Measurements of flow harmonics with the event plane and cumulant methods from the ATLAS experiment

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Topics covered

- Integrated flow measurement using the Event Plane method
  - Method description and justification
  - Three tracking techniques and their performance
  - Comparison of the measurements
  - Elliptic flow scaling

ATLAS-CONF-2012-117

- Flow measurements with cumulants
  - Method description
  - Two and four particle cumulants differential measurement
  - Comparison between the experiments
  - Integrated results
  - Fluctuations

ATLAS-CONF-2012-118

Event plane method and integrated v_2

- Event Plane method
  - for each event estimate the event plane angle and resolution
    - using FCal 3.2<|η|<4.8
  - correlate tracks with EP angle
    - using ID |η|<2.5

$$\Psi_2 = \frac{1}{2}\tan^{-1}\frac{\sum E_{Ti}^{towers} w_i \sin(2\phi_i)}{\sum E_{Ti}^{towers} w_i \cos(2\phi_i)}$$

$$R = \sqrt{\left\langle \cos[2(\Psi_2^N - \Psi_2^P)] \right\rangle}$$

$$v_2 = \left\langle \cos[2(\phi^{P,N} - \Psi_2^{N,P})] \right\rangle / R$$

- Integration: weight differential $\mathbf{v_2}$ by number of particles in bins of $\mathbf{p_T}$ and **η**
  - corrected by efficiency and fake rates

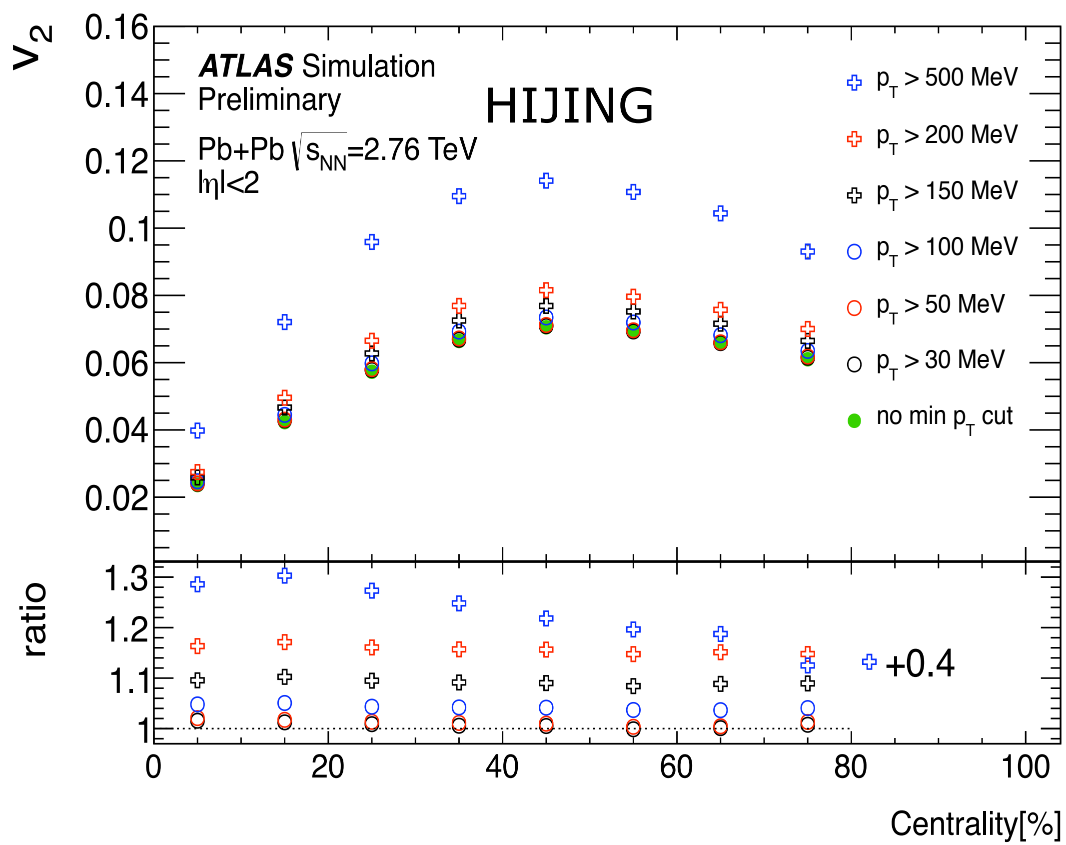
$$v_2^{\text{int}} = \sum_k \sum_i N_{ik}^c v_{2ik} / \sum_k \sum_i N_{ik}^c$$

$$N_{ik}^c = N_{ik}^c (1 - f_{ik}) / \varepsilon_{ik}$$

v_2\{EP\} integrated down to very low-p_T

Reaching low $\mathbf{p_T}$ reduces uncertainty on the integrated $\mathbf{v_2}$

→ no assumptions about the spectra and $\mathbf{v_2}$ at low $\mathbf{p_T}$



In practice

- $\mathbf{N_{ch}}$ drops down at very low-$\mathbf{p_T}$ **(<0.1 GeV)**
- $\mathbf{v_2}$ **($\mathbf{p_T}$)** also drops

→ inclusion of **~0 GeV** particles not needed/ necessary if sufficiently low $\mathbf{p_T}$ can be reached

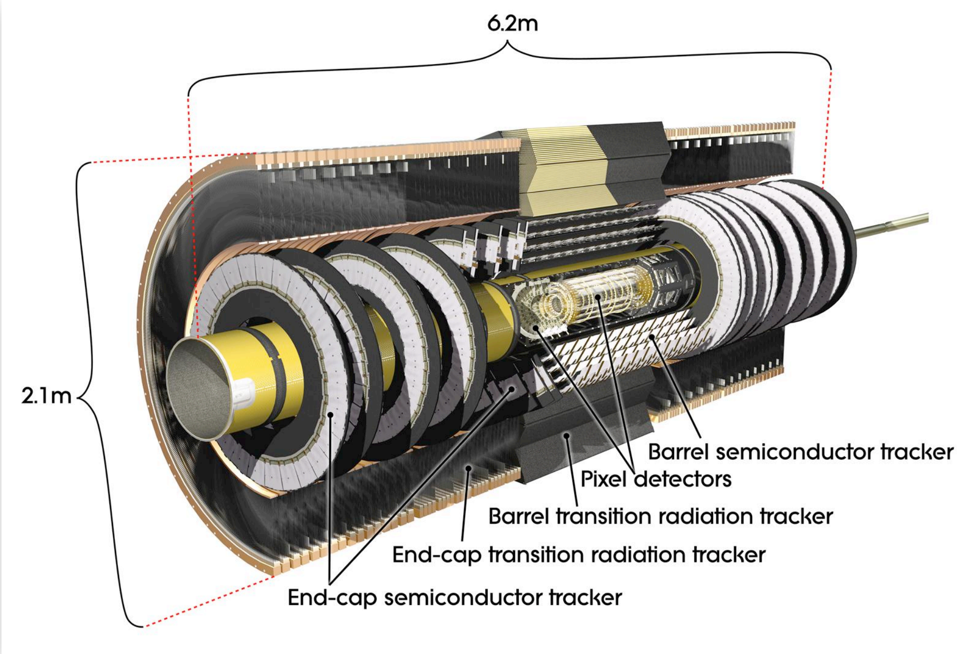
0.1 GeV → ~5%

0.2 GeV → ~20%

Means to reliably reach p_T~0

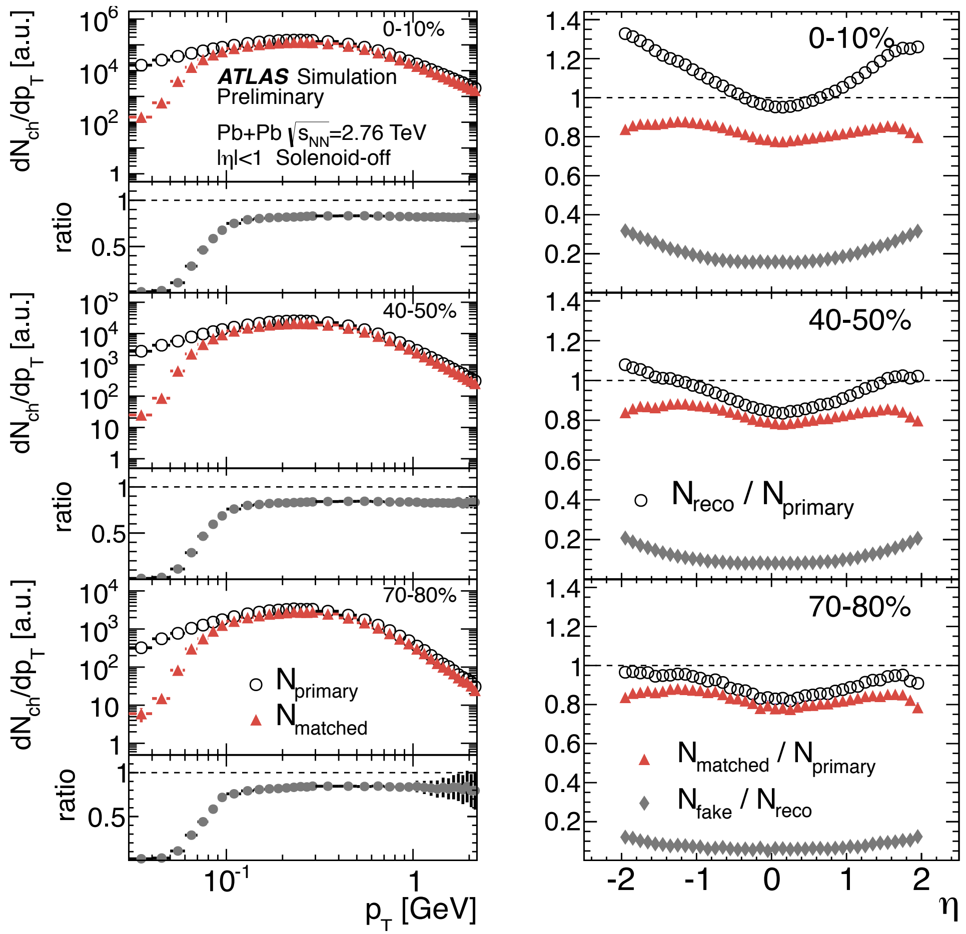
Three tracking techniques

- ***Pixel tracklets*** built from 2 hits in first two layers of pixel detector and vertex position
  - without solenoid magnetic field, $\mathbf{p_T>0.03}$ **GeV** fully efficient $\mathbf{p_T>0.1}$ **GeV**
  - no $\mathbf{p_T}$ measurement



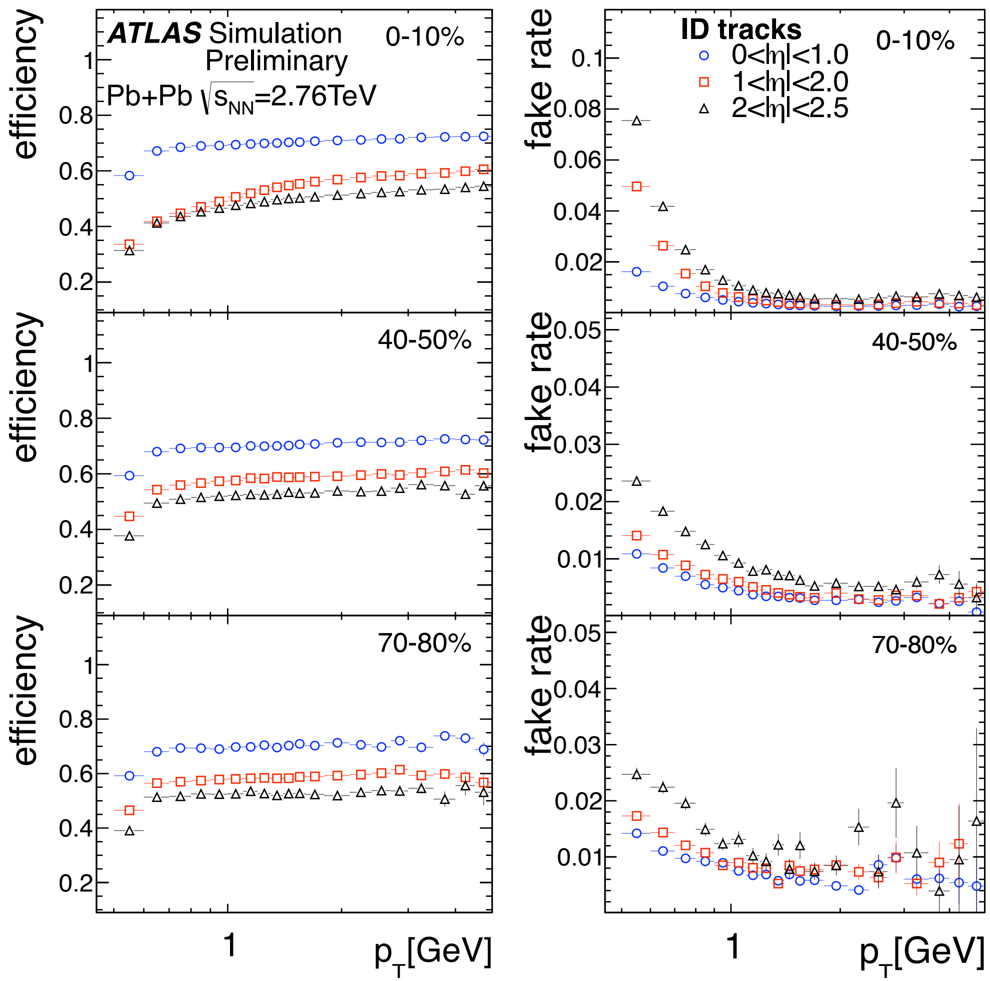
- ***Pixel tracks*** built from hits (3 in the barrel) in the Pixel only
  - with magnetic field, $\mathbf{p_T>0.1}$ **GeV**
- ***ID tracks*** (Pixels + SCT) for crosscheck
  - with magnetic field, $\mathbf{p_T>0.5}$ **GeV**

Pixel tracklets performance



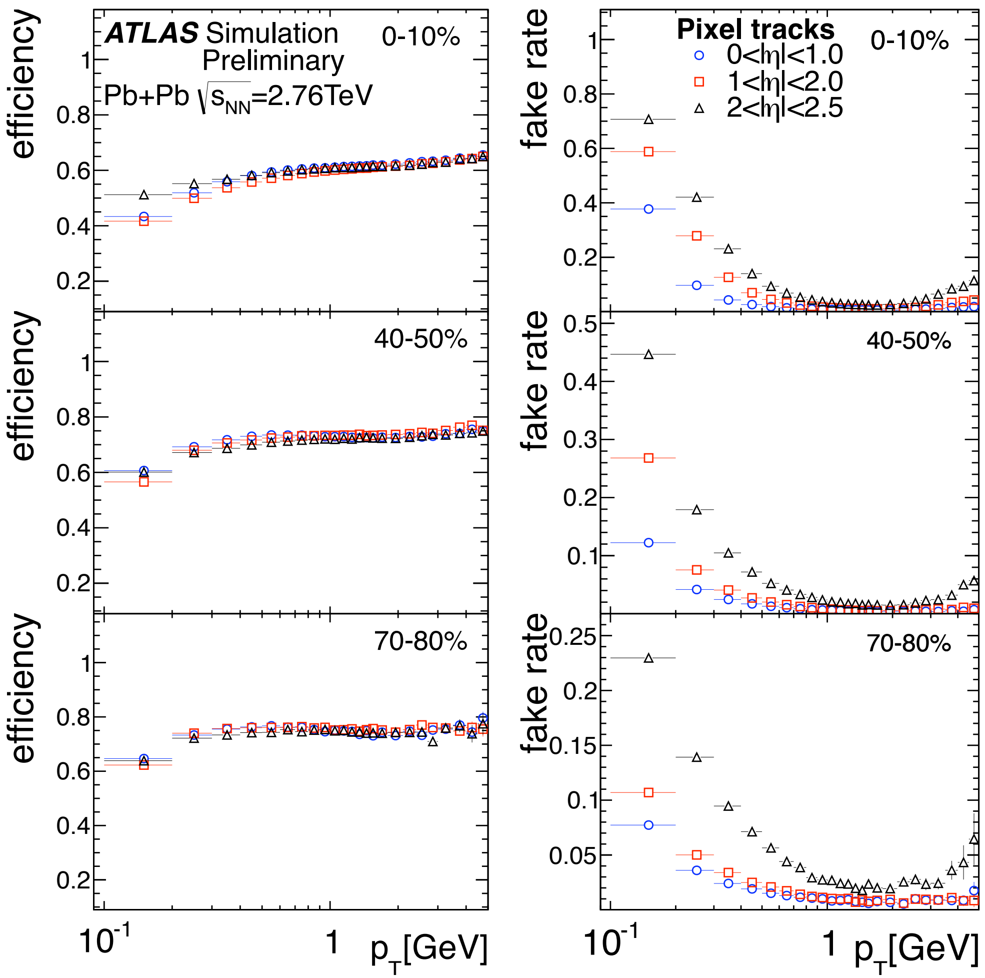
- Tracklets reach down to **0.03 GeV**, stably efficient above **p_T>0.1 GeV** at the level of **~80%**
- Efficiency also stable with **η** and centrality
- Fake rates grow with centrality and **η** region of **|η|>2** excluded from the analysis

ID tracks (Pixel+SCT) performance



- Minimum $\mathbf{p_T}$**=0.5 GeV**
- Efficiency stable with $\mathbf{p_T}$**>0.7 GeV** also stable with centrality
- Fake rate well below 10% in most central collisions, affecting mostly low-$\mathbf{p_T}$ and higher **η**

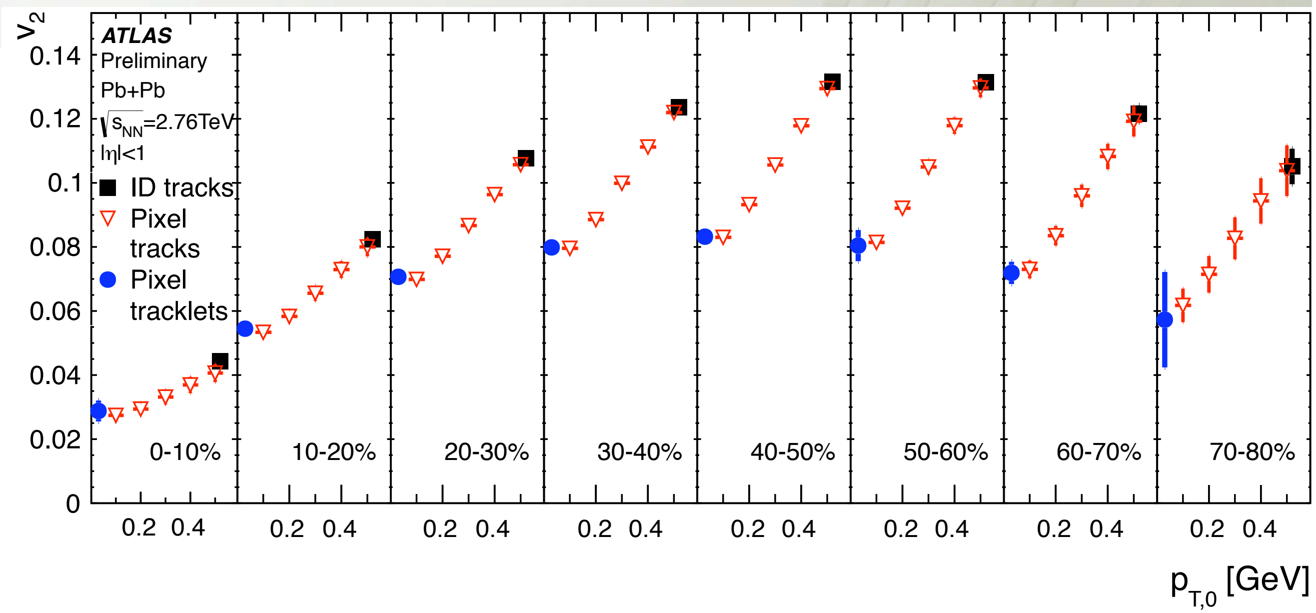
Pixel tracks performance

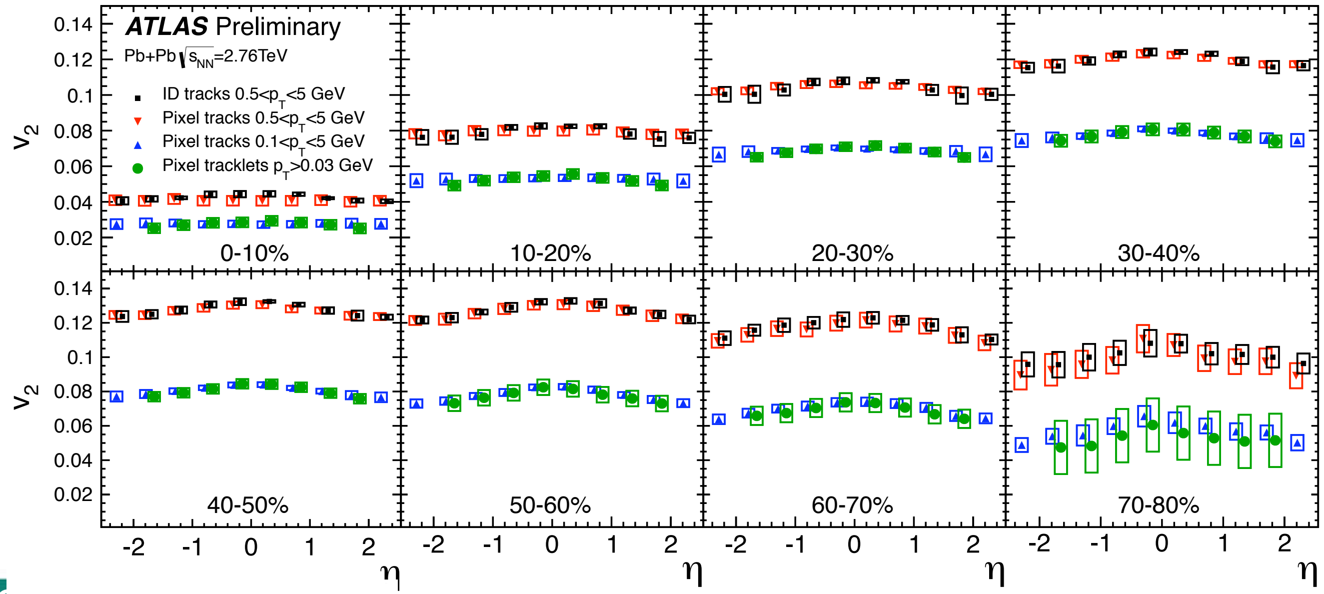


- Efficiency weakly dependent on $\mathbf{p_T}$, reaching as low as **0.1 GeV**
- Low $\mathbf{p_T}$ region is plagued with fake tracks, up to 40% in mid-**η**

Consistency between measurements

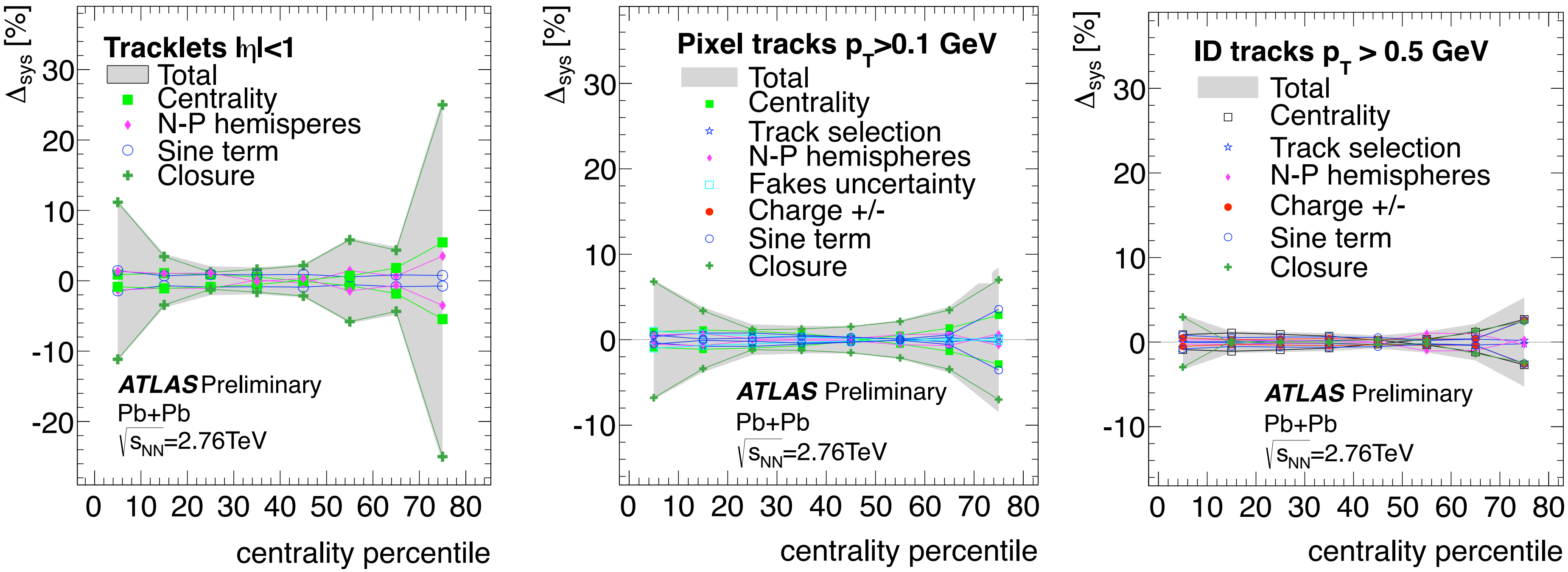
- Varied lower integration limit of pixel tracks measurement, to match:
  Tracklets (**0.1 GeV**)
  ID tracks (**0.5 GeV**)
- Consistent results for $\mathbf{v_2}$ and $\mathbf{v_2(\eta)}$
- Weak **η** dependence can be observed





Uncertainties

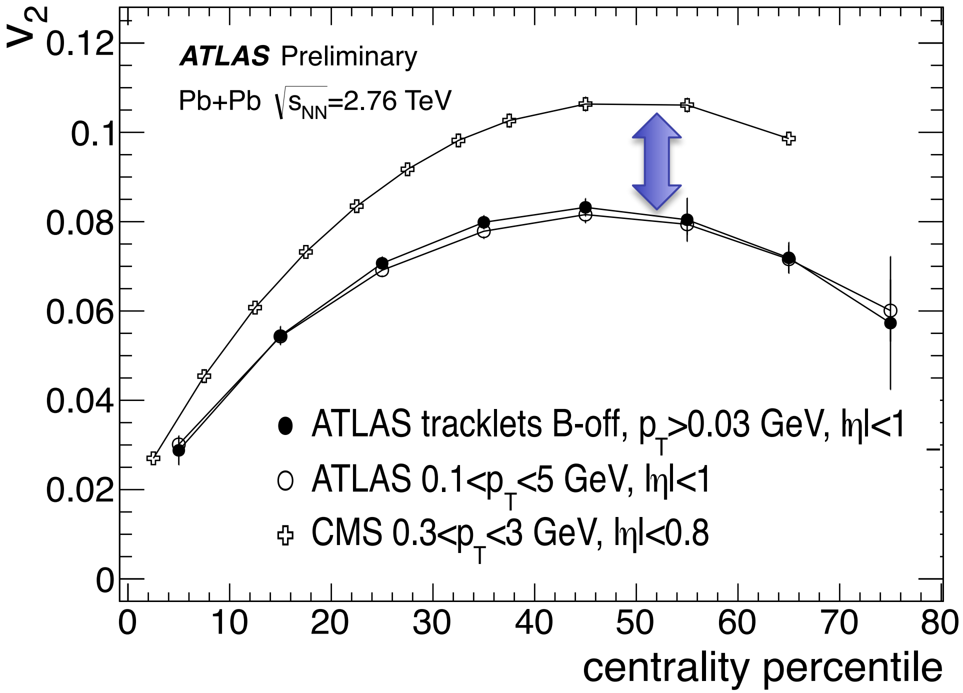
Number of sources in the overall uncertainty considered

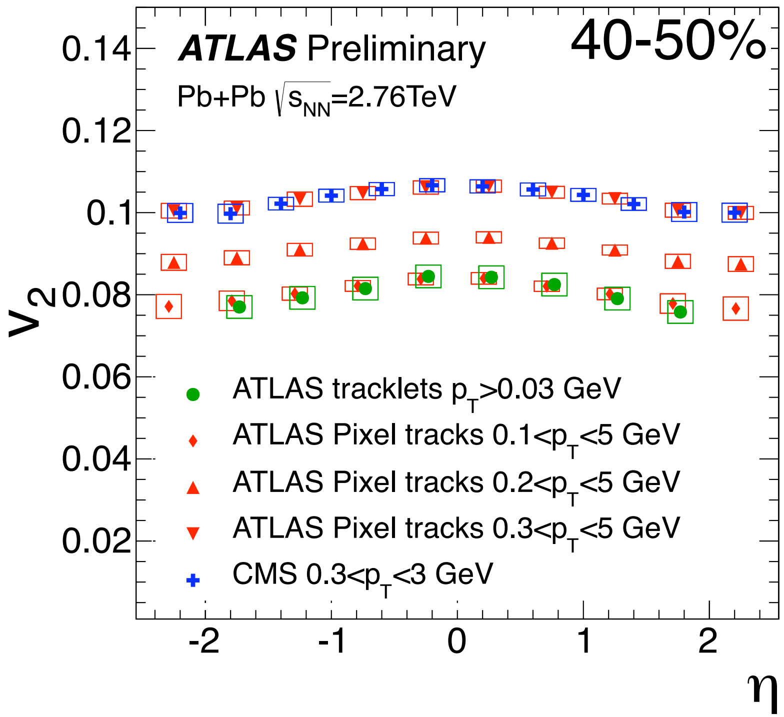


In case of low-$\mathbf{p_T}$ measurements dominant source is the MC test (closure) contribution

All other contributions at the level of 1-2%

Comparison to CMS



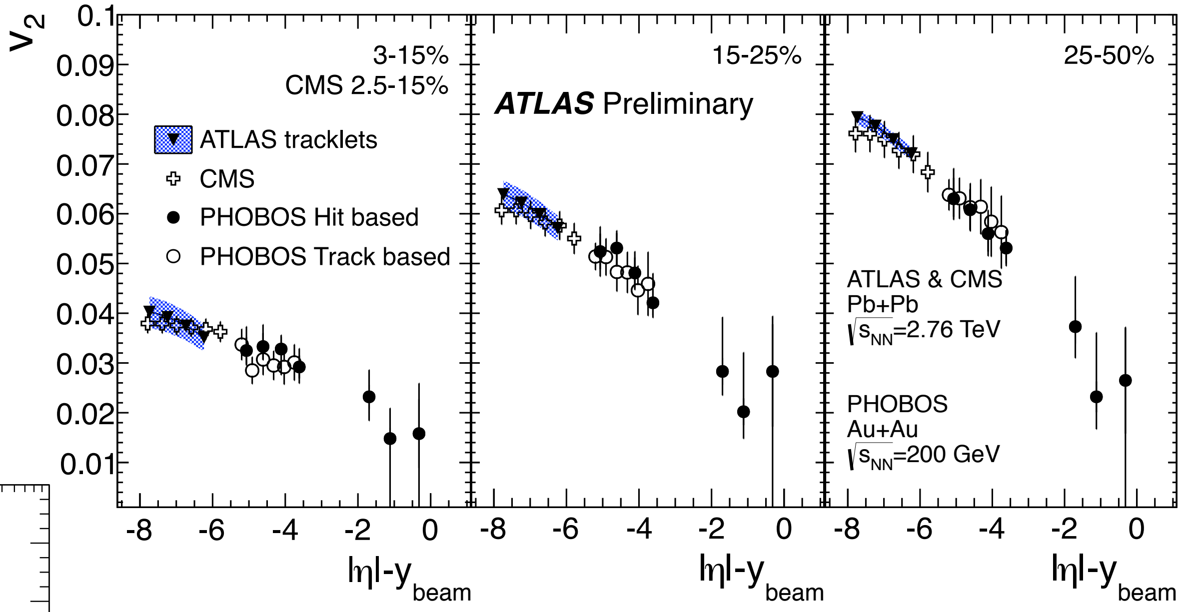


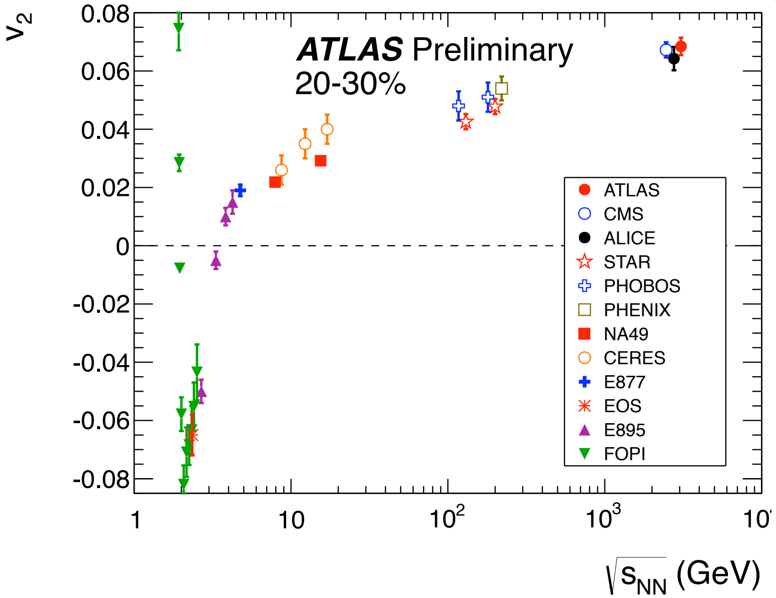
Measurement is sensitive to the low-$\mathbf{p_T}$

Agreement when the integration threshold tuned to match one from CMS (**0.3 GeV**)

v_2 scaling properties

$v_2(|\eta|-y_{beam})$
ATLAS Pixel tracklets
CMS extrapolated to
p_T=0 from **0.3 GeV**





$v_2(\sqrt{s_{NN}})$ ATLAS Pixel tracklets
compatible with ALICE and CMS

Cumulant method

- Why to use it?
  - **v_2** harmonic measured with Event Plane folds in the non-flow contributions: jets, resonance decays, ...
  - In the **2k**-th cumulant **$v_2\{2k\}$** non-flow contributions involving <2k particles are invisible
  - Numerically difficult → nested loops over particles **$\mathcal{O}(N^{2k})$** → Generating Functions of correlations and cumulants used as enabling technique → numerical complexity **$\mathcal{O}(N)$**
- In ATLAS ID tracks used
  - Reference flow measured from **$0.5<p_T<12$ GeV**, **$|\eta|<2.5$**
  - **$v_2\{2\}$** 0-80%, **$v_2\{4\}$** 5-70%

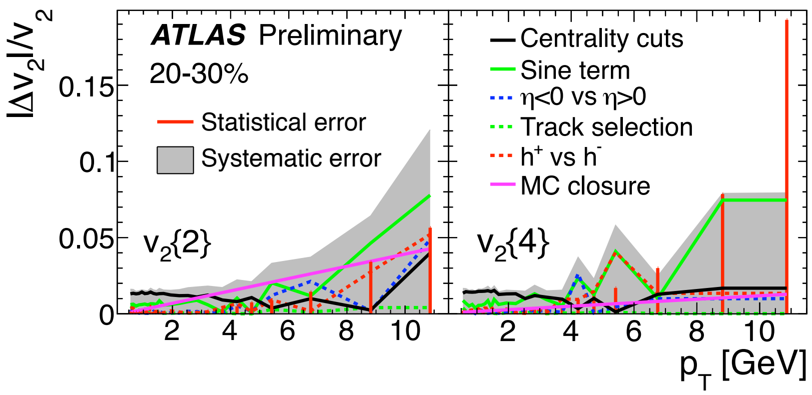
Cumulants results

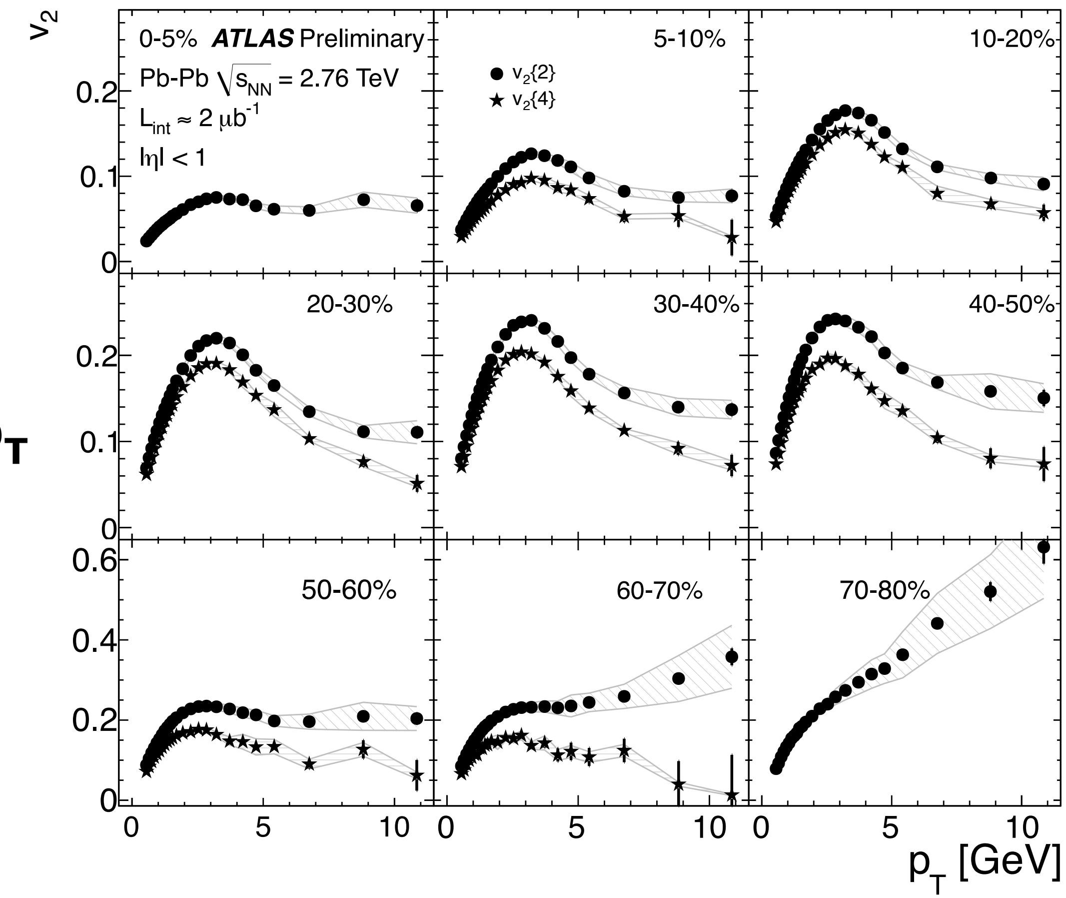
The $v_2\{2\}$ systematically above $v_2\{4\}$
→ Differences due to non-flow and/or event-by-event fluctuations

→At high-p_T $v_2\{2\}$ likely determined by the influence of jets

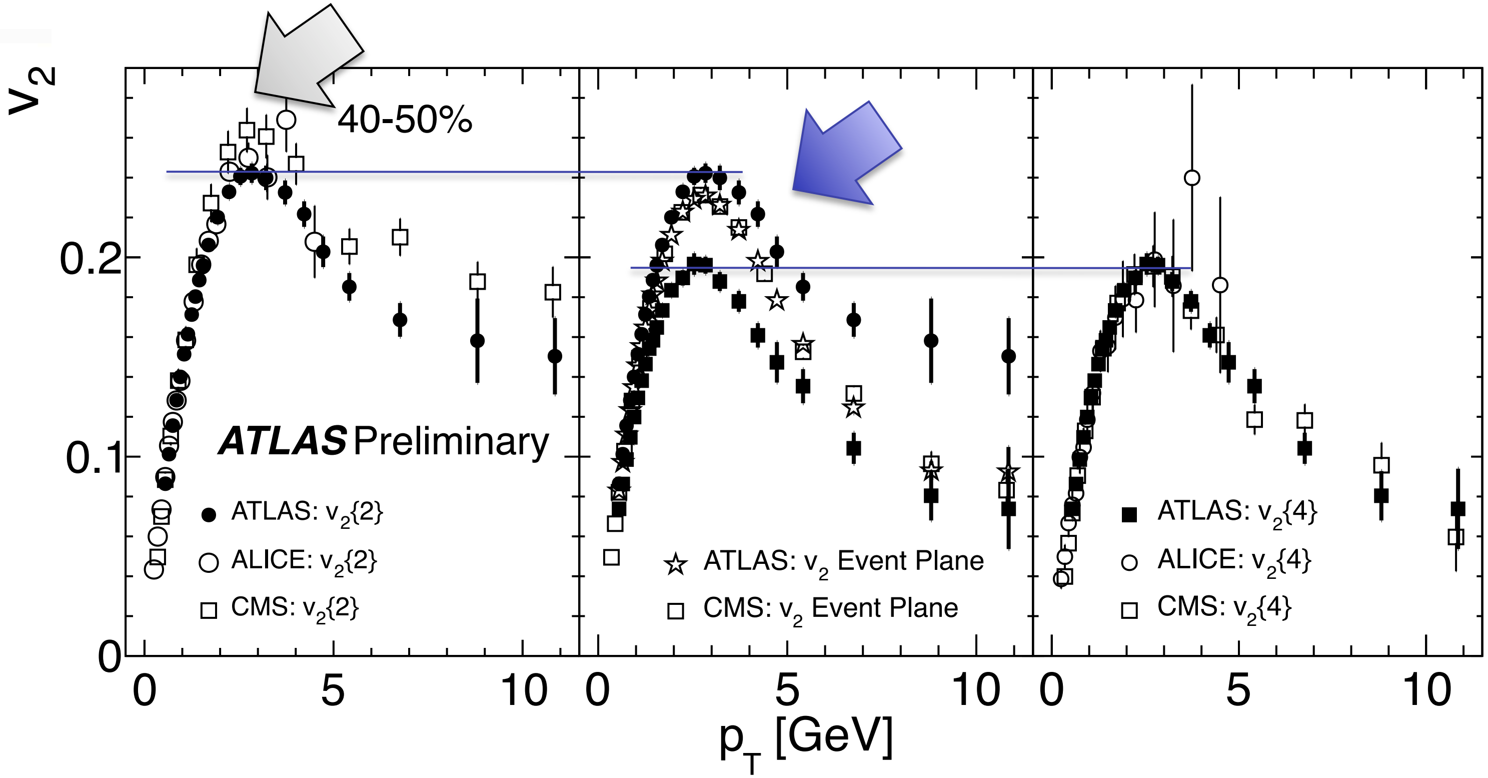
For $v_2\{2\}$ no single major source of uncertainty

Uncertainties dominated by statistics for $v_2\{4\}$ for high p_T





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



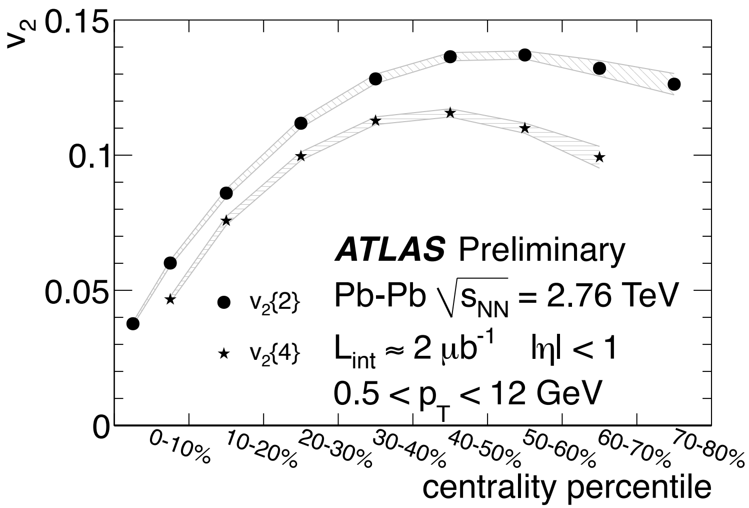
Good agreement between LHC experiments

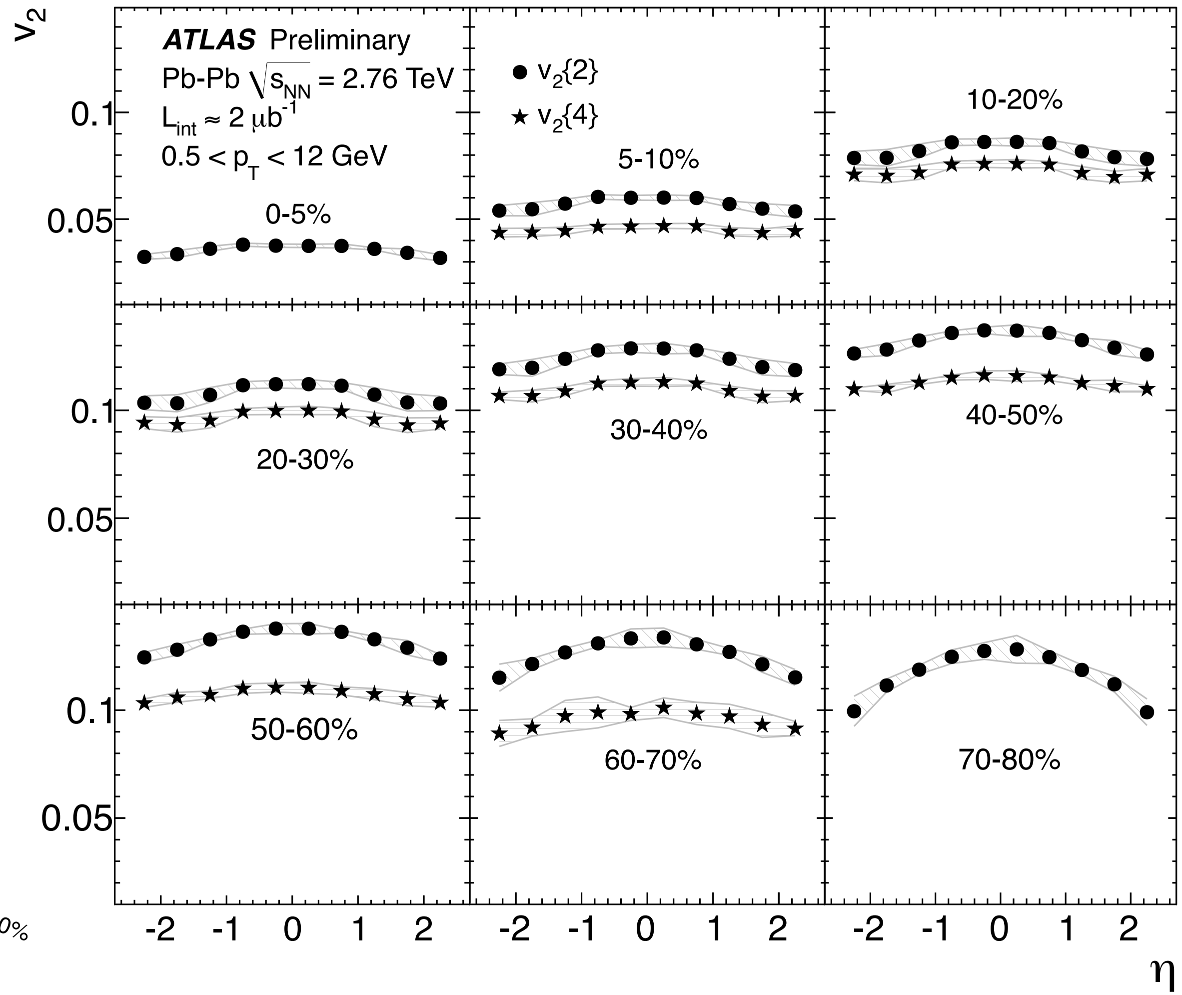
- **$v_2\{4\}$** agrees very well
- **$v_2\{2\}$** a bit off at high-**p_T** between ATLAS and CMS

- The **$v_2\{EP\}$** lies between **$v_2\{2\}$** and **$v_2\{4\}$**

Pseudorapidity dependence integrated flow

The difference observed in the differential measurement propagates to the integrated ones





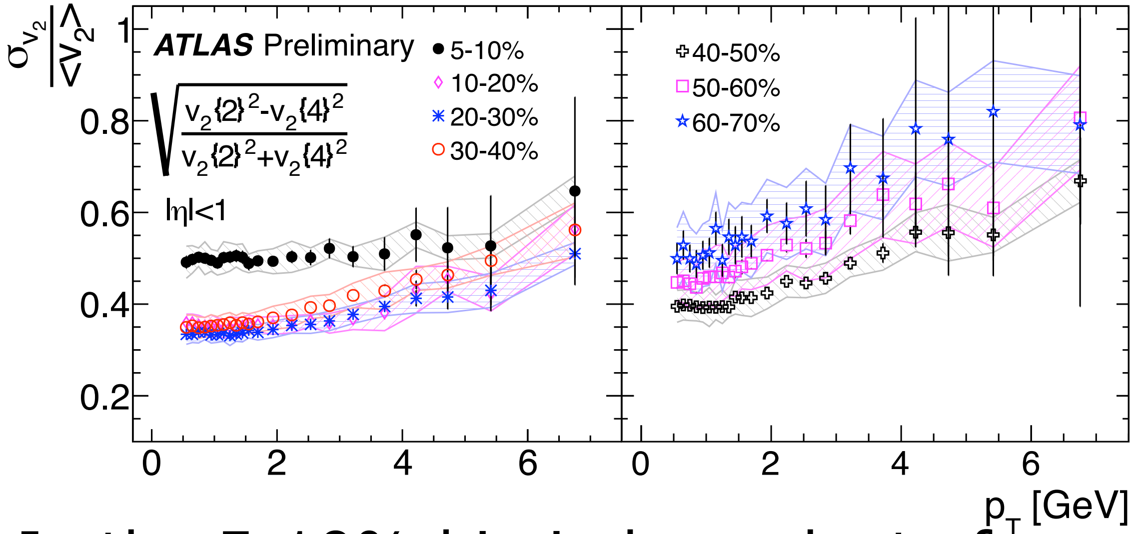
ATLAS - cumulant method - integrated flow

Event-by-event fluctuations

Difference between $\mathbf{v_2\{2\}}$ and $\mathbf{v_2\{4\}}$ may also measure the fluctuations of eccentricity

A. Voloshin, A. Poskanzer, A. Tang, A. Wang
arXiv:0708.0800

$$\frac{\sigma_2}{v_2} = \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$$



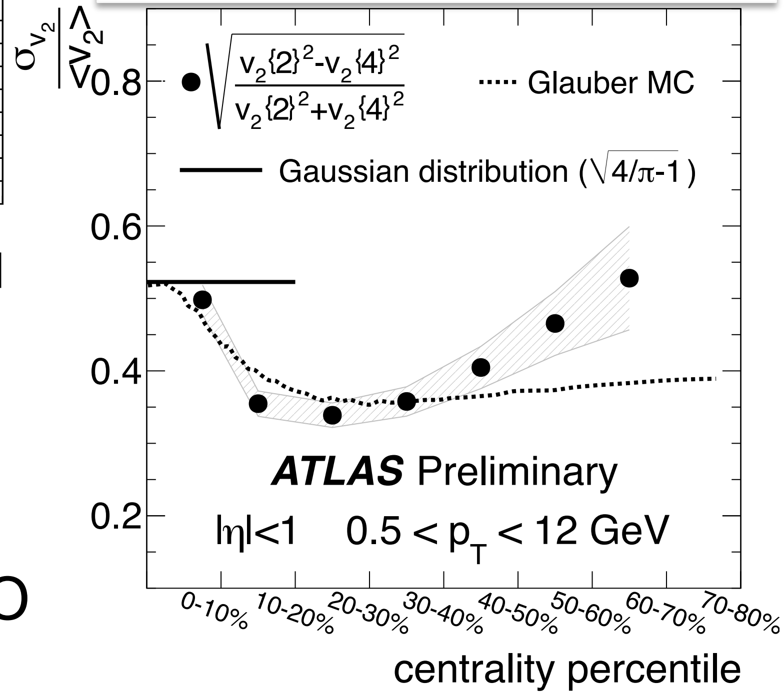
In the 5-10% bin independent of $\mathbf{p_T}$

less central collisions and higher $\mathbf{p_T}$
→ stronger $\mathbf{p_T}$ dependence

Evolution with centrality

→ compares well with the GLISSANDO model for central collisions

W. Broniowski, M. Rybczynski, P. Bozek
arXiv:0710.5731



Summary

- Integrated $\mathbf{v_2}$ flow harmonic measured using the EP method
  - three tracking techniques used to reach $\mathbf{p_T}$ down to ~**0.03 GeV**

  no extrapolation required!
  - lower $\mathbf{p_T}$ leads to reduced integrated $\mathbf{v_2}$
- The $\mathbf{v_2(\eta)}$ consistent with CMS and extrapolation of scaling trend found at RHIC
- The $\mathbf{v_2(\sqrt{s_{NN}})}$ → agreement with ALICE and CMS

- Differential $\mathbf{v_2}$ flow harmonic was measured using 2 and 4 particles cumulants
  - results compatible with CMS and ALICE
  - clearly observed suppression $\mathbf{v_2\{2\}}$ → $\mathbf{v_2\{4\}}$
  - $\mathbf{v_2\{2\} > v_2\{EP\} > v_2\{4\}}$
- Event-by-event elliptic flow fluctuations ~40%
  - independent of $\mathbf{p_T}$ only in 5-10% bin, weak $\mathbf{p_T}$ dependence up to **~1.5 GeV**