Flow and Correlations in $\sqrt{s_{NN}}$ = 2.76 TeV Pb+Pb Collisions with ATLAS Detector at the LHC

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Quark Matter 2012

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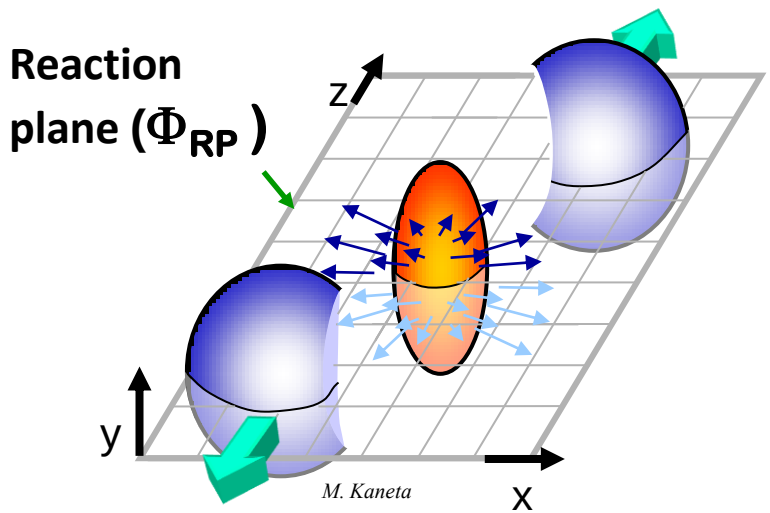
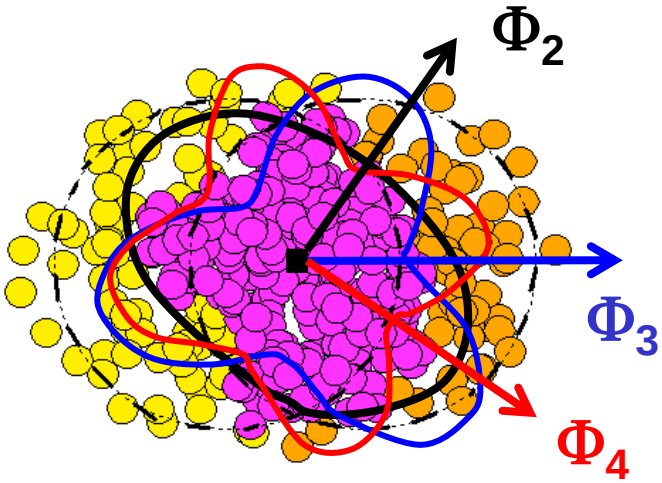
Outline

- **Harmonic flow (v_2-v_6) measurement**
  - **Event plane (EP) method**
  - **Multi-particle cumulants**
  - **Two-particle (2P) correlations**
- **Dipolar Flow, v_1**
- **Event-by-event v_2,v_3 and v_4 distributions**
  - **Flow harmonic fluctuations, $\sigma_n/\langle v_n \rangle$**
- **Reaction plane correlations**

Azimuthal Anisotropy of Produced Particles

Strongly interacting QGP





- **Pressure gradients lead to azimuthal anisotropy**

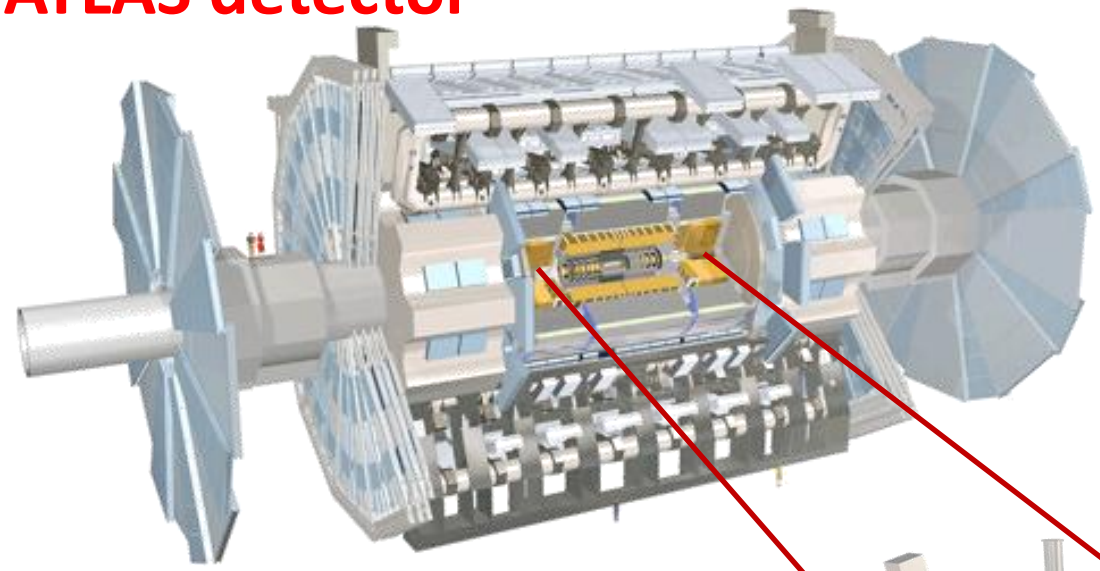
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]$$

$$v_n = \langle \cos[n(\phi - \Phi_n)] \rangle$$

- **Initial shape of the interaction region (v_2- elliptic flow)**
- **Initial spatial fluctuations of interacting nucleons (higher orders, v_n)**

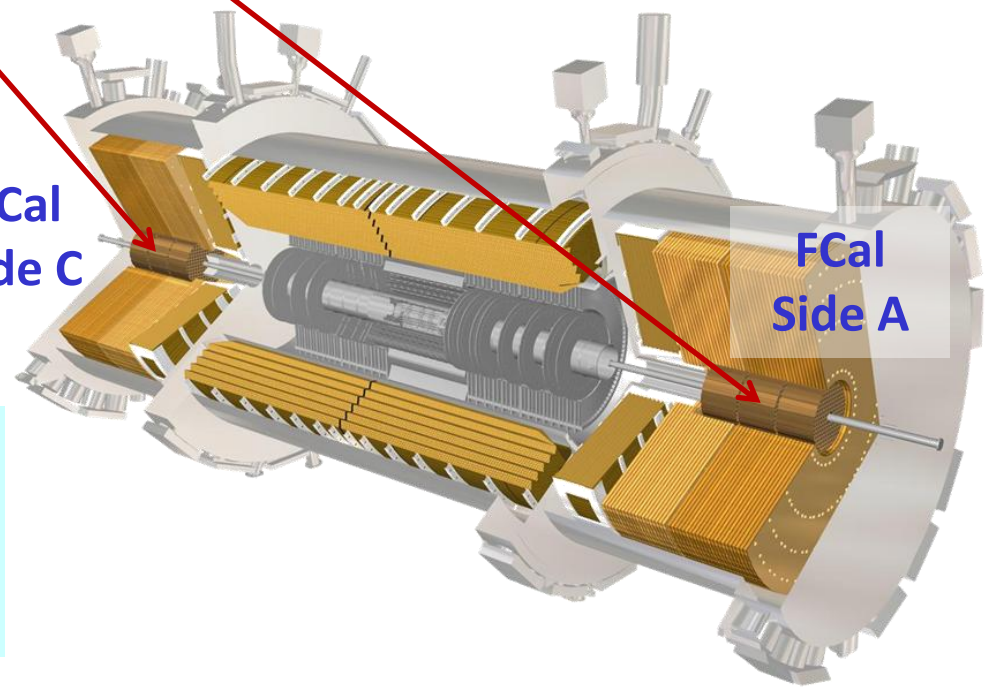
Event Plane Measurement

ATLAS detector



- Pb-Pb 2010 run
  - $\sqrt{s_{NN}} = 2.76\,\text{TeV}$
  - ~50 M MB events

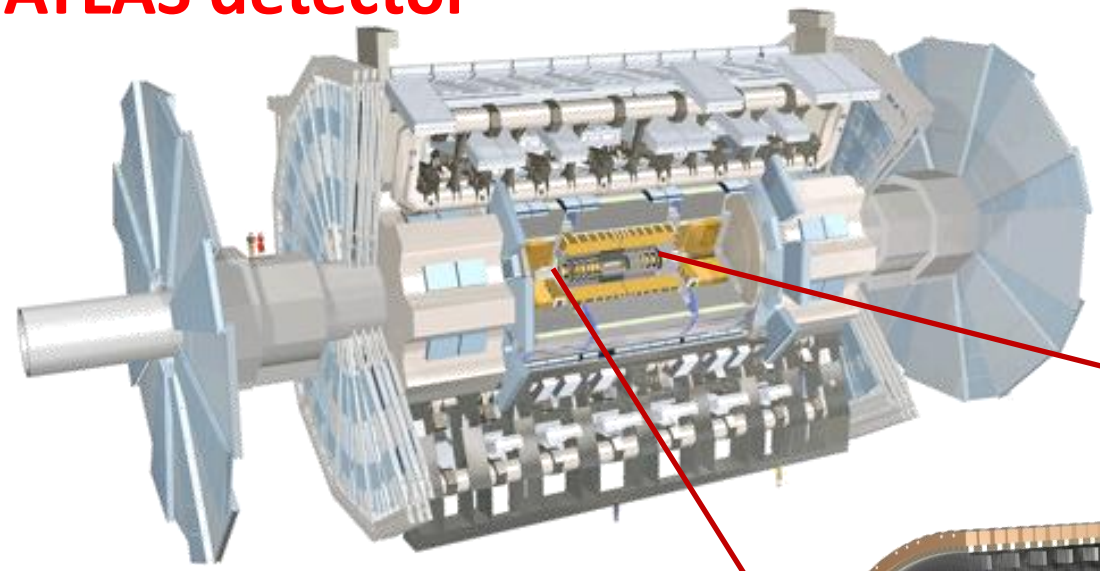
Forward Calorimeter



Event plane determination is based on E_T measured in FCal ($3.1<|\eta|<4.9$)

v_n Harmonics Measurement

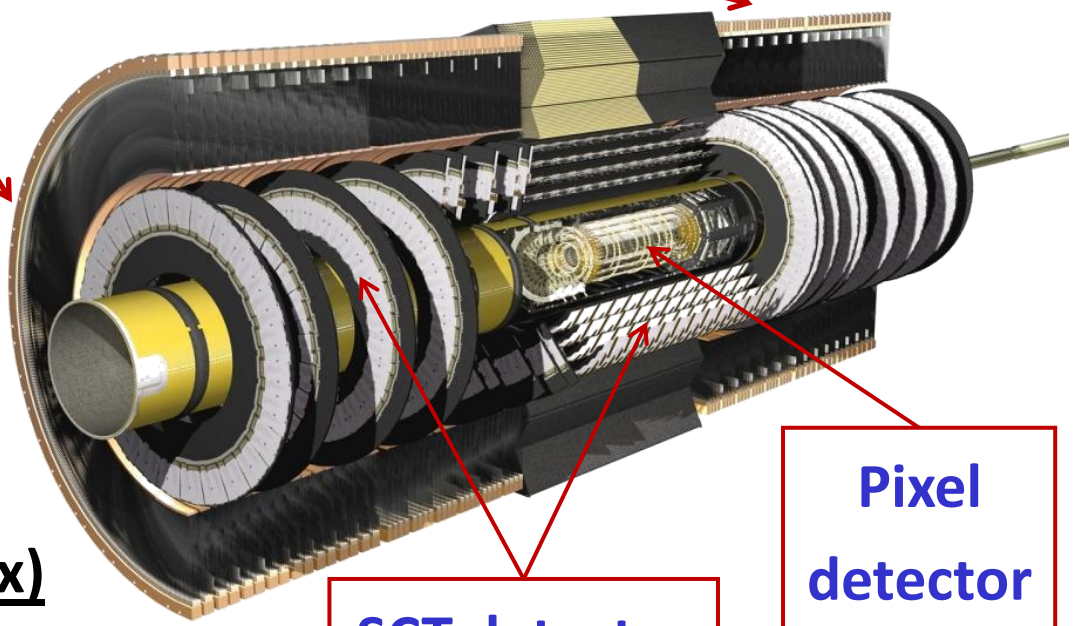
ATLAS detector



Fourier harmonics are measured with charged particles reconstructed in the inner detector

- $-2.5 < \eta < 2.5$

Inner detector, ID



Pixel detector

SCT detector

ID tracks (Pixel+SCT)

- $p_T > 0.5$ GeV

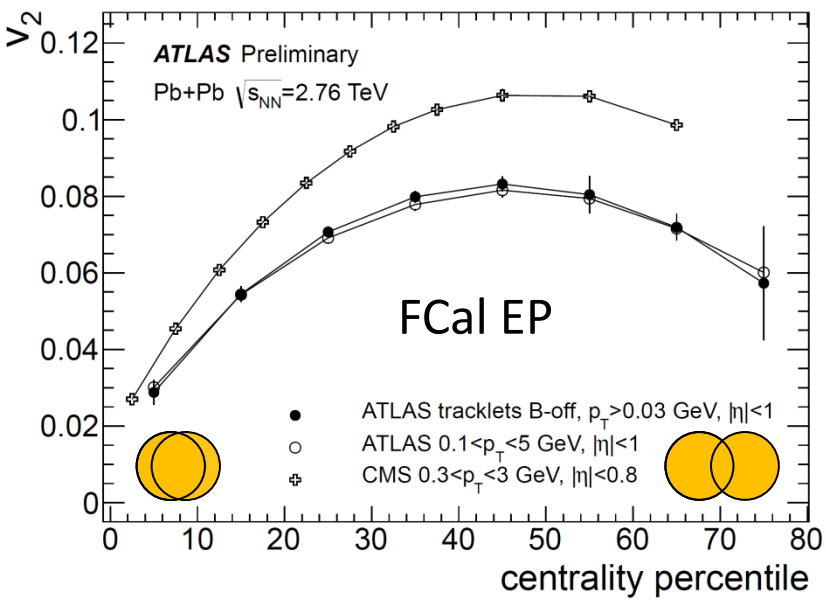
Pixel tracks

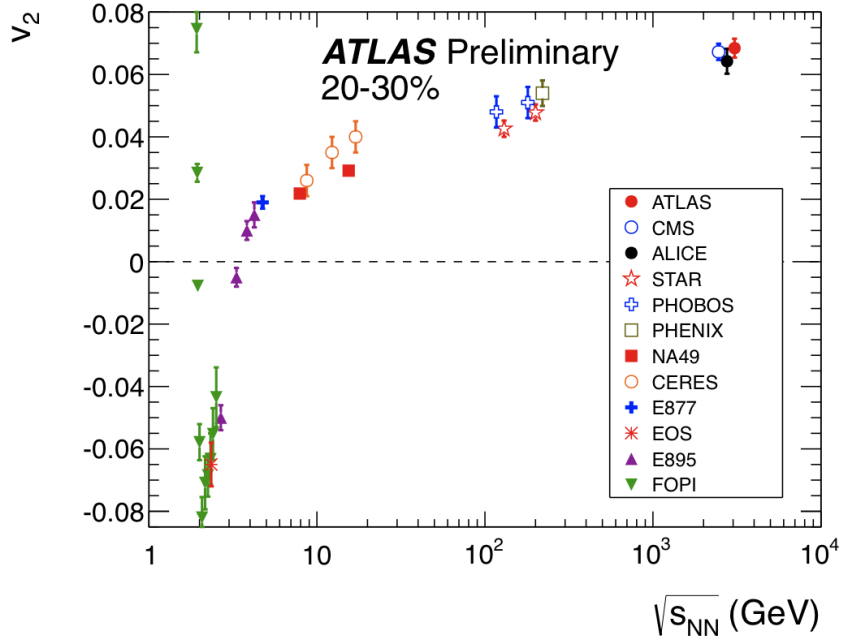
- $p_T > 0.1$ GeV

Tracklets (2 pixel hits+vertex)

- $p_T > 0.03$ GeV (B-off)

Integrated v_2 down to very low p_T





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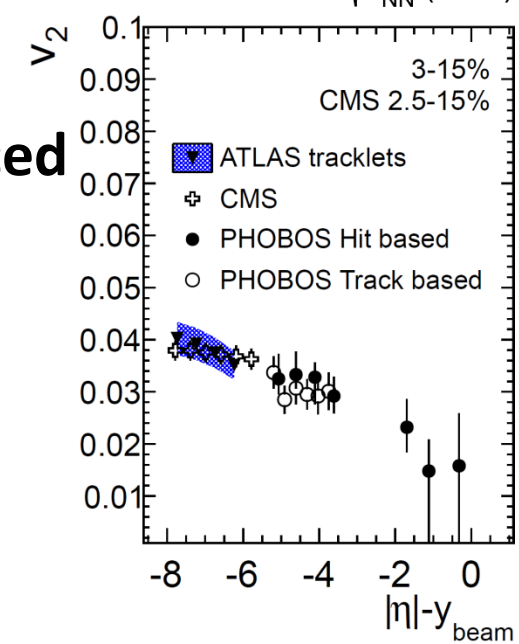


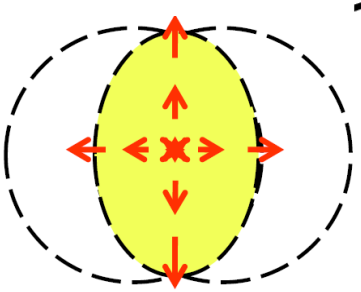
- **Integrated v_2 (p_T>30 MeV) is significantly reduced if compared to CMS results (p_T > 300 MeV)**
- **$v_2(\eta)$ shows weak pseudorapidity dependence but (within systematics) is also consistent with the trend observed by PHOBOS at RHIC**

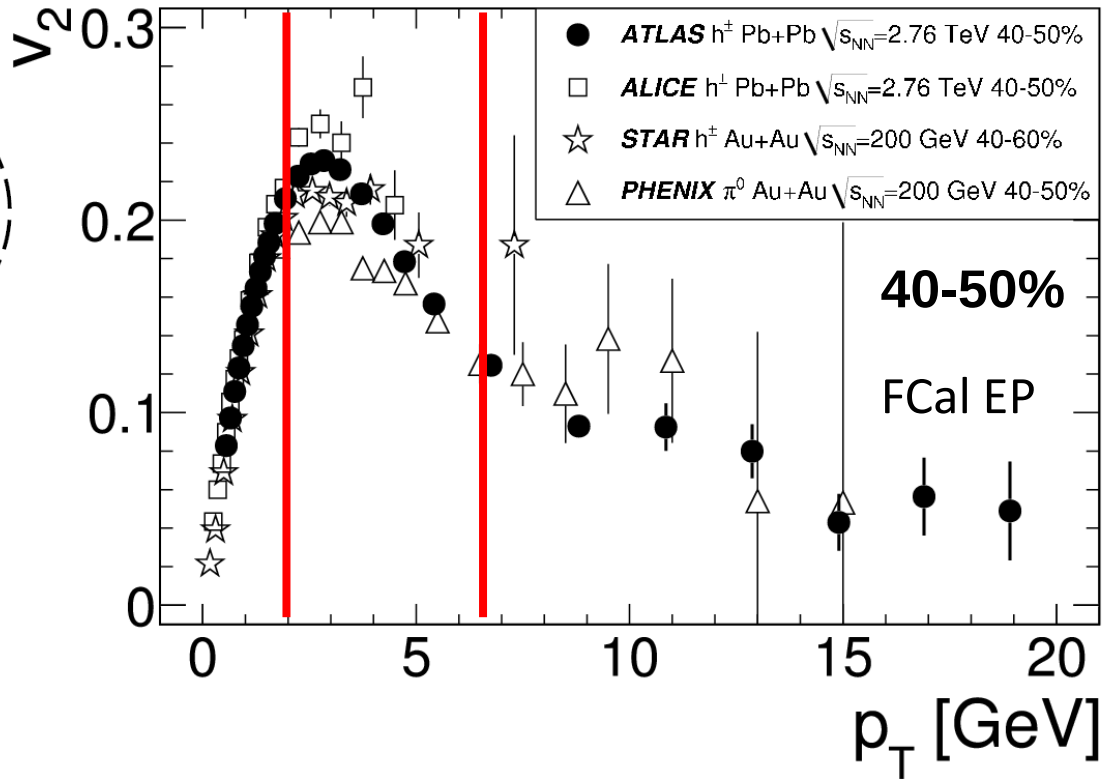
Elliptic Flow in Wide pT Range

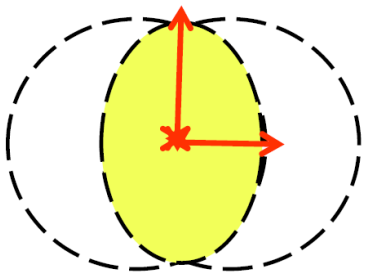
Low p_T:
hydro expansion

Medium p_T:
coalescence

High p_T:
jet quenching







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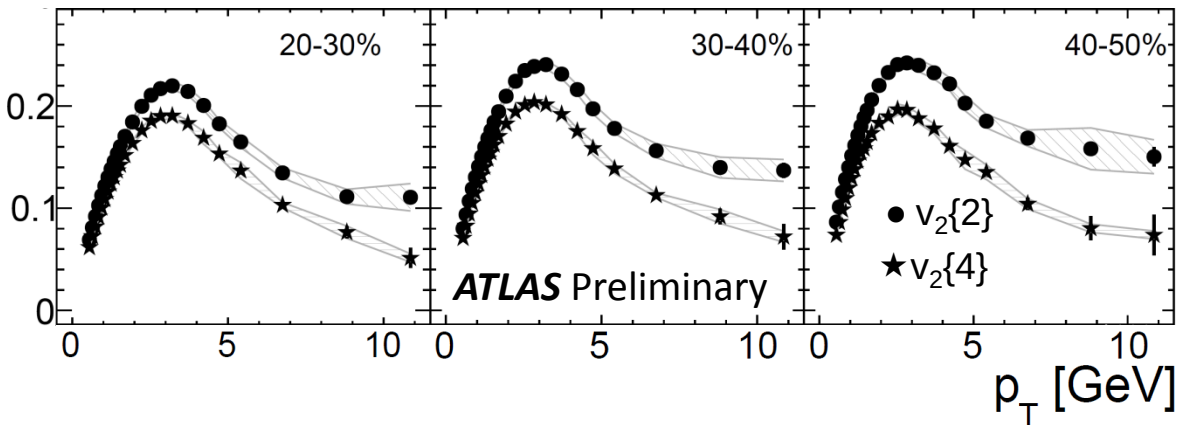
- **Rapid rise up to $p_T \approx 2$ GeV, decrease within 3-8 GeV and weak dependence beyond 8-10 GeV**
- **v_2 shows similar p_T-dependence at the LHC and RHIC energy**

Cumulant Harmonics: $v_2\{2\}$ and $v_2\{4\}$

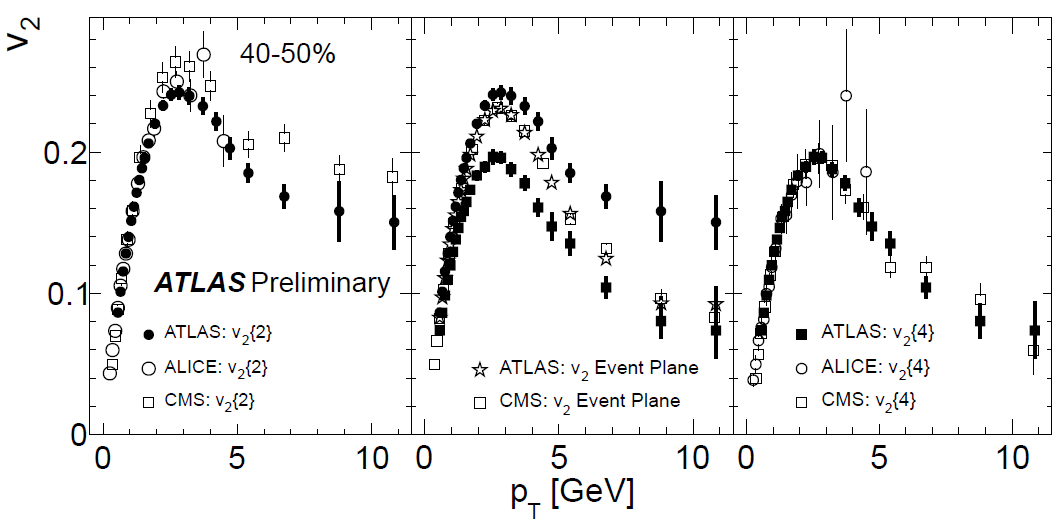
Elliptic flow harmonics of charged particles were obtained with the cumulant generating function method



N. Borghini, P.M.Dinh and J.Y. Ollitrault Phys.Rev.C 64 (2001) 054901

ATLAS-CONF-2012-118

Strong reduction of v_2 is observed by using four-particle cumulants

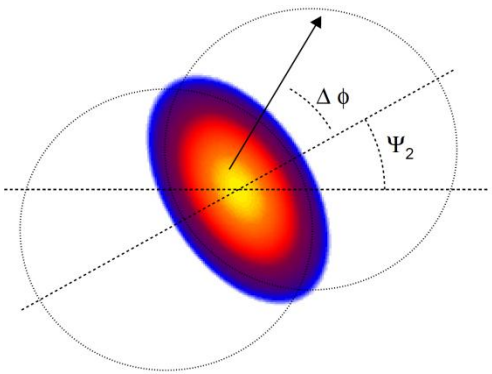


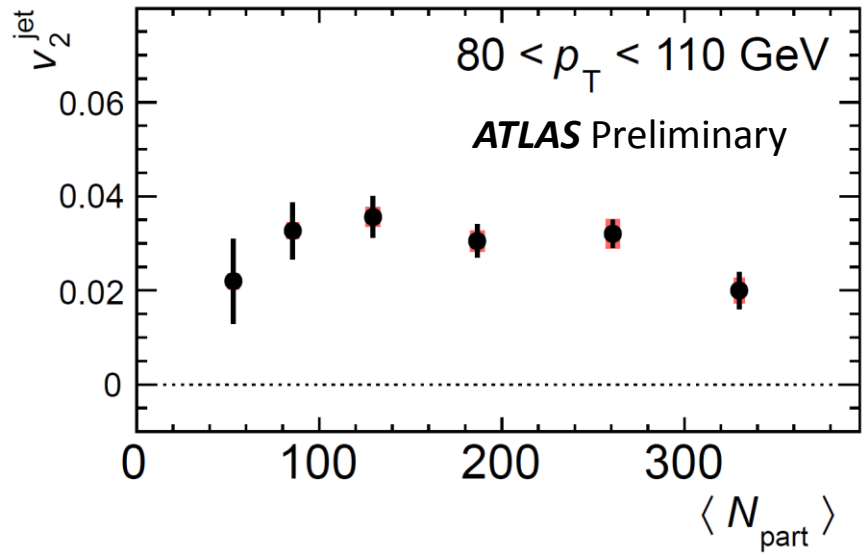
- **$v_2\{4\}$: consistent between ATLAS, ALICE and CMS**
- **$v_2\{2\}$: good agreement at low p_T, at high p_T CMS obtained stronger flow**

T. Bold, *parallel 7D Fri.*

Jet v_2 at very High p_T: 50-200GeV

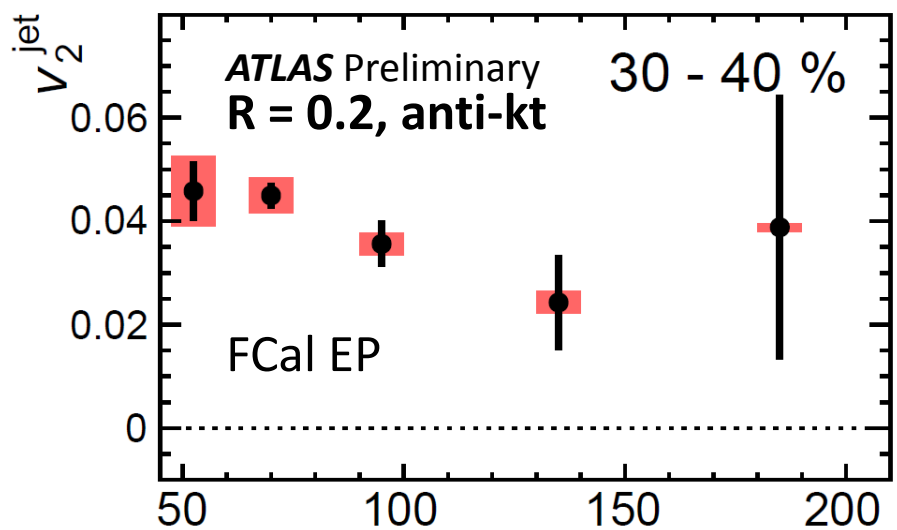
Azimuthal variation of the jet yield was characterized by the elliptic flow parameter, v_2^{jet}





Insight on the path length dependence of jet quenching in the hot medium

- **Centrality dependence observed at lower transverse momenta**
- **v_2^{jet} decreases with p_T**



Aaron R. Angerami, *parallel 2B Tue.*

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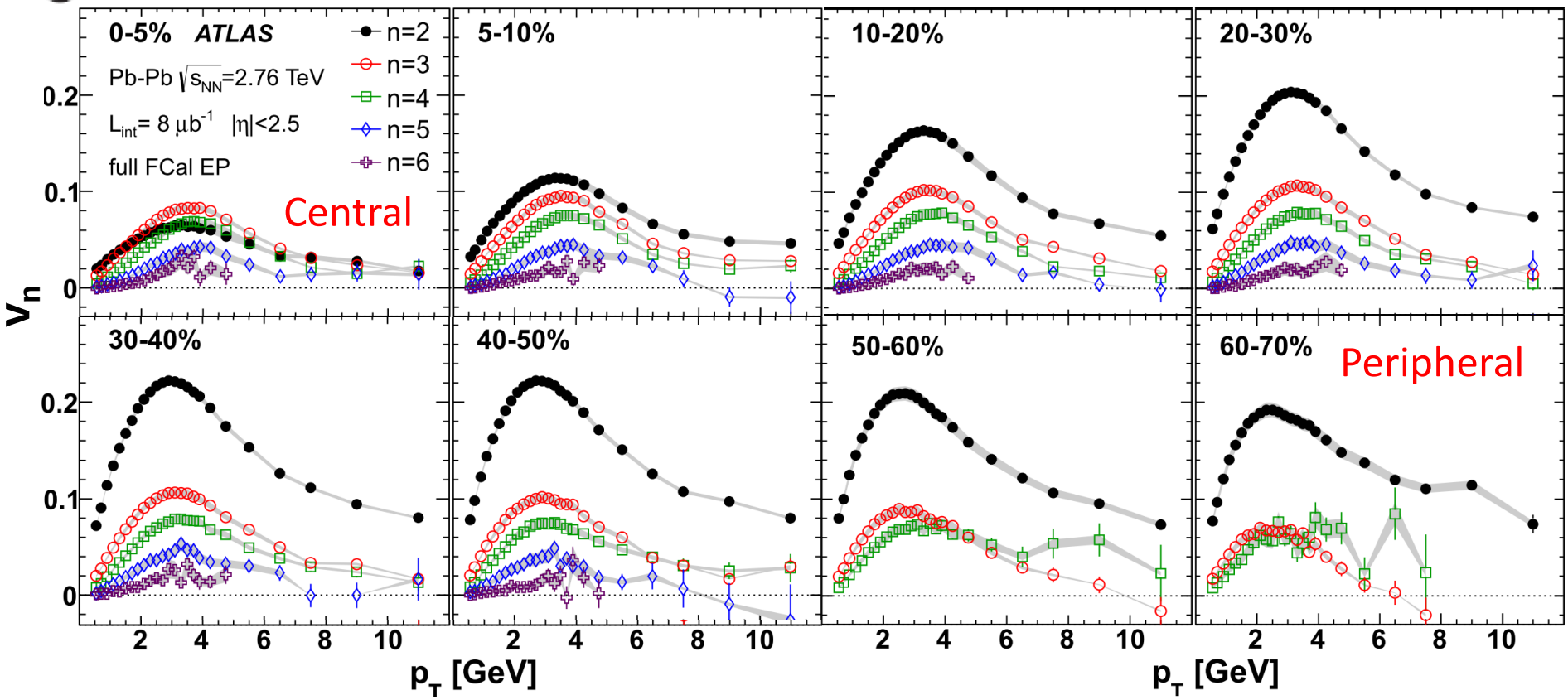
Higher Order Flow Harmonics (v_2-v_6)

ATLAS, Phys. Rev. C 86, 014907 (2012)



- Significant $v_2 - v_6$ are measured in broad range of p_T, η and centrality
- p_T dependence for all measured amplitudes show similar trend
- Stronger centrality dependence of v_2 than higher order harmonics
- In most central collisions (0-5%): v_3, v_4 can be larger than v_2

Two-Particle Correlation

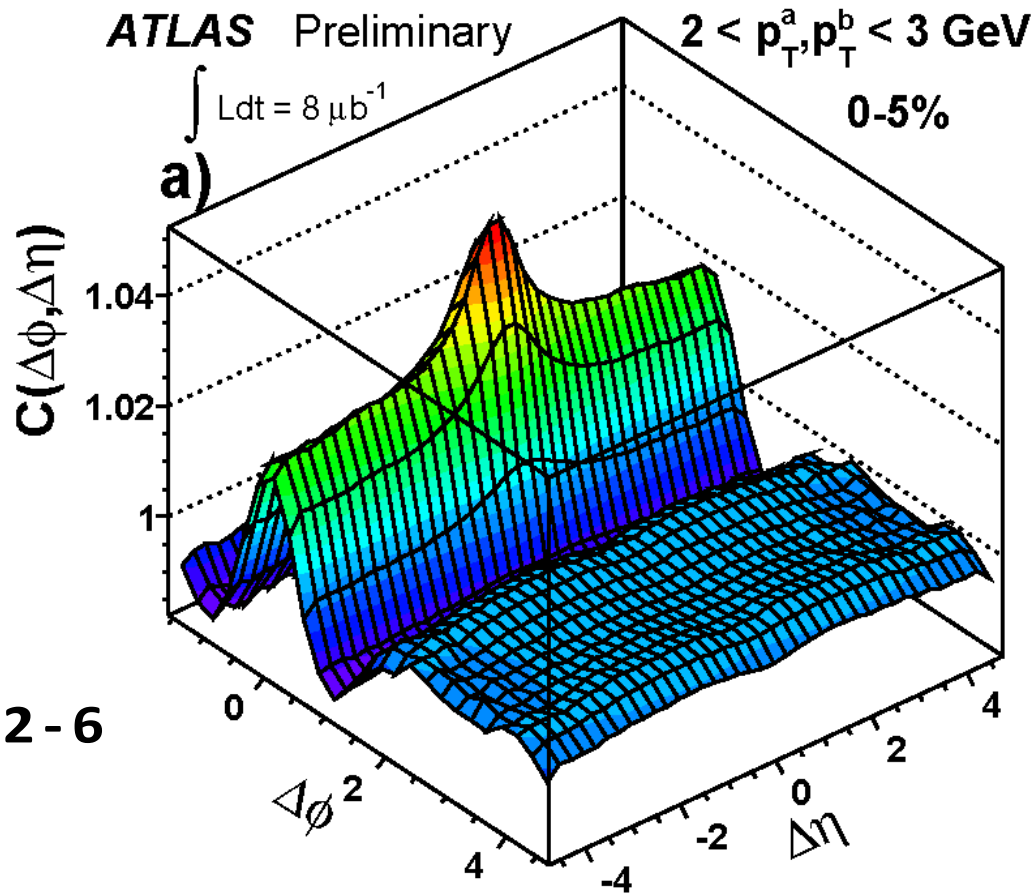
ATLAS, Phys. Rev. C 86, 014907 (2012)

1-D (η projected) correlation function (|Δη|>2):

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

$$v_{n,n} = \langle \cos(n\Delta\phi) \rangle$$

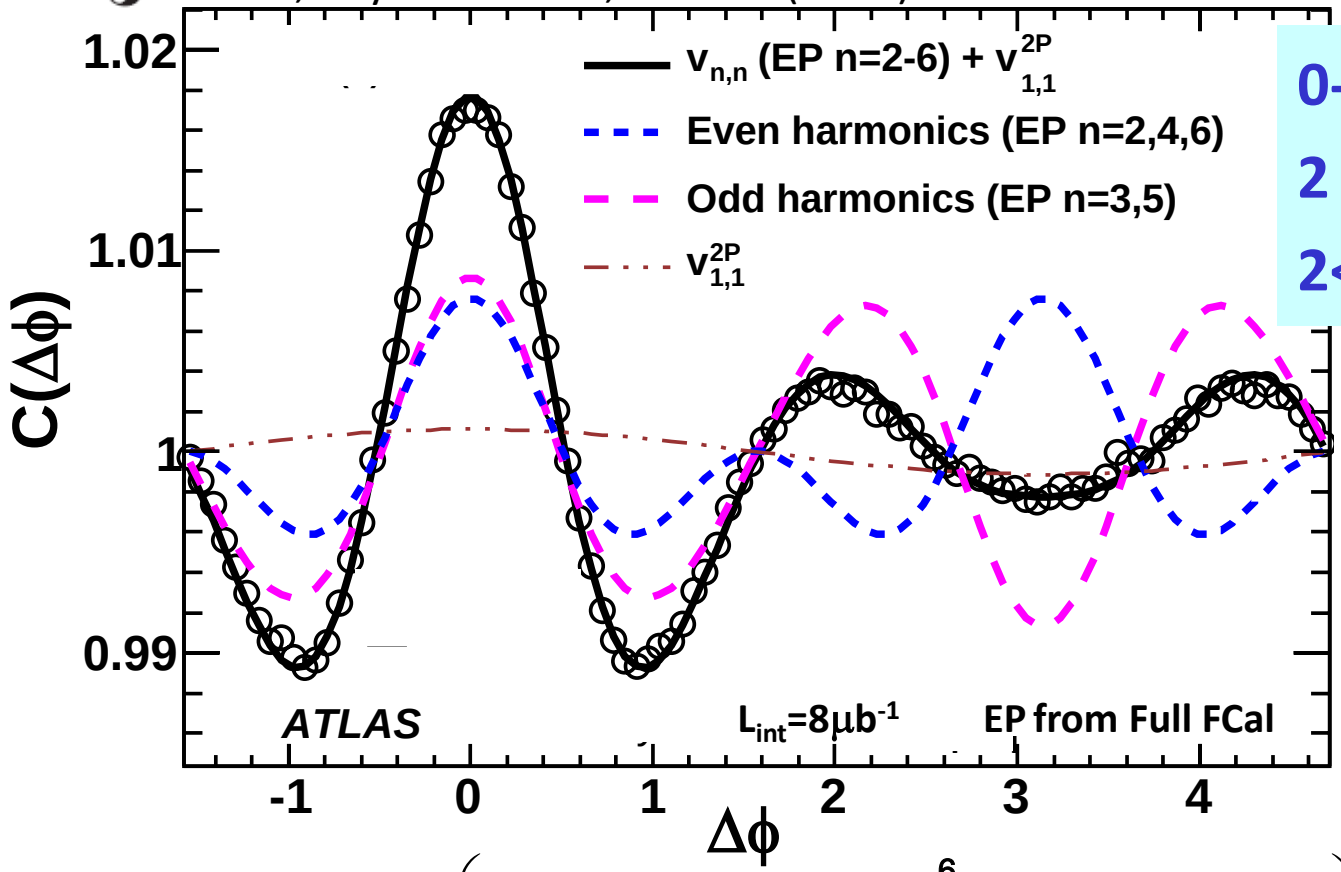
$$v_{n,n}^{2P}\left(p_T^a, p_T^b\right) \approx v_n^{EP}(p_T^a)\, v_n^{EP}(p_T^b), n = 2 - 6$$



D. Derendarz, *parallel 2A Tue.*

Decomposition of Two-Particle Correlation Function

ATLAS, Phys. Rev. C 86, 014907 (2012)



0-1%, Pb-Pb

$2 < p_T < 3$ GeV

$2<|\Delta\eta|<5$

$$C(\Delta\phi) = b^{2P}\left(1 + 2v^{2P}_{1,1}\cos\Delta\phi + 2\sum_{n=2}^{6} v_n^{EP} v_n^{EP}\cos n\Delta\phi\right)$$

Two-particle correlation function structure at low p_T can be explained by flow harmonics v_2-v_6 and $v_{1,1}$ term

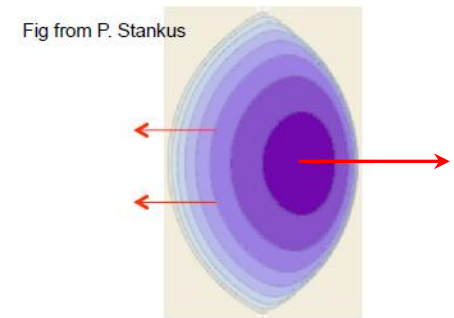
D. Derendarz, *parallel 2A Tue.*

Dipolar Flow, v_1

J. Jia, *parallel 4A Thu.*

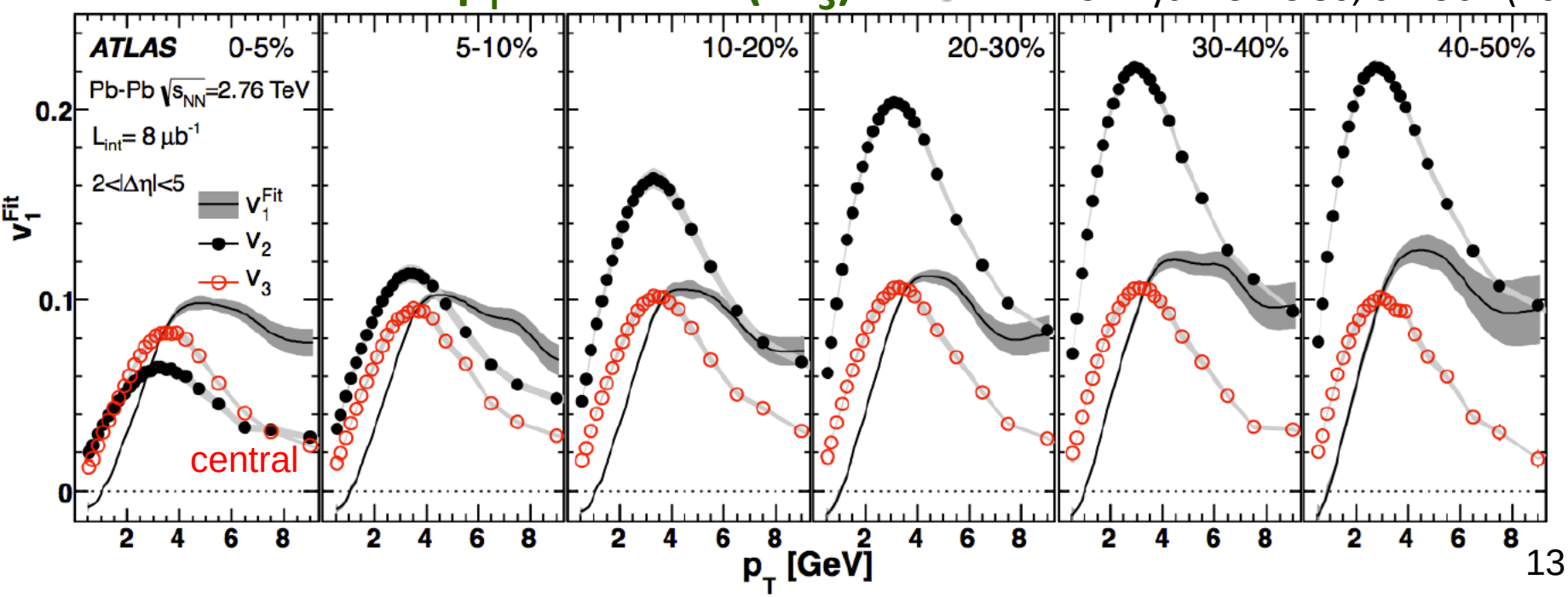
- $v_{1,1}(p_T^a, p_T^b)$ is consistent with contributions from rapidity-even v_1 and global momentum conservation

$$v_{1,1}^{2P}\left(p_T^a, p_T^b\right) \approx v_1(p_T^a)v_1(p_T^b) - \frac{p_T^a p_T^b}{M < p_T^2 >}$$



- Two-component fit is used to extract v_1
  - v_1 crosses zero at $p_T \approx 1$ GeV
  - Maximum at $p_T \approx$ 4-5 GeV ($\sim v_3$)

ATLAS Phys. Rev. C 86, 014907 (2012)

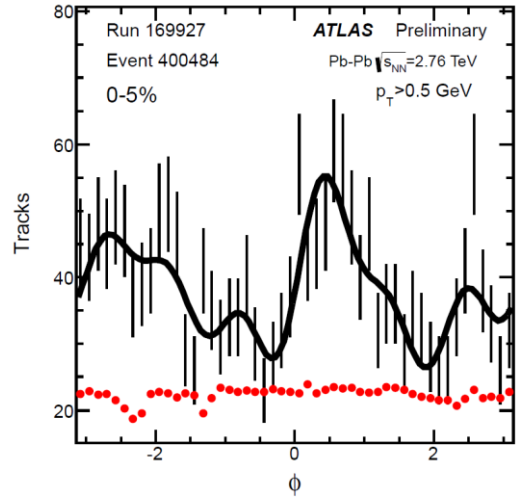


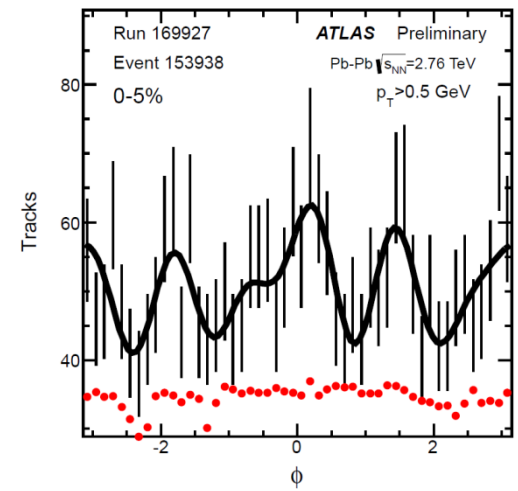
Measurement of Event-by-Event v_n

The azimuthal distribution of charged particles in single event:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n^{obs} \cos n(\phi - \Phi_n)$$

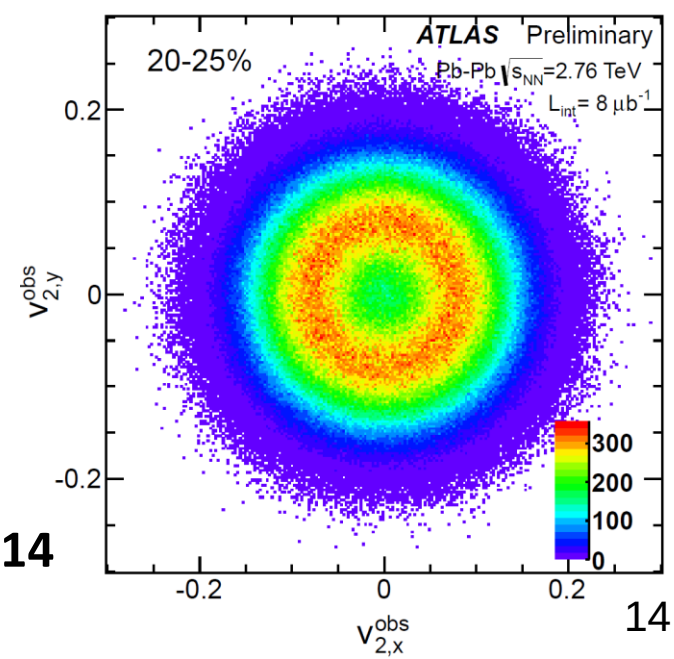
$$= 1 + 2\sum_{n=1}^{\infty} (v_{n,x}^{obs} \cos n\phi + v_{n,y}^{obs} \sin n\phi)$$





$$v_n^{obs} = \sqrt{(v_{n,x}^{obs})^2 + (v_{n,y}^{obs})^2} \rightarrow v_n$$

Flow vector distribution:



Due to finite multiplicity, flow vector is smeared randomly around true flow vector
→ corrected by unfolding

J. Jia, *parallel 4A Wed.*

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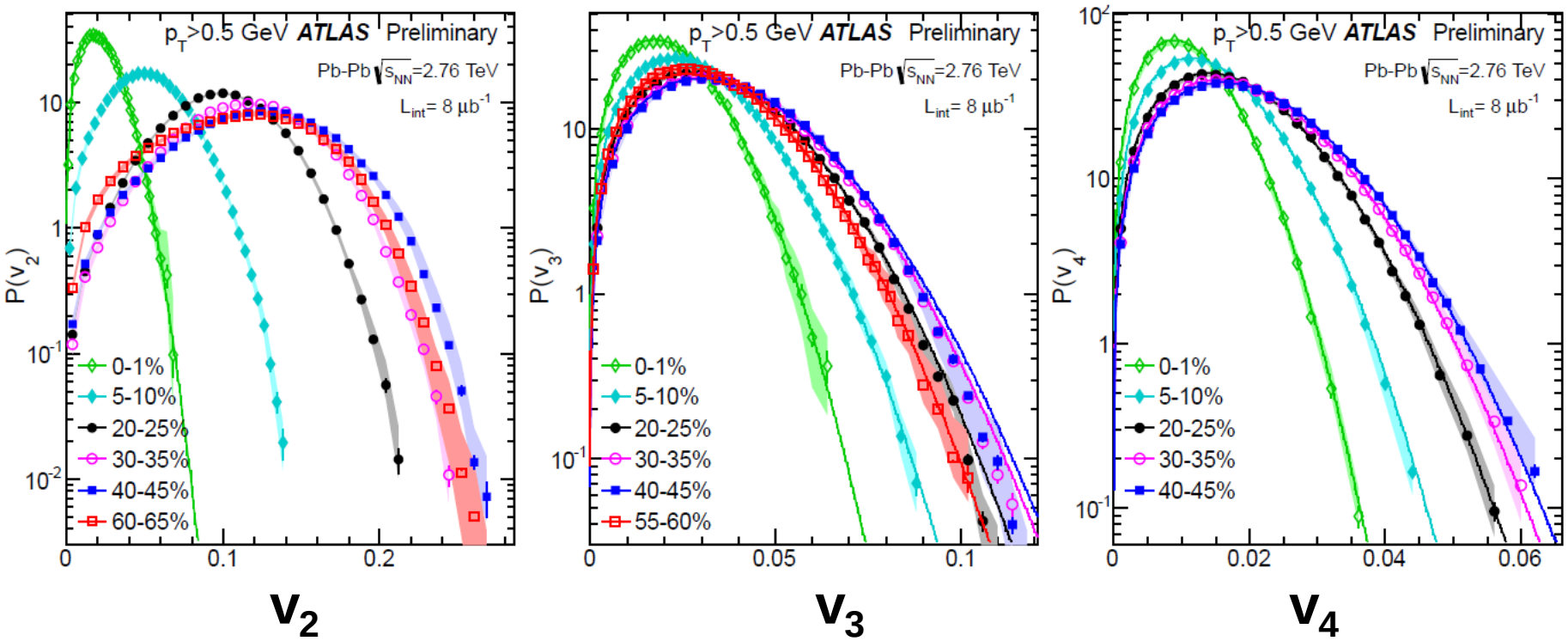
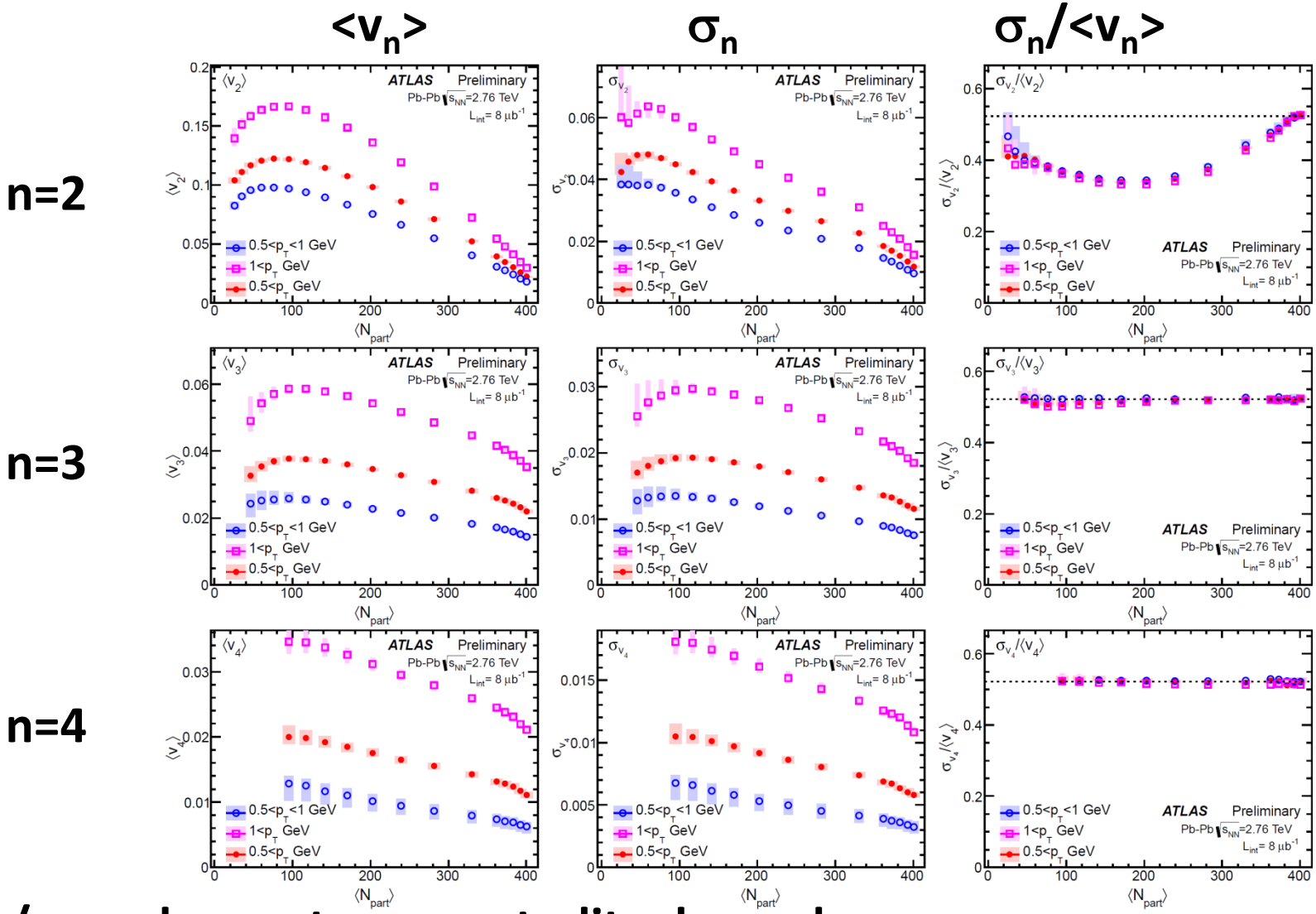
Unfolded v_2, v_3 and v_4 Distributions



- v_n distributions normalized to unity for n = 2,3 and 4
- Lines represent radial projections of 2D Gaussians, rescaled to $\langle v_n \rangle$
  - for v_2 only in the 0-2% of most central collisions
  - for v_3 and v_4 over all centralities

Direct measure of flow harmonics fluctuations



$\sigma_2/\langle v_2 \rangle$ shows strong centrality dependence

$\sigma_3/\langle v_3 \rangle$ and $\sigma_4/\langle v_4 \rangle$ are consistent with Gaussian fluctuations

Same relative fluctuations for $0.5<p_T<1$GeV, $p_T>0.5$GeV and $p_T>1$GeV

Dotted lines indicate the Gaussian limit: $\frac{\sigma_n}{\langle v_n \rangle} = \sqrt{\frac{4}{\pi} - 1} \approx 0.523$

Comparison to Glauber and MC-KLN models

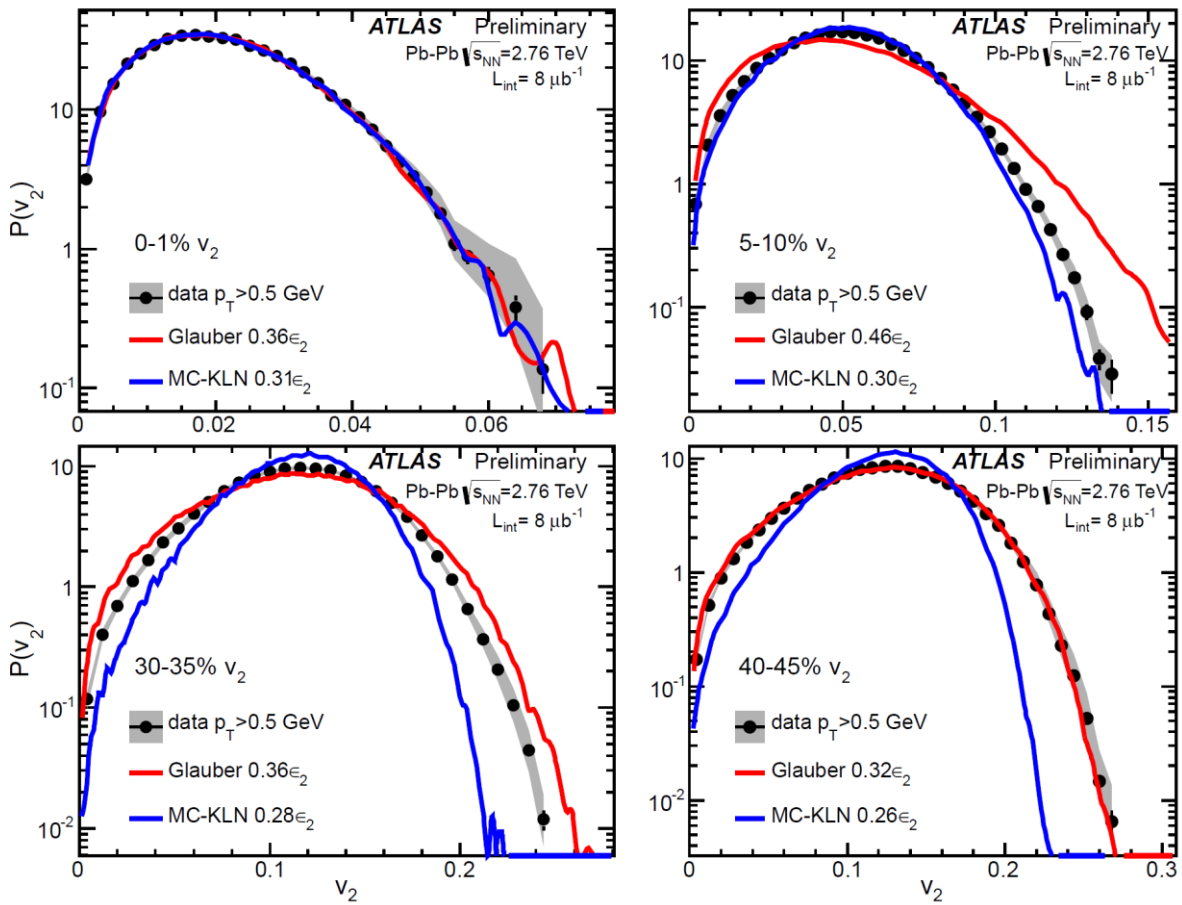
Eccentricity distributions from MC Glauber and MC-KLN models

arXiv:nucl-ex/0701025, Phys. Rev. C 74, 044905 (2006)

$$\varepsilon_n = \frac{\sqrt{<r^n \cos n\phi>^2 + <r^n \sin n\phi>^2}}{<r^n>}$$

$<\varepsilon_2>$ rescaled to $<v_2>$

- Both work in 0-1%
- MC-KLN better in 5-10%
- MC Glauber better in 30-50%



J. Jia, *parallel 4A Wed.*

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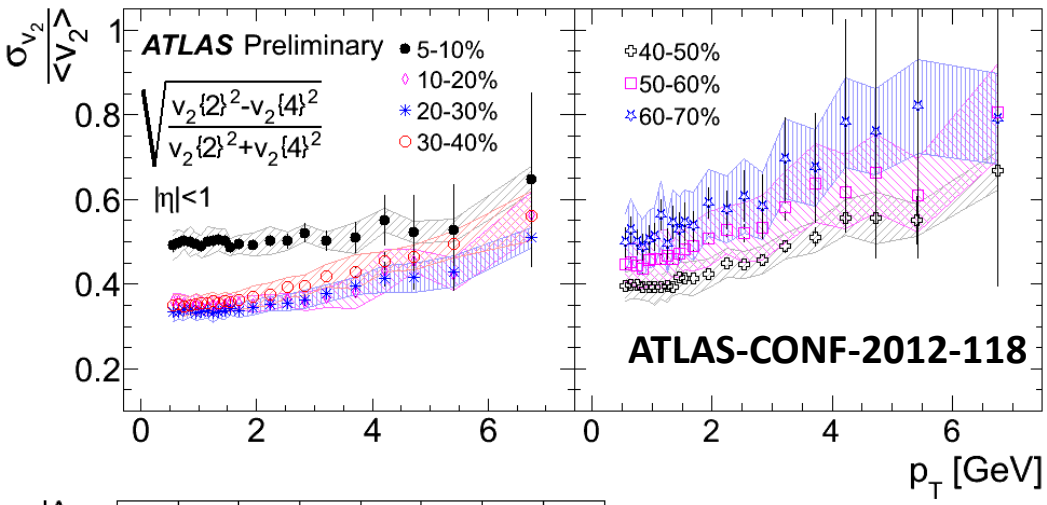
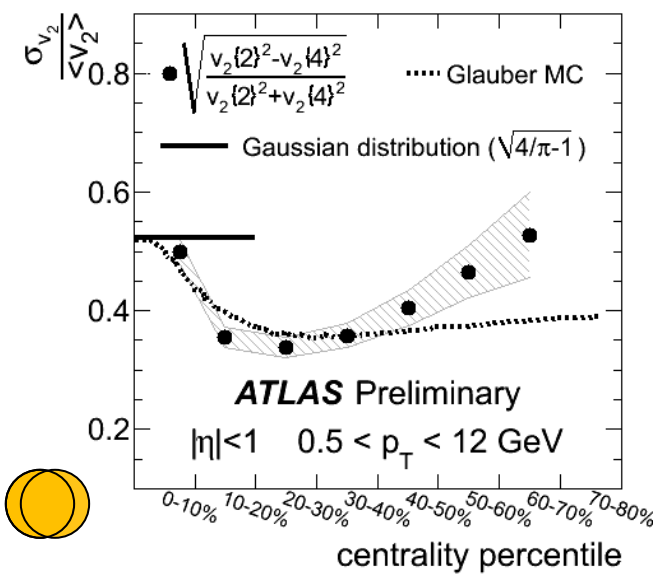
Event-by-Event Fluctuations from $v_2\{2\}$ and $v_2\{4\}$

Cumulant method provides a measure of elliptic flow fluctuations



N. Borghini, P.M.Dinh and J.Y. Ollitrault Phys.Rev. C64 (2001) 054901

- **Relative flow fluctuations are independent of p_T for 5-10% cent. bin**
- **For less central collisions $\sigma_2/\langle v_2\rangle$ increases with p_T**



- **$\sigma_2/\langle v_2\rangle$ agrees with the Glauber MC model prediction over a large centrality range but very peripheral collisions**

Glissando Glauber MC , W. Broniowski, M. Rybczyński, and P. Bożek, arXiv:0710.5731

T. Bold, *parallel 7D Fri.*

The Reaction Plane Correlations

- **Study non-linear response of the medium to initial fluctuations.**

$$\frac{dN_{events}}{d(k(\Phi_n - \Phi_m))} \propto 1 + 2\sum_{j=1}^{\infty} V^j_{n,m} \cos jk(\Phi_n - \Phi_m)$$

J.Jia, 1203.5095, 1205.3585

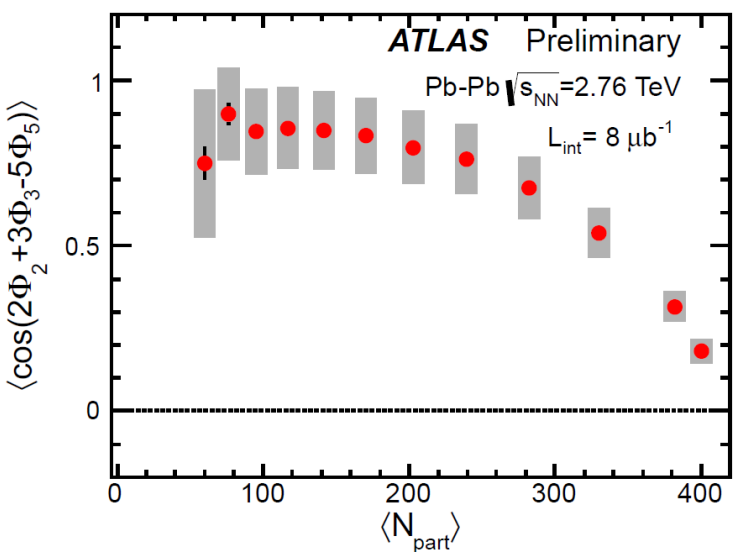
ATLAS-CONF-2012-049

$$V^j_{n,m} = \langle \cos jk(\Phi_n - \Phi_m) \rangle$$

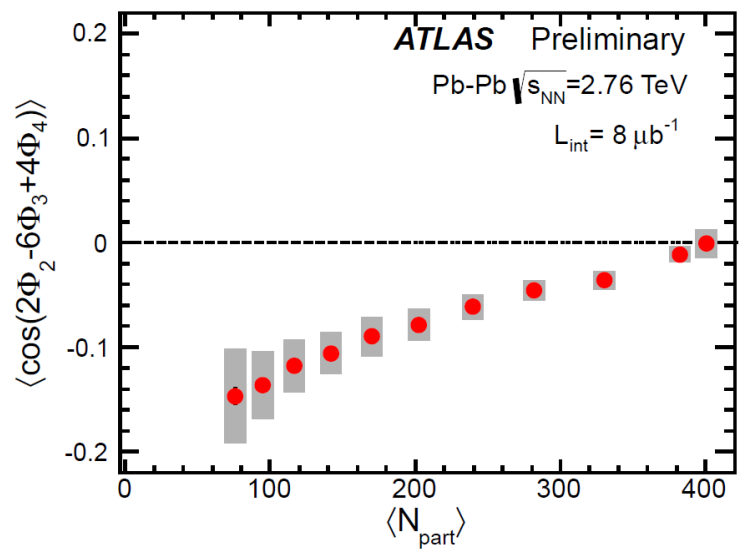
k – least common multiple of n & m

- **Correlators (V) measured with event planes from full η-range of calorimeter (-4.8 to 4.8), corrected for resolution**

$$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$$



$$\langle \cos(2\Phi_2 - 6\Phi_3 + 4\Phi_4) \rangle$$



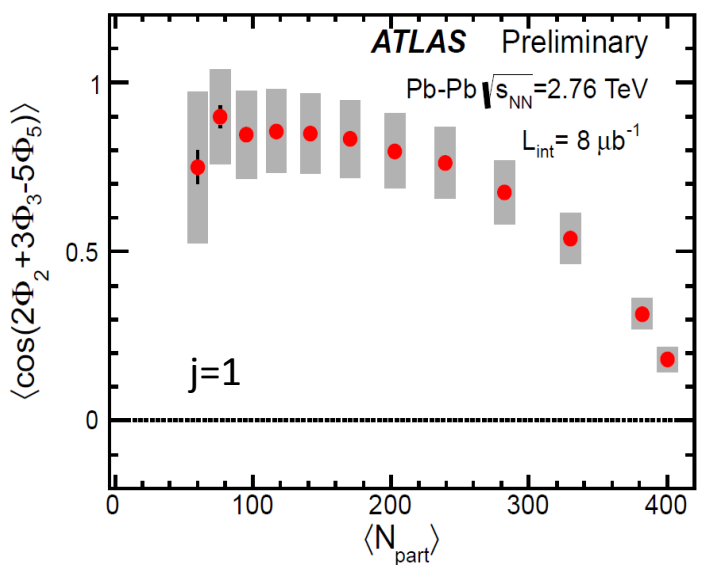
Reaction Plane Correlations

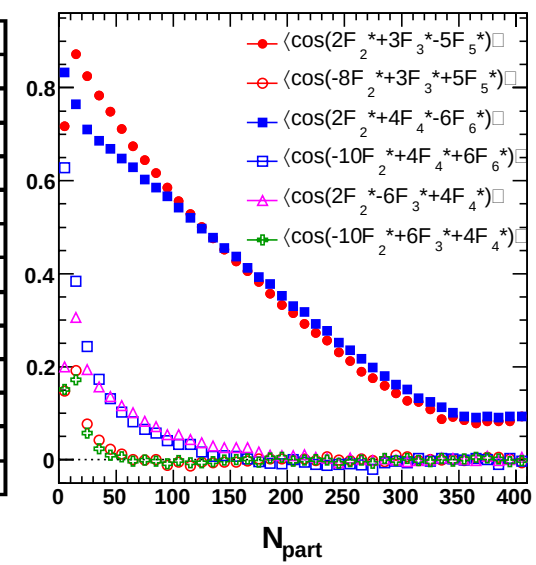
- Significant correlations are measured between two and three reaction planes (ATLAS-CONF-2012-049):
  - $\langle \cos 4(\Phi_2 - \Phi_4) \rangle$, $\langle \cos 8(\Phi_2 - \Phi_4) \rangle$, $\langle \cos 12(\Phi_2 - \Phi_4) \rangle$, $\langle \cos 6(\Phi_3 - \Phi_6) \rangle$
  - $\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$, $\langle \cos(2\Phi_2 + 4\Phi_4 - 6\Phi_6) \rangle$, $\langle \cos(-10\Phi_2 + 4\Phi_4 + 6\Phi_6) \rangle$
  - Correlation is very small but nonzero for $\langle \cos 6(\Phi_2 - \Phi_3) \rangle$
  - Correlation is negative for $\langle \cos(2\Phi_2 - 6\Phi_3 + 4\Phi_4) \rangle$
- Some correlators in magnitude similar to Glauber model, but not all
- Fluctuations in the initial geometry and dynamical evolution of the medium are important

S. Mohapatra, *parallel 7D Fri.*

$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$

MC Glauber Model predictions
J. Jia , S. Mohapatra, arXiv1203.5095





Summary

- ATLAS measured significant flow harmonics of charged particles in Pb-Pb collisions at the LHC energy $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ (v1-v6)
- Elliptic flow in broad range of p_T and η ($|\eta|<2.5$):
  - Integrated v_2 was obtained for $p_T > 0.03$ GeV
  - Cumulant harmonics $v_2\{2\}$ and $v_2\{4\}$ were measured ($0.5 < p_T < 12$ GeV)
  - Jet quenching characterized with v_2^{jet} for jets at p_T up to 200 GeV
- Higher order flow harmonics and directed flow term ($v_{1,1}$) can explain structures in the two-particle azimuthal correlations
  - Diploar flow, v_1, extracted from $v_{1,1}$ term
- Unfolded event–by–event v_2, v_3 and v_4 distributions provide direct information on relative flow fluctuations:
  - $\sigma_2/\langle v_2\rangle$ shows strong centrality dependence
- Relative fluctuations of elliptic flow from 2- and 4-particle cumulants are consistent with the Glauber MC model
- Mixed reaction plane correlations were obtained

Related Talks:

- **Aaron R. Angerami**, *Measurements of jet suppression with ATLAS,* ***parallel 2B Tue.***
- **Tomasz Bold**, *Measurements of flow harmonics with the cumulant method from the ATLAS experiment,* ***parallel 7D Fri.***
- **Dominik Derendarz**, *Measurement of elliptic and higher-order harmonics at sqrt(s_NN)=2.76TeV Pb-Pb collisions with the ATLAS detector,* ***parallel 2A Tue.***
- **Jiangyong Jia**, *Measurement of dipolar flow and event-by-event harmonic flow distributions in Pb-Pb collisions at sqrt(s_NN)=2.76TeV,* ***parallel 4A Wed.***
- **Soumya Mohapatra**, *Measurement of event plane correlations in Pb-Pb collisions with the ATLAS detector,* ***parallel 7D Fri.***

ATLAS, Phys. Lett. B707 (2012) 330-348

ATLAS, Phys. Rev. C86, (2012) 014907

ATLAS-CONF-2012-049

ATLAS-CONF-2012-114

ATLAS-CONF-2012-116

ATLAS-CONF-2012-117

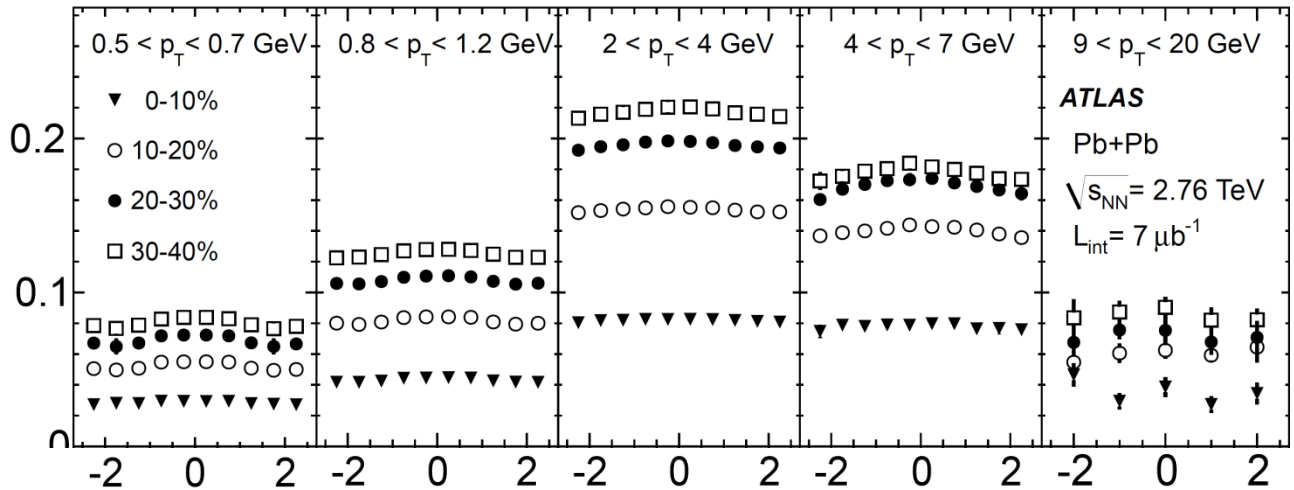
ATLAS-CONF-2012-118

Backups

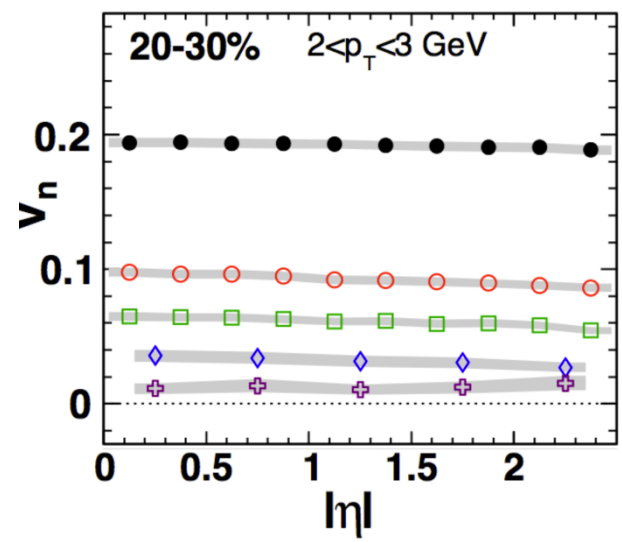
Pseudorapidity Dependence of v_2

ATLAS, Phys. Lett. B707 (2012) 330-348

***v_2* drops by about 5–10% over the range |*η*|=0-2.5**



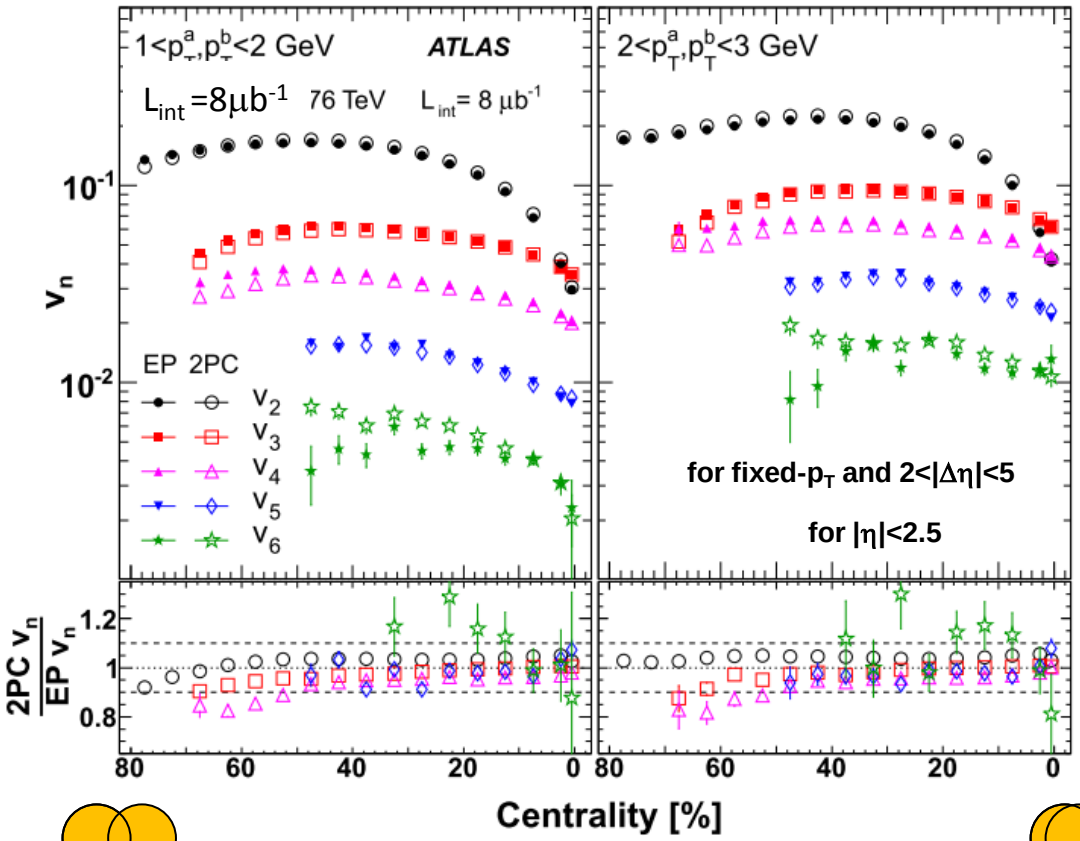
- **At RHIC , PHOBOS measured v_2 to decrease by ~30% within η range from 0 to 2.5 (p_T>0)**
- **v_n coefficients are ~boost invariant**



D. Derendarz, *parallel 2A Tue.*

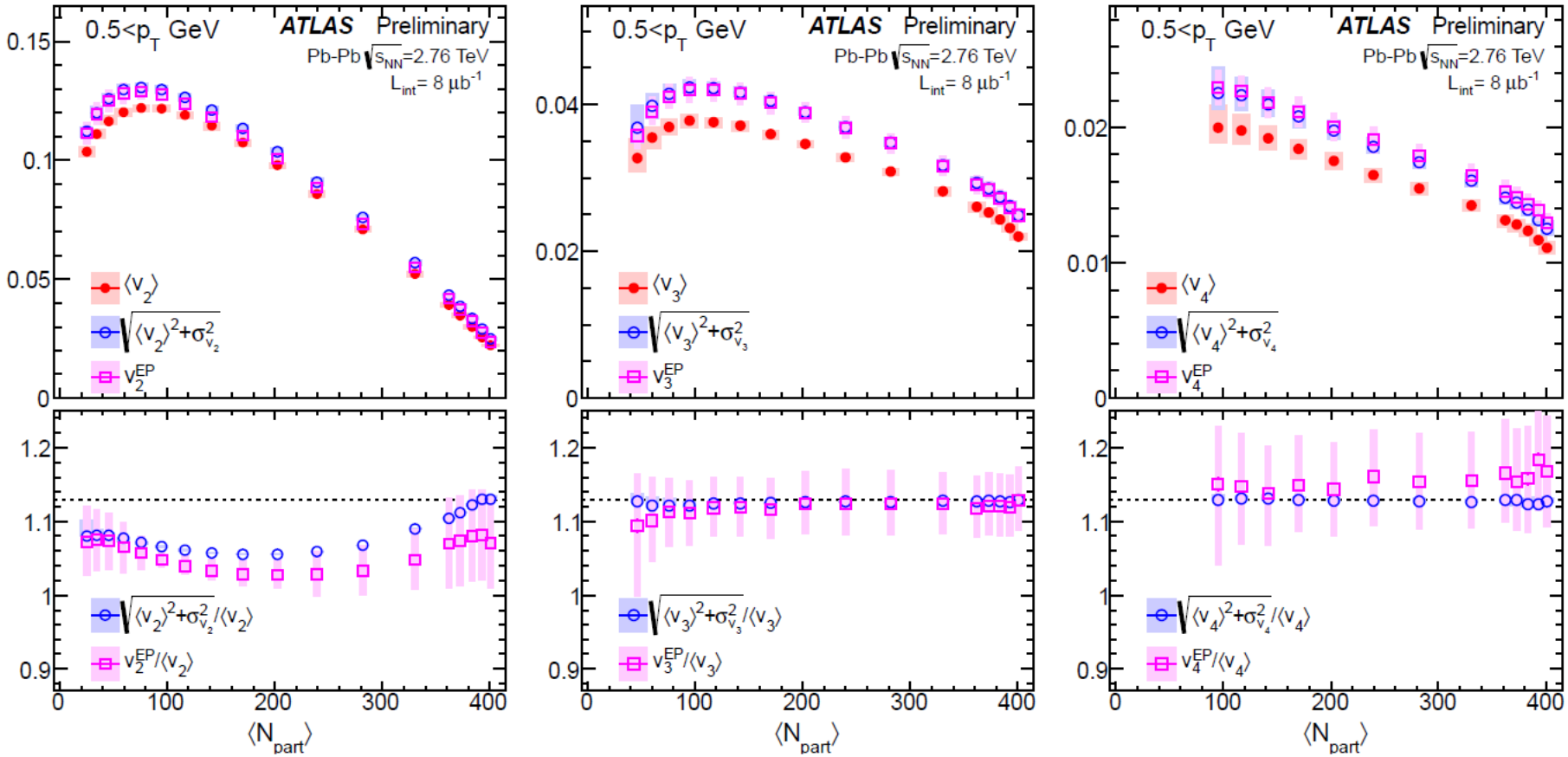
Two-Particle Correlation vs EP Results

Flow harmonics, up to v_6, are extracted with 2p correlation method



Agreements are at 5% level 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)

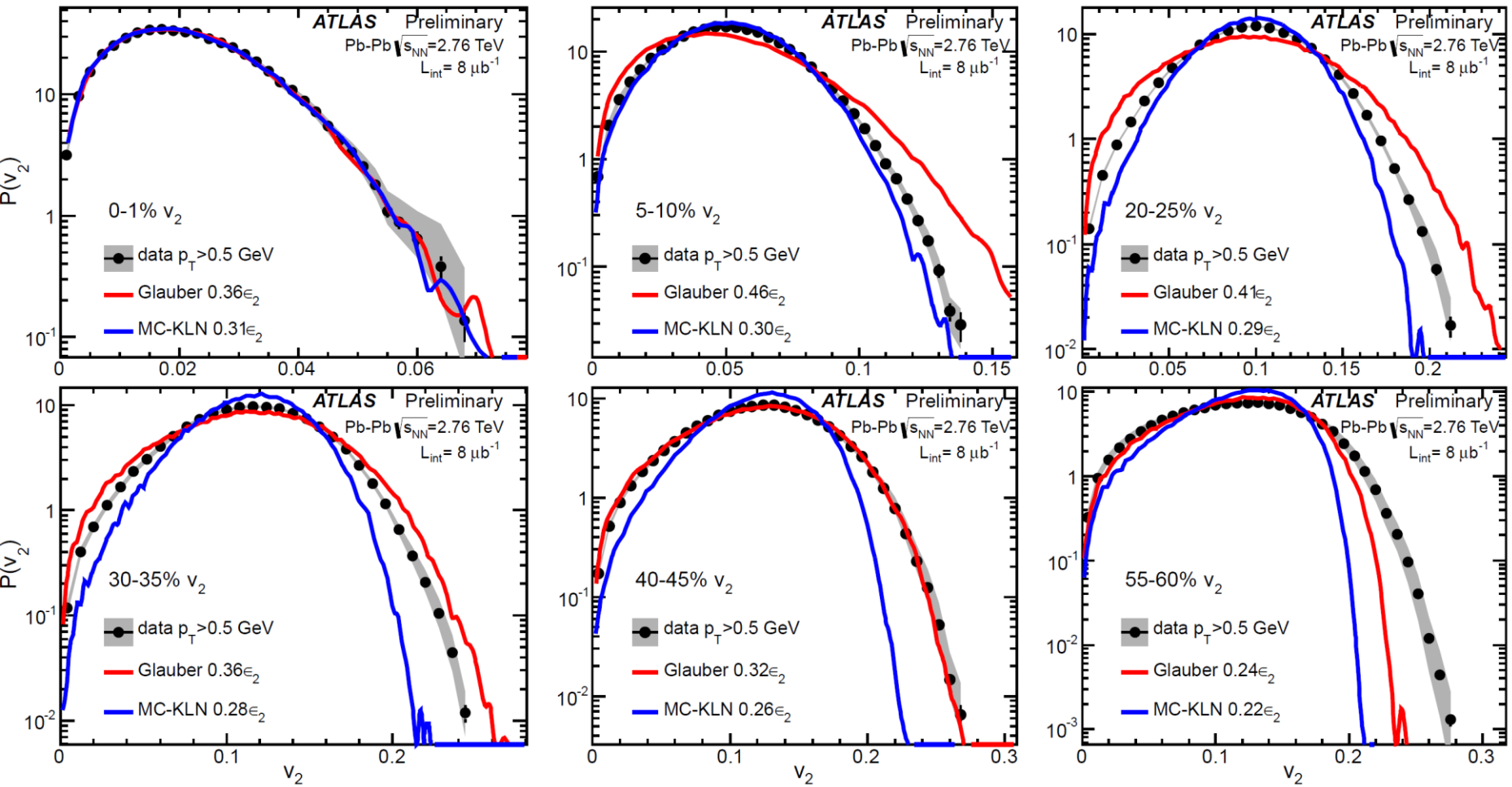
Comparison to v_n from Event Plane Method



$$< \mathbf{v}_n > \leq \mathbf{v}_n^{\mathbf{EP}} \leq \sqrt{< \mathbf{v}_n >^2 + \sigma_n^2}$$

Dotted lines indicate the Gaussian limit: $\dfrac{\sqrt{< \mathbf{v}_n >^2 + \sigma_n^2}}{< \mathbf{v}_n >} = \dfrac{2}{\sqrt{\pi}} \approx 1.13$

Comparison to MC Models



The EbE v2 distributions compared with the eccentricity distributions from two initial geometry models: a Glauber model (red lines) and the MC-KLN model (blue lines).

Response Function

ATLAS-CONF-2012-114

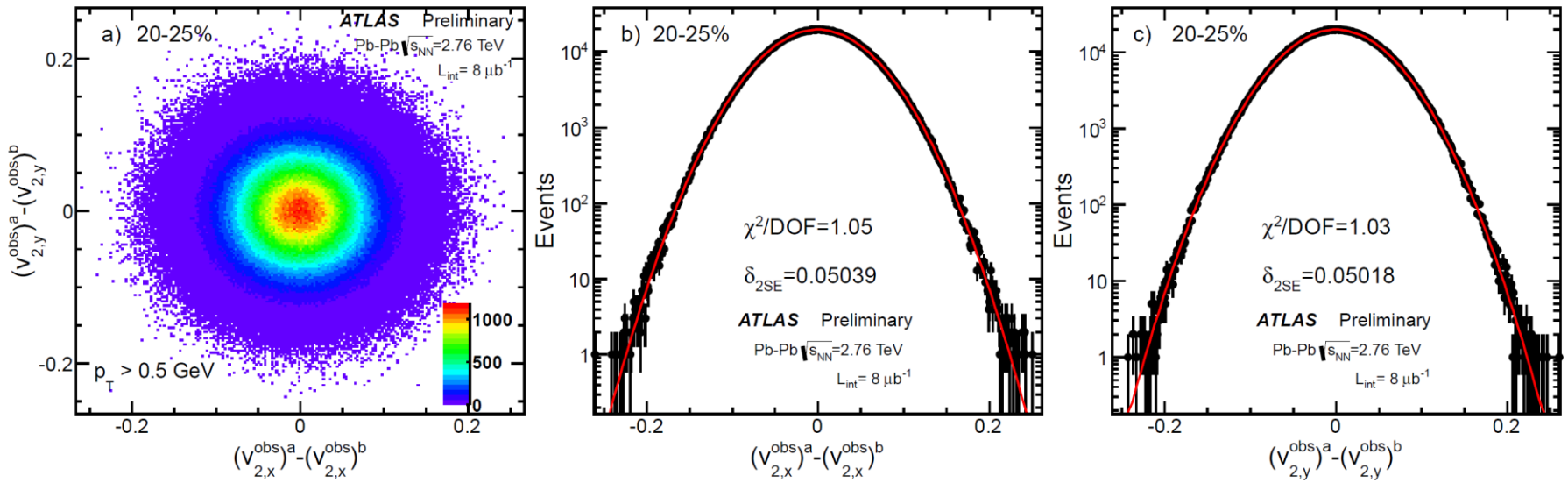
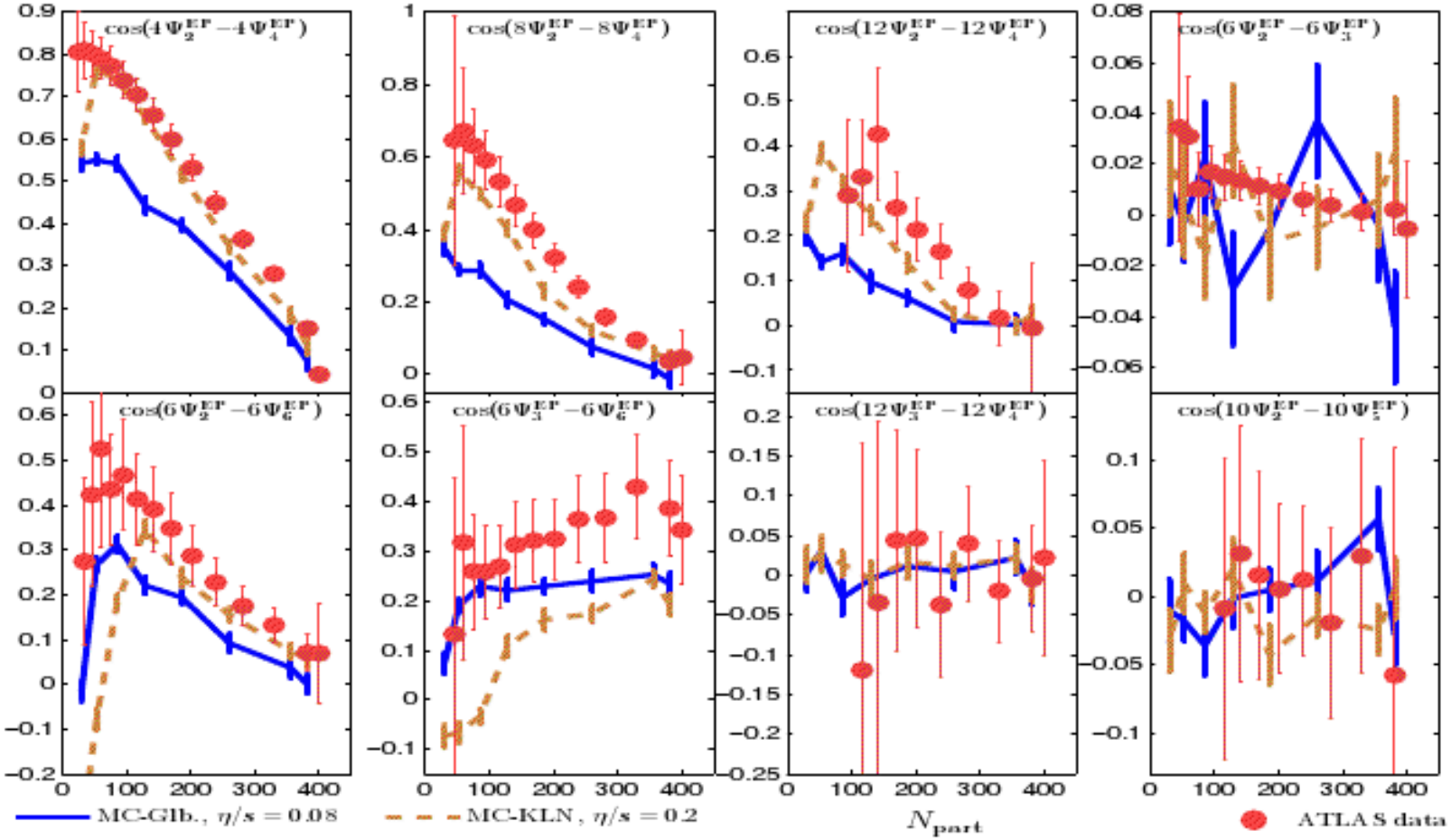


Figure 3: (left) The distribution of the difference between the per-particle flow vectors of the two half-IDs for events in 20-25% centrality interval. (middle) The projection on to the x-axis overlaid with a fit to a Gaussian. (right) The projection on to the y-axis overlaid with a fit to a Gaussian. The width from the fit, δ_{2SE}, and the quality of the fit, χ^2/DOF are shown.

Higher order event plane correlations in PbPb@LHC

Data: ATLAS Coll., J. Jia et al., Hard Probes 2012

Event-by-event hydrodynamics: Zhi Qiu (VISH2+1, MC-Glauber with $(\eta/s)_{\rm QGP}=0.08$ and MC-KLN with $(\eta/s)_{\rm QGP}=0.2$)



- VISH2+1 reproduces qualitative features of the centrality dependence of all measured event-plane correlations but is quantitatively off by up to 50%
- Larger η/s for MC-KL leads to stronger event-plane correlations (preferred by the data?)