Measurement of the Azimuthal Anisotropy

(v_n coefficients and Reaction-Plane Correlations in ATLAS)

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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

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Jiangyong Jia
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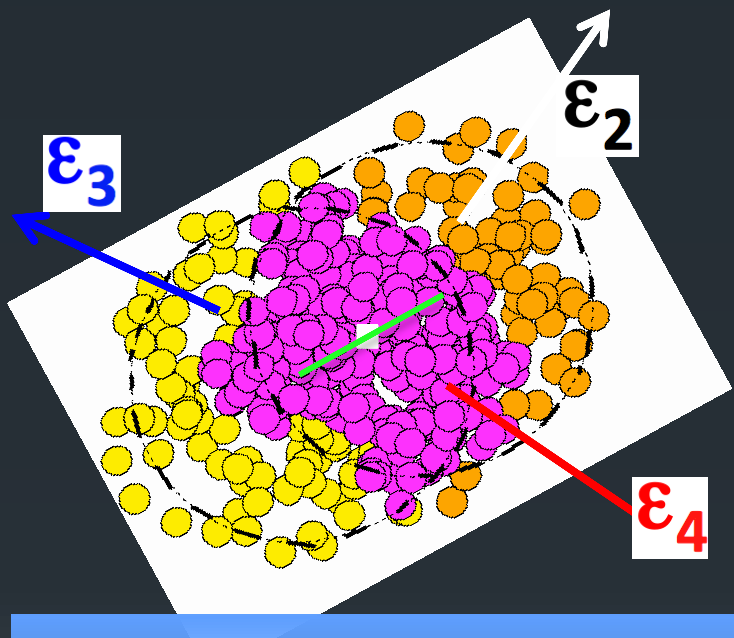
Sasha Milov

Introduction and Motivation

Initial spatial fluctuations of nucleons lead to higher moments of deformation in the fireball, each with its own orientation.



Singles: $\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos(n(\phi - \Phi_n))$

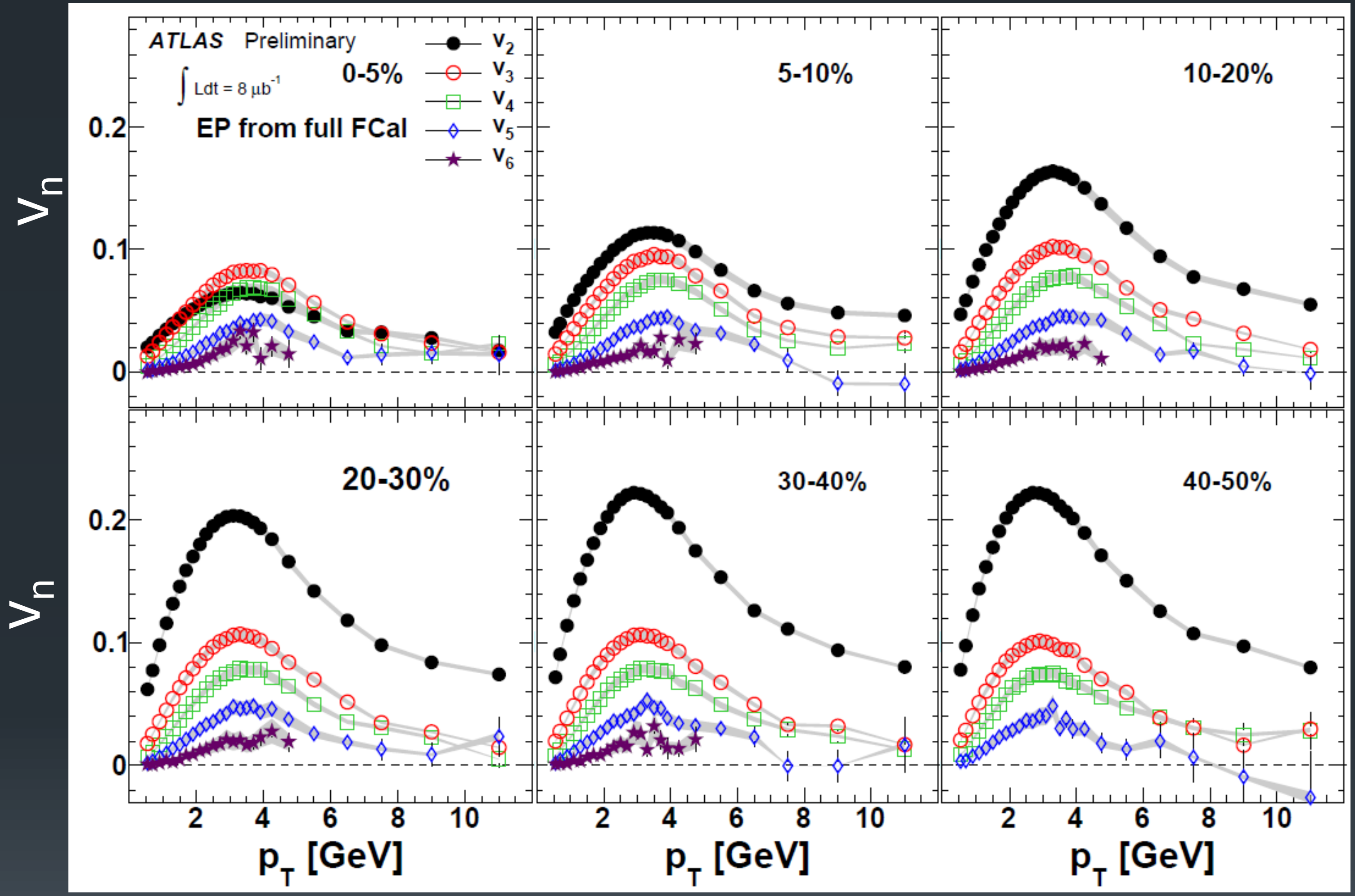
$(\Phi_n - \Phi_m)$ Correlations

Pairs: $\frac{dN_{Pairs}}{d\Delta\phi} \propto 1 + 2\sum_n v_n^a\, v_n^b \cos(n\Delta\phi)$

- Studying the v_n and correlations between the Φ_n gives insight into the initial geometry and **expansion mechanism** of the fireball and about the properties of the hot-dense medium.

So the goals are **initial geometry** and **η/s**

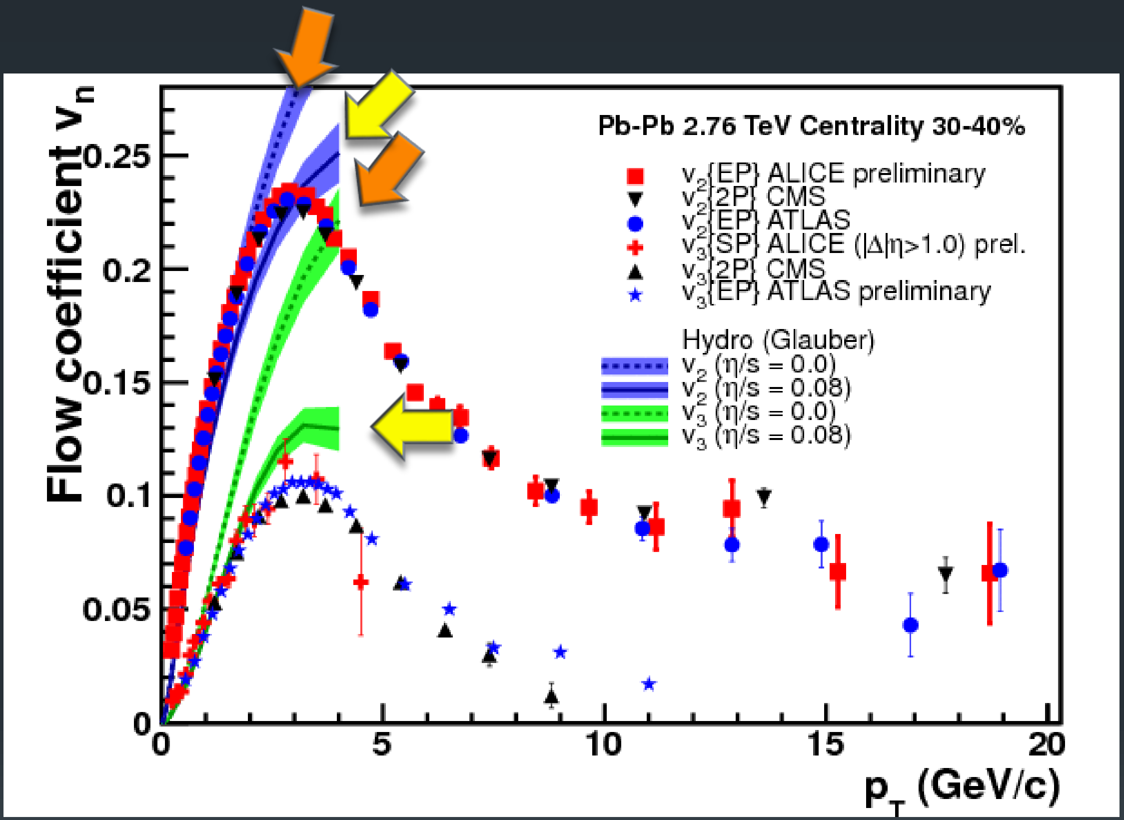
p_T Dependence of v_n



$$\langle \cos(n(\varphi - \psi_n)) \rangle$$

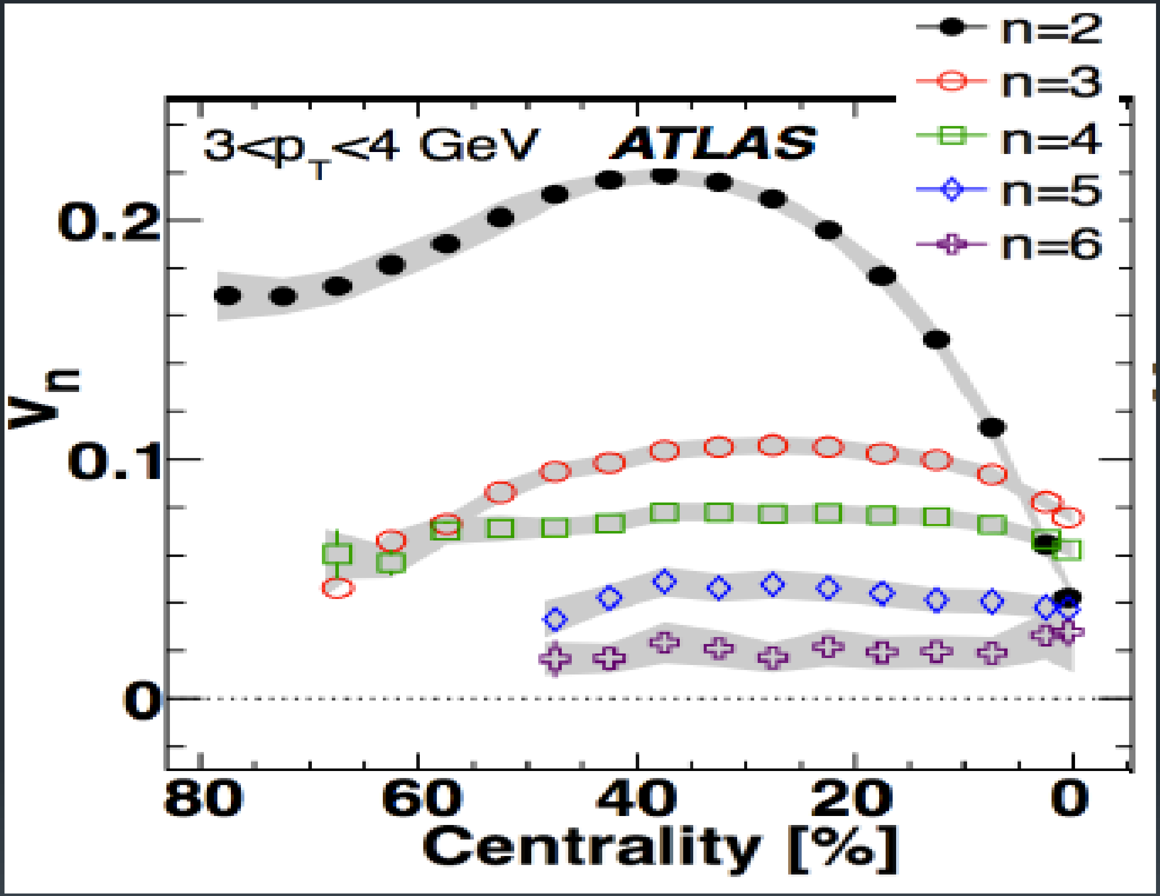
- V_2 is dominant (except for ~0 centrality)
- Similar trend across all harmonics (v_n increase till 3-4GeV then decrease)

V_n dependence on p_T in theory and reality



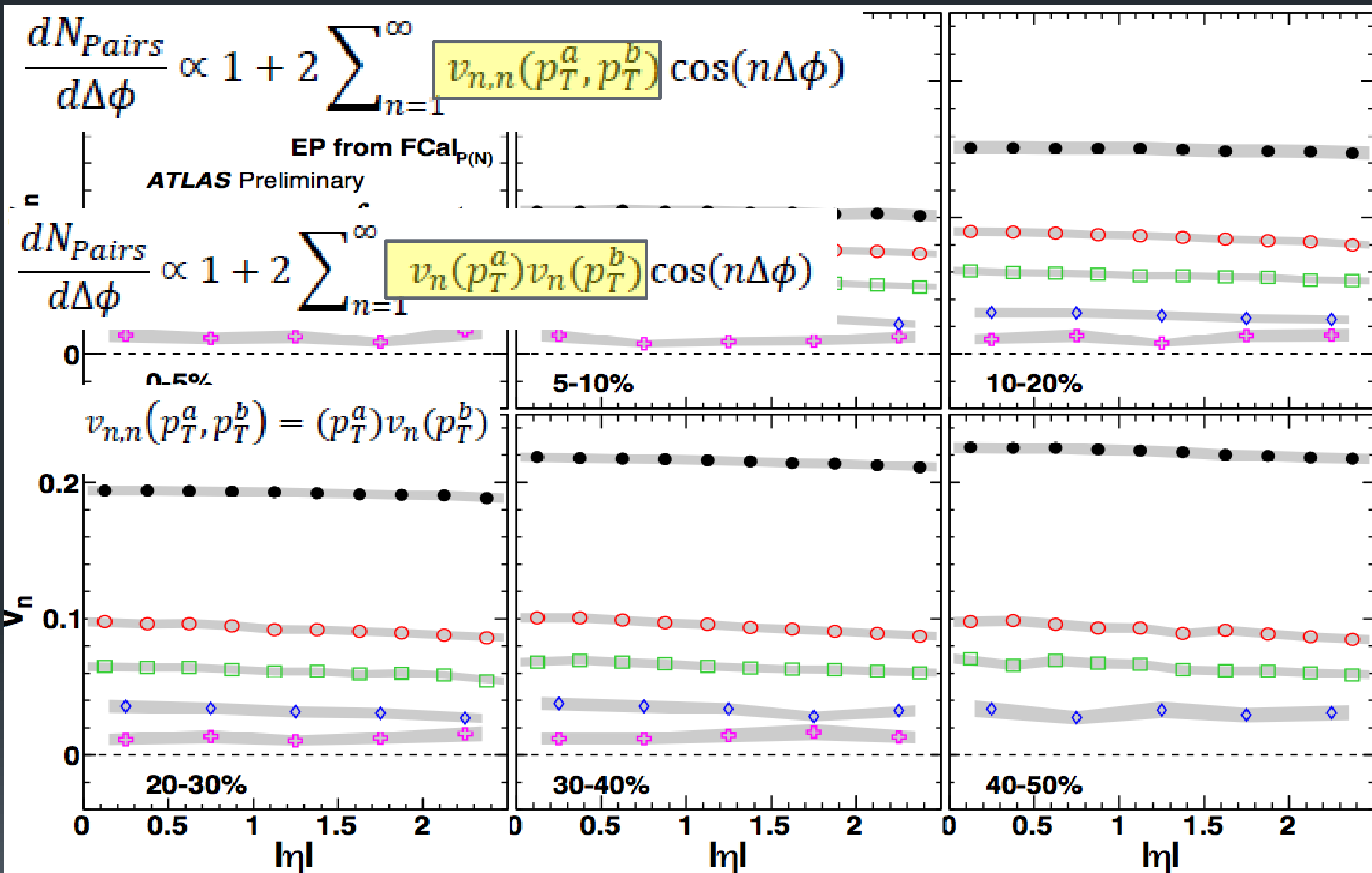
For perfect superfluid $\eta/s=1/4\pi$

Centrality Dependence of v_n



V_2 differs from all other v_n since it has dynamical origin while the others are due to fluctuations. In most central collisions(0-5%), where the system is isotropic, v_3, v_4 can be larger than v_2.

η Dependence of v_n



• weak dependence on η allows factorization

Two Particle Correlation

Correlation function

$$C(\Delta\phi, \Delta\eta) = \frac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)}$$

Coefficients

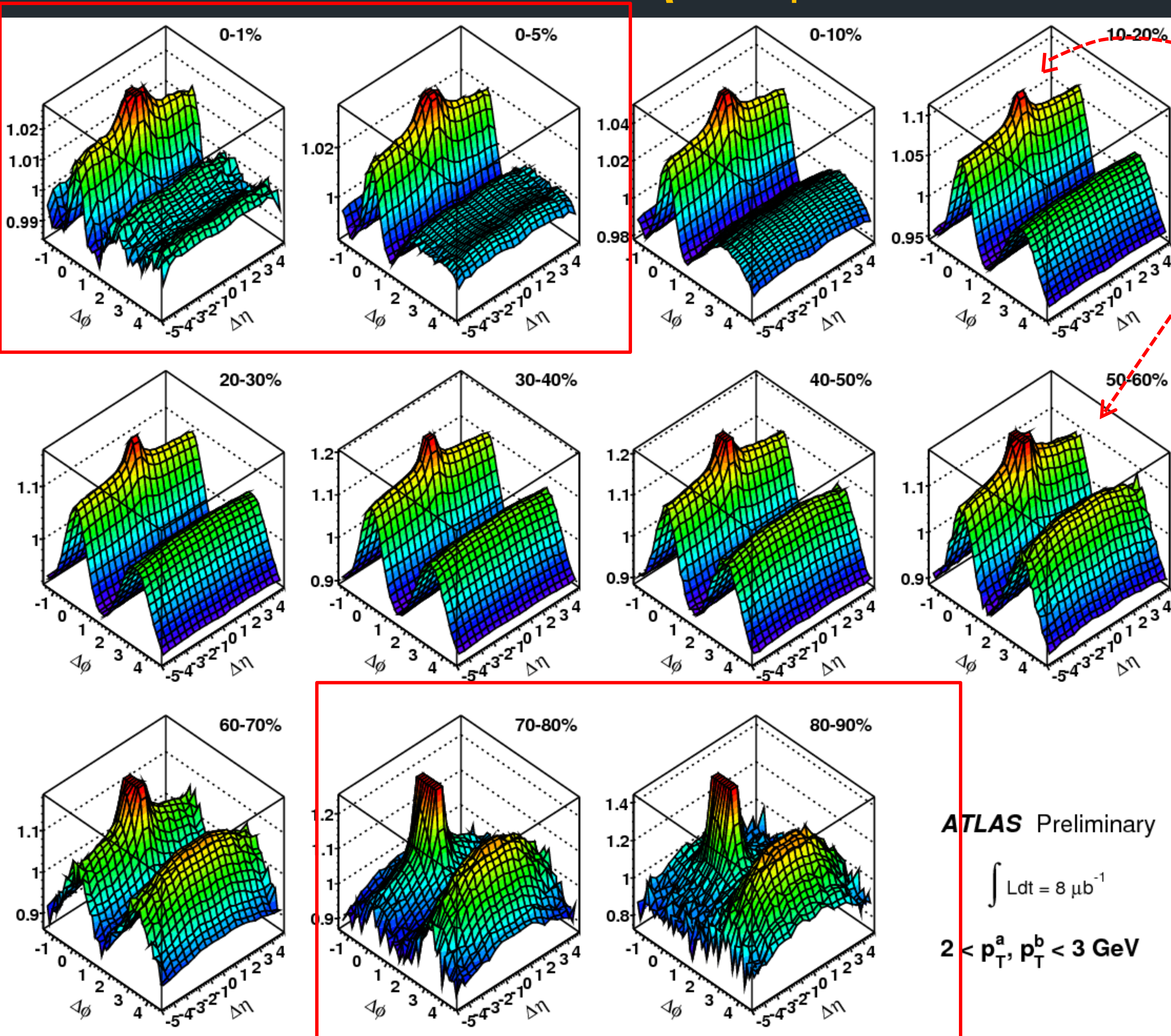
$$v_{n,n} = \langle \cos(n\Delta\phi) \rangle = \frac{\sum_{m=1}^{N} \cos(n\Delta\phi_m) C(\Delta\phi_m)}{\sum_{m=1}^{N} C(\Delta\phi_m)}$$

Two particle correlation

$$\frac{dN_{Pairs}}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_{n,n}(p_T^a, p_T^b) \cos(n\Delta\phi)$$

$$\frac{dN_{Pairs}}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n(p_T^a) v_n(p_T^b) \cos(n\Delta\phi)$$

Two Particle Δη–Δϕ Correlations



Near-side jet peak is always visible

Ridge seen in central and mid-central collisions, weak Δη dependence

Ridge strength first increases then decreases with centrality

Away side has double hump structure in most central events

Peripheral events have jet related peaks (truncated) only

Can this reproduce the v_n harmonics ??

Obtaining Harmonics from Correlations

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

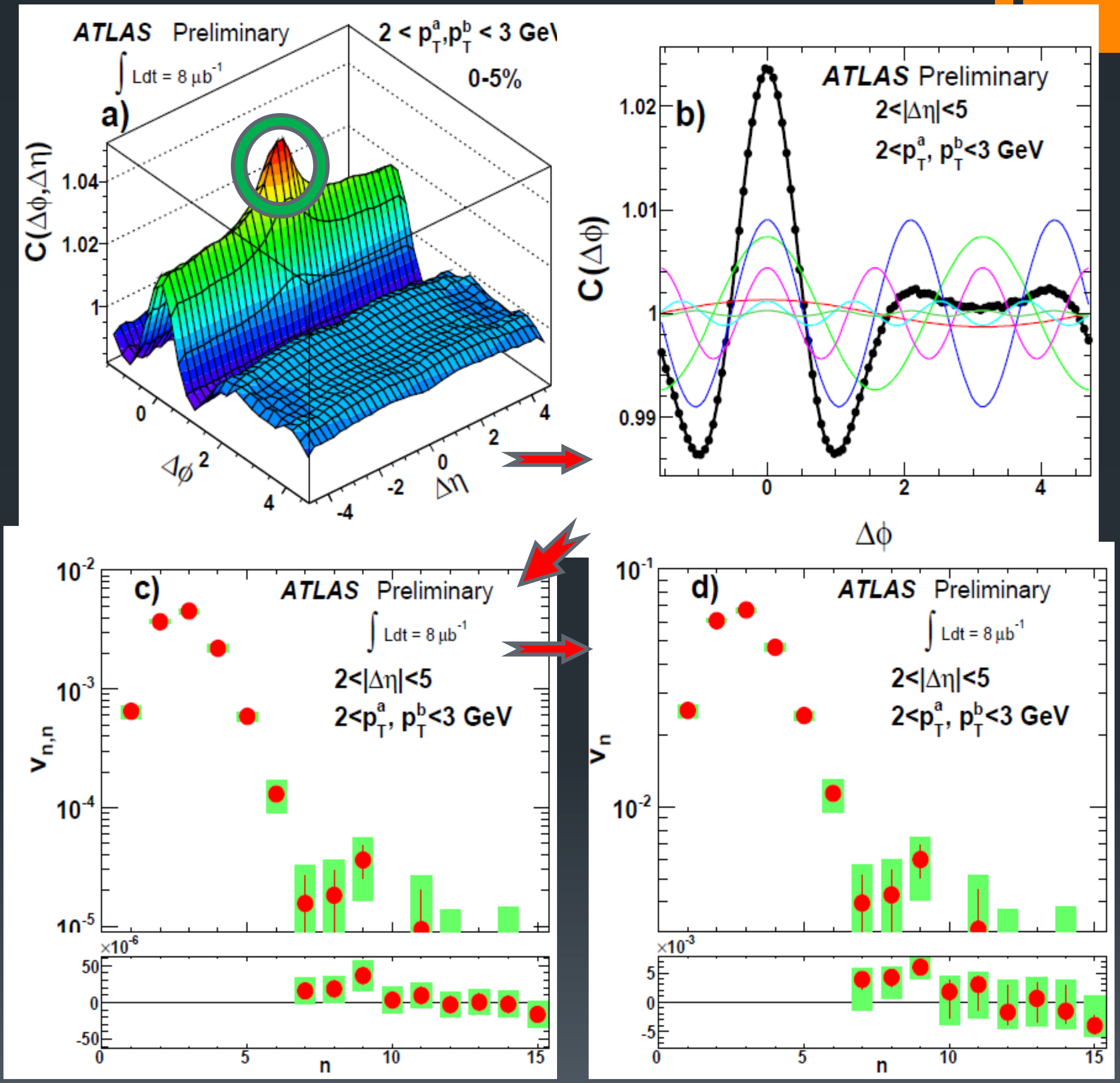
b) Remove the near side jet peak by $\Delta\eta>2$ cut

c) The corresponding 1D correlation function in $\Delta\phi$ for $2<|\Delta\eta|<5$

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

e) Corresponding v_n values

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

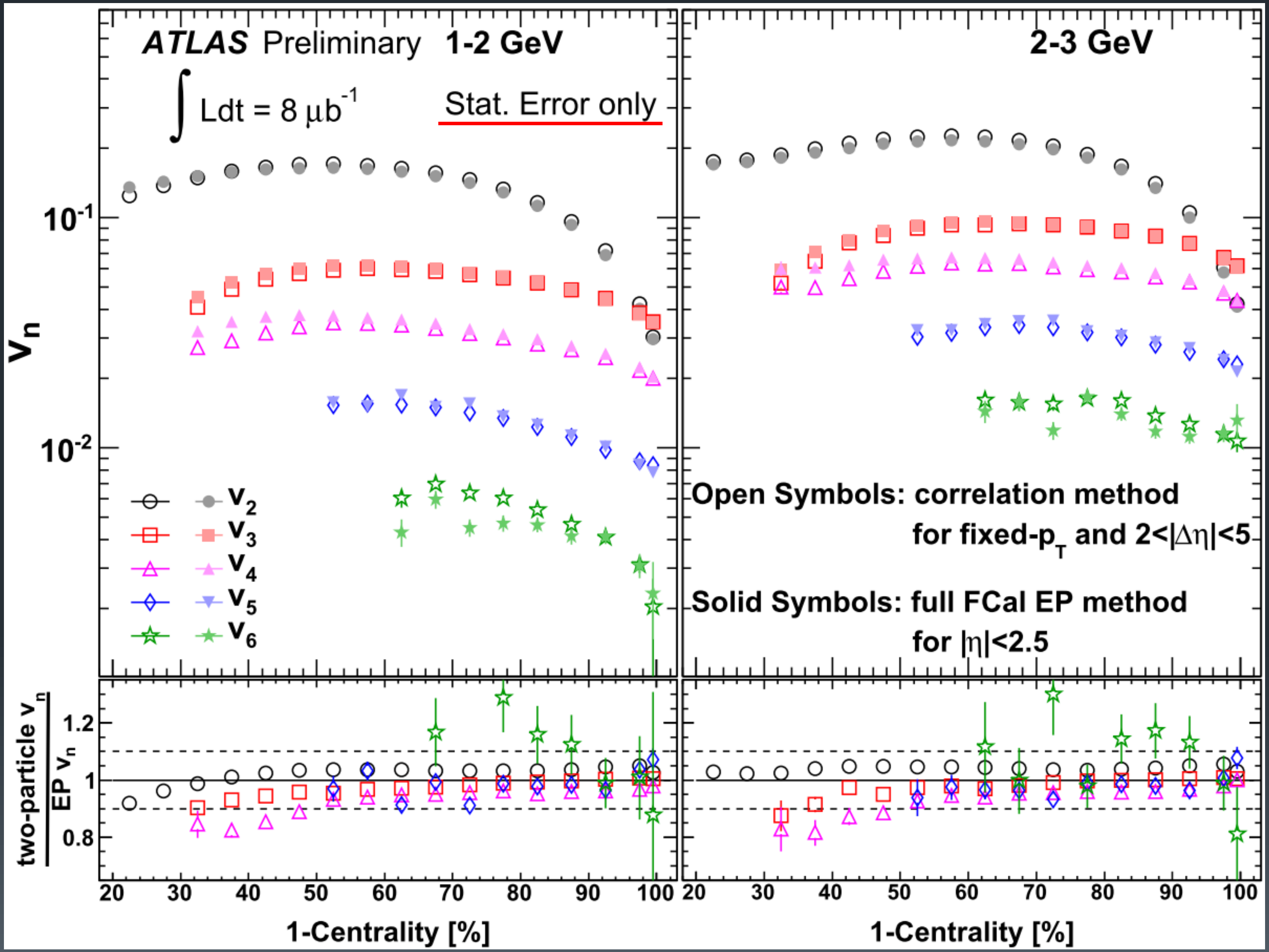


Bands indicate systematic errors

Comparison between the two Methods

Centrality Dependence

Non central



Central

Good agreement between the EP and 2PC techniques.

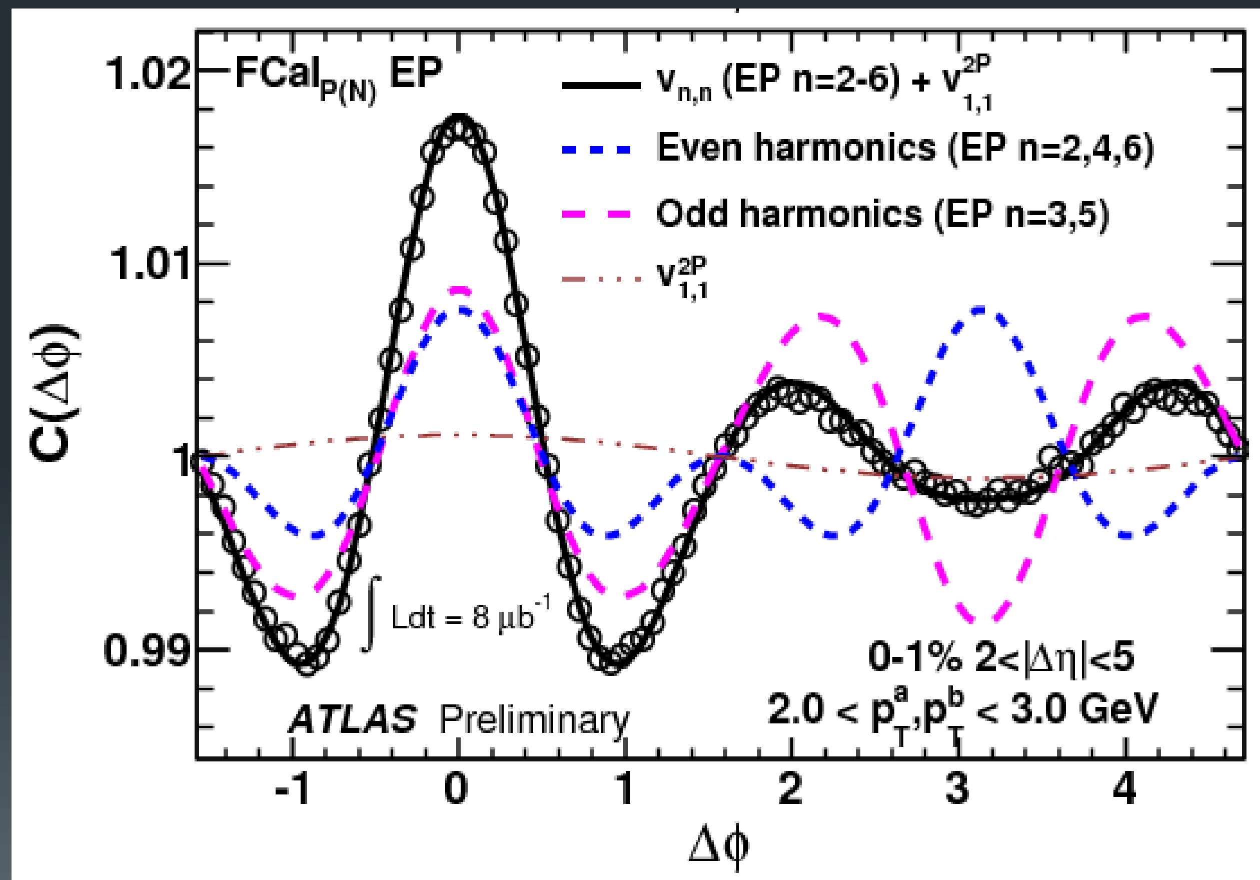
Recovering the Correlations from EP v_n

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

From 2PC

From EP

- Chose $v_{1,1}$ and normalization to be the 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

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

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

$$k = LCM(n, m)$$

arXiv:1203.5095

arXiv:1205.3585

- Where

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

And

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

Two-Plane Correlations

$\langle \cos(1´\ 4(F_2 - F_4)) \rangle$ $\langle \cos(2´\ 4(F_2 - F_4)) \rangle$ $\langle \cos(3´\ 4(F_2 - F_4)) \rangle$

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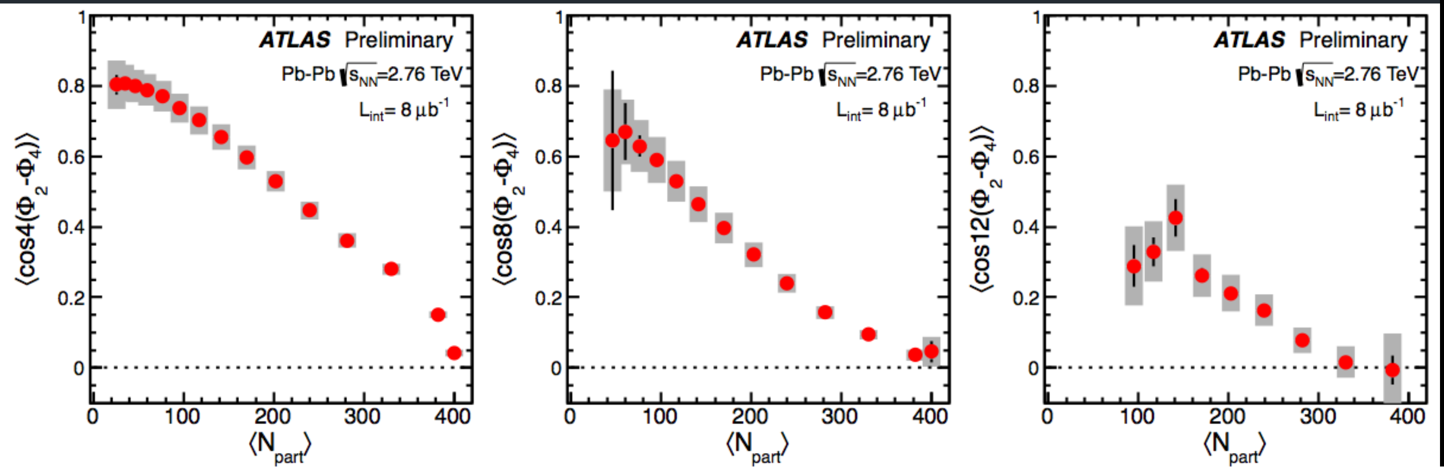

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Conclusion

- Event-plane and two-particle correlation techniques are applied to extract the values of the v_2-v_6 coefficients.
- The results of the two methods are in good agreement
- Each v_n acts as independent cross-check for η/s.

- The features in two-particle correlations for $|\Delta\eta|>2$ and $p_T<4.0$ *GeV* are accounted for by the collective flow of the medium.
  - In particular, double hump and ridge arise due to interplay of even and odd harmonics

- The v_n can be thought of as diagonal components of a "Flow Matrix".
- Studying the two and three-plane correlations gives access to the off diagonal entries.

- These measurements together give insight into the initial geometry expansion mechanism of the fireball.

BACKUP SLIDES

BACKUP SLIDES

$v_{1,1}$ and v_1 - Direct Flow

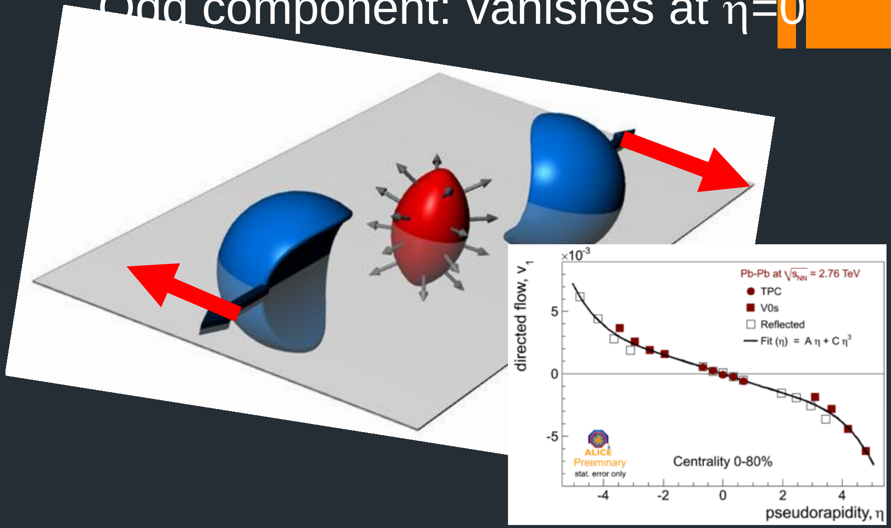
- For $v_{1,1}$ the factorization breaks :: due to global momentum conservation.

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

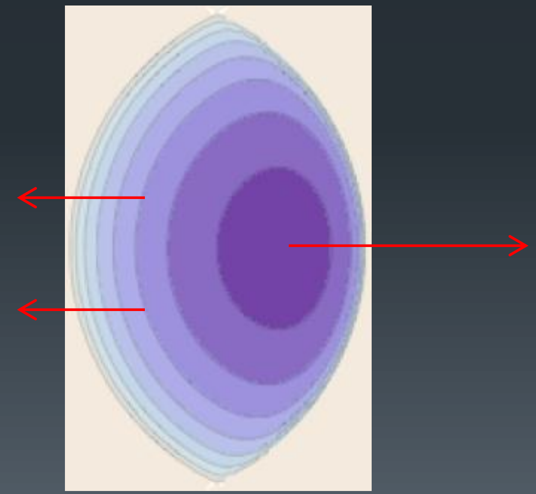
- Second term is leading order approximation for momentum conservation
- $V_1(\eta)$ has rapidity odd and rapidity even components:
- Odd component is <0.005 for $|\eta|<2$ at LHC, thus has small contribution to $v_{1,1}$ ($<2.5\times10^{-5}$)
- If rapidity even component has weak η dependence, then:

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

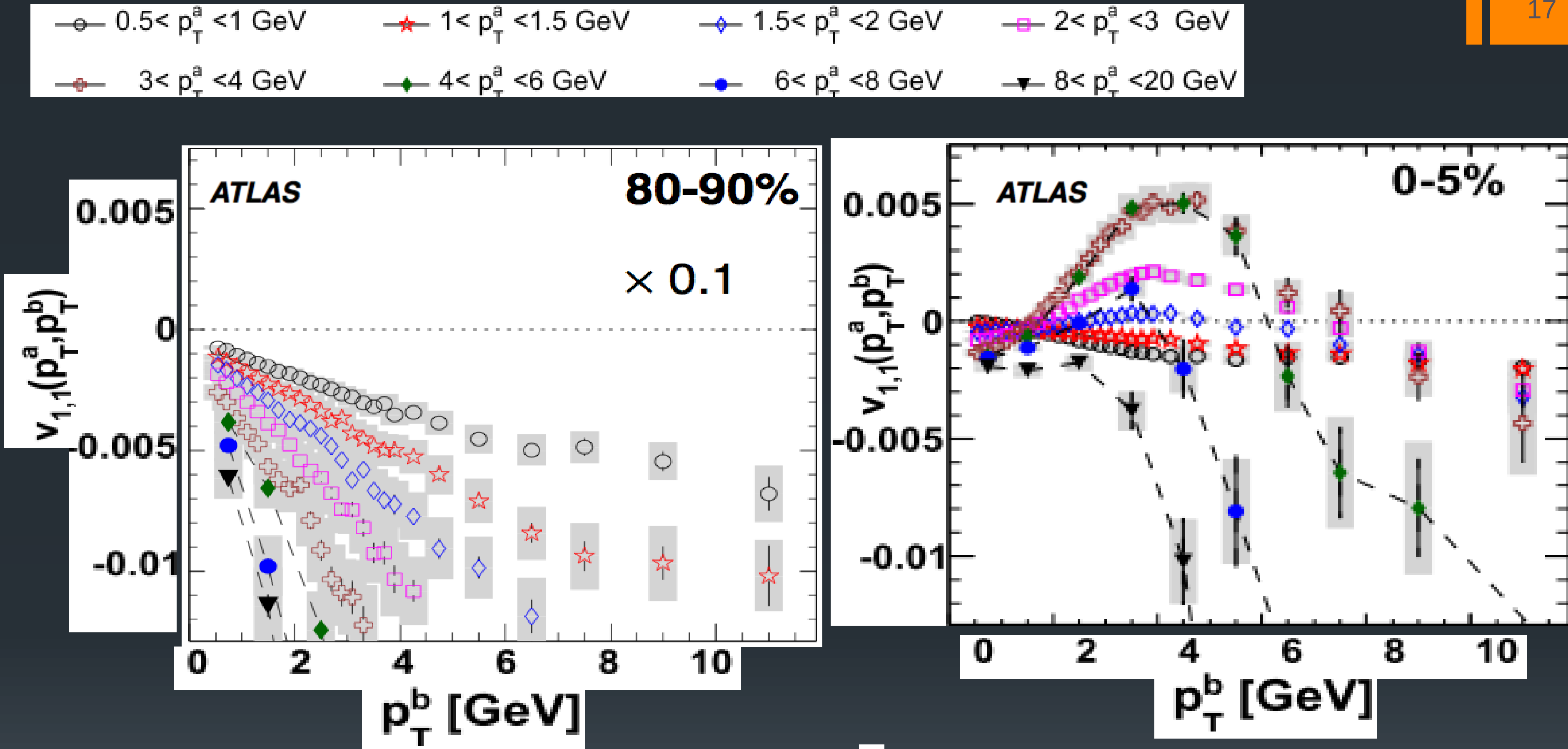
Odd component: vanishes at η=0



Even component: ~boost invariant in η



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

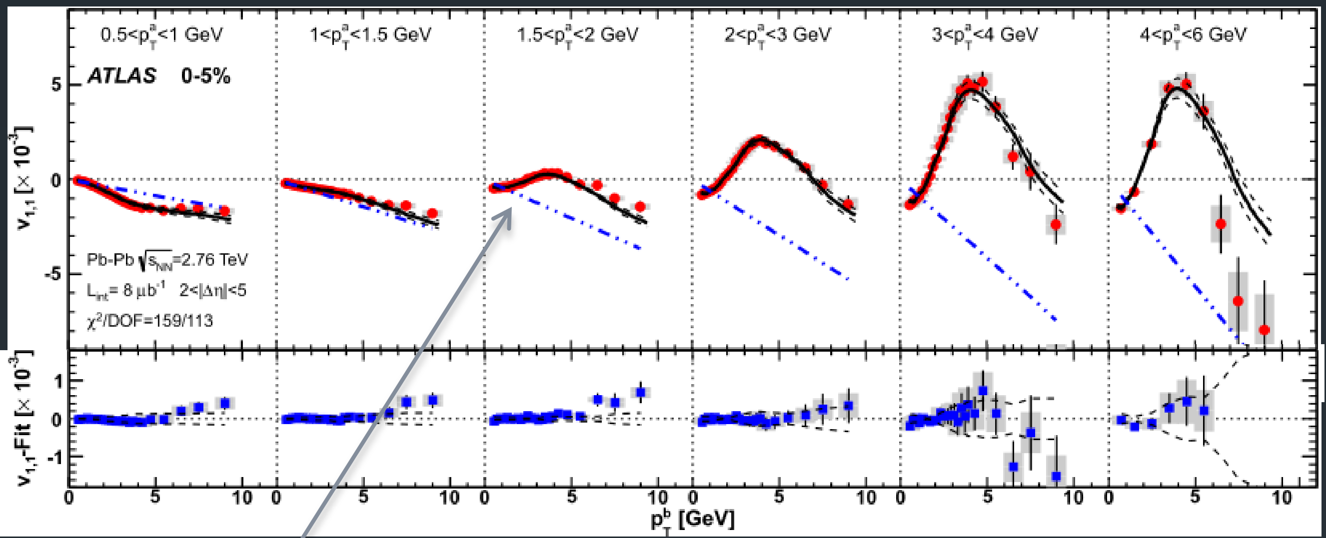


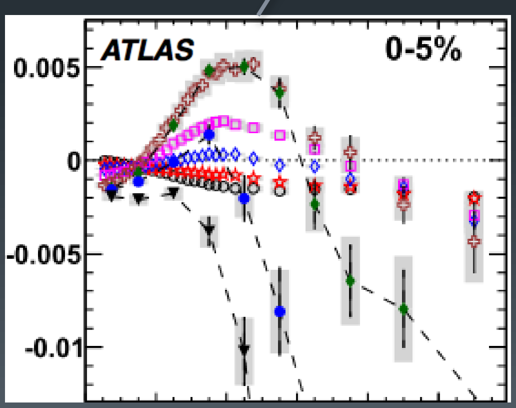
$$\frac{p_T^a \times p_T^b}{M\langle p_T^2\rangle}$$

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

Extracting the η-even v_1 (p_T)

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



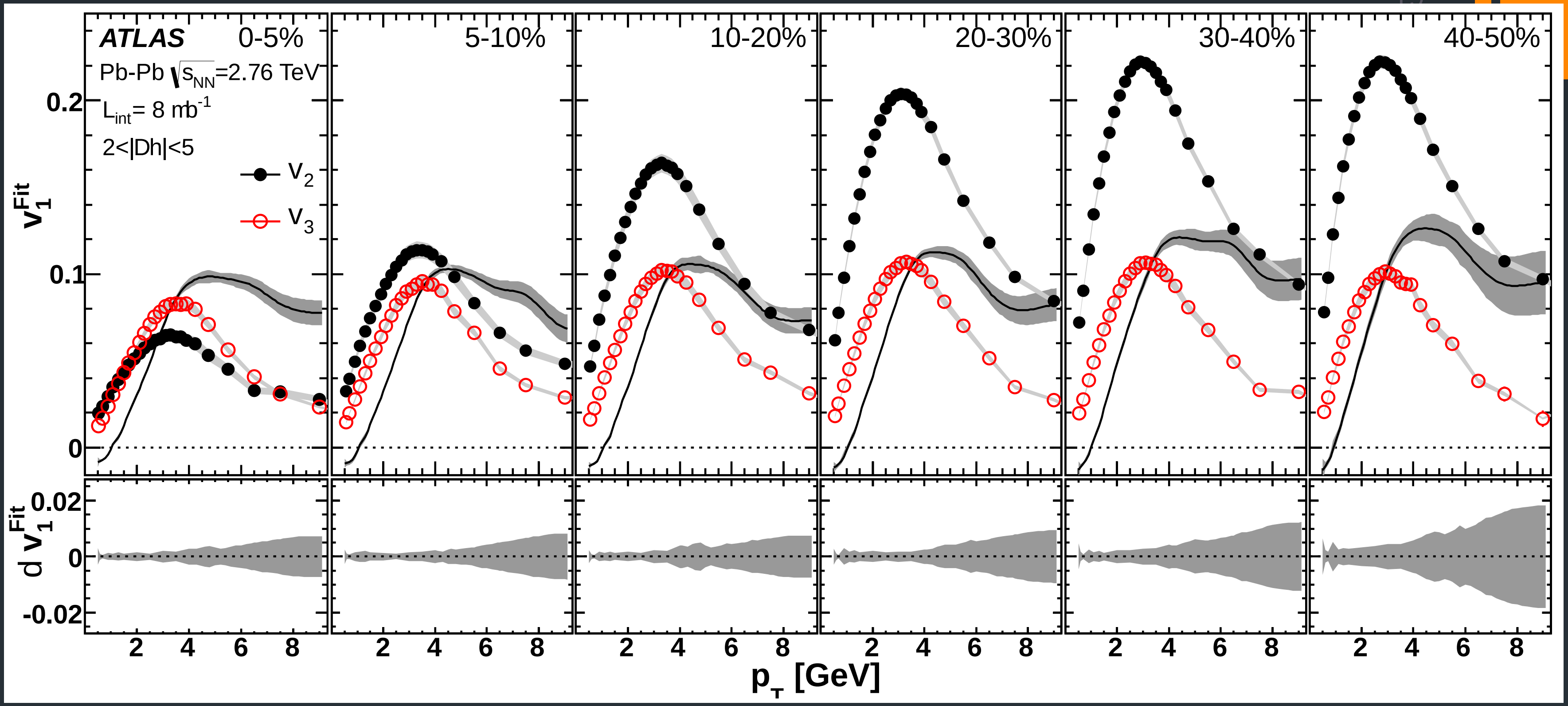


Red Points: $v_{1,1}$ data

Black line : Fit to functional form

Blue line: momentum conservation component

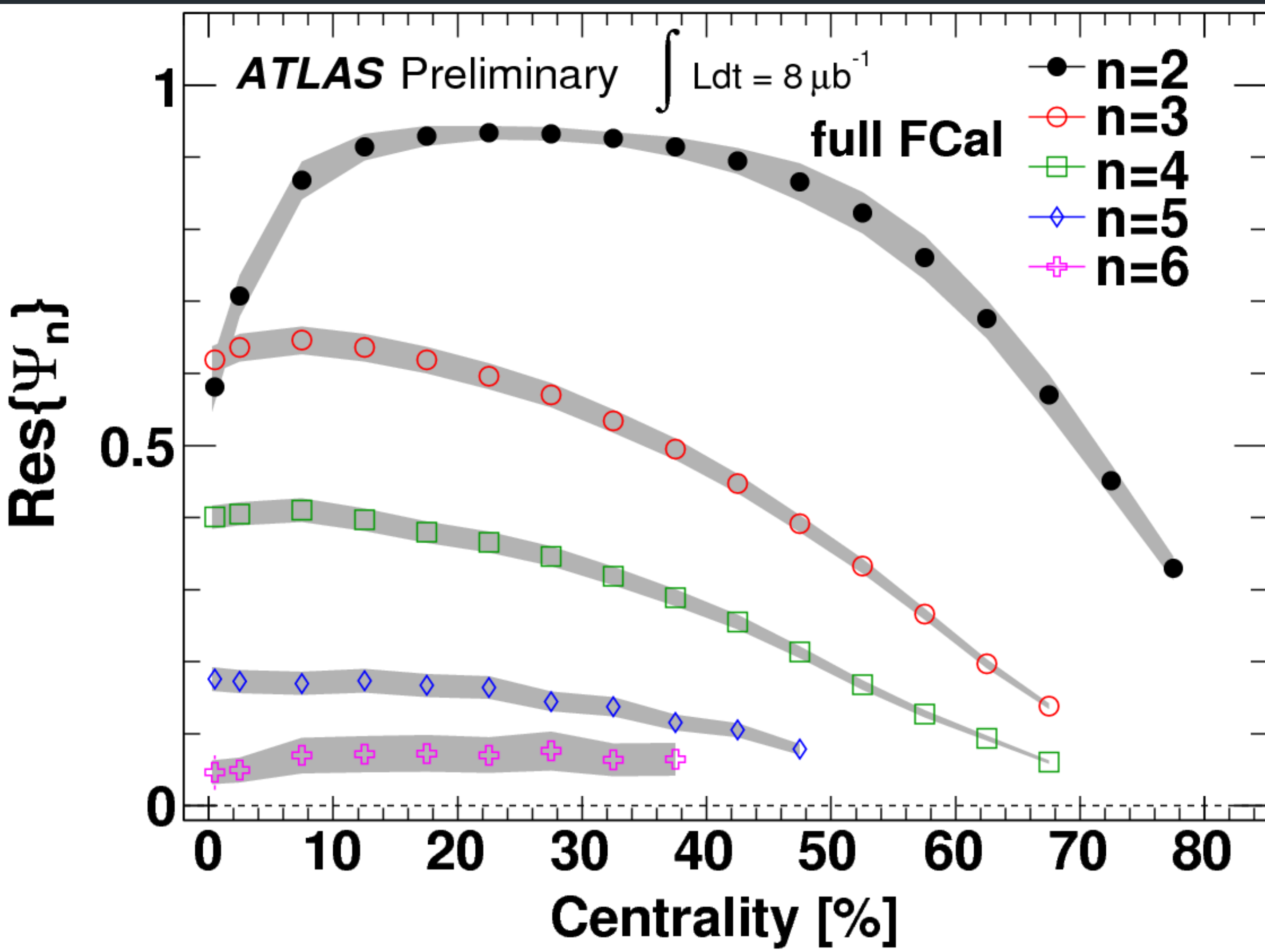
η-even v_1 (p_T)



- 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

Event Plane Method

$$v_n = \frac{v_n^{\mathrm{obs}}}{\mathrm{Res}\{\Psi_n\}} = \frac{\langle \cos n\,(\phi - \Psi_n)\rangle}{\langle \cos n\,(\Psi_n - \Psi_{\mathrm{RP},n})\rangle}$$



Bands indicate systematic errors

$$\langle \cos(n(\varphi - \psi_n))\rangle$$

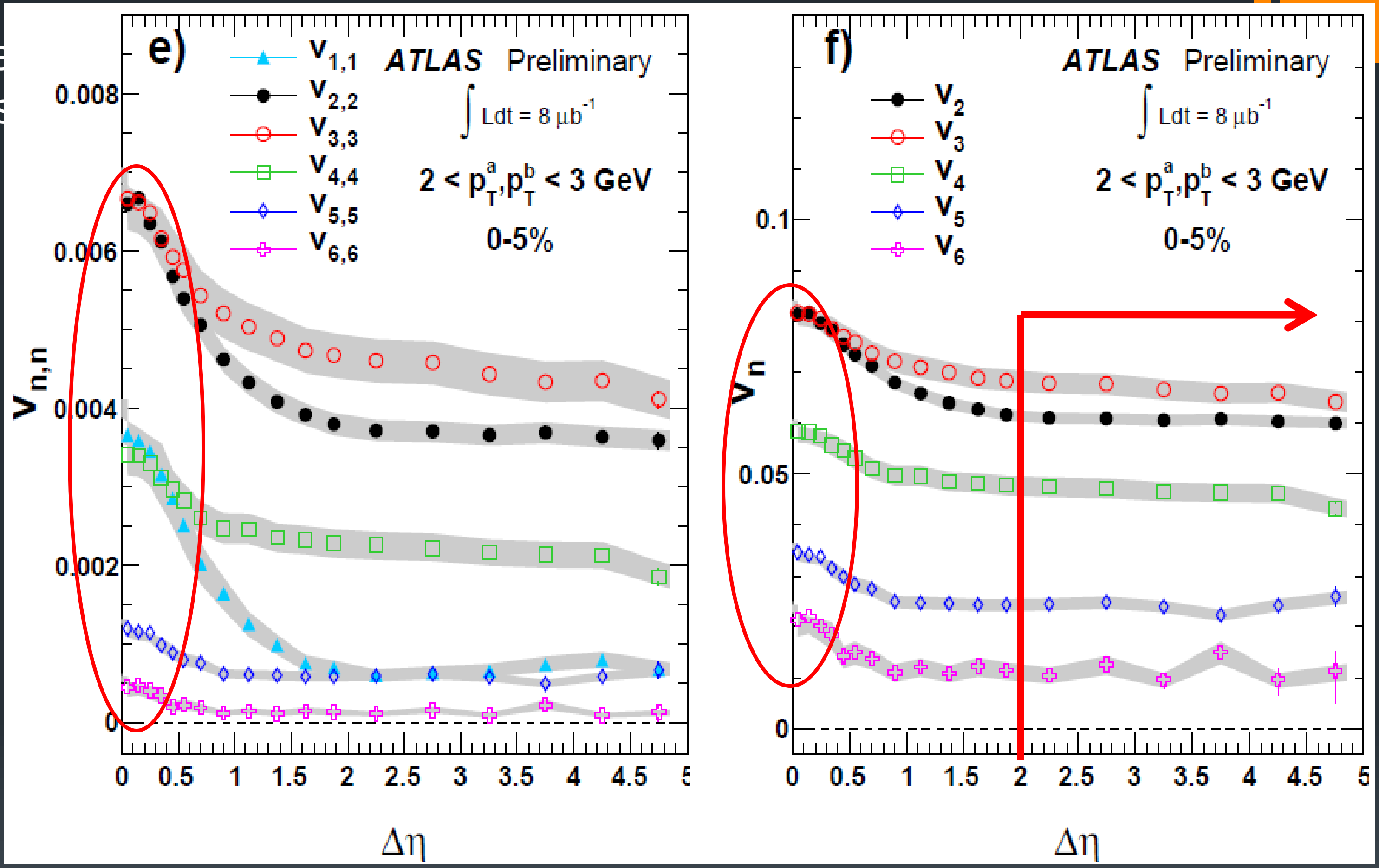
$$\frac{\langle \cos(n(\varphi - \psi_n))\rangle}{\langle \cos(n(\psi_n - \phi_n))\rangle}$$

Δη dependence of v_n

- Repeat procedure in narrow Δη slices to obtain v_n vs Δη.

- v_n values peak at low Δη, due to jet bias.

- Relatively flat afterwards, so we require a |Δη| >2 gap (to remove near-side jet).



Bands indicate systematic errors

Three-Plane correlations

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

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

- The following three plane correlations are studied:
  - 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≤*n*≤6) where the resolution is good enough to make measurements.

arXiv:1203.5095

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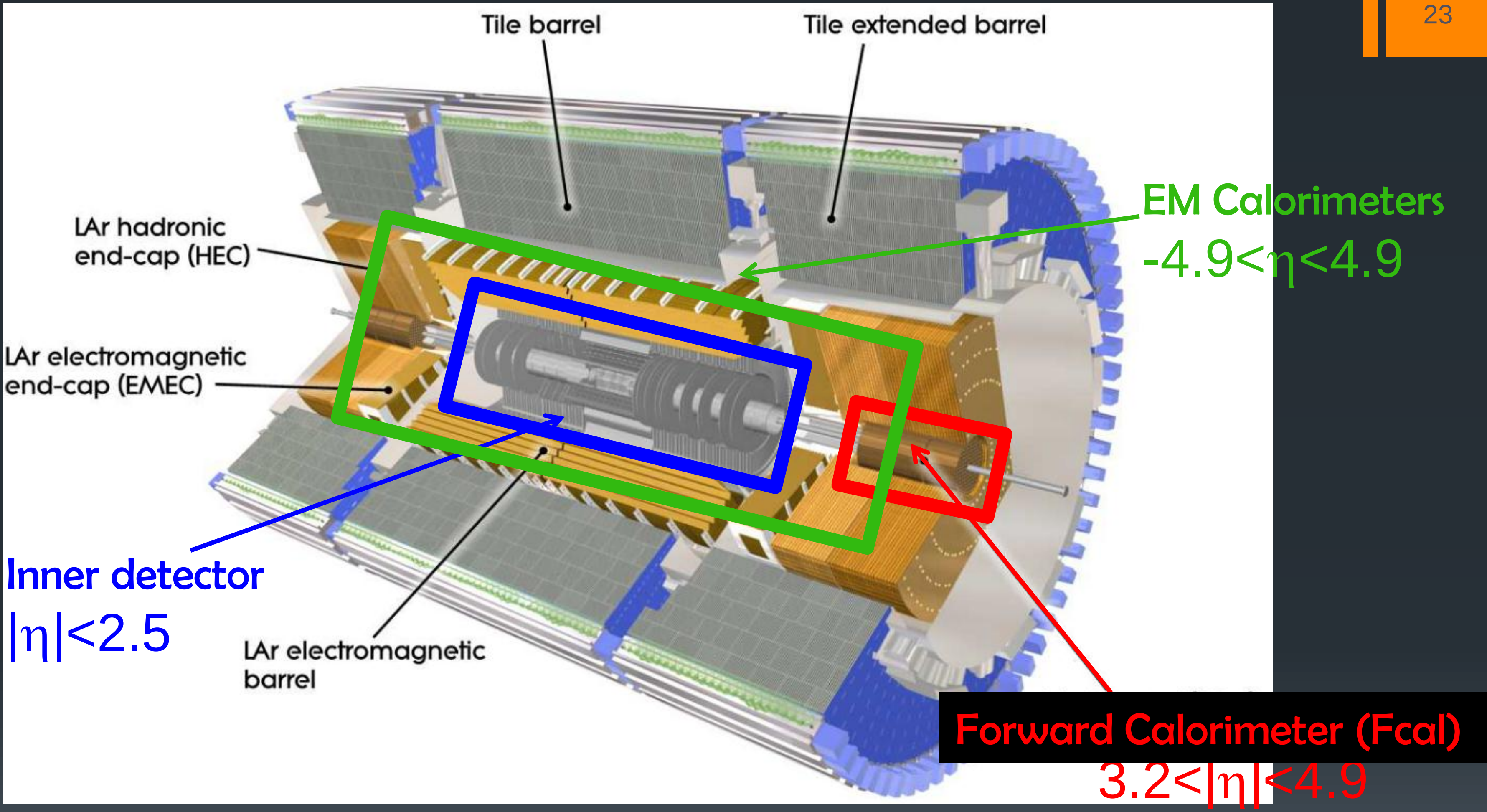
- One way to think of the three-plane correlations is as combination of two plane correlations:
  - $2\Phi_2+4\Phi_4-6\Phi_6 = 4(\Phi_4-\Phi_2) -6(\Phi_6-\Phi_2)$
  - $-10\Phi_2+4\Phi_4+6\Phi_6 = 4(\Phi_4-\Phi_2) +6(\Phi_6-\Phi_2)$
  - Thus three plane correlations are the correlation of two angles relative to the third.

The 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 Technique

Need to use

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos(n(\phi - \Phi_n))$$

Φ_n Reaction plane

But Φ_n is unknown.
Use instead

$$\tan(n\Psi_n) = \frac{Q_{y,n}}{Q_{x,n}}$$

Ψ_n Event plane angle

Where

$$Q_{x,n} = \sum E_T \cos(n\phi) - \langle \sum E_T \cos(n\phi) \rangle$$

$$Q_{y,n} = \sum E_T \sin(n\phi) - \langle \sum E_T \sin(n\phi) \rangle$$

And, finally

$$v_n = \frac{v_n^{obs}}{Res\{\psi_n\}} = \frac{\langle \cos\left(n(\phi - \psi_n)\right) \rangle}{\langle \cos\left(n(\psi_n - \Phi_n)\right) \rangle}$$