Measurement of elliptic and higher order flow at $\sqrt{s_{NN}} = 2.76 TeV$ Pb+Pb Collisions with the ATLAS detector

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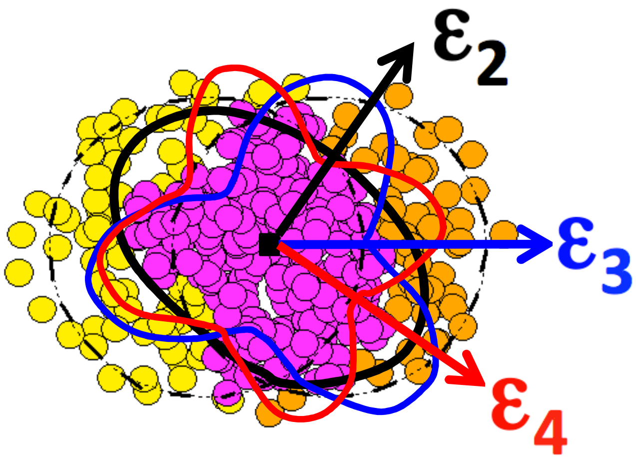
Introduction and Motivation

- 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



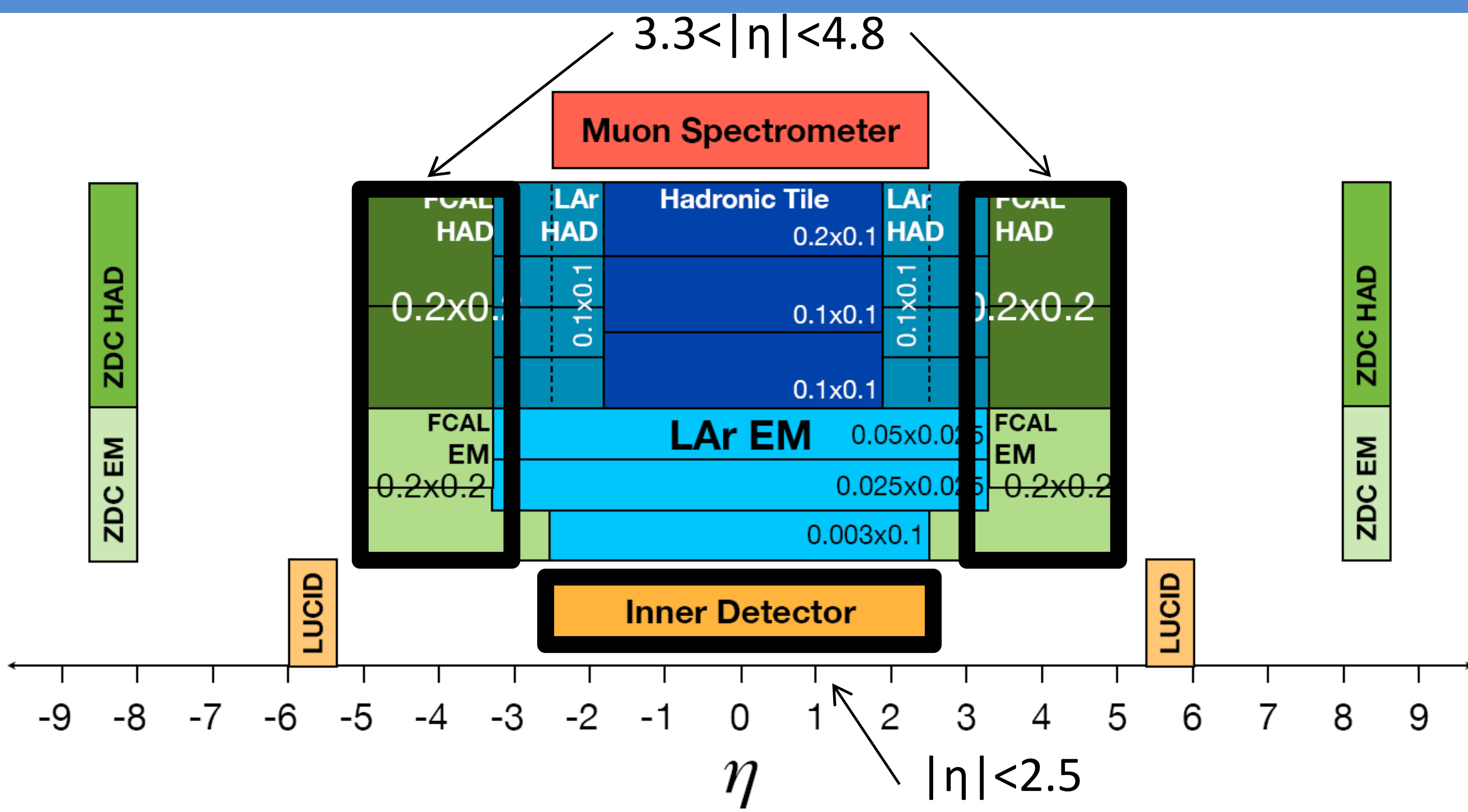
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

$$\tan(n\Psi_n) = \frac{\langle r^n \sin n\phi\rangle}{\langle r^n \cos n\phi\rangle}$$

Singles:	$\frac{dN}{d\phi} \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n} \cos n\left(\phi - \Psi_n\right)$	**EP method**
Pairs:	$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2\mathrm{v}_\mathrm{n}^\mathrm{a}\mathrm{v}_\mathrm{n}^\mathrm{b} \cos\left(n\Delta\phi\right)$	**2PC method**

- The harmonics v_n carry information about the medium: initial geometry, η/s
- Understanding of higher order v_n can shed light on the physics origin of "ridge" and "cone" seen in 2P correlations

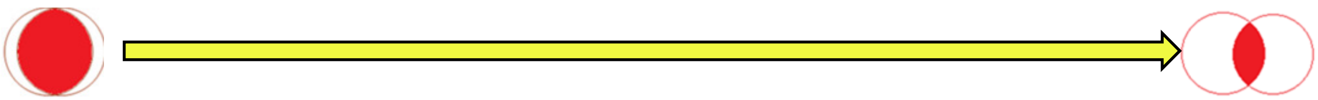
ATLAS Detector

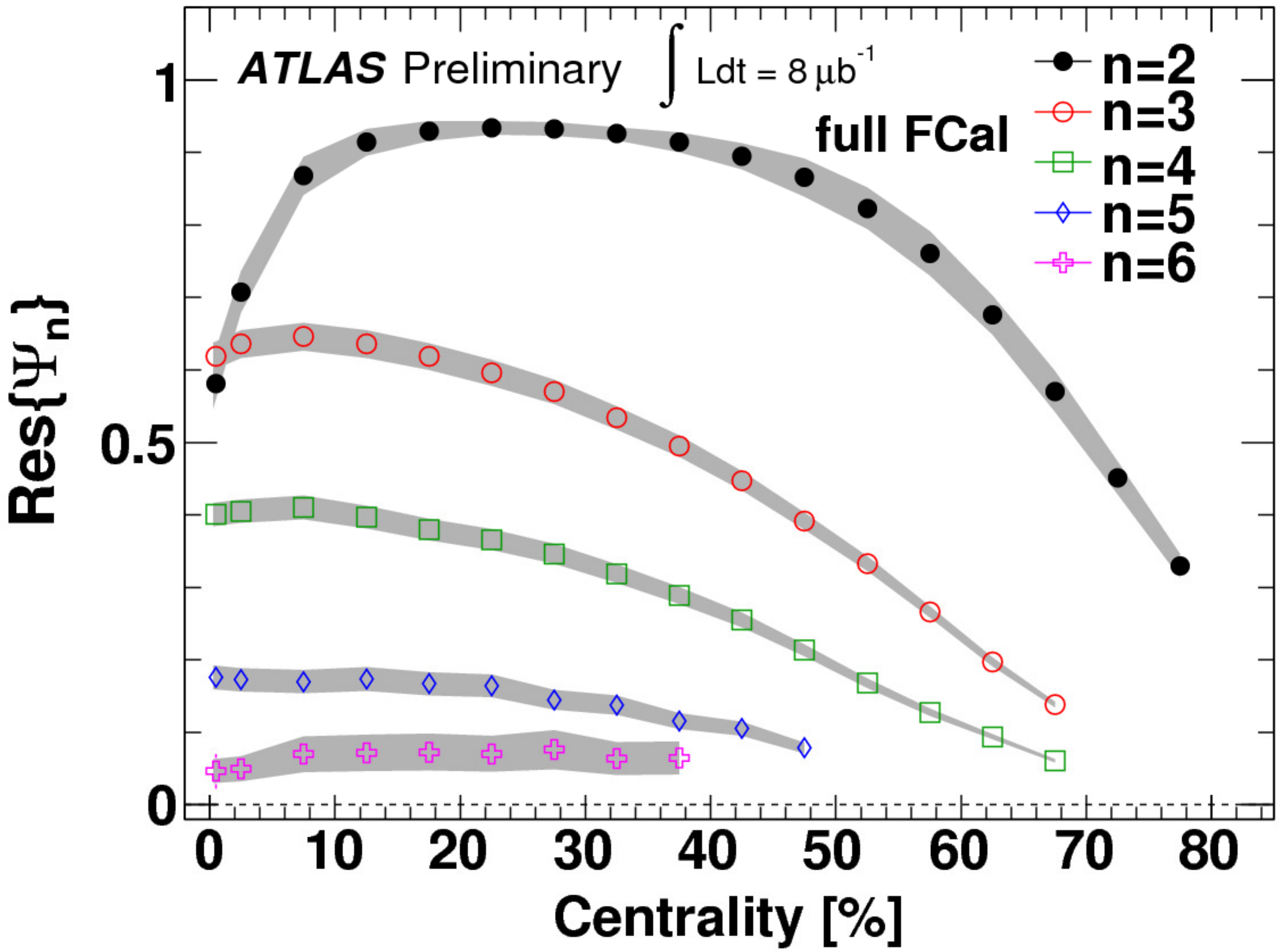


- Tracking coverage : $|\eta|<2.5$
- FCal coverage : $3.3<|\eta|<4.8$ (used to determine Event Planes)

Event Plane Method

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

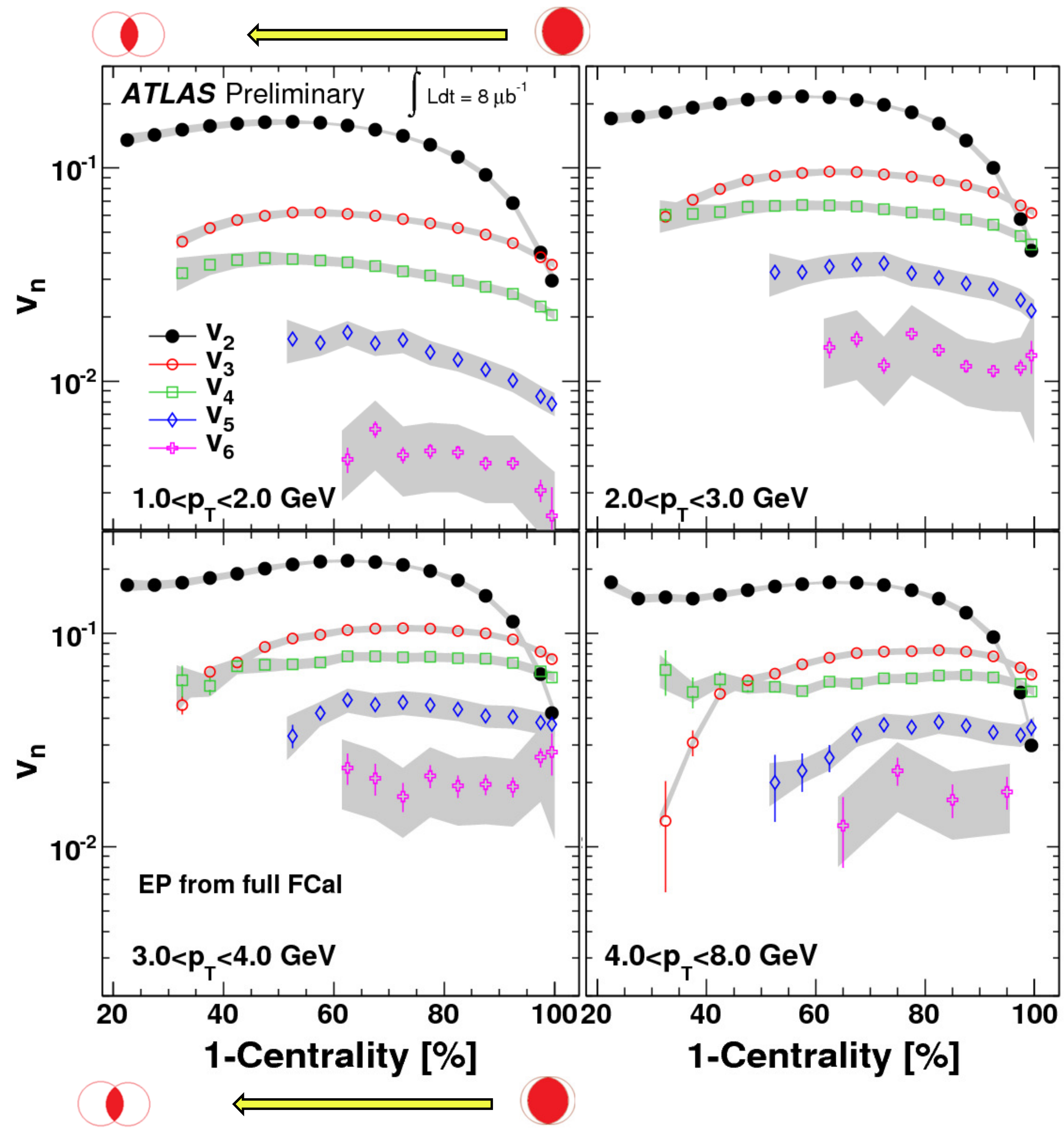




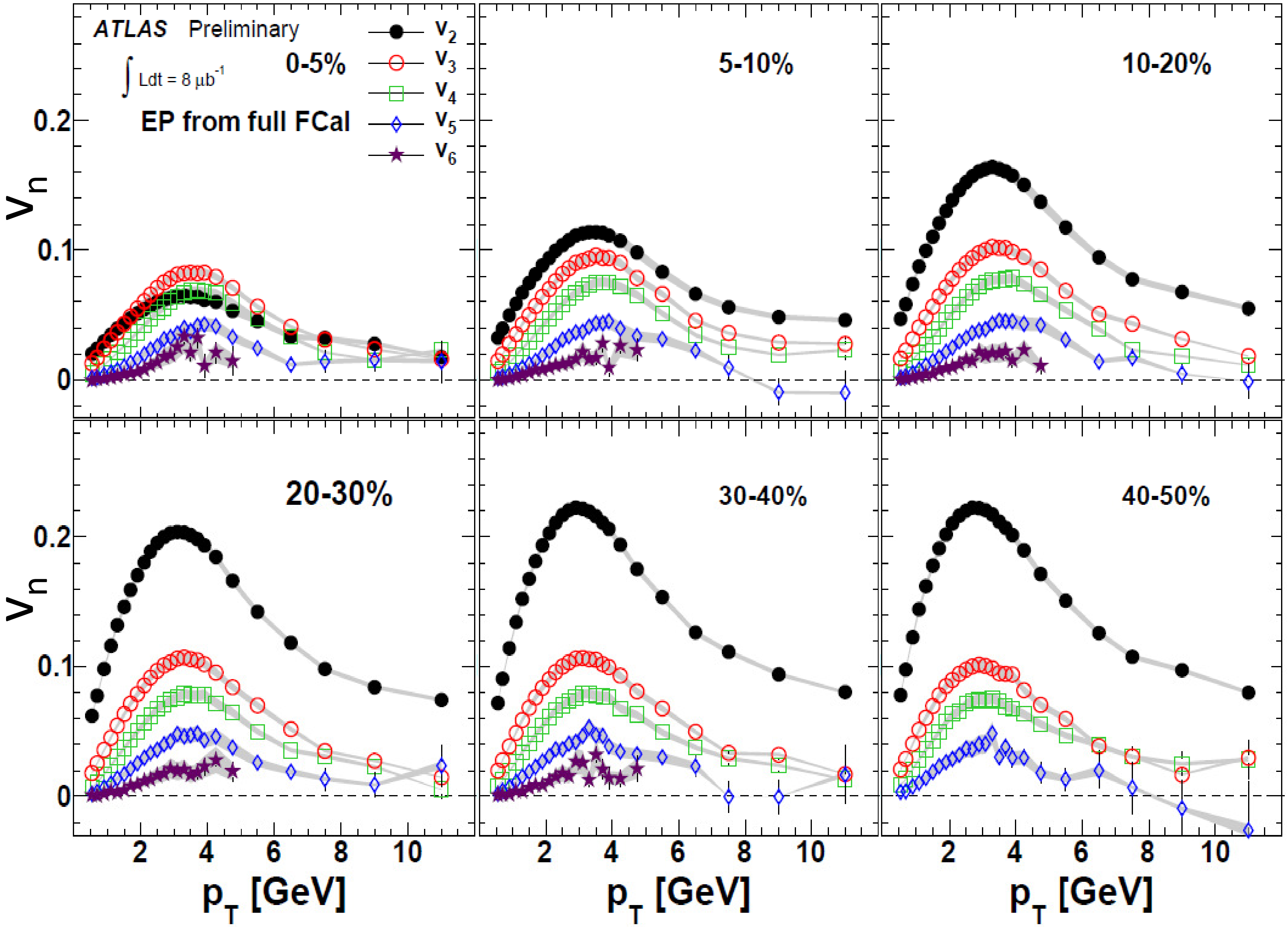
Bands indicate systematic errors

Centrality dependence of v_n

- 5% Centrality bins + 0-1% centrality bin
- v_2 has a stronger centrality dependence.
- Other v_n are flatter.
- In most central collisions, v_3,v_4 can be larger than v_2 at high enough p_T

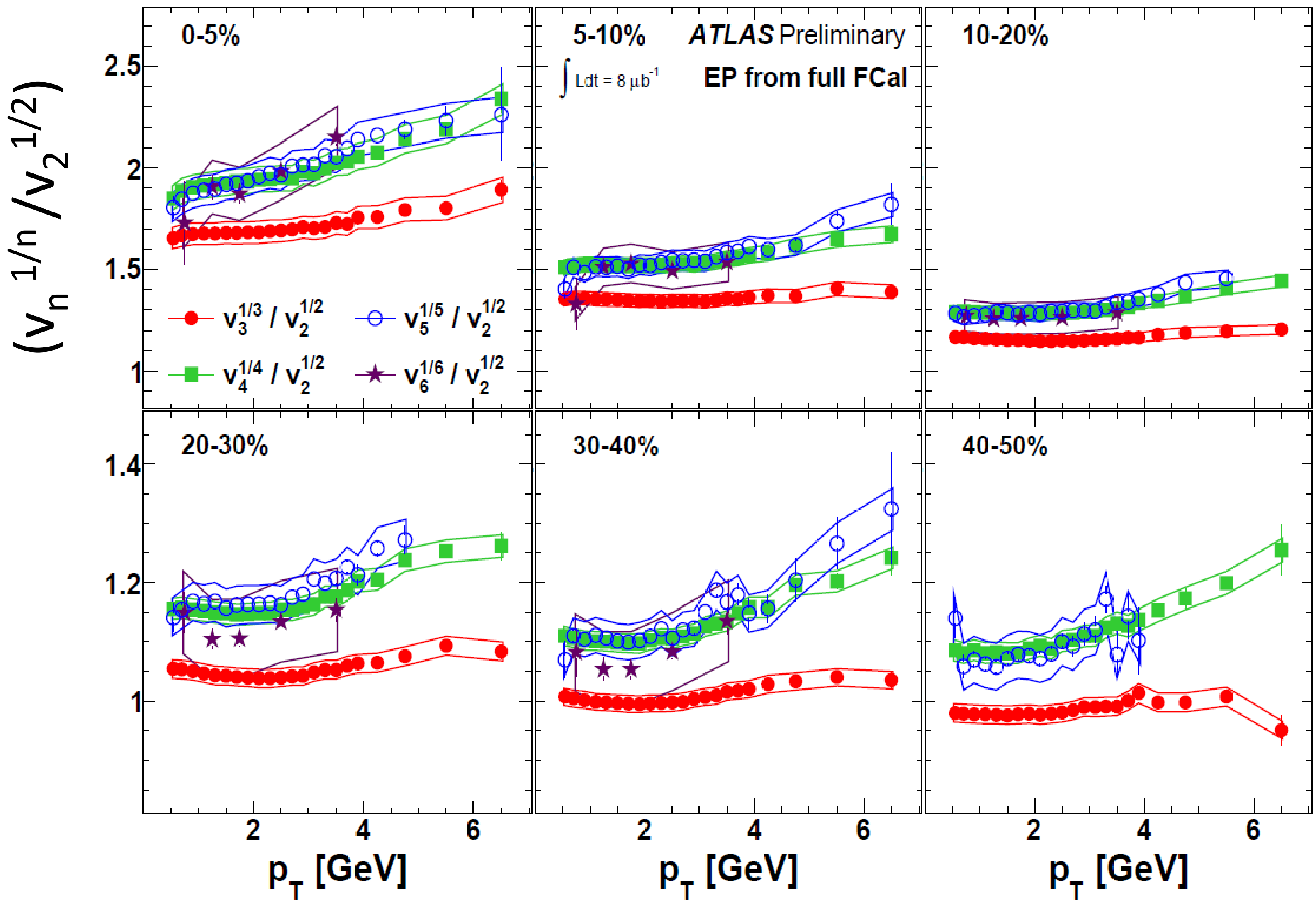


p_T Dependence of v_n



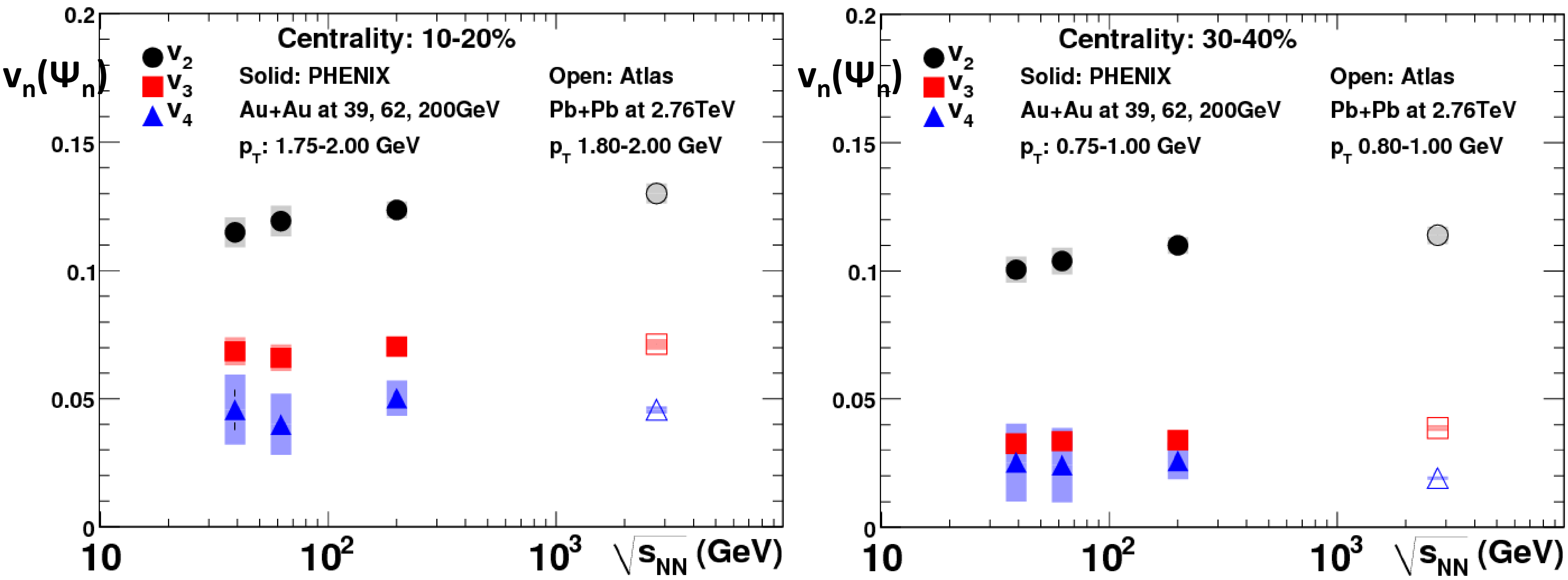
- Similar trend across all harmonics (increase till 3-4GeV then decrease)
- In most central collisions(0-5%): v_3, v_4 can be larger than v_2.

v_n scaling



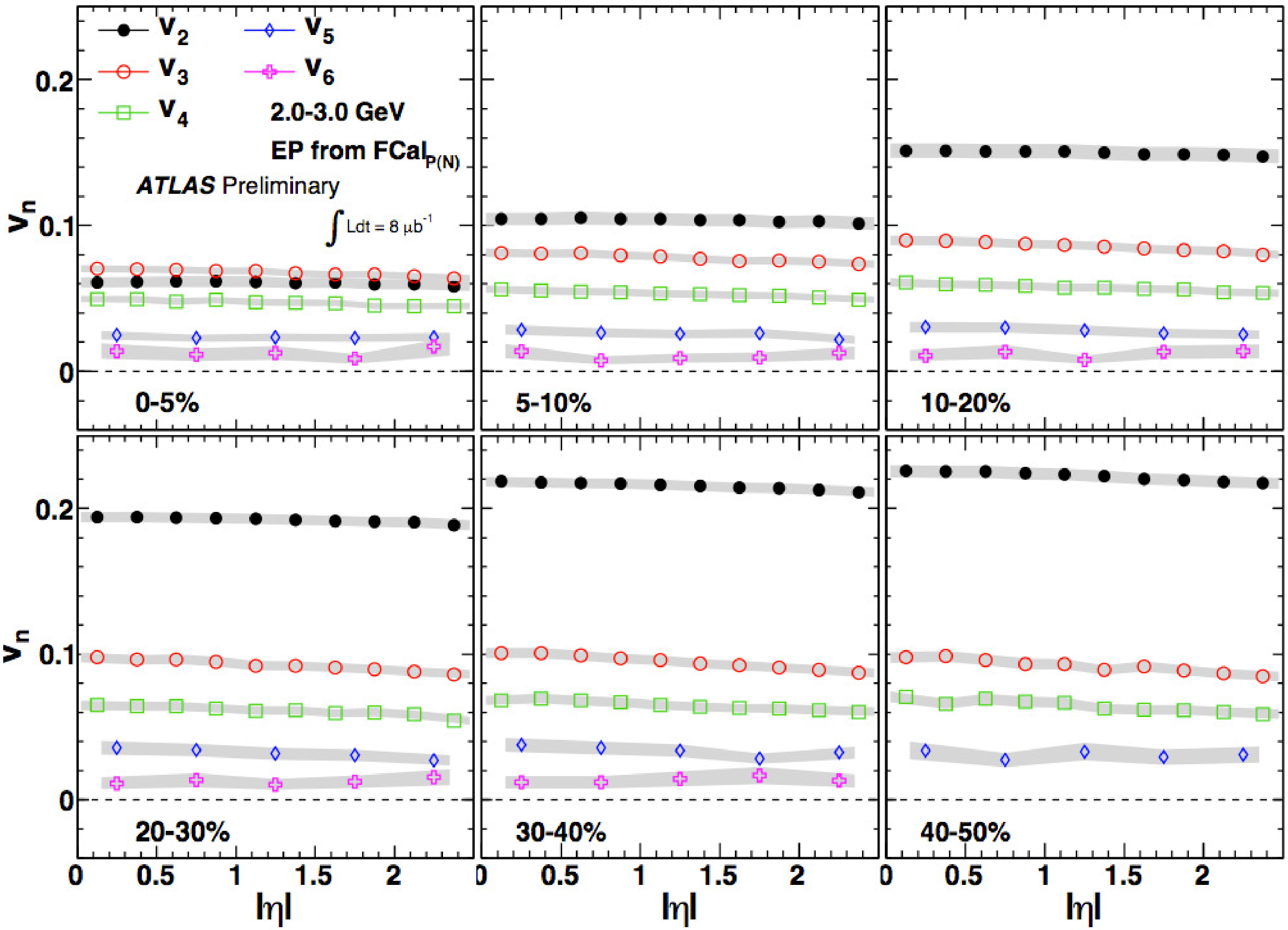
- Observe scaling: $v_n^{1/n} = k v_2^{1/2}$, where "k" is only weakly dependent on p_T.
- R.Lacey et al. (http://arxiv.org/abs/1105.3782)

v_n from RHIC to LHC



From
Xiaoyang Gong
Quark Matter 2011 Talk

η Dependence of v_n



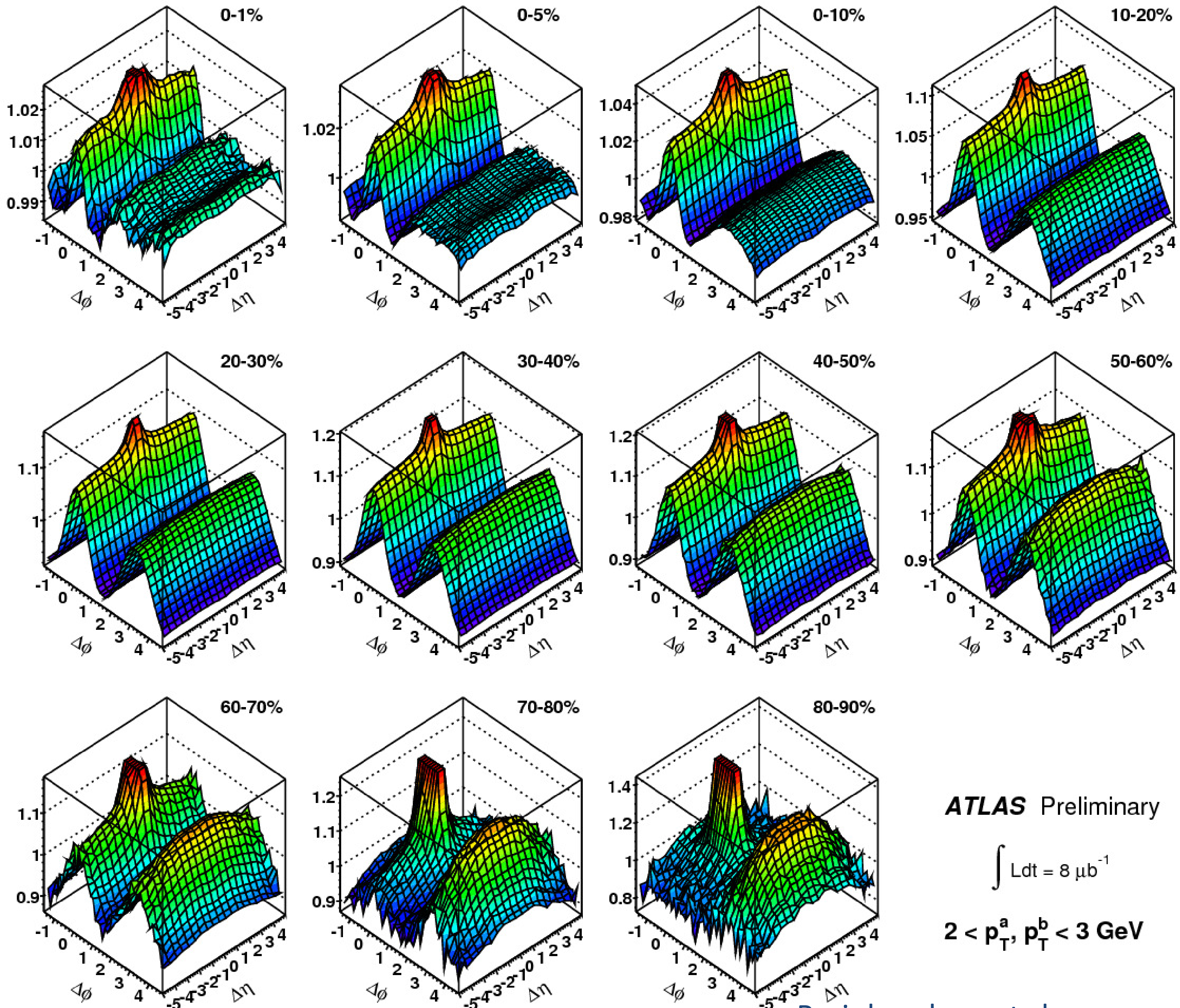
- weak dependence on η (~5% drop within acceptance)

- For Correlations:

$$v_{n,n}^{a,b} = v_n^a \times v_n^b$$

relation is true only if the η dependence is weak

Two Particle Δη–Δϕ correlations



Near-side jet peak is always visible

Ridge seen in central and mid-central collisions, weak η 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 only

Peripheral events have near side peak truncated

Obtaining harmonics from correlations

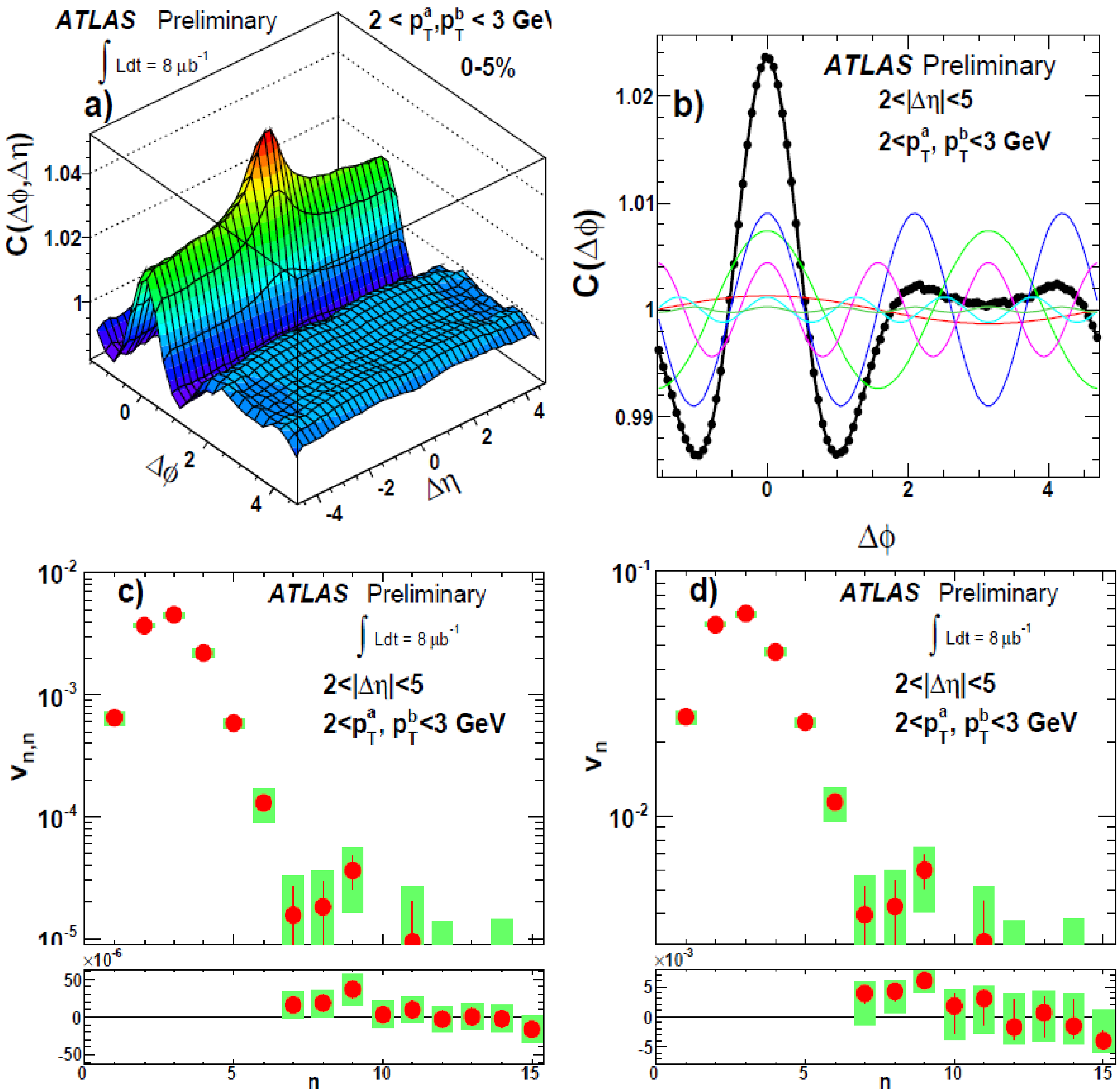
a) The 2D correlation function in $\Delta\eta,\Delta\phi$.

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

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

d) Corresponding v_n values

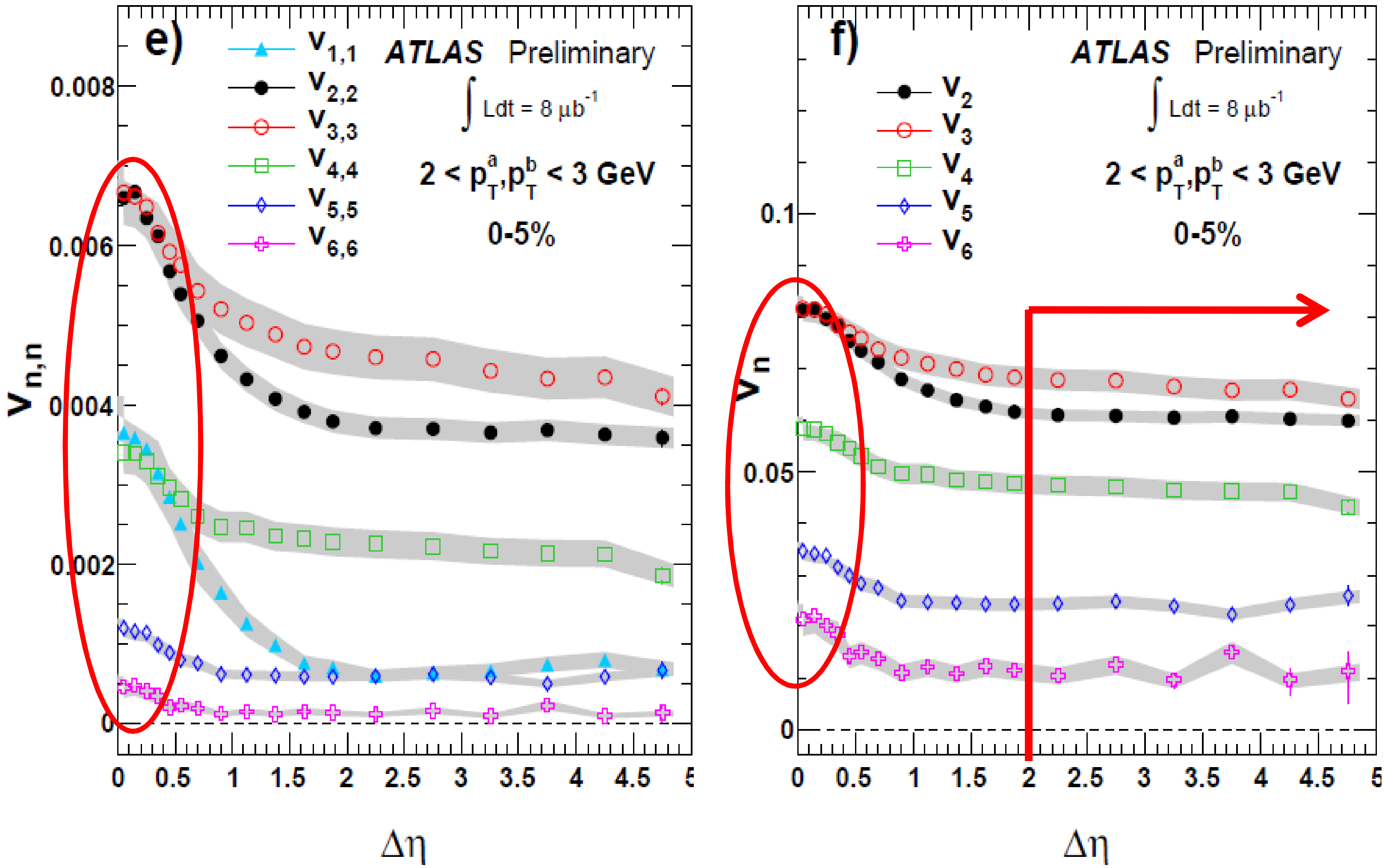
$$v_n\left(p_T^a\right)=\sqrt{v_{n,n}\left(p_T^a,p_T^a\right)}$$



Bands indicate systematic errors

$\Delta\eta$ dependence of v_n

- Repeat procedure in narrow $\Delta\eta$ slices to obtain v_n vs $\Delta\eta$.
- v_n values peak at low $\Delta\eta$, due to jet bias.
- Relatively flat afterwards, so we require a $|\Delta\eta| > 2$ gap (to remove near-side jet).



Bands indicate systematic errors

Universality of v_n

- $v_{n,n}$ is expected to factorize into single v_n for flow

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

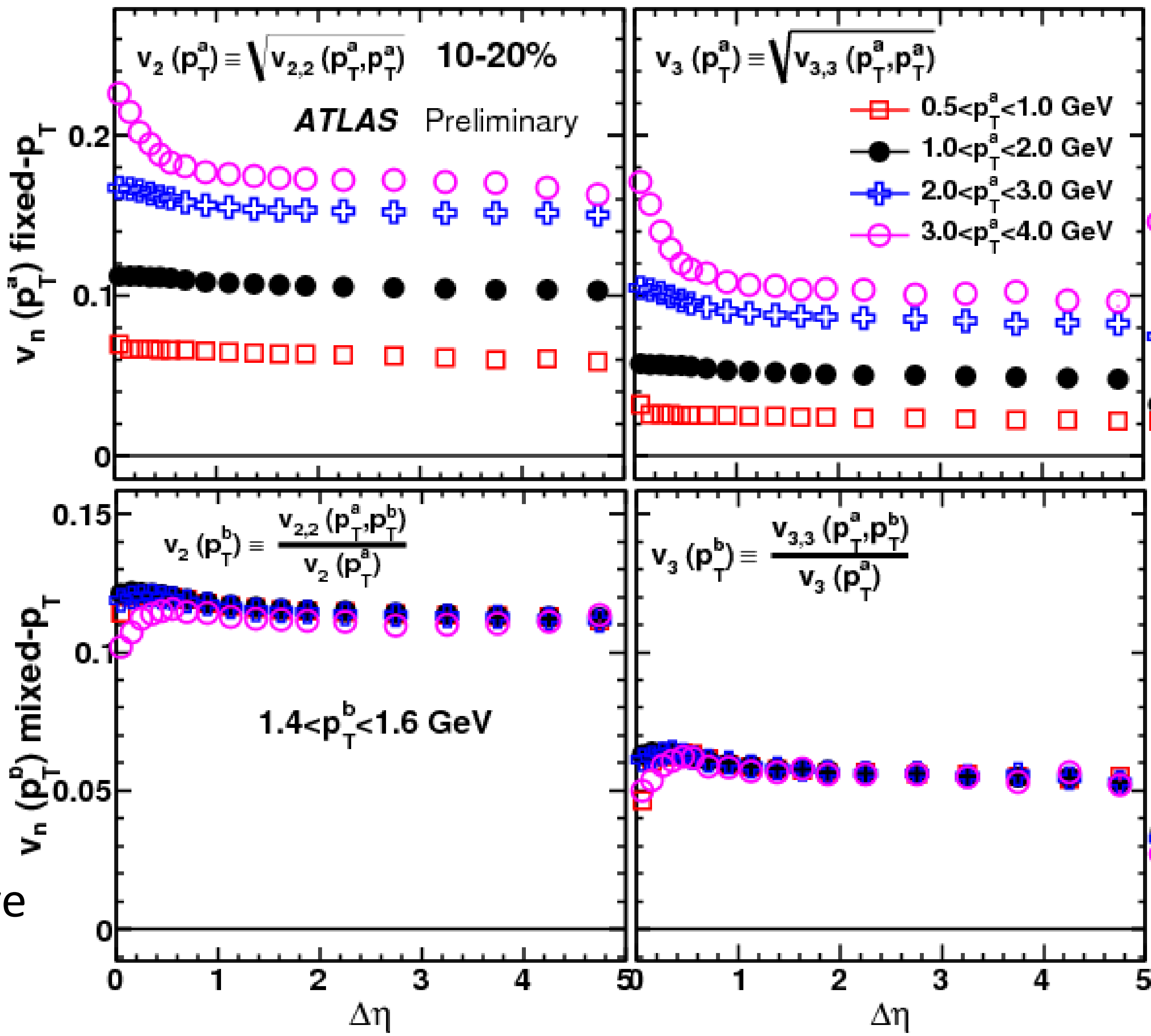
- Obtain v_n using "fixed p_T" correlations

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

- cross-check via "mixed-p_T" correlation

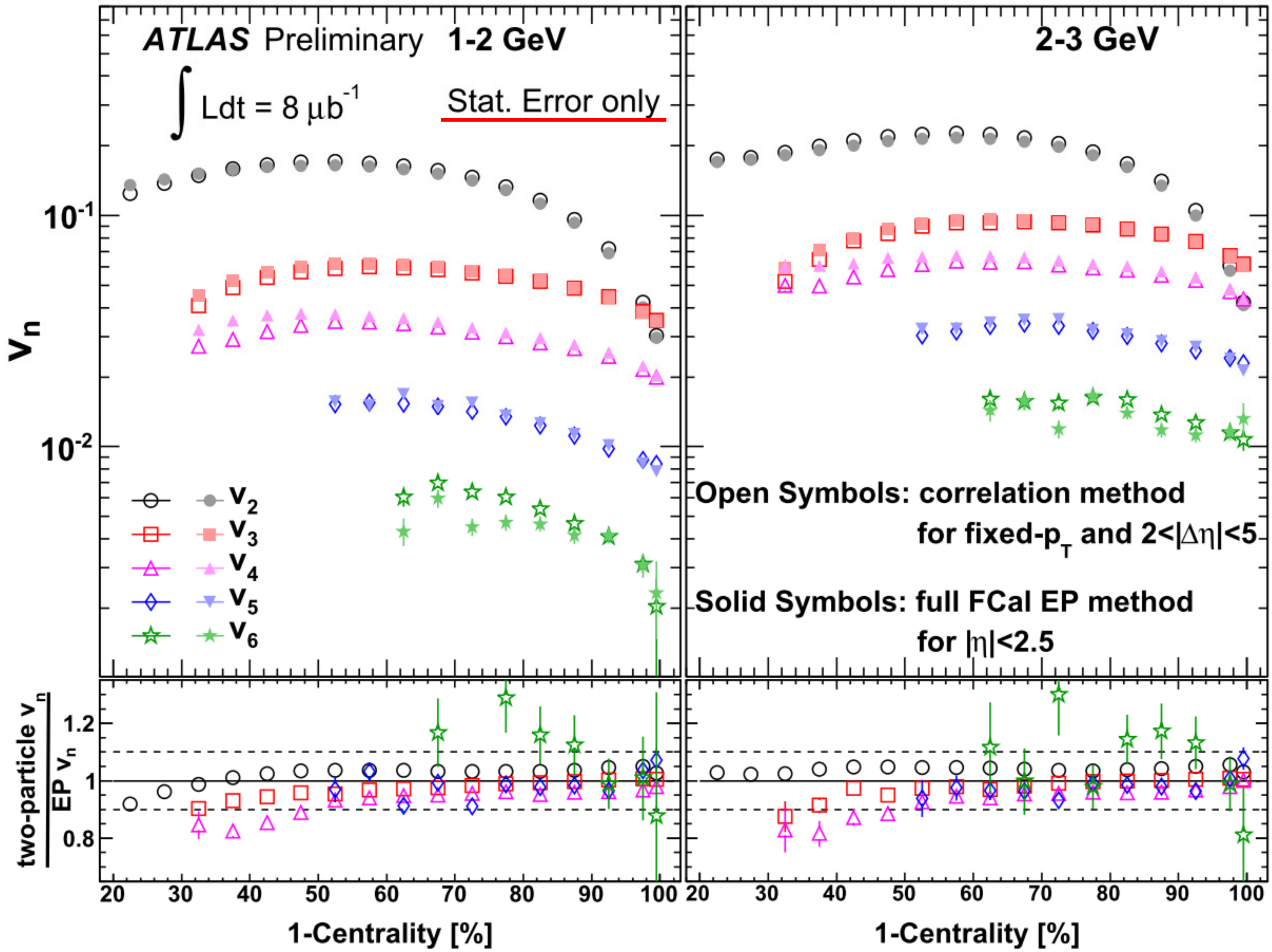
$$v_n\left(p_T^b\right)=v_{n,n}\left(p_T^a,p_T^b\right)\Big/v_n\left(p_T^a\right)$$

- Indeed, $v_{n,n}$ factorizes! (above certain $\Delta\eta$)

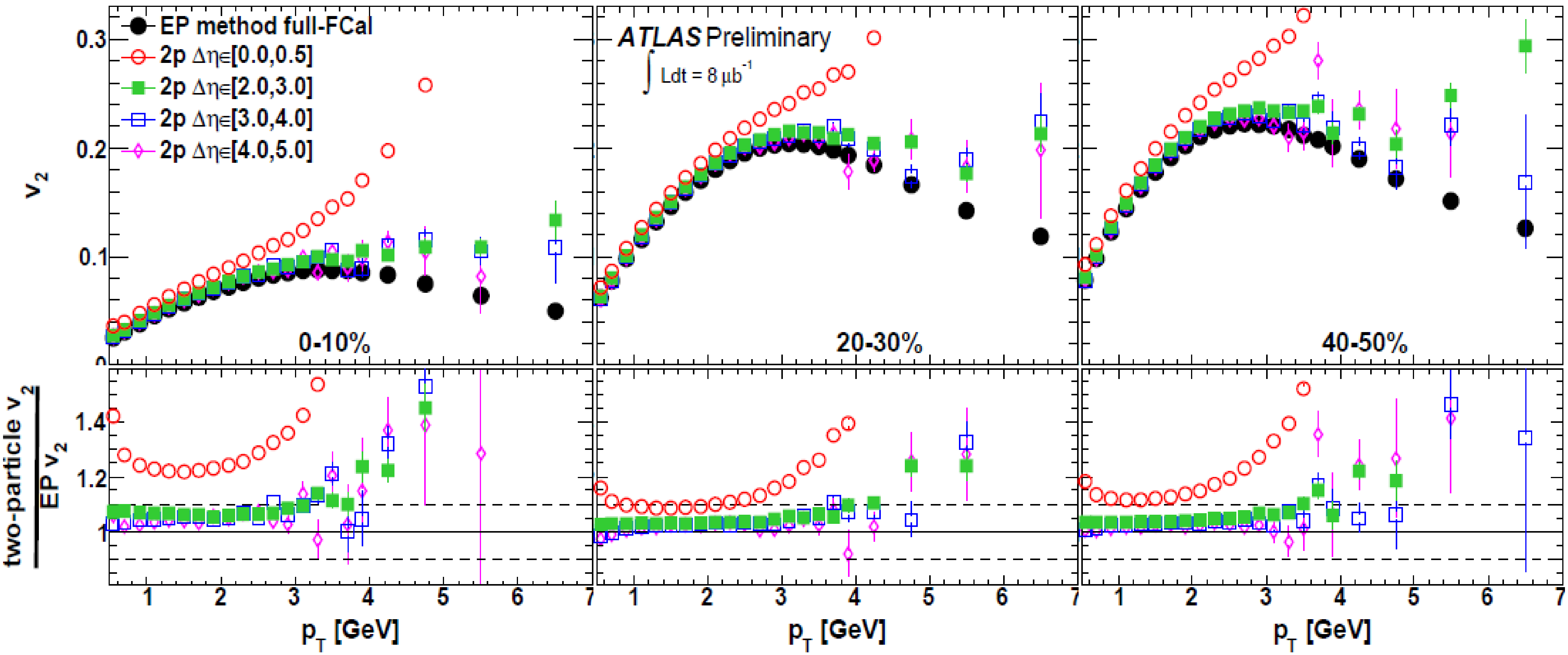


Comparison between the two methods

Centrality Dependence

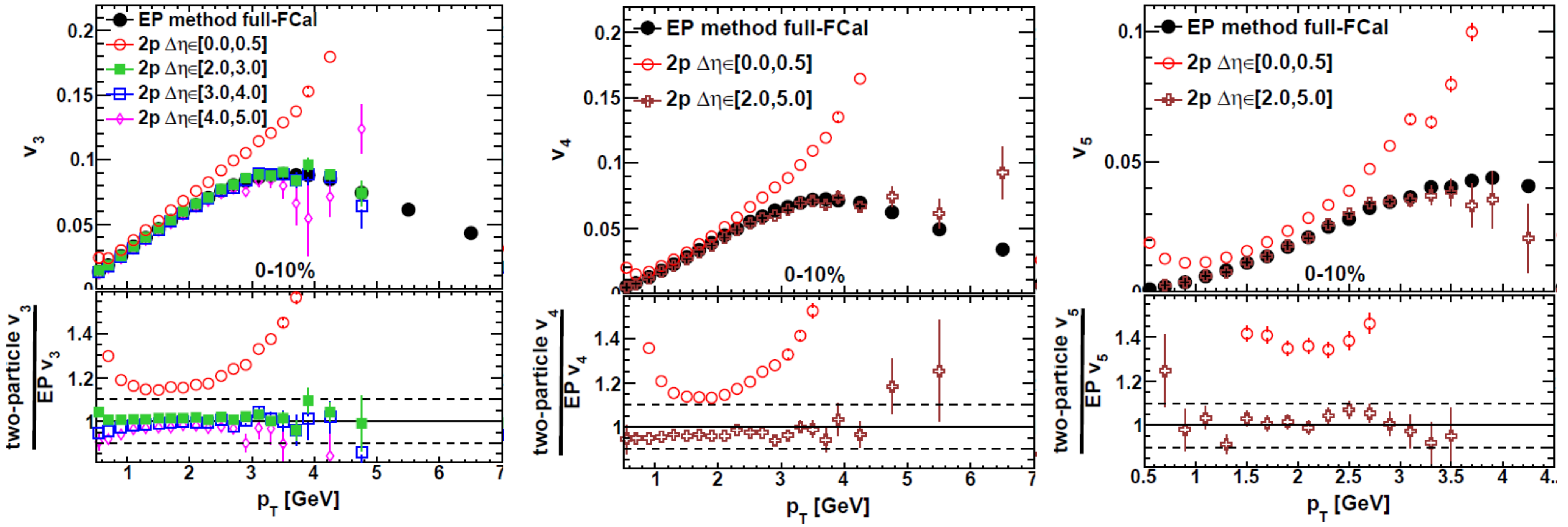


p_T Dependence of v_2



- The 2PC v_n for $|\Delta\eta|<0.5$ deviates from the EP results (for all p_T)
- Good agreement seen for $|\Delta\eta|>2$ at $p_T<4$ GeV.
- See deviations for $p_T>4$ GeV even for $|\Delta\eta|>2$ due to increased away-side jet contribution (which swings along $\Delta\eta$).

p_T Dependence of other v_n



We see similar trend as v_2

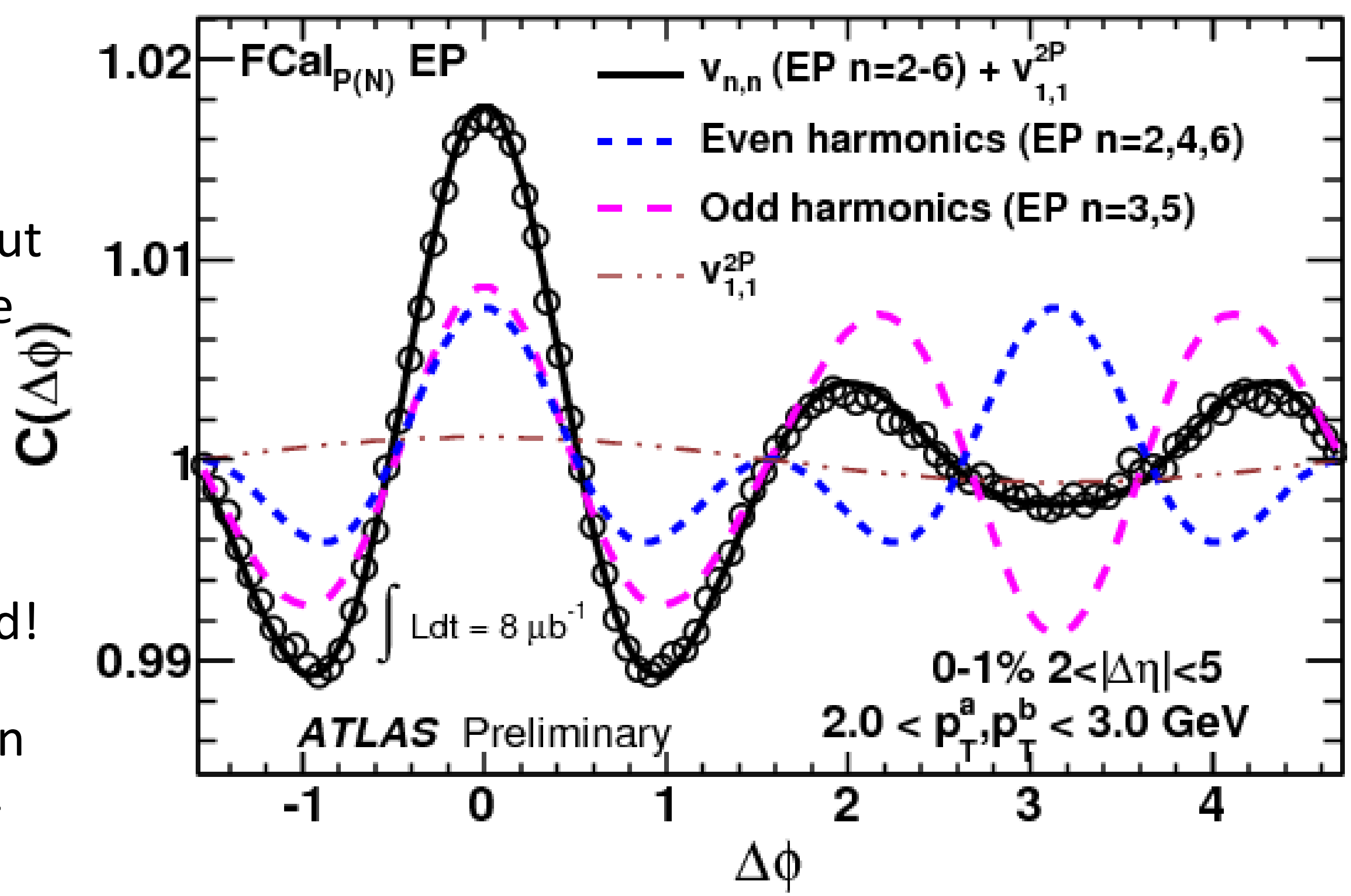
Recovering the correlations from EP v_n

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

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.



Summary

- Measured v_2-v_6 by both correlation and event-plane analysis.
  - Significant and consistent v_2-v_6 were observed by the two methods.
  - Measured in phase space much larger than at RHIC.
  - Each v_n can act as independent cross-check for η/s.
- Noted that v_2 doesn't change drastically from RHIC to LHC
- Observed that the v_n follow a simple scaling relation: $v_n^{1/n} \propto v_2^{1/2}$.
- Concluded that the features in two particle correlations for $|\Delta\eta|>2$ at low and intermediate p_T ($p_T<4.0GeV$) can be accounted for by the collective flow of the medium.
  - Double hump and ridge arise due to interplay of even and odd harmonics

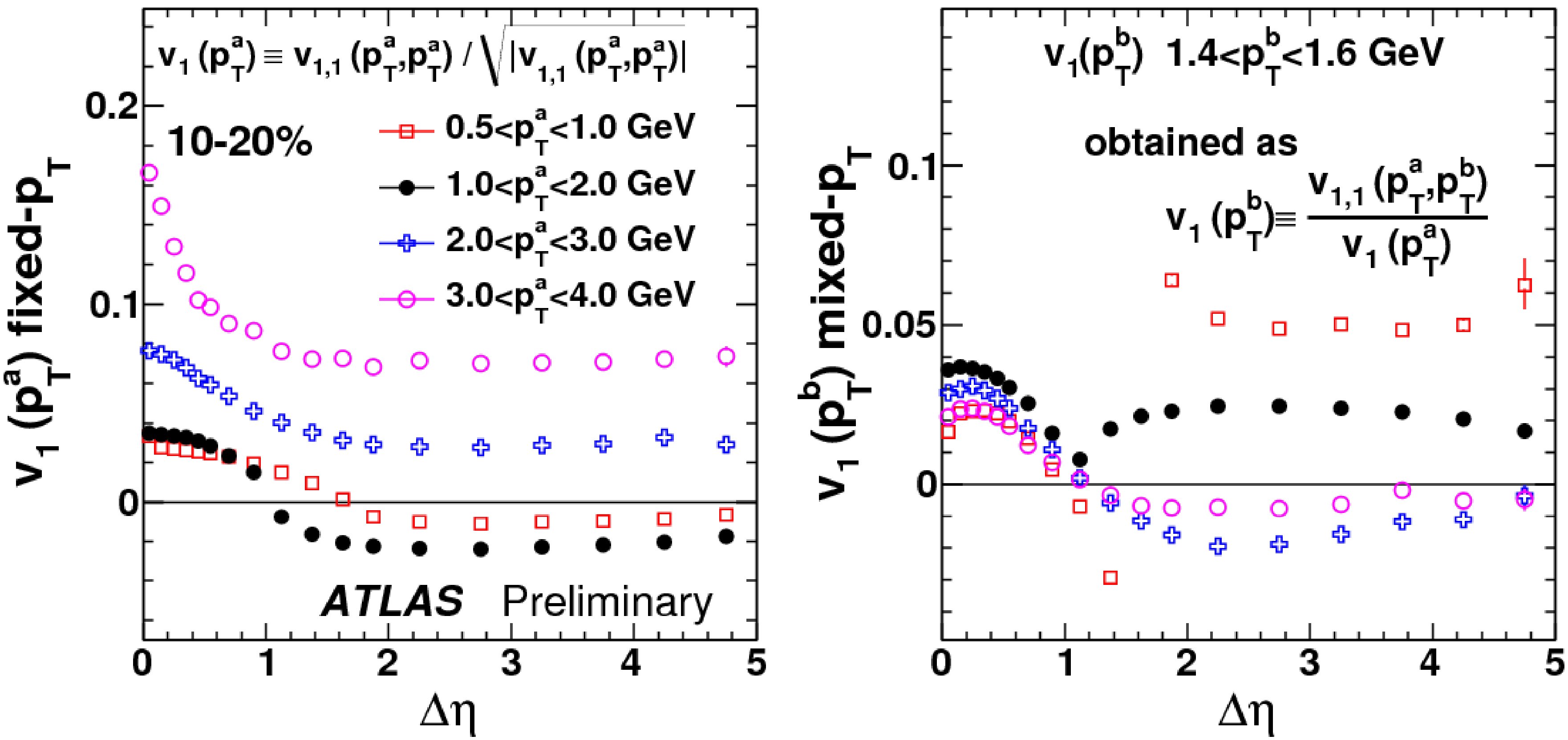
For more results see:

- ATLAS v_n analysis note : http://cdsweb.cern.ch/record/1352458
- ATLAS HI public results page :
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

BACKUP SLIDES

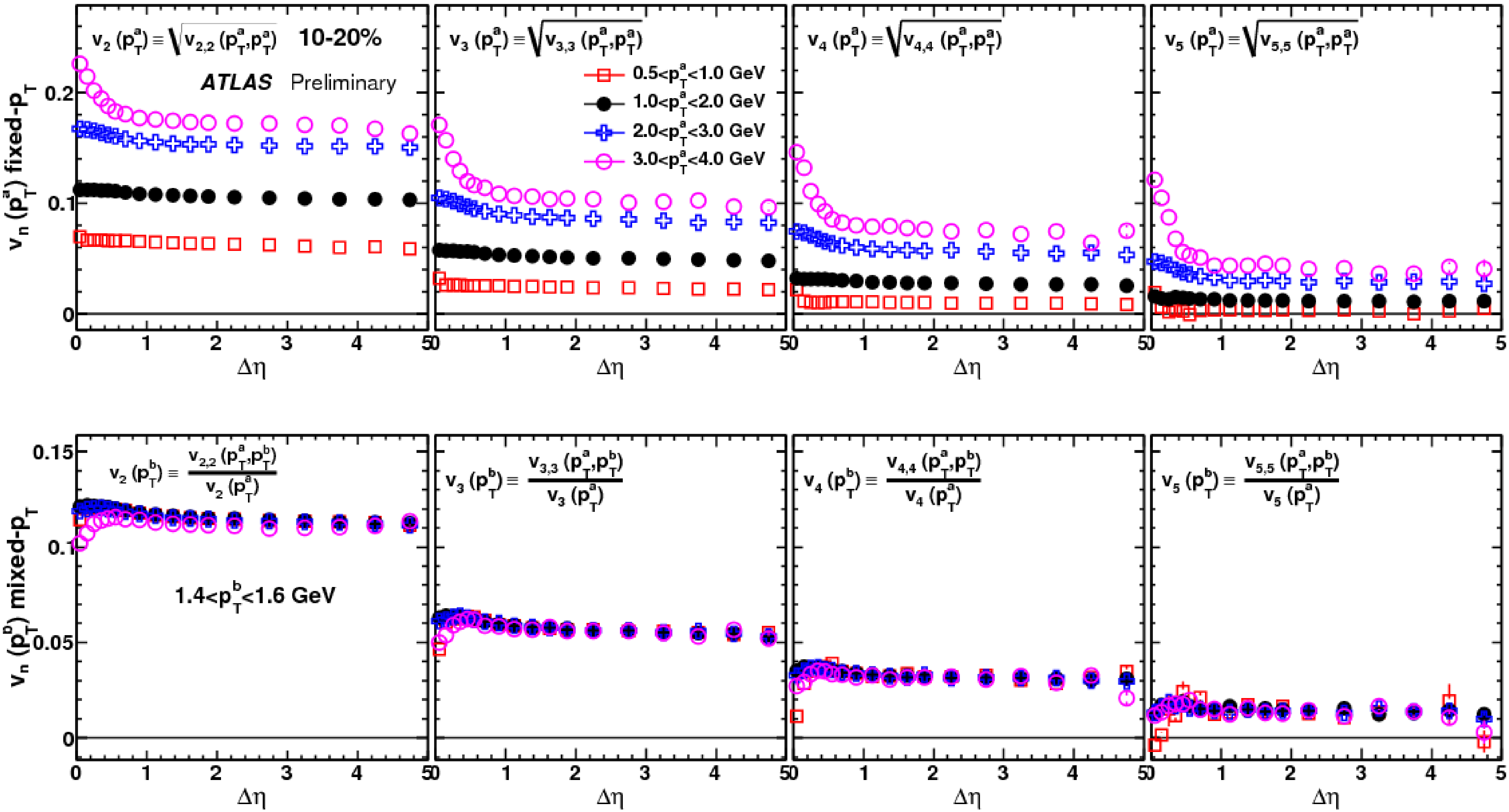
BACKUP SLIDES

Breakdown of $v_{1,1}$ scaling

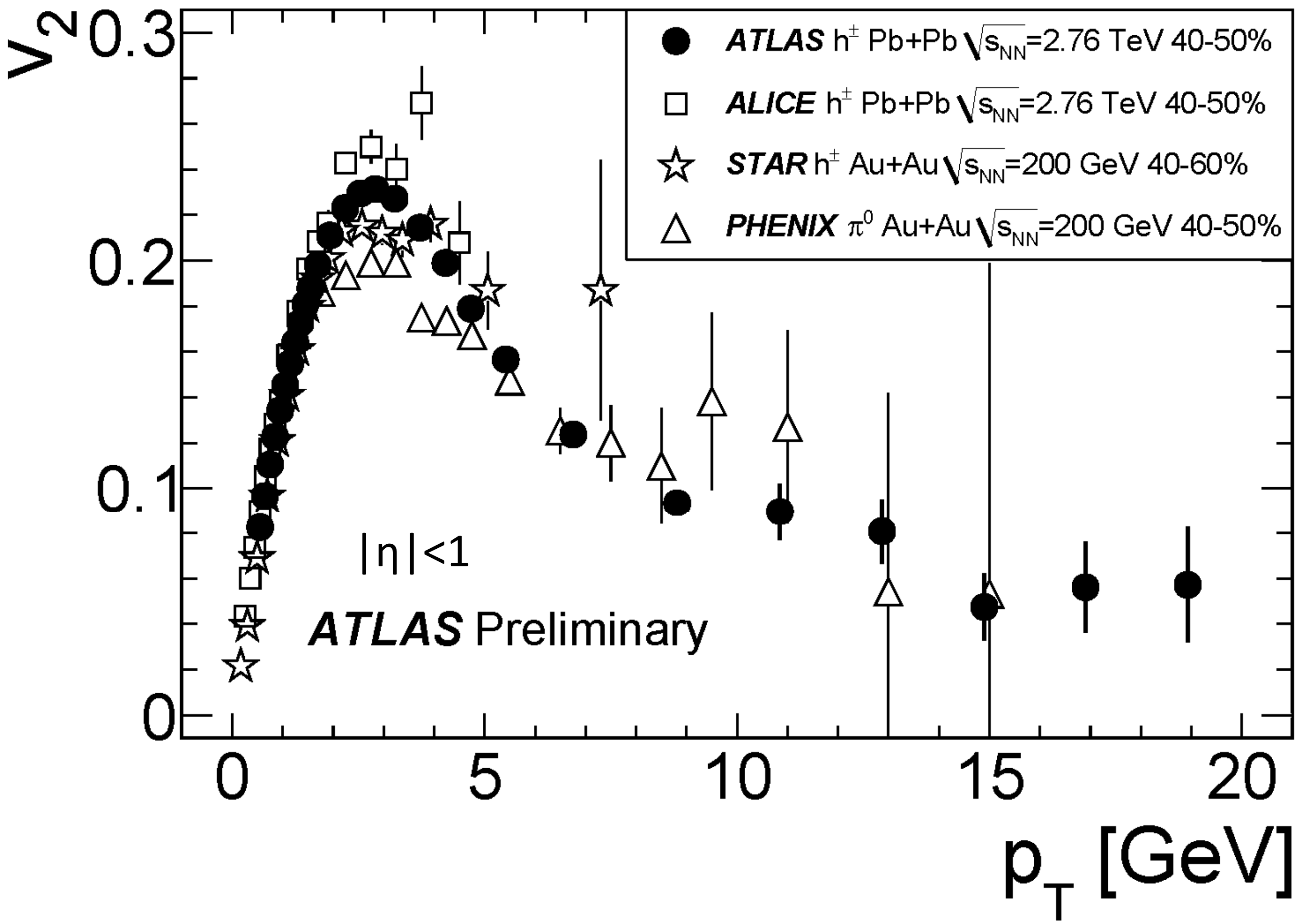


- Left panel: : $v_1(p_T^a)$ vs $\Delta\eta$ for four fixed-p_T correlations.
  - We see that $v_{1,1}(p_T^a)$ can become negative showing eta dependence of v_1
- Right panel: $v_1(p_T^b)$ vs for target p_T in (1.4,1.6) GeV
  - We see that $v_1(p_T^b)$ depends on p_T^a showing the breakdown of the scaling relation

Universality of v_n

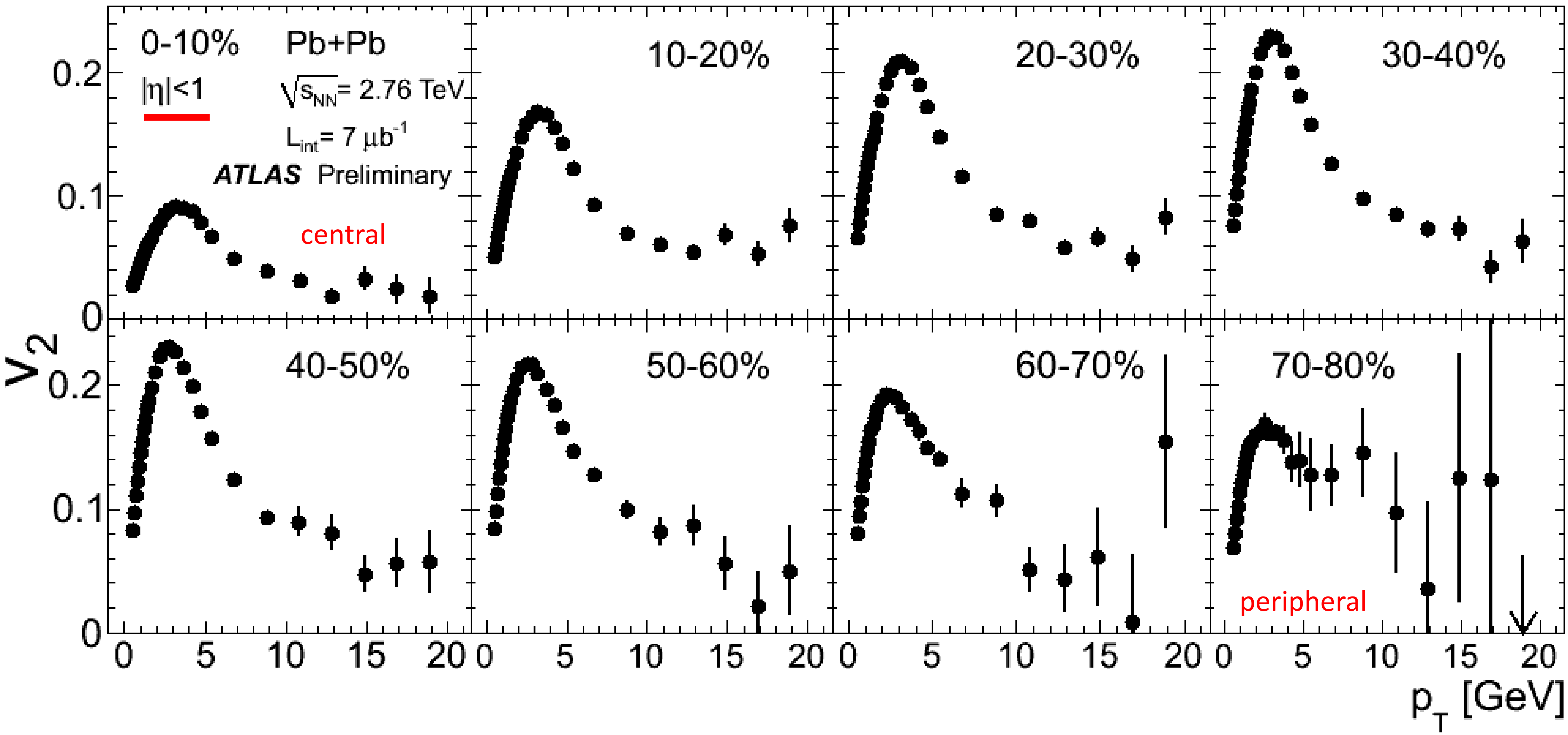


v_2 Comparison to RHIC



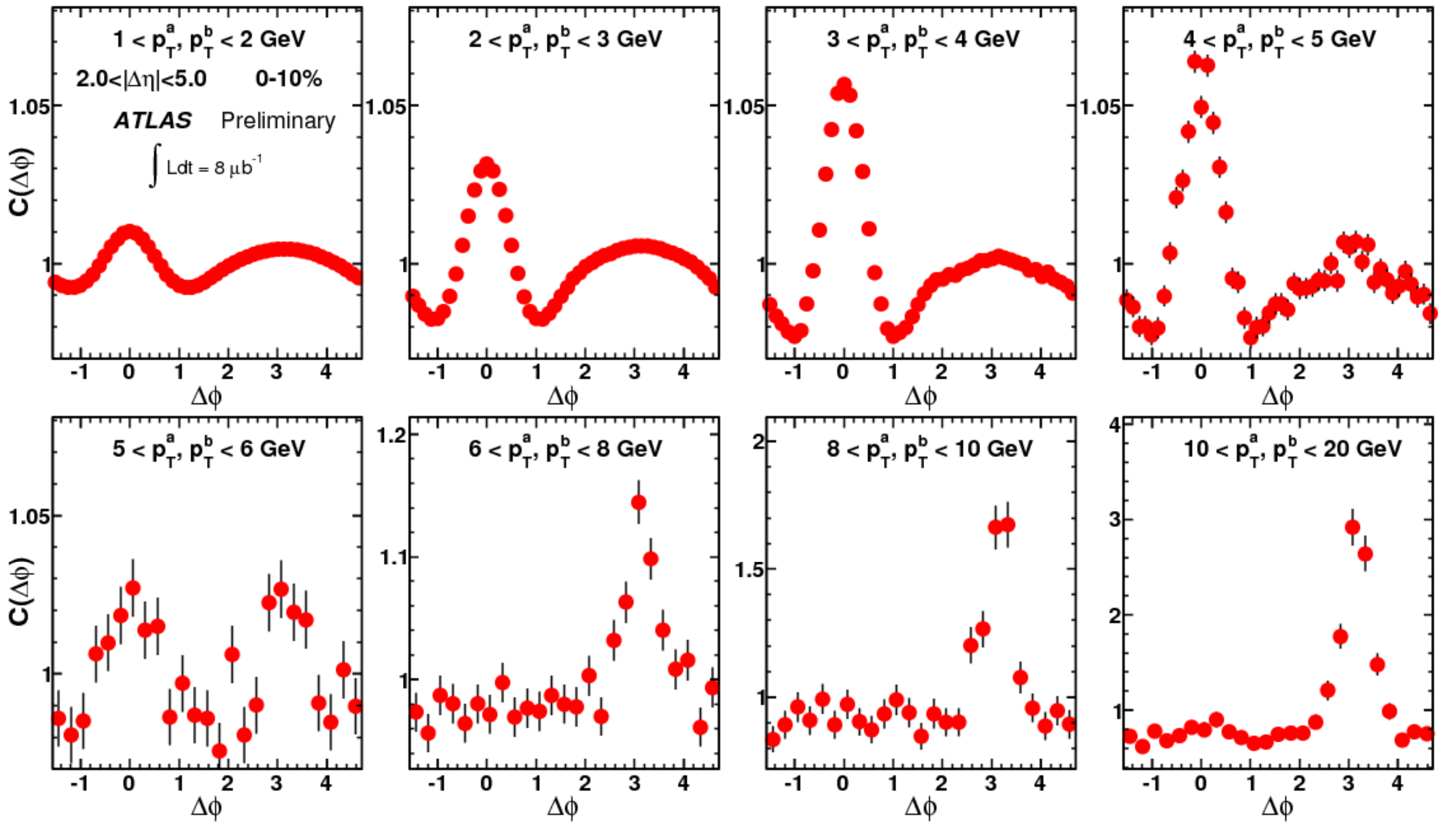
- **Similar magnitude and p_T dependence in overlapping p_T range**

v_2 out to 20GeV



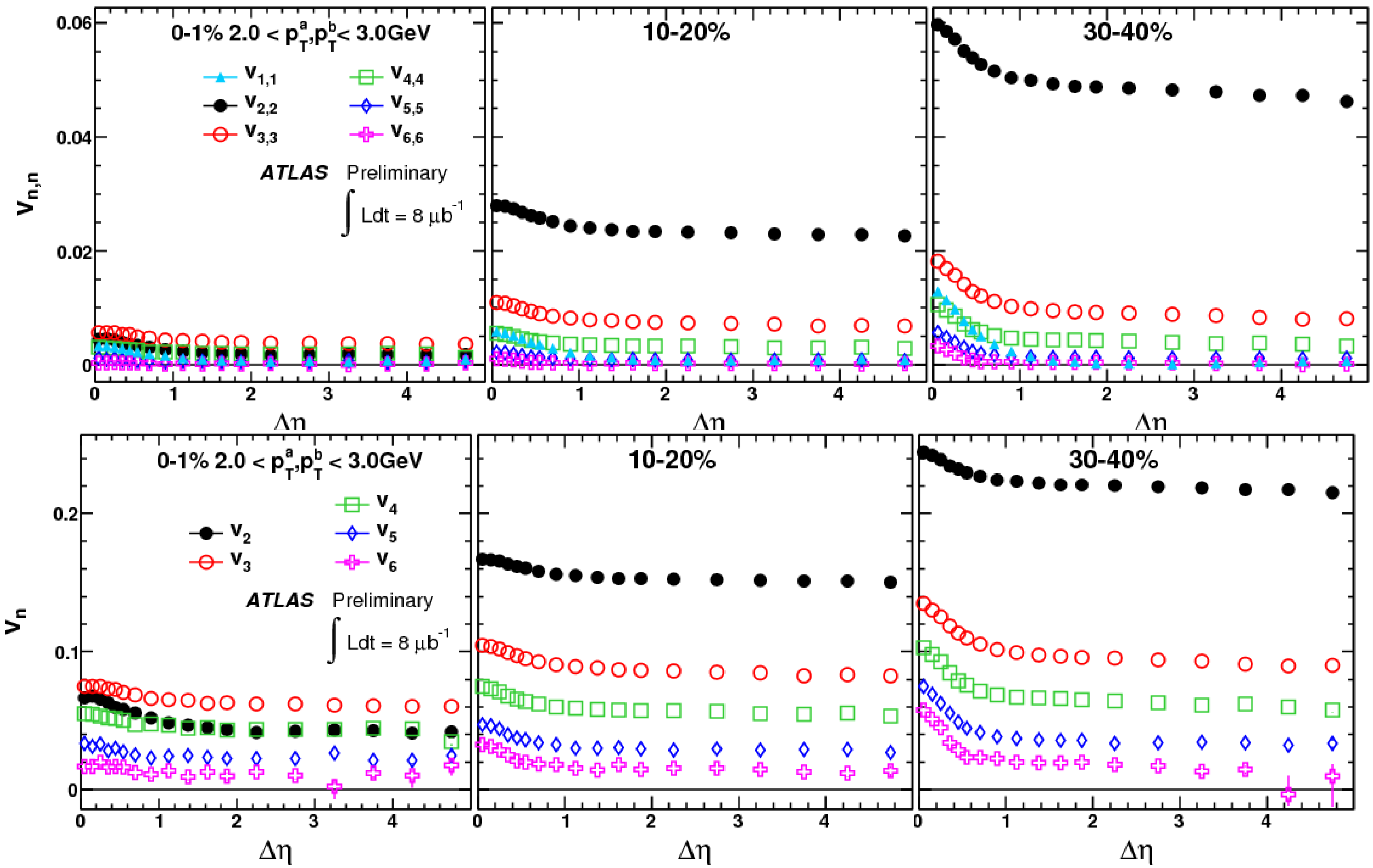
- **Charged hadrons, p_T=0.5-20 GeV, mid-rapidity, |η|<1**

p_T evolution of $\Delta\phi$ correlations

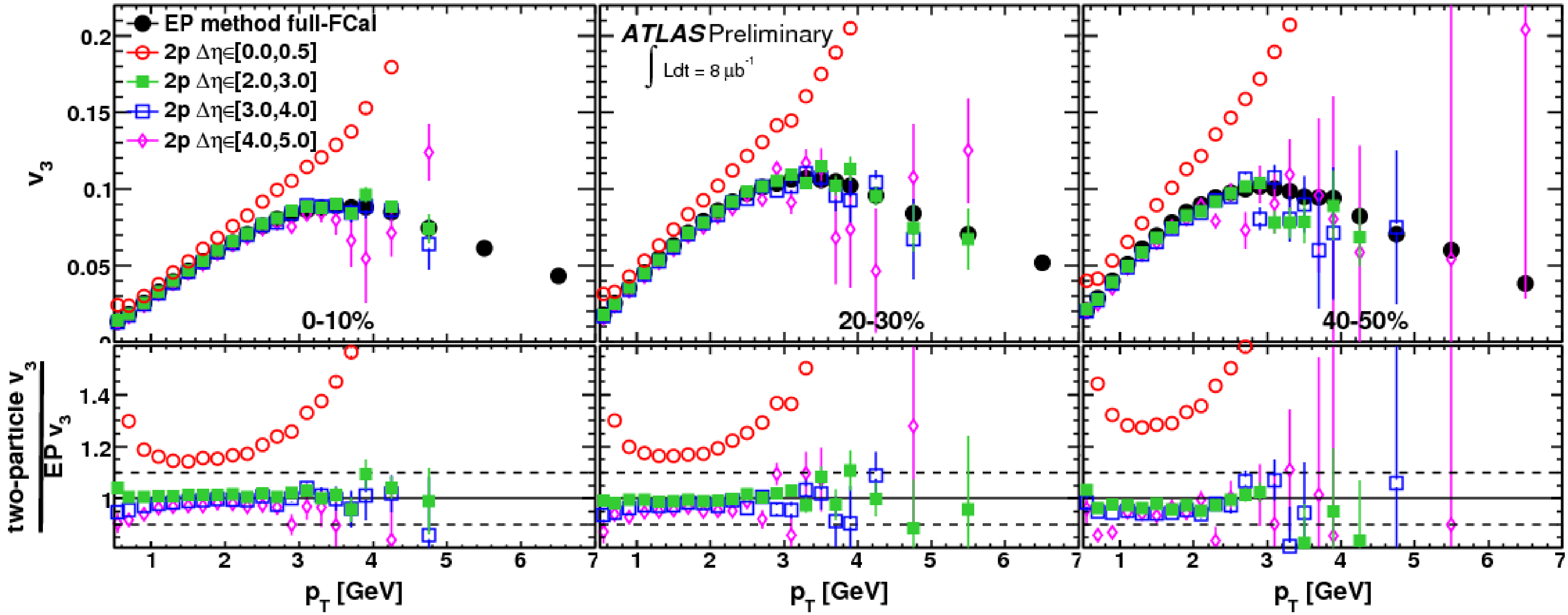


- p_T evolution of two-particle $\Delta\phi$ correlations for 0-10% centrality selection, with a large rapidity gap ($|\Delta\eta|>2$) to suppress the near-side jets and select only the long range components.

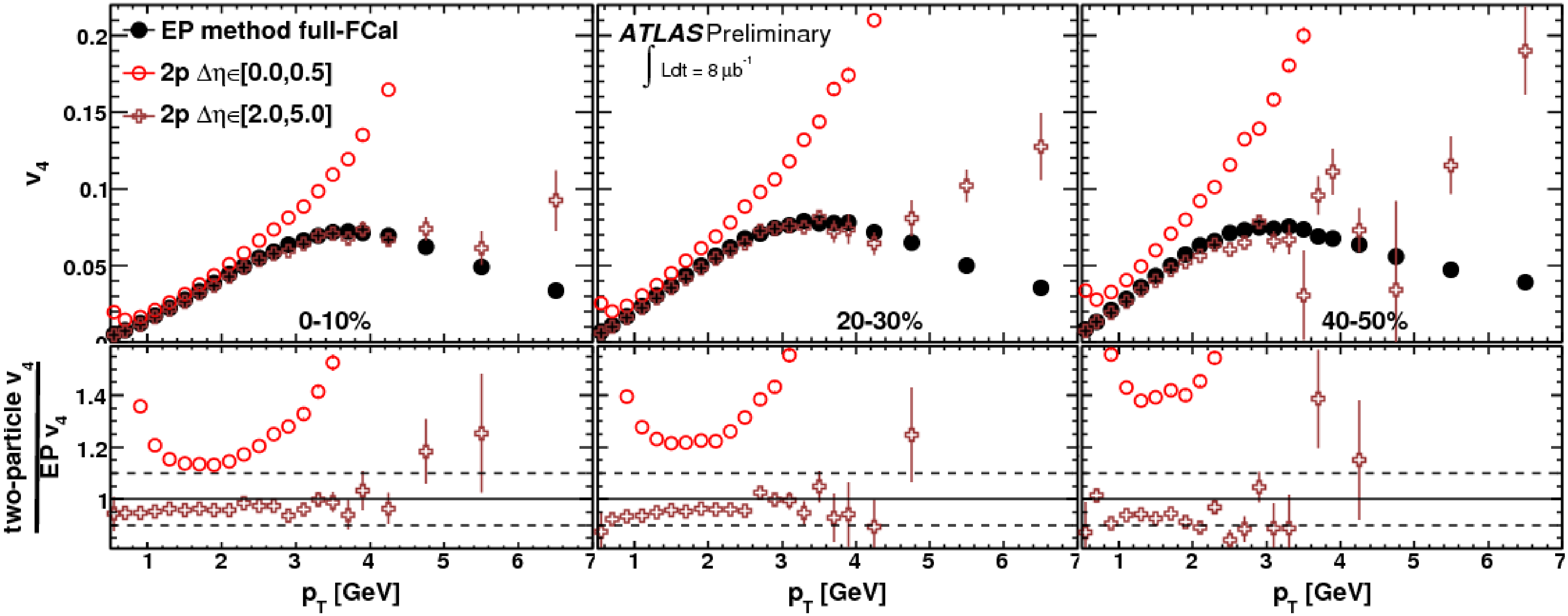
$v_{n,n}$ and v_n vs Δη for other centralities



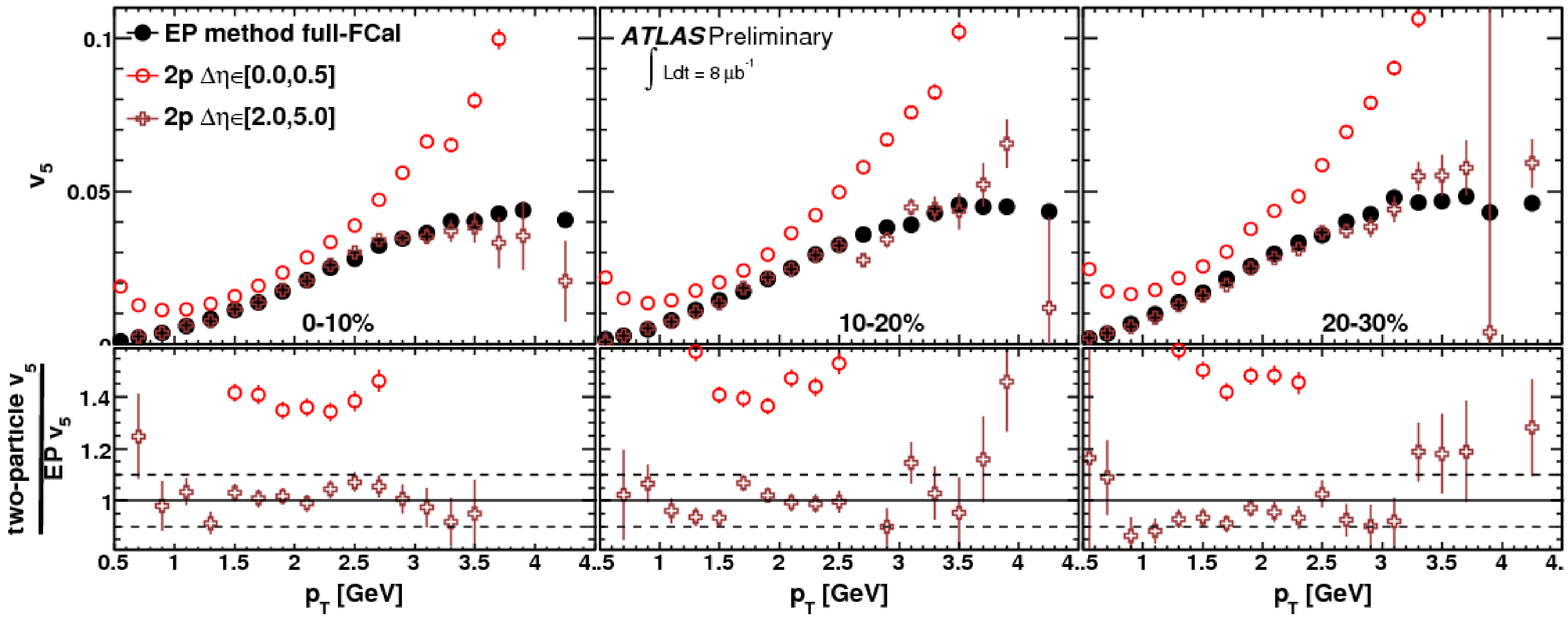
p_T Dependence of v_3 (2PC)



p_T Dependence of v_4 (2PC)

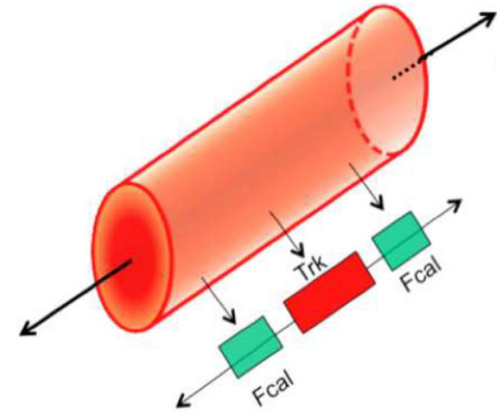


p_T Dependence of v_5 (2PC)



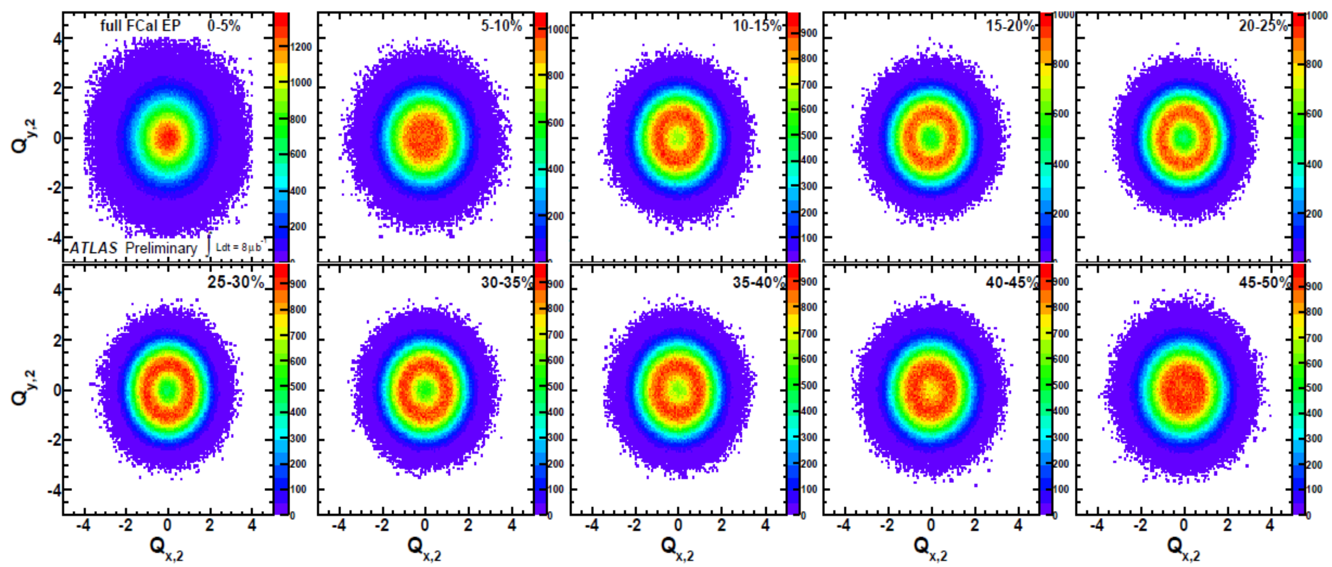
Q vector example

- The EP is determined with the Q-vector method using flow in FCal



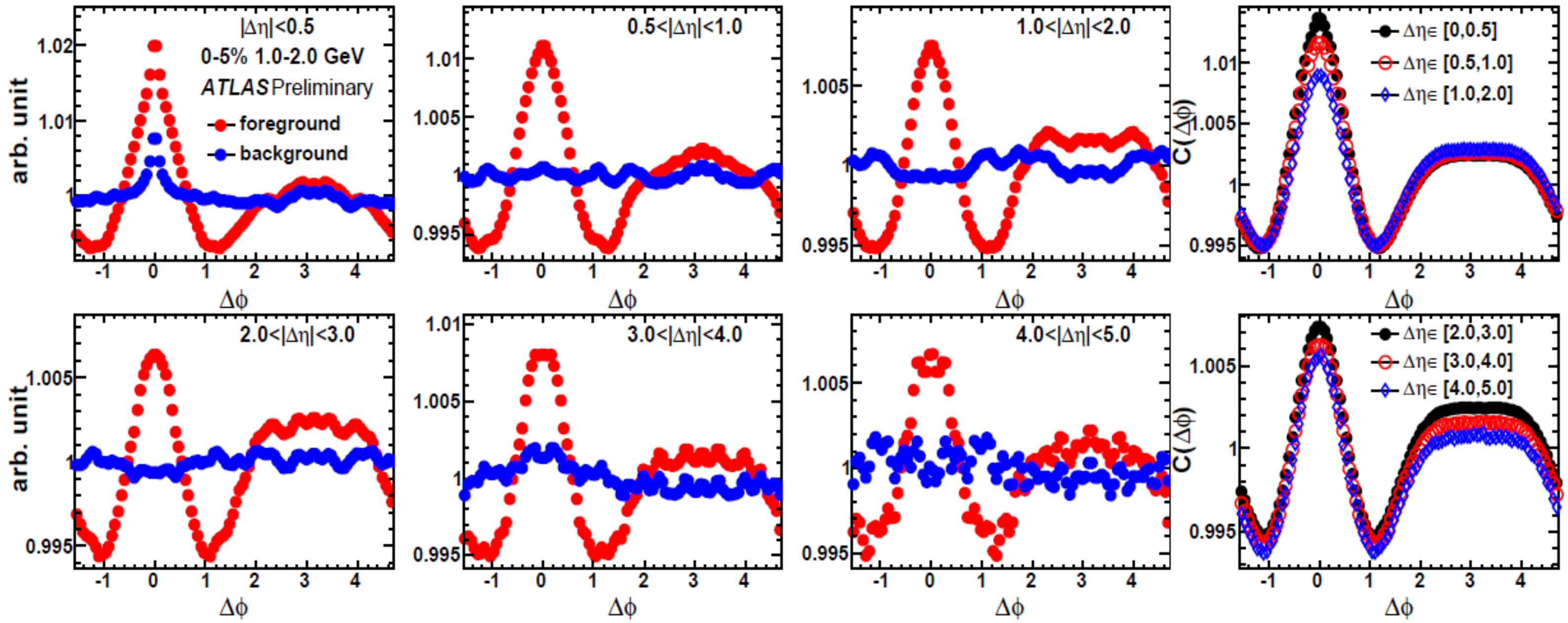
$$Q_{x,n} = \sum_i E_i \cos(n\phi_i)\ ;\ Q_{y,n} = \sum_i E_i \sin(n\phi_i);\Psi_n = \frac{1}{n}\tan^{-1}(\frac{Q_{y,n}}{Q_{x,n}})$$

- In mid-central collisions, the Q_2 vector is distributed in a ring-like structure indicating the excellent ability of the FCal in determining the reaction plane



- In Central and mid-central collisions and for higher harmonics, the ring blurs out

Two Particle Correlations

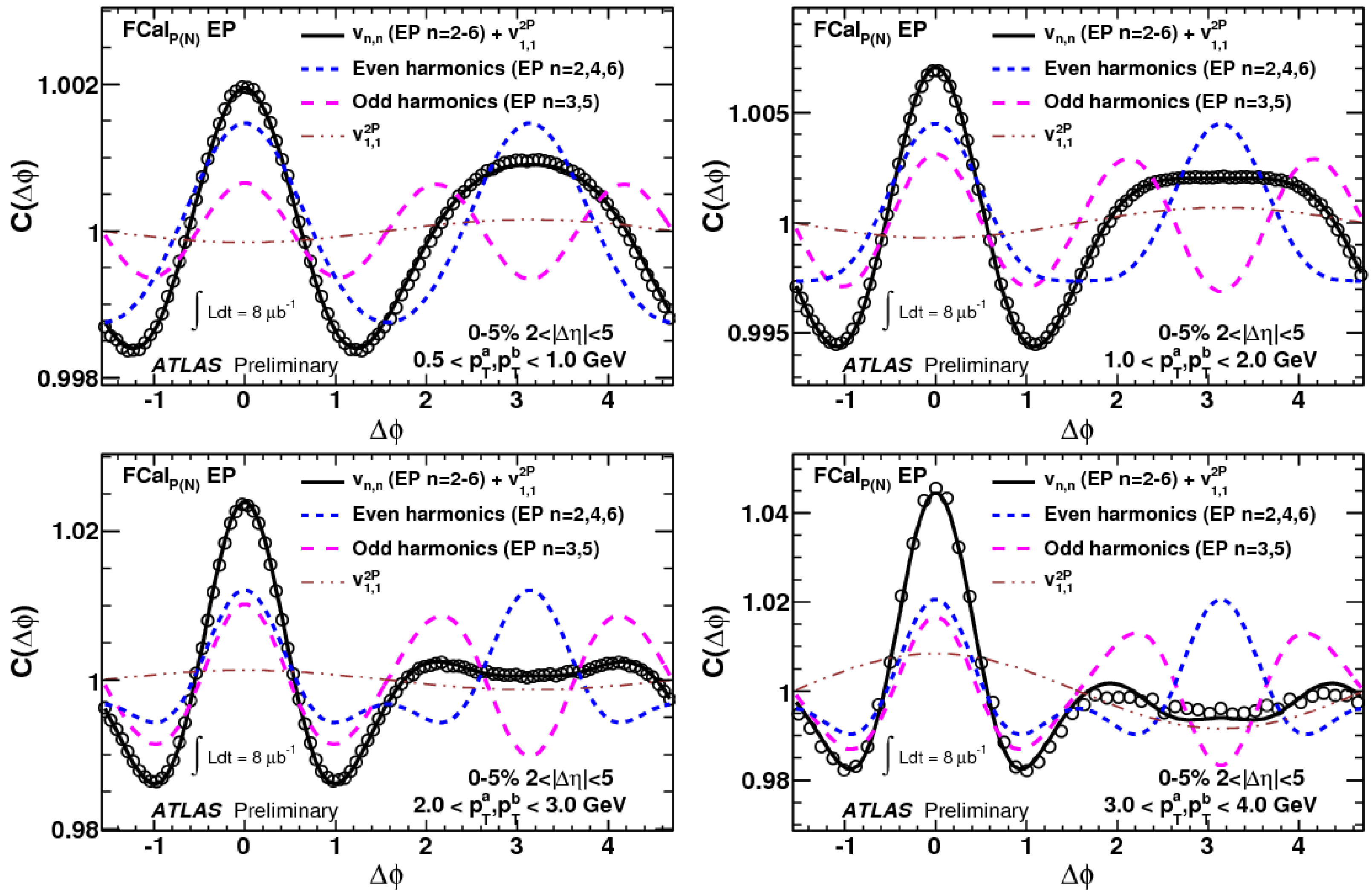


- The correlations are constructed by dividing foreground pairs by mixed background pairs.

$$C(\Delta\phi) = \frac{\text{Foreground Pairs}(\Delta\phi)}{\text{Mixed Pairs}(\Delta\phi)}$$

- Mixed background pairs account for detector acceptance. Final correlation contains only physical effects.
- The detector acceptance causes fluctuations ~ 0.001 in the foreground pairs, which mostly cancels out in the ratio.

Recovering 0-1% correlation



Recovering 0-5% correlation