Measurement of elliptic flow and higher-order flow harmonics from the event plane and two particle correlation methods in $\sqrt{s_{NN}}$ = 2.76 TeV Pb+Pb collisions with ATLAS detector at the LHC

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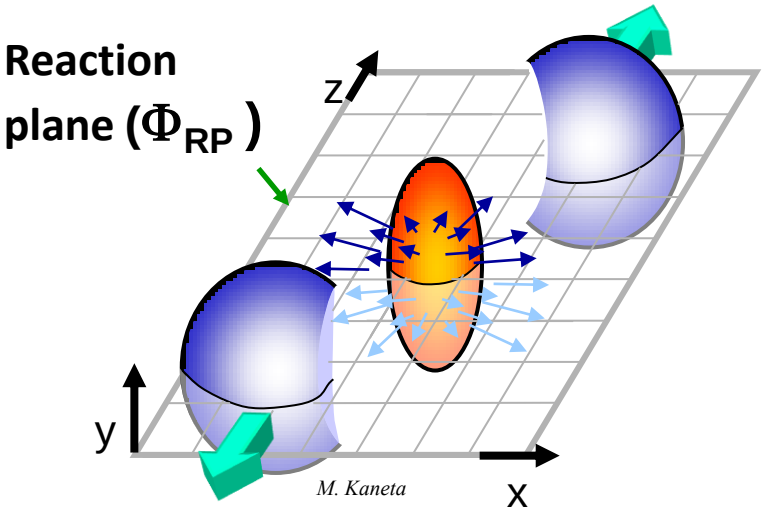
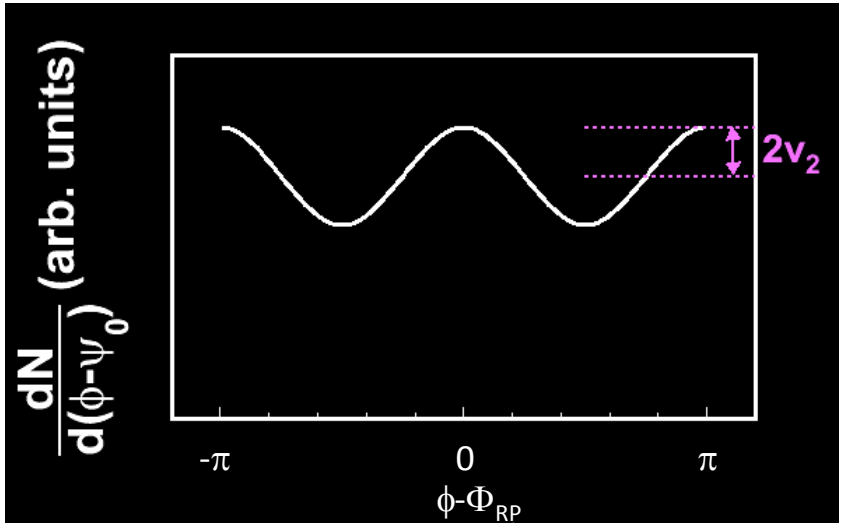
Azimuthal Anisotropy of Produced Particles

Strongly interacting QGP





- **Pressure gradients lead to azimuthal anisotropy**

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

v_2 – elliptic flow

$$v_n = \langle \cos(n(\phi - \Phi_{RP})) \rangle$$

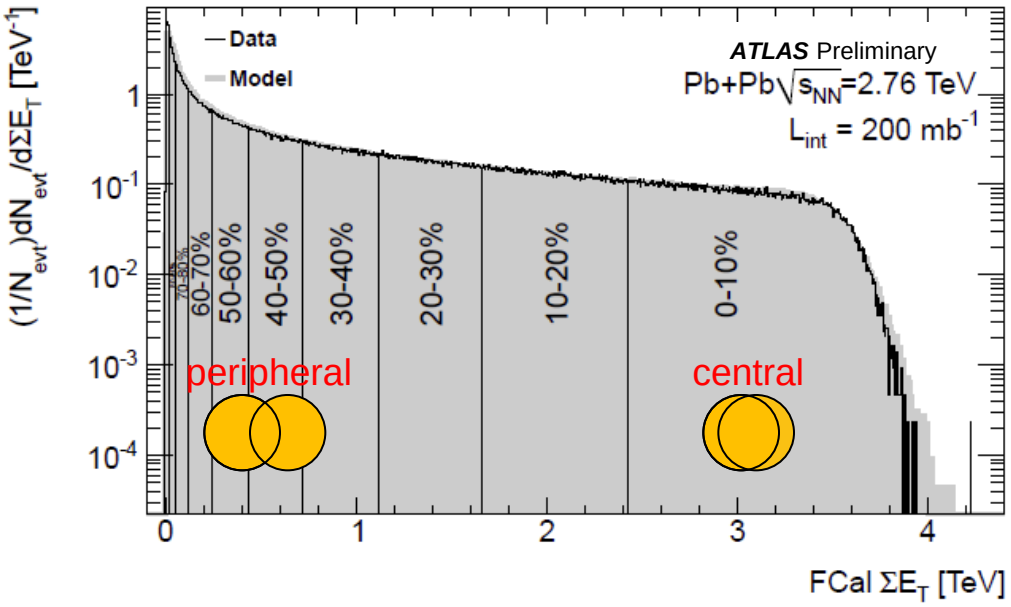
Event Selection and Centrality Determination

First heavy ion run at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$

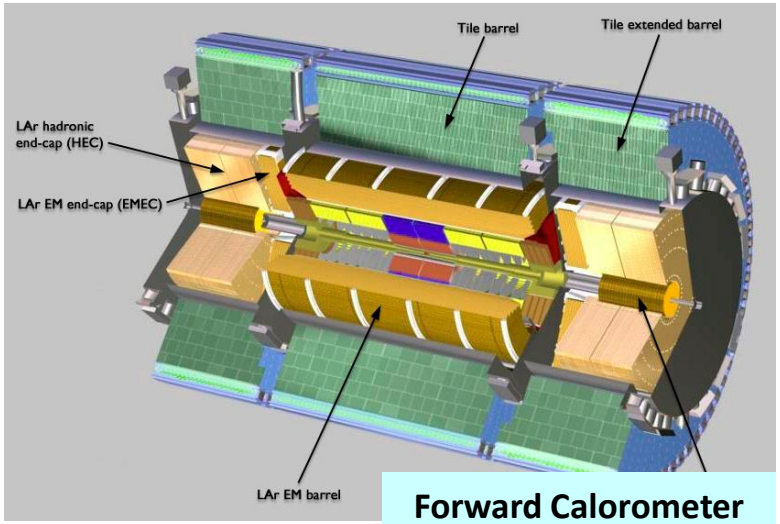
- Nov 4th-Dec 6th, 2010
- **~40 M Pb+Pb** events (~7 μb^{-1}) enter flow analysis after Data Quality, trigger cuts

Pb+Pb events are divided into 10% centrality bins according to measured total transverse energy in forward calorimeter (FCal)

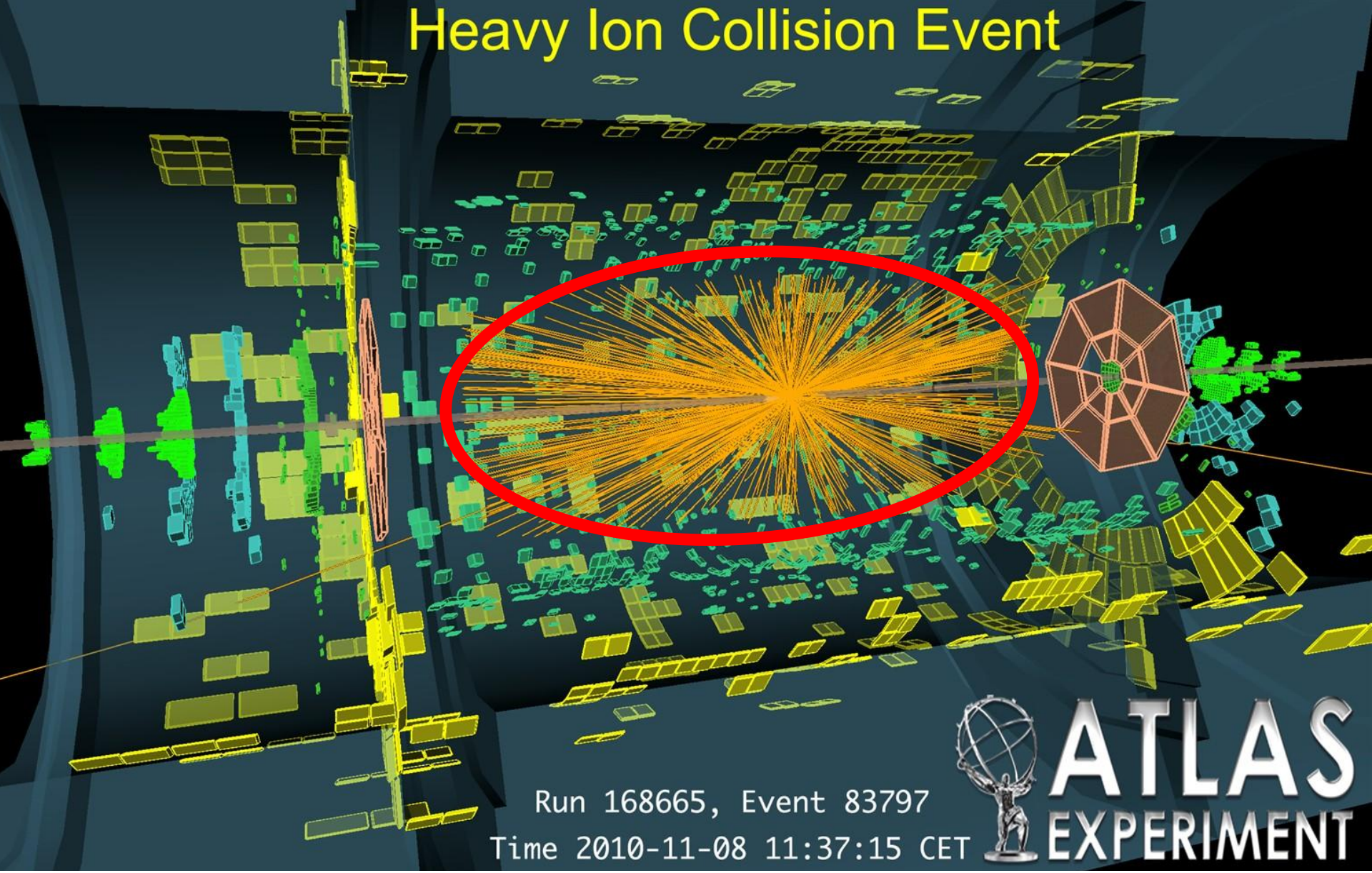
E_T in Forward Calorimeter



ATLAS Calorimeter System

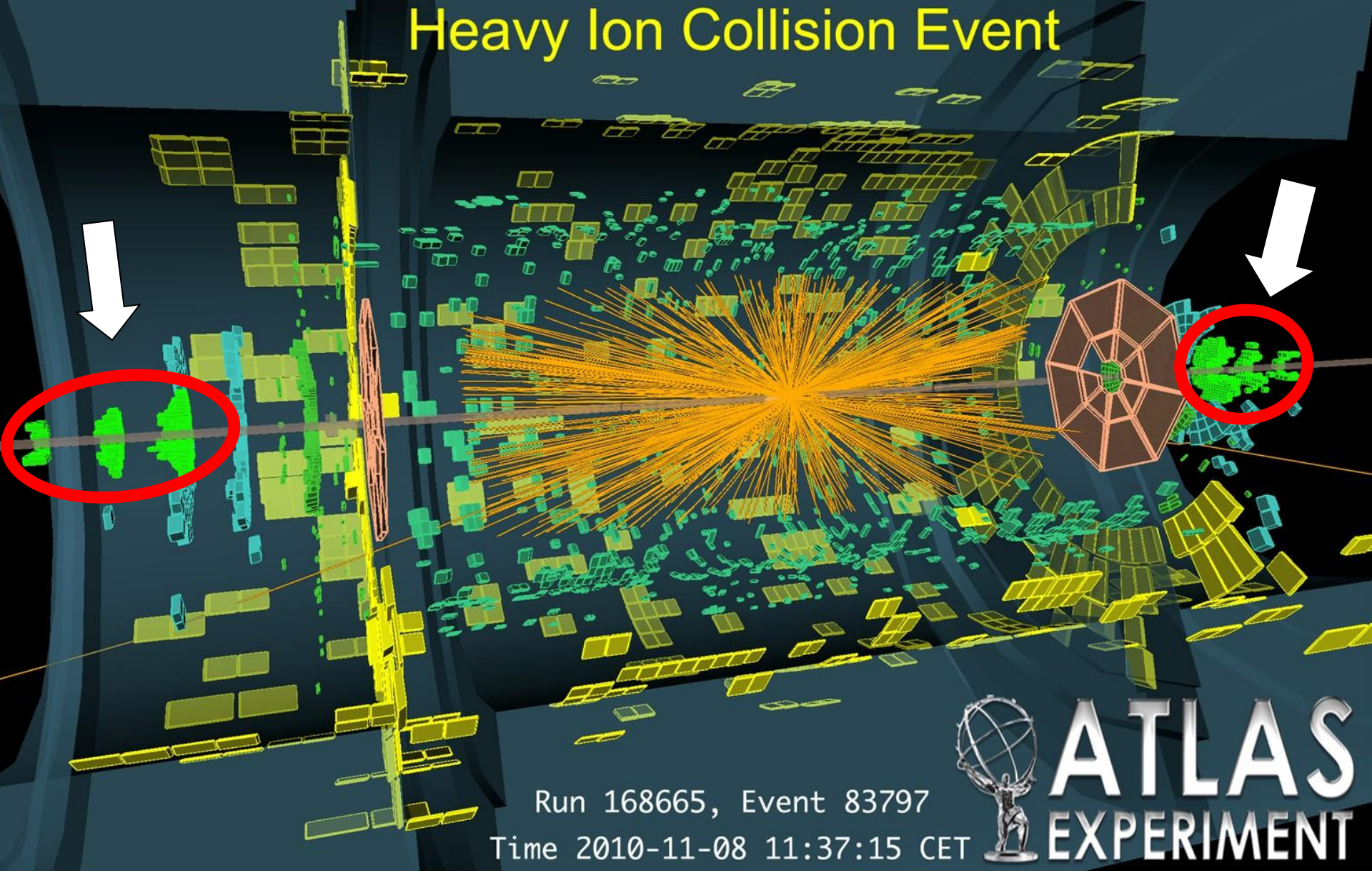


Forward Calorometer
3.2<|η|<4.9,(one arm)



Tracks from Inner Detector are used for v_n determination

p_T = 0.5-20 GeV, $|\eta|<2.5$, full azimuthal acceptance



For event plane determination forward calorimeter is used,

$3.2<|\eta|<4.8$, full azimuthal acceptance

Azimuthal Anisotropy in Pb+Pb collisions

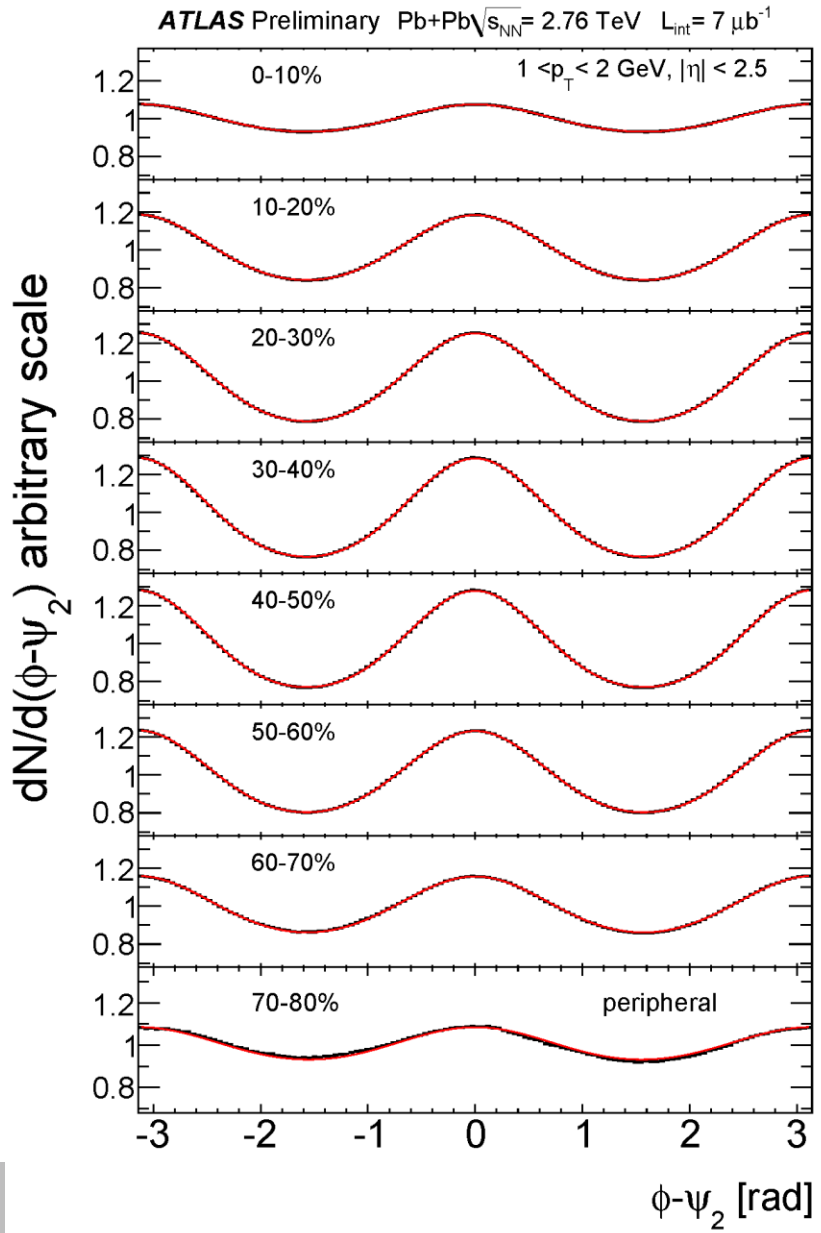
Φ_{RP} is approximated by event plane obtained for each FCal sub-event

$$\psi_n^{P/N} = \frac{1}{n}\tan^{-1}\frac{\sum_{i(P/N)} E_{T,i}^{tower} w_i \sin(n\phi_i)}{\sum_{i(P/N)} E_{T,i}^{tower} w_i \cos(n\phi_i)}$$

E_T^{tower} – tower transverse energy of FCal1

v_2 (not corrected for EP resolution) is consistent with v_2 extracted from fits (shown in red) to the azimuthal distributions:

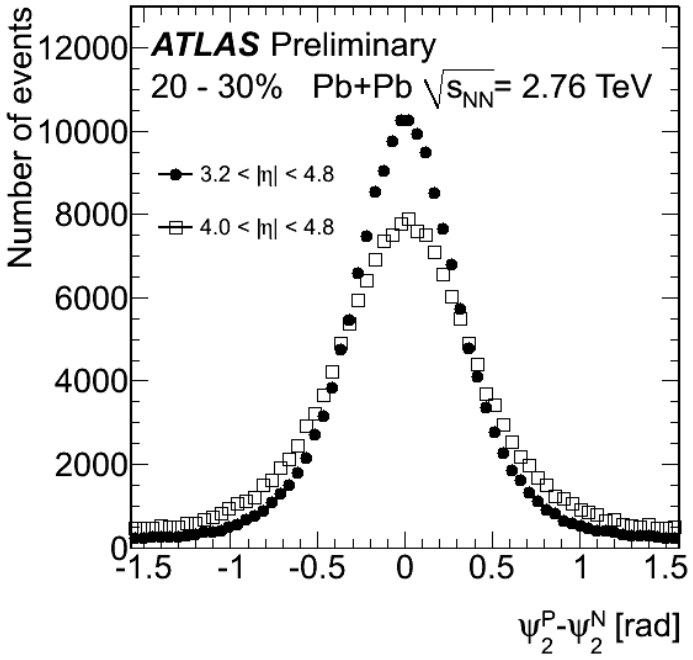
$$1 + \sum_{n=1}^{6} v_n \cos(n\phi)$$

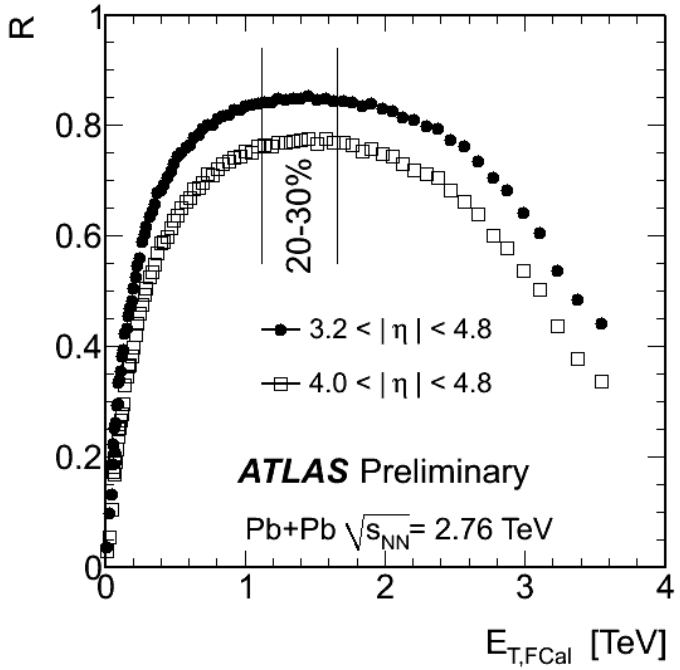


Resolution Correction in ATLAS

A.M. Poskanzer, S. A. Voloshin, Phys. Rev. **C58,** 1671 (1998)

$$R = \sqrt{< \cos(n(\Psi_2^P - \Psi_2^N) >}$$





Best resolution corrections for elliptic flow measurement are in semi-central Pb+Pb collisions (20-30%) and in full FCal η acceptance

$$v_n = < \cos(n(\phi - \Psi_n^{P/N})) > / R$$

Systematic Uncertainties

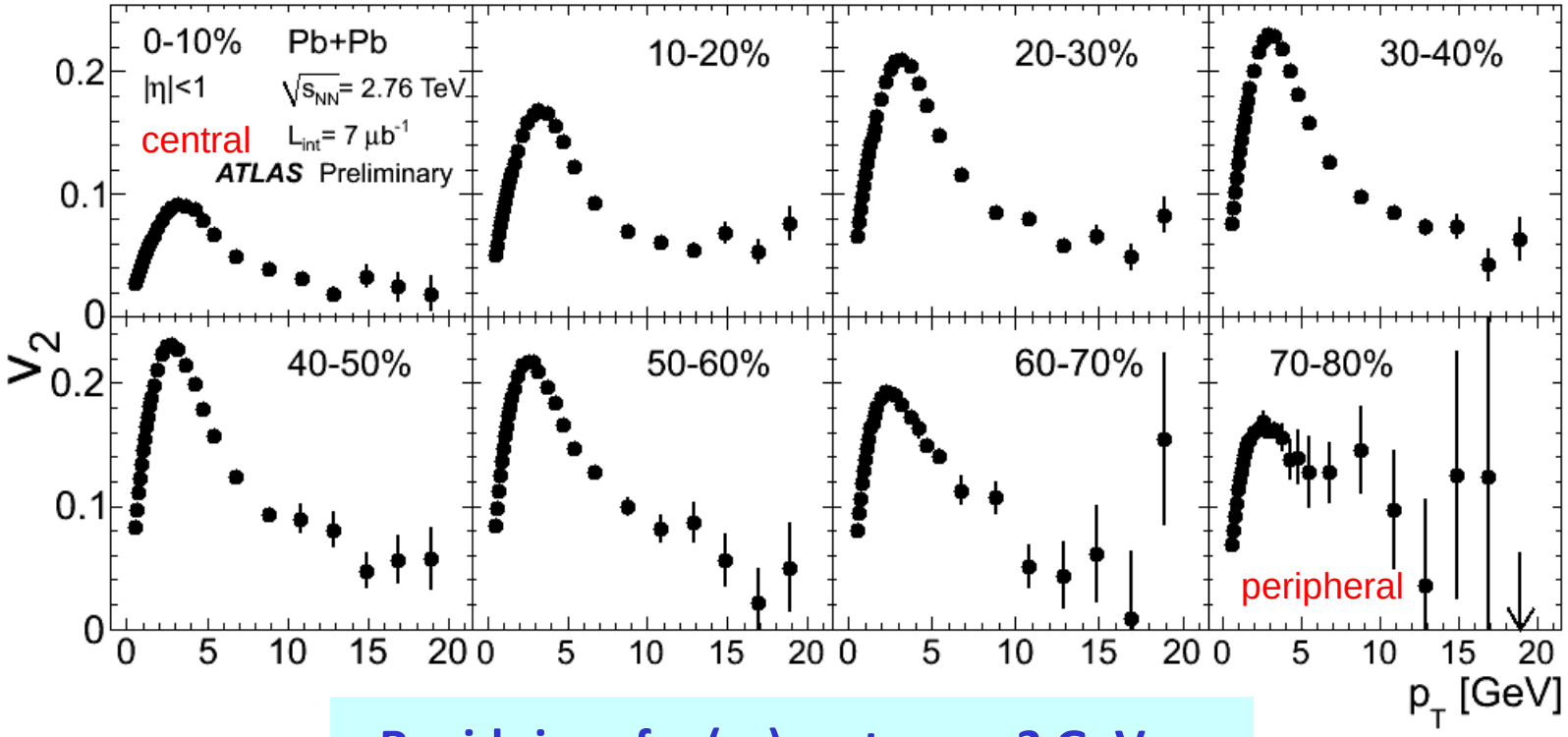
Systematic uncertainties were evaluated by varying different aspects of the analysis

- Reduced FCal η-acceptance for EP determination
- Residual deviations from zero of $\langle \sin(2(\phi-\psi_2)) \rangle$ term
- Tighter impact parameter tracking cuts ($|d0|$, $|z0 \sin\theta| < 0.5$ mm)
- Negative vs. positive tracks
- Asymmetry with respect to η-reflection
- Dependence on data collection time
- Monte Carlo reconstruction using the same analysis procedure
- Centrality determination cuts (overall scale)

Systematic and statistic uncertainties are combined in quadrature

Elliptic Flow in Wide p_T Range

- Charged particles, p_T = 0.5-20 GeV, midrapidity, $|\eta|<1$



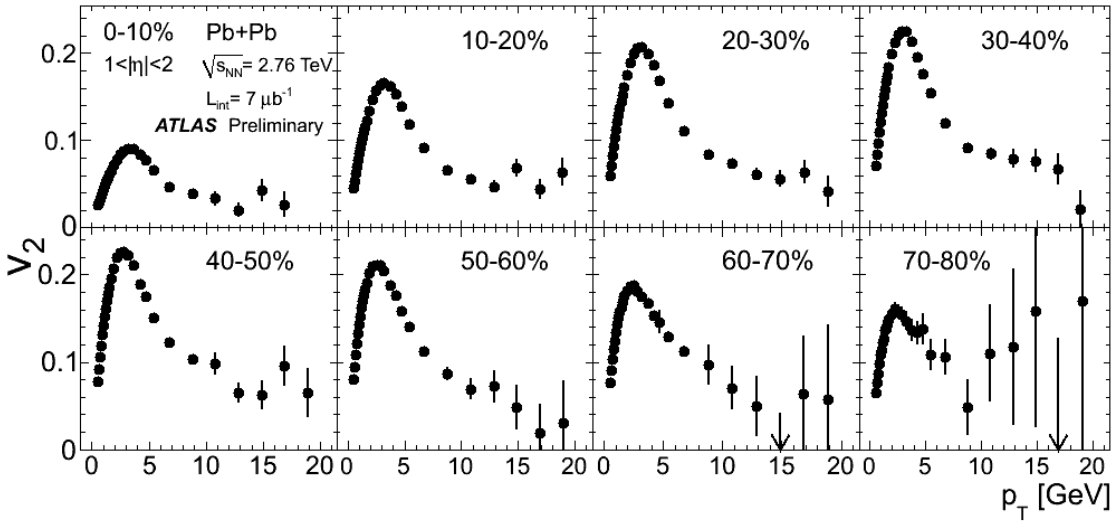
- Rapid rise of $v_2(p_T)$ up to p_T = 3 GeV
- Decrease within 3-8 GeV
- Weak p_T dependence beyond 8-10 GeV

Strongest elliptic flow is in mid-central Pb+Pb collisions (30-40% and 40-50%)

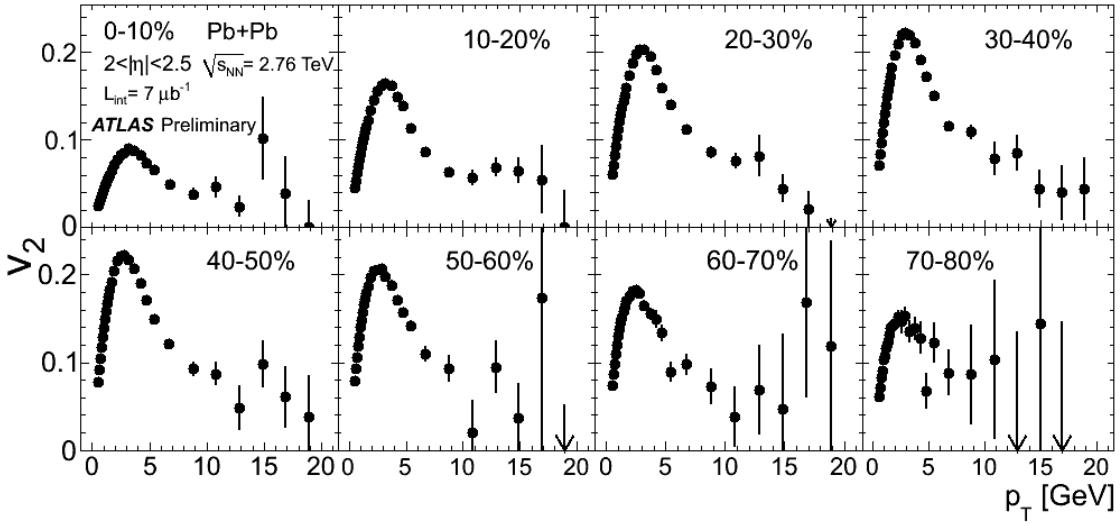
p_T-dependence of Elliptic Flow at Large η

The same trends are also observed at larger pseudorapidity:

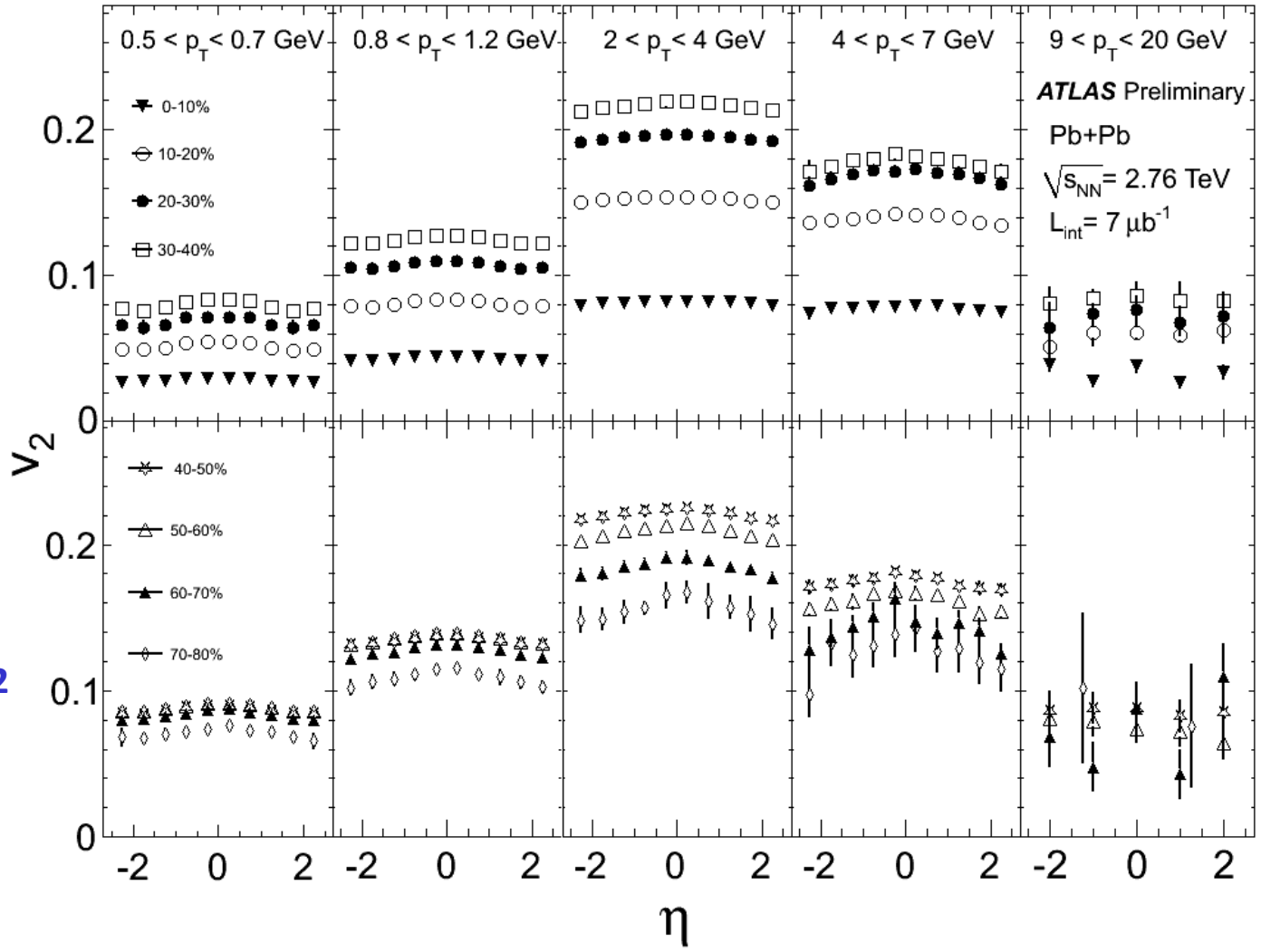
- $1 < |\eta| < 2$



- $2 < |\eta| < 2.5$



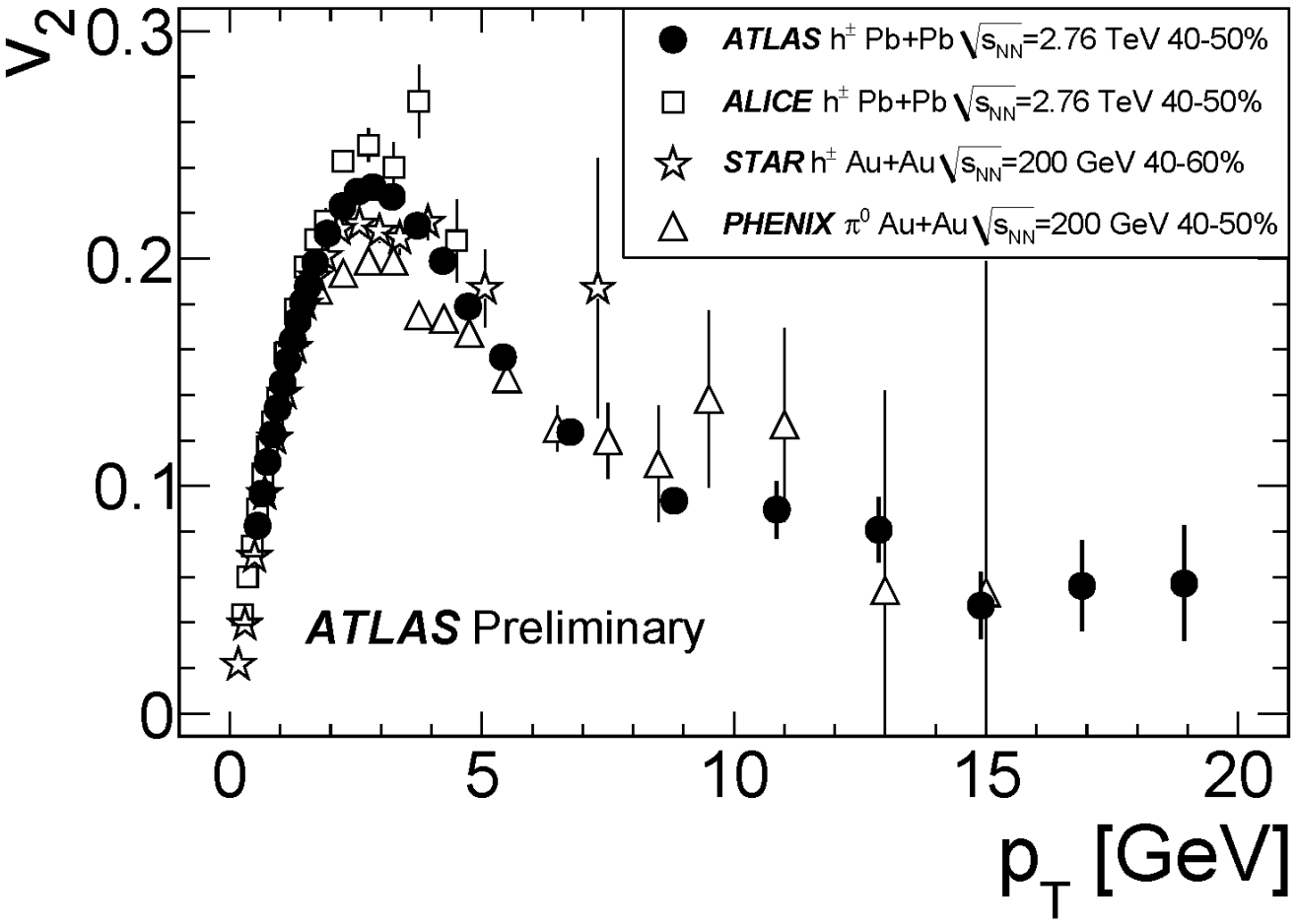
Pseudorapidity Dependence of v_2



No substantial η dependence of v_2 is observed

At RHIC , in PHOBOS v_2 decreases by ~30% within η range from 0 to 2.5 (p_T>0)

Comparison to Other Experiments

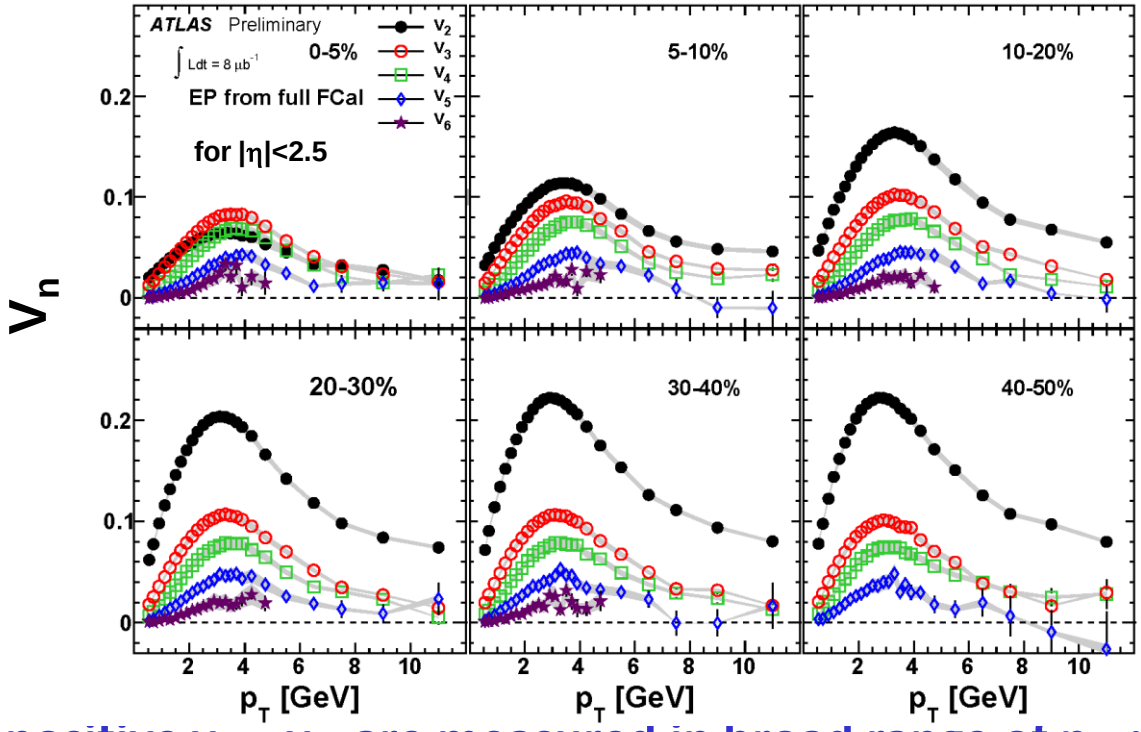


Similar dependence both at low and high p_T

Higher Order Flow Harmonics

Higher Fourier harmonics, up to v_6, are extracted via EP method

Full FCal event used for EP determination to improve resolution for higher harmonics measurement



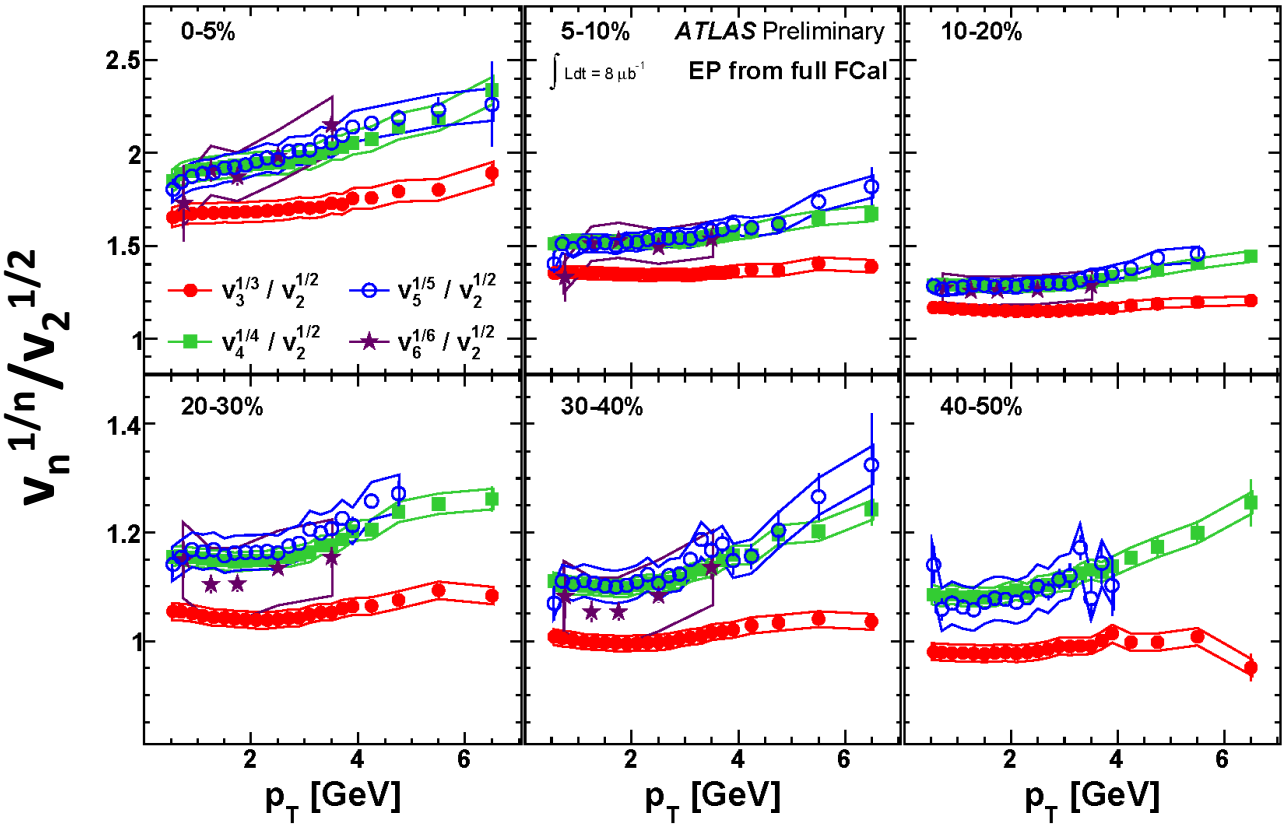
- Significant positive $v_2 - v_6$ are measured in broad range of p_T, η and centrality
- p_T dependence for all measured amplitudes is similar
- Very week η dependence of all harmonics

Jiangyong Jia presentation , ATLAS-CONF-2011-074, http://cdsweb.cern.ch/record/1352458

$v_n^{1/n}/v_2^{1/2}$ vs p_T over Broad Centrality Range

Hydrodynamic approach suggests scaling of v_n , e.g. $v_4 \sim v_2^2$

PHENIX PRL 105, 062301 (2010).



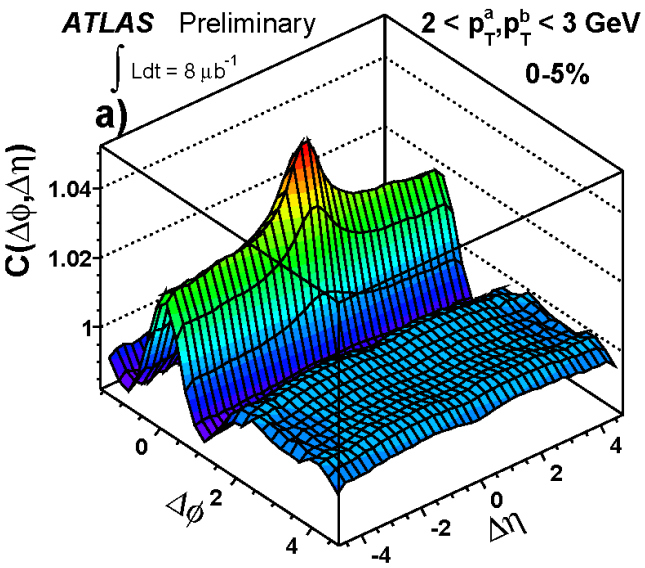
$v_n^{1/n}/v_2^{1/2}$ weakly depends on p_T

Two-particle Correlation Method

The two-particle correlation function:

$$C(\Delta\phi,\Delta\eta)=\frac{N_s(\Delta\phi,\Delta\eta)}{N_m(\Delta\phi,\Delta\eta)}$$

where N_s and N_m are number of same- and mixed event track pairs separated at $\Delta\phi$ and $\Delta\eta$.

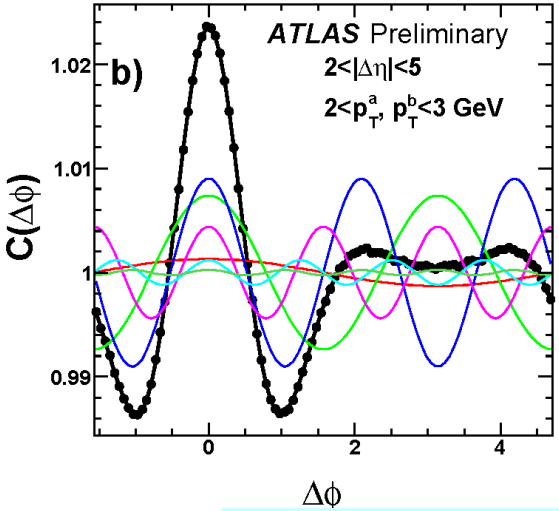


1-D (η projected) correlation function:

$$\frac{dN}{d\Delta\phi}\sim 1+2\sum_n v_{n,n}\cos(n\Delta\phi)$$

where $v_{n,n}$ are calculated via Discrete Fourier Transform (DFT) method:

$$v_{n,n}=<\cos(n\,\Delta\phi)>=\frac{\sum_m \cos(n\,\Delta\phi_m)C(\Delta\phi_m)}{\sum_m C(\Delta\phi_m)}$$



It is expected that for flow modulations:

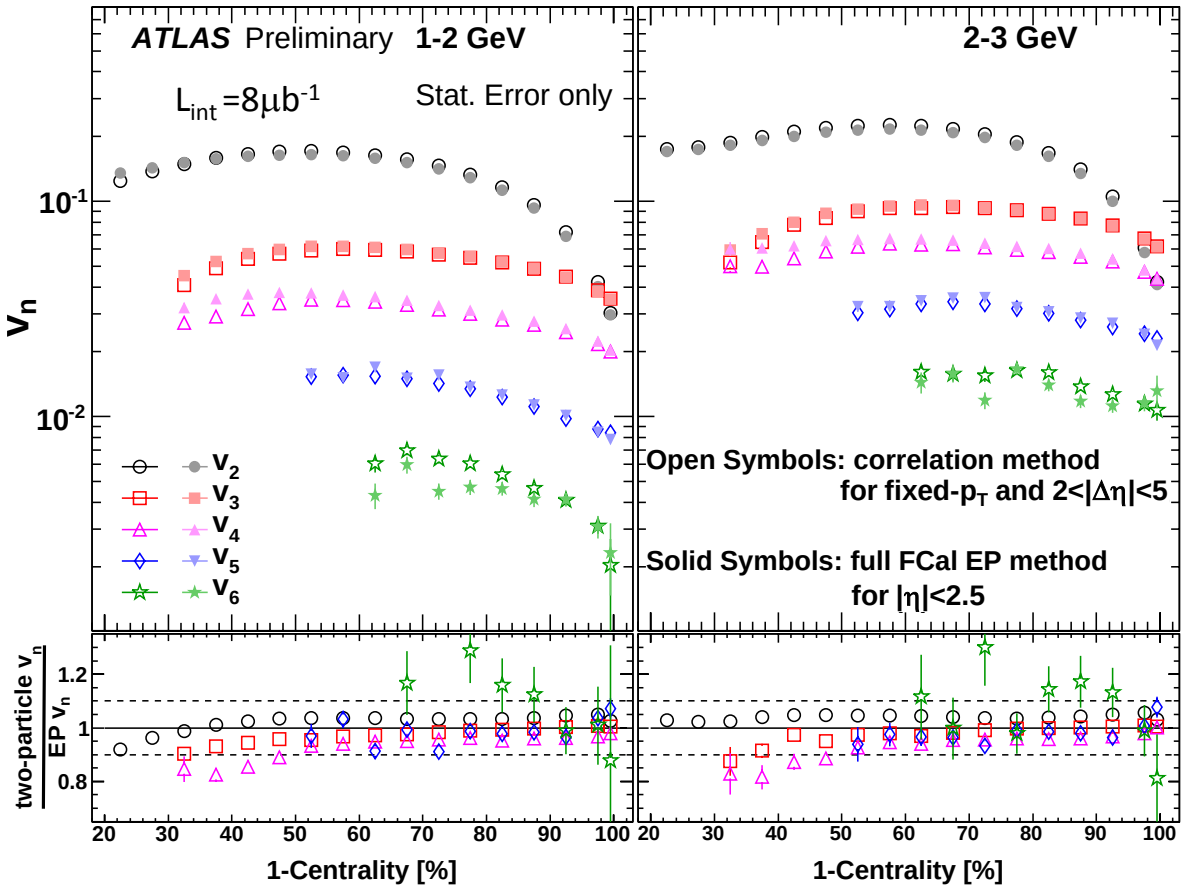
$$v_{n,n}(p_T^a,p_T^b)=v_n(p_T^a)v_n(p_T^b)$$

And for "fixed-p_T" correlations:

$$v_n=\sqrt{v_{n,n}}$$

Jiangyong Jia presentation
ATLAS-CONF-2011-074

Two Particle Correlation vs EP Results



The agreements are within 5% for v_2, v_3, v_4 over a broad centrality range

v_5 and v_6 agree at 10% and 15% level respectively

(agreement within the systematic errors for the both methods)

Summary

- v_2 was measured for the first time in wide p_T , η and centrality range at the LHC energy
  - In p_T, v_2 is rapidly rising up to ~3 GeV, then decreasing within 3-8 GeV, and at highest p_T (up to 20 GeV) weakly changes
  - $v_2(\eta)$ remains approximately constant for $|\eta|<2.5$
- Elliptic flow and higher flow harmonics (up to v_6) were measured with the event plane and two particle correlation methods
  - Results of both methods agree at 5-15% level and are consistent (p_T=1-3 GeV)
  - Similar p_T and η dependence of all measured amplitudes is observed
  - Very week η dependence of all harmonics
- Many new flow results available to constrain models of the dynamical evolution of the medium created at the LHC.

Event Plane Method of v_n Measurement in ATLAS

A.M. Poskanzer, S. A. Voloshin, Phys. Rev. **C58,** 1671 (1998)

Φ_{RP} approximated with each (P/N) FCal1 sub-event:

$$\Psi_n^{P/N} = \frac{1}{n}\tan^{-1}\frac{\sum_{i(P/N)} E_{T,i}^{tower} w_i \sin(n\phi_i)}{\sum_{i(P/N)} E_{T,i}^{tower} w_i \cos(n\phi_i)}$$

Flattening procedure applied (w_i)

Resolution correction:

$$R = \sqrt{< \cos(n(\Psi_n^P - \Psi_n^N) >}$$

Flow harmonics obtained with tracks:

$$v_n = < \cos(n(\phi - \Psi_n^{P/N})) > / R$$

When calculating v_n with tracks EP from the opposite hemisphere is used to maximize pseudorapidity gap and lower autocorrelations (jets)