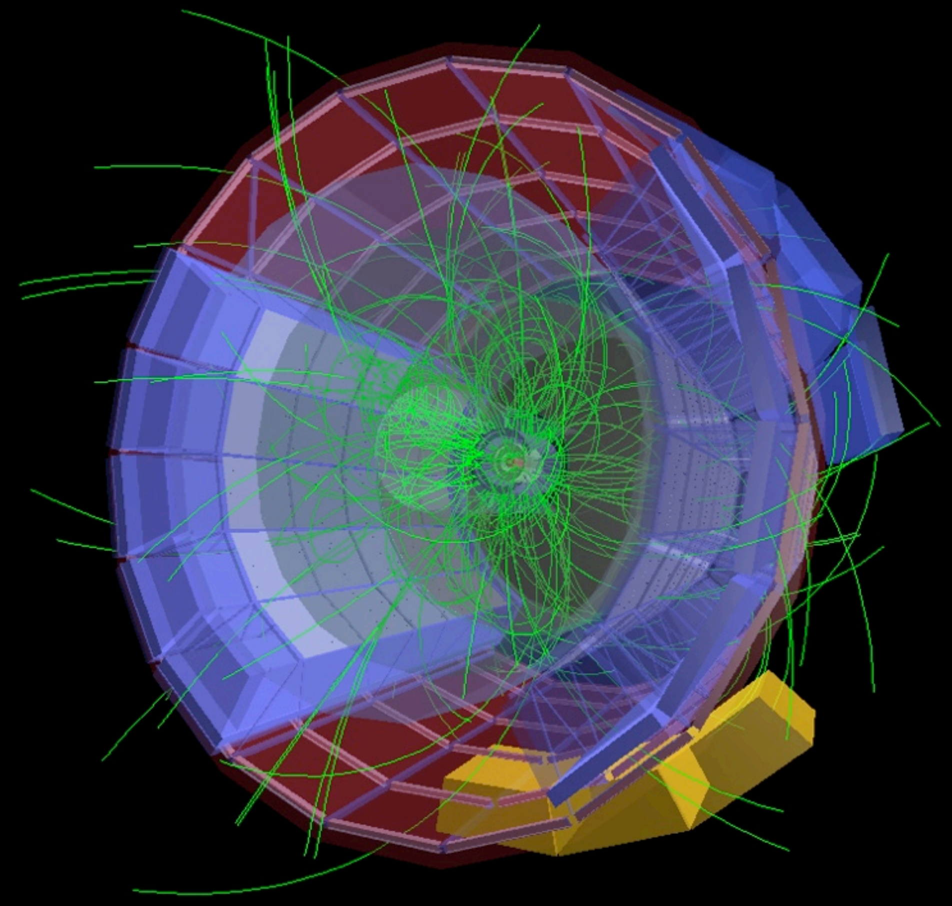
Angular Correlations

Niels Bohr Institute



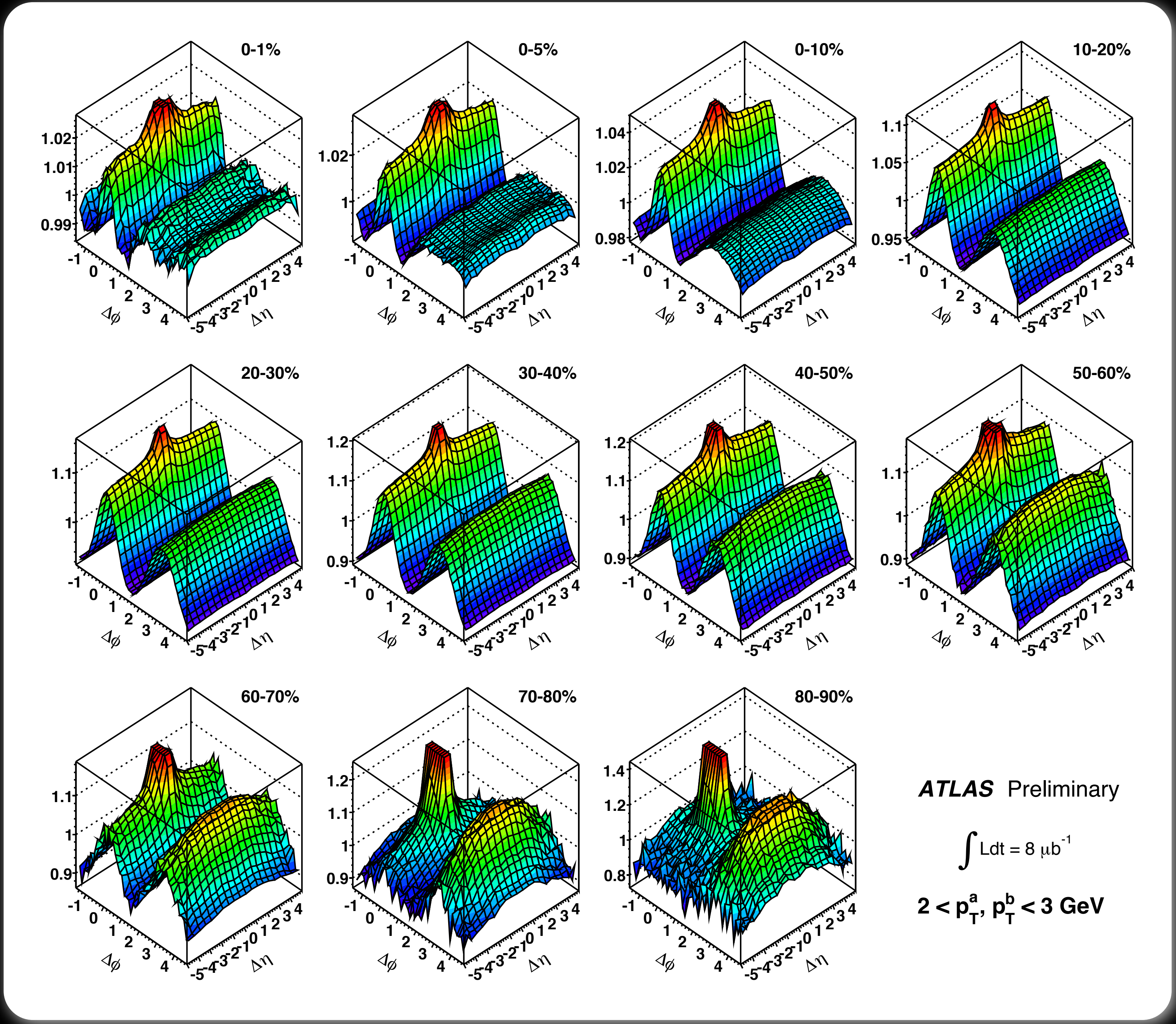
Raimond Snellings
Utrecht University

7-11-2011

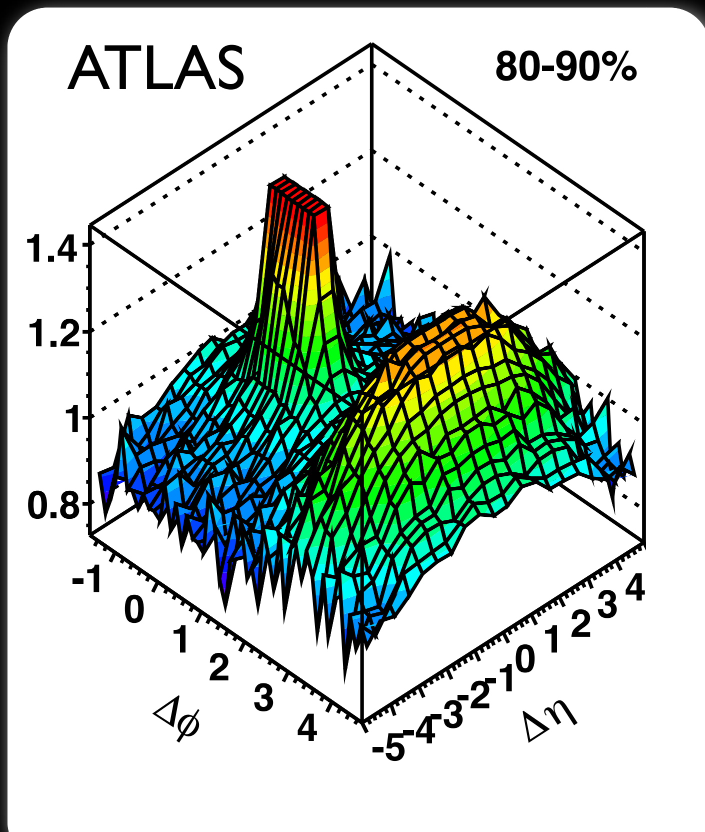
Angular Correlations at the LHC

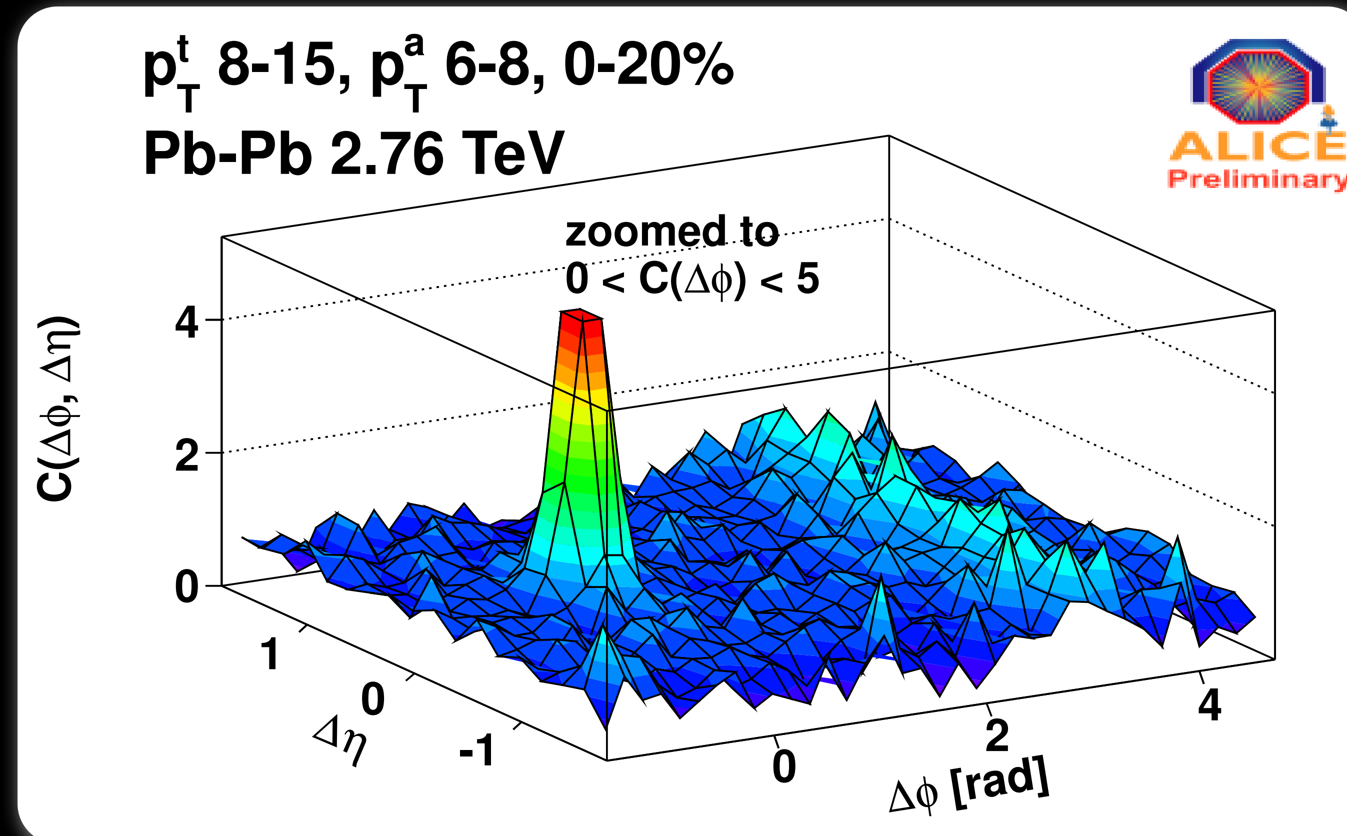
$$C(\Delta\phi\Delta\eta) \equiv \frac{N_{\mathrm{mixed}}}{N_{\mathrm{same}}} \frac{\mathrm{d}^2 N_{\mathrm{same}}/\mathrm{d}\Delta\phi \mathrm{d}\Delta\eta}{\mathrm{d}^2 N_{\mathrm{mixed}}/\mathrm{d}\Delta\phi \mathrm{d}\Delta\eta}$$

Contributions to the two-particle ΔΦ , Δη angular correlation come from anisotropic flow, jets, resonances, HBT, etc



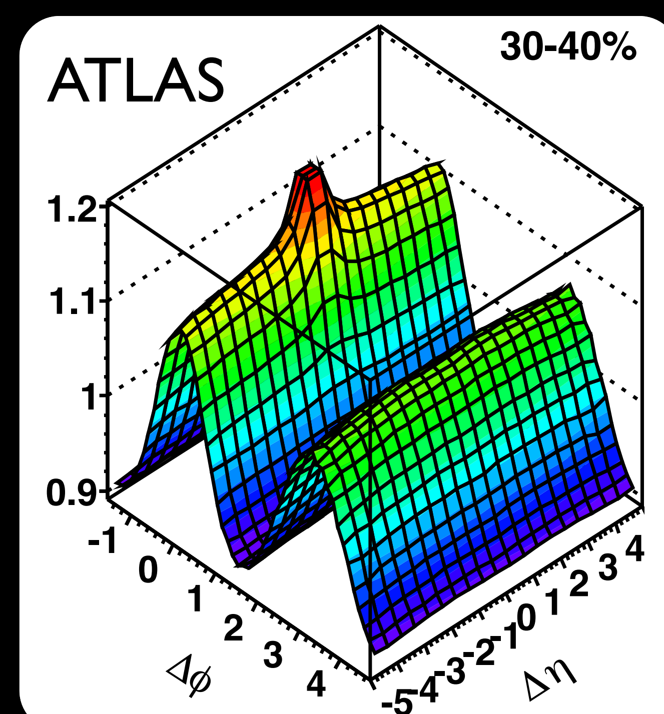
Angular Correlations

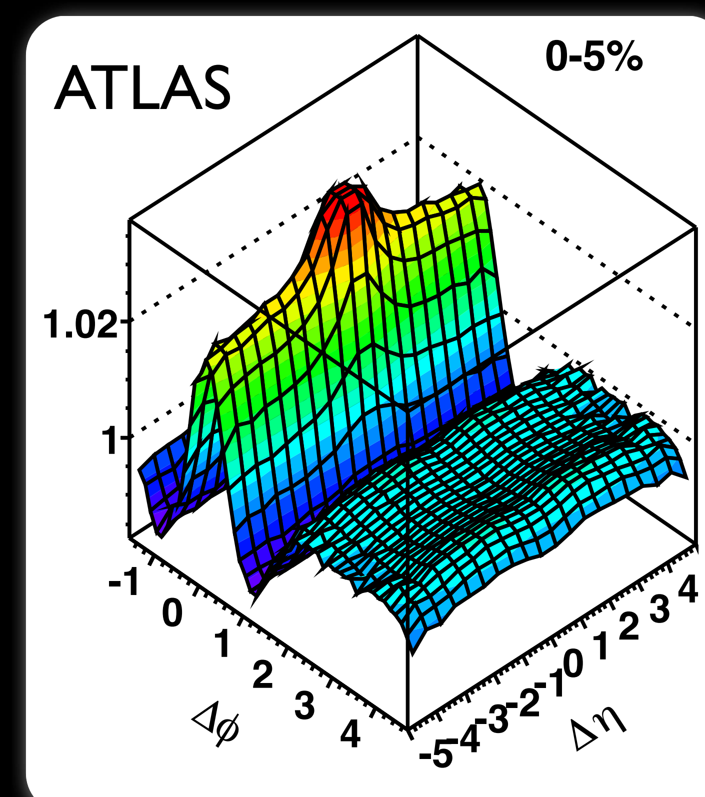




For very peripheral collisions or when triggered with a high-p_t charged particle the dominant contribution to two particle angular correlations is due to jet-correlations

More central heavy-ion collisions look very very different!





measure anisotropic flow

$$\langle v_n \rangle = \langle\langle e^{in(\phi_1 - \Psi_n)} \rangle\rangle$$

- since the common symmetry plane cannot be measured event-by-event, we measure quantities which do not depend on it's orientation: multi-particle azimuthal correlations

$$\begin{aligned}
\langle\langle e^{in(\phi_1 - \phi_2)} \rangle\rangle &= \langle\langle e^{in(\phi_1 - \Psi_n - (\phi_2 - \Psi_n))} \rangle\rangle \\
&= \langle\langle e^{in(\phi_1 - \Psi_n)} \rangle \langle e^{-in(\phi_2 - \Psi_n)} \rangle\rangle \\
&= \langle v_n^2 \rangle
\end{aligned}$$

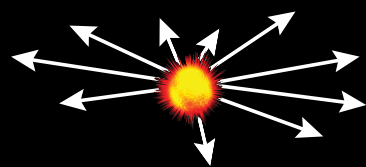
- assuming that <u>only</u> correlations with the symmetry plane are present - not a very good assumption (jets, resonances, etc)!

Can we isolate the flow?

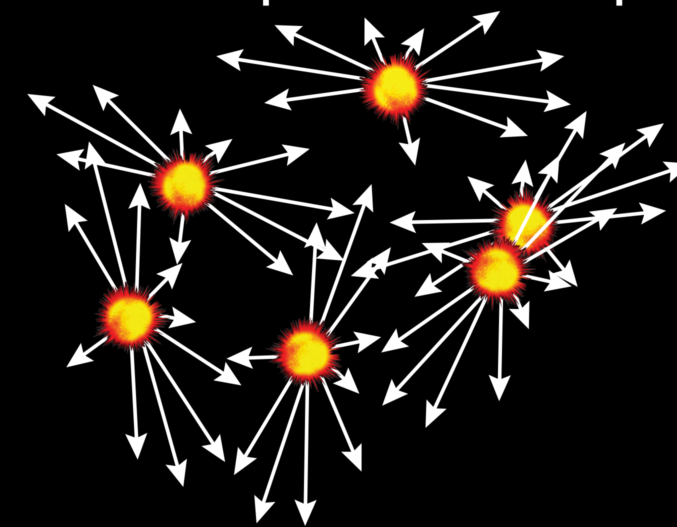
- flow is a collective effect
  - flow "factorizes"
    - $\langle v_i v_j \rangle / \langle v_j \rangle = \langle v_i v_k \rangle / \langle v_k \rangle$
      - correlate particles separated in rapidity
      - correlate particles separated in p_t
  - multi-particle correlation
    - build cumulants

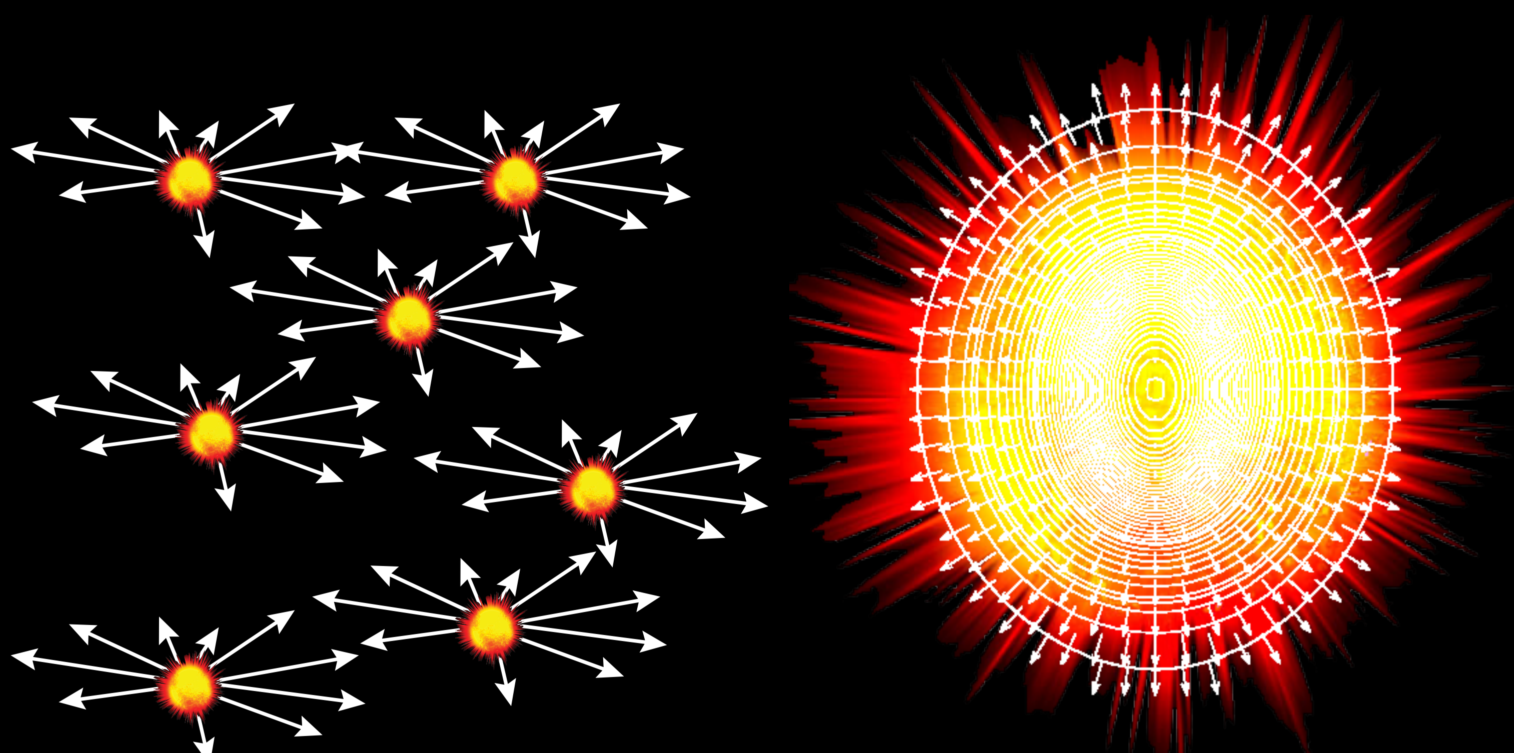
Collective Motion

p+p



A+A independent # of p+p





A+A collective behavior

tests if we are dealing with a common symmetry plane!

multi-particle correlations

- for detectors with uniform acceptance 2[nd] and 4[th] cumulant are given by:

Borghini, Dihn and Ollitrault, PRC 64, 054901 (2001)

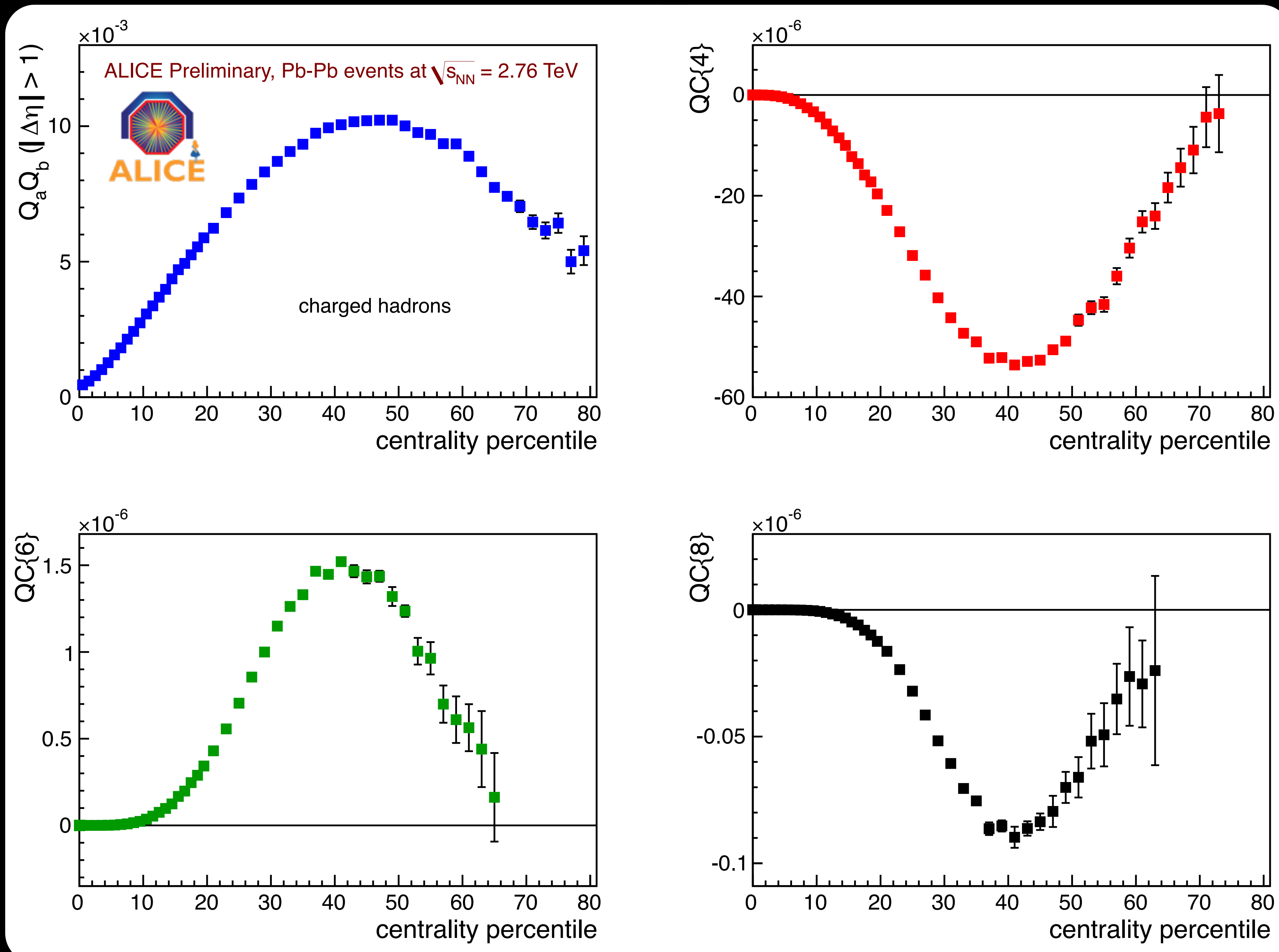
$$
\begin{aligned}
c_n\{2\} &\equiv \left\langle\!\left\langle e^{in(\phi_1-\phi_2)} \right\rangle\!\right\rangle = v_n^2 + \delta_2 \\
c_n\{4\} &\equiv \left\langle\!\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle\!\right\rangle - 2\left\langle\!\left\langle e^{in(\phi_1-\phi_2)} \right\rangle\!\right\rangle^2 \\
&= v_n^4 + 4v_n^2\delta_2 + 2\delta_2^2 - 2(v_n^2+\delta_2)^2 \\
&= -v_n^4
\end{aligned}
$$

we got rid of two particle nonflow correlations!

we can remove nonflow order by order

v_2 from cumulants

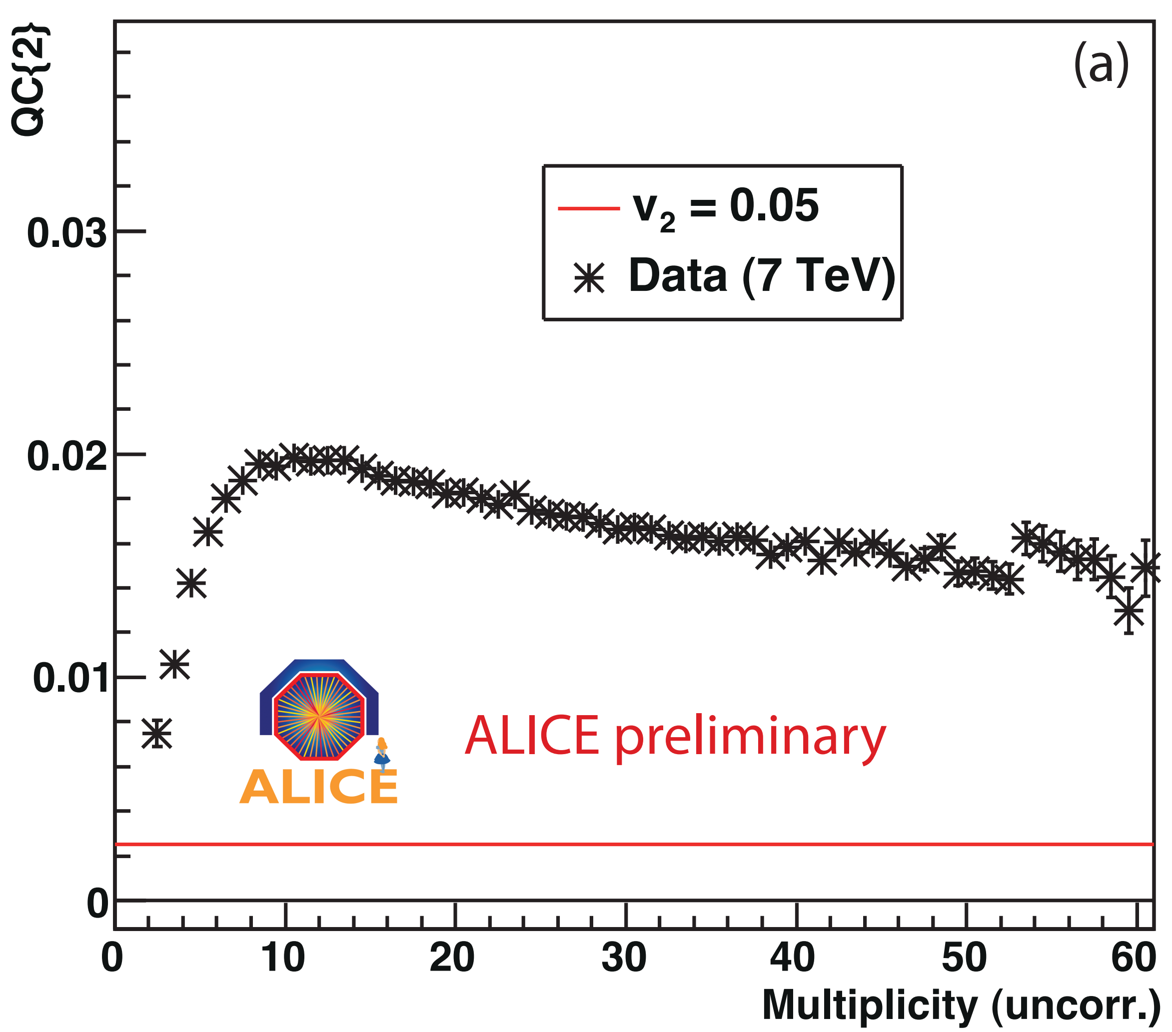
Method used : A.Bilandzic, R.Snellings, S. Voloshin,
Phys.Rev. C83 (2011) 044913

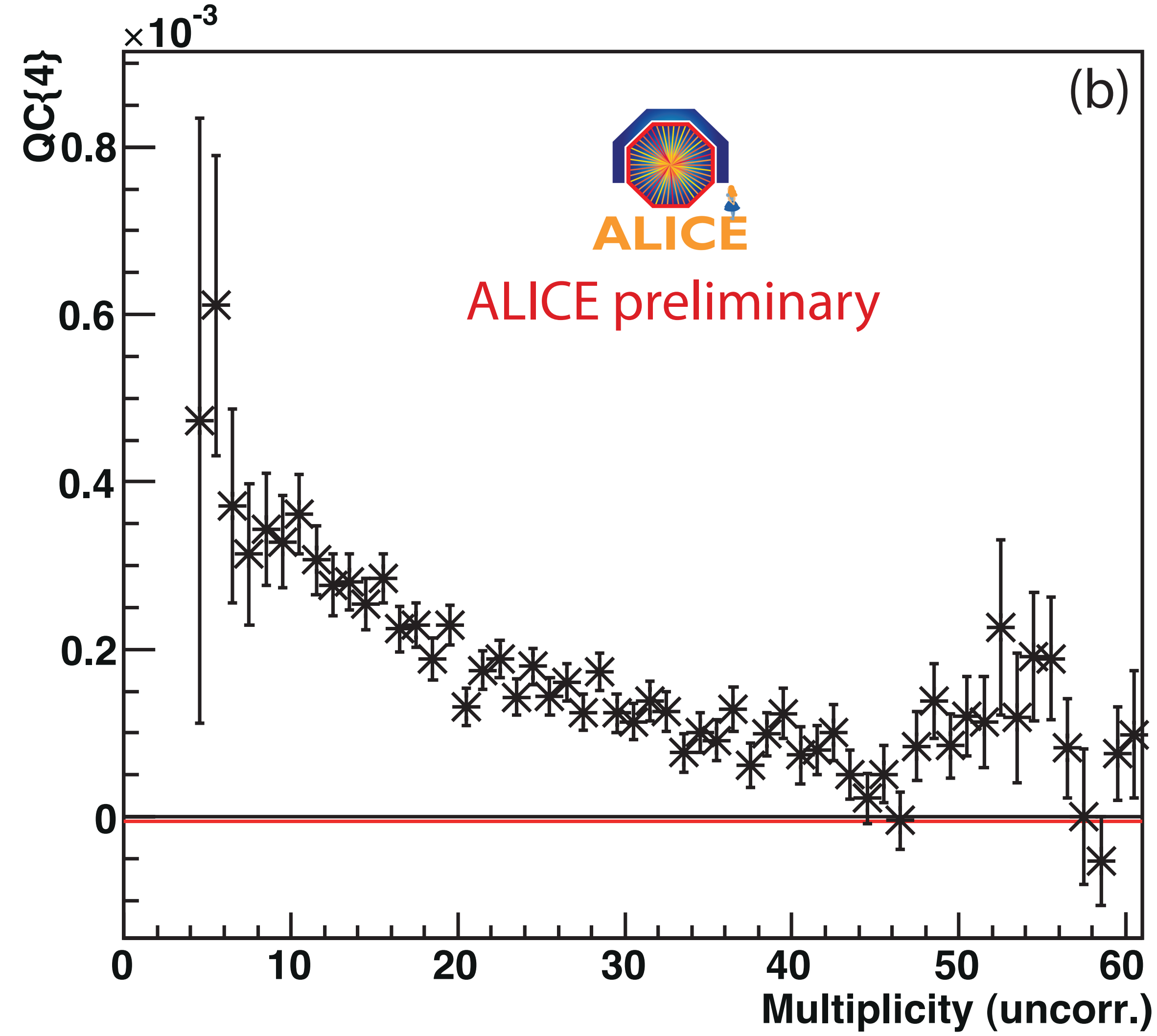


$$QC\{2\} = v^2\{2\}$$
$$QC\{4\} = -v^4\{4\}$$
$$QC\{6\} = 4v^6\{6\}$$
$$QC\{8\} = -33v^8\{8\}$$

cumulants show behavior as expected when correlations are dominated by collective flow

What about p-p?



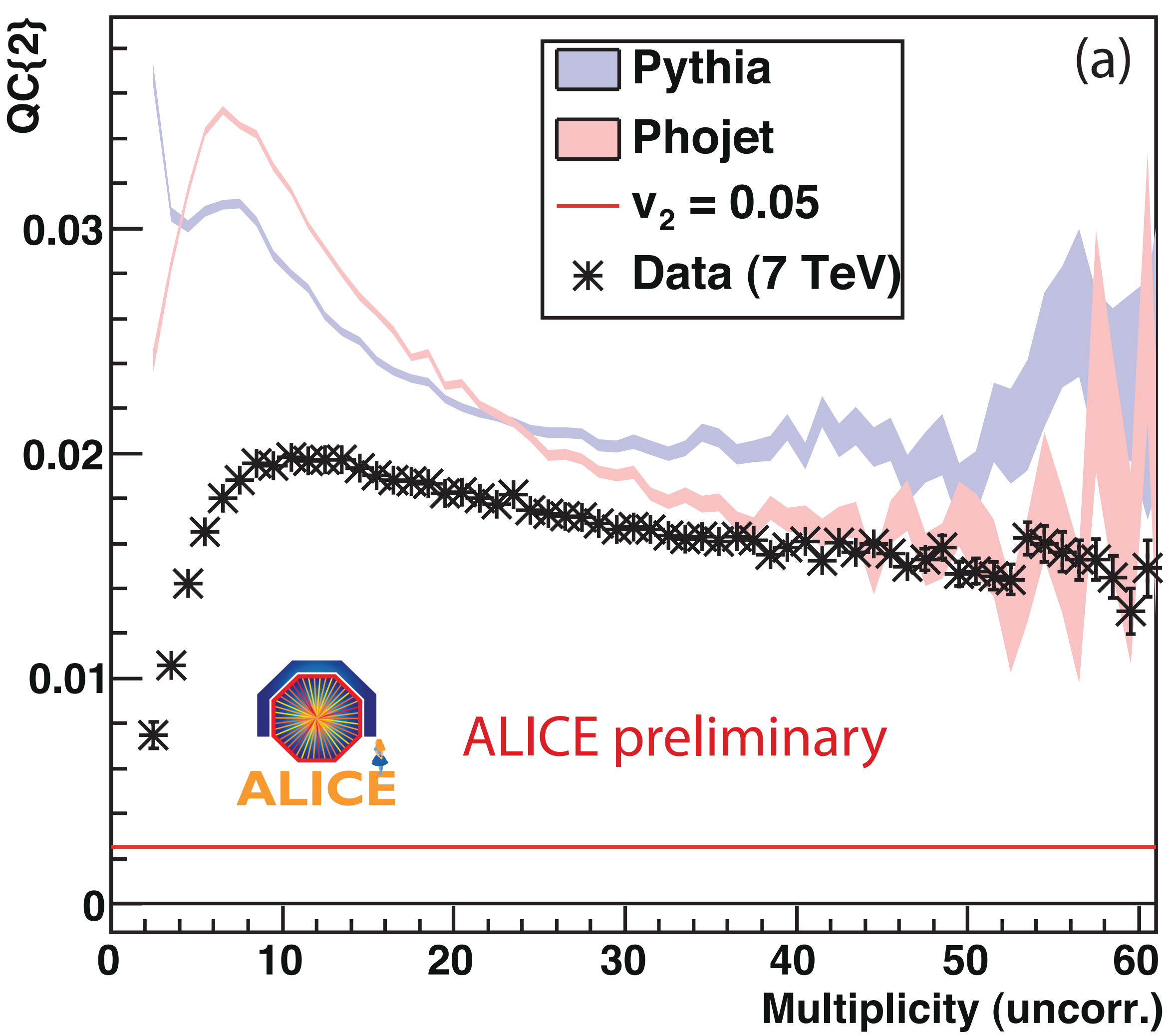


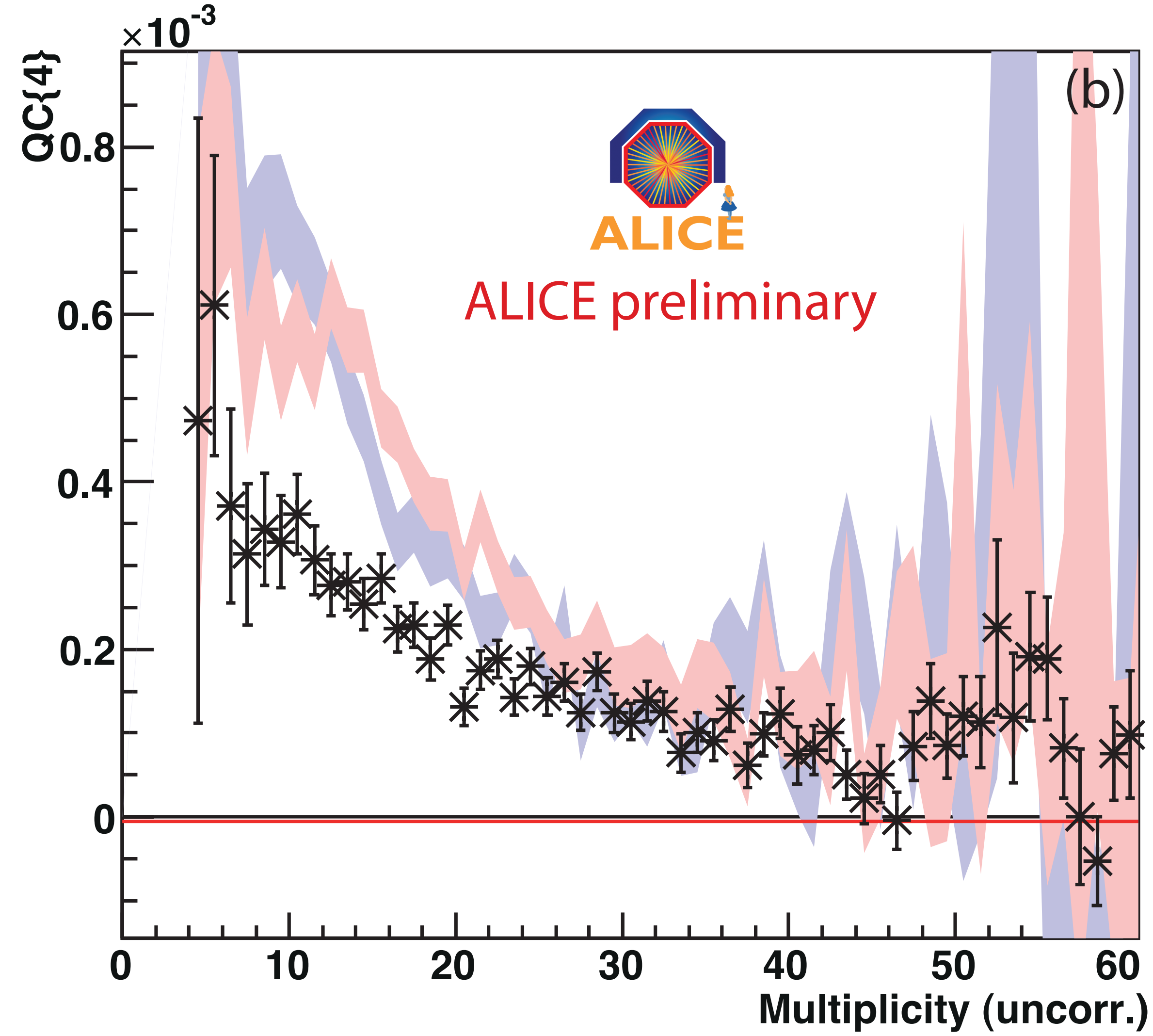
remember QC{2} = v^2, QC{4} = $-v^4$

the 2 and 4-particle correlations decrease with increasing number of particles produced which is typical behavior of correlations involving only few particles

the 4-particle cumulant, QC{4}, even has the wrong sign compared to true flow!

What about p-p?





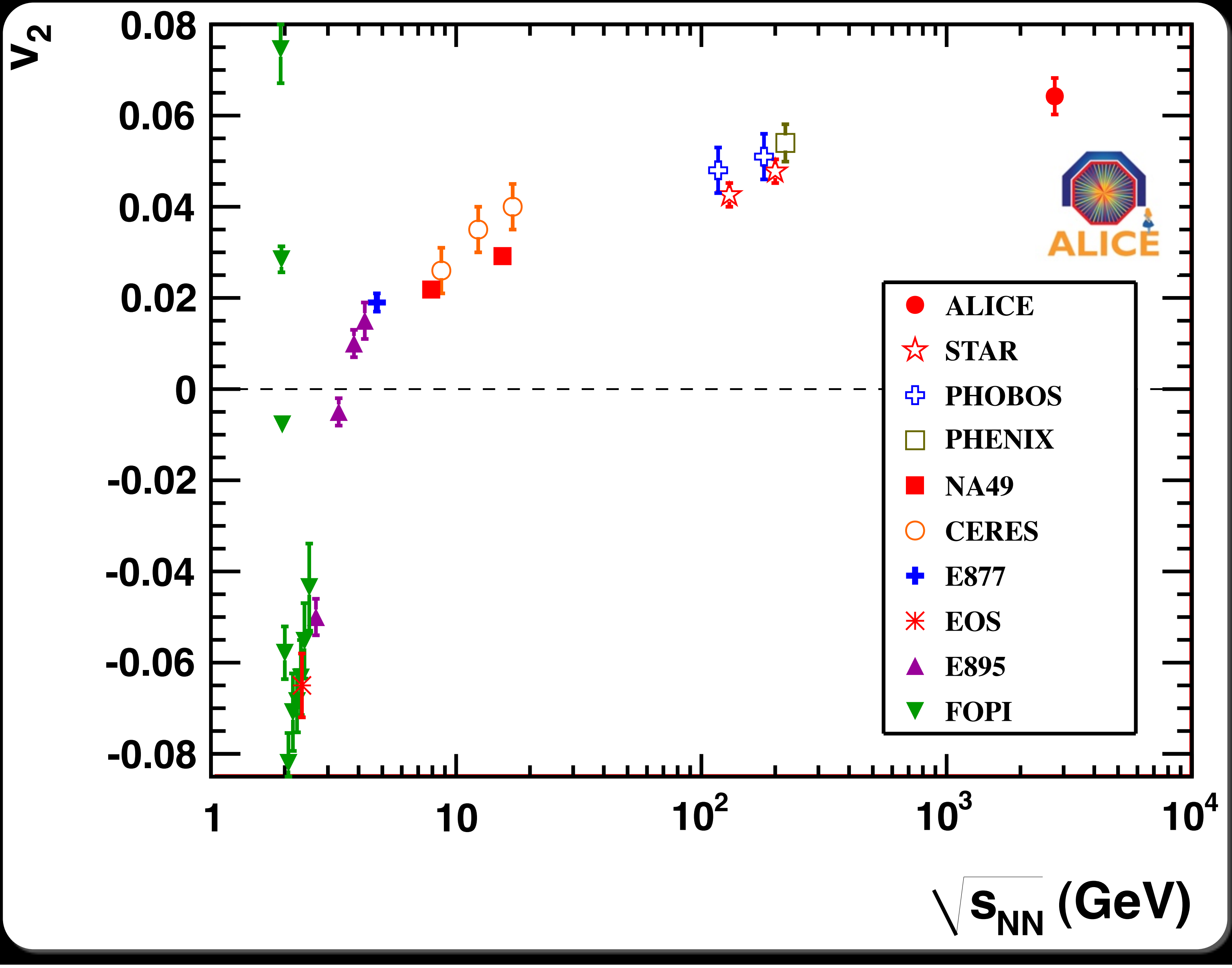
remember $QC\{2\} = v^2$, $QC\{4\} = -v^4$

models like PYTHIA and PHOJET have the correct sign for the correlations and capture the general trends observed in p-p

no evidence for elliptic flow in this multiplicity range

The Perfect Liquid

K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)



The system produced at the LHC behaves as a very low viscosity fluid (a perfect fluid), constraints dependence of η/s versus temperature

Flow Analysis Methods

flow analysis methods have different sensitivity to nonflow and fluctuations

I focus on the cumulants

Borghini, Dihn and Ollitrault, PRC 64, 054901 (2001)
Bilandzic, Snellings and Voloshin, PRC 83, 044913 (2011)

$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2 + \delta$$

$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$

$$v_n^2\{6\} = \bar{v}_n^2 - \sigma_v^2$$

$$v_n^2\{8\} = \bar{v}_n^2 - \sigma_v^2$$

excellent opportunity to study flow fluctuations and from these get a handle on initial conditions!

Flow Fluctuations

when (2-particle) nonflow is corrected for or negligible!

in limit of "small" (not necessarily Gaussian) fluctuations

$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2$$

$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$

$$v_n^2\{2\} + v_n^2\{4\} = 2\bar{v}_n^2$$

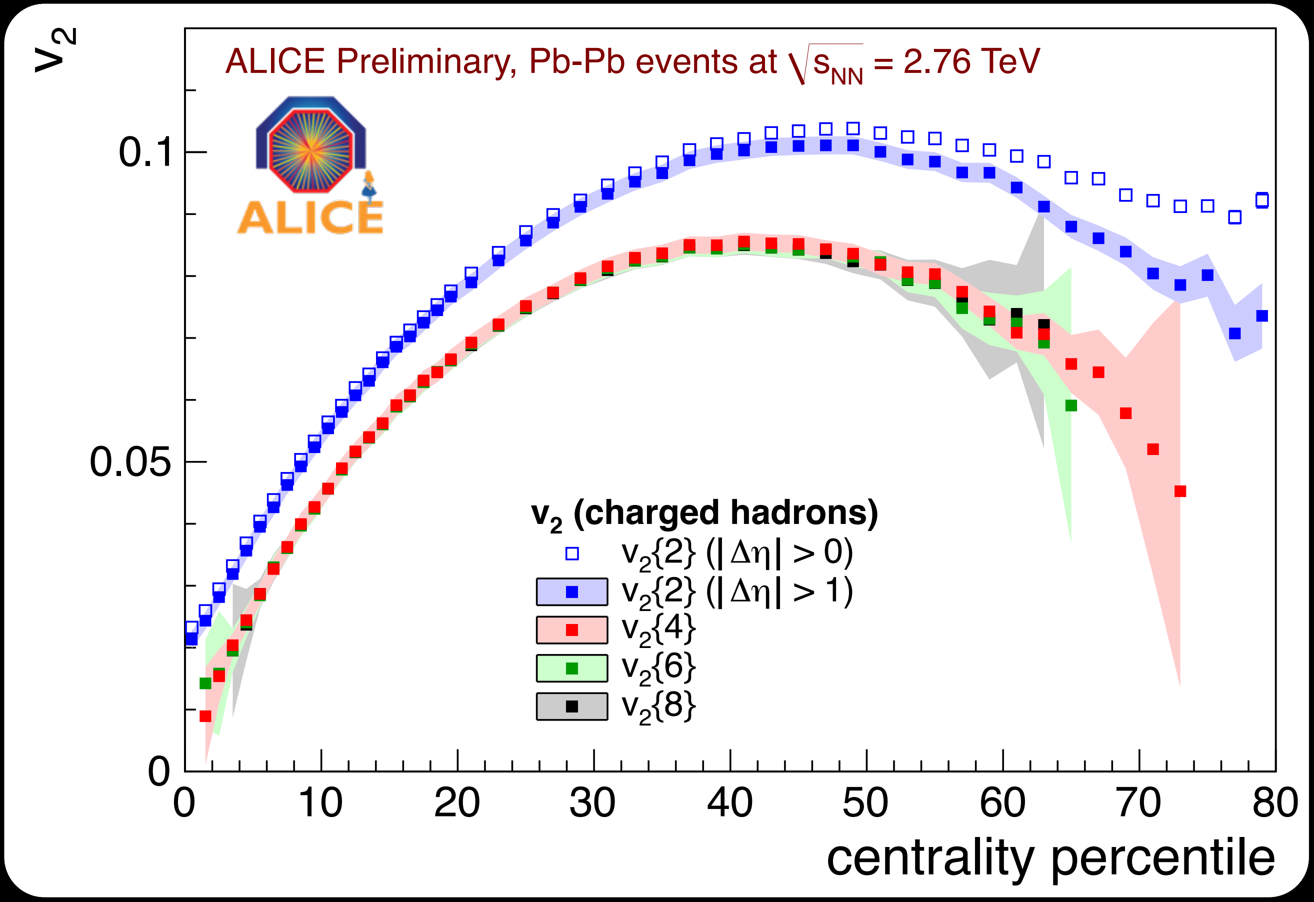
$$v_n^2\{2\} - v_n^2\{4\} = 2\sigma_v^2$$

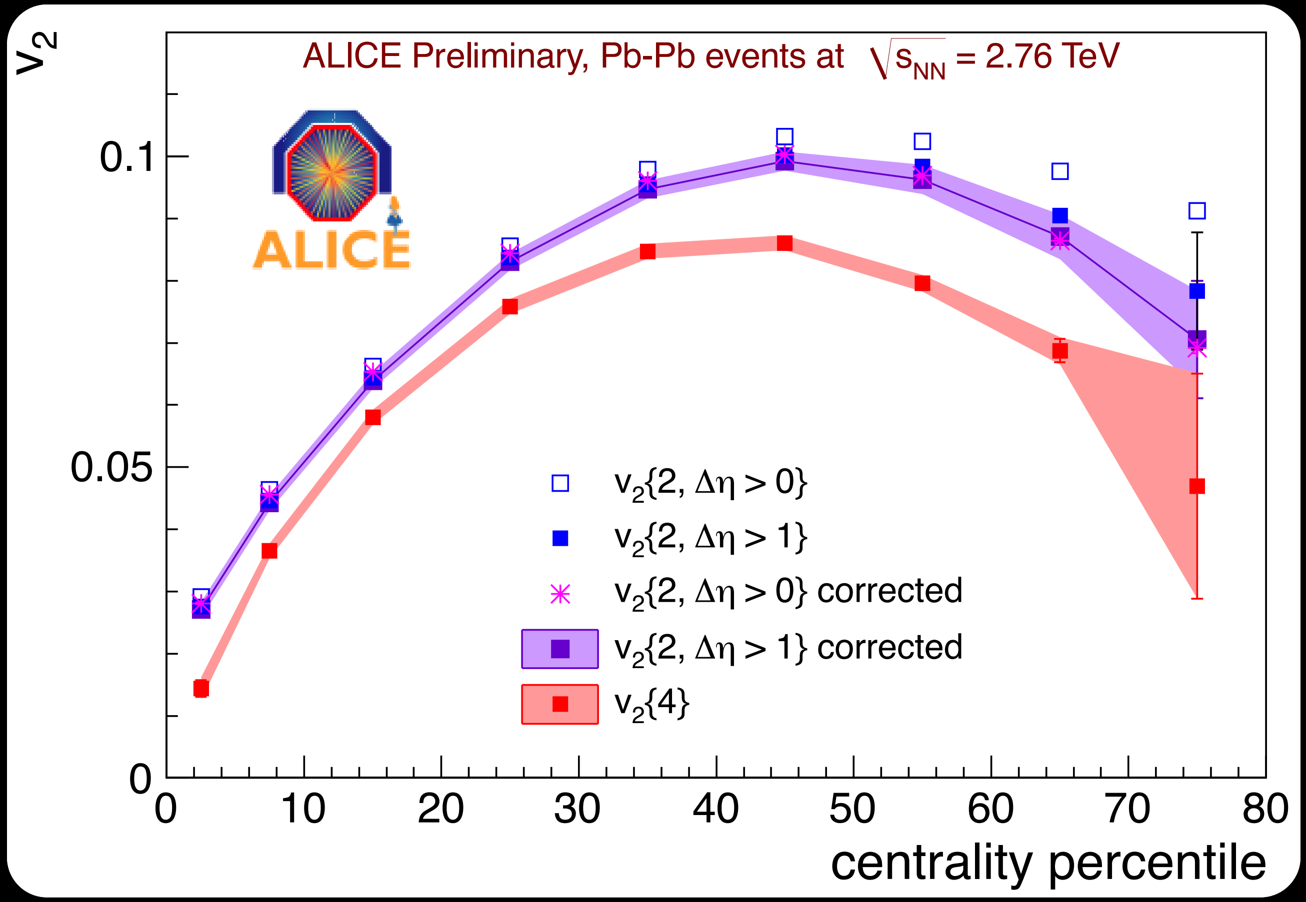
in limit of only (Gaussian) fluctuations

$$v_n\{4\} = 0$$

$$v_n\{2\} = \frac{2}{\sqrt{\pi}}\bar{v}_n$$

v_2 versus centrality in ALICE

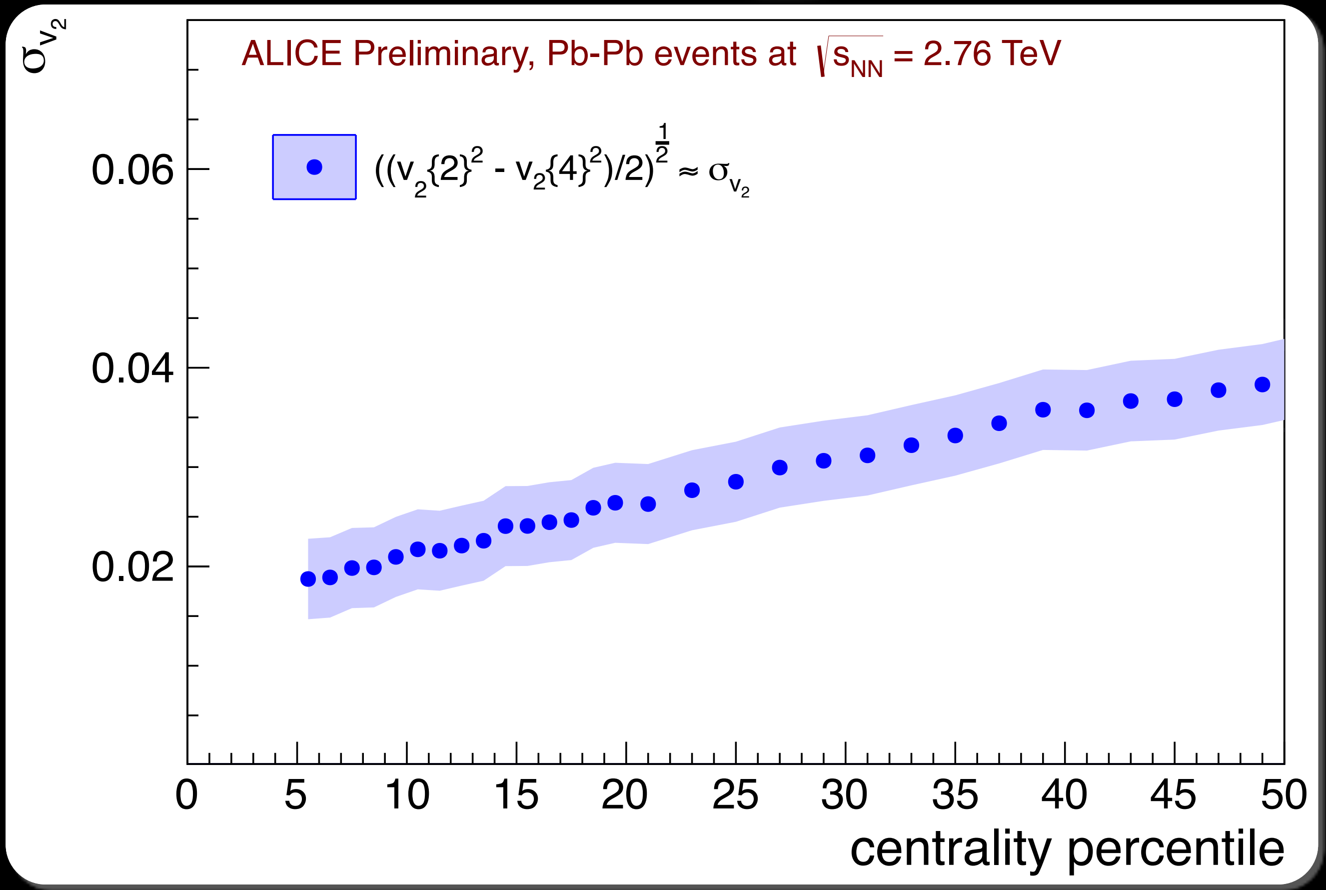


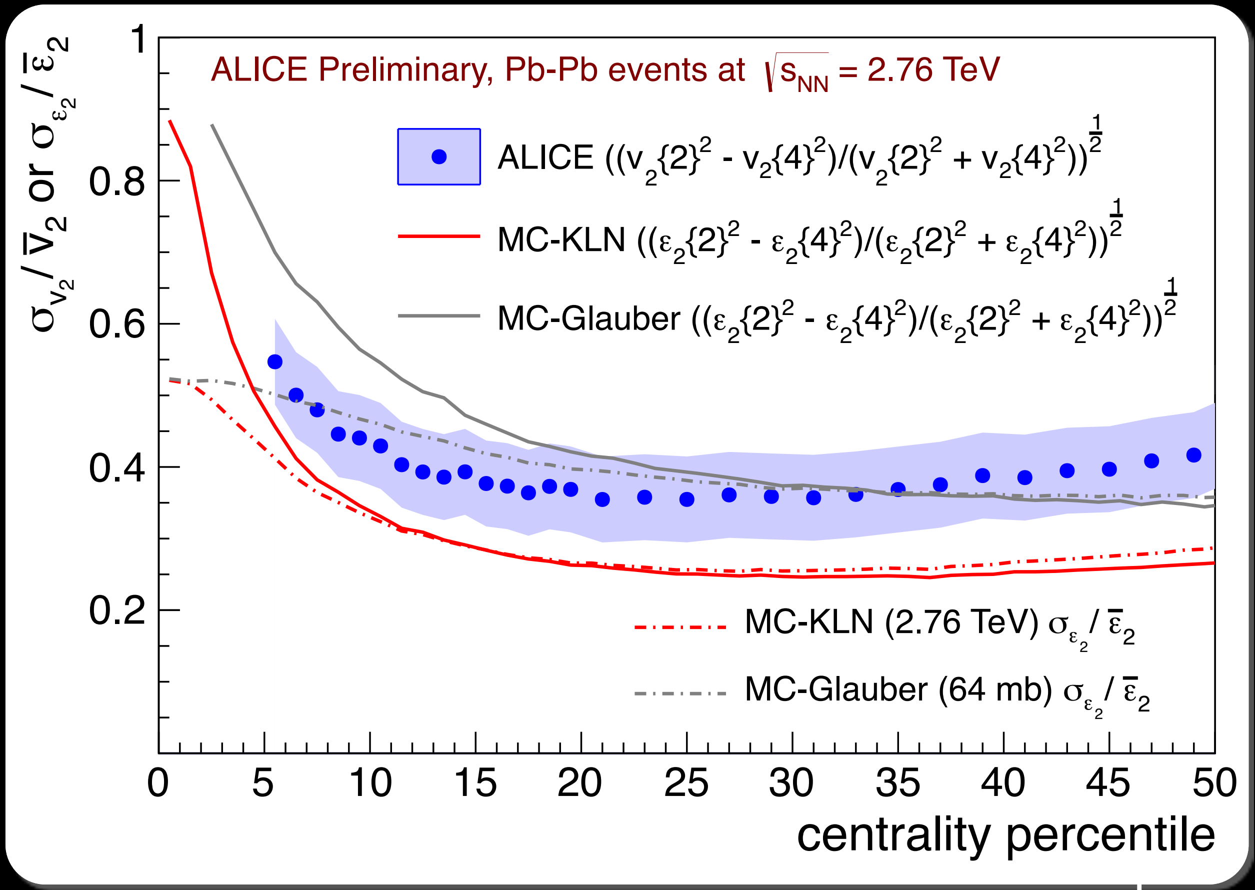


Two particle v_2 estimates depend on $\Delta\eta$
Higher order cumulant v_2 estimates are consistent within uncertainties

Two particle v_2 estimates are corrected for nonflow based on HIJING
The estimated nonflow correction for $\Delta\eta > 1$ is included in the systematic uncertainty

v_2 Fluctuations





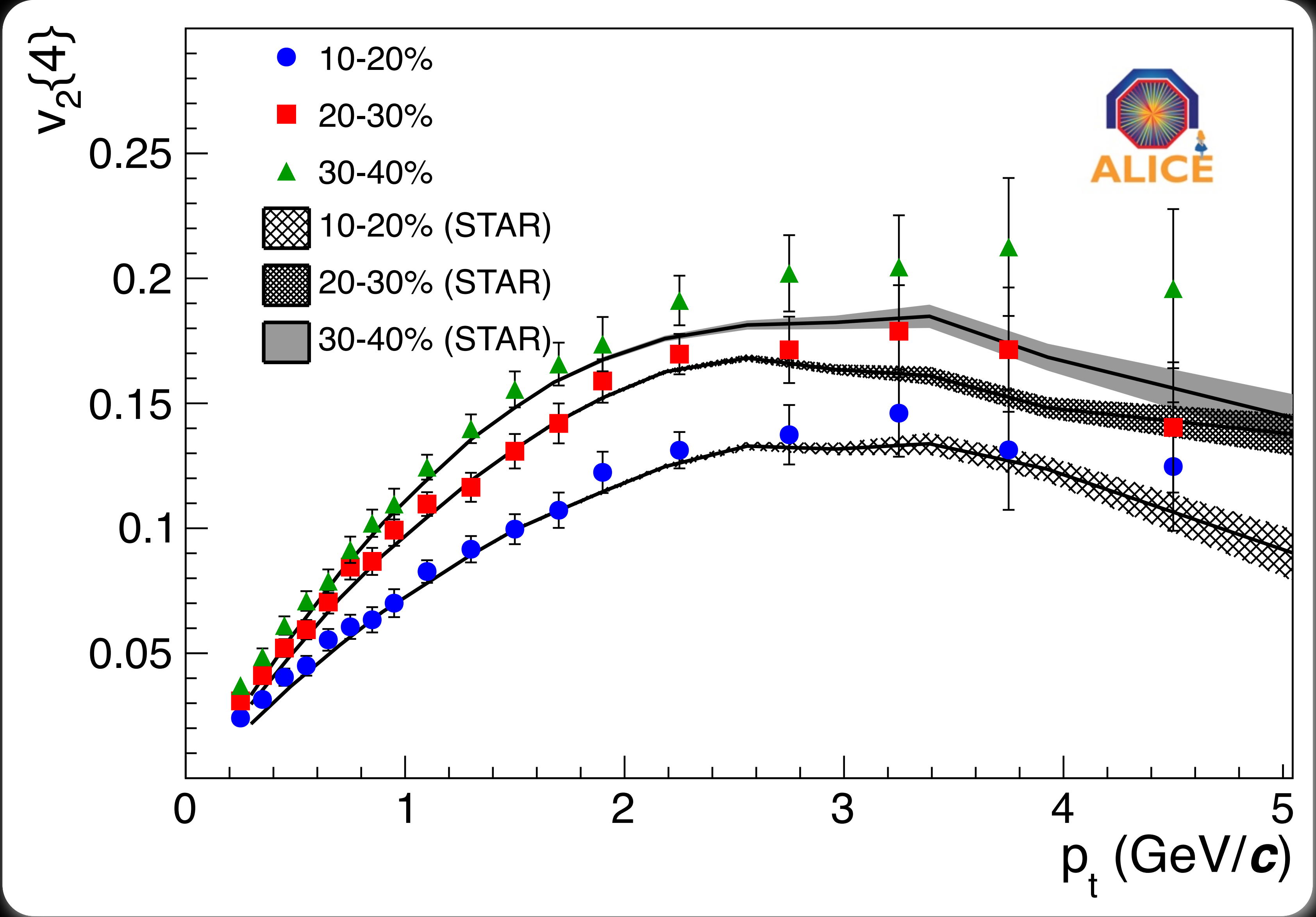
$$\sigma_{v_n} \simeq [\frac{1}{2}\left(v_n^2\{2\} - v_n^2\{4\}\right)]^{\frac{1}{2}} \qquad \frac{\sigma_{v_n}}{\bar{v}_n} \simeq \left(\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}\right)^{\frac{1}{2}}$$

Fluctuations are significant and for more central collisions not in agreement with the eccentricity fluctuations in MC-Glauber and MC-KLN CGC

tune initial conditions? what are the other contributions?

need to compare to full model calculations!

v_2 as function of p_t

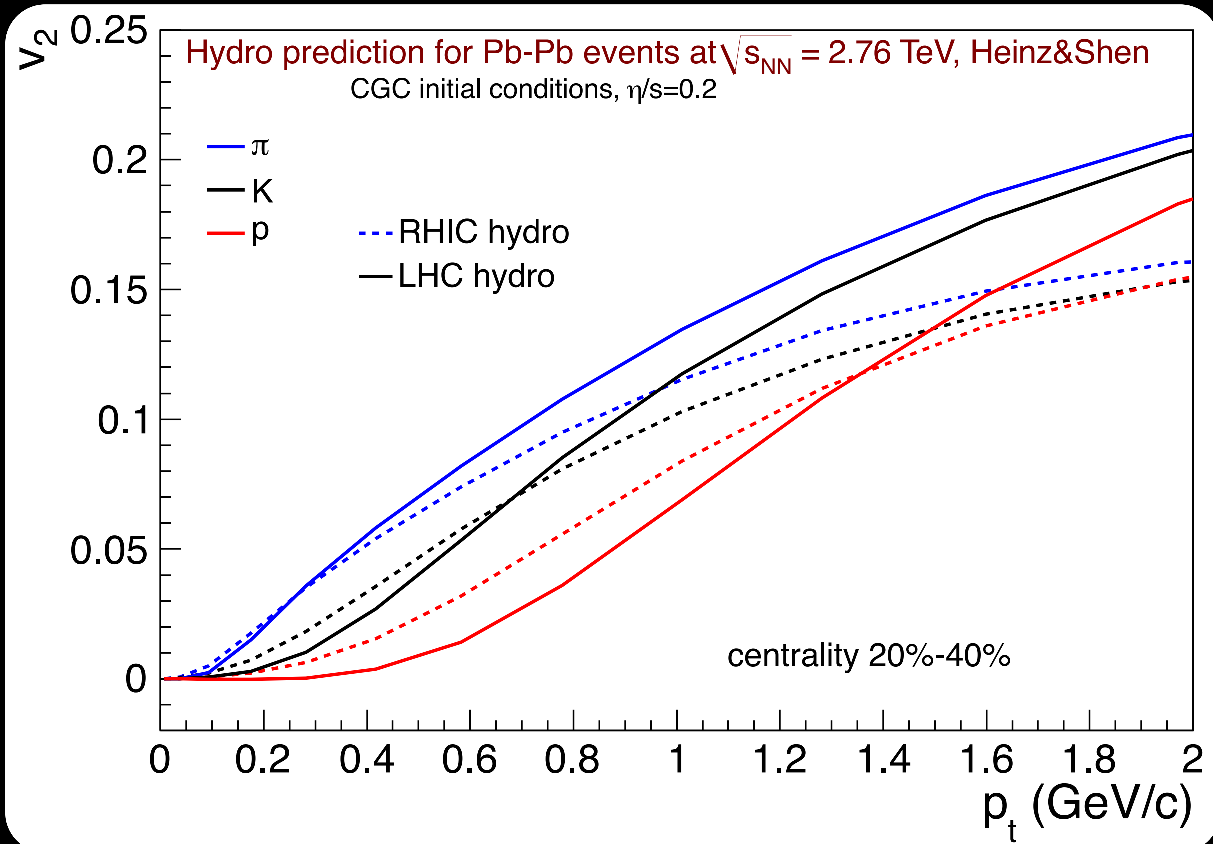


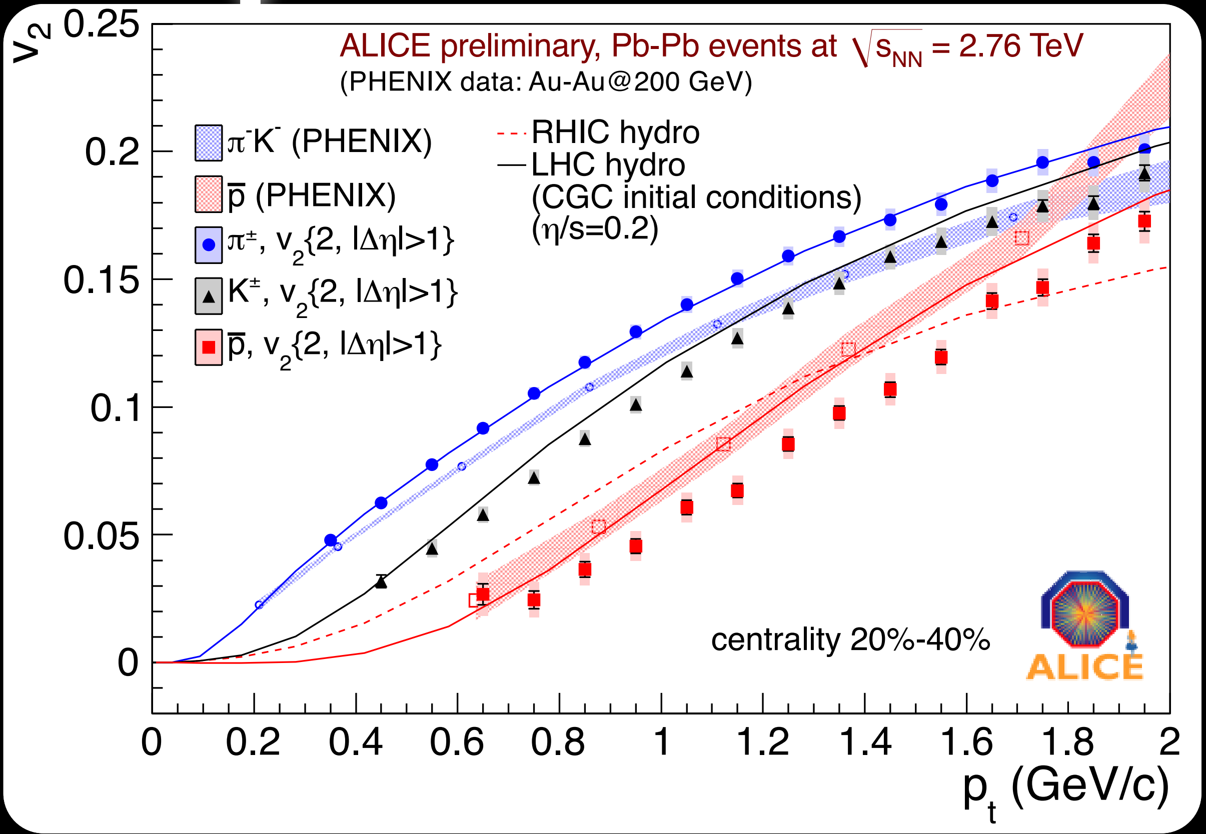
K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)

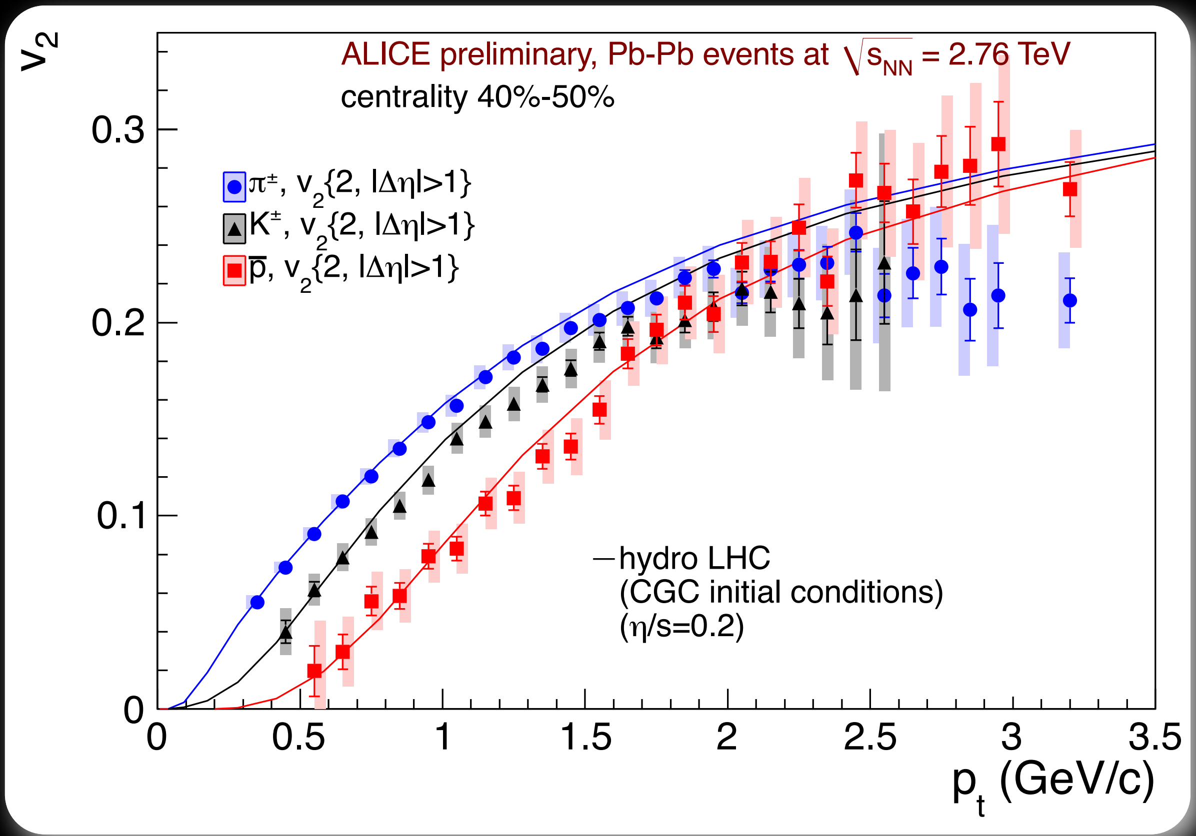
Elliptic flow as function of transverse momentum does not change much from RHIC to LHC energies, can we understand that?

v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226





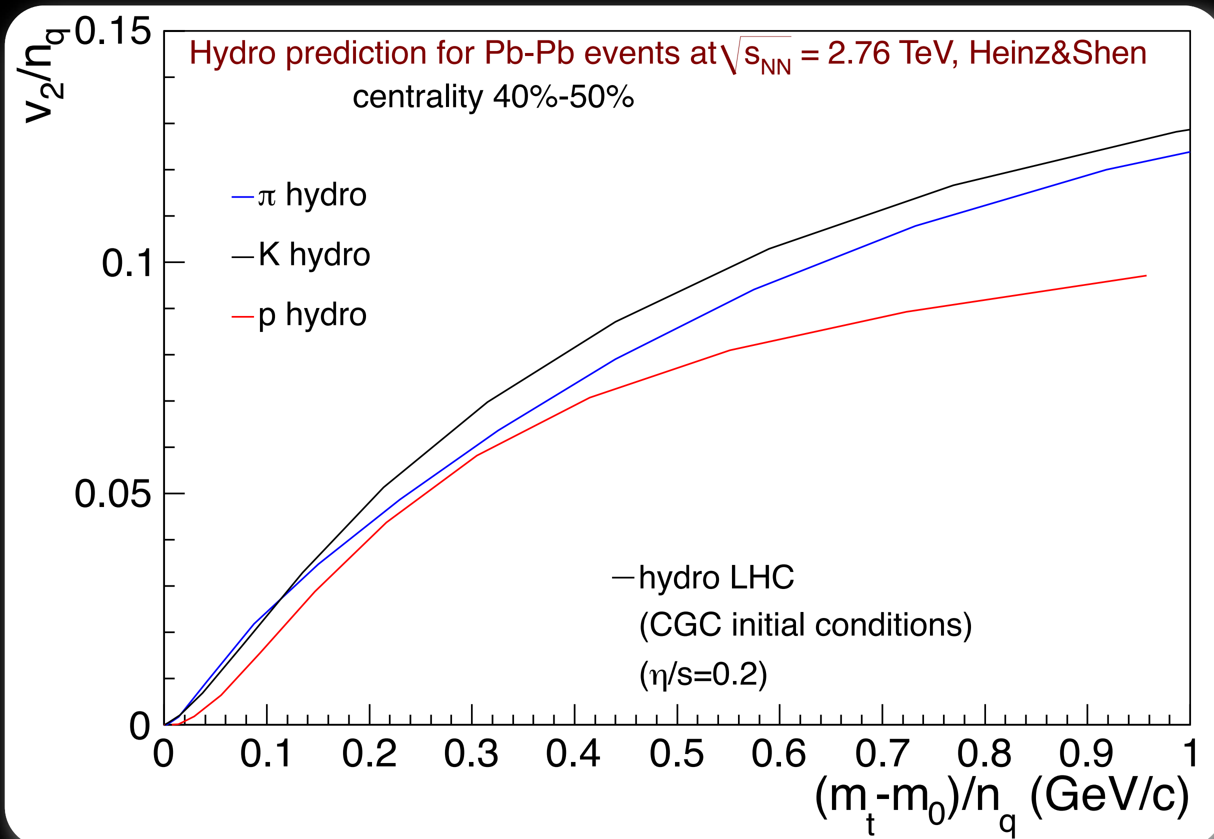


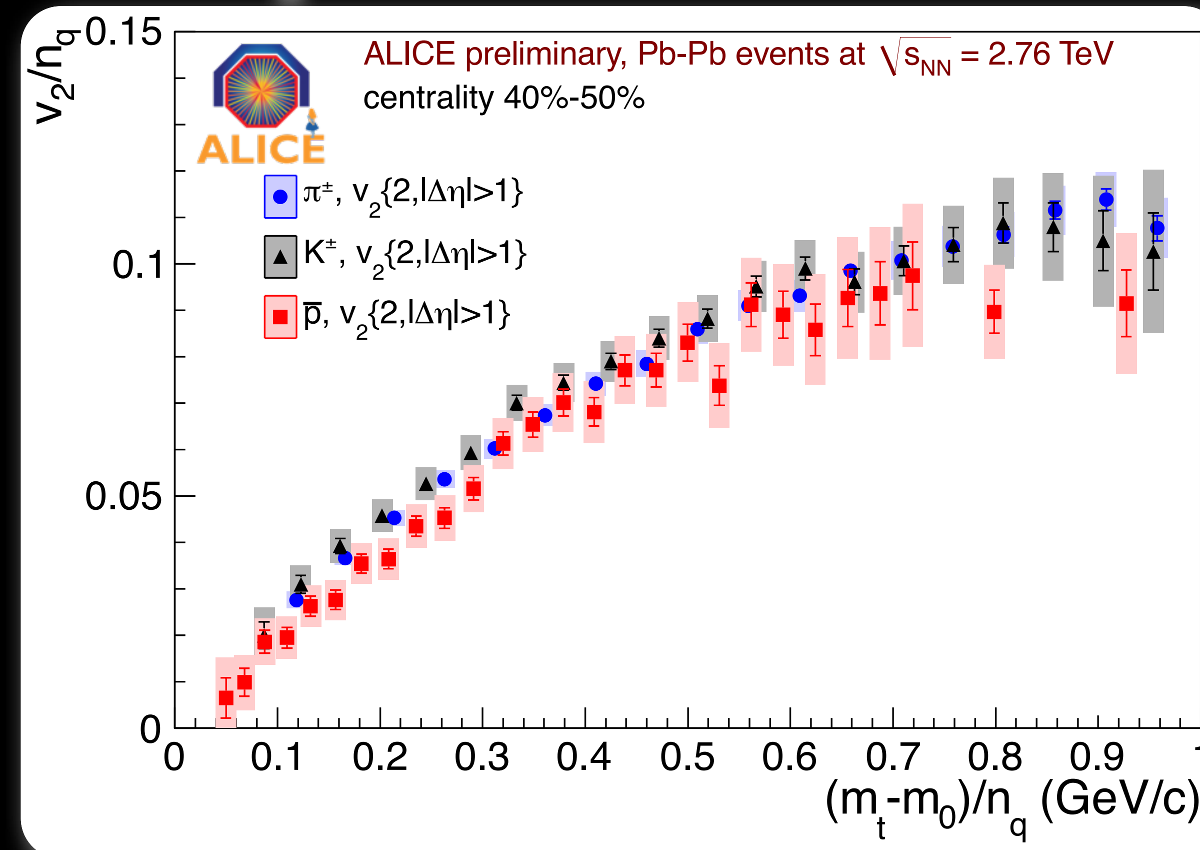
the mass splitting increased compared to RHIC energies

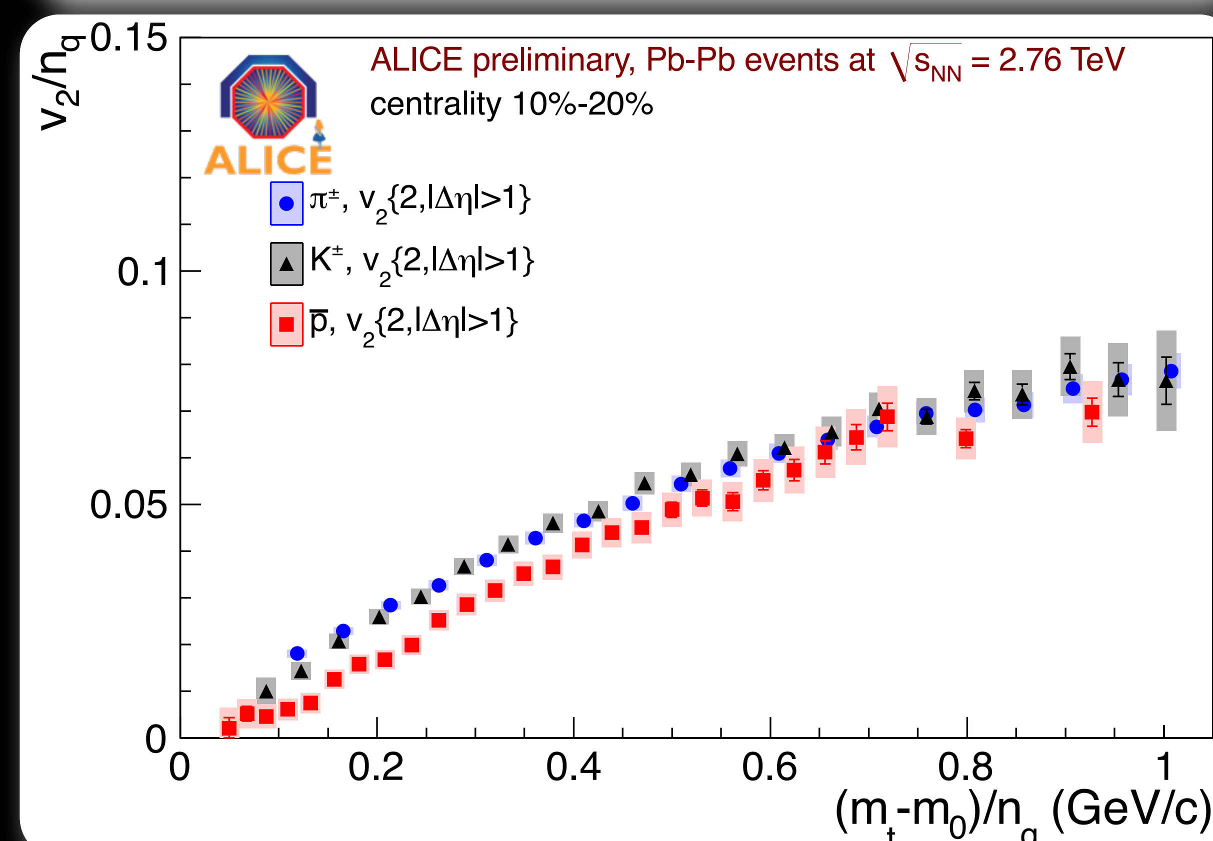
pion and kaon v_2 are described well with hydrodynamic predictions using MC-KLN CGC initial conditions and $\eta/s = 0.2$

v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

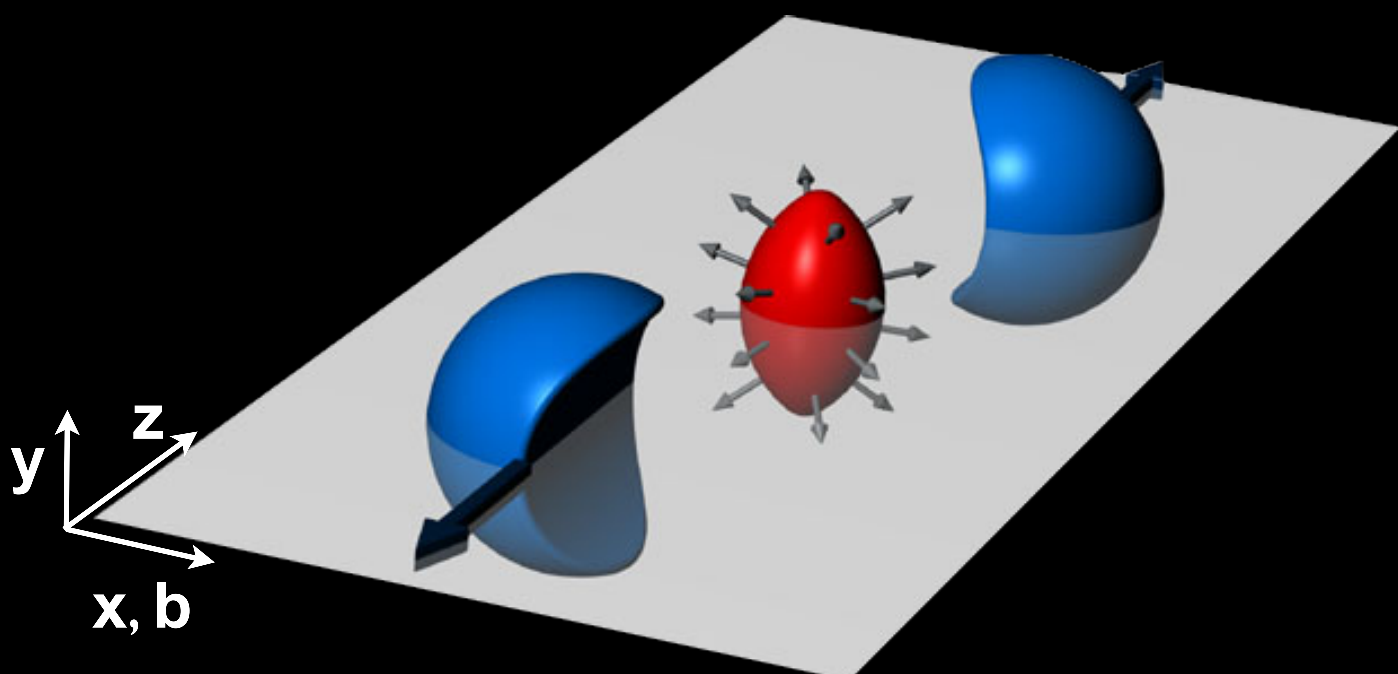




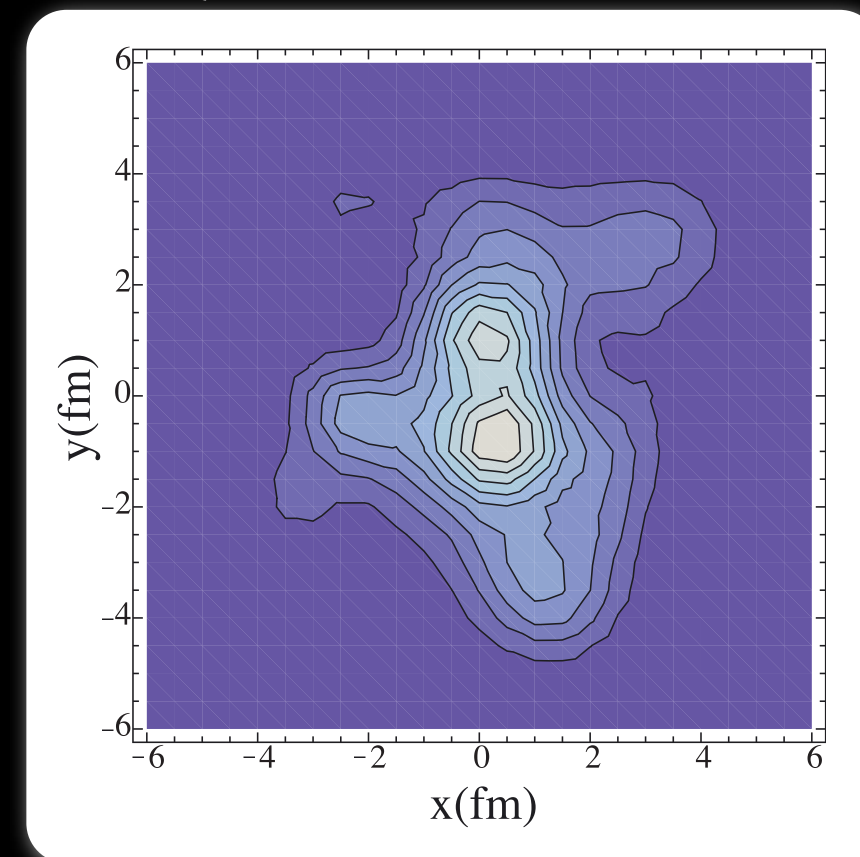


at small $(m_t-m_0)/n_q$ the scaling in the data resemble the scaling as observed in hydrodynamics

Initial conditions and v_n



G. Qin, H. Petersen, S. Bass, and B. Muller



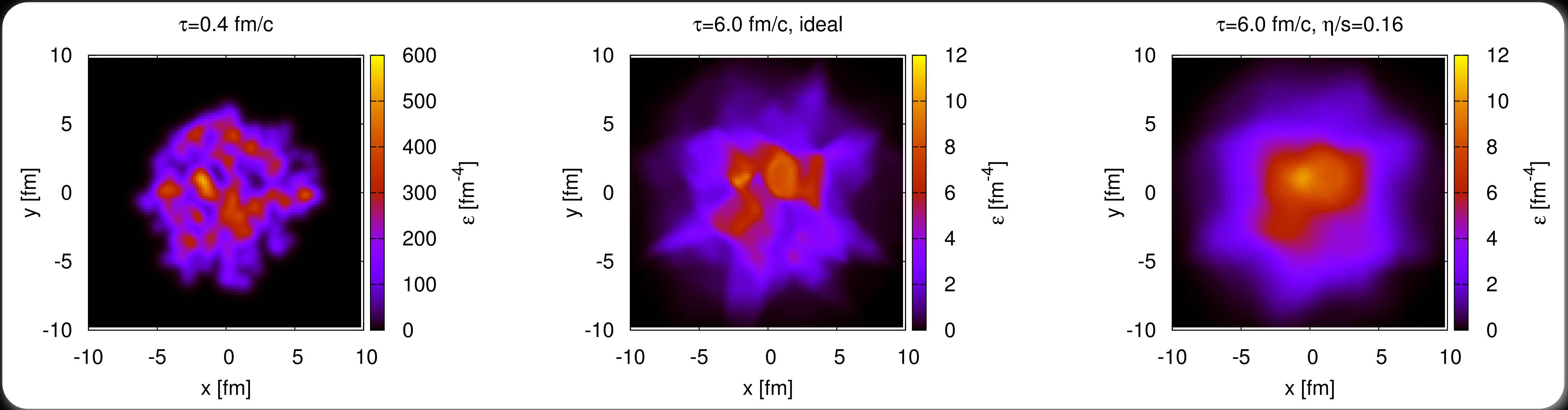
$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=2,4,6,\ldots}^{\infty} 2v_n \cos n(\phi - \Psi_R)$$

$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_n)$$

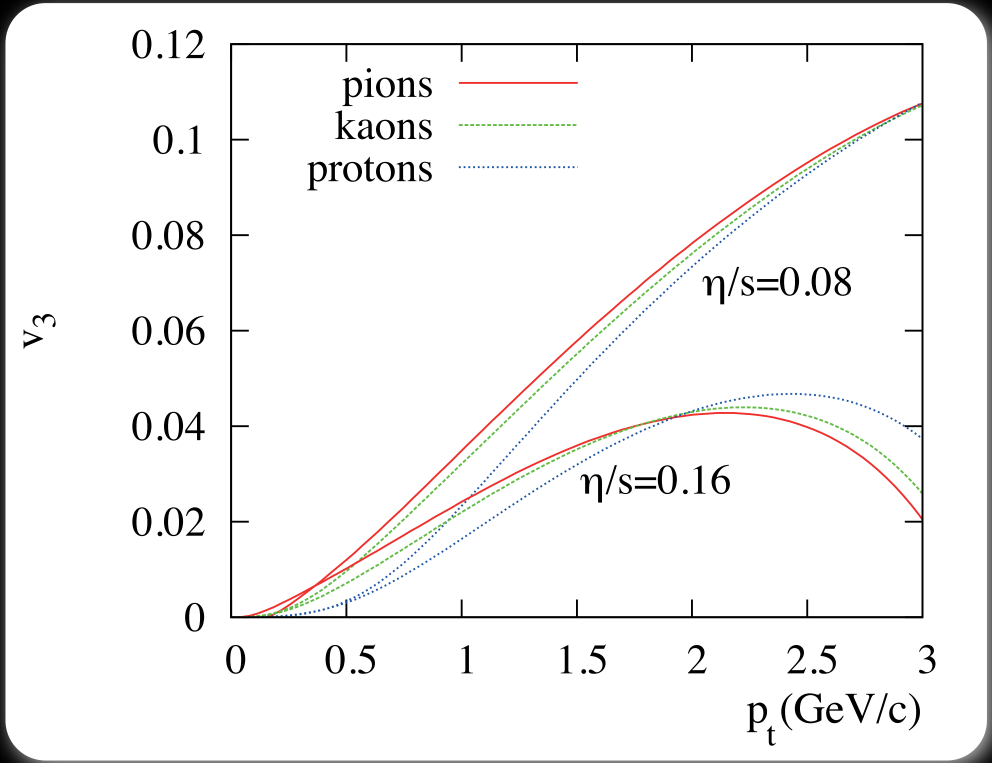
initial spatial geometry not a smooth almond (for which all odd harmonics are zero due to reflection symmetry) may give rise to higher odd harmonics which give additional independent constraint on the initial conditions!!!

Shear Viscosity

Music, Sangyong Jeon



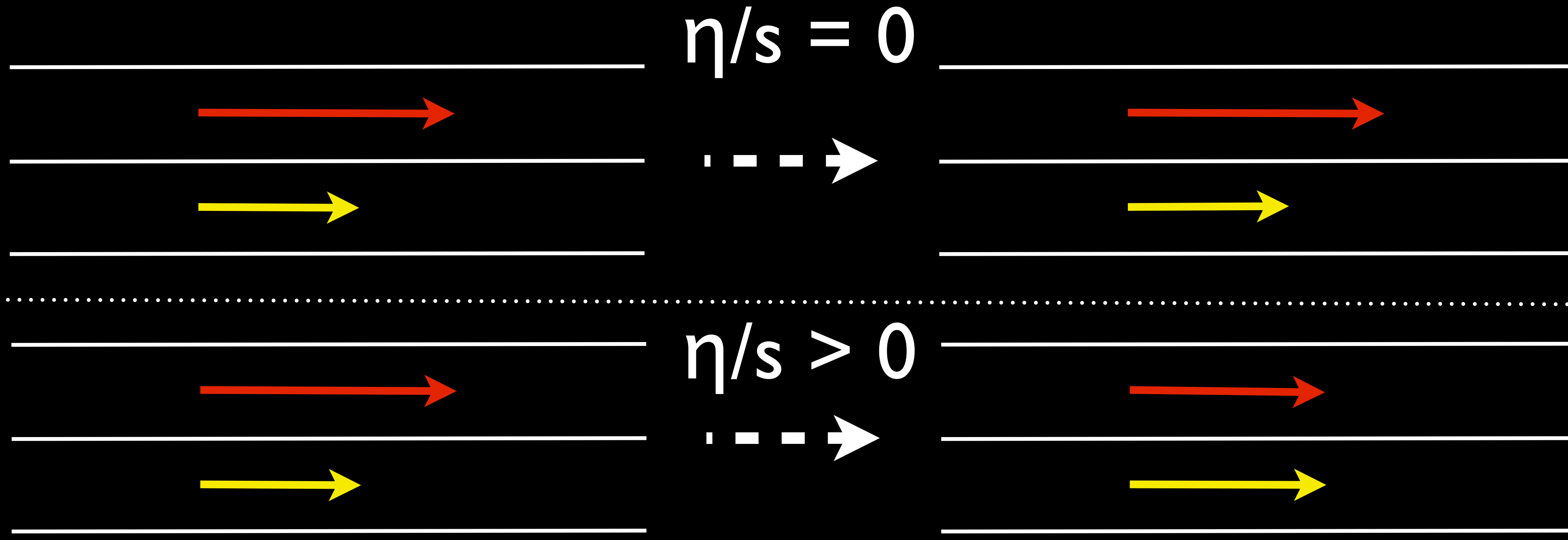
initial conditions ideal hydro η/s=0 viscous hydro η/s=0.16

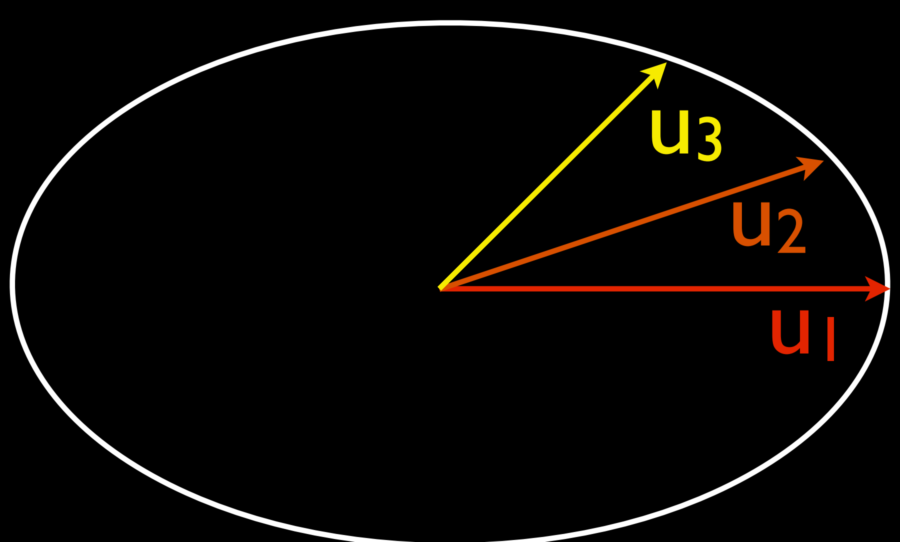


Larger η/s clearly smoothes the distributions and suppresses the higher harmonics (e.g. v_3)

Hydro: Alver, Gombeaud, Luzum & Ollitrault, Phys. Rev. C82 (2010)

Shear Viscosity





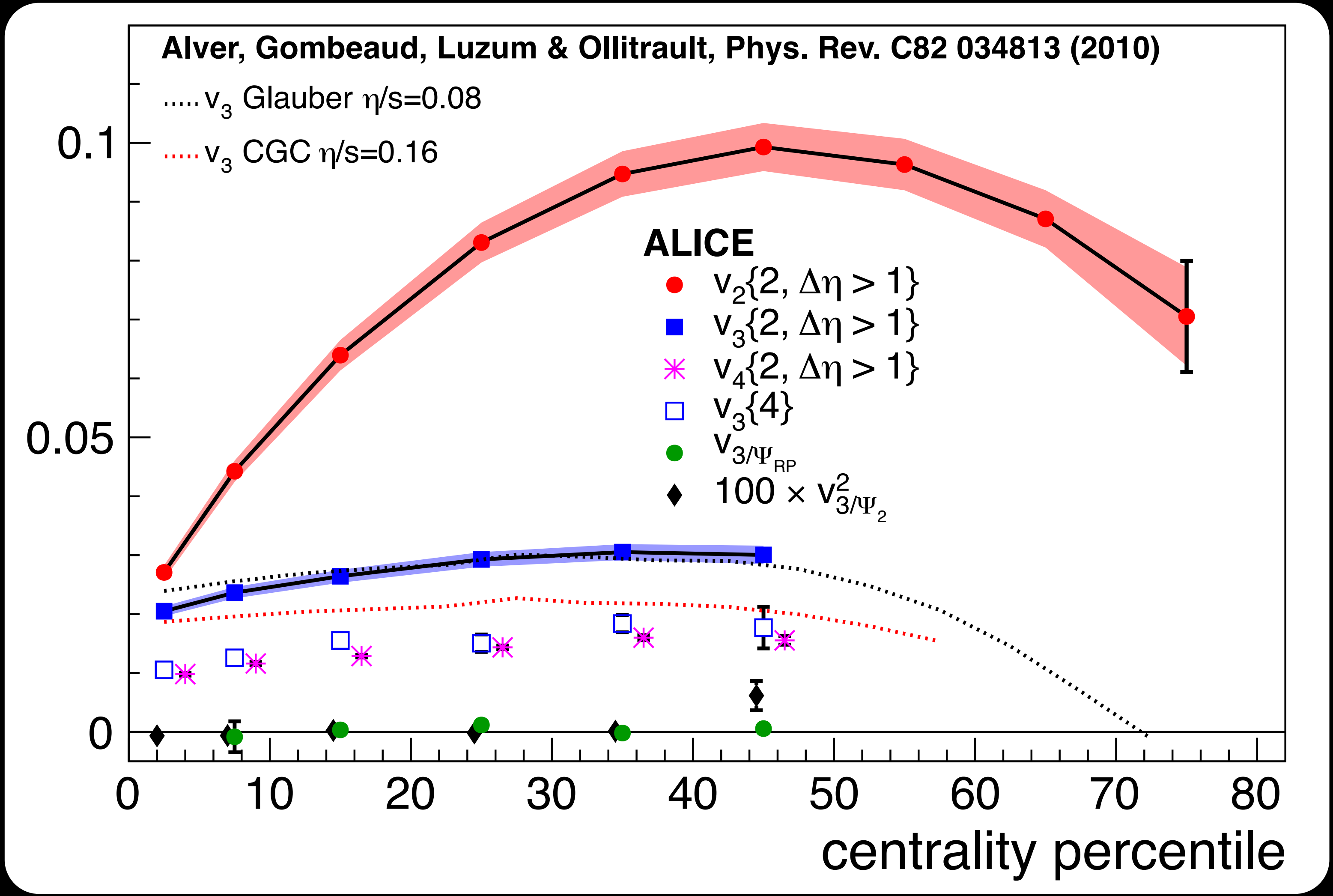
$u_1 > u_2 > u_3$ shear viscosity will make them equal and destroy the elliptic flow v_2

higher harmonics represent smaller differences which get destroyed more easily, and which, if measurable, makes them more sensitive probes to η/s

Triangular Flow

We observe significant v_3 which compared to v_2 has a different centrality dependence

The centrality dependence and magnitude are similar to predictions for MC Glauber with $\eta/s=0.08$ but above MC-KLN CGC with $\eta/s=0.16$

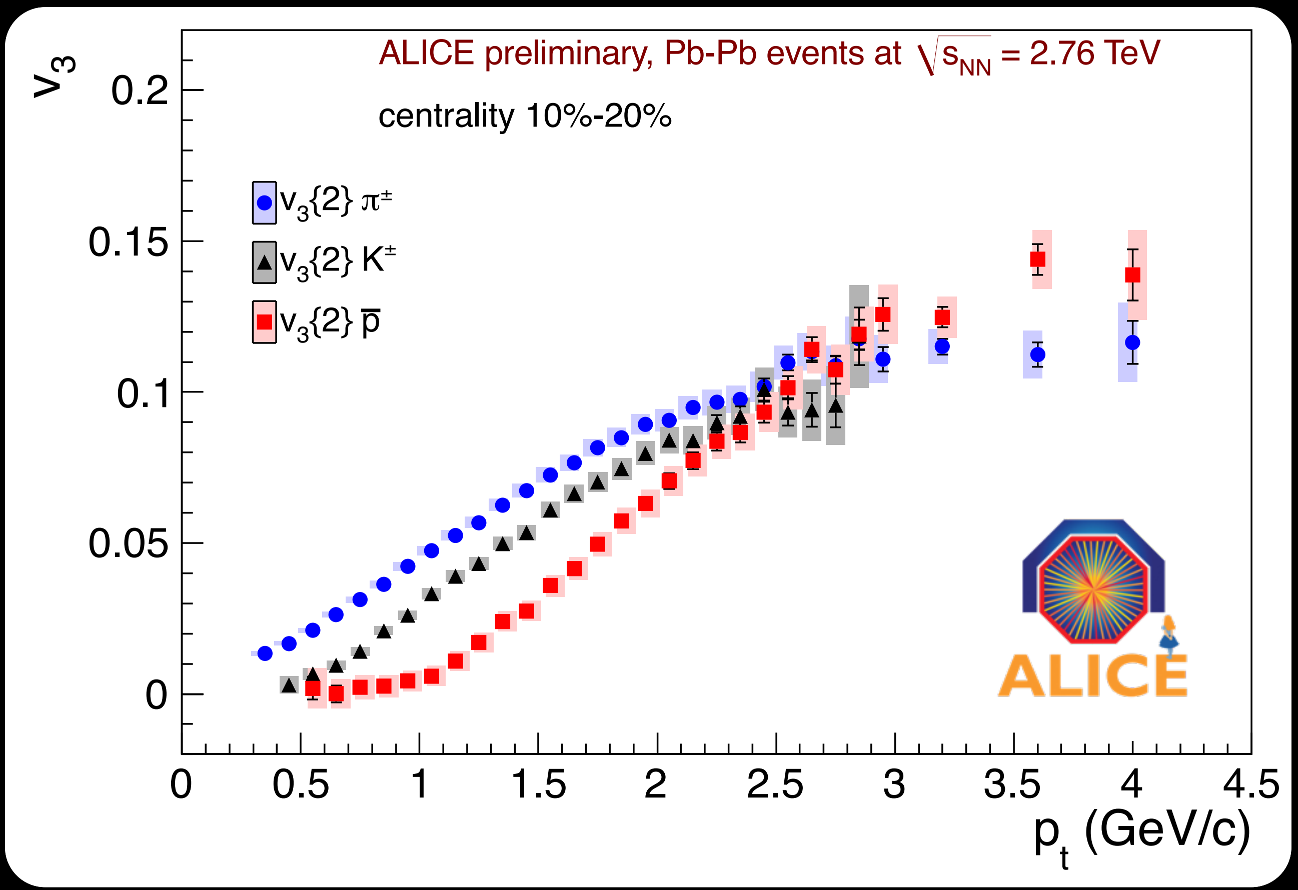


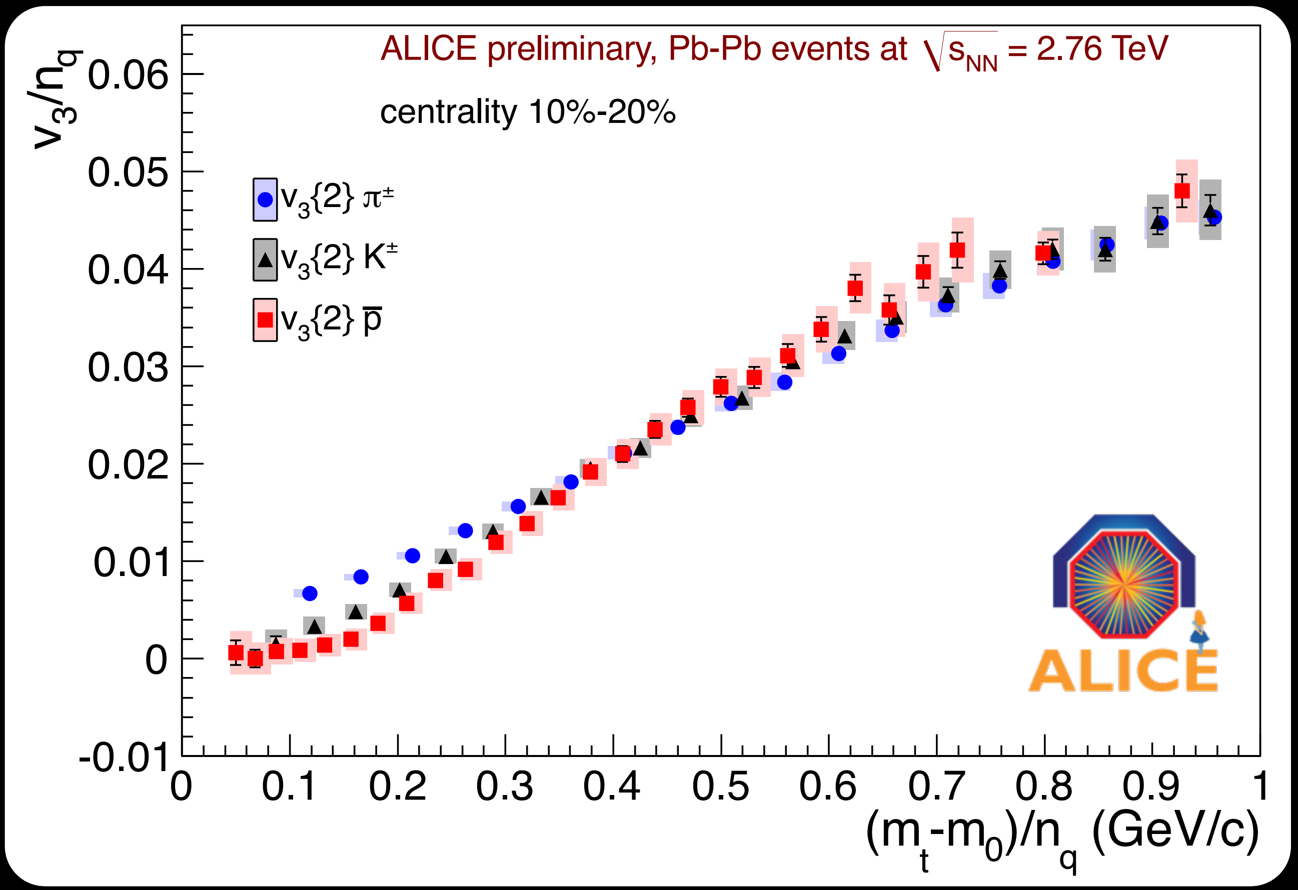
ALICE Collaboration, arXiv:1105.3865 accepted for PRL

The v_3 with respect to the reaction plane determined in the ZDC and with the v_2 participant plane is consistent with zero as expected if v_3 is due to fluctuations of the initial eccentricity

The $v_3\{2\}$ is about two times larger than $v_3\{4\}$ which is also consistent with expectations based on initial eccentricity fluctuations

Triangular Flow

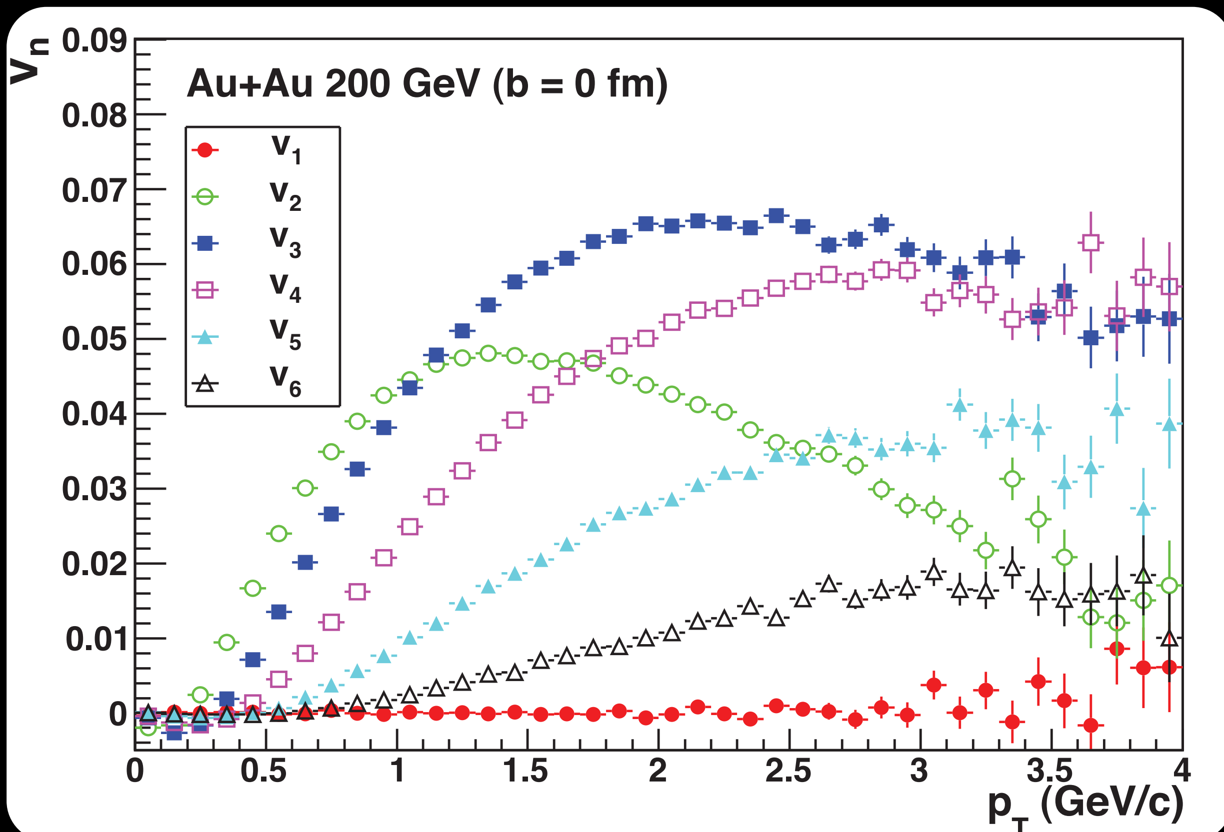




The behavior of v_3 as function of p_t for pions, kaons and protons shows the same features as observed for v_2

(the mass splitting, the crossing of the pions with protons at intermediate p_t)

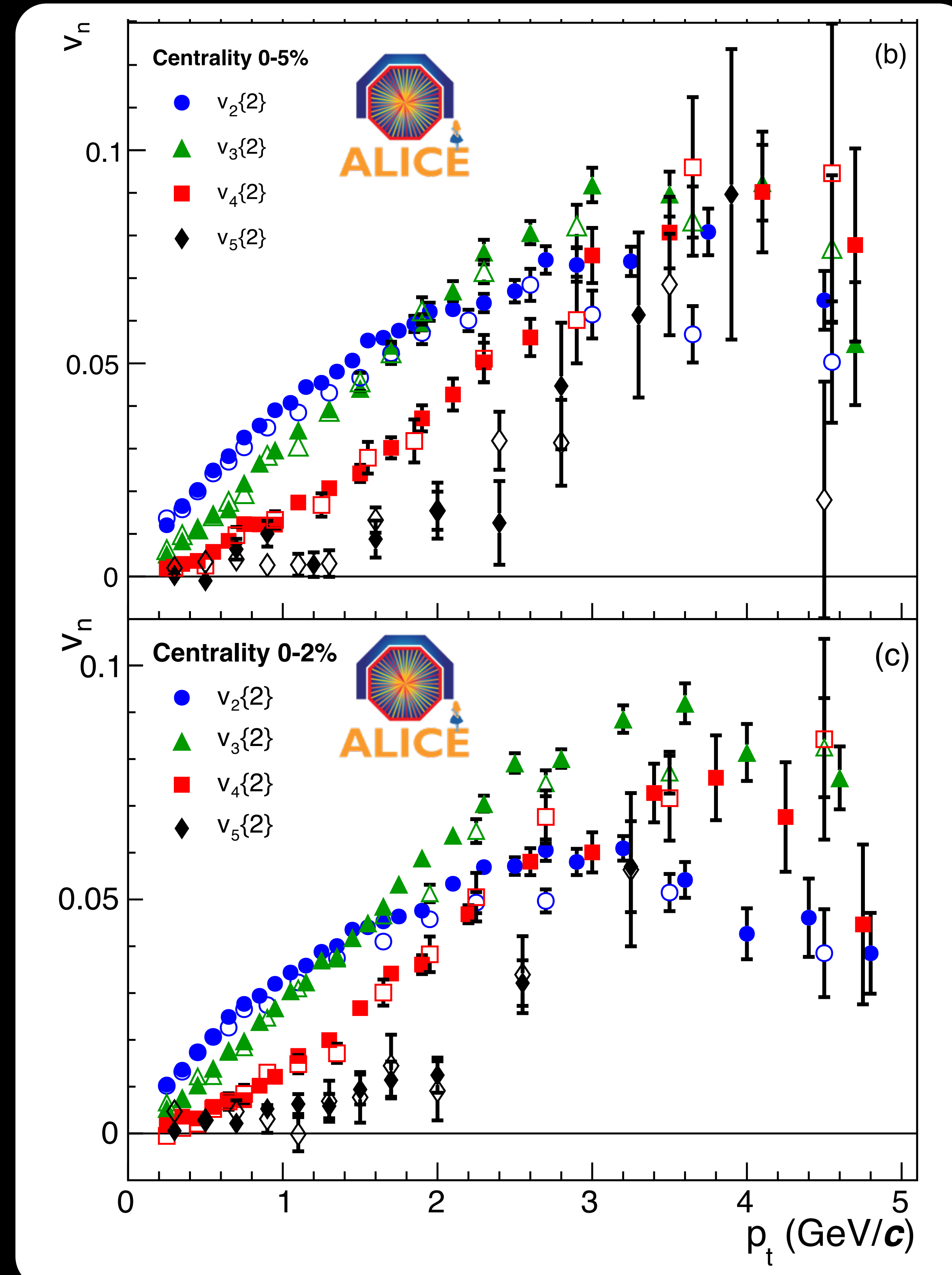
Geometry and Harmonics



G-L Ma and X-N Wang, arXiv:1011.5249v2

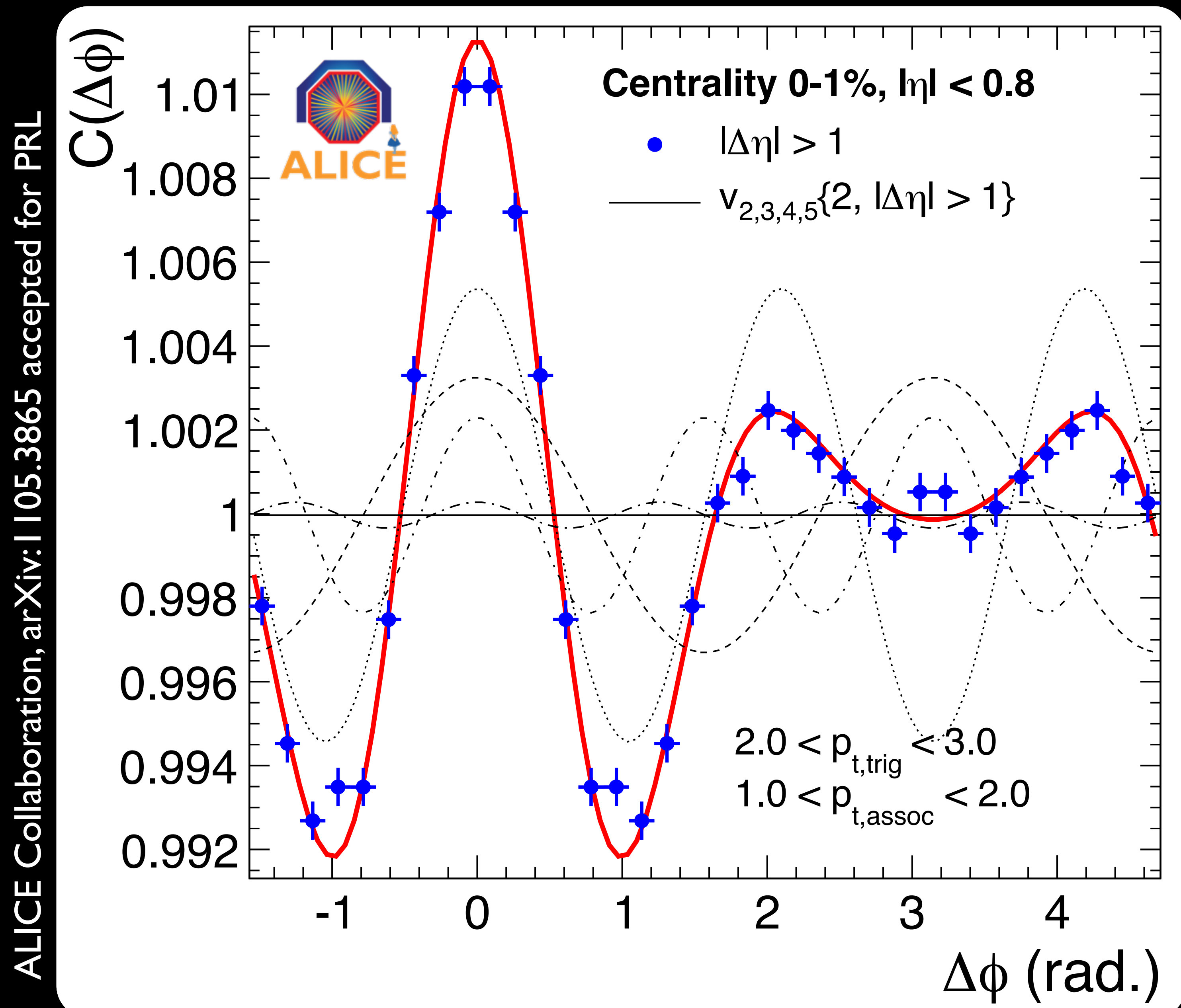
For central collisions at intermediate p_t the higher harmonics v_3 and v_4 cross v_2 and become the dominant harmonics

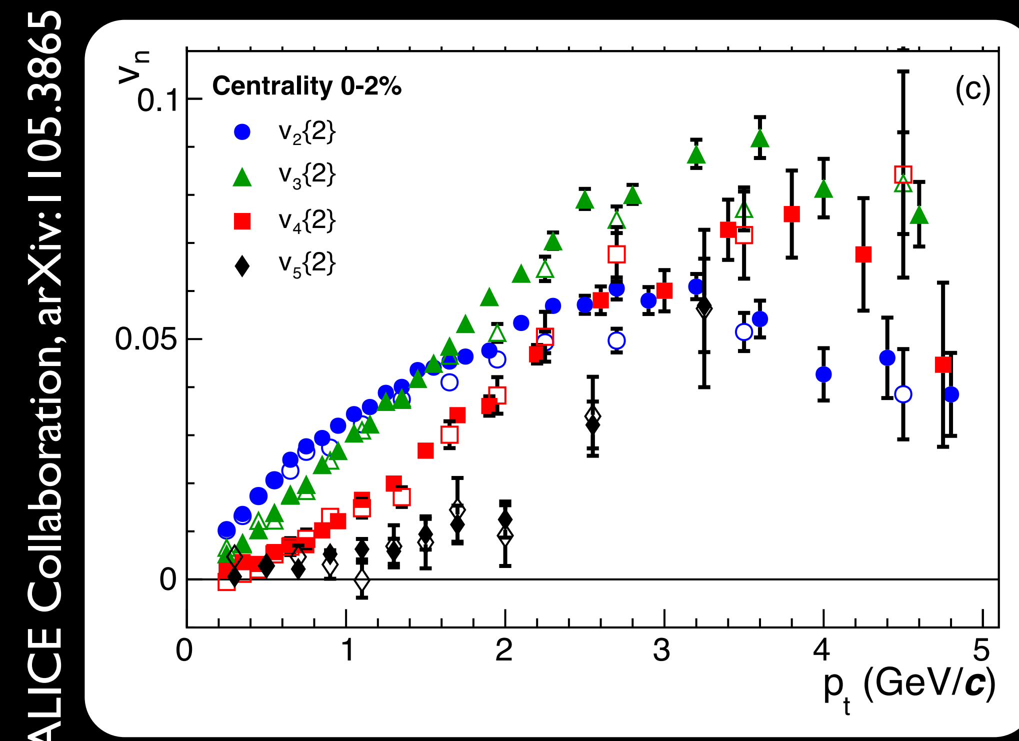
For more central collisions this occurs already at lower p_t



ALICE Collaboration, arXiv:1105.3865 accepted for PRL

Geometry





We observe a doubly-peaked structure in the azimuthal correlation function opposite to the trigger particle before the subtraction of v_2

The red line shows the sum of the measured anisotropic flow Fourier coefficients. The flow coefficients give a natural explanation of the observed correlation structure known as the Mach cone and ridge

$$C(\Delta\phi) \equiv \frac{N_{\mathrm{mixed}}}{N_{\mathrm{same}}} \frac{\mathrm{d}N_{\mathrm{same}}/\mathrm{d}\Delta\phi}{\mathrm{d}N_{\mathrm{mixed}}/\mathrm{d}\Delta\phi}$$

Conclusions

- Anisotropic flow measurements provided strong constraints on the properties of hot and dense matter produced at RHIC and LHC energies and have lead to the new paradigm of the QGP as the so called perfect liquid
  - At the LHC we observe even stronger flow than at RHIC which is expected for almost perfect fluid behavior
- The first measurements of v_3, v_4 and v_5 have recently been made at RHIC and the LHC and indicate that these flow coefficients behave as expected from fluctuations of the initial spatial eccentricity (geometry!) and a created system which has a small η/s
  - provide new strong experimental constraints on η/s and initial conditions

Thanks