Recent Results on Flow and Correlations in Heavy Ion Collisions from the ATLAS Experiment

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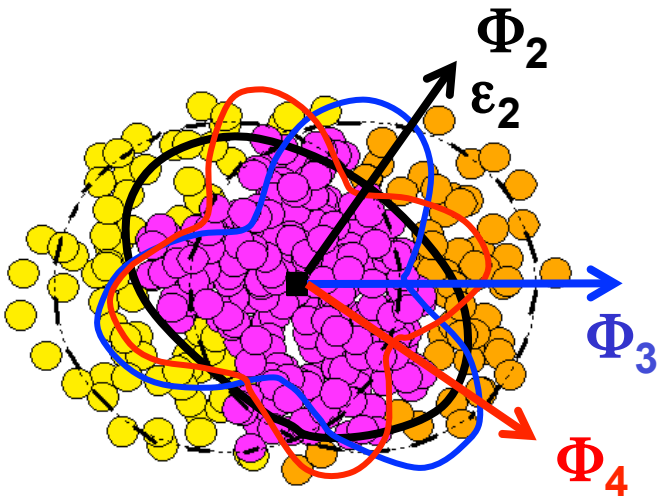
Azimuthal Anisotropy of Produced Particles



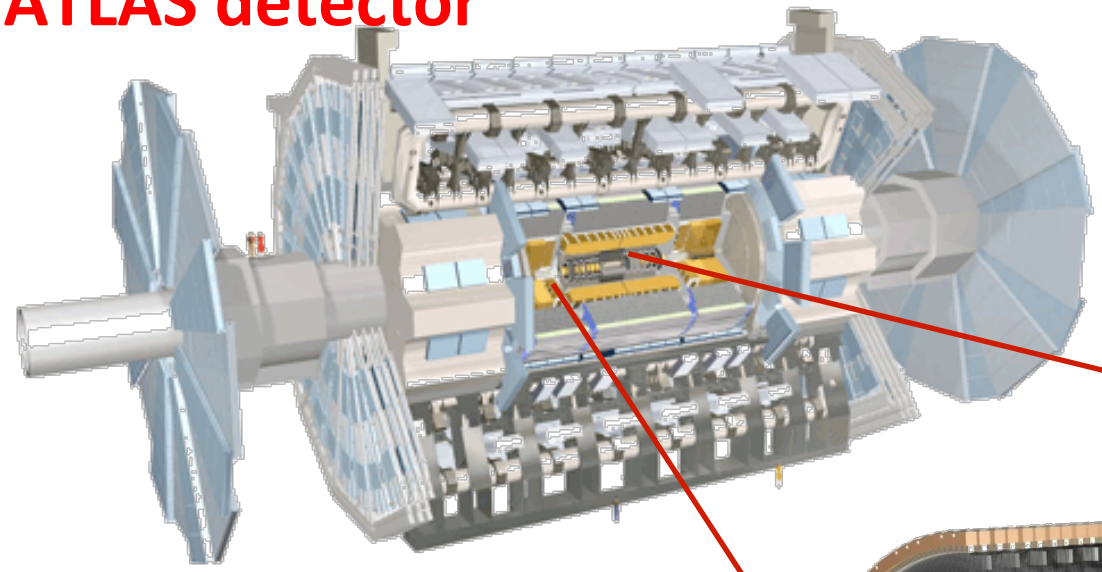
- **Pressure gradients in the formed dense system induce azimuthal anisotropy**

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]$$

- **v_n Fourier harmonics are sensitive to the initial geometry (v_2) and its fluctuations (higher orders, v_3, v_4, …)**

v_n Harmonics Measurement

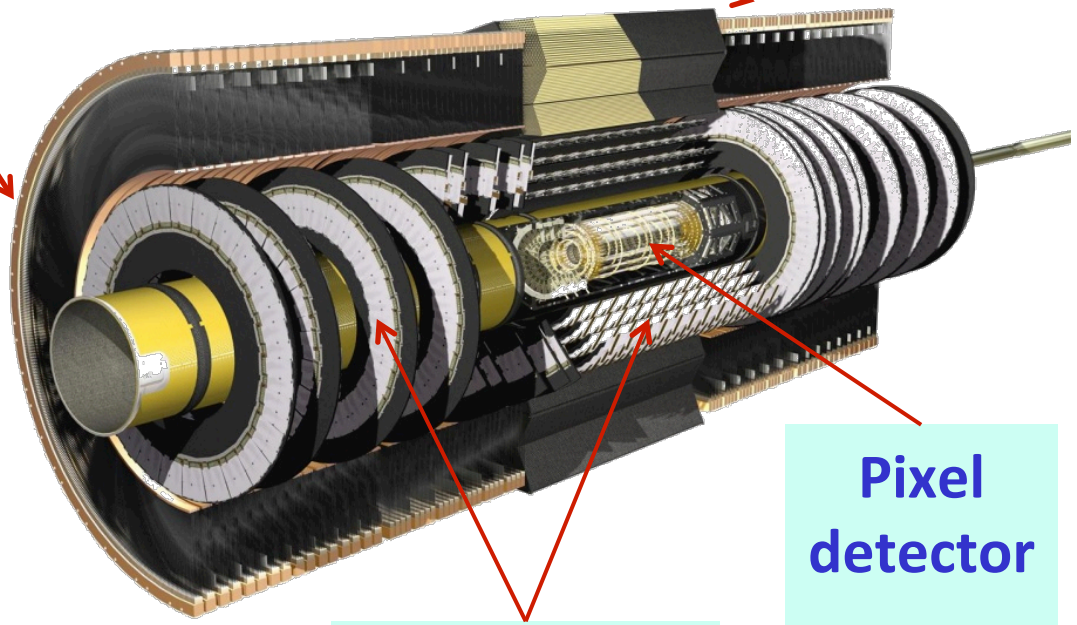
ATLAS detector



Pb+Pb ~7μb^{-1} MB (50M ev.)
$\sqrt{s_{NN}} = 2.76$ TeV

p+Pb ~28nb^{-1} MB+HMT
$\sqrt{s_{NN}} = 5.02$ TeV

Inner detector, ID



Pixel detector

SCT detector

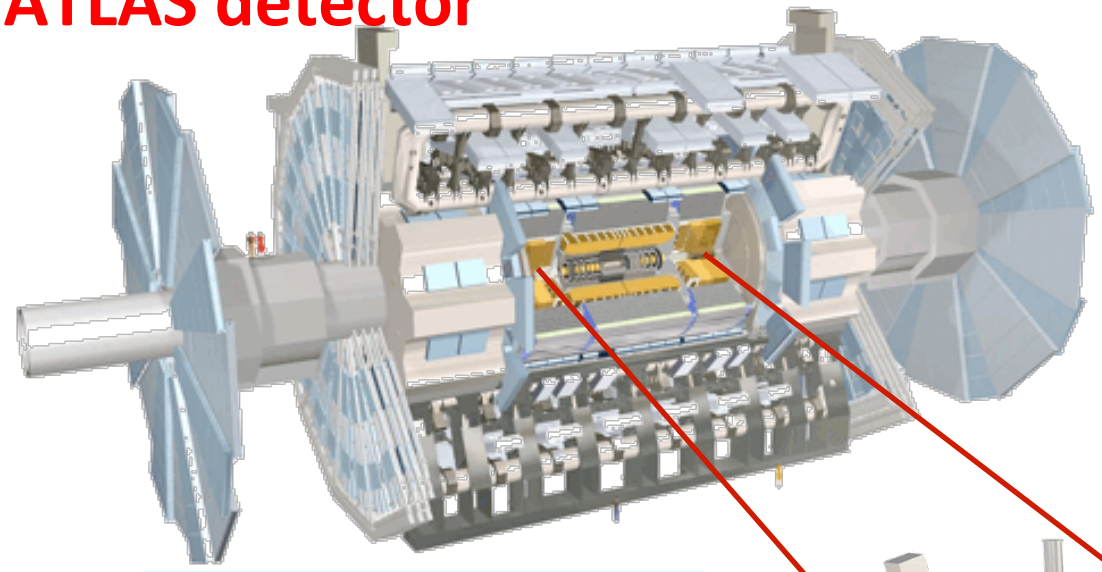
Fourier harmonics are measured with charged particles reconstructed in the inner detector

ID tracks (Pixel+SCT)

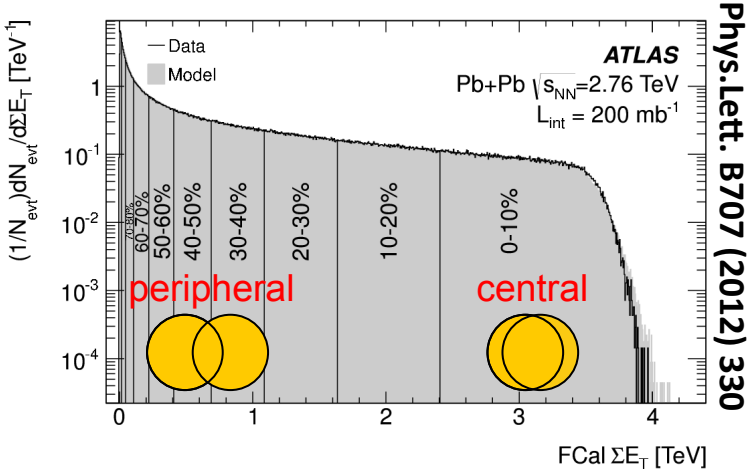
- $|\eta| < 2.5$, 2π ϕ acceptance
- $p_T > 0.5$ GeV for Pb+Pb
  > 0.3 GeV for p+Pb

Event Centrality/Activity in Pb+Pb and p+Pb

ATLAS detector

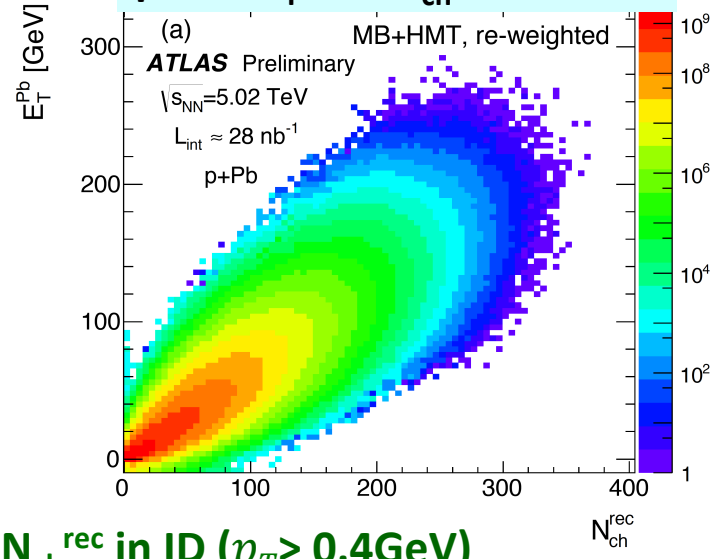


Pb+Pb: FCal ΣE_T



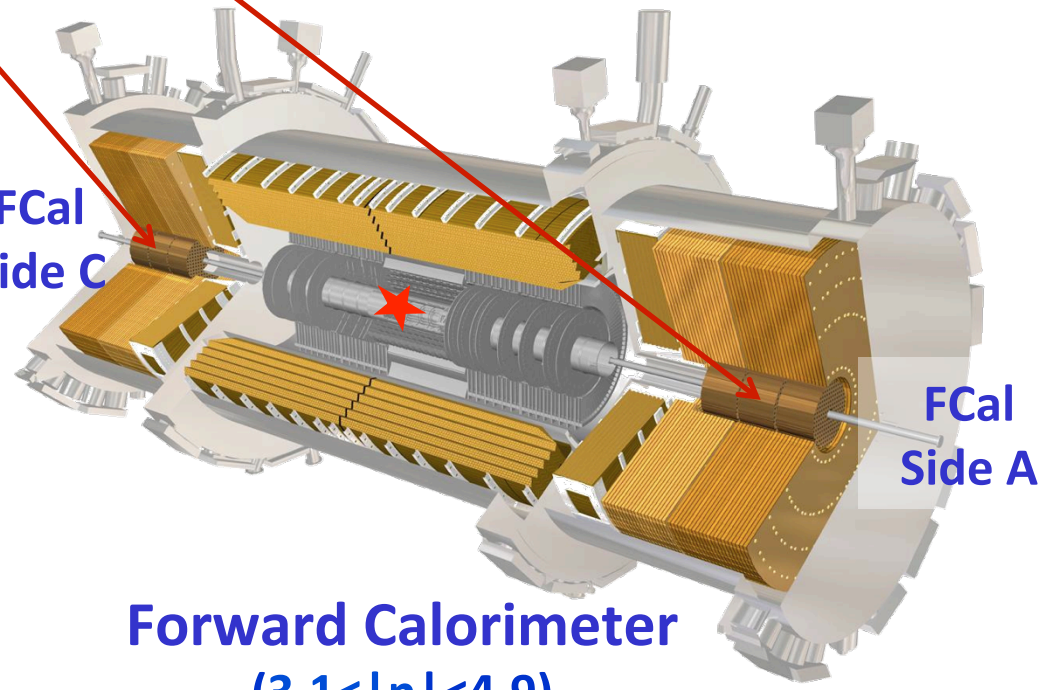
Phys.Lett. B707 (2012) 330

p+Pb: E_T^{Pb} vs N_{ch}^{rec}



N_{ch}^{rec} in ID (p_T> 0.4GeV)

E_T^{Pb} in FCal on Pb-going side



Forward Calorimeter

(3.1<|η|<4.9)

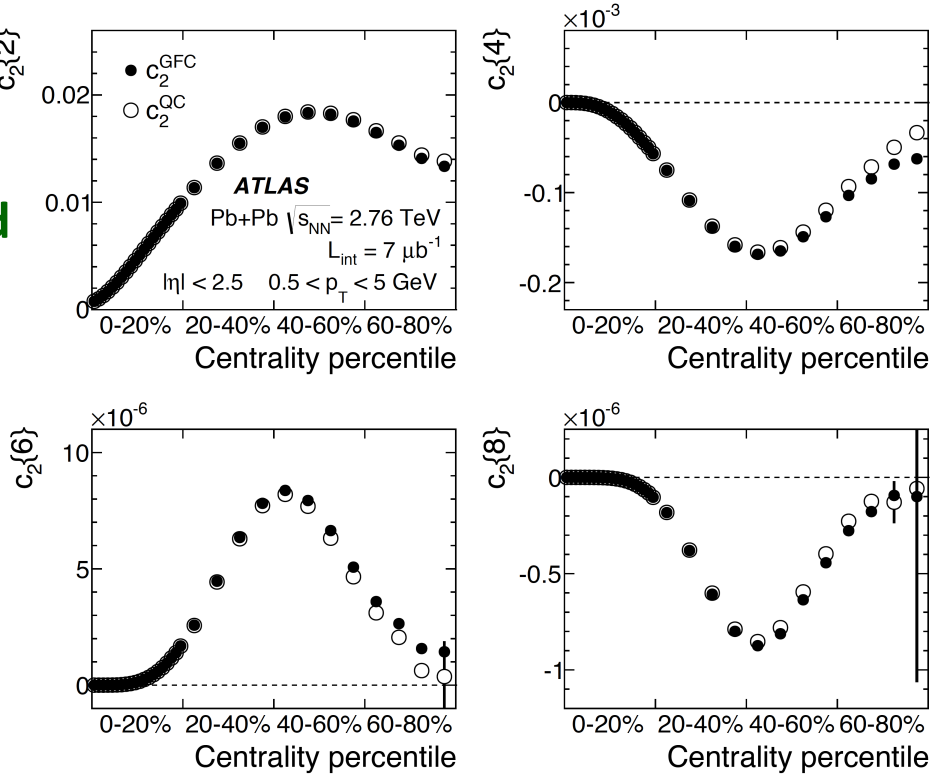
The Multiparticle Cumulat Method

- **Recently ATLAS has measured v_n using multiparticle correlations/ cumulants**

$$\left\langle corr_n\{2k\}\right\rangle \equiv \left\langle \cos[n(\varphi_1 + \ldots - \varphi_{k+1} - \ldots.)]\right\rangle = \left\langle v_n^{2k}\right\rangle$$

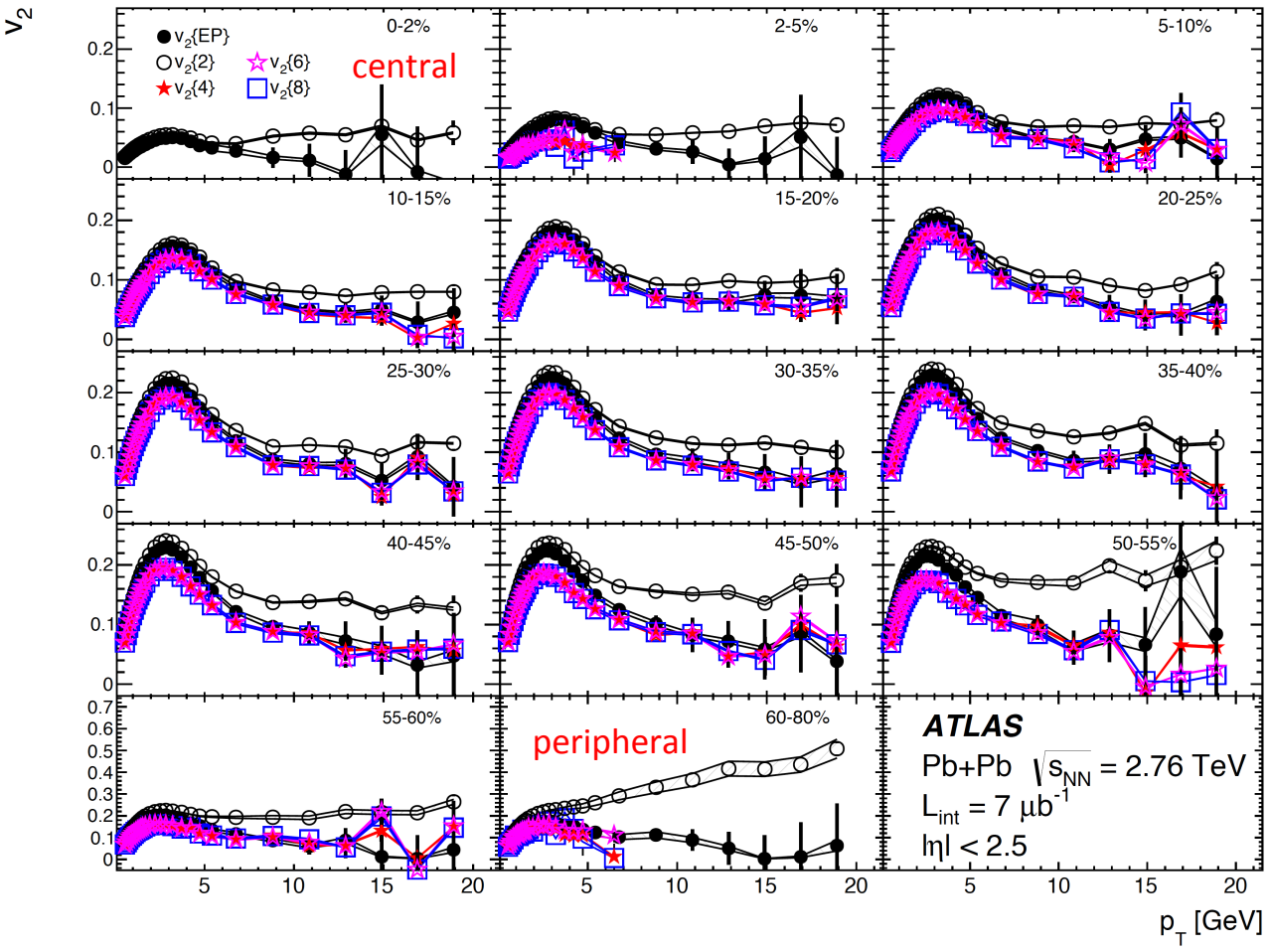
- **Using higher order cumulants, correlations not related to the initial geometry are suppressed**
  - **Generating function method is used to obtain multiparticle correlations**
  - **GFC and QC methods give similar results in broad centrality range**
- **Centrality range limited to**
  - **2-80% for v_2**
  - **0-60% for v_3**
  - **0-25% for v_4**

arXiv:1408.4342



Eliptic Flow, $v_2\{2,4,6,8\}$, for Pb+Pb Collisions

arXiv:1408.4342



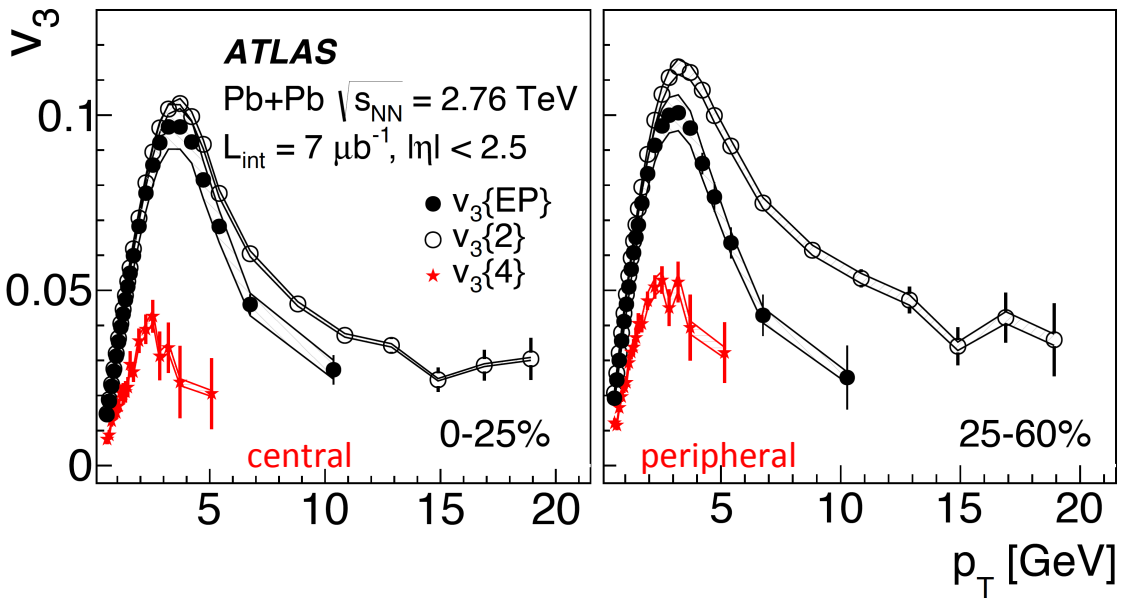
- $v_2\{2\}$ shows the strongest flow signal (jet-like correlations visible at high p_T)

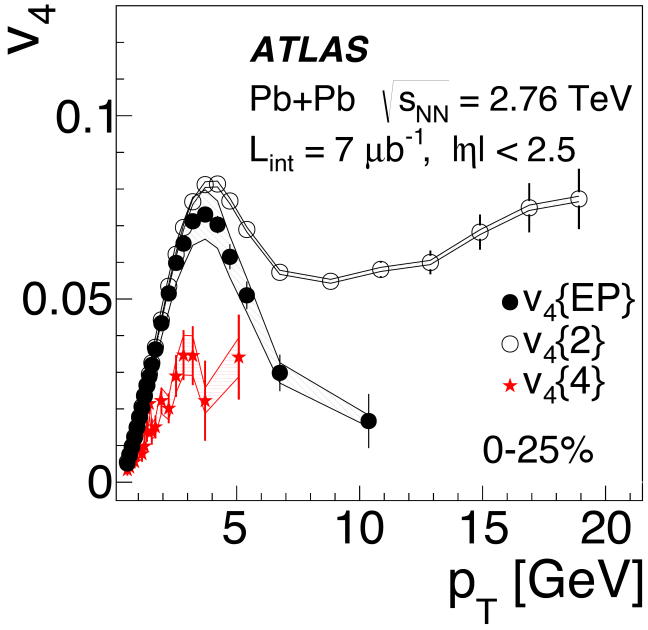
- Lower values of v_2 are obtained for 4-, 6-, 8-particle cumulants:

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

Higher Order Flow Harmonics: $v_3\{2,4\}$, $v_4\{2,4\}$

arXiv:1408.4342



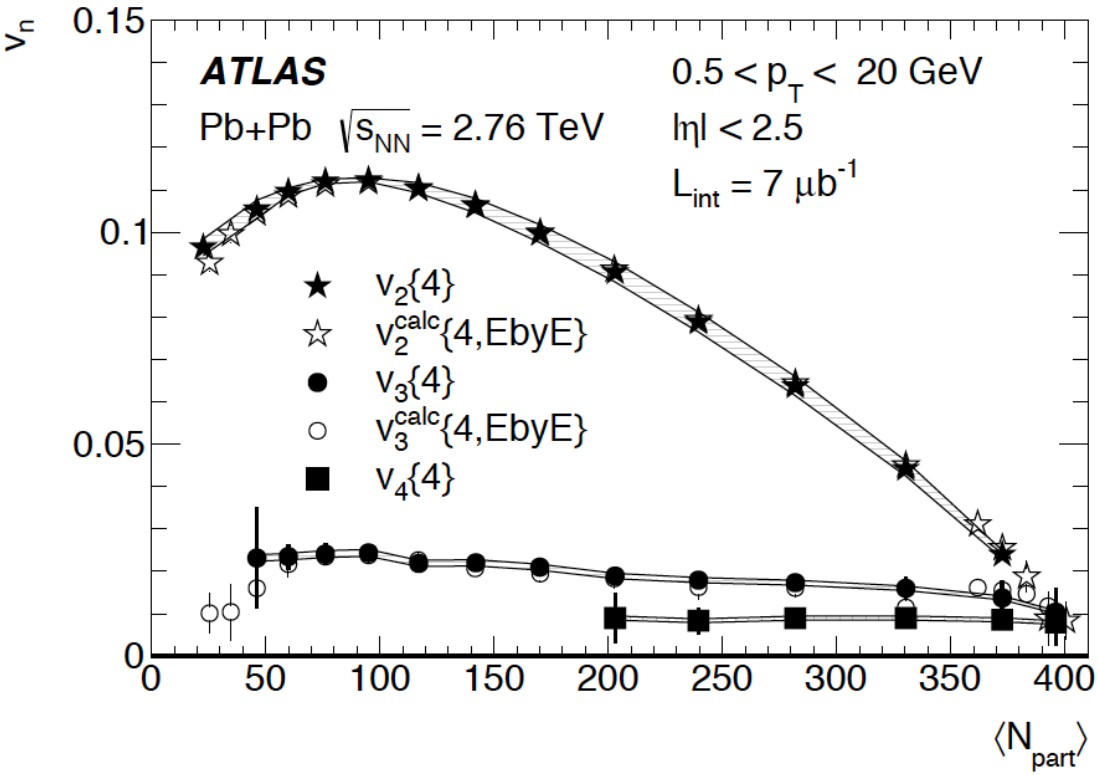


- **Significant values of $v_3\{4\}$ and $v_4\{4\}$ are measured**

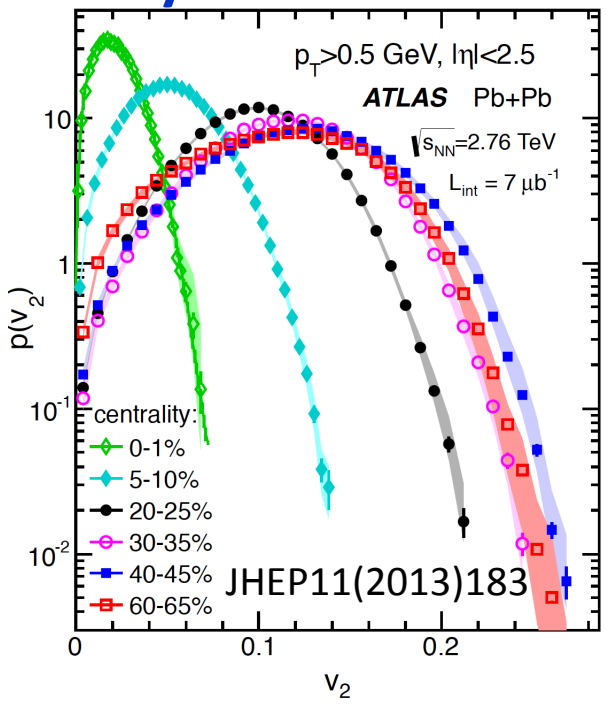
$$v_n\{2\} > v_n\{EP\} > v_n\{4\}$$

$v_n\{4\}$ vs $\langle N_{part} \rangle$

arXiv:1408.4342



EbyE method



- Strong centrality dependence of v_2
- $v_2\{4\} >> v_3\{4\} > v_4\{4\}$
- Weak centrality dependence of v_3 and v_4
- Good agreement between $v_{2,3}\{4\}$ and $v_{2,3}^{calc}\{4,EbyE\}$

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

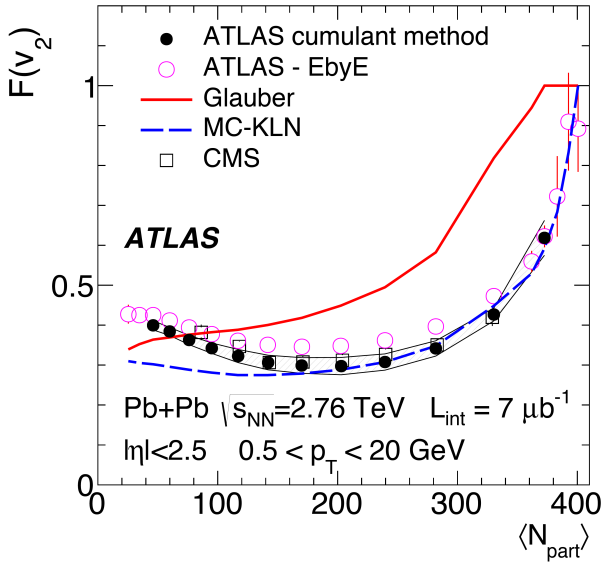
$$v_n^{calc}\{4,EbyE\} = -\left\langle v_n^4 \right\rangle + 2\left\langle v_n^2 \right\rangle^2$$

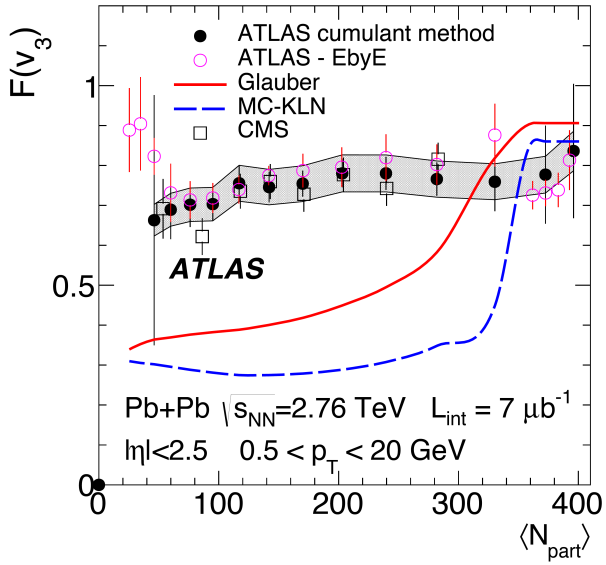
Event-by-Event Fluctuations of v_n

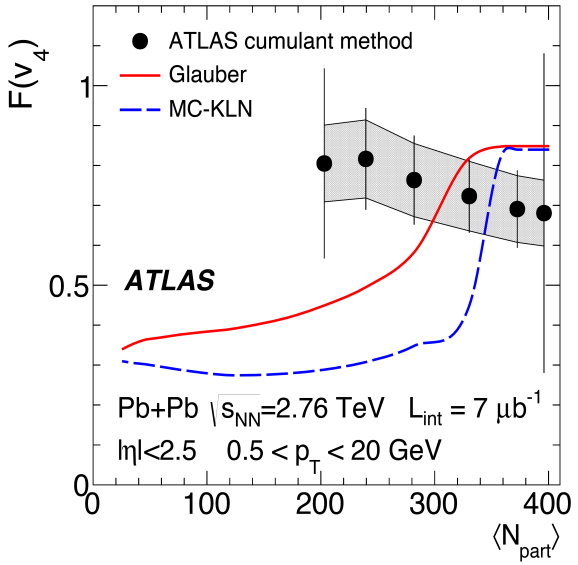
Measure of event-by-event flow harmonics fluctuations:

$$F(v_n) = \sqrt{\frac{v_n\{EP\}^2 - v_n\{4\}^2}{v_n\{EP\}^2 + v_n\{4\}^2}}$$

arXiv:1408.4342



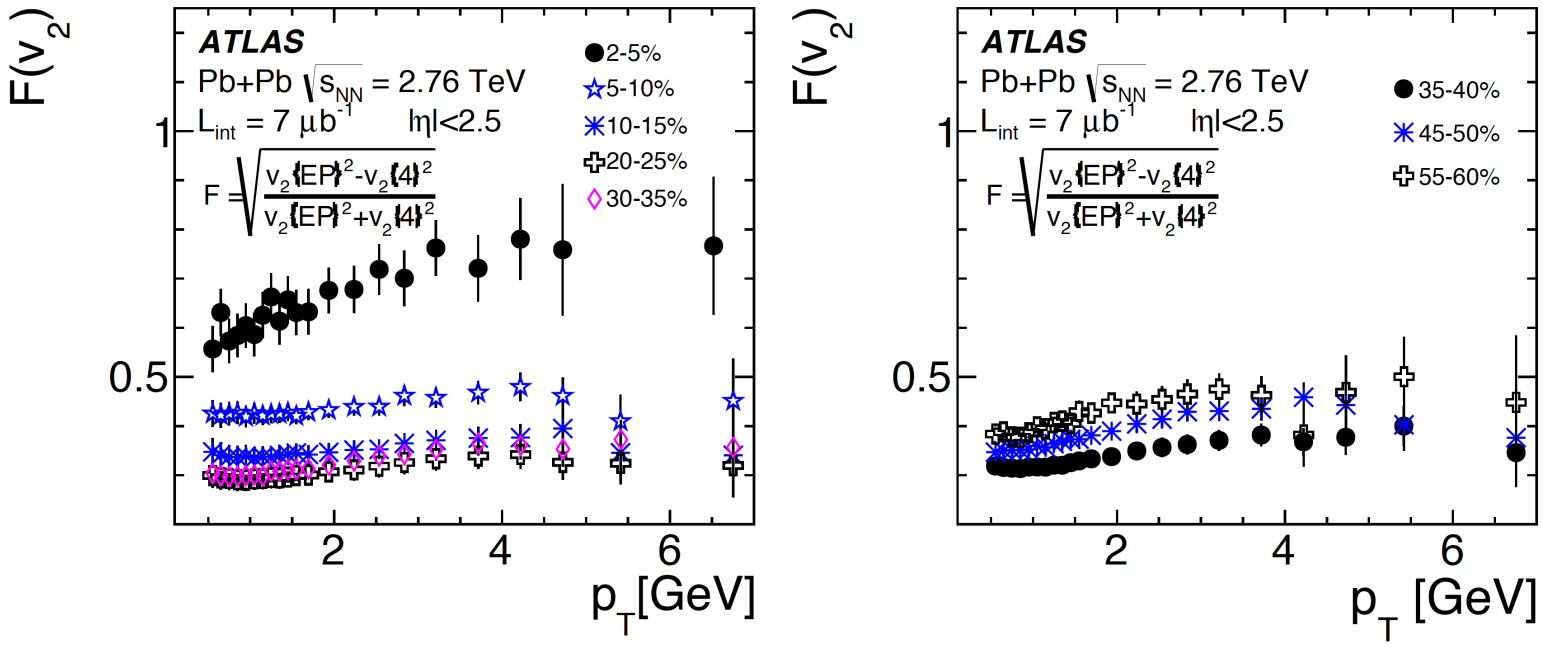




- Large magnitudes of F are obtained for v_2 (in central), v_3 and v_4
- For v_2 strong centrality dependence is observed with smallest fluctuations for mid-central collisions
- $F(v_2)$ and $F(v_3)$ consistent with EbyE and CMS measurements
- MC models of initial geometry fail to describe these fluctuations

Event-by-Event Fluctuations of v_2 vs p_T

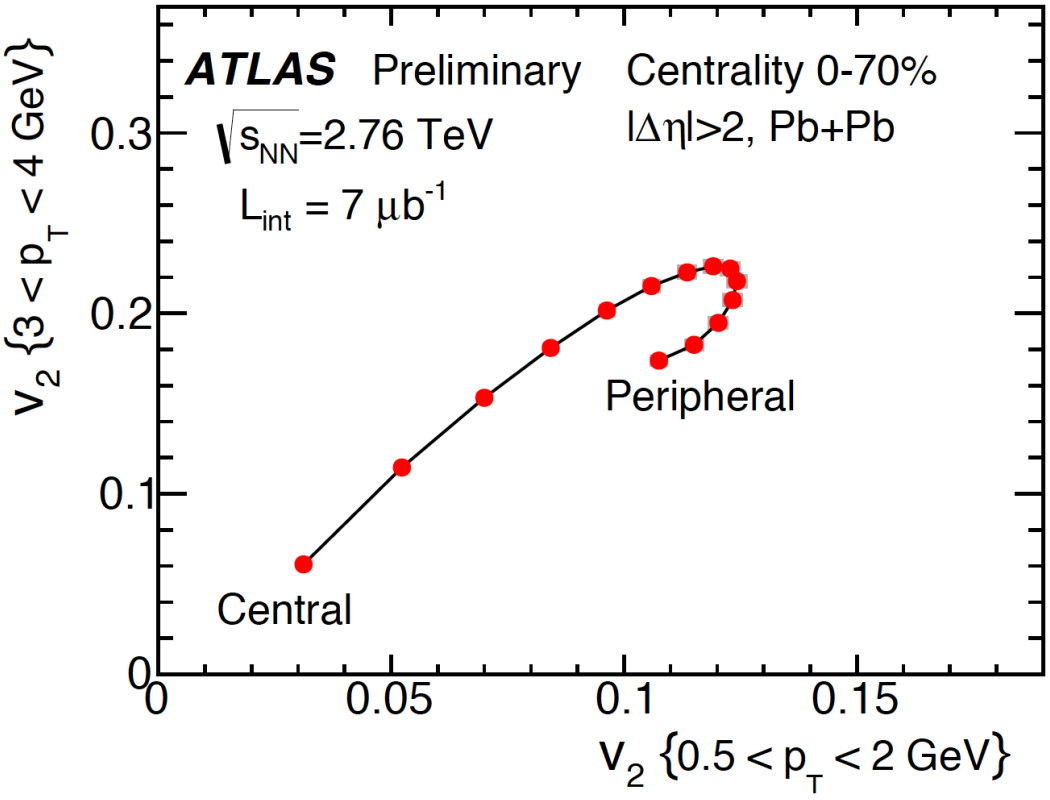
arXiv:1408.4342



- **Flow fluctuations depend weakly on p_T , with exception of 2-5% centrality bin where a significant increase of the flow fluctuations is observed with increasing p_T**

Pb+Pb Event–Shape Engineering

Study v_n correlations using the two-particle correlation method.
To suppers non-flow effects gap of $|\Delta\eta| > 2$ was used



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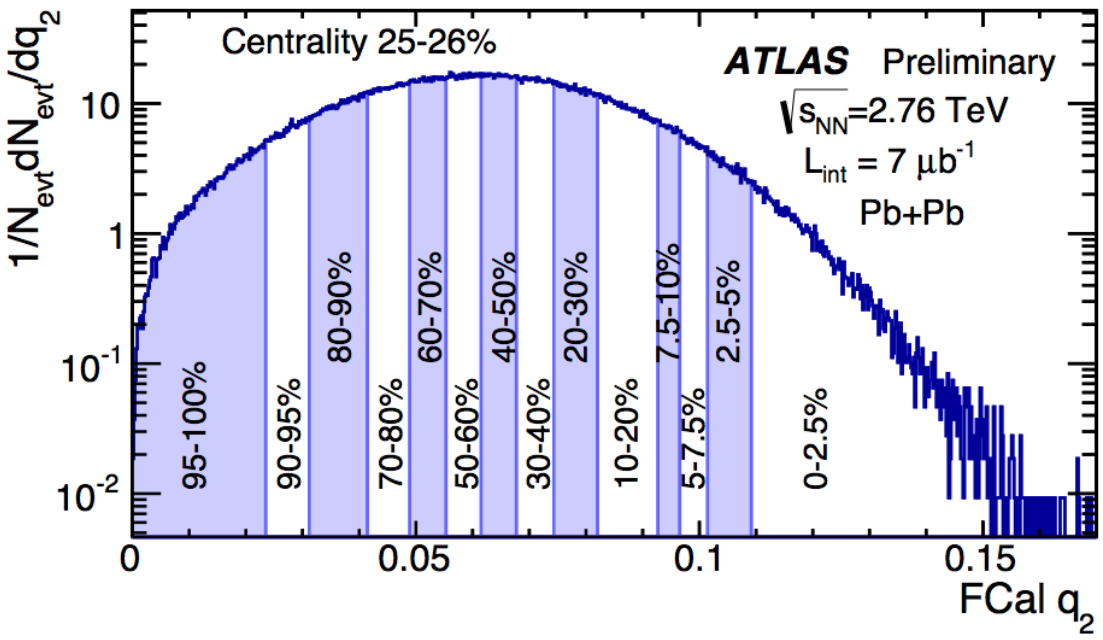
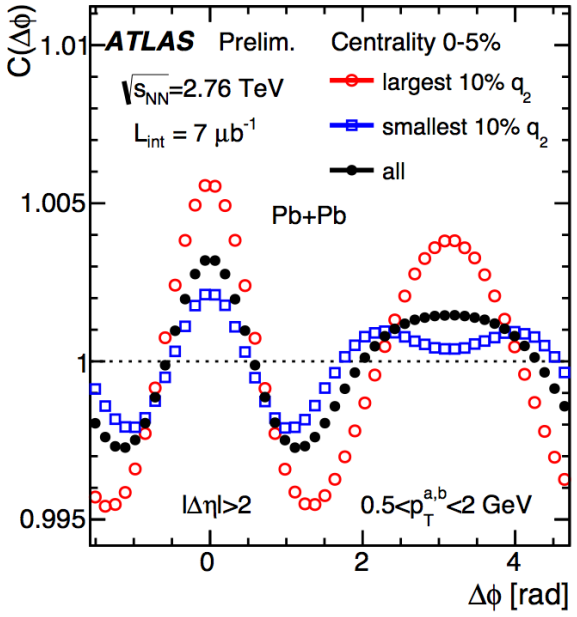
Non monotonic (boomerang-like) variations of v_2 correlations in 5% centrality bins are observed ⇒Viscosity dumping effect?

Event–shape Selection (q_2)





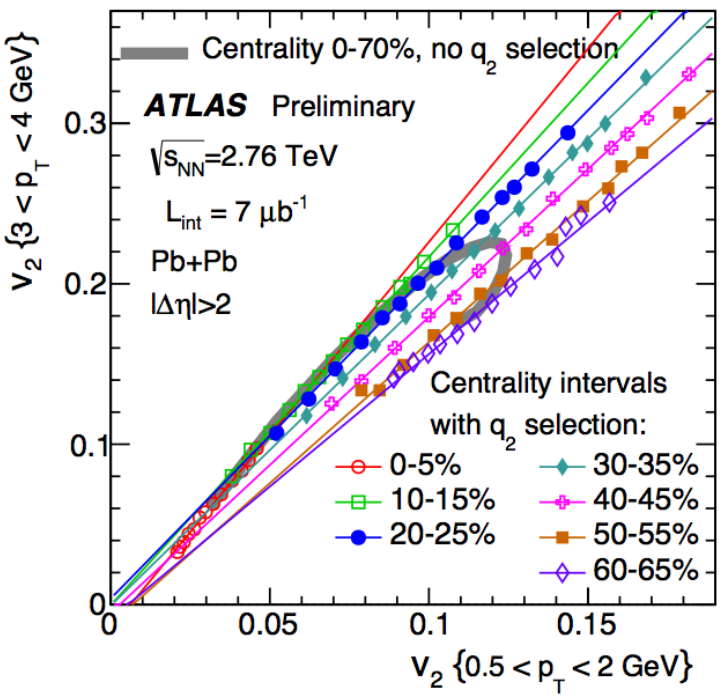
q_2 flow vector calculated using FCal tower transverse energies ($w_i=E_T$)

$$\vec{q}_2 \quad = \quad (q_{x,2}, q_{y,2}) = \frac{1}{\Sigma w_i}(\Sigma[w_i \cos 2\phi_i], \Sigma[w_i \sin 2\phi_i]) - \langle \vec{q}_2 \rangle_{evts}$$

q_2 selects events of different shapes in each centrality bin

Events with larger q_2 have "more elliptic" geometry

v_2-v_2 Correlations in q_2



Within one centrality bin the correlation v_2-v_2(high p_T) is linear

- **Indicates that viscous correction are controlled by system size, not shape**
- **Correlation well parameterized by linear function**

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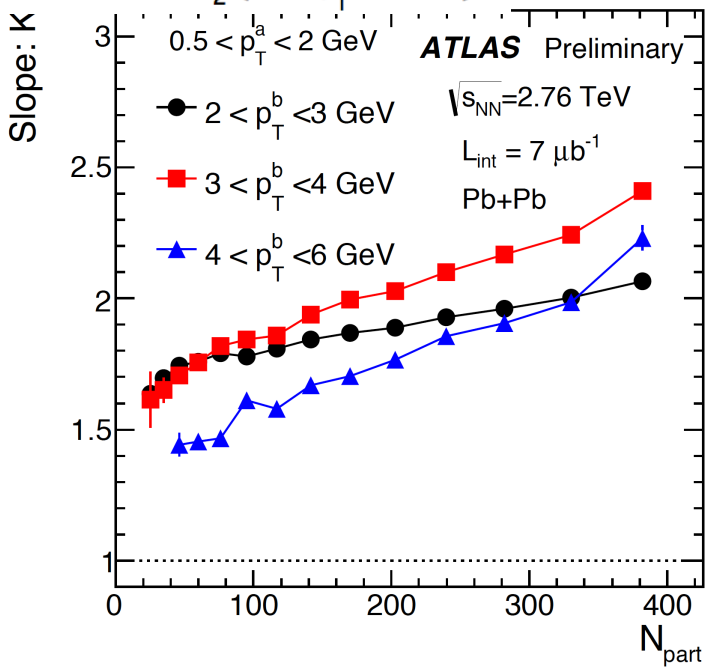
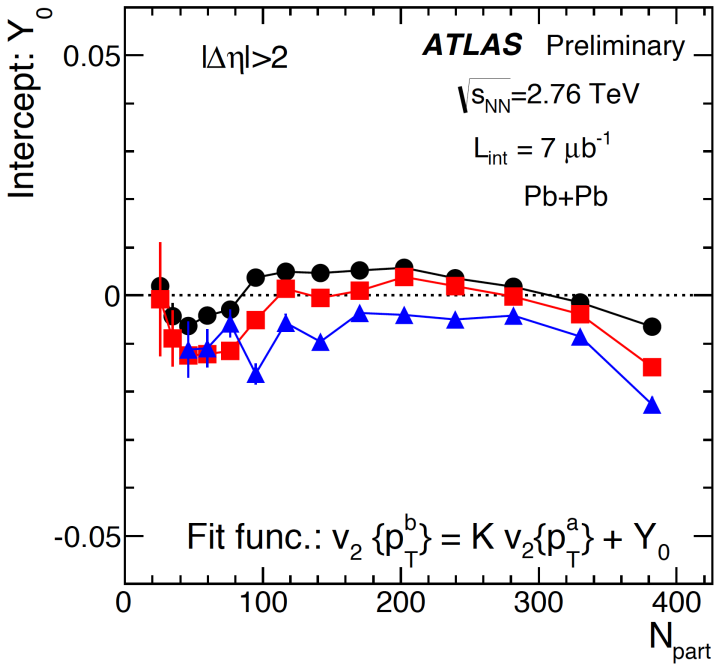
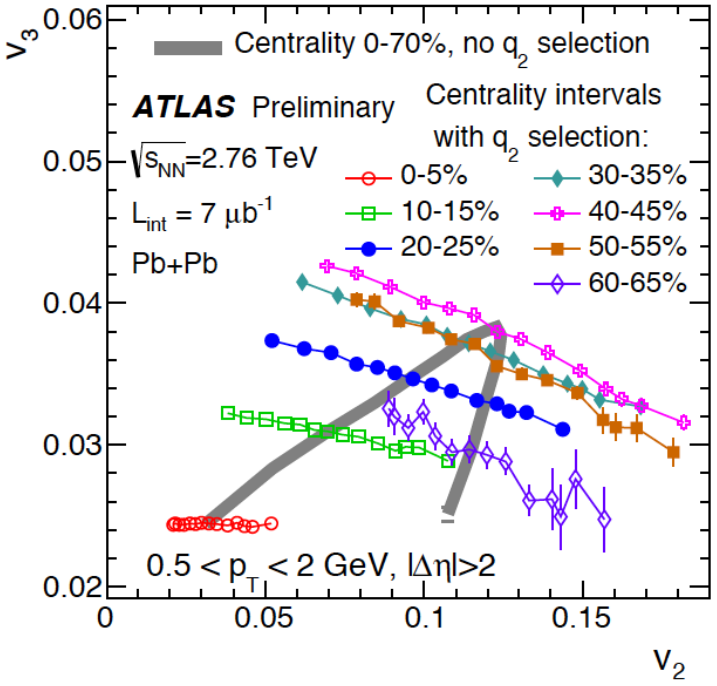




v_2-v_3 Correlations



Anti-correlation between v_2 and v_3 at fixed centrality

- **Driven by the initial eccentricities: $v_2 \sim \varepsilon_2$ and $v_3 \sim \varepsilon_3$, (e.g. expected in multi-phase transport model)**
- **Correlations well parameterized by linear function**

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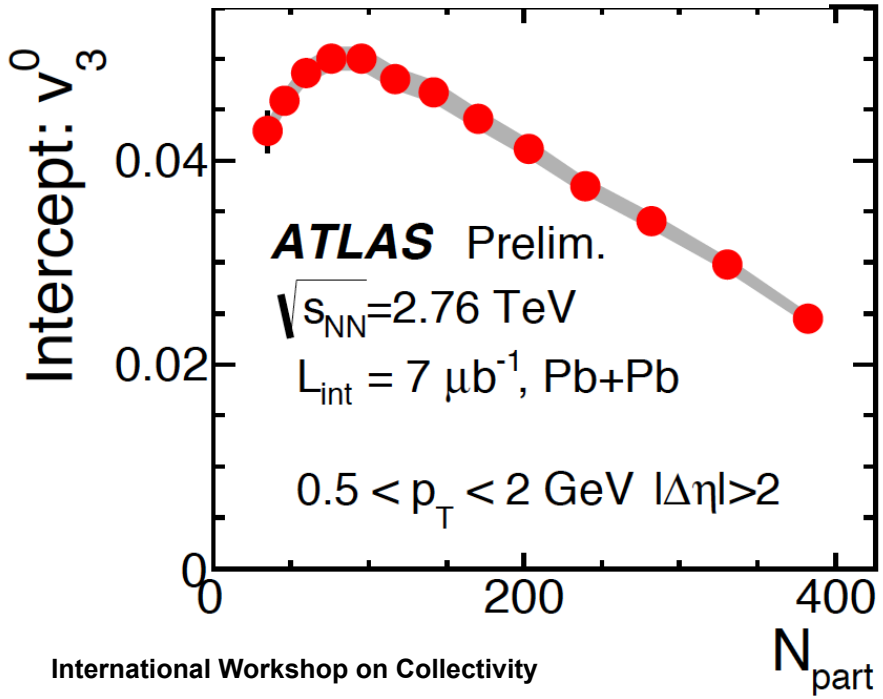
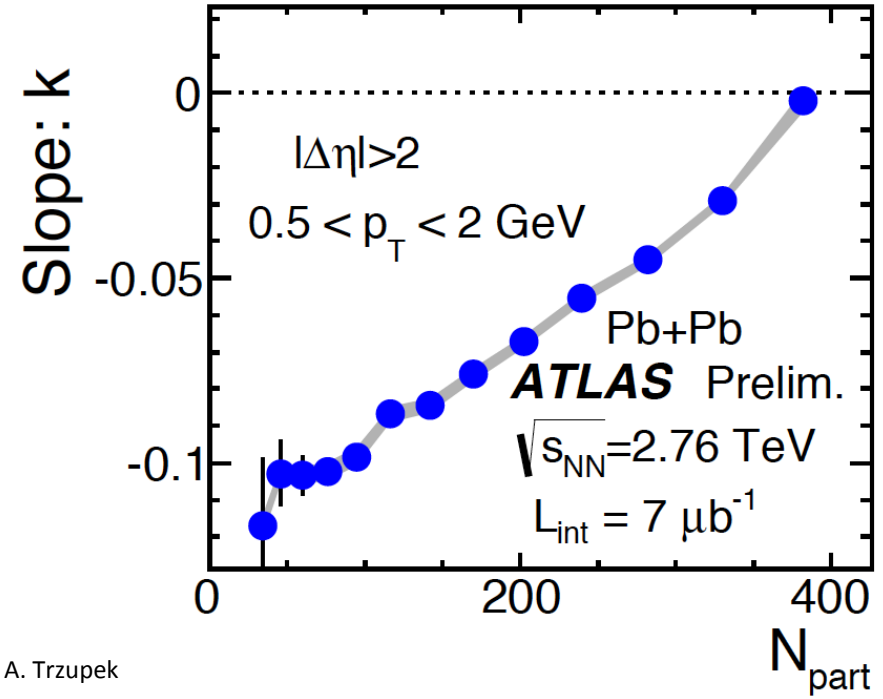
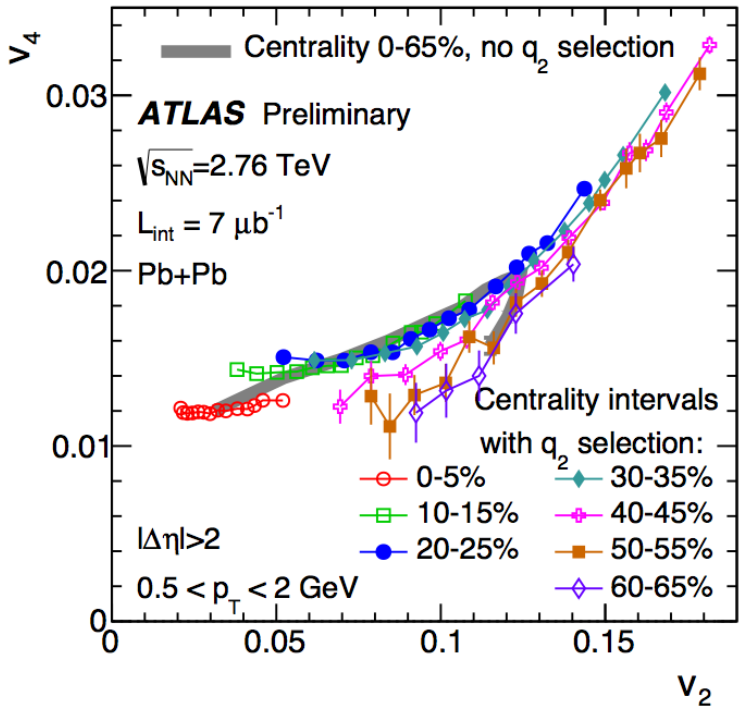




v_2-v_4 Correlations



- **Observe non-linear correlations between v_2 and v_4, well parameterized by**

$$v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$$

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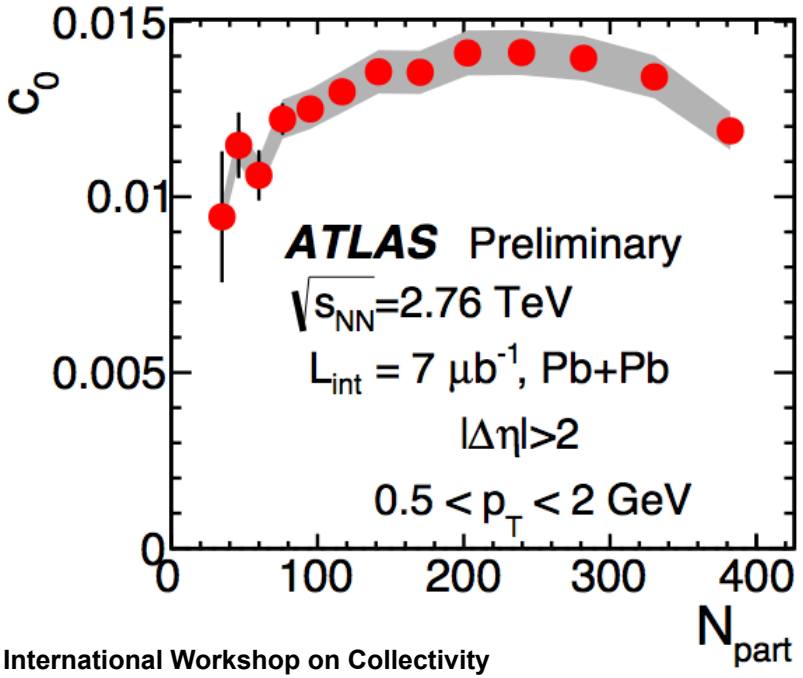
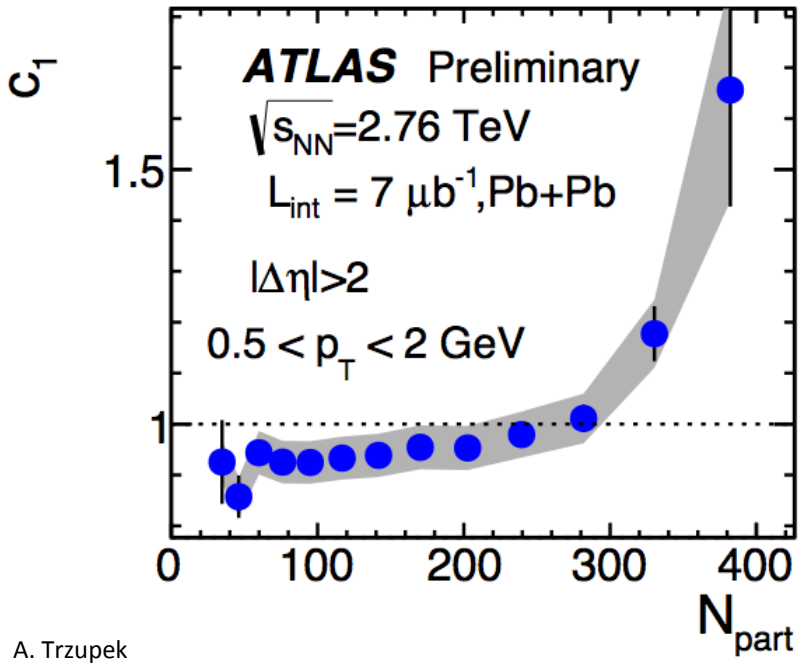




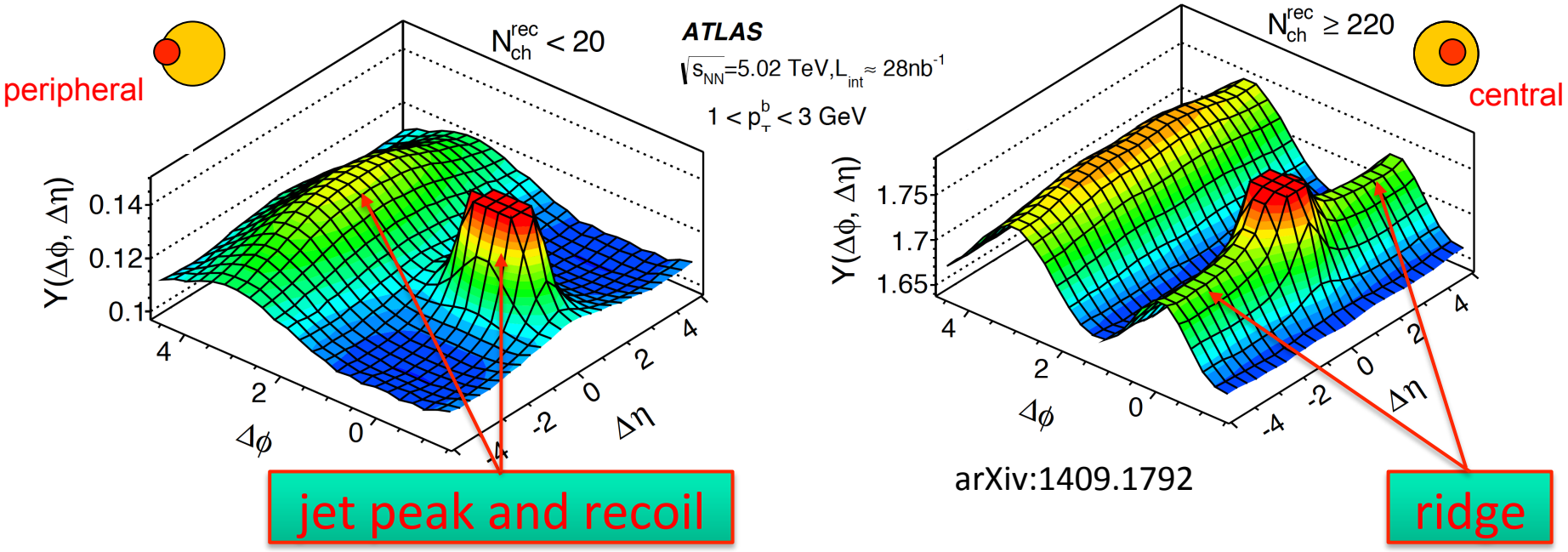
Collective Flow in p+Pb?

To extract flow coefficients, 2P correlation method was applied to p+Pb collisions. "Per Trigger Yield (PTY)":

$$Y(\Delta\phi,\Delta\eta)=\frac{\int B(\Delta\phi,\Delta\eta)d\Delta\phi d\Delta\eta}{\pi\eta_{\Delta}^{\max}}\left(\frac{S(\Delta\phi,\Delta\eta)}{B(\Delta\phi,\Delta\eta)}\right)$$

S (B) – same (mixed) event pairs per trigger particle

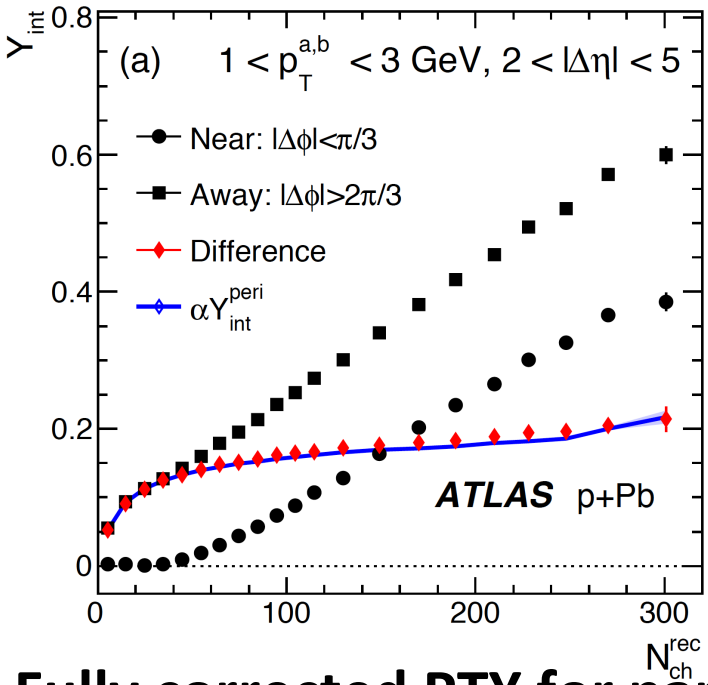
The near-side ridge is clearly visible in the central p+Pb events while it is absent in peripheral events



Two-particle Correlations in p+Pb Collisions

The contribution to PTY from jet peak, recoil and combinatorial background is estimated by rescaling PTY for peripheral collisions

arXiv:1409.1792



$$Y^{\mathrm{sub}}(\Delta\phi) = Y(\Delta\phi) - \alpha Y^{\mathrm{corr}}_{\mathrm{peri}}(\Delta\phi)$$

$$Y^{\mathrm{corr}}(\Delta\phi) = \frac{\int B(\Delta\phi)d\Delta\phi}{\pi}\left(\frac{S(\Delta\phi)}{B(\Delta\phi)} - b_{\mathrm{ZYAM}}\right)$$

The scaling factor, α, is a ratio of PTY (near jet peak, Δη≈Δφ≈0) in given centrality class to PTY in peripheral collisions:

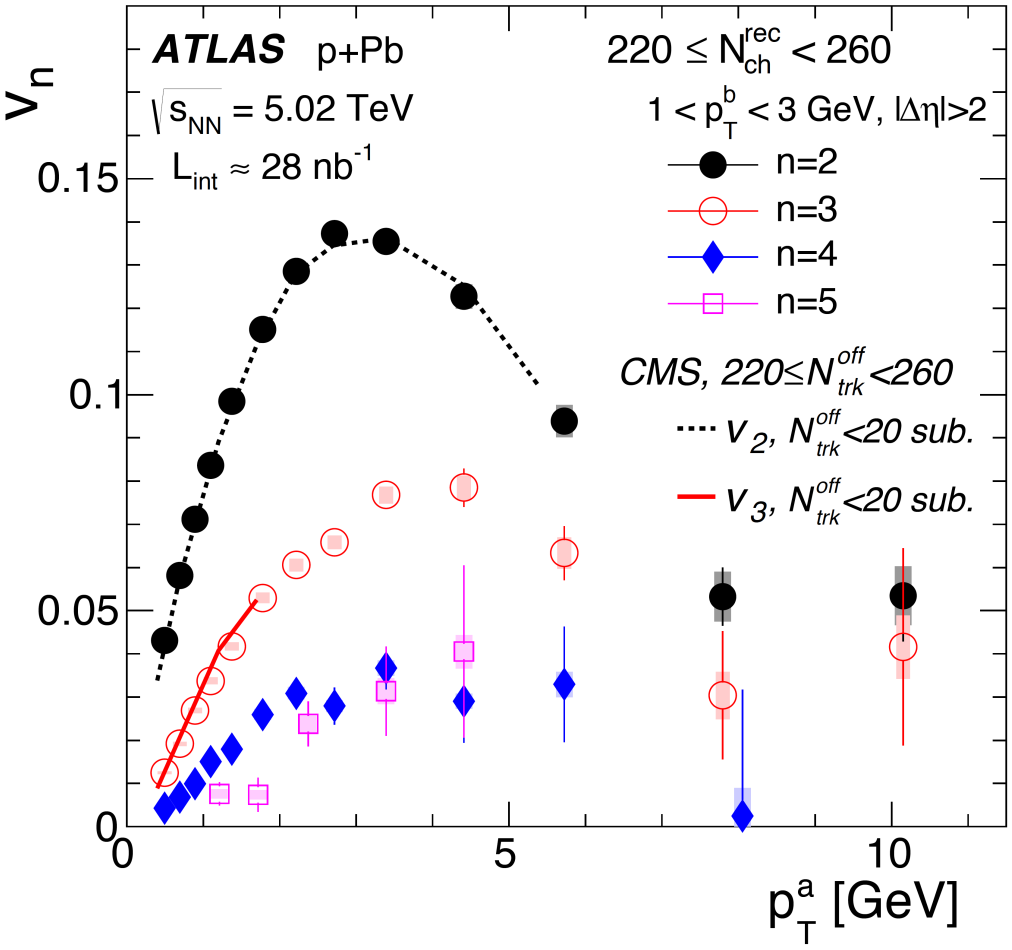
$$\alpha = Y^{\mathrm{N-Peak}} / Y^{\mathrm{N-Peak}}_{\mathrm{peri}}$$

Fully corrected PTY for particles of $|\Delta\eta|>2$, $Y^{\mathrm{sub}}(\Delta\varphi)$, is expanded into a Fourier series with $v_{n,n}$ amplitudes.
Assuming factorization, flow coefficients are obtained

$$v_n(p_{\mathrm{T}}) = v_{n,n}(p_{\mathrm{T}}, p_{\mathrm{T}}^{\mathrm{ref}}) / \sqrt{v_{n,n}(p_{\mathrm{T}}^{\mathrm{ref}}, p_{\mathrm{T}}^{\mathrm{ref}})}$$

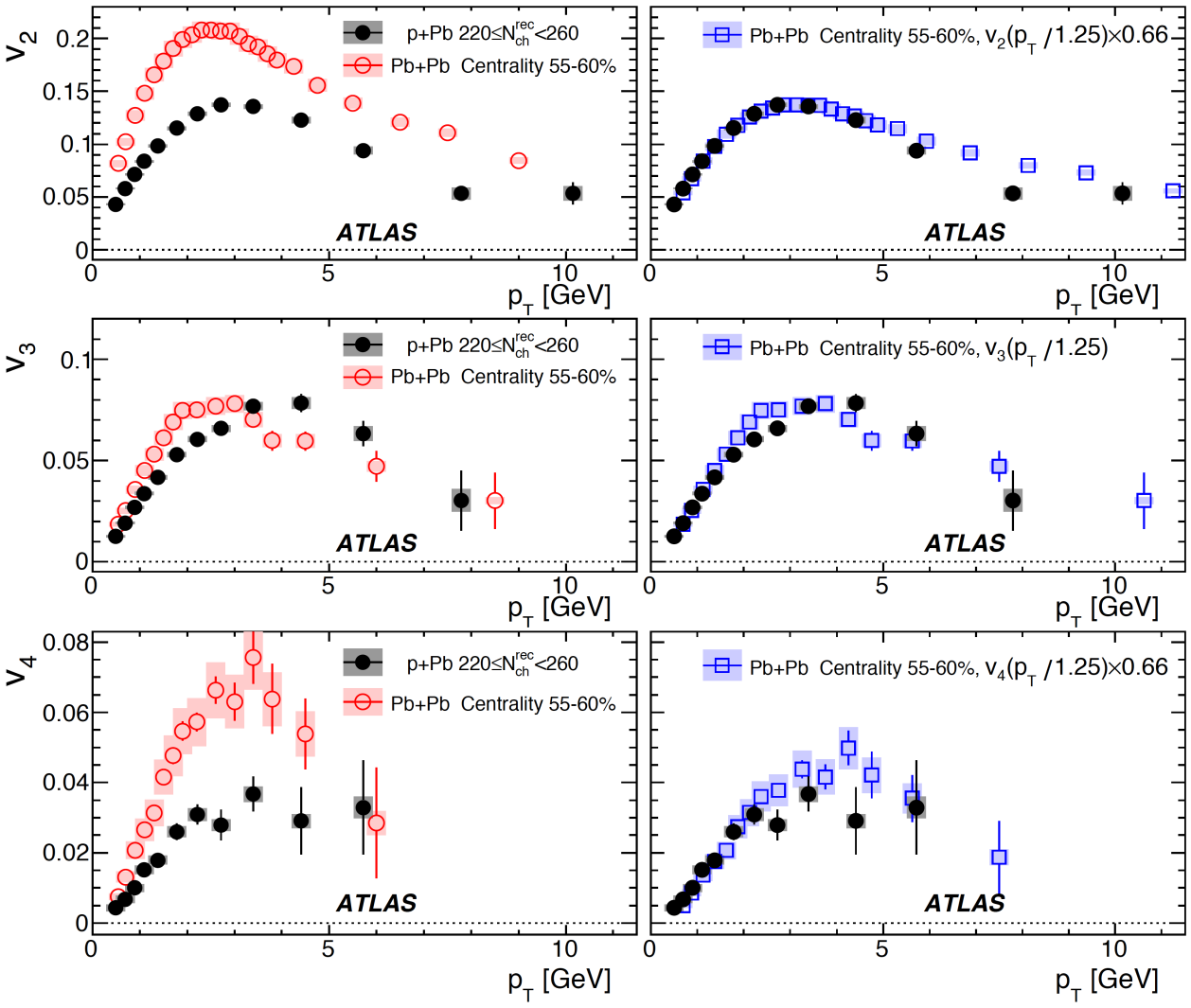
v_2 , v_3 ,v_4 and v_5 in p+Pb Collisions

arXiv:1409.1792



- Increase of v_n at low p_T up to 2-3 GeV then decrease
- Non-zero values of v_2 and v_3 at high p_T
- Good agreement with CMS experiment for v_2 and v_3

Comparison of v_n in p+Pb and Pb+Pb Collsions



arXiv:1409.1792

Similar event activity of p+Pb and Pb+Pb collisions

In the right panel, p_T axis of Pb+Pb EP harmonics is rescaled by 1.25 to account for differences in $\langle p_T \rangle$ and then v_n of Pb+Pb are scaled to match p+Pb values (arXiv:1312.6770)

Good agreement between v_n harmonics for p+Pb collisions and the scaled harmonics for Pb+Pb interactions

Summary

- **High-precision measurements of azimuthal anisotropy in Pb+Pb and p+Pb collisions performed in the ATLAS experiment**
- **Reduction of flow harmonics when calculated with higher order cumulants in Pb+Pb collisions**

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

  $v_3\{2\} >> v_3\{4\}$, $v_4\{2\} >> v_4\{4\}$
- **EbyE fluctuations of v_2 , v_3 and v_4 obtained from cumulant method**

  Strong centrality dependence for elliptic flow

  Large values and weak N_{part} dependence of fluctuations for v_3 and v_4 indicate large fluctuation in the shape of the initial geometry
- **v_n correlations in centrality and q_2 bins evaluated for Pb+Pb**

  v_2(low-p_T)-v_2(high-p_T) correlations indicate that viscous effects are controlled by system size, not the system shape

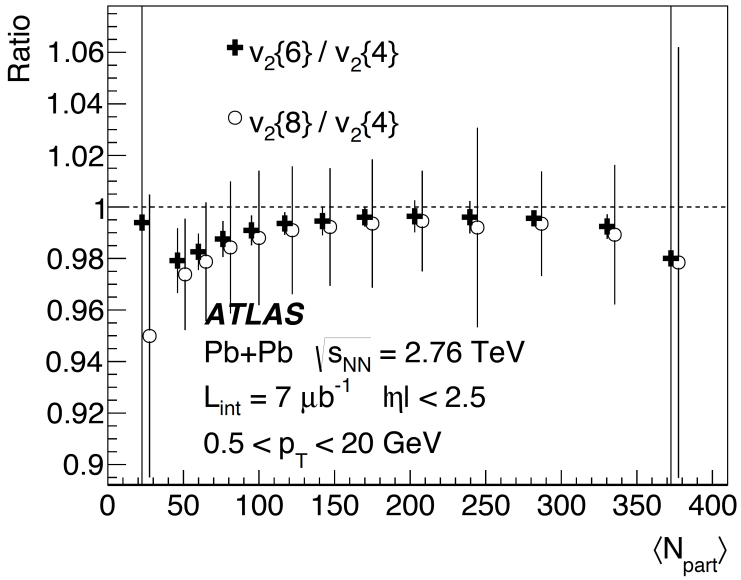
  Small anti-correlation v_2 - v_3 and strong non-linear correlation v_2-v_4 observed
    - Indicate non-linear response to initial geometry
    - Linear & non-linear contributions extracted by two component fits
- **v_2 ,…, v_5 harmonics measured in p+Pb collisions**

  p_T-dependence of $v_{2\text{-}5}$ similar to the rescaled v_n for peripheral Pb+Pb collisions

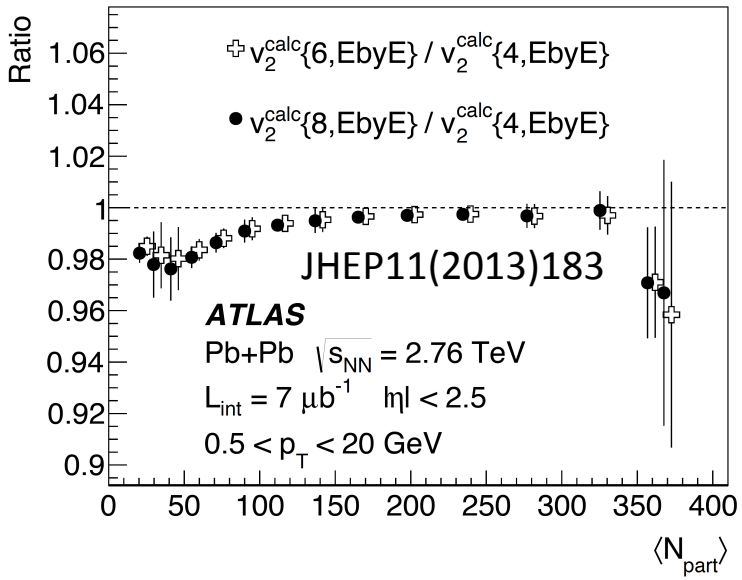
Backups

Comparison of $v_2\{4\}$ to $v_2\{6\}$ and $v_2\{8\}$

Cumulant method



EbyE method

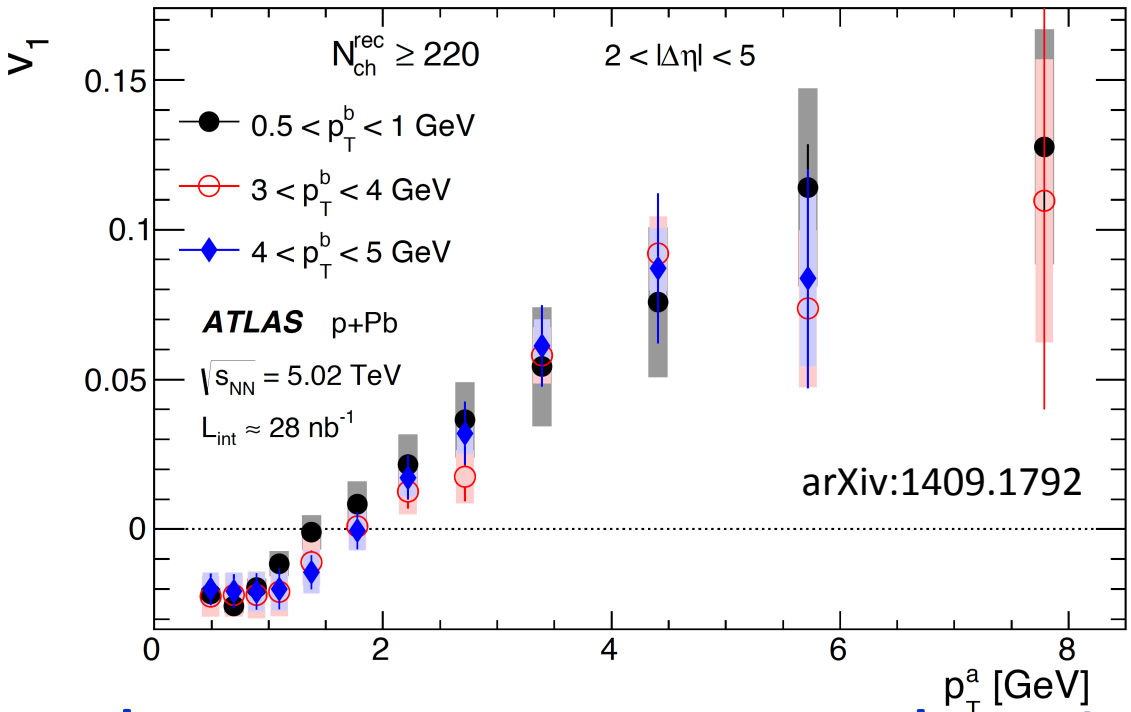


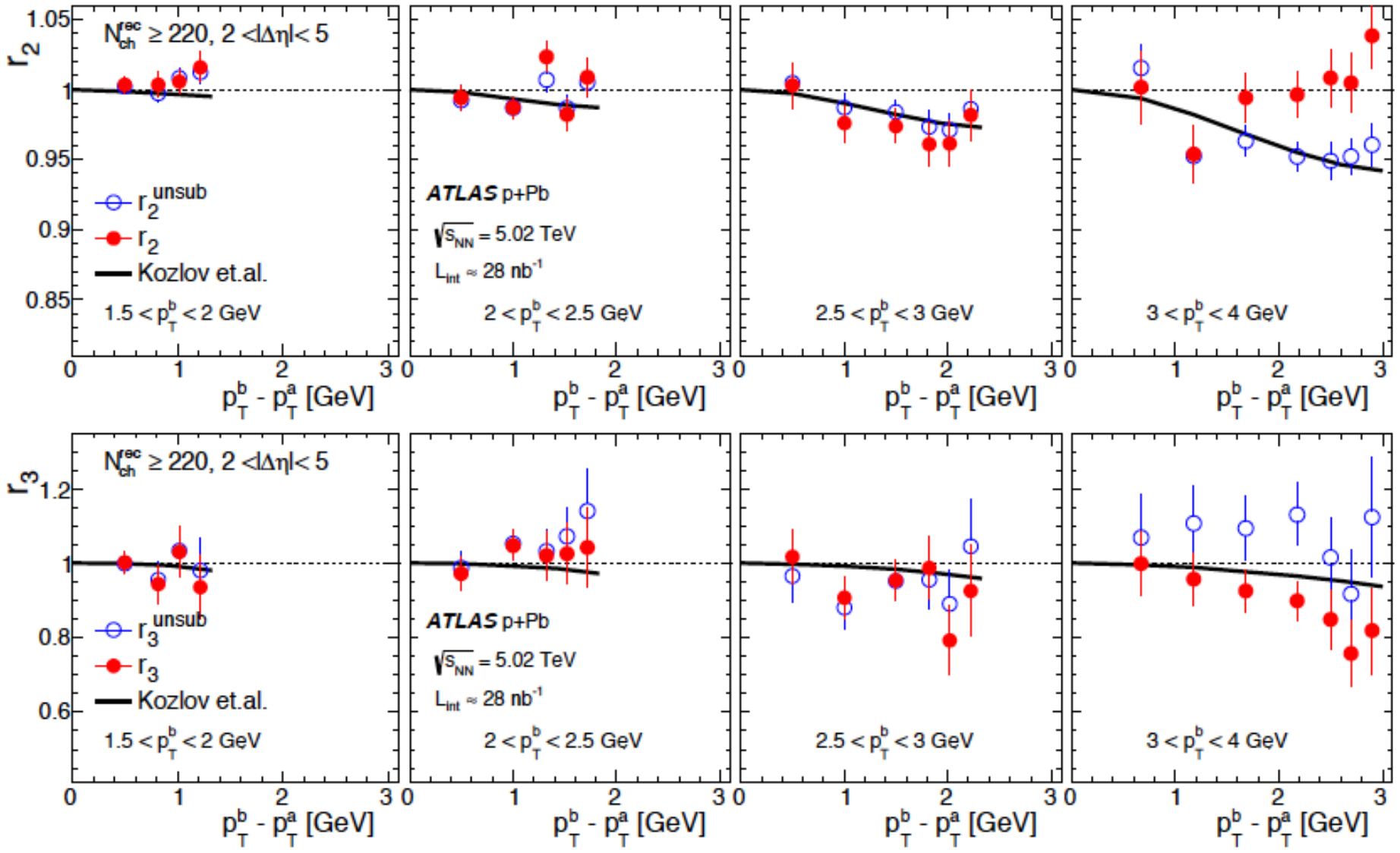
- The elliptic flow harmonic $v_2\{4\}$ contains some residual non-flow correlations (at a level of 2%), which are absent in $v_2\{6\}$ and $v_2\{8\}$
- $p(v_n)$ not fully described by Bessel-Gaussian function which requires: $v_2\{2\} > v_2\{4\} = v_2\{6\} = v_2\{8\}$

Dipolar Flow in p + Pb Collisons

Assuming factorization, accounting for the global momentum conservation and the sign change

$$v_1(p_T) \equiv \frac{v_{1,1}(p_T, p_T^{ref})}{v_1(p_T^{ref})} \qquad v_1(p_T^{ref}) = \mathrm{sign}(p_T - p_T^0)\sqrt{|v_{1,1}(p_T^{ref}, p_T^{ref})|}$$



- **Negative at low p_T , crosses zero at around p_T ~ 1. 5 GeV, and increases to 0.1 at p_T of 4–6 GeV**
- **$v_1(p_T)$ in p+Pb collisions similar to $v_1(p_T)$ in Pb+Pb collisions**

$$r_n(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{b}}) = \frac{v_{n,n}(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{b}})}{\sqrt{v_{n,n}(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{a}}) v_{n,n}(p_{\mathrm{T}}^{\mathrm{b}}, p_{\mathrm{T}}^{\mathrm{b}})}}$$