The flow harmonics measurements with the event plane and multiparticle cumulant methods in Pb+Pb collisions at 2.76 TeV in ATLAS

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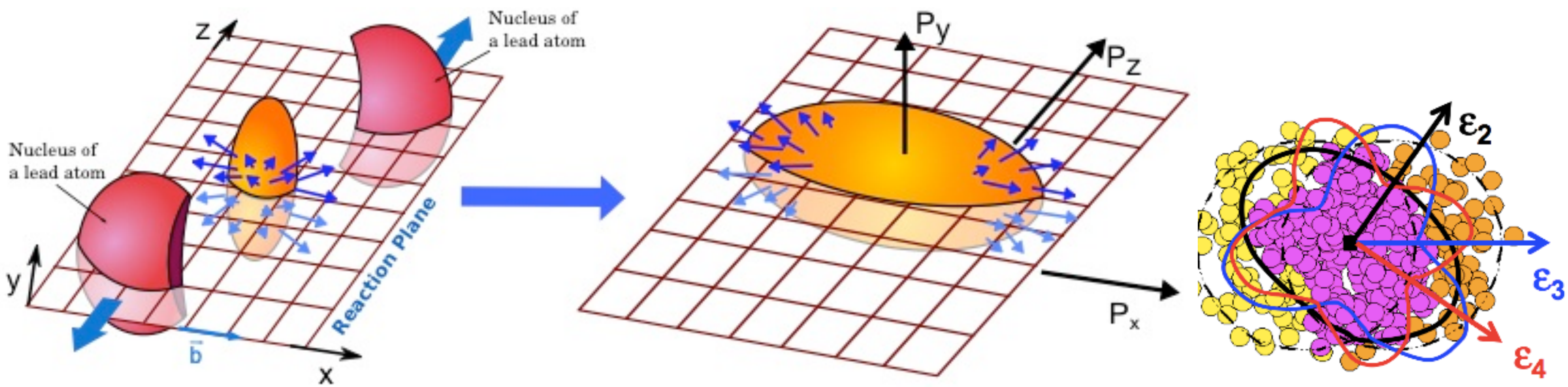
Azimuthal anisotropy of charged particles



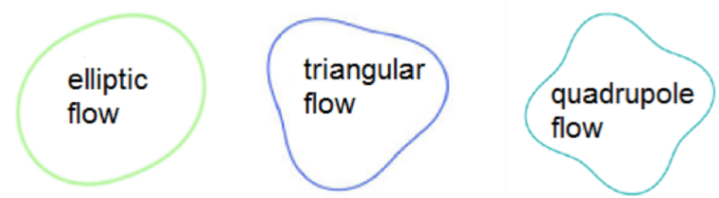
Initial spatial anisotropy → Momentum-space anisotropy

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left[1 + 2\sum_{n=0}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]\right]$$

flow harmonics

shape of participant zone:

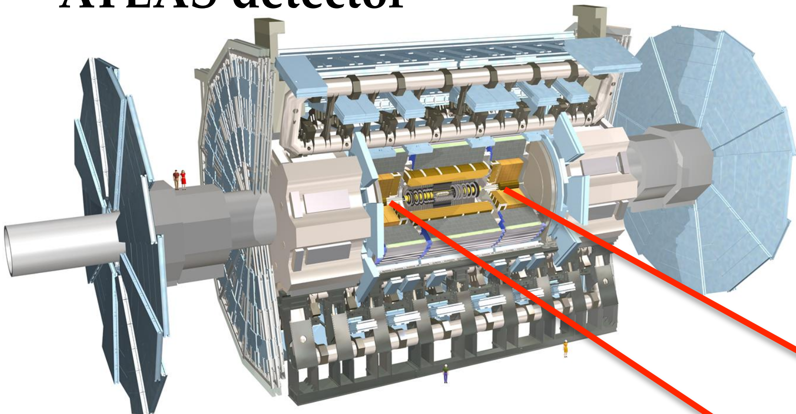
v_2 v_3 v_4



- **Azimuthal anisotropy results from different pressure gradients in different spatial directions**
- **v_2 - elliptical shape of the collision zone**
- **Higher order v_n – initial spatial fluctuations**
- **non-zero v_n measured up to n = 6**
  (ATLAS:Phys.Lett.B 707 (2012) 330-348; Phys.Rev. C86 (2012) 014907)

v_n harmonics measurement

ATLAS detector



Pb+Pb Data 2010

$\sim 7\mu^{-1}$MinBias

$\sqrt{s_{NN}} = 2.76$ TeV

Forward Calorimeter

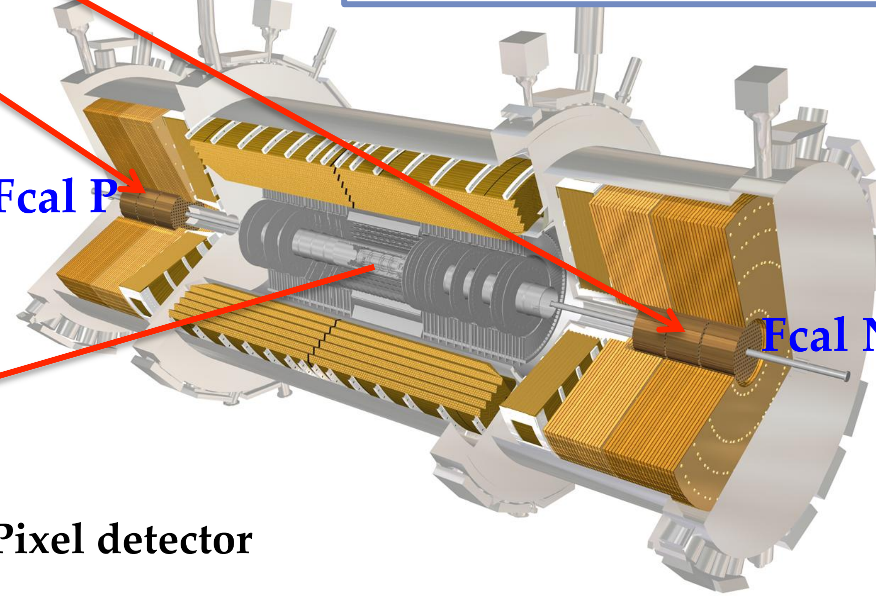
(3.1 < |η| < 4.9)

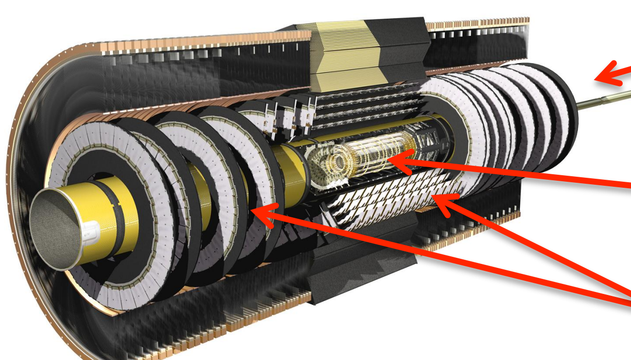
- **Event plane angles are measured using FCal → Ψ^N & Ψ^P**
- **Centrality definition**

Inner Detector (Pixel+SCT)

Flow measurements is based on charged tracks reconstructed in ID

- **|η| < 2.5**
- **2π ϕ acceptance**
- **p_T > 0.5 GeV**





Multiparticle cumulant and event plane methods

Flow harmonics are affected by contributions from particle correlation unrelated to the initial geometry → non-flow effects (correlation due to energy and momentum conservation, resonance decays, jet production…)

Event plane

Phys.Rev.C58:1671-1678,1998

$$v_n = \frac{\langle cos(n[\phi - \Psi_n^{N|P}])\rangle}{R}$$

$$R = \sqrt{\langle cos(n[\Psi_n^N - \Psi_n^P])\rangle}$$

R – event plane resolution

- **η-gap (> 3) to supresses short range correlation**

Cumulant

Phys.Rev. C63 (2001) 054906

- **Cumulant are defined with correlation:**

$$\langle corr_n\{2k\}\rangle = \langle cos[n(\phi_1 + ... - \phi_{k+1} - ...)]\rangle$$

$$c_n\{2\} = \langle corr_n\{2\}\rangle$$ **→ 2 particle cumulant**

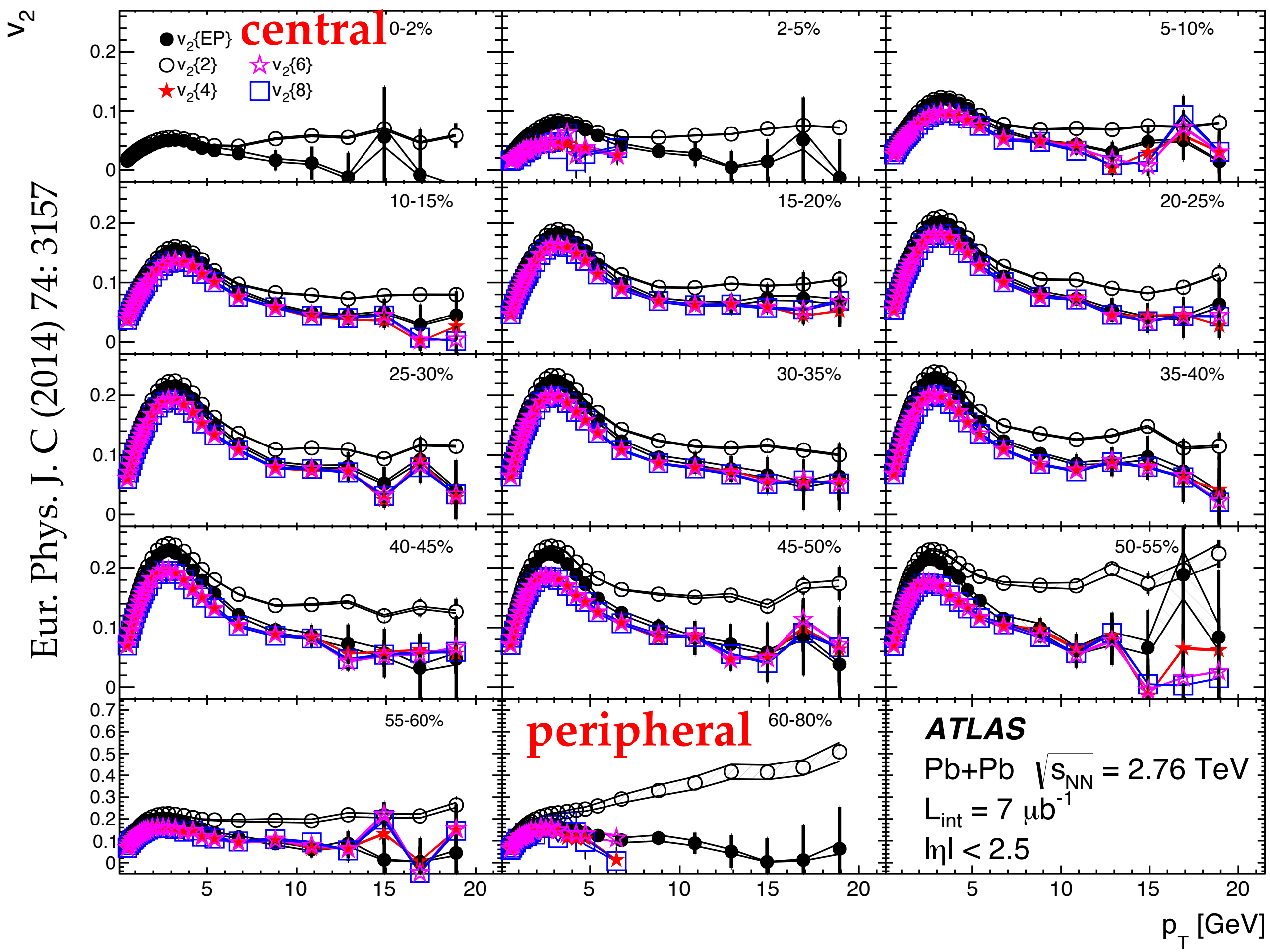
$$c_n\{4\} = \langle corr_n\{4\}\rangle - 2\langle corr_n\{2\}\rangle^2$$ **→ 4 particle cumulant**

$$v_n\{2\} = \sqrt{c_n\{2\}}, \ v_n\{4\} = \sqrt[4]{c_n\{4\}}$$

- **higher order cumulants (>2) do not contain contribution from lower order particle correlation→ supression of non-flow effects**
- **In this analysis cumulants up to 8-th order are calculated using the generating function method (Phys.Rev.C64:054901,2001)**

Elliptic flow for Pb+Pb collisions

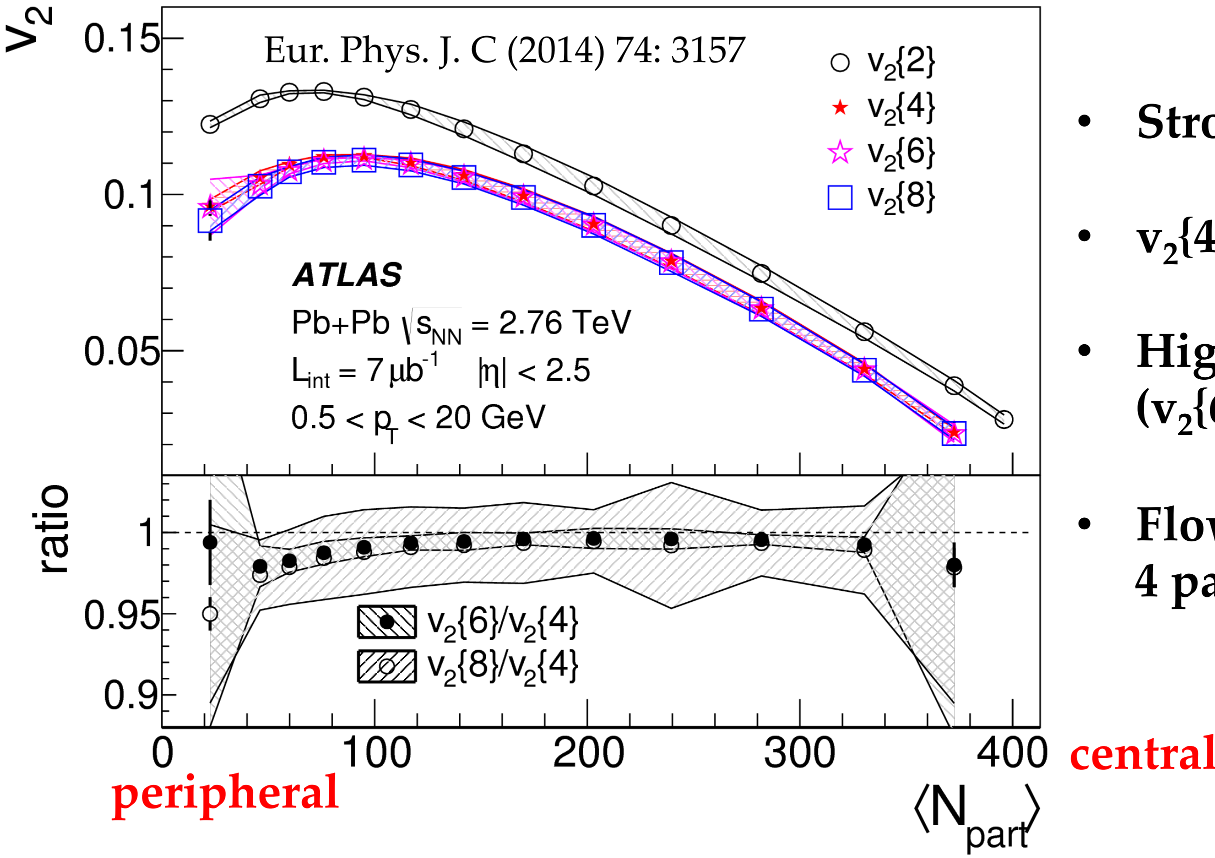
$v_2\{EP\}$ and $v_2\{2,4,6,8\}$



- $v_2\{EP\}$ systematically smaller than $v_2\{2\}$
  → short-range correlation removed due to η-gap
- $v_2\{4,6,8\}$ values lower than $v_2\{2\}$
- $v_2\{4\}$,$v_2\{6\}$ and $v_2\{8\}$ consistent
  → non-flow suppression

$v_2\{2\} > v_2\{EP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$

Centrality dependence of the integrated elliptic flow harmonics
$v_2\{2,4,6,8\}$

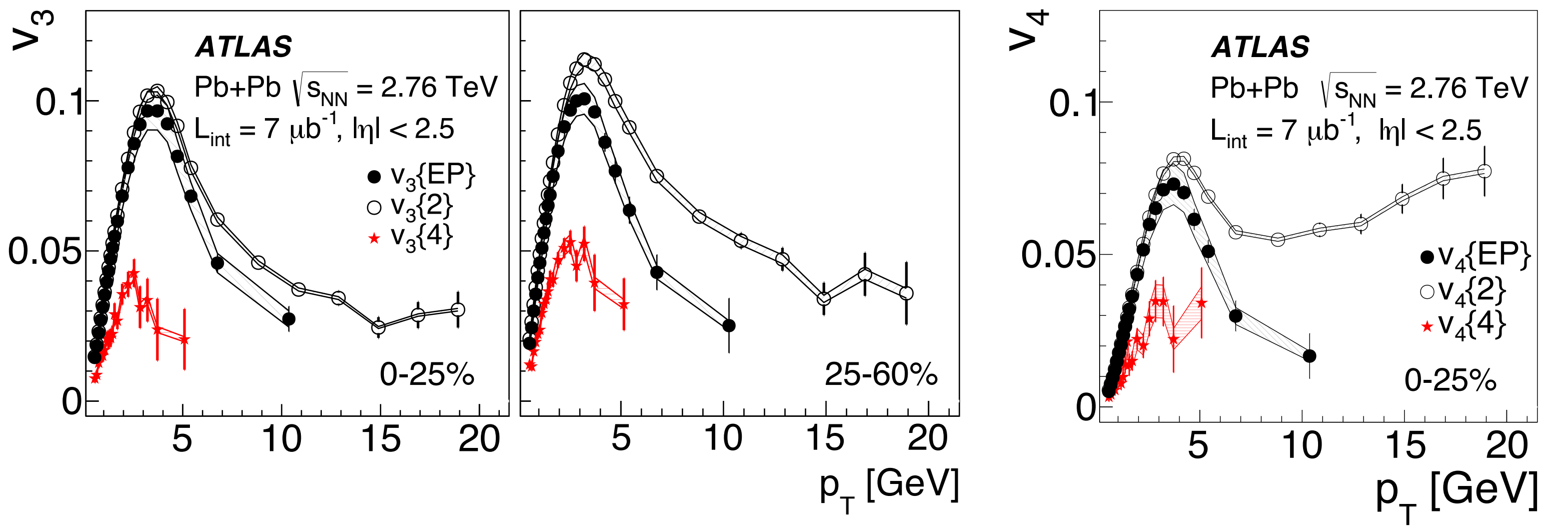


- **Strong centrality dependence**
- **$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$**
- **Higher order flow cumulants ($v_2\{6,8\}$) are consistent with $v_2\{4\}$**
- **Flow effects excluded from 4 particle correlation**

$< N_{part} >$ – average number of interacting nucleons (wounded)

Higher order flow coefficients

$v_{3/4}$\{EP\} and $v_{3/4}$\{2,4\}

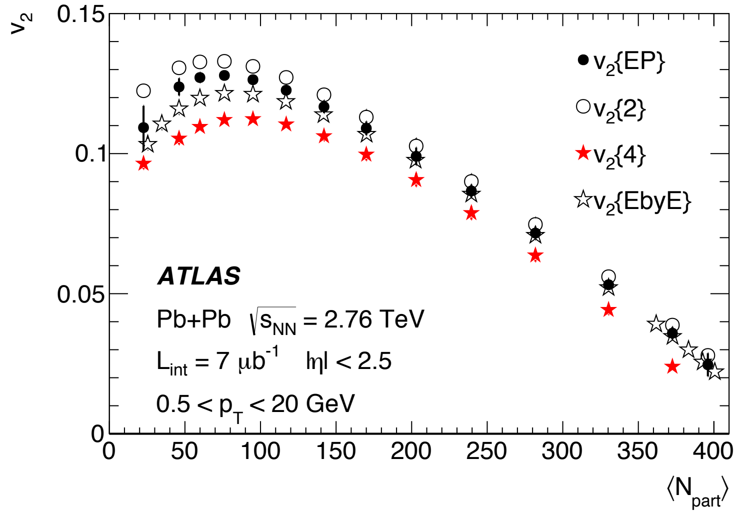


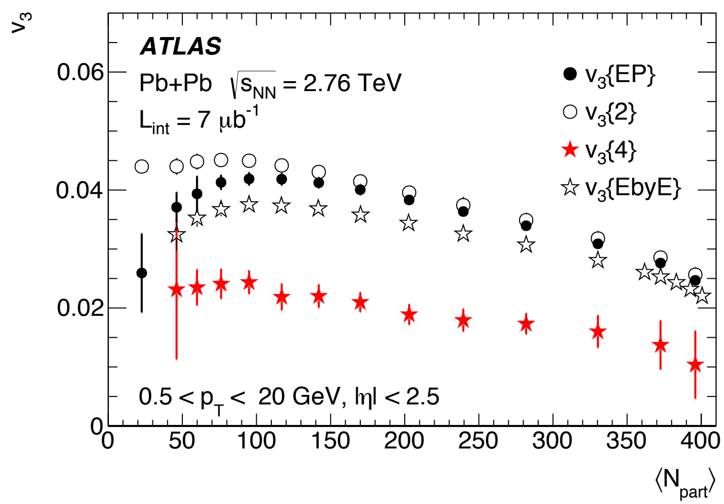
Eur. Phys. J. C (2014) 74: 3157

- $v_n\{2\} > v_n\{EP\} > v_n\{4\}$
- **Difference between $v_n\{4\}$ and $v_n\{EP\}$ (~50%) larger than for v_2 (~30%)**
- **Fluctuation of higher-order harmonics much stronger than fluctuations of v_2**

Centrality dependence of the integrated flow harmonics

v_n\{EP\} and v_n\{2,4\}





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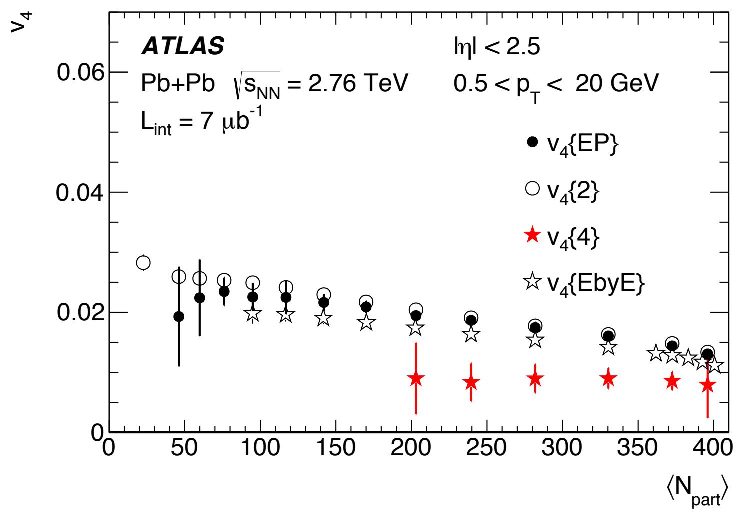


- $v_n\{2\} > v_n\{EP\} > v_n\{4\}$
- strong centrality dependence of v_2\{2,4\} and v_2\{EP\}
- weak centrality dependence of v_n\{2,4\} and v_n\{EP\} (n = 3,4)

Summary

- High-precision measurements of azimuthal anisotropy in Pb+Pb collisions performed in the ATLAS experiment

- Elliptic flow $v_2\{2,4,6,8\}$ and $v_2\{EP\}$ were measured in broad range of centrality, η (|η|<2.5) and p_T ($0.5 < p_T < 20$ GeV)

- Higher order cumulants in Pb+Pb collisions:
  - Reduction of flow harmonics

    $v_2\{2\} > v_2\{EP\} > v_2\{4\}$

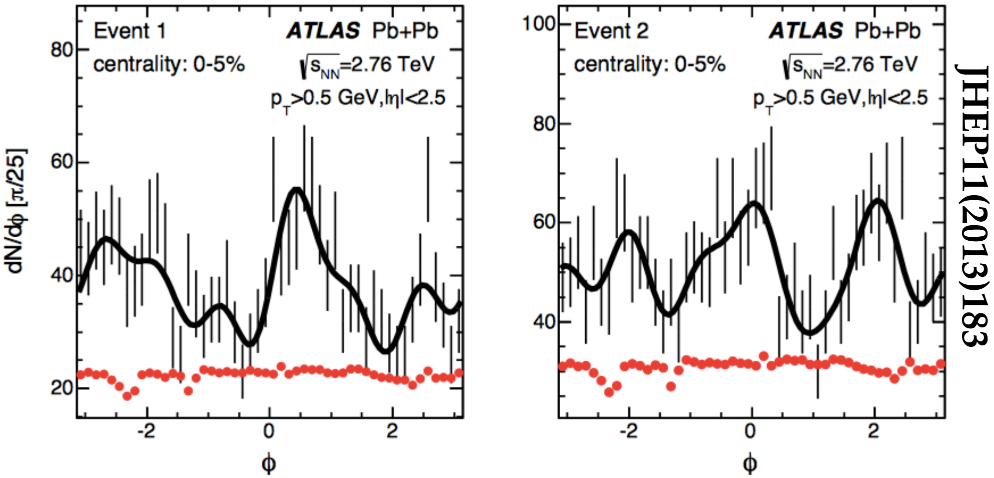
    $v_3\{2\} \gg v_3\{4\}$, $v_4\{2\} \gg v_4\{4\}$
  - Non-flow effects supressed ($v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$)
  - Several measurements of the same harmonics

- Azimuthal anisotropy is one of signatures of Quark-Gluon Plasma

Backup slides

Event by Event (EbyE) measurement

Azimuthal distributions of charged particles in single events:

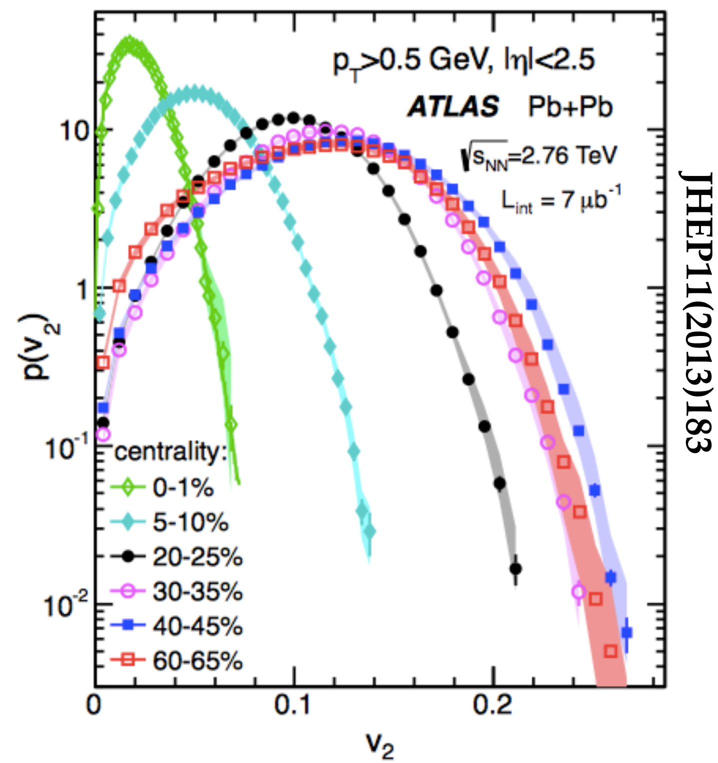


- $v_n\{2k\}$ coefficients can be calculated analytically from the moments of EbyE v_n distributions, $p(v_n)$, e.g.

$$v_n^{calc}\{4, \text{EbyE}\} = -\langle v_n^4 \rangle + 2\langle v_n^2 \rangle^2$$

$$\langle v_n^k \rangle = \sum v_n^k p(v_n)$$

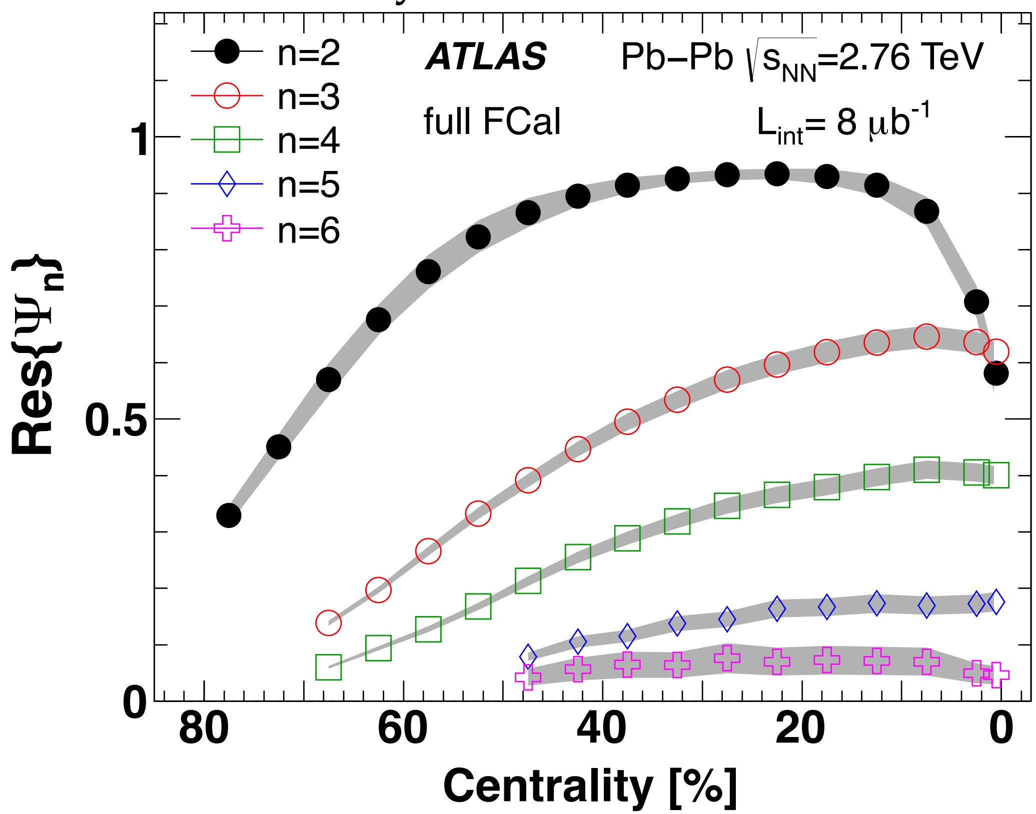
- Response function (unfolded distribution of v_2):



- v_n distributions widen from central to peripheral events

Event plane resolution

Phys.Rev. C86 (2012) 014907



- **The event plane resolution R is obtained using two sub-events**
- **Significant resolution for harmonics n = 2 – 6**
- **Flow harmonics:**

$$v_n = \frac{\langle cos(n[\phi - \Psi_n^{N|P}])\rangle}{R}$$

$$R = \sqrt{\langle cos(n[\Psi_n^N - \Psi_n^P])\rangle}$$

- **Reaction plane (Ψ^{RP}) is estimated using event plane ($\Psi_n^{N|P}$) measured in FCal:**

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

N – negative η
P – positive η

Centrality definition

Phys.Lett. B707 (2012) 330-348