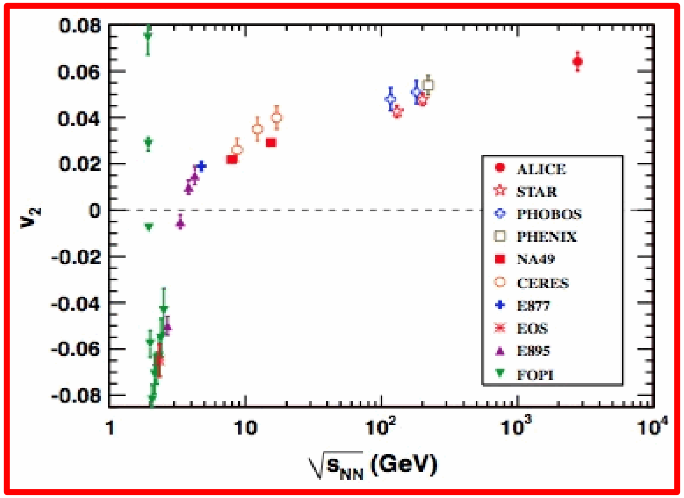
8th International Workshop on
Critical Point and Onset of Deconfinement (CPOD 2013)
March 11th-15th, 2013 Napa, California

Charged particle anisotropic flow (v_2, v_3, v_4) in Pb-Pb collisions at midrapidity measured by ALICE

Ranbir Singh (for the ALICE Collaboration)
University of Jammu, Jammu

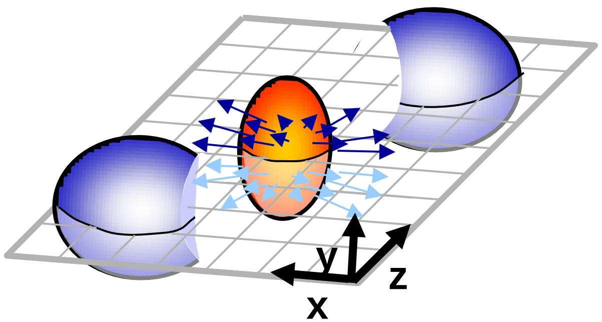
OUTLINE :

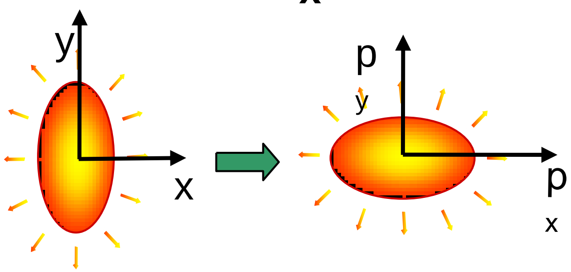
- Motivation
- ALICE experiment
- Flow Method used
- Results
- Summary



MOTIVATION

The measurement of the anisotropic flow allows to study :





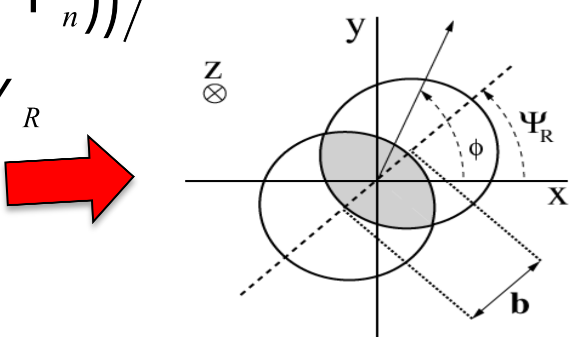
the initial conditions

the equation of state

transport properties of the system created

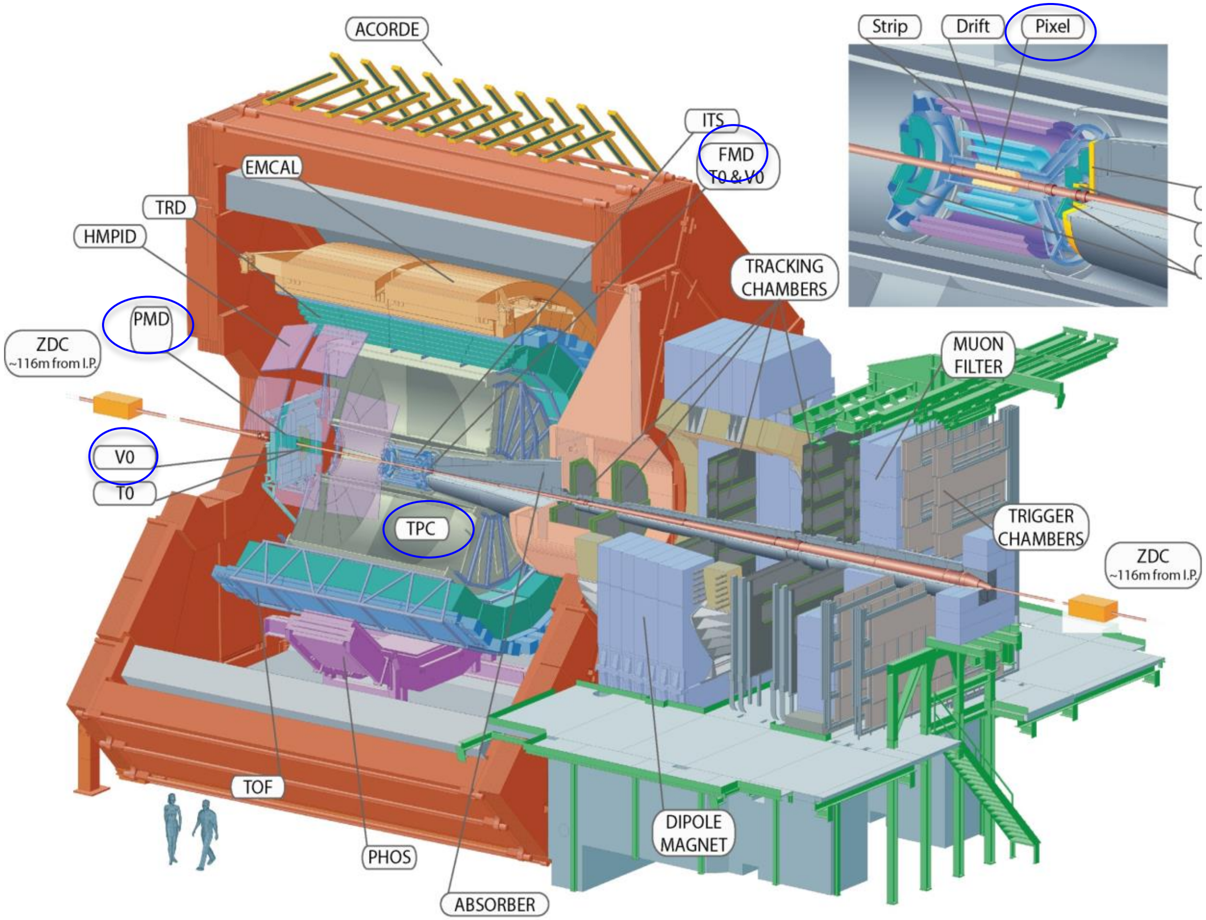
Anisotropic flow is quantified by the Fourier coefficients v_n in the azimuthal distribution of the produced particles: $v_n = \langle \cos(n(\phi - \Psi_n)) \rangle$

- Without fluctuations odd harmonics are zero and $\Psi_n = \Psi_R$ where Ψ_R is the reaction plane angle defined as :



- Fluctuations in the spatial positions of the participating nucleons results in non-zero odd harmonics

ALICE – A Schematic View



SPD
- ✓ Charged particle tracking
- ✓ $-2. < \eta < 2.$
- ✓ Full azimuth ($0 < \phi < 2\pi$)

TPC
- ✓ Charged particle tracking
- ✓ $-0.8 < \eta < 0.8$
- ✓ Full azimuth ($0 < \phi < 2\pi$)

VZERO
- ✓ Centrality selection
- ✓ Event plane determination
- ✓ $-3.7 < \eta < -1.7$, $2.8 < \eta < 5.1$
- ✓ Full azimuth ($0 < \phi < 2\pi$)

PMD
- ✓ Event plane determination
- ✓ $2.3 < \eta < 3.9$
- ✓ Full azimuth ($0 < \phi < 2\pi$)

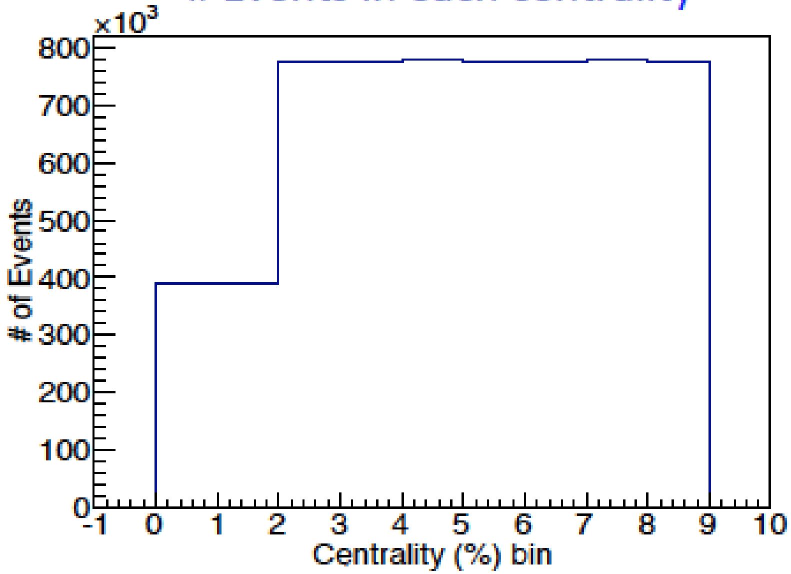
FMD
- ✓ Charged particle multiplicity
- ✓ $-3.7 < \eta < -1.7$, $1.7 < \eta < 5$
- ✓ Full azimuth ($0 < \phi < 2\pi$)

DATA Sample:
2010 Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
Events analysed ~ 10 M

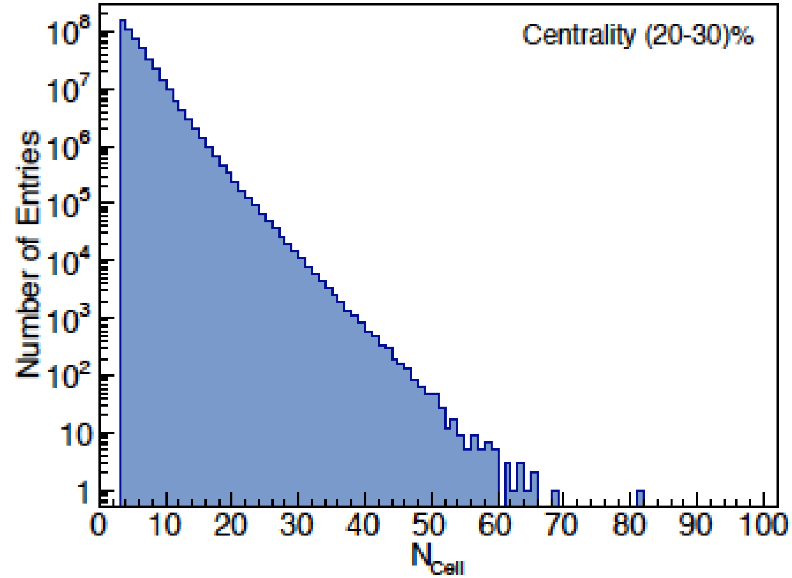
A large η-gap between TPC and event plane detectors ensures the suppression of non-flow correlations.

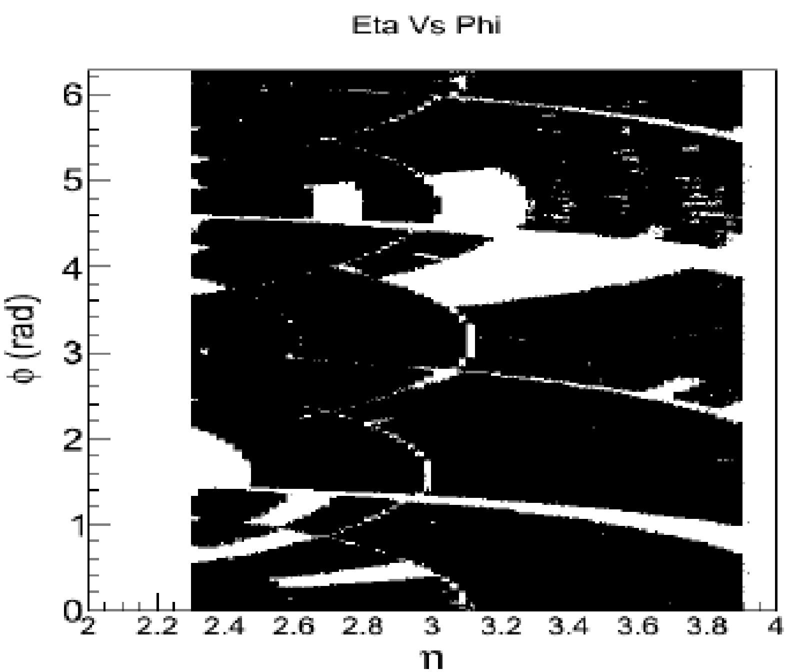
QA Plots :

Events in each centrality

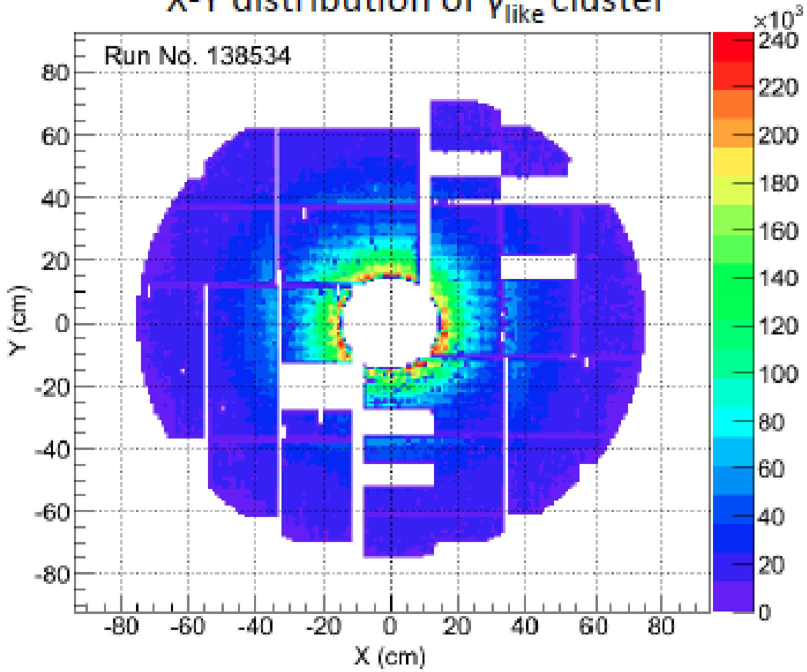


NCell distribution





X-Y distribution of γ_{like} cluster



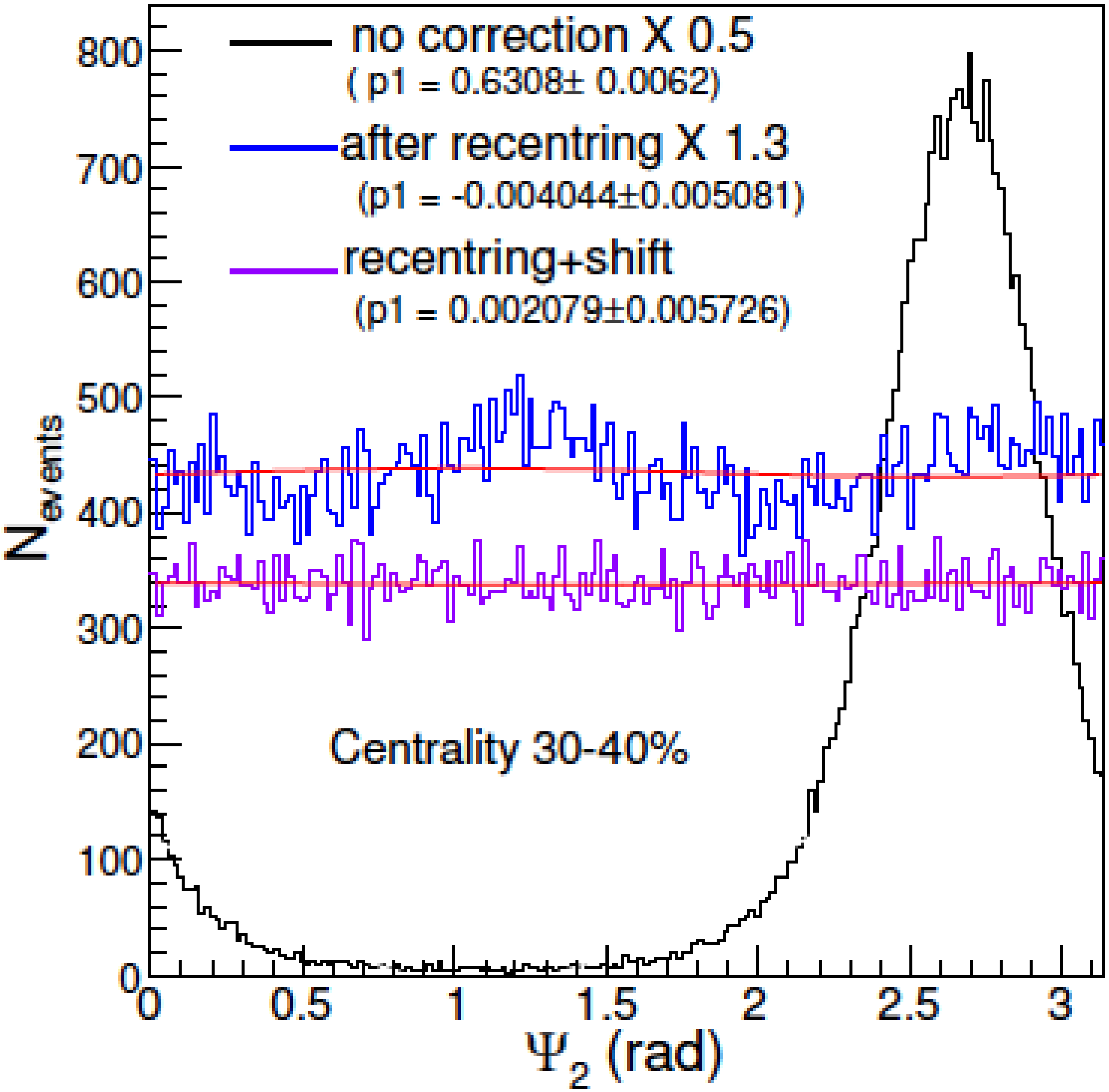


Fig. 7: Ψ_2 distributions, uncorrected, after corrections.

METHODS : Event Plane and Cumulants

ALICE

Event plane method :

The event plane angle : $$\Psi_n = \frac{1}{n}\tan^{-1}\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}$$

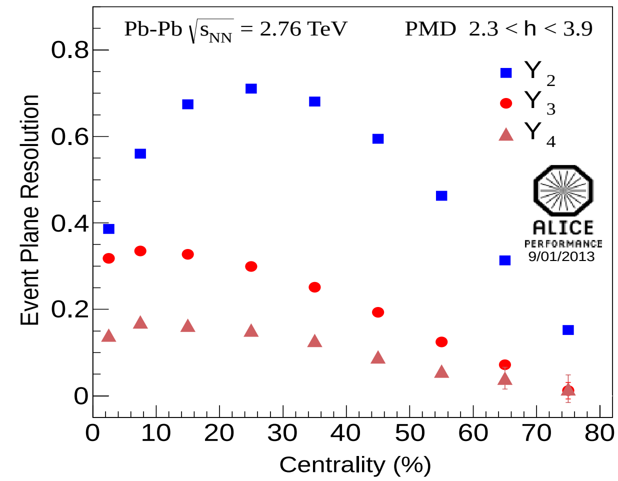
Estimate of v_n : $$v_n\{EP\} = \frac{v_n^{obs}}{R_n}$$

Resolution calculated using three sub-event method.

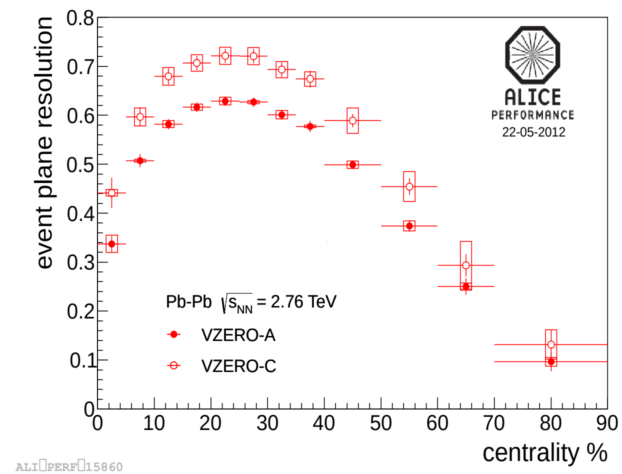
$$R_{A,n} = \sqrt{\frac{\langle\cos(n(\Psi_A - \Psi_B))\rangle\langle\cos(n(\Psi_A - \Psi_C))\rangle}{\langle\cos(n(\Psi_B - \Psi_C))\rangle}}$$

Poskanzer and Voloshin, Phys.Rev.C 58,1671 (1998).

PMD Event Plane Resolution



VZERO Event Plane Resolution



Cumulants : For the detectors with uniform acceptance 2nd and 4th order cumulants are given by

$$c_n\{2\} \equiv \langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle = v_n^2 + \delta_2$$

$$c_n\{4\} \equiv \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - 2\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle^2$$

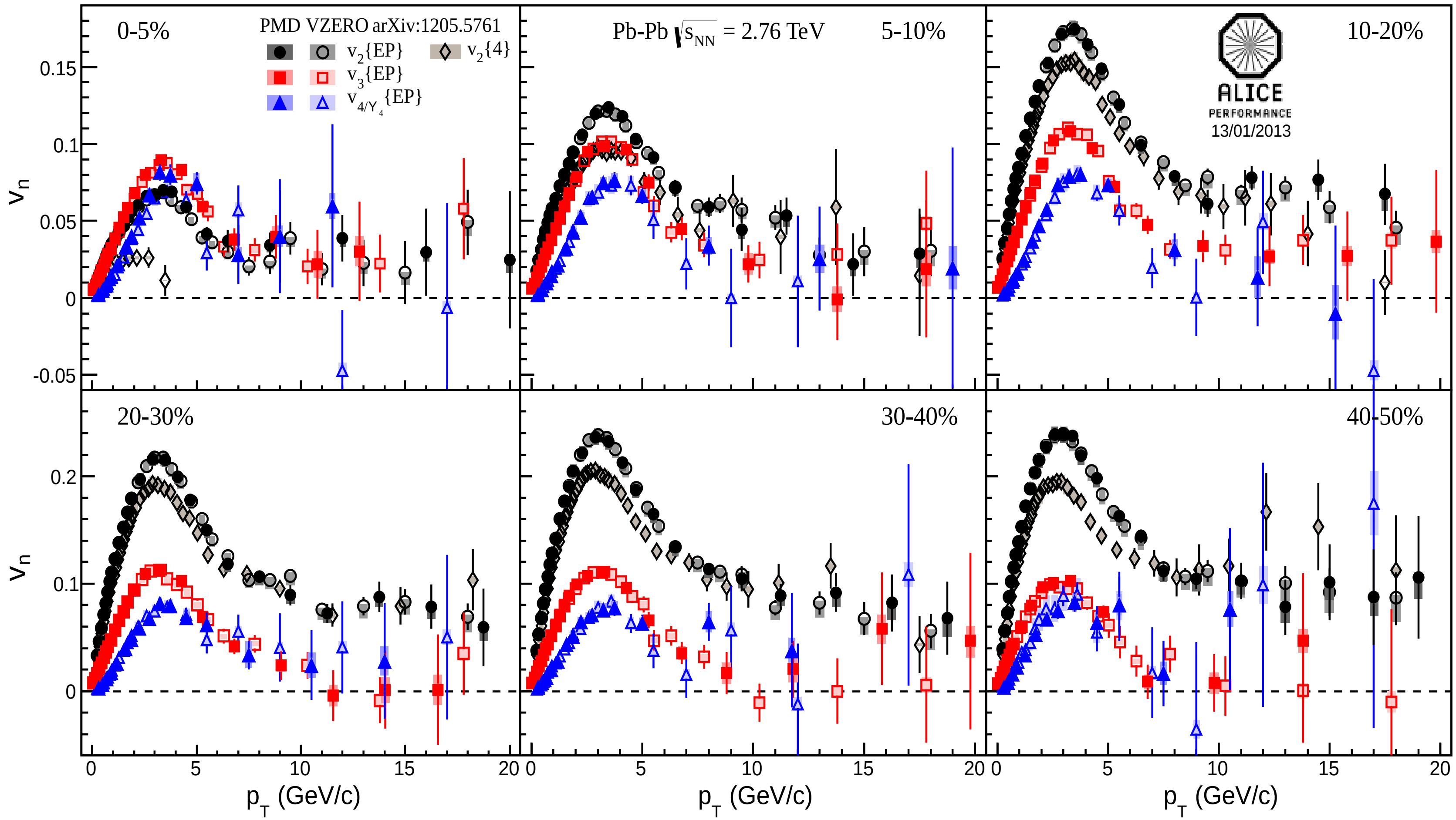
$$= v_n^4 + 4v_n^2\delta_2 + 2\delta_2^2 - 2(v_n^2+\delta_2)^2$$

$$= -v_n^4$$

δ_2 - contribution from the non-flow correlations, $\delta_2 \sim 1/M$

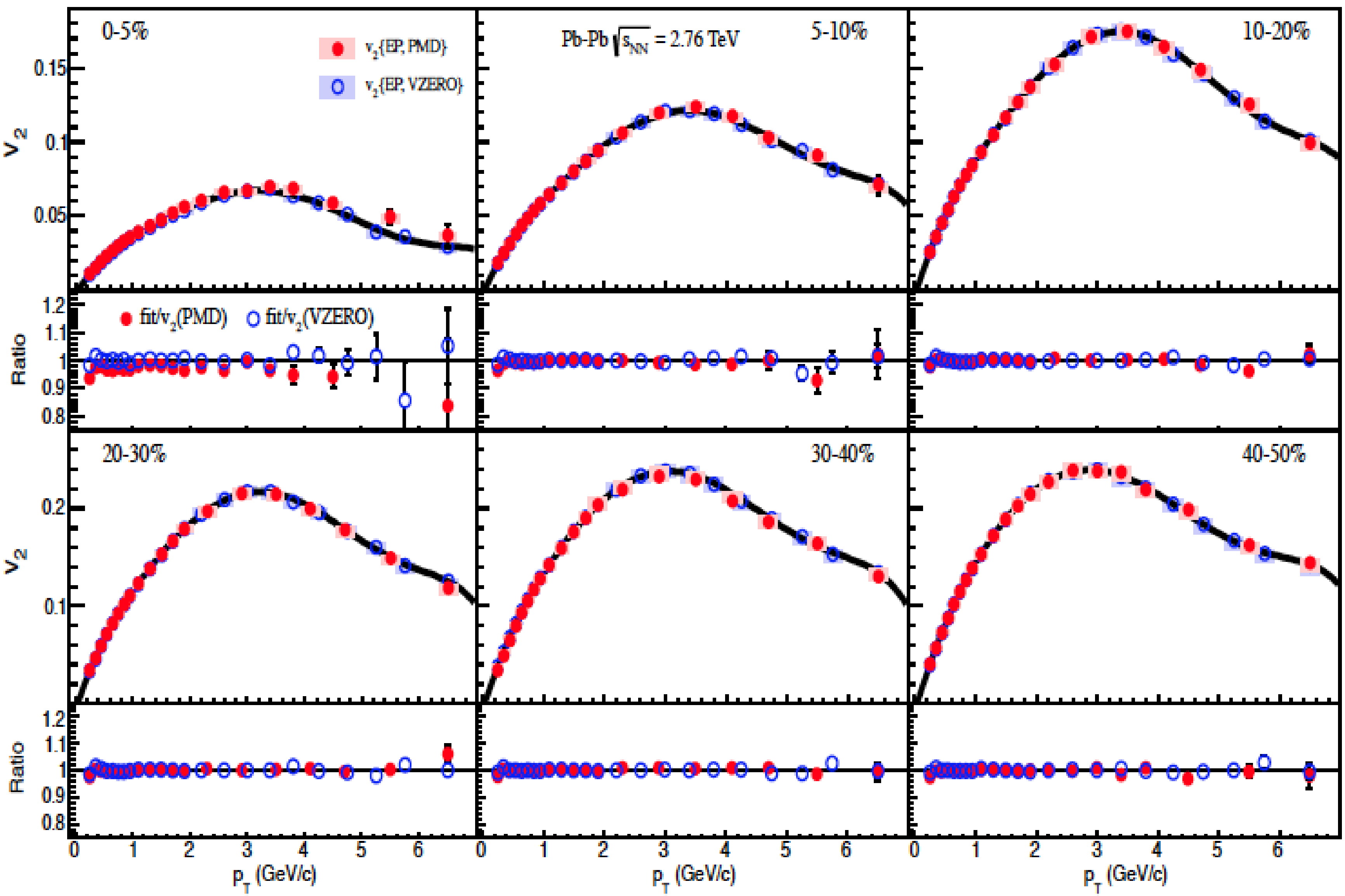
Borghini, Dhin and Ollitrault, Phys. Rev. C 64, 054901 (2001).

RESULTS : v_n(n=2-4) vs p_T for different centralities

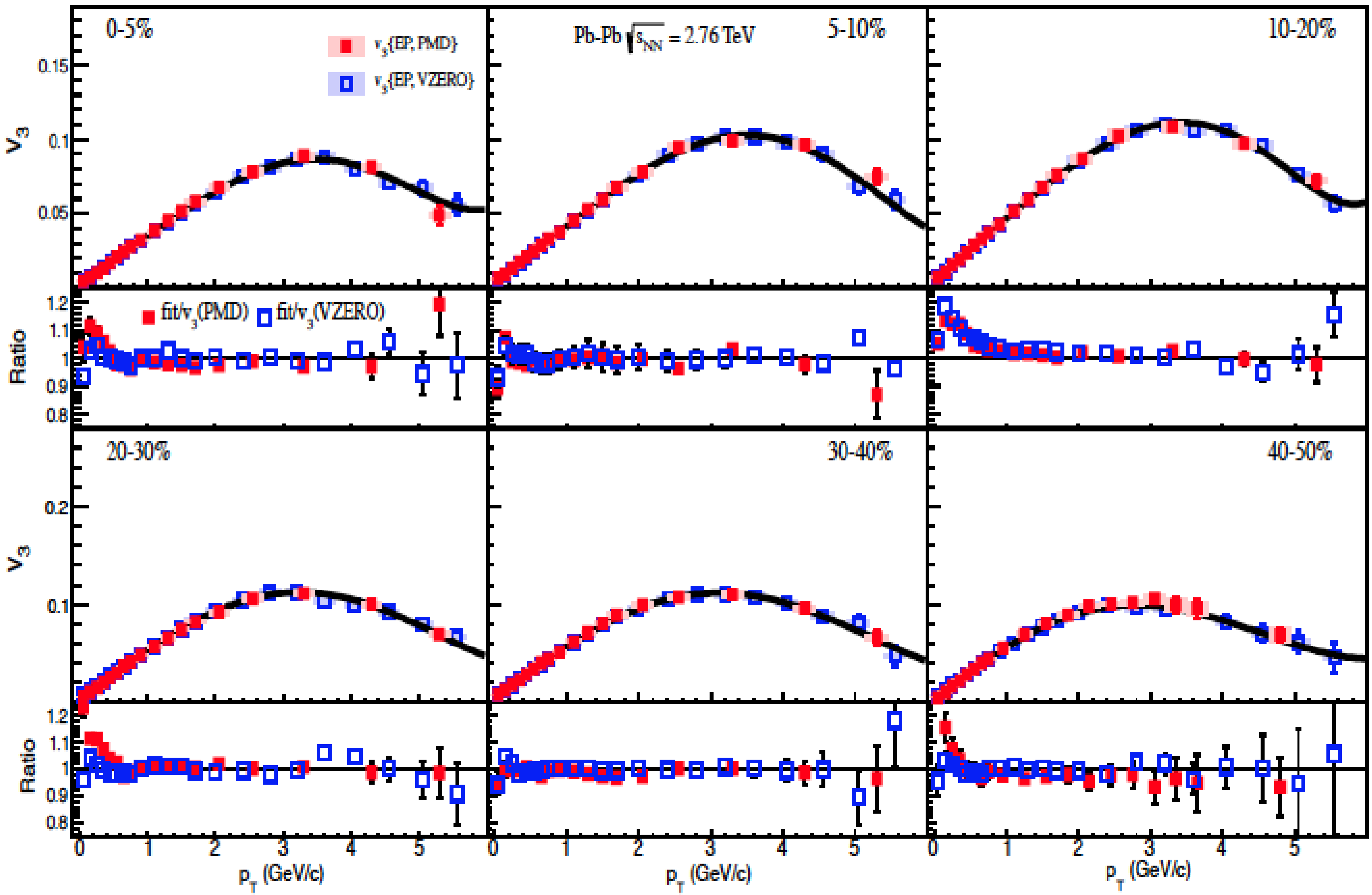


- $v_n(p_T)$ peaks at about 3-4 GeV/c and depends weakly on p_T above 8 GeV/c.
- v_2 is higher than v_3 and v_4 for all centralities except 0-5%.
- Observed non-zero v_3 refers to the fluctuating initial conditions.

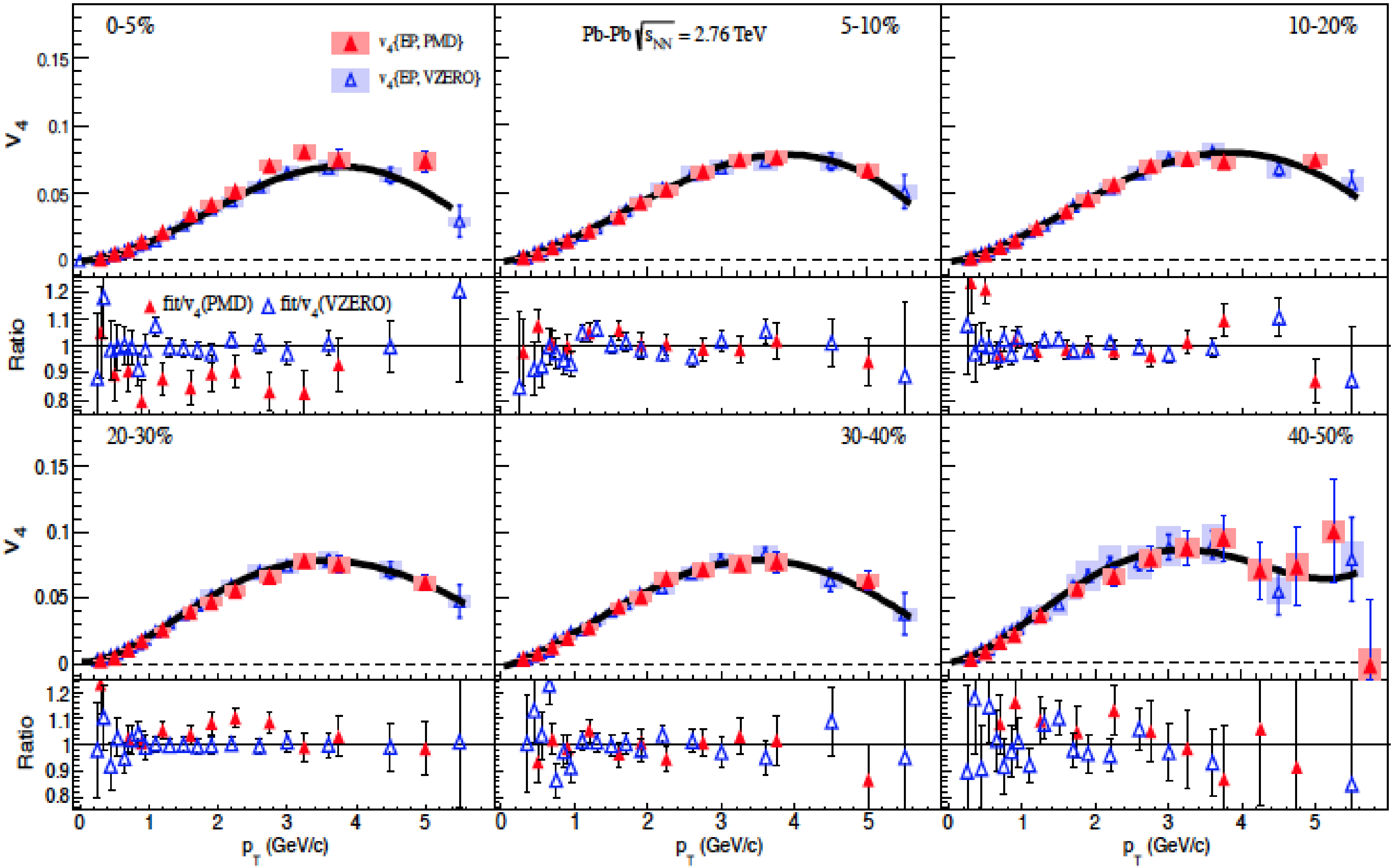
Ratio plots for $v_2(p_T)$:



Ratio plots for $v_3(p_T)$:

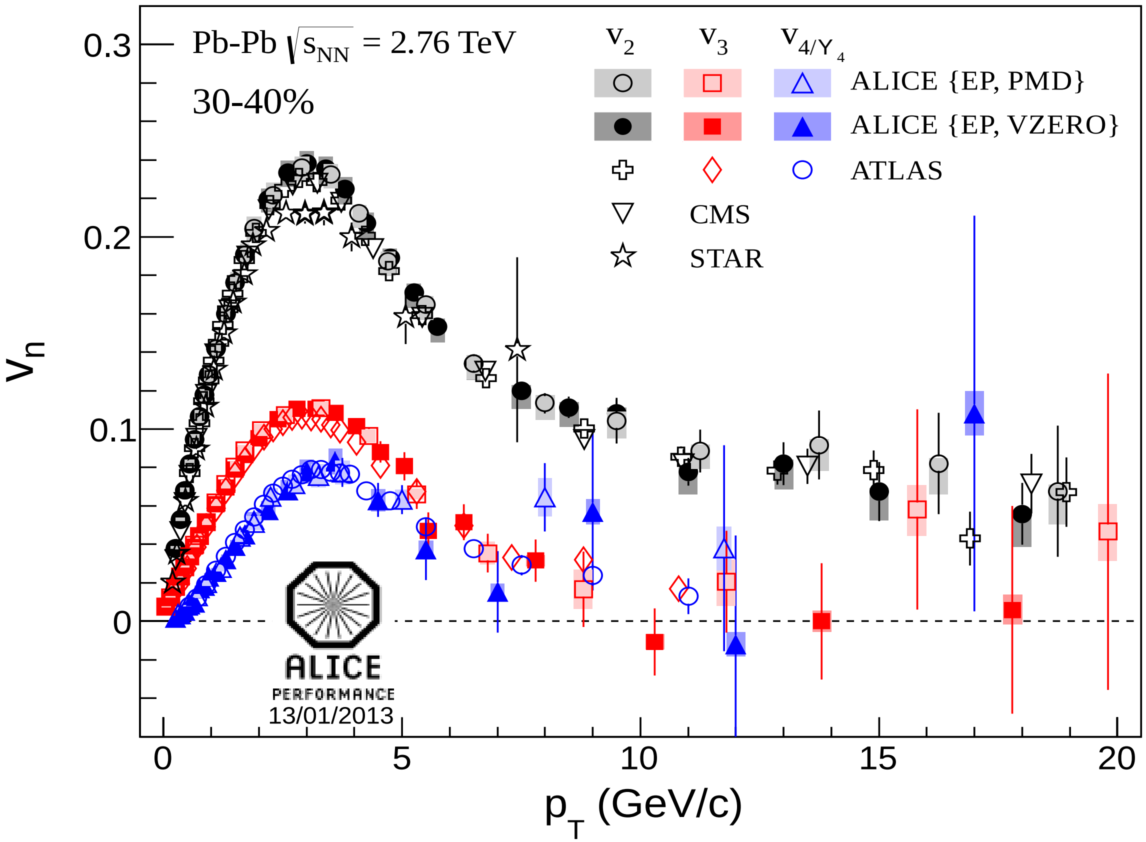


Ratio plots for $v_4(p_T)$:



RESULTS : v_n(n=2-4) vs p_T (0.2 - 20 GeV/c)

A comparison with the results from other experiments at RHIC and LHC



ALICE Collaboration
arXiv:1205.5761

CMS Collaboration
arXiv:1204.1409

ATLAS Collaboration
Phys. Lett. B 707, 330-348(2012)

STAR Collaboration
*Phys. Rev. C **72**, 014904 (2005)*

- v_n results from different LHC experiments show nice agreement.
- v_2 measured at LHC ($\sqrt{s_{NN}}$=2.76TeV) has a similar magnitude to that at RHIC ($\sqrt{s_{NN}}$=200GeV) .

Systematic checks :

Standard Cuts : nHits > 70; dcaXY < 3.0 cm and dcaZ < 3.0 cm and |zVertex| < 10 cm

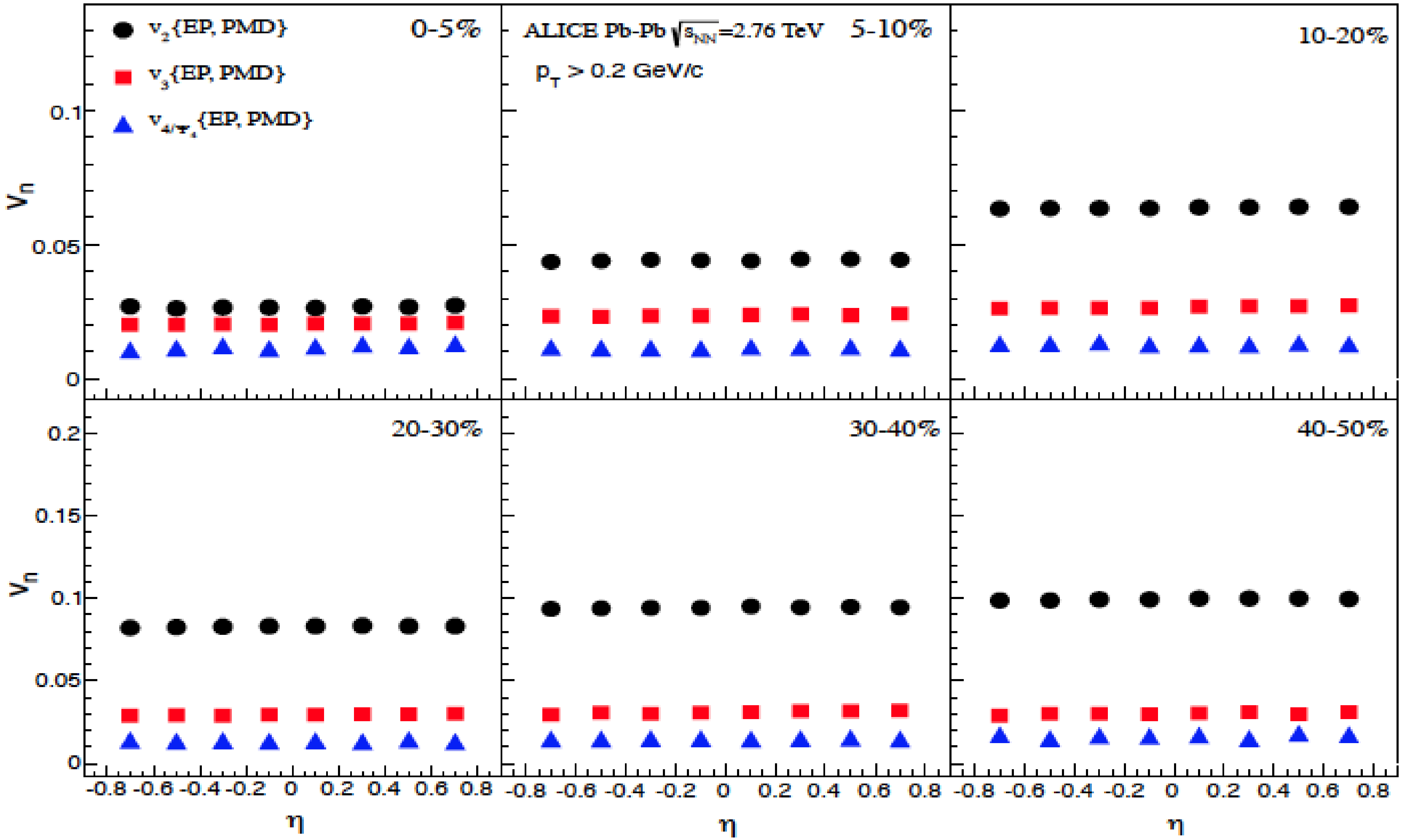
Cuts variation in nHits : 1) > 60, 2) > 75, 3) > 80, 4) > 85 and 5) > 90

Cuts variation in dcaXY : 1) < 4.0 2) < 2.5, 3) < 2.0, 4) < 1.5, 5) < 1.0 and 6) < 0.5

Cuts variation in dcaZ : 1) < 4.0 2) < 2.5, 3) < 2.0, 4) < 1.5, 5) < 1.0 and 6) < 0.5

For detailed study and ratio plots : *https://aliceinfo.cern.ch/Notes/node/144*

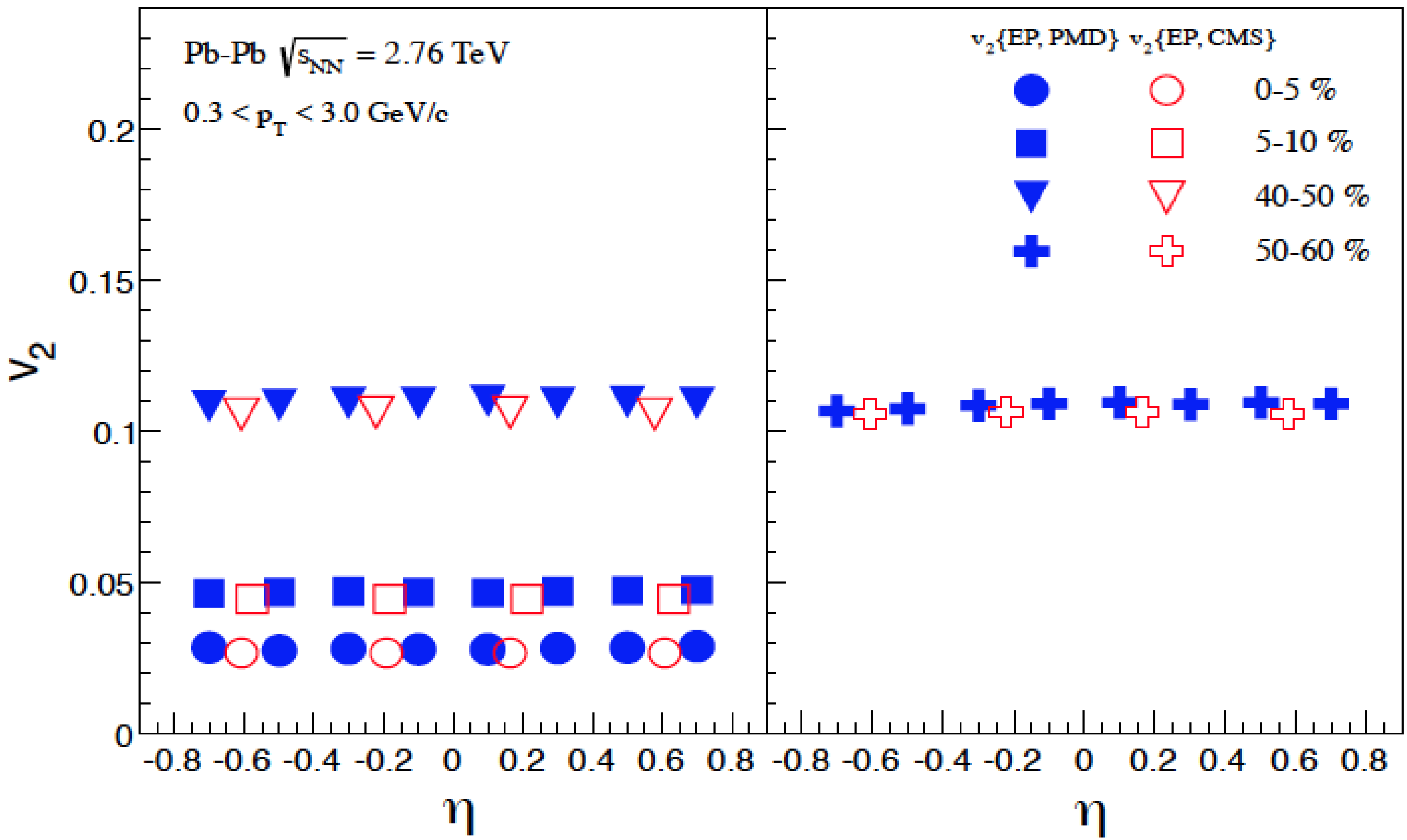
RESULTS : v_n (n=2, 3) vs η



Note : Statistical errors are shown only.

Comparison of v_2 vs. η with CMS $v_2\{EP\}$

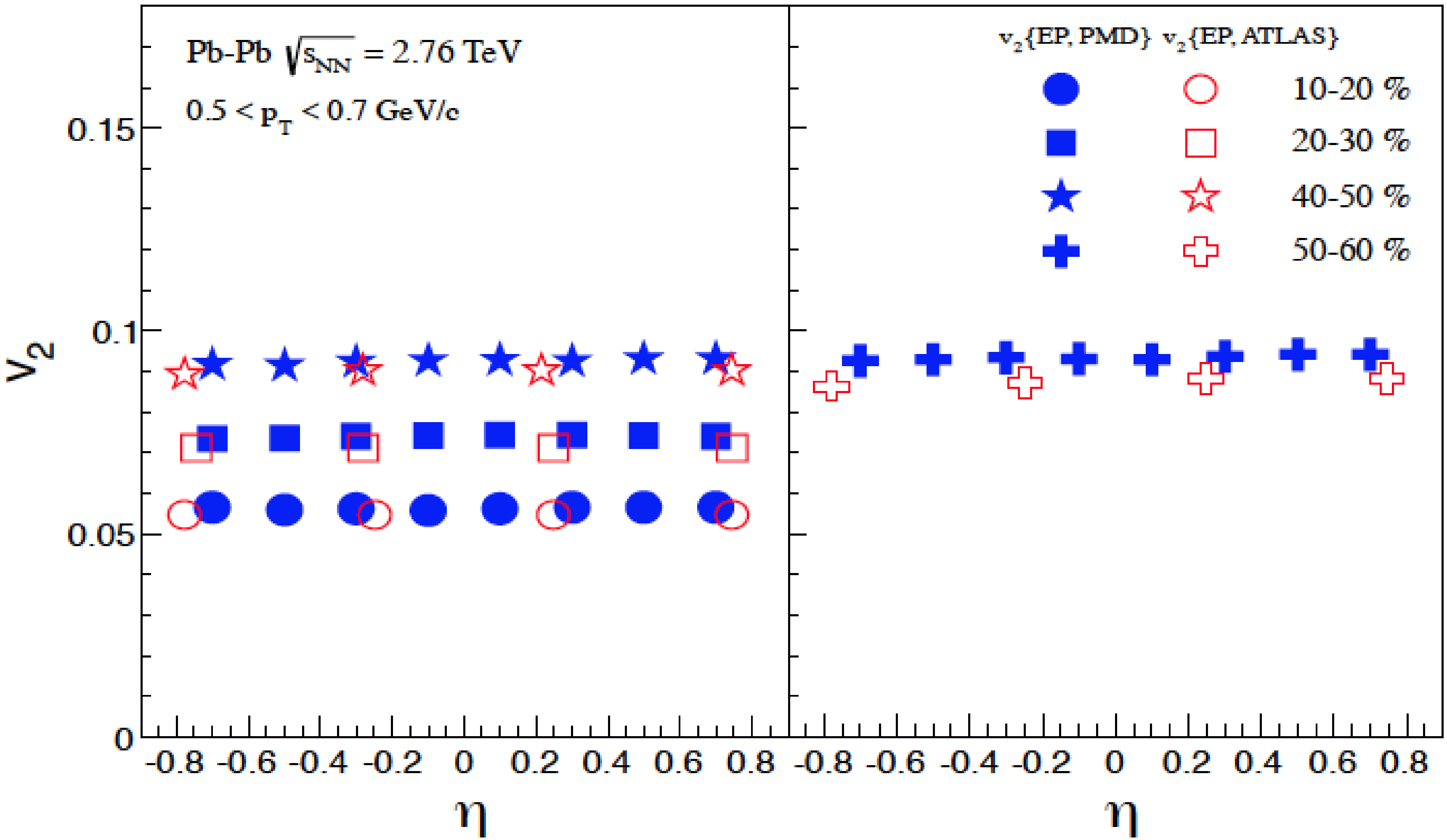
p_T cut is same ($0.3 < p_T < 3.0$ GeV/c) both for $v_2\{EP,PMD\}$ and CMS results



CMS results : arXiv:1204.1409

Comparison of v_2 vs. η with ATLAS $v_2\{EP\}$

p_T cut is same ($0.5 < p_T < 0.7$ GeV/c) both for $v_2\{EP,PMD\}$ and ATLAS results

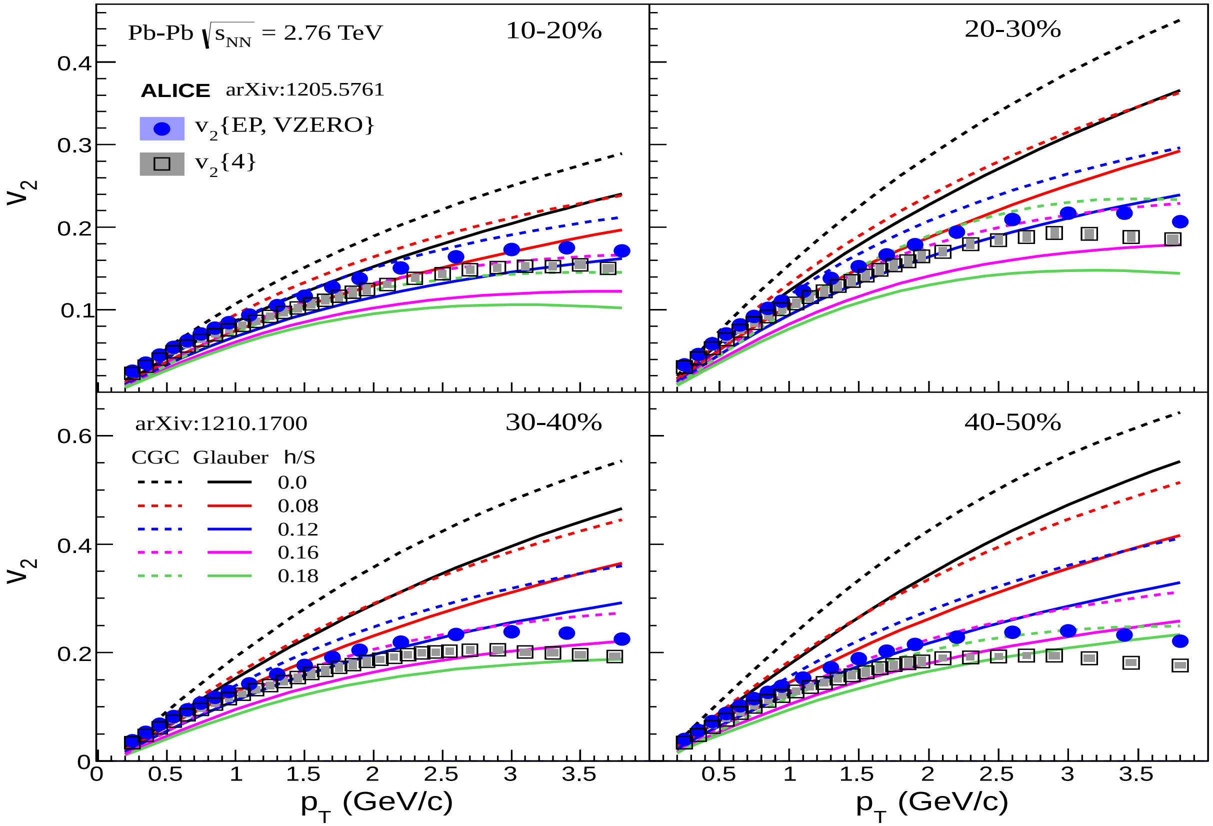


ATLAS results : *Phys.Lett.B 707 (2012) 330-348*

RESULTS : v_2 vs p_T (Comparison with Hydro results)

Hydrodynamic model calculations are done with different sets of initial conditions : Glauber and Color Glass Condensate (CGC)

Roy, Mohanty and Chaudhary, arxiv:1210.1700.



For Glauber initial condition
- data prefers η/S between 0.0 to 0.12

For CGC initial condition
- data prefers η/S between 0.08 to 0.16

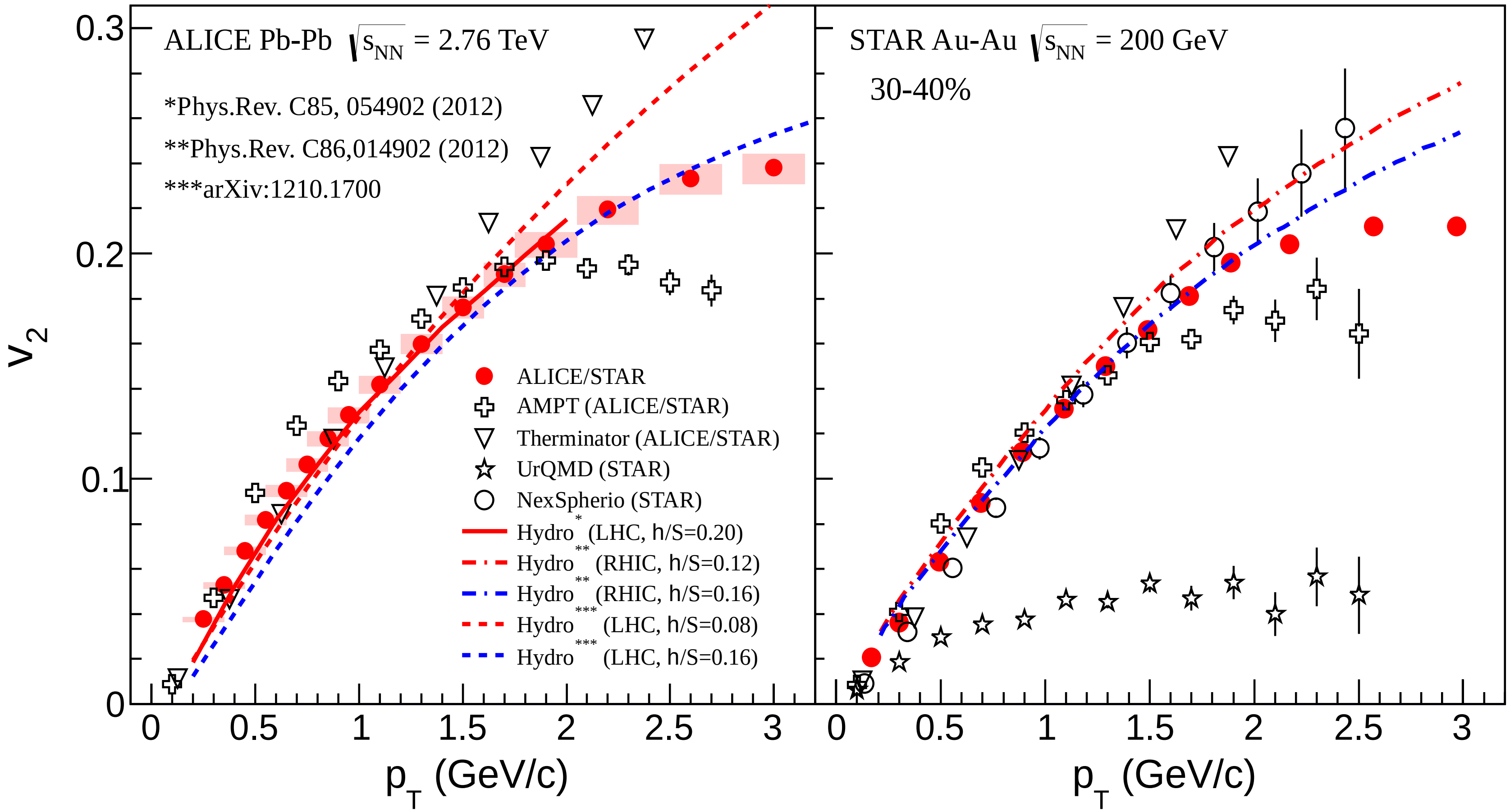
Another hydro study using a hybrid model VISHNU predicts $\eta/S \approx 0.20–0.24$ at LHC energies.

- VISHNU - (2+1)d viscous hydrodynamic with the microscopic hadronic transport model UrQMD
- Initial conditions from MC-Glauber and MC-KLN

Song, Bass and Heinz, Phys.Rev.C83:054912,2011

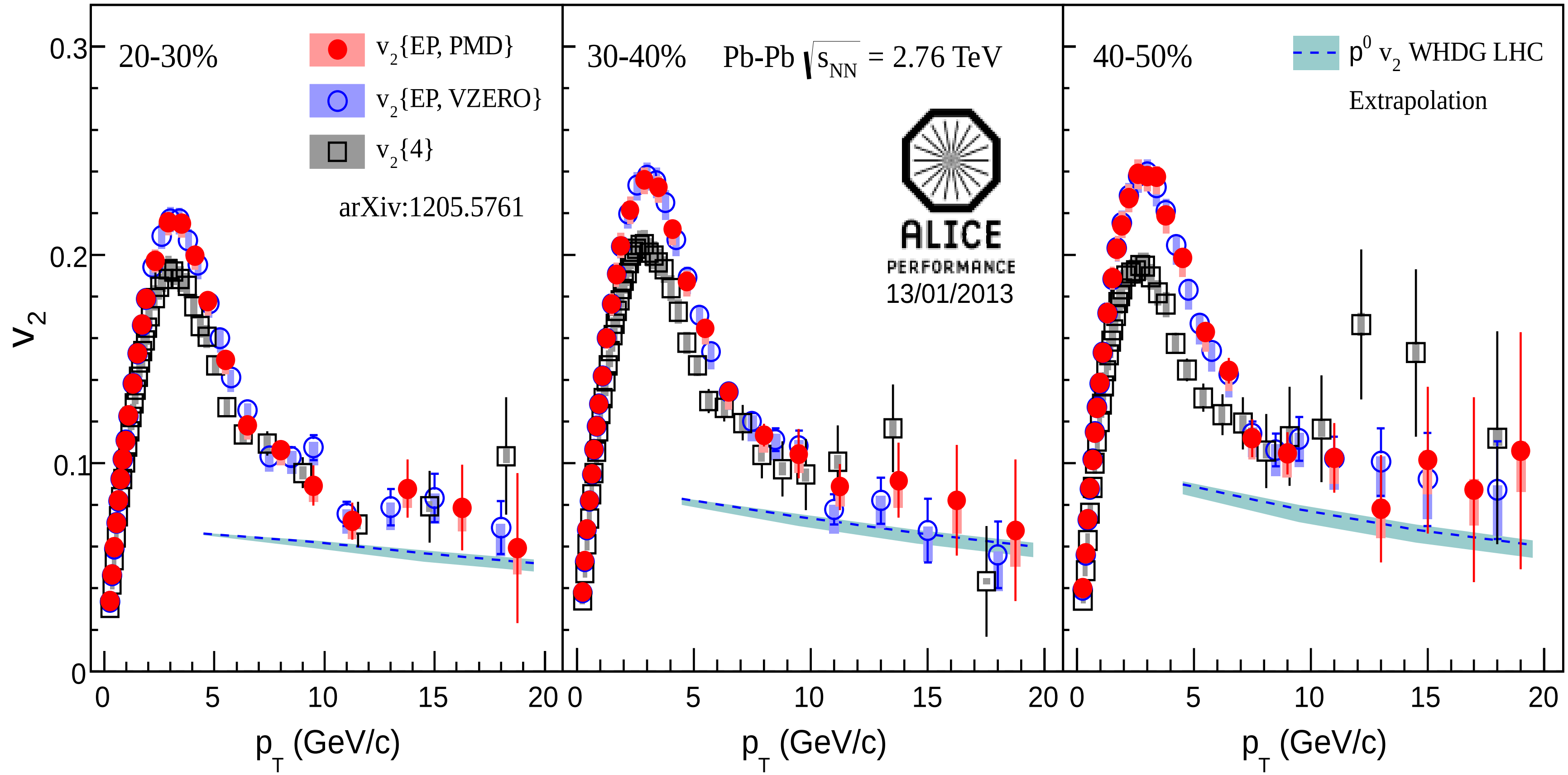
RESULTS : v_2 vs p_T (Comparison with other models)

A comparison with transport models and hydro results.



- NexSpherio and AMPT results are in good agreement with STAR data.
- AMPT and Therminator shows a good agrrement with ALICE data in low pT (<2GeV) range.

RESULTS : v_2 vs p_T (Comparison with WHDG model)



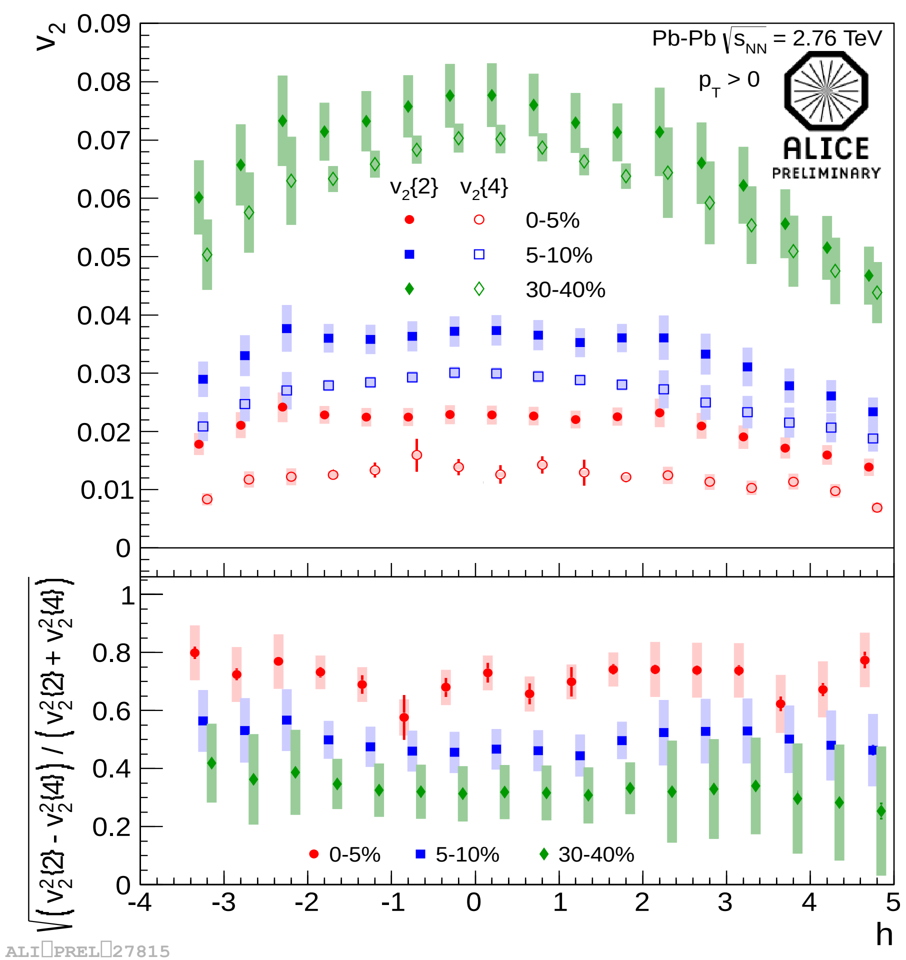
- High p_T (≥7- 8 GeV/c) region is dominated by the hadron production from jet-fragmentation
- For p_T > 10 GeV/c, $v_2(p_T)$ in agreement with WHDG model calculations

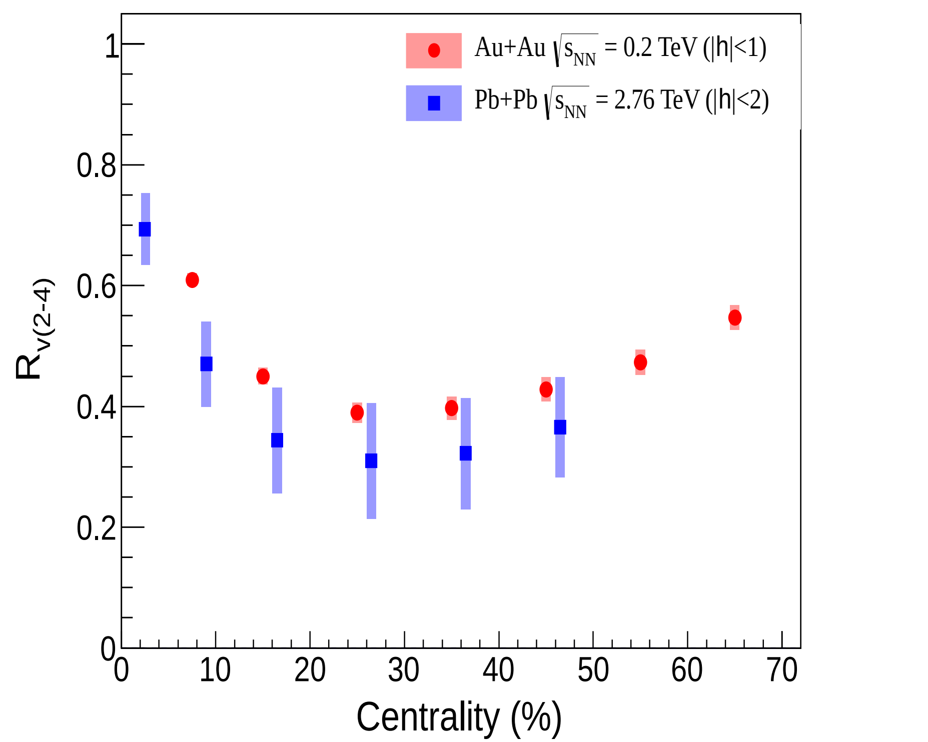
*W. A. Horowitz and M. Gyulassy, J. Phys. G **38**, 124114 (2011).*

RESULTS : Elliptic flow fluctuations

Estimate of the flow fluctuation :

$$R_{v(2-4)} = \frac{\sigma_{v_2}}{\langle v_2 \rangle} \approx \sqrt{\frac{v_2^2\{2\} - v_2^2\{4\}}{v_2^2\{2\} + v_2^2\{4\}}}$$



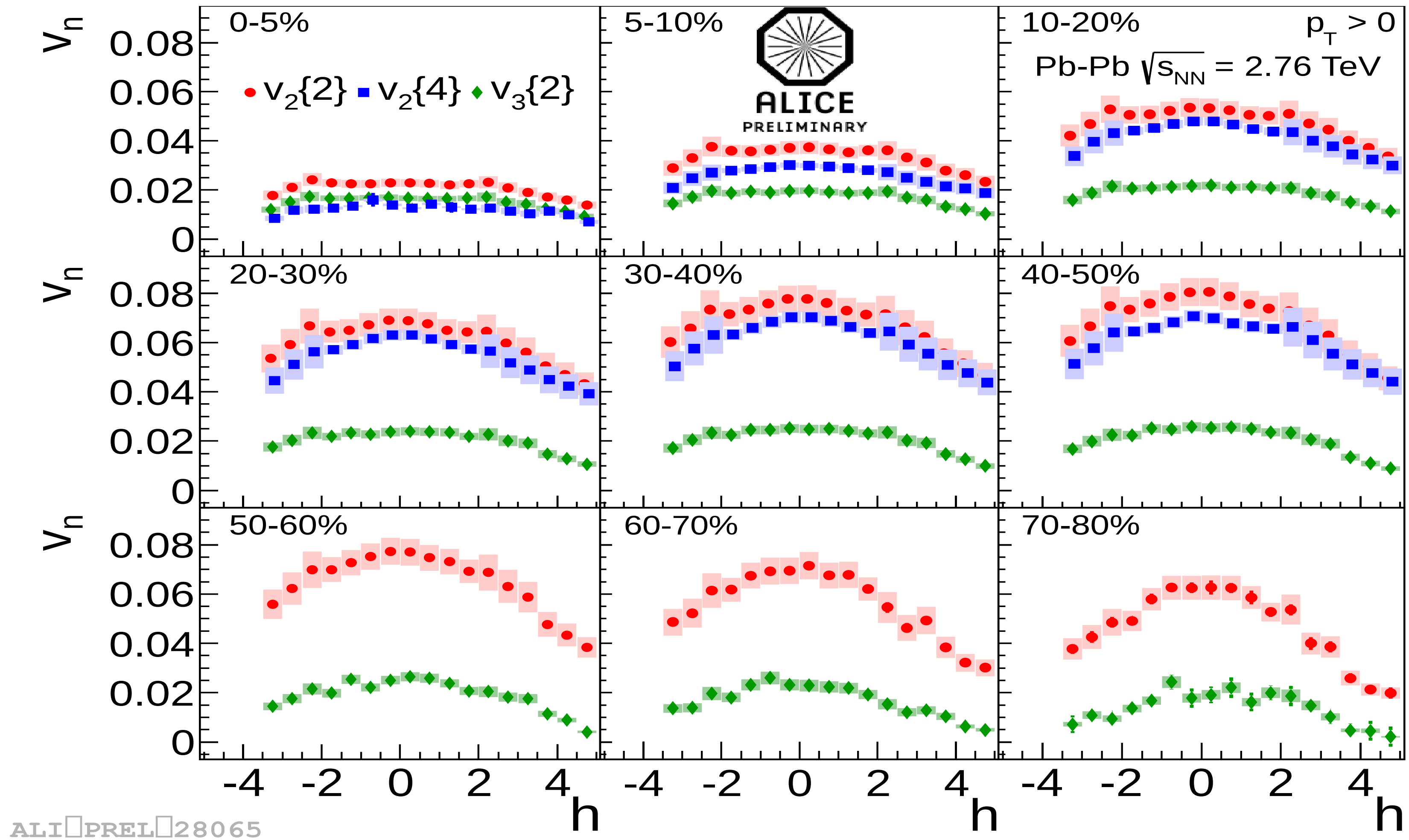


Fluctuations at forward rapidity are similar to fluctuations at mid-rapidity.

At midrapidity fluctuations at LHC are consistent to that at RHIC*

** STAR collaboration, Phys. Rev. C86 (2012) 0.*

RESULTS : v_n (n=2, 3) vs η



- v_2 has strong centrality dependence
- v_3 shows weaker centrality dependence (expected for flow fluctuations)
- Difference between $v_2\{2\}$ and $v_2\{4\}$ gives an estimate of flow fluctuations and it has weak dependence on rapidity

SUMMARY :

- Charged particle v_n is measured in Pb-Pb collisions at $\sqrt{s_{NN}}$ =2.76 TeV with the ALICE detector over a broad range of pseudorapidity, $|\eta|<5$ and of transverse momentum, $0.2 < p_T < 20$ GeV/c.
- Observed non-zero v_3 arises due to fluctuating initial conditions.
- $v_2(p_T)$ at LHC energies is comparable to that at RHIC energies.
- At low p_T, comparison of $v_2(p_T)$ with the hydro calculations suggest low value of the shear viscosity to entropy ratio (η/S).
- At high p_T, $v_2(p_T)$ agrees with the WHDG model which accounts for the path length dependence of the parton energy loss.
- Elliptic flow fluctuations, $R_{v(2-4)}$, measured over a wide range of rapidity and have similar magnitude at forward and mid-rapidity.
- Strong centrality dependence of $v_2(\eta)$ is observed, while $v_3(\eta)$ has weaker dependence on centrality.