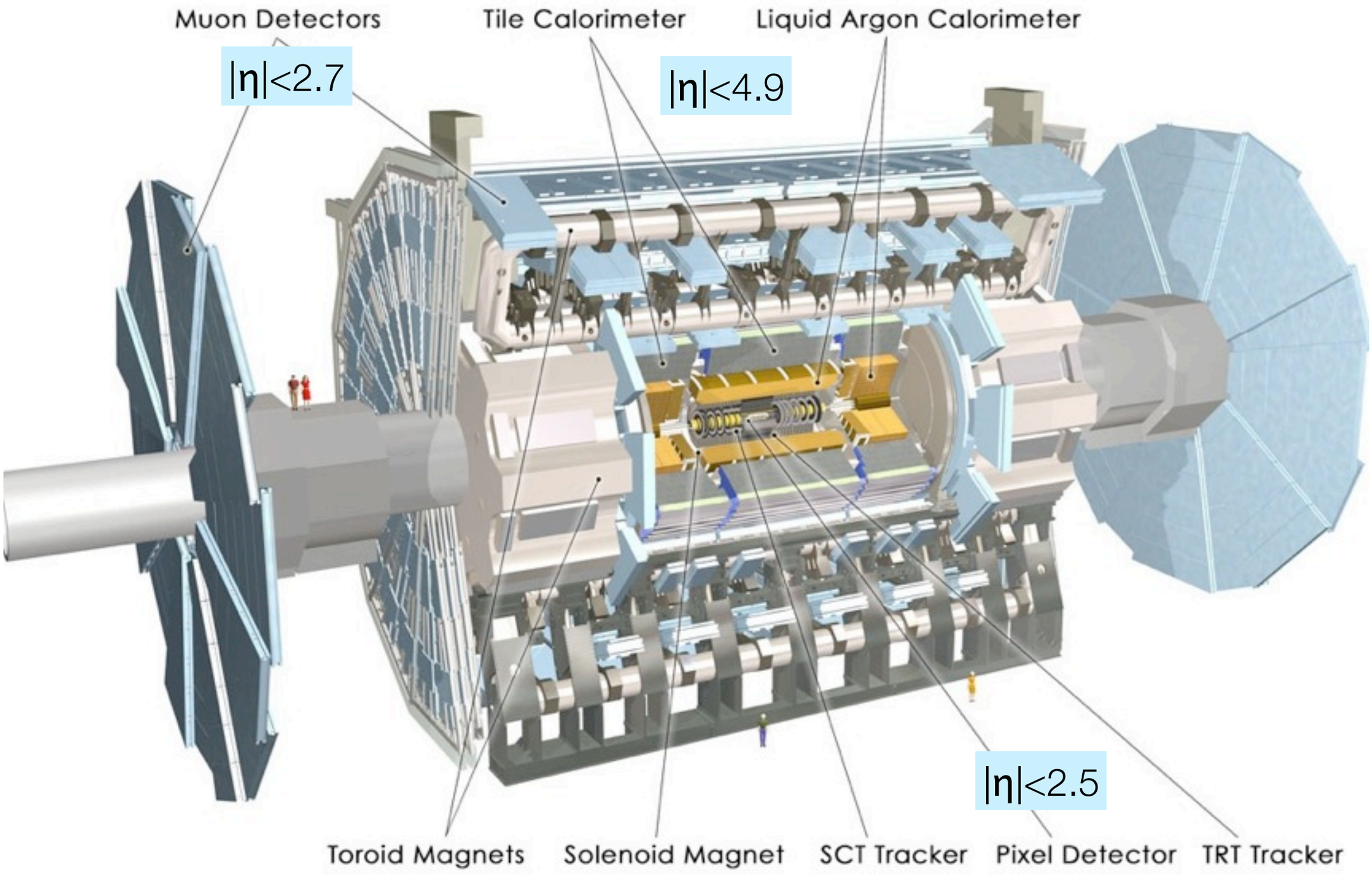
Recent Heavy Ion Results with the ATLAS Detector at the LHC

Peter Steinberg, for the ATLAS Collaboration
Brookhaven National Laboratory
August 10, 2011
DPF 2011, Brown University

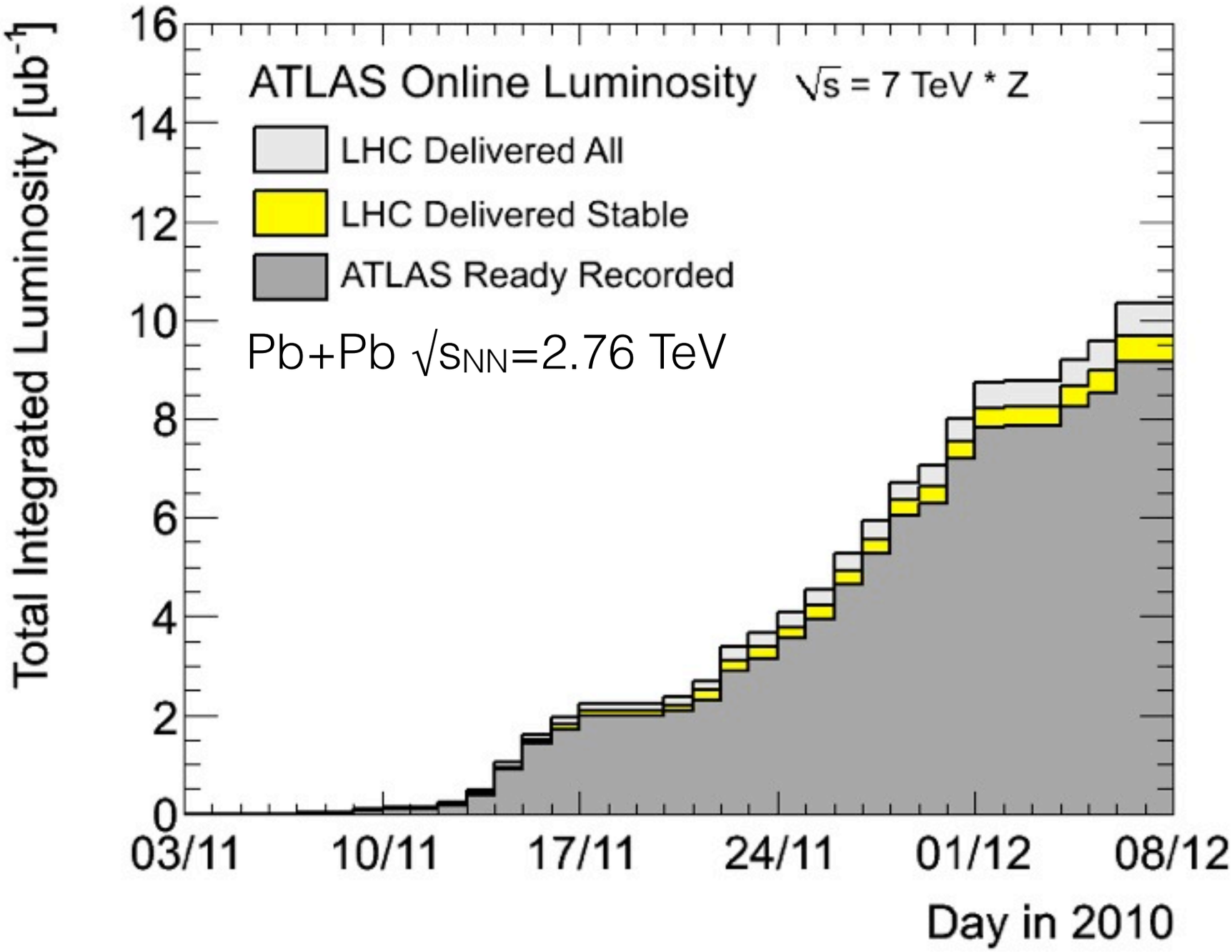
The ATLAS Detector



Run 169226, Event 379791
Time 2010-11-16 02:53:54 CET

ATLAS
EXPERIMENT

Integrated luminosity for 2010 Pb+Pb run



10 μb^{-1} delivered, 9 μb^{-1} recorded by ATLAS, ~8 μb^{-1} w/ solenoid

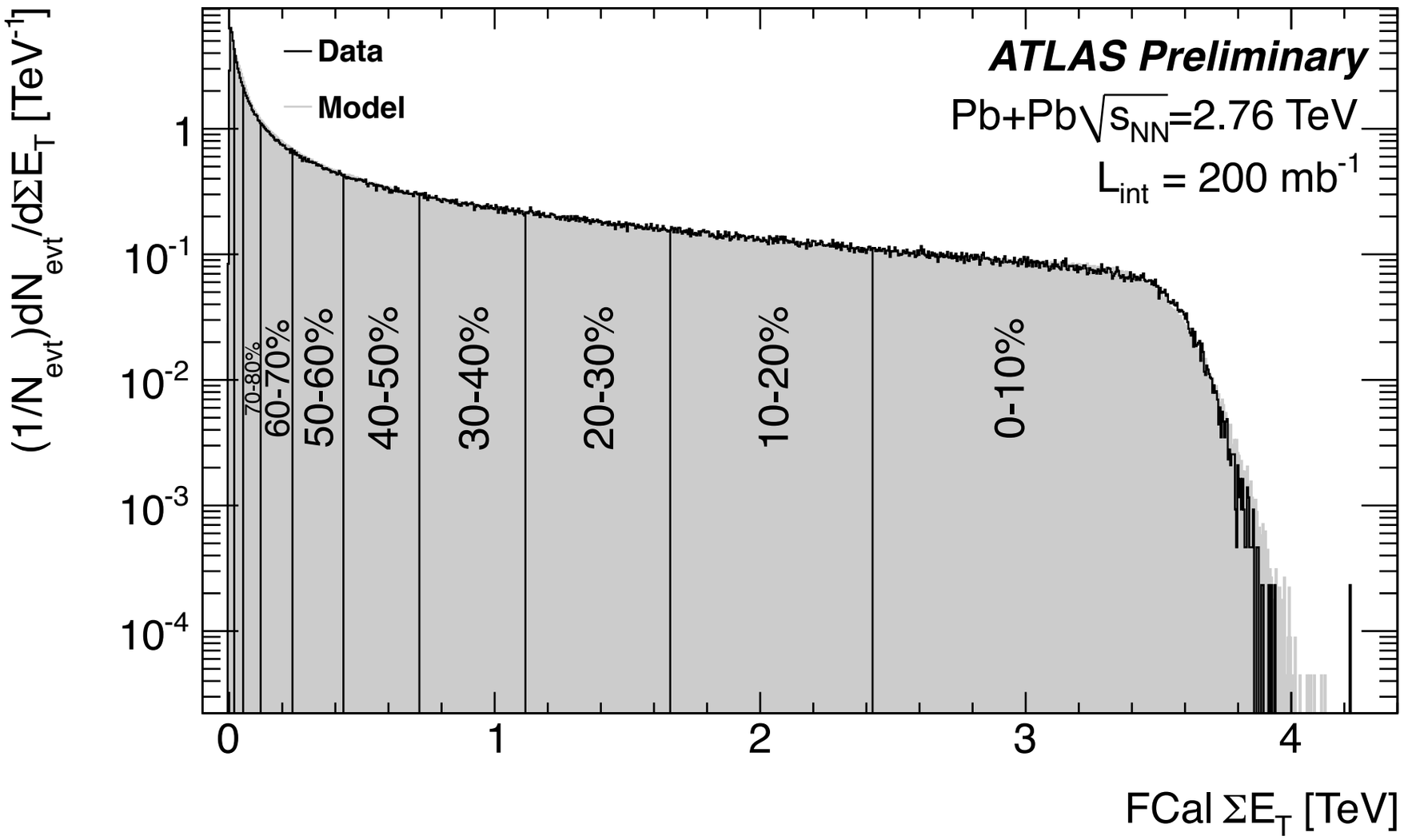
Survey of basic properties of heavy ions @ LHC

- **Global properties**
  - Multiplicity
  - Collective flow (& connection to correlations)

- **How do high p_T processes vary with centrality?**
  - Measurement of jet energy loss in hot, dense medium

- **We have addressed this with a large sample of minimum bias events**
  - Triggered on combination of forward scintillators and zero degree calorimeters
  - No high p_T triggers (jets, muons, etc.) used to select events

Centrality estimation

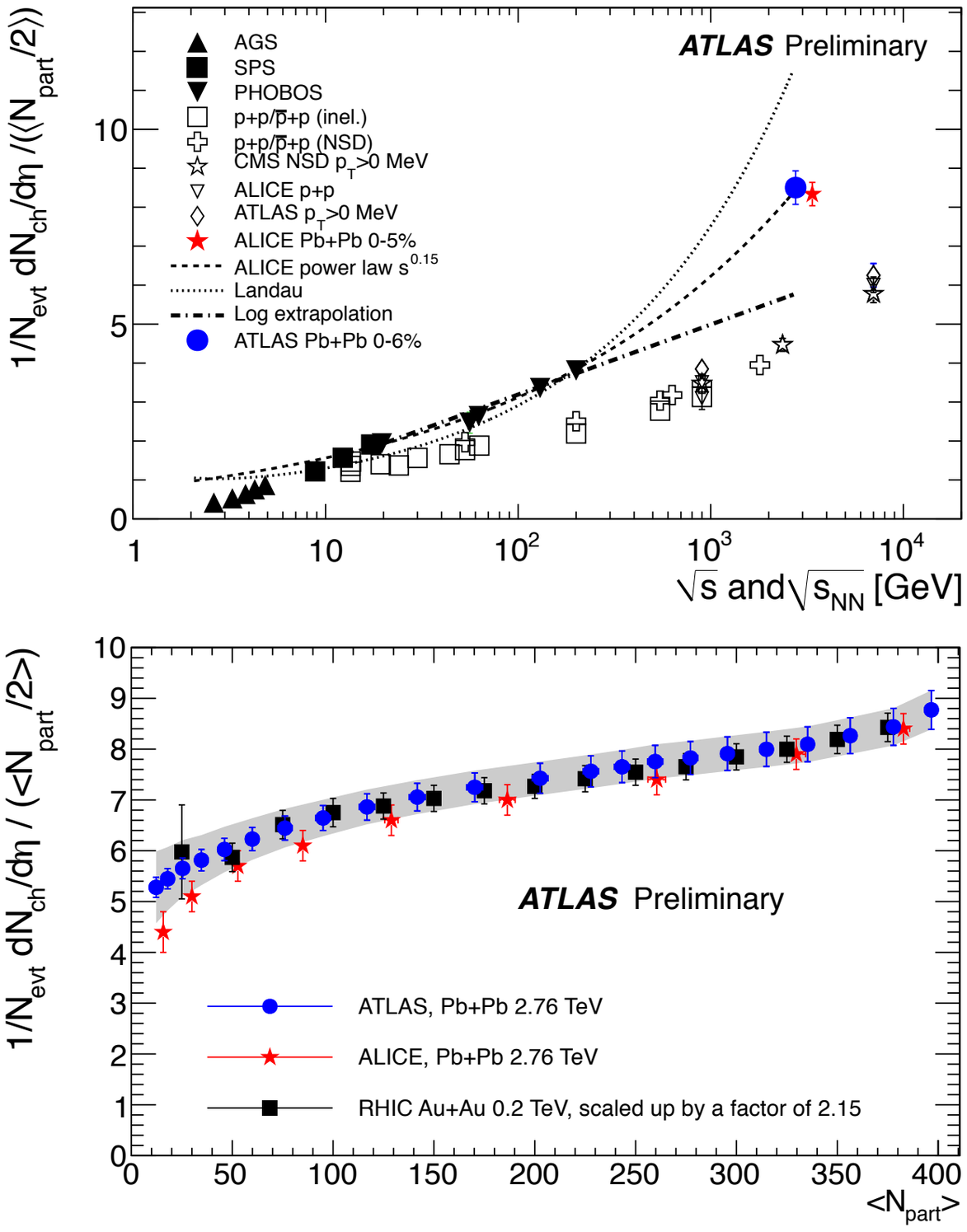


Energy sum in FCal (3.2<|η|<4.9) compared with Glauber MC ⊗ p+p data

Integrals of normalized data & MC distributions agree to 2% above & below range of fiducial ΣE_T cut, consistent with sampling f=100±2% of inelastic total cross section.

We calculate $\langle N_{part} \rangle$ and $\langle N_{coll} \rangle$ by binning in the simulated FCal variable.

Charged particle multiplicity



Pixel “tracklets” in solenoid-off data, to measure down to $p_T>0$

Yield per participant pair increases by factor of two relative to RHIC, in agreement with ALICE measurement

Similar centrality dependence to that found at RHIC (which itself was similar to top SPS energies):

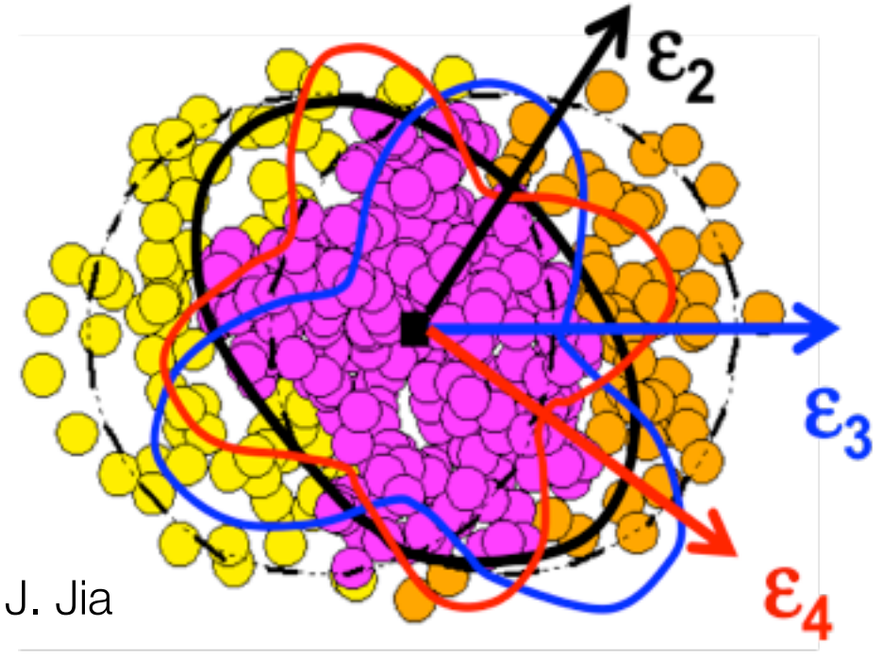
Confirmation of what appears to be a robust scaling feature in HI

Flow measurements

Elliptic flow at RHIC showed that spatial deformations in the initial overlap region closely correlated with momentum anisotropies:

ATLAS has new measurements with increased **η** dependence, and at high p_T

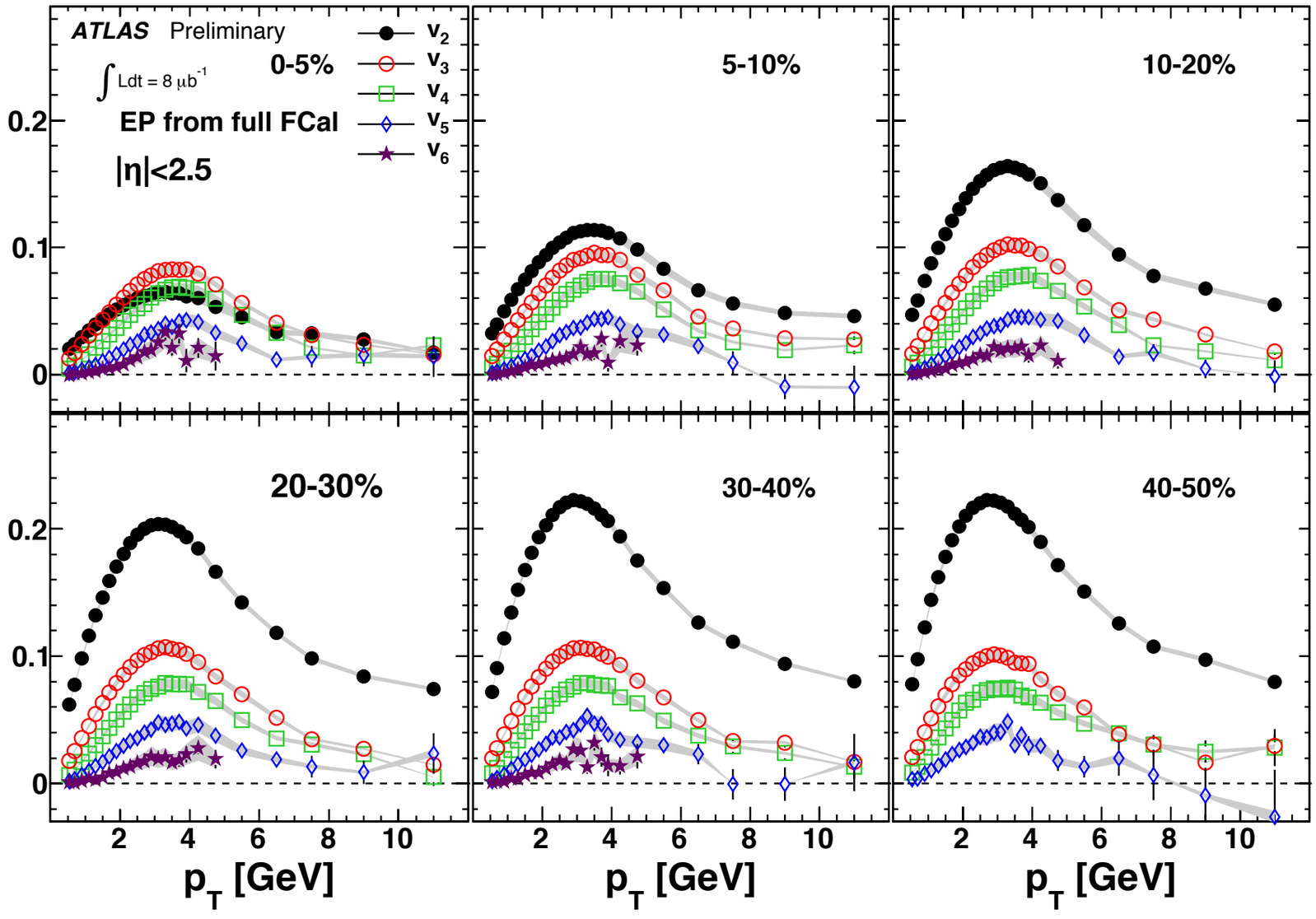
With the high multiplicities & large acceptance of ATLAS, we are also studying higher order components of the transverse flow



$$E\frac{d^3N}{dp^3} = \frac{1}{p_{\mathrm{T}}}\frac{d^3N}{d\phi dp_{\mathrm{T}}dy} = \frac{1}{2\pi p_{\mathrm{T}}}\frac{E}{p}\frac{d^2N}{dp_{\mathrm{T}}d\eta}\left(1+2\sum_{n=1}^{\infty}v_n\cos\left[n(\phi-\Phi_{RP})\right]\right)$$

Do v_n directly reflect higher order deformations in initial state? Higher modes should be more sensitive to viscous effects

Higher order moments vs. p_T and centrality

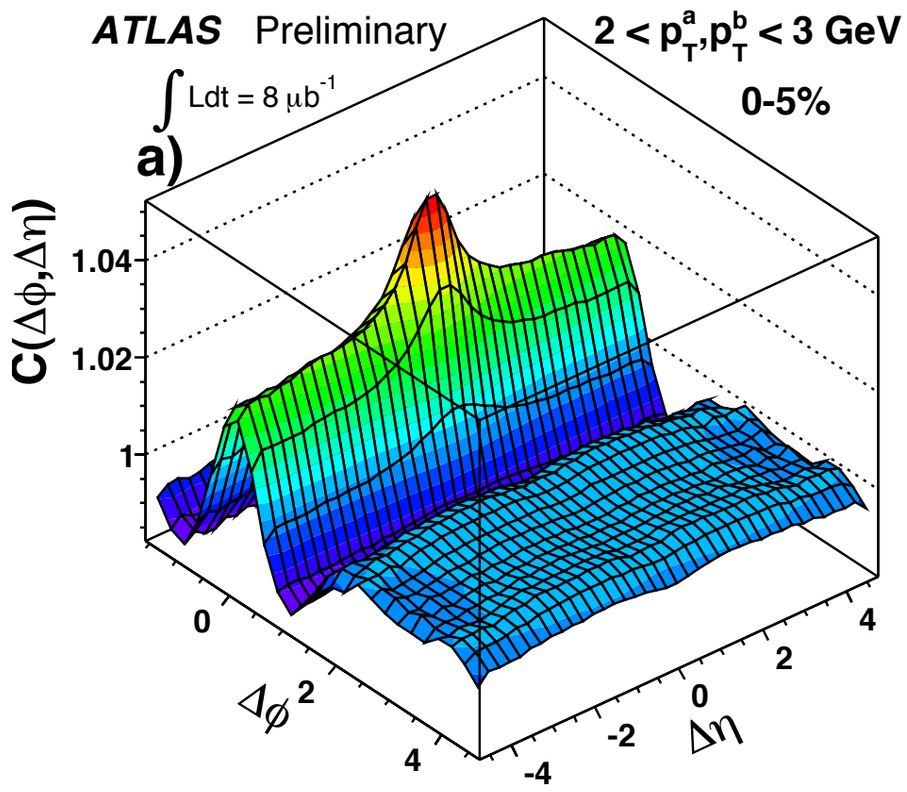


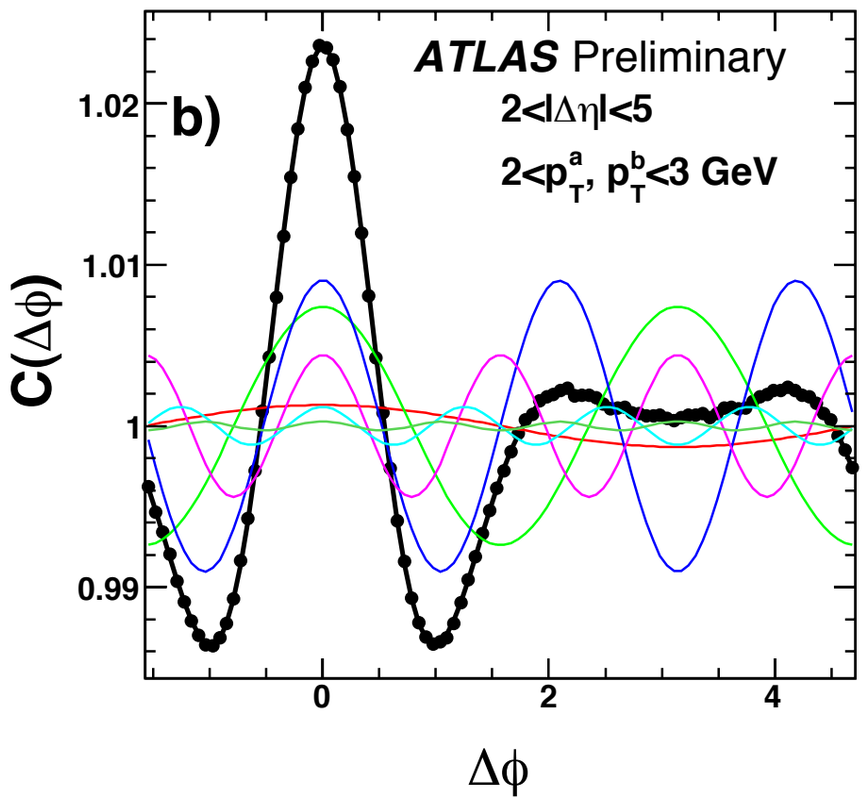
Similar p_T dependence for all flow coefficients.

Weak centrality dependence observed for v_3-v_6

For the 5% most central events **$v_2 < v_3$**

Two particle correlations



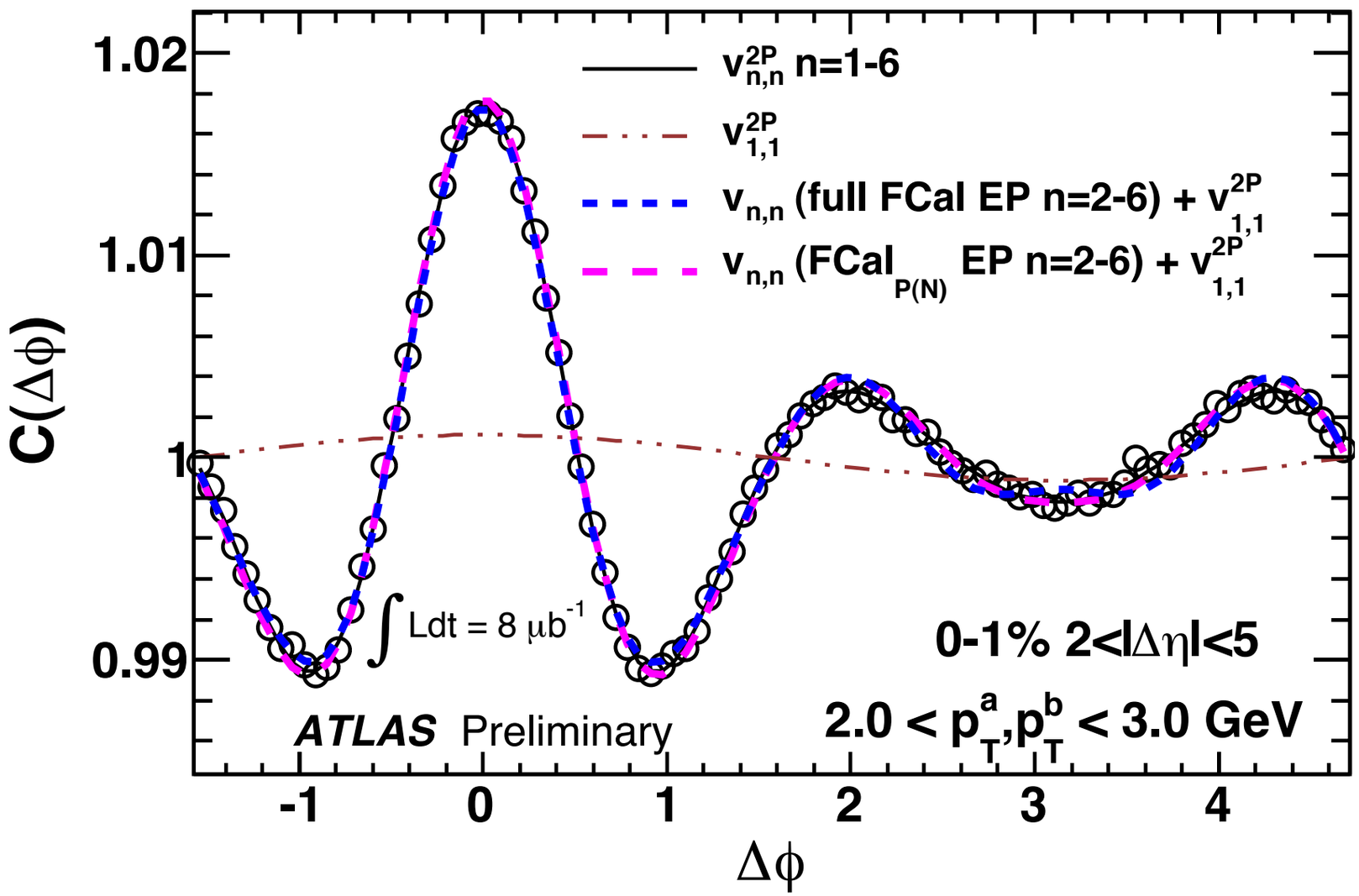


Two-particle correlations studied using discrete Fourier transform (DFT): $v_{n,n} \sim v_n^2$

$$C(\Delta\phi) = \frac{\int N_{\mathrm{s}}(\Delta\phi, \Delta\eta) d\Delta\eta}{\int N_{\mathrm{m}}(\Delta\phi, \Delta\eta) d\Delta\eta} \qquad v_{n,n} = \langle \cos(n\Delta\phi) \rangle = \frac{\sum_{m=1}^{N} \cos(n\Delta\phi_m) C(\Delta\phi_m)}{\sum_{m=1}^{N} C(\Delta\phi_m)}$$

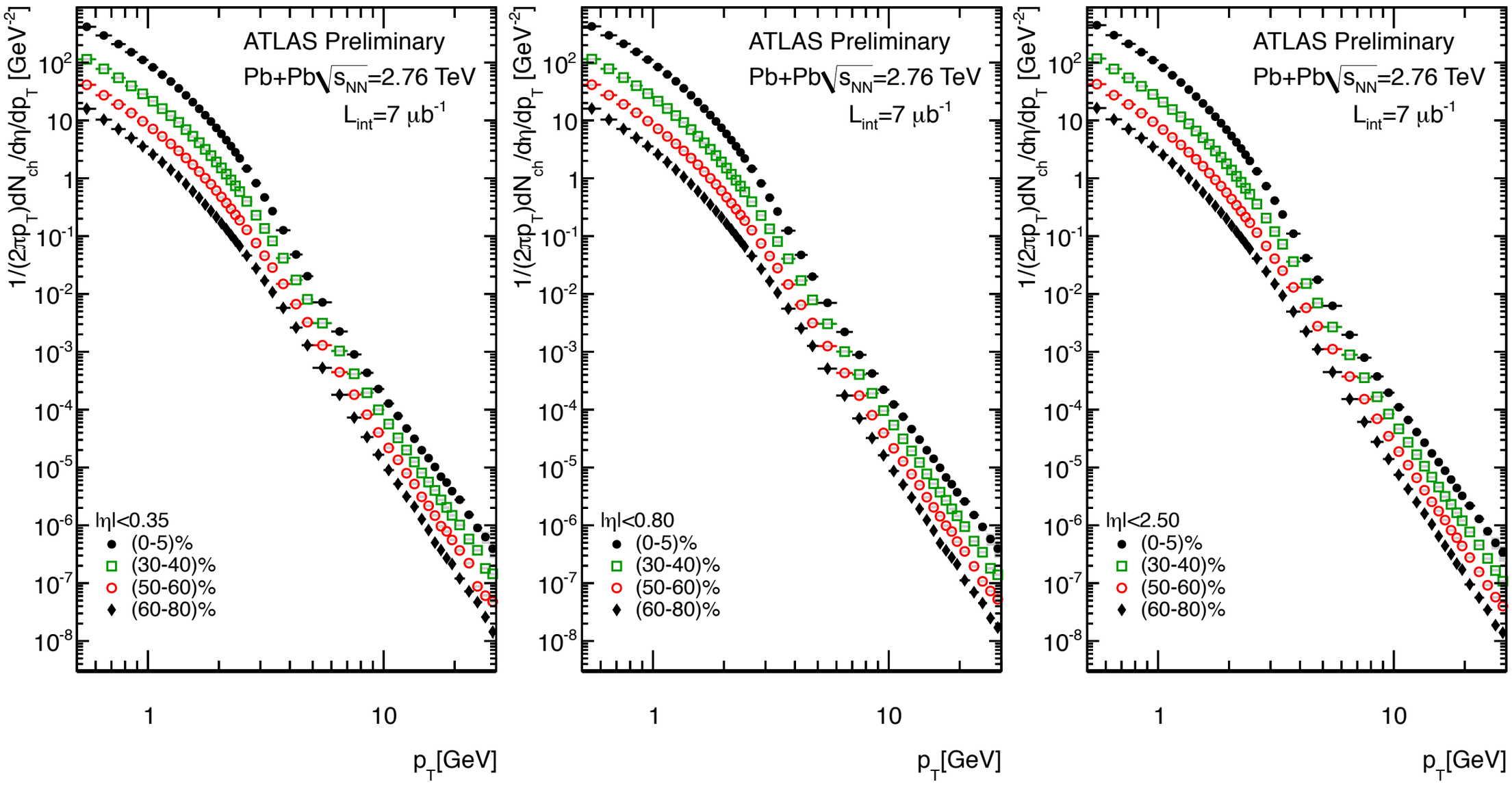
Complementary approach to event plane, to check consistency:
at long range, no more jet & resonance correlations (but non-trivial structure)

Reconstructing 2PC with event plane results



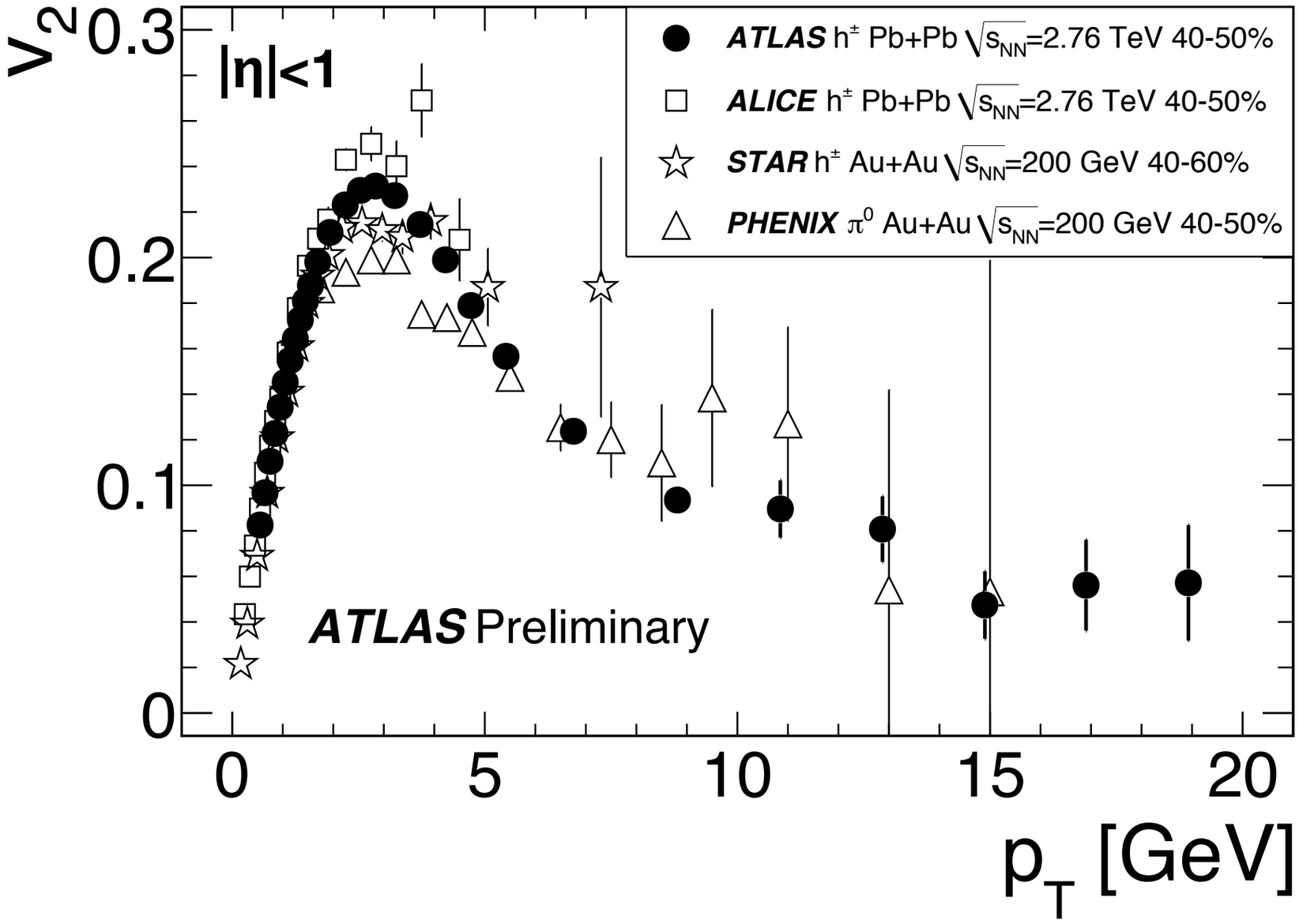
We find excellent agreement of DFT and EP results.
In fact, event plane measurements provide nearly-identical information as 2 particle correlations: “ridge” and “cone” at large Δη should no longer be seen as “jet related” phenomena

Charged particle spectra



Corrected for efficiency, secondaries, fakes, resolution.
Cutoff at 30 GeV due to small, systematic differences in track errors between data and MC (under investigation)

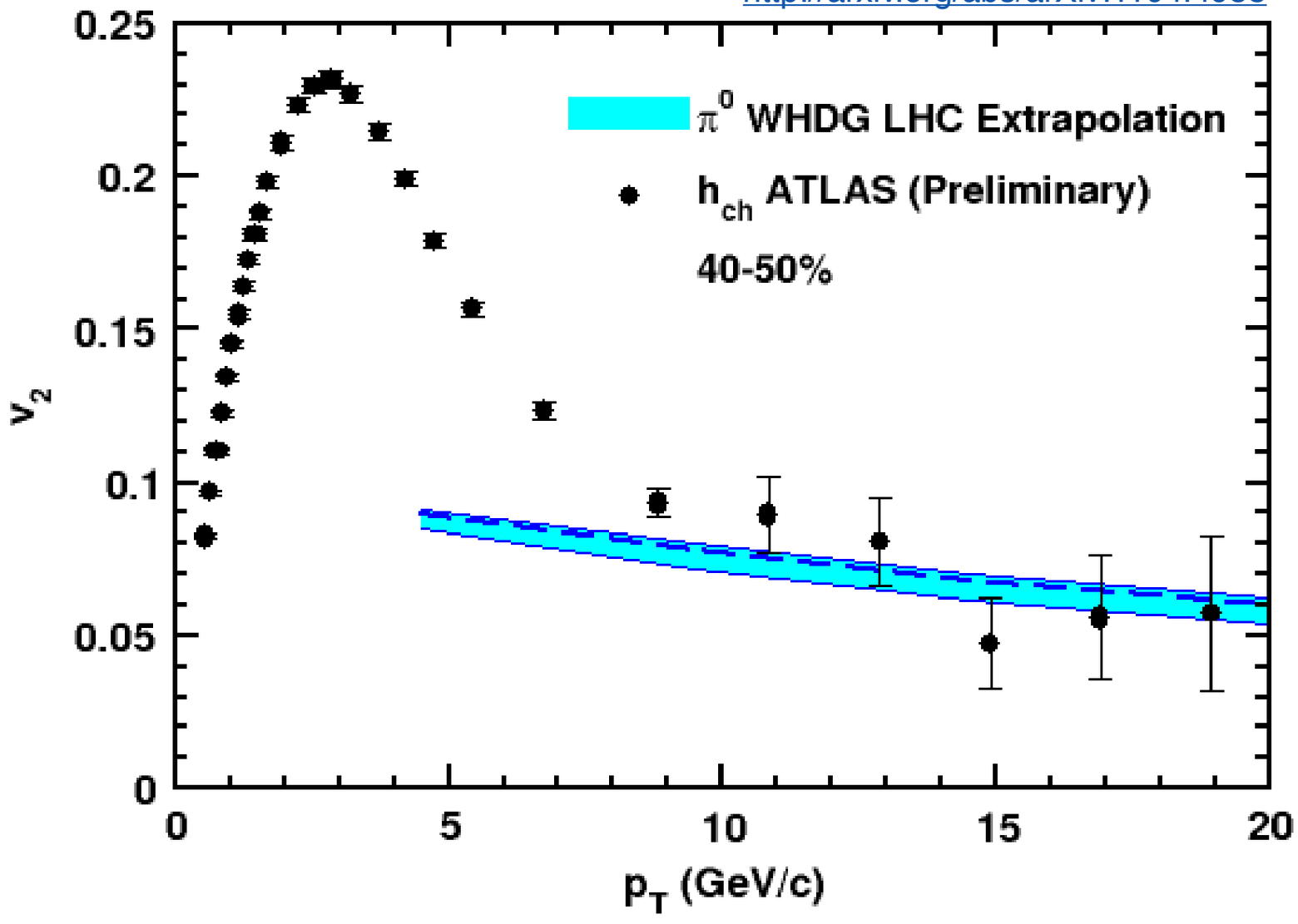
v_2 at high p_T

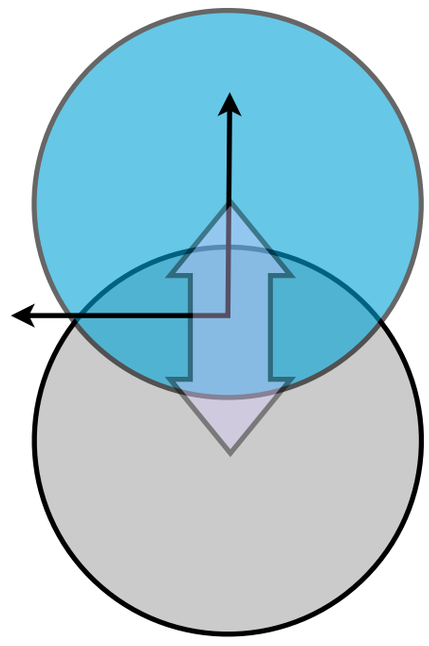


At fixed centrality, the p_T dependence seems to scale
(within large errors for PHENIX at high p_T): differential parton energy loss?

Differential energy loss

W. Horowitz & M. Gyulassy, QM2011
http://arxiv.org/abs/arXiv:1104.4958



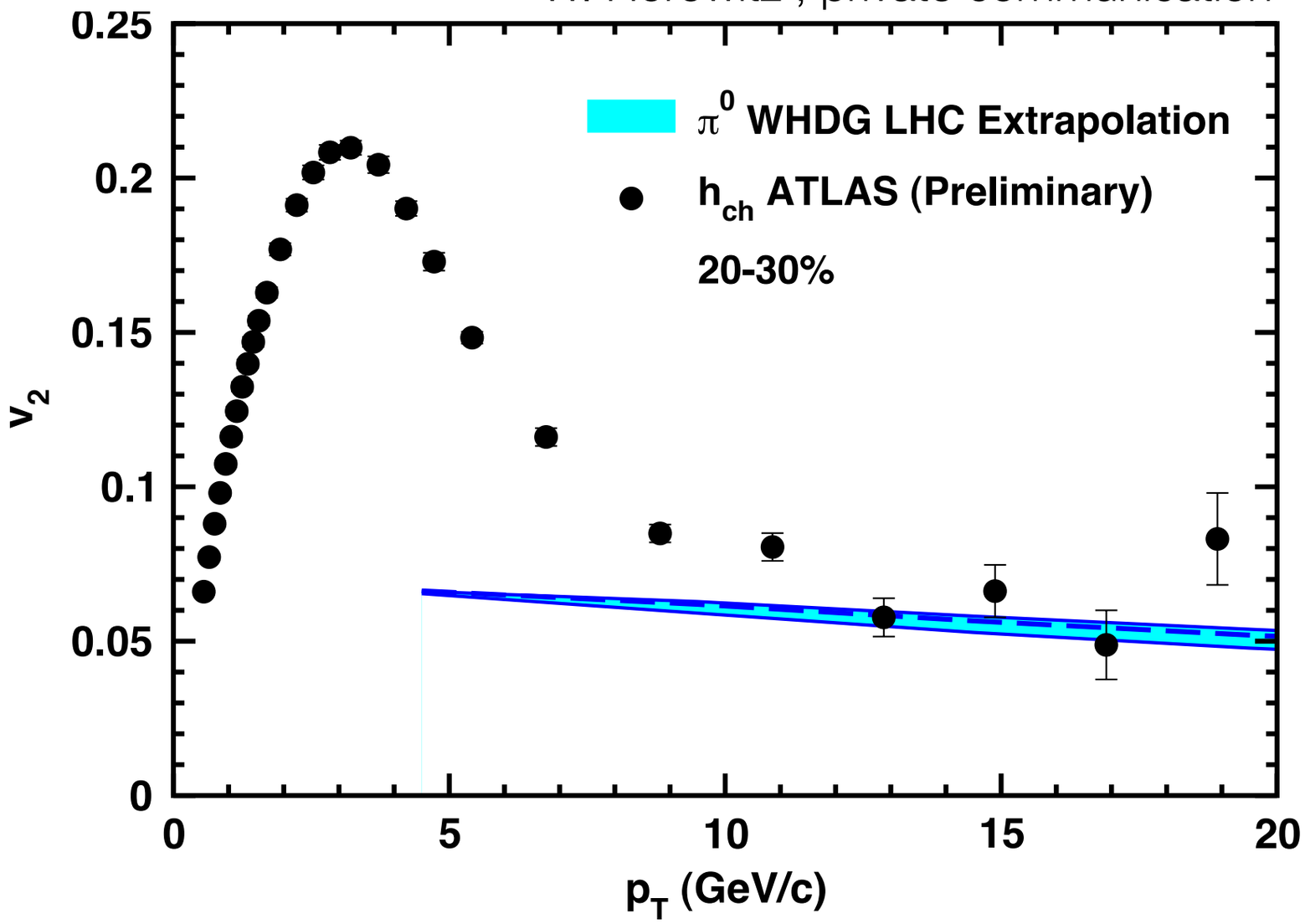


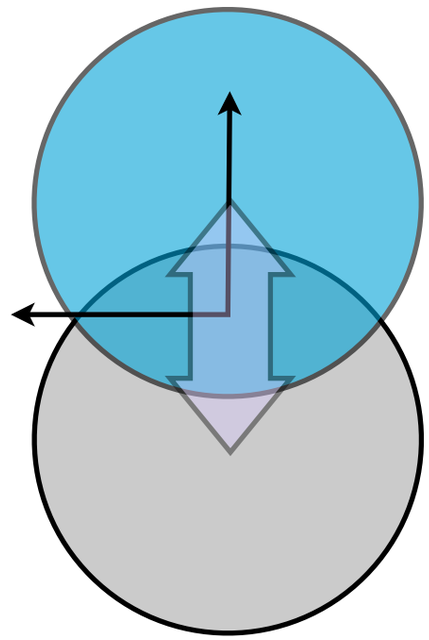
less energy loss
“in-plane”

Quantitative comparisons between energy loss calculations and v_2 at high momentum, reflecting differential energy loss.
Impressive agreement, despite predicting too-low R_{AA}

Differential energy loss

W. Horowitz , private communication



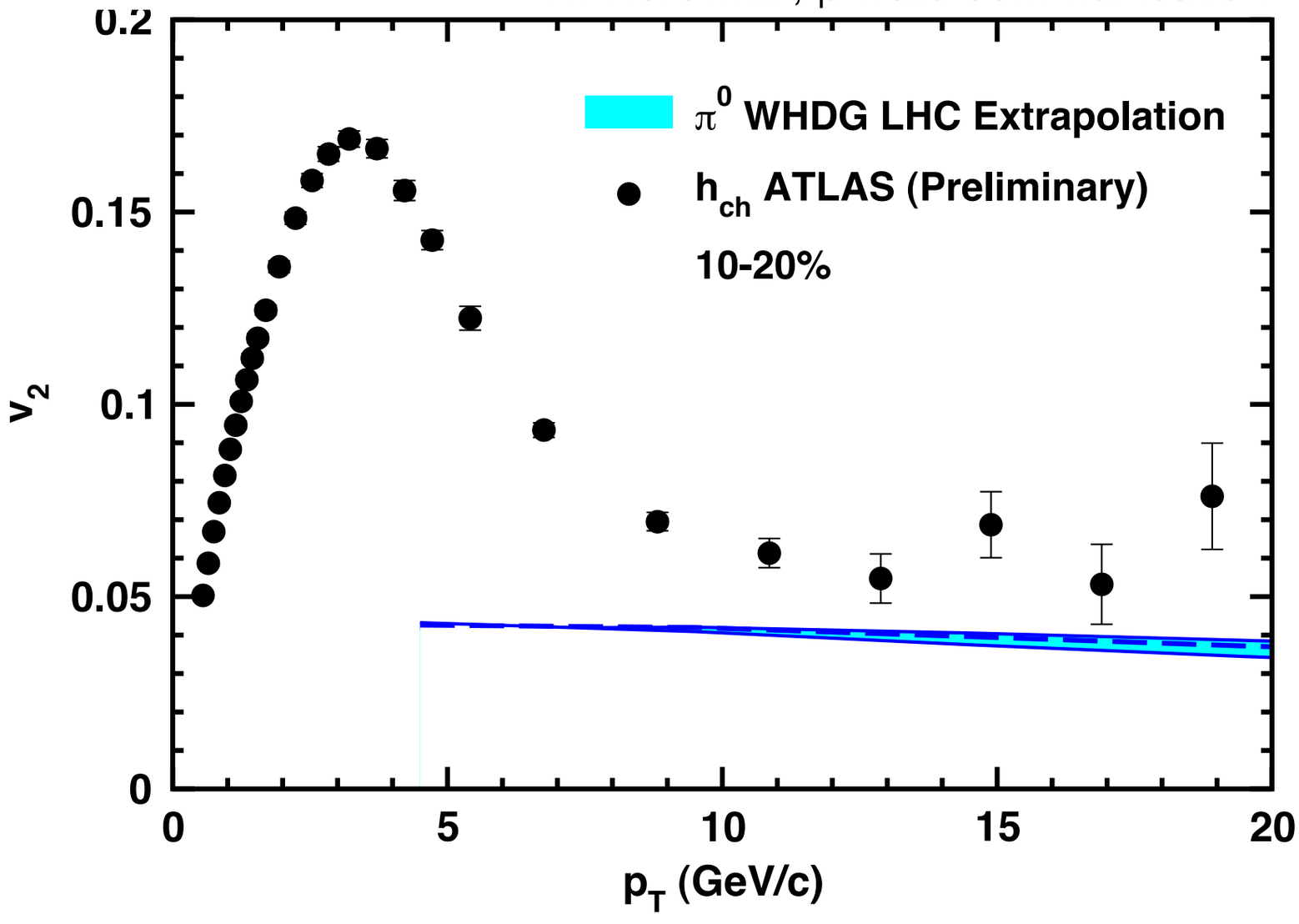


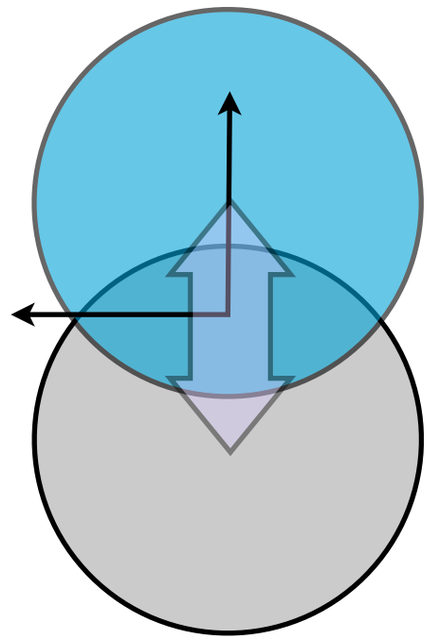
less energy loss
“in-plane”

Quantitative comparisons between energy loss calculations and v_2 at high momentum, reflecting differential energy loss.
Impressive agreement, despite predicting too-low R_{AA}

Differential energy loss

W. Horowitz , private communication





less energy loss
“in-plane”

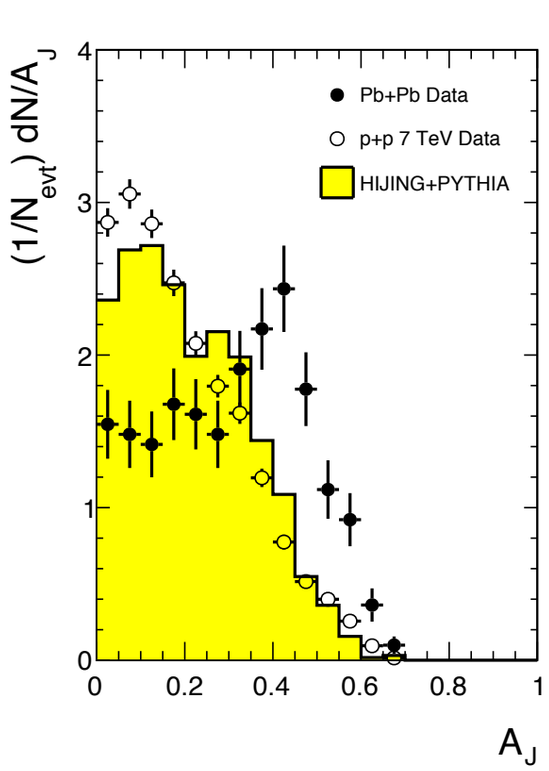
In most central events, see discrepancies possibly arising from lack of fluctuations in theoretical calculation

Hard probes of heavy ion collisions

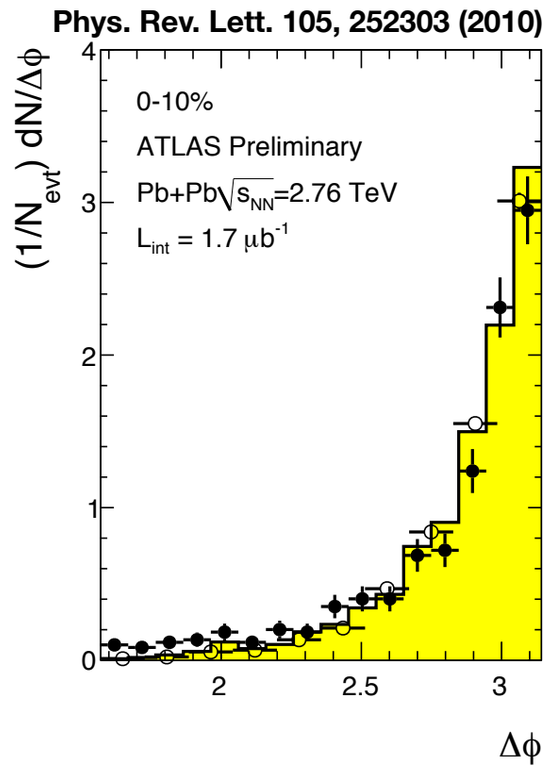
The LHC provides much higher rates of hard processes than provided previously: new opportunities for studying the microscopic properties of the medium

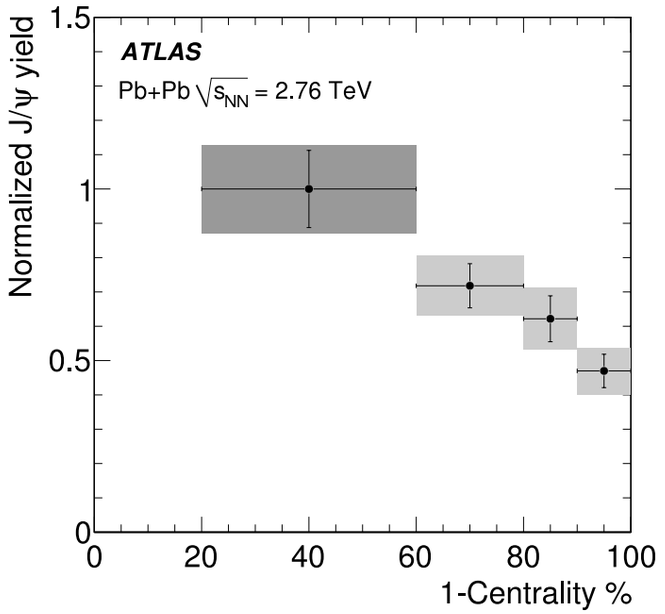
ATLAS published first observations of the centrality dependence of dijet asymmetries

ATLAS also first measured suppression of J/ψ & observed production of Z bosons

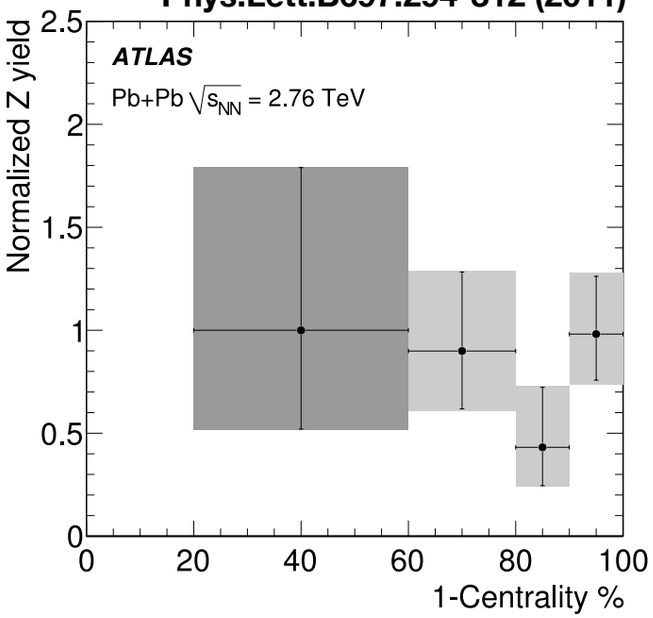


Phys. Rev. Lett. 105, 252303 (2010)

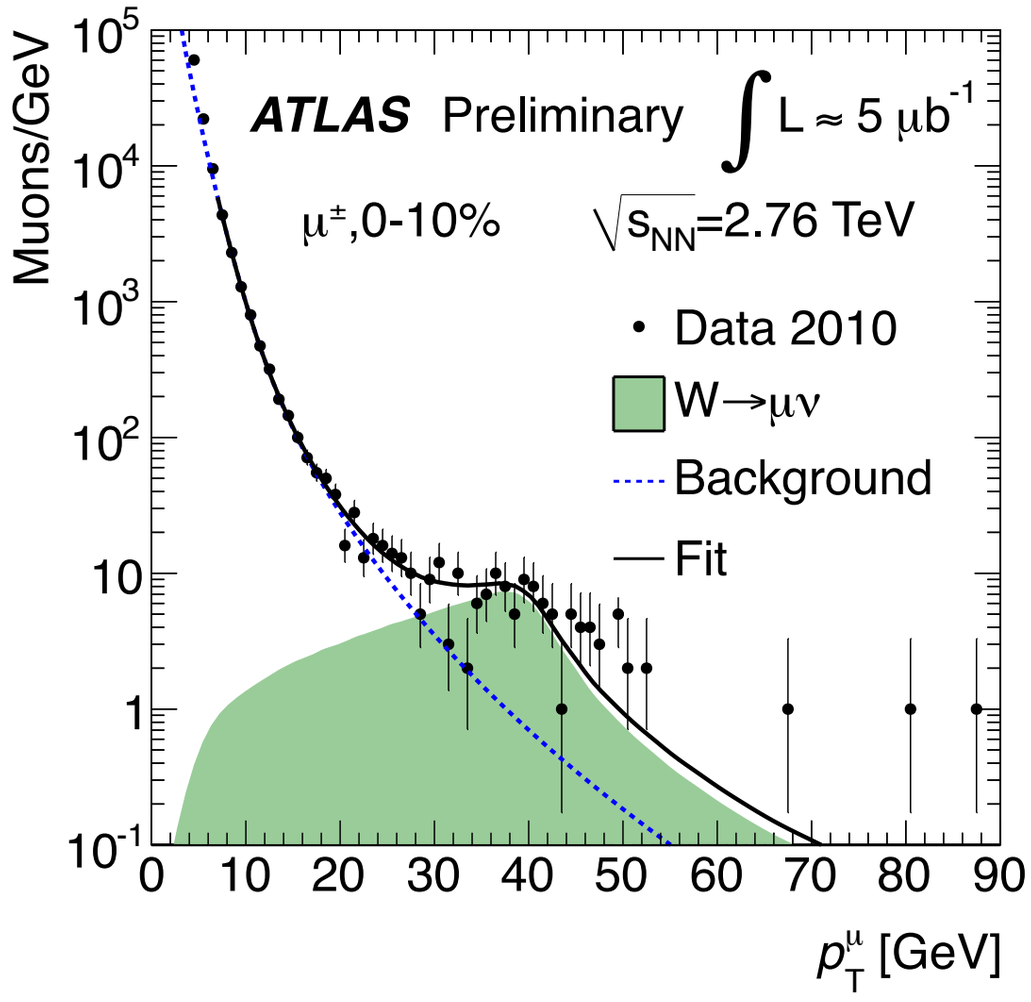


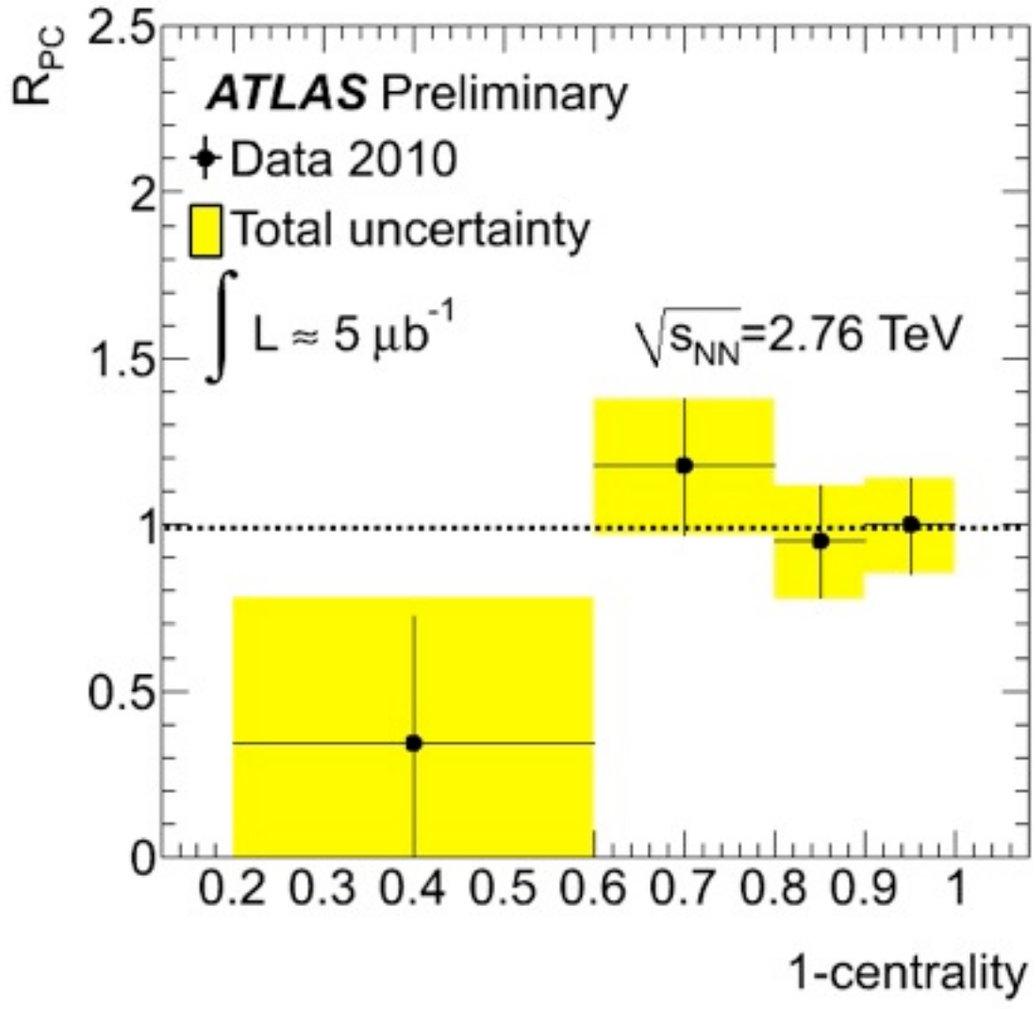


Phys.Lett.B697:294-312 (2011)



Hard probes: N_{coll} scaling from $W^{\pm}$ production



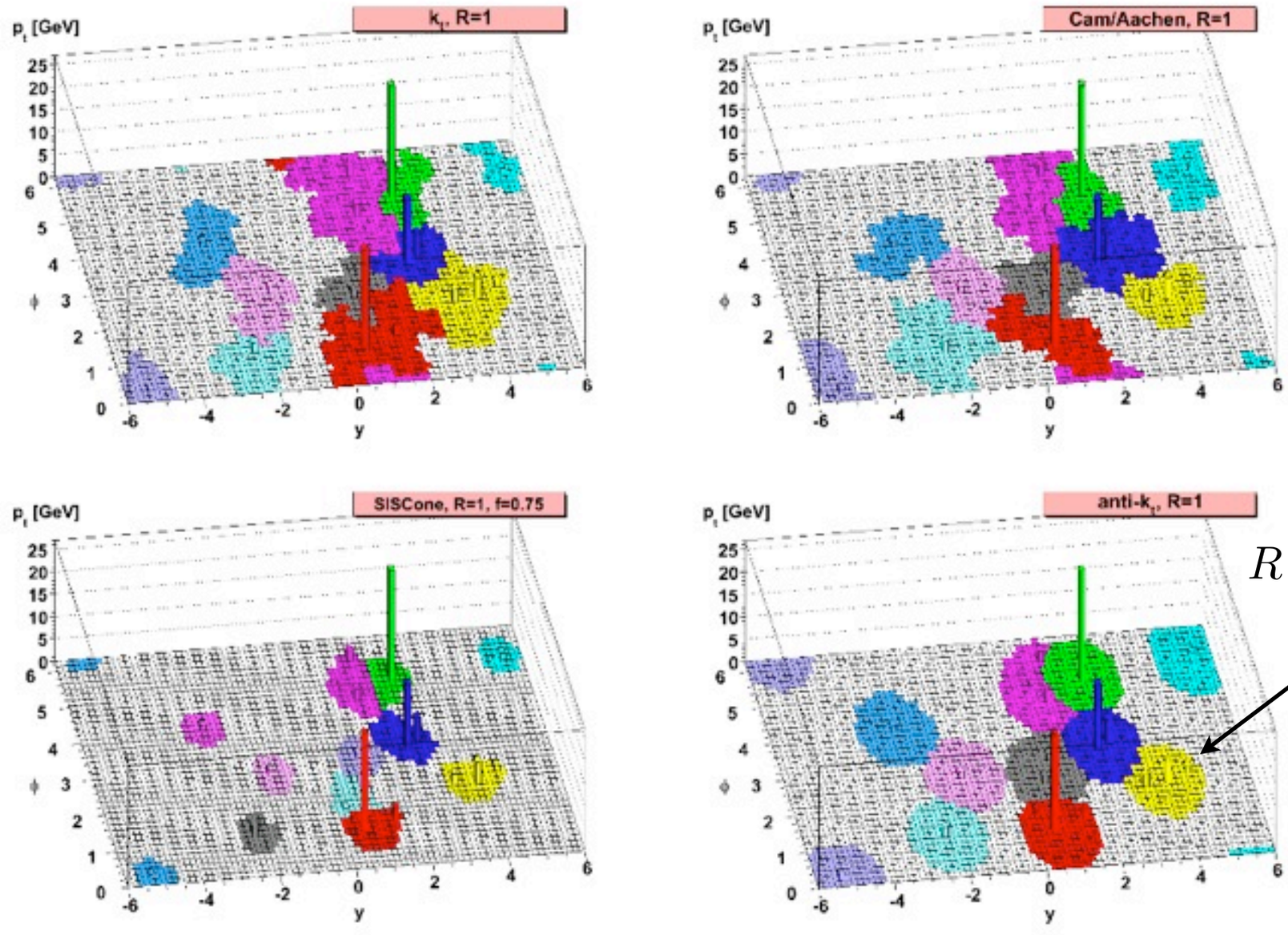


W yields extracted using an empirical fit to single muon spectra: heavy flavor (adapted from p+p) and simulated PYTHIA $W^{\pm}$ template

Pinned to <u>most central</u> events (R_{PC}), ~N_{coll} scaling observed.

Jet reconstruction algorithms

Cacciari, Soyez, Salam (2008)



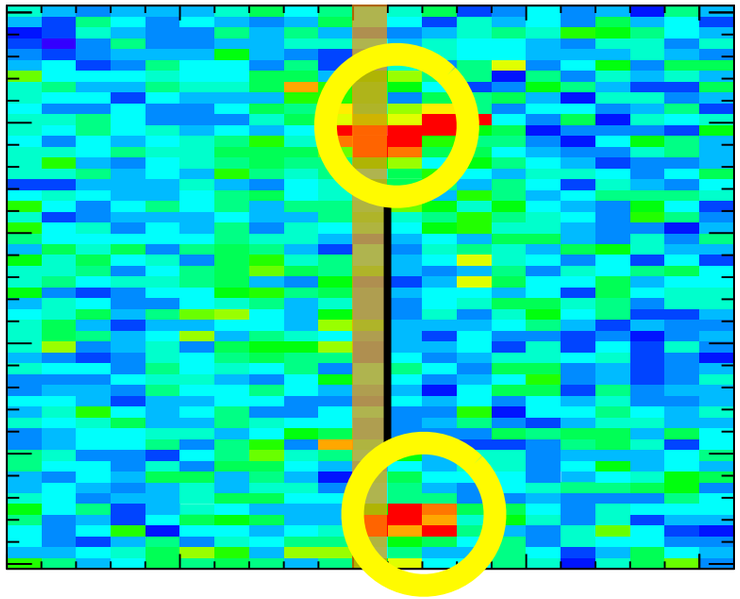
Out of large variety of algorithms, ATLAS uses “anti-k_t”: consistent jet shape (e.g. R=0.4), widely used in HEP & HI

Subtracting the underlying background

- **ATLAS has excellent longitudinal segmentation**
  - Underlying event estimated and subtracted for each layer, and in 100 slices of Δη=0.1

$$E_T{}_{sub}^{cell} = E_T^{cell} - \rho^{layer}(\eta) \times A^{cell}$$

  - ρ is estimated event by event, averaged over full azimuth



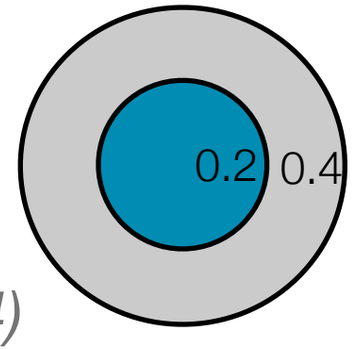
- **Remove jets from the averaging**
  - We use the anti-k_t algorithm to remove jets which have a large "core" region

$$D = E_T{}_{max}^{tower} / \langle E_T^{tower} \rangle > 5$$

  - Cross checked with a standard "sliding window" algorithm
- **NB: No jets are removed - but only real jets will have a large energy above the background level!**

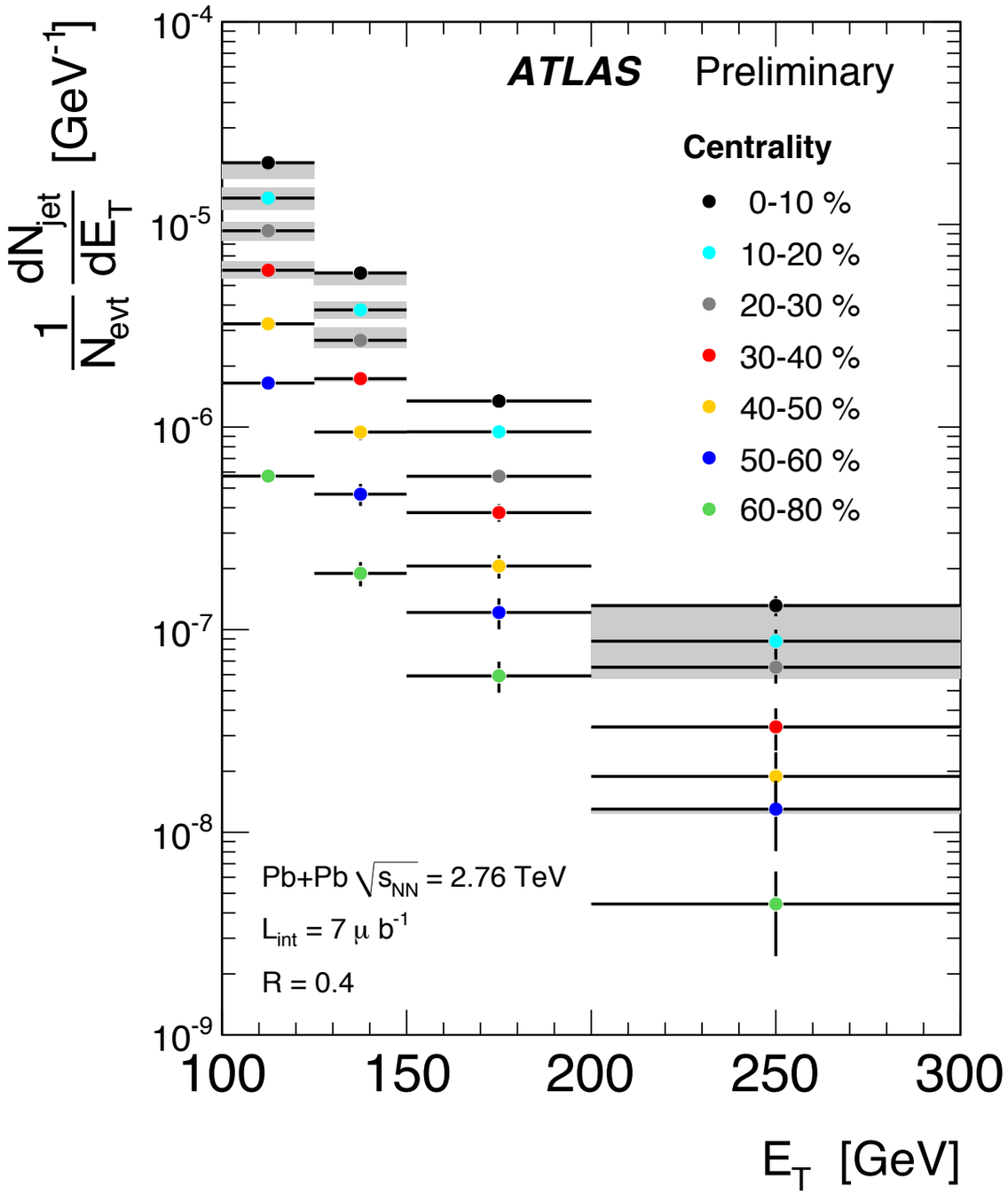
Jet yields in HI

- **First ATLAS results were an observation of asymmetric dijets, with a relative rate that increased with collision centrality**
- **Recent work involves more detailed background subtraction**
  - Elliptic flow
  - Iterative method to remove bias of jet on background
  - Systematic comparison of jets of different sizes
    - *R=0.2 without flow correction used. E_T (R=0.2) ~ 0.7 x E_T (R=0.4)*

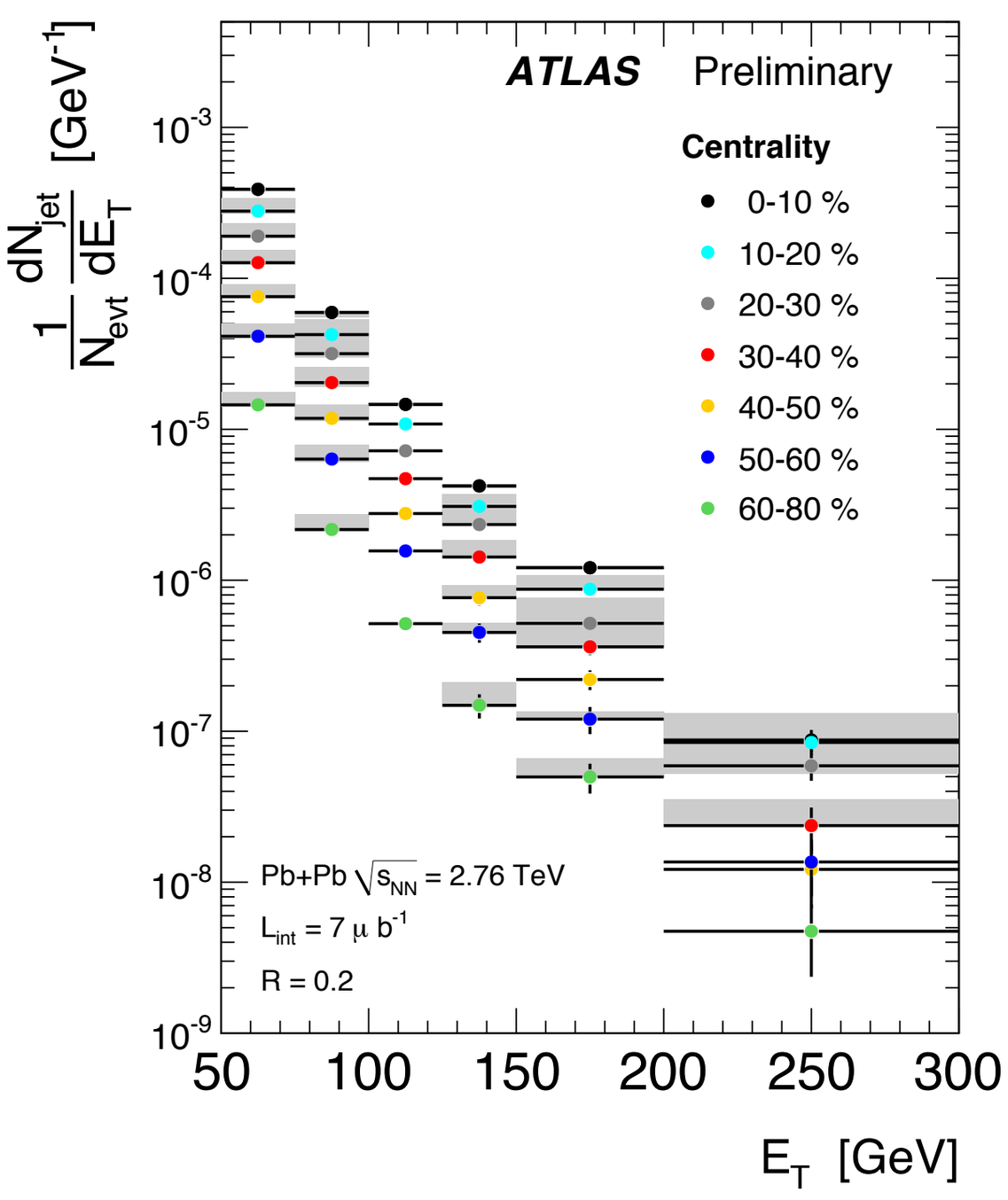


- **Extensive MC studies of jet performance**
  - jet energy scale (JES) and jet energy resolution (JER) based on PYTHIA dijets embedded into HIJING with a flow afterburner
- **Centrality-dependent spectral unfolding**

Jet Spectra R=0.4 & R=0.2

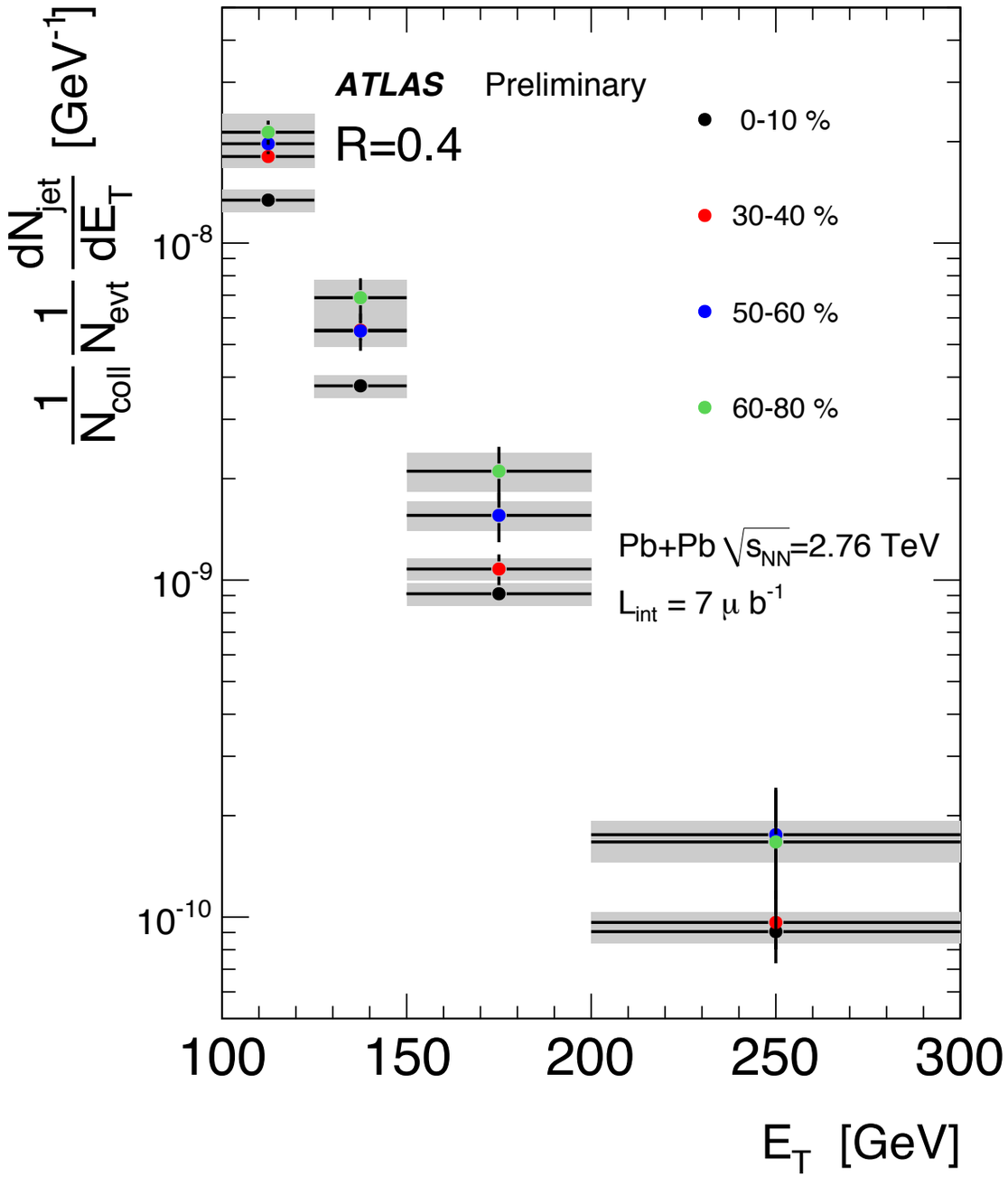


R=0.4

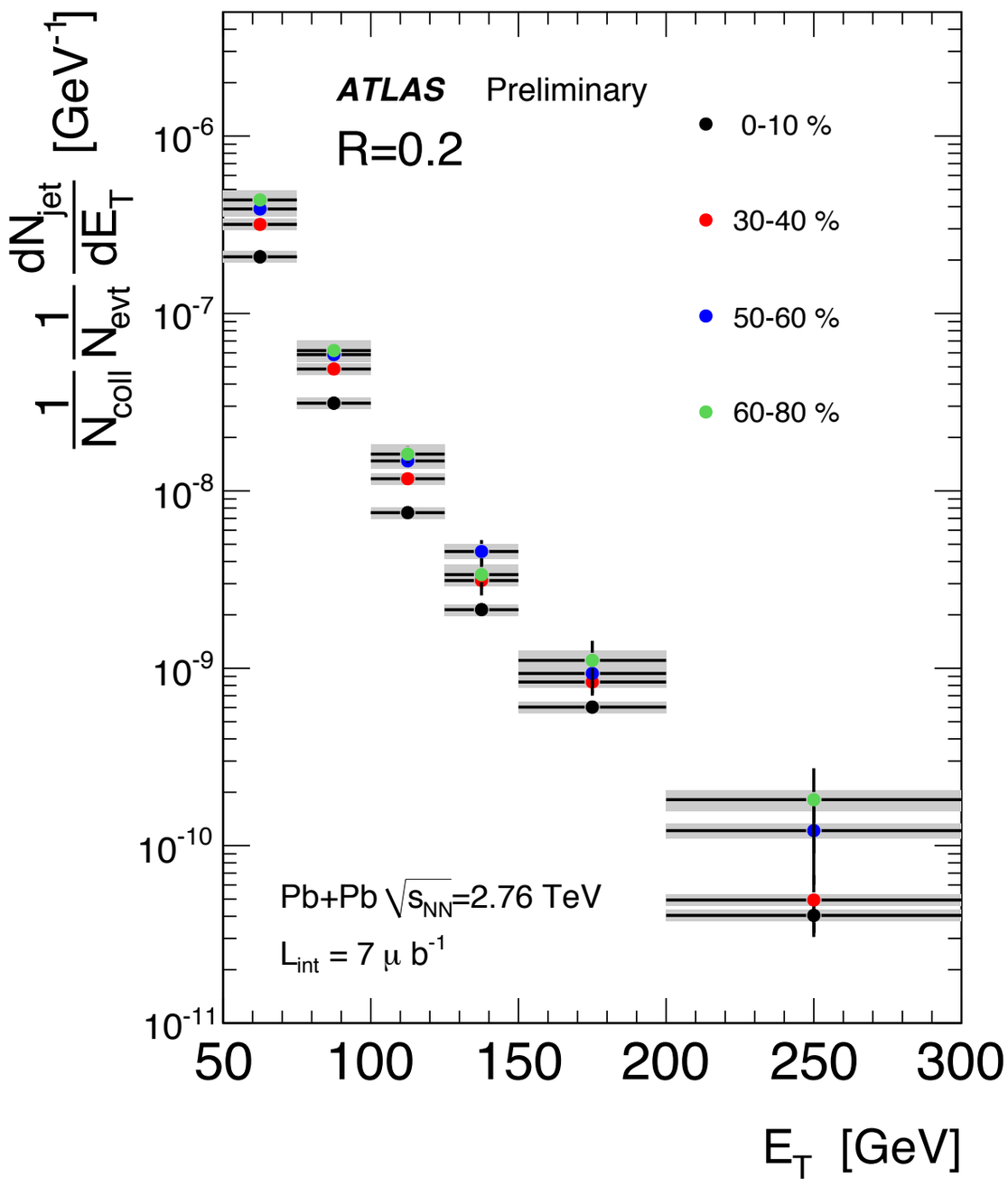


R=0.2

Scaled by N_{coll} (selected bins)

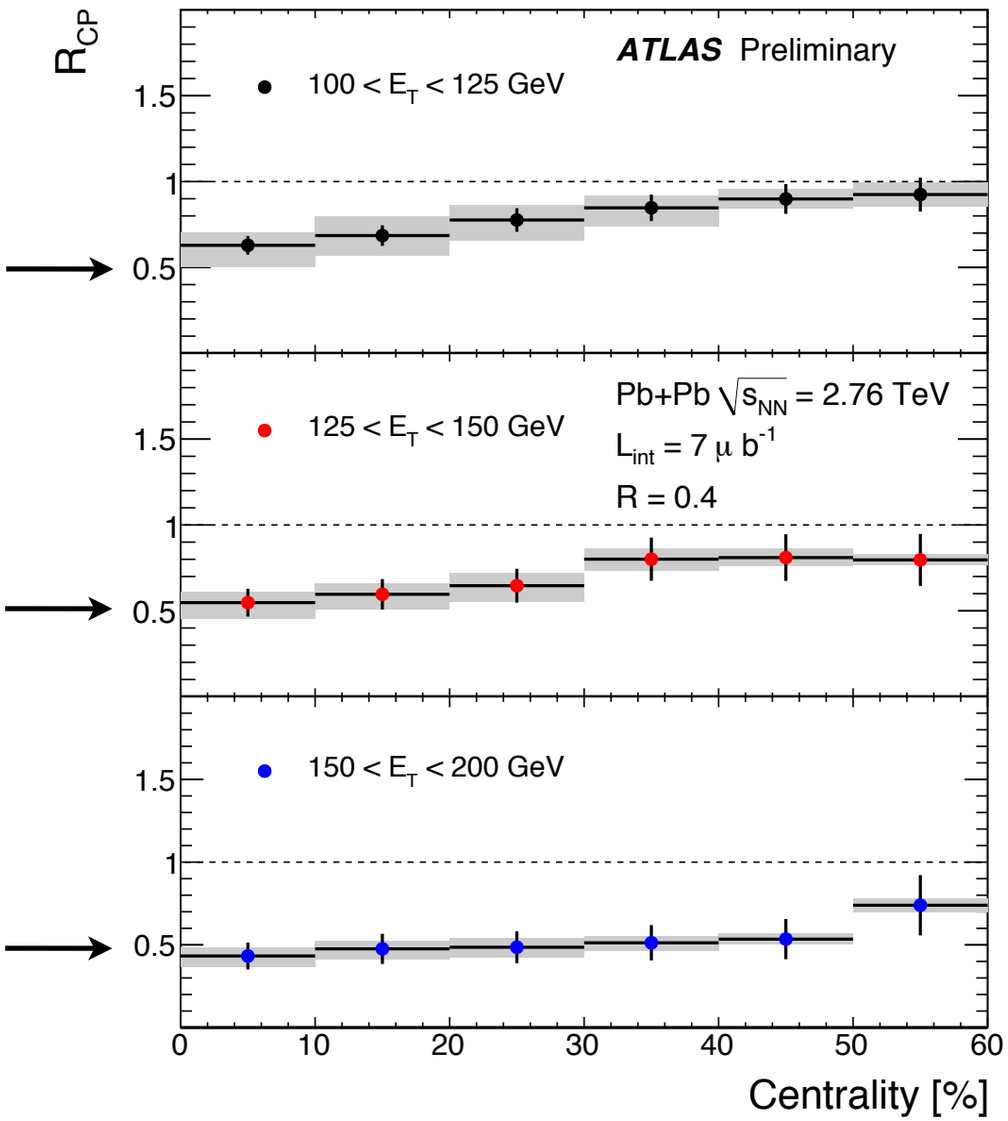


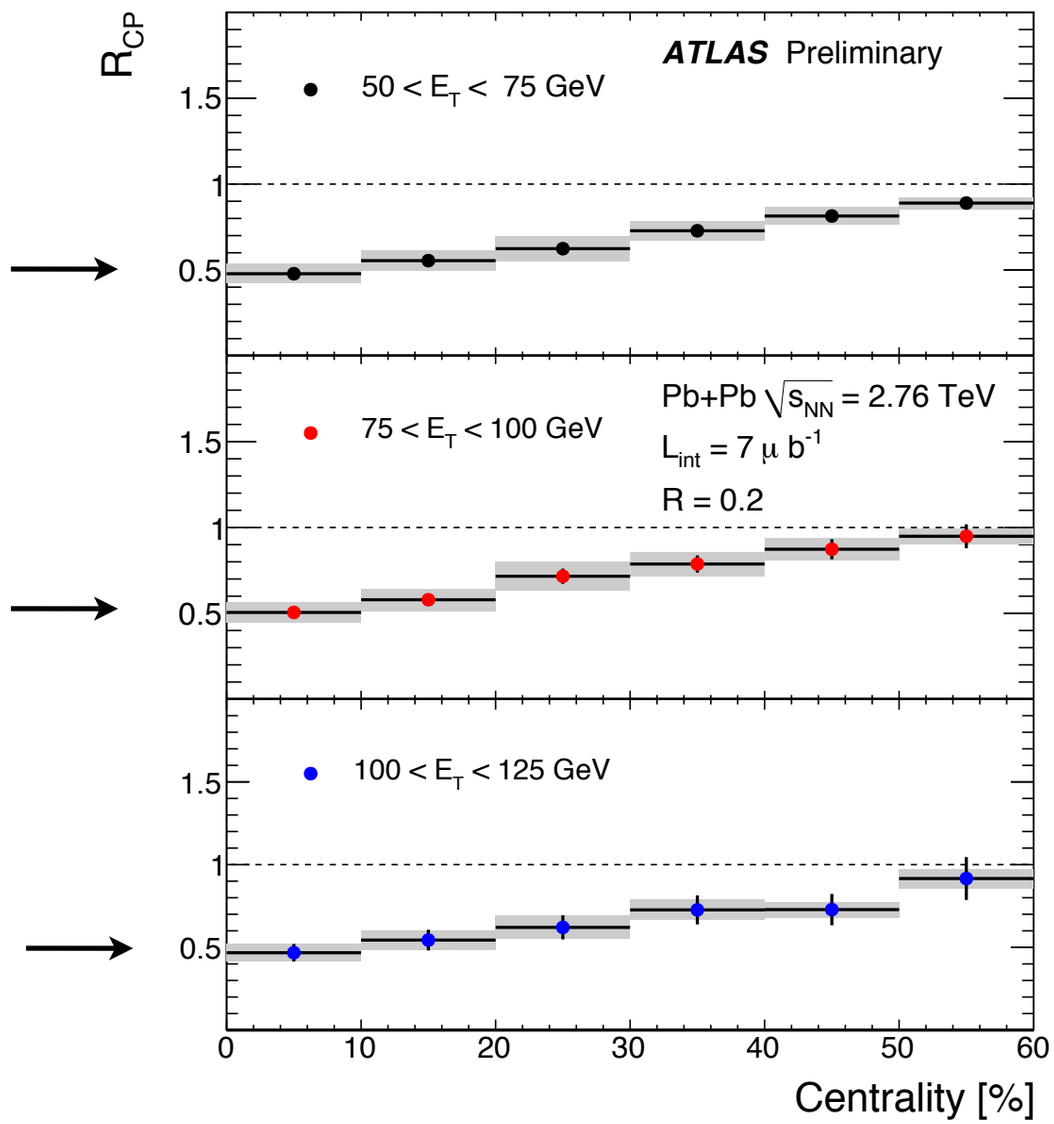
R=0.4



R=0.2

R_{CP} vs. centrality in E_T bins



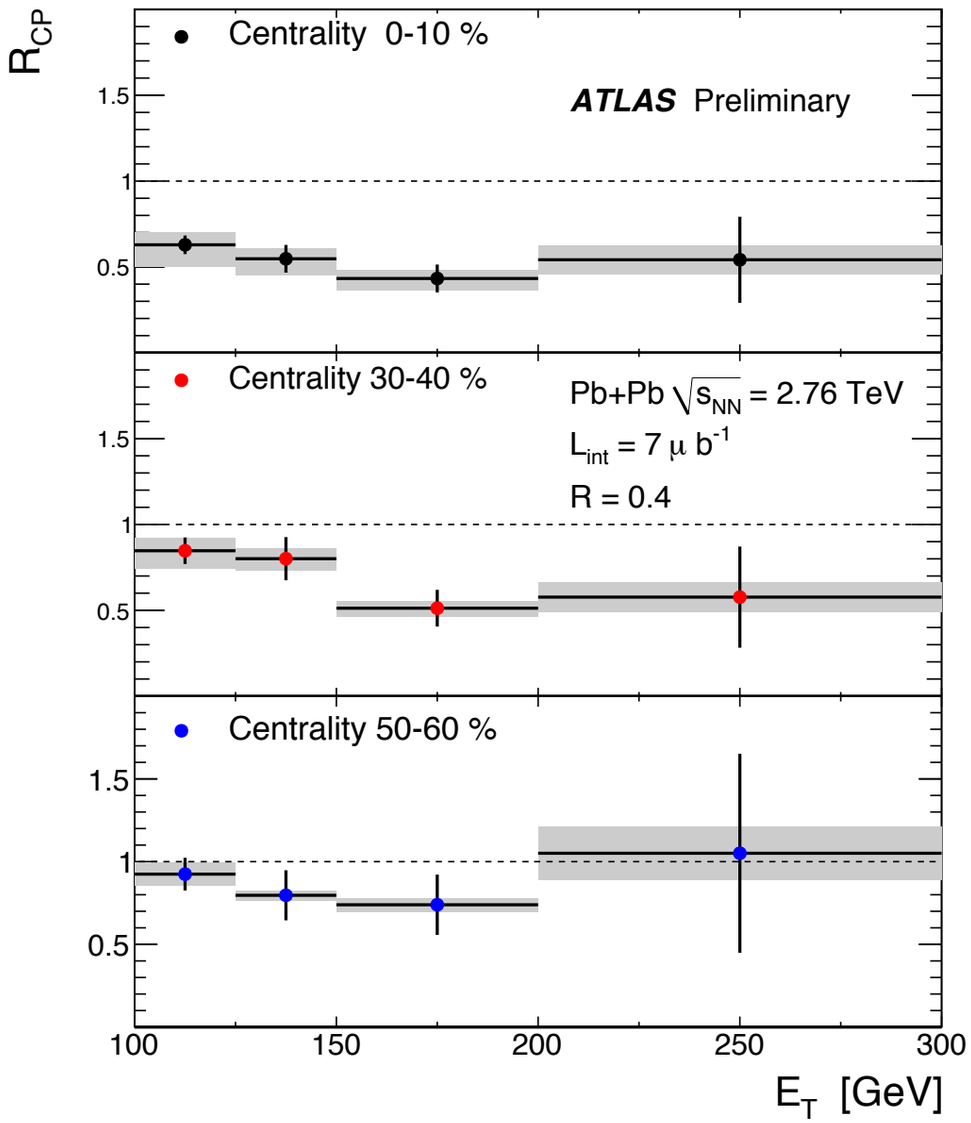


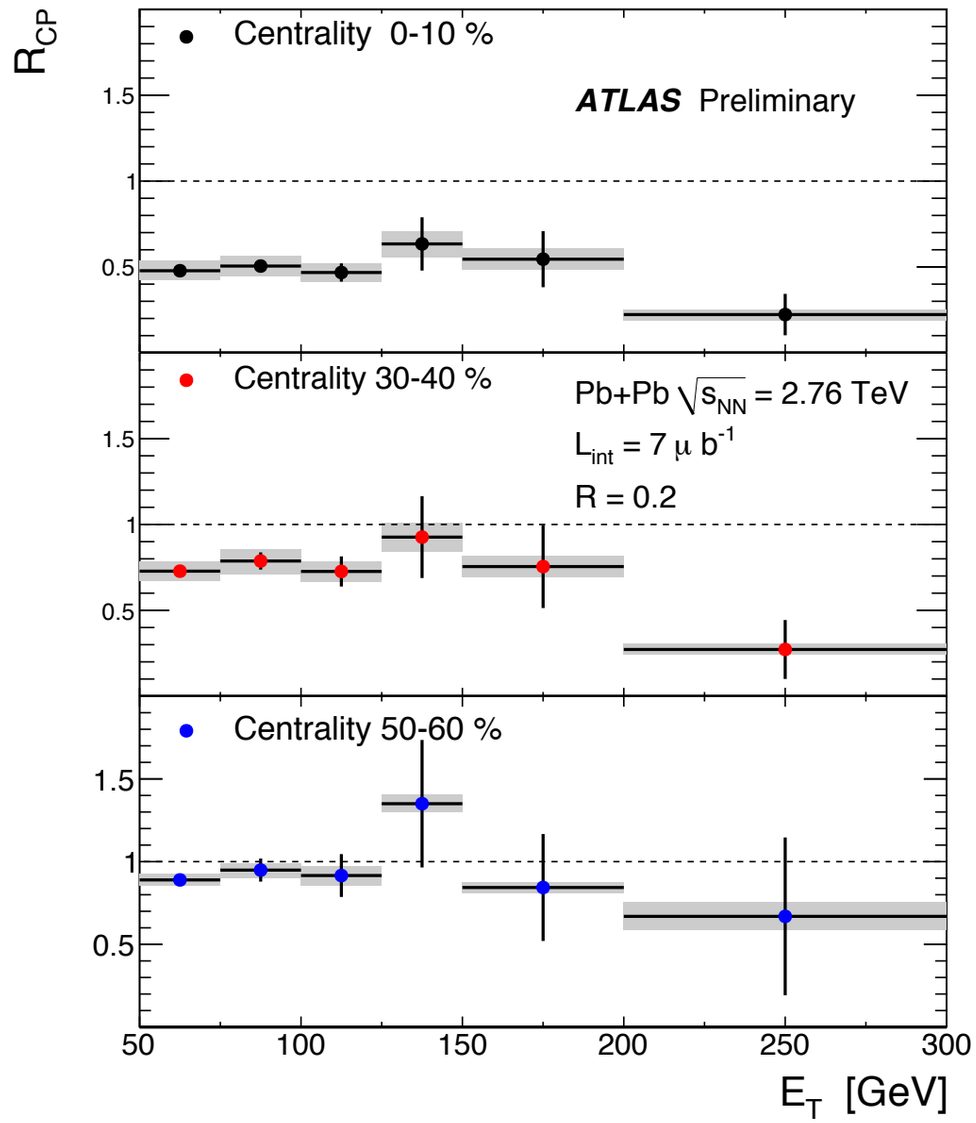
Suppression characterized by central/peripheral ratio (pinned on 60-80%)

$$R_{\mathrm{CP}} = \frac{\frac{1}{N_{\mathrm{coll}}{}^{cent}}\, E\frac{\mathrm{d}^3 N^{cent}}{\mathrm{d}p^3}}{\frac{1}{N_{\mathrm{coll}}{}^{periph}}\, E\frac{\mathrm{d}^3 N^{periph}}{\mathrm{d}p^3}}.$$

tends to ~0.5 in central bin

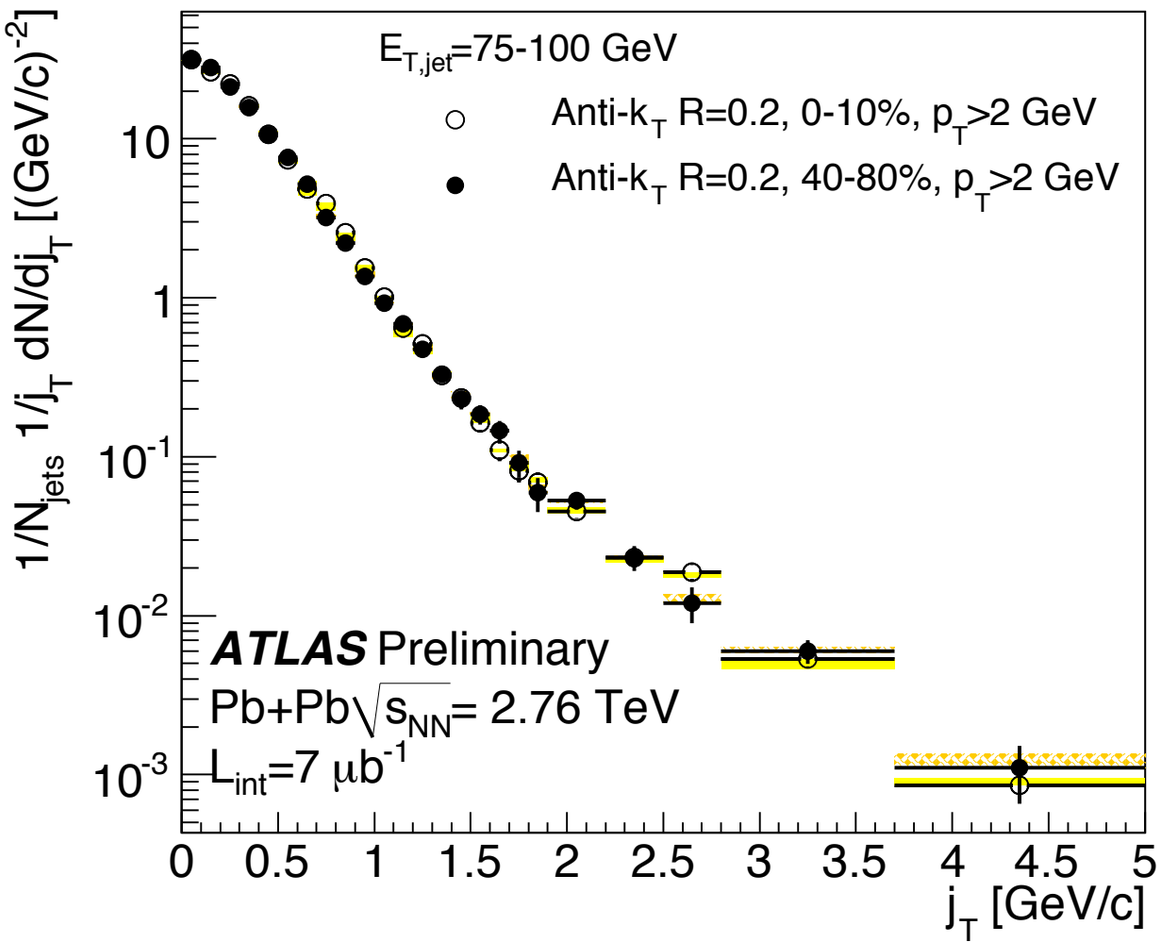
R_{CP} vs. E_T in centrality bins

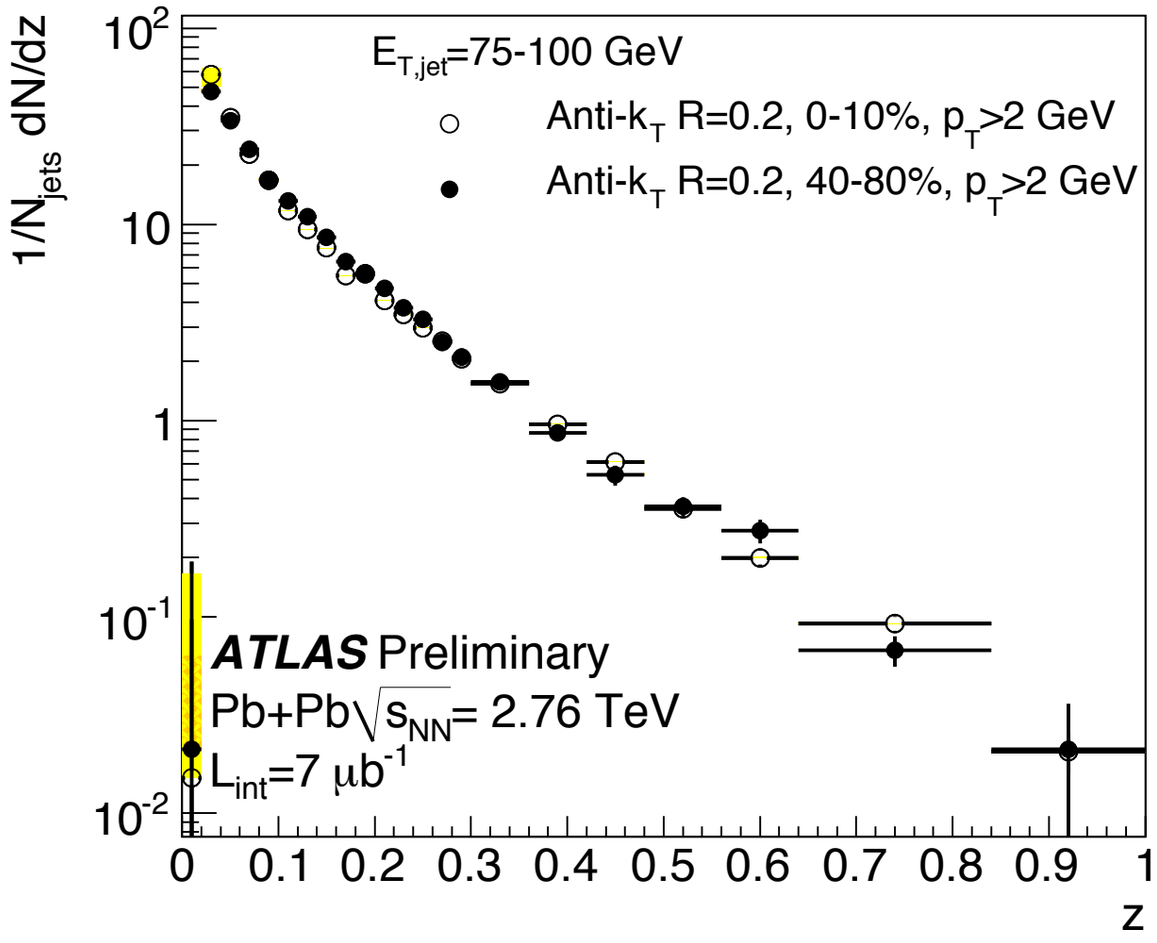




No appreciable E_T dependence of R_{CP} for R=0.4 & 0.2

Fragmentation Functions



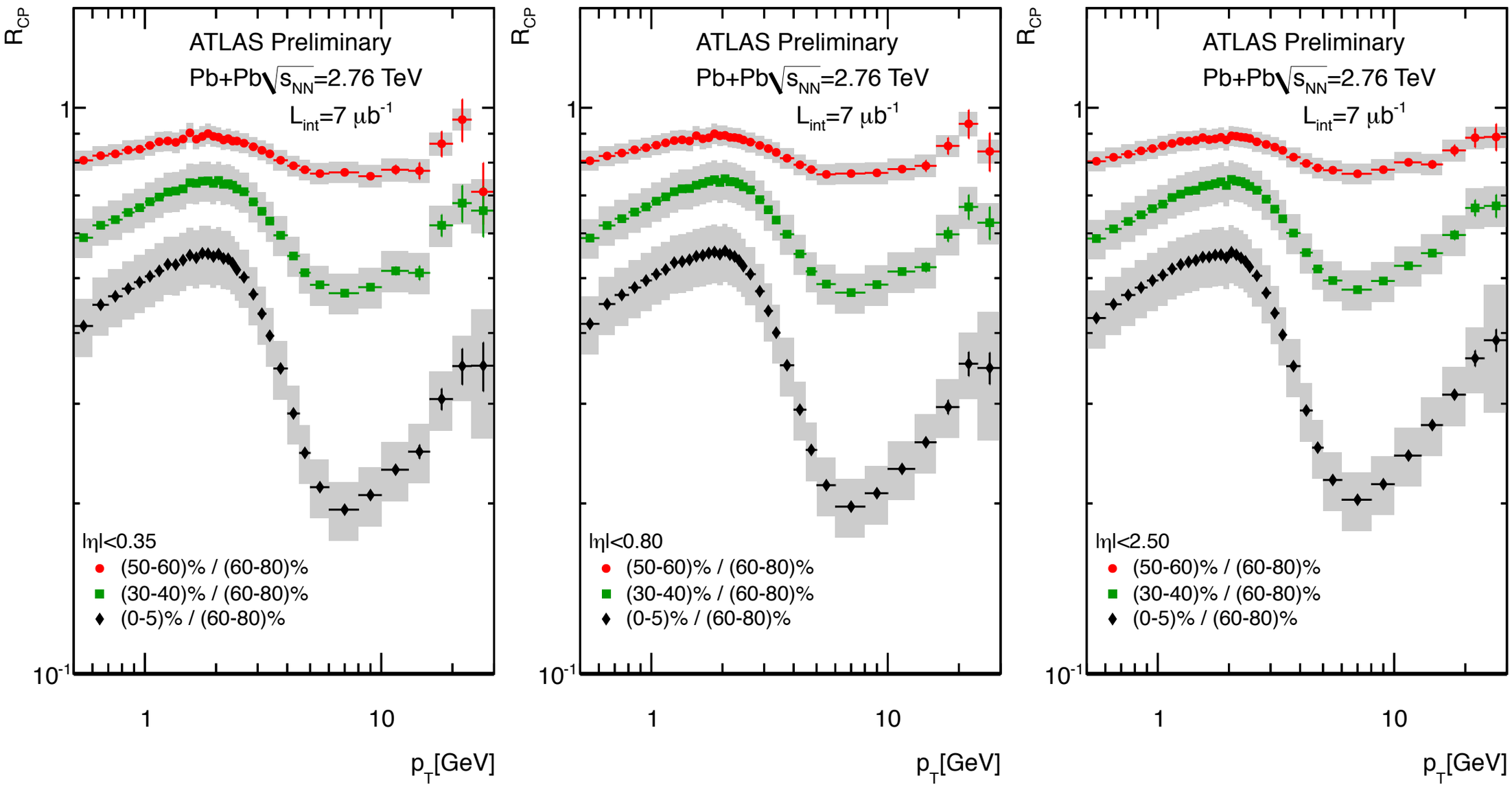


p_T cut to suppress underlying event, and background subtracted using region outside jet cone

Yellow bands represent uncertainties from background subtraction

No strong modification of fragmentation functions between peripheral and central: surprising in a radiative energy loss scenario?

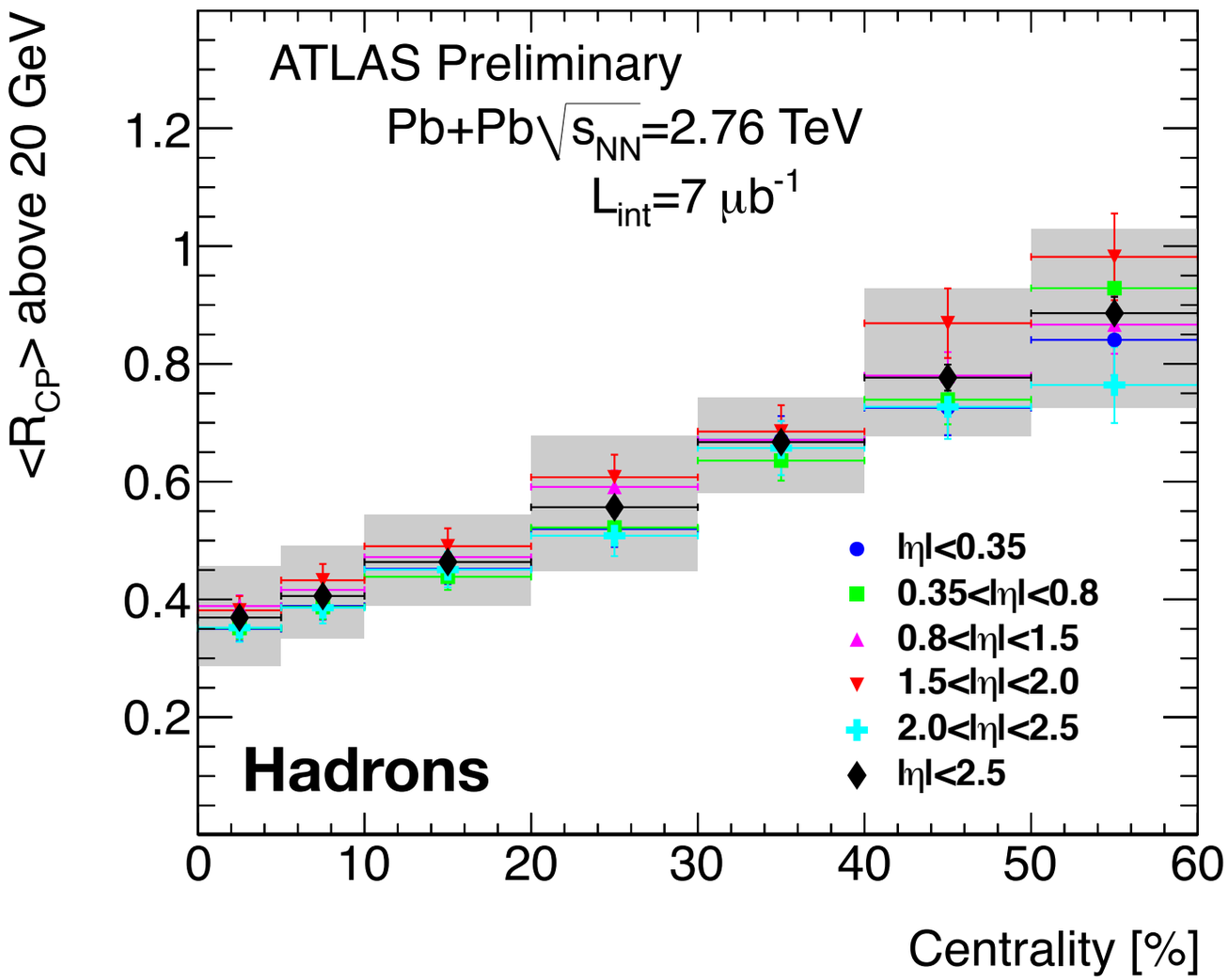
Charged particle R_{CP}

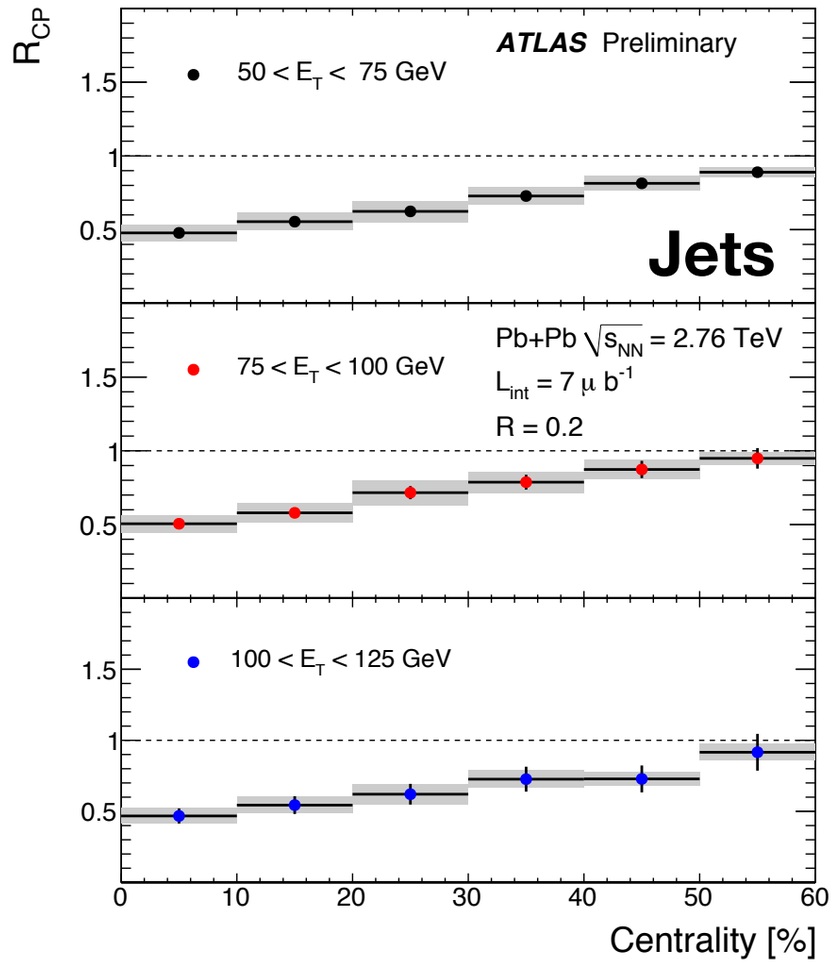


Strong suppression seen in more central events via charged R_{CP}

No η dependence observed

Centrality dependence of charged hadron R_{CP}





R_{CP}(p_T>20 GeV) shows systematic suppression, very similar to jets
(but R_{CP} still rising with p_T at 30 GeV)
Pseudorapidity dependence dominated by statistics in 60-80%

The first ATLAS asymmetry measurement

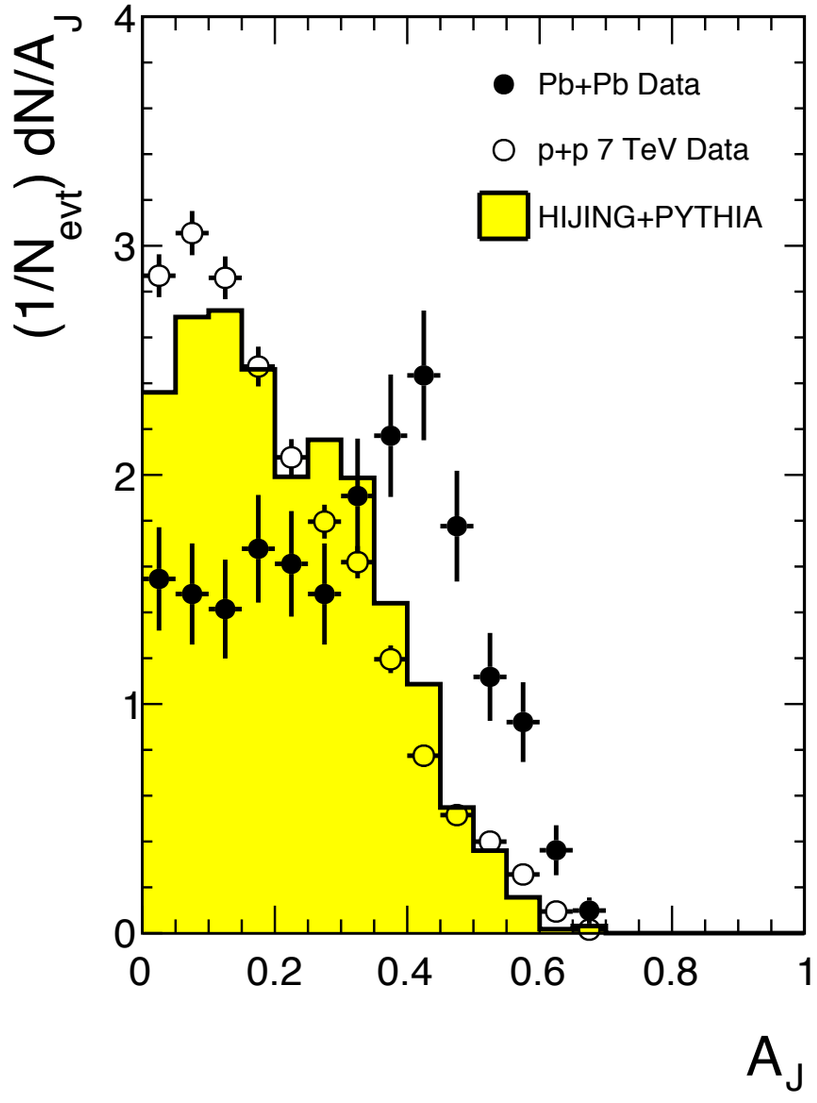
Asymmetry defined as:

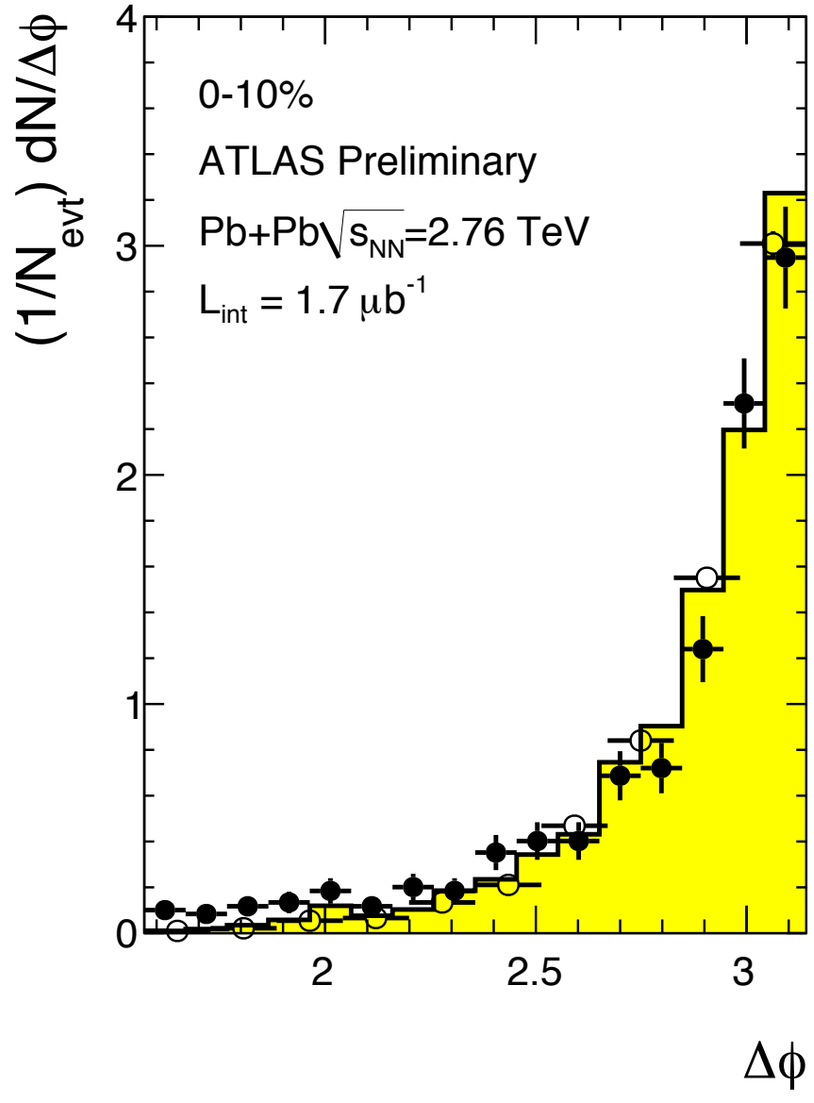
$$A_{\mathrm{J}} = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

for $\Delta\phi > \pi/2$

$E_{T1} > 100\mathrm{GeV}$

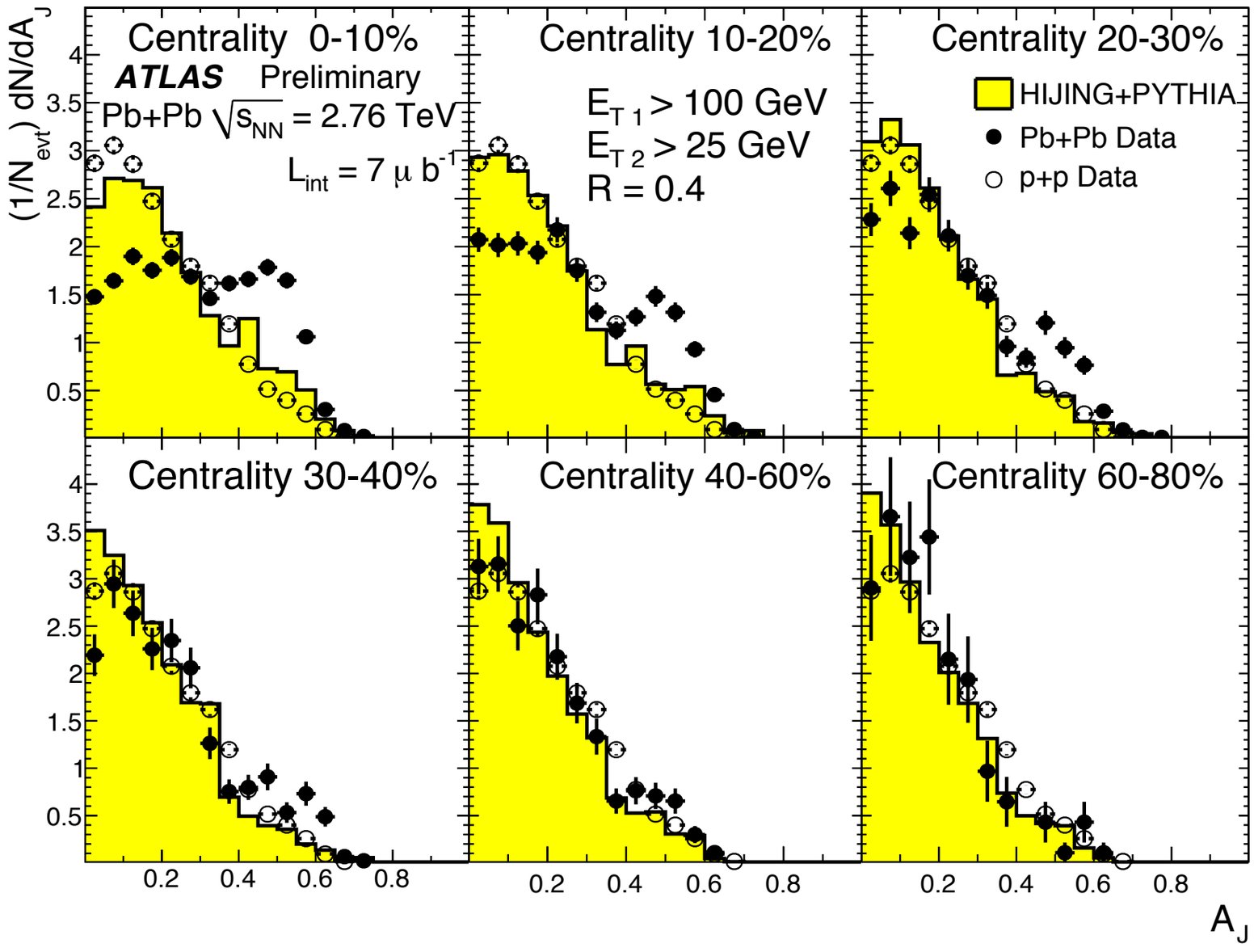
$E_{T2} > 25\mathrm{GeV}$





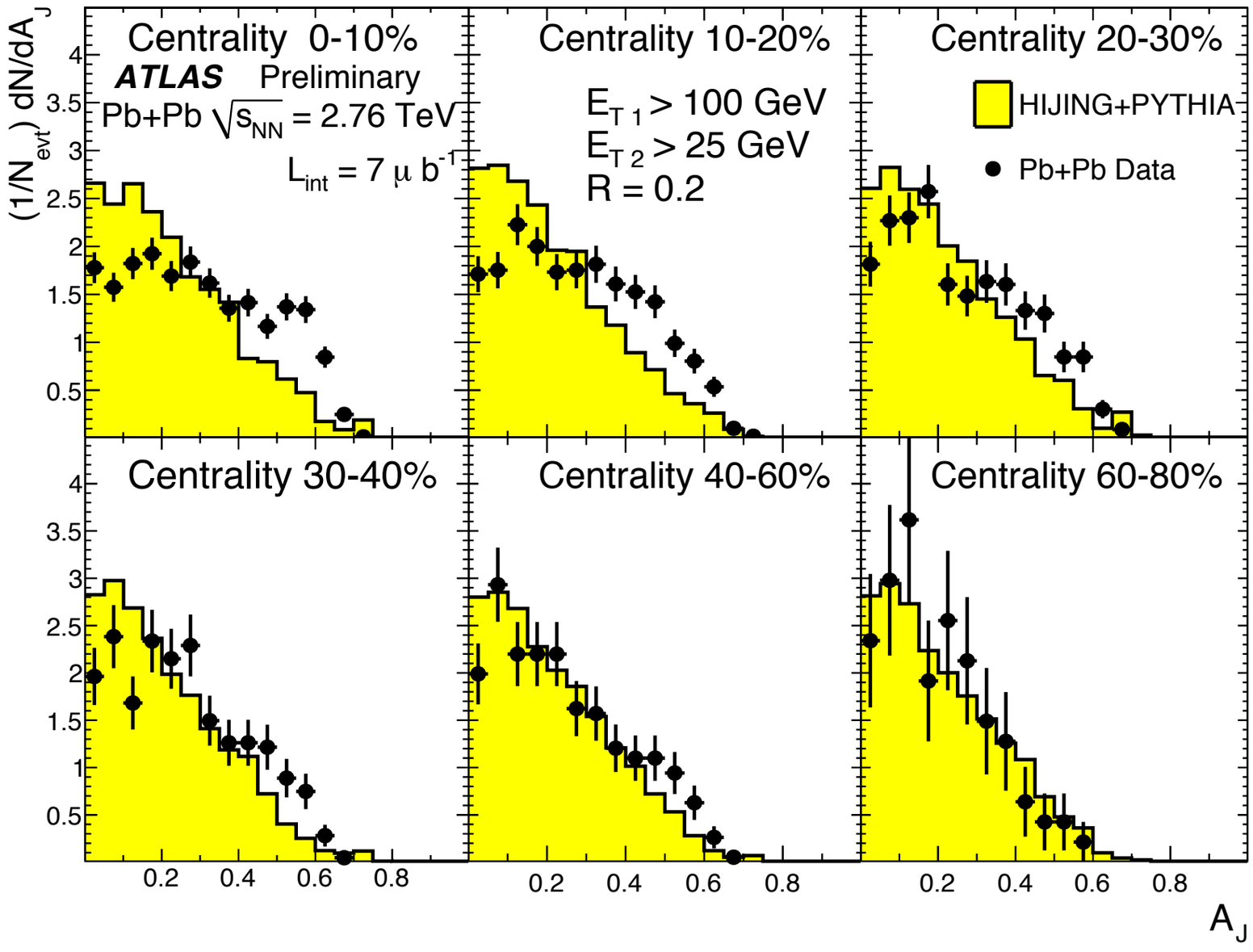
First measurements: broad asymmetry distribution, back-to-back angular distribution

Asymmetry, updated



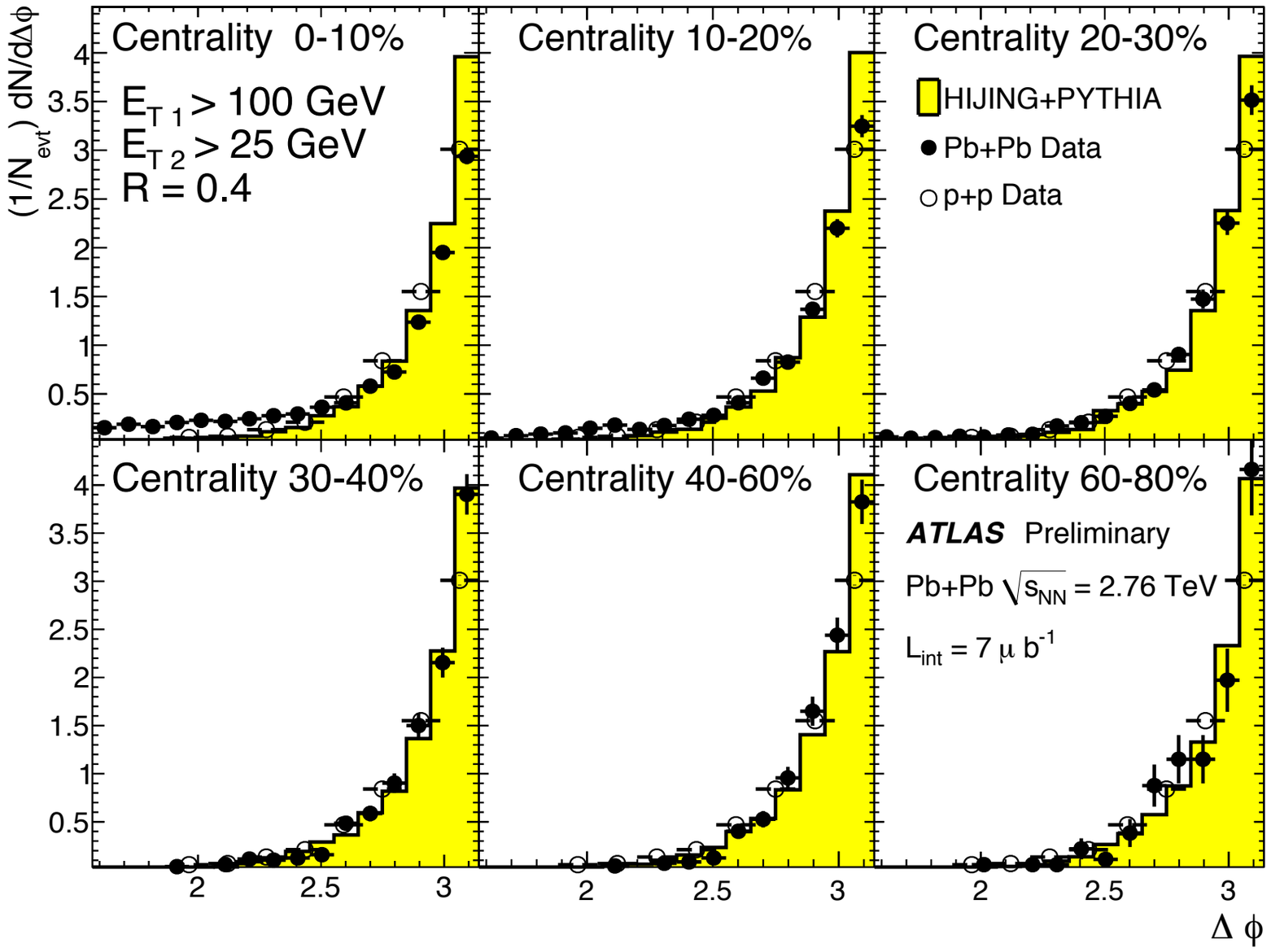
New results incorporate a flow-sensitive background, better control of jet energy, higher statistics

Asymmetry, updated



Asymmetry results robust, persist for R=0.2 jets,
with much less sensitivity to background fluctuations

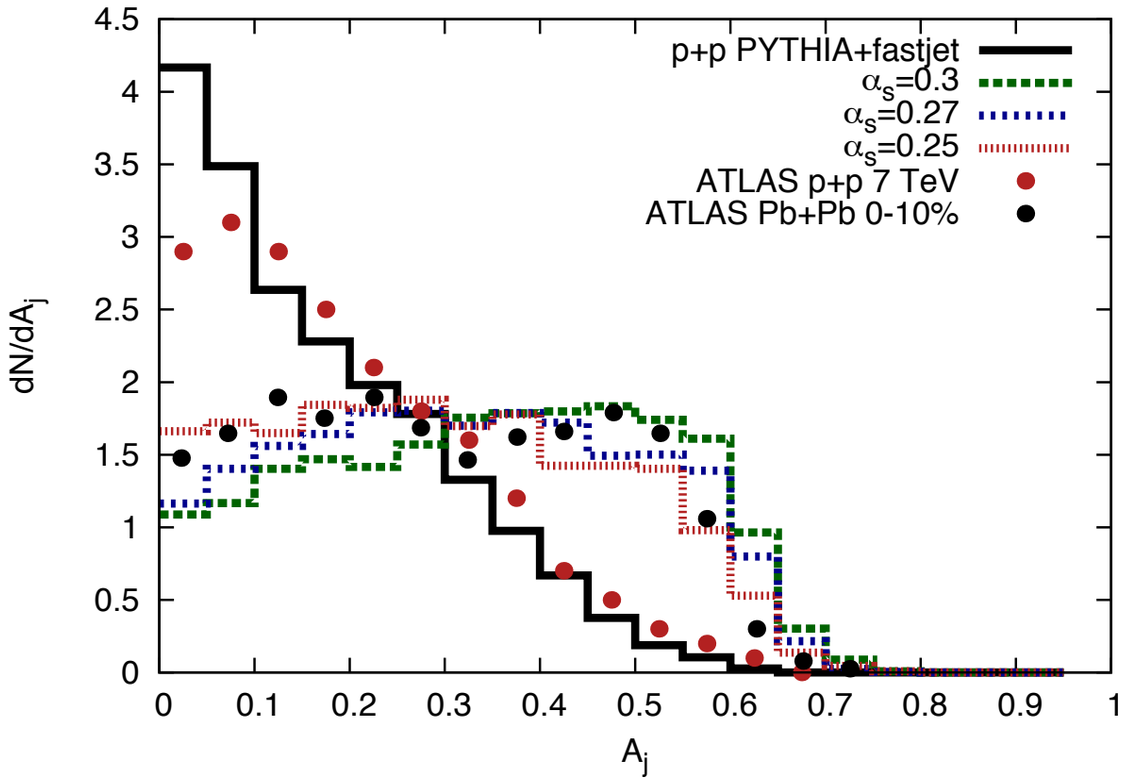
Asymmetry, updated

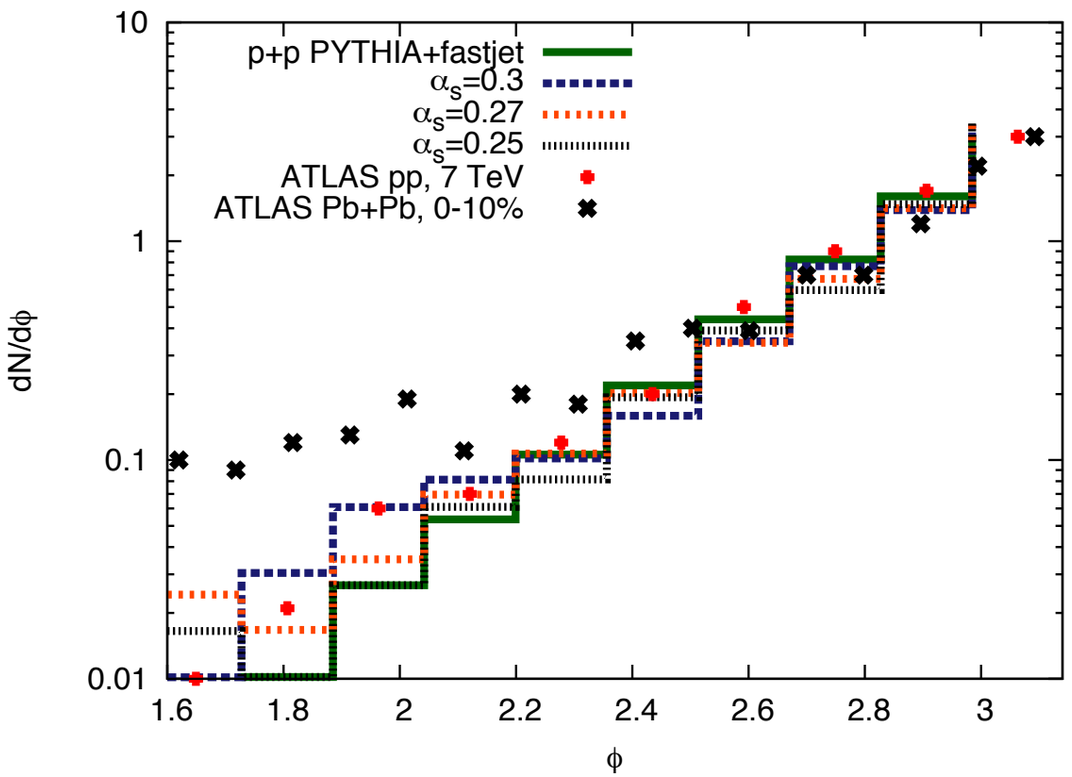


Dijets are produced back-to-back at all centralities,
even when asymmetry distribution has been modified.
Possible small contribution from fake jets in central events at large $\Delta\phi$

Modeling jet asymmetry

Young, Schenke, Gale, Jeon (2011 v2)





Theory community is already making use of this data.

MARTINI (jet quenching, radiative and collisions E-loss)
using **MUSIC** (hydro) background
can model salient features of asymmetry data:
"flat" A_J distribution and **peaked Δϕ distribution**

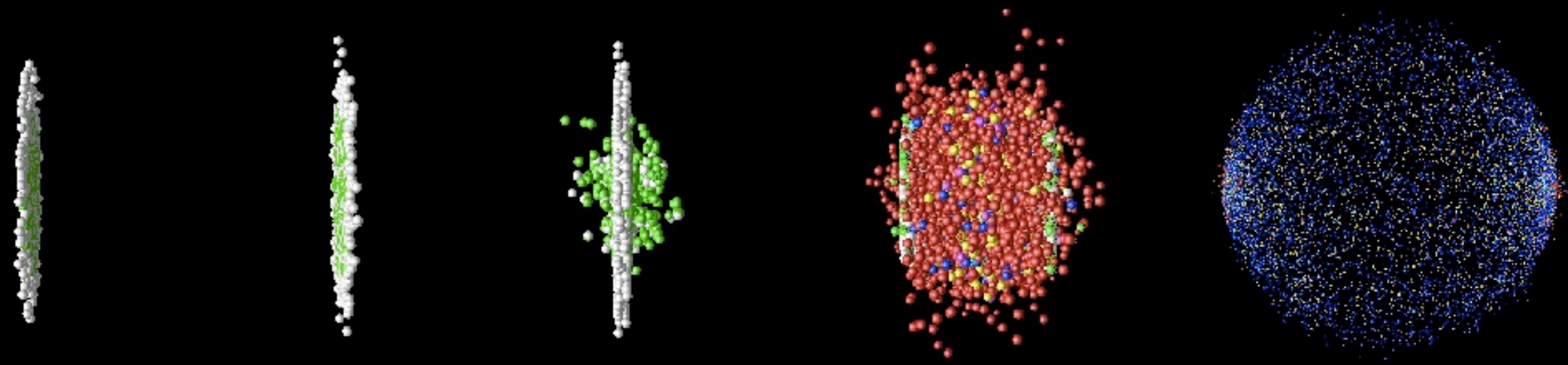
Conclusions

- **Global observables**
  - Centrality dependence of inclusive multiplicity scales with beam energy
  - Transverse momentum dependence of v_2 scales out to highest p_T (modulo large errors at RHIC).
    - *New comparisons with energy loss calculations.*
    - Detailed study of higher order flow coefficients challenges ridge & cone interpretation. New information to help constrain viscous hydro models.
- **High p_T observables**
  - $W^{\pm}$ production consistent with simple scaling with N_{coll}
  - Jet production systematic suppressed by a factor of ~2 relative to peripheral collision.
  - Charged hadron R_{CP} measured out to 30 GeV: centrality dependence of suppression similar to jets
  - Asymmetries robust, and being successfully modeled in recent calculations

Plans

- **Looking forward to a productive 2011**
  - Quark Matter publications imminent
  - More systematic studies of jets, high p_T charged particles, heavy flavor
  - Electromagnetic processes (especially photons)
- **2011 LHC Pb+Pb run expected to begin mid-November**
  - Higher luminosities, requiring careful triggering on high p_T jets, muons and electromagnetic processes
  - Will allow more detailed studies of hard processes & quarkonia with improved statistics
- **Exciting time for HI physics: two machines and 5 experiments!**

Heavy ion collisions: the first 3×10^{-23} seconds



Initial Nuclei

Energy Stopping & Hard Collisions

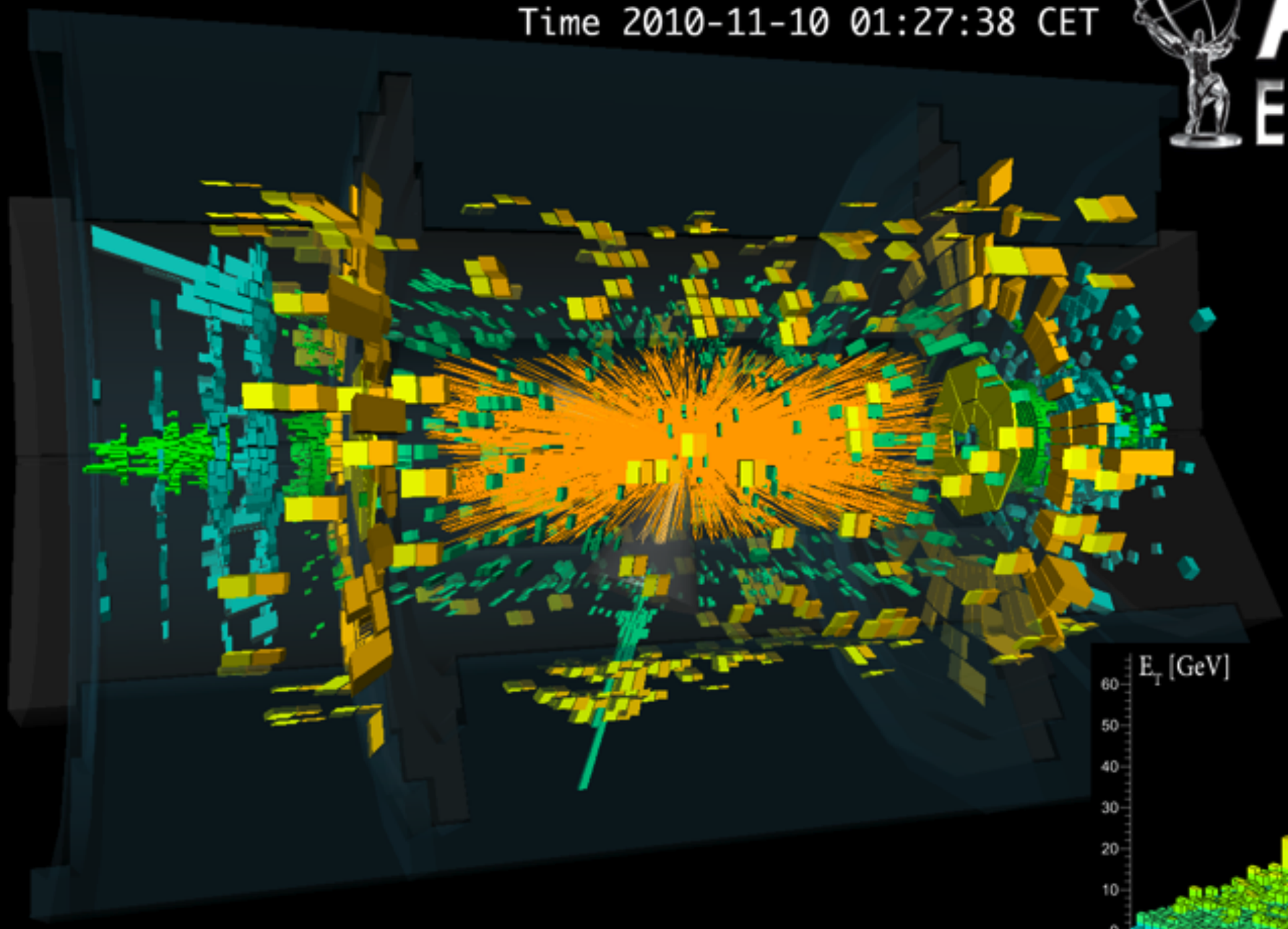
Hydrodynamic Evolution

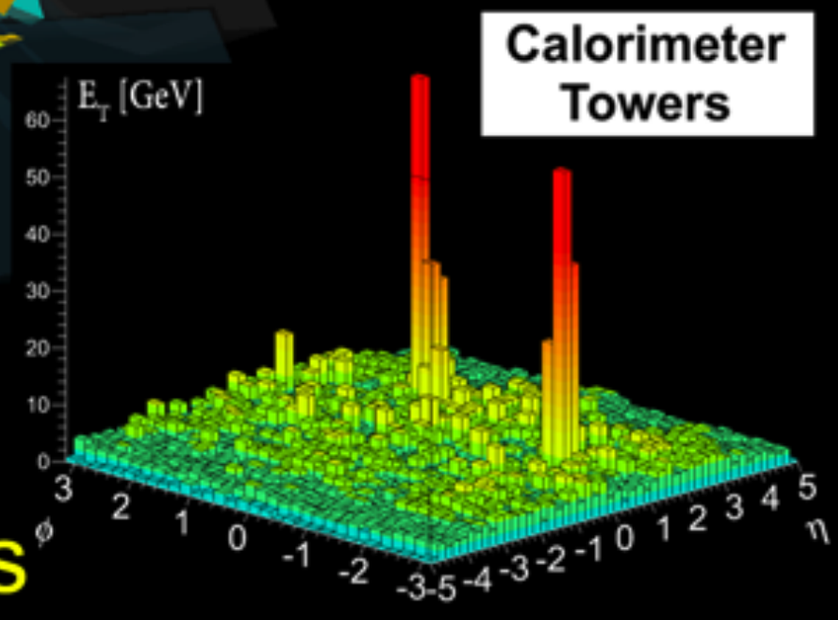
Hadron Freezeout

The goal of heavy ion physics is to “rewind the movie”
to study the hot, dense medium formed in the early moments

Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET

ATLAS EXPERIMENT



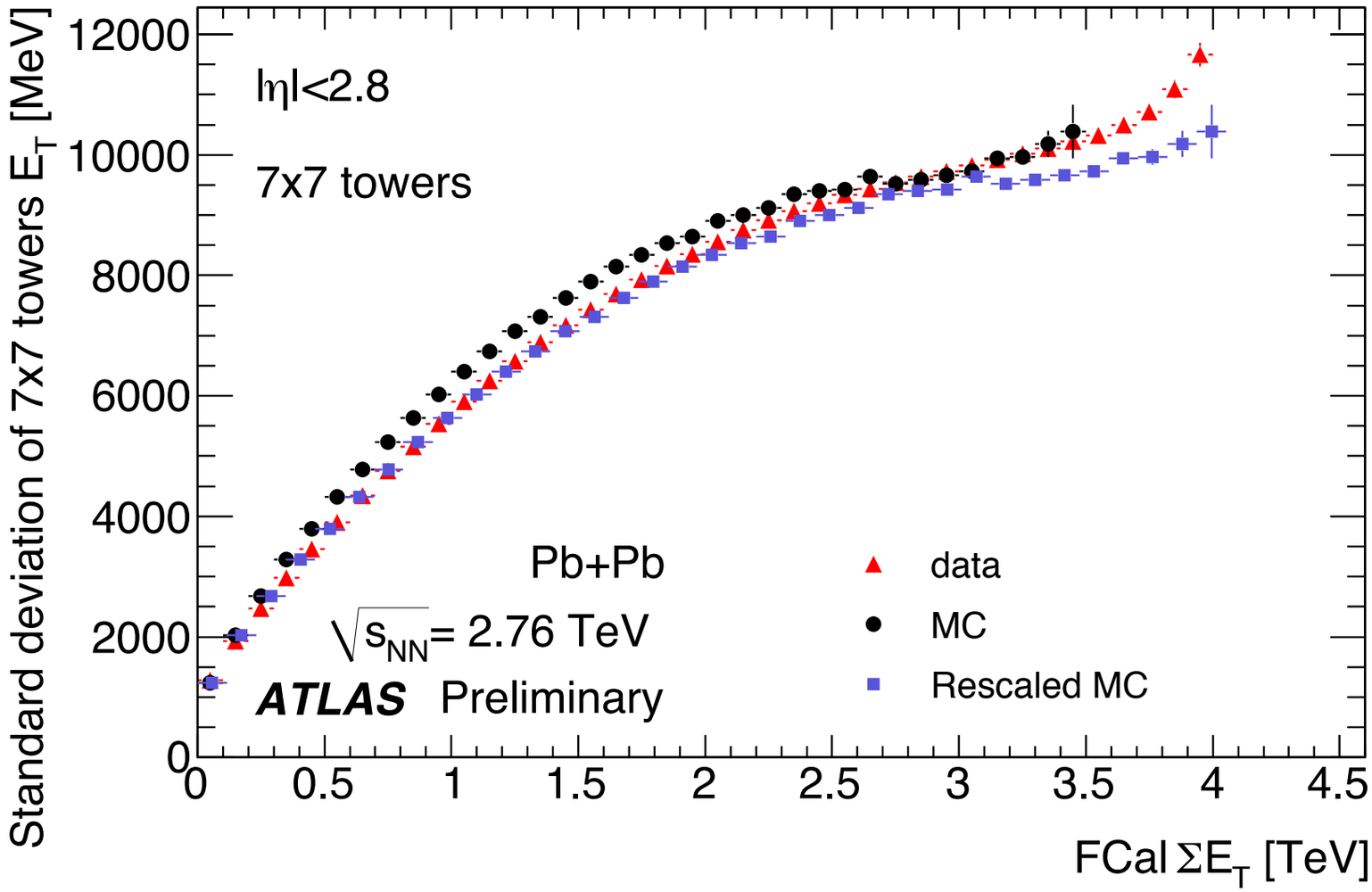


Heavy Ion Collision Event with 2 Jets

Minimum bias triggering

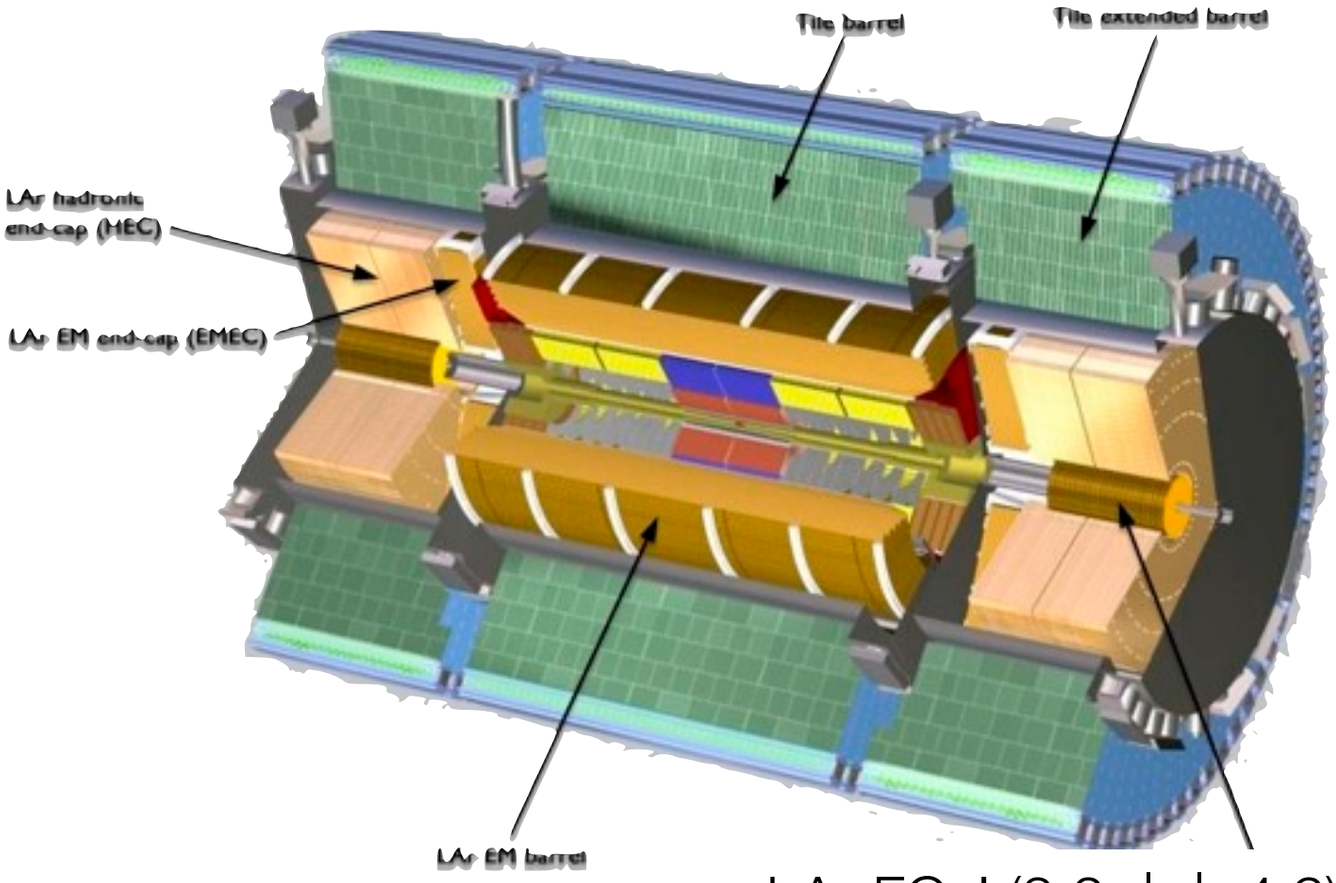
- **The 2010 data set was taken with a minimum bias trigger configuration**
  - Coincidence of minimum bias trigger scintillators ($2.1<|\eta|<3.9$)
  - Coincidence of neutrons in Zero Degree Calorimeters
- **Offline requirements of**
  - MBTS time difference $|\Delta t|<3$ ns
  - Coincidence in ZDC
  - Reconstructed vertex in Inner Detector
- **Efficient rejection of**
  - Beam-gas events
  - Inelastic photonuclear events
- **No physics triggers (e.g. jets, muons) used in event selection**

Underlying event fluctuations



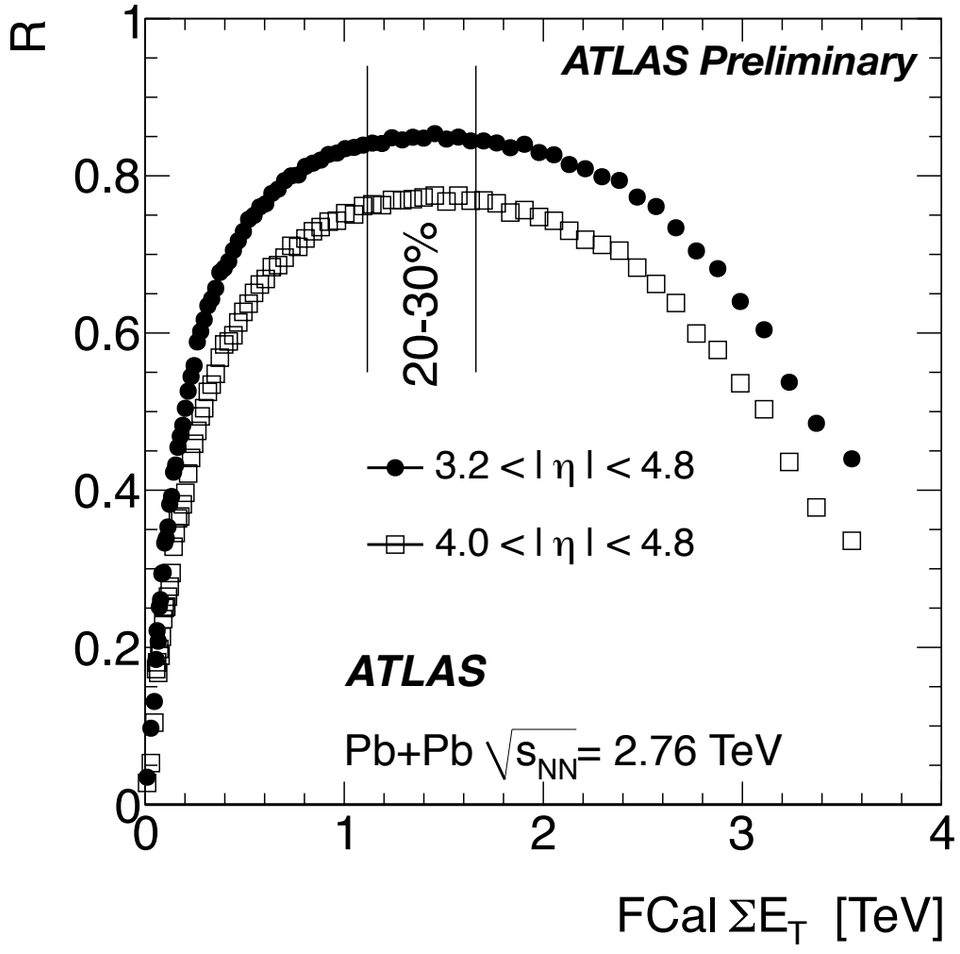
Detailed look at variable-size square patches in data and MC. After 15% adjustment of FCal ΣE_T scale, good agreement over nearly full centrality range

Elliptic flow measurements



LAr FCal (3.2<|η|<4.9)

$$R = \sqrt{\langle \cos[2(\Psi_2^N - \Psi_2^P)] \rangle},$$

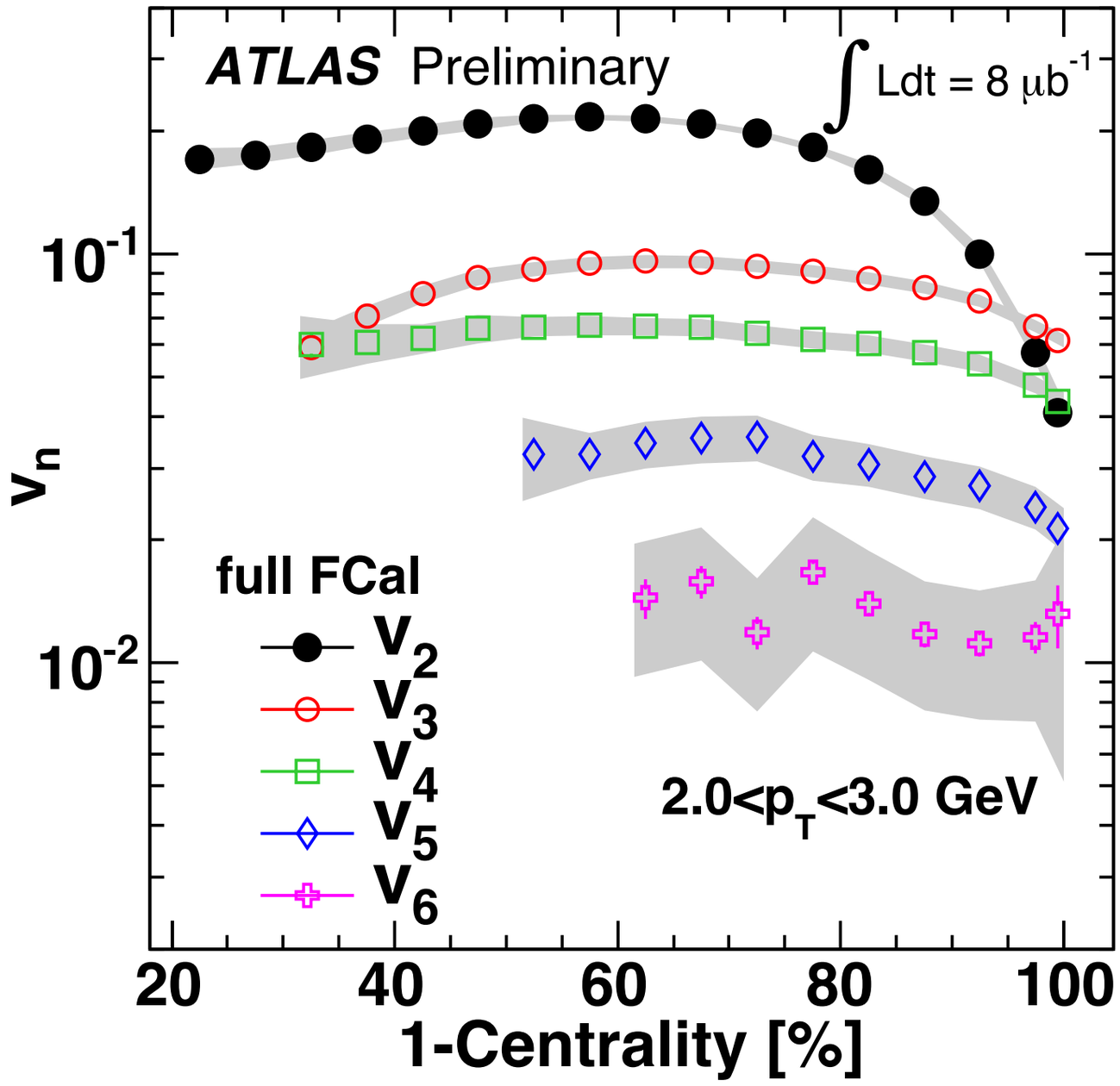


ATLAS forward calorimeter used for event plane determination.
Resolution correction factor for subevents ~75-85% in mid-central events.
Tested in subregions of calorimeter acceptance.

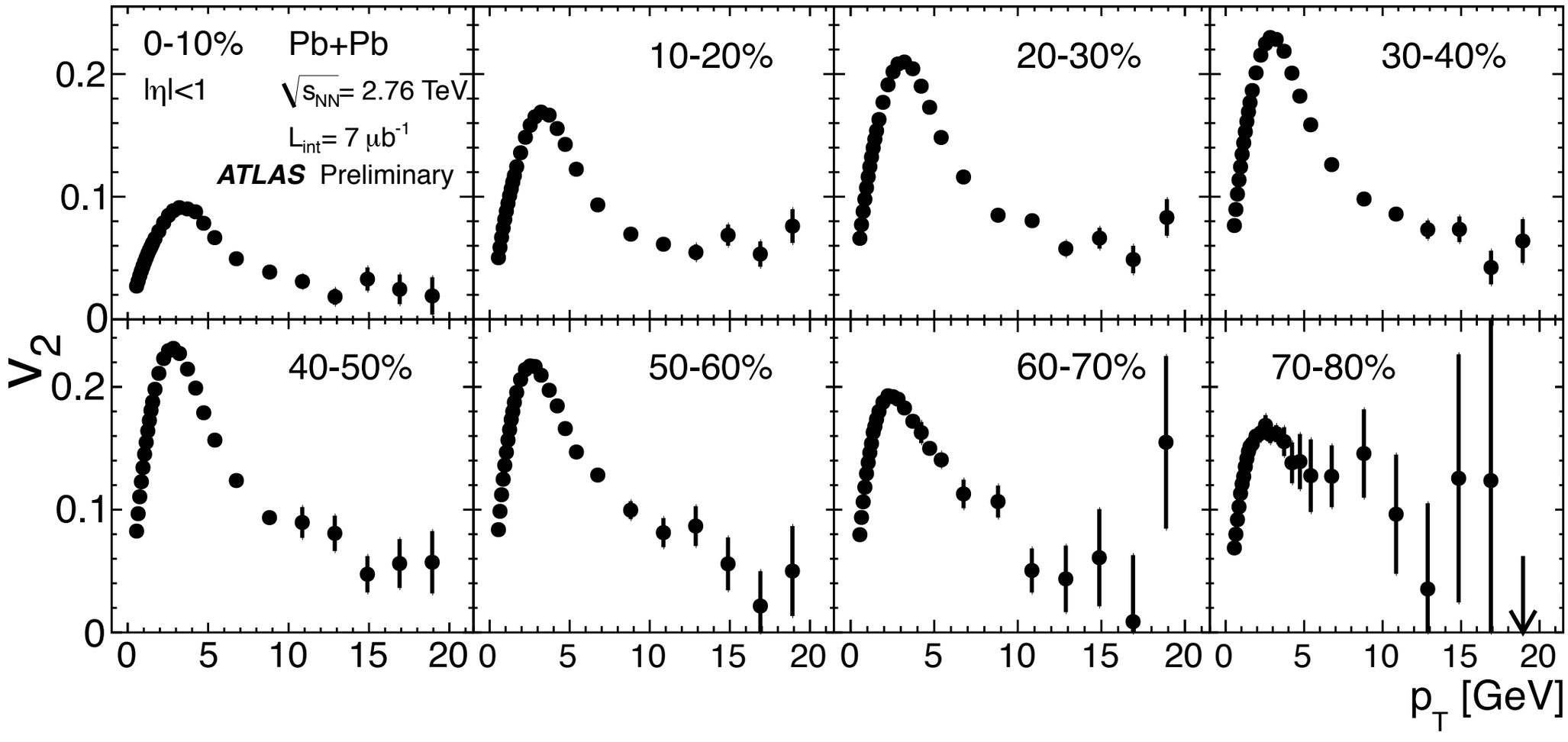
Higher order moments vs. p_T and centrality

At all moderate p_T values (only 2-3 GeV shown here) weak centrality dependence for v_3-v_6

v_2 is <u>not</u> the largest component for central events.



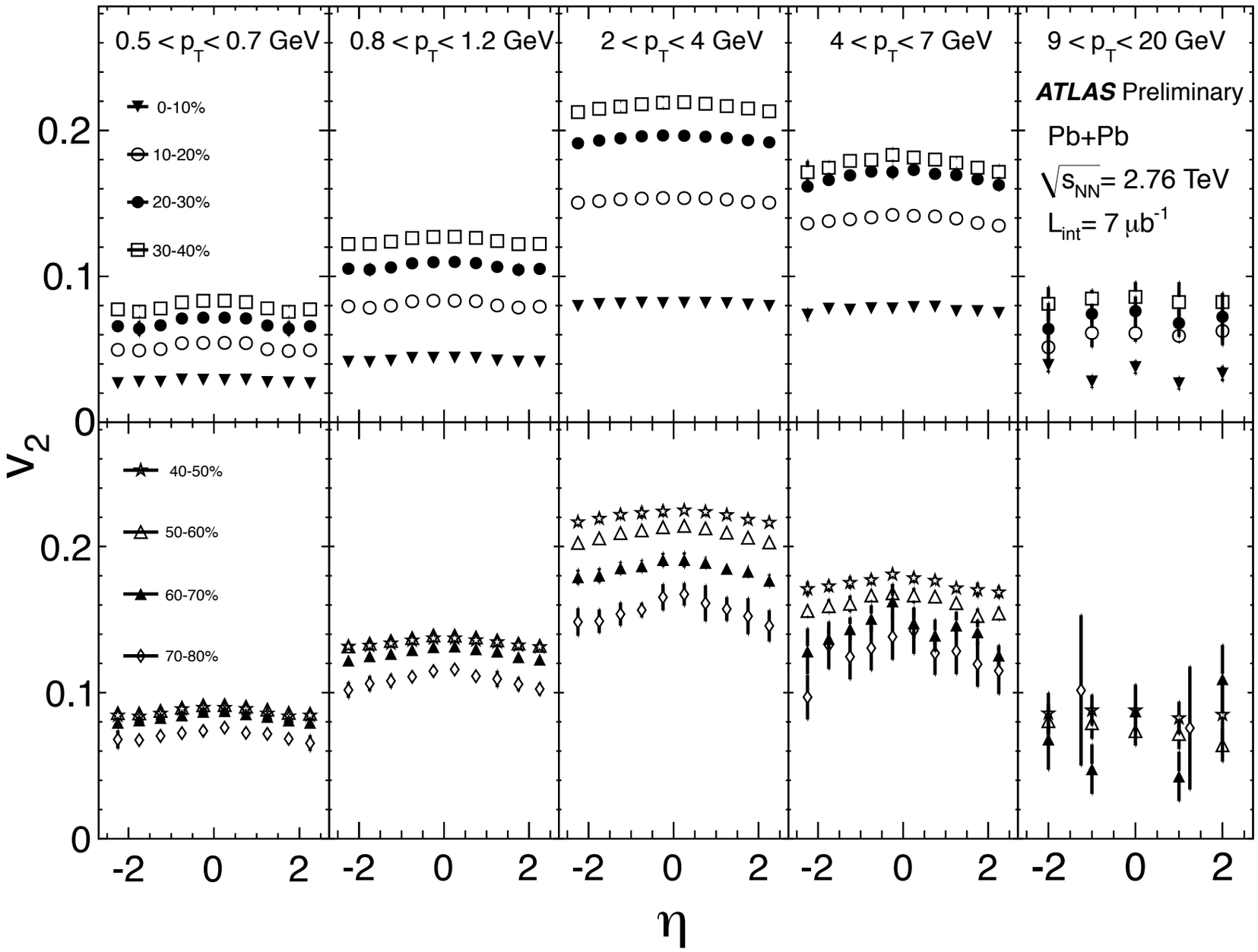
Transverse momentum dependence of v_2



Centrality and p_T dependence of v_2:
Rapid rise up to 3-4 GeV, less rapid decrease to 8-9 GeV,
and then weak p_T dependence out to 20 GeV.

Pseudorapidity dependence

Very weak
η dependence
above 500 MeV

Measurements
out to |η|=2.5
show systematic,
but small
decrease of v_2

Very different than
RHIC which had
a strong η dependence