Measurement of v_n coefficients and Reaction-Plane Correlations in ATLAS

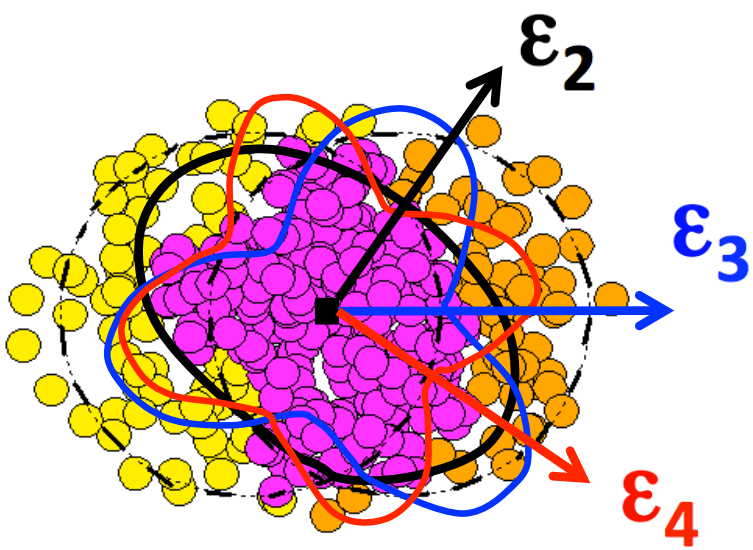
Soumya Mohapatra
Stony Brook University
for the **ATLAS** Collaboration

- ATLAS paper on v_n : http://arxiv.org/abs/1203.3087
- ATLAS Reaction-Plane Correlation Note: http://cdsweb.cern.ch/record/1451882

Hard Probes
27th May-1st June 2012

Introduction and motivation

- Initial spatial fluctuations of nucleons lead to higher moments of deformations in the fireball, each with its own orientation.
- The spatial anisotropy is transferred to momentum space by collective flow.



Singles: $$\frac{dN}{d\phi} \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n} \cos n\left(\phi - \Phi_n\right)$$

Pairs: $$\frac{dN_{Pairs}}{d\Delta\phi} \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n}^\mathrm{a}\mathrm{v}_\mathrm{n}^\mathrm{b} \cos\left(n\Delta\phi\right)$$

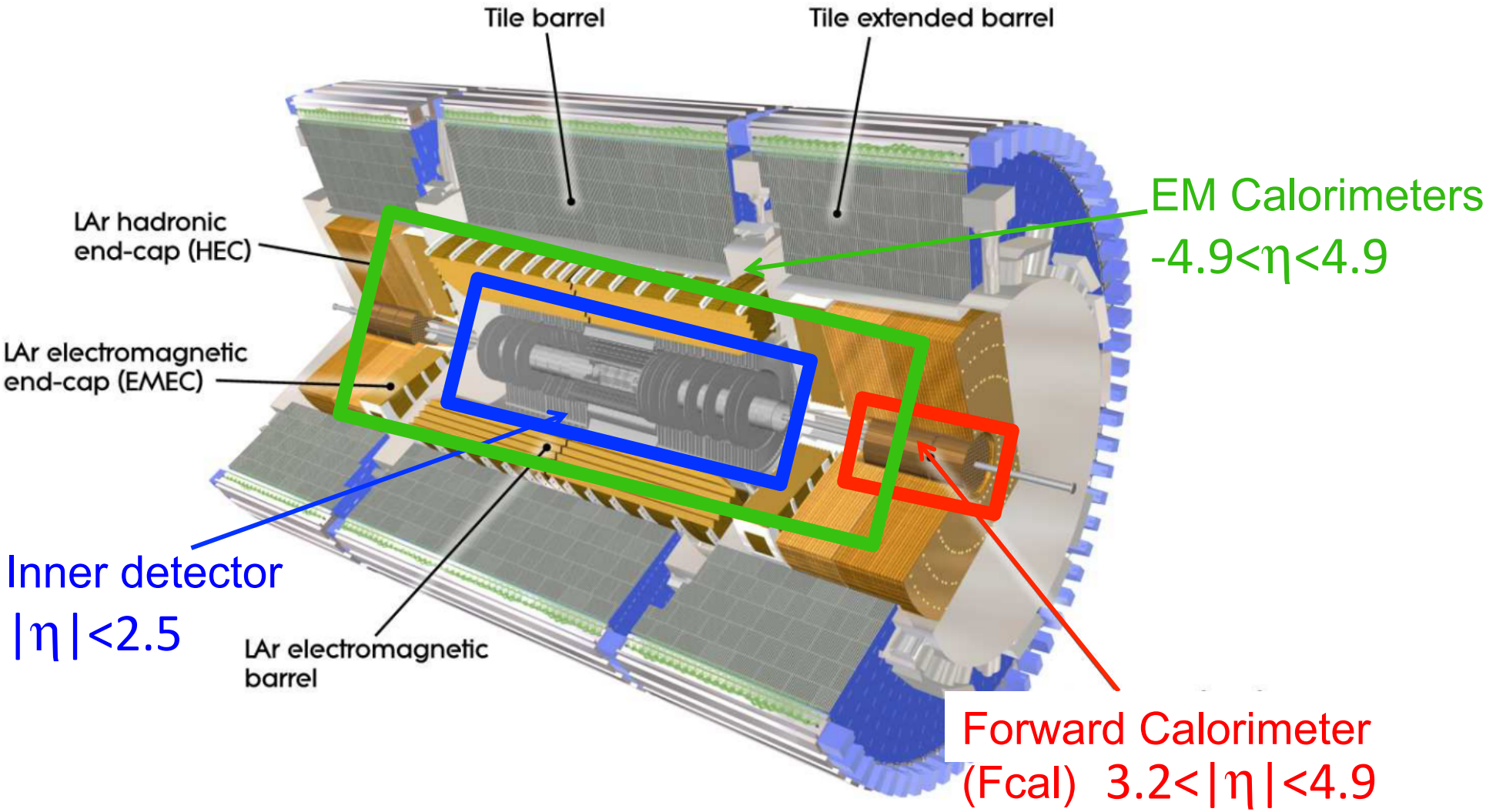
$(\Phi_n - \Phi_m)$ *correlations*

See Monday's Talk by J. Jia (parallel 1-C)

$$\varepsilon_n = \sqrt{\frac{\left\langle r^n \cos(n\phi)\right\rangle + \left\langle r^n \sin(n\phi)\right\rangle}{r^n}} \qquad \tan(n\Phi_n^*) = \frac{\left\langle r^n \sin(n\phi)\right\rangle}{\left\langle r^n \cos(n\phi)\right\rangle}$$

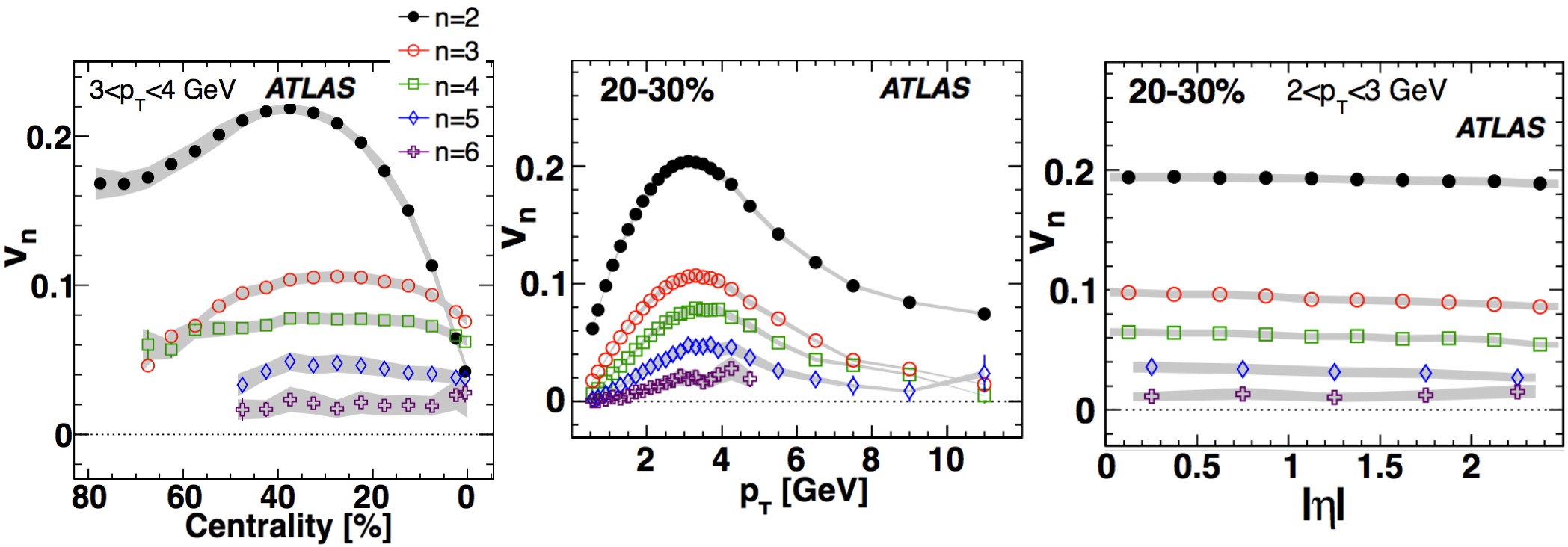
- Studying the v_n and correlations between the Φ_n gives insight into the initial geometry and expansion mechanism of the fireball.

ATLAS Detector



- Tracking coverage : $|\eta|<2.5$
- FCal coverage : $3.2<|\eta|<4.9$ (used to determine Event Planes)
- For reaction plane correlations use entire EM calorimeters ($-4.9 < \eta < 4.9$)

Event Plane $v_n(\eta, p_T$,centrality)



- Features of Fourier coefficients
  - v_n coefficients rise and fall with centrality.
  - v_n coefficients rise and fall with p_T.
  - v_n coefficients are ~boost invariant.

Obtaining harmonics from correlations

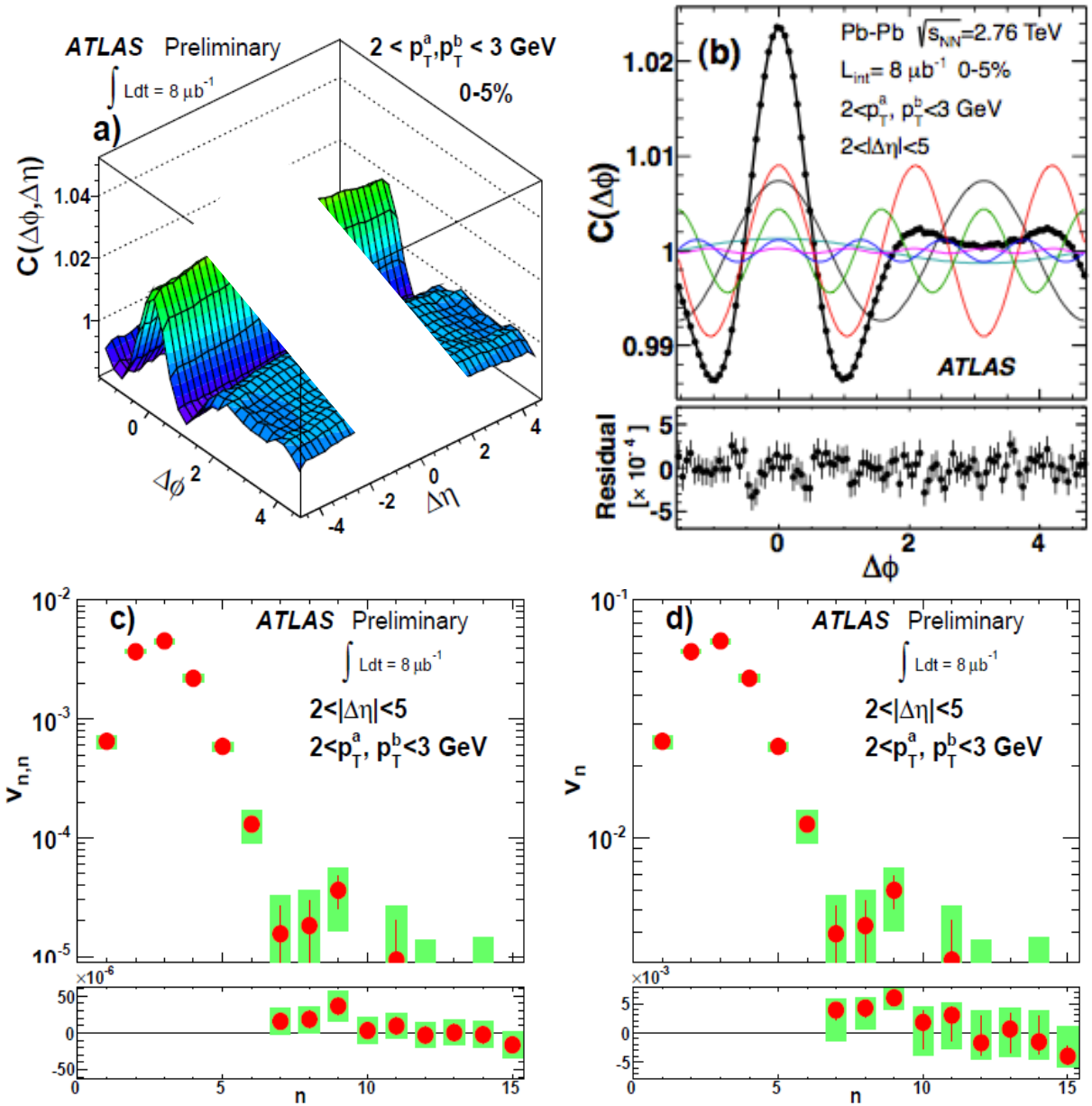
a) The 2D correlation function in $\Delta\eta,\Delta\phi$.

b) The corresponding 1D correlation function in $\Delta\phi$ for $2<|\Delta\eta|<5$ (the $|\Delta\eta|$ cut removes near side peak)

c) The $v_{n,n}$ obtained using a Discrete Fourier Transformation(DFT)

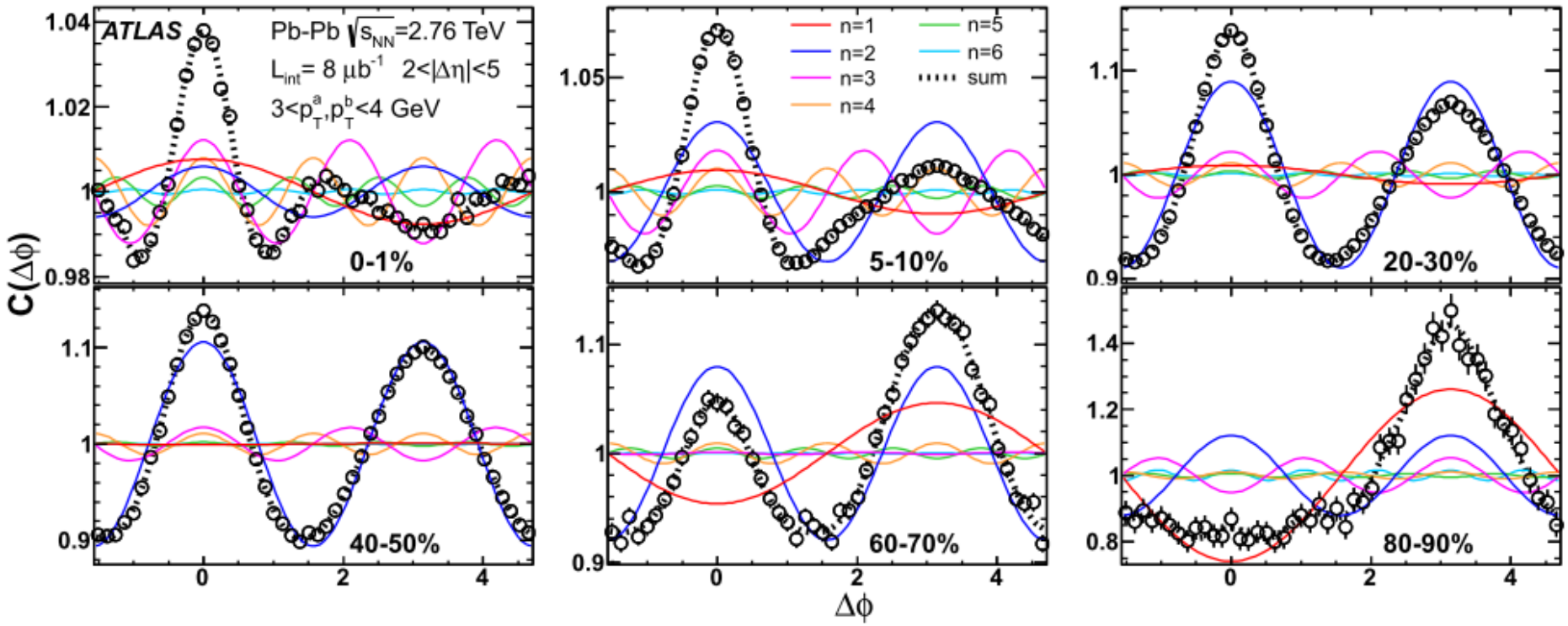
d) Corresponding v_n values

$$v_n\left(p_T^a\right)=\sqrt{v_{n,n}\left(p_T^a,p_T^a\right)}$$



Bands indicate systematic errors

Centrality evolution of correlations

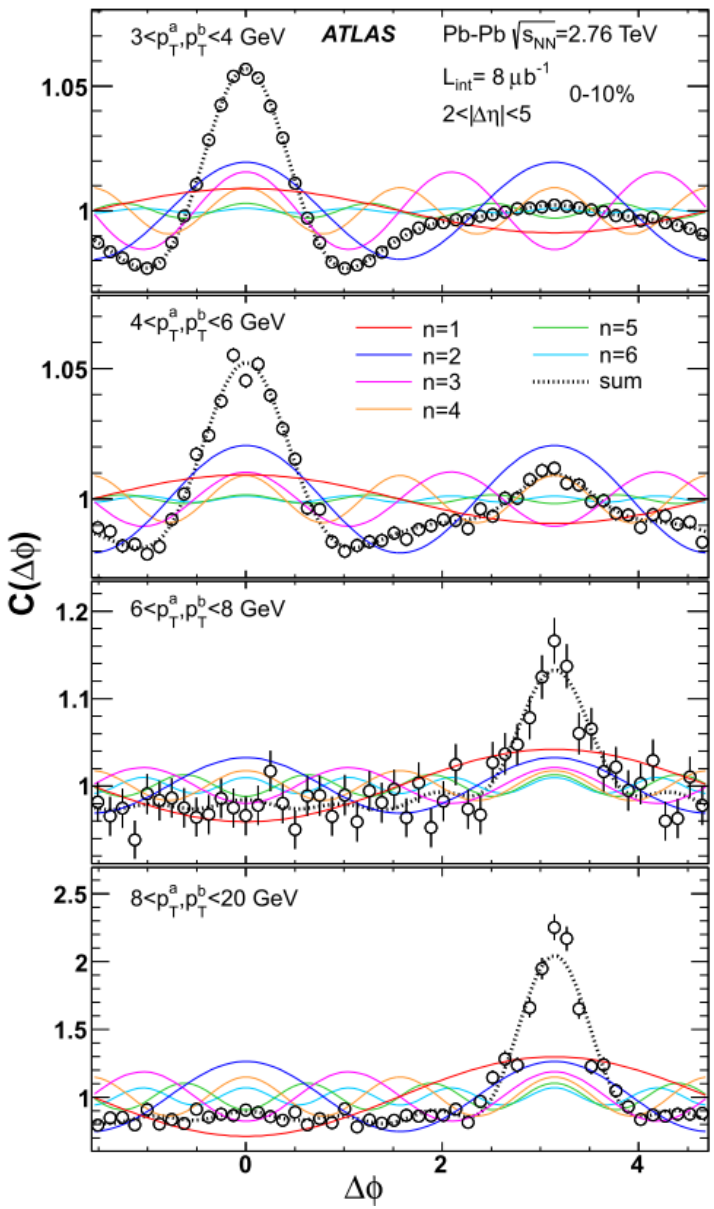


- If single particle v_n dominates then near side peak must be larger than away side.

$$\frac{dN^{ab}}{d\Delta\phi} \propto \left(1 + 2\sum v_n^a v_n^b \cos(n\Delta\phi)\right)$$

- True till 50% centrality.
- Negative $v_{1,1}$ is indicator of auto-correlation from away side jet.

p_T evolution of correlations



$3<p_T^a,p_T^b<4$ GeV

$4<p_T^a,p_T^b<6$ GeV

Larger near side peak

$6<p_T^a,p_T^b<8$ GeV

$8<p_T^a,p_T^b<20$ GeV

Larger away side peak:
Auto-correlation from
away side jet

p_T dependence of 2PC v_n

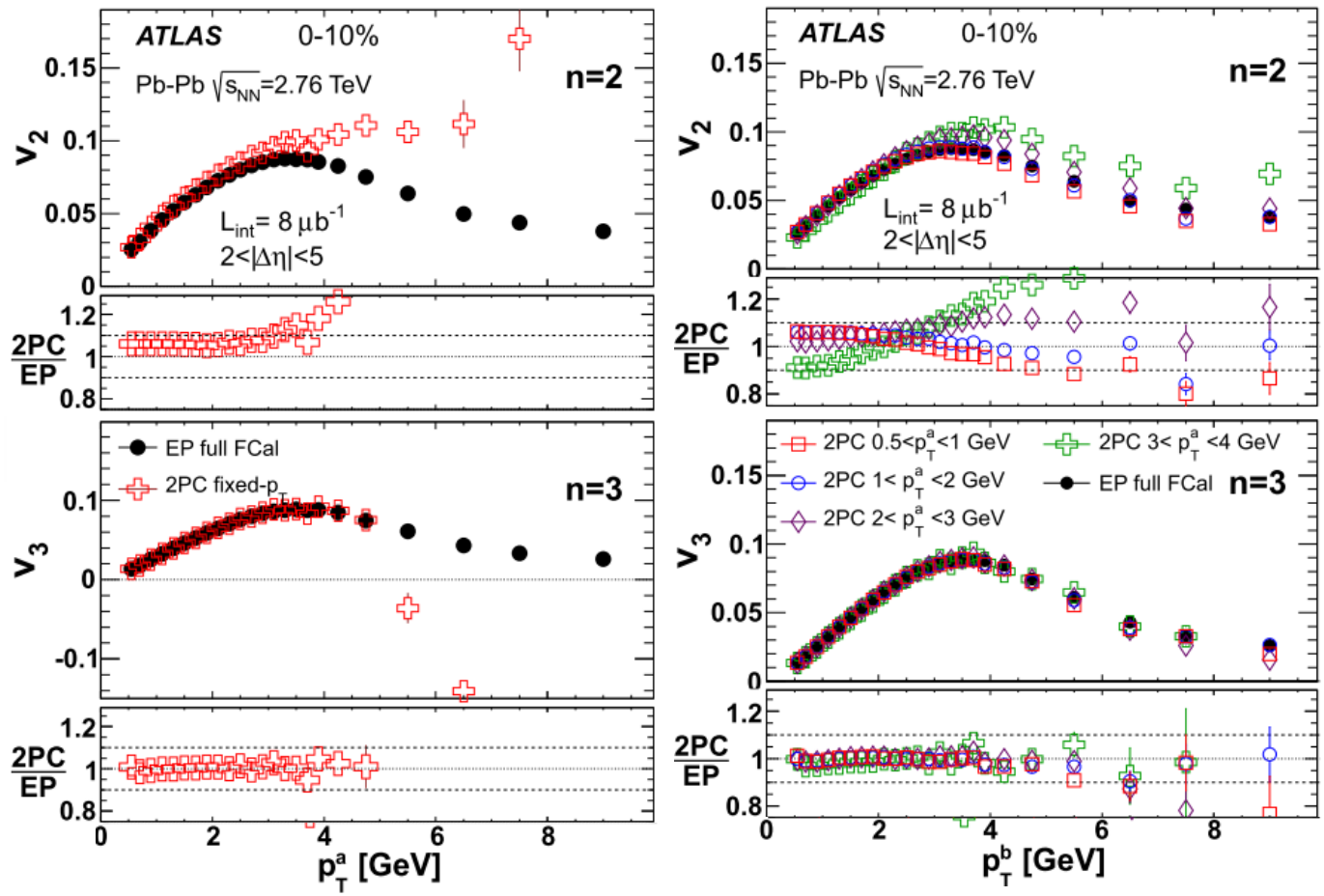
$$v_{n,n}\left(p_T^a, p_T^b\right) = v_n\left(p_T^a\right) v_n\left(p_T^b\right)$$

- Obtain v_n using "fixed p_T" correlations

$$v_n\left(p_T^a\right) = \sqrt{v_{n,n}\left(p_T^a, p_T^a\right)}$$

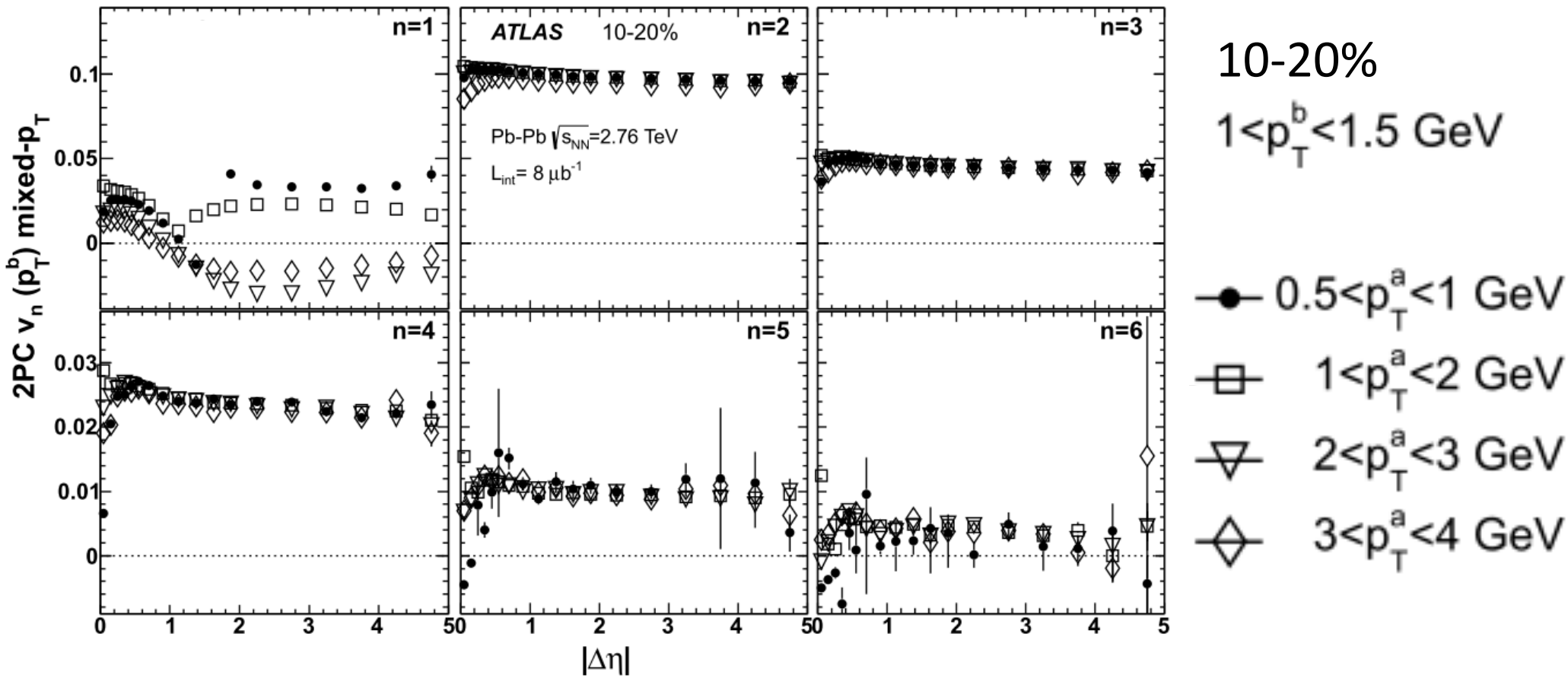
- cross-check via "mixed-p_T" correlation

$$v_n\left(p_T^b\right) = v_{n,n}\left(p_T^a, p_T^b\right) \Big/ v_n\left(p_T^a\right)$$



Factorizations works for soft-soft and soft-hard correlations!

Universality of v_n



- For harmonics $n \geq 2$, the scaling holds very well (for $|\Delta\eta|>2$).
- For $v_{1,1}$ the scaling doesn't hold.
  - $v_1(p_T^b)$ depends on p_T^a showing the breakdown of the scaling relation.
  - Breakdown is mainly due to contributions from global momentum conservation

$v_{1,1}$ and v_1 Story

- For $v_{1,1}$ the factorization breaks :: Influenced by global momentum conservation.

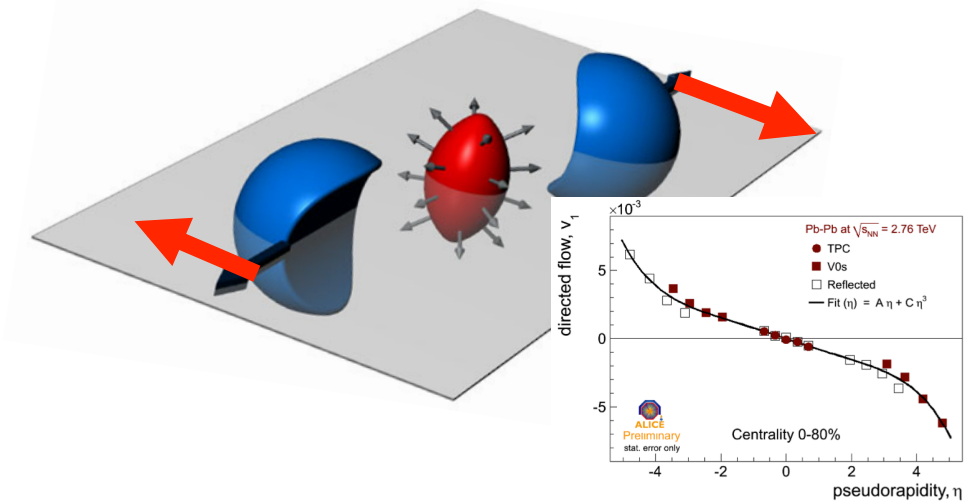
$$v_{1,1}(p_T^a, p_T^b, \eta^a, \eta^b) \approx v_1(p_T^a, \eta^a) \times v_1(p_T^b, \eta^b) - \frac{p_T^a \times p_T^b}{M\left\langle p_T^2 \right\rangle}$$

  - Second term is leading order approximation for momentum conservation

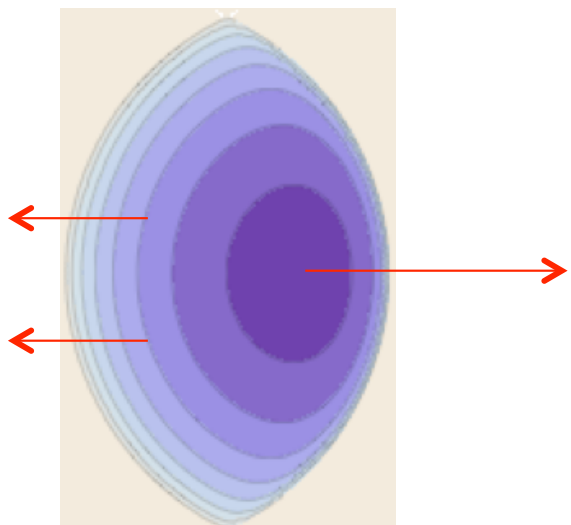
- $V_1(\eta)$ has rapidity odd and rapidity even components:
- Odd component is <0.005 for $|\eta|$ <2 at LHC, thus has contribution to v_{11} ($<2.5\times10^{-5}$)
- If rapidity even component has weak η dependence, then:

$$v_{1,1}(p_T^a, p_T^b) \approx v_1(p_T^a) \times v_1(p_T^b) - \frac{p_T^a \times p_T^b}{M\left\langle p_T^2 \right\rangle}$$

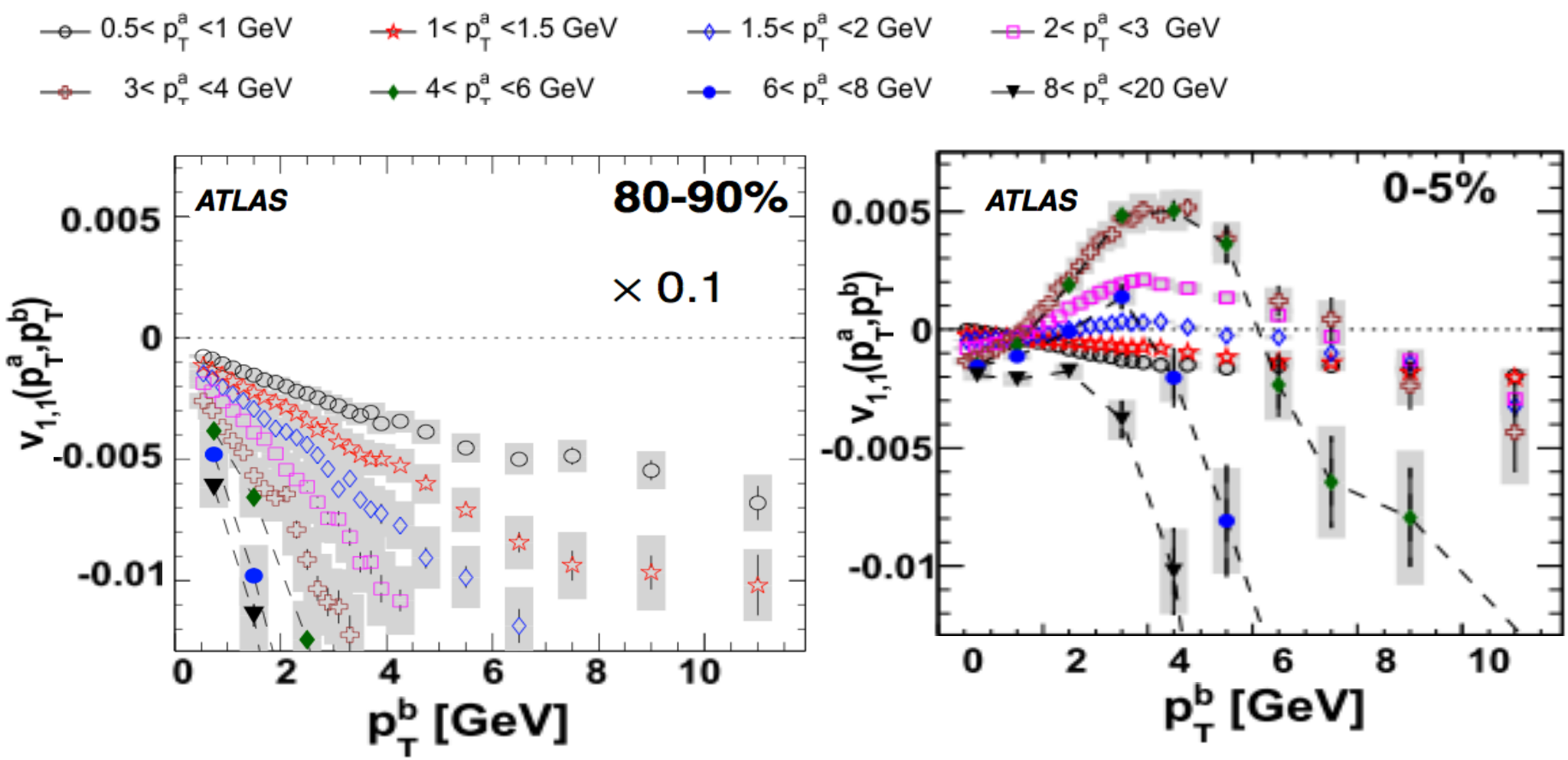
Odd component: vanishes at η=0



Even component: ~boost invariant in η



$v_{1,1}(p_T^a, p_T^b)$

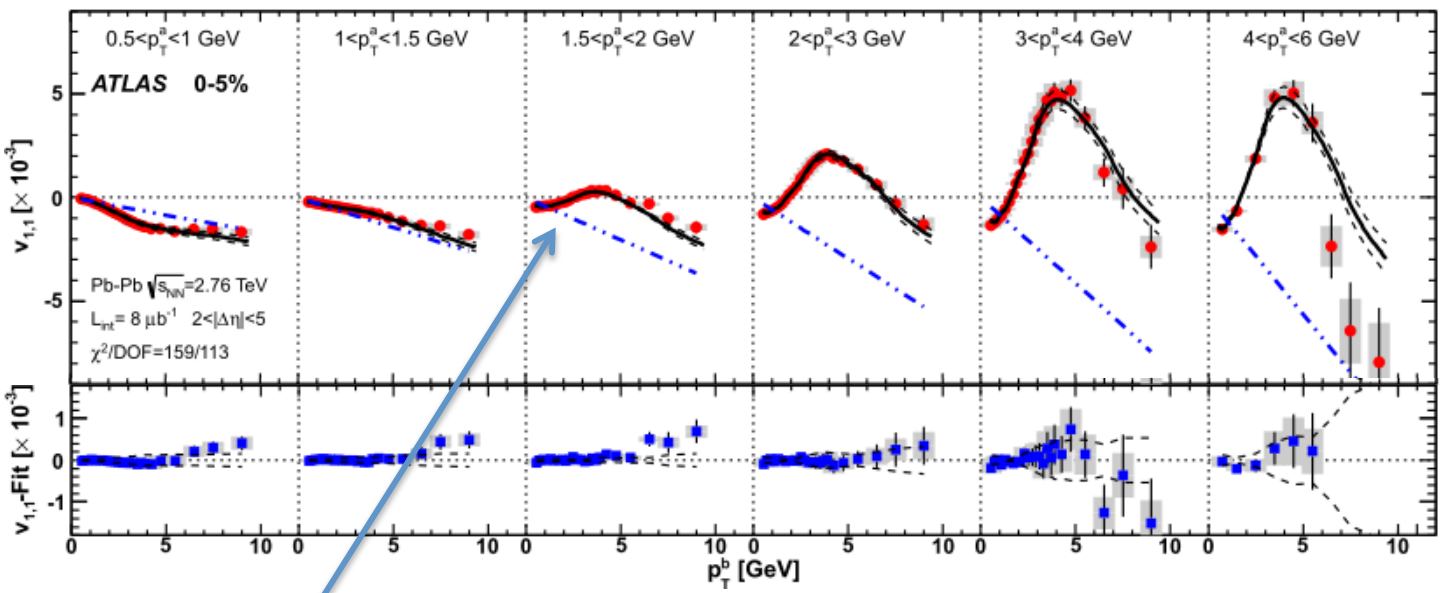


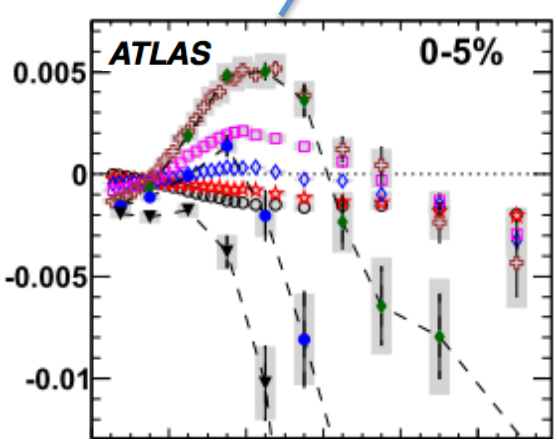
$$-\frac{p_T^a \times p_T^b}{M\left\langle p_T^2 \right\rangle}$$

$$v_{1,1}(p_T^a, p_T^b) \approx v_1(p_T^a) \times v_1(p_T^b) - \frac{p_T^a \times p_T^b}{M\left\langle p_T^2 \right\rangle}$$

Extracting the η-even v_1 (p_T)

$$v_{1,1}(p_T^a, p_T^b) = v_1^{Fit}(p_T^a) \times v_1^{Fit}(p_T^b) - c(p_T^a \times p_T^b)$$



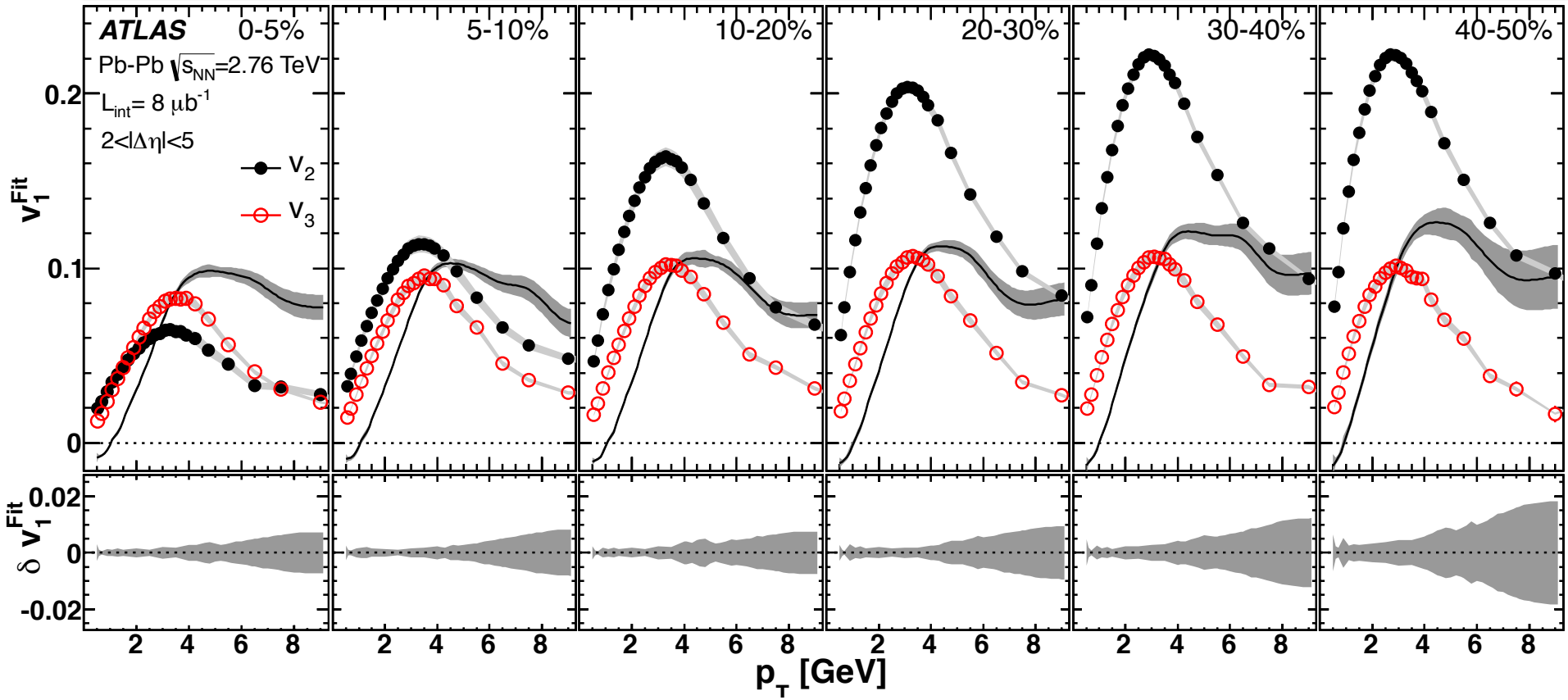


Red Points: v11 data

Black line : Fit to functional form

Blue line: momentum conservation component

η-even v_1 (p_T)



- Significant v_1 values observed :: p_T dependence similar to other harmonics
- v_1 is negative for p_T<1.0GeV :: expected from hydro calculations.
- Value is comparable to v_3 :: showing significant dipole moment in initial state

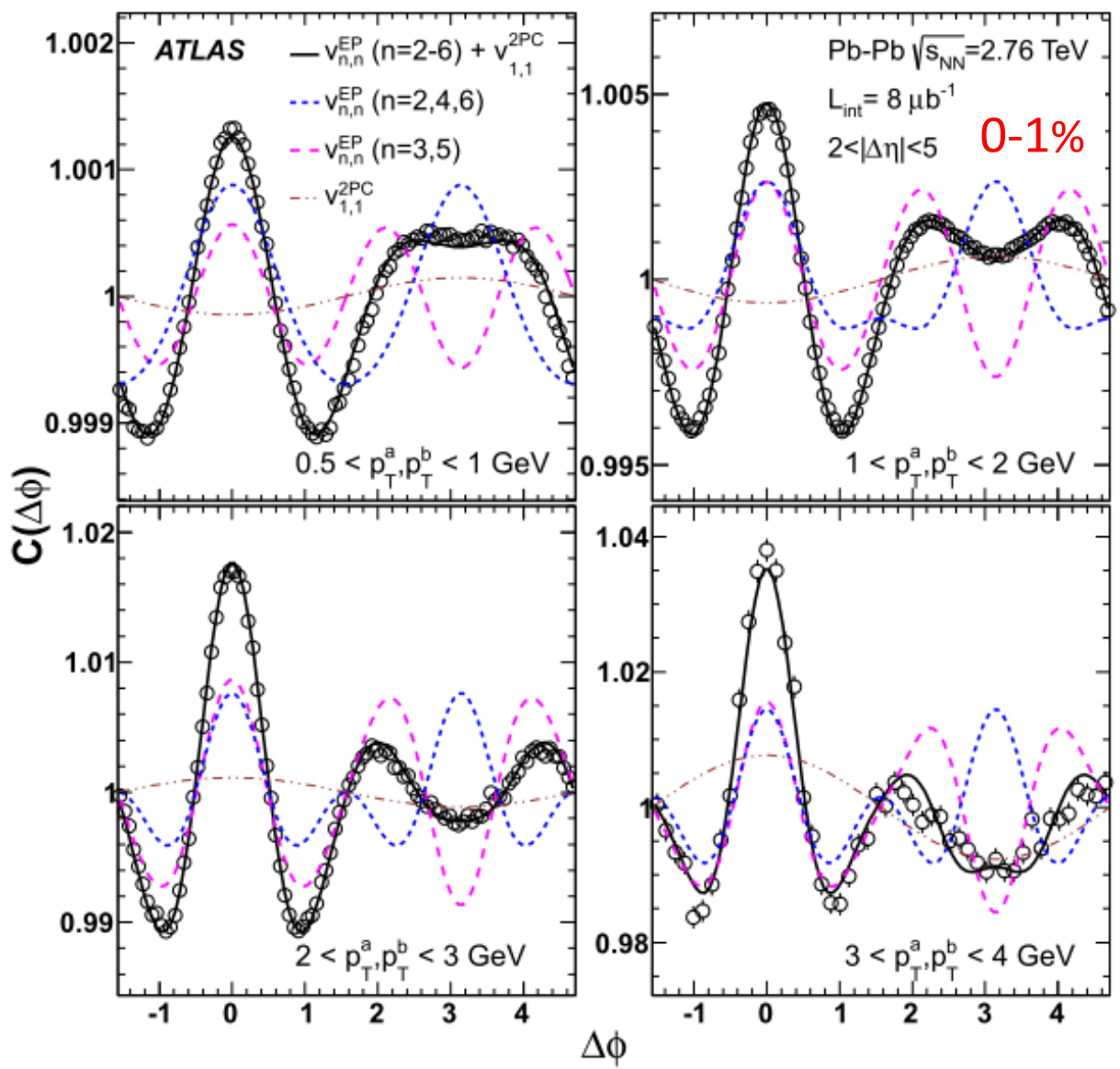
Recovering the correlations from EP v_n

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

From 2PC method

From EP method

- Chose $v_{1,1}$ and normalization to be same as original correlation function, but all other harmonics are from EP analysis.
- Correlation function is well reproduced, ridge and cone are recovered!
- Common physics origin for the near and away-side long range structures.



Reaction-Plane Correlations

See Monday's talk by J. Jia (Parallel 1-C) for details.

- Further insight into initial geometry can be obtained by studying correlations between the Φ_n:

$$\frac{dN_{events}}{d(k(\Phi_n - \Phi_m))} = 1 + 2\sum_{j=1}^{\infty} V_{n,m}^{j} \cos(j \times k(\Phi_n - \Phi_m)) \;\; : k = LCM(m,n)$$

arXiv:1203.5095

$$V_{n,m}^{j} = \langle \cos(j \times k(\Phi_n - \Phi_m)) \rangle$$

arXiv:1205.3585

- The measured correlations are corrected by the resolution factors:

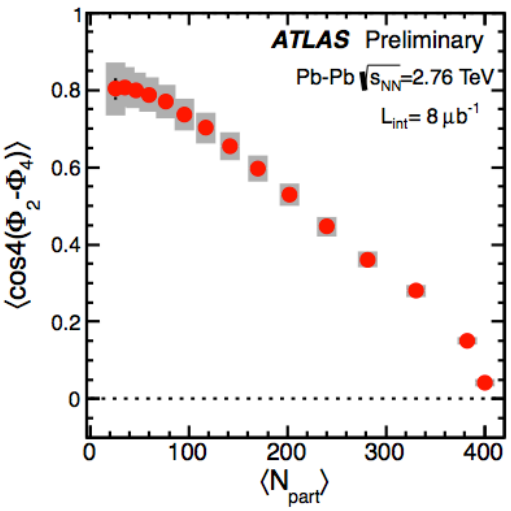
$$\langle \cos(j \times k(\Phi_n - \Phi_m)) \rangle = \frac{\langle \cos(j \times k(\Psi_n - \Psi_m)) \rangle}{\mathrm{Res}(j \times k\Psi_n) \times \mathrm{Res}(j \times k\Psi_m)} \;\; :: \;\; \Phi_n = True, \; \Psi_n = Measured$$

arXiv: 1105.3928
PHENIX but no corrections for reso.

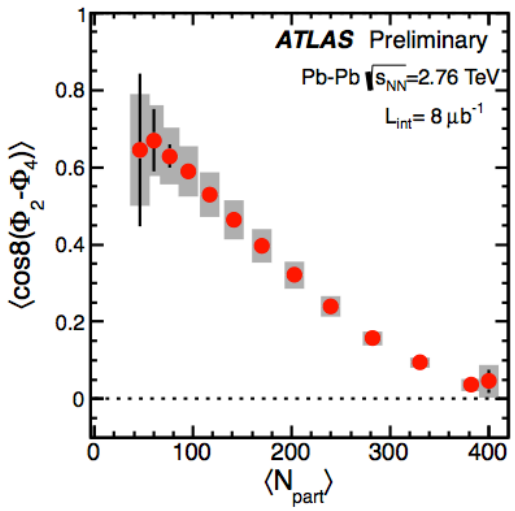
- All correlations of planes ($2 \leq n,m \leq 6$) where the resolution is good enough to make conclusive measurements are studied.

Two-Plane Correlations

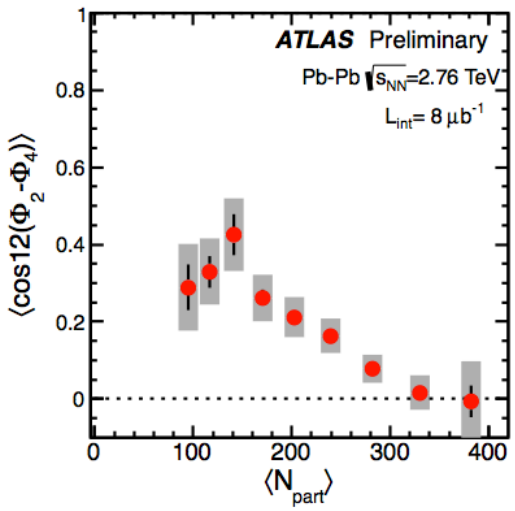
$\langle \cos(1\times 4(\Phi_2-\Phi_4))\rangle$



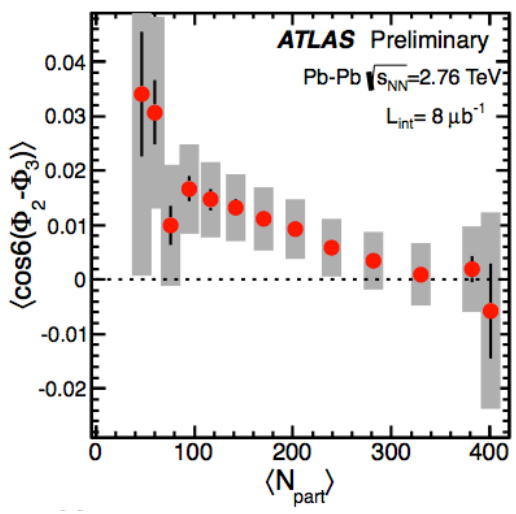
$\langle \cos(2\times 4(\Phi_2-\Phi_4))\rangle$



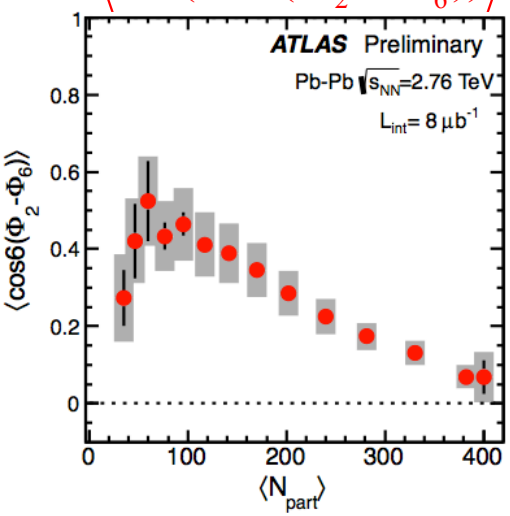
$\langle \cos(3\times 4(\Phi_2-\Phi_4))\rangle$



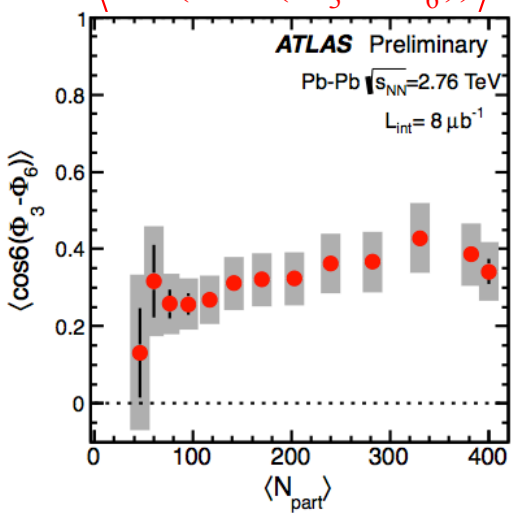
$\langle \cos(1\times 6(\Phi_2-\Phi_3))\rangle$



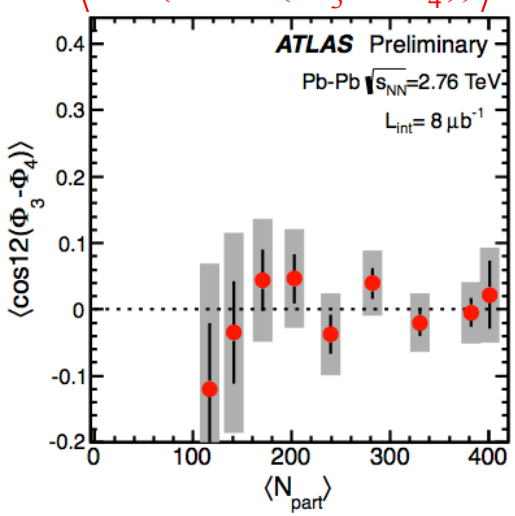
$\langle \cos(1\times 6(\Phi_2-\Phi_6))\rangle$



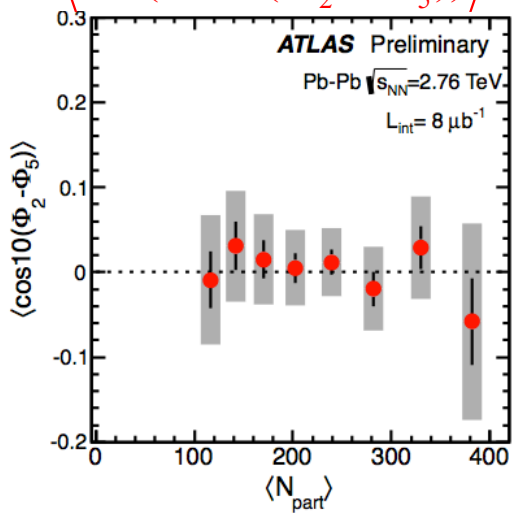
$\langle \cos(1\times 6(\Phi_3-\Phi_6))\rangle$



$\langle \cos(1\times 12(\Phi_3-\Phi_4))\rangle$



$\langle \cos(1\times 10(\Phi_2-\Phi_5))\rangle$



Three-Plane correlations

- The procedure can be generalized to measure correlations involving three or more planes:

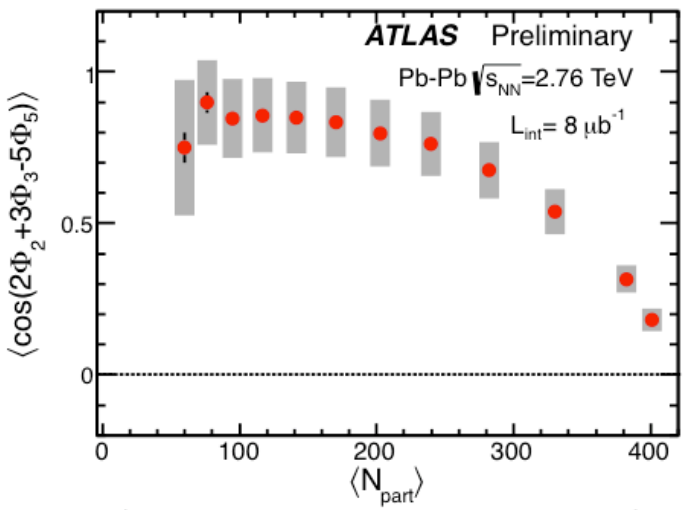
$$\left\langle \cos(c_1\Phi_1 + 2c_2\Phi_2 ... lc_l\Phi_l)) \right\rangle \;:\; c_1 + 2c_2 + ... lc_l = 0 \quad arxiv:1104.4740$$

- The following three plane correlations are studied: arXiv:1203.5095 arXiv:1205.3585
  - $2-3-5$: $2\Phi_2+3\Phi_3-5\Phi_5$, $8\Phi_2-3\Phi_3-5\Phi_5$
  - $2-4-6$: $2\Phi_2+4\Phi_4-6\Phi_6$, $-10\Phi_2+4\Phi_4+6\Phi_6$
  - $2-3-4$: $2\Phi_2-6\Phi_3+4\Phi_4$, $-10\Phi_2+6\Phi_3+4\Phi_4$
  - They involve combinations of planes ($2 \le n \le 6$) where the resolution is good enough to make measurements.
- One way to think of the three-plane correlations is as combination of two plane correlations:
  - $2\Phi_2+4\Phi_4-6\Phi_6 = 4(\Phi_4-\Phi_2)-6(\Phi_6-\Phi_2)$
  - $-10\Phi_2+4\Phi_4+6\Phi_6 = 4(\Phi_4-\Phi_2)+6(\Phi_6-\Phi_2)$
  - Thus three plane correlations are the correlation of two angles relative to the third.

Three-Plane Correlations

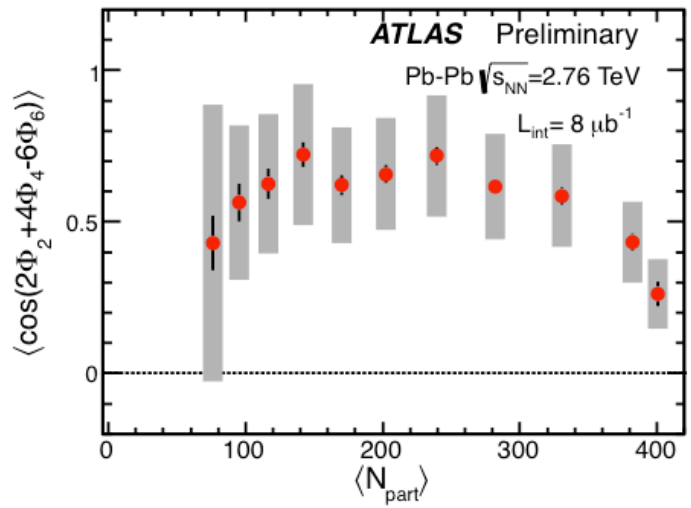
"2-3-5" correlation

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



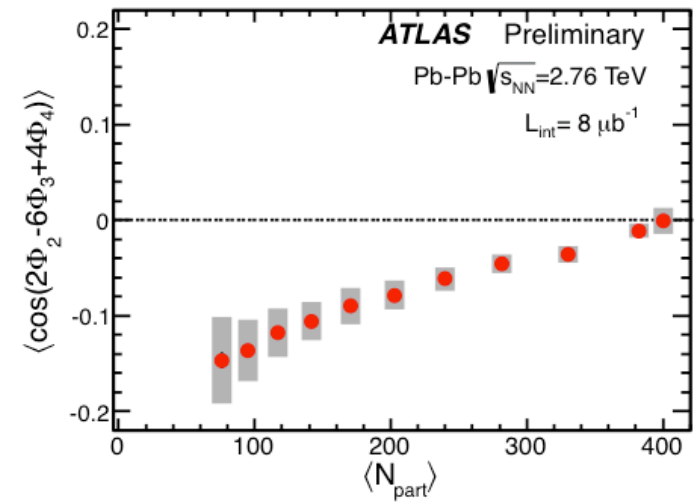
"2-4-6" correlation

$$\left\langle \cos\left(2\Phi_2 + 4\Phi_4 - 6\Phi_6\right)\right\rangle$$

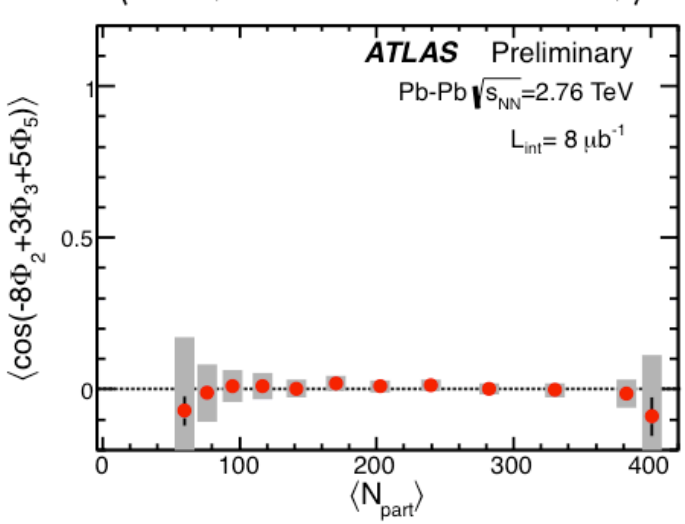


"2-3-4" correlation

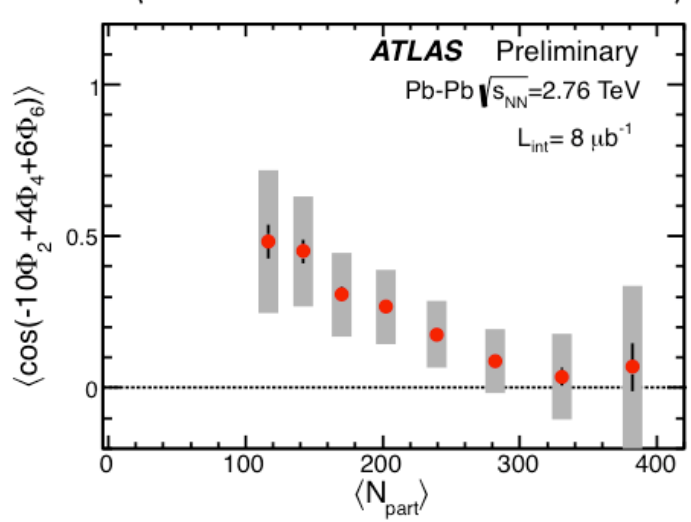
$$\left\langle \cos\left(2\Phi_2 - 6\Phi_3 + 4\Phi_4\right)\right\rangle$$



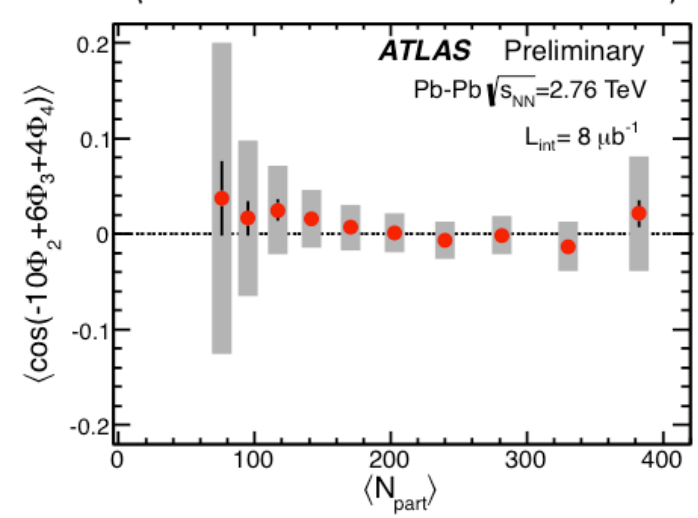
$$\left\langle \cos\left(-8\Phi_2 + 3\Phi_3 + 5\Phi_5\right)\right\rangle$$



$$\left\langle \cos\left(-10\Phi_2 + 4\Phi_4 + 6\Phi_6\right)\right\rangle$$

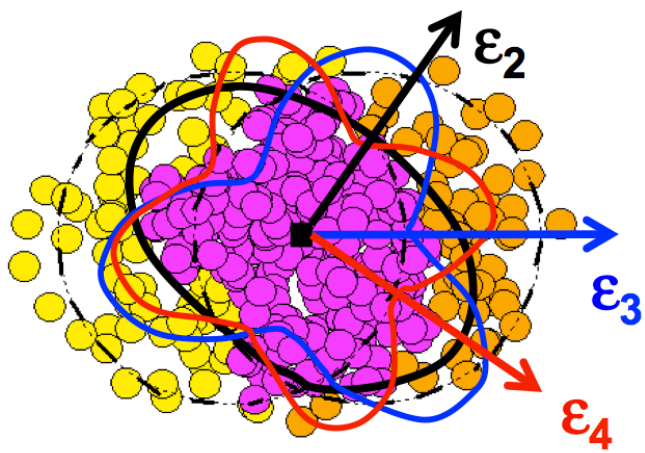


$$\left\langle \cos\left(-10\Phi_2 + 6\Phi_3 + 4\Phi_4\right)\right\rangle$$



Rich centrality dependence patterns are observed

Expectation from Glauber model

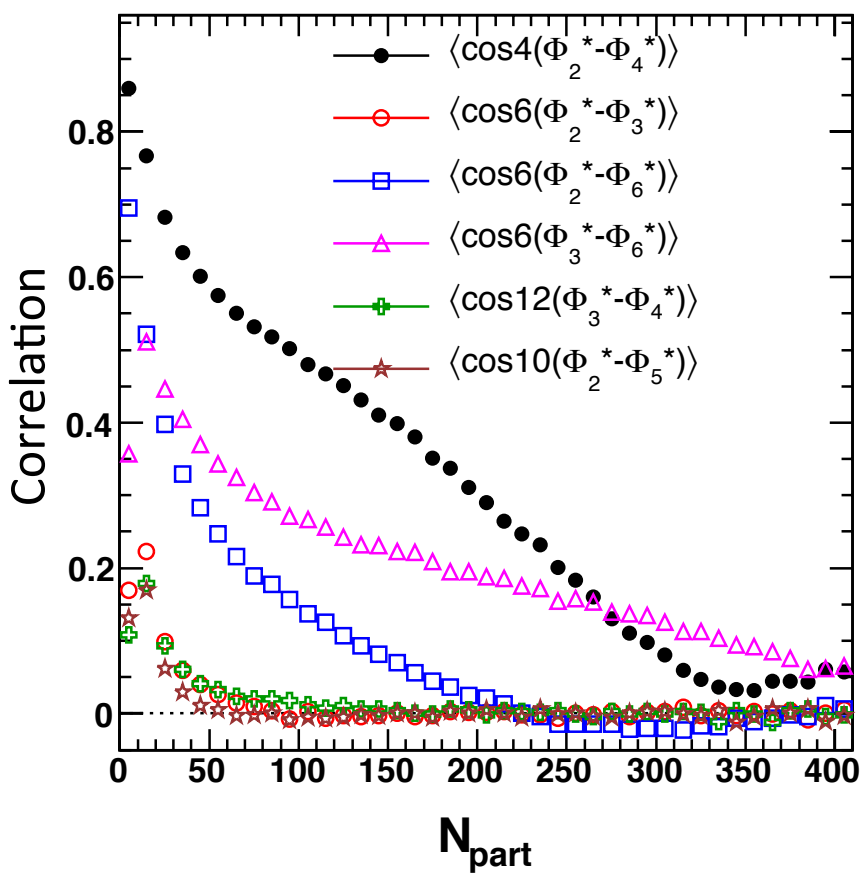


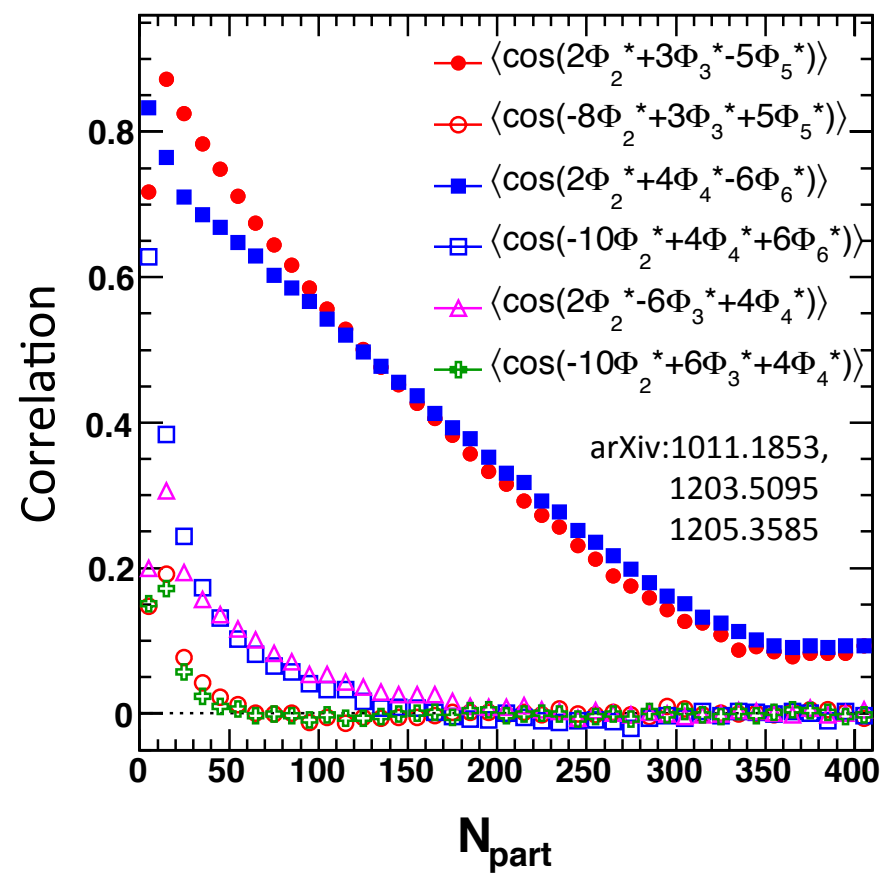
- Plane directions in configuration space

$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \cos(n\phi)\rangle^2}}{\langle r^n \rangle}$$

$$\Phi_n^* = \frac{\mathrm{atan2}(\langle r^n \sin n\phi\rangle, \langle r^n \cos n\phi\rangle)}{n}$$

- Expected to be strongly modified by medium evolution in the final state





Summary

- Measured the v_n harmonics over a large p_T eta and centrality range.
- Studied the factorization behavior of $v_{n,n}$
  - It factorizes for n=2 to n=6 as long as one particle has low p_T (< 3GeV).
  - Factorization breaks for n=1.
- Extracted dipolar flow v_1 from $v_{1,1}$ via a two component fit (accounting for momentum conservation).
  - v_1 is comparable to v_3, indicating significant dipole deformation in the initial state.
- Concluded that the features in two particle correlations for $|\Delta\eta|>2$ at low and intermediate p_T (p_T<4.0*GeV*) can be accounted for by the collective flow.
  - Double hump and ridge arise due to interplay of even and odd harmonics
- The v_n can be thought of diagonal components of a larger "Flow Matrix".
  - Studying the two and three plane correlations gives access to the off diagonal entries and beyond.
- These measurements together give insight into the initial geometry expansion mechanism of the fireball.