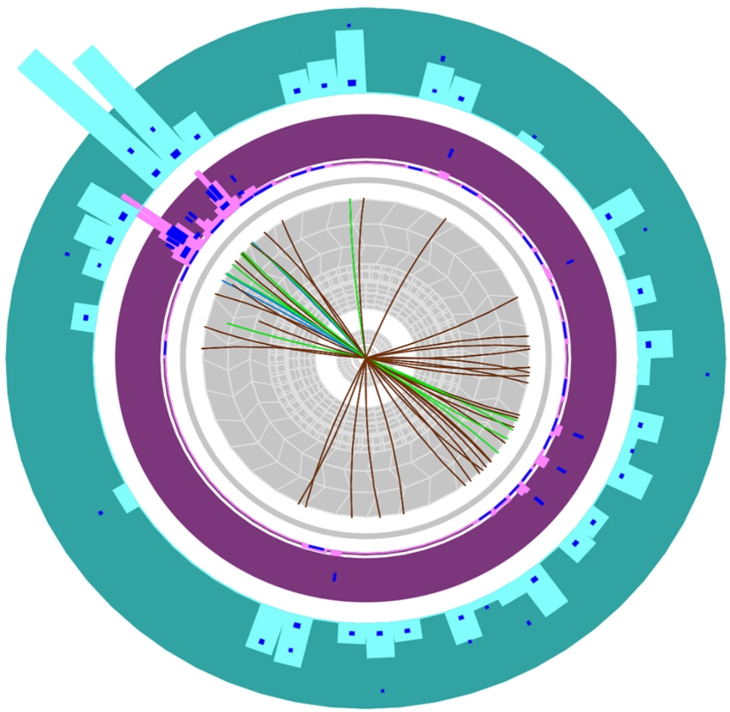
Measurements of Jets and Jet Properties in $\sqrt{s_{NN}}=2.76$ TeV PbPb Collisions with the ATLAS Detector at the LHC



Martin Rybář,

for the ATLAS collaboration

IPNP

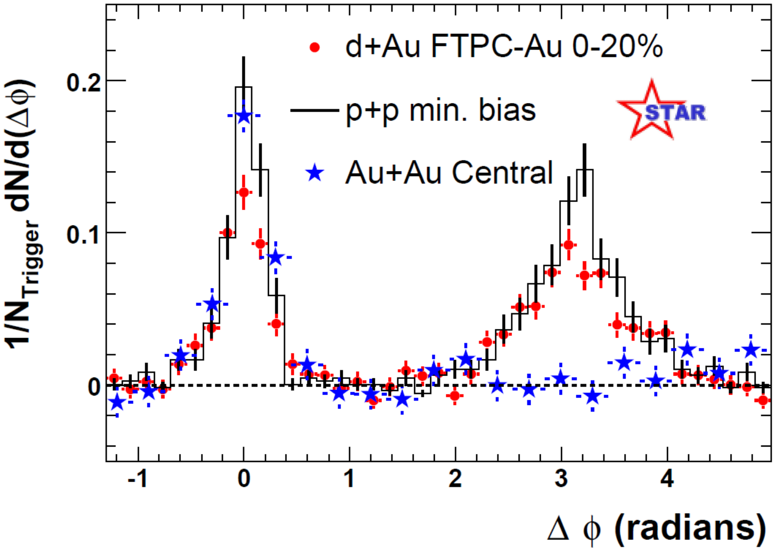
Charles University

Hard Probes 2012, May 31, 2012

Jets in Heavy Ion Collisions

- How do partons lose energy in hot medium - Quark Gluon Plasma (QGP)?
- How does the medium modify the parton showers?
- RHIC's measurements of high p_T particles

➡ the first evidence for jet quenching.

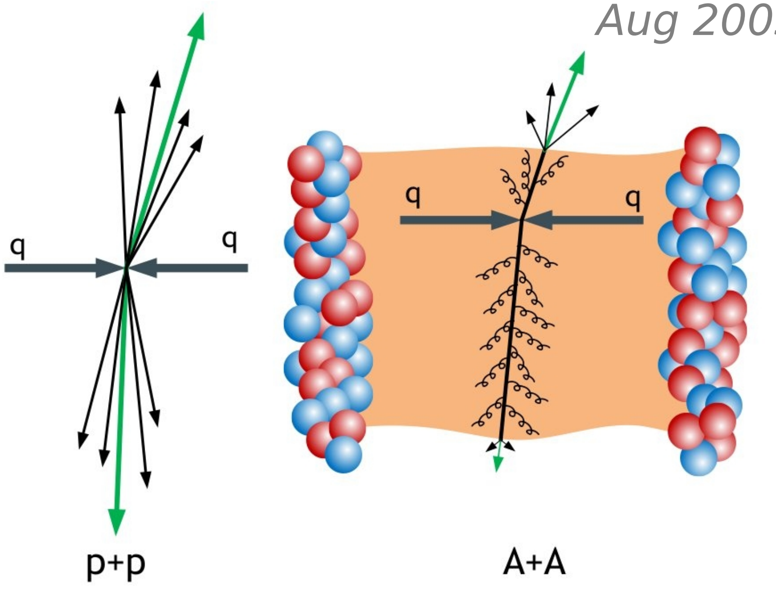


arXiv:nucl-ex/0306024v3, 18 Aug 2003

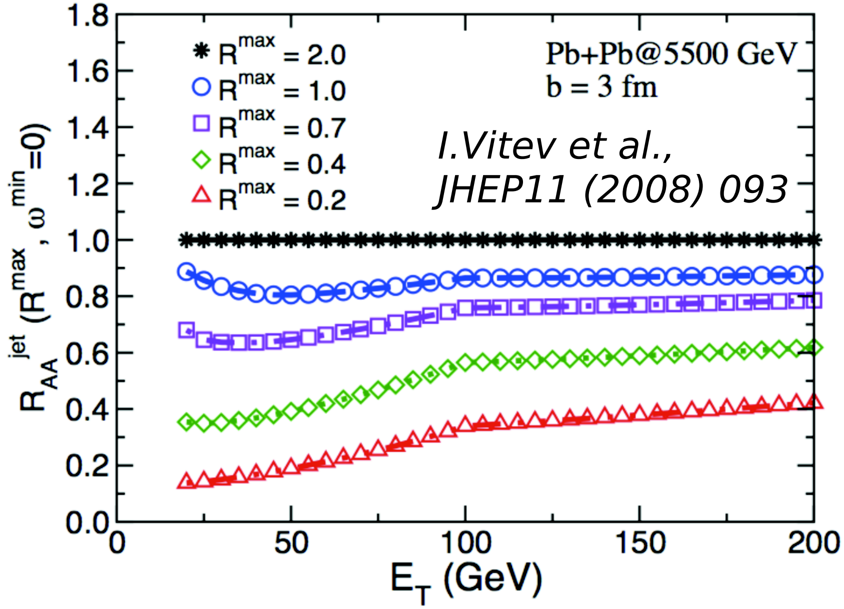
- Need to do the full jet reconstruction to understand the effect in more detail:

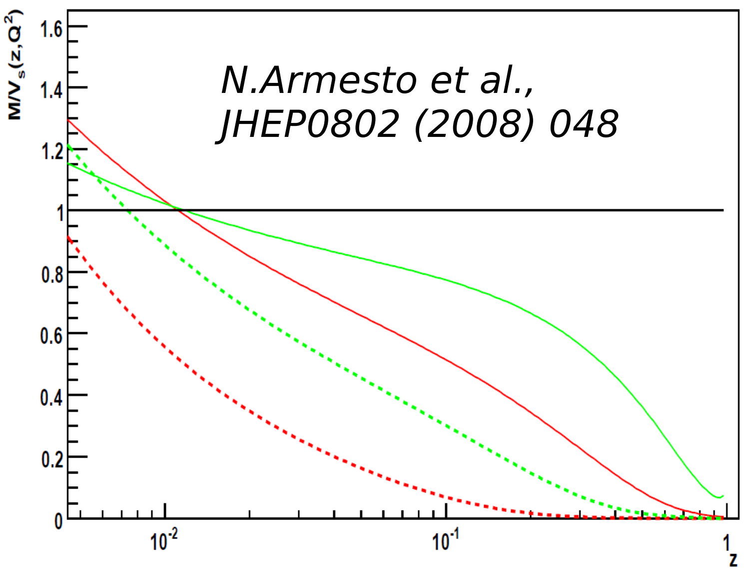
➡ Does the energy remain inside the jet but redistributed among fragments?

➡ Or is it the energy redistributed to the medium out of the cone?



Jets in Heavy Ion Collisions





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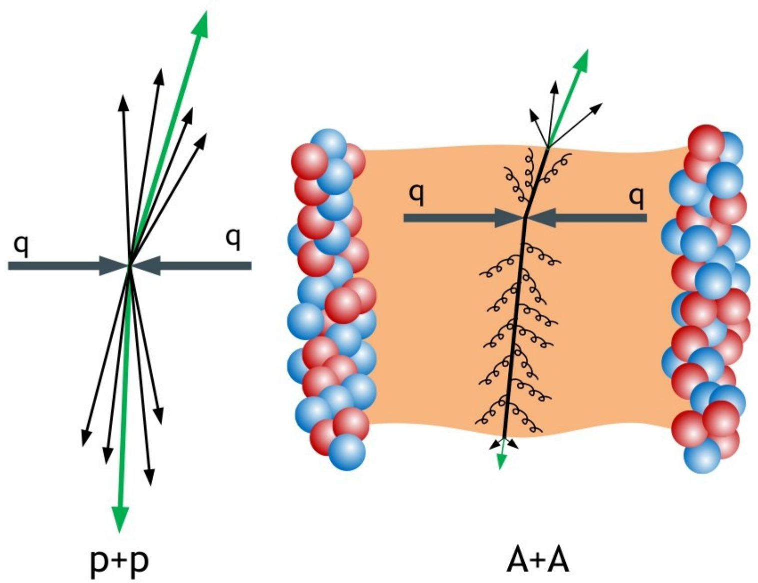
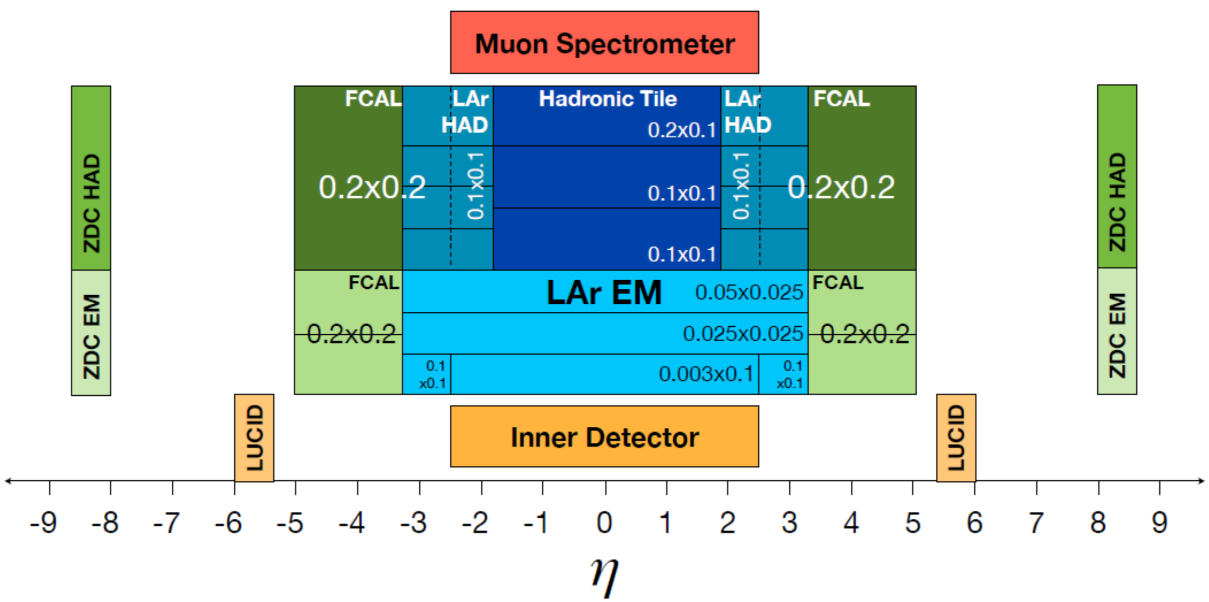
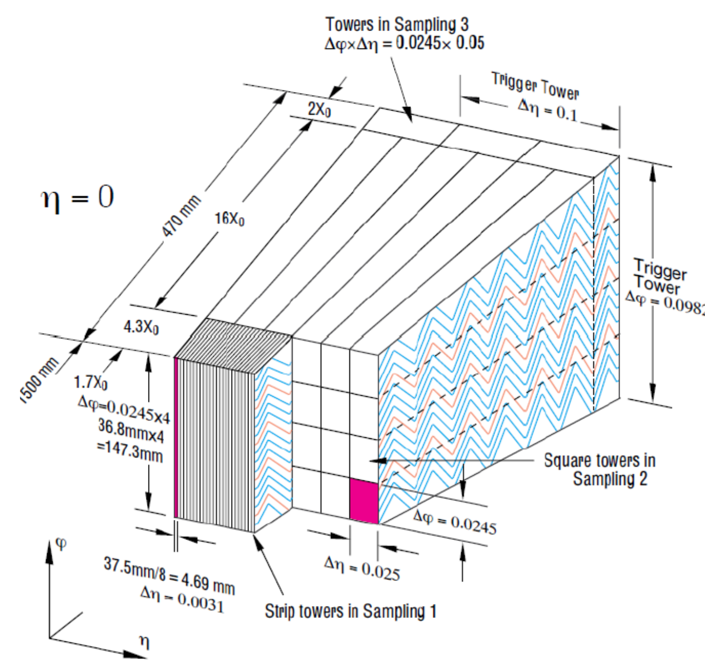


The ATLAS Detector

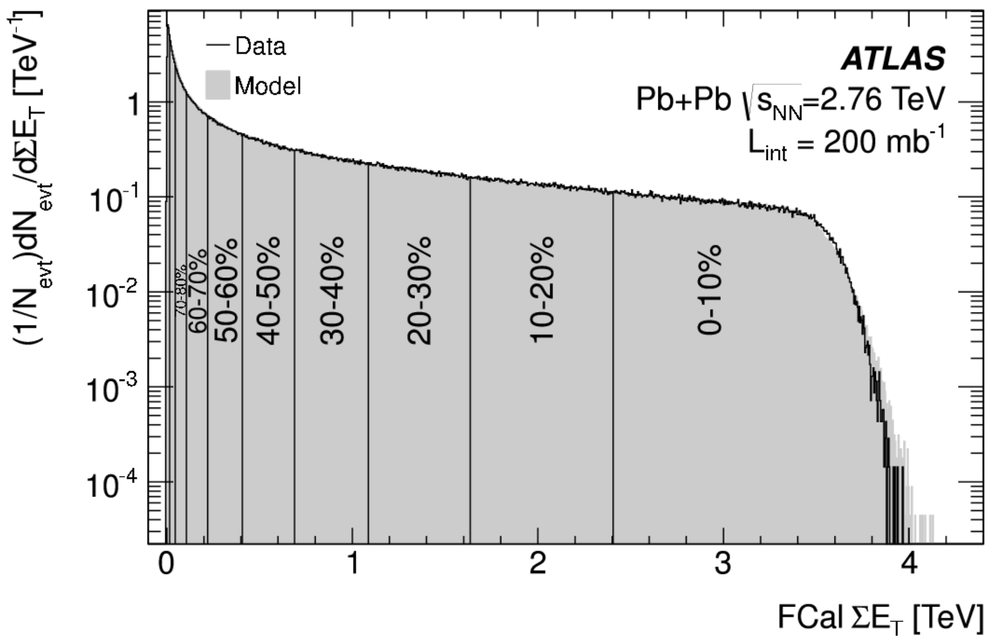
- ATLAS is a general-purpose p-p experiment, but the detector can be very well used for heavy ion physics!
- Large pseudorapidity coverage and full azimuthal acceptance.
- Fine granularity and longitudinal segmentation.
- Precise inner detector in a 2T solenoid field.
- Extensive system of muon chambers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

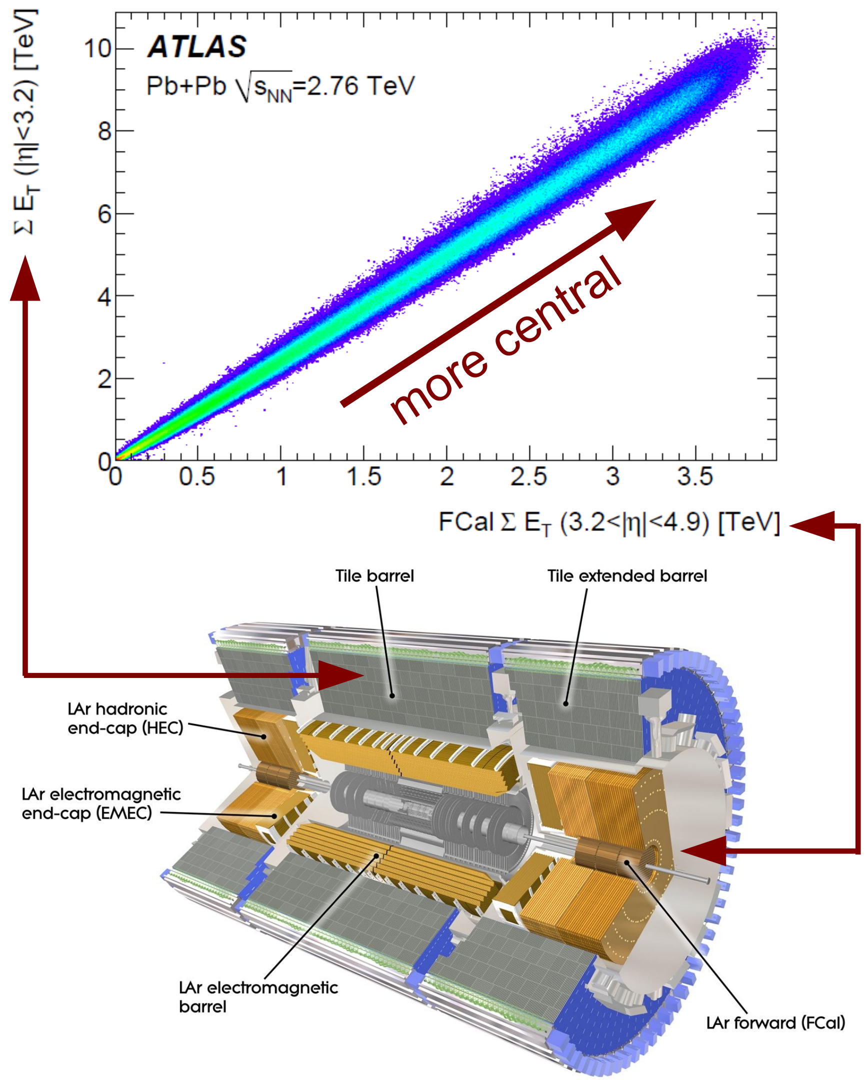




Centrality

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





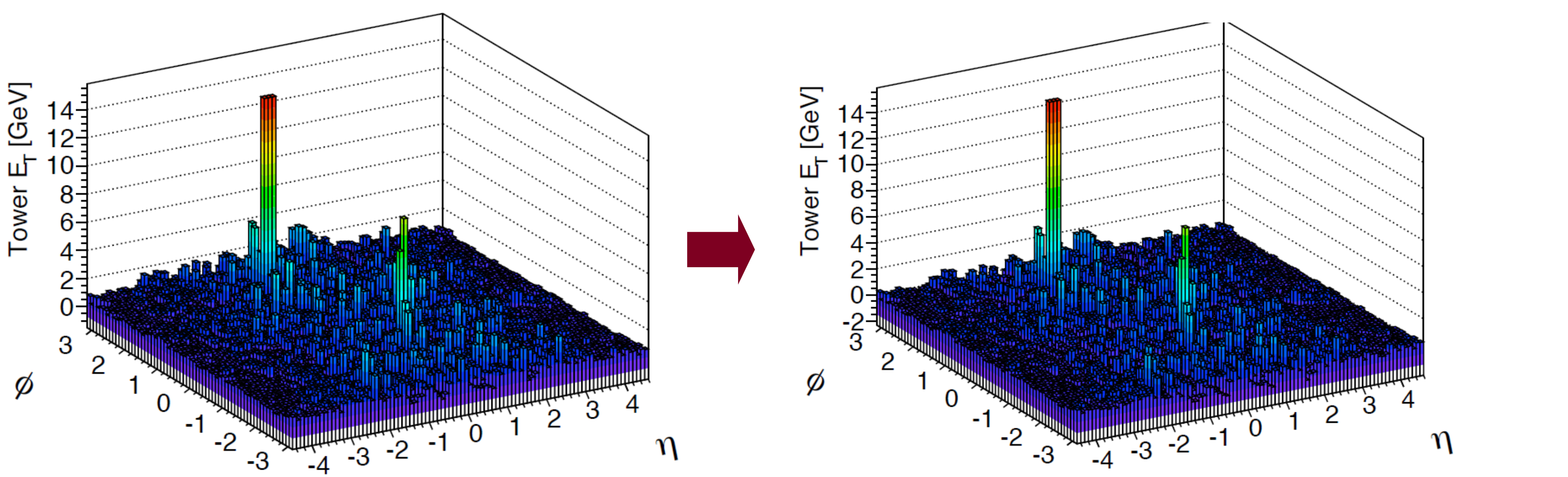
Jet Reconstruction at ATLAS

- Reconstruction algorithm anti-k_t (0.2, 0.3, 0.4, 0.5).
- Input: calorimeter towers 0.1 x 0.1 (Δη x Δφ).
- Event-by-event background subtraction: $E_{Tsub}^{cell} = E_T^{cell} - \rho^{layer}(\eta) \times A^{cell}$

→ Anti-k_t reconstruction prior to a background subtraction.

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

- We exclude jets 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 avoid biasing subtraction from jets.
- Jets corrected for flow contribution.

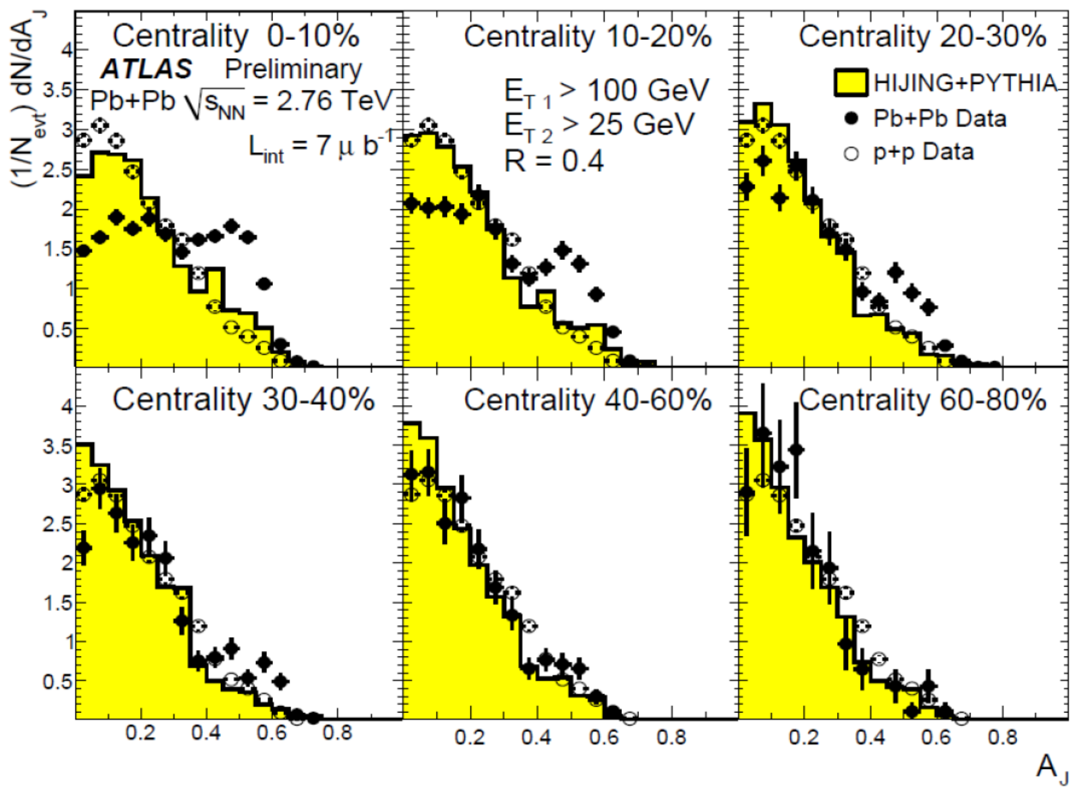


The First ATLAS HI Jet measurement: Di-jet Analysis

- Dijet imbalance quantified by asymmetry variable A_J.

$$A_J \equiv \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

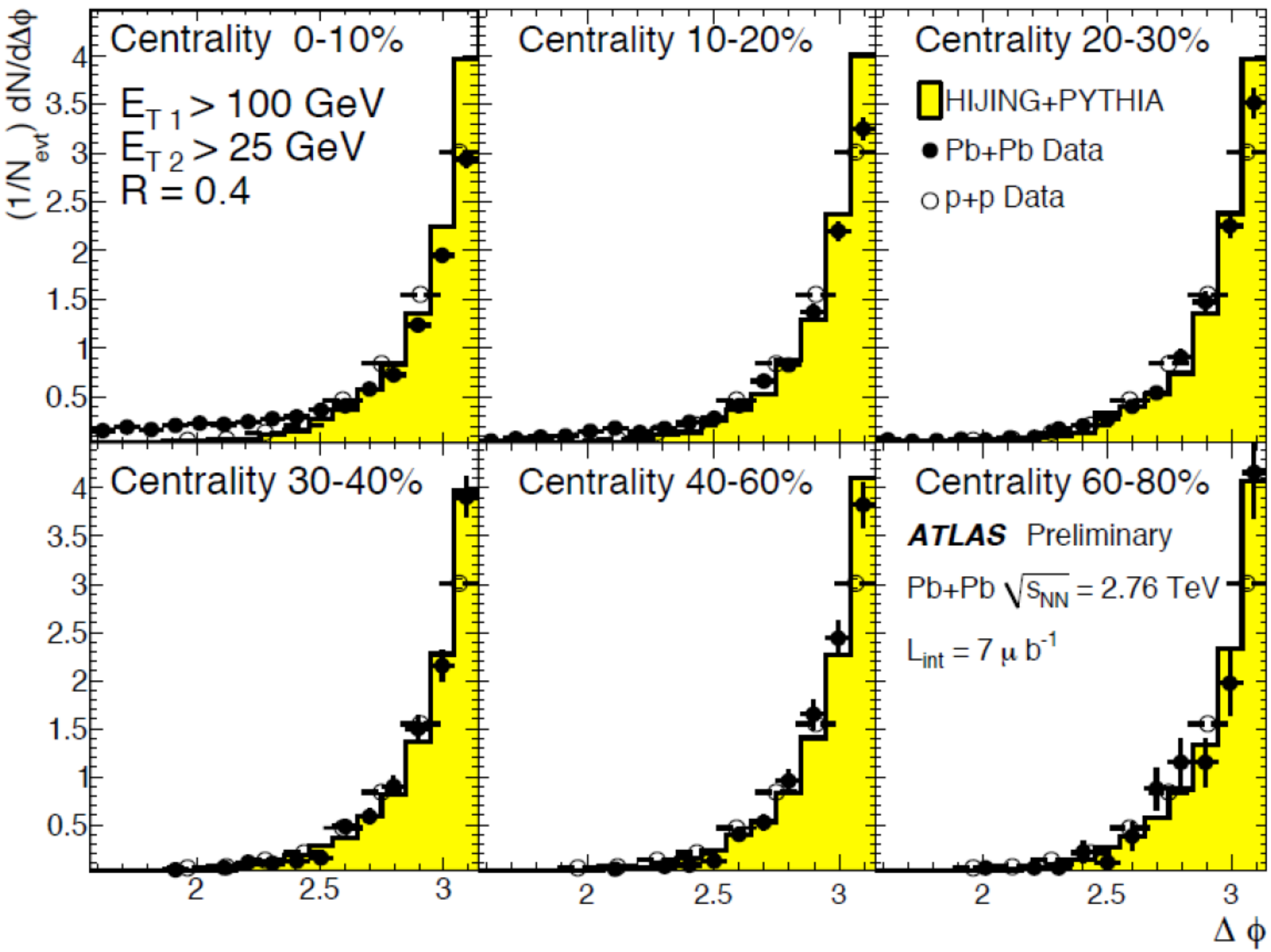
- Data compared with Pythia di-jet (parton p_T 35-280 GeV) embedded to HIJING with no quenching.
- Sub-leading jet: highest E_T jet in opposite hemisphere.
- Events selected with minimum bias trigger (MBTS and ZDC).
- Leading jet: $E_{T,1}$>100 GeV
- Sub-leading jet: $E_{T,2}$>25 GeV
- |η|<2.8



Increasing asymmetry with increasing centrality.

- Enhancement at high A_J is caused by events where the sub-leading jet is coming from background fluctuation.

Di-jet Analysis: dφ Distribution



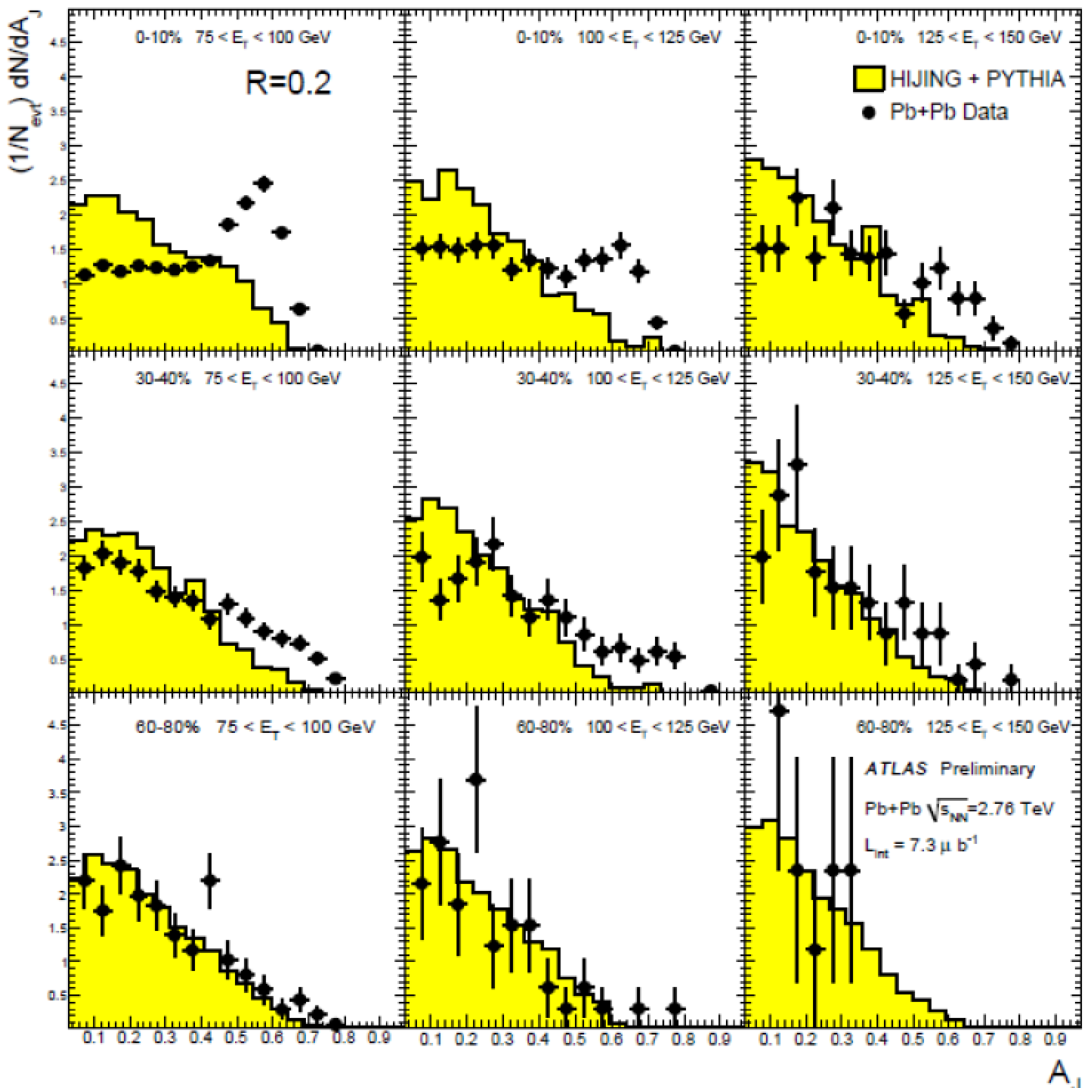
$\Delta\varphi_{12}$ peaked at π.

- Jets remain still back-to-back even in central collisions!

Di-jet Analysis: R=0.2 jet and E_T Dependence

Increasing leading jet E_T → smearing the peak at high A_J

Decreasing centrality
peaking at low asymmetries

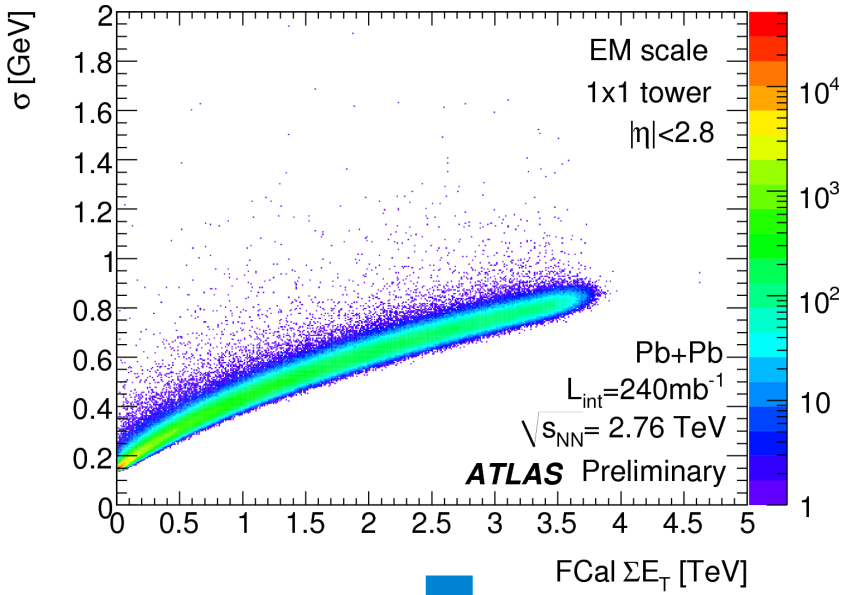


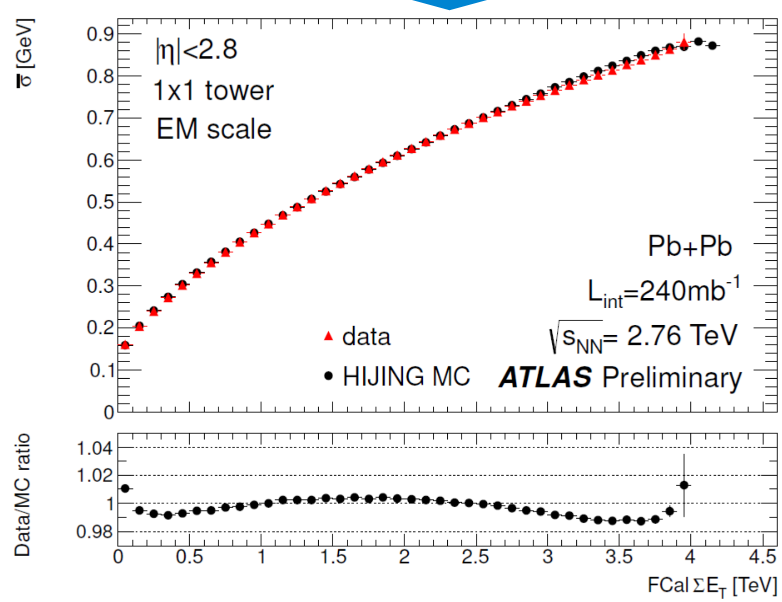
- For R=0.2 jets with 75 GeV<E_T<100GeV peak at A_J~ 0.55.
- This corresponds to $E_{T,2}$ ~20 GeV.
- With increasing $E_{T,2}$:

→ approximately at the same $E_{T,2}$ but larger A_J

Study of Background Fluctuations

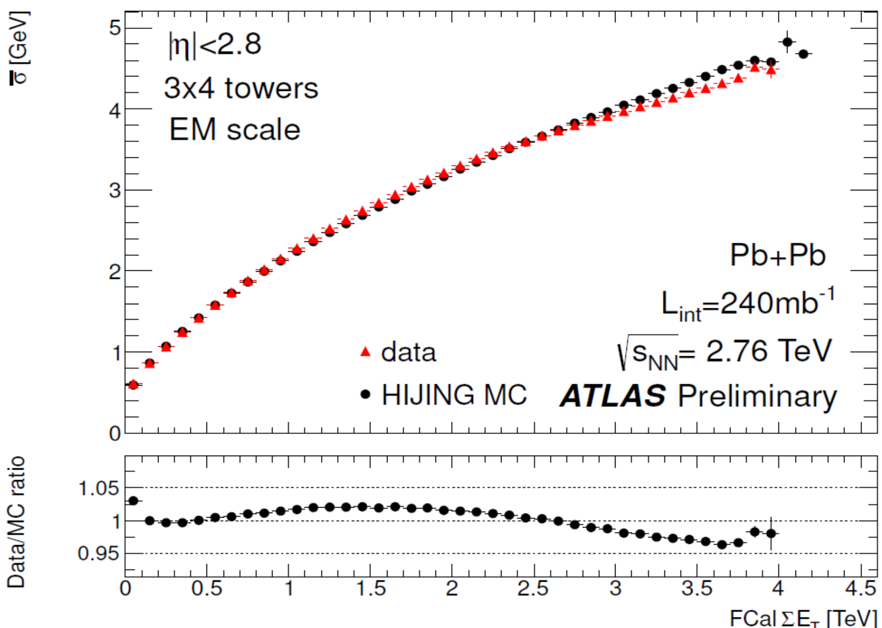
- Study physics of underlying event fluctuations → it can provide a basic information about correlations in the underlying event.
- Independent validation of JER.
- The size of fluctuations is characterized by standard deviation $\sigma = \sqrt{\langle E_T^2 \rangle - \langle E_T \rangle^2}$ and plotted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



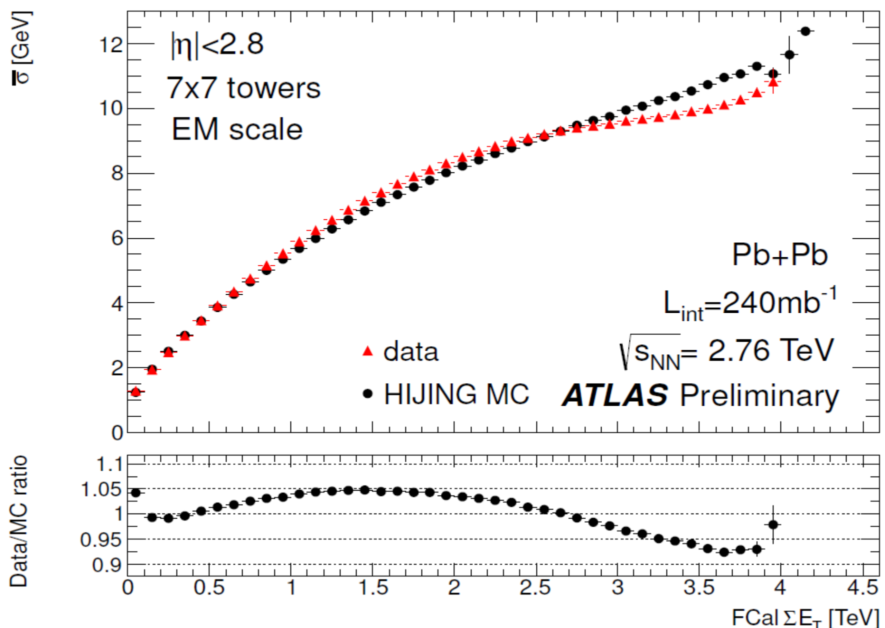


Background Fluctuations

- 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

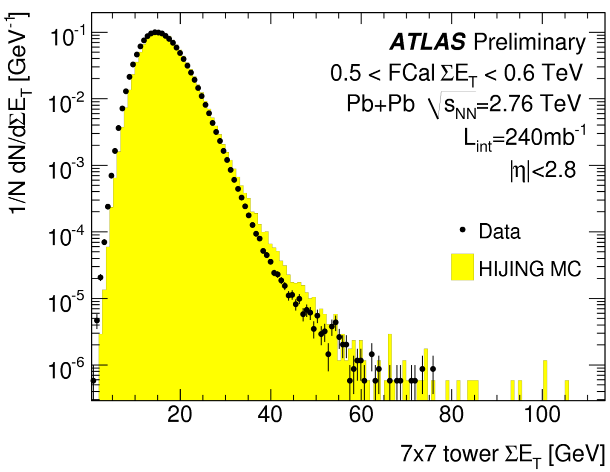


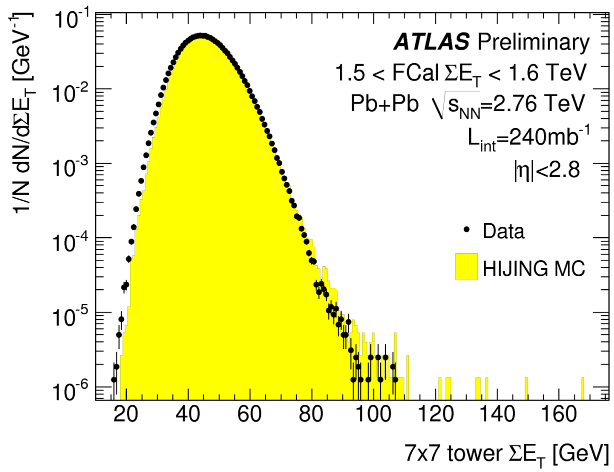
R=0.4 jets

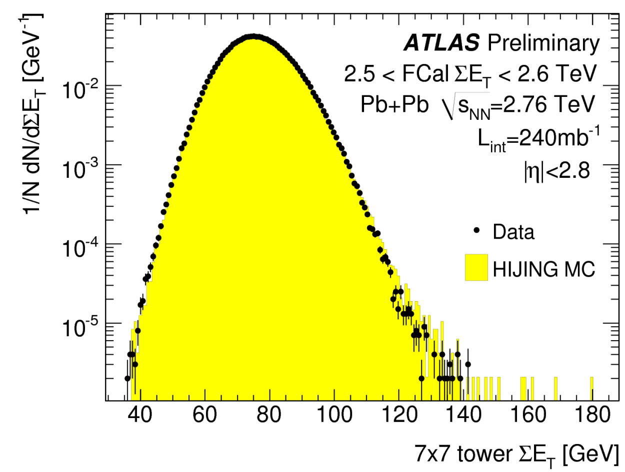
- An agreement between data and MC is better than 5% for R=0.2 jets.
- Fluctuations in data are at most 5% higher than in MC for R=0.4 jets.
- Fluctuations are higher in MC in the most central events.

Detail study of Underlying Event

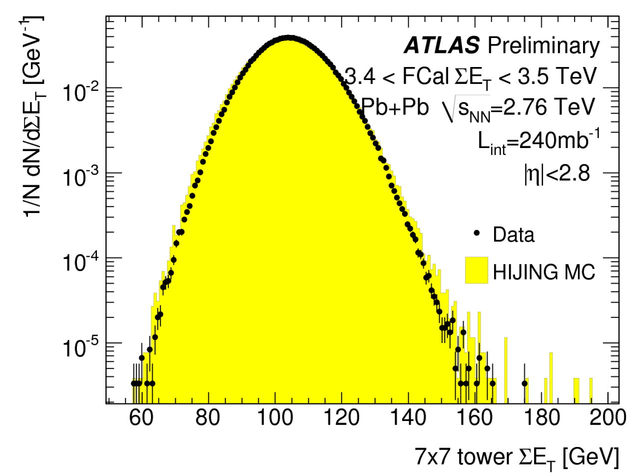
- Data and MC are compared in a narrow bin of FCal ΣE_T:







- 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.



Physics of Jet Quenching

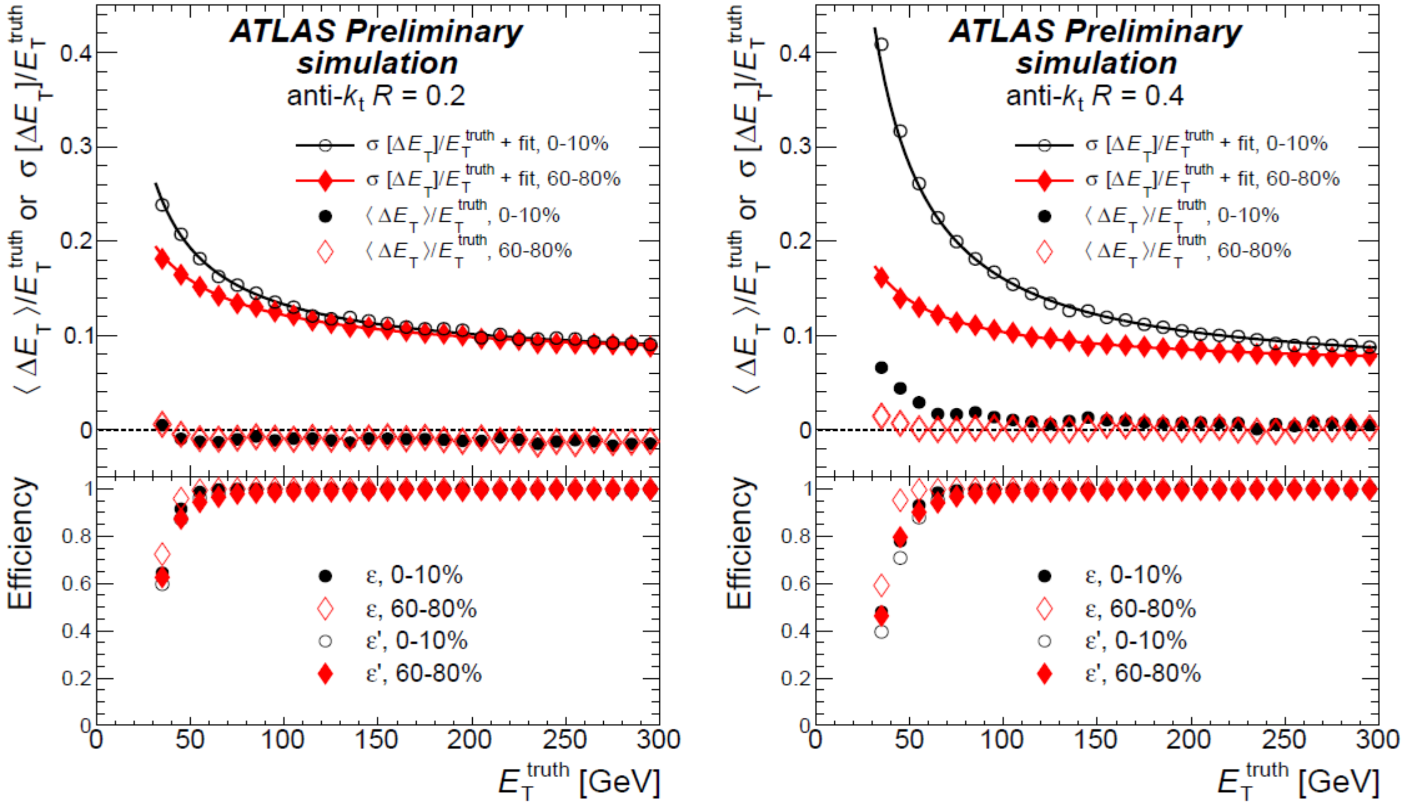
- Measurement of an inclusive jet production is another probe of jet quenching.
- The jet suppression is quantified by R_{CP} – central to peripheral ratio defined as
$$R_{CP} = \frac{1/N_{coll}^{cent}}{1/N_{coll}^{periph}} \frac{1/N_{evnt}^{cent}\, dN/dE_T}{1/N_{evnt}^{periph}\, dN/dE_T}$$
- Some predictions of radiative energy loss suggest that energy can be recovered by expanding the jet cone.

➡ We measured R_{CP} for different jet radii to study the role of radiative energy loss.

- We identify and reject “fake” jets – UE fluctuations from soft particles by requirement of matching calorimeter jet to a track jet or EM cluster above 7 GeV.
  - ➡ Measurement is restricted to |η| < 2.1
  - ➡ Efficiency η~80% at 50 GeV.
  - ➡ Residual fake rate estimated to be ~2% at 50 GeV.

Performance of the Jet Reconstruction

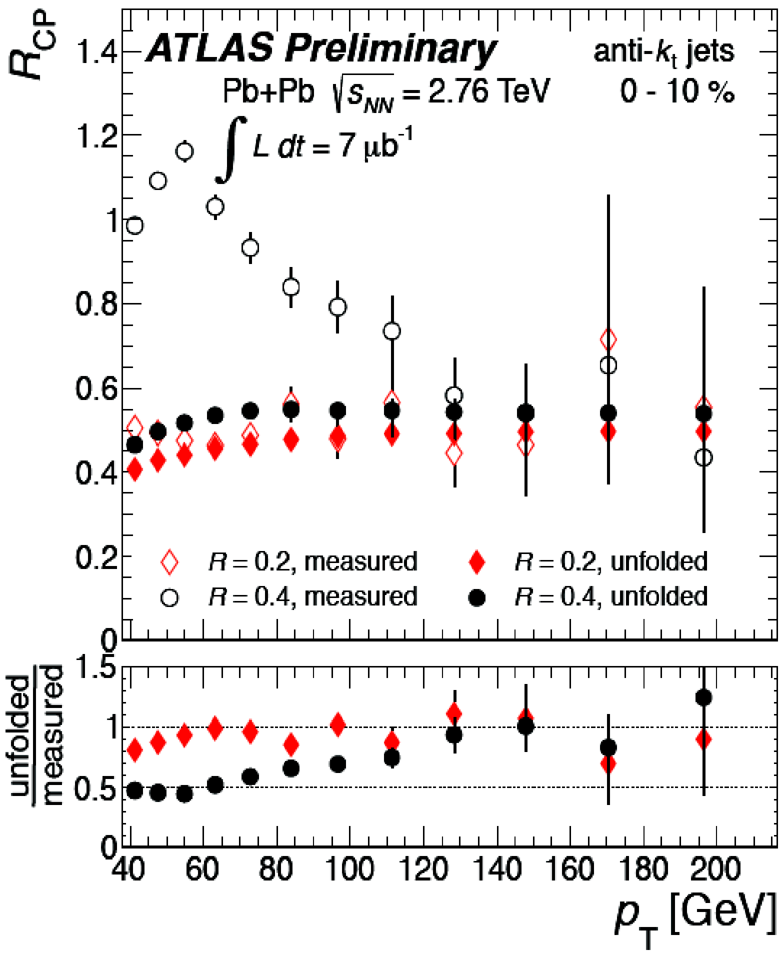
- Performance is evaluated using pp hard scattering events from Pythia overlying on top of HIJING MB events without quenching.



- 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.

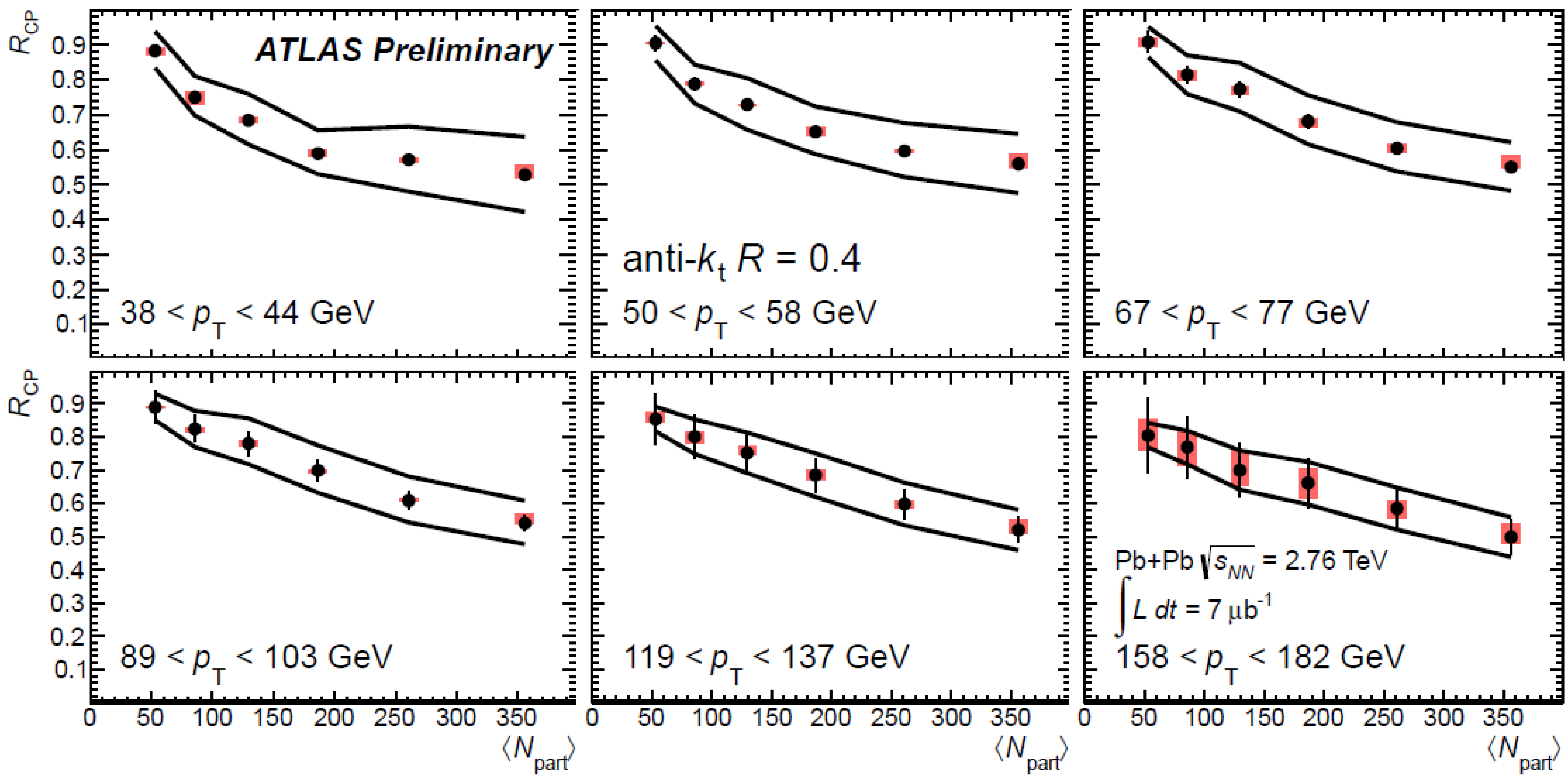
Jet Spectra and Unfolding

- SVD unfolding was used to account effect of bin migration caused by detector and UE effects.
- MC overlay samples were used to generate response matrix
- Several checks have been performed.



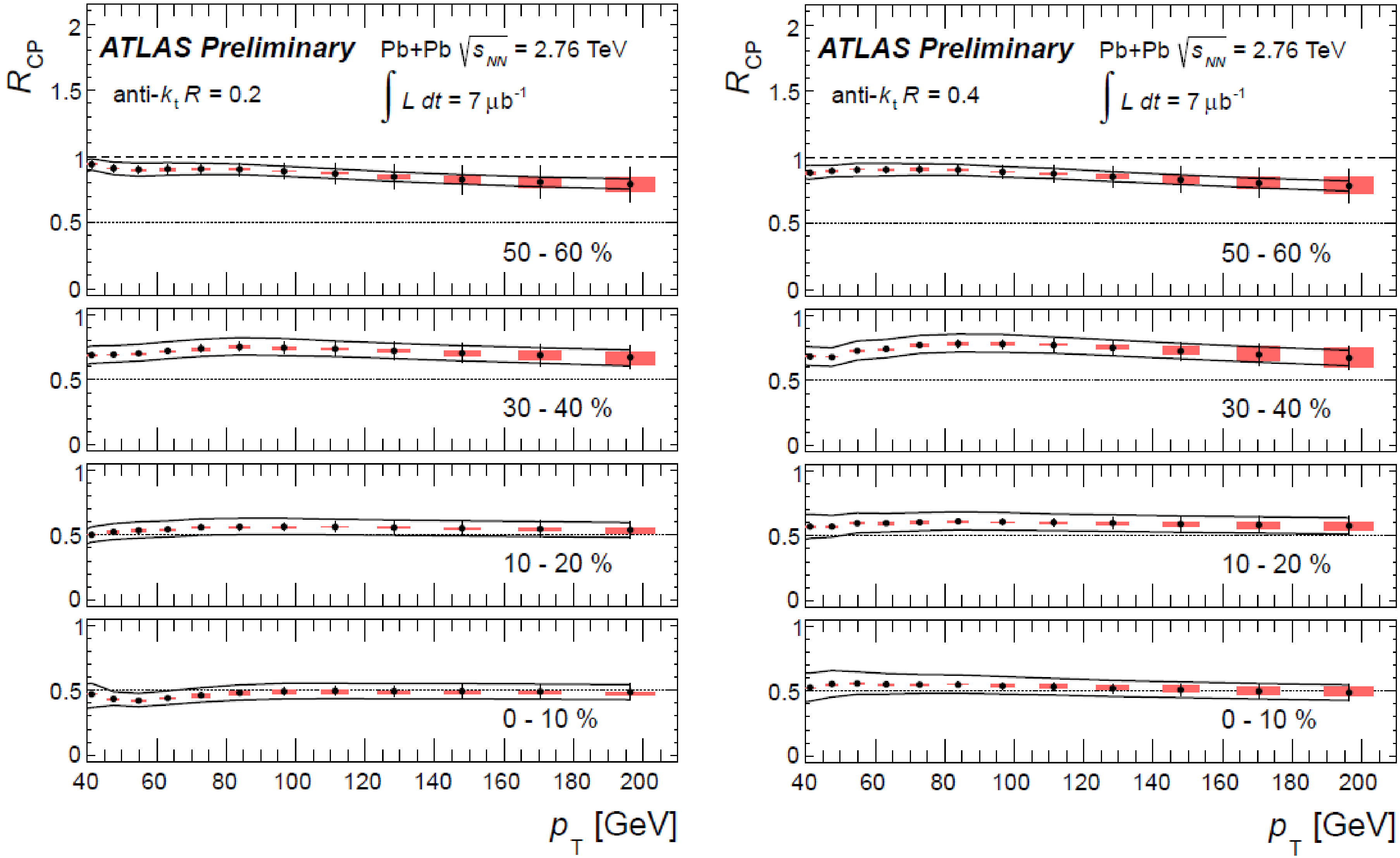
- Small effect on R=0.2 jets.
- R_{CP} is reduced for R=0.4 by factor of two for low E_T jets.

Centrality Dependence of Jet R_{CP}



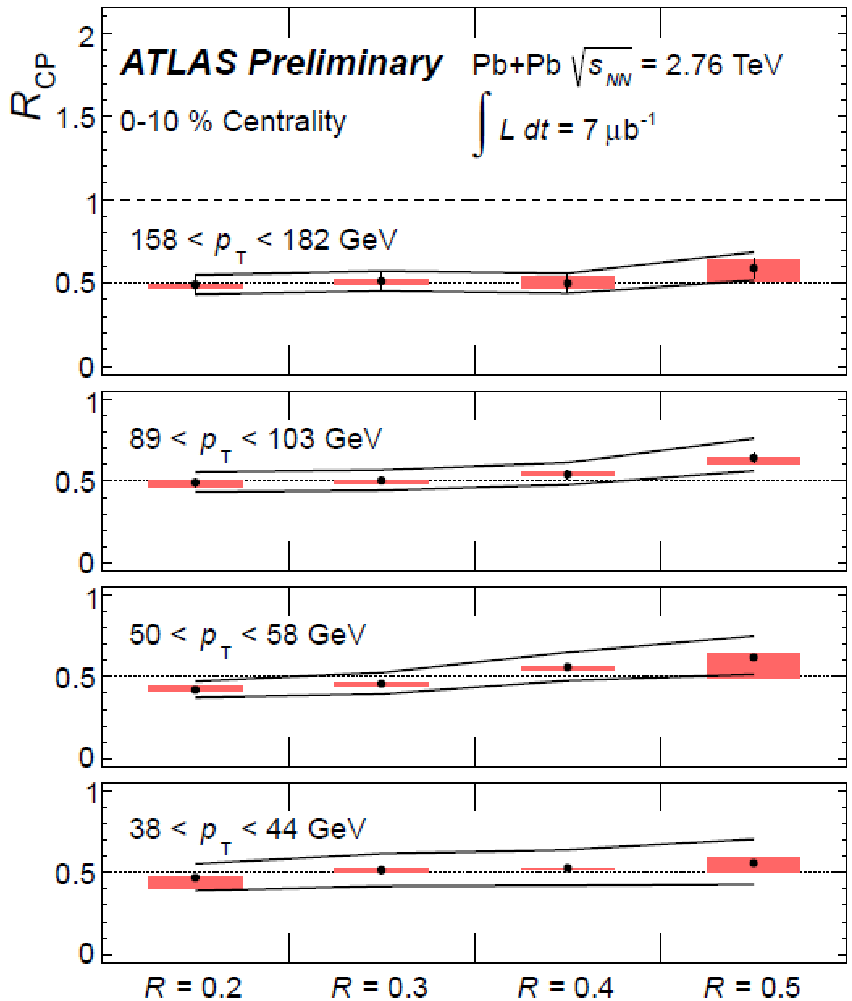
- Factor of 2 suppression in central with respect to peripheral collisions.
- Increasing suppression with increasing centrality.
  - The increase is linear for high p_T, quick turns on at low p_T.
  - Similar result is observed also for other jet radii.

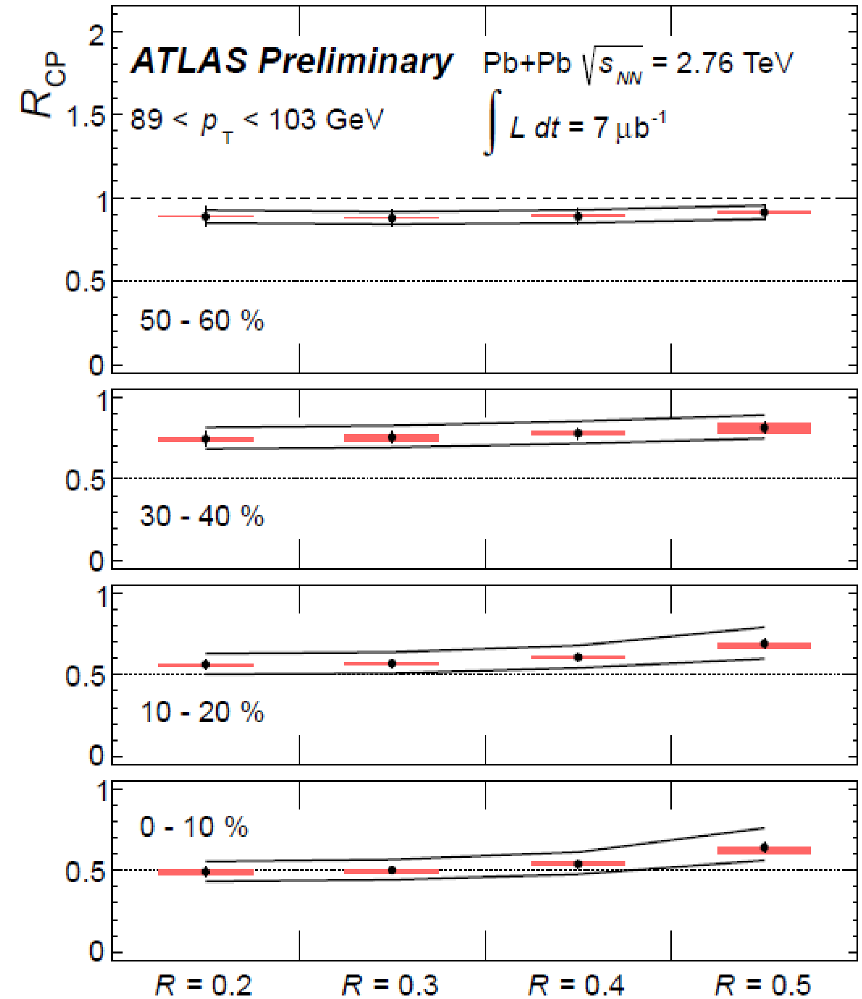
Jet R_{CP} as a Function of Jet p_T



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

Jet R_{CP} as a Function of Jet Radius

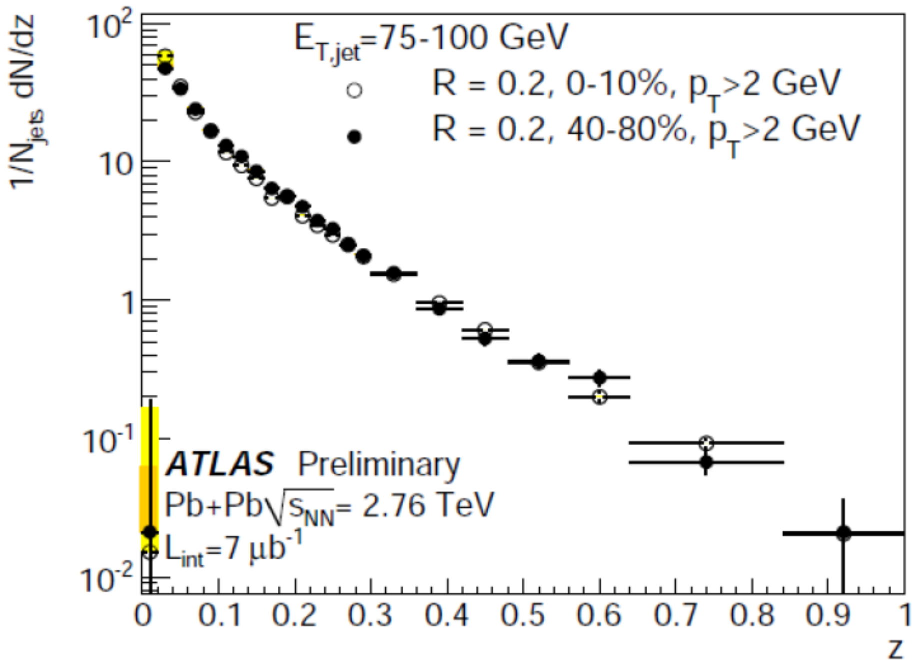




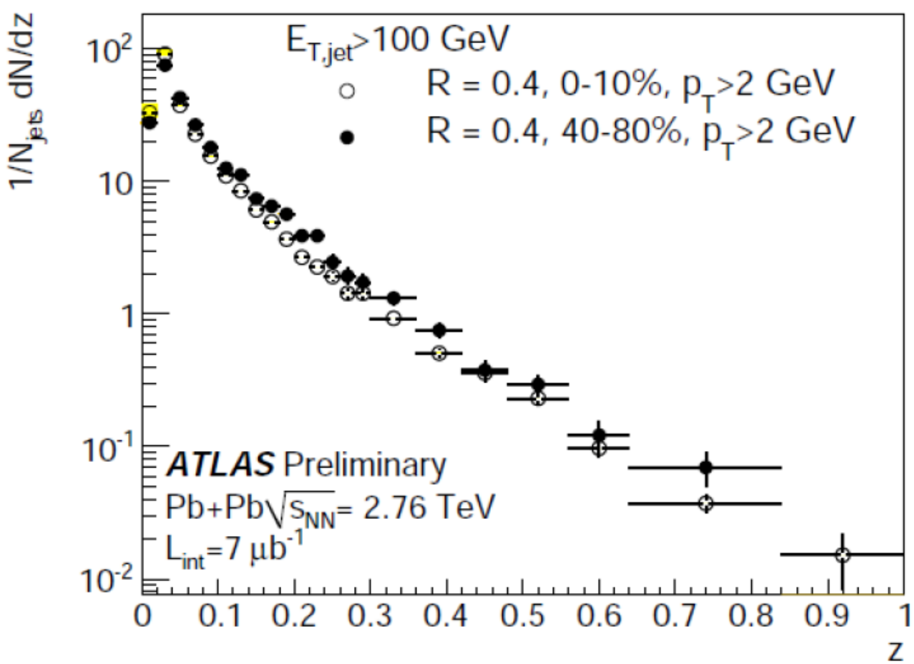
- Weak dependence on jet radius is observed.
- A small difference is present only at very low p_T.

Jet Fragmentation: Longitudinal Structure

- Longitudinal structure is described by $D(z) = (1/N_{jet}) dN/dz$, where $z = p_T^{had}/E_T^{jet} \cos \Delta R$



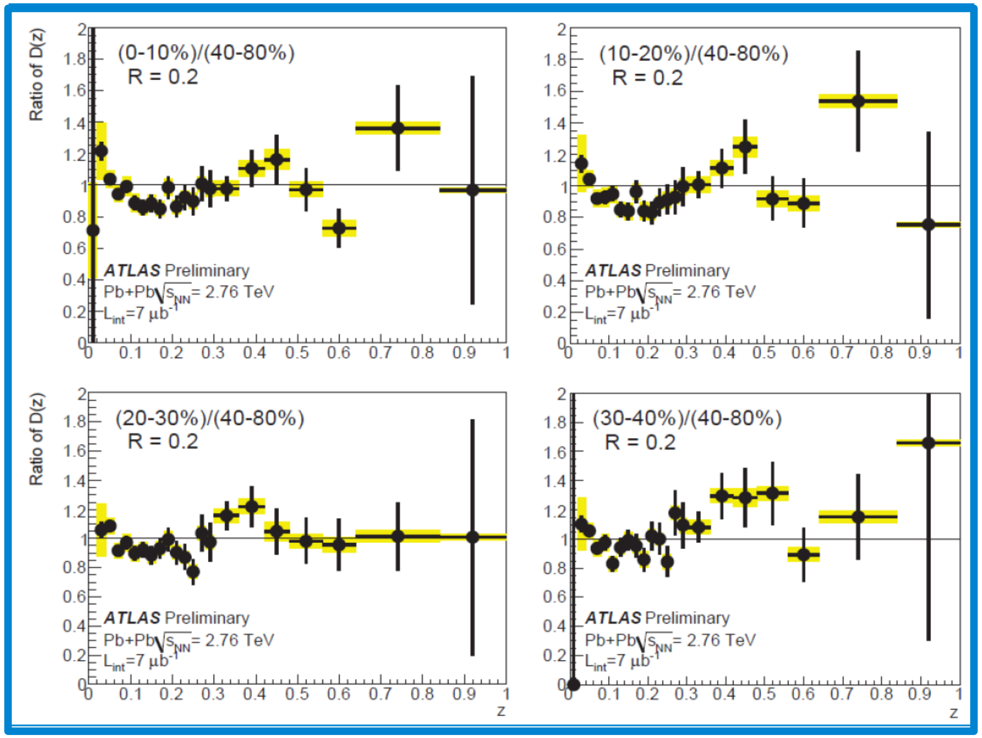
R=0.2

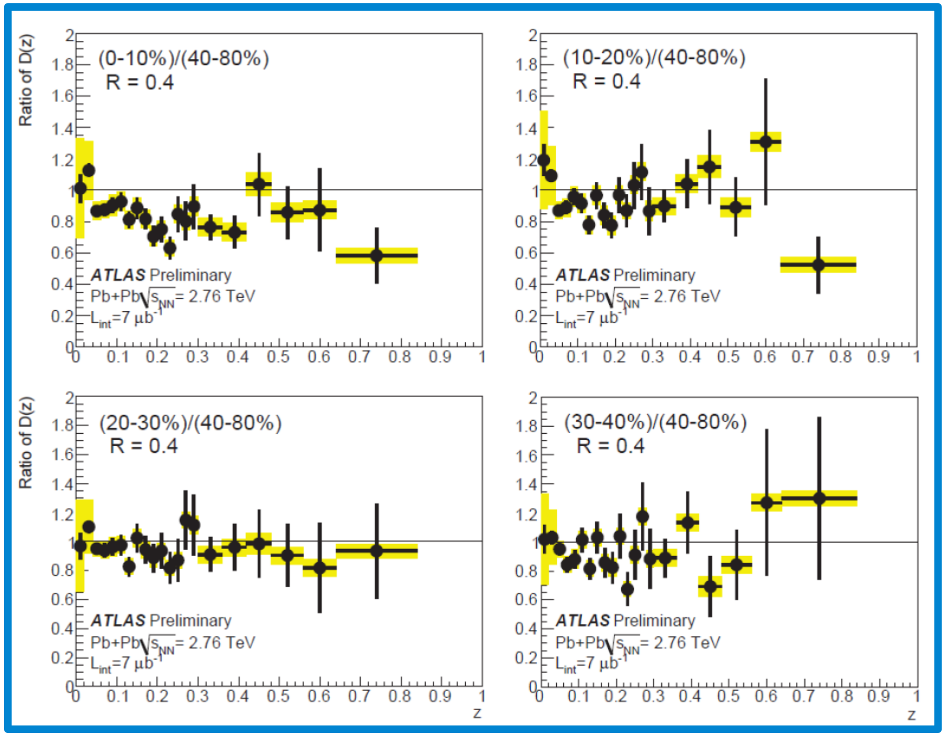


R=0.4

- Charged hadrons with p_T>2 GeV.
- UE contributions is subtracted.
- No correction for resolution is applied.

Jet Fragmentation: Longitudinal Structure





R=0.2 **R=0.4**

- No strong modification of fragmentation functions in central collisions with respect to peripheral ones.
- Possibly mild suppression at intermediate z (0.05-0.3) and enhancement at very low z (<0.05).

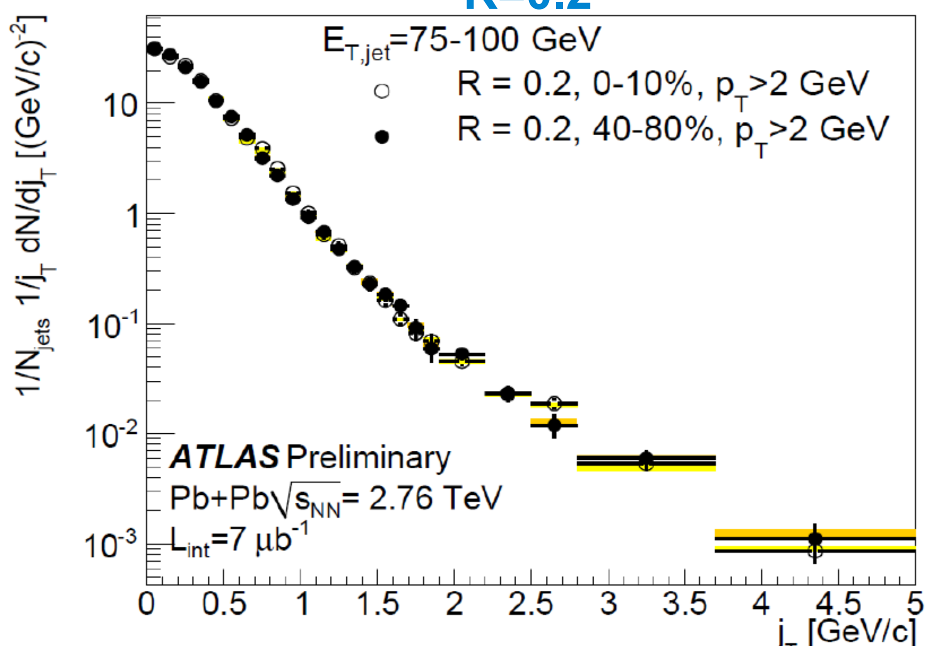
Jet Fragmentation: Transverse Fragmentation Function

Characterized by j_T distribution: transverse momentum of charged particles:

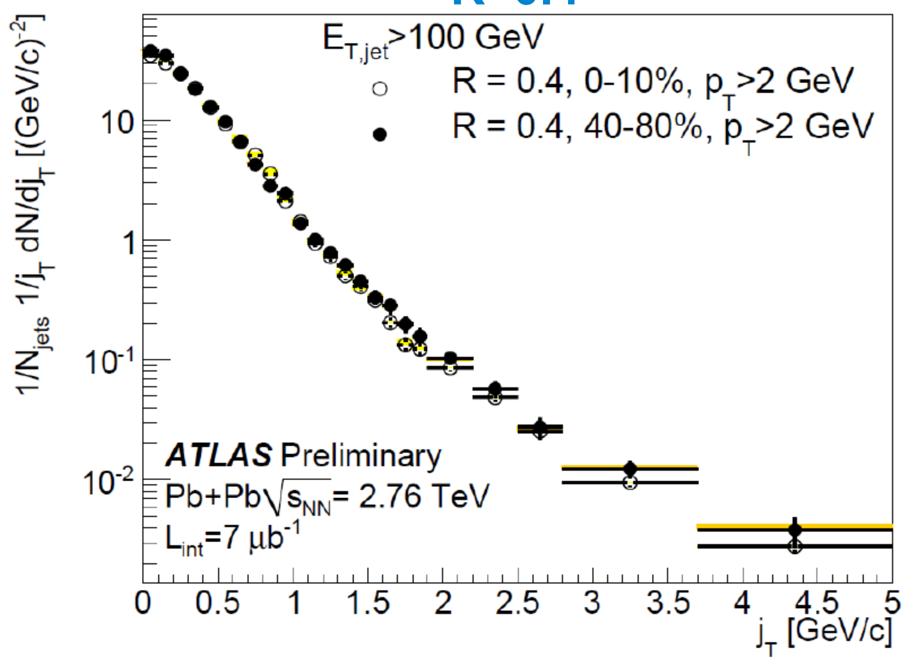
$$D(j_T) = (1/N_{jet})(1/j_T)dN/dj_T, \text{ where } j_T = p_T^{had} \sin \Delta R$$

- 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

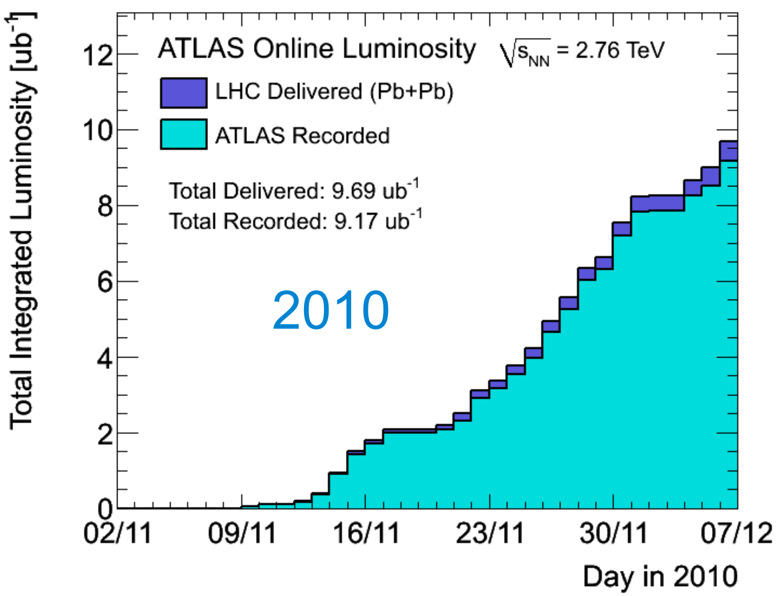


R=0.4

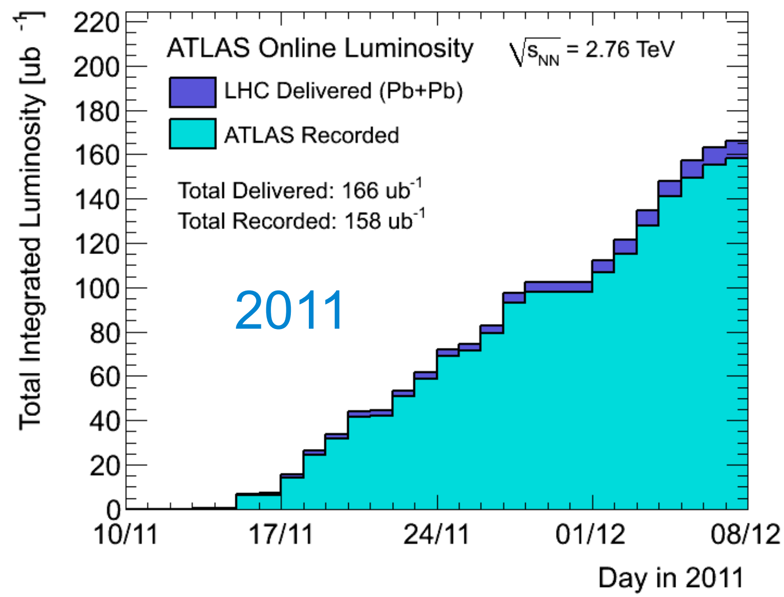


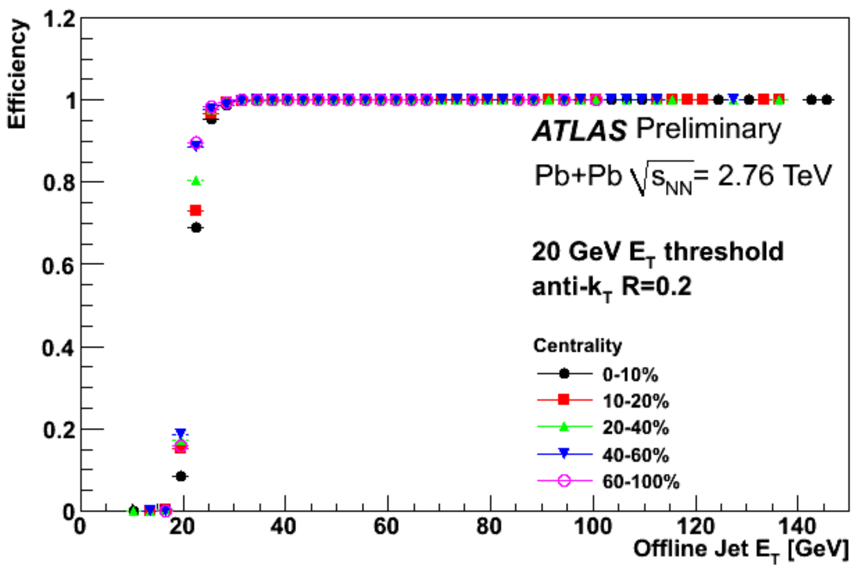
➡ No significant change in j_T distribution from peripheral to central collisions in R=0.4 and R=0.2 jets.

Jets in 2011 HI run



17x more data!



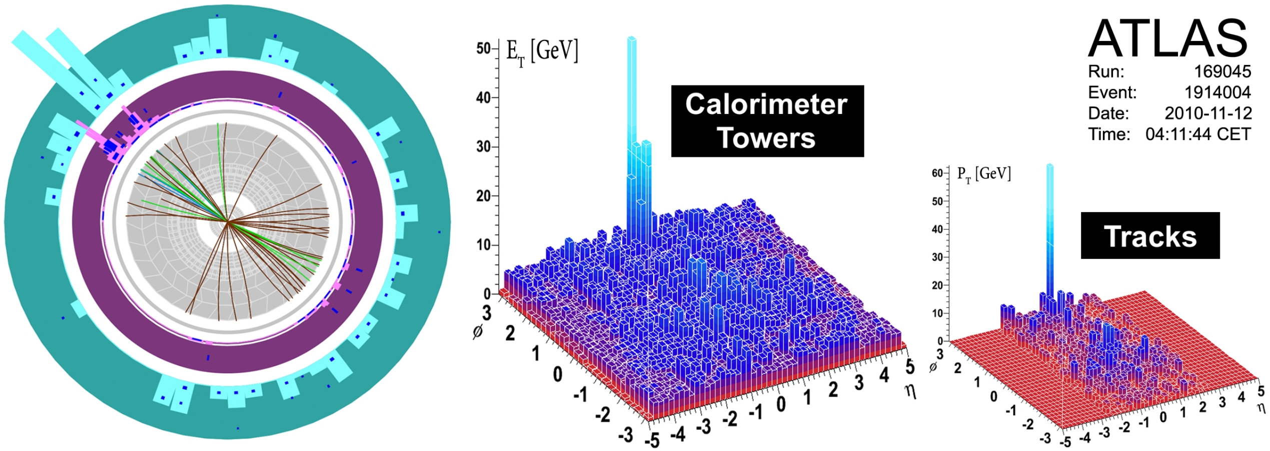


- Jets were recorded using HLT algorithm.
- Similar background subtraction procedure as used in offline algorithm was performed in HLT.

➡ Efficiency is centrality independent.

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 jet suppression is very weak on jet p_T and jet size except low p_T region.
- Study of jet structure show no significant broadening of j_T distribution and small modification of longitudinal fragmentation functions.
- New interesting results from 2011 run are expected!

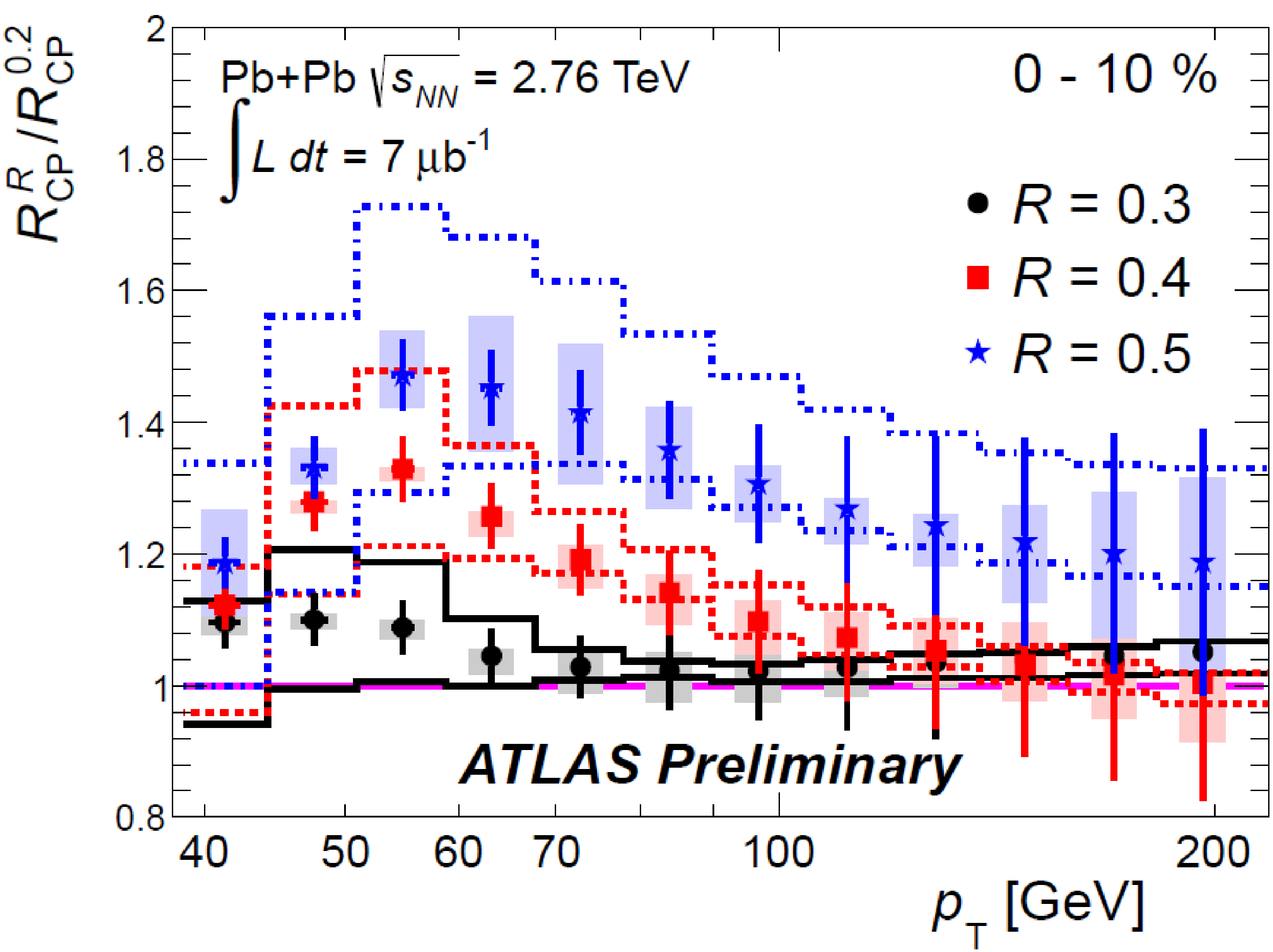


Backup

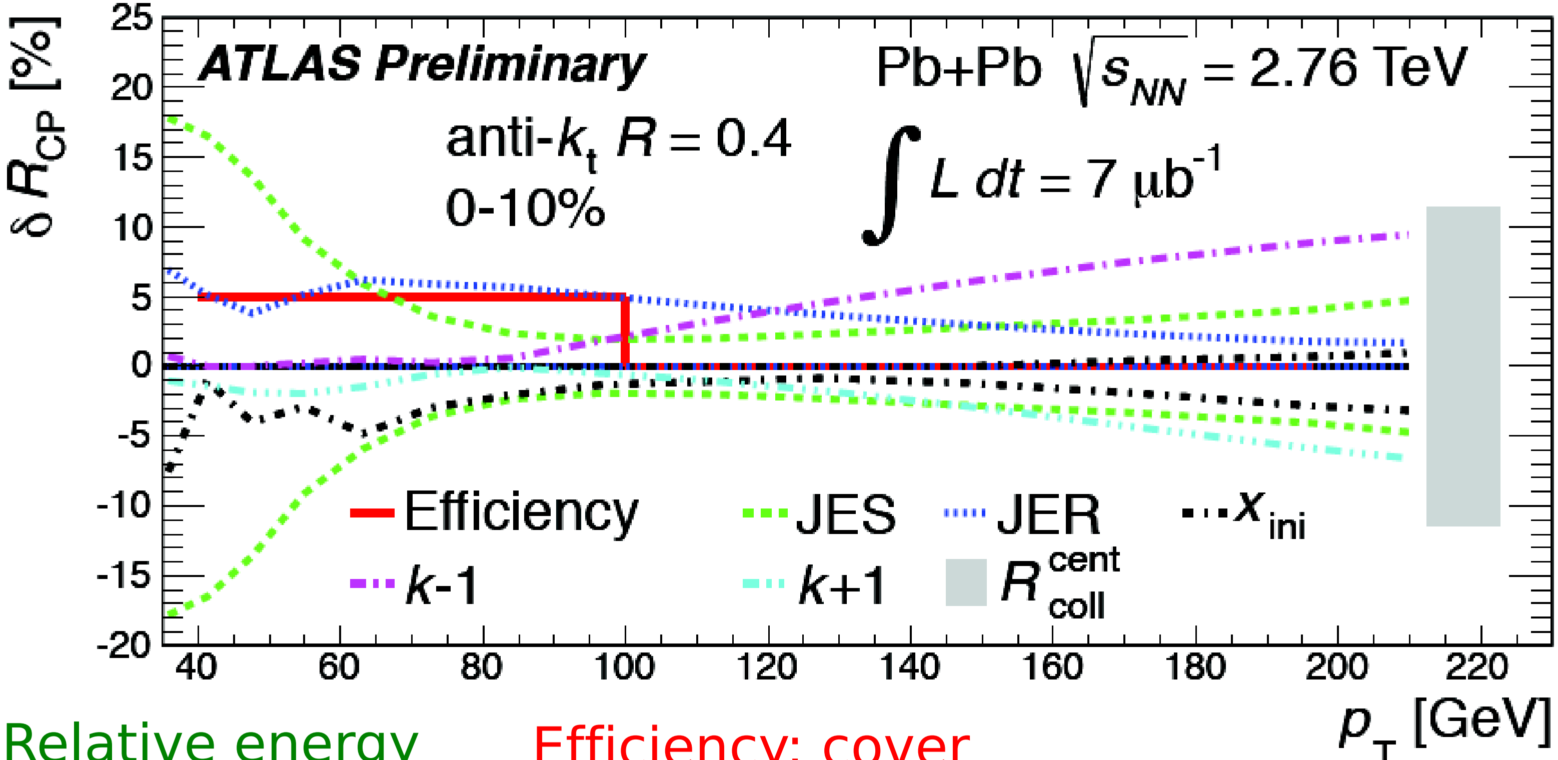
ATLAS Detector Status

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%

R_{CP} – R dependence



R_{CP} – Systematics



JES: Relative energy scale differences central and peripheral

JER: Possible disagreement between data and MC in UE fluctuations

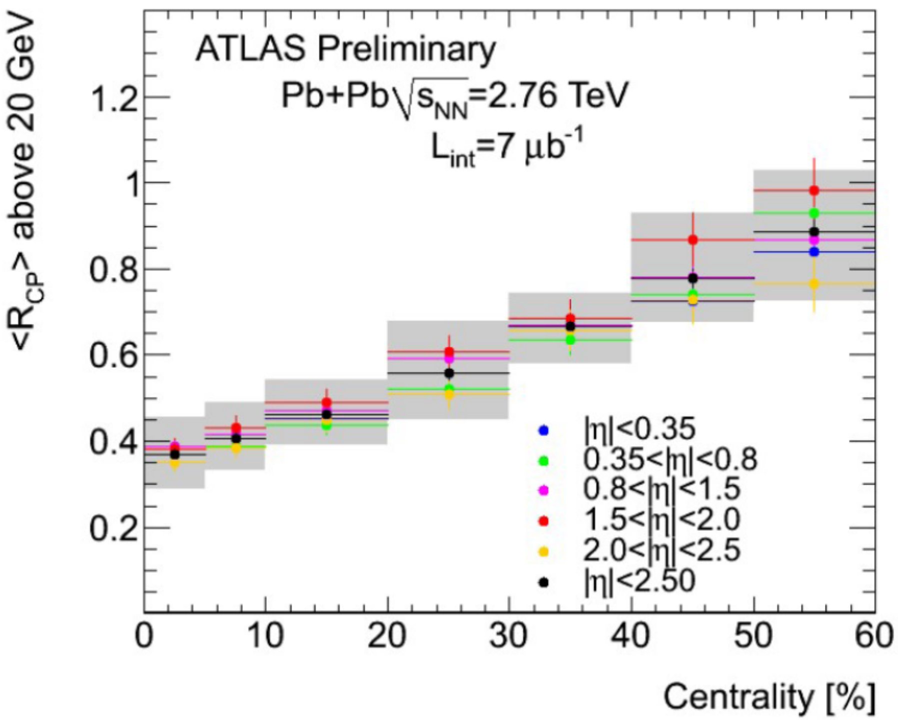
Efficiency: cover possible MC/data differences, 5% for pT < 100 GeV

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

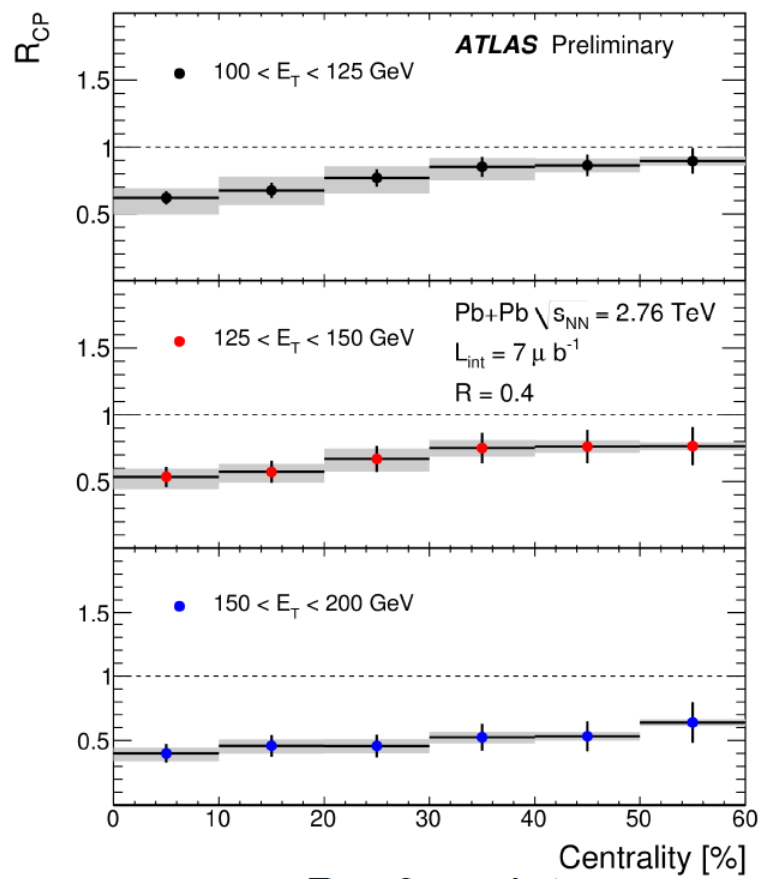
R_{coll}: sensitive to centrality determination, σ_{NN}

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

Comparison R_{CP} from Charged Particle and Jets



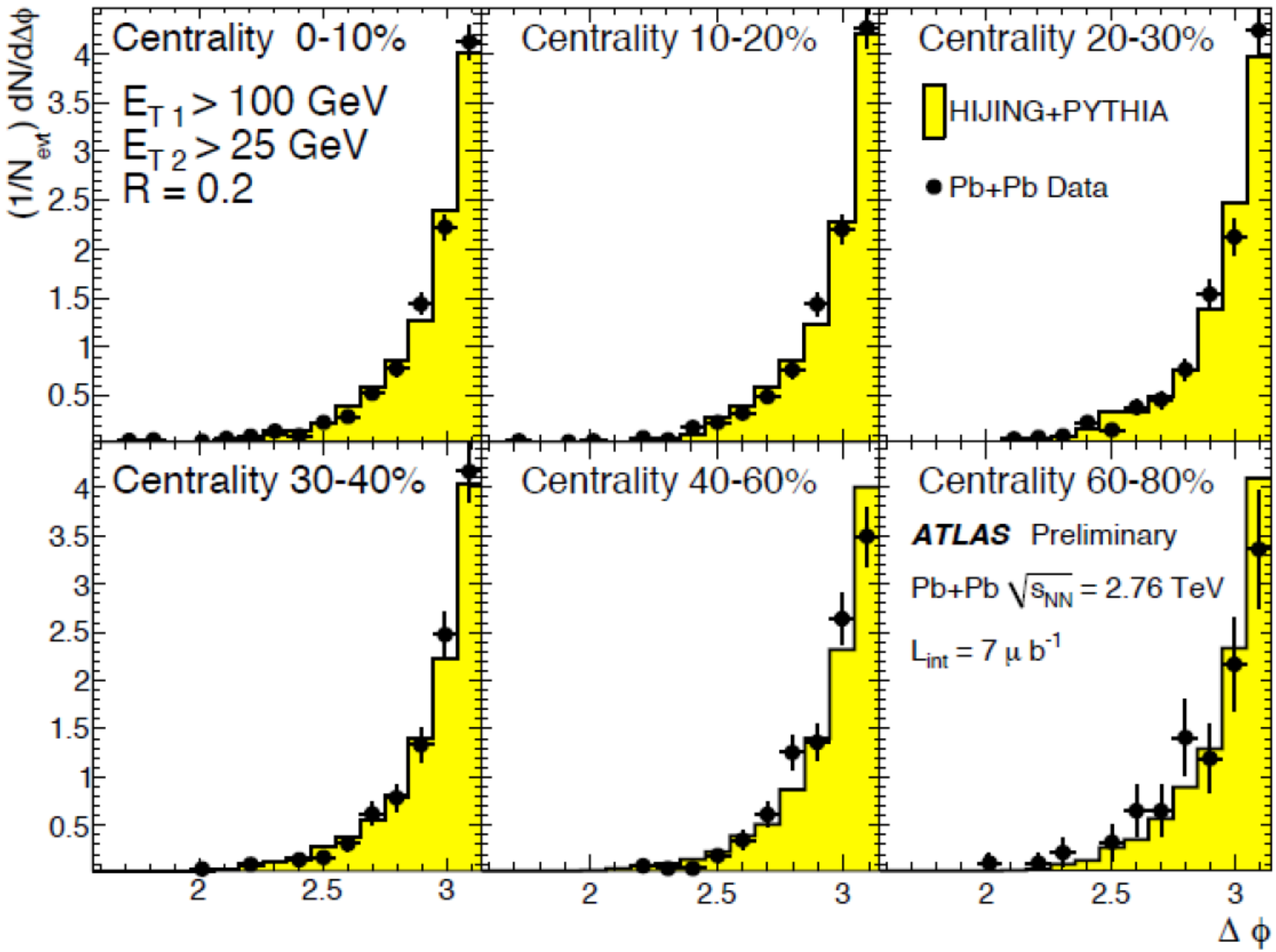
R_{CP} from charged particles above 20 GeV



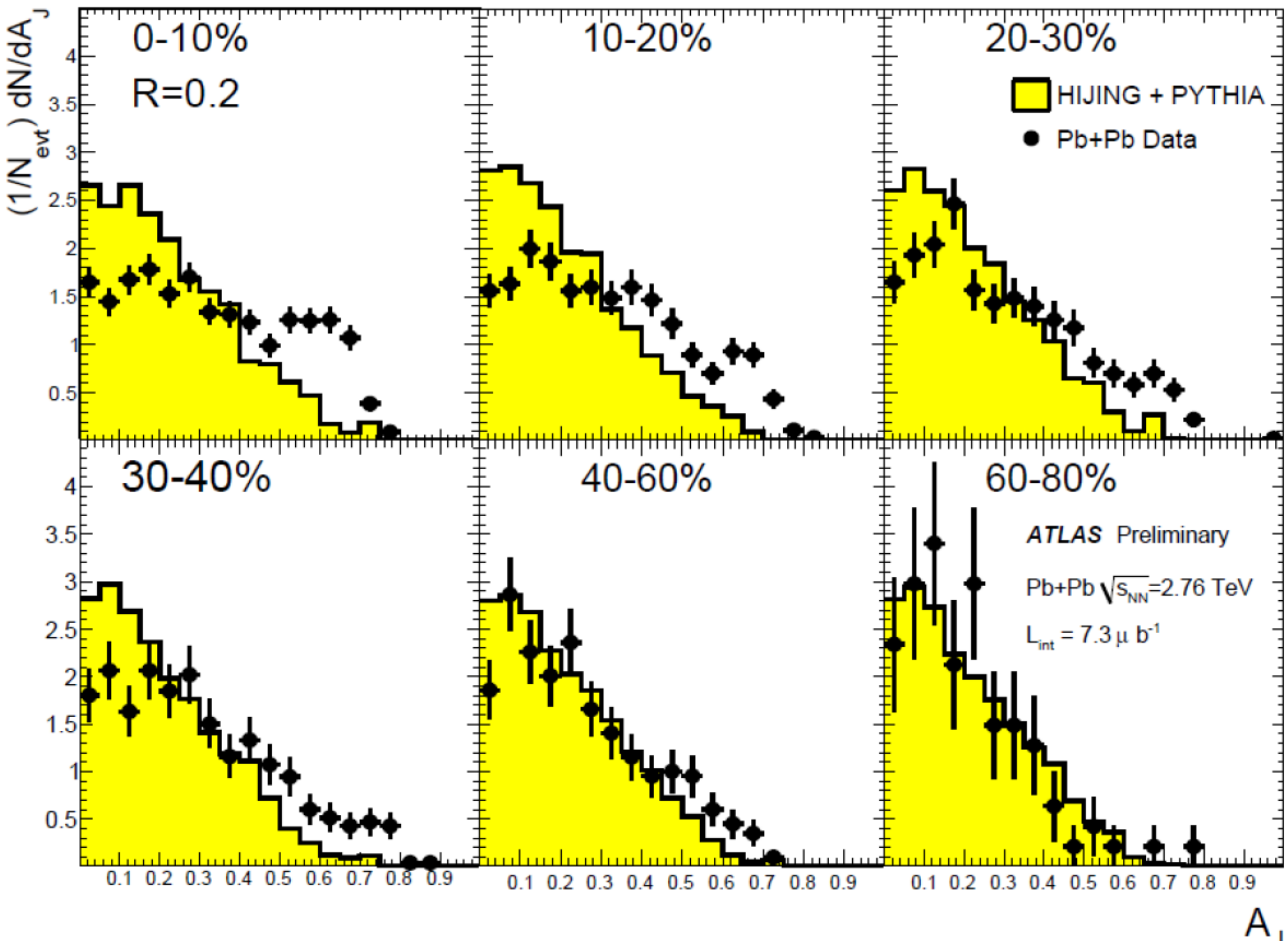
R_{CP} from jets.

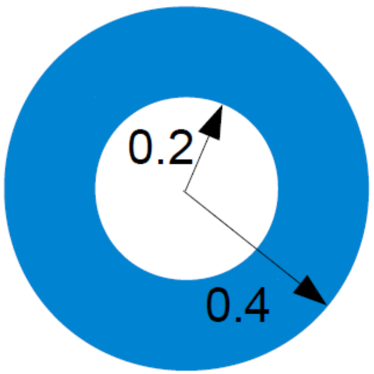
➡ R_{CP} from charged particles and jets are of similar magnitude.

R=0.2: dφ distribution



Di-jet Analysis: R=0.2 jets



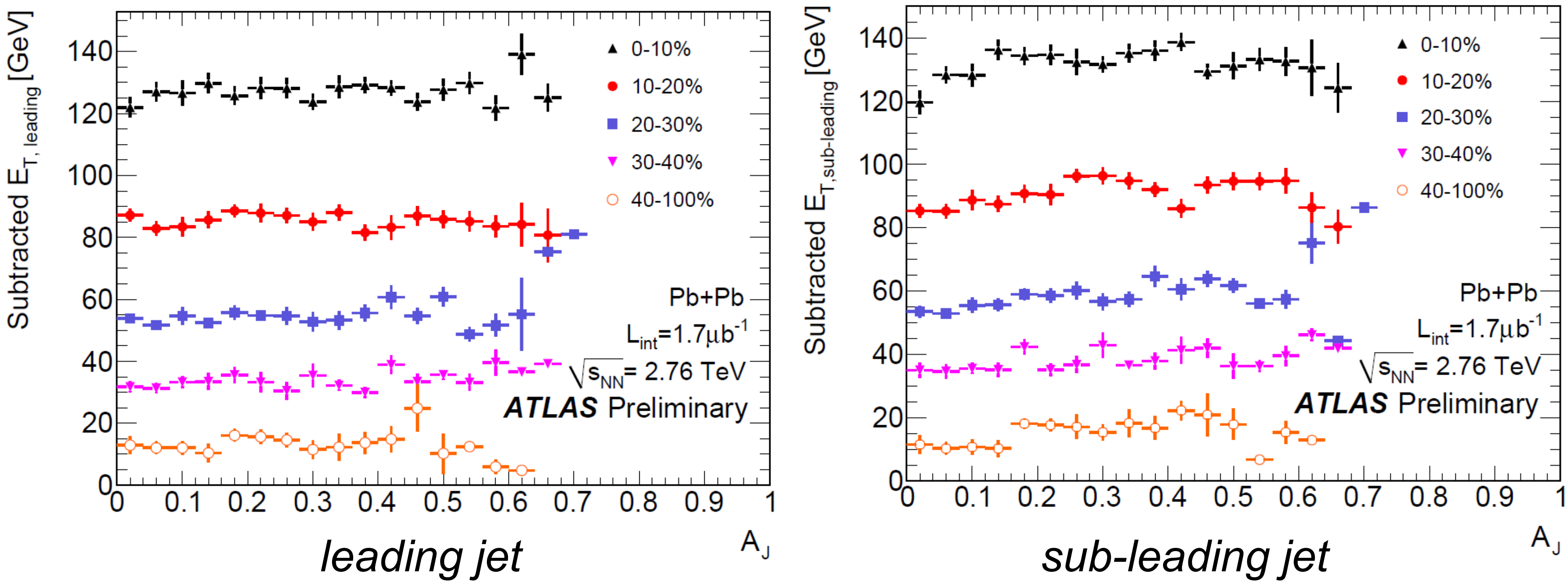


Two times smaller effect of underlying event fluctuations

- Strong asymmetry modification is still observed.

Subtracted E_T

- Mean subtracted energy as a function of asymmetry



→ no asymmetry dependence

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

Transverse Energy in 1x1 tower window