Recent ATLAS results on flow measurements in lead-lead and proton-lead collisions

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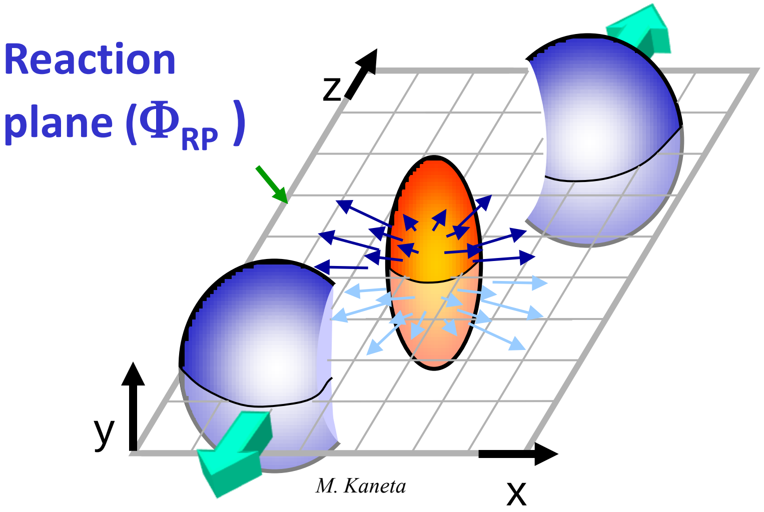
Azimuthal Anisotropy of Produced Particles

Strongly coupled QGP

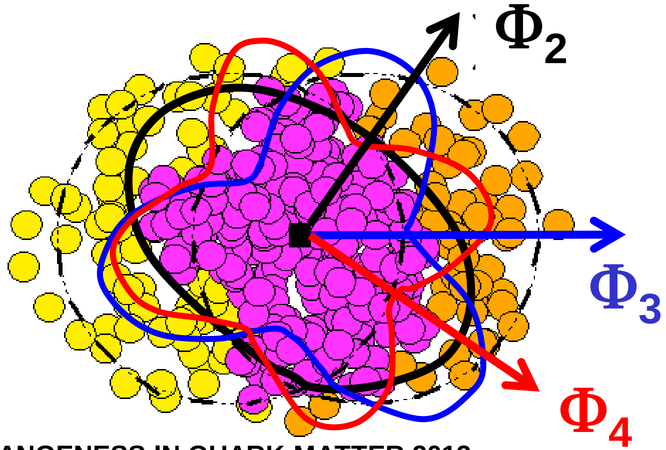


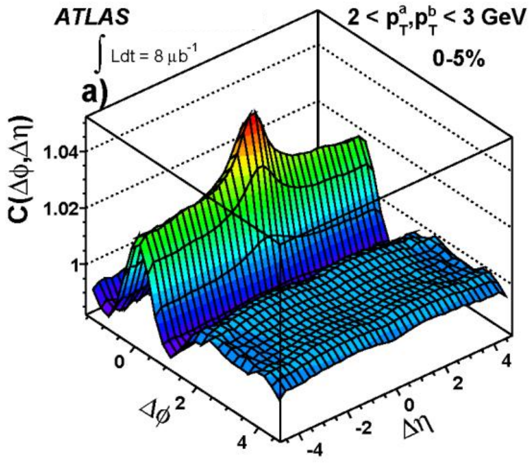
- **Pressure gradients lead to azimuthal anisotropy**

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

- **Initial shape of the interaction region (v_2- elliptic flow)**

- **Initial spatial fluctuations of interacting nucleons (higher orders, v_n)**

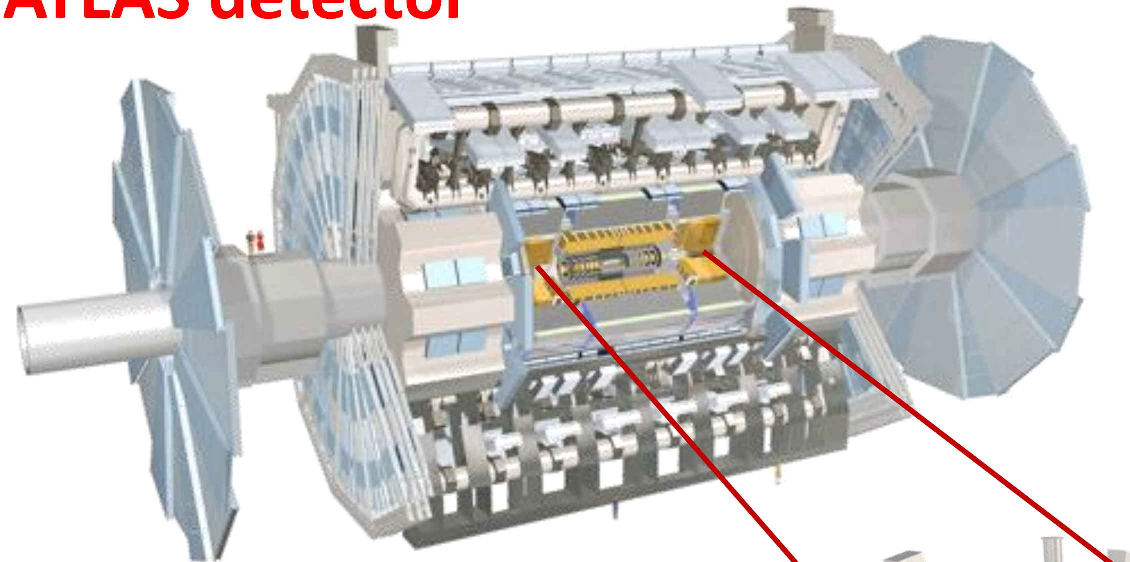




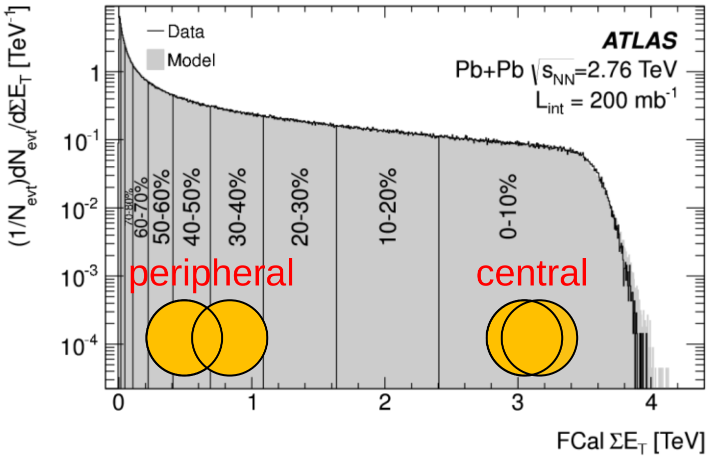
Ridge in Pb+Pb collisions

Event Centrality Measurement in Pb+Pb and p+Pb

ATLAS detector



Pb+Pb 2010,~50 M MB events



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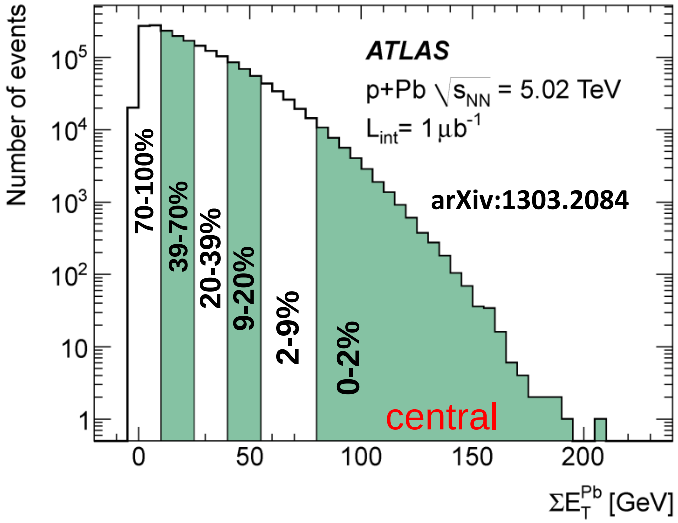
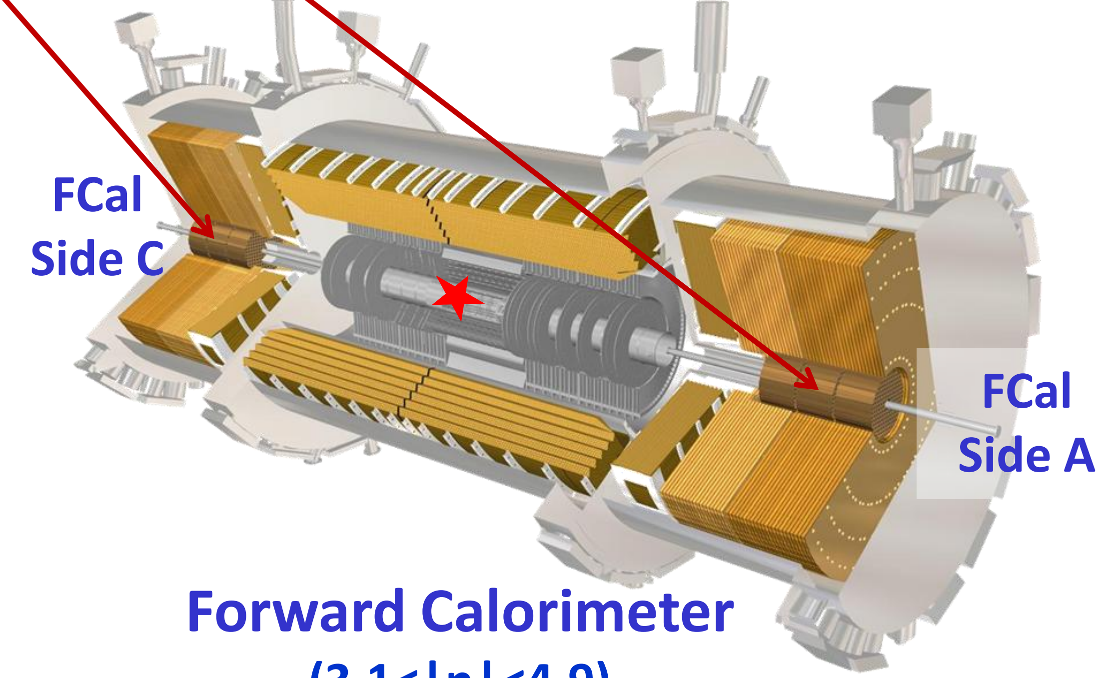
p+Pb 2012, ~1.9 M MB events



Phys. Lett. B 725 (2013) 60

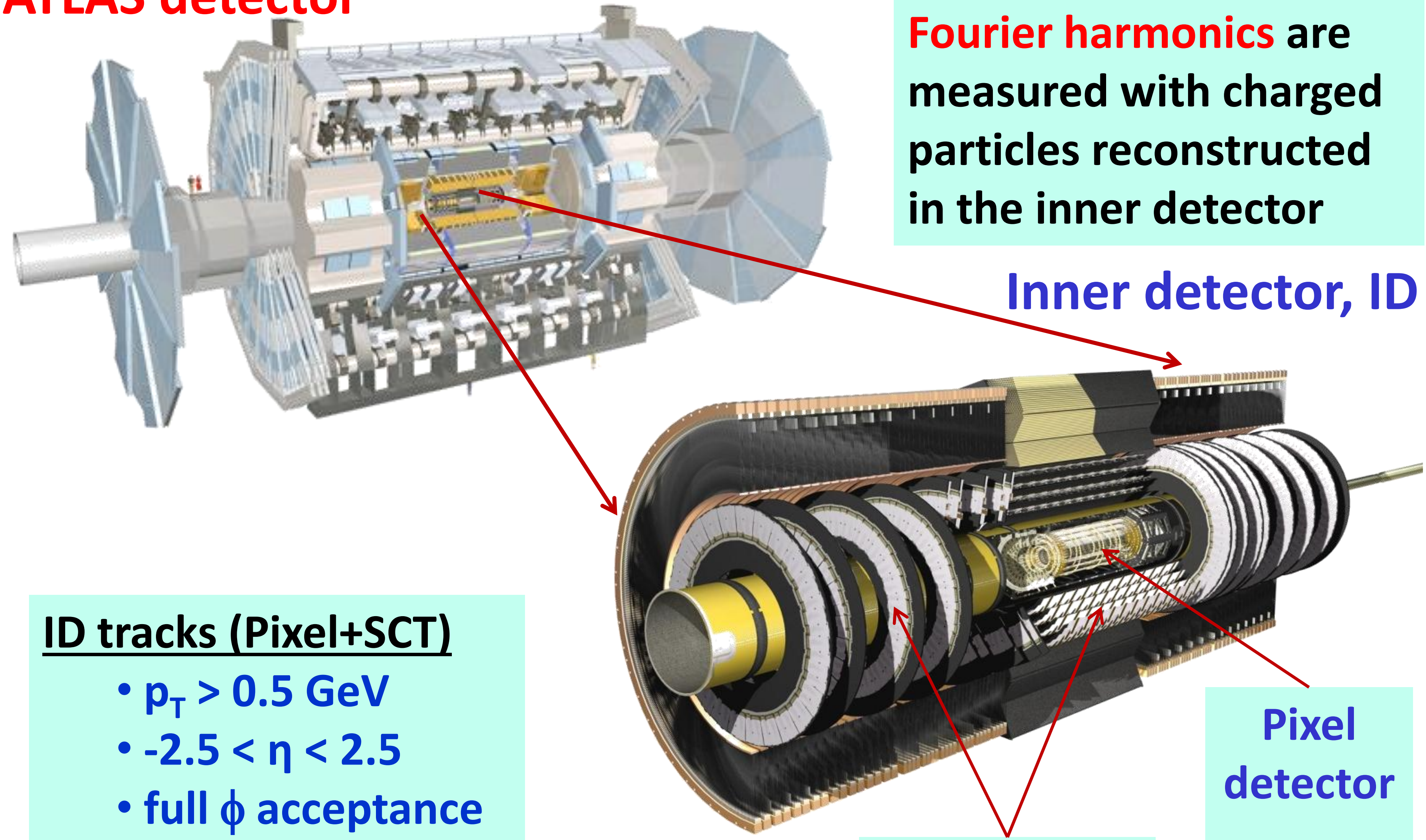
ΣE_T^{Pb} measured at "Pb-side" of FCal (A)



Forward Calorimeter

(3.1<|η|<4.9)

v_n Harmonics Measurement



ATLAS detector

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

Inner detector, ID

Pixel detector

SCT detector

ID tracks (Pixel+SCT)

- $p_T > 0.5$ GeV
- $-2.5 < \eta < 2.5$
- full ϕ acceptance

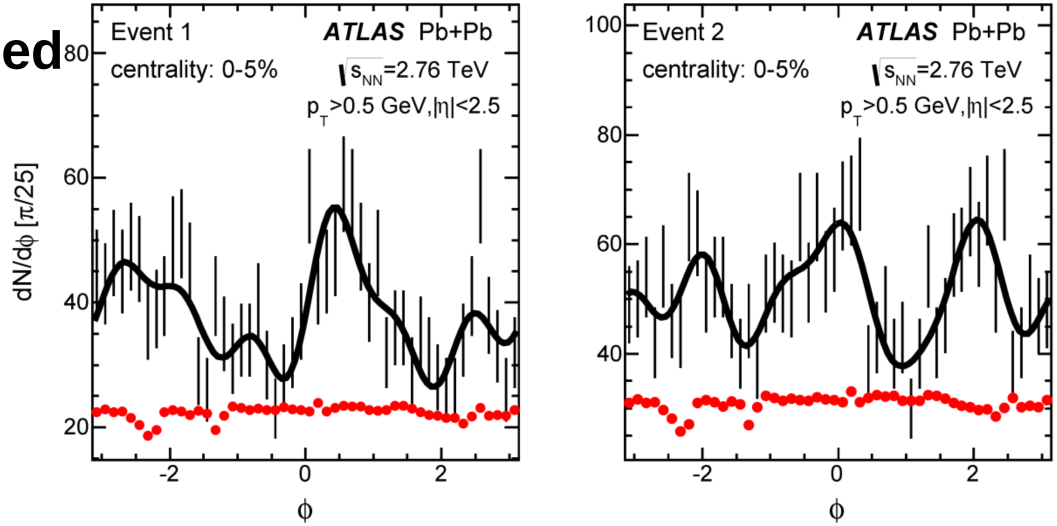
Measurement of Event-by-Event v_n in Pb+Pb

Azimuthal distributions of charged particles in single events

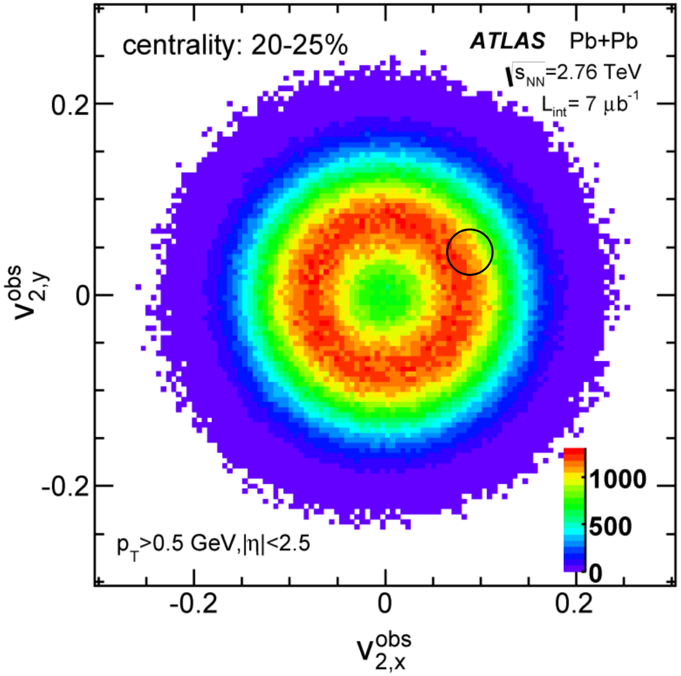
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n^{obs} \cos n(\phi - \Phi_n)$$

$$= 1 + 2\sum_{n=1}^{\infty} (v_{n,x}^{obs} \cos n\phi + v_{n,y}^{obs} \sin n\phi)$$

$$v_n^{obs} = \sqrt{(v_{n,x}^{obs})^2 + (v_{n,y}^{obs})^2} \rightarrow v_n$$



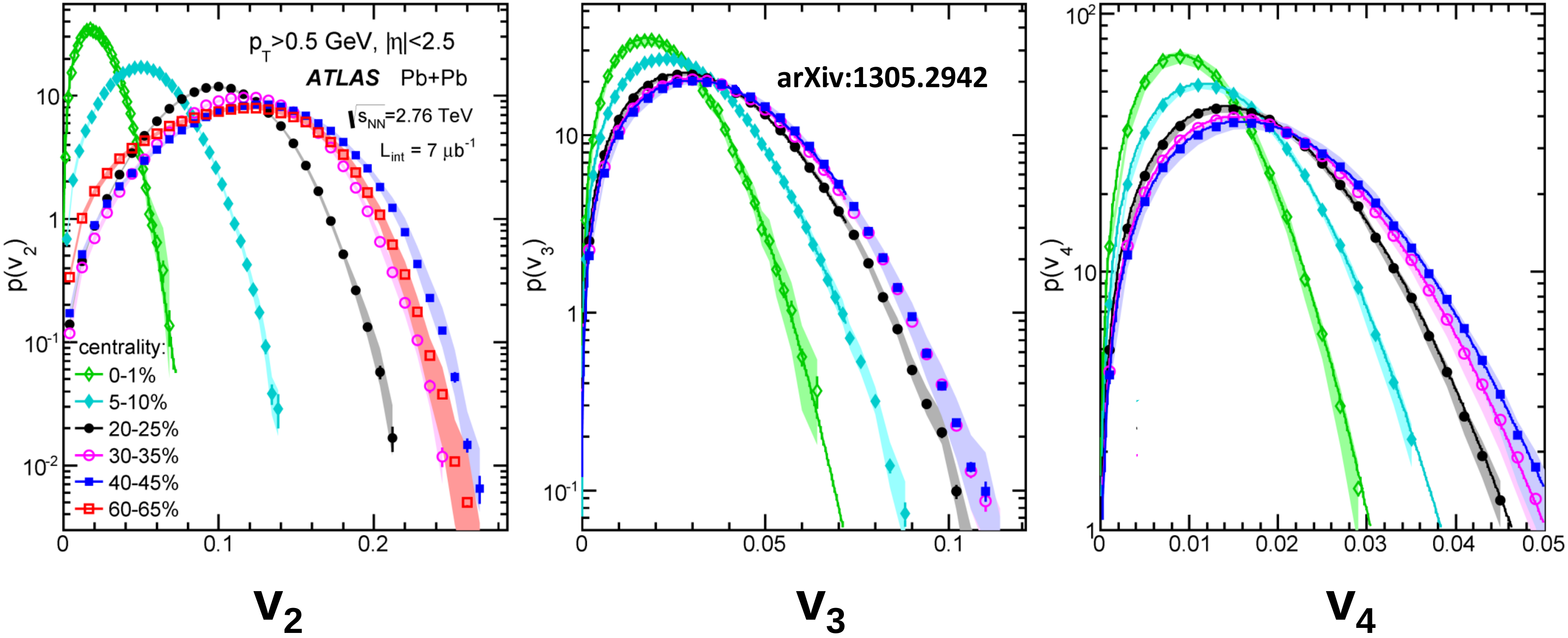
Flow vector distribution:



Due to finite multiplicity, flow vector is smeared around true flow vector
→ corrected by unfolding

ATLAS, arXiv:1305.2942

Unfolded Distributions of v_2, v_3 and v_4 in Pb+Pb



Direct measure of flow harmonics fluctuations

- v_n distributions normalized to unity for n = 2,3 and 4.
  Lines represent radial projections of 2D Gaussians, rescaled to $\langle v_n \rangle$

$$P(v_n) = \frac{v_n}{\sigma^2} e^{-\frac{v_n^2}{2\sigma^2}},$$

- ➢ for v_2 only in 0-2% of most central collisions
- ➢ for v_3 and v_4 over all centralities

Event-by-Event Fluctuations of v_2, v_3 and v_4 in Pb+Pb

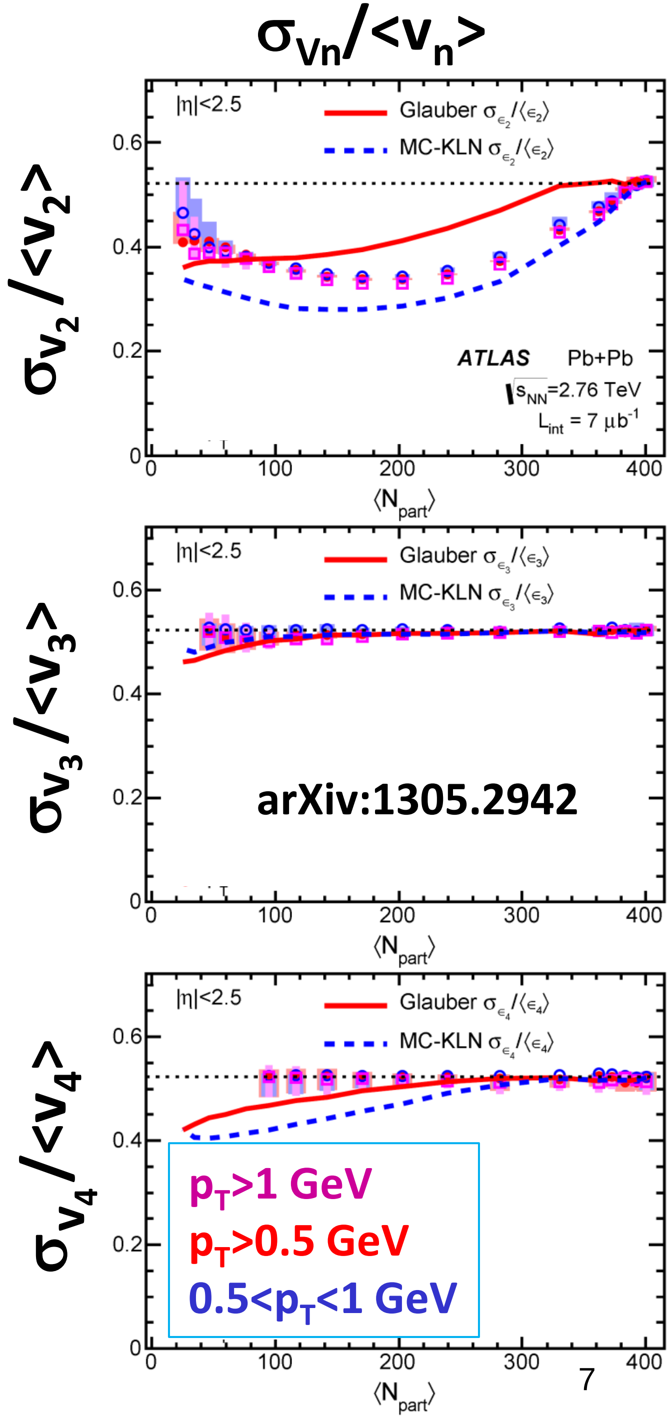
- σ_{v_2} /<v_2> shows strong centrality dependence

- σ_{v_3} /<v_3> and σ_{v_4} /<v_4> are consistent with Gaussian fluctuations

- Same relative fluctuations for $0.5<p_T<1$GeV, $p_T>0.5$GeV and $p_T>1$GeV

Dotted lines indicate the Gaussian limit:

$$P(v_n) = \frac{v_n}{\sigma^2} e^{-\frac{v_n^2}{2\sigma^2}}, \qquad \frac{\sigma_{\mathrm{Vn}}}{<\mathbf{v}_n>} = \sqrt{\frac{4}{\pi}-1} \approx 0.523$$


σ_{Vn}/<v_n>

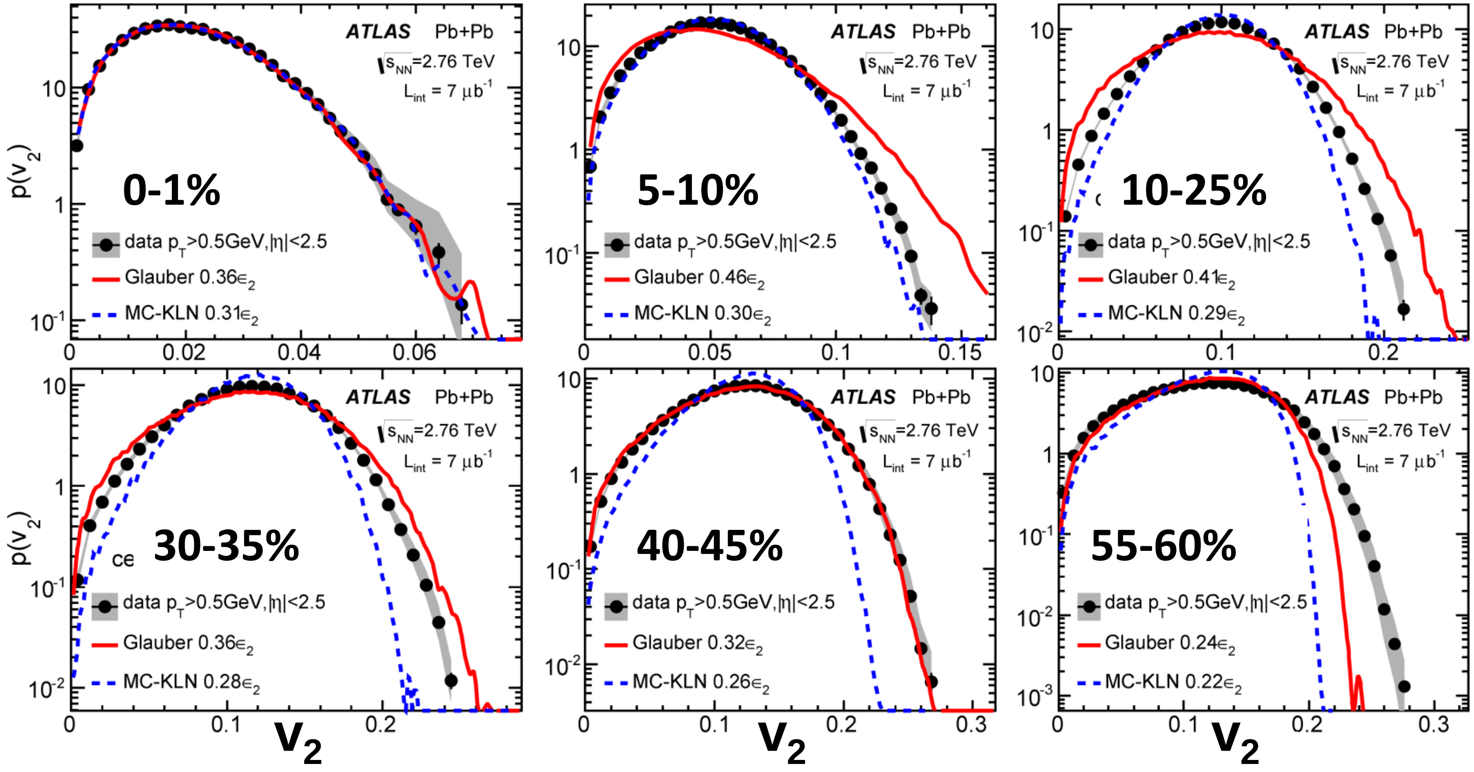
Comparison to MC Glauber and KLN models

Eccentricity distributions from MC Glauber and KLN models

$$\varepsilon_n = \frac{\sqrt{< r^n \cos n\phi >^2 + < r^n \sin n\phi >^2}}{< r^n >}$$

arXiv:nucl-ex/0701025, Phys. Rev. C 74, 044905 (2006)

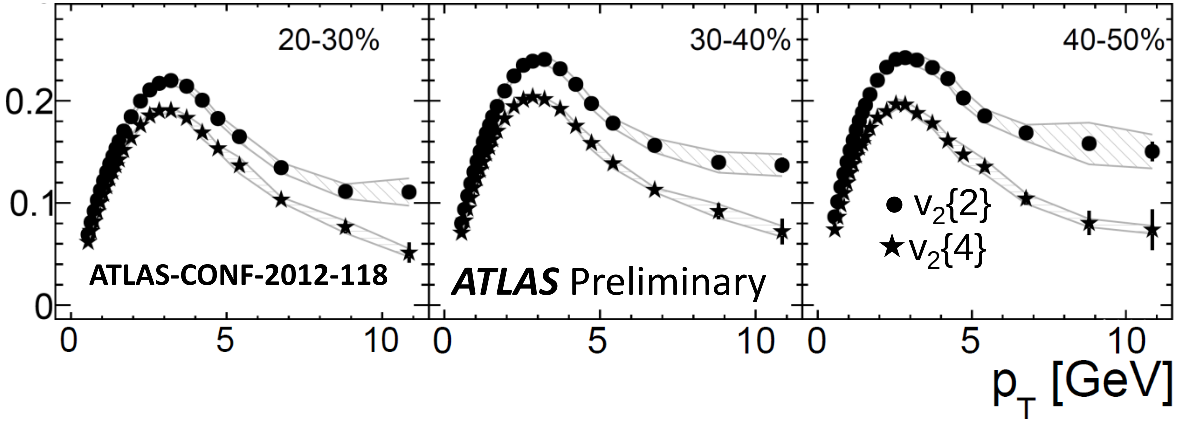
$< \varepsilon_2 >$ rescaled to $< v_2 >$



- Both work in 0-1%
- MC KLN better in 5-10%
- MC Glauber better in 30-60%

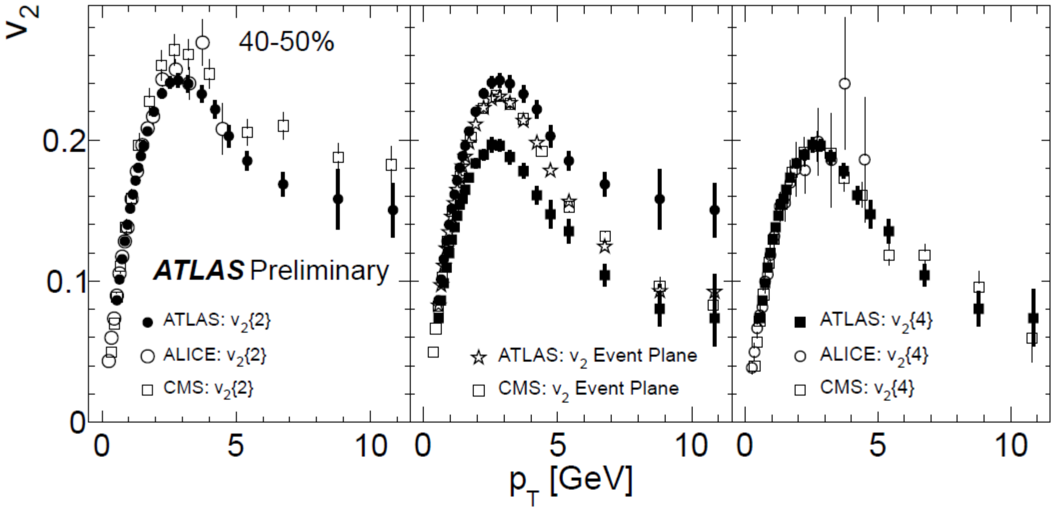
Cumulant Harmonics: $v_2\{2\}$ and $v_2\{4\}$ in Pb+Pb

Elliptic flow harmonics of charged particles were obtained with the cumulant generating function method



N. Borghini, P.M.Dinh and J.Y. Ollitrault Phys.Rev.C 64 (2001) 054901

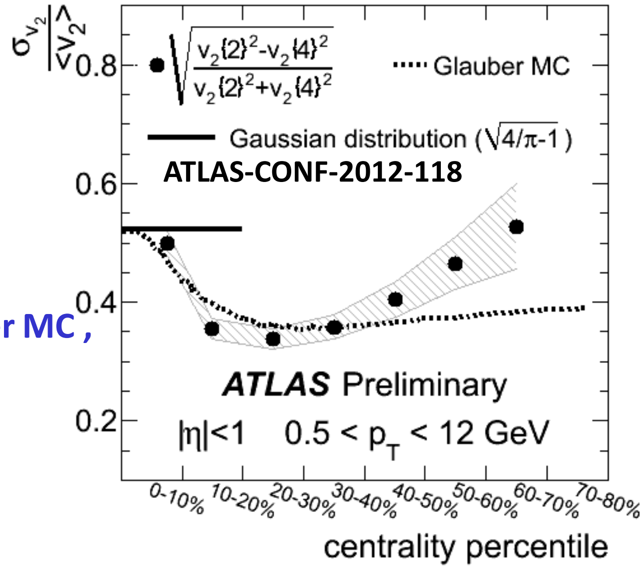
Strong reduction of v_2 is observed by using four-particle cumulants



- **Excellent agreement of $v_2\{4\}$ between ATLAS, ALICE and CMS**

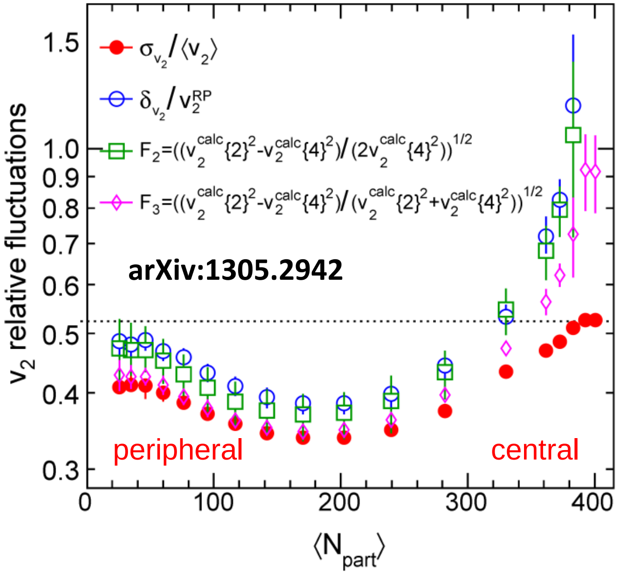
Event-by-Event Fluctuations from $v_2\{2\}$ and $v_2\{4\}$

Cumulants method:

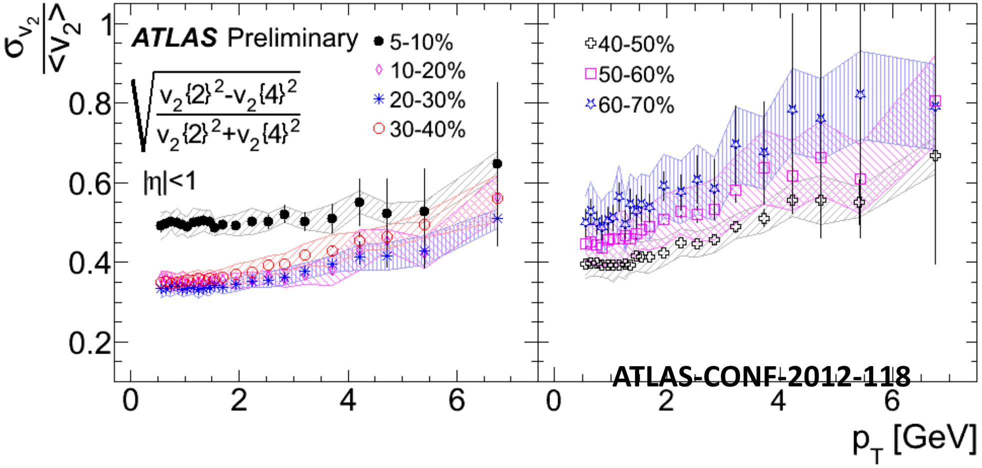


Glissando Glauber MC , arXiv:0710.5731

Event-by-event method:



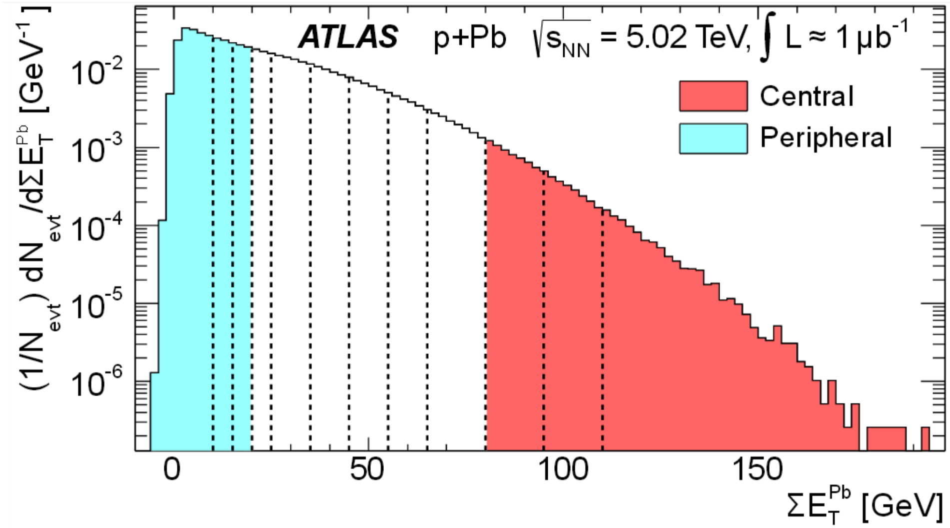
- $\sigma_{v2}/<v_2>$ **from cumulants is consistent with MC Glauber and EbyE results (in 5-50%)**
  - **Relative flow fluctuations are independent of p_T for 5-10% cent. bin**
  - **For less central collisions $\sigma_{v2}/<v_2>$ increases with p_T**



Collective flow in p+Pb?

ATLAS, Phys. Rev. Lett. 110, 182302 (2013)

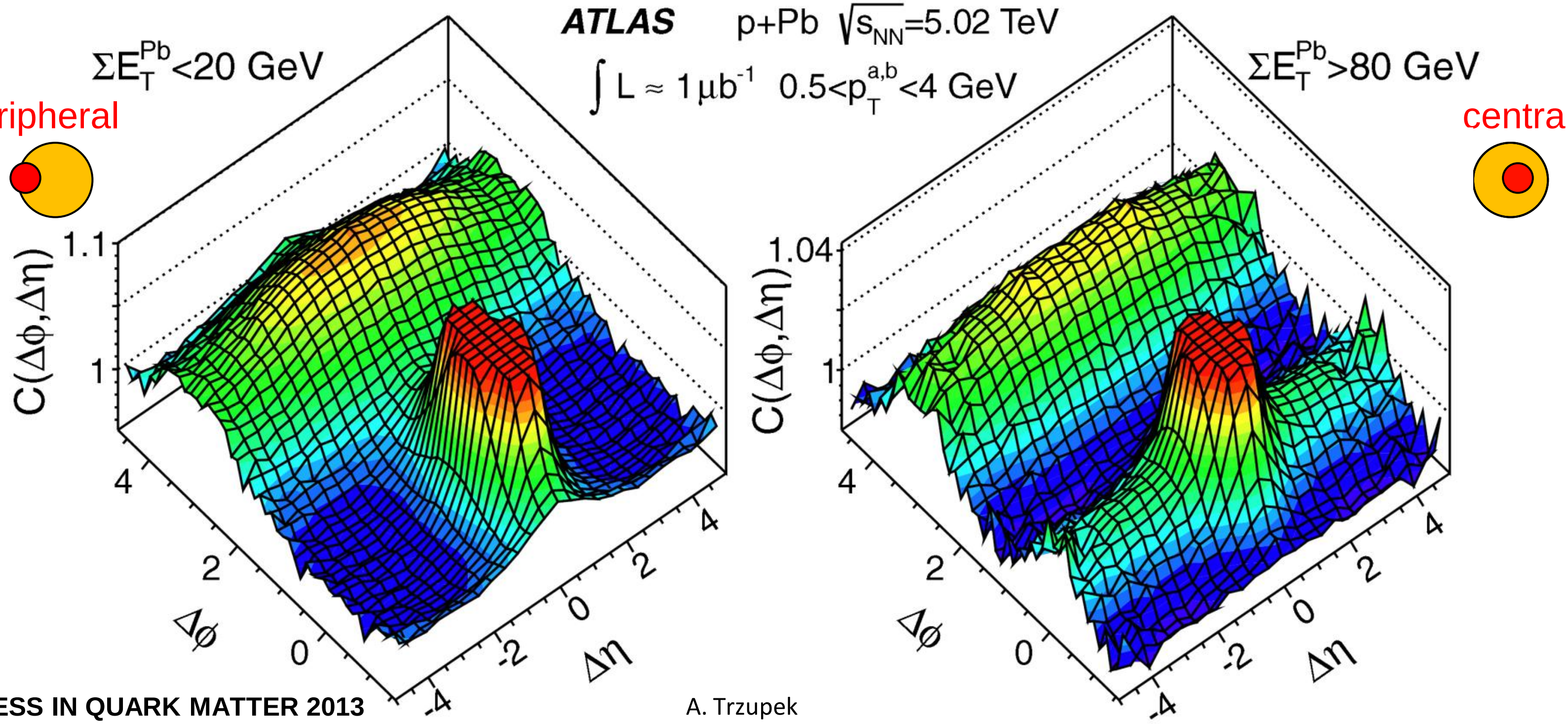
The near-side ridge is clearly visible in the central events while it is absent in peripheral one



$$C(\Delta\phi) = \frac{S(\Delta\phi)}{B(\Delta\phi)}$$

Same event pairs

Mixed events pairs



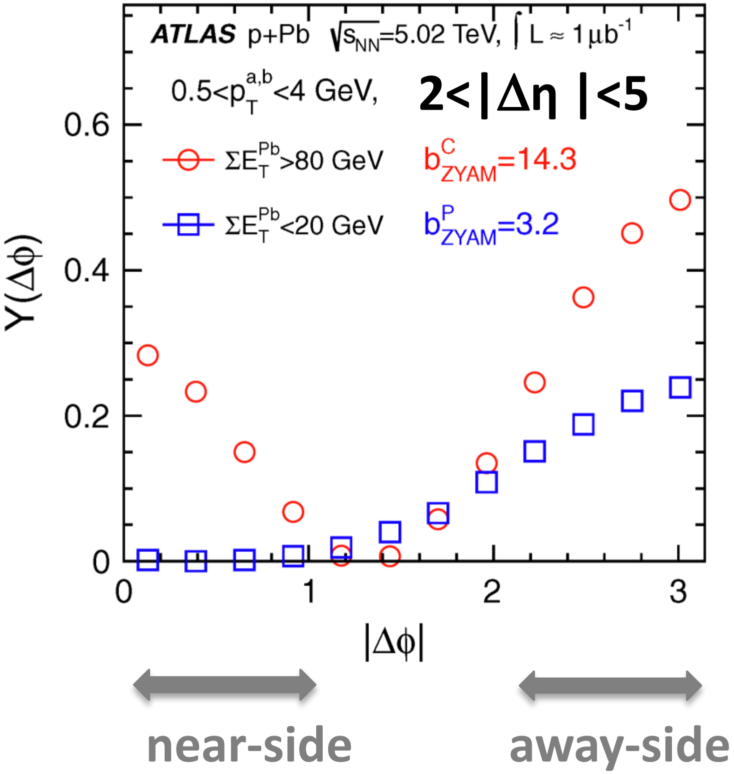
peripheral

central

Two-particle Correlations in p+Pb Collisons

”Per trigger yield” corrected for combinatorial background (b_{ZYAM}):

$$Y(\Delta\varphi) = \frac{\int B(\Delta\varphi)d\Delta\varphi}{\pi N_a} C(\Delta\varphi) - b_{ZYAM}$$



For central events $Y(\Delta\varphi)^{cent}$ has two near-side and (larger) away-side peaks

For peripheral events $Y(\Delta\varphi)^{periph}$ has only one, away-side peak, characteristic for recoil contribution

Recoil subtraction:

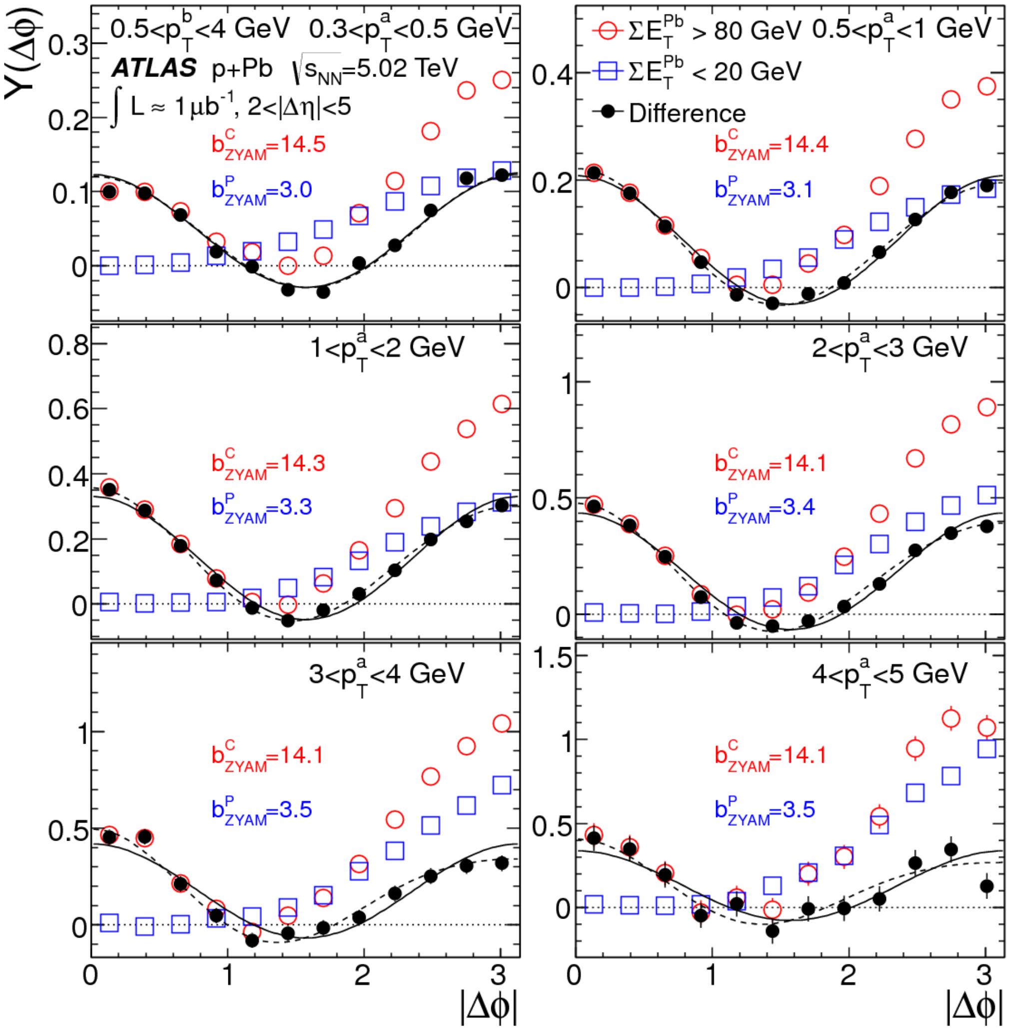
$\Delta Y(\Delta\varphi) = Y(\Delta\varphi)^{cent} - Y(\Delta\varphi)^{periph}$

central : ΣE_T^{Pb}>80 GeV (0-2%)

peripheral: ΣE_T^{Pb}<20 GeV (48-100%)

After Recoil Subtraction: $\Delta Y(\Delta\varphi)$

$\Delta Y(\Delta\varphi) = Y(\Delta\varphi)^{cent} - Y(\Delta\varphi)^{periph}$ for different ranges in p_T^a



ATLAS, Phys. Rev. Lett. 110, 182302 (2013)

$\Delta Y(\Delta\varphi)$ is symmetric around $|\Delta\varphi|=\pi/2$

Long-range component

= Recoil + $\Delta\varphi$-symmetric

$\Delta\varphi$-symmetric component fits:

—— $a_0 + 2a_2\cos 2\Delta\varphi$

- - $a_0 + 2a_2\cos 2\Delta\varphi + 2a_3\cos 3\Delta\varphi$

$$\boxed{a_n = \langle \Delta Y(\Delta\varphi)\cos n\Delta\varphi \rangle}$$

Harmonics of Recoil Subtracted Correlation in p+Pb

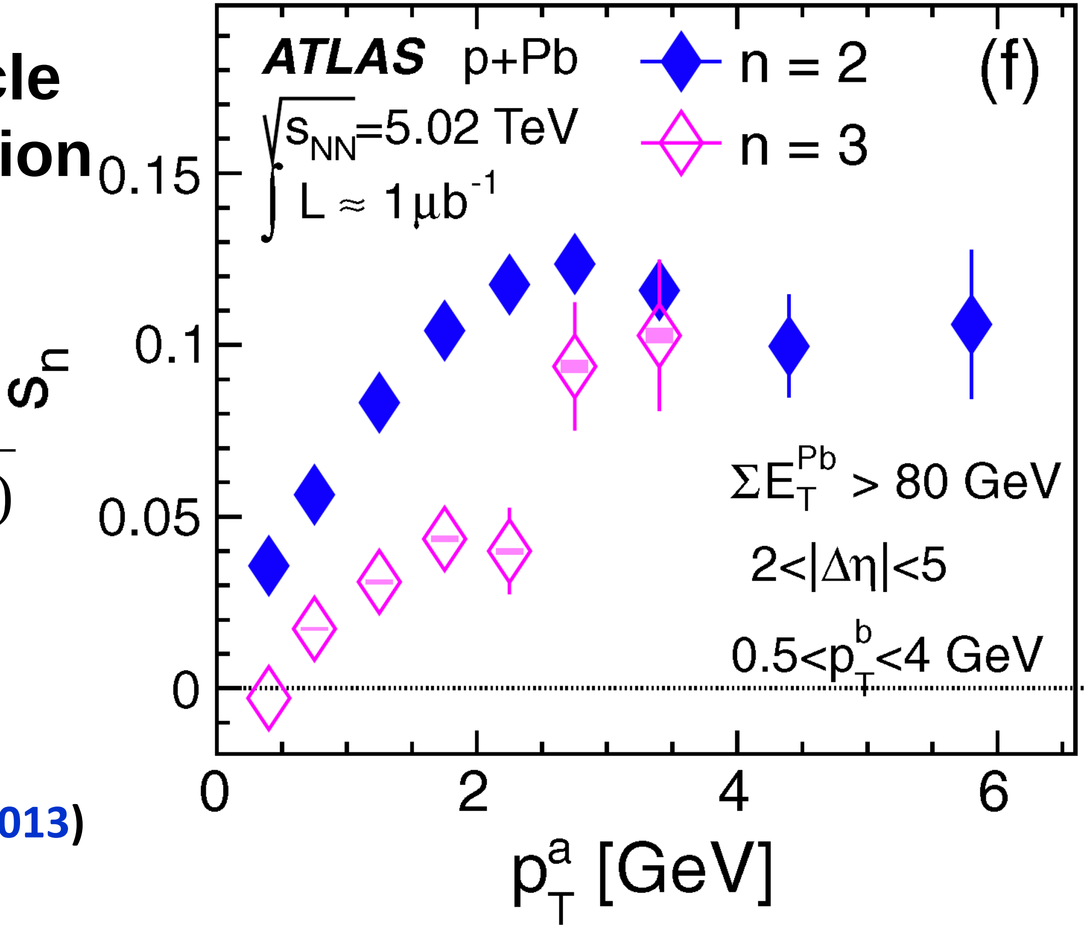
$$c_n = \langle C_{R.S.}(\Delta\phi)\cos(n\Delta\phi)\rangle = a_n /(b^{c}_{ZYAM} + a_0), n = 2,3 \quad \leftrightarrow \quad v_{n,n}$$

Convert to a single-particle level assuming factorization

$$c_n(p_T^a, p_T^b) = s_n(p_T^a)\cdot s_n(p_T^b)$$

$$s_n(p_T^a) = c_n(p_T^a, p_T^b)/\sqrt{c_n(p_T^b, p_T^b)}$$

$$\boxed{s_n \longleftrightarrow v_n\{2PC\}}$$



ATLAS, Phys. Rev. Lett. 110, 182302 (2013)

- **s_2 increases with p_T up to ~3 GeV, then drops**
- **$s_3 < s_2$ over the measured p_T**

Four-particle Cumulants in p+Pb Collisions

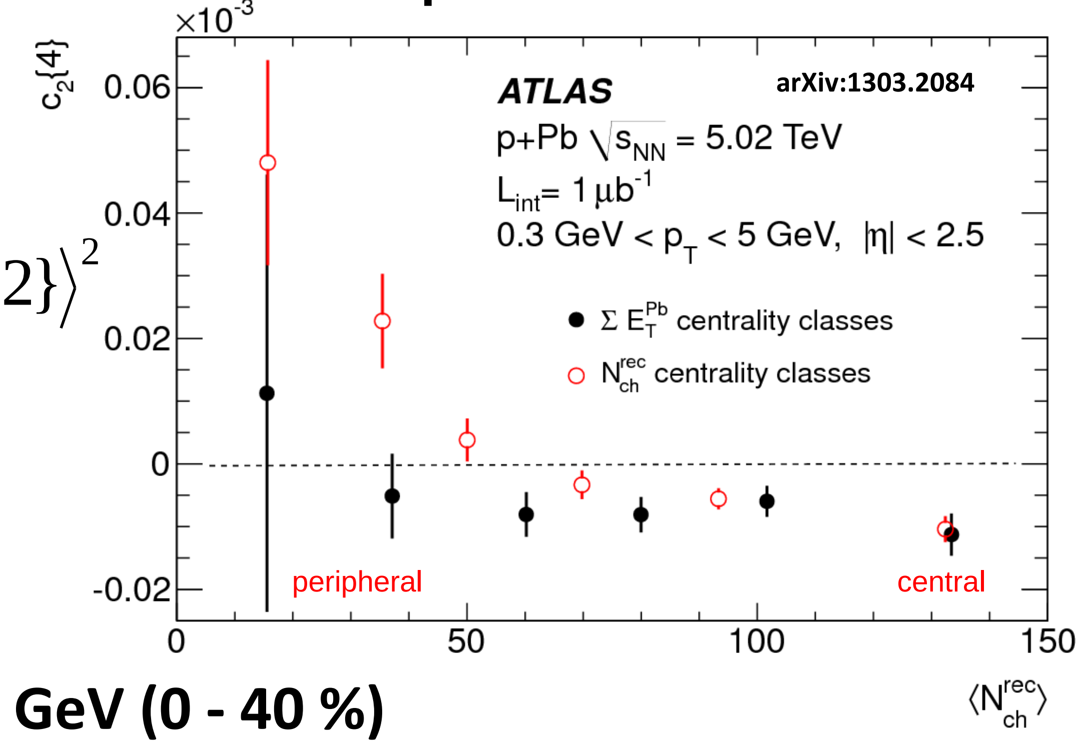
ATLAS, Phys. Lett. B 725 (2013) 60

$c_2\{4\}$ – free from non-flow effects of two-particle correlations

A. Bilandzic,R. Snellings, S. Voloshin, Phys. Rev. C83,044913(2011)

$$c_2\{4\} = \langle corr_2\{4\}\rangle - 2\langle corr_2\{2\}\rangle^2$$

$$v_2^{ref}\{4\} = \sqrt[4]{-c_2\{4\}}$$



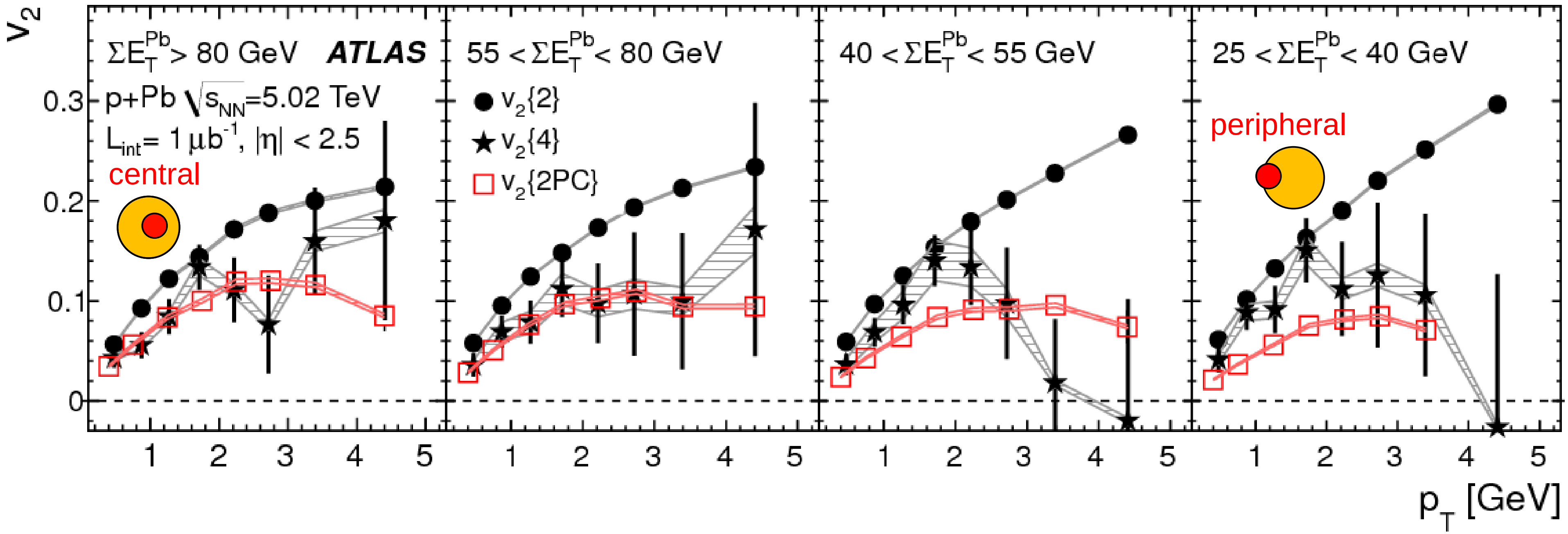
- **$c_2\{4\}$(+2σ) < 0 for ΣE_T^{Pb} >25 GeV (0 - 40 %)**
- **$c_2\{4\}$ (ΣE_T^{Pb} centrality) agree with $c_2\{4\}$ (N_{ch} centrality) for N_{ch}^{rec} > 70**

Clear sign of significant flow-like 4-particle correlations in central (high multiplicity) p+Pb collisions

p_T - dependence of $v_2\{4\}$ in p+Pb

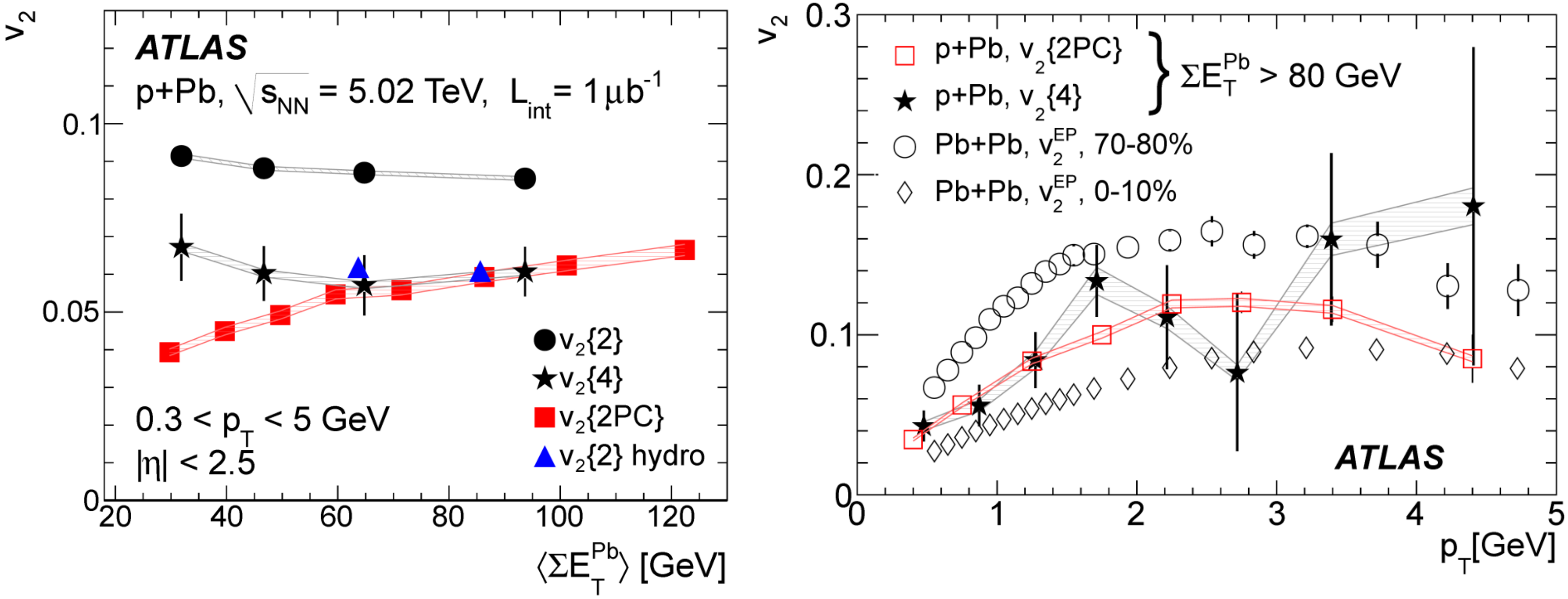
$$v_2\{4\}(p_T) = \frac{-d_2\{4\}(p_T)}{\sqrt[3/4]{-c_2\{4\}}}$$

ATLAS, Phys. Lett. B 725 (2013) 60



- **Strong reduction of v_2 when using four-particle cumulants**
- **Good agreement with $v_2\{2PC\}$ for ΣE_T^{Pb} >55 GeV (0 - 20 %)**
- **Differences for ΣE_T^{Pb} <55 GeV:**
  - **recoil subtraction, non-flow in $v_2\{4\}$ or both**

Centrality Dependence of $v_2\{4\}$ in p+Pb



- **Significant $v_2\{4\} \approx 0.06$**
  - Weaker/stronger than in peripheral/central Pb+Pb collisions
  - Systematically larger, by 15-20%, than $v_2\{4\}_{CMS}$ arXiv:1305.0609
- **Good agreement with the hydrodynamic predictions**

(P. Bożek, W. Broniowski Phys. Lett. B718,1557 (2013))

Summary

- High-precision measurements on azimuthal anisotropy in Pb+Pb and p+Pb collisions were performed by ATLAS
- Unfolded event–by–event v_2, v_3 and v_4 distributions provide direct information on relative flow fluctuations:
  - $\sigma_2/<v_2>$ shows strong centrality dependence
- v_n distributions are not fully consistent with the eccentricity distributions from the Glauber and/or KLN MC models.
- Elliptic flow $v_2\{2\}$ and $v_2\{4\}$ were measured in broad range of centrality, η (|η|<2.5) and p_T ($0.5 < p_T < 12$ GeV)
  - Relative fluctuations of elliptic flow from 2- and 4-particle cumulants are consistent with the MC Glauber model anf E-by-E (in 5-50% centrality bin)
- Collective flow in p+Pb?
  - Long Range azimuthal correlations (ridge) observed in p+Pb
  - Symmetric near side and away side ridge(s) with similar p_T and centrality dependence are measured
  - $v_2\{4\}$ and $v_2\{2PC\}$ show similar p_T and centrality dependence, consistent with v2 for HI collisions