Jet fragmentation and jet properties in $\sqrt{s_{NN}}=2.76$ TeV PbPb Collisions using the ATLAS Detector at the LHC

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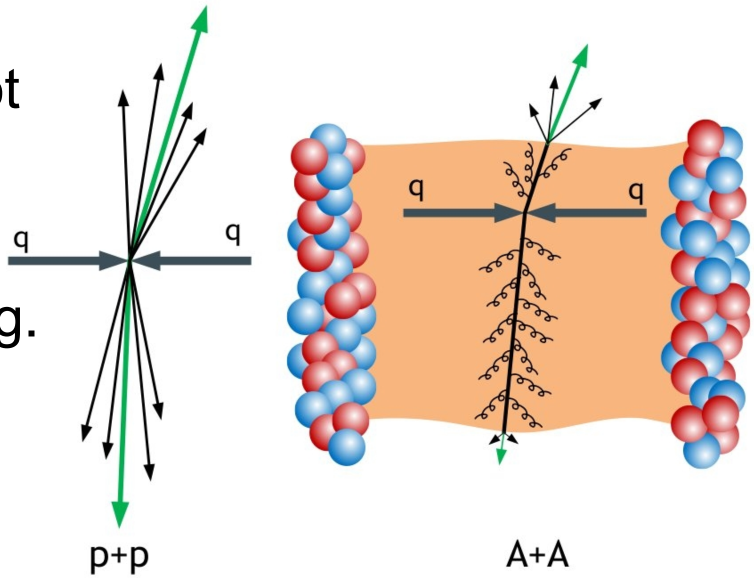
Jets in Heavy Ion Collisions

- 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*
- More detailed measurements are needed to answer questions:

➡ Is the energy redistributed to the medium out of the jet cone?

➡ Or does the energy remain inside the jet but redistributed among fragments?

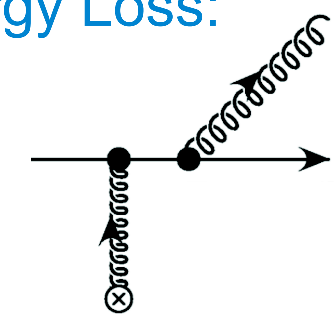
Radiative Energy Loss

- How does the medium modify the parton showers?

➡ Measurement of fragmentation functions.

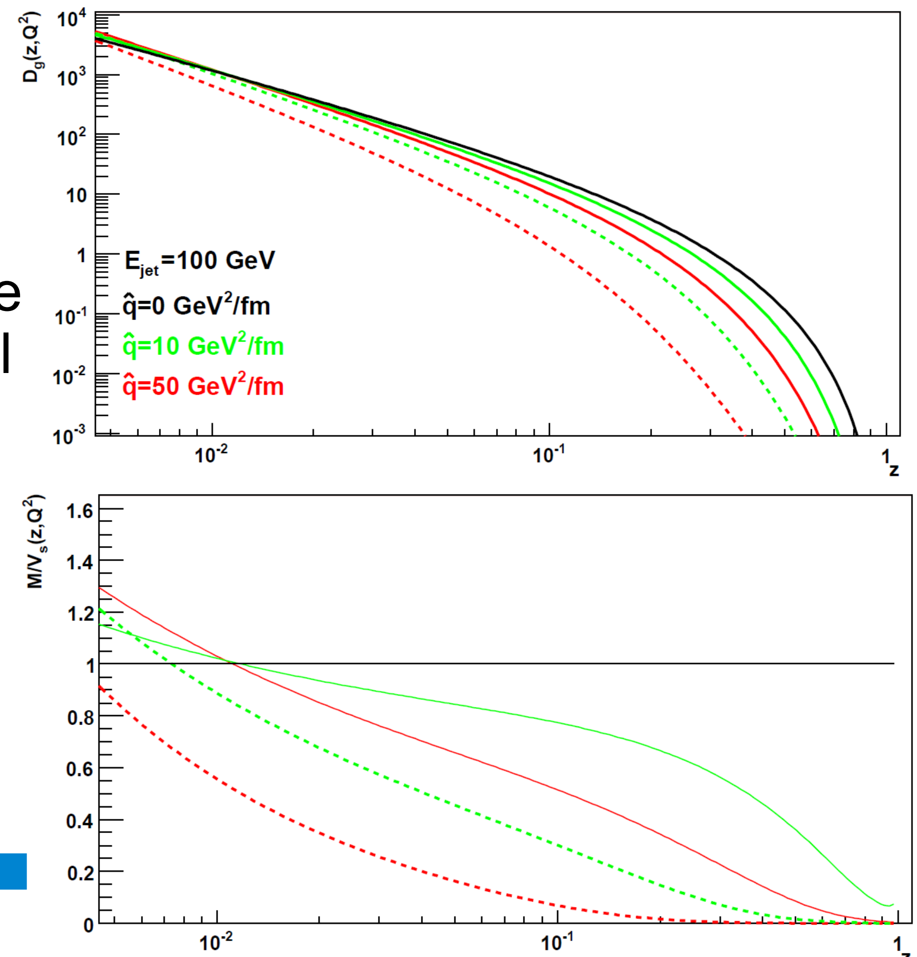
- A modification of jet internal structure was predicted by different theoretical models.

Radiative Energy Loss:



High z region of fragmentation function is sensitive to radiative energy loss.

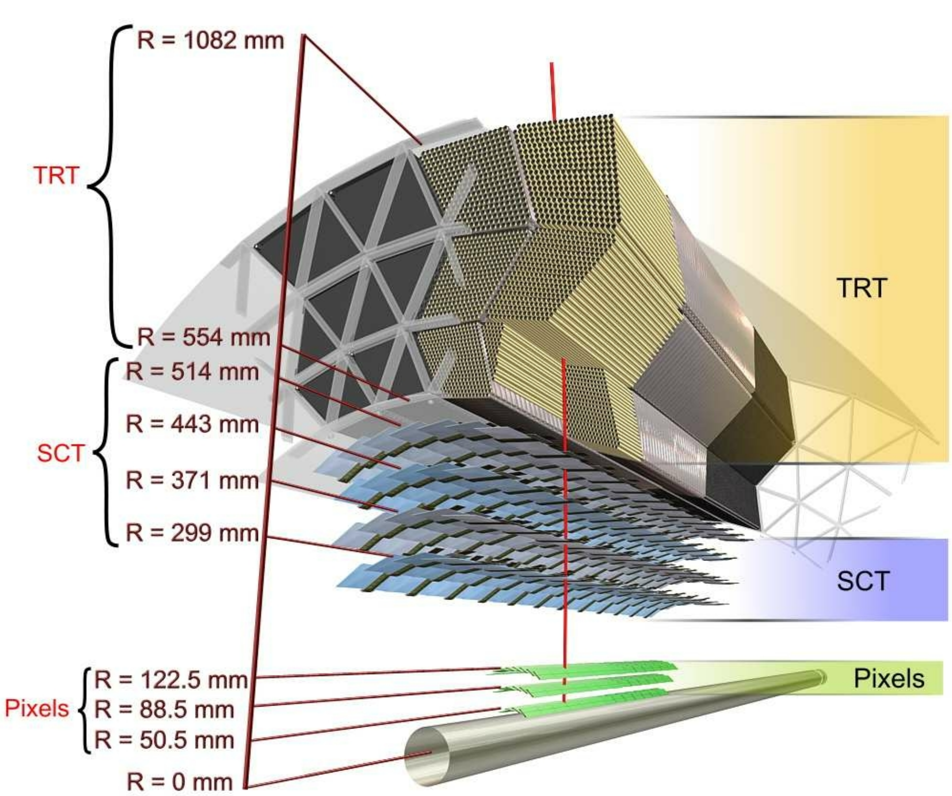
N.Armesto et al., JHEP0802 (2008) 048:



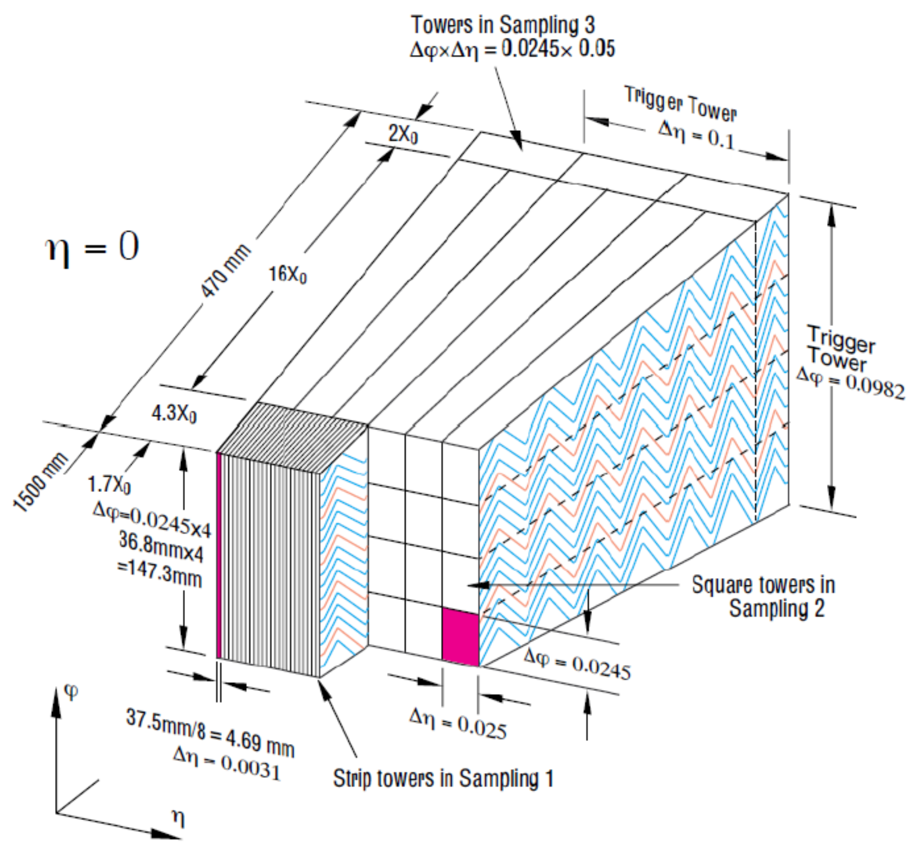
Calculations of medium modified fragmentation functions of 100 GeV jets for three values of the transport parameter and two in-medium path lengths.

The ATLAS Detector

- Large pseudorapidity coverage and full azimuthal acceptance.
- Fine granularity and longitudinal segmentation of ATLAS calorimeter.
- Precise inner detector in a 2T solenoid field.



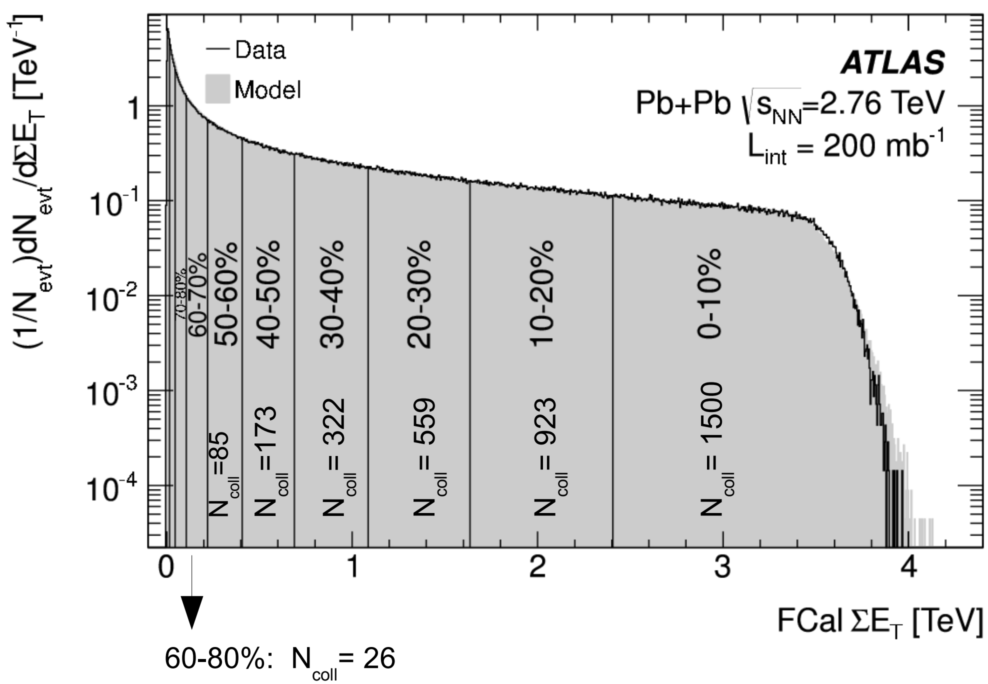
ATLAS inner detector

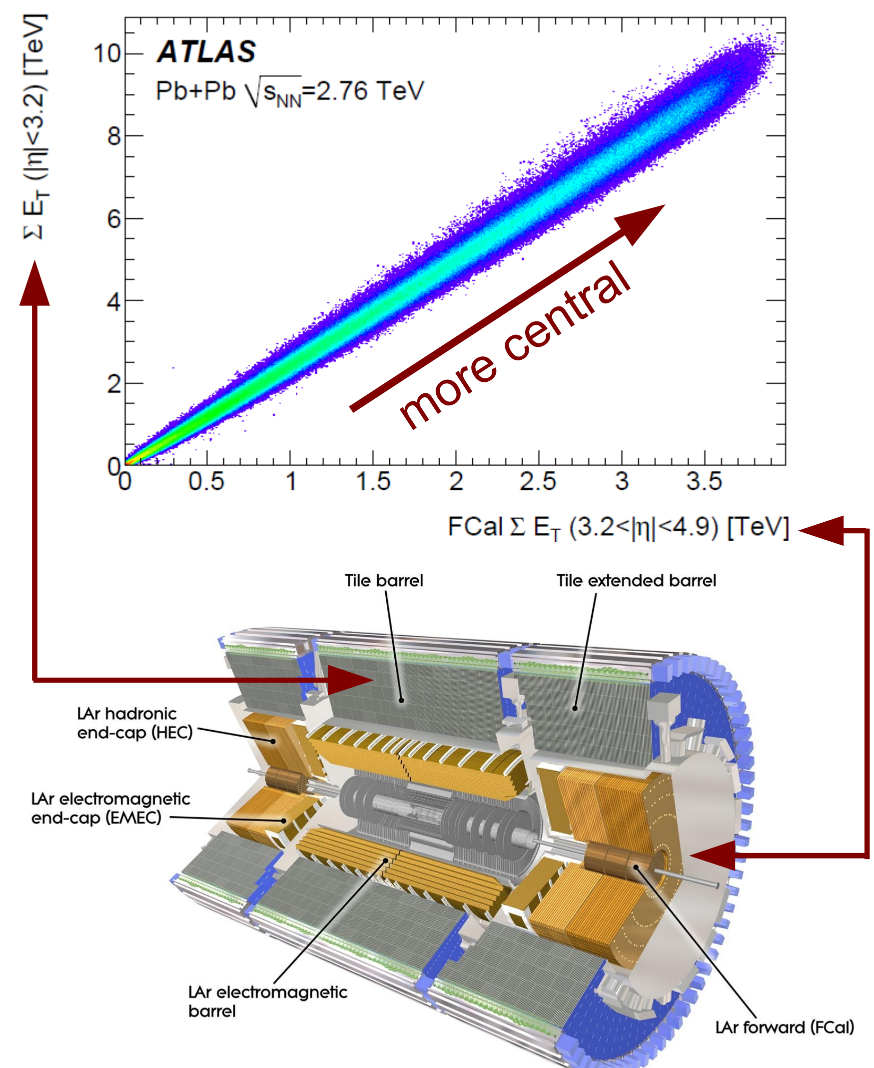


ATLAS calorimeter

Centrality

- Characterize centrality by percentile of total cross-section using total E_T.
- Measured in Forward Calorimeter ($3.2<|\eta|<4.9$).





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 (Δη x Δφ).
- Event-by-event background subtraction:

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

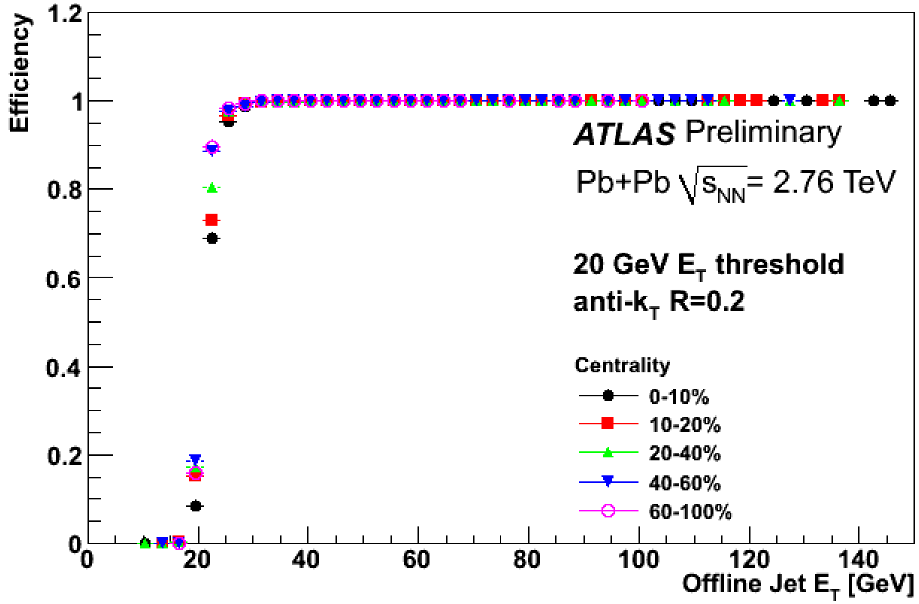
➡ Anti-k_t reconstruction prior to a background subtraction.

➡ 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.

Data and MC

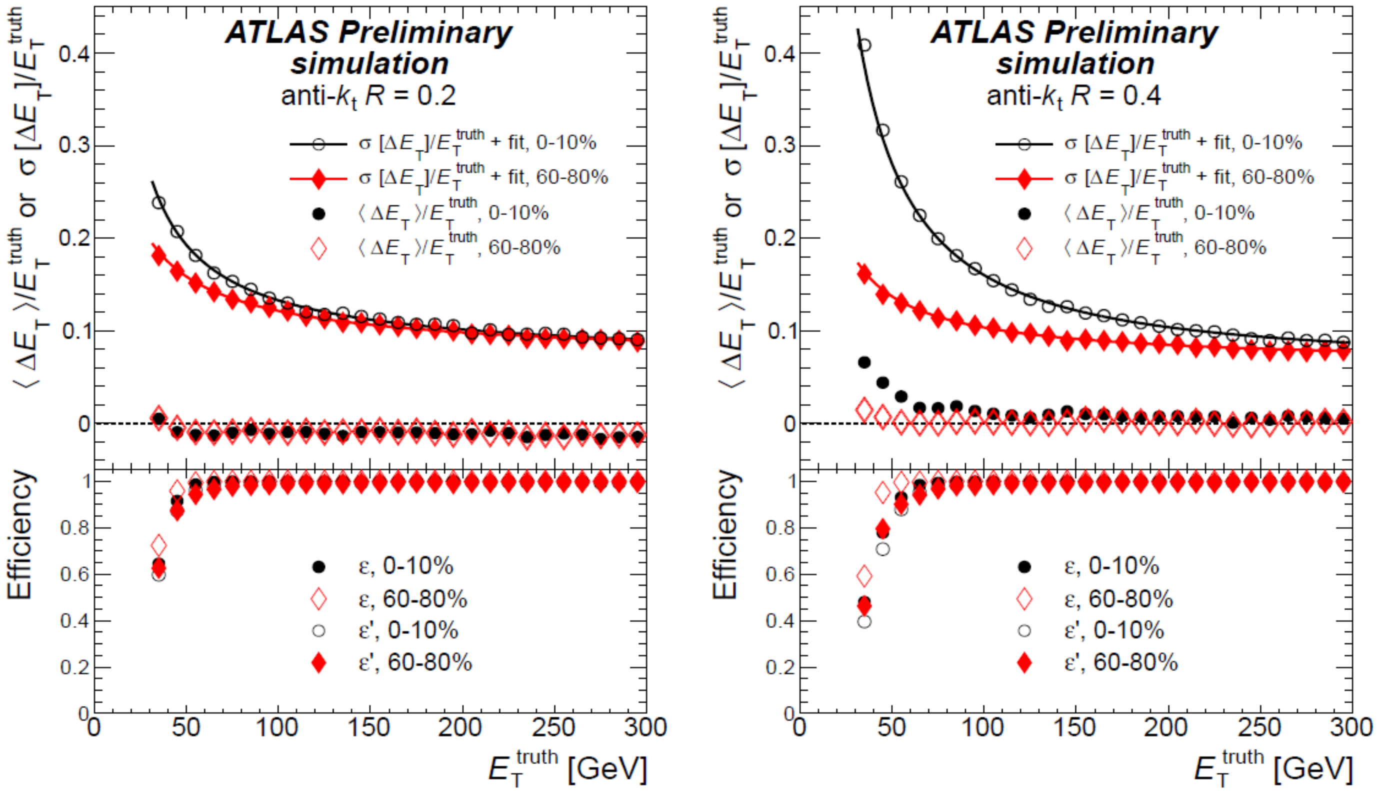
- Data set was recorded in 2011 and corresponds to integrated luminosity of 0.14 nb^{-1}.
- High level jet triggers (HLT) seeded by L1 minimum bias (MB) triggers were used to select events.
- Jet trigger algorithm required a R=0.2 jet with E_T > 20 GeV.
- All events were required to satisfy MB events selection: good timing and vertex.
- MC Pythia di-jet events embedded into MC HIJING and data overlay were used for performance evaluation.



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.

Performance of Jet Reconstruction

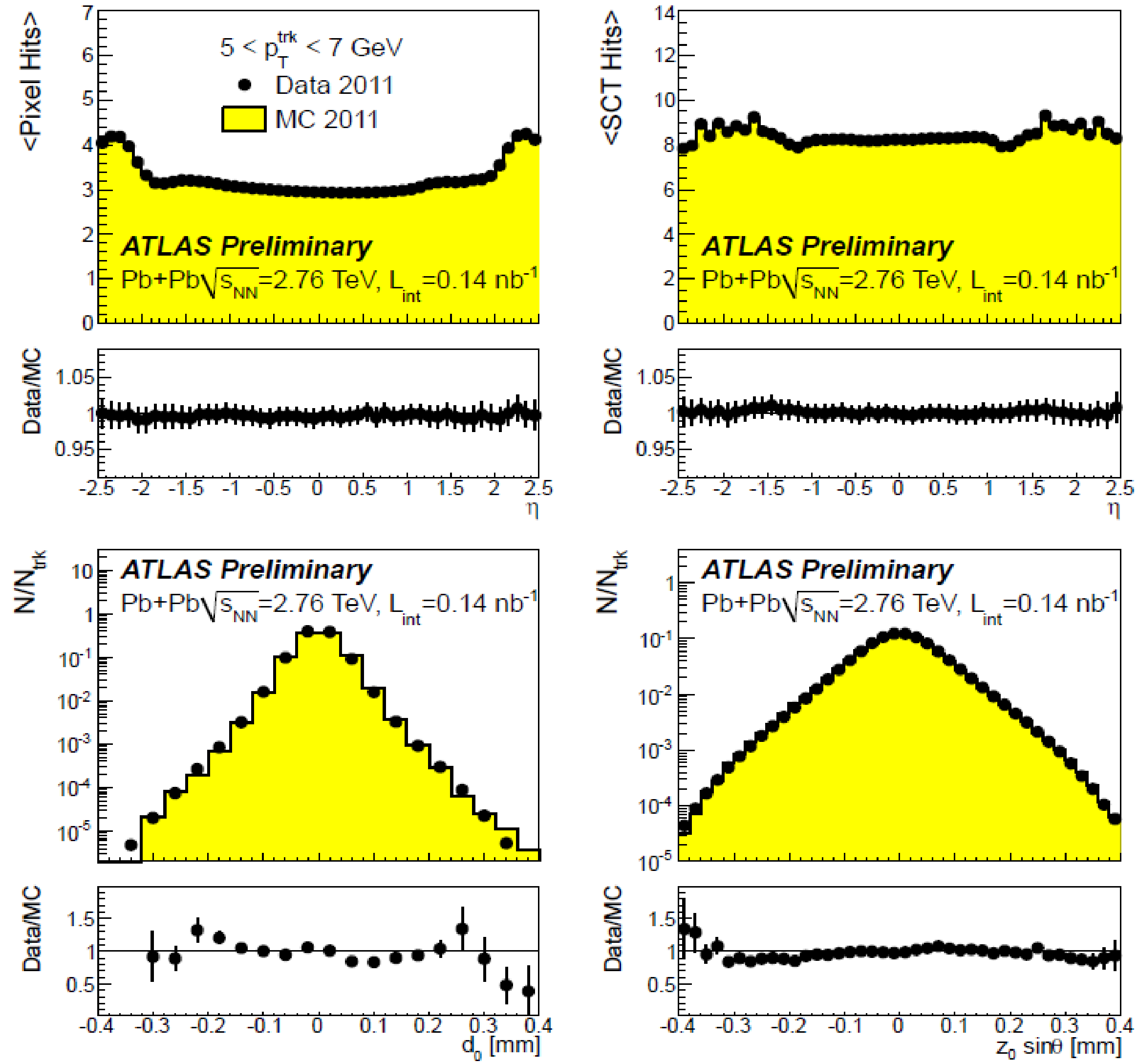


ATLAS collaboration, arXiv:1208.1967v1

- Jet energy resolution is well described by $\sigma(\Delta E_T)/E_T = 1/E_T(a.\sqrt{E_T}+b+c.E_T)$ where where *a* and *c* terms are sampling and constant contributions to the calorimeter resolution and the term with parameter *b* describes contribution from UE.
- *b* term was found to be consistent with the result from fluctuation analysis: *ATLAS collaboration, ATLAS-CONF-2012-045*

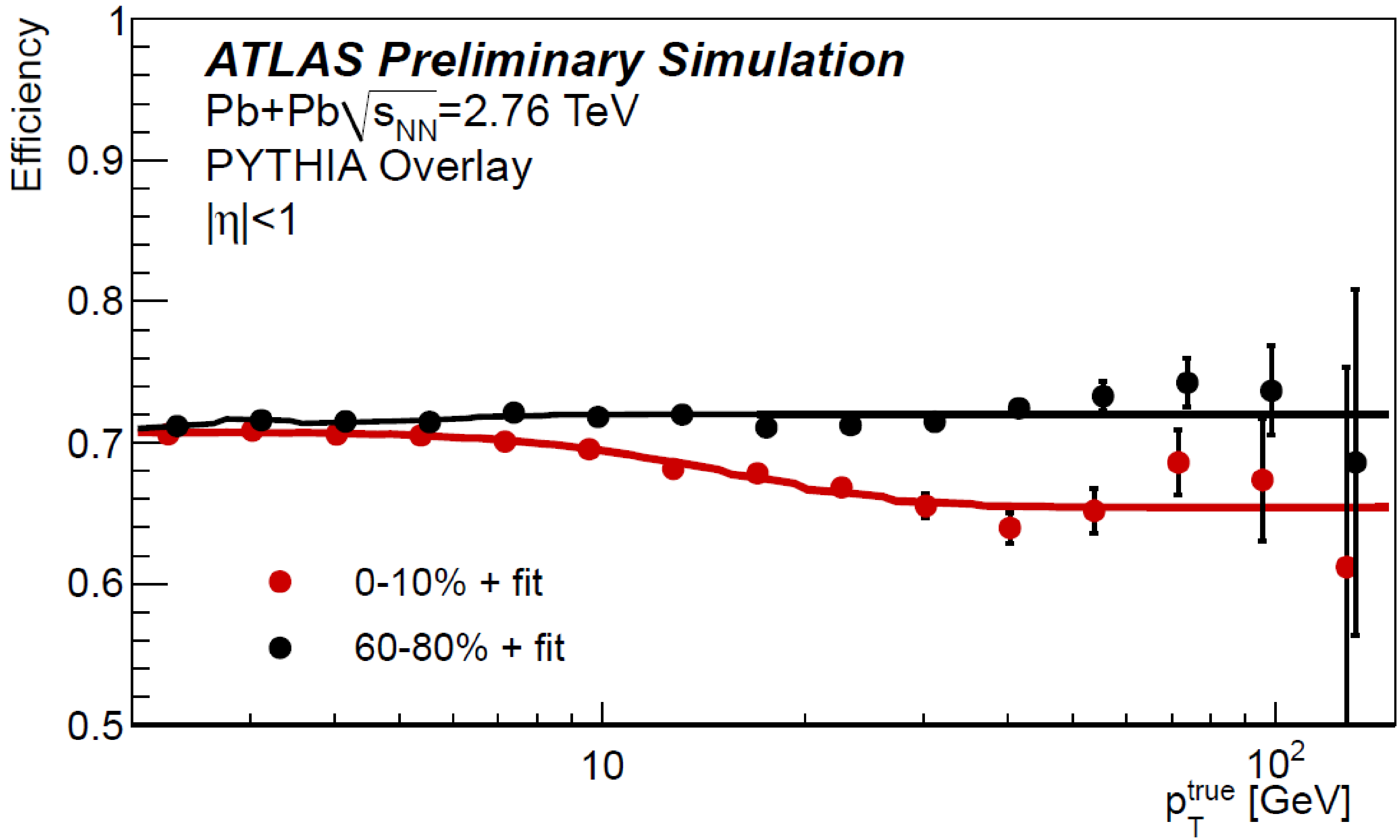
Performance of the Track Reconstruction

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



- Very good description of detector response by MC.

Tracking efficiency



- Efficiency was parametrized as $\varepsilon(p_T, \eta) = \varepsilon(p_T) \times \varepsilon(\eta)$.

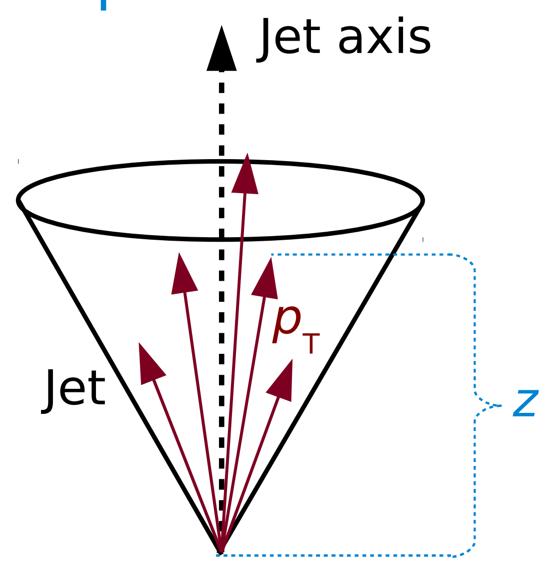
Fragmentation functions

- We measured two sets of fragmentation distributions describing the longitudinal jet structure: *ATLAS collaboration, ATLAS-COM-CONF-2012-159*

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

Spectra of charged particles in jets

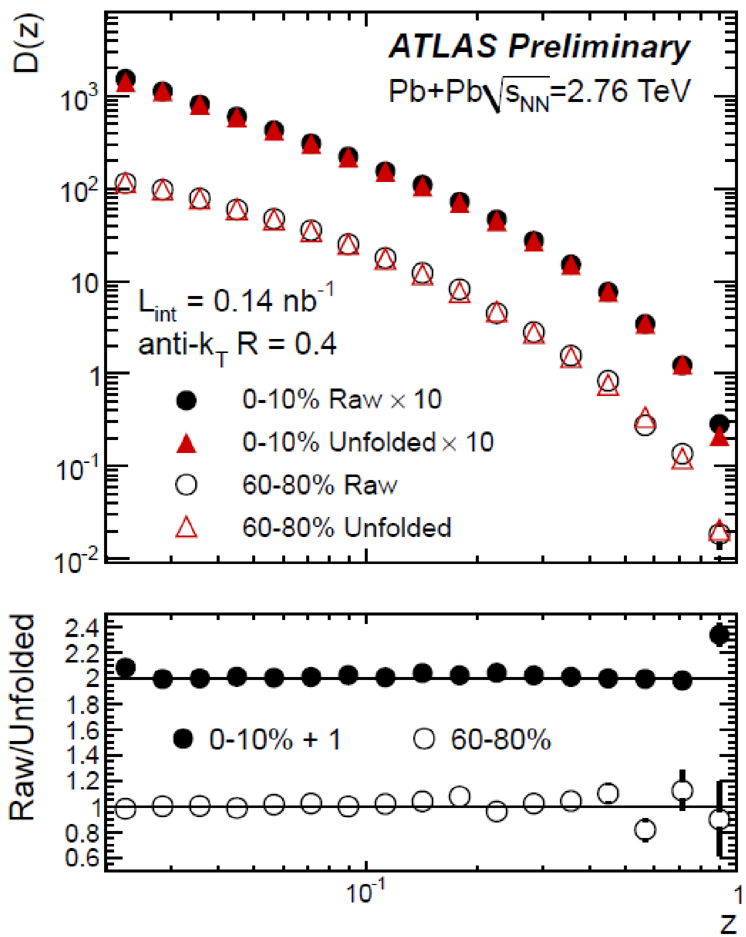
Fragmentation function

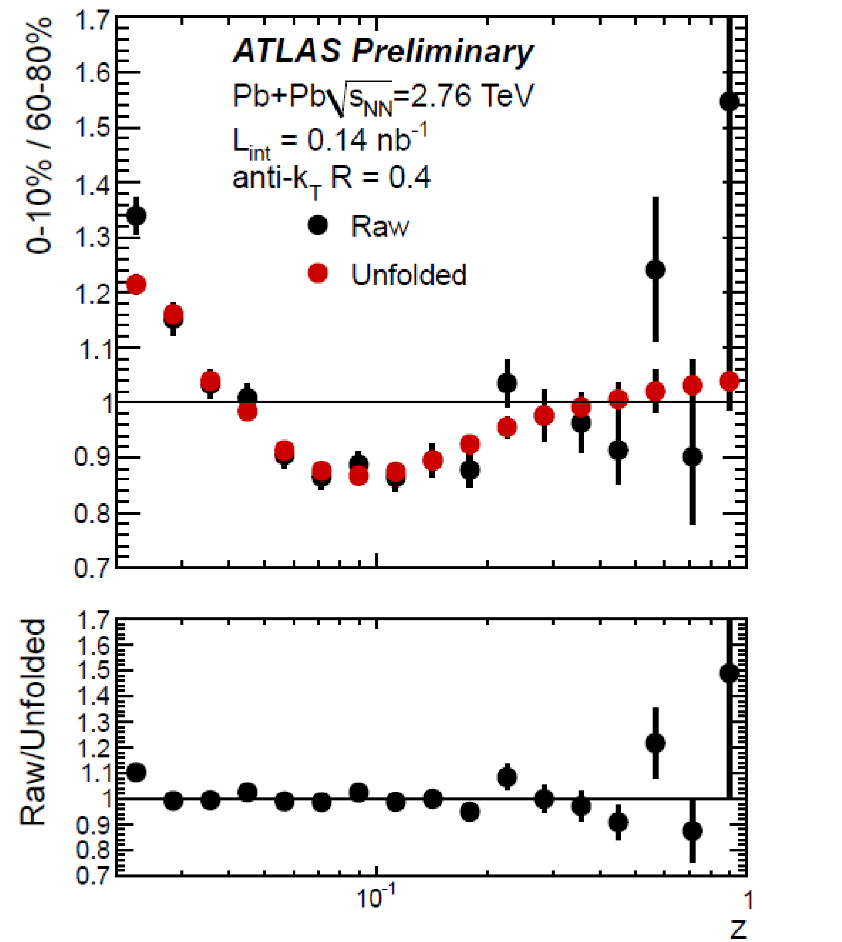


- UE fragmentation distributions were estimated event-by-event using grid of R=0.4 cones:
  - Cones with track with p_T > 4 GeV were excluded.
  - Flow modulation of the UE was imposed on the background.
  - Background was corrected to account for a pseudorapidity dependence of the UE.

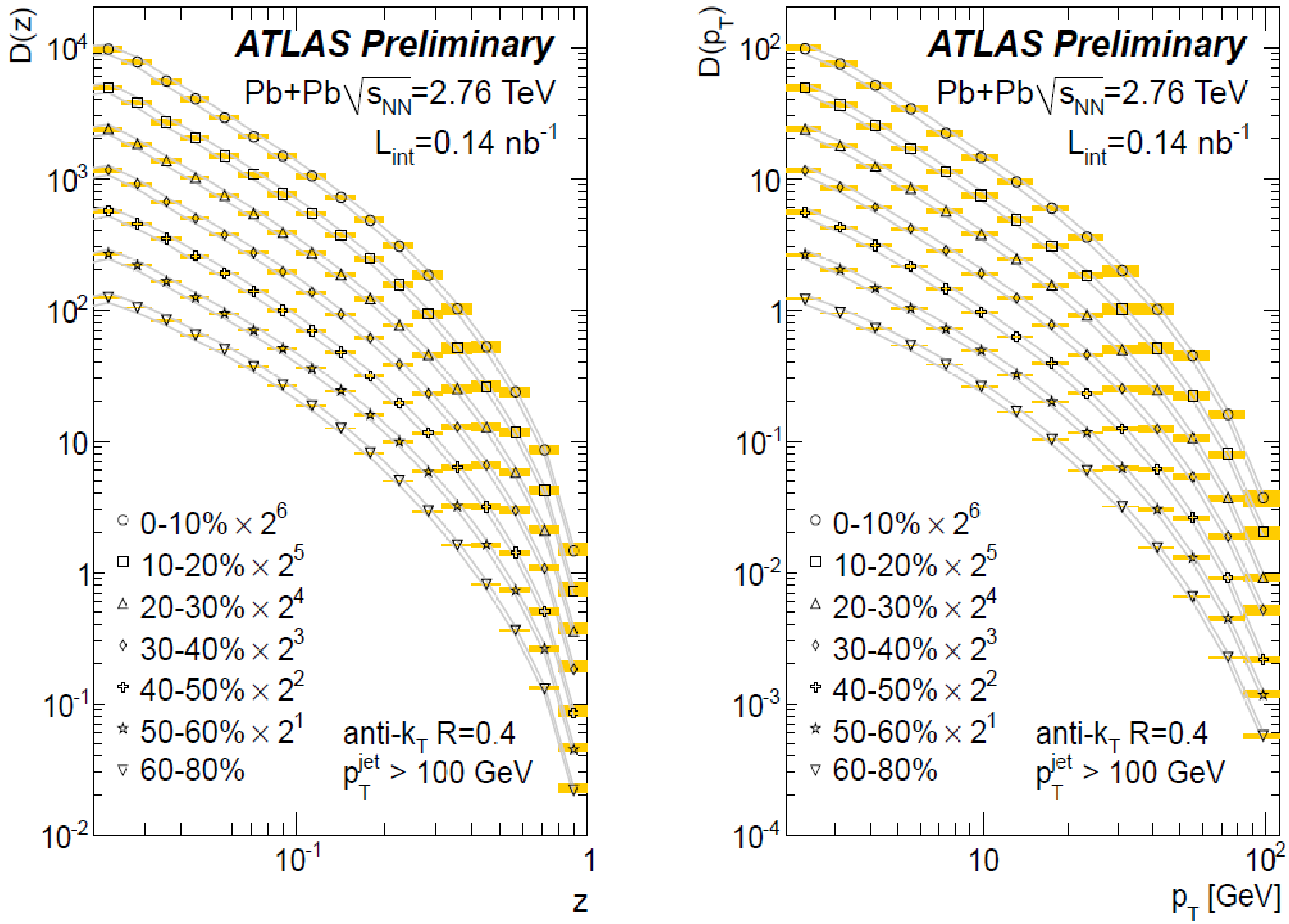
Results of Subtraction and Unfolding

- 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.





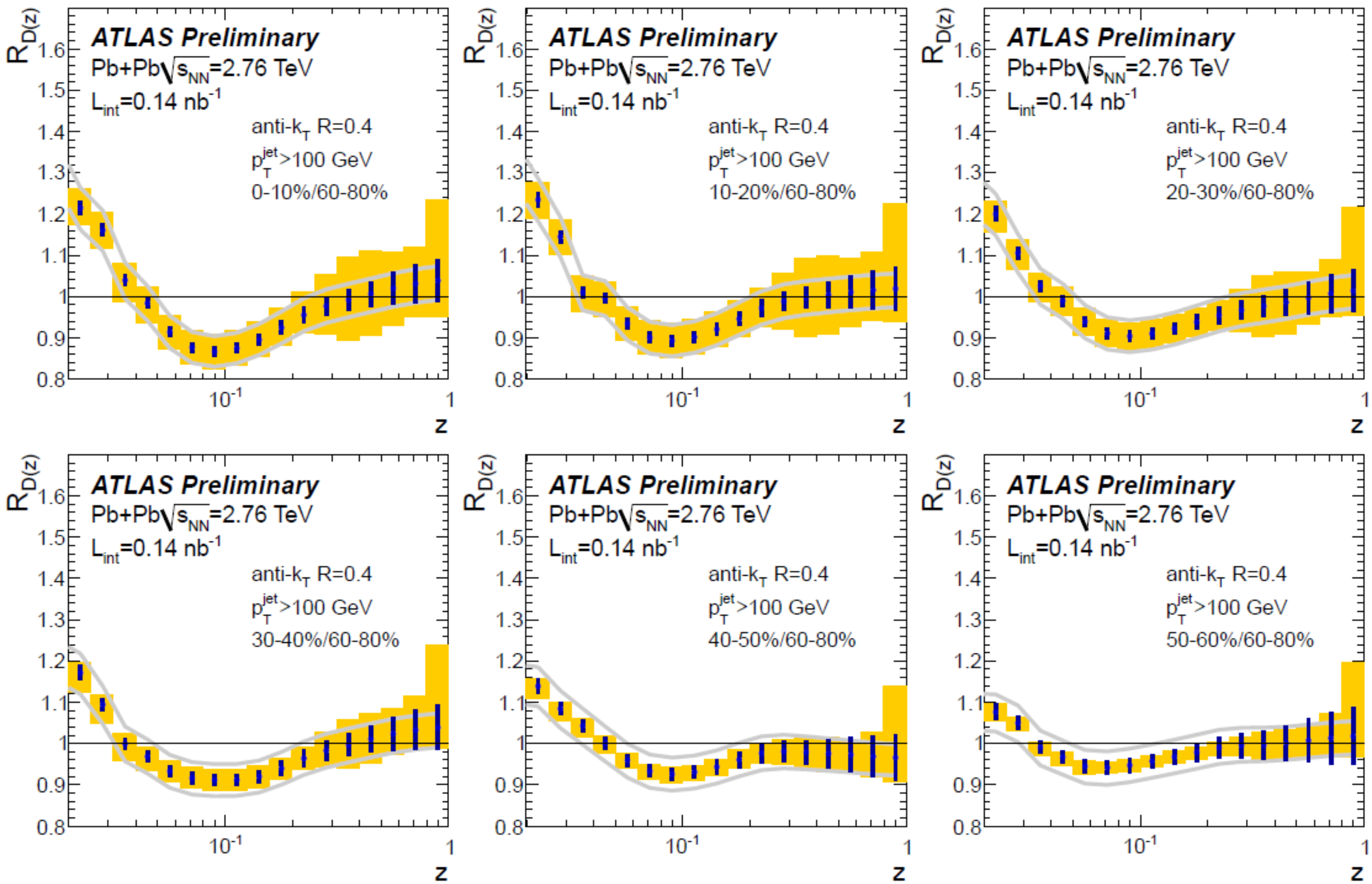
Unfolded fragmentation functions



- 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

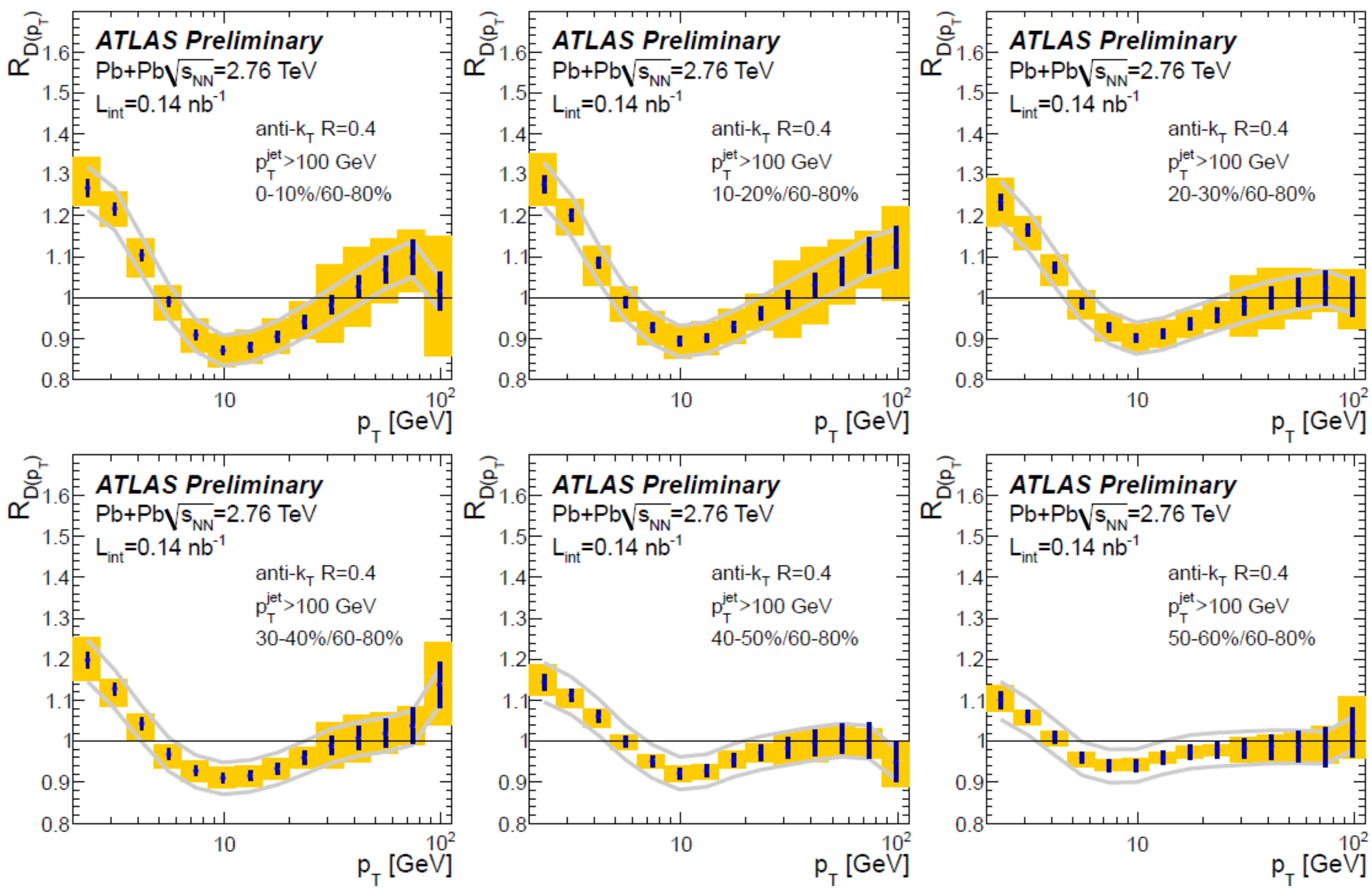
uncorrelated or partially correlated systematic errors: regularization, JES, JER, tracking efficiency, non-zero central to peripheral ration of D(z) and D(p_T) in MC.

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 in central collisions with respect to peripheral ones.

$D(p_T)$ centrality dependence



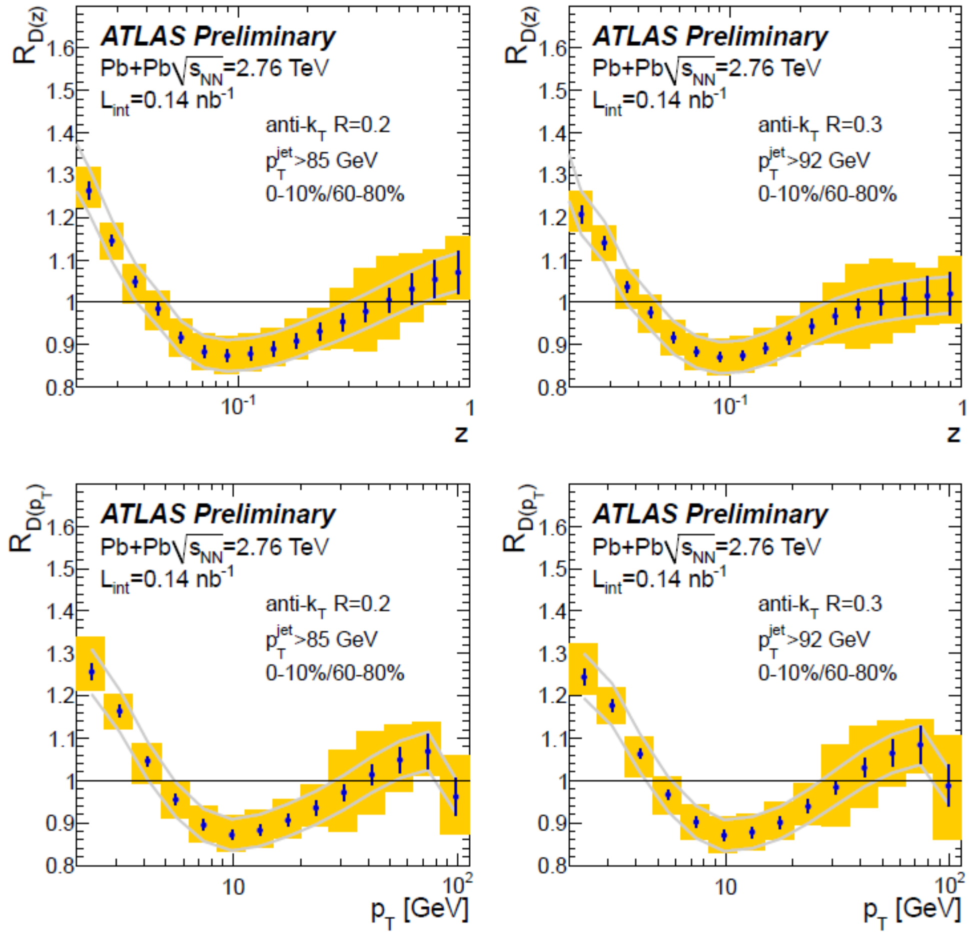
Shaded bands: uncorrelated or partially correlated systematic errors

Solid lines: 100% correlated systematic errors

➡ Similar behaviour as for D(z) distribution.

R-dependence of Fragmentation Functions

- Cross-check of possible biases done by measuring the distributions using smaller jet radii with the minimum p_T corresponding to that of R=0.4 jets.
- The cone of 0.4 around the jet axis for track-jet matching was kept.



Shaded bands: uncorrelated or partially correlated systematic errors

Solid lines: 100% correlated systematic errors

➡ No qualitative or quantitative changes from R=0.4 jets!

Conclusions

- We have presented a measurement of two sets of fragmentation variables.
- Study of jet internal structure shows increasing size of modification of fragmentation functions with increasing centrality.
- We do not observe any modification at high p_T or z.
- We observe ~15% suppression at intermediate z or p_T in the most central collisions with respect to peripheral ones.
- 25% enhancement at very low z or p_T is observed in the most central collisions with respect to peripheral collisions.

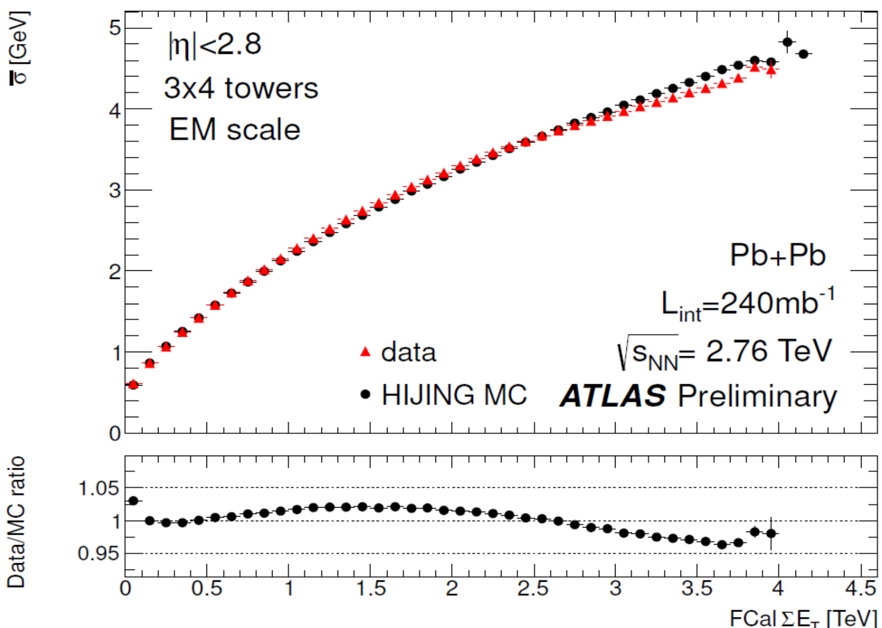
Backup

ATLAS Detector Status

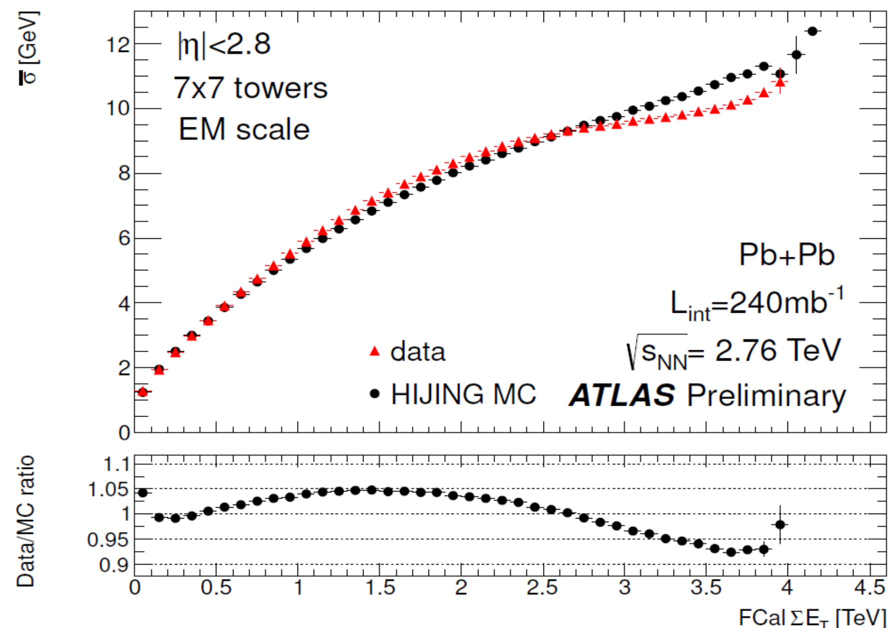
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.9%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	99.5%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	98.4%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	97.7%
RPC Barrel Muon Chambers	370 k	93.8%
TGC Endcap Muon Chambers	320 k	99.7%

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

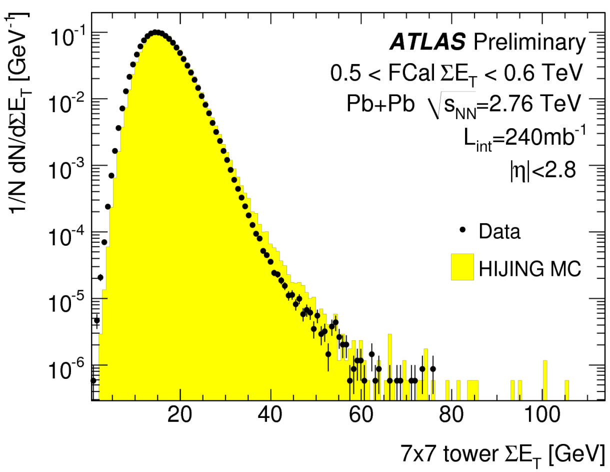


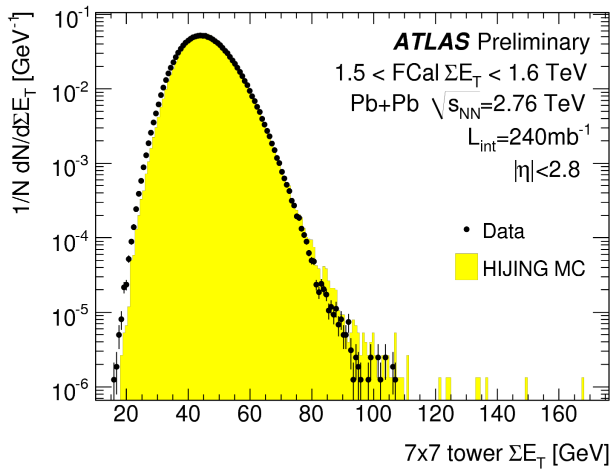
R=0.4 jets

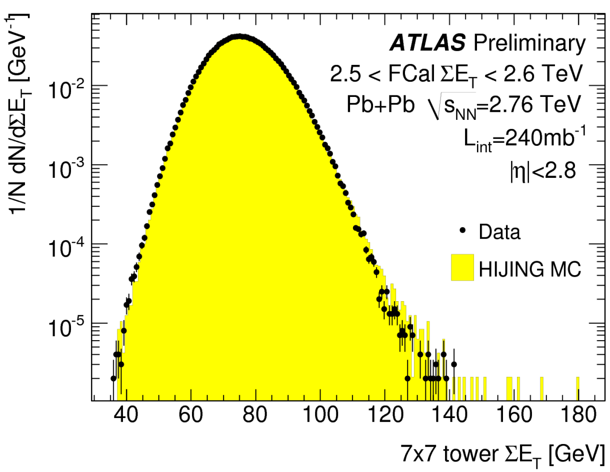
- An agreement between data and MC is better than 5% for R=0.2 jets.
- Fluctuations in data are at most 5% higher than in MC for R=0.4 jets.
- Fluctuations are higher in MC in the most central events.

Detail study of Underlying Event

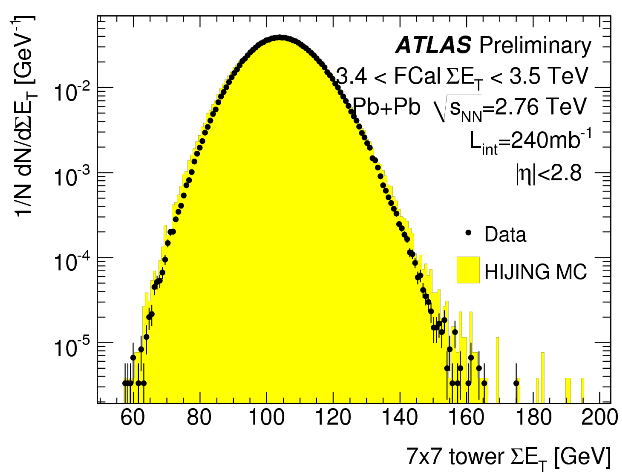
- Data and MC are compared in a narrow bin of FCal ΣE_T:



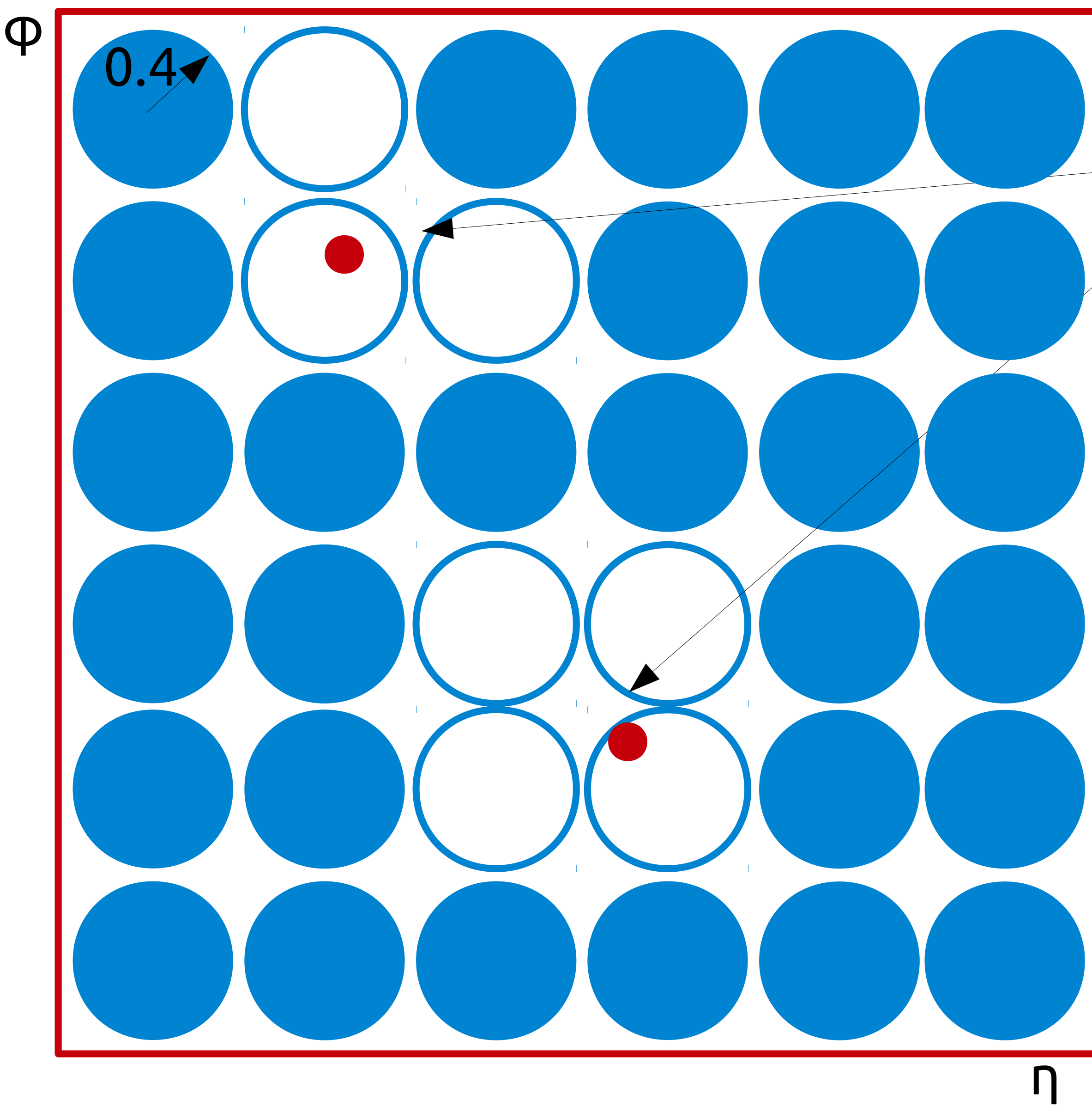




- HIJING over-predicts the size of upward fluctuations.
- HIJING over-predicts the size of downward fluctuations in central collisions.
- Where the spread in fluctuations is larger in data than in MC it is because data has larger downward fluctuations.

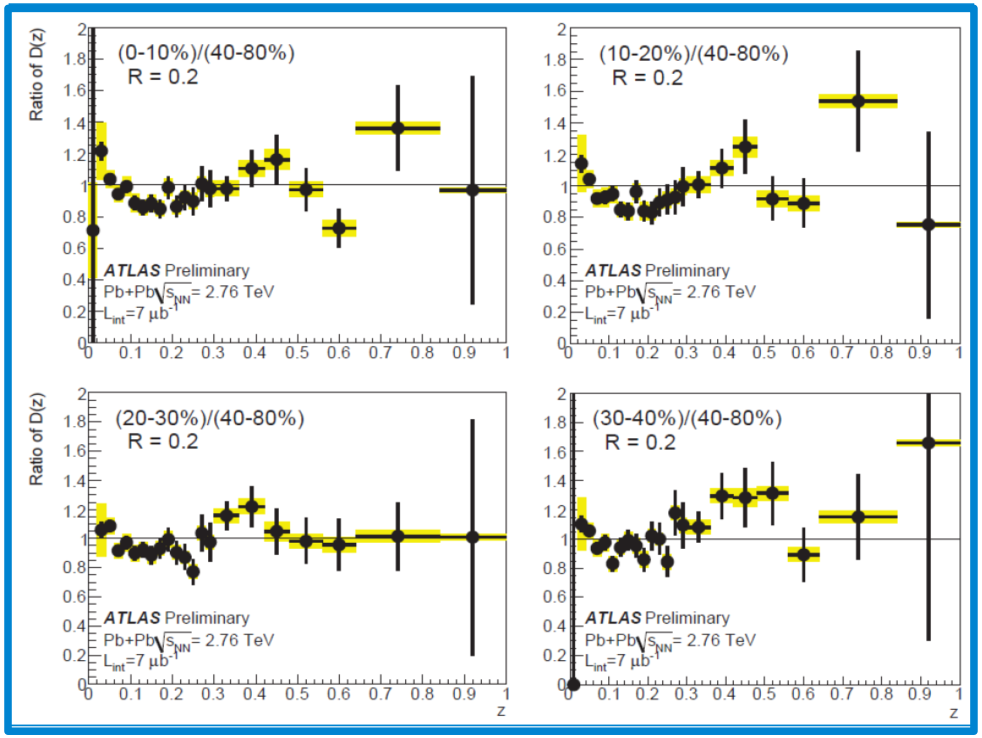


UE subtraction

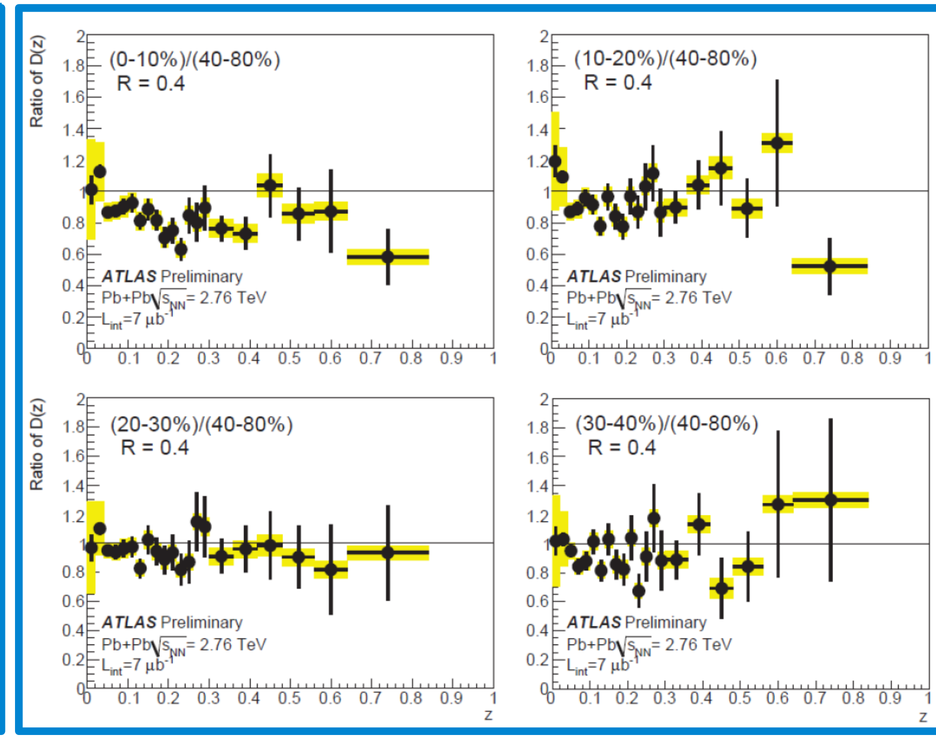


- Inner detector covered by a grid of cones
  Cones matching (dR<0.8) to a track > 4 GeV were excluded.
- Flow modulation of the UE was imposed on the background.
- Background was corrected to account for a pseudorapidity dependence of the UE.

Jet Fragmentation: Longitudinal Structure, QM2011



R=0.2



R=0.4

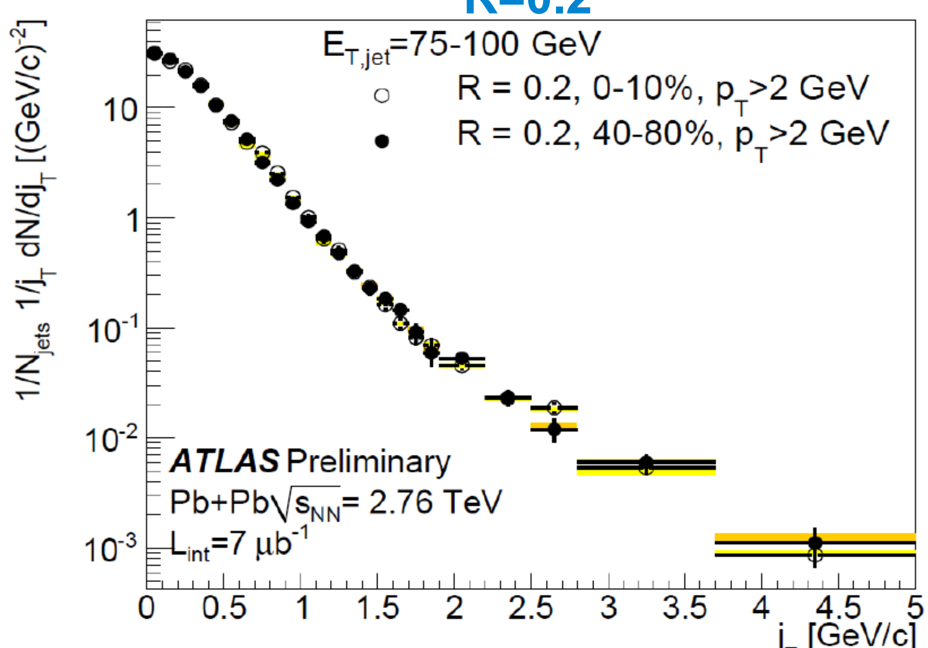
Jet Fragmentation: Transverse Fragmentation Function, QM 2011

j_T distribution: transverse momentum of charged particles:

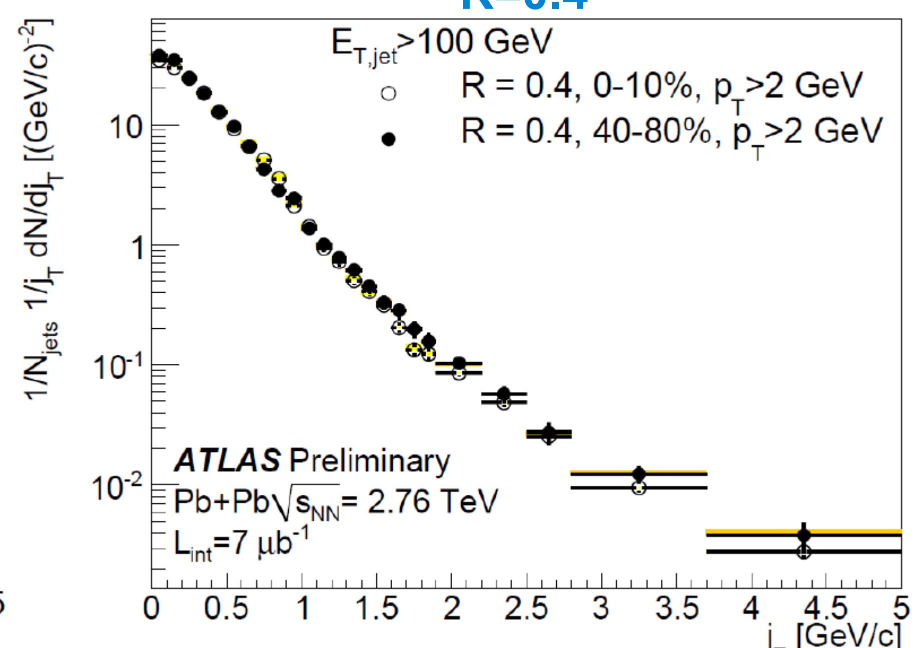
$$D(j_T) = (1/N_{jet})(1/j_T)dN/dj_T\text{, where } j_T = p_T^{had}\sin\Delta R$$

- Axis of R=0.4 jet is replaced by axis of the nearest R=0.2 jet with E_T > 25 GeV which has better position resolution.

R=0.2

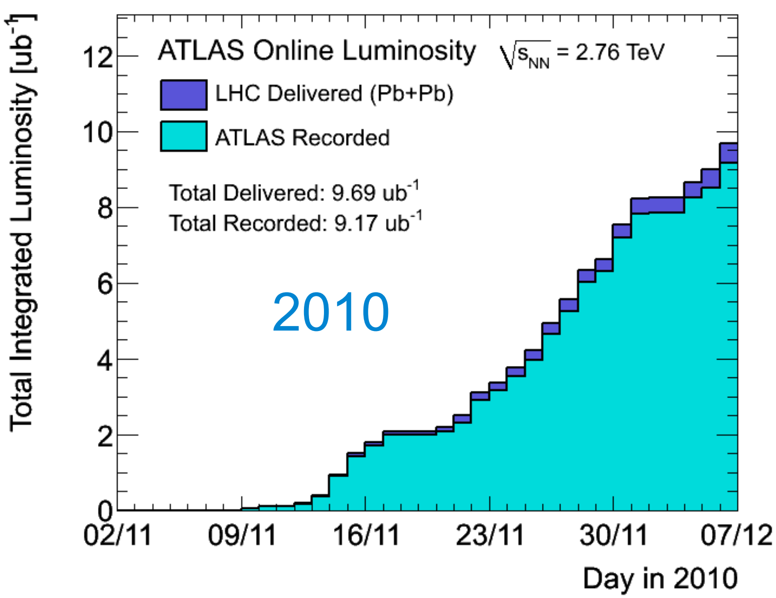


R=0.4



➡ No significant change in j_T distribution from peripheral to central collisions in R=0.4 and R=0.2 jets.

Jets in 2011 HI run



17x more data!