Measurement of elliptic and higher-order flow harmonics at 2.76 TeV Pb+Pb collisions with the ATLAS detector.

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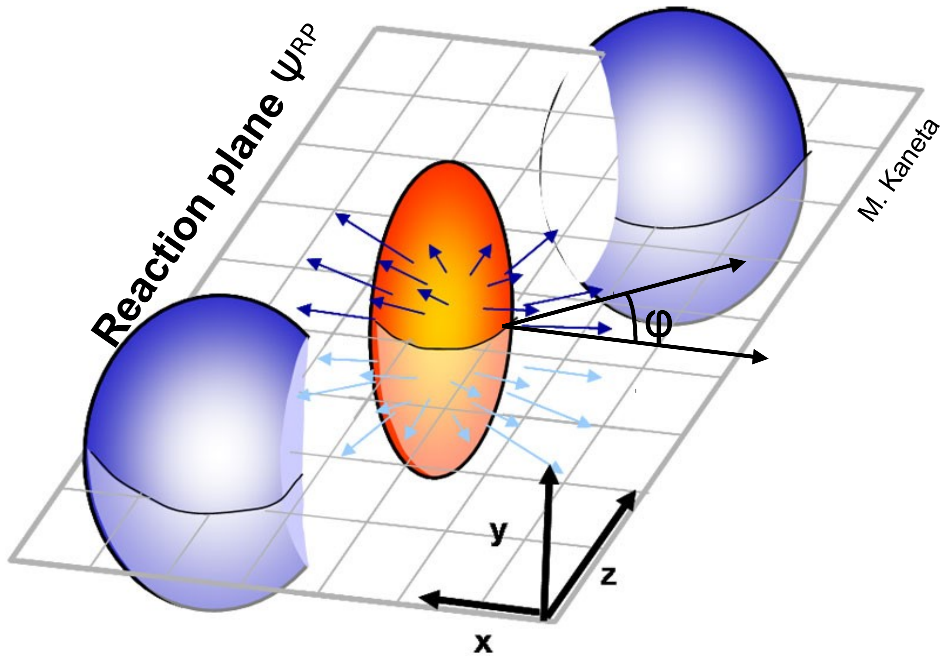
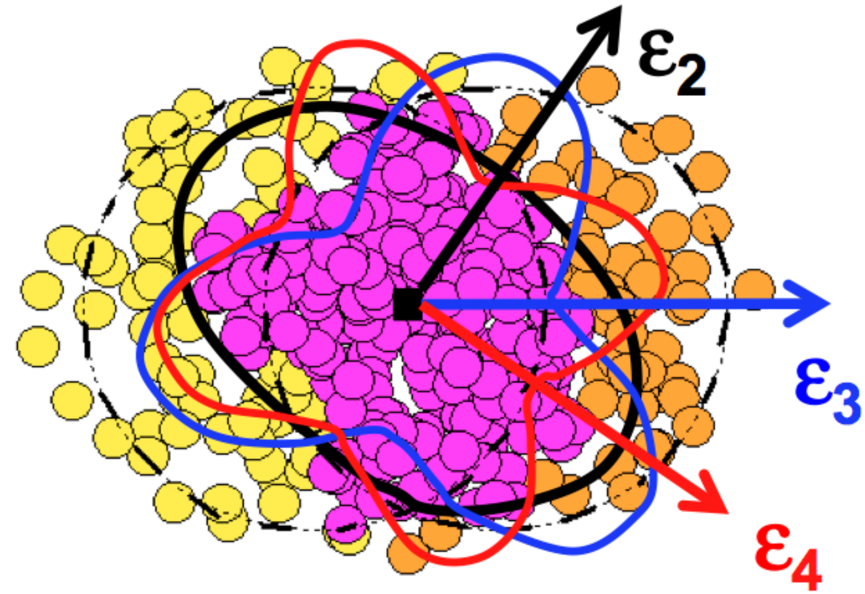
Azimuthal anisotropy in heavy ion collisions





Pressure gradients lead to azimuthal anisotropy

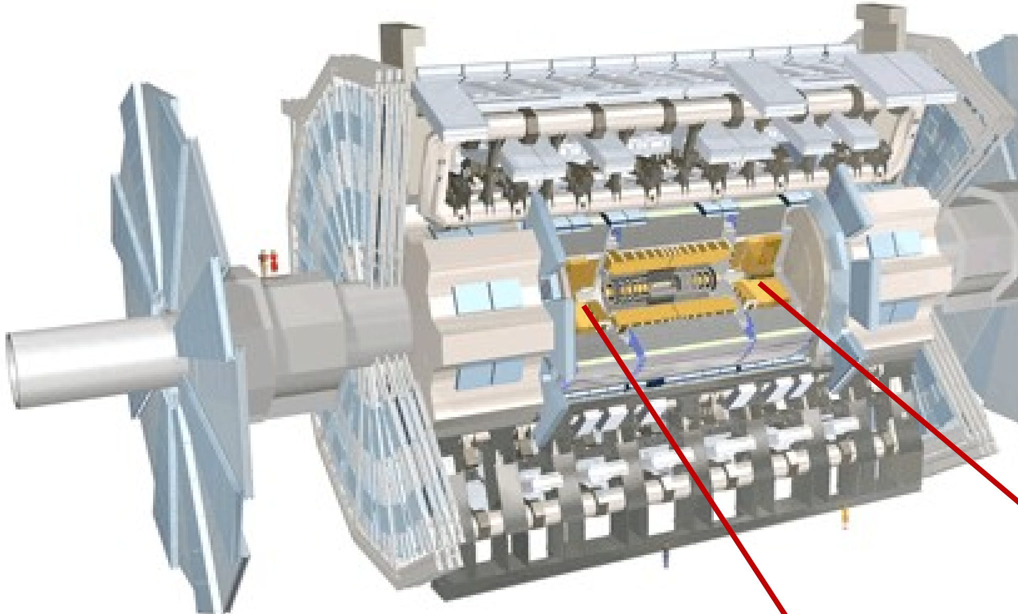
$$\frac{dN}{d\phi} = N_0\left(1 + 2v_1\cos\left(\phi - \Psi_1\right) + 2v_2\cos\left(2\left(\phi - \Psi_2\right)\right) + 2v_3\cos\left(3\left(\phi - \Psi_3\right)\right) + \ldots\right)$$

directed flow (v_1) | elliptic flow (v_2) | triangular flow (v_3)

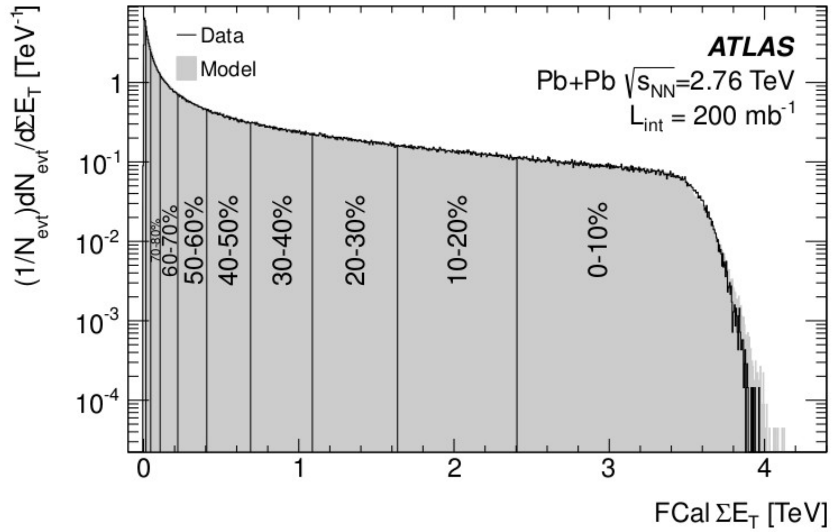
Fourier harmonics $v_n = \langle\cos\left(n\left(\Phi - \Psi_n\right)\right)\rangle$

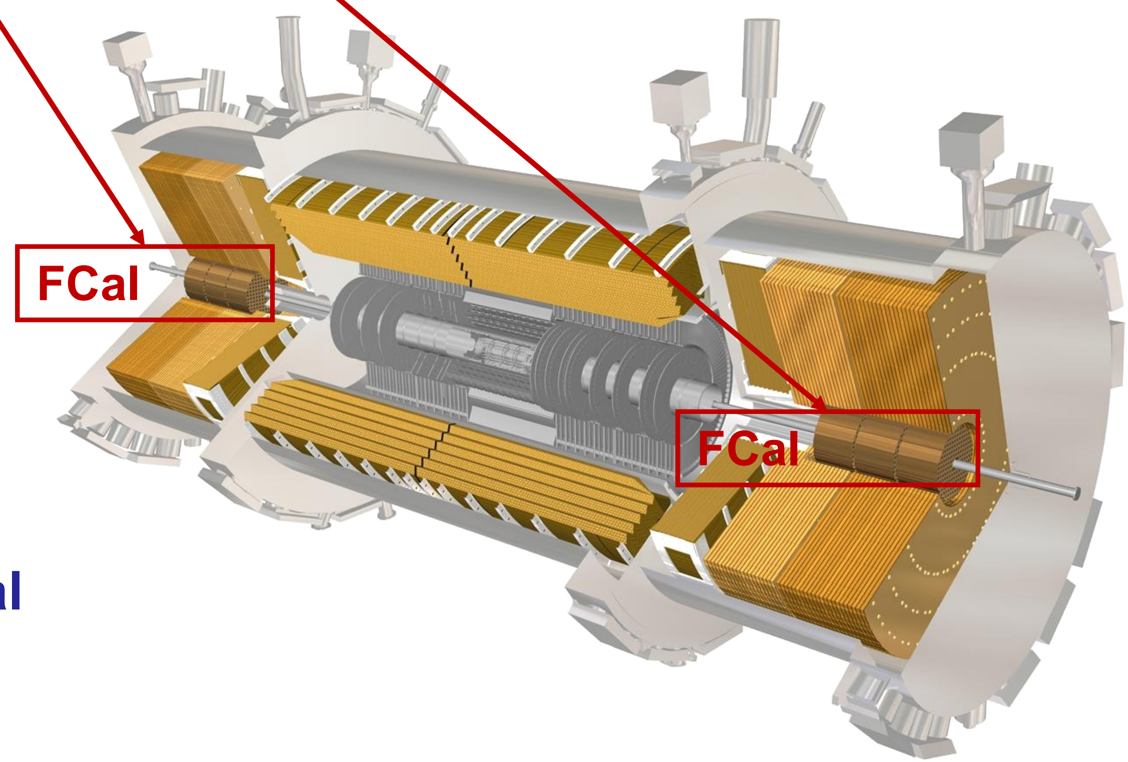
- **Initial shape of the interaction region (v_2 - elliptic flow)**
- **Initial spatial fluctuations of interacting nucleons (higher orders, v_n)**

ATLAS detector



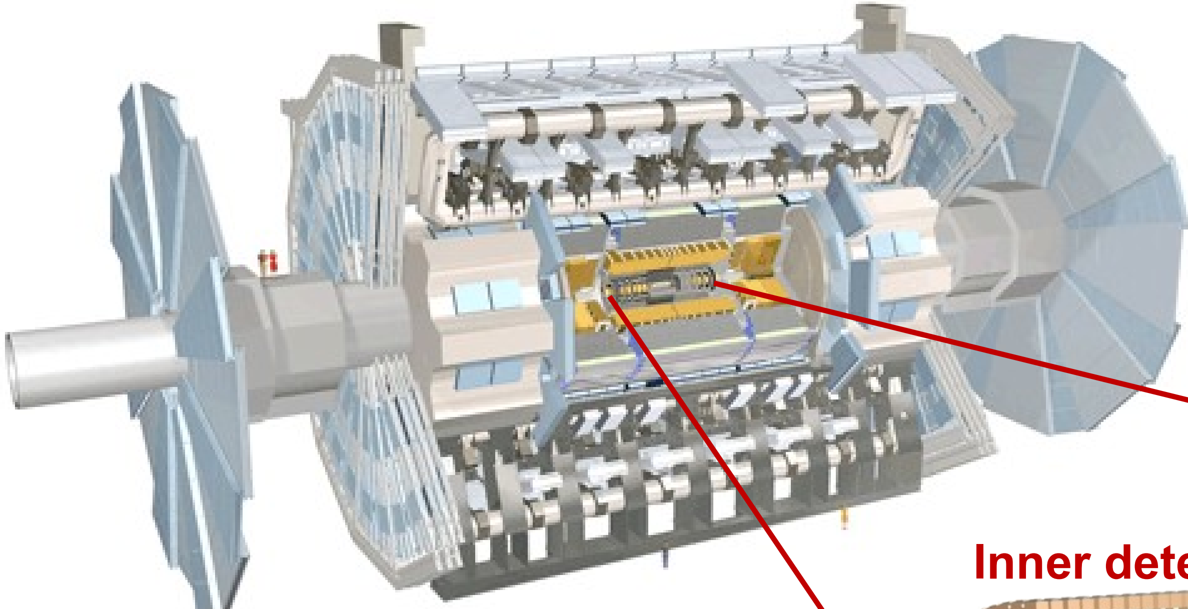
Centrality determination



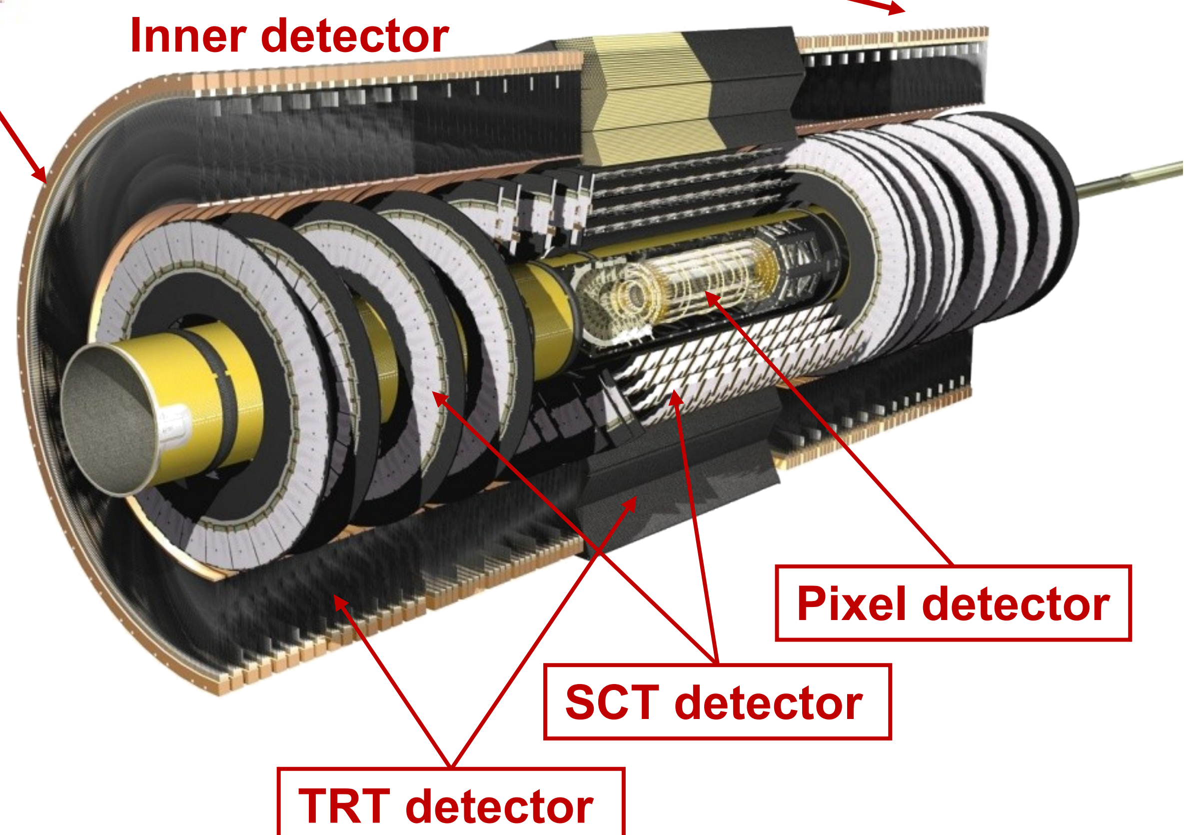


- Energy deposited in entire FCal (3.1<|η|<4.9) is used for centrality determination
- Event plane measurement is based on energy deposition in the first sampling layer of FCal

ATLAS detector



The ATLAS Inner Detector is a composite tracking system consisting of silicon and gaseous detectors.



Three tracking techniques:

- **ID tracks:**
  $p_T > 0.5$ GeV
- **Pixel tracks:**
  $p_T > 0.1$ GeV
- **Two point pixel tracklets (B-off):**
  $p_T > 0.03$ GeV

Integrated v_2 down to very low p_T

- **Integrated v_2 flow harmonic measured using the EP method**
- **Reaching low p_T reduces uncertainty on the integrated v_2**

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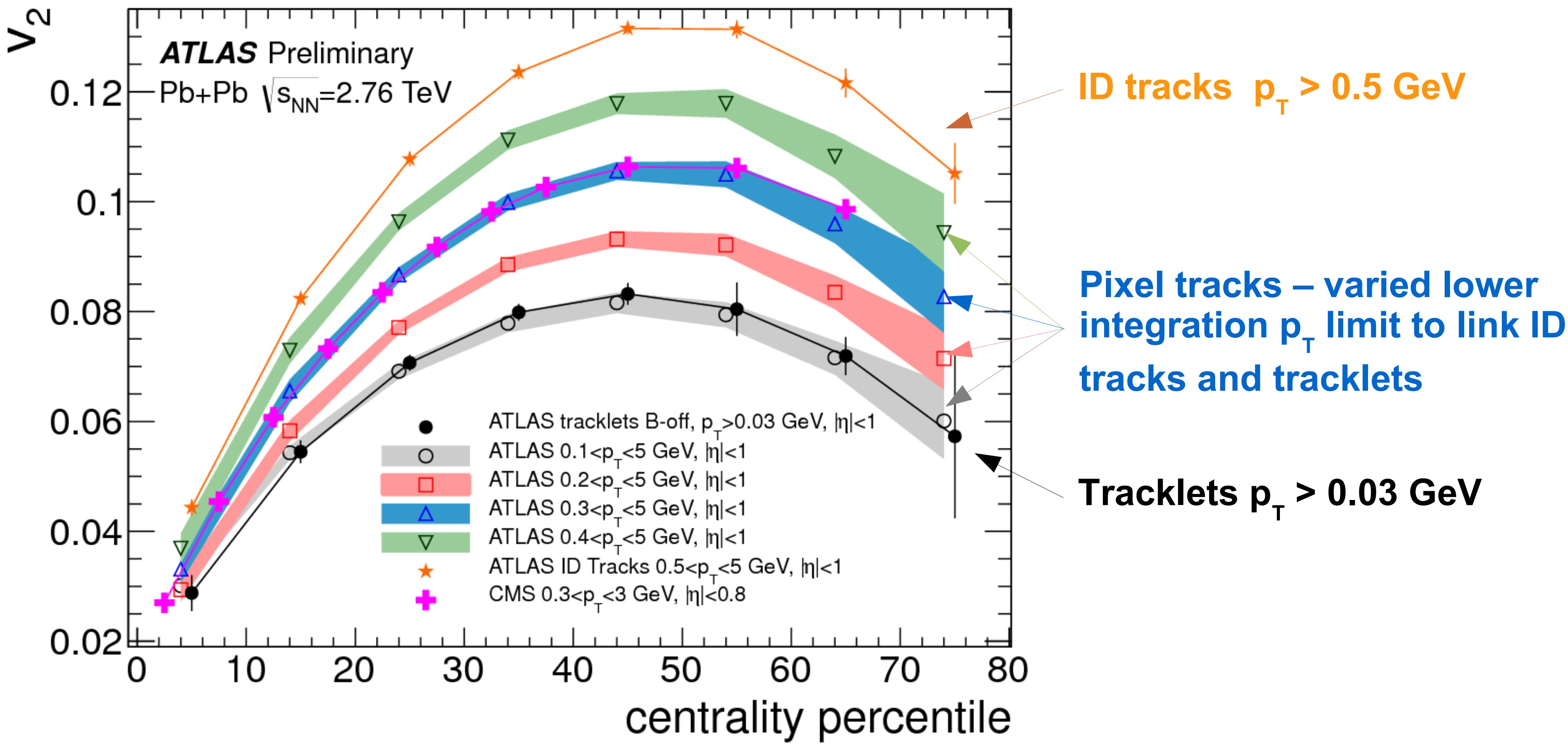
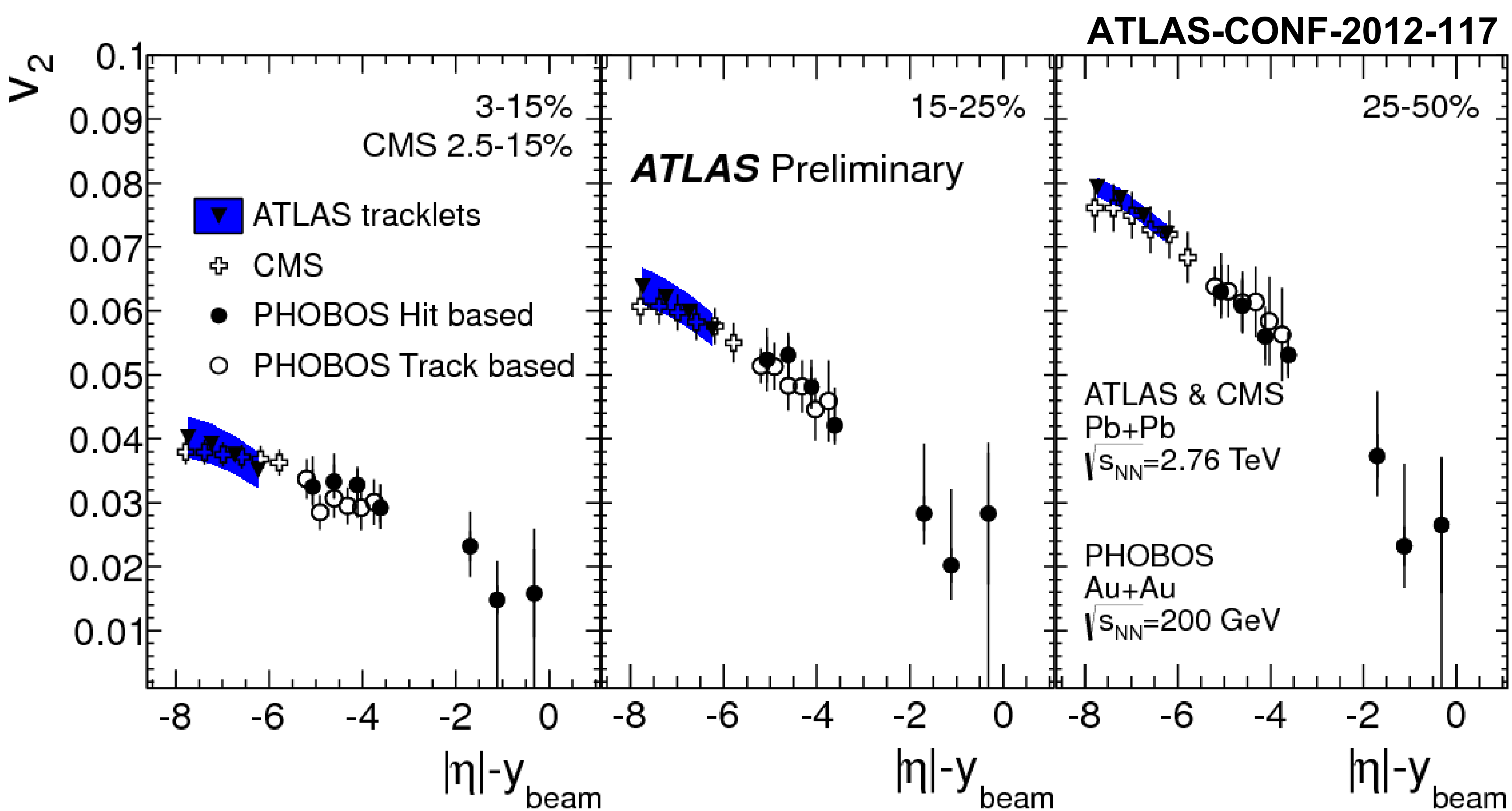


Pseudorapidity dependence of integrated v_2

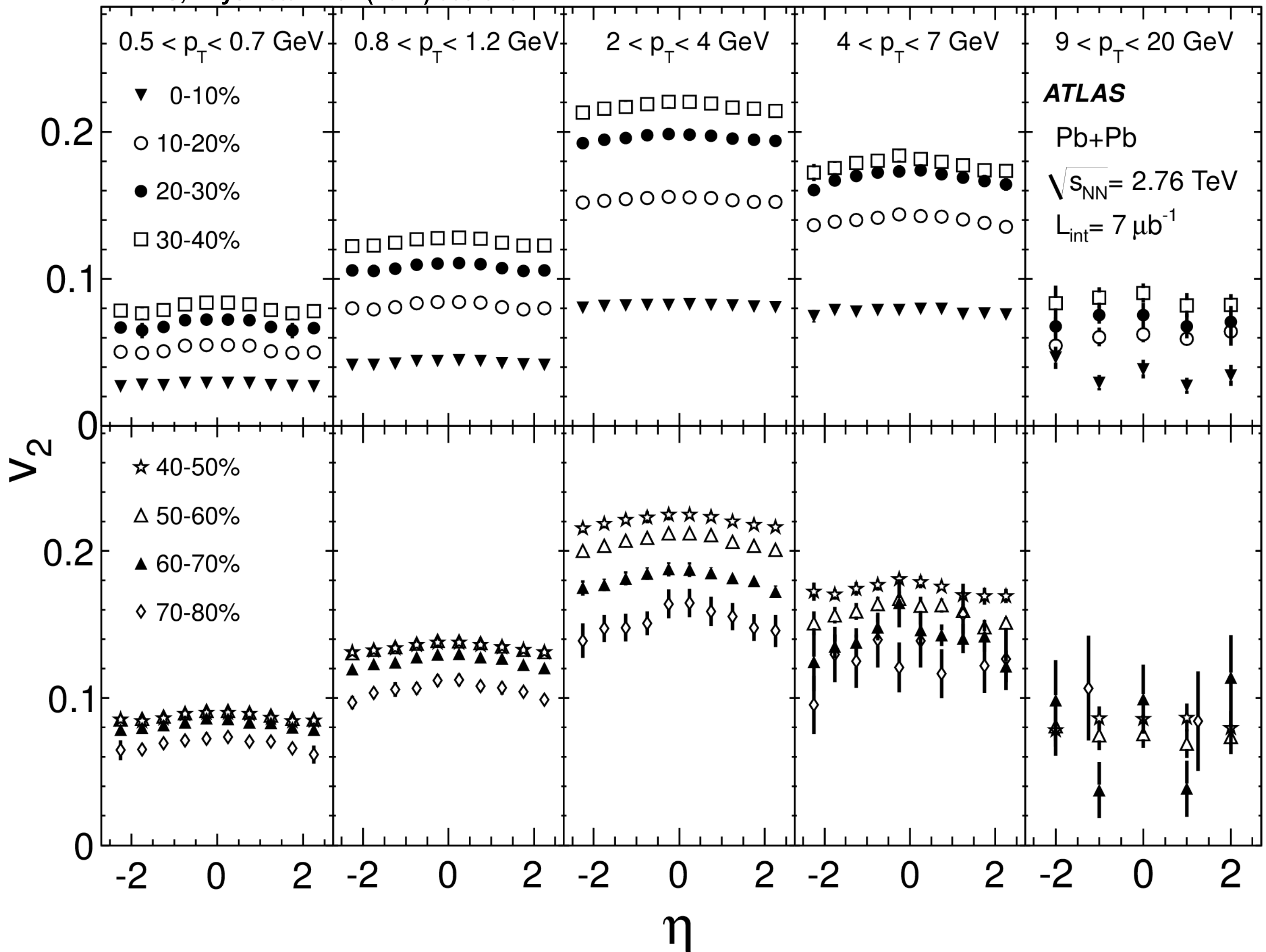
- $v_2(\eta)$ integrated over p_T, shows weak pseudorapidity dependence

- $v_2(\eta)$ scaling with $\eta - y_{beam}$ consistent with the trend observed by PHOBOS at RHIC (Phys.Rev.C72:051901,2005)



Pseudorapidity dependence of v_2

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



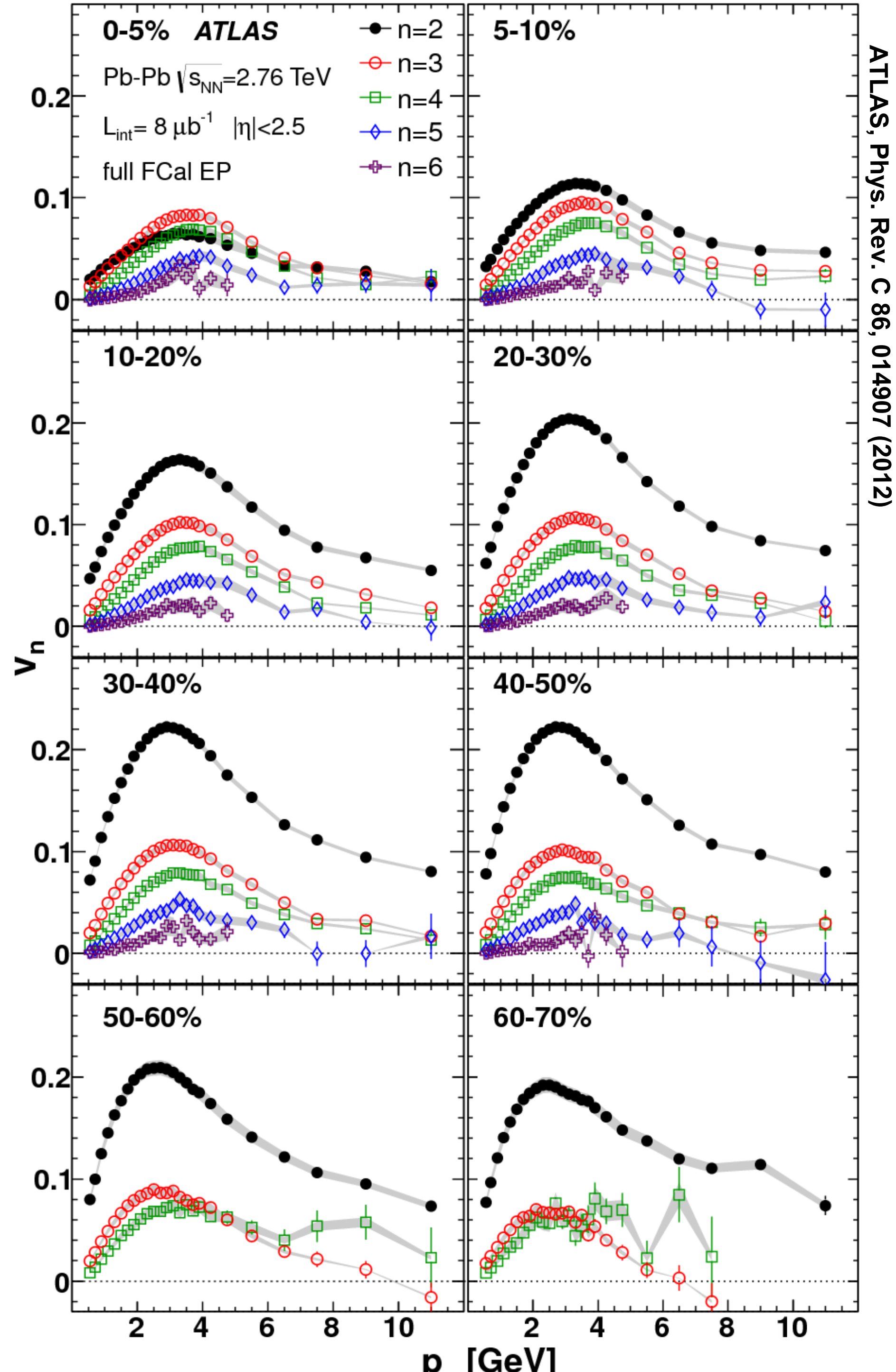
- **No substantial η dependence for any p_T or centrality interval is observed (v_2 drops by about 5–10% over the range |η|=0–2.4)**
- **Different from PHOBOS measurements at RHIC in which v_2 decreases by ~30% within the same η range** (PHOBOS Phys. Rev. C72 (2005) 051901)

Higher order flow harmonics - p_T dependence

- The p_T-dependence of v_2-v_6 for several centrality selections

- Similar p_T-dependence for all harmonics

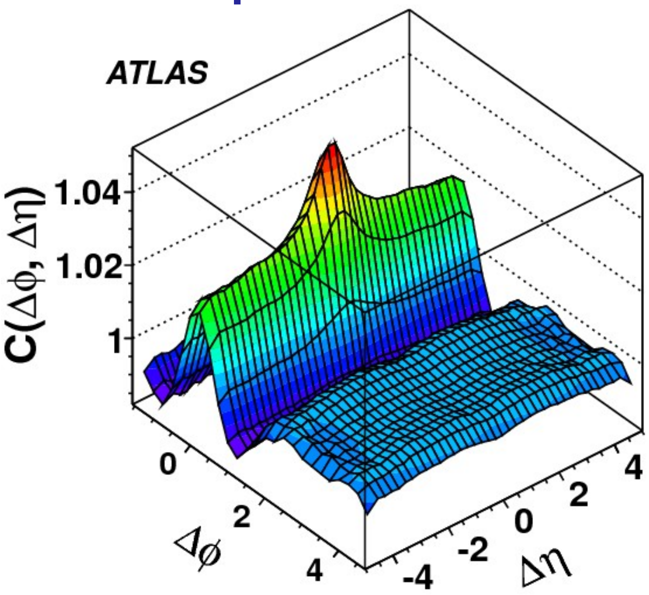
- v_n generally decreases for larger n, except in the most central events:
  - v_3 dominates in p_T range ~2-7 GeV
  - v_4>v_2 in p_T range ~3-5 GeV



Two-particle correlation method

The two-particle correlation function: $C(\Delta\phi,\Delta\eta)=\frac{N_s(\Delta\phi,\Delta\eta)}{N_m(\Delta\phi,\Delta\eta)}$

N_s – same event pairs
N_m – mixed event pairs



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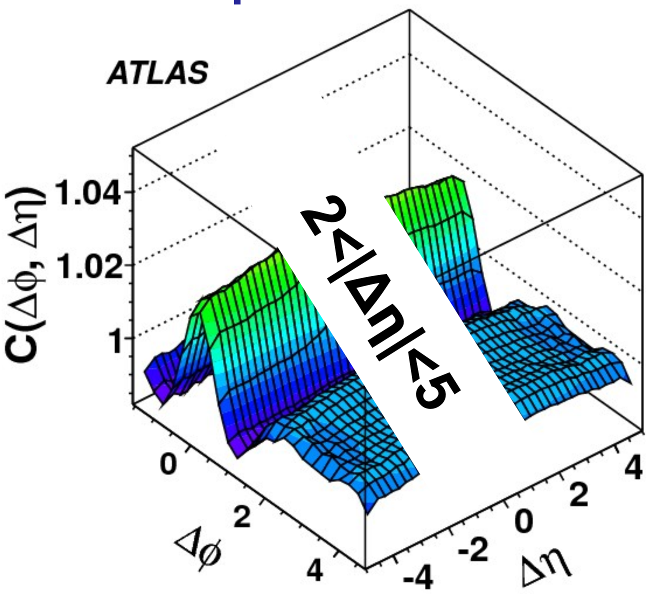
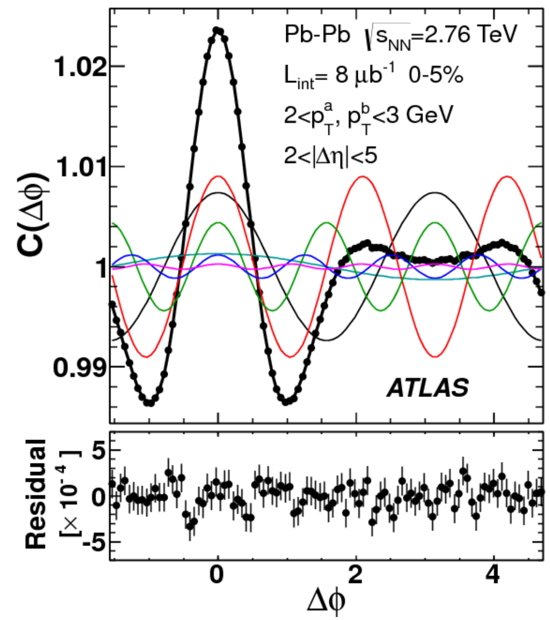


Projected onto Δφ

1D correlation function

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



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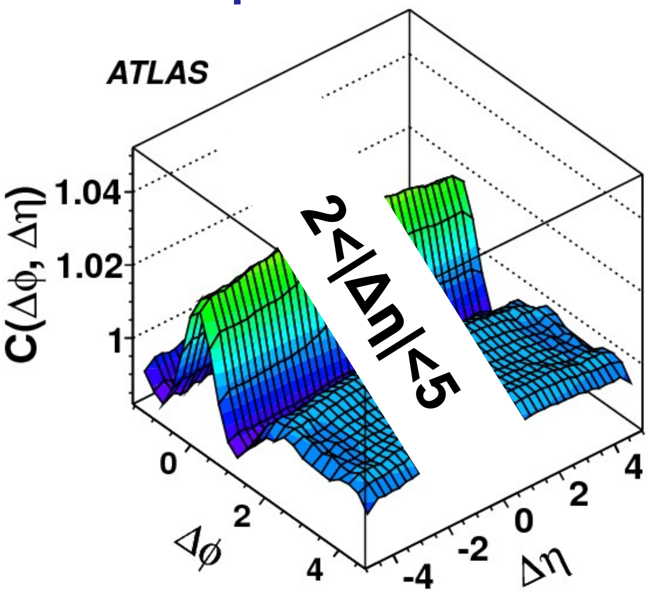

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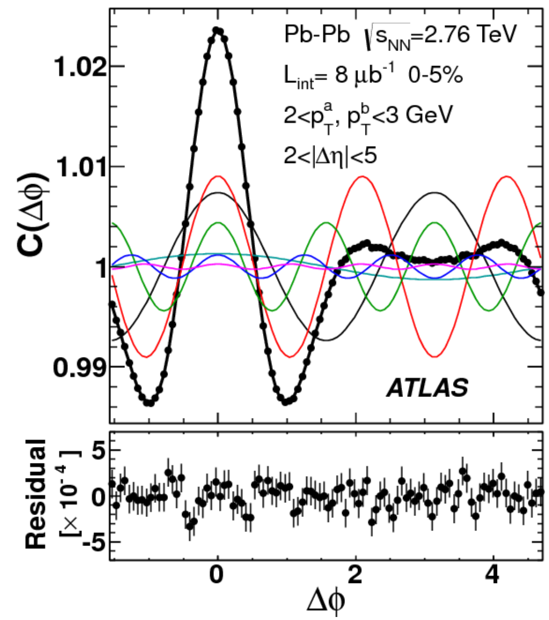
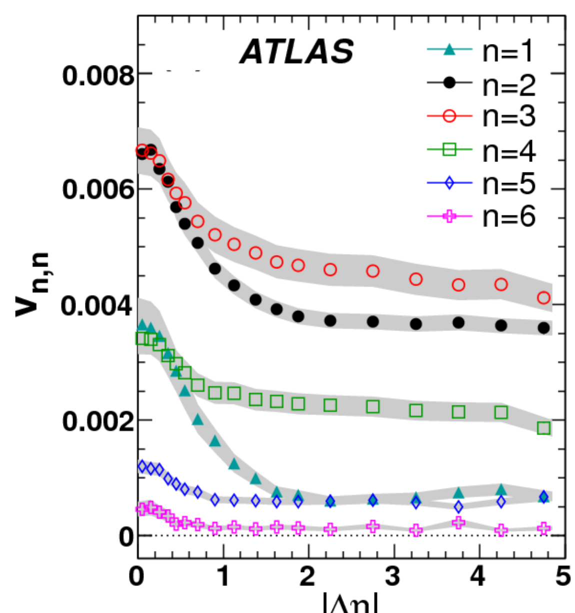


$v_{n,n}$ are calculated via Discrete Fourier Transform (DFT) :

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



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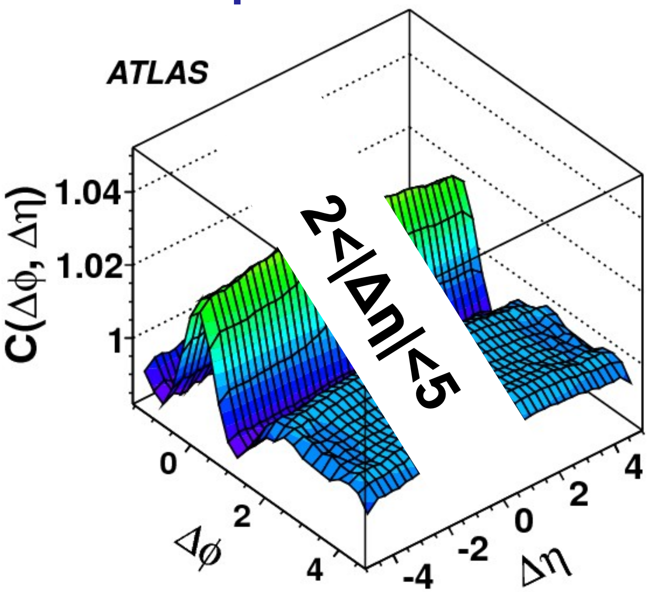

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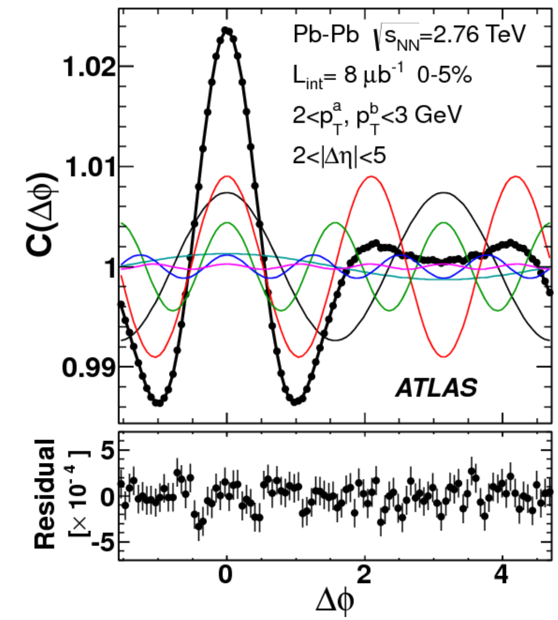

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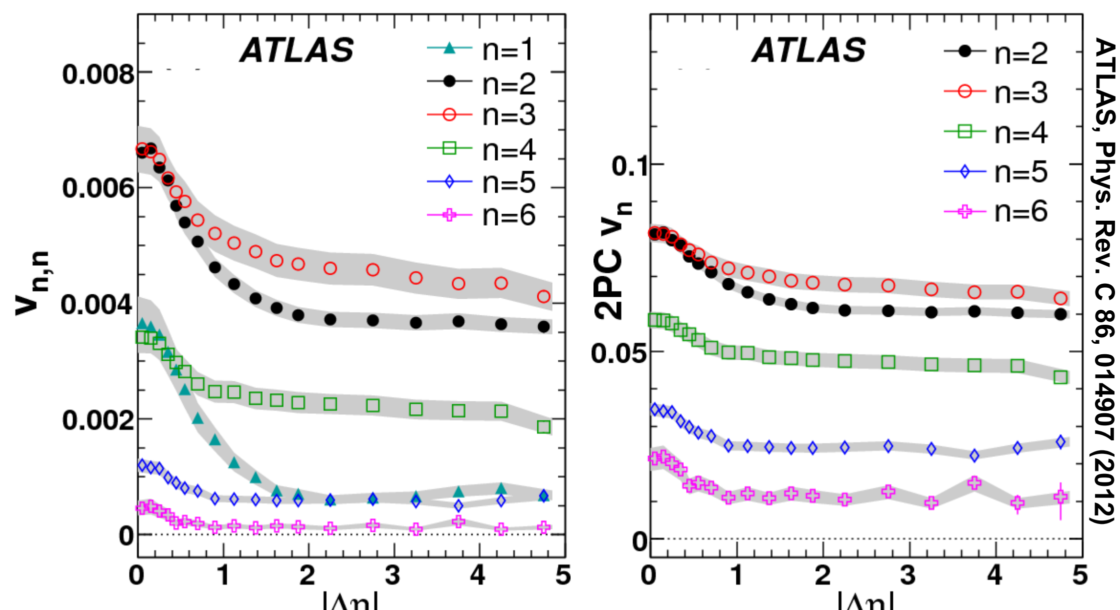
It is expected that for flow modulations:

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

And for "fixed-pT" correlations:

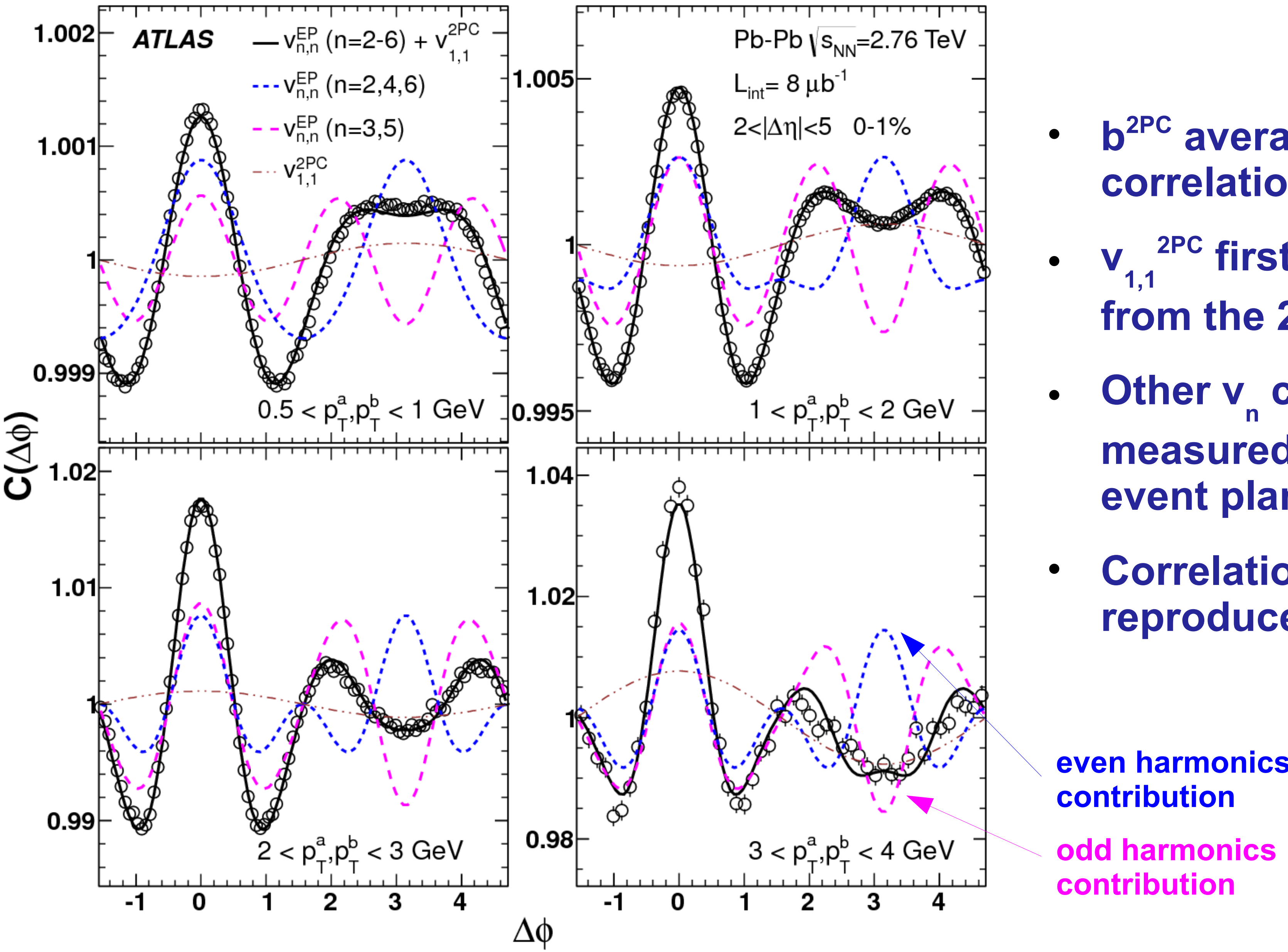
$$v_n=\sqrt{v_{n,n}}$$



Two particle correlation vs EP results

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

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



- b^{2PC} average of the correlation function
- $v_{1,1}^{2PC}$ first harmonic from the 2PC analysis
- Other v_n components measured with the event plane method
- Correlation function reproduced very well

Elliptic flow with cumulant method

• **Elliptic flow harmonics of charged particles obtained with the cumulant generating function method**
(N. Borghini, P.M.Dinh and J.Y. Ollitrault Phys.Rev.C 64 (2001) 054901)

• **v_2 measurement (e.g. with the Event Plane method) is distorted by non-flow effects (not related to initial geometry)**

• **Cumulants of multi-particle (>2) correlations eliminates non flow contributions**

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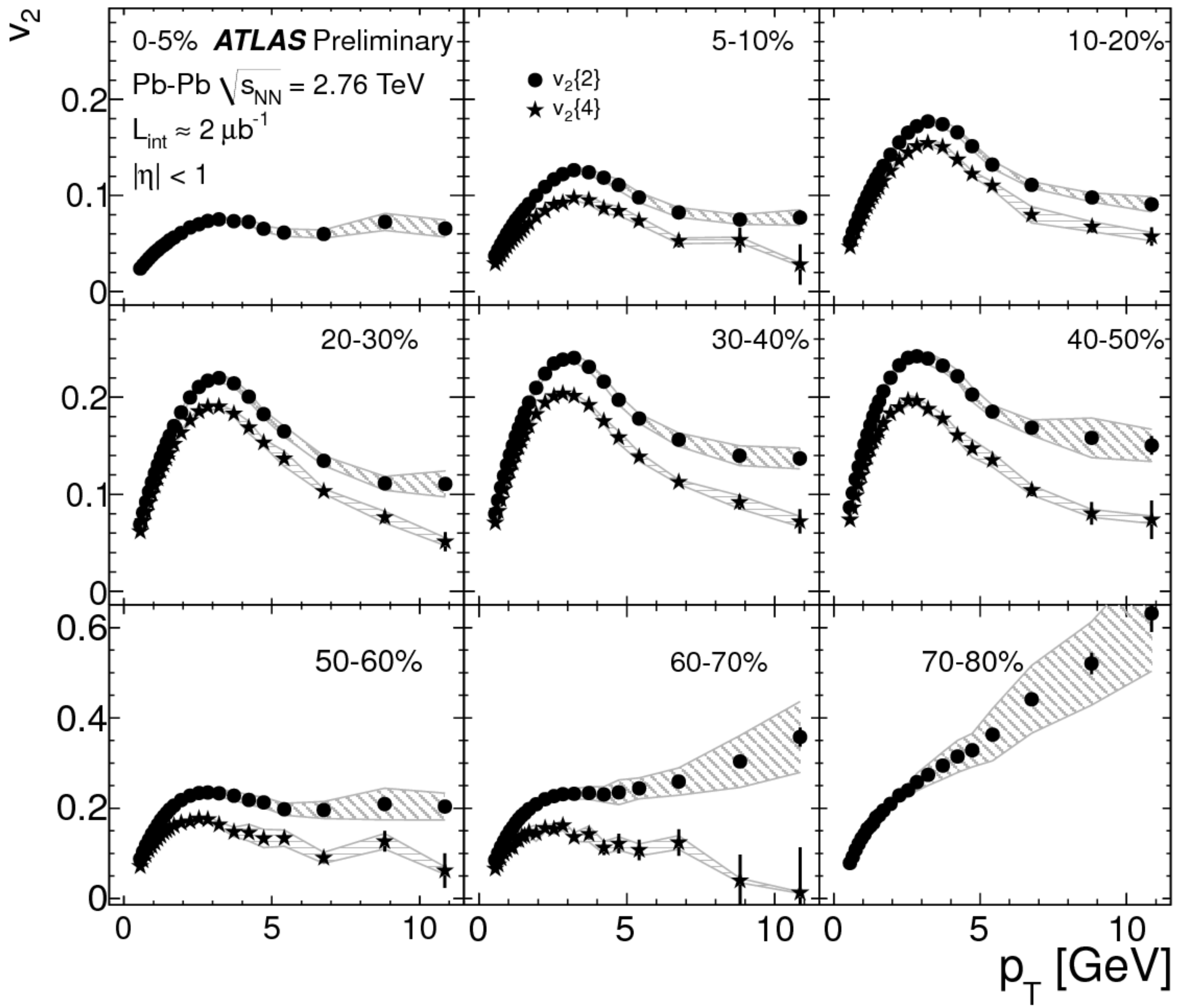

Comparison of $v_2\{2\}$, $v_2\{4\}$ and $v_2\{EP\}$

- **Strong reduction of v_2 is observed by using four-particle cumulants**
- **$v_2\{4\}$ consistent between ATLAS, ALICE and CMS**
- **The $v_2\{EP\}$ lies between $v_2\{2\}$ and $v_2\{4\}$**

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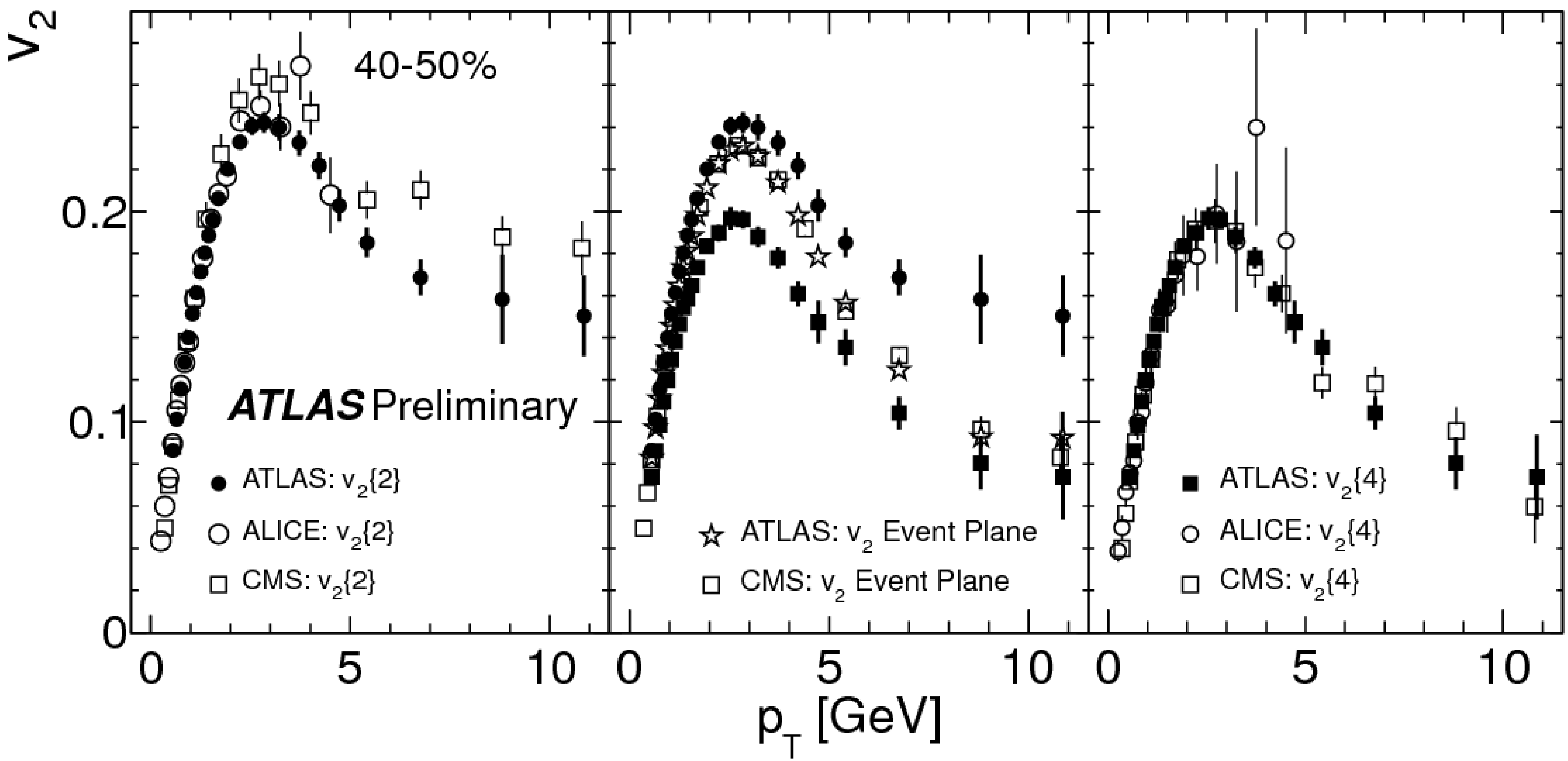
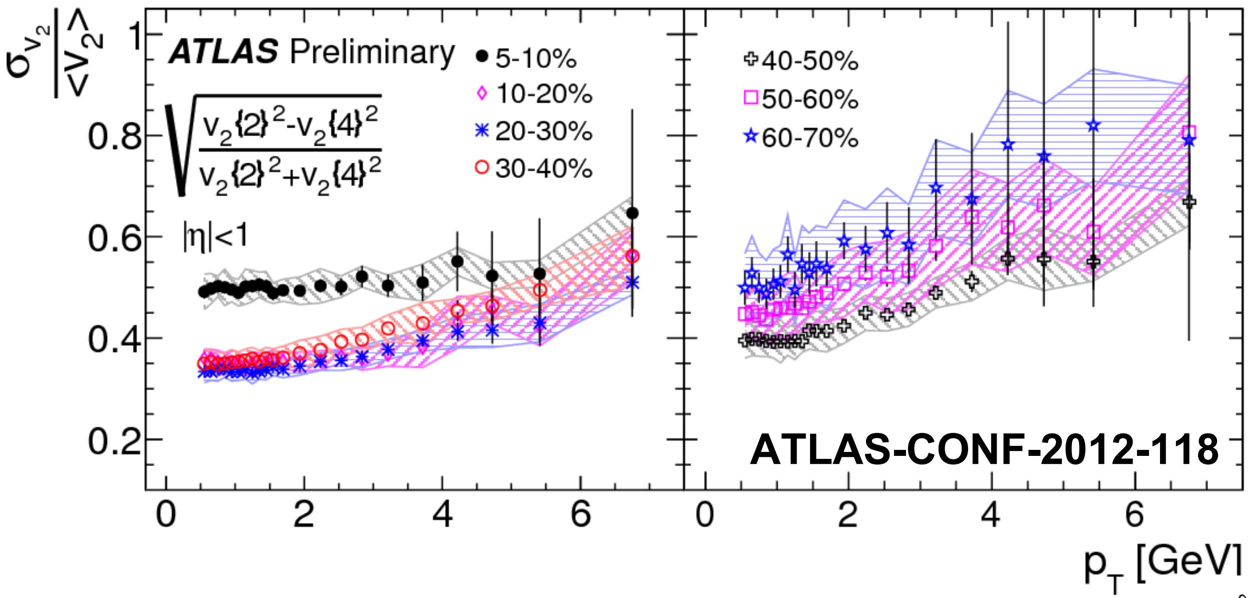


Elliptic flow fluctuations (cumulant method)

- **Cumulant method provides a measure of elliptic flow event–by-event fluctuations** (N. Borghini, P.M.Dinh and J.Y. Ollitrault Phys.Rev. C64 (2001) 054901)



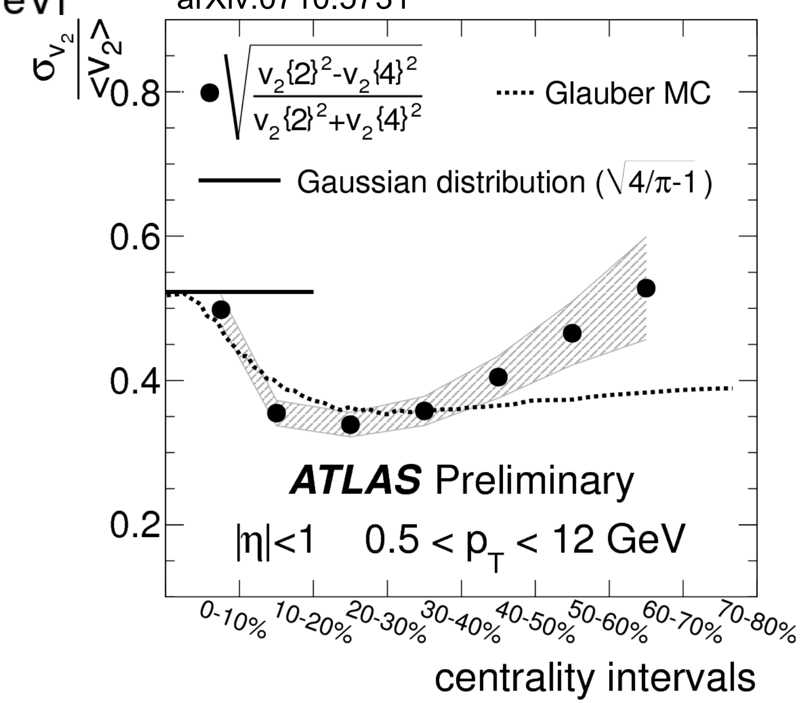
$$\frac{\sigma_2}{< v_2 >} \approx \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$$

- **For the 5-10% centrality fluctuations independent of p_T**

- **For less central collisions $\sigma_2/<v_2>$ increases with p_T**

- **$\sigma_2/<v_2>$ agrees with the Glauber MC model prediction with the except of peripheral collisions**

W. Broniowski, M. Rybczyński, P. Bożek
arXiv:0710.5731

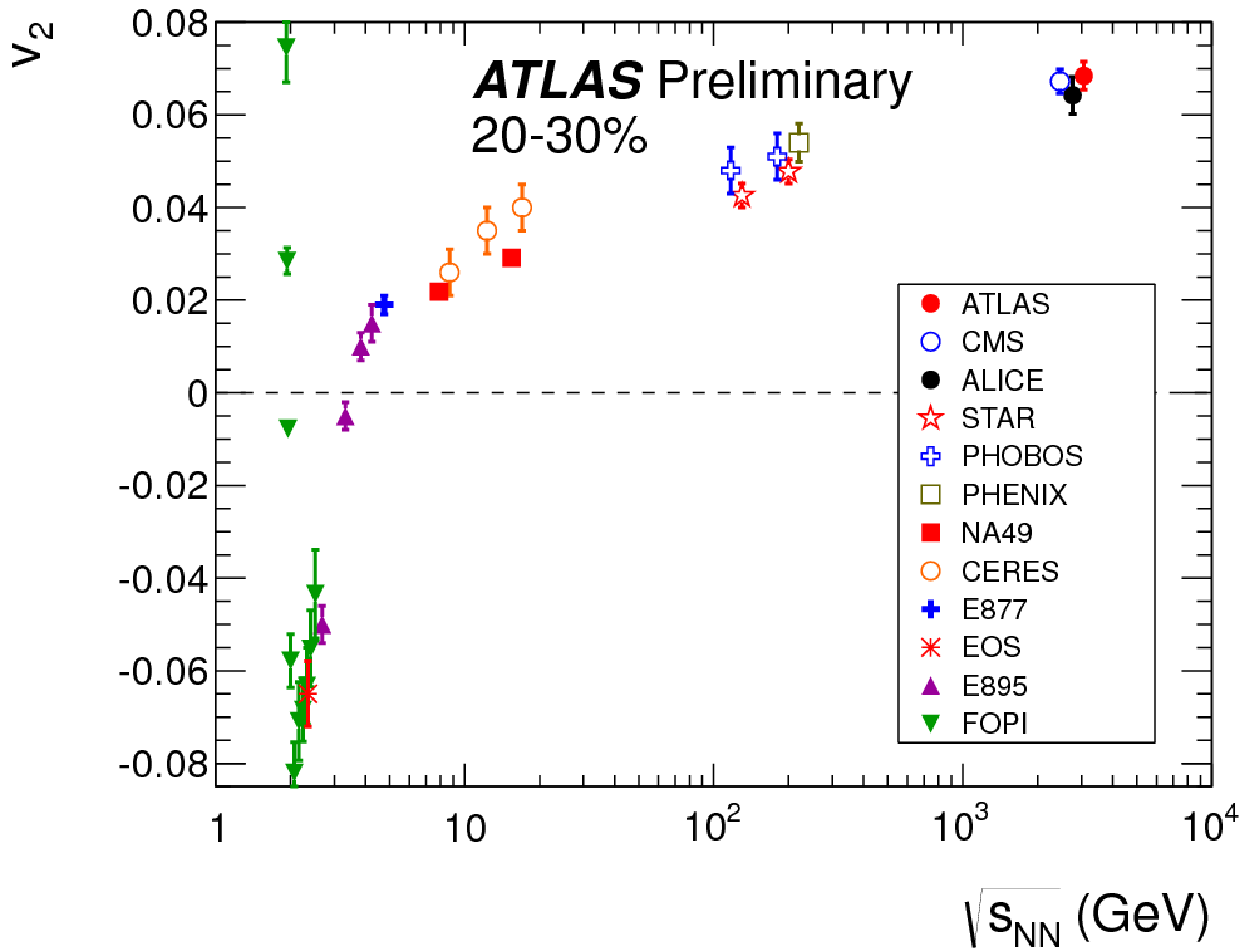


Summary

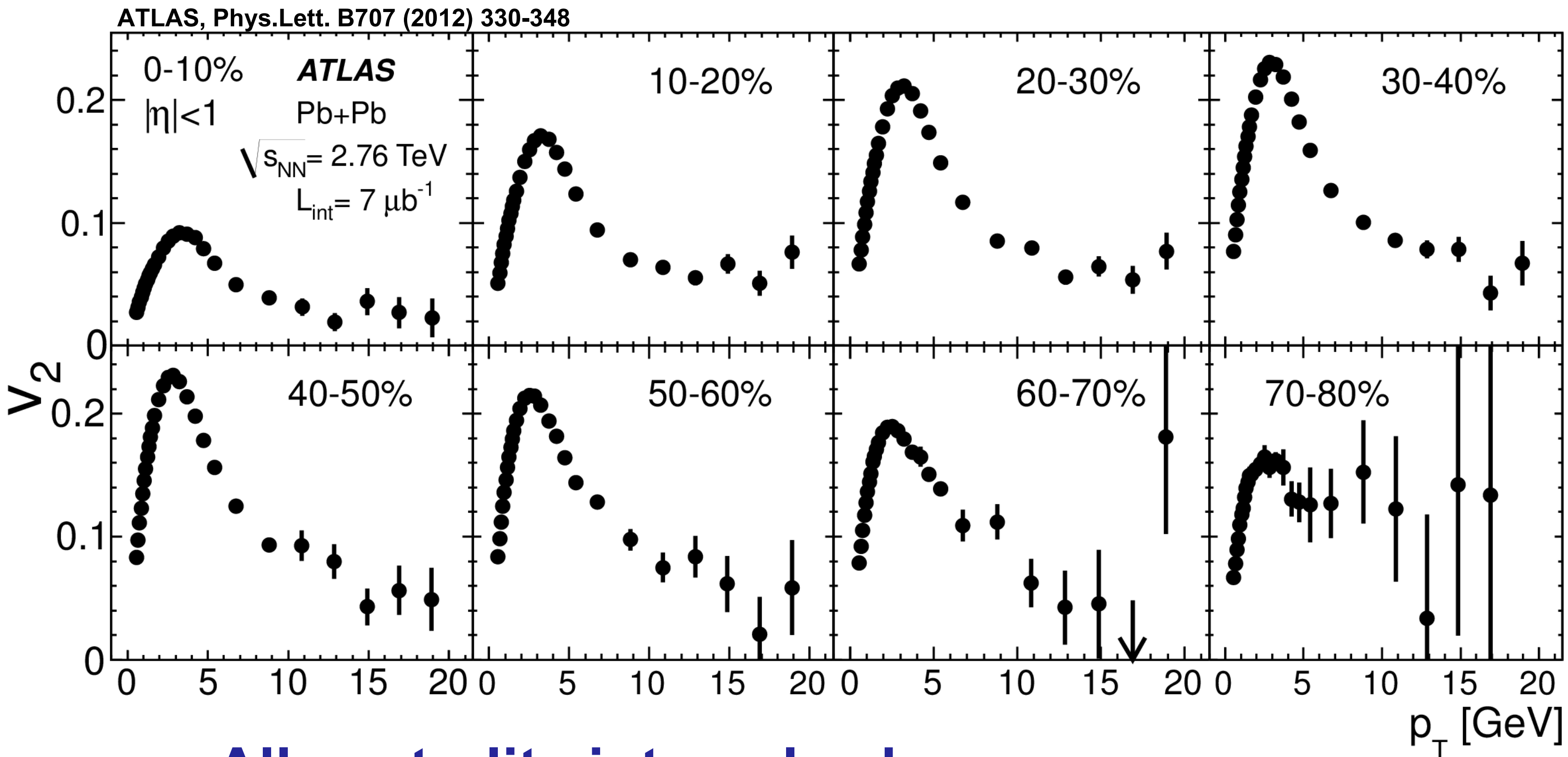
- ATLAS measured integrated v_2 flow harmonic reaching very low p_T
- Differential v_2 and higher order flow harmonics were measured with various methods in wide p_T, η and centrality range
- $v_n(p_T)$ shows the same trends
  - rise up to ~3 GeV
  - decrease within 3-8 GeV
  - varies weakly at high p_T
- $v_n(\eta)$ remains approximately constant
- Relative fluctuations of elliptic flow from 2- and 4-particle cumulants are consistent with the Glauber MC model

Backup slides

Integrated v_2



p_T dependence of the v_2 of charged particles

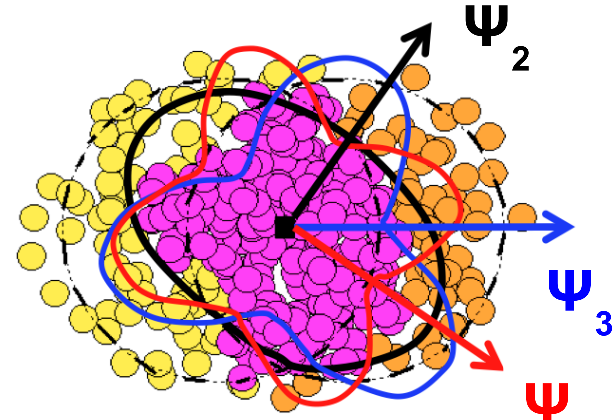


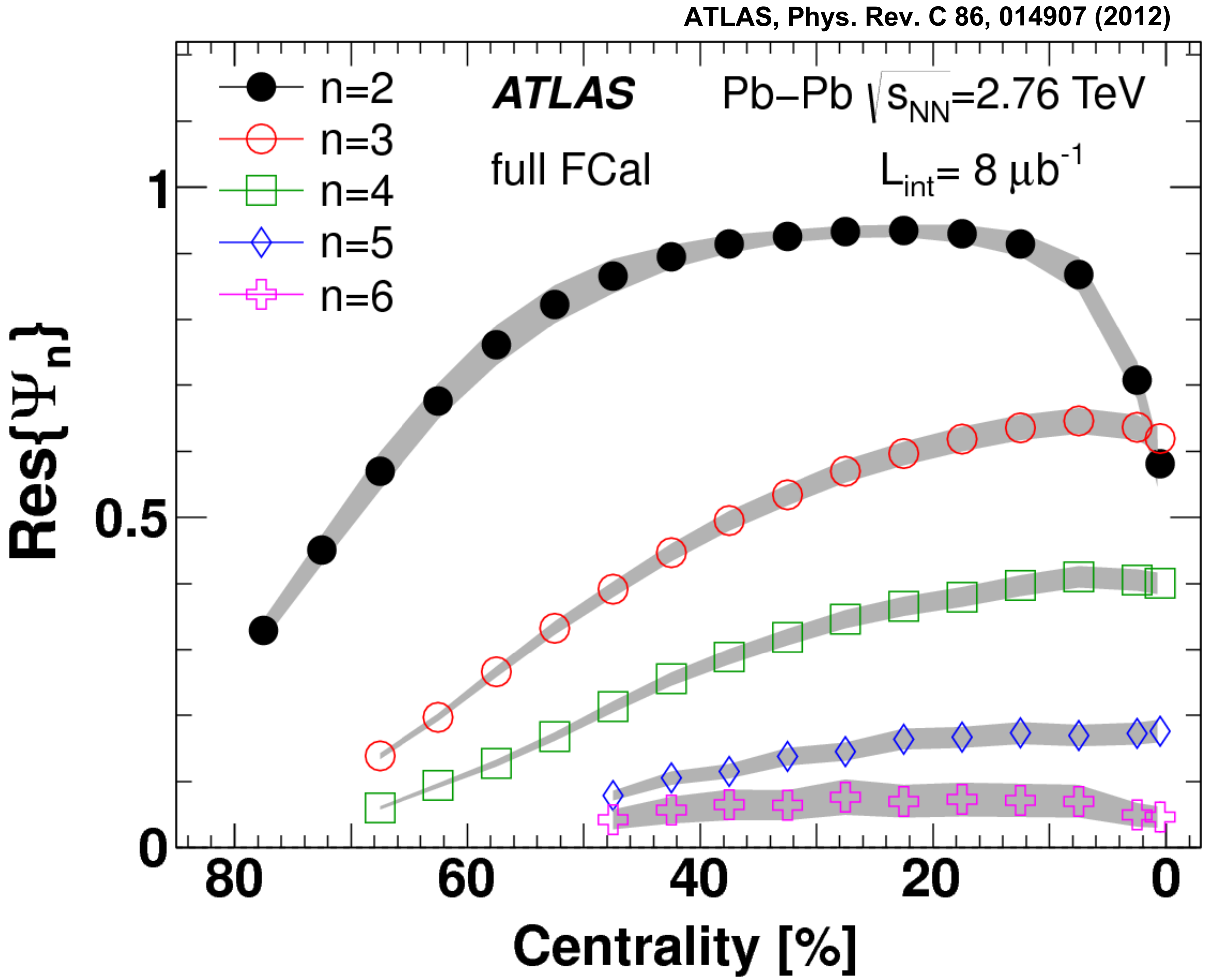
- **All centrality intervals shows:**
  - **Rapid rise in $v_2(p_T)$ up to p_T ~ 3 GeV**
  - **Decrease out to 7-8 GeV**
  - **Weak p_T-dependence above 9-10 GeV**
- **The strongest elliptic flow at LHC is observed in centralities 30-50%**

Event plane determination

- **Reaction plane (Ψ^{RP}) is approximated by event plane (Ψ_n^{EP}) measured in FCal:**

$$\Psi_n^{EP} = \frac{1}{n}\tan^{-1}\frac{\sum_i E_{T,i}^{tower} w_i \sin(n\phi_i)}{\sum_i E_{T,i}^{tower} w_i \cos(n\phi_i)}$$

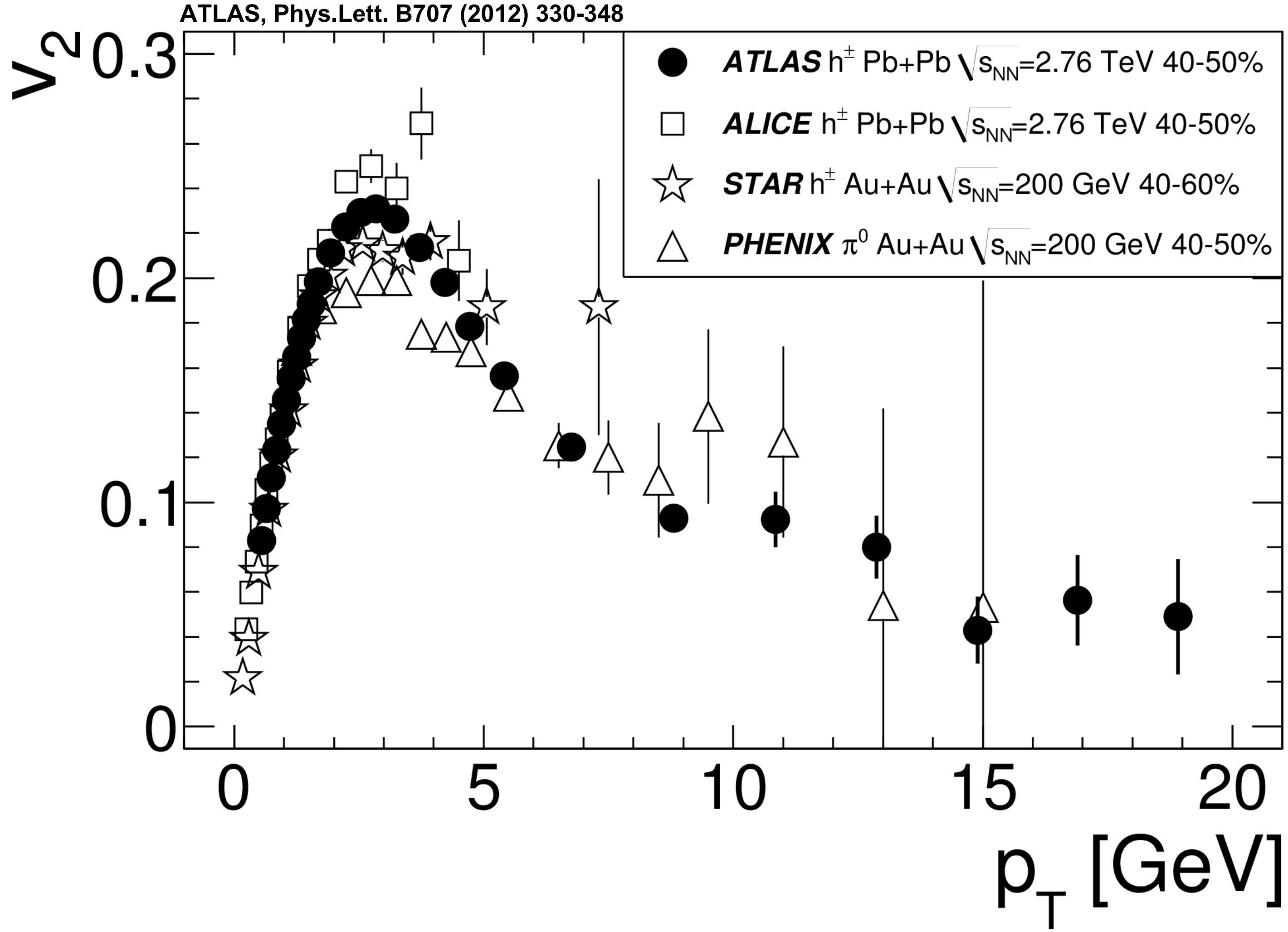




- **The event plane resolution correction factor R is obtained using two-sub event and various tree-subevent method**
- **Significant resolution for harmonics n=2 – 6**
- **Resolution corrected harmonics:**

$$v_n = \langle \cos(n(\Phi - \Psi_n)) \rangle / R$$

Comparison with ALICE and RHIC experiments



- **All data sets are quite consistent for both low and high p_T**

Higher order harmonics scaling

- **Hydrodynamics model suggests scaling $v_4 \sim v_2^2$ (PHENIX PRL 105, 062301 (2010))**
- **The p_T-dependence of the $v_n^{1/n}/v_2^{1/2}$ (n=3-6) ratio for several centrality selections**
- **Weak p_T-dependence of the ratio except 5% most central events**
- **Ratio for n=3 systematically lower than for n=4, 5**

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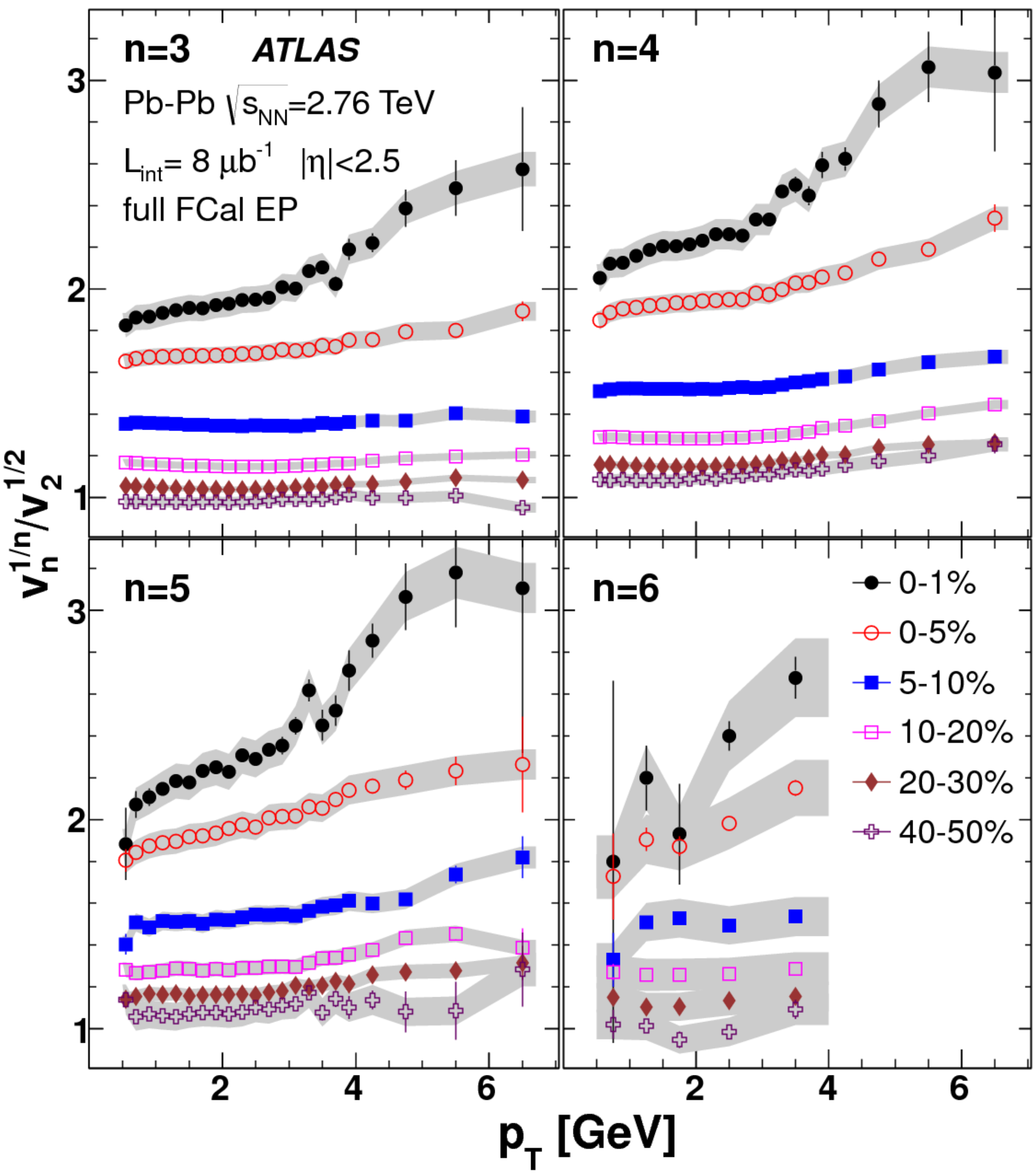

Two particle correlation vs EP results

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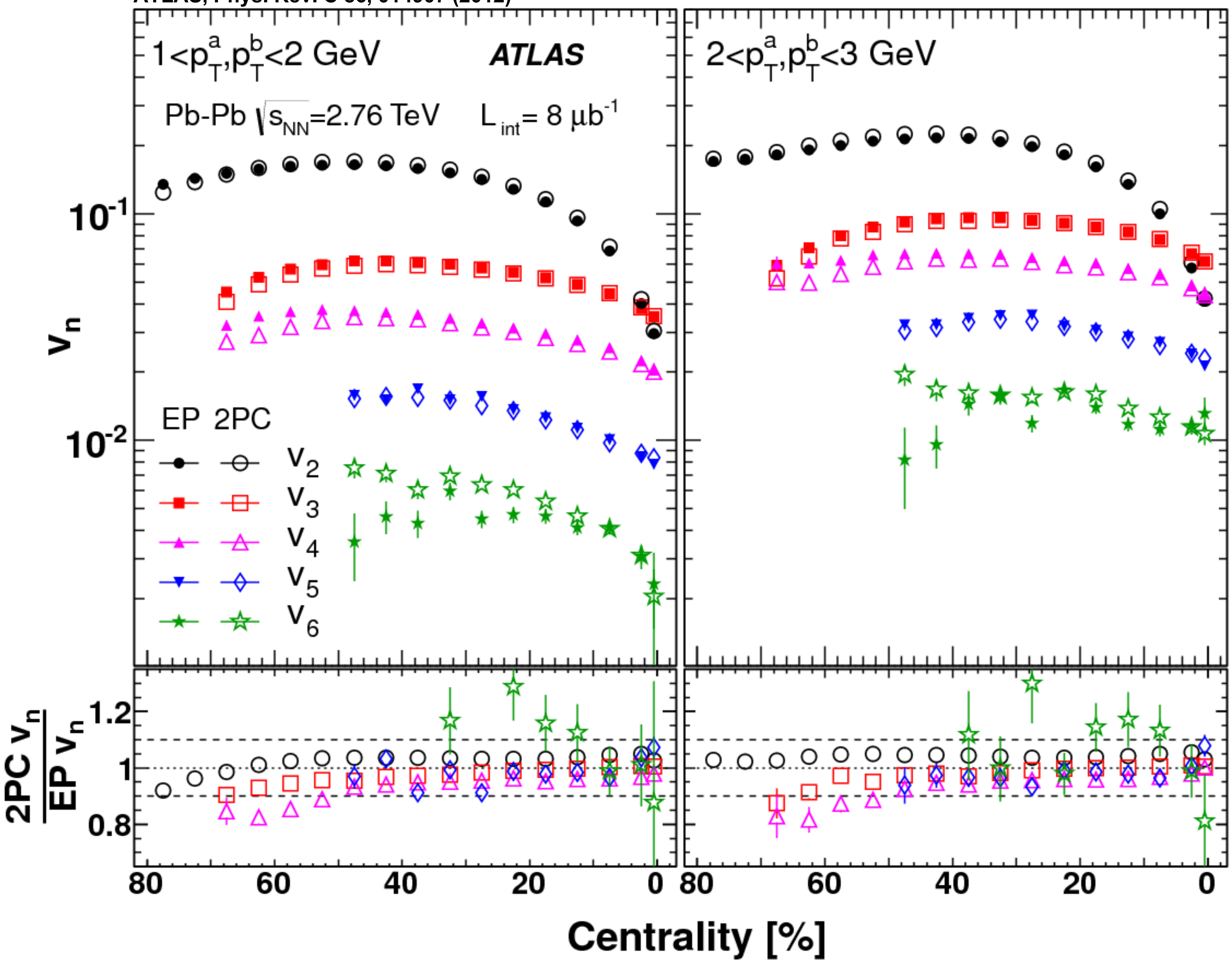

Good agreement between both methods in the selected kinematical range (p_T 1-3 GeV, 2<|η|<5)