Angular Correlations of Hadrons Measured at the LHC

Rencontres du Vietnam

Frontiers of QCD: From Puzzles to Discoveries

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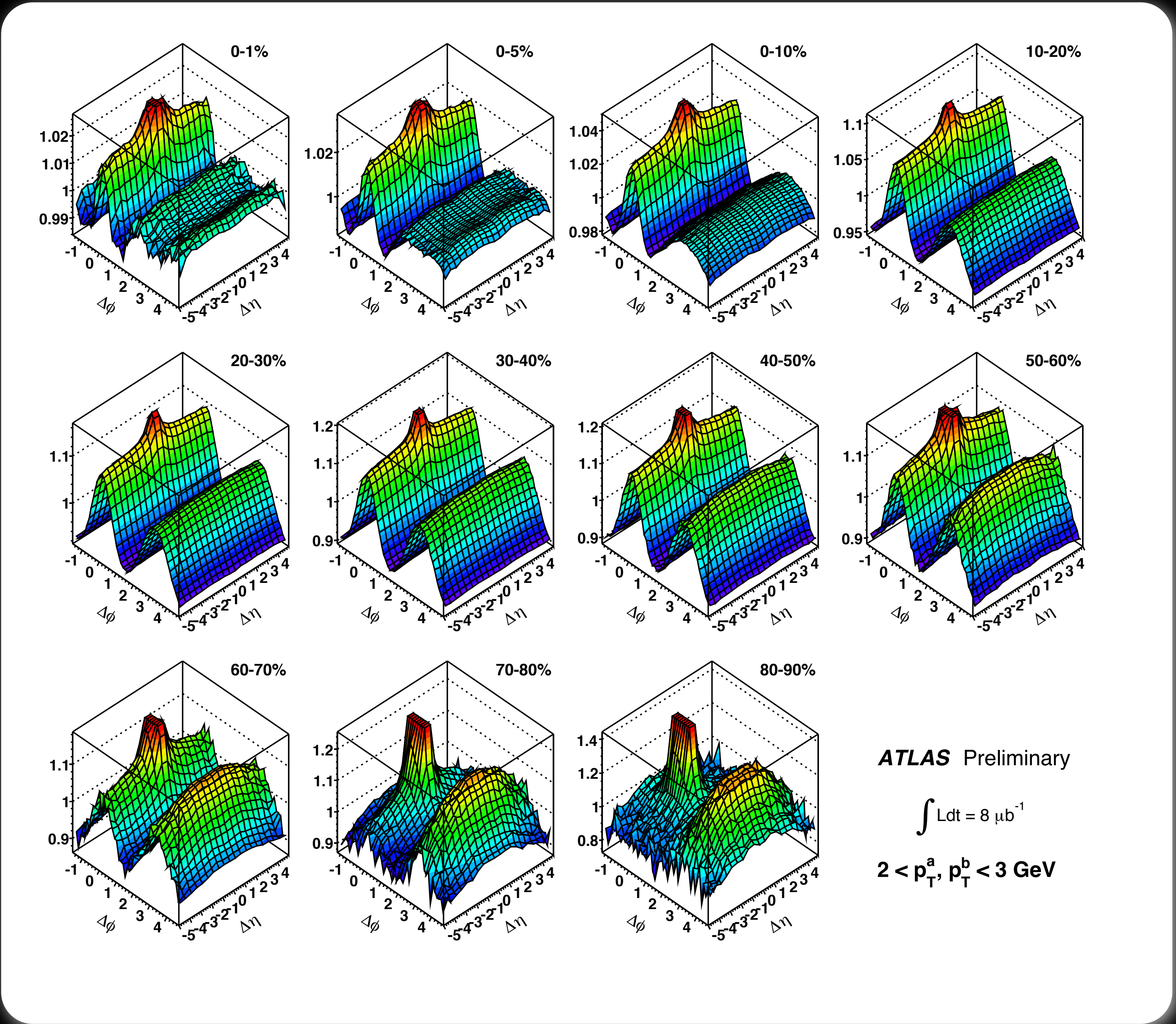
20-12-2011

Angular Correlations

ATLAS-CONF-2011-074

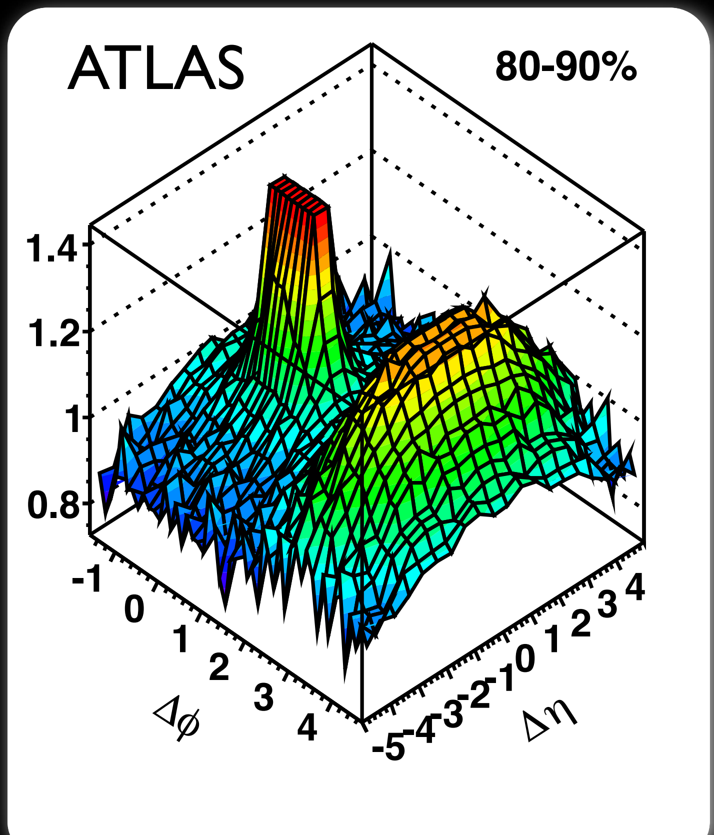
$$C(\Delta\phi\Delta\eta) \equiv \frac{N_{\mathrm{mixed}}}{N_{\mathrm{same}}} \frac{\mathrm{d}^2 N_{\mathrm{same}}/\mathrm{d}\Delta\phi\mathrm{d}\Delta\eta}{\mathrm{d}^2 N_{\mathrm{mixed}}/\mathrm{d}\Delta\phi\mathrm{d}\Delta\eta}$$

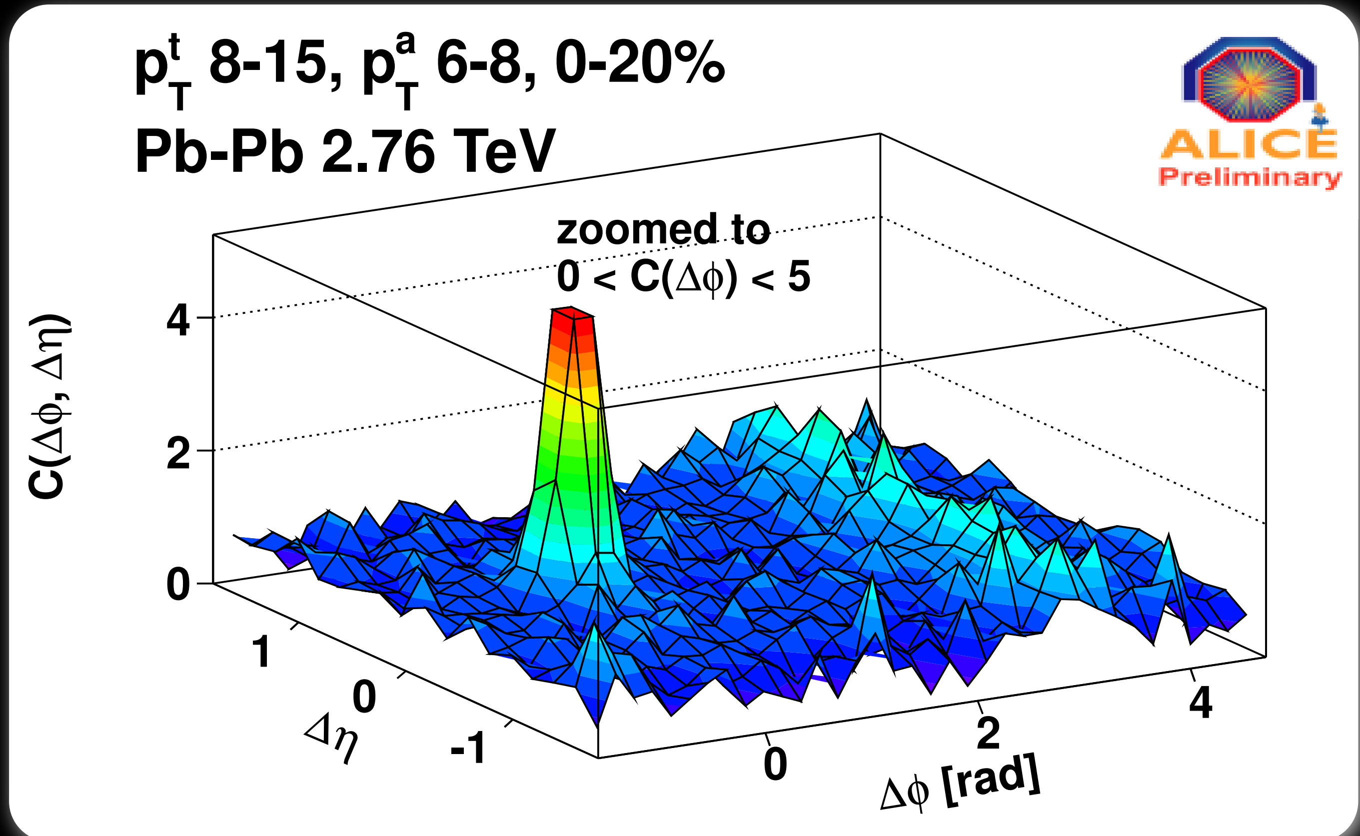
Contributions to the two-particle ΔΦ , Δη angular correlation come from anisotropic flow, jets, resonances, HBT, etc



see also CMS HIN-11-006

Angular Correlations

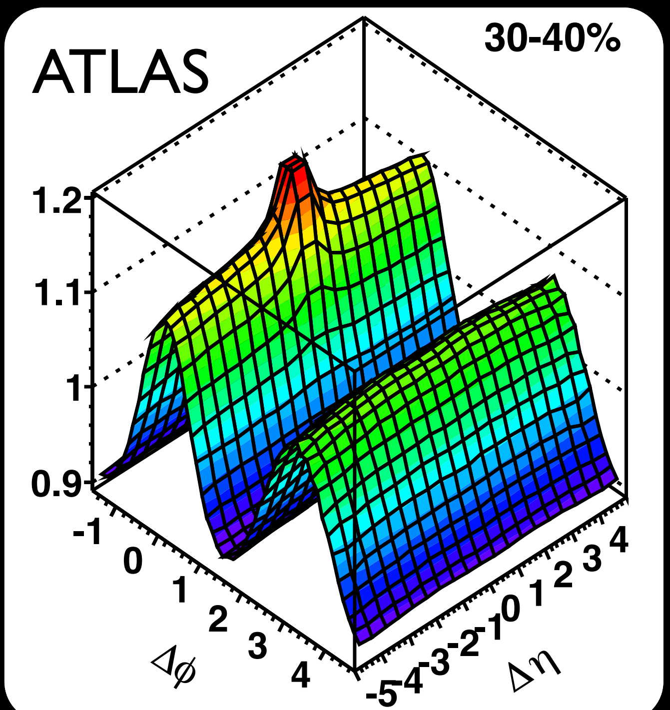


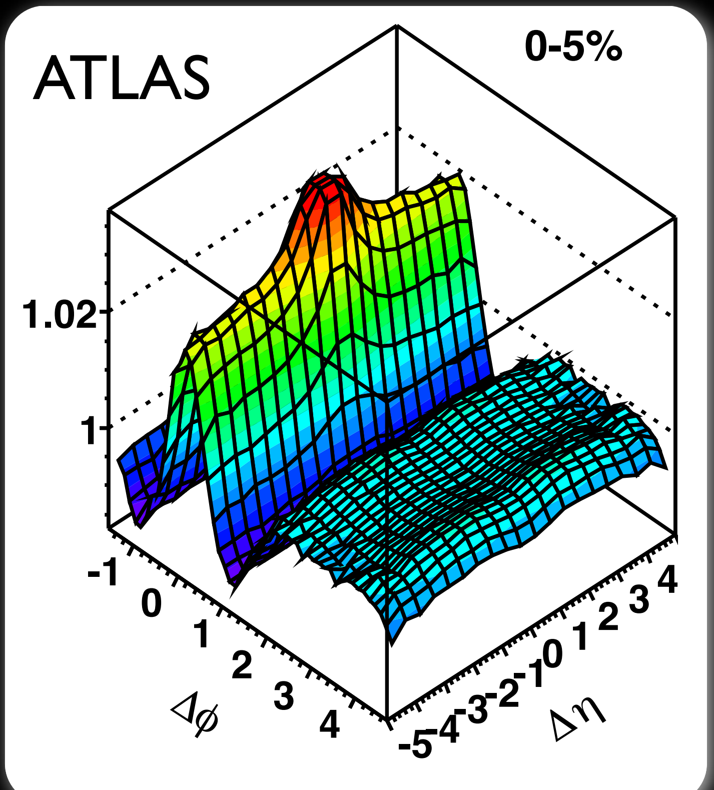


For very peripheral collisions or when triggered with a high-p_t particle the dominant contribution to the two particle angular correlations is due to jet-correlations

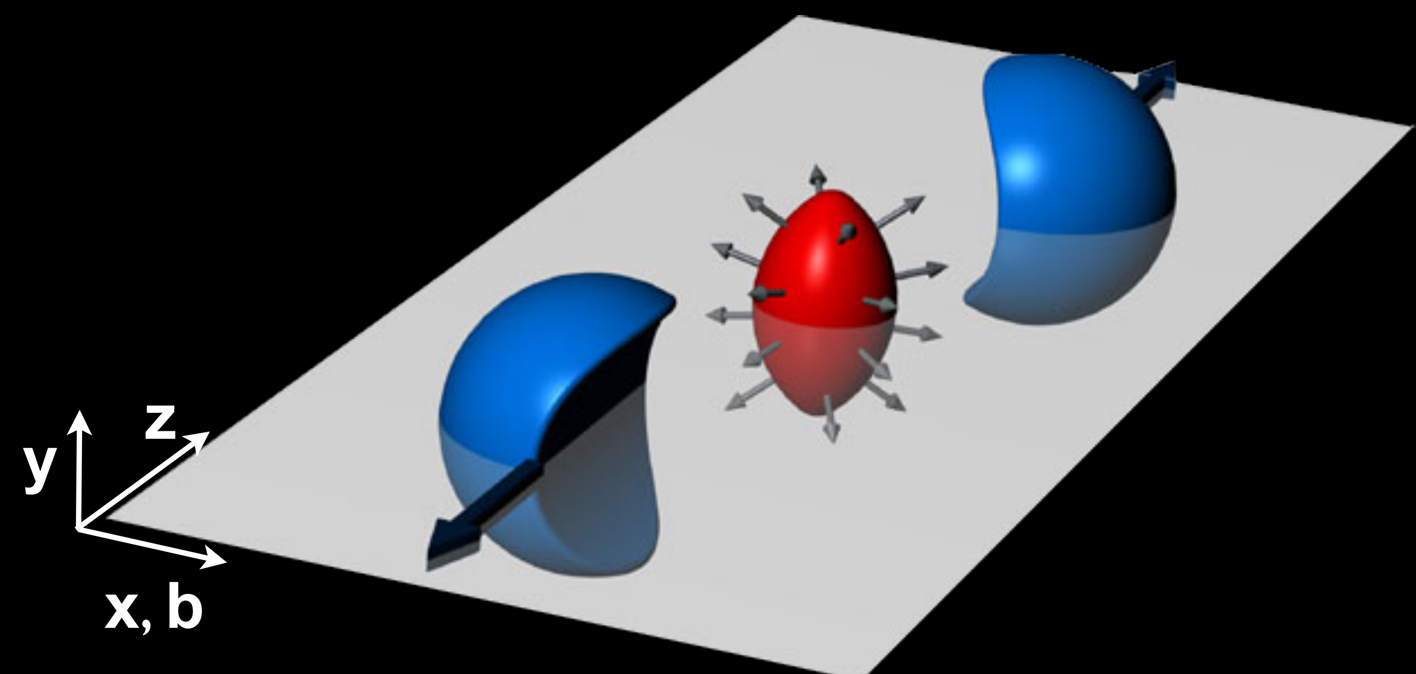
More central heavy-ion collisions look very very different!

anisotropic flow

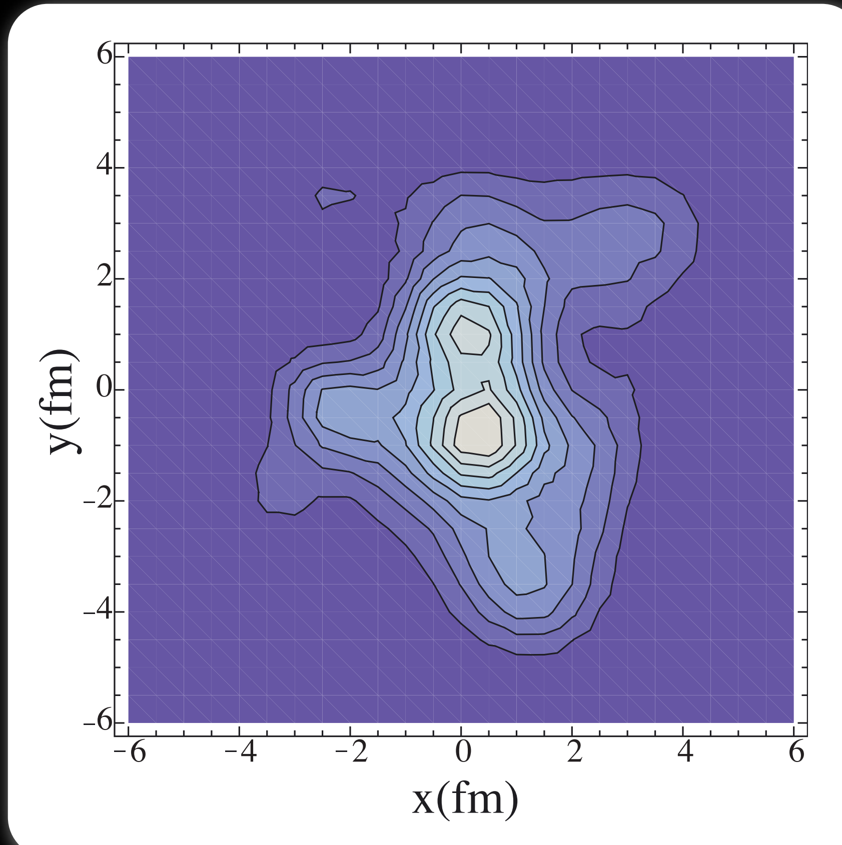




Anisotropic Flow v_n



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 event-by-event (for which all odd harmonics and sin $n(\Phi-\psi_R)$ are zero due to symmetry) may give rise to higher odd harmonics and symmetry planes in momentum space (detailed probes of initial conditions)

measure anisotropic flow

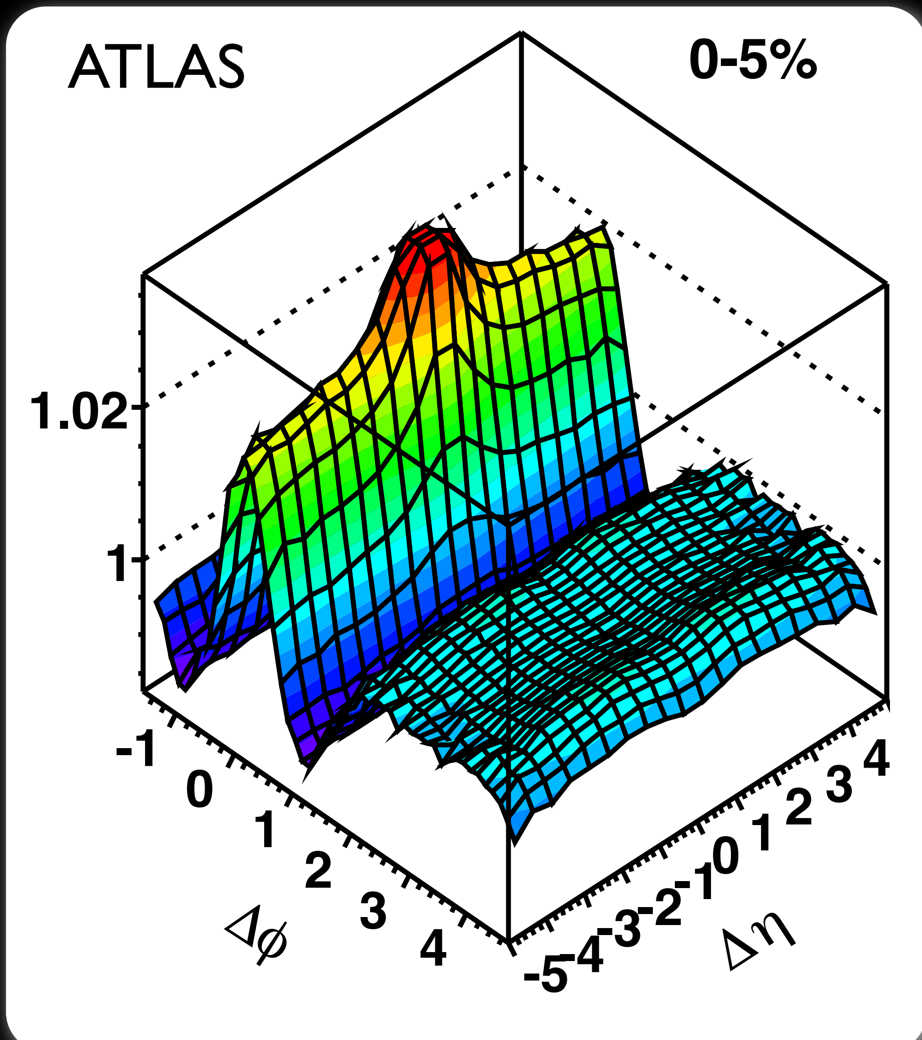
$$\langle v_n \rangle = \langle\langle e^{in(\phi_1 - \Psi_n)} \rangle\rangle$$

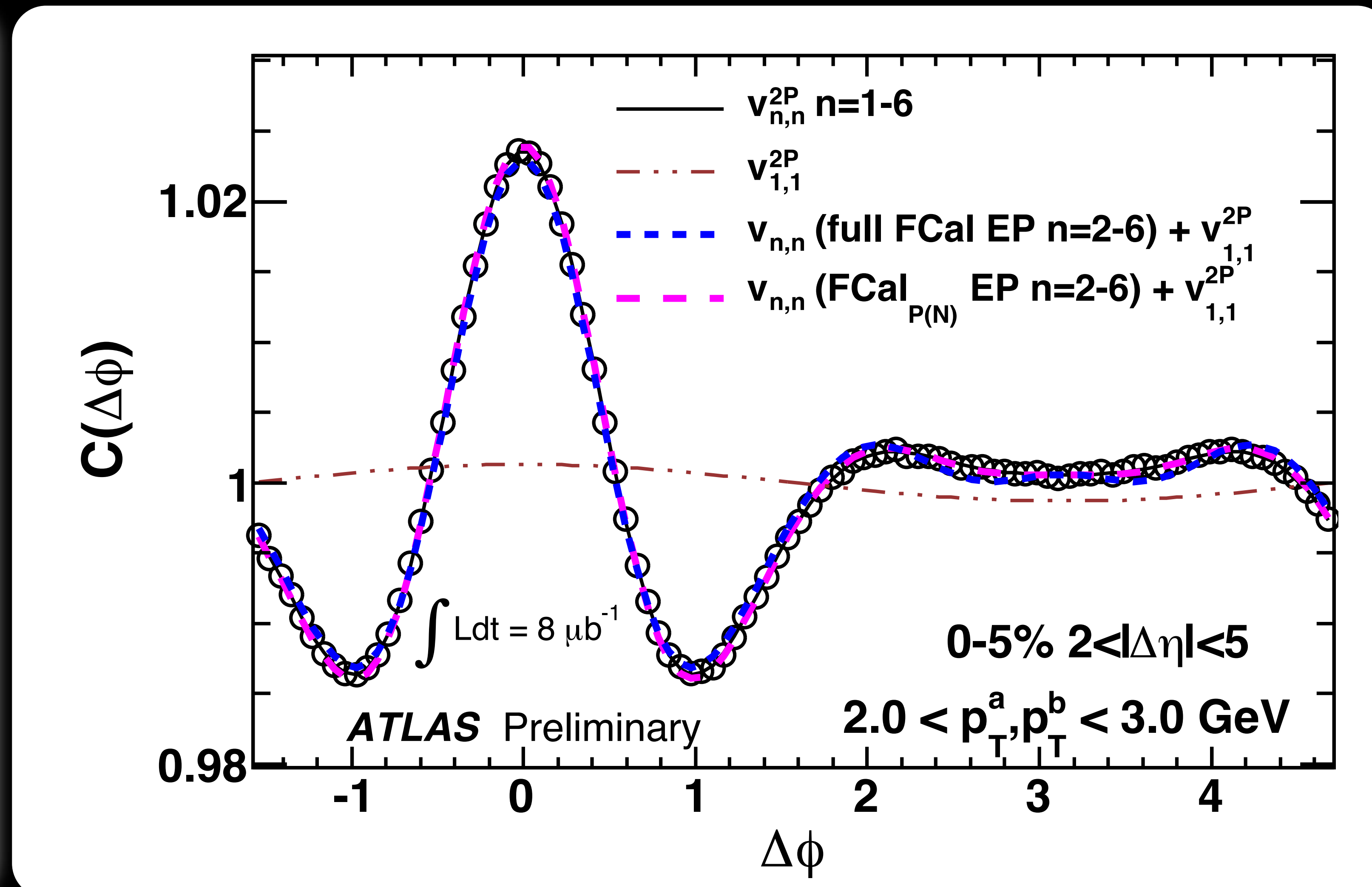
- since the common symmetry planes cannot be measured event-by-event, we measure quantities which do not depend on their orientation: two and multi-particle azimuthal correlations

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

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

Angular Correlations





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Two particle azimuthal correlations can be described efficiently with the first 6 v_n coefficients

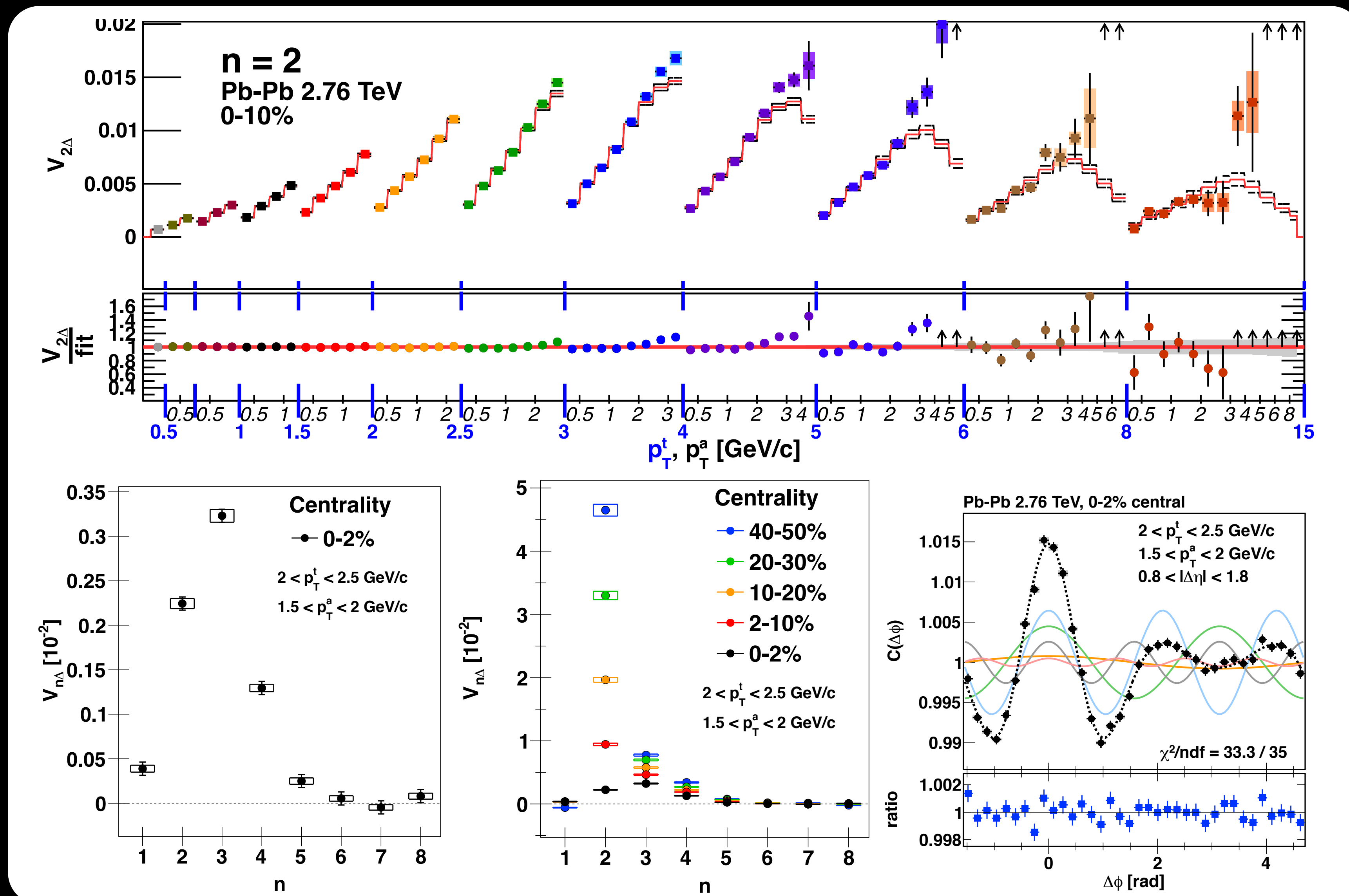
Can we isolate the flow?

- if nonflow is negligible flow "factorizes" → ←

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

  - test with particles separated in rapidity
  - test with particles separated in p_t
- flow is a collective effect
  - multi-particle correlations
    - Lee-Yang Zeroes, cumulants, q-vectors, etc

does it factorize?



ALICE
arXiv:1109.2501

- yes it does (to a large extent for more central collisions)
- how large is the flow where factorization "breaks"?
  - to quantify that one needs other techniques (multi-particle)

multi-particle correlations

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

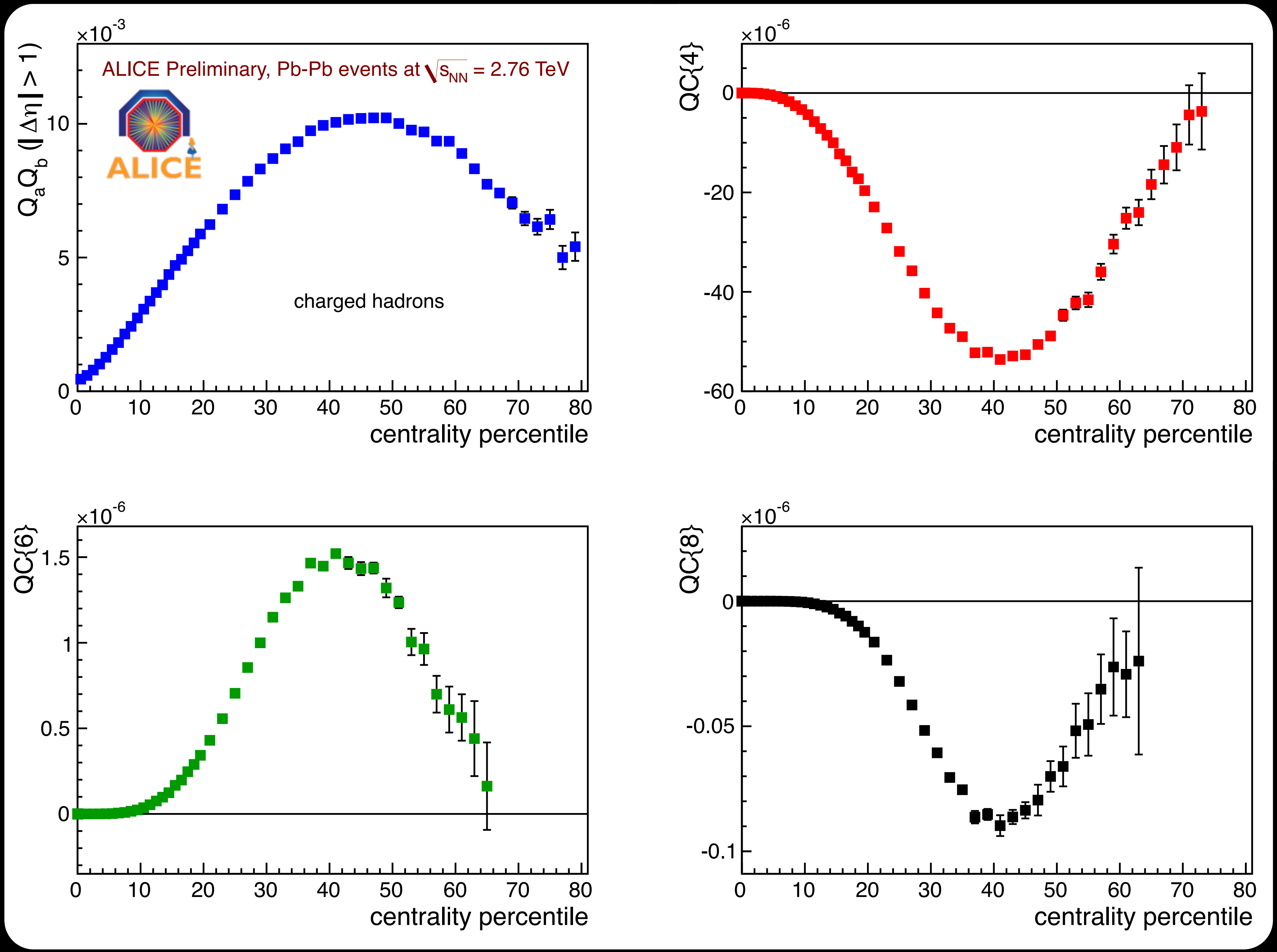
Borghini, Dihn and Ollitrault, PRC 64, 054901 (2001)

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

we got rid of two particle nonflow correlations!

we can remove nonflow order by order

v_2 from cumulants

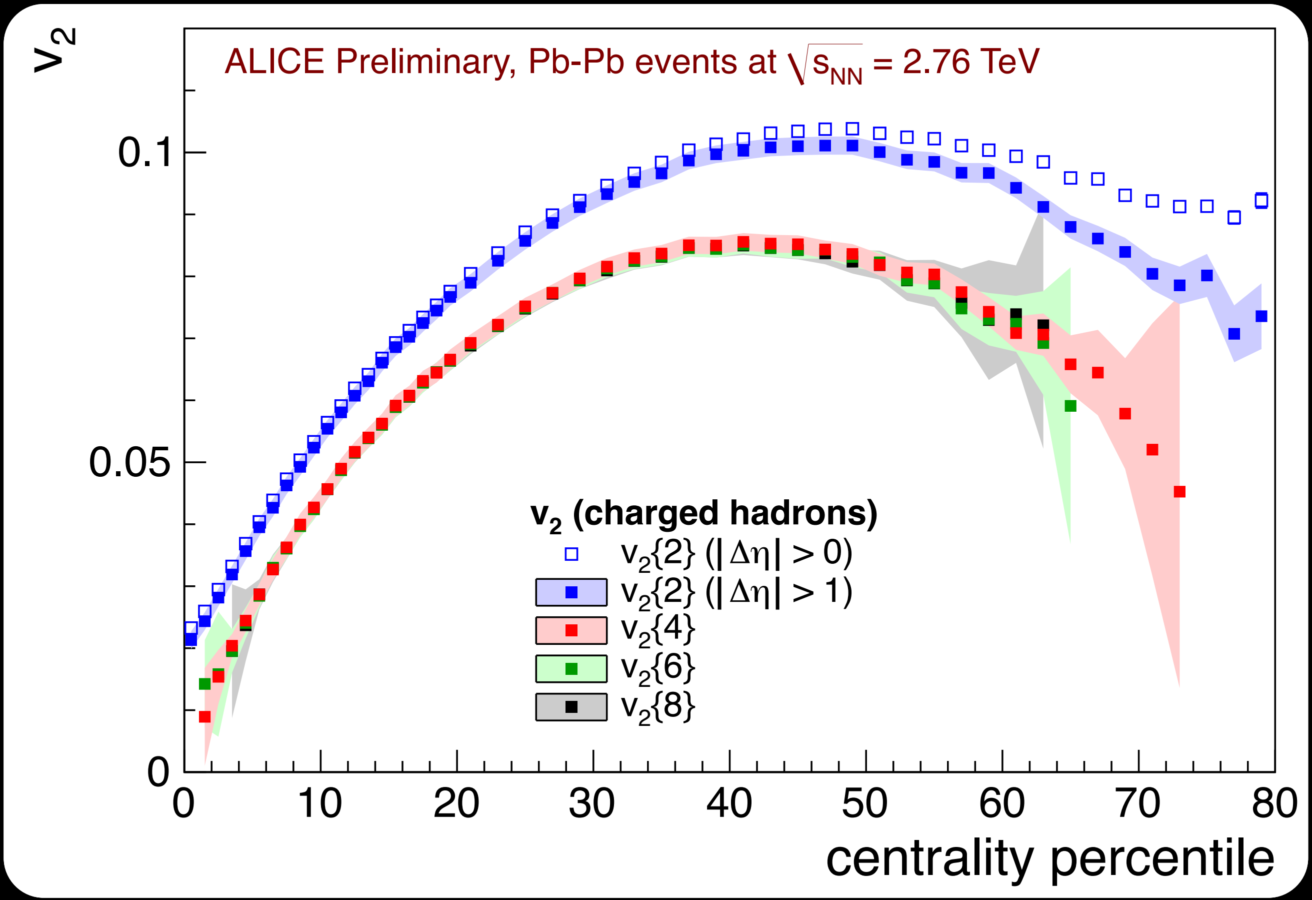


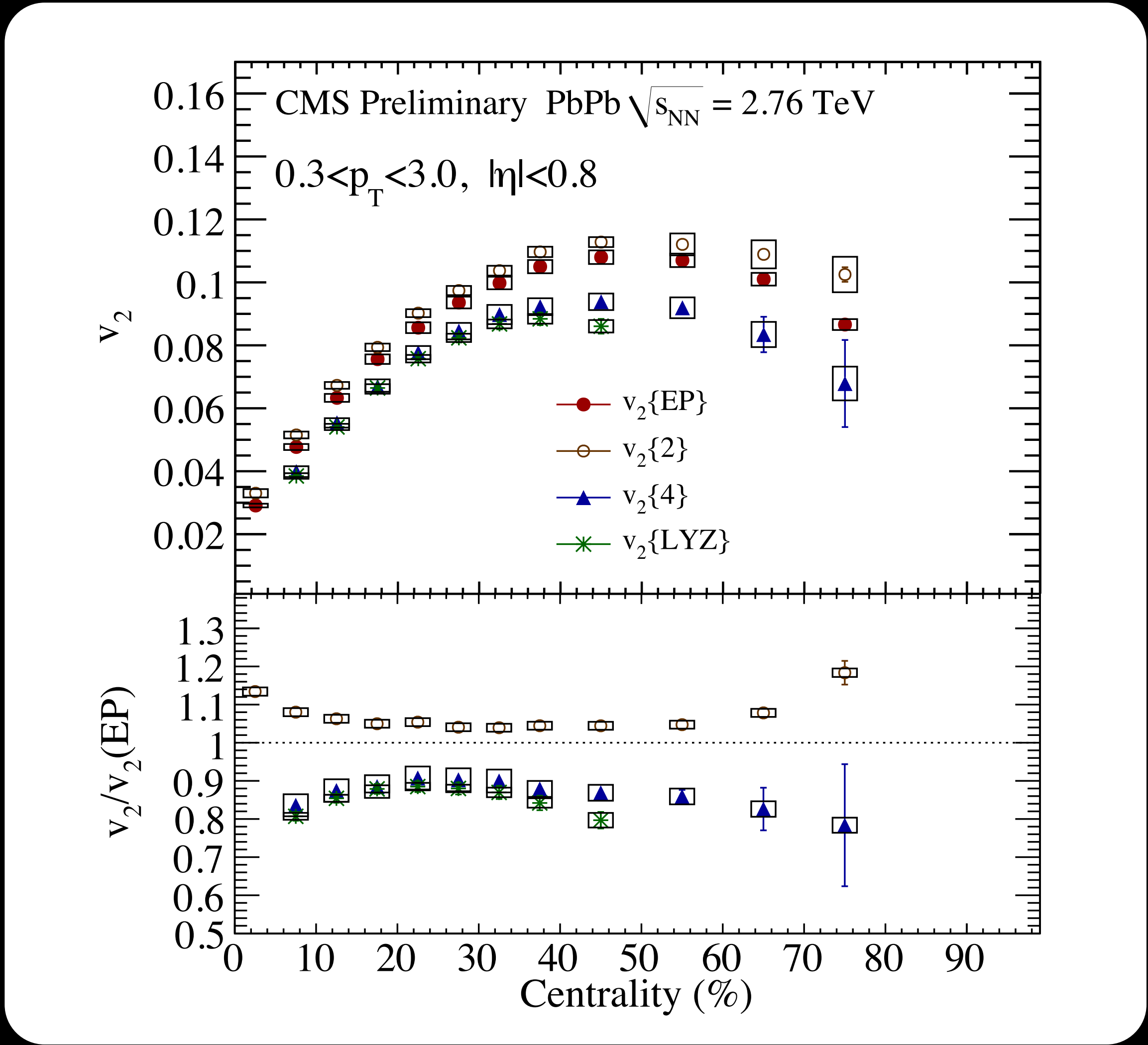
$$QC\{2\} = v^2\{2\}$$
$$QC\{4\} = -v^4\{4\}$$
$$QC\{6\} = 4v^6\{6\}$$
$$QC\{8\} = -33v^8\{8\}$$

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

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

v_2 from multi-particle correlations



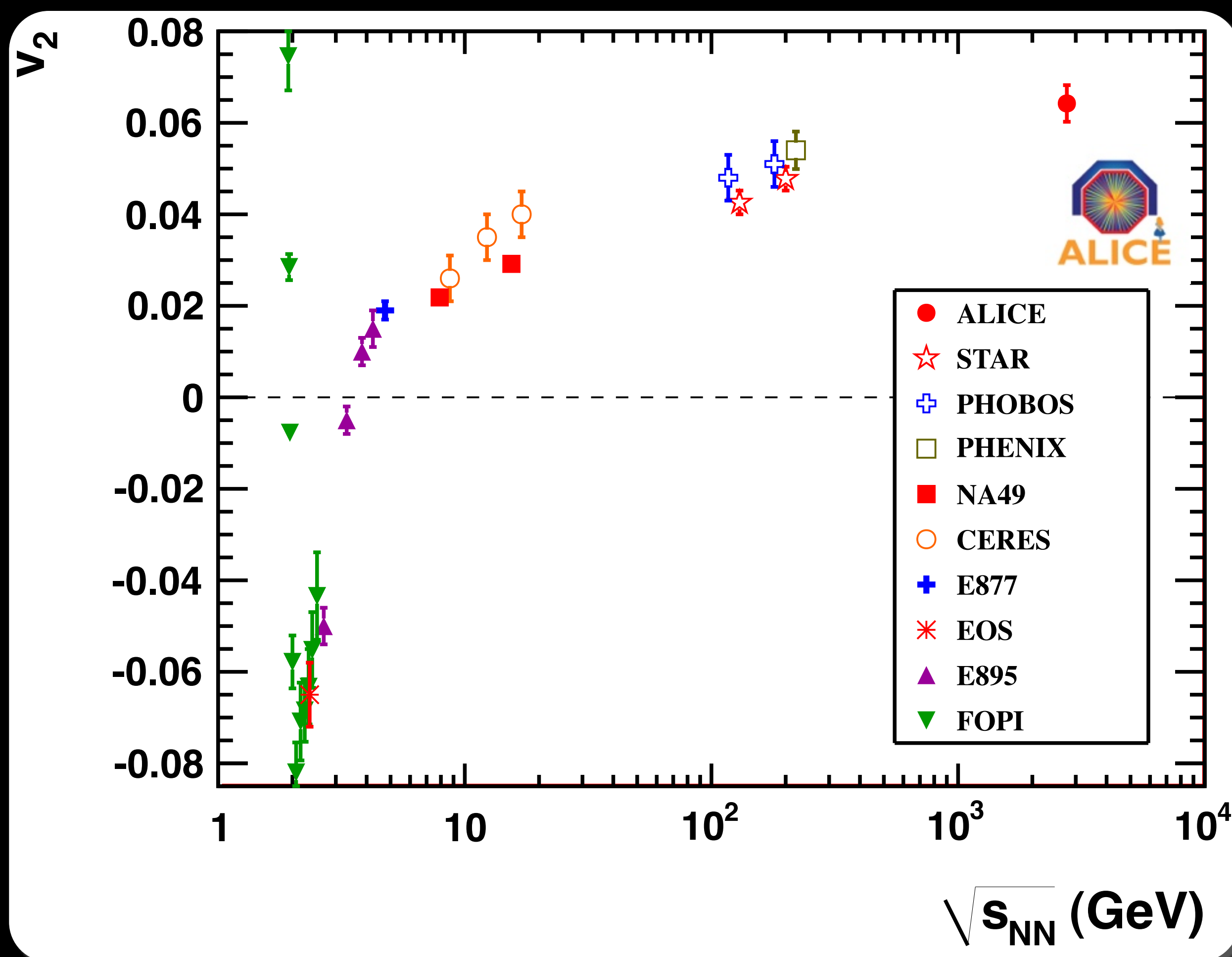


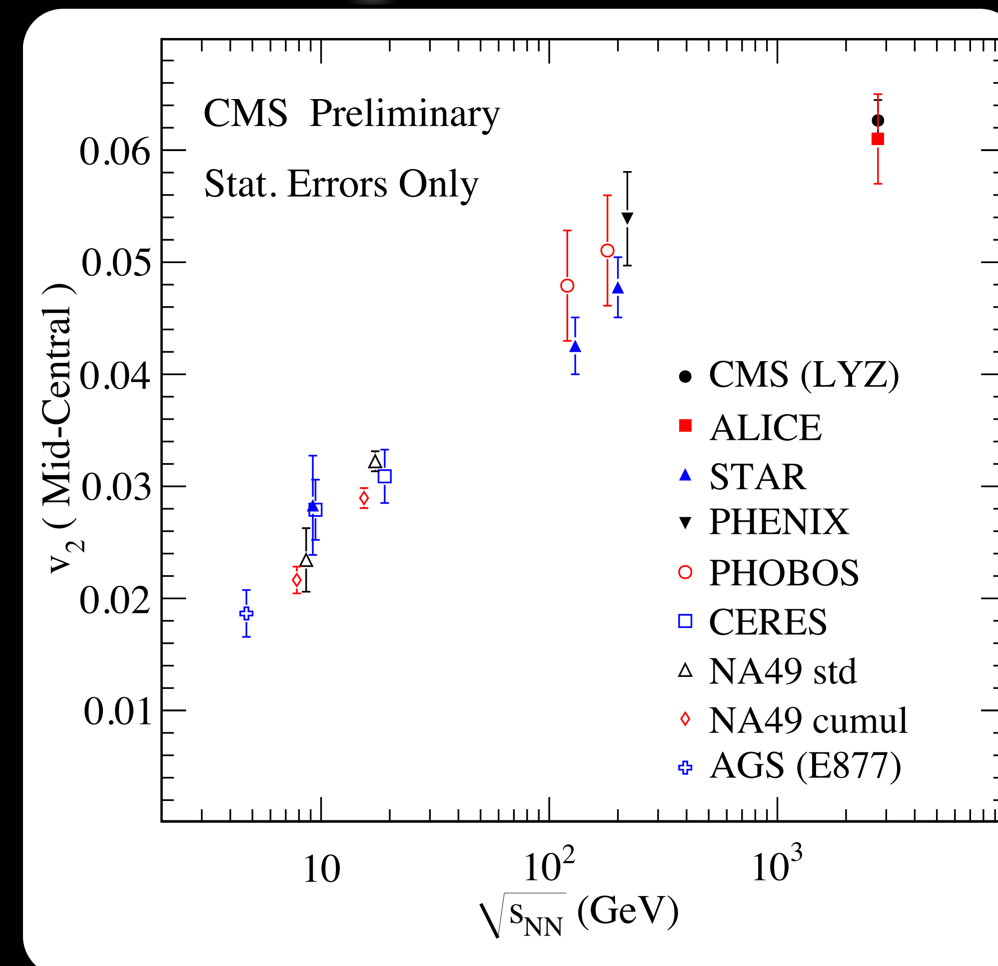
CMS PAS HIN-10-002

behavior as expected when correlations are dominated by collective flow (difference between 2 and multi-particle estimates mainly due to e-by-e fluctuations in the flow

The Perfect Liquid

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



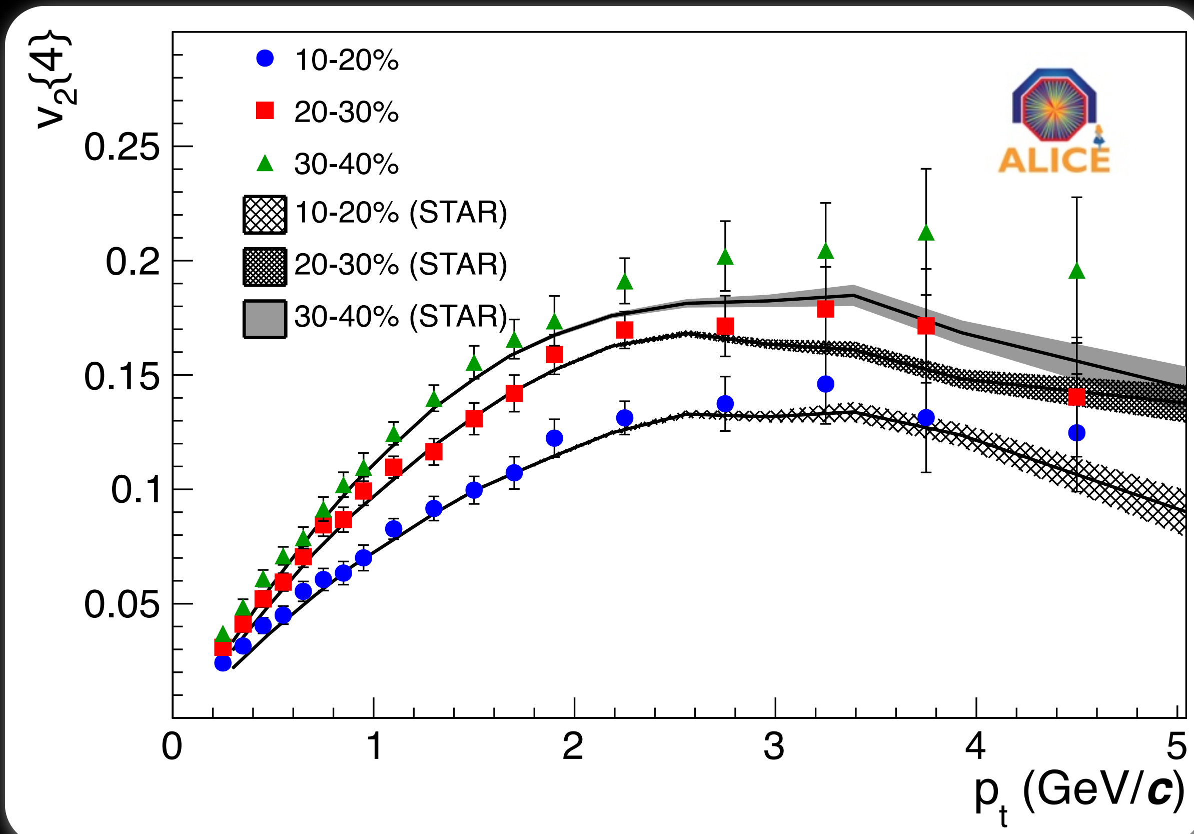


CMS PAS HIN-10-002

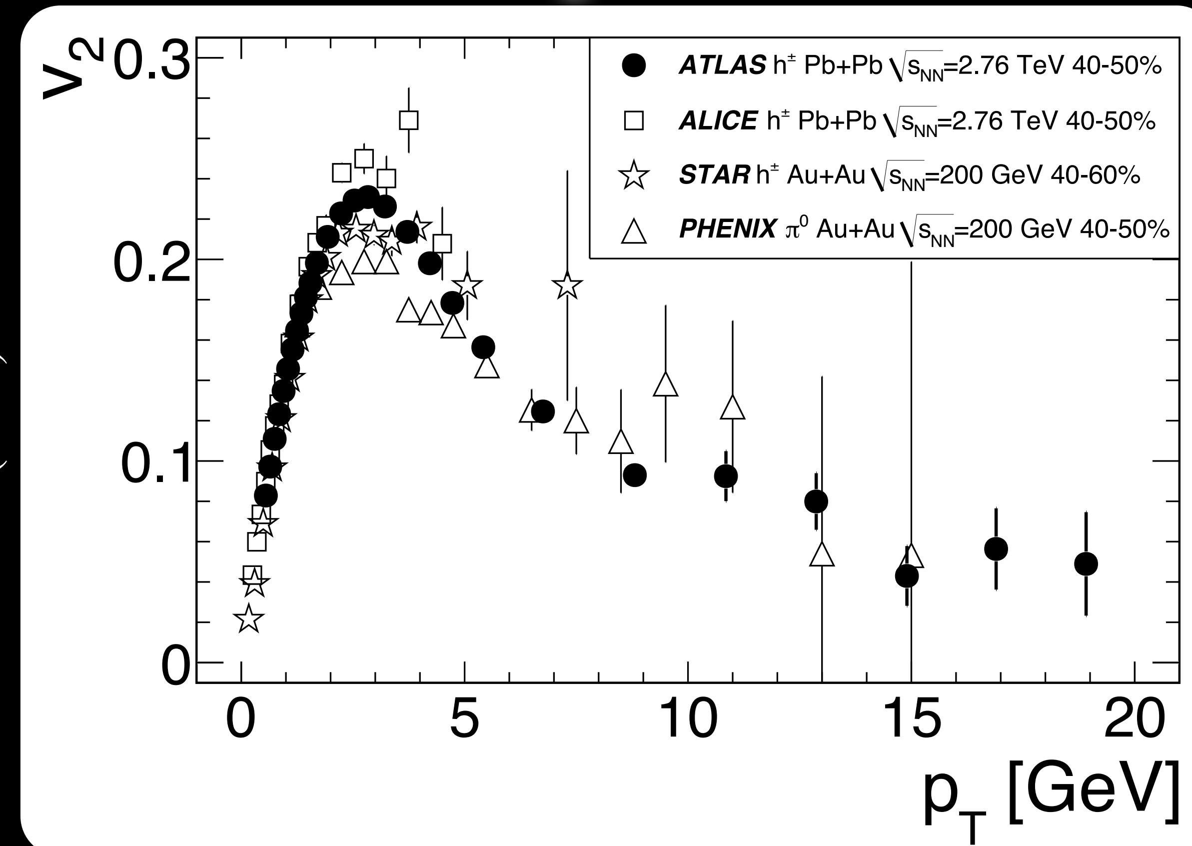
The flow increases about 30%. The system produced at the LHC behaves as a very low viscosity fluid, constrains dependence of η/s versus temperature

v_2 as function of p_t

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

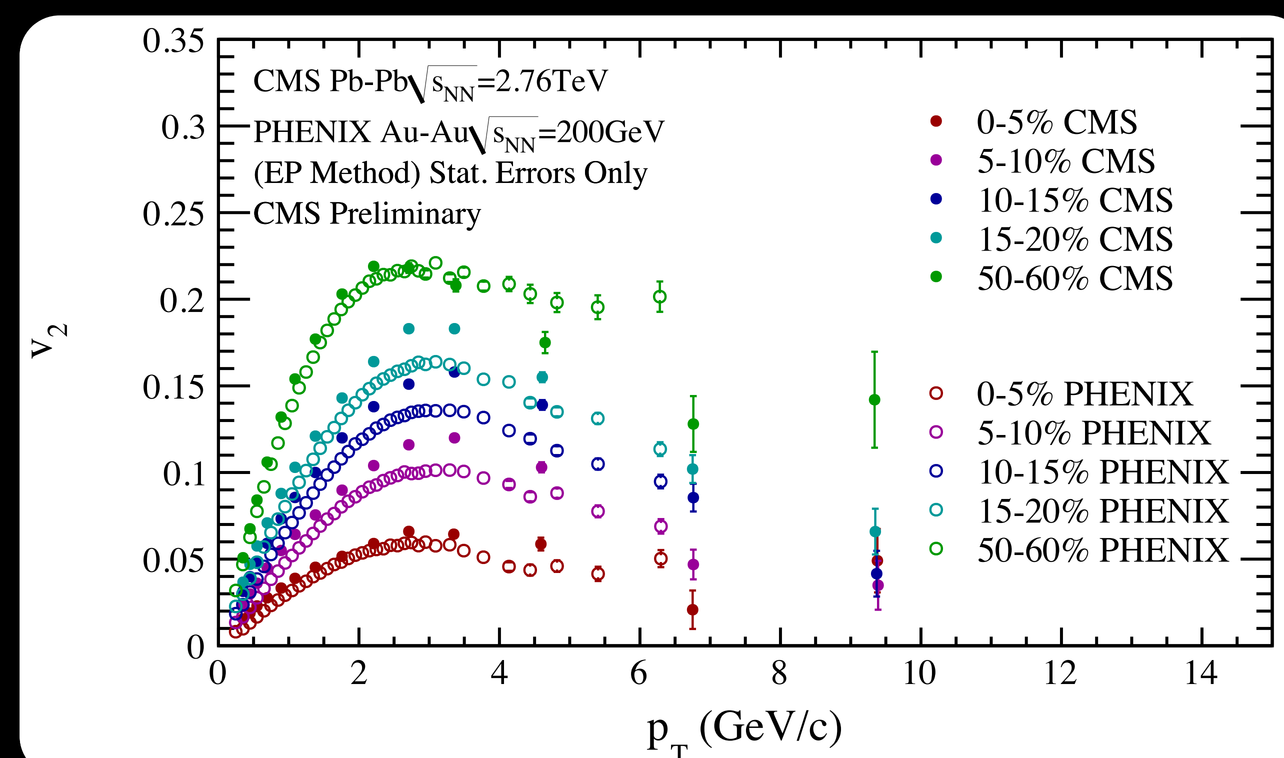


G. Aad et al. (ATLAS Collaboration)
arXiv: 1108.6018 (2011)



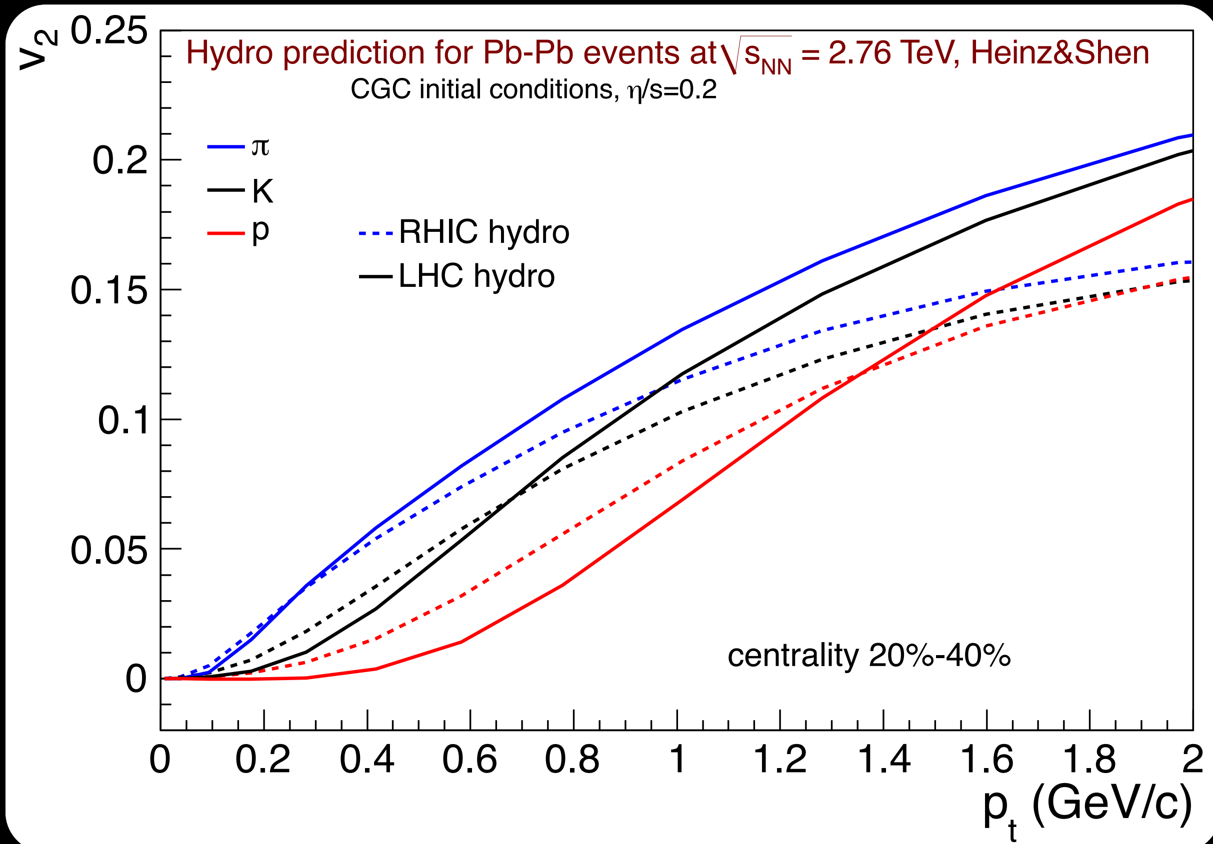
Elliptic flow as function of transverse momentum does not change much from RHIC to LHC energies, can we understand that?

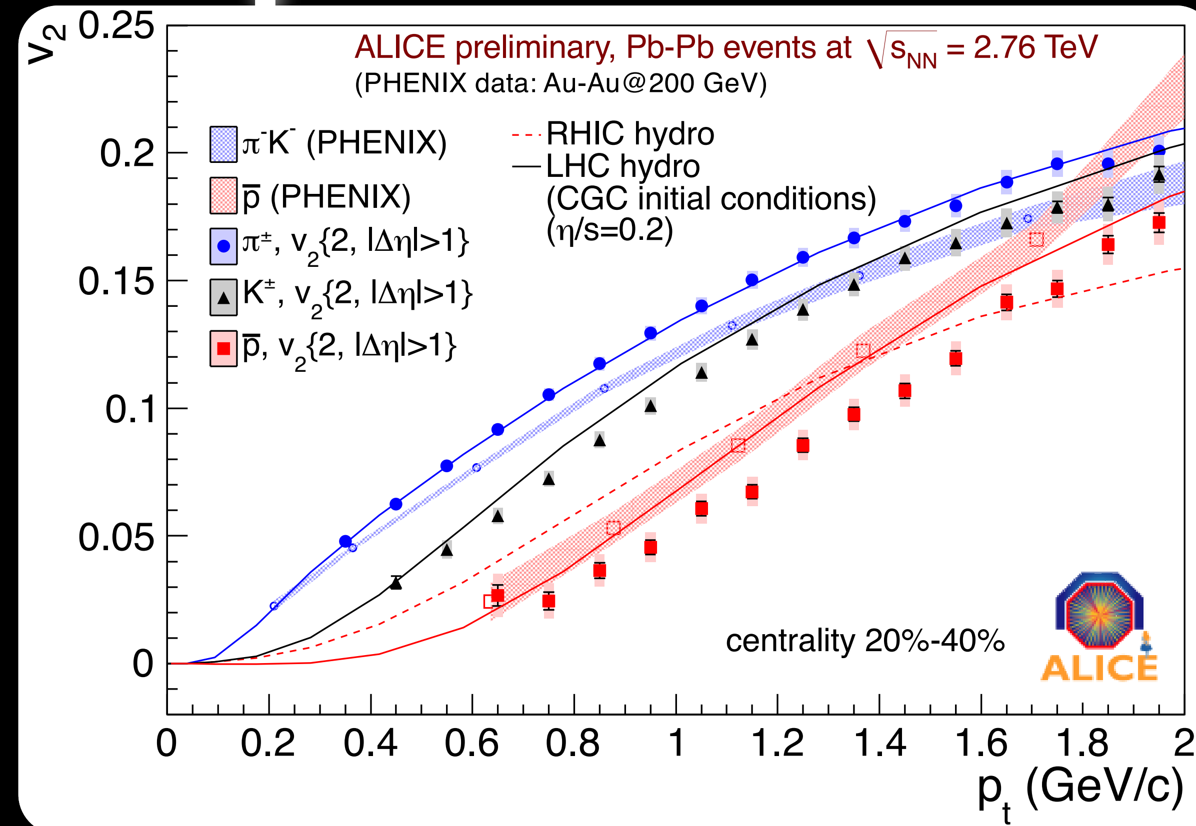
CMS PAS HIN-10-002



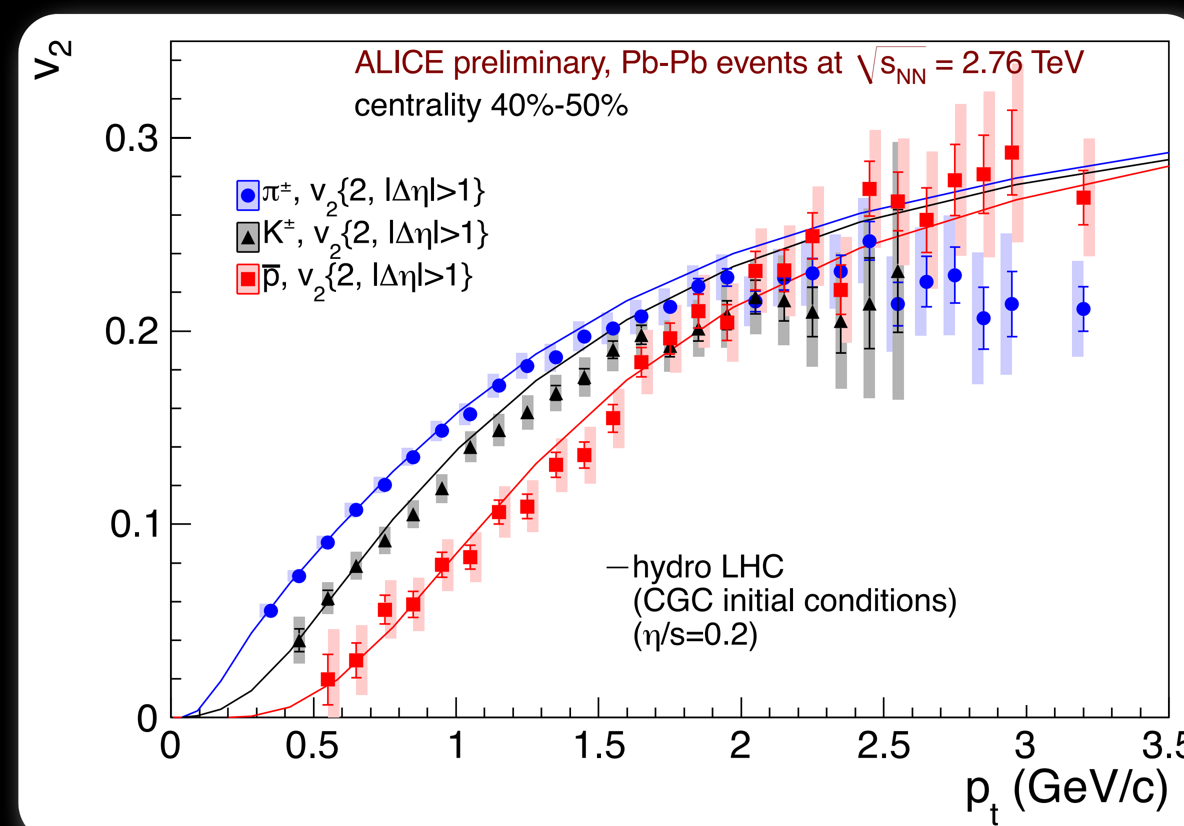
v_2 for identified particles

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





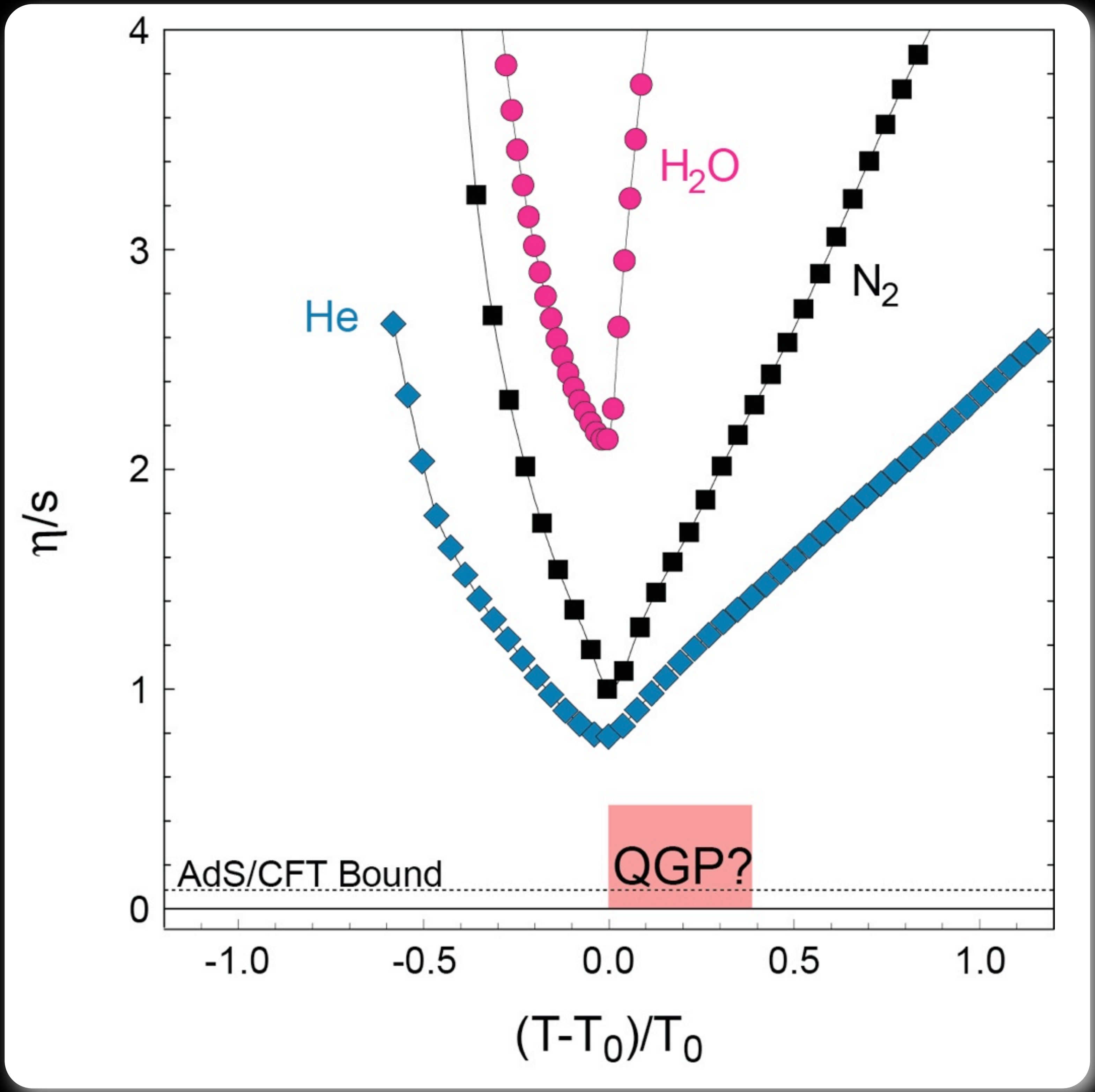
- the mass splitting increased compared to RHIC energies
- pion and kaon v_2 are described rather well with hydrodynamic predictions for protons hadronic contribution important



The Perfect Liquid?

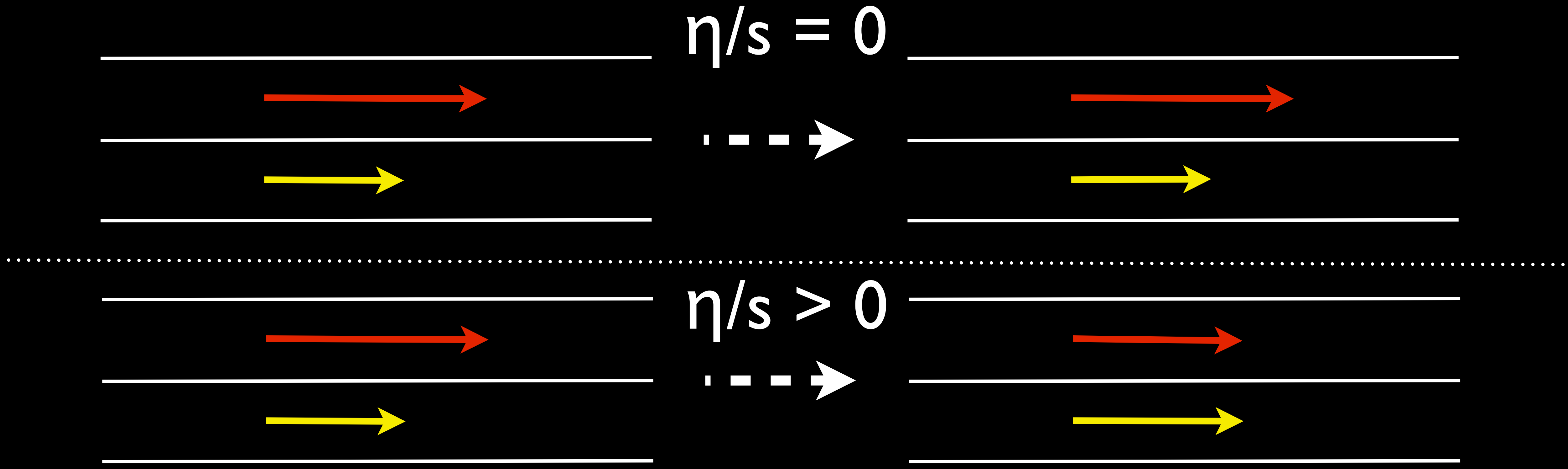
in calculations the RHIC v_2 results are close to the ideal hydrodynamical limit.

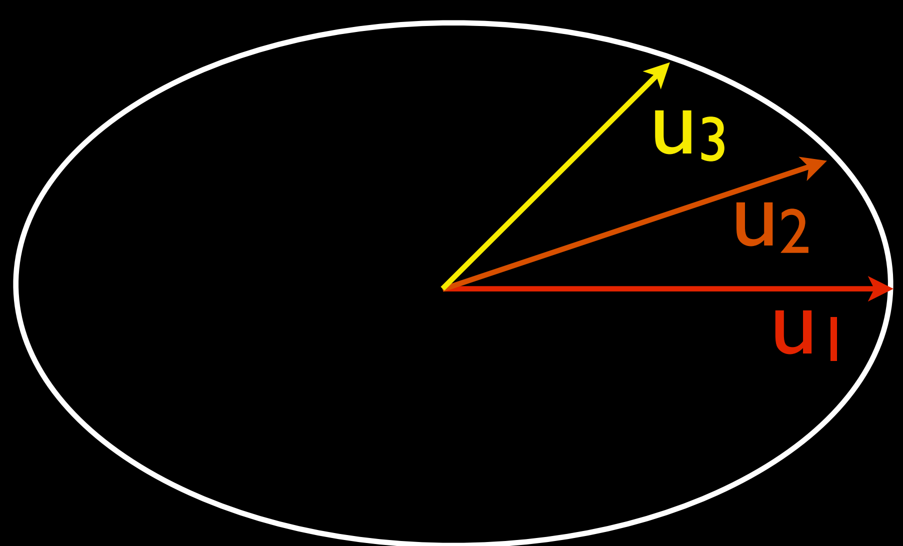
these calculations place an upper limit on η/s which is smaller than ~ 4 x AdS/CFT bound



Based on R. Lacey et al., PRL 98 (2007) 092301

Shear Viscosity

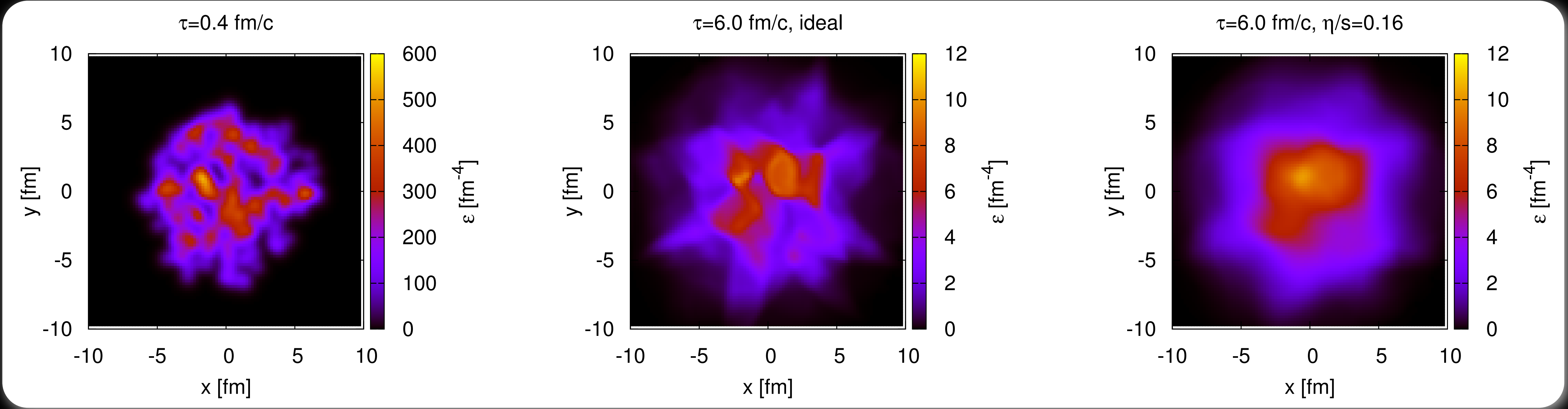




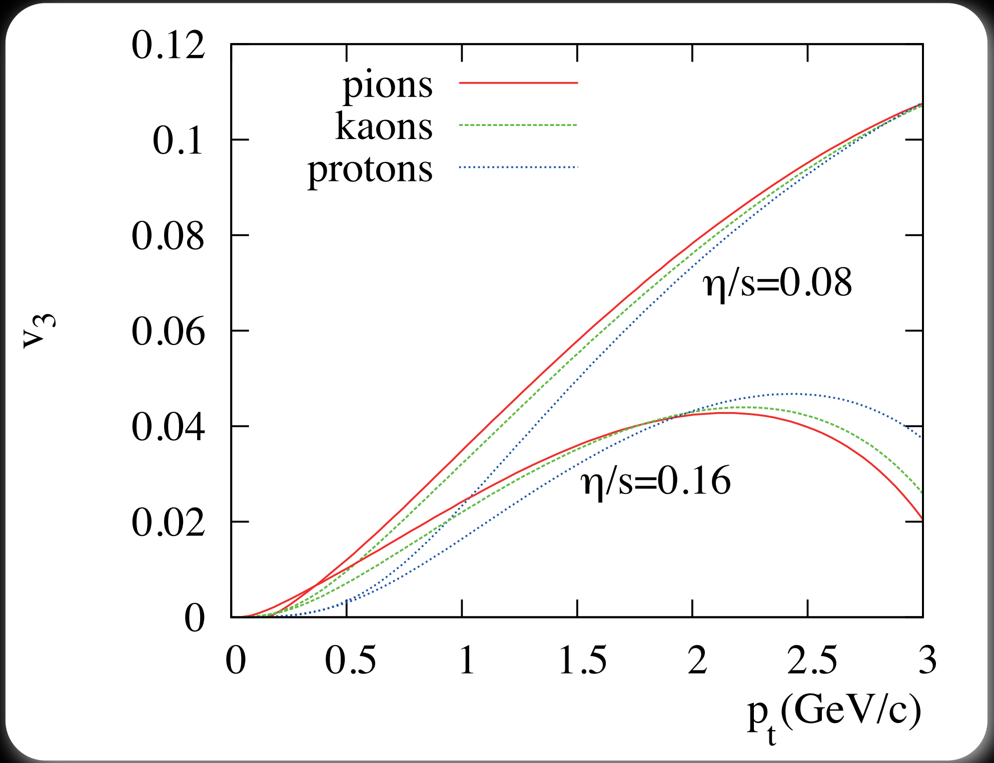
$u_1 > u_2 > u_3$ shear viscosity will make them equal and destroy the elliptic flow v_2
higher harmonics represent smaller differences which get destroyed more easily, and which, if measurable, makes them more sensitive probes to η/s

Shear Viscosity

Music, Sangyong Jeon



initial conditions   ideal hydro $\eta/s=0$ viscous hydro $\eta/s=0.16$



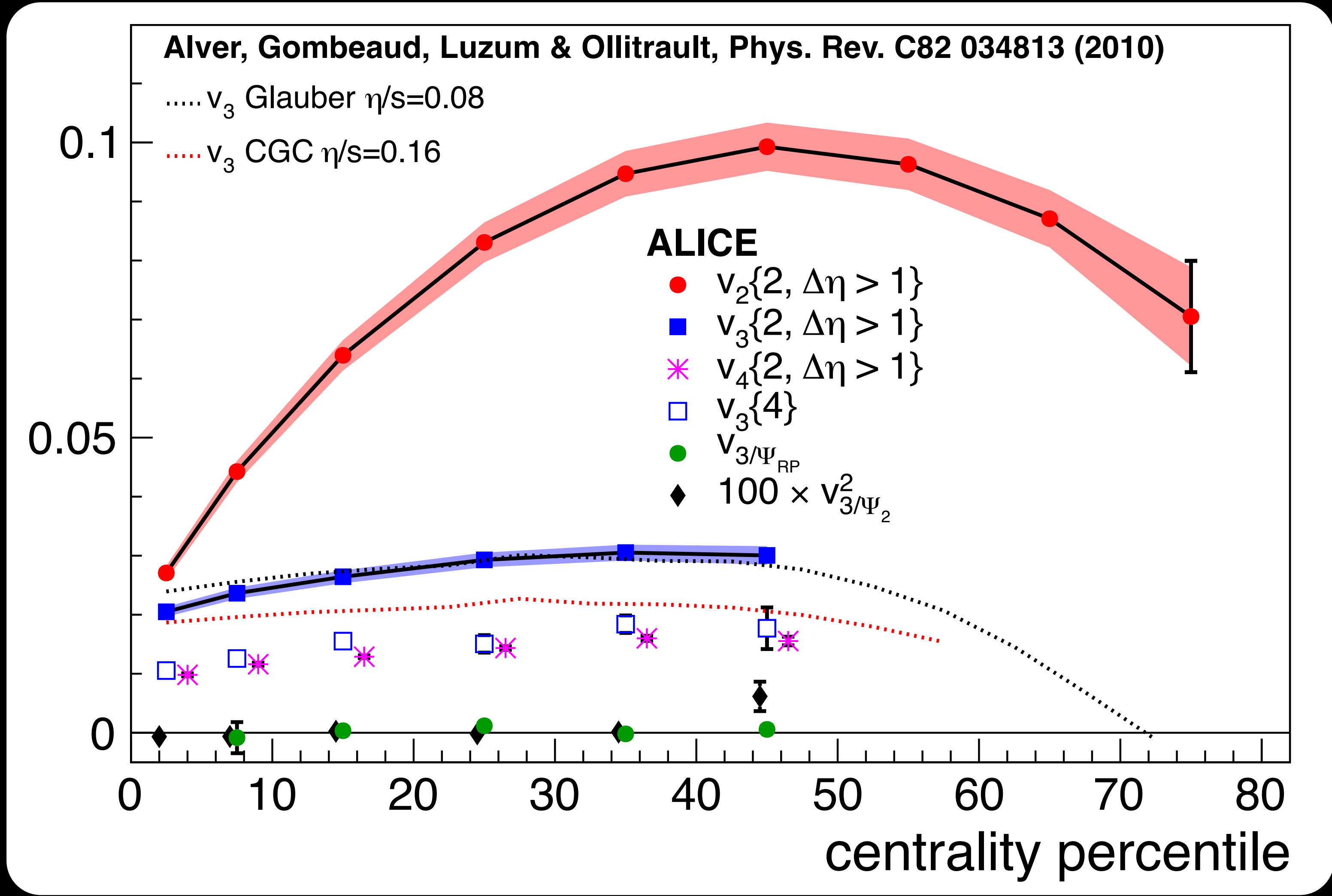
Larger η/s clearly smoothes the distributions and suppresses the higher harmonics (e.g. v_3)

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

the v_n's

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

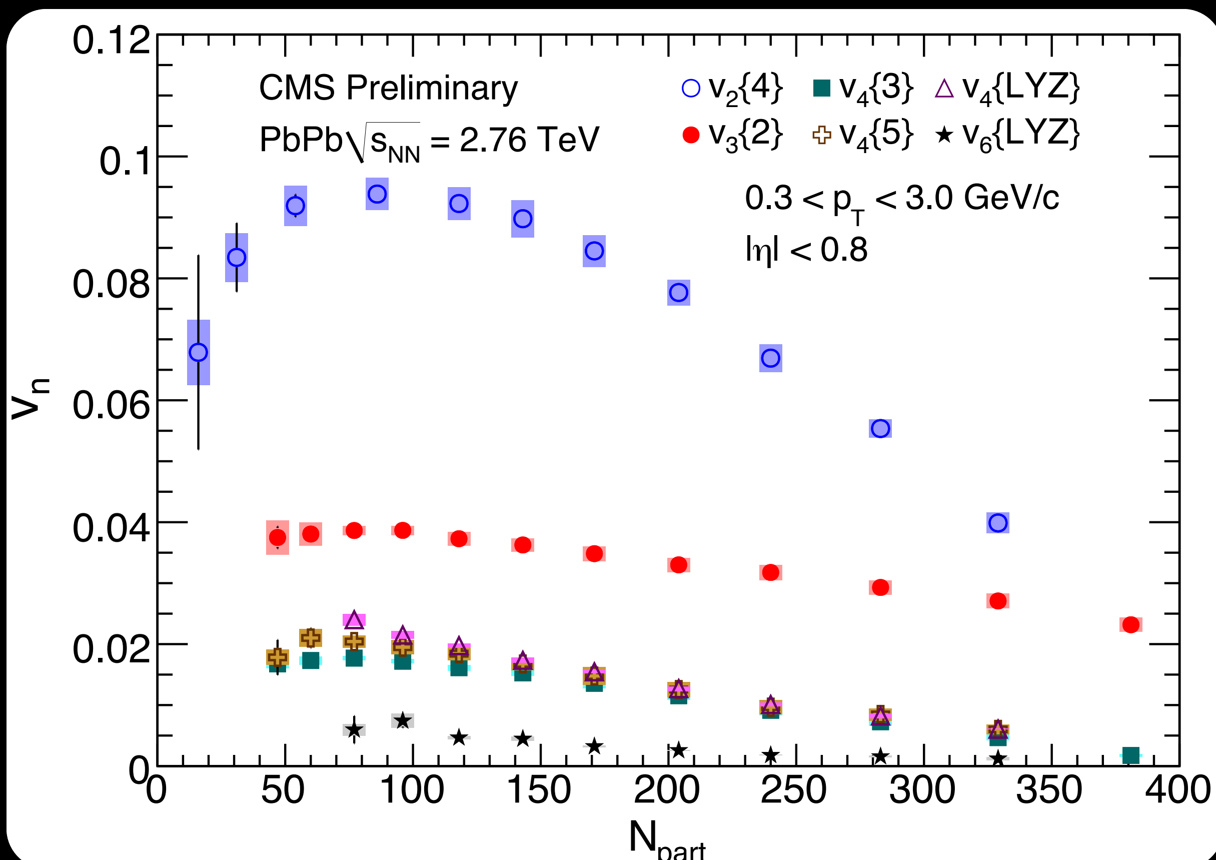
The $v_3\{2\}$ is about two times larger than $v_3\{4\}$ which is also consistent with expectations based on initial eccentricity fluctuations



ALICE Collaboration, arXiv:1105.3865
PRL 107 (2011) 032301

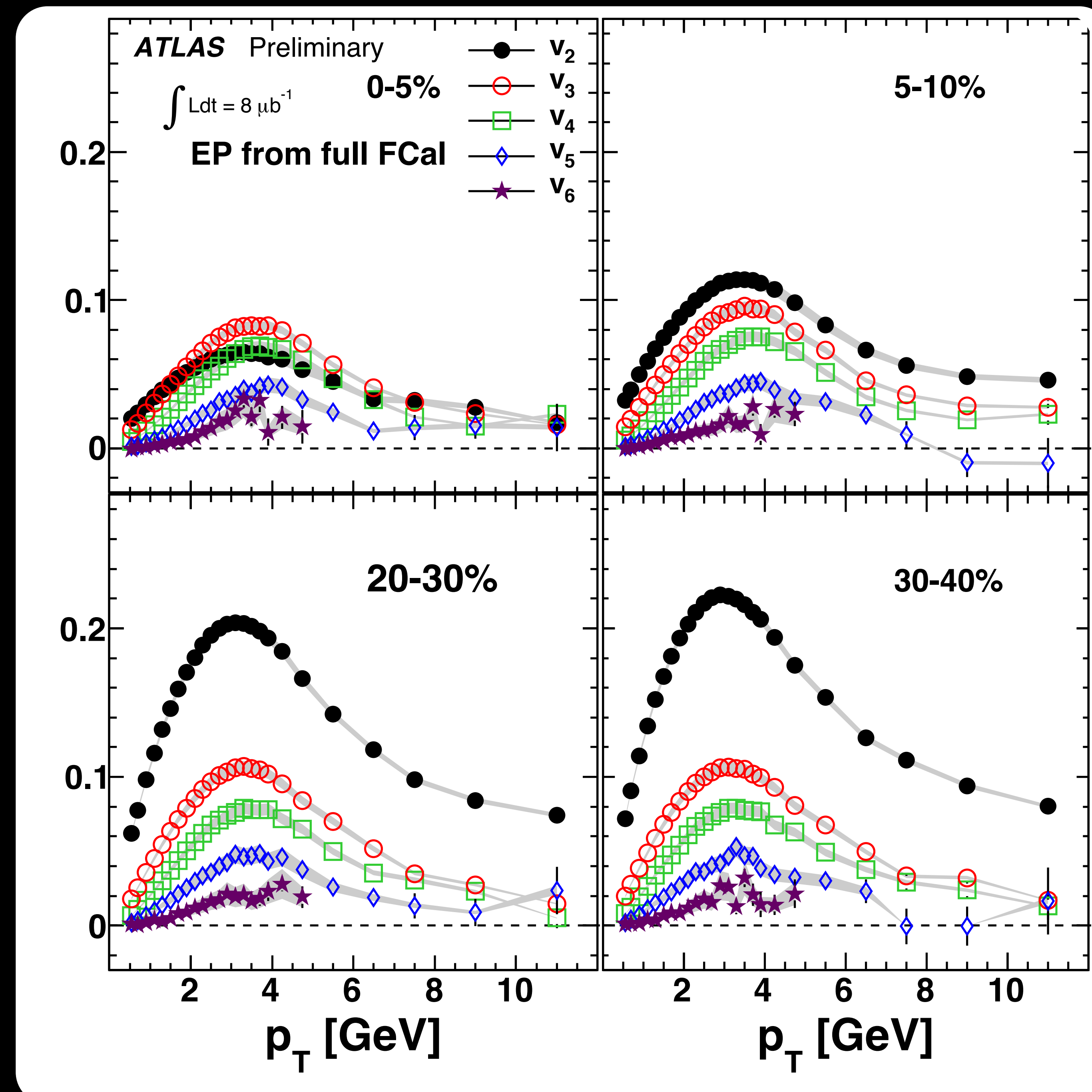
We observe significant v_3 and v_4 which compared to v_2 has a different centrality dependence (already strong constrain for η/s)

the v_n's



CMS PAS HIN-11-005

For most central collisions v_3 and v_4 become at intermediate p_t larger than v_2



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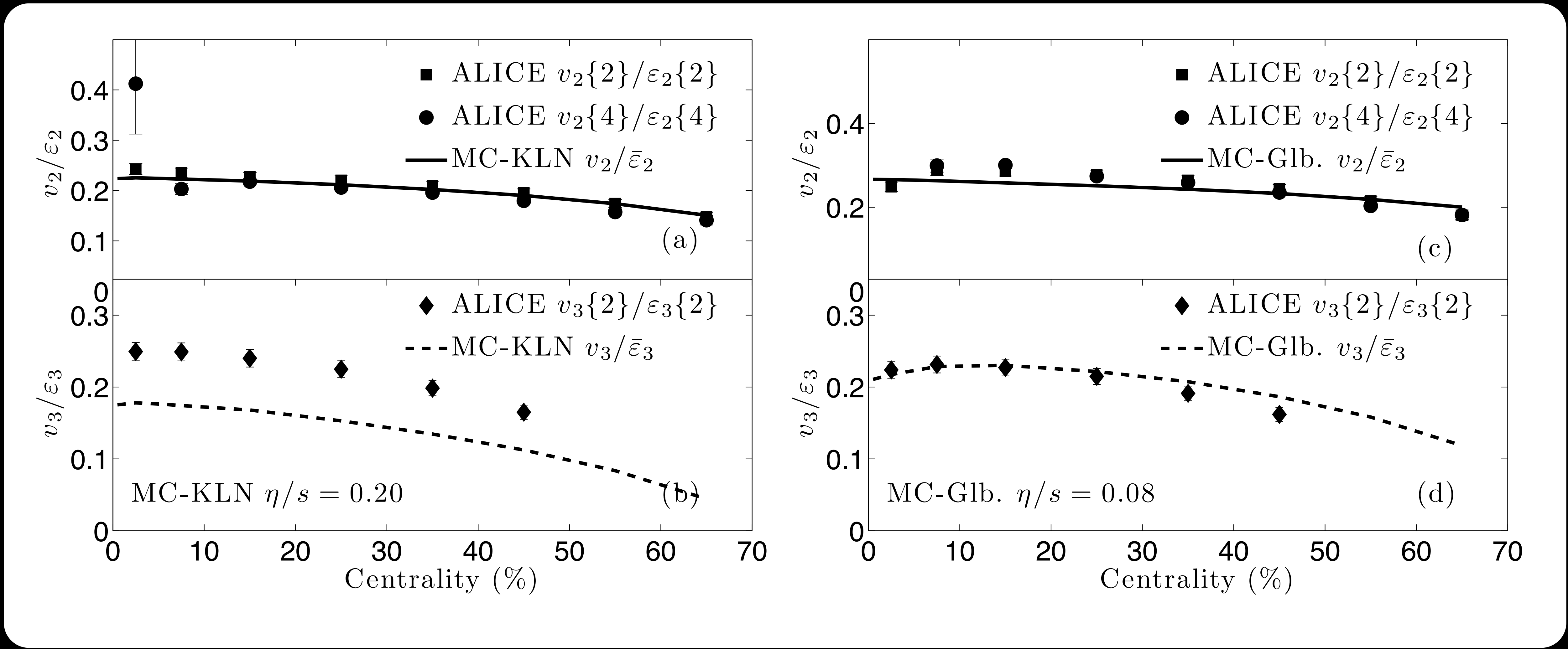
Elliptic and Triangular Flow



Qui, Shen and Heinz, arXiv:1110.3033

The centrality dependence and magnitude are better described by predictions using MC Glauber with η/s=0.08

Flow Analysis Methods

flow analysis methods have different sensitivity to nonflow and fluctuations

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

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

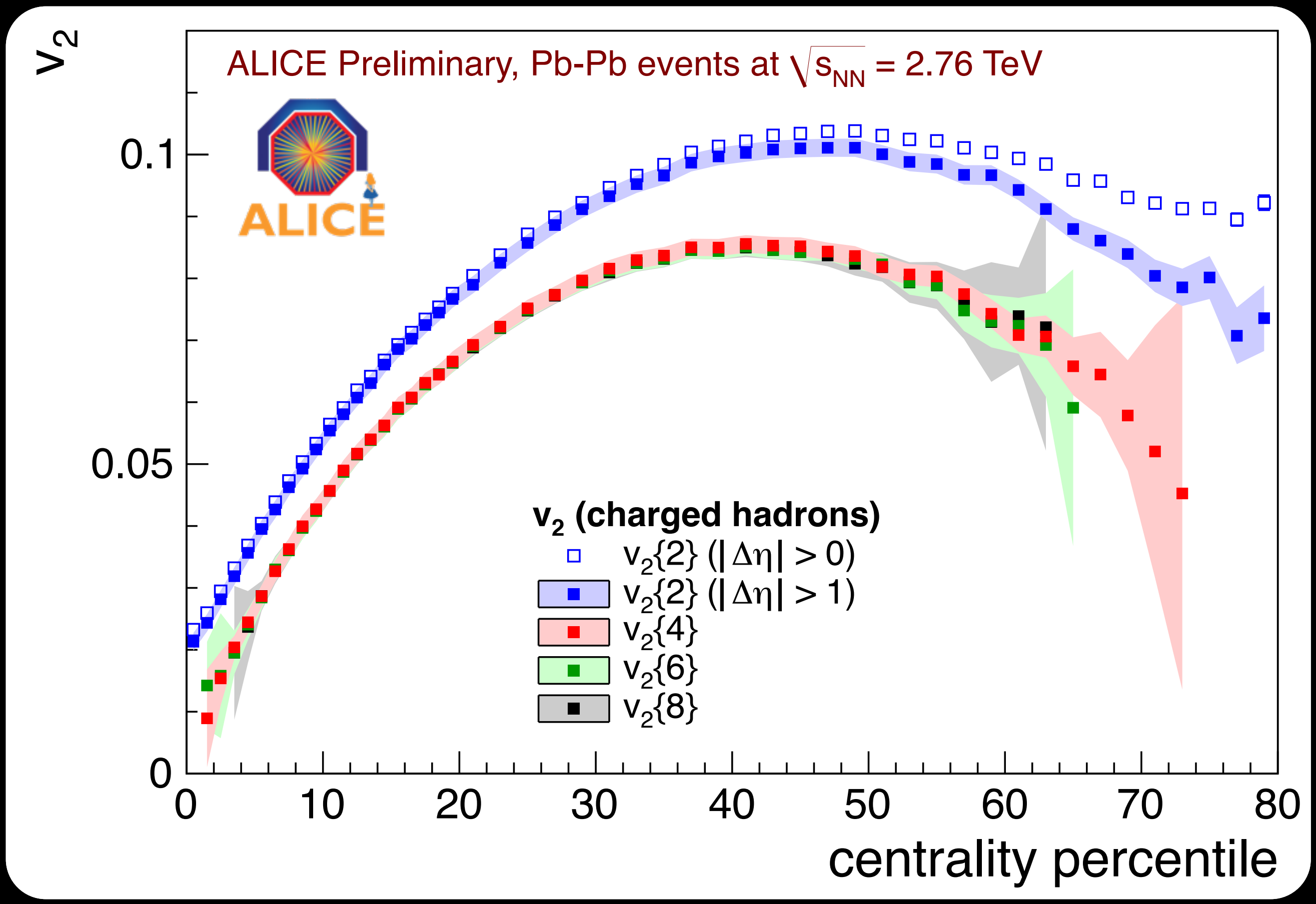
$$v_n^2\{6\} = \bar{v}_n^2 - \sigma_v^2$$

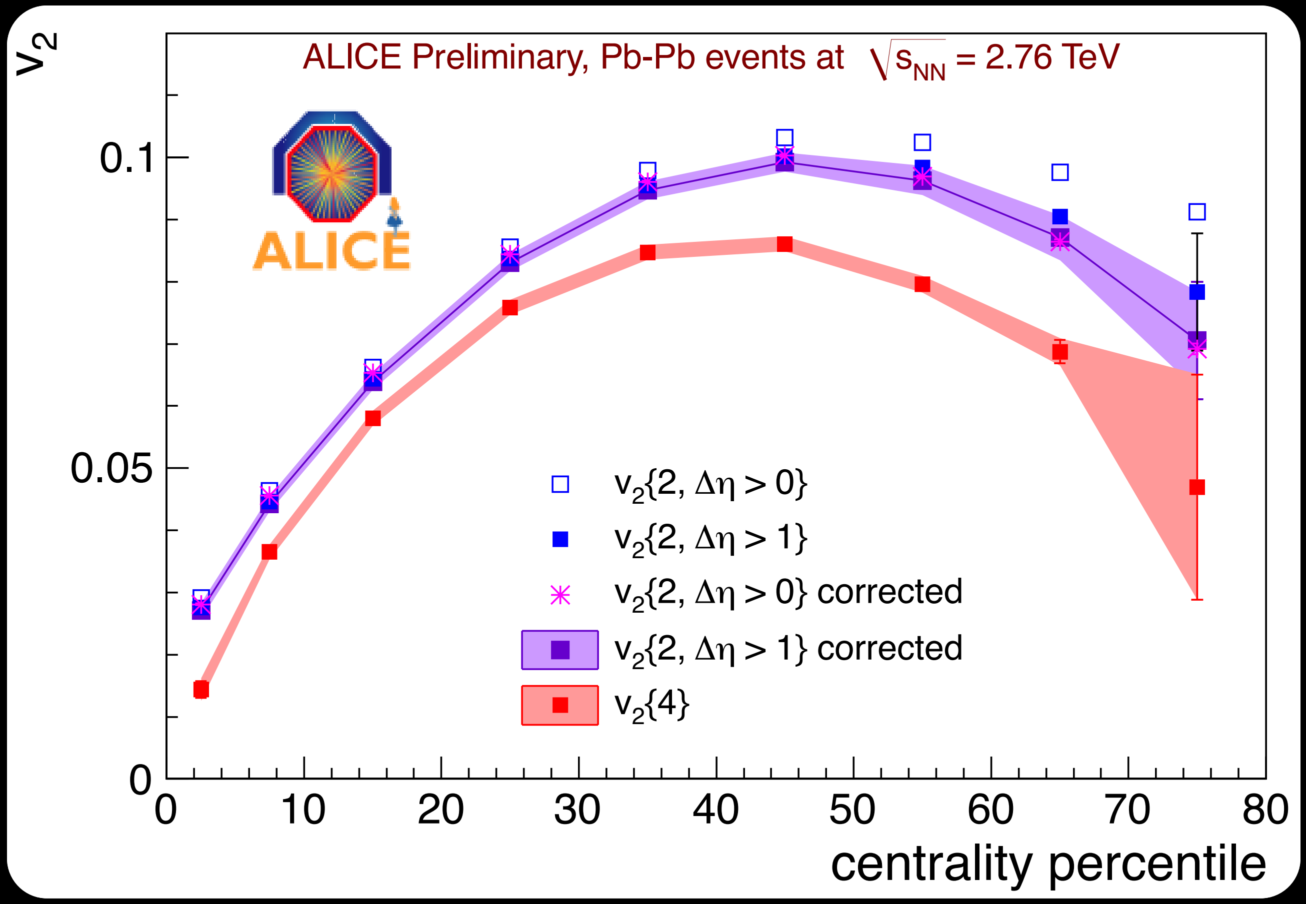
$$v_n^2\{8\} = \bar{v}_n^2 - \sigma_v^2$$

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

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

v_2 versus centrality

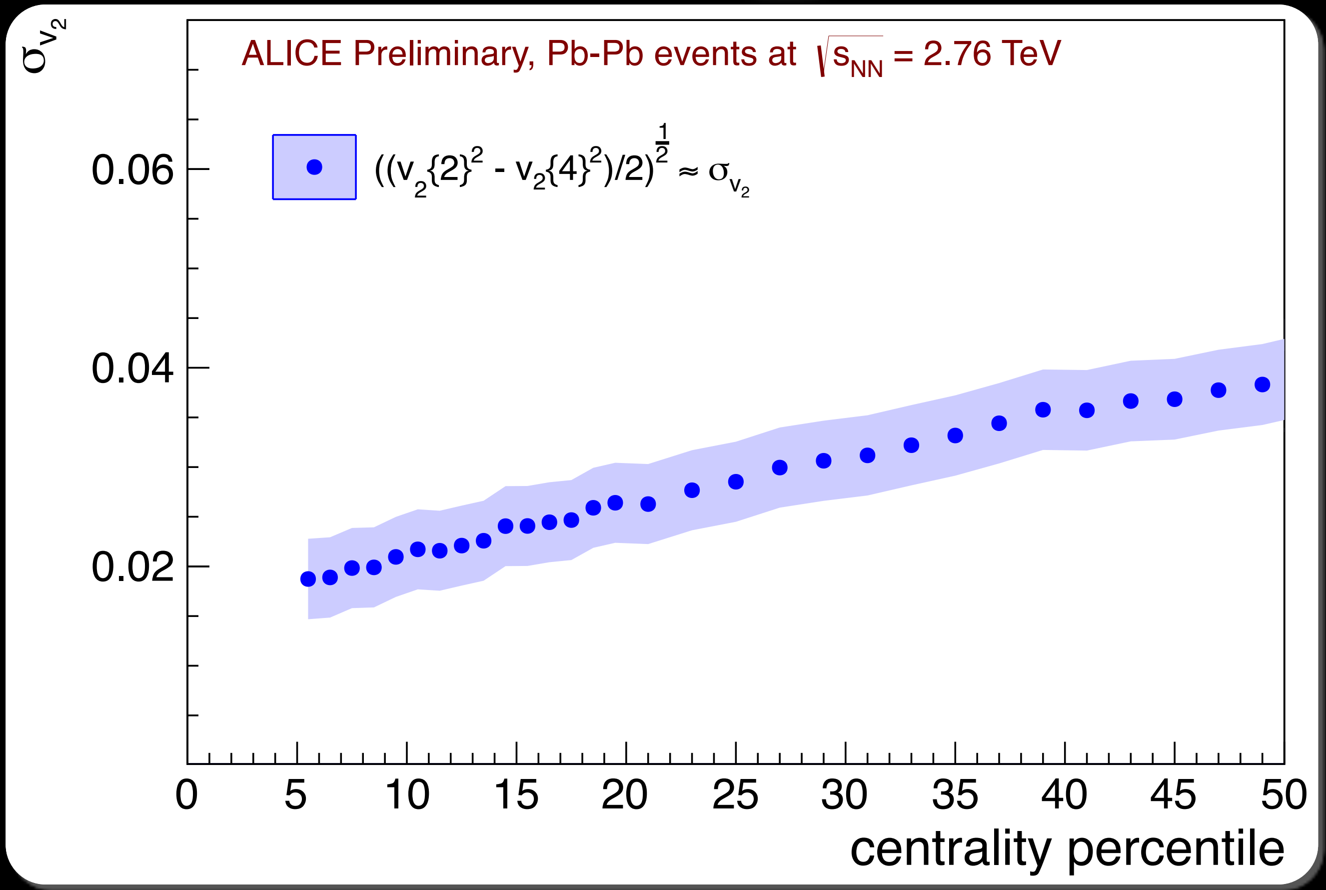


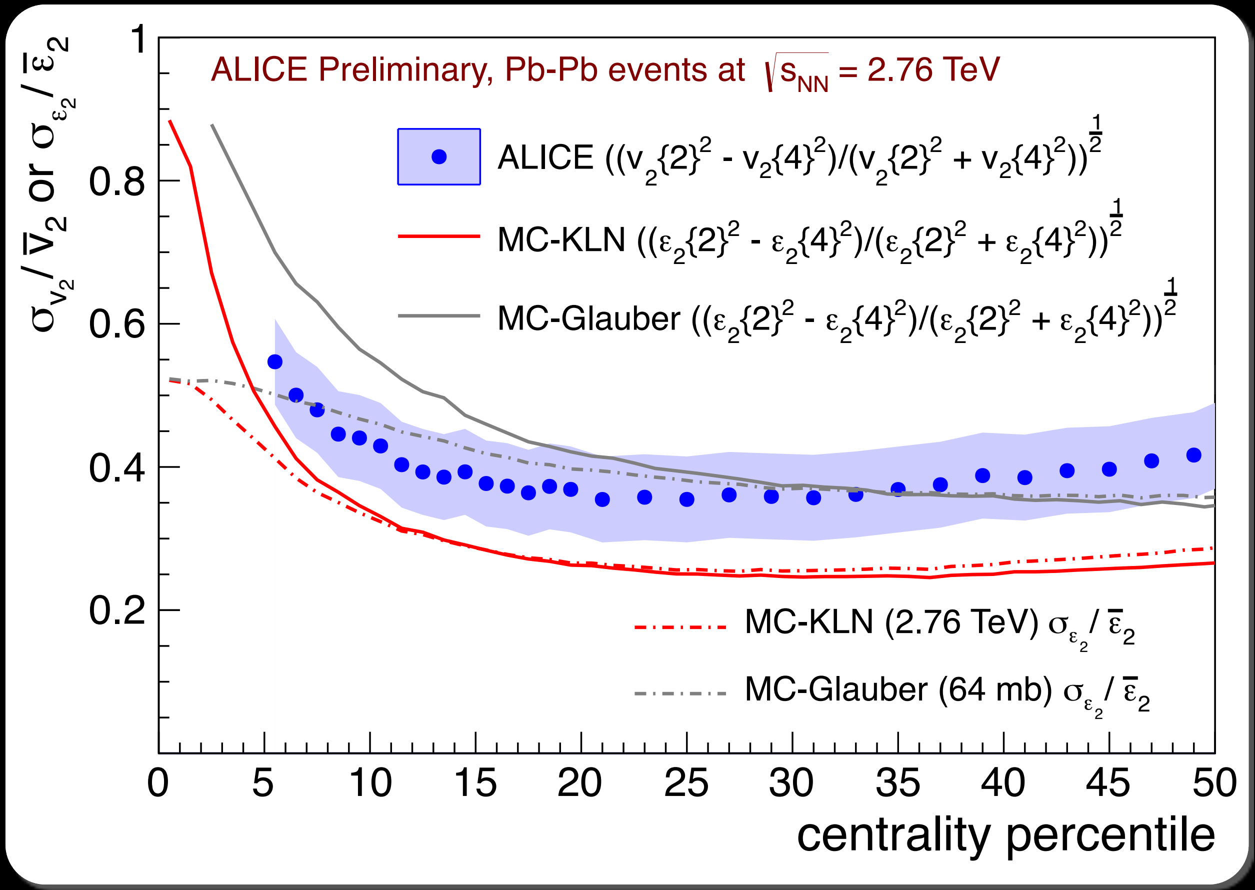


Two particle v_2 estimates depend on $\Delta\eta$
Higher order cumulant v_2 estimates are consistent within uncertainties

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





$$\sigma_{v_n} \simeq [\frac{1}{2}\left(v_n^2\{2\} - v_n^2\{4\}\right)]^{\frac{1}{2}}$$

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

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

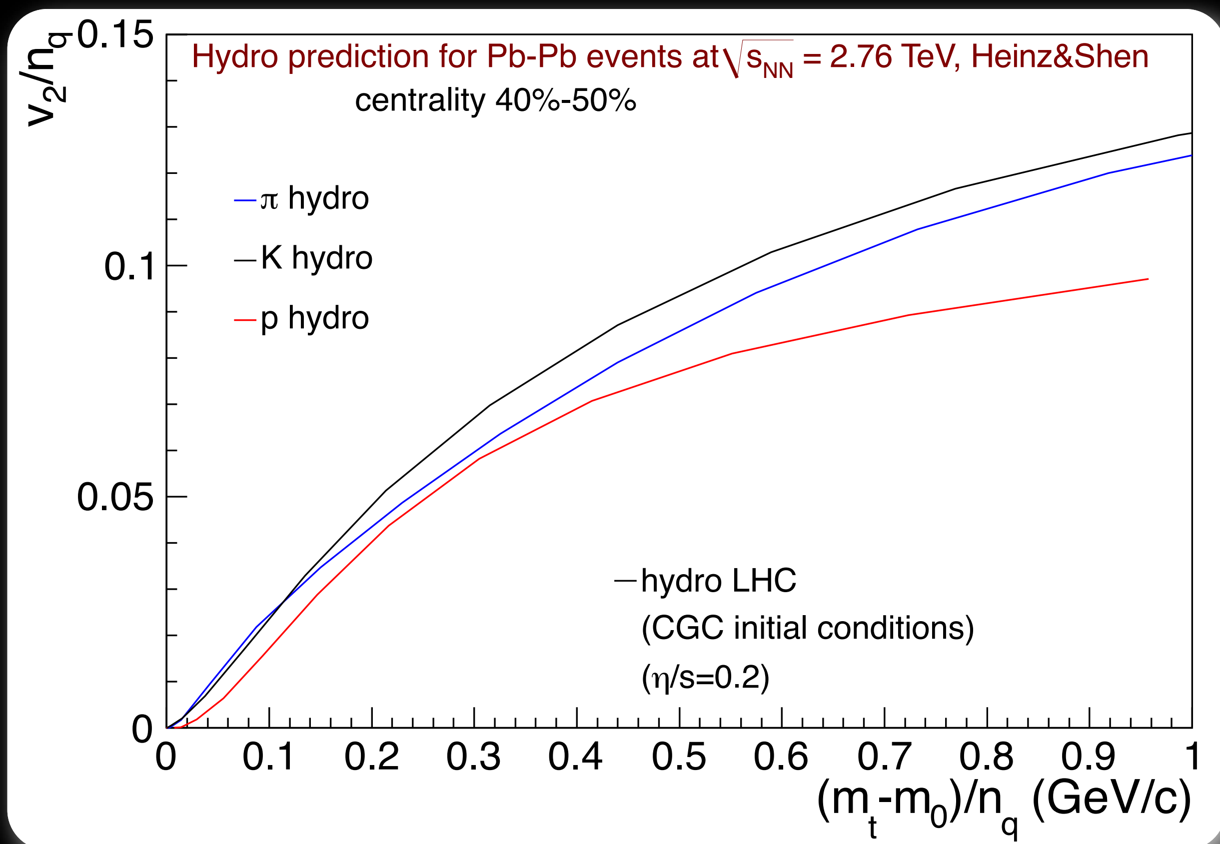
Conclusions

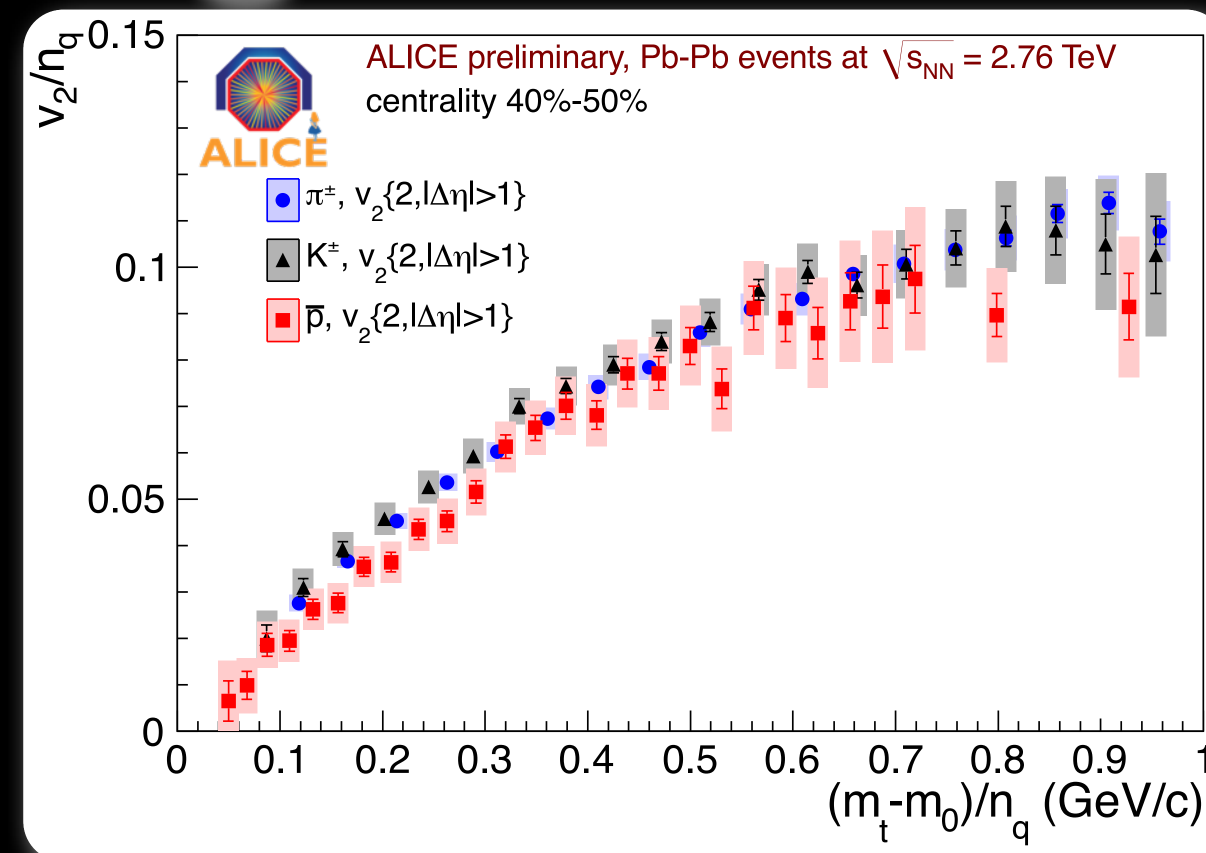
- Anisotropic flow measurements provided strong constraints on the properties of hot and dense matter produced at RHIC and LHC energies and have led to the new paradigm of the QGP as the so called perfect liquid
  - At the LHC we observe even stronger flow than at RHIC which is expected for almost perfect fluid behavior
- The first measurements of v_3 and higher v_n's have recently been made at RHIC and at 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

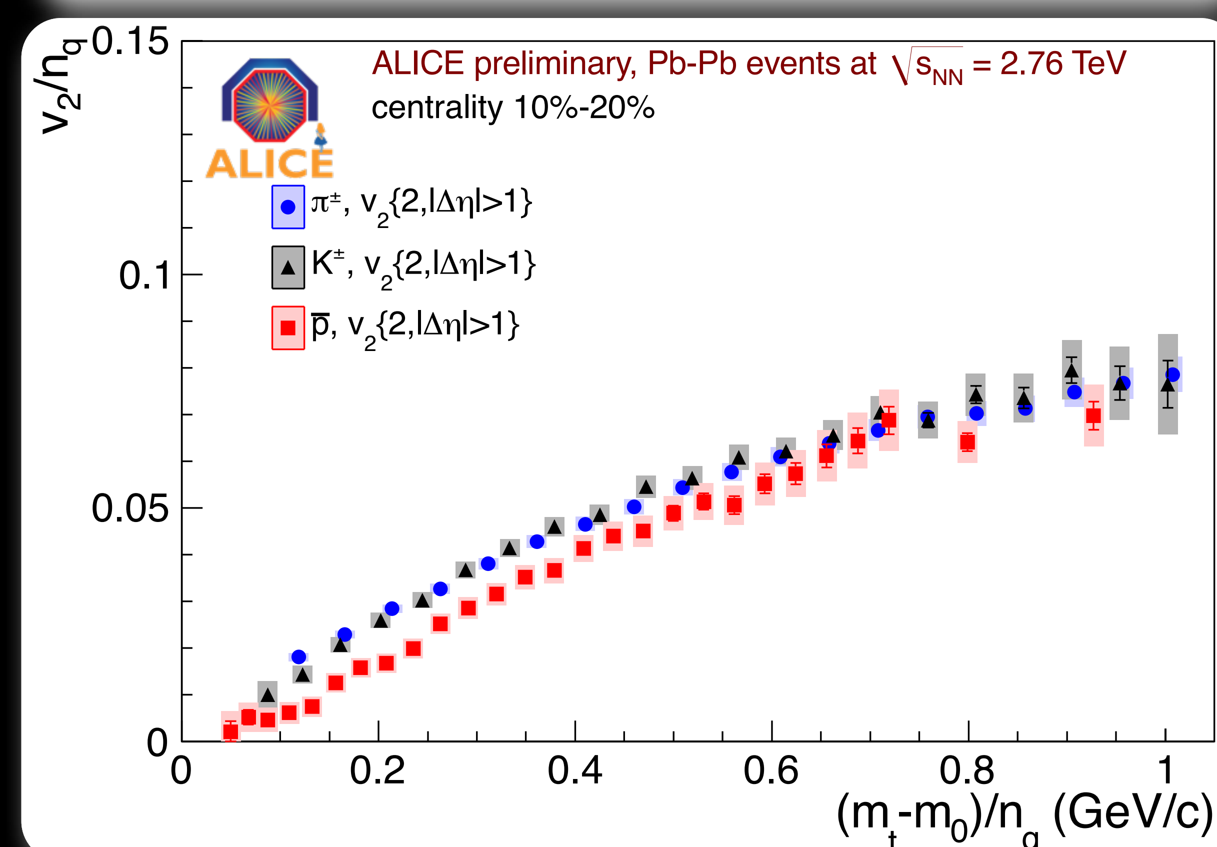
Thanks

v_2 scaling?

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

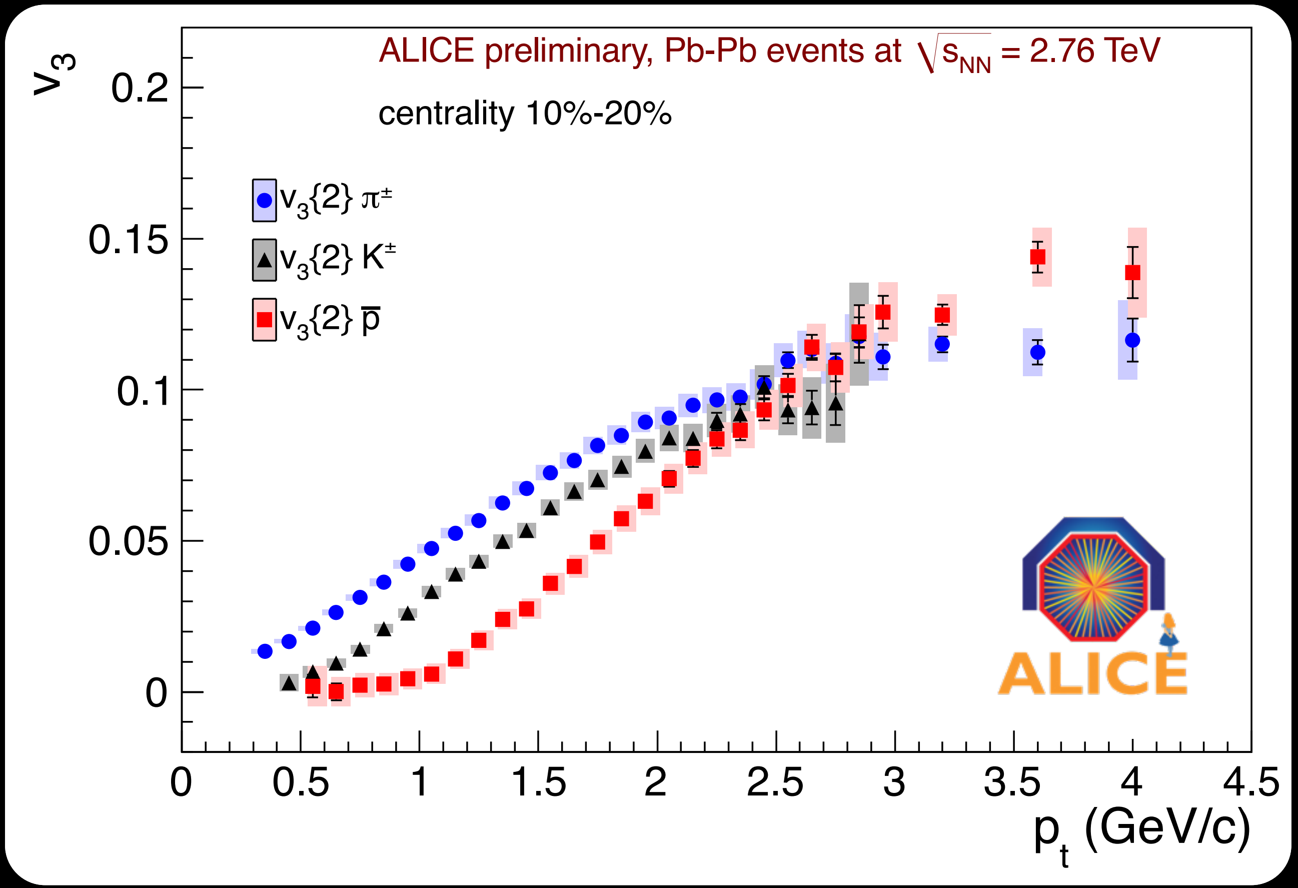


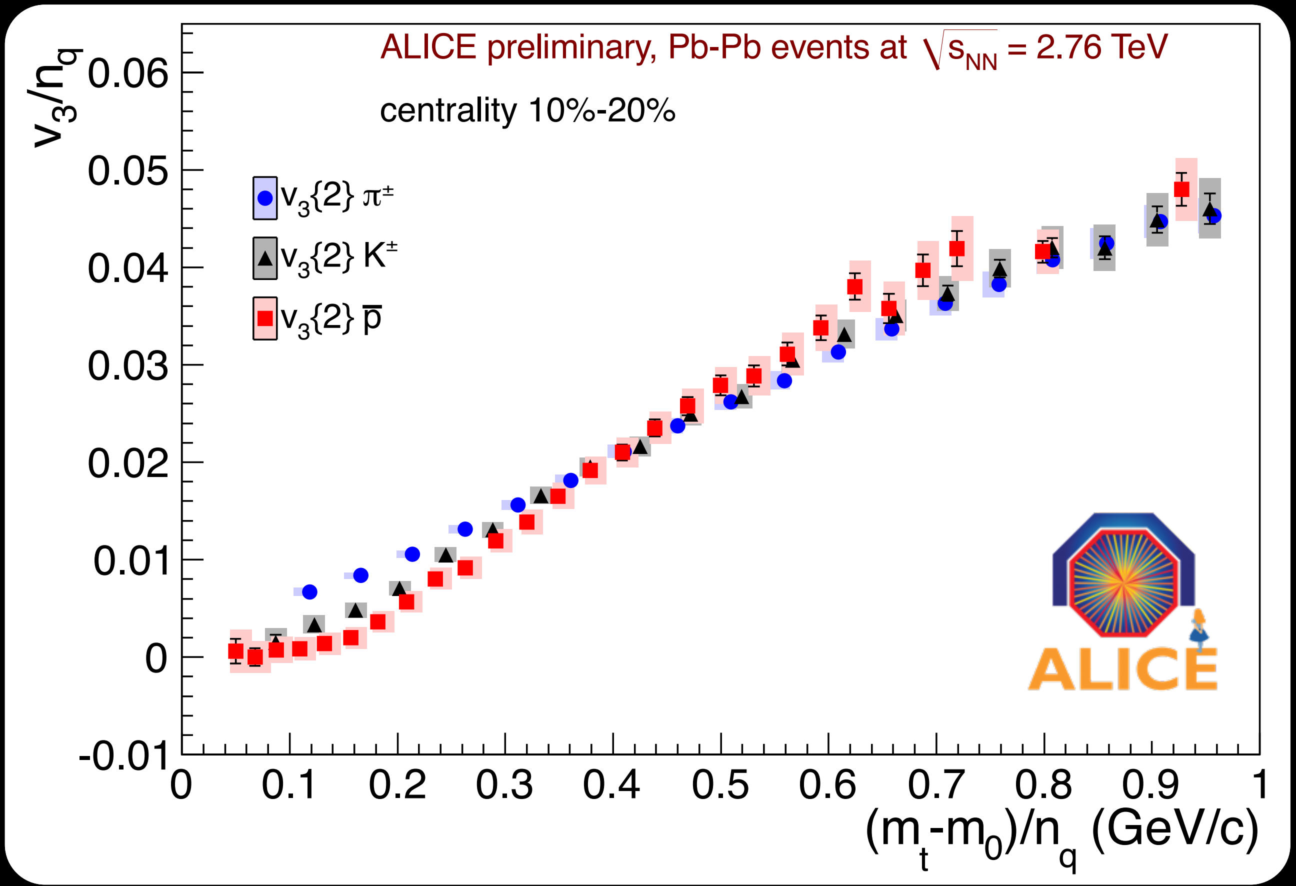




at small $(m_t-m_0)/n_q$ the scaling in the data resemble the scaling as observed in hydrodynamics

$v_3(m,p_t)$ and the scaling

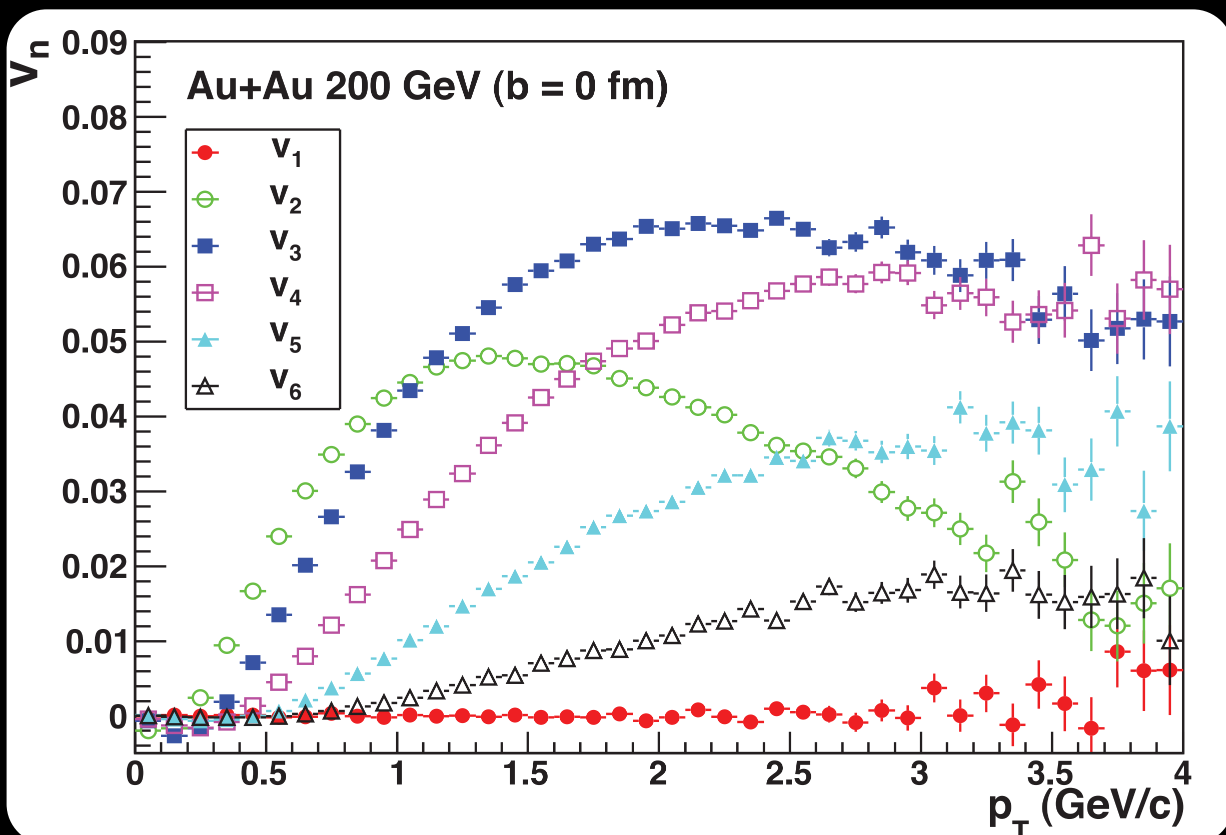




The behavior of v_3 as function of p_t for pions, kaons and protons shows the same features as observed for v_2

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

Geometry and Harmonics

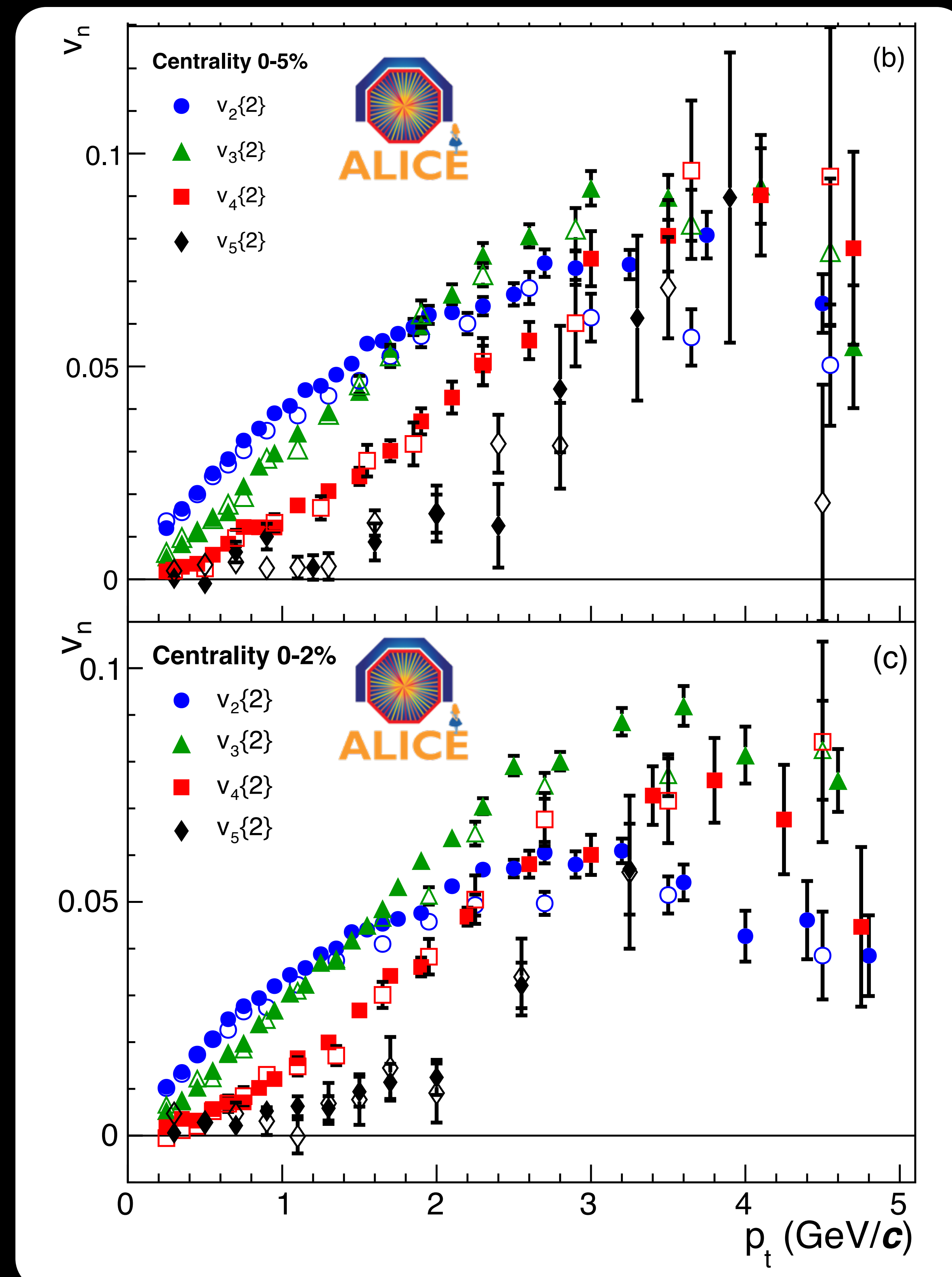


G-L Ma and X-N Wang, arXiv:1011.5249v2

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

Why do they cross??

For more central collisions this occurs already at lower p_t



ALICE Collaboration, arXiv:1105.3866 PRL

Flow Fluctuations

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

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

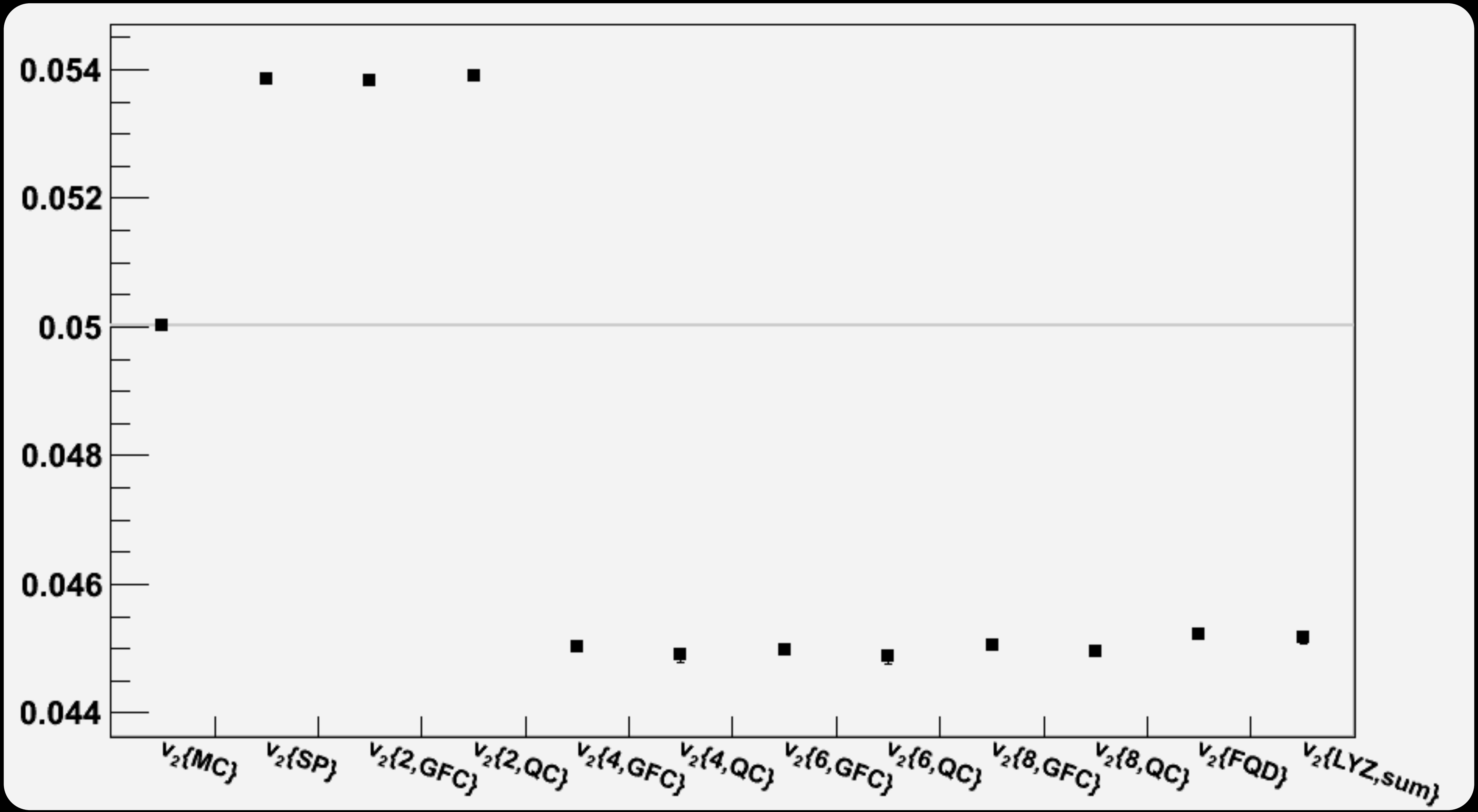
$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2$$
$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$
$$v_n^2\{2\} + v_n^2\{4\} = 2\bar{v}_n^2$$
$$v_n^2\{2\} - v_n^2\{4\} = 2\sigma_v^2$$

in limit of only (Gaussian) fluctuations

$$v_n\{4\} = 0$$
$$v_n\{2\} = \frac{2}{\sqrt{\pi}}\bar{v}_n$$

Flow Fluctuations

Example: input v_2 = 0.05 +/- 0.02 (Gausian), M = 500, $N = 1 \times 10^6$



Gaussian fluctuation behave as predicted also for Lee Yang Zeroes and fitting Q distribution (more on that later)