ATLAS Results on Pb+Pb Collisions

Helena Santos, LIP-Lisbon

for the ATLAS Collaboration

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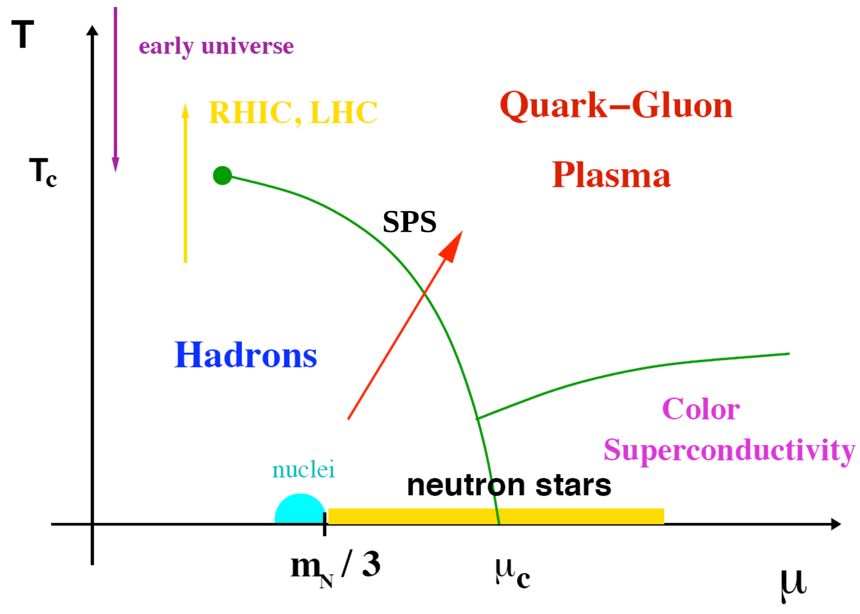
Heavy Ion Physics

- Systematic study of a hot, dense and strongly coupling systems

- Extending our understanding of QCD by studying distinct phases of matter: hadronic vs. partonic deconfined system (Plasma of Quarks and Gluons)

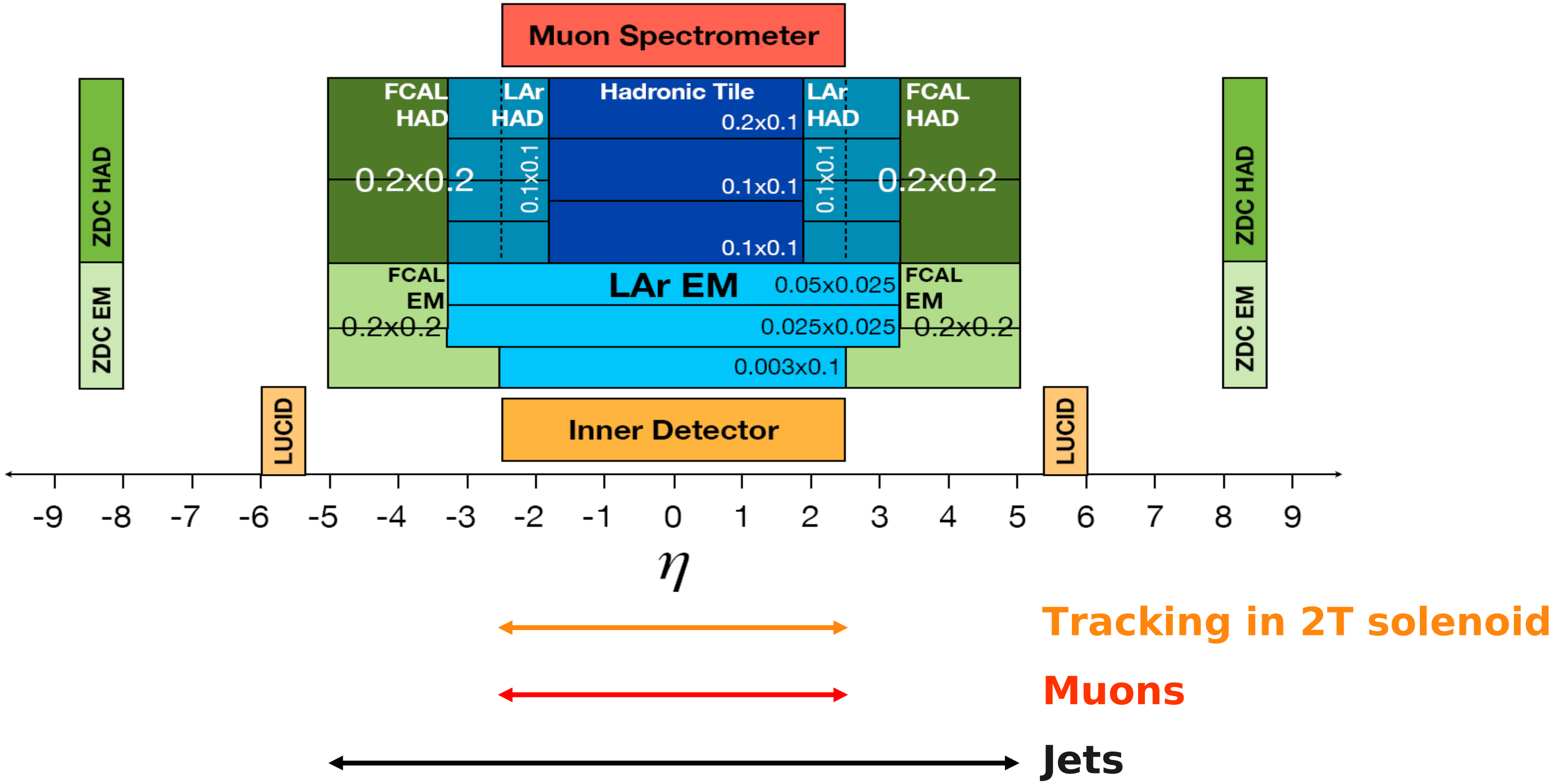


$\sqrt{s}$: 17 GeV@SPS 200 GeV@RHIC 2.76 TeV@LHC

Colliding nuclei: Pb+Pb Au+Au Pb+Pb

ATLAS Acceptance

Full azimuthal coverage

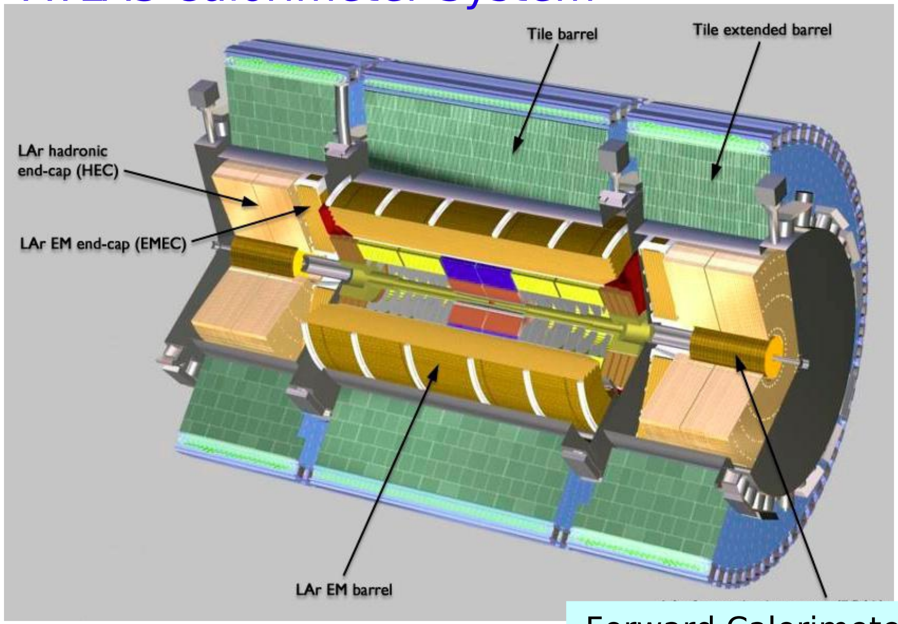


Triggers used in the 2010 Pb+Pb run:

- Coincidence in (Level-1) Minimum Bias Trigger Scintillators (2.1<|η|<3.9)
- Coincidence in Zero Degree Calorimeter (|η|>8.3)
- No physics signature triggers (e.g., jets, muons) used in event selection

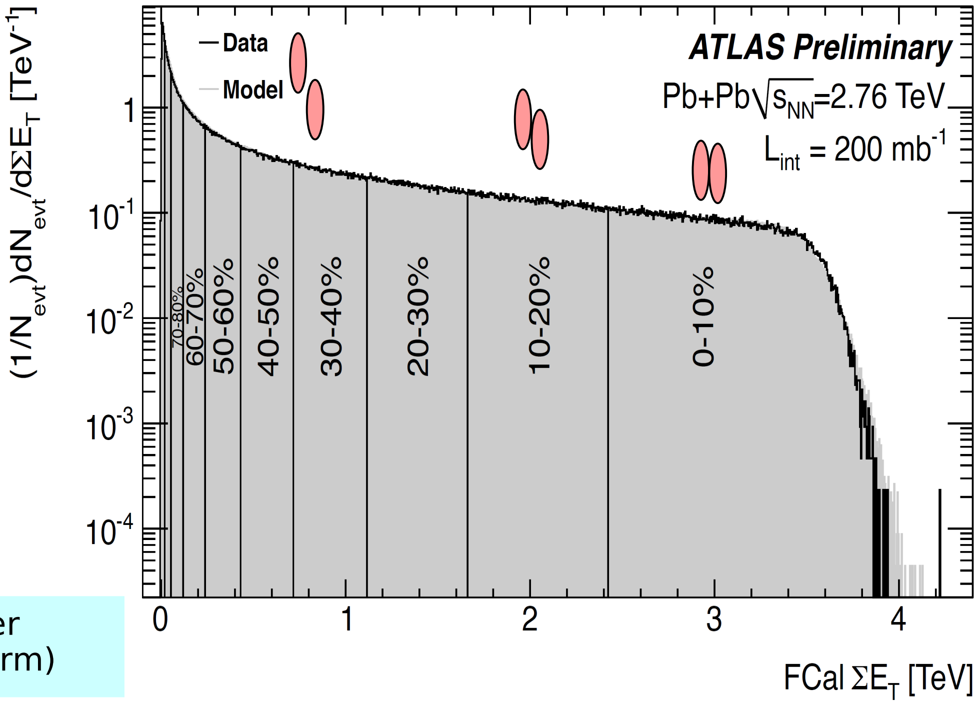
Collision's Centrality

ATLAS Calorimeter System



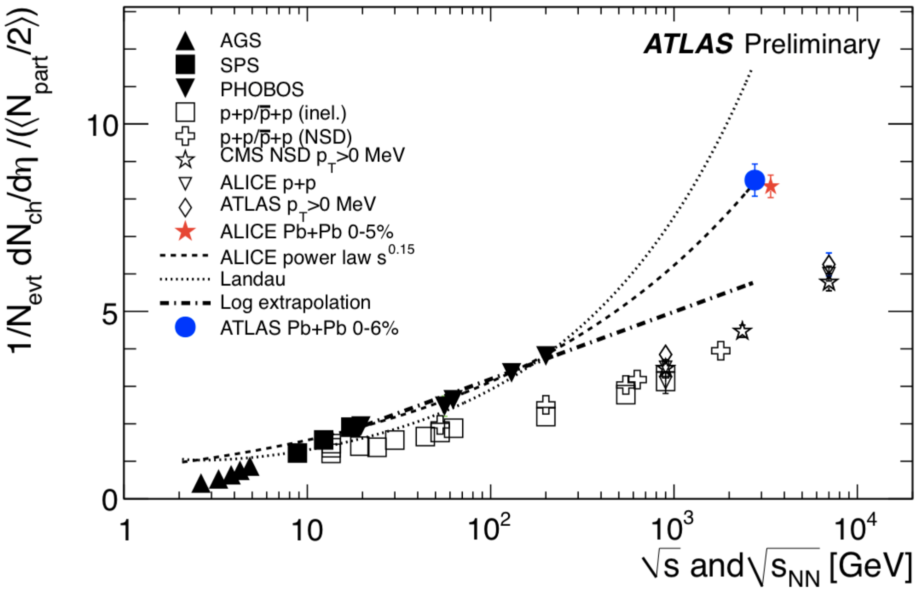
Forward Calorimeter
$3.2<|\eta|<4.9$,(one arm)

ET in Forward Calorimeter

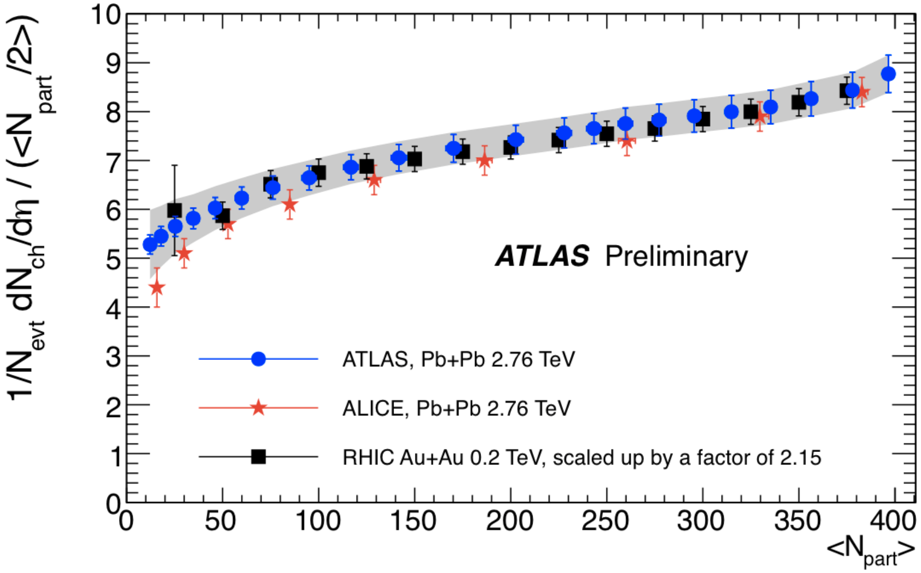


- Transverse energy in FCal compared to Glauber MC model ⊗ p+p data
- Sampling fraction f = 100 ± 2%, after all trigger and selection cuts
- $\langle N_{part} \rangle$ and $\langle N_{coll} \rangle$ for each centrality bin are estimated using the same Glauber
  - 80-100% range is excluded in analyses that involve nuclear modification factors due to the large systematic uncertainties affecting these calculations

Charged Particle Multiplicity



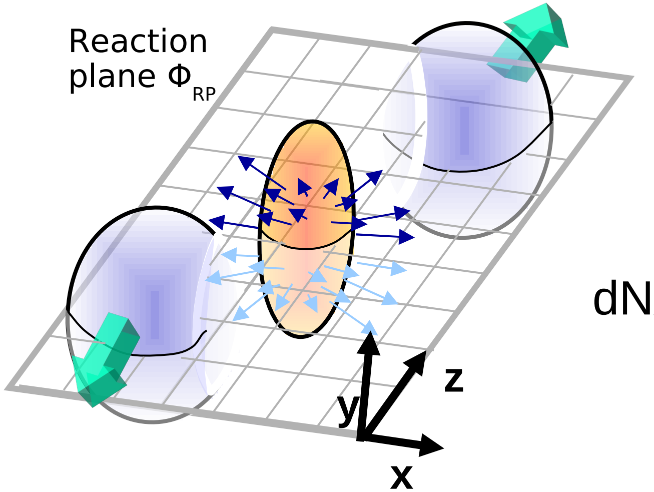
- Yield per participant pair increases by factor of two relative to RHIC, in agreement with ALICE measurement (shifted for clearness)
- Charged particle multiplicity by nucleon pair follows a power law



- Variation with centrality consistent between LHC and RHIC (scaled by 2.15)

- Pixel “tracklets” in solenoid off to measure down to p_T>0
- Integrated luminosity: 1 μb^{-1}

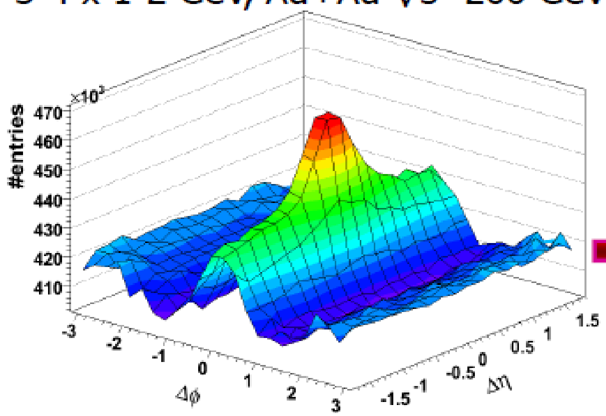
Azymuthal Anisotropic Flow

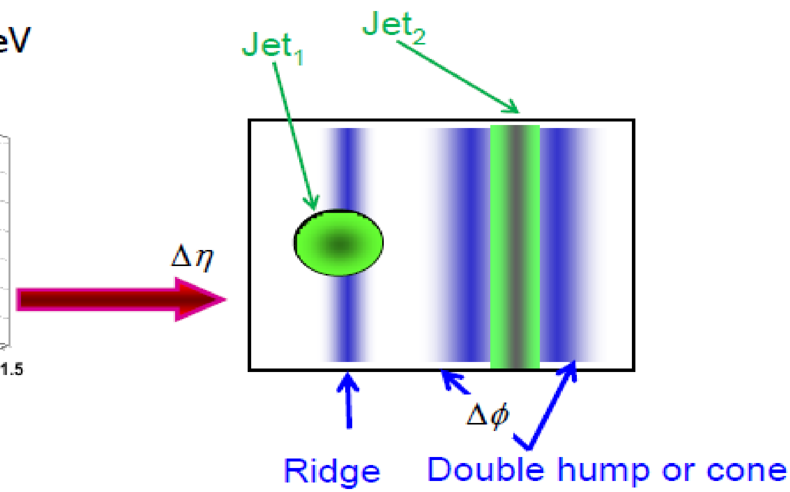


Anisotropic spatial collective motion leads to anisotropic distributions in the momentum space

$$dN/d(\phi-\Phi_{RP}) = N_0\,(1 + 2v_1\cos(\phi-\Phi_{RP}) + 2v_2\cos(2(\phi-\Phi_{RP})) + 2v_3\cos(3(\phi-\Phi_{RP}))\ \ldots)$$

Long range structure at RHIC
3-4 x 1-2 GeV, Au+Au √s=200 GeV

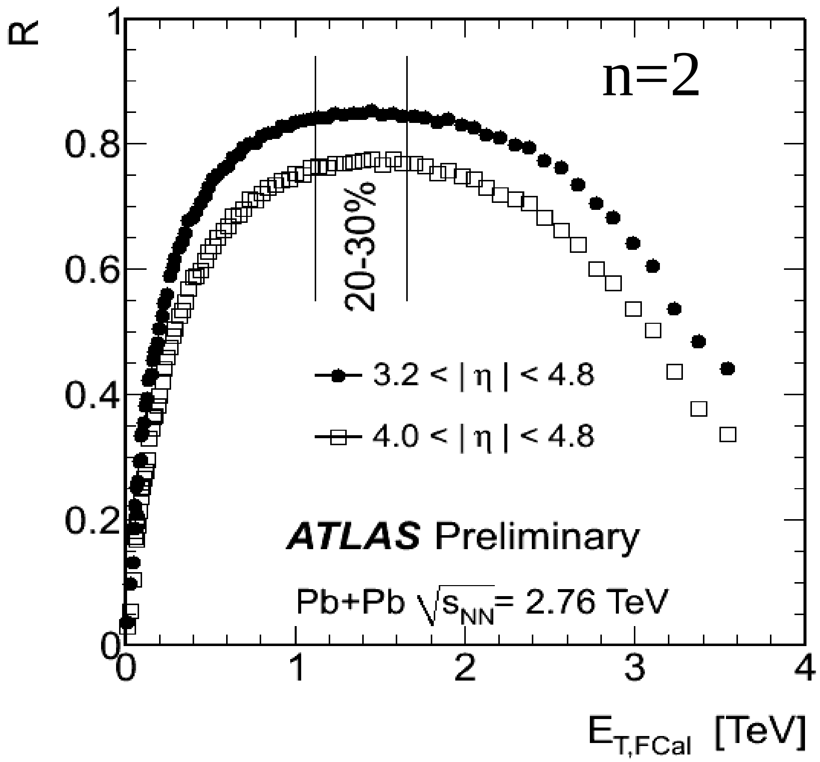


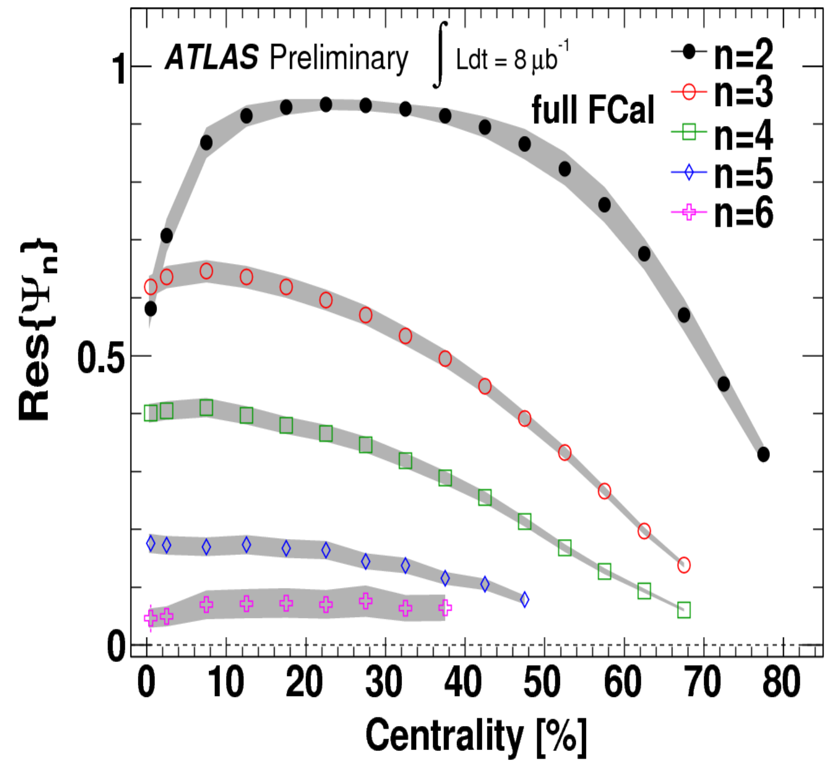


- What is the physics responsible for “ridge” and “cone” effects in 2-particle correlations?
  - Is due to jet-medium interactions or fluctuations+flow?

Event Plane Resolution

$$R \equiv \sqrt{\left\langle \cos\left[n\left(\Psi_n^N - \Psi_n^P \right) \right] \right\rangle}; \qquad v_n = \frac{v_n^{obs}}{Res\,\Psi_n}$$



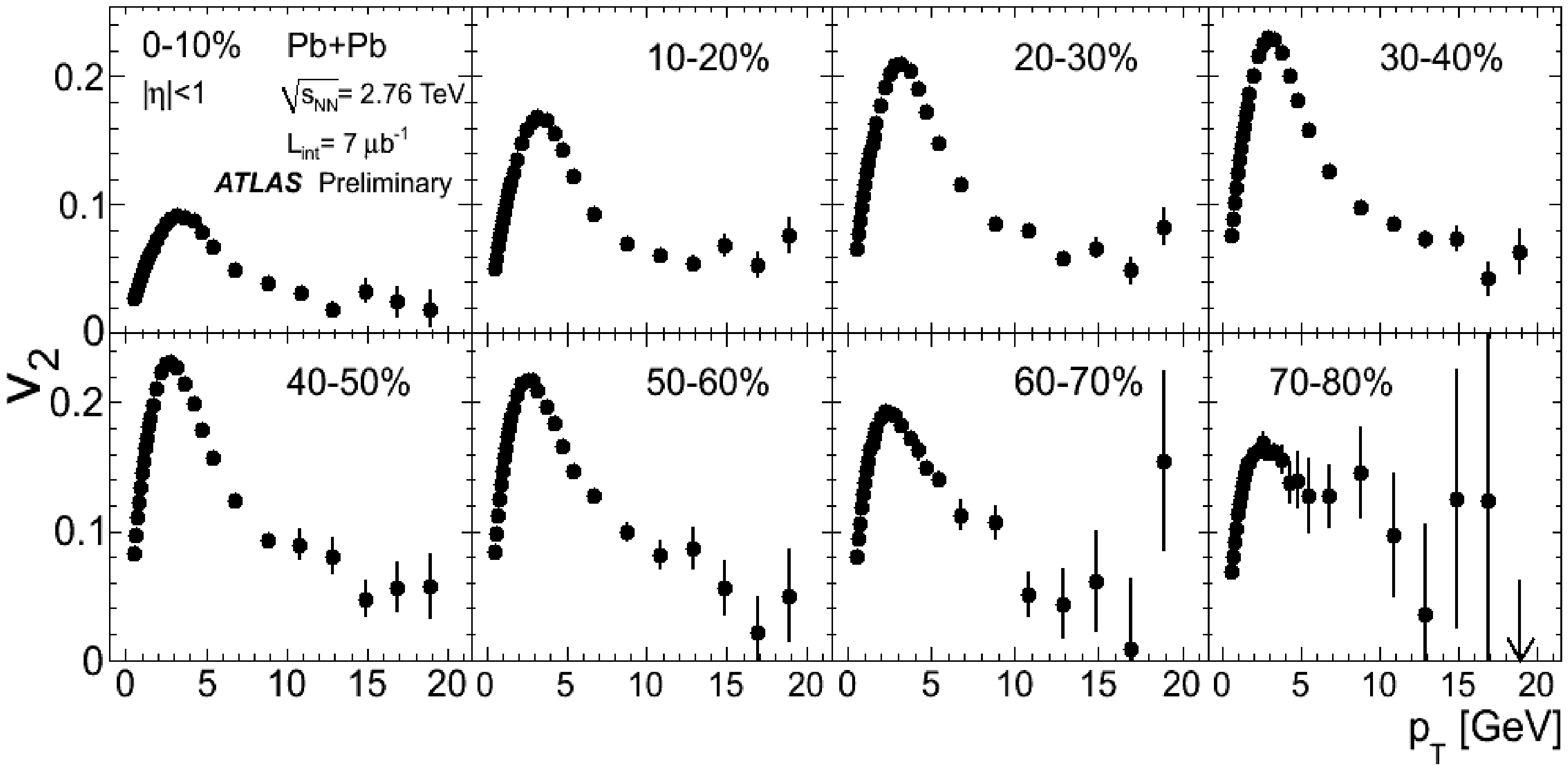


- Best resolution correction for v_2 is obtained in semi-central collisions and in full FCal acceptance

- Significant resolution for n=2-6
- Systematic errors estimated via 2-sub-event and several 3-sub-event methods

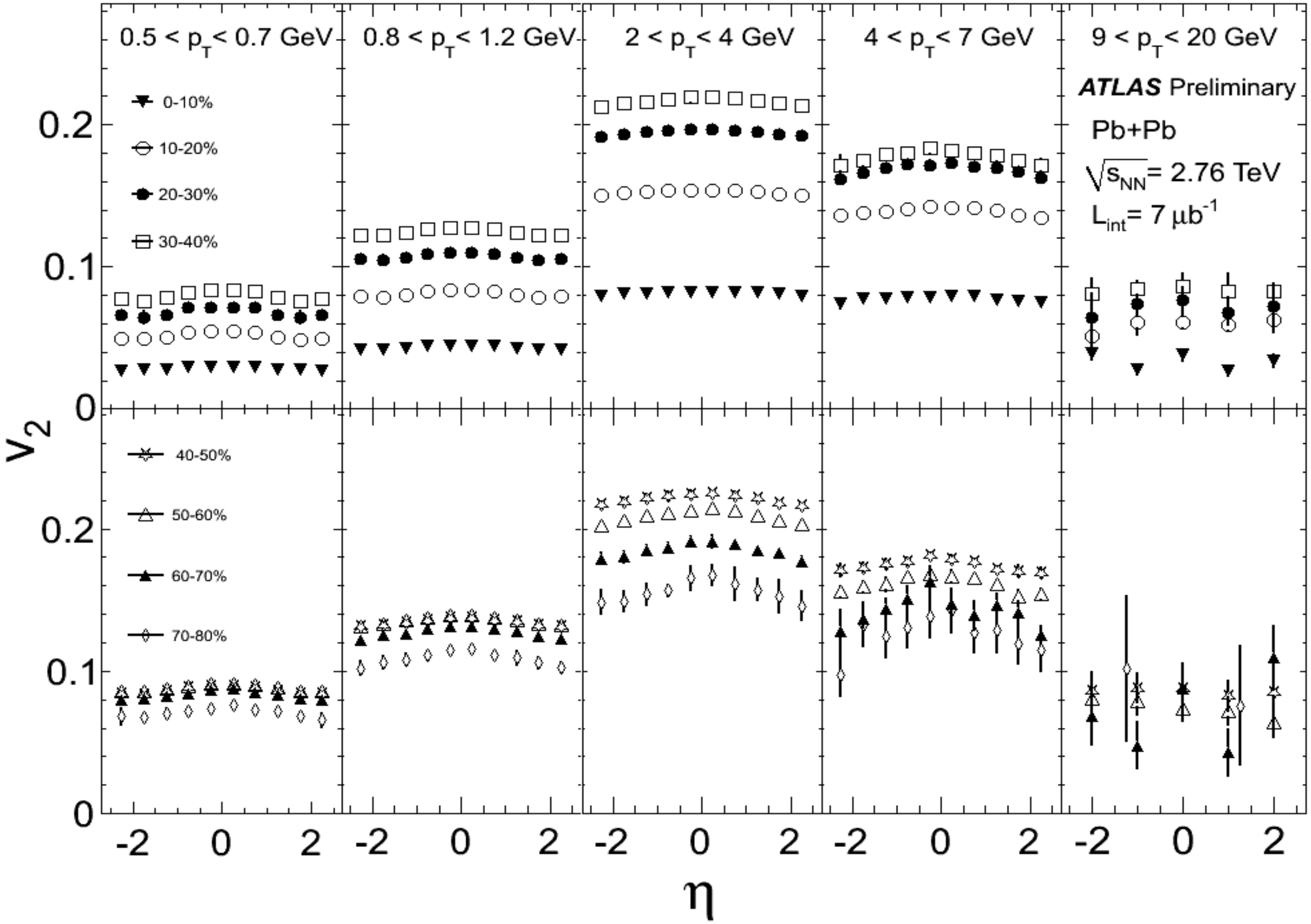
Elliptic Flow - v_2

Tracks within |η|<2.5 are correlated to the event plane, which has been measured using the FCAL sector in the opposite hemisphere – $FCAL_{P(N)}$ method



- Rapid rise of $v_2(p_T)$ up to p_T= 3 GeV; decrease down to 8 GeV
- Strongest elliptic flow is in mid-central collisions (30-40% and 40-50%)
- Weak p_T dependence beyond 8-10 GeV in central collisions

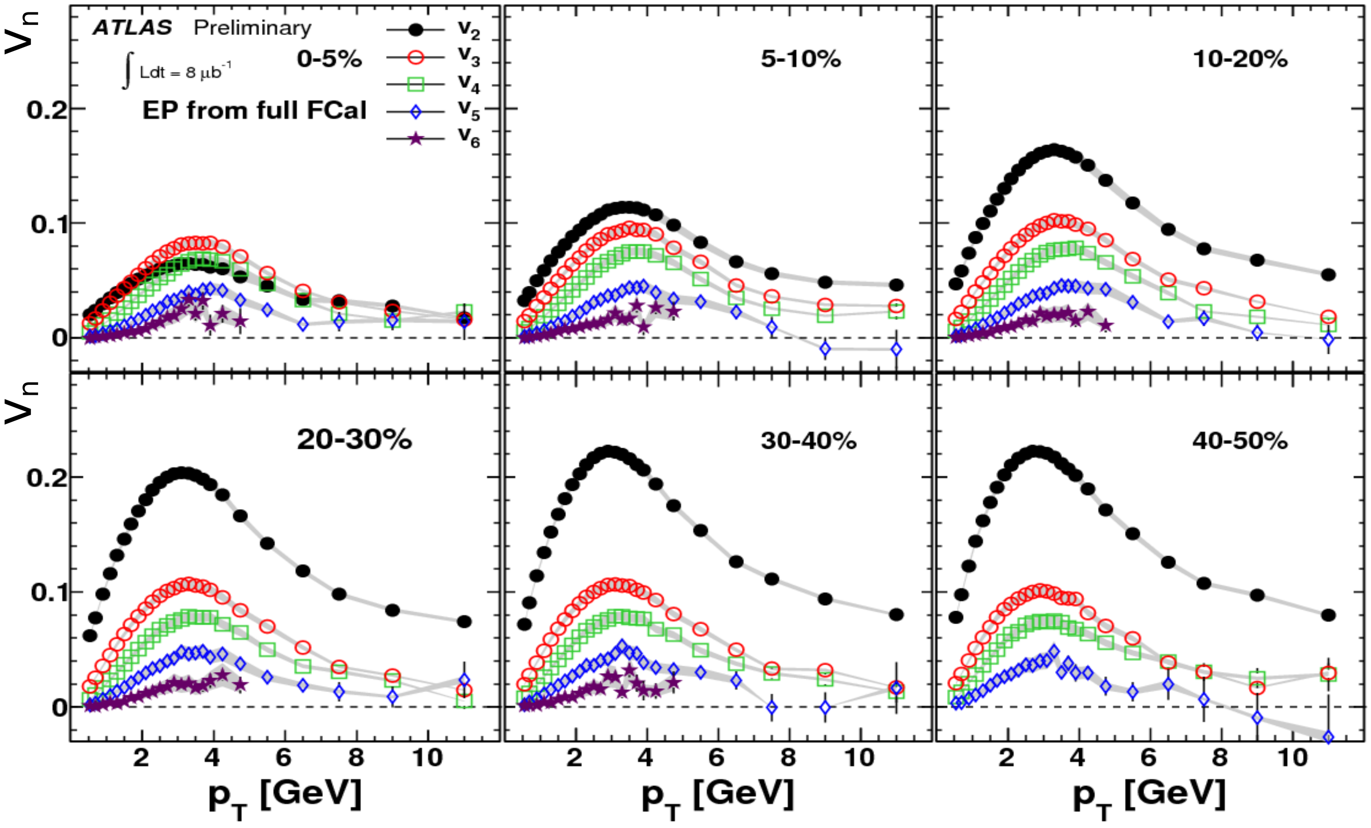
Pseudorapidity dependence of v_2



Weak dependence, as opposed to RHIC/PHOBOS where v_2 decreases by 30% from η=0 to 2.5 (but, p_T>0, while here p_T>500 MeV)

Higher-order Flow Coefficients

Higher Fourier harmonics, up to v_6, are extracted via event plane method

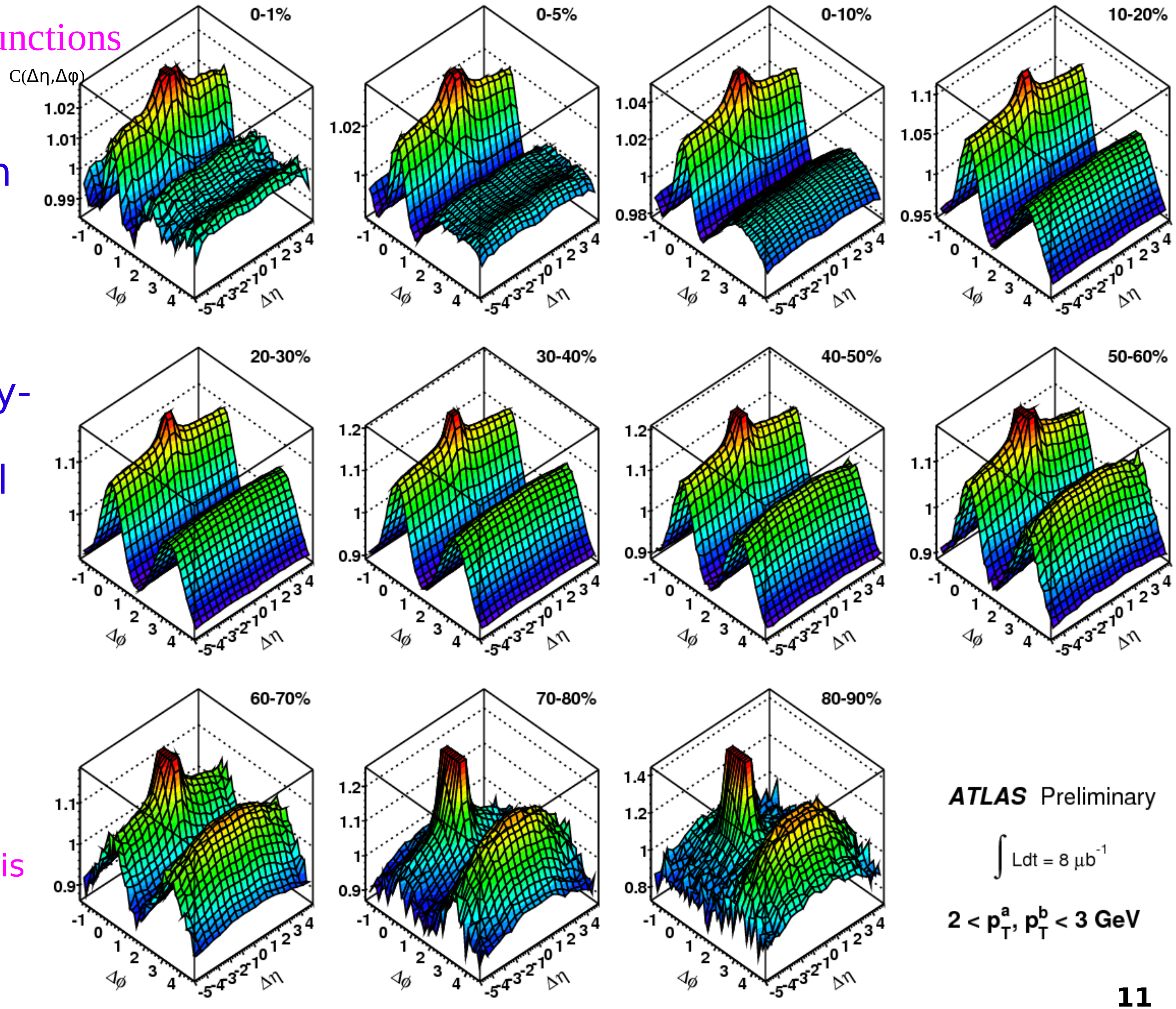


- Significant positive $v_2 - v_6$ are measured in broad range of p_T and centrality
- Strongest magnitude variations for v_2, which is lower than v_3 in 0-5% bin
- Similar p_T dependence for all measured amplitudes

The Rise and Fall of “ridge/cone”

2-particle correlation functions

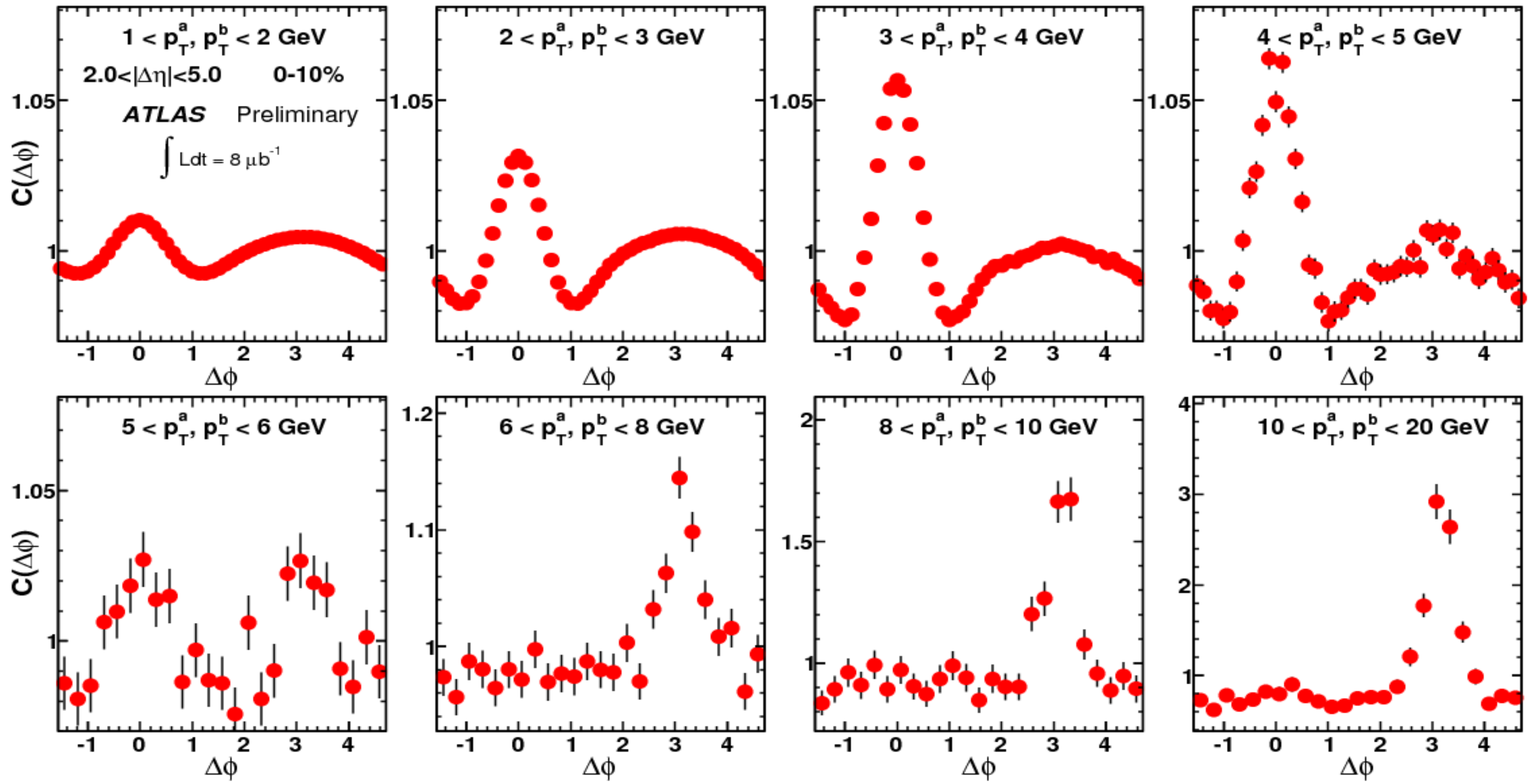
- Long and short range structures in central events
- Jet-related peaks appear in the away-side moving towards peripheral collisions



Near-side side jet peak is truncated from top to better reveal the long-range “ridge” structure

Rise and Fall of "ridge/cone" - p_T evolution

For the 0-10% centrality bin measure the p_T dependence of the "ridge/cone effect", for particles with large pseudorapidity gap, $|\Delta\eta| > 2$



- Strength of long range components first increase to 4-5 GeV then decrease
- The transition from flow-"dominance" to jet-"dominance" occurs at ~5-6 GeV

Leptonic Probes

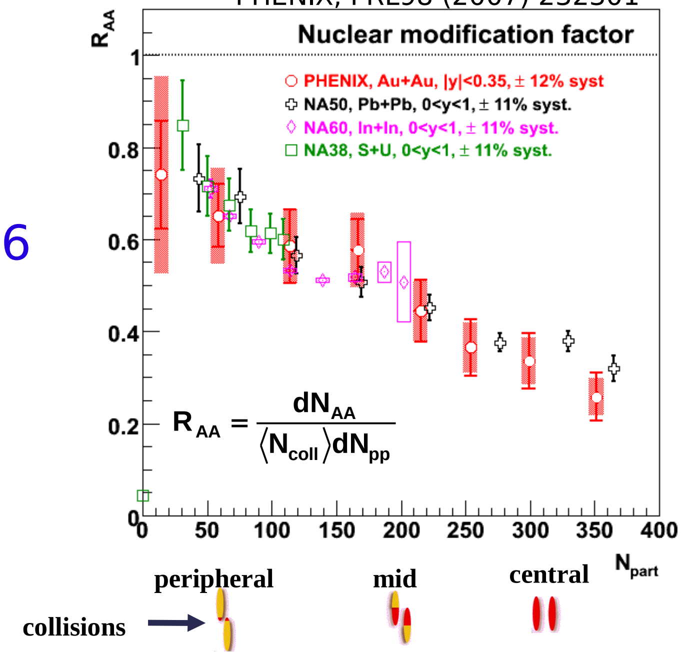
Quarkonia suppression is predicted by lattice QCD calculations

State	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

J/psi anomalous suppression by Debye colour screening was predicted by Matsui and Satz, 1986

R_{AA} was shown to be the same at SPS and RHIC

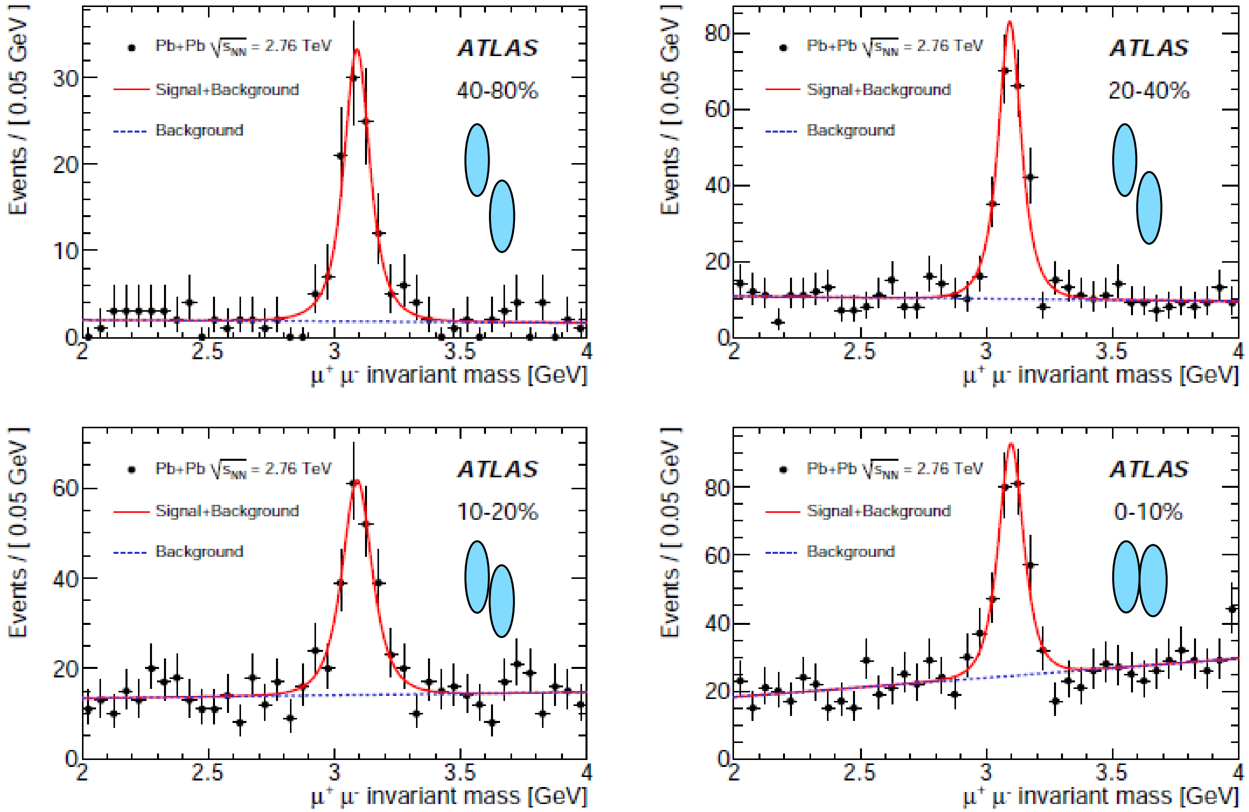
PHENIX, PRL98 (2007) 232301



How Z and W bosons are affected by the hot and dense medium? They were never observed in pre-LHC Heavy Ion Collisions…

Inclusive J/psi Production

Phys.Lett.B697:294-312,2011



- J/psi → $\mu^+\mu^-$ channel explored
- Integrated luminosity analysed: 7 μb^{-1}

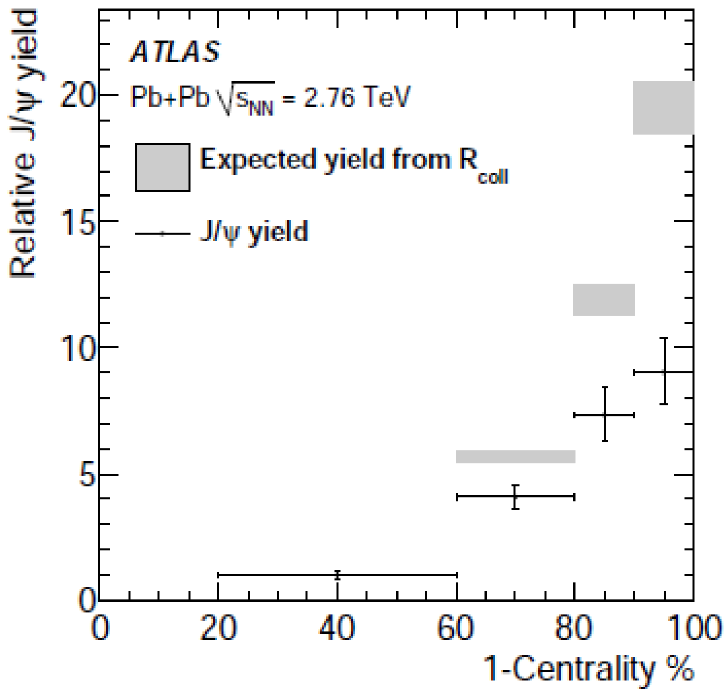
- Muons combined in the Inner Tracker and Muon Spectrometer with p_T>3 GeV and $|\eta|$<2.5
- J/psi yields in each centrality bin are obtained with a sideband technique. (fits are just for cross check)
- J/psi mass window: 2.95—3.25 GeV

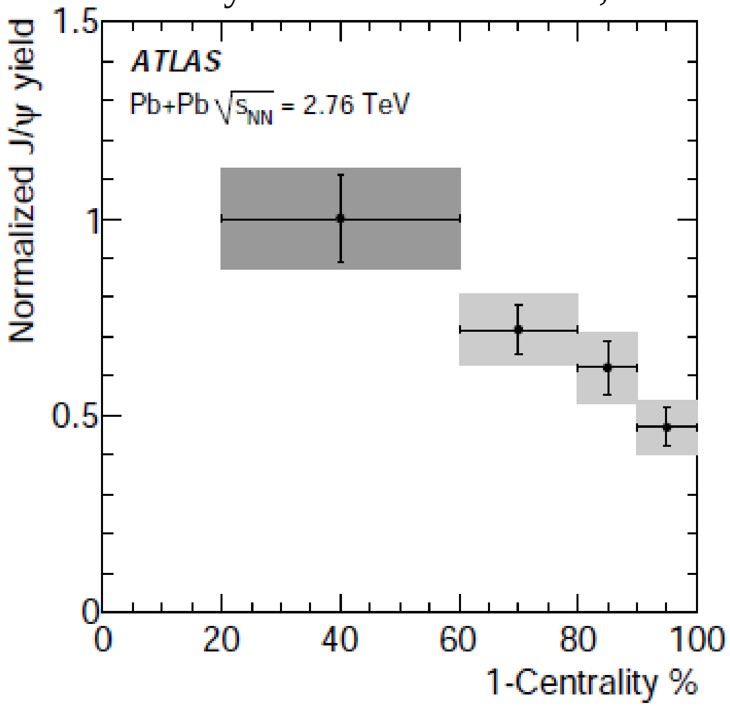
J/psi Suppression

- Relative J/psi yield = $N_{cbin}/N_{40\text{-}80\%}$;
- Normalized J/psi yield = $(N_{cbin}/N_{40\text{-}80\%}).(N_{coll,40\text{-}80\%}/N_{coll,cbin})$

(All bins are corrected for reconstruction efficiencies and bin width)

Phys.Lett.B697:294-312,2011





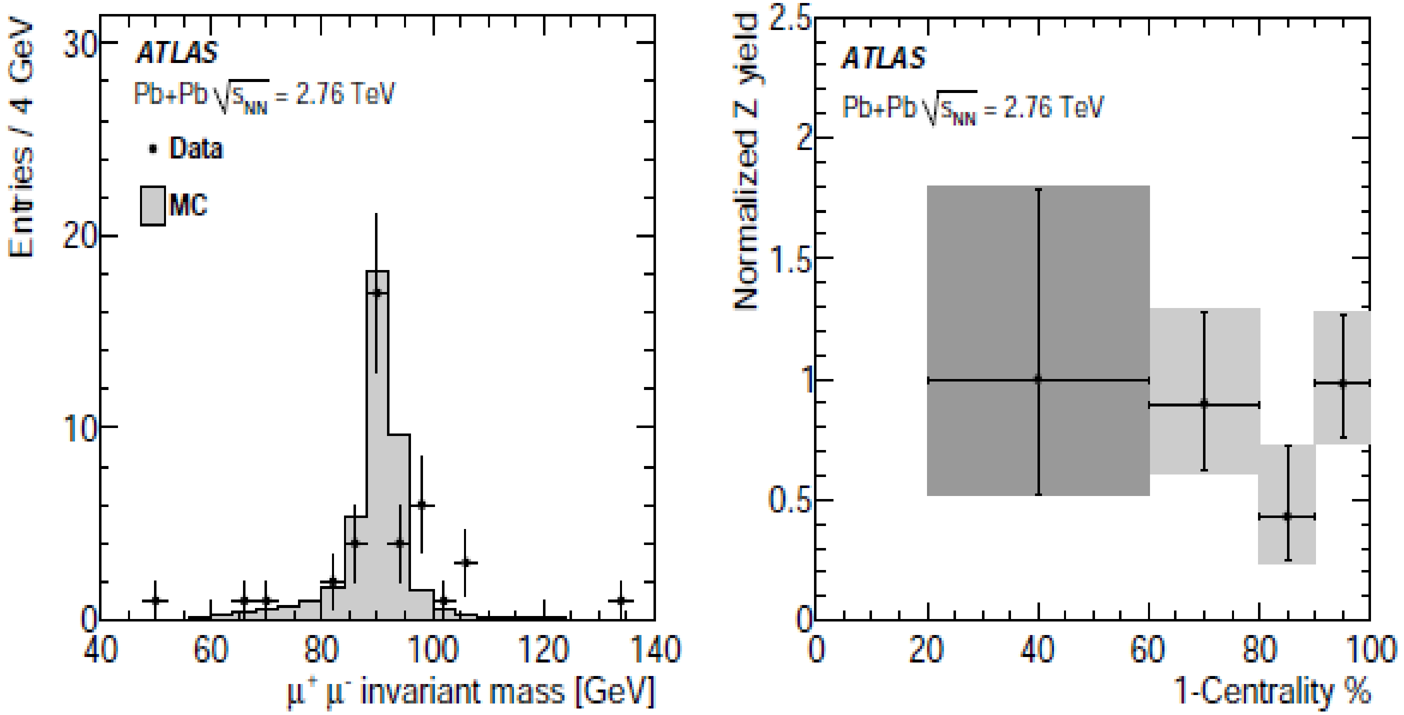
J/psi yield significantly decreases from peripheral to central collisions

Similar trending in LHC, RHIC and SPS

Z Production

- Z → $\mu^+\mu^-$ channel explored
- Integrated luminosity analysed: 7 μb^{-1}

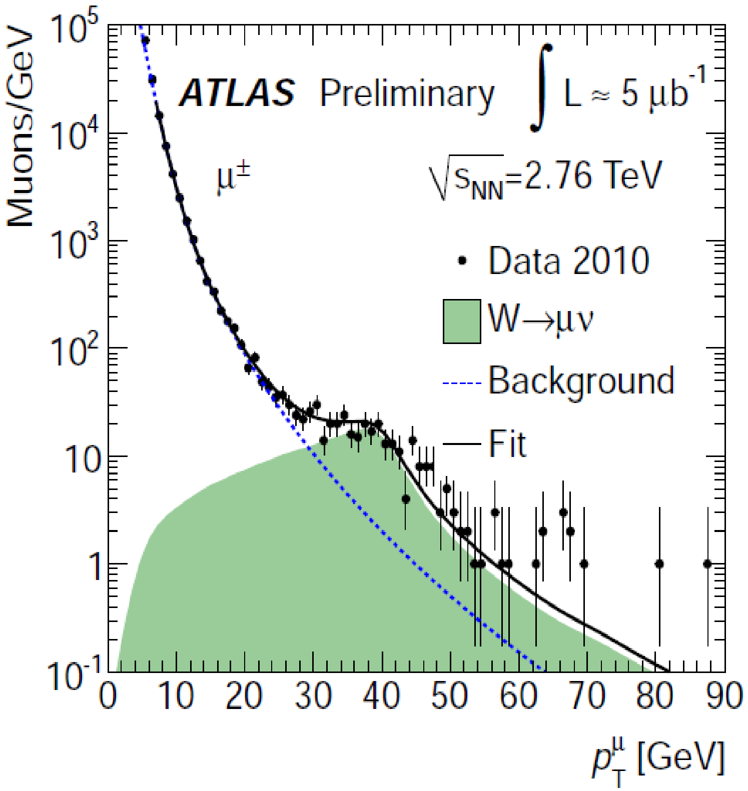
Phys.Lett.B697:294-312,2011

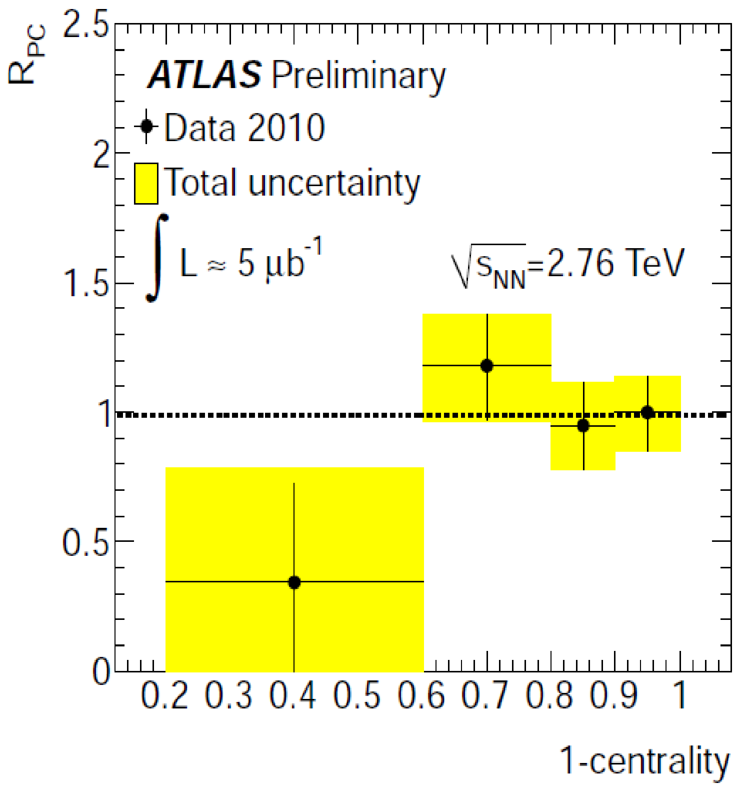


- Muons combined in the Inner Tracker and Muon Spectrometer with p_T>20 GeV and $|\eta|$<2.5
- 38 candidates in the mass window 66-116 GeV

Not enough statistics to draw conclusions on the normalized yield

W Production





- Veto dimuons with $m_{\mu\mu}$>60 GeV (DY & Z candidates) and decays in flight
- Build a template from W → μν MC@2.76 TeV pp
- use a function to describe background
- Find the best estimate of the number of W

R_{pc} result is consistent with no W suppression, as expected
⇒ W bosons yields for a given centrality are a direct measure of N_{coll}

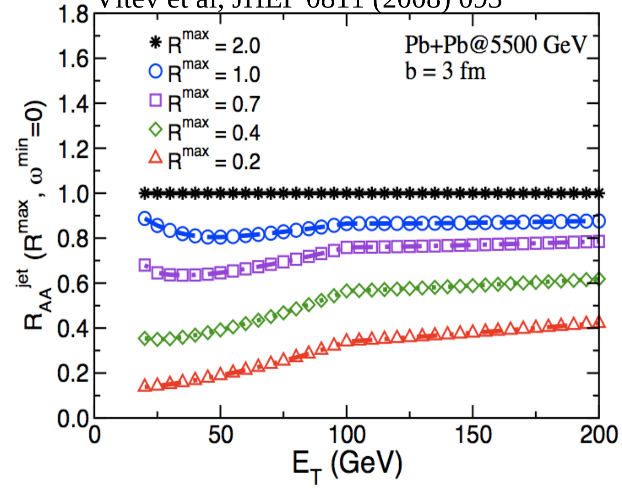
Jets in Pb+Pb Collisions

Expectations from models:

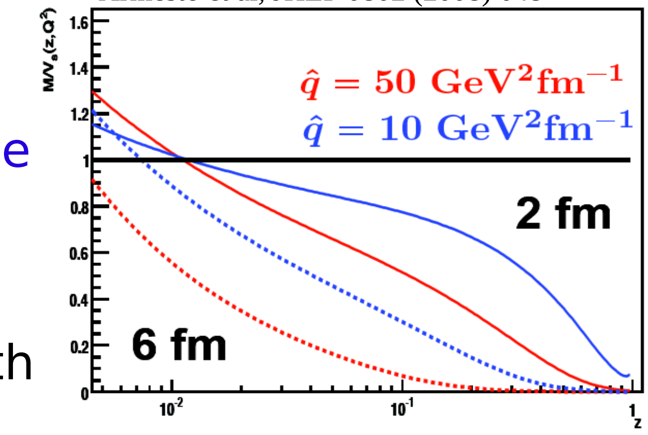
- Medium-induced radiation may cause energy deposition outside jet cone

- Predictions of radiative energy loss suggest energy can be recovered by expanding jet cone

Vitev et al, JHEP 0811 (2008) 093



Armesto et al, JHEP 0802 (2008) 048



- High z region of fragmentation function sensitive to medium induced radiation

Jets are reconstructed using anti-k_T algorithm with two choices of R parameter (R=0.4 and R=0.2)

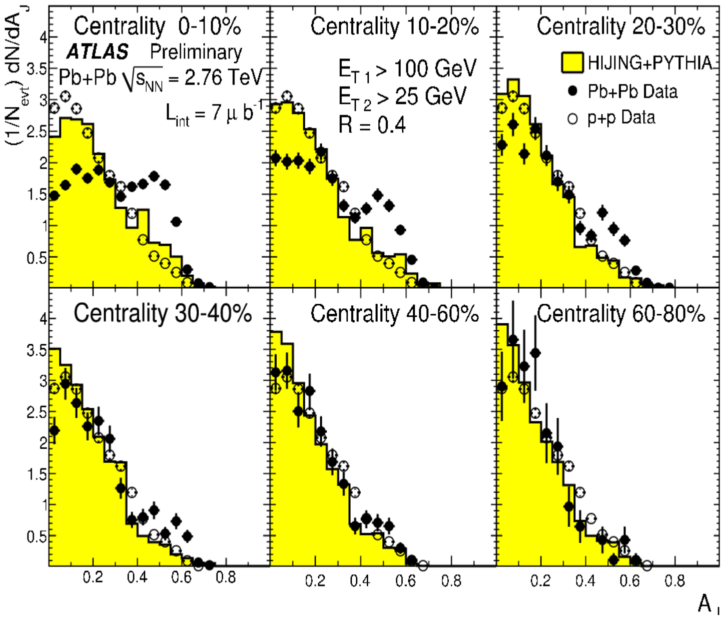
- Inputs are 0.1x0.1 ($\Delta\eta$x$\Delta\phi$) calorimeter towers
- Average background estimated event-by-event per calorimeter sampling layer and per 0.1 η strip

Di-jet Asymmetry

- Enhancement of asymmetric di-jets, relatively to p+p and PYTHIA+HIJING
  → first indication of jet suppression

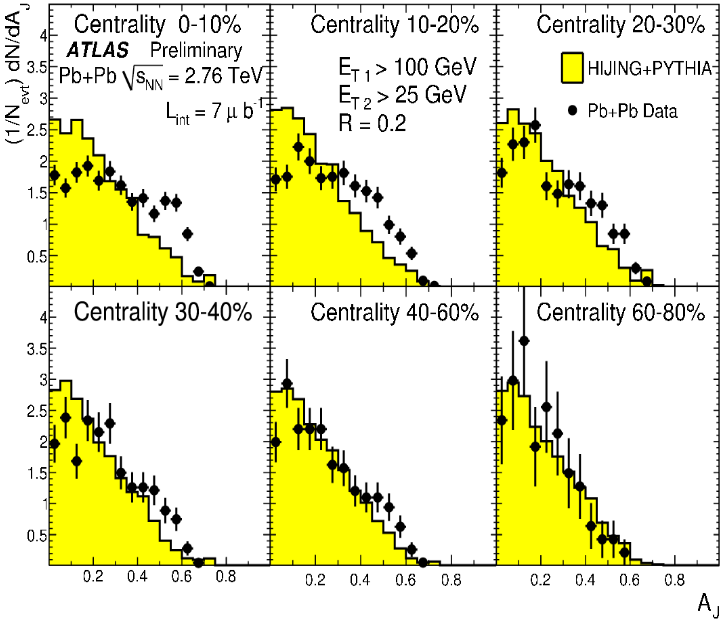
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \qquad E_{T1} > 100\,GeV \qquad E_{T2} > 25\,GeV$$

- Flatter distribution for R=0.2 jets



$|\eta| < 2.8$

R=0.4

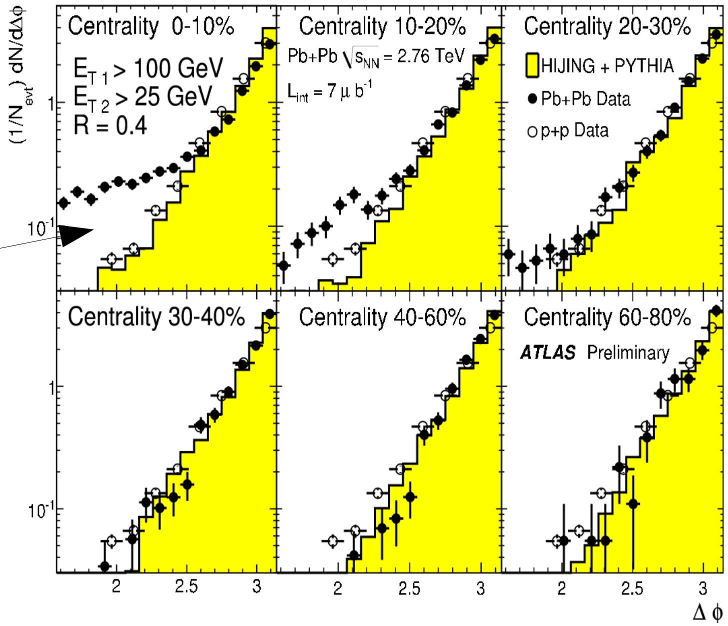


R=0.2

Di-jet Azimuthal Correlation

$\Delta\phi=\pi$ acoplanarity remains, while A_J is changing

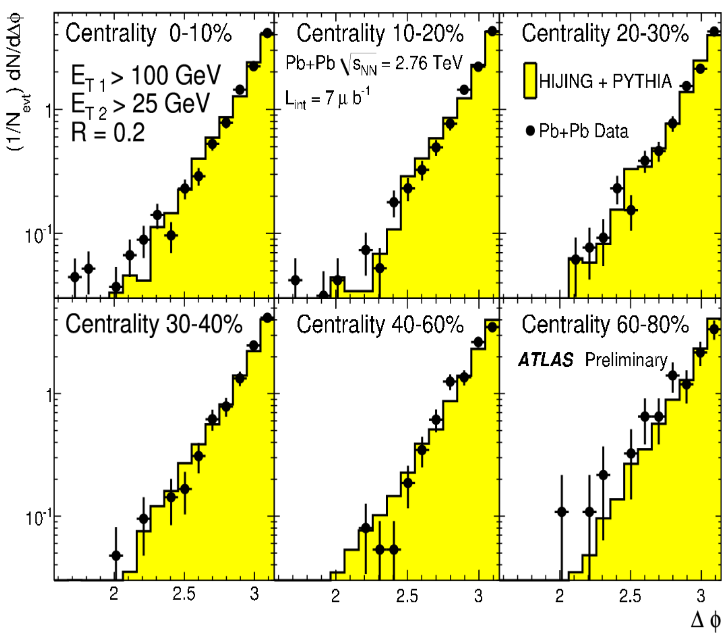
- Consistent with combinatoric contribution to R=0.4 di-jet $\Delta\phi$ distribution
  - 2nd jet "missing" and uncorrelated jet used



$|\eta|< 2.8$

R=0.4

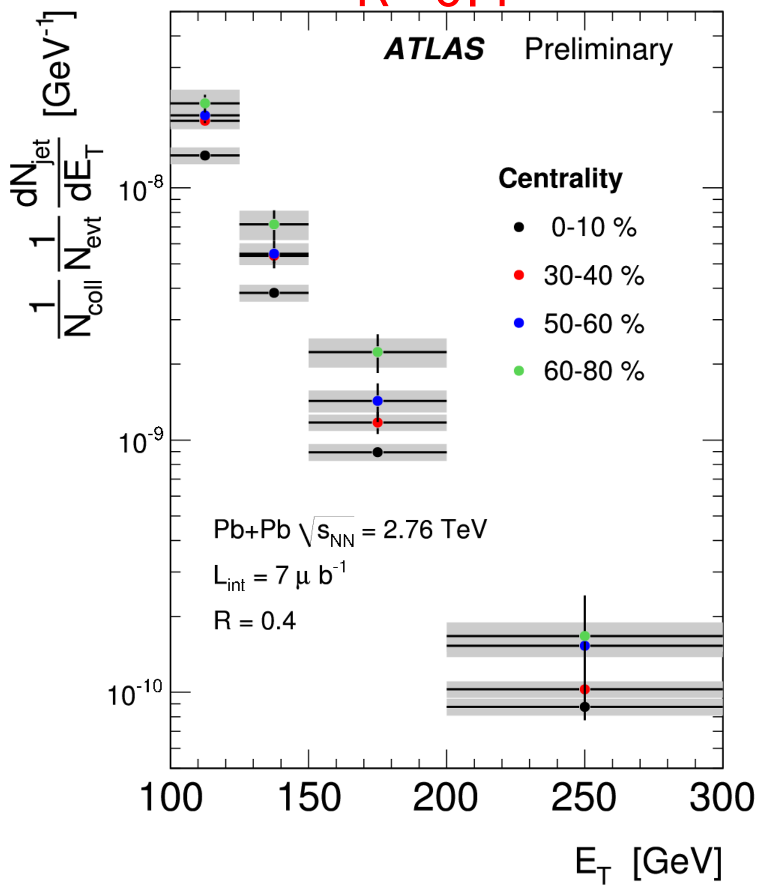
- But, combinatoric contribution much smaller for R=0.2
  - Yet, equally strong asymmetry modification



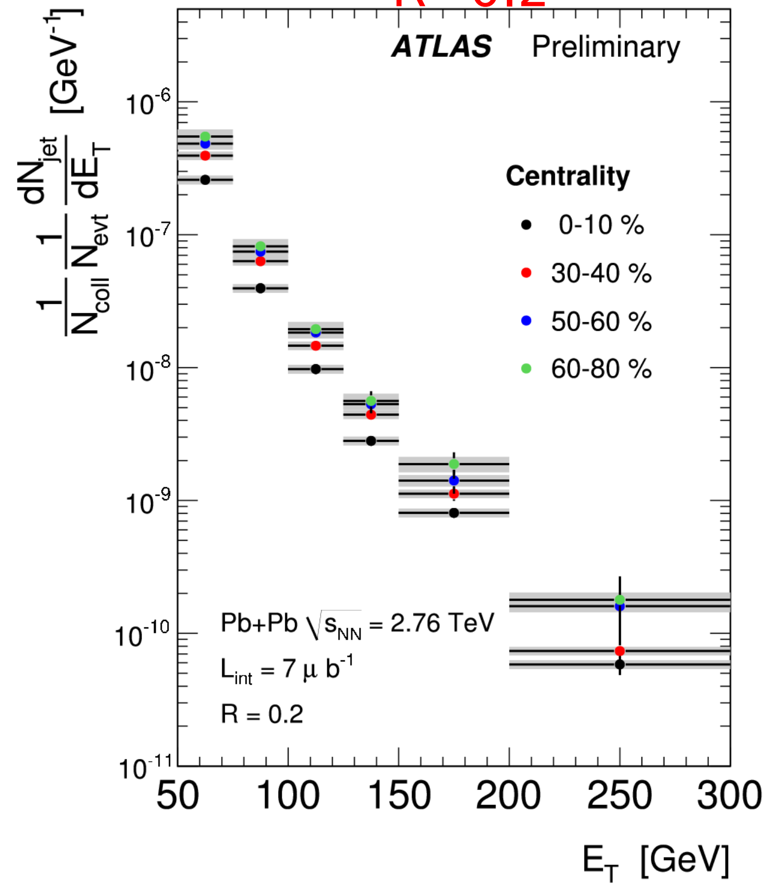
R=0.2

p_T Spectra of R=0.4 & 0.2 Jets

R=0.4



R=0.2

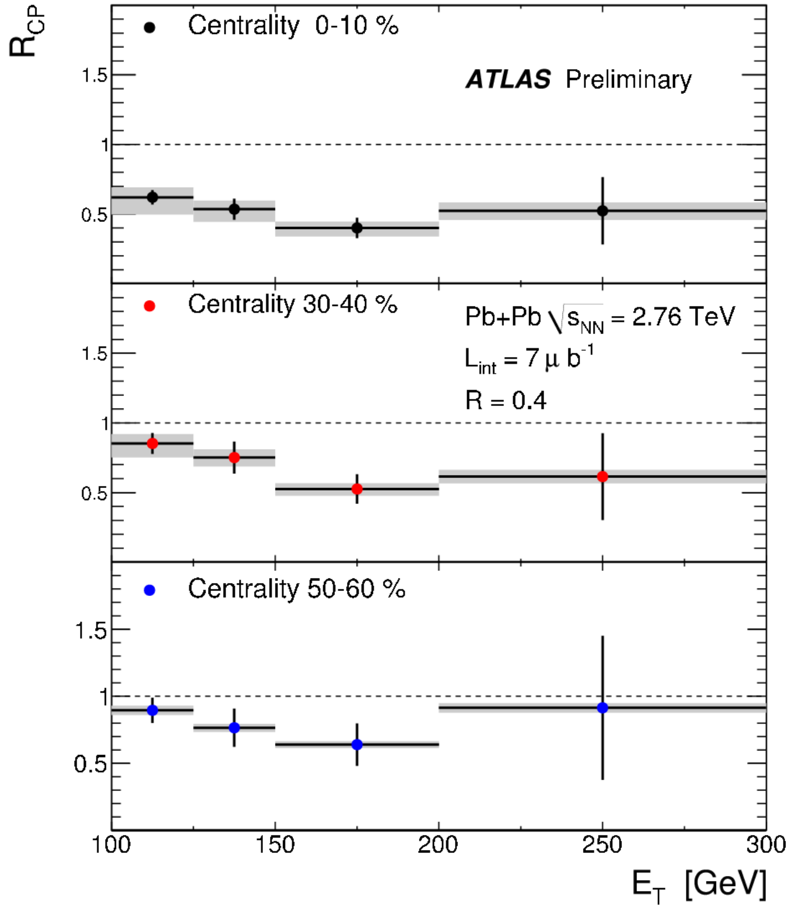


- Jet energy resolution is dominant in E_T and centrality dependent systematic uncertainty
- Systematic errors on N_{coll} estimates up to 8% in the most central bin
- Centrality independent systematic error of 22% in the normalization due to 4% jet energy scale uncertainty (not shown)

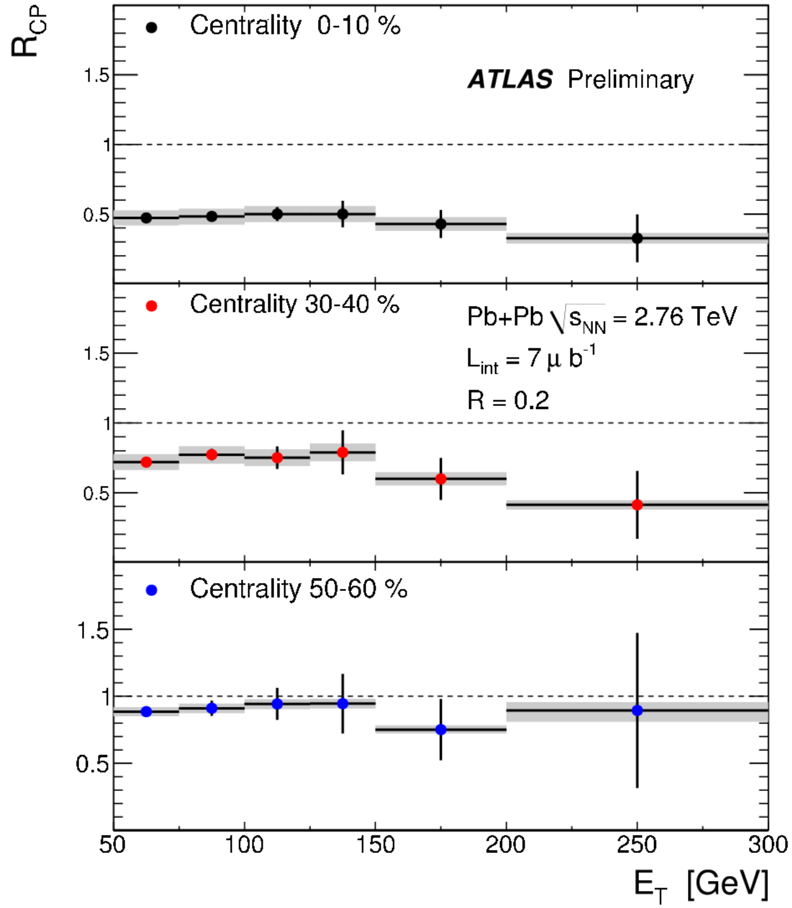
R_{CP} versus E_T and Centrality

Reference is the jet yield in the 60-80% centrality interval

R=0.4



R=0.2

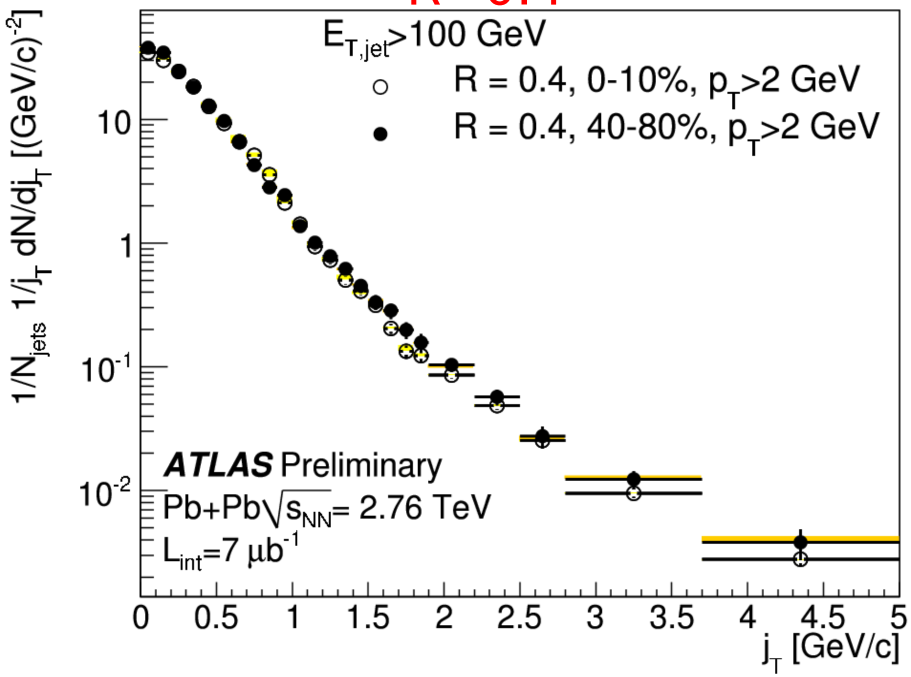


- Increasing jet suppression with centrality, up to a factor of 2 in the most central collisions, well beyond statistical and systematic errors
- Suppression not dependent on the reported E_T and on jet size

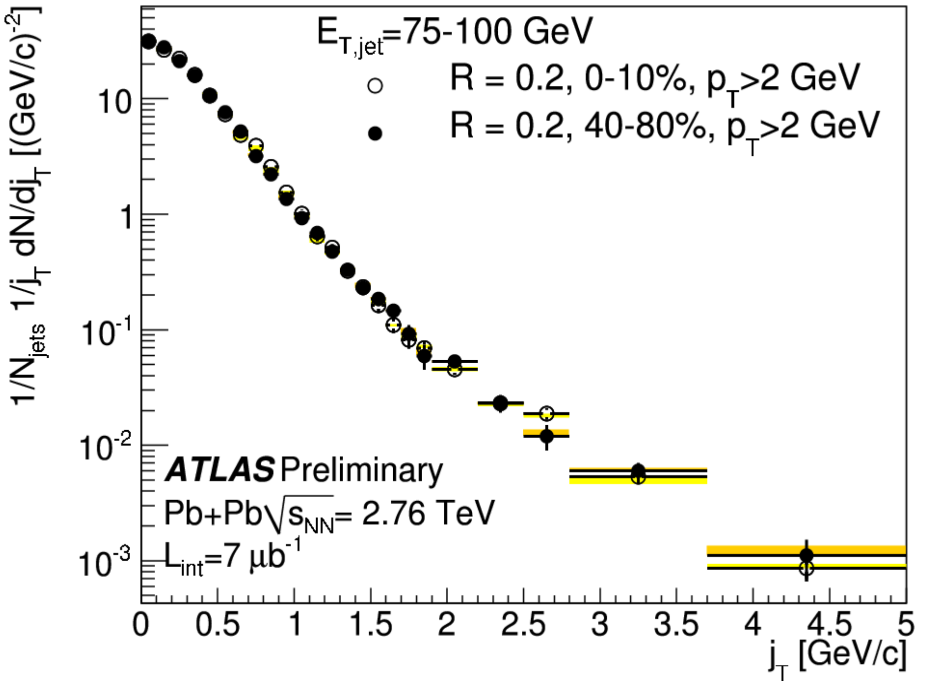
Jet Fragmentation - j_T

Measure the p_T of the fragments normal to the jet axis

R=0.4

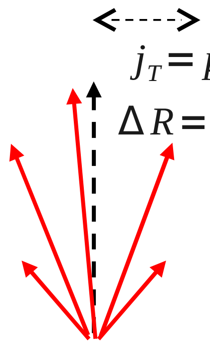


R=0.2



- Not unfolded for angular resolution

transverse structure



$$j_T = p_T^{had} \sin \Delta R$$

$$\Delta R = \sqrt{(\eta^{had} - \eta^{jet})^2 + (\phi^{had} - \phi^{jet})^2}$$

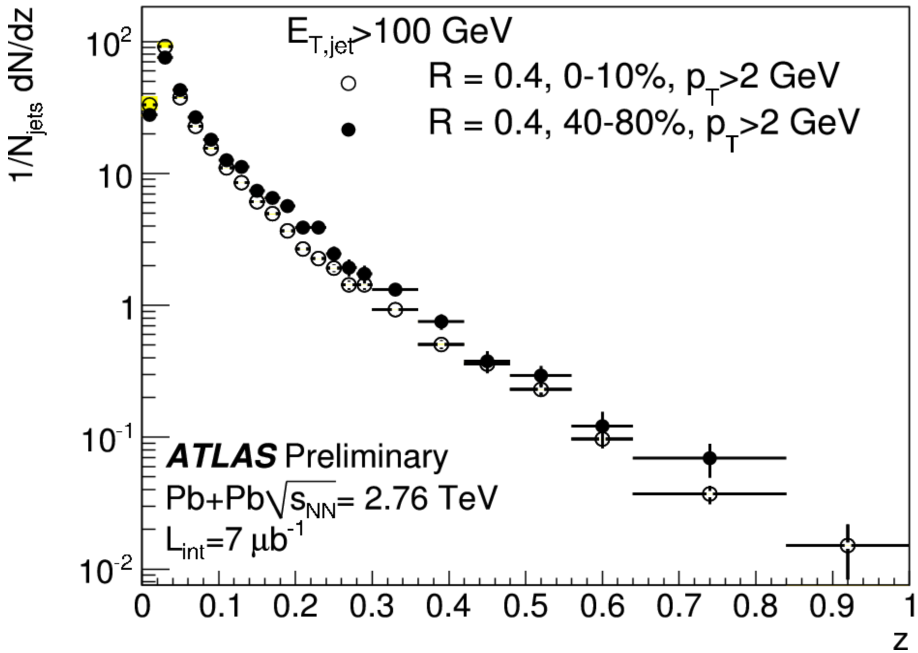
All charged particles with p_T>2 GeV

Compare central to peripheral collisions → lack of broadening

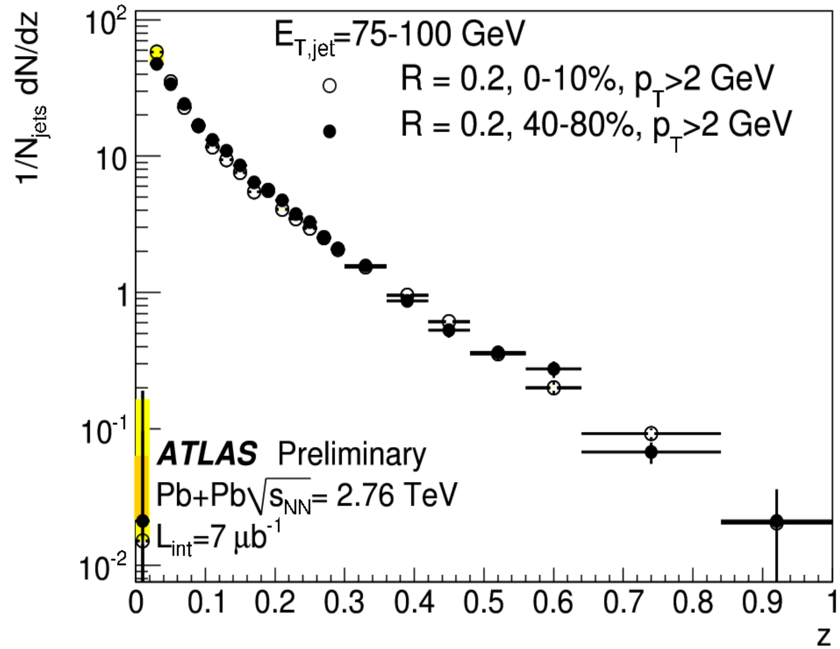
Jet Fragmentation - D(z)

Measure the p_T of the fragments parallel to the jet axis

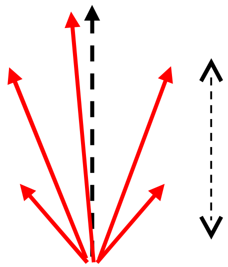
R=0.4



R=0.2



longitudinal structure



$$z \equiv \left(\frac{p_{T,had}}{E_{T,jet}}\right) \cos \Delta R$$

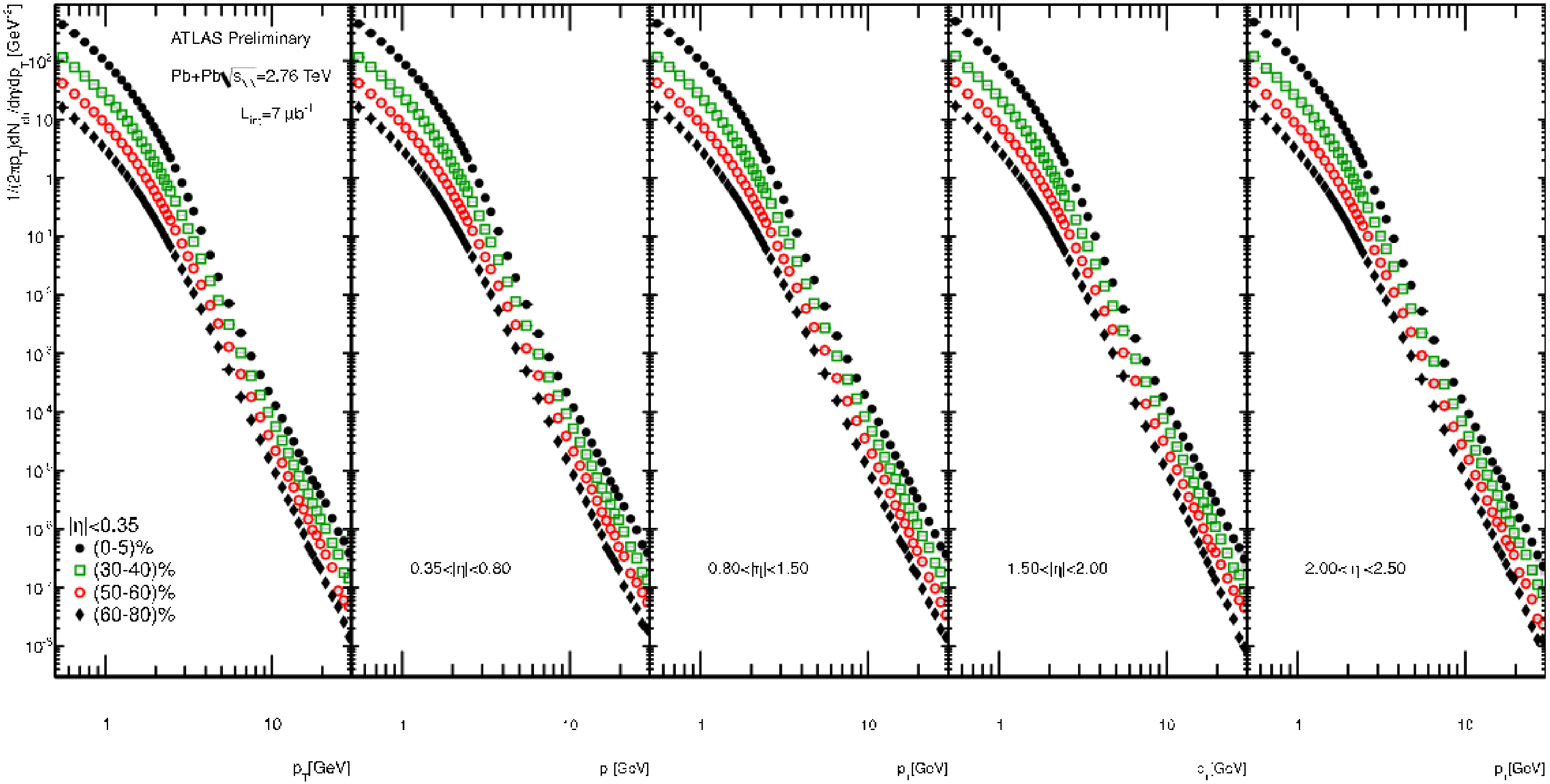
Weak D(z) modification in central collisions relative to peripheral

- ~20%, not dependent on z, for R=0.4 jets
- ~20% in z~0.1-0.3 for R=0.2

Results do not confirm the expectations

Charged Hadron p_T Spectra

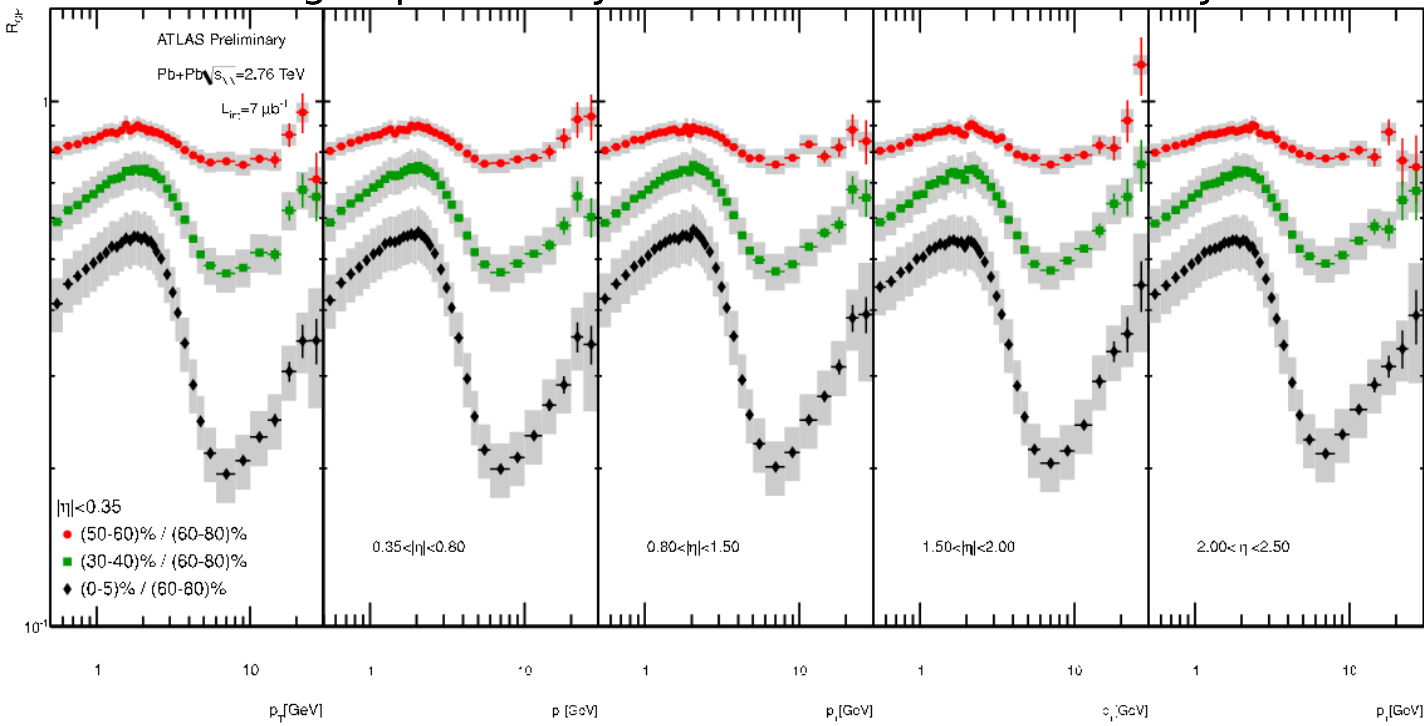
Strongly related to the observed jet suppression



- Corrected for efficiency, secondaries, fakes and resolution
- Cutoff at 30 GeV due to systematic differences in track errors (σ_{d0} and $\sigma_{z0\sin\theta}$) between data and MC (under investigation)

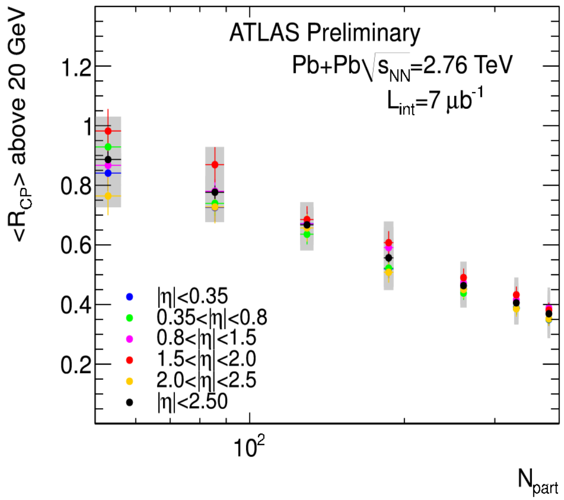
Charged Hadron R_{cp}

Reference is the charged particles yield in the 60-80% centrality interval



- Strong suppression is seen in more central events, 0-5%
- No η dependence is observed

- Centrality pattern for hadrons with p_T>20 GeV resembles jet R_{cp}



Highlights from the 2010 Pb+Pb Run

Global observables:

- Centrality dependence of inclusive multiplicity scales with beam energy
- Elliptic flow and higher harmonics show similar p_T, η and centrality behaviour
- The long range “ridge” and “cone” structures in two-particle correlation function at low p_T can be explained by flow effects

Leptonic probes:

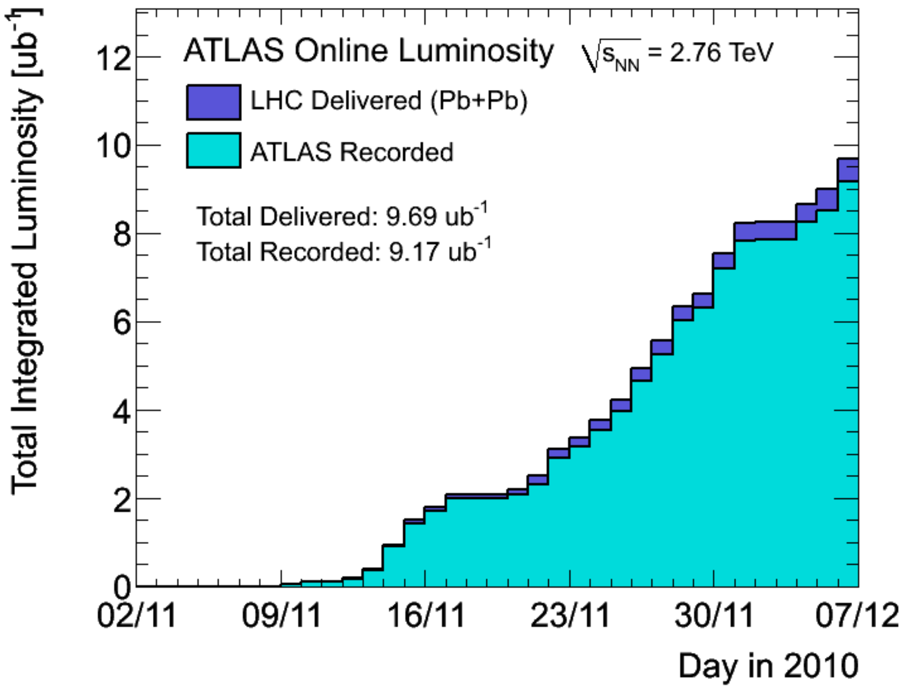
- J/psi suppression pattern similar at LHC, RHIC and SPS
- Z and $W^{\pm}$ productions consistent with simple scaling with N_{coll}

High p_T observables:

- Jet production suppressed by a factor of 2 in central collisions
- Weak modifications of z and j_T fragment distributions
- Charged hadron R_{cp} is measured out to 30 GeV; centrality dependence of suppression similar to jets

Backup

2010 Pb+Pb Run



First heavy ion run:

- $\sqrt{s_{NN}}$ = 2.76 TeV
- Nov 7th - Dec 6th, 2010
- ATLAS recorded 9.17 μb^{-1} of Pb+Pb data
- Data recording efficiency > 95%

Fraction of data passing data-quality criteria > 99%

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.7	100	100	99.2	100	100	100	100	99.6	100	100

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in PbPb collisions at $\sqrt{s_{NN}}$=2.76 TeV between November 8th and 17th (in %).

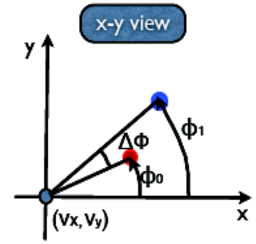
Tracking Methods

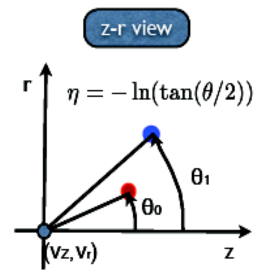
Two methods used:

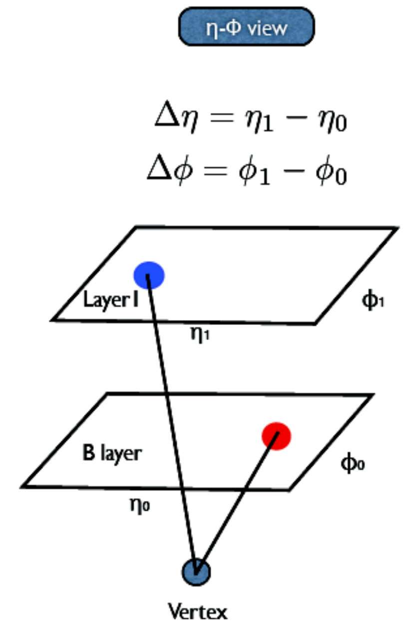
1 – Kalman Filter based tracking algorithm - ATLAS standard

2 - “Two-point tracklets”
Select high quality clusters
Select cluster pairs aligned with primary vertex:

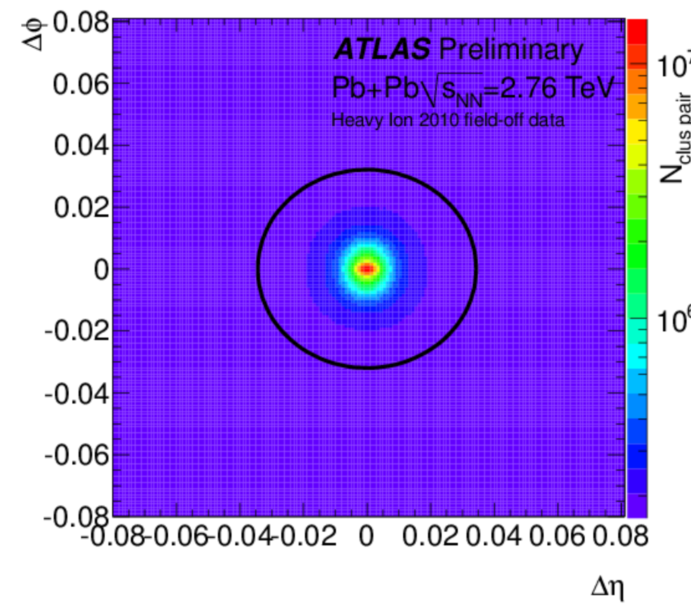
$$\sqrt{\left(\frac{\Delta\eta}{\sigma_{\Delta\eta}}\right)^2 + \left(\frac{\Delta\phi}{\sigma_{\Delta\phi}}\right)^2} < 3 * \sqrt{2}$$



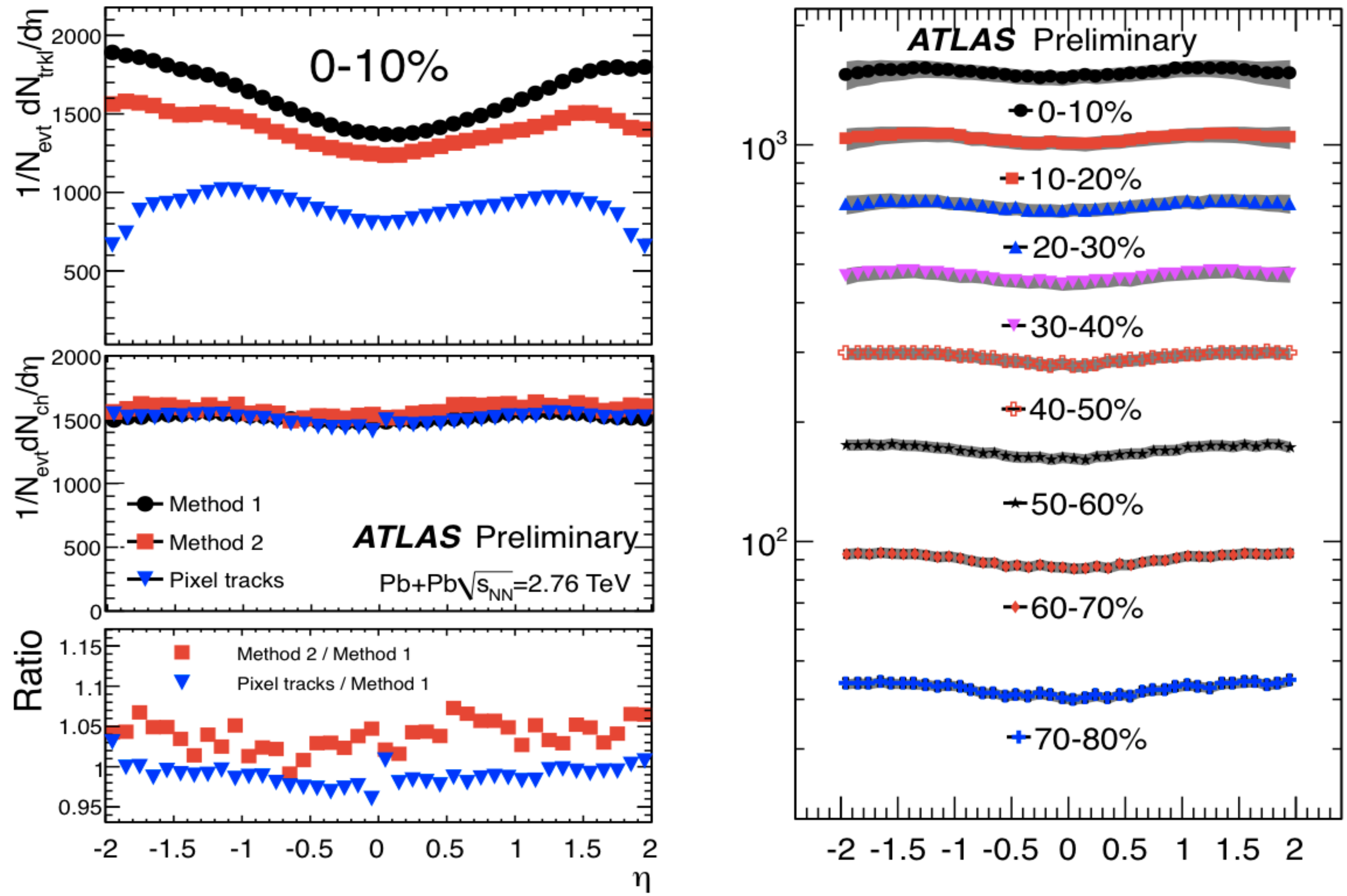




ΔΦ vs Δη for all layer-0 and layer-1 pixel clusters pairs



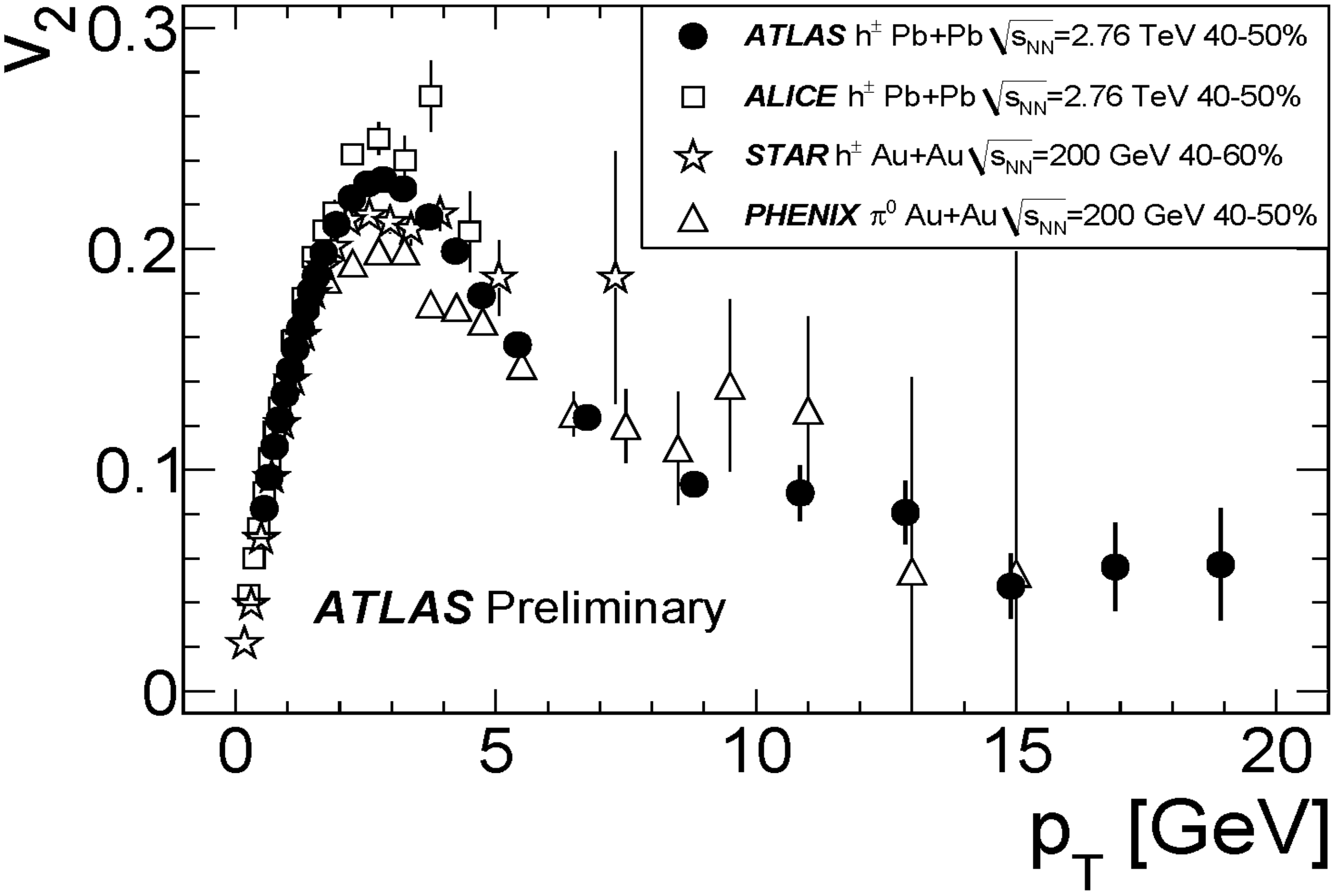
$dN_{trk}/d\eta$ distributions



Raw (top) and corrected (middle) $dN^{trk}/d\eta$ using “two-point tracklets” and pixel tracking

5% increase from η=0 to η=1
Not sensitive to centrality

V_2 – Comparisons



Jet Reconstruction

- Underlying event estimated and subtracted for each longitudinal layer and for 100 slices of $\Delta\eta = 0.1$:

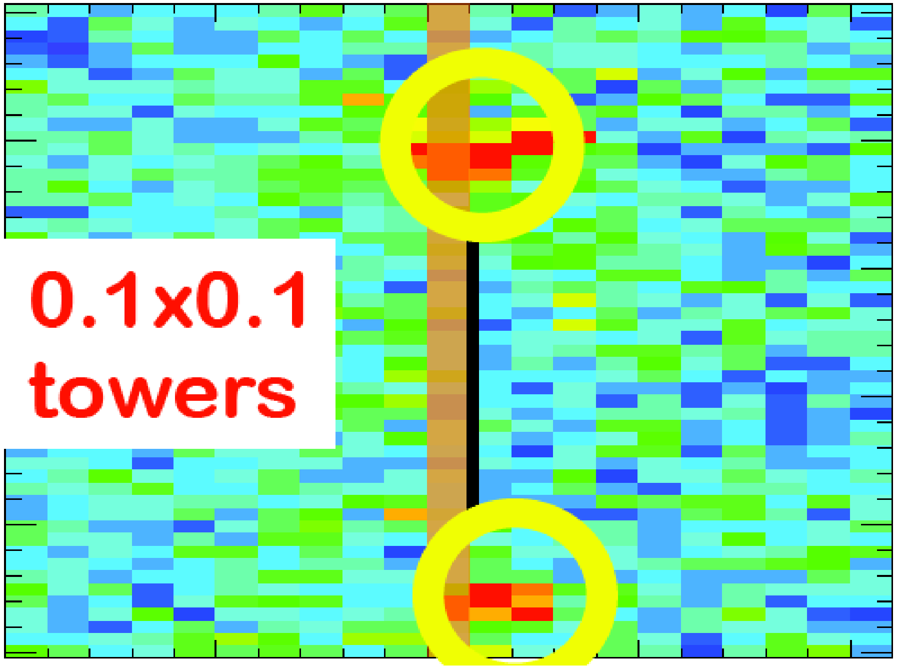
$$E_{T,subt}^{cell} = E_T^{cell} - \rho x A^{cell}$$

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

- Two methods to avoid biasing ρ due to jets

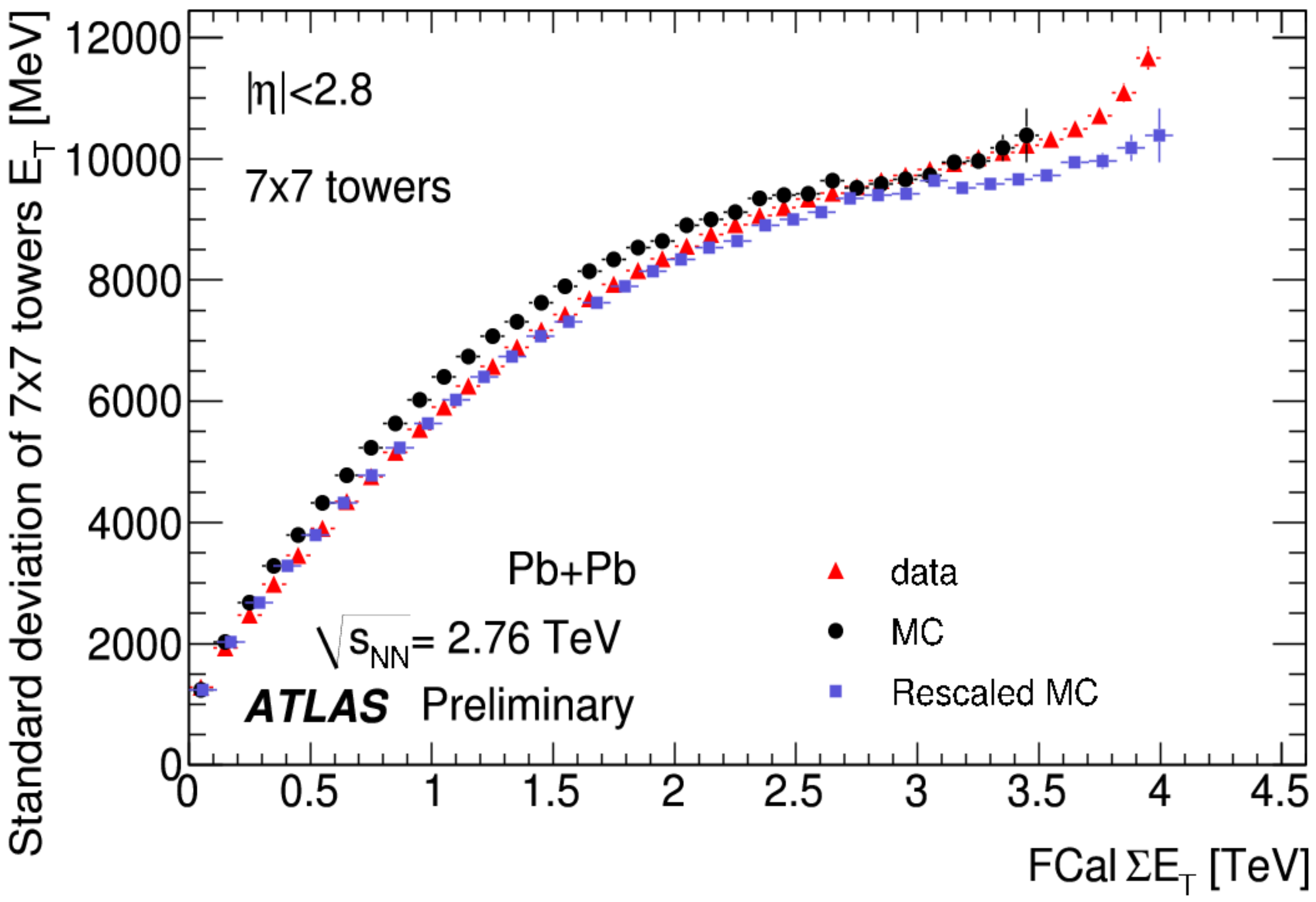
  1 - Sliding window exclusion
  2 - Exclude cells in jets satisfying

$$D = E_{T,max}^{tower} / \langle E_T^{tower} \rangle > 5$$



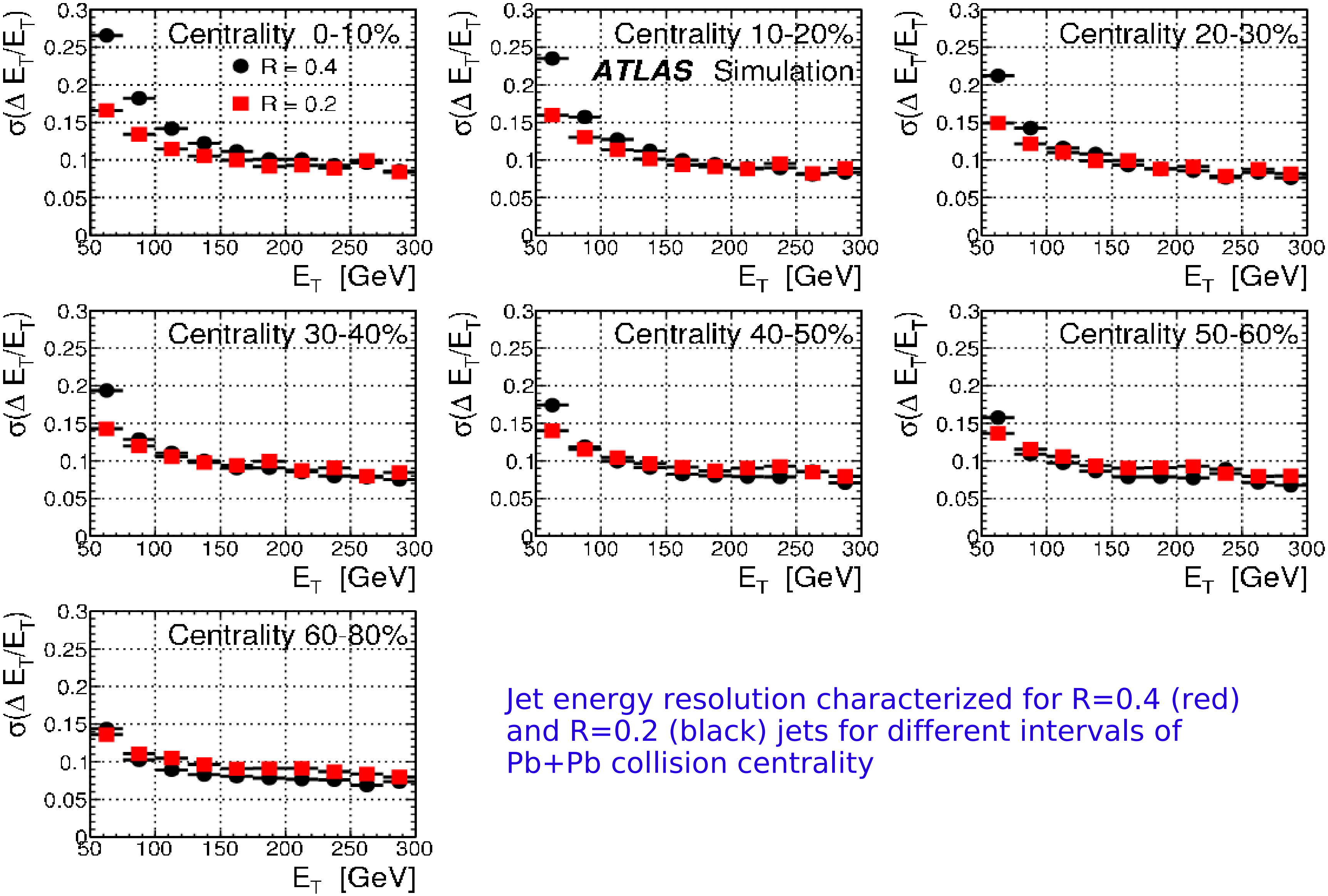
- For R = 0.4, add an iteration step to ensure jets with E_T>50 GeV are always excluded from ρ estimate
- Correct for underlying event v_2

Calorimeter fluctuations



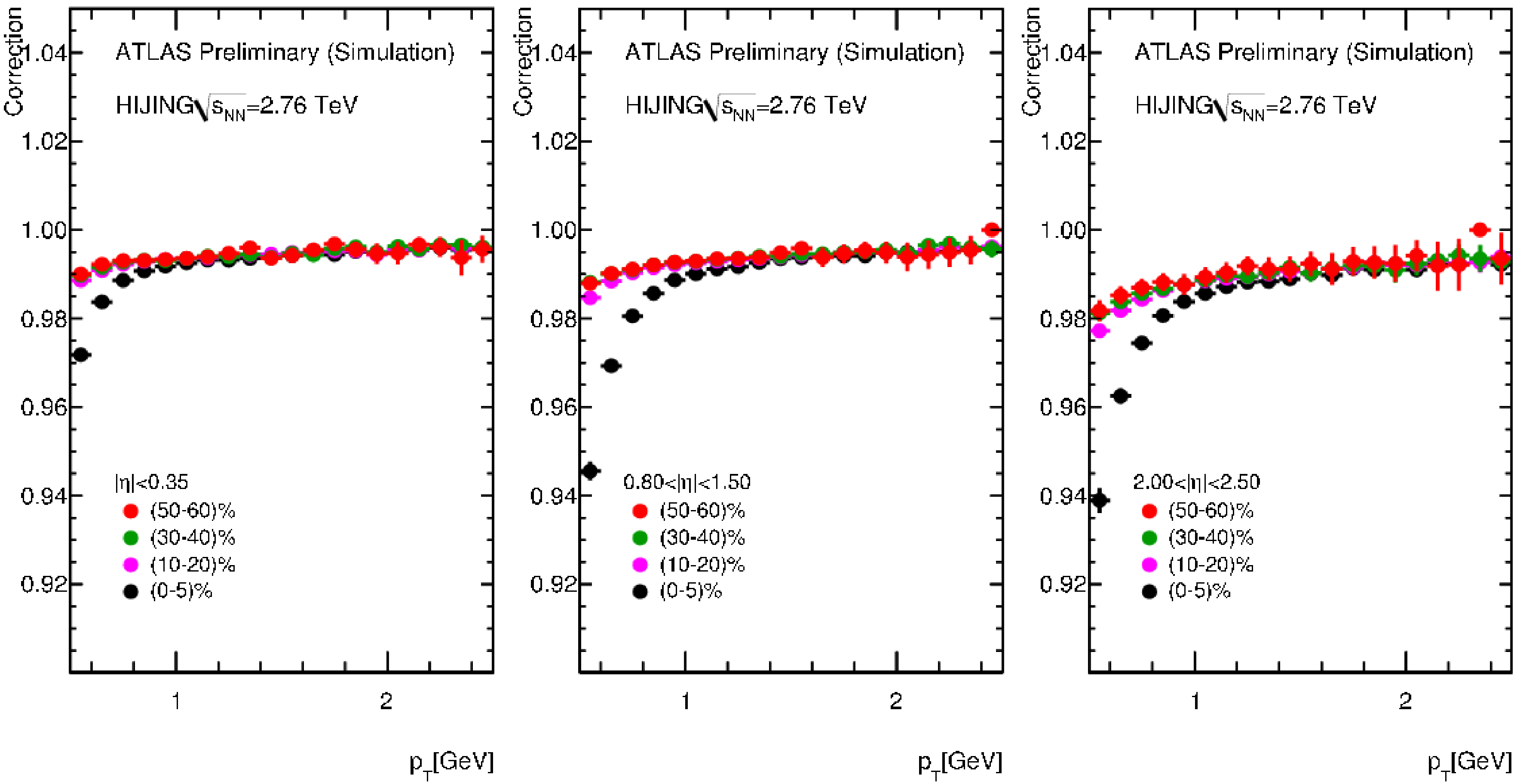
Comparison of the per-event standard deviation of summed ET for 7X7 groups of towers between Pb+Pb data and the HIJING+GEANT Monte Carlo simulated events as a function of FCal Σ ET. The Monte Carlo results are shown with and without the rescaling of the FCal ET values.

Jet Energy Resolution



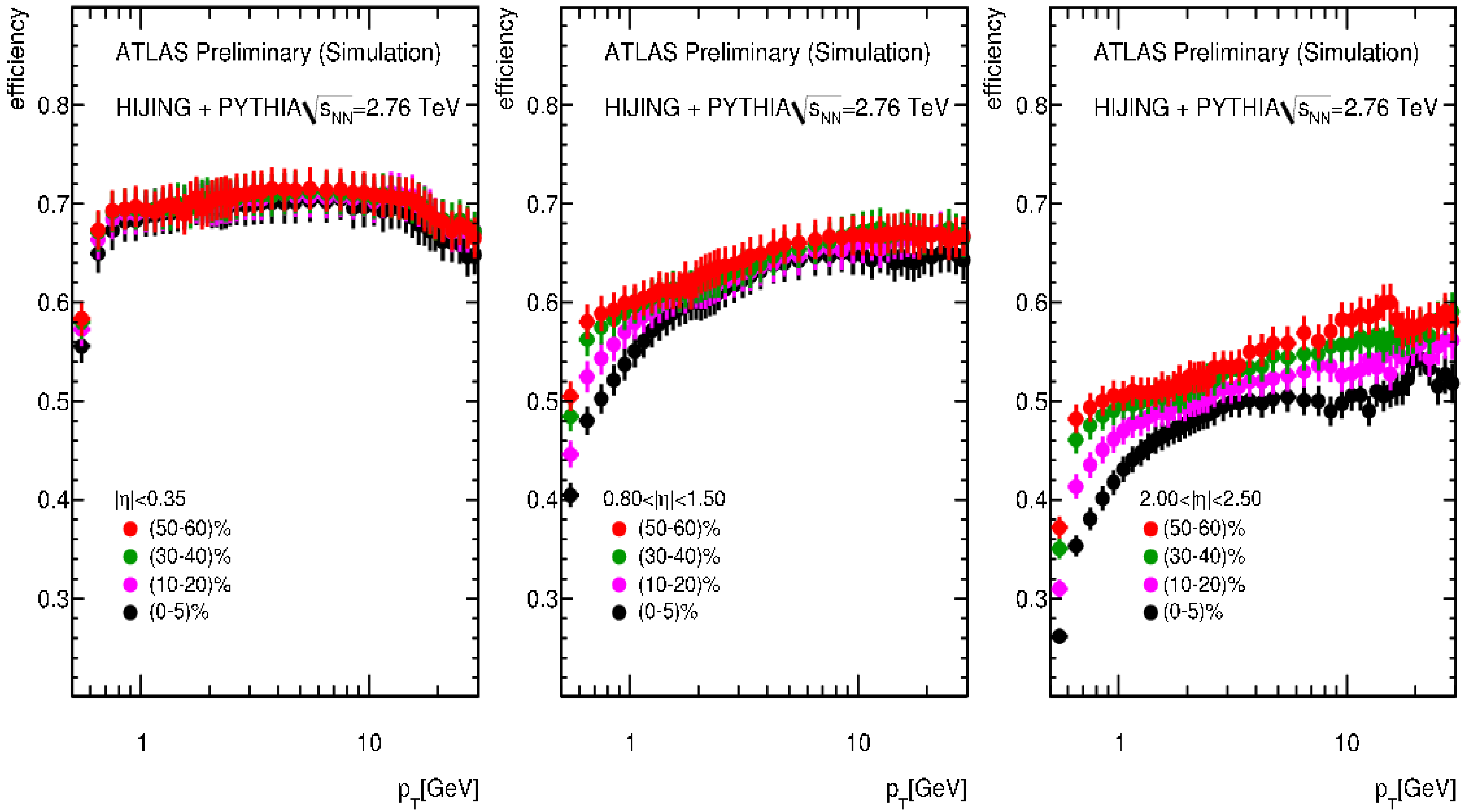
Jet energy resolution characterized for R=0.4 (red) and R=0.2 (black) jets for different intervals of Pb+Pb collision centrality

Correction for Off Vertex Tracks



Combined fake and secondary correction at low p_T calculated with HIJING

Tracking Efficiency



Tracking efficiency calculated from the minimum-bias HIJING and HIJING+jet samples.