Flow and n-th order harmonics

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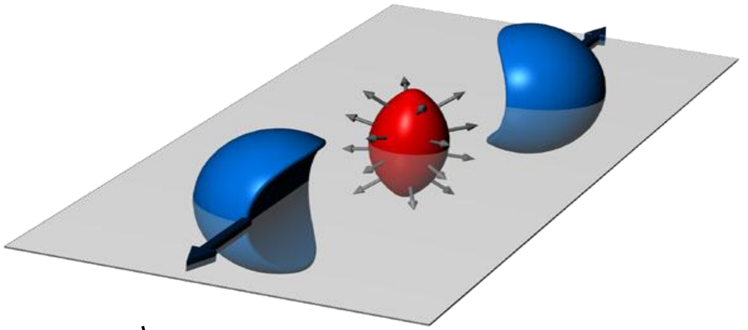
Outline

Topics I will try to cover:

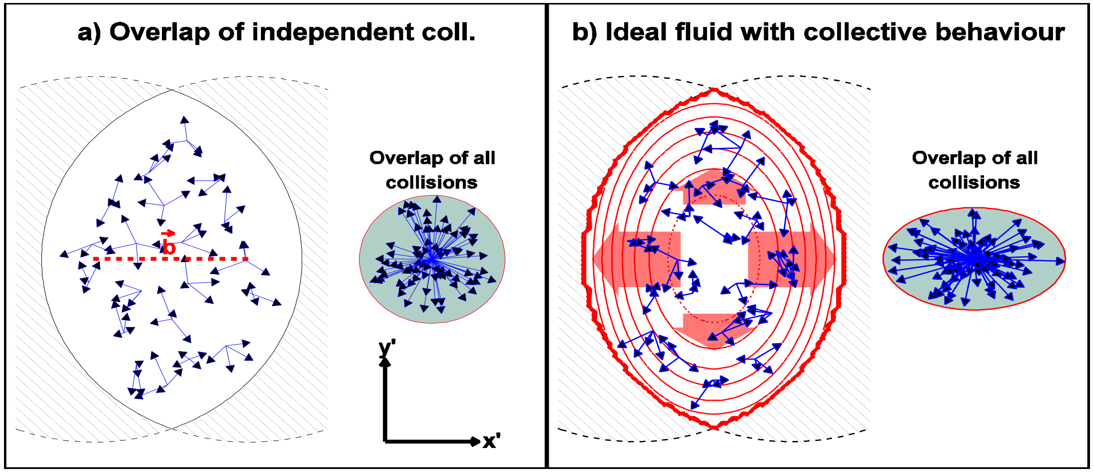
- the role of anisotropic flow measurement to constrain models: the initial state and η/s
- η-dependence of anisotropic flow
- the impact of PID in flow measurements
- non-linearity in higher harmonic flow
- event shape engineering: what we can learn

Why anisotropic flow?



Effects due to an asymmetry in the **initial state of the collision** can be used to probe the QGP.

→ Coordinate space Eccentricity $\varepsilon_2 = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$

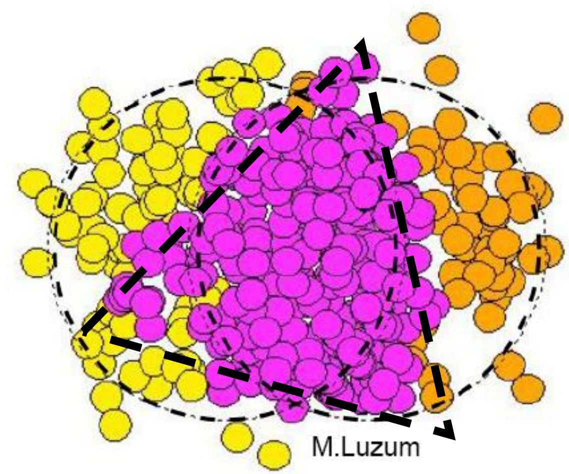


Depending on medium **transportation properties**, initial asymmetries produce asymmetries in momentum space → Elliptic flow

$$v_2 = \langle \cos(2(\varphi - \psi_{RP})) \rangle$$

The role of higher order harmonics

$$E\frac{d^3N}{dp^3}=\frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left(1+\sum_{n=1}2v_n\cos\left(n\left[\varphi-\Psi_n\right]\right)\right)$$



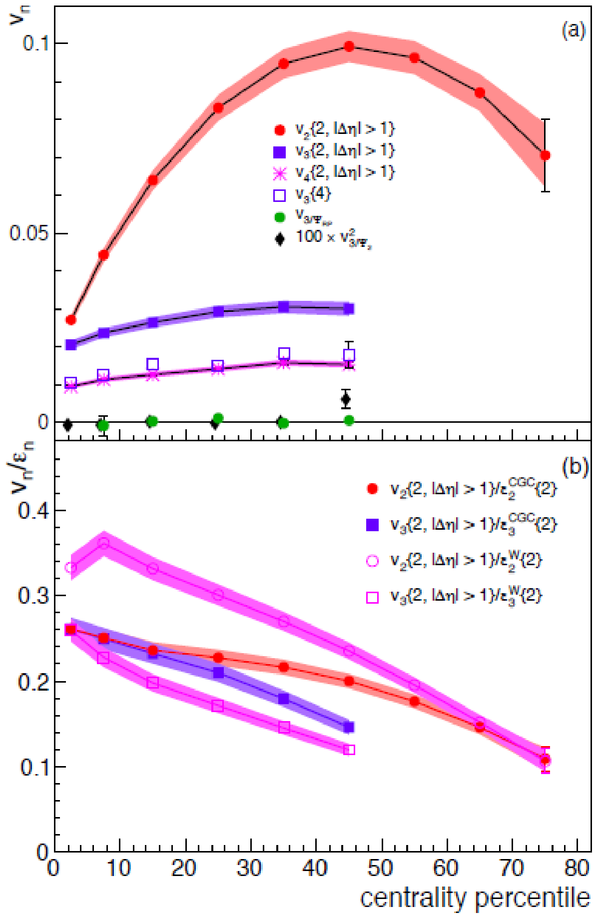
The geometrical properties of each single collision (which in general is not head on) are directly connected with an elliptic asymmetry (v_2).

But event-by-event fluctuations may produce other changes in the shape of the energy density profile in the interacting region affecting the measured value of v_2 and leading to non-zero values for v_3, v_4, … , v_n

Therefore, we need to measure higher order harmonics too in order to constrain (inputs in the) models:

→Geometry properties and fluctuations

v_2 vs other harmonics



ALICE PRL107, 0302301 (2011)

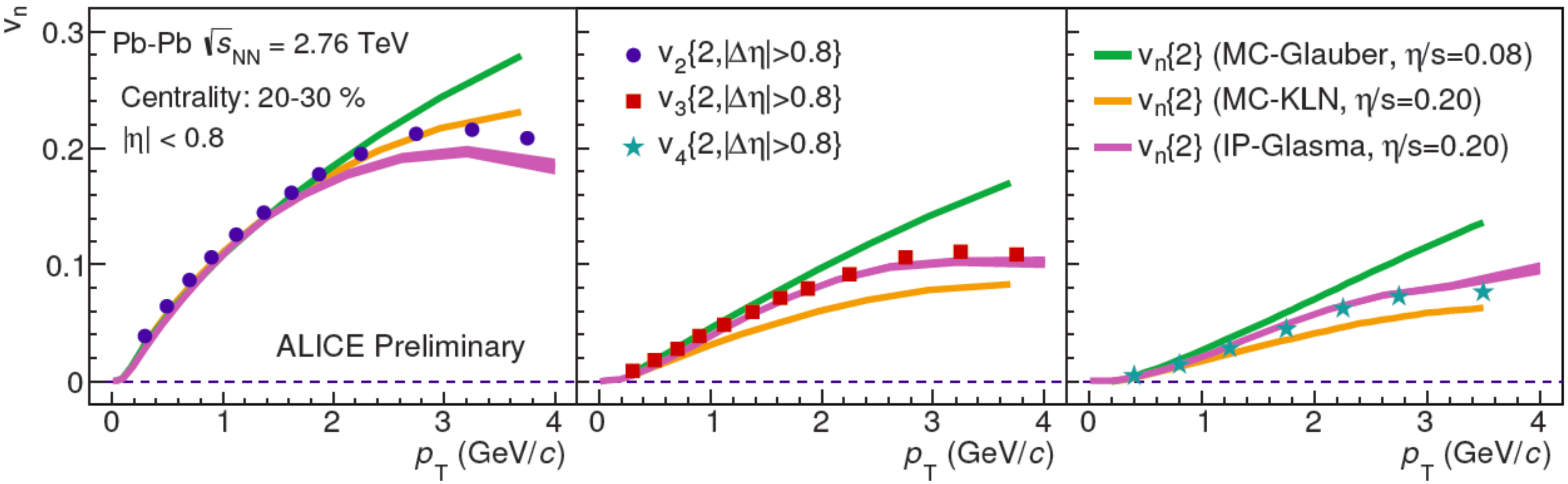
Different harmonics were measured from the beginning in the LHC experiments with high precision.

Results were used to characterize the v_n dependence on centrality, momentum, particle mass, η

All the measurements are crucial to extract properities like: shear viscosity η/s, EoS, …

v_2 vs other harmonics

IP-GLASMA: PRL 110, 012302



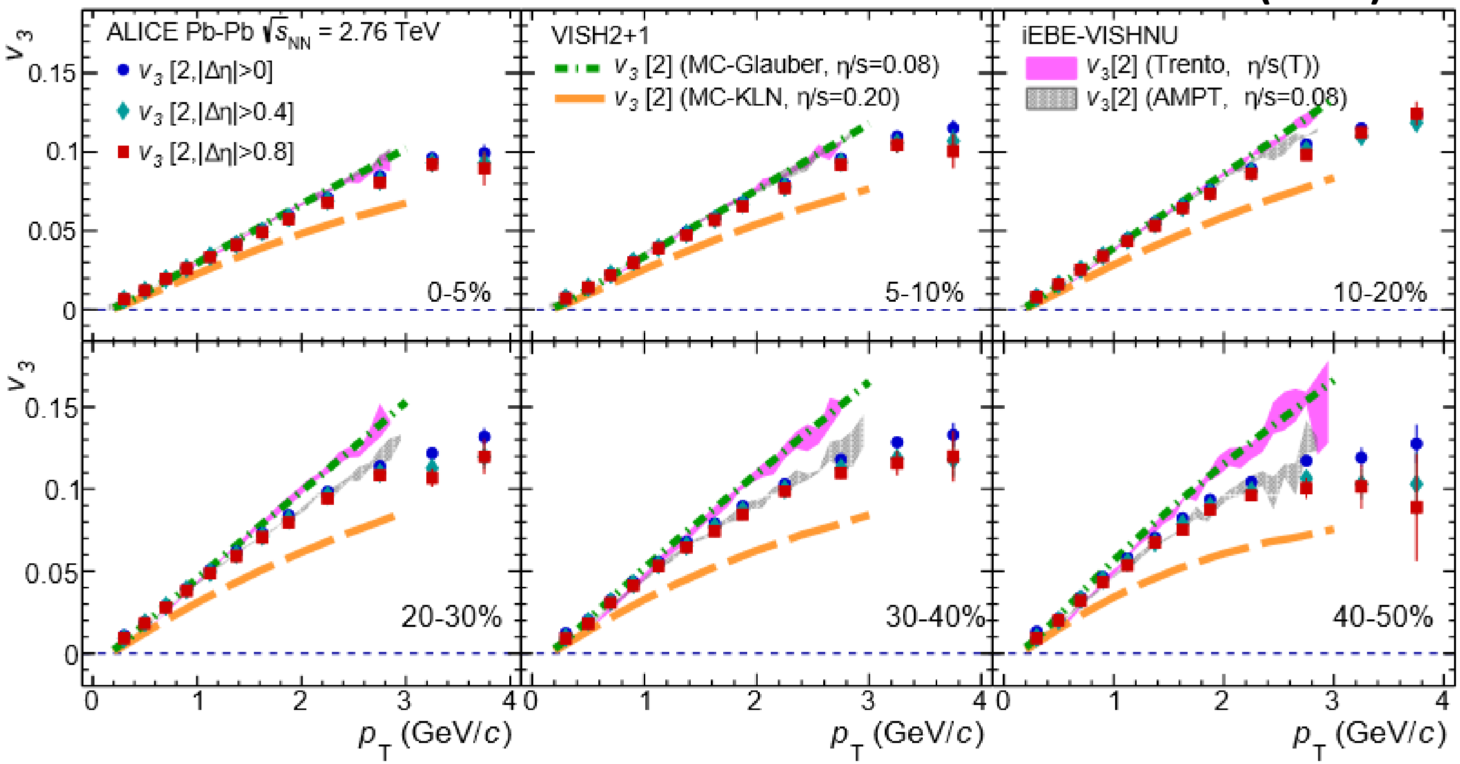
The comparison of v_2, v_3, v_4 with models is really necessary to constrain Initial Condition (IC) and η/s.

The best description was achieved with the IP-Glasma initial conditions and $\eta/s = 0.2$

→ Fluctuations are very important to describe higher order harmonics. MC-Glauber IC requires a much lower η/s to describe v_2 but it is then not able to describe v_n.

v_2 vs other harmonics

ALICE: JHEP 1709 (2017) 032



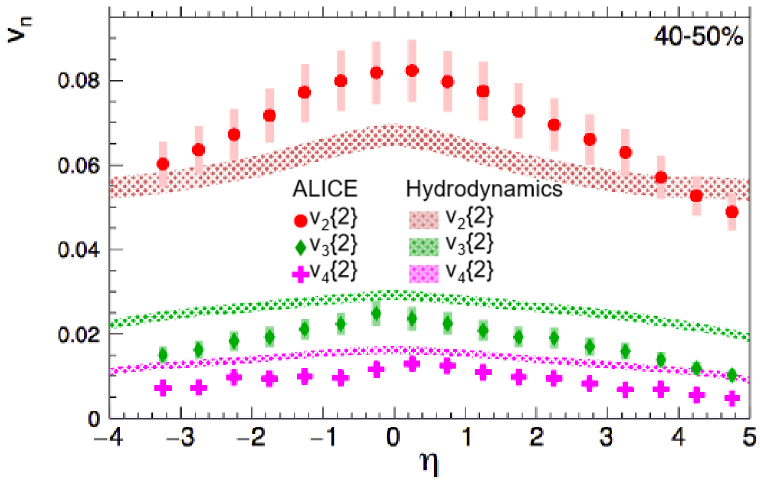
However, we need to be careful before reaching any conclusion.

For instance AMPT initial collision allows to recover good agreement with η/s = 0.08

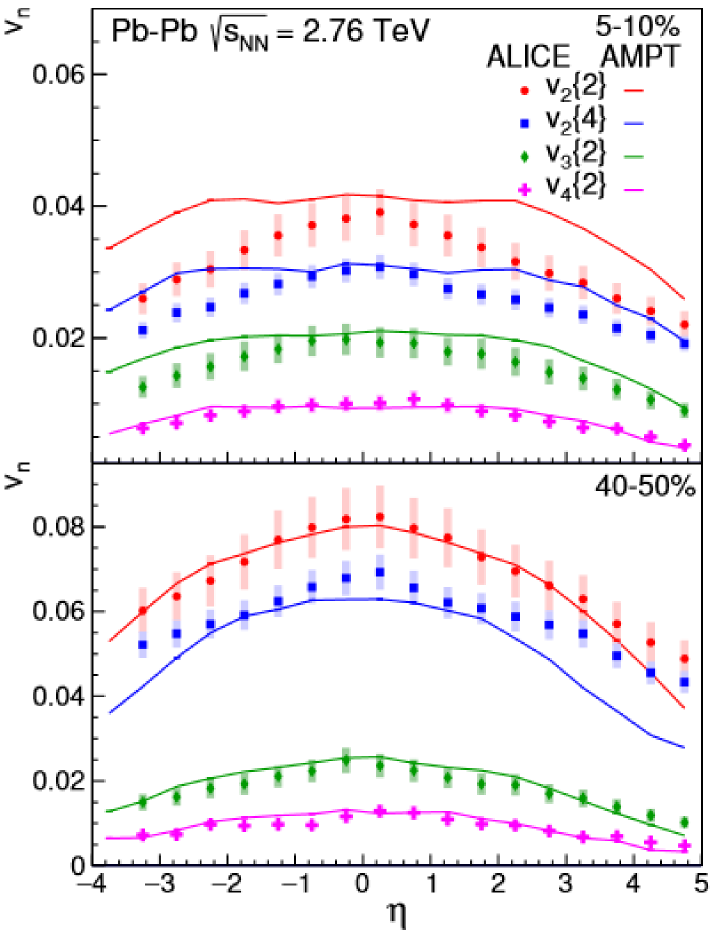
→ We still need other constrains!

v_n vs η

PLB 762 (2016) 376



$\eta/s(T)$ tuned on RHIC $v_n(\eta)$

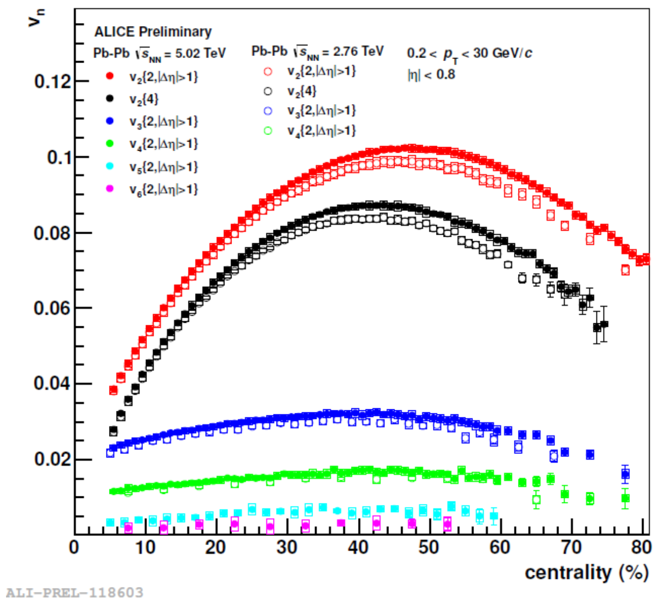


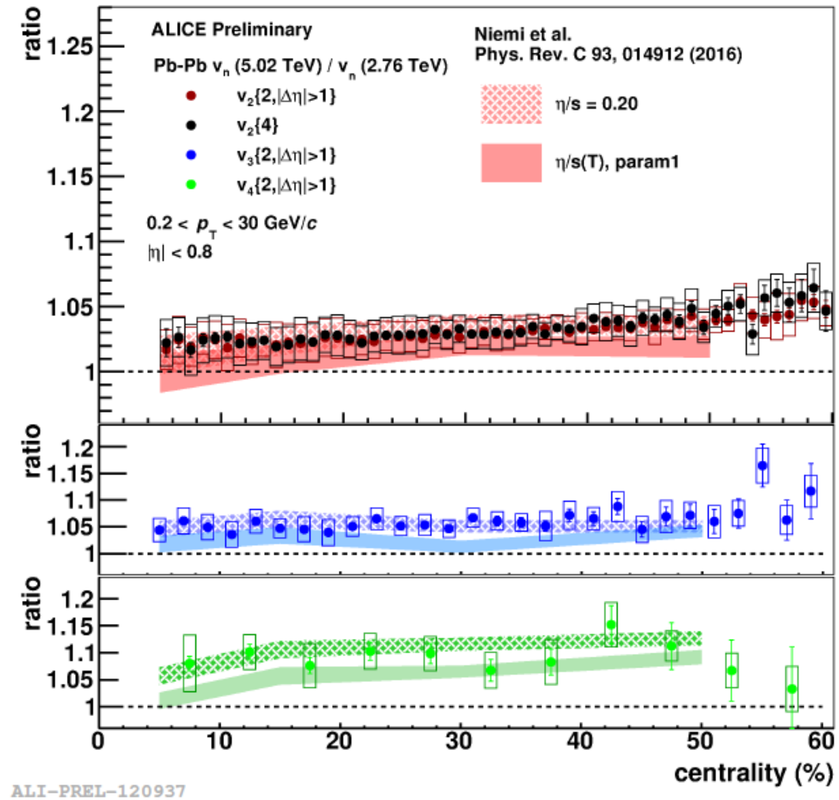
tuned on 40-50% $v_n(p_T)$

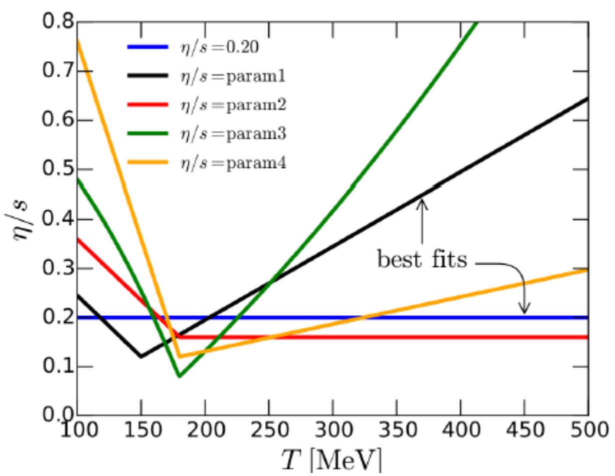
Also the v_n pseudorapidity dependence was extracted. Hydrodynamics model fitted at RHIC are not able to reproduce the behavior LHC. AMPT (w/o hydro!) works fine at 40-50% (but it was tuned in those conditions)

→ New input for theoriticians

2.76 ATeV vs 5.02 ATeV







Theoretical uncertainties partially cancel in the ratio → high potential to test T-dependence of η/s (here for EKRT IC)

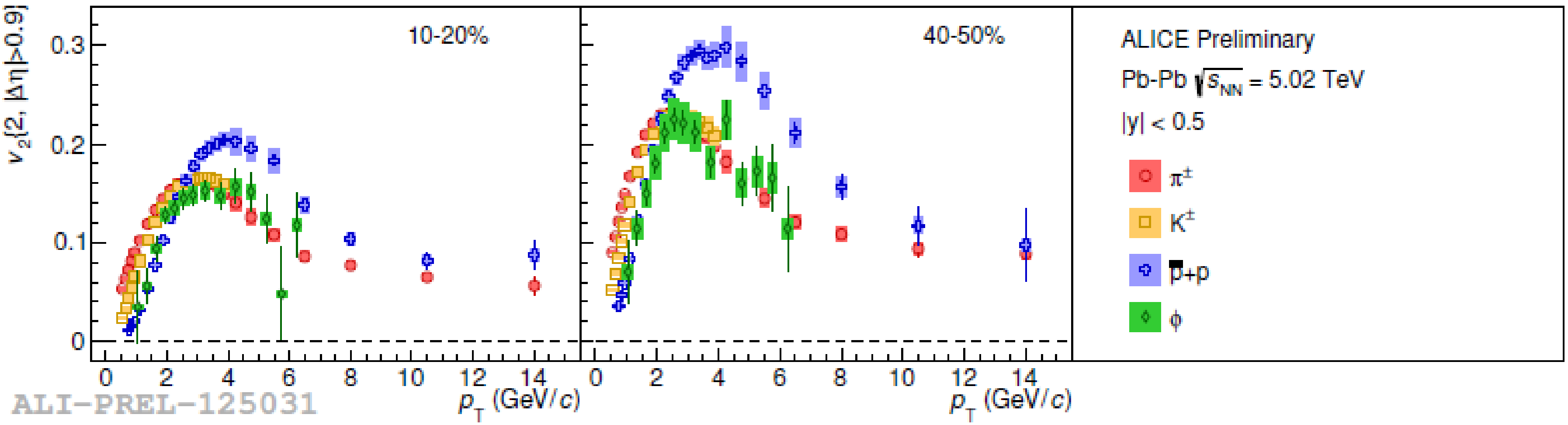
The role of PID in v_n measurements

Particle identification is a powerful tool to characterize the anisotropic flow depending on the mass/quark content of the particles:

- Mass scaling at lower momentum
- Meson/baryon behavior
- Quark scaling at intermediate momentum
- ...

To save time I will focus only on the most recent results at 5.02 ATeV (what is new with respect previous results)!

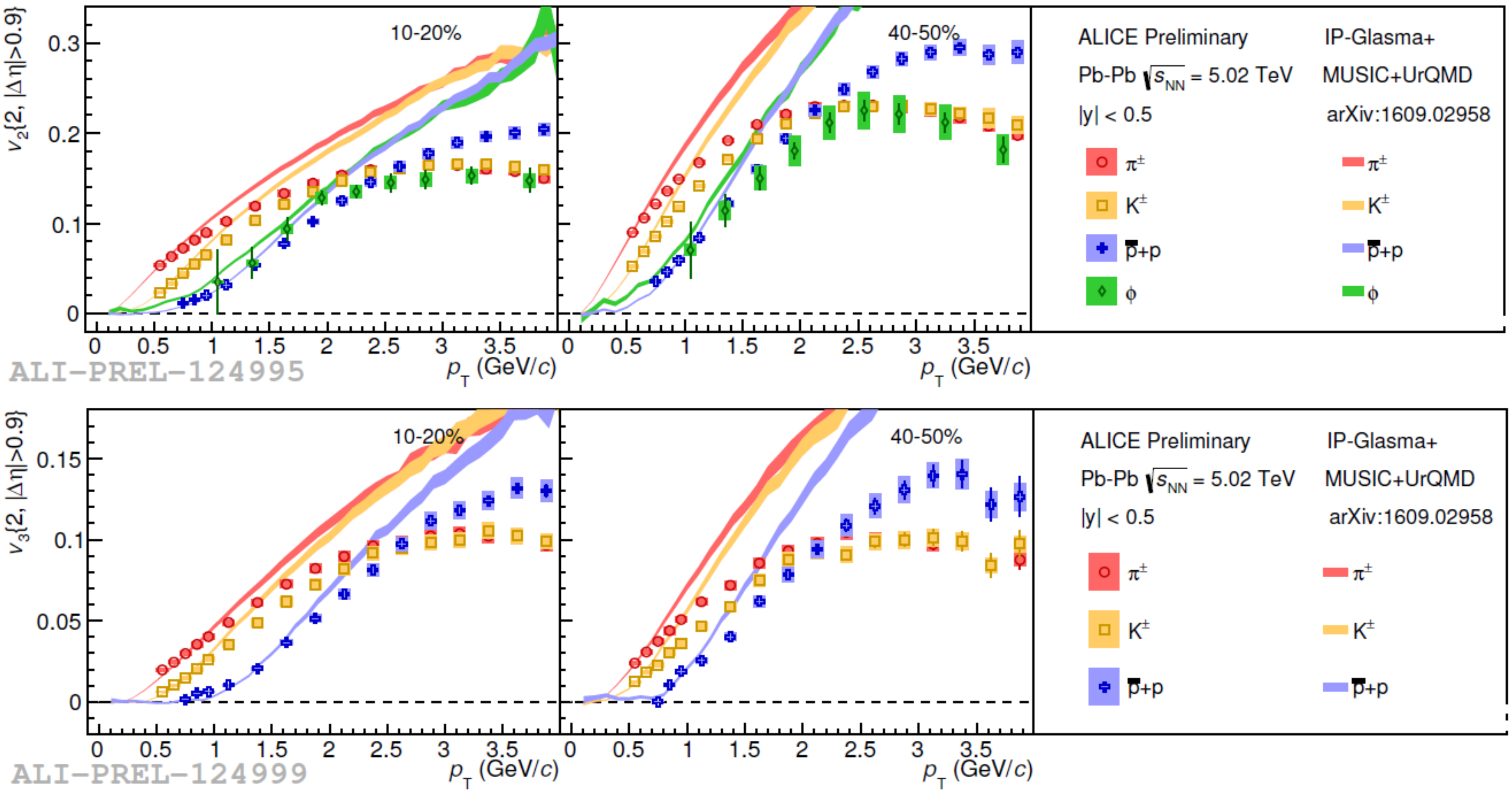
ϕ meson v_2



Higher statistics was available at Run-2 and the ϕ-meson v_2 was measured with a much higher precision.

In the low momentum region it has a similar behavior as the proton (same mass) but for intermediate p_T it “stays” with mesons.

v_2 (PID) vs hydro



New data were compared with predictions.

The predictions (IP-Glasma) have some tension in pheripheral collisions.

Non-linearity of higher order harmonics

$$\overrightarrow{V_m} = v_m e^{-im\Psi_m}$$
$$\overrightarrow{V_n} = v_n\, e^{-in\Psi_n}$$

Given two flow vectors, what kind of correlation can we observe between v_n, v_m and Ψ_n, Ψ_m?

While v_2 and v_3 depend on ε_2 and ε_3 respectively times the medium response (linear behavior), high order harmonics receive contribution also from lower orders (PRC 89 (2014) 064904 and PLB 744 (2015) 82):

$$\begin{aligned} V_4 &= V_{4L} + \chi_4 (V_2)^2 \\ V_5 &= V_{5L} + \chi_5 V_2 V_3 \\ V_6 &= V_{6L} + \chi_{62} (V_2)^3 + \chi_{63} (V_3)^2 \\ V_7 &= V_{7L} + \chi_7 (V_2)^2 V_3, \end{aligned}$$

Can the two contributions be disentangled? What can we learn?

Mixed harmonics

$$v_5\{\Psi_{23}\} = \frac{\mathrm{Re}\{V_4 V_2^* V_3^*\}}{\sqrt{\langle |V_2|^2 |V_3|^2 \rangle}} = \frac{\langle v_5 v_2 v_3 (5\Psi_5 - 2\Psi_2 - 3\Psi_3)\rangle}{\sqrt{\langle v_2^2 v_3^2\rangle}}$$

Non linear part (at LHC) can be studied using mixed harmonics providing precise constraints on the initial conditions and temperature dependence of η/s.

$$\chi_{5,23} = \frac{v_5\{\Psi_{23}\}}{\sqrt{\langle v_2^2 v_3^2\rangle}}$$

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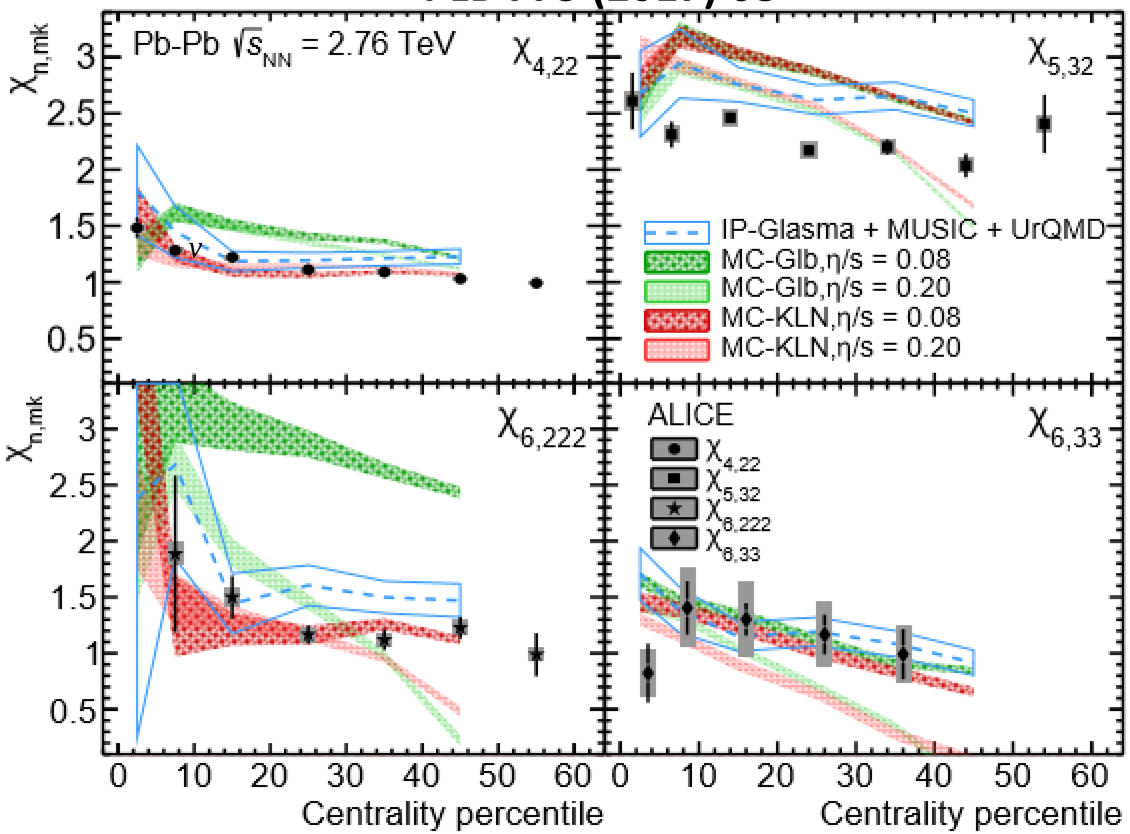


Reaction plane correlations

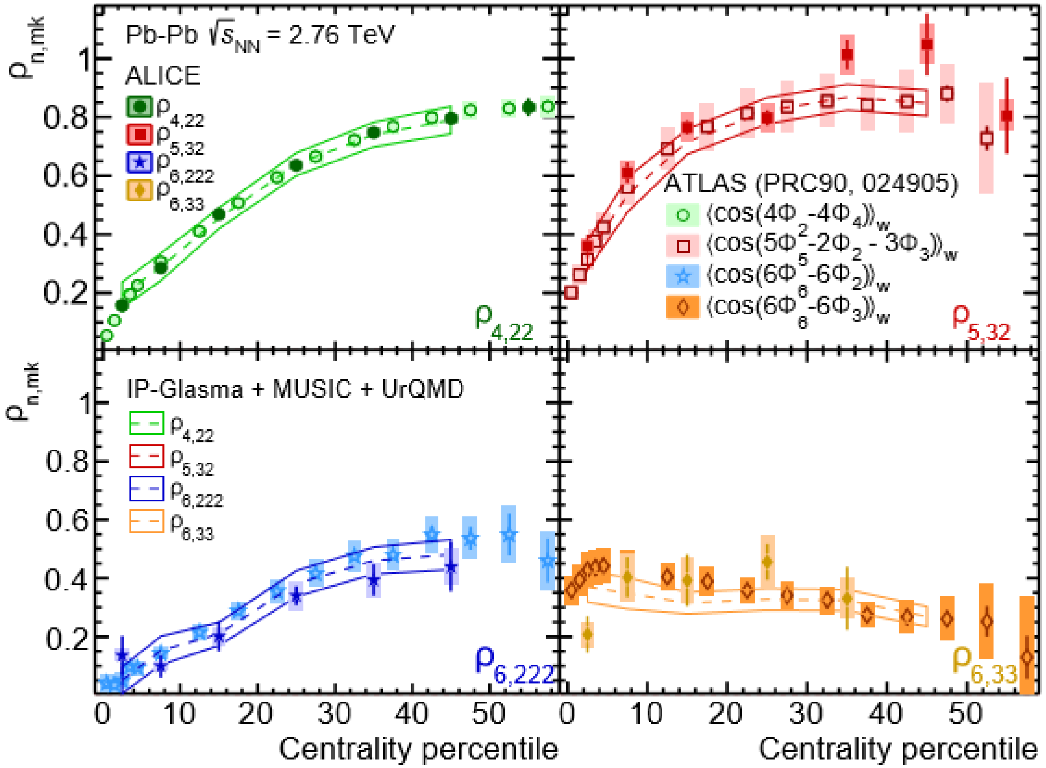
$$\rho_{4,22} = \langle \cos(4\Psi_4 - 4\Psi_2) \rangle,$$

$$\rho_{5,32} = \langle \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2) \rangle,$$

$$\rho_{6,222} = \langle \cos(6\Psi_6 - 6\Psi_2) \rangle,$$

$$\rho_{6,33} = \langle \cos(6\Psi_6 - 6\Psi_3) \rangle.$$

Comparison with IP-GLASMA and $\eta/s = 0.095$



Event shape engineering (ESE)

ESE is a technique to select events with specific features (i.e. eccentricity) within a given centrality class.

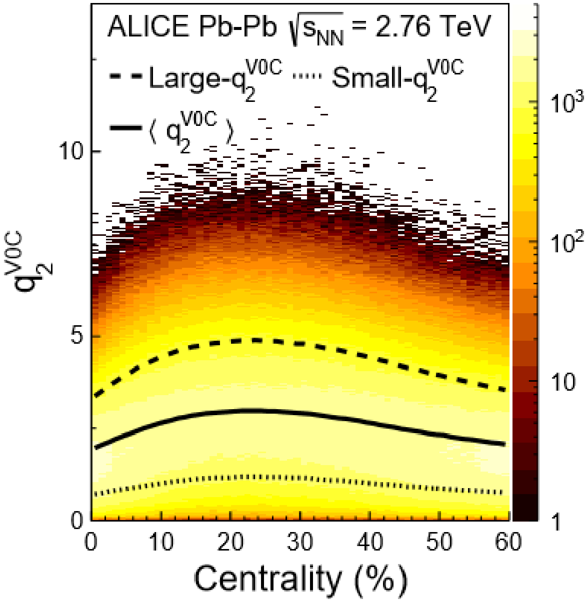
Such an approach allows to compare other observables (v_2, p_T-spectra, chiral magnetic effects, …) in events which only differ for the shape.

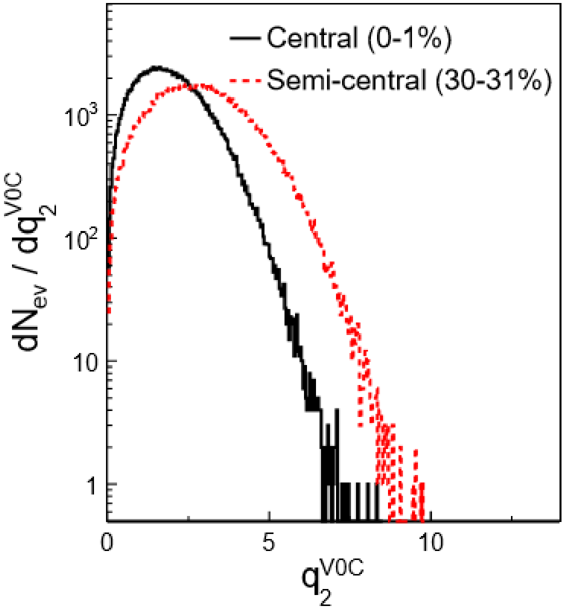
$$Q_{n,x} = \sum_i \cos(n\varphi_i)$$

$$Q_{n,y} = \sum_i \sin(n\varphi_i)$$

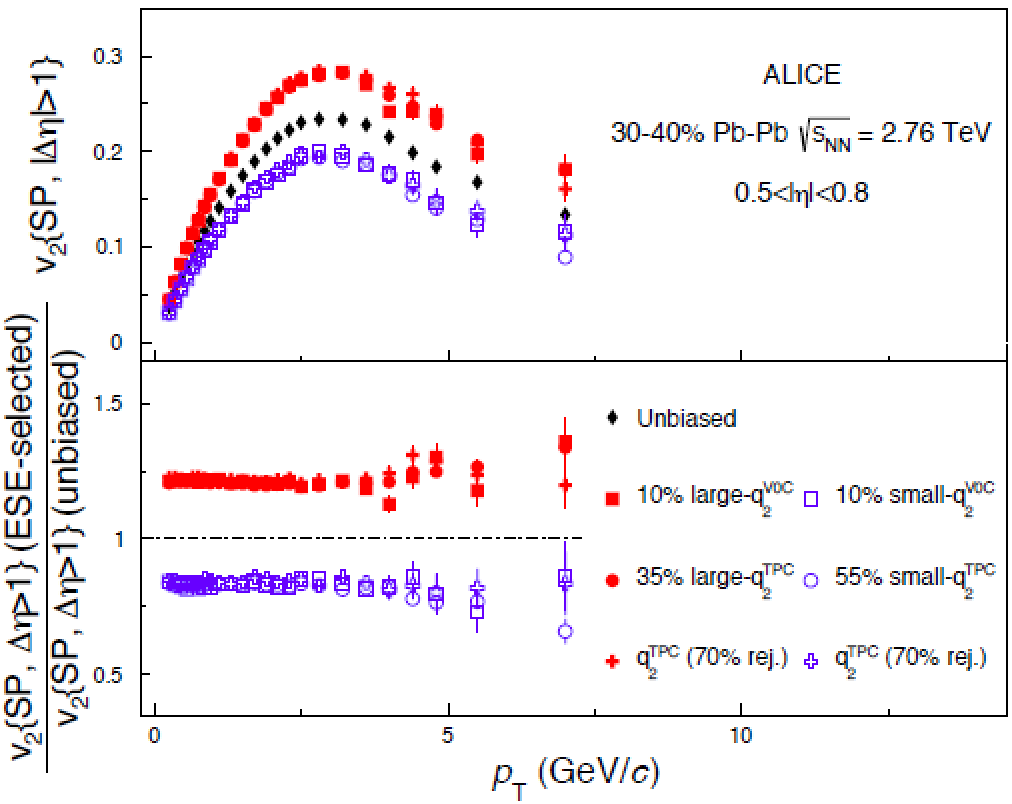
$$Q_n = \{Q_{n,x}, iQ_{n,y}\}$$

$$q_n = |Q_n| / \sqrt{M}$$





ESE selection



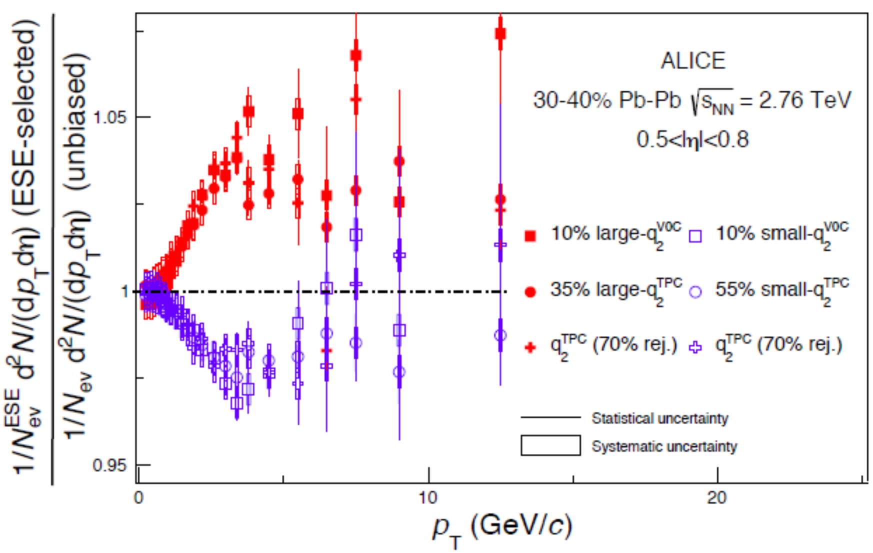
PRC 93 (2016) 034916

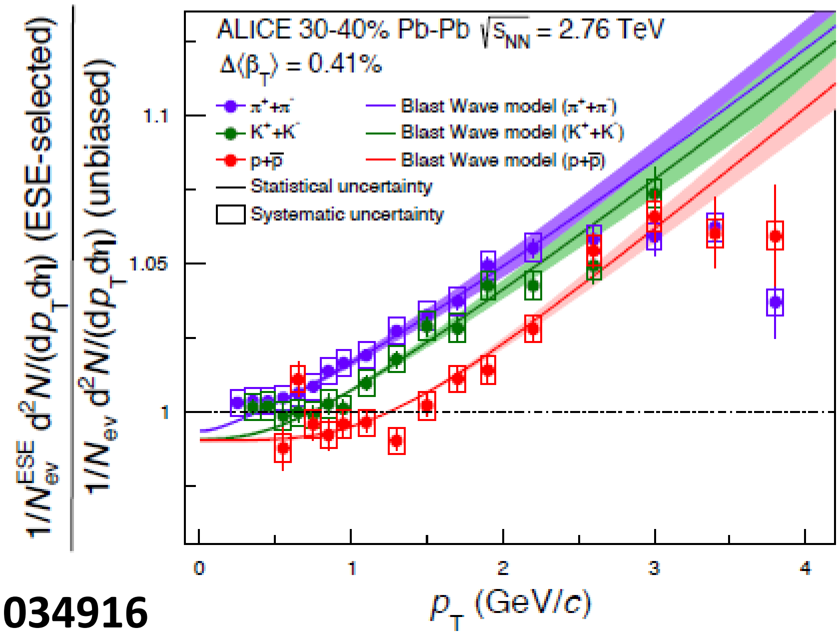
It allows to change v_2, to test how other observables behave (if correlated or not).

Flatness of the ratio indicates that non-flow contribution are negligible.

ESE: v_2 vs p_T

Inclusive/Identified spectra ratios ESE-selection/unbiased





PRC 93 (2016) 034916

Positive correlation between v_2 and p_T may indicate a correlation between radial and elliptic flow.

Summary for discussion

The amount of information we are able to collect looking at the harmonic decomposition of the final distribution of products is now very impressive.

It spans over several kinematic variables (η, p,), conditions/centralities and harmonics order allowing to strength the constraints on theoretical predictions.

The gold aim is to infer the value of the shear viscosity and now also its dependence on the system temperature.

What I didn't cover here:

- Chiral magnetic effects (arXiv:1709.04723 with ESE)
- Light (anti)nuclei v_n
- Heavy quarks v_n

What next: near and distant future

- New observable is now accessible both from the esperimental and theoretical points of view.
- → Higher order harmonics + mixed harmonics
- We benefitted of the increasing statistics in Run-2 for several observables (i.e. ϕ meson) [expected more relavant for Run-3]
- ESE selection is a promising tool to enphasize and then measure correlations between the properties of the system → may be largely used in future.