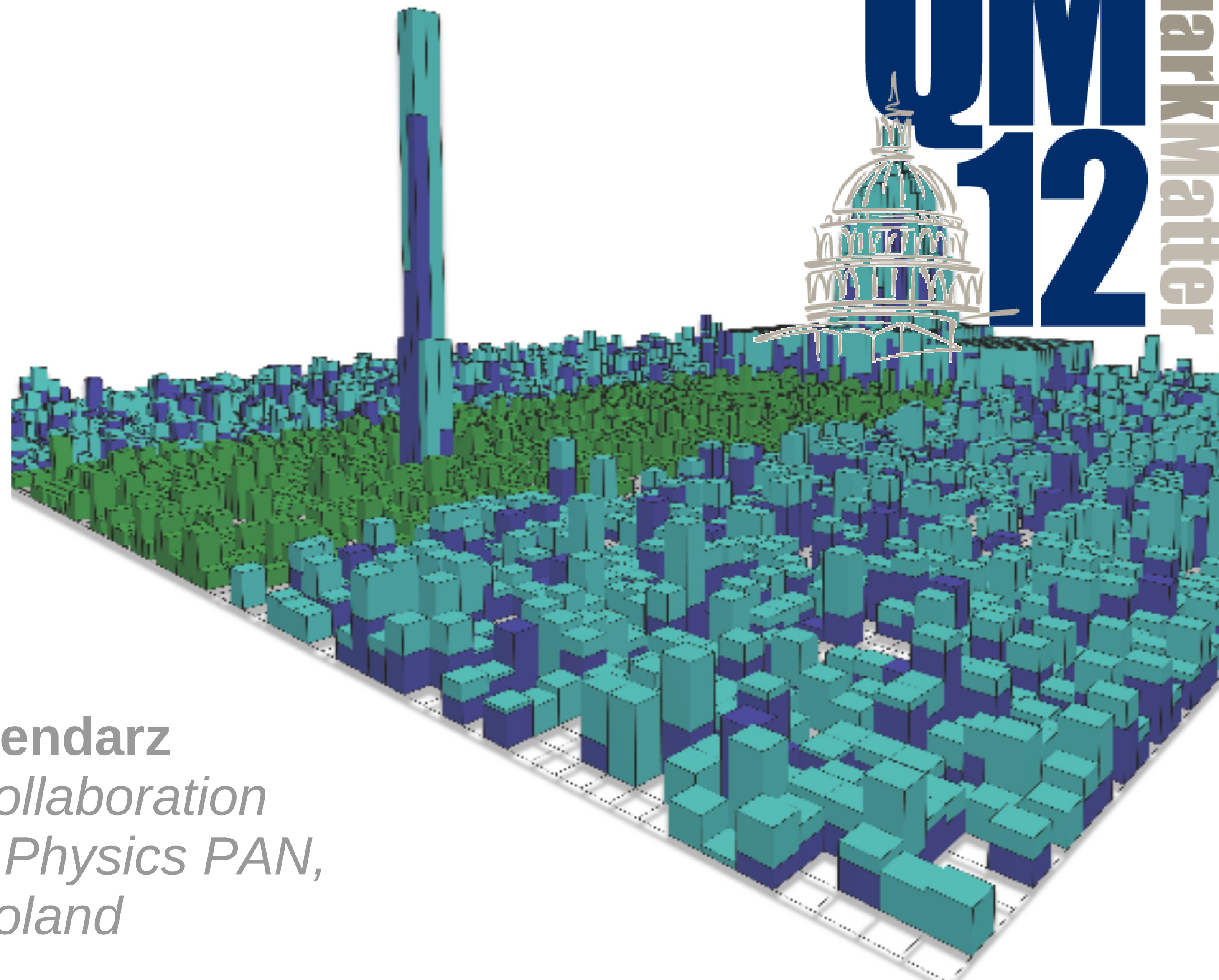
Measurement of elliptic and higher-order harmonics at 2.76 TeV Pb+Pb collisions with the ATLAS detector.



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Why azimuthal anisotropy in AA is interesting?

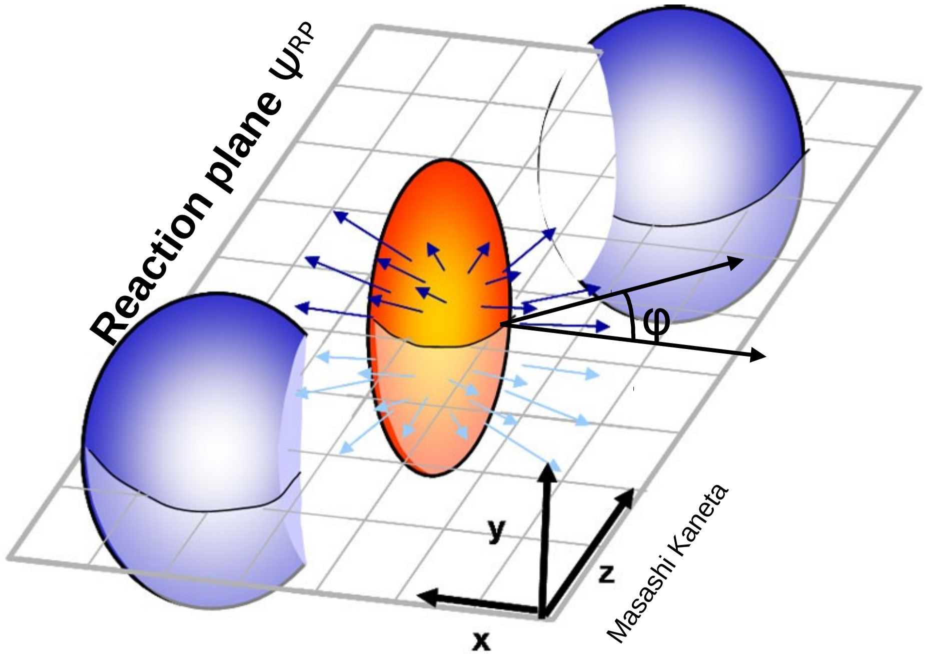
- **Signature of strongly interacting QGP**
- **Sensitive to**
  - Initial shape of the interaction region (v_2)
  - Initial spatial fluctuations of nucleons (higher orders)

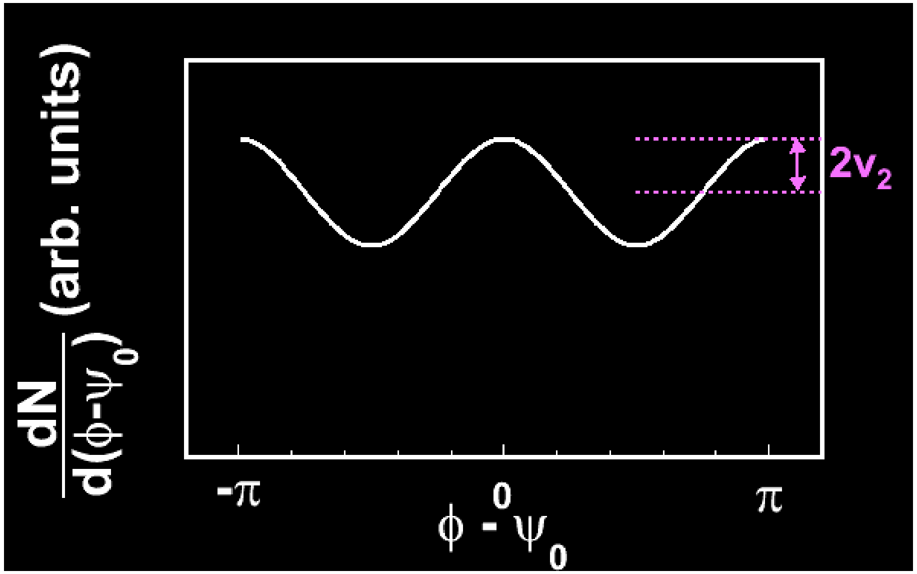
    Related to ridge, Mach cone.
- **Mechanism of particle production**
  - Low p_T (< ~2GeV): hydro expansion (perfect liquid)

    (Nucl. Phys. A Volume 757)
  - Medium p_T (~2-6 GeV): coalescence models

    (Nucl. Phys. A Volume 757, D. Molnar and S. Voloshin, nucl-th/0302014)
  - High p_T: constrain on jet quenching models

Azimuthal anisotropy in heavy ion collisions





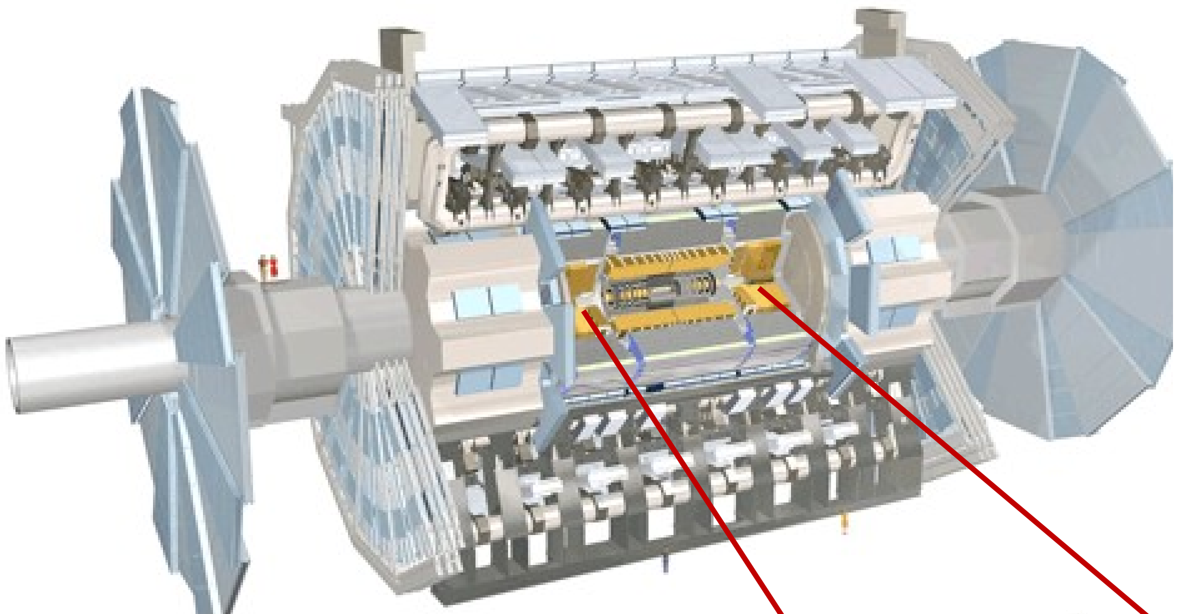
Pressure gradients lead to azimuthal anisotropy

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

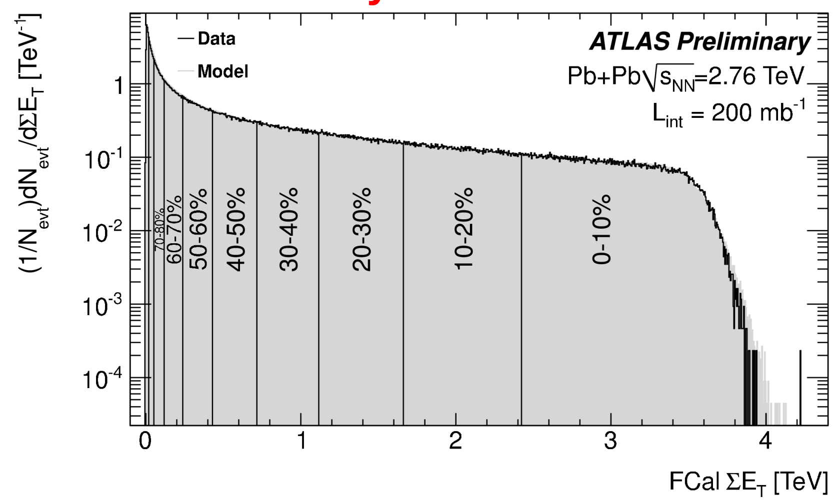
directed flow (v_1) — elliptic flow (v_2) — triangular flow (v_3)

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

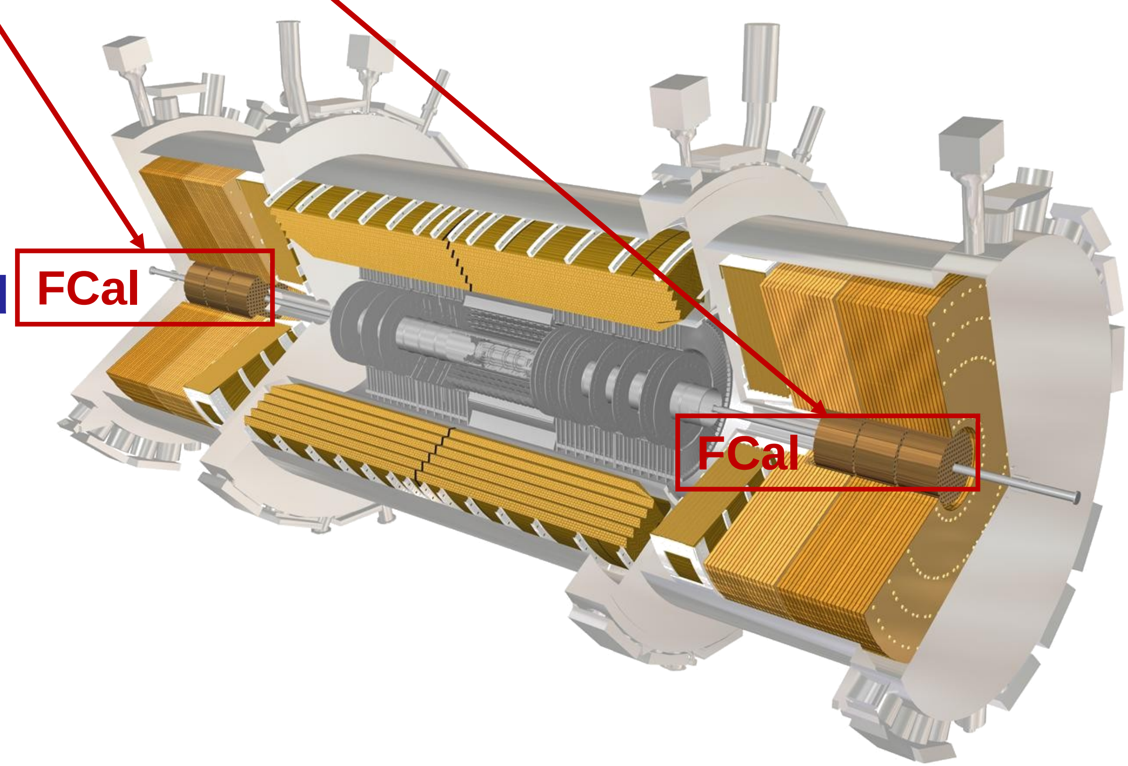
ATLAS detector



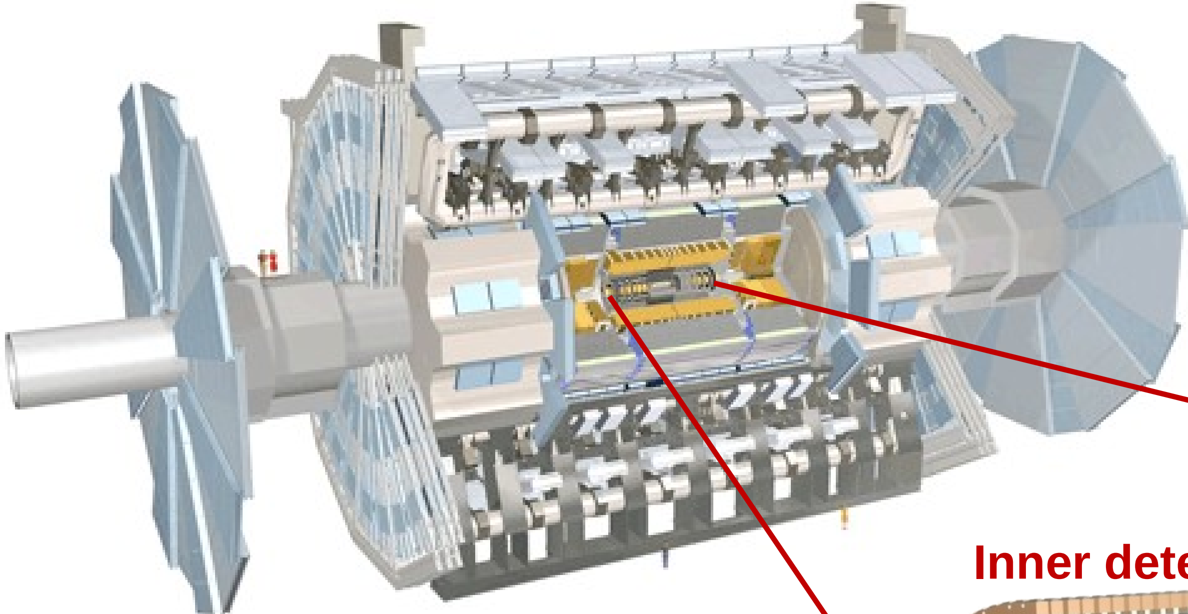
Centrality determination

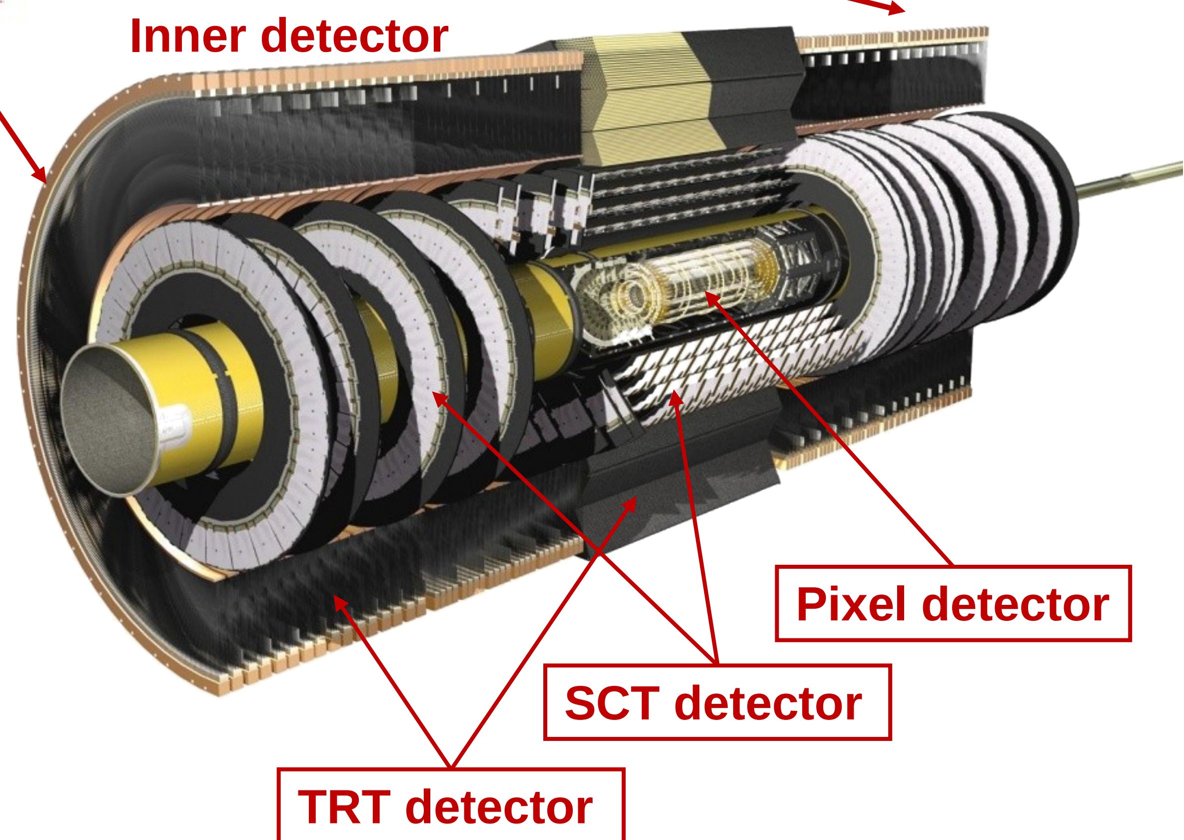


- **Energy deposited in entire FCal is used for centrality determination**
- **Event plane is measured based on energy deposition in the first sampling layer of FCal**
- **Fourier harmonics are reconstructed in inner detector from charged particle tracks :**
    - **p_T > 0.5 GeV**
    - **$|\eta|$<2.5**



ATLAS detector





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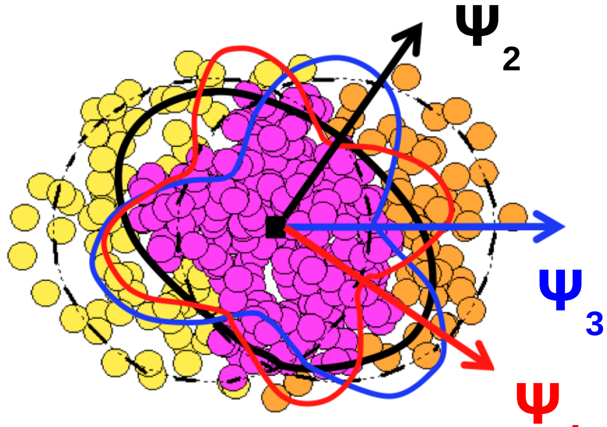
  - **p_T > 0.5 GeV**
  - **$|\eta|<2.5$**

Event plane determination

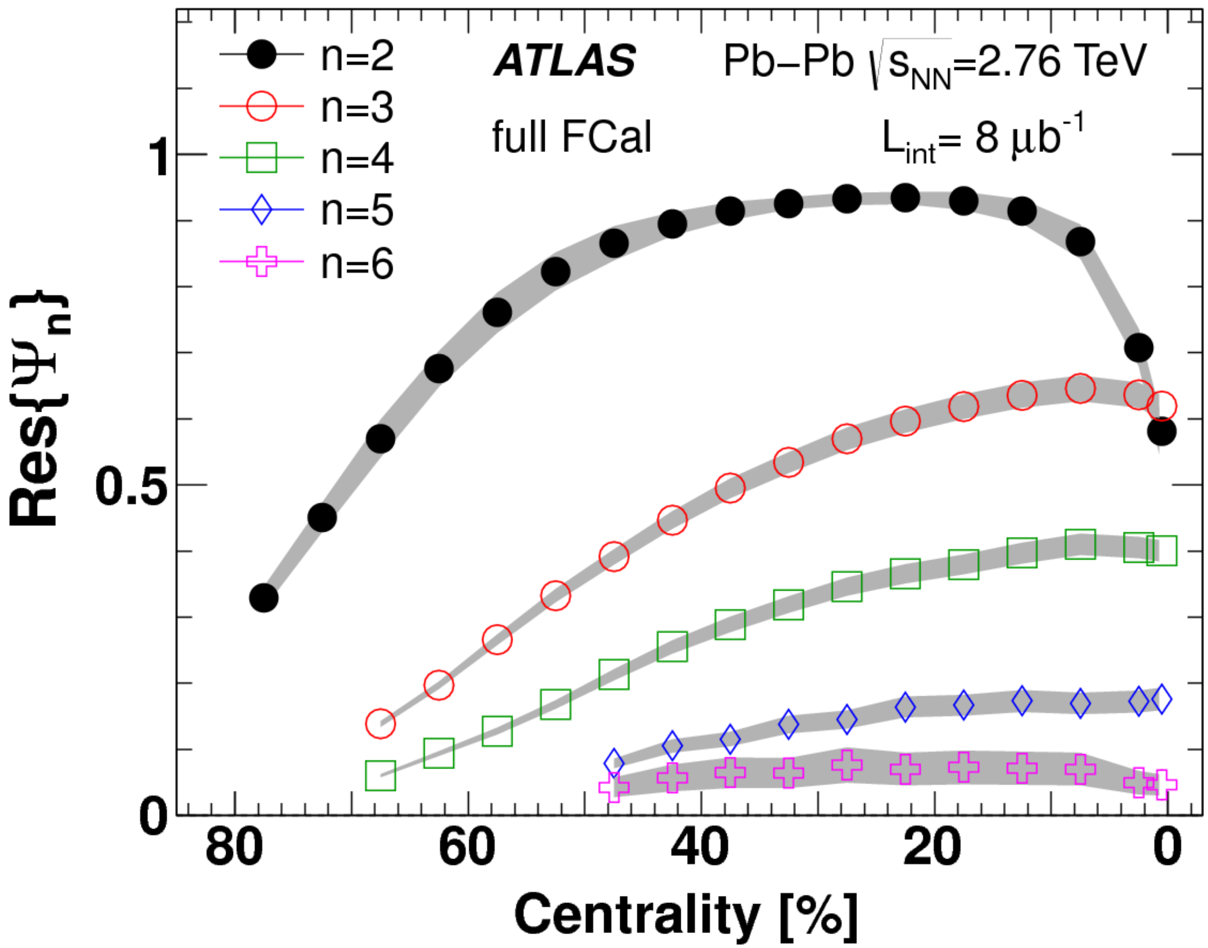
- **Reaction plane (Ψ^{RP}) is approximated by event plane (Ψ_n^{EP}) measured in FCal:**

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



~400 nucleons

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

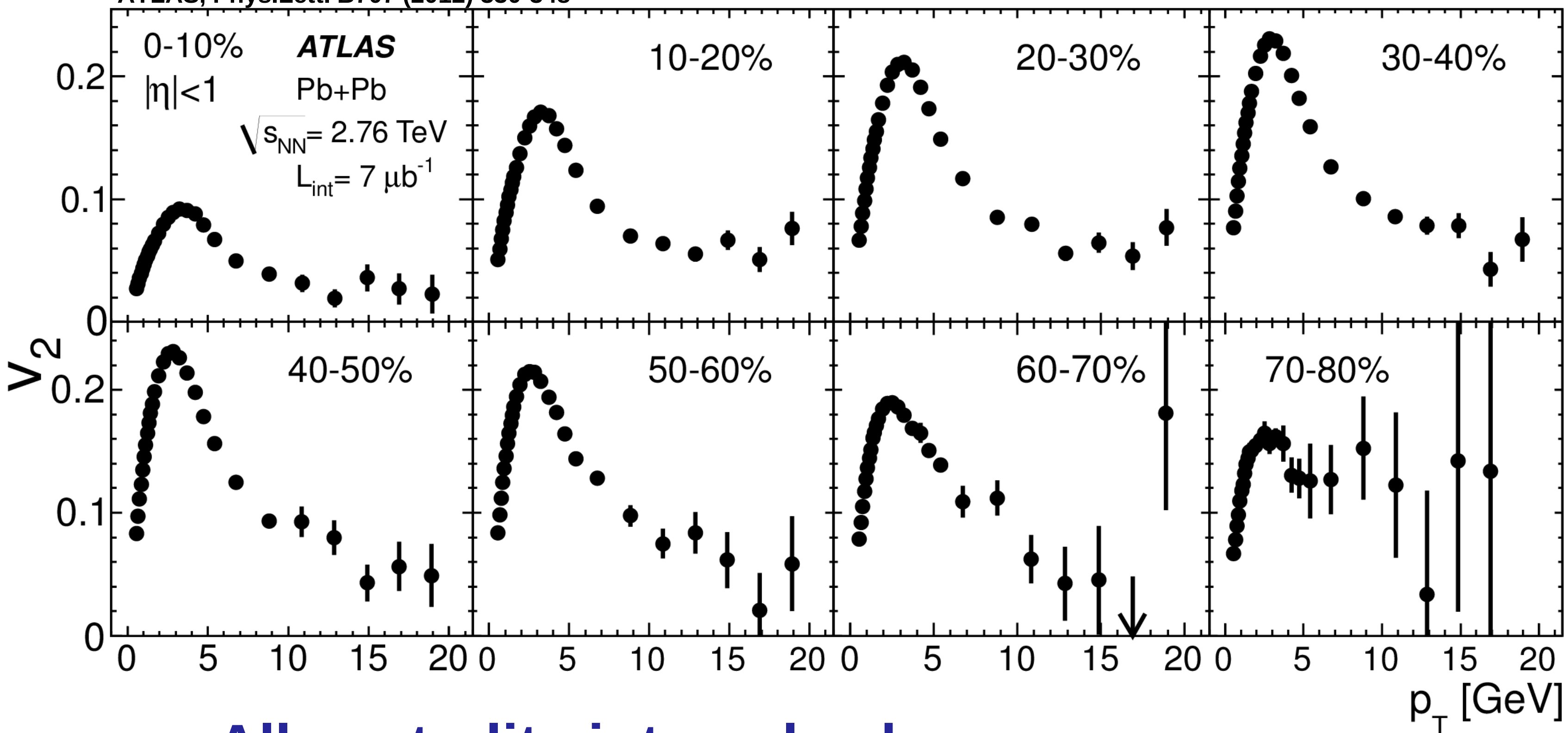


- **The event plane resolution correction factor R is obtained using two-sub event and various tree-subevent method**
- **Significant resolution for harmonics n=2 – 6**
- **Resolution corrected harmonics:**

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

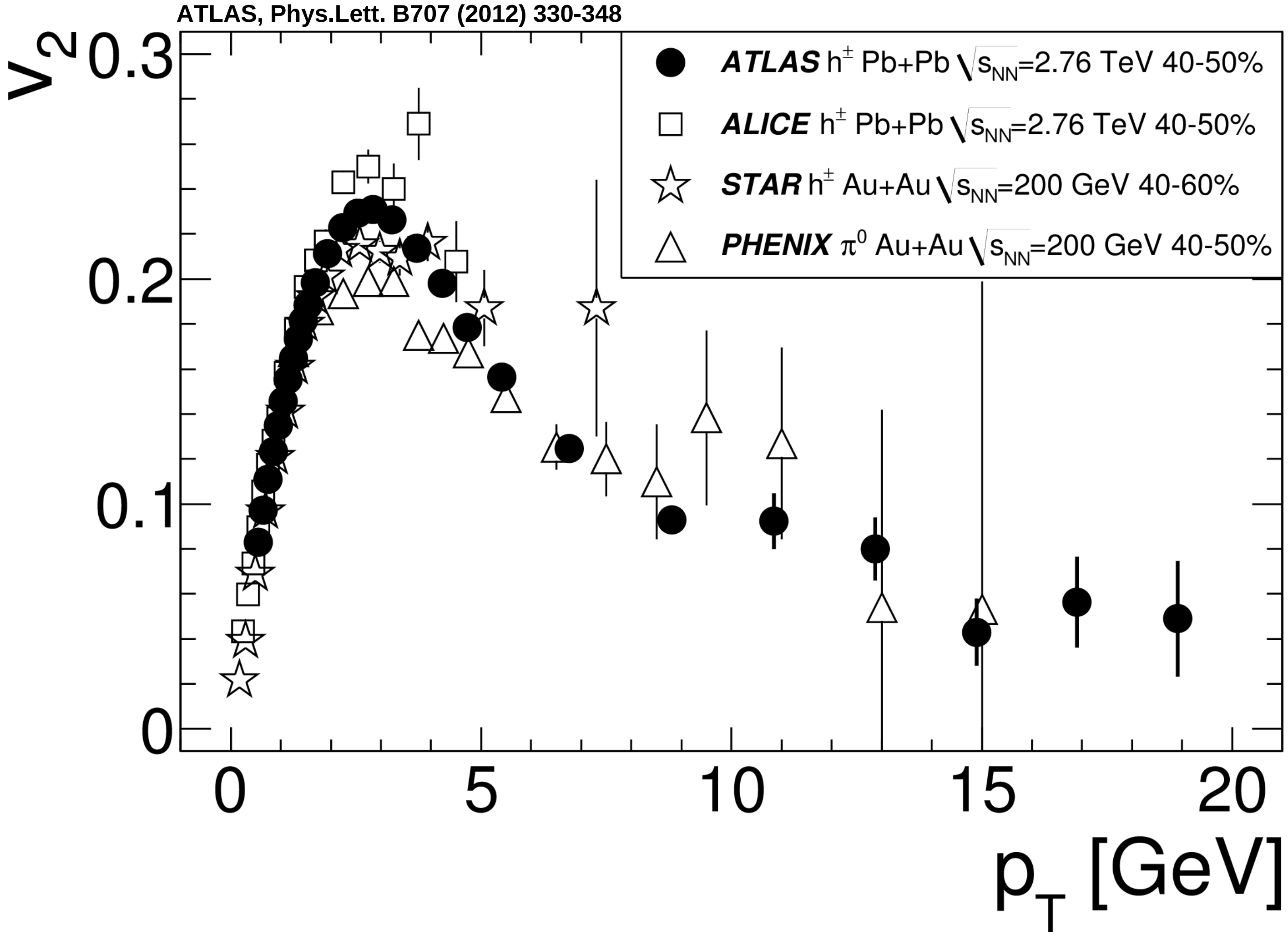
p_T dependence of the v_2 of charged particles

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



- **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%**

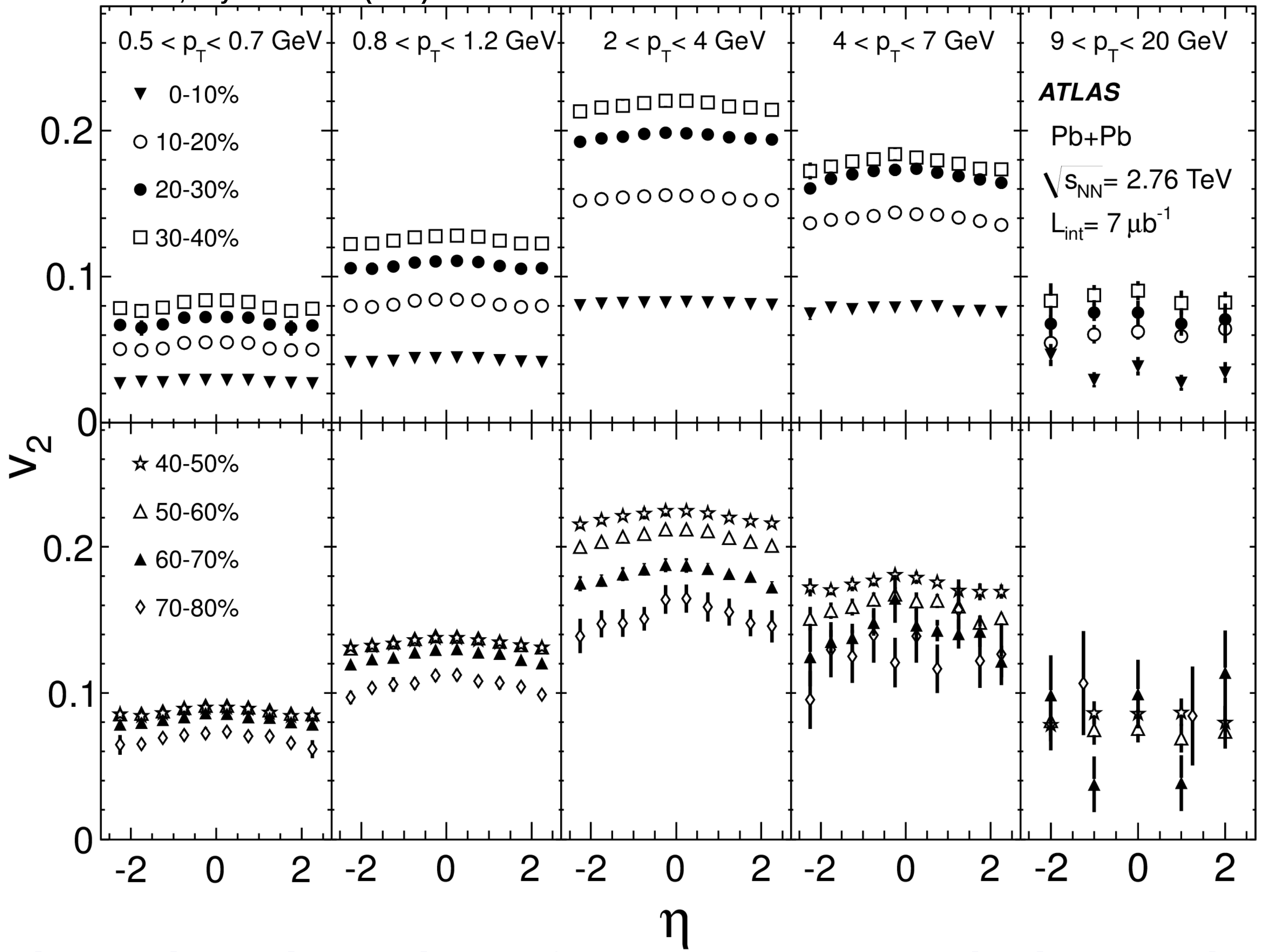
Comparison with ALICE and RHIC experiments



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

Pseudorapidity dependence of the v_2

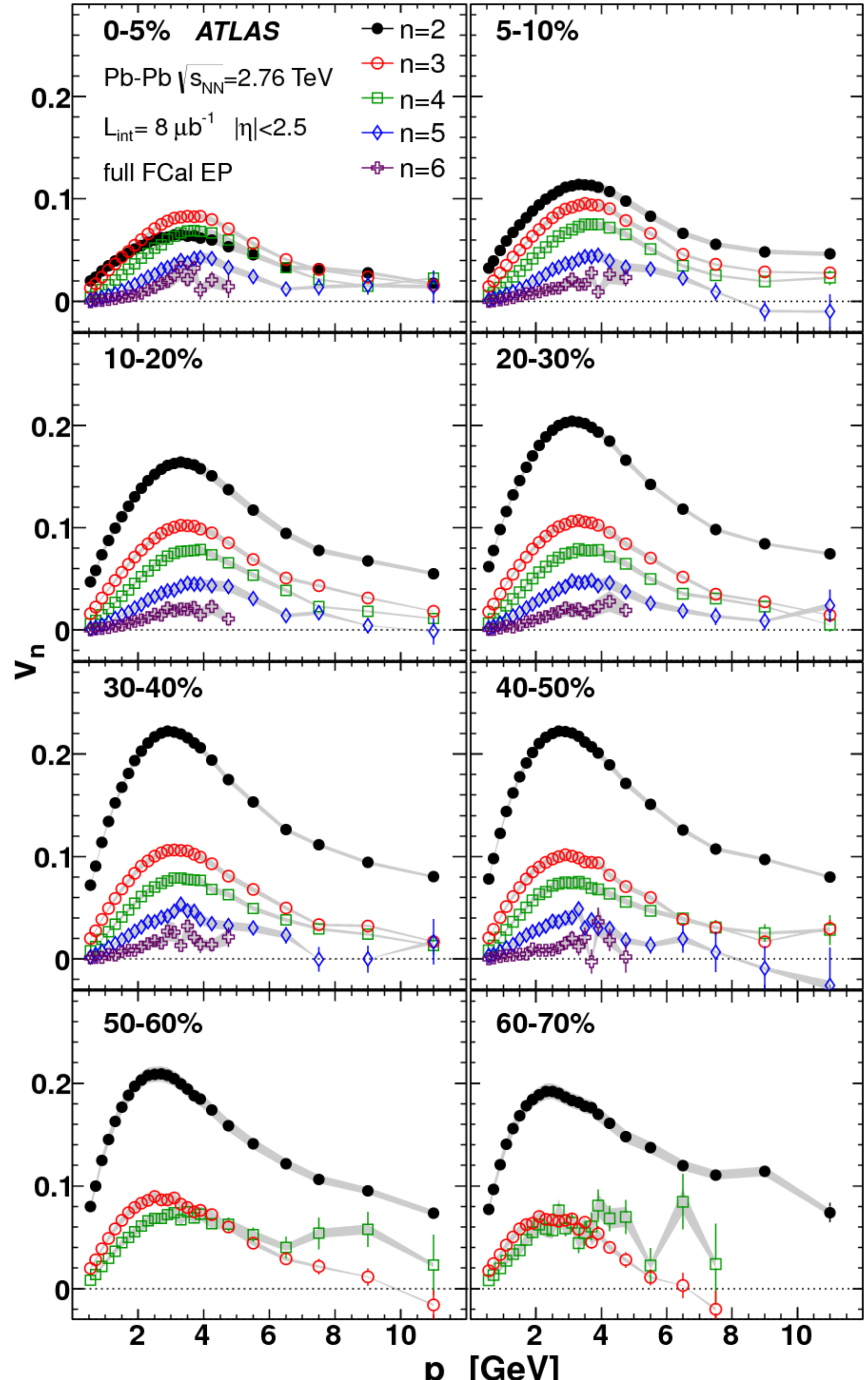
ATLAS, Phys.Lett. B707 (2012) 330-348



- **No substantial η dependence for any p_T or centrality interval is observed**
- **Different than 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

- 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



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

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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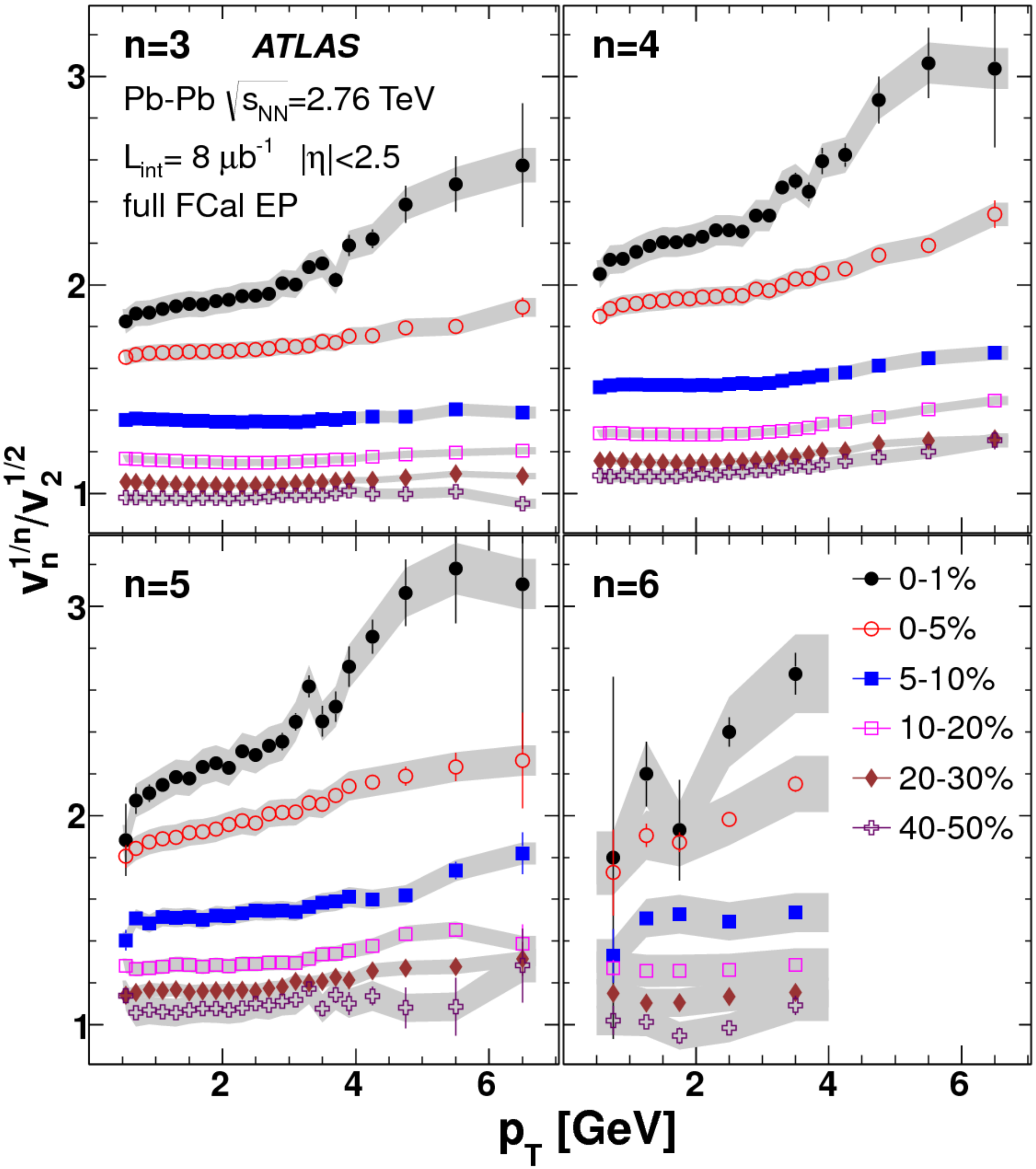
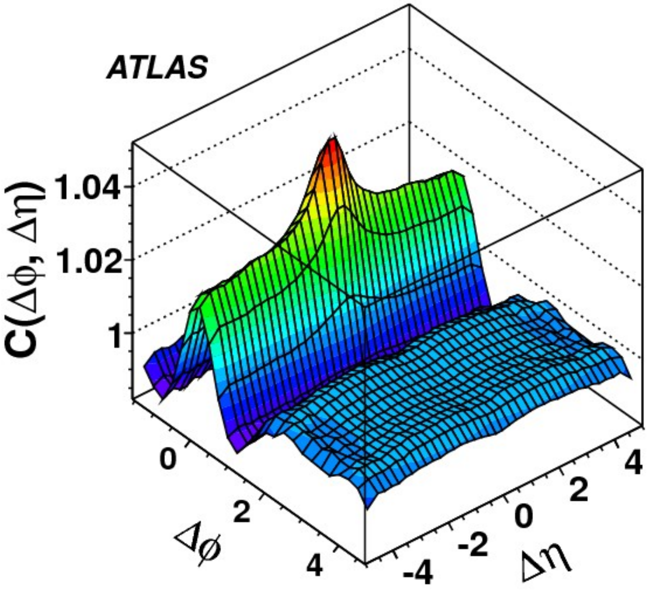


Two-particle correlation method

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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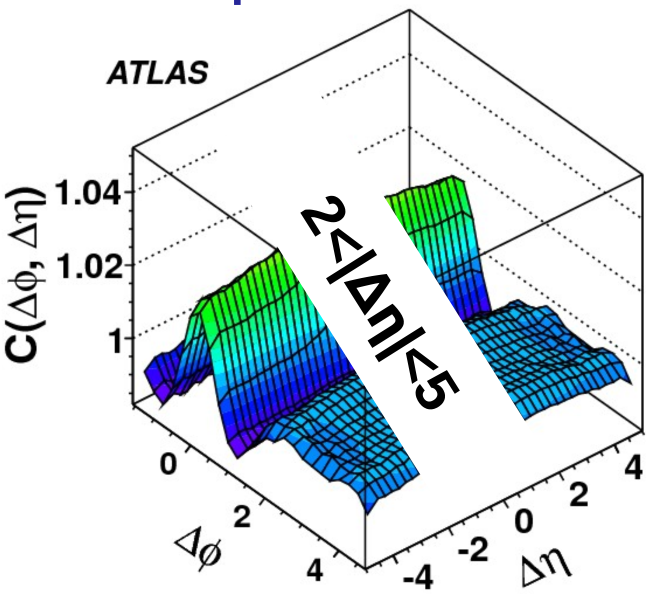
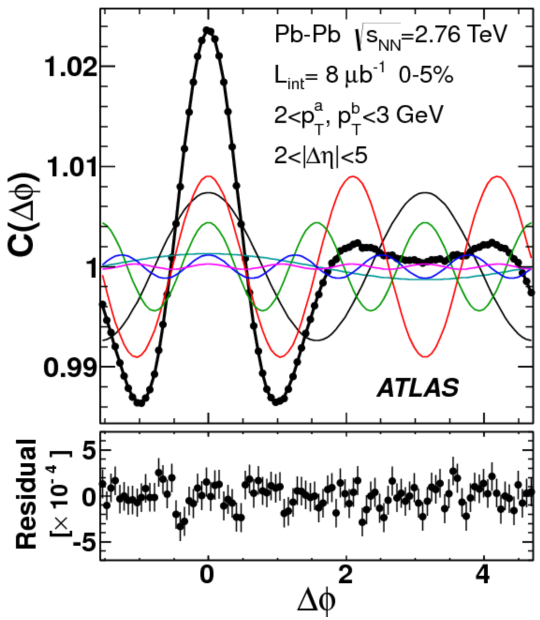


Projected onto Δφ

1D correlation function

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



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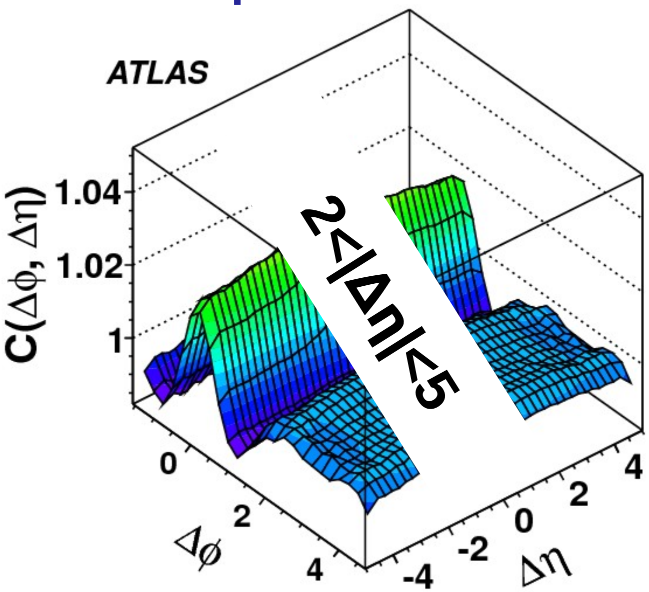

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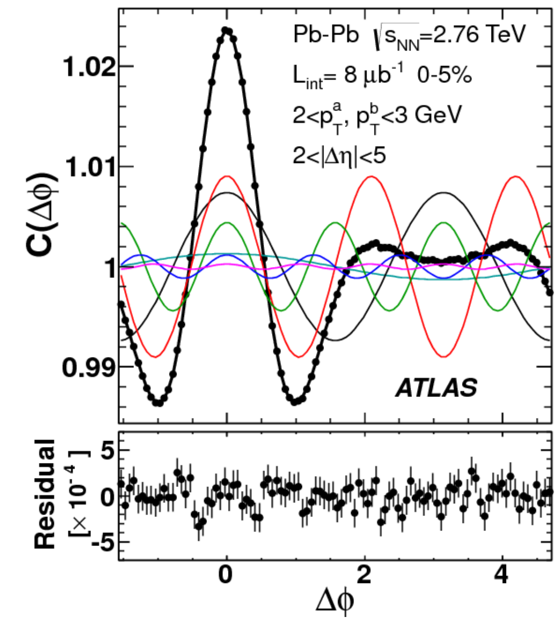
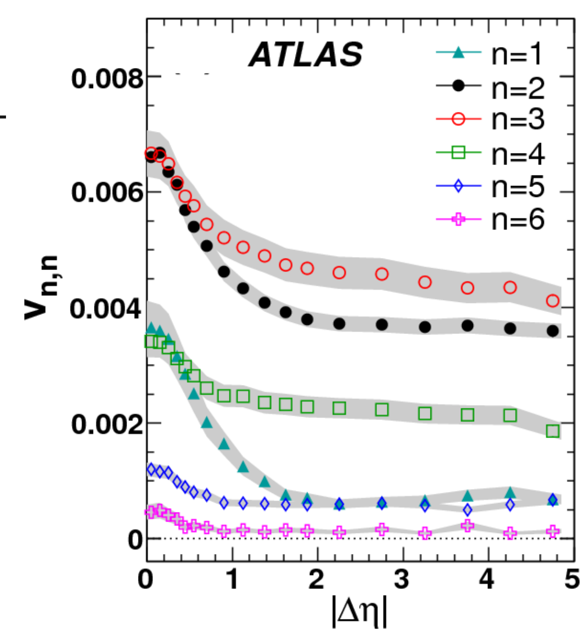


$v_{n,n}$ are calculated via Discrete Fourier Transform (DFT) :

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



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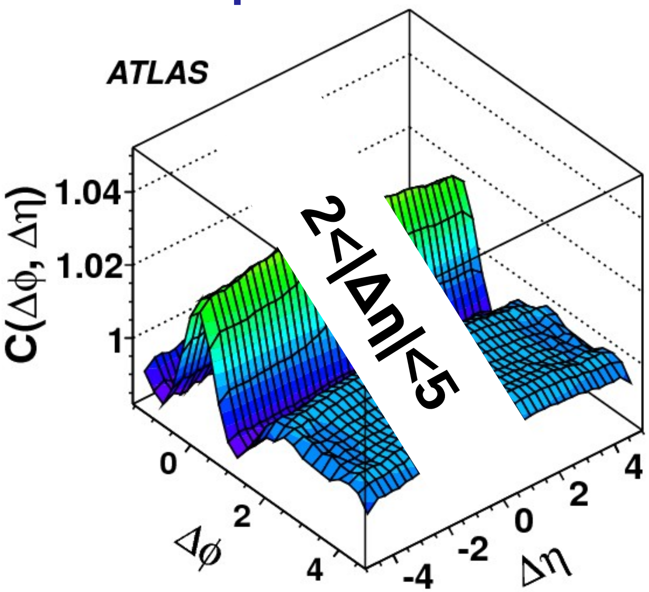

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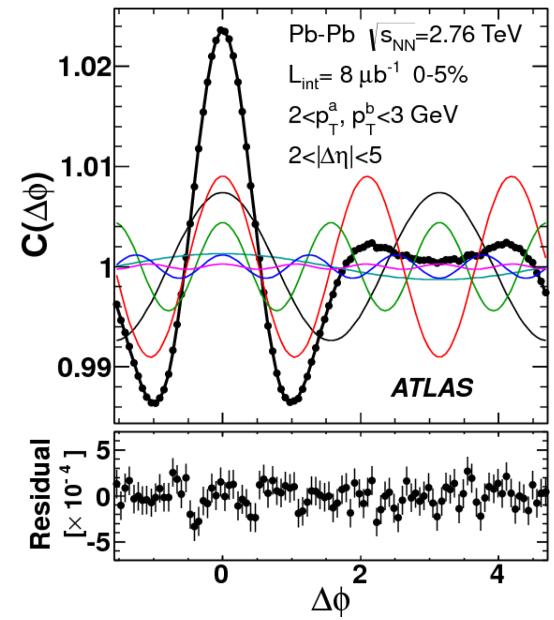

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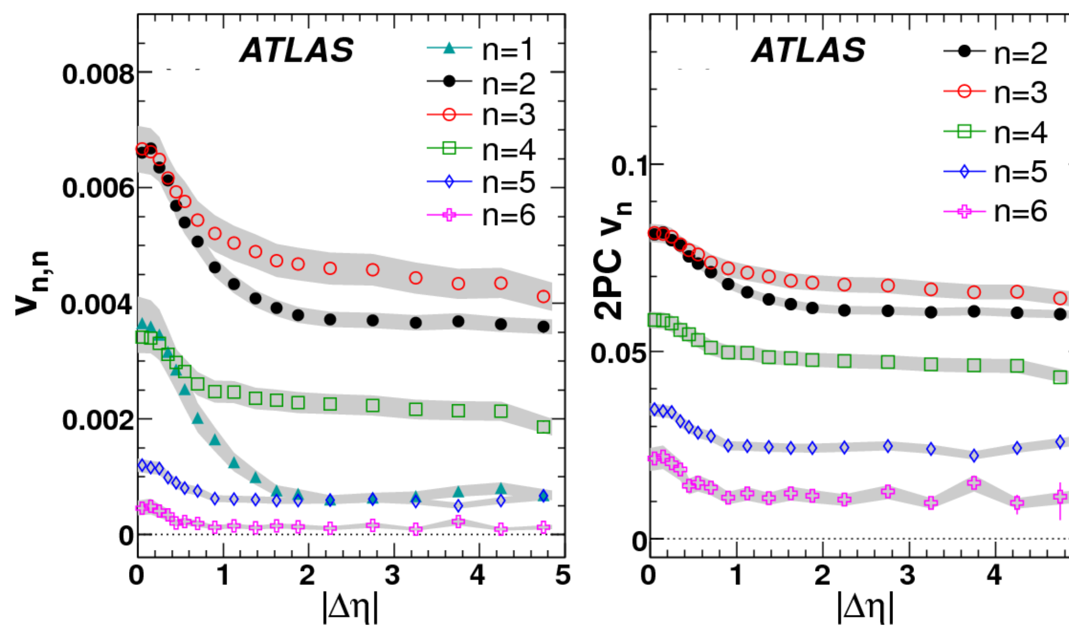
It is expected that for flow modulations:

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

And for "fixed-pT" correlations:

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



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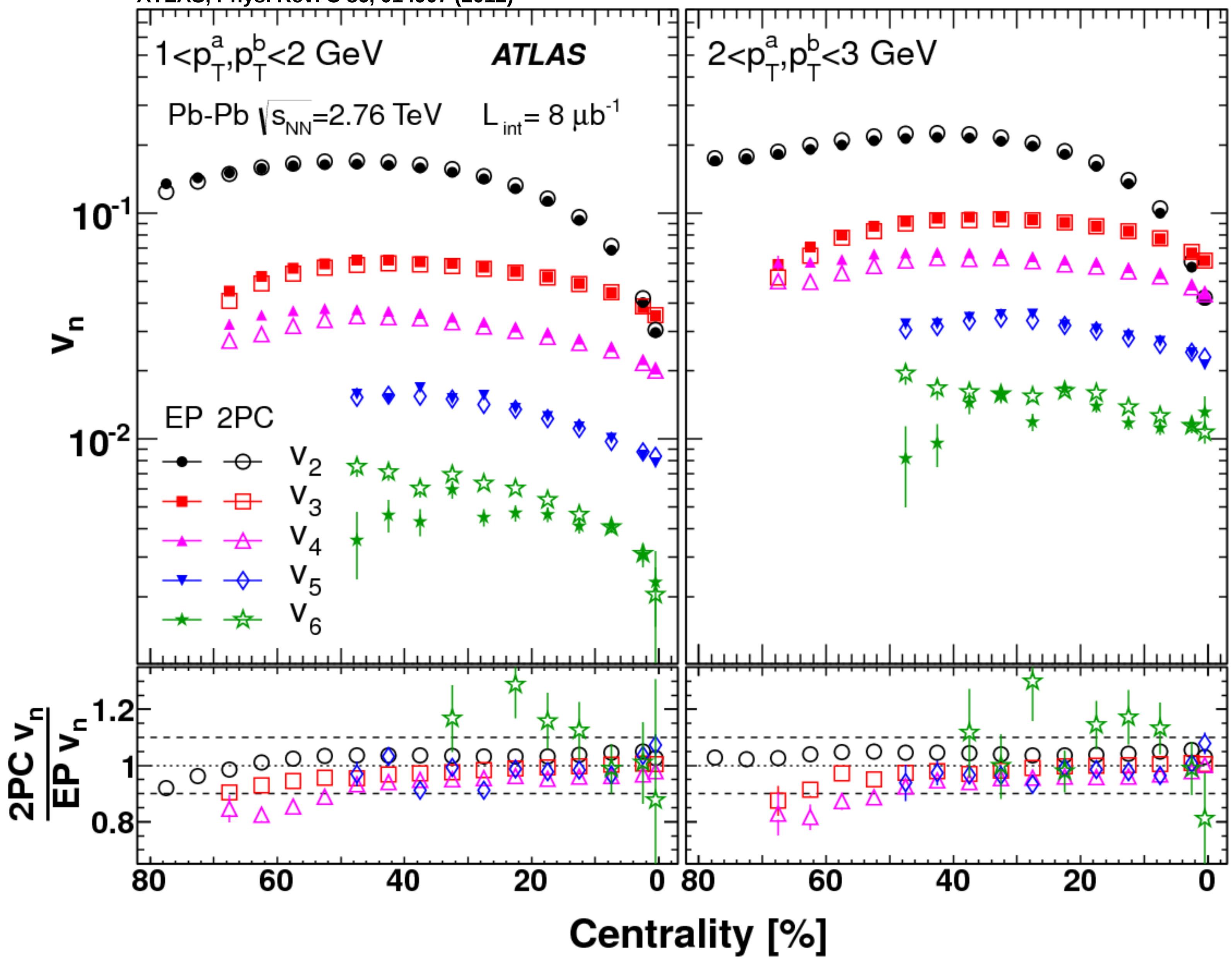
Two particle correlation vs EP results

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

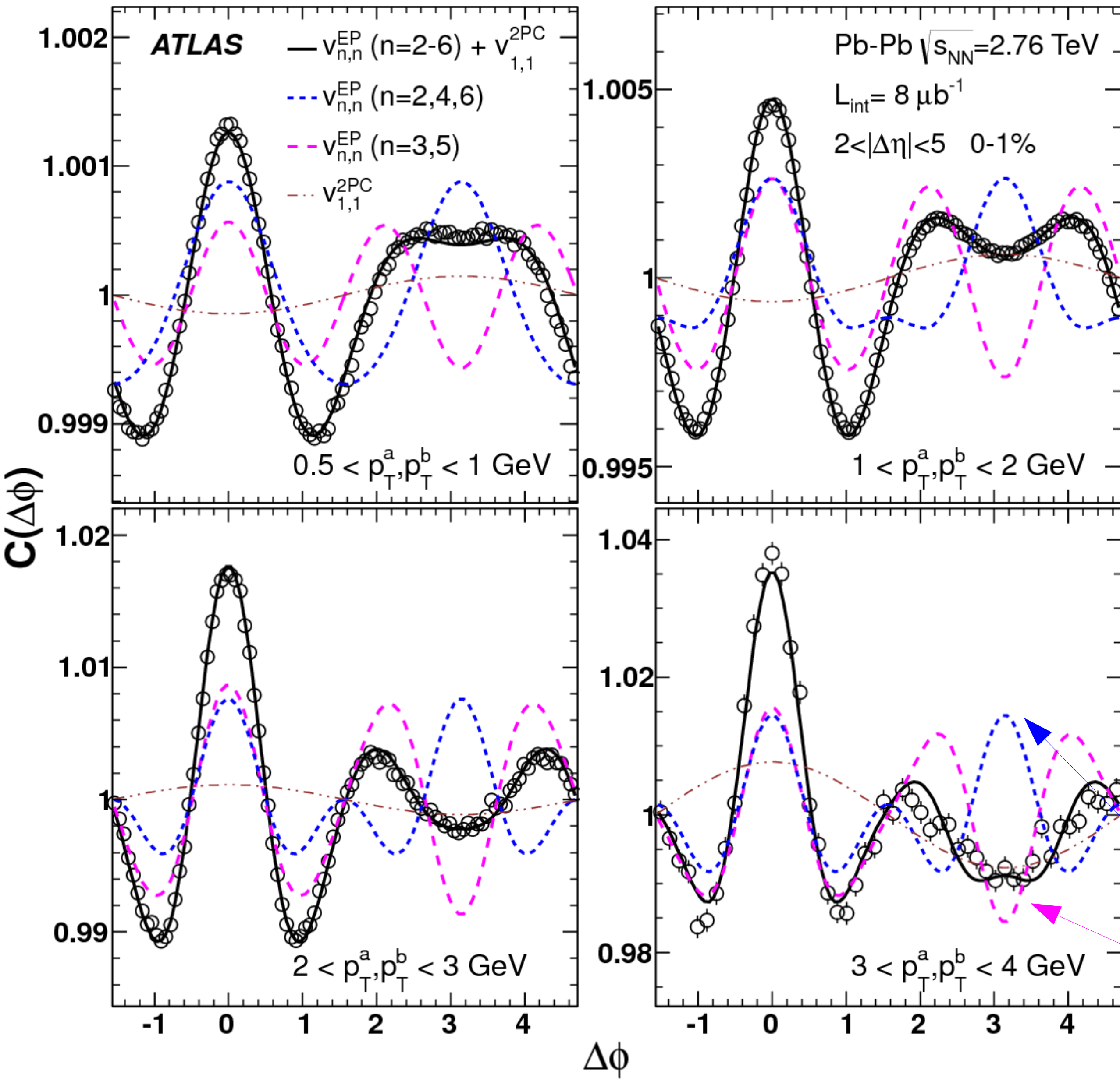


Good agreement between both methods in the selected kinematical range (p_T 1-3 GeV, 2<|η|<5)

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

More details on v_1:
J. Jia talk 15 Aug 11:20 AM
Session: Parallel 4A

- Other v_n components measured with the event plane method
- Correlation function reproduced very well

even harmonics contribution

odd harmonics contribution

Summary

- **ATLAS measured v_2 and higher order flow harmonics up to v_6 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 out to 20 GeV**
- **$v_n(\eta)$ remains approximately constant**
- **v_3 is dominating in the most central collisions**
- **v_n's follow approximate scaling relation $v_n^{1/n} \propto v_2^{1/2}$**
- **Good agreement between event plane and two particle correlation results for v_n**