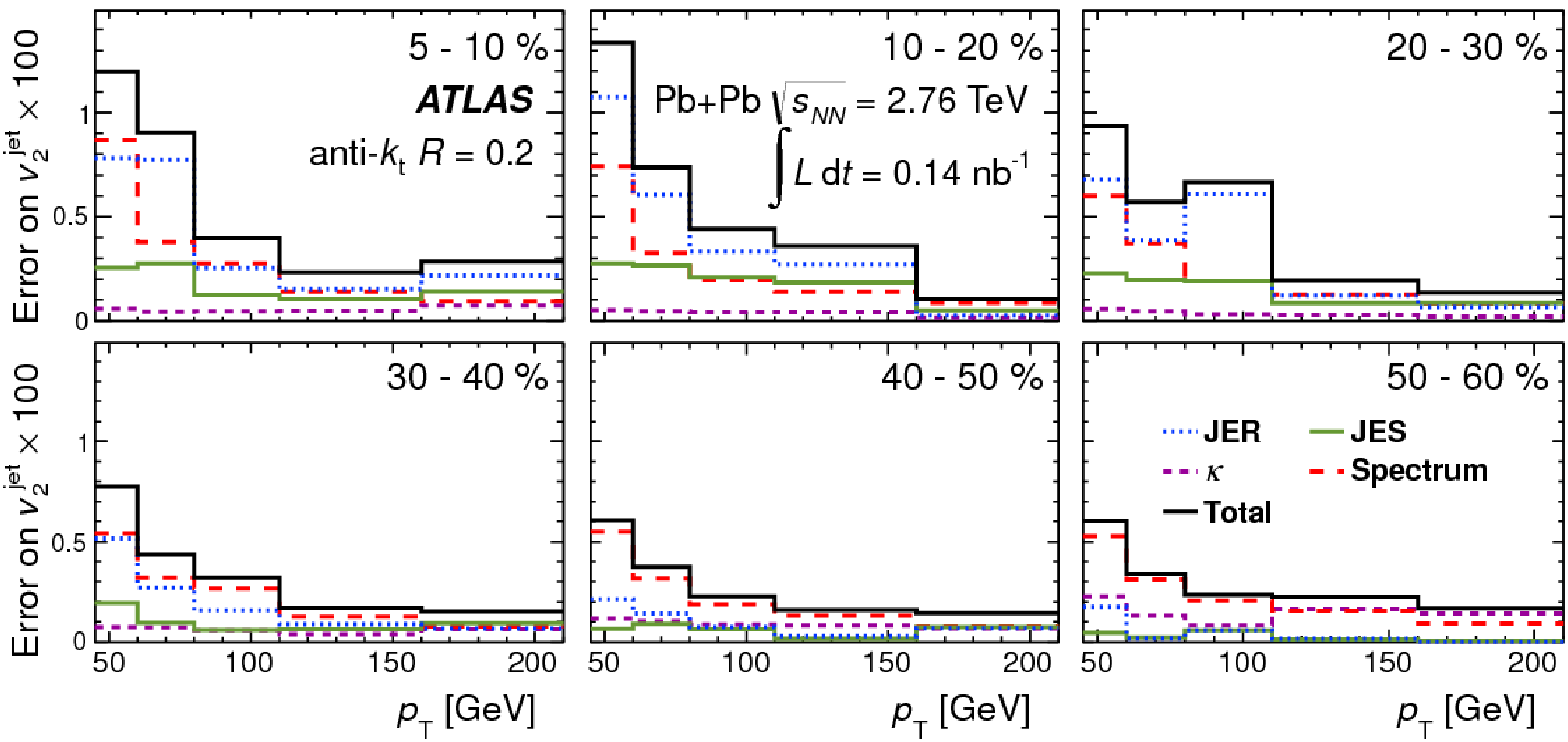
- HIJING over-predicts the size of upward fluctuations.
- HIJING over-predicts the size of downward fluctuations in central collisions.
- Where the spread in fluctuations is larger in data than in MC it is because data has larger downward fluctuations.



Azimuthal dependence of jet yields: JES and JER



Azimuthal dependence of jet yields: Systematic uncertainties

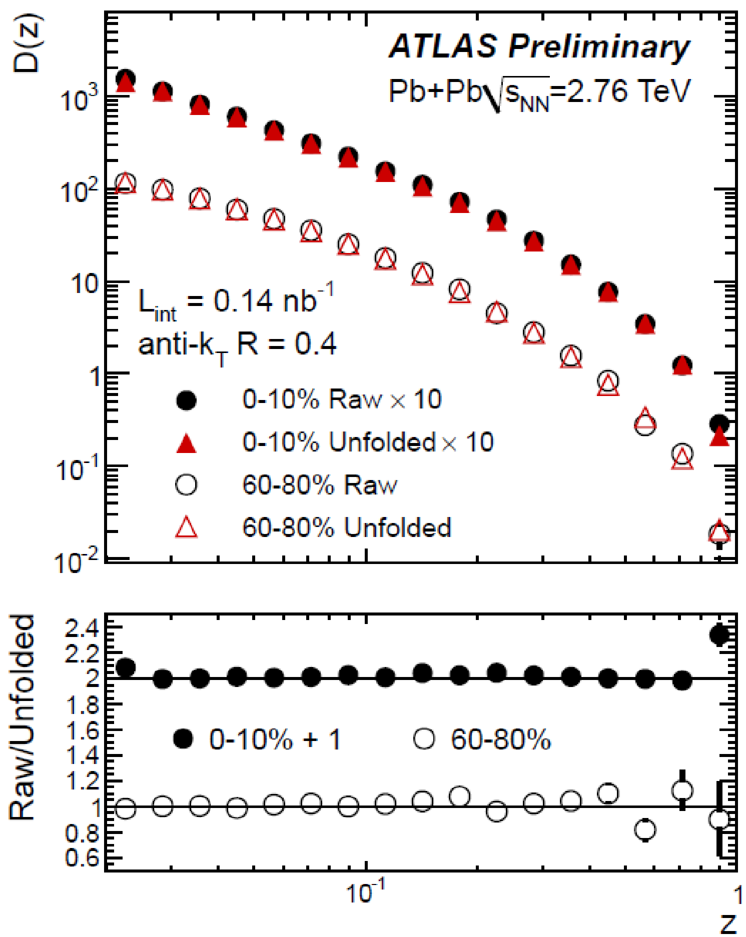


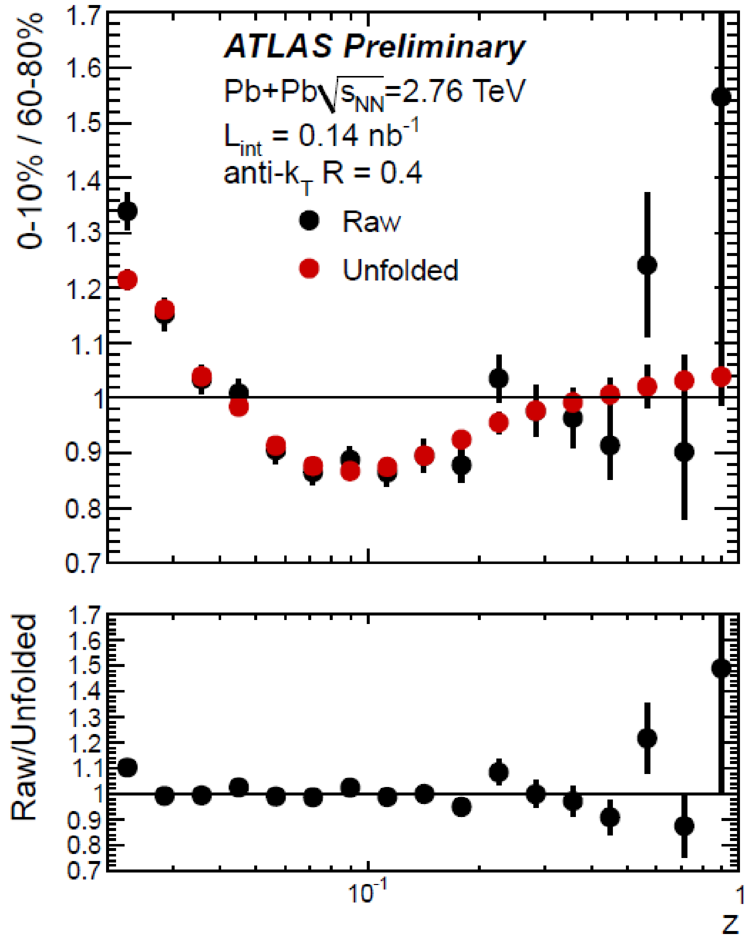
Fragmentation analysis: analysis setup

- Seven centrality bins and three jet p_T ranges: p_T> 85 (R=0.2), 92 (R=0.3), 100 GeV (R=0.4).
- Charged particles with p_T > 2 GeV in cone of 0.4 around the jet axis were used.
- Jet required to be isolated (to avoid biases from split jets).
- b-jet candidates were excluded from the analysis.
- Jet p_T was corrected to reduce the effect of the jet up-feeding due to JER.
- “fake” jets (from UE fluctuations) were identified and rejected by requirement of matching calorimeter jet to a track jet or electro-magnetic cluster > 7 GeV.
  - ➡ Measurement is restricted to $|\eta| < 2.1$.
  - ➡ We operate on trigger and jet reconstruction efficiency plateau for selected jet energies.
  - ➡ Residual fake rate is negligible for selected jet energies.

Results of Subtraction and Unfolding

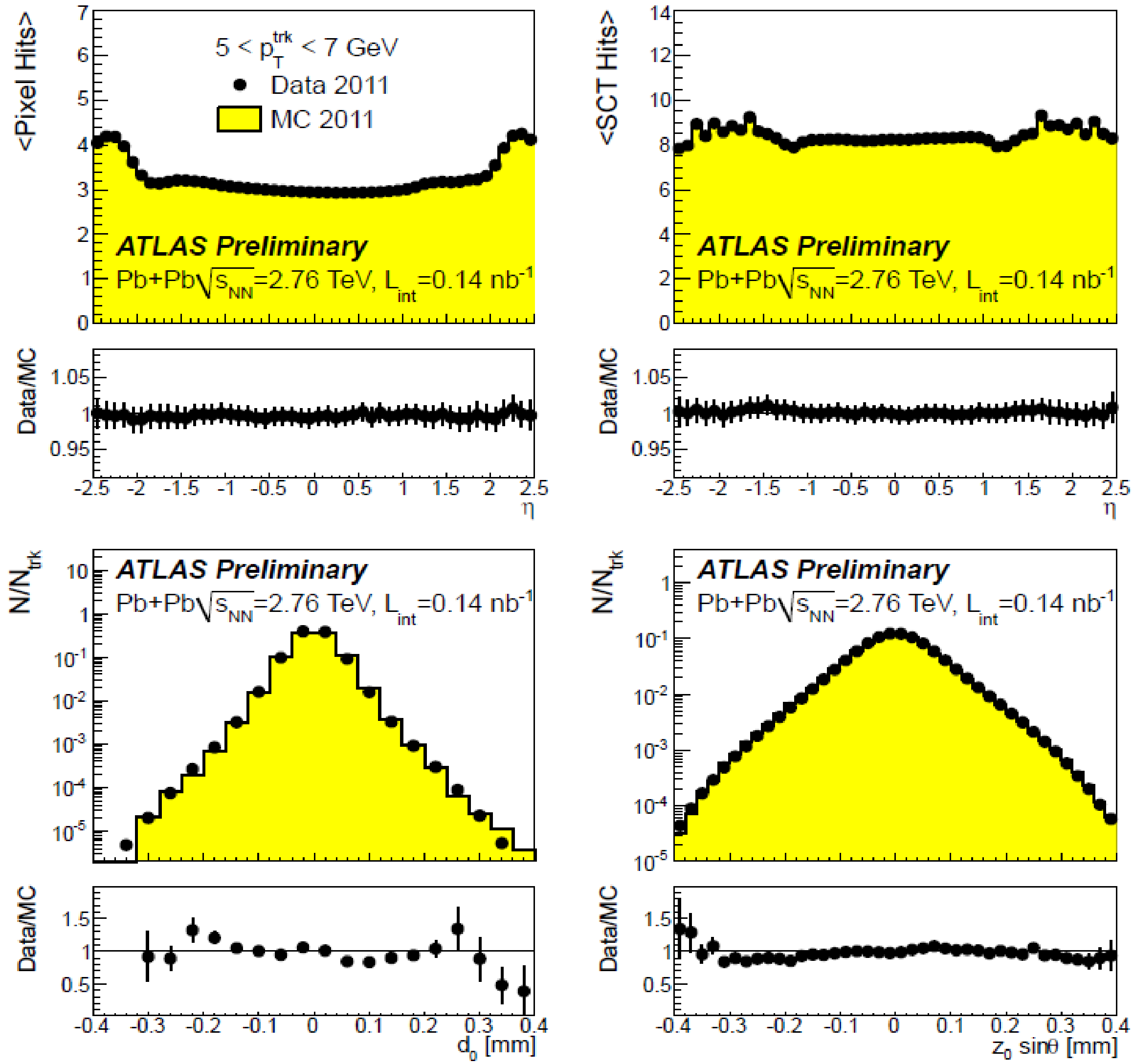
- SVD unfolding was used to correct detector effects and to reduce the effect of statistical fluctuations.
- D(z) unfolding accounts for track momentum and jet energy resolution, D(p_T) for track momentum resolution.





Performance of the Track Reconstruction

- Performance was evaluated using Pythia particles embedded into HIJING MB events.



- Very good description of detector response by MC.