INTERNATIONAL WORKSHOP ON
DISCOVERY PHYSICS AT THE LHC

KRUGER 2012

SOUTH AFRICA

Flow with ALICE

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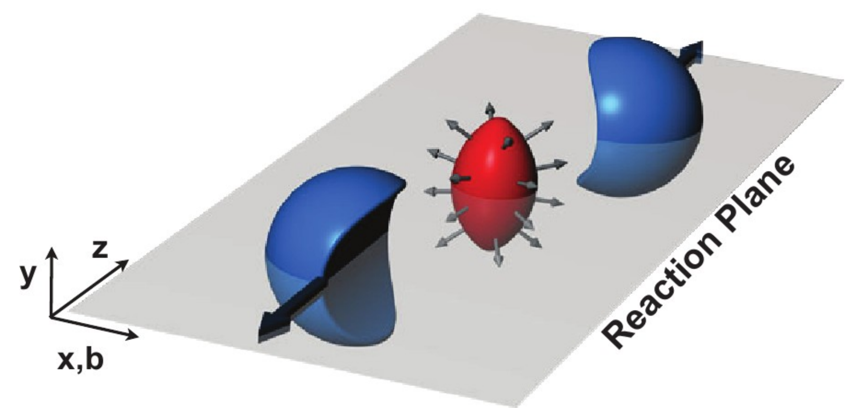
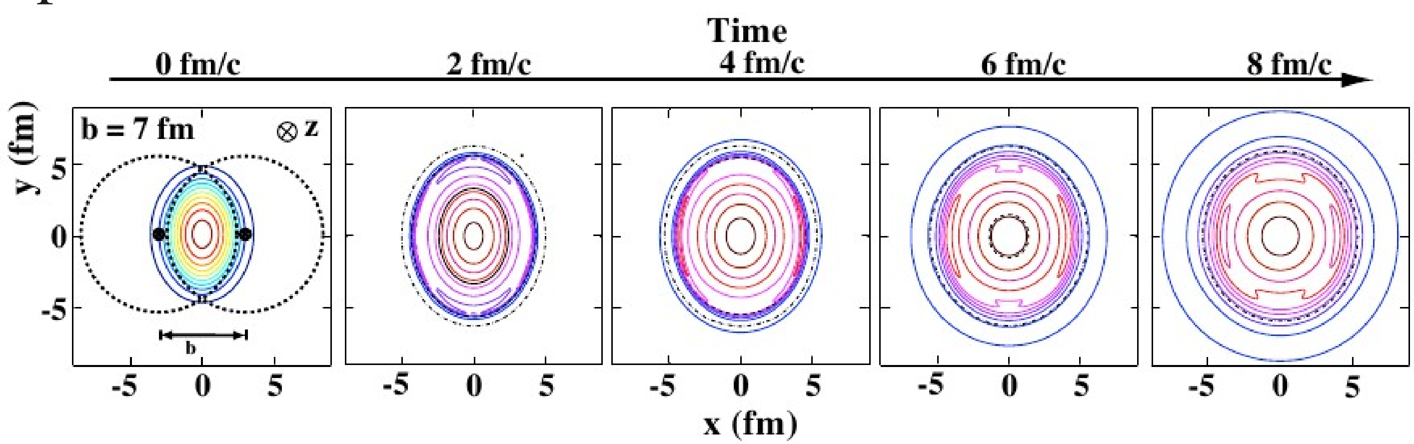
(for the ALICE collaboration)

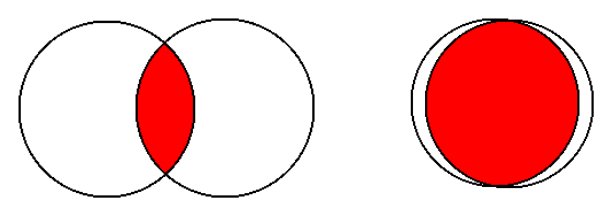
Flow in heavy ion collisions

- The shape of the fireball initially (to first order) determined by the overlap of colliding nuclei.
- Expansion driven by pressure gradients translates initial shape into anisotropy in momentum space of the particles.





Magnitude of anisotropy depends on centrality:
Impact parameter determines eccentricity.



Flow – final state anisotropy

- Anisotropy is characterized by the Fourier expansion of the particle yield:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_n))\right)$$

(S. Voloshin and Y. Zhang, Z.Phys.C70,1996)

- Flow coefficients:

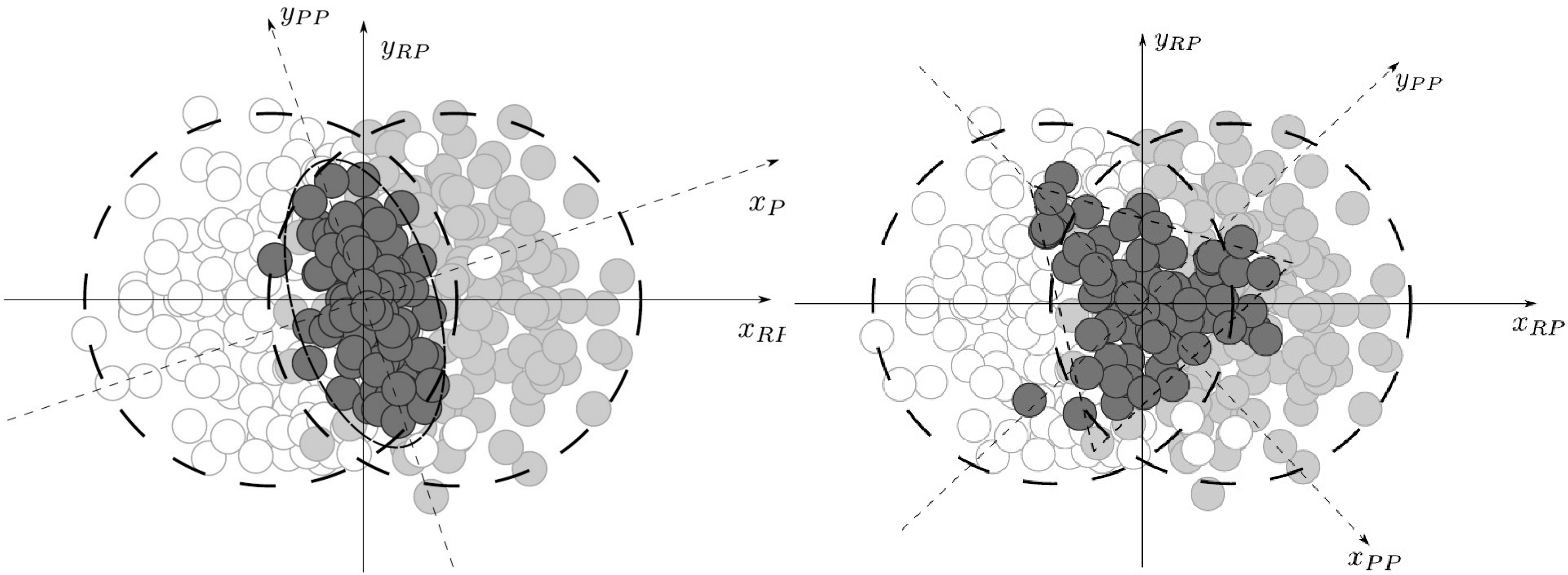
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

v_1 – directed flow

v_2 – elliptic flow

v_3 – triangular flow

Initial conditions

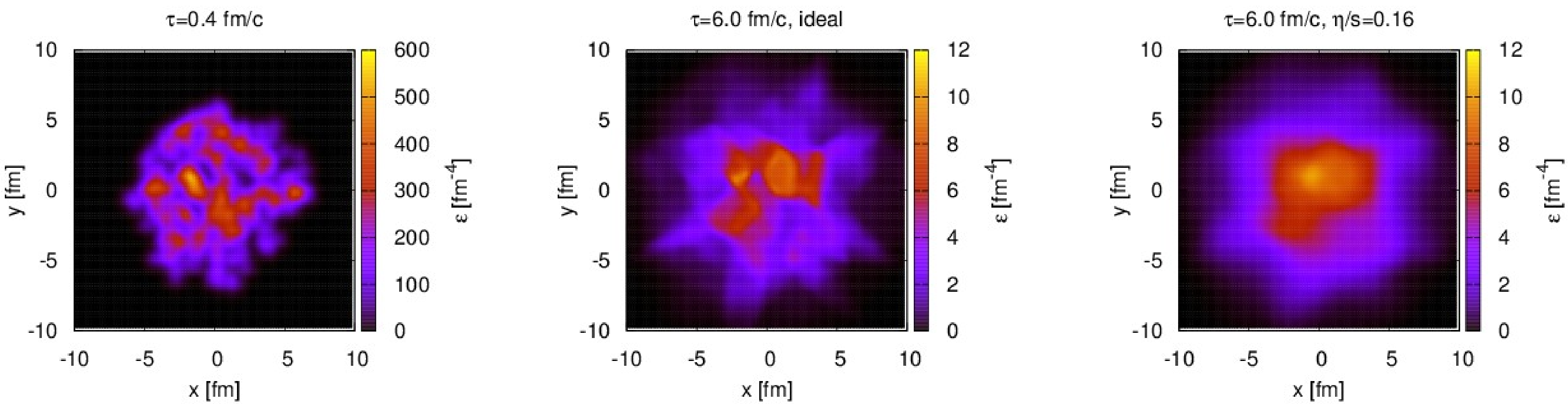


$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

- Positions of participants fluctuate event-by-event.
- Interaction region shape fluctuates → non-zero odd harmonics.
- Many symmetry planes, possible correlations can be studied.

Probing the medium properties

ideal

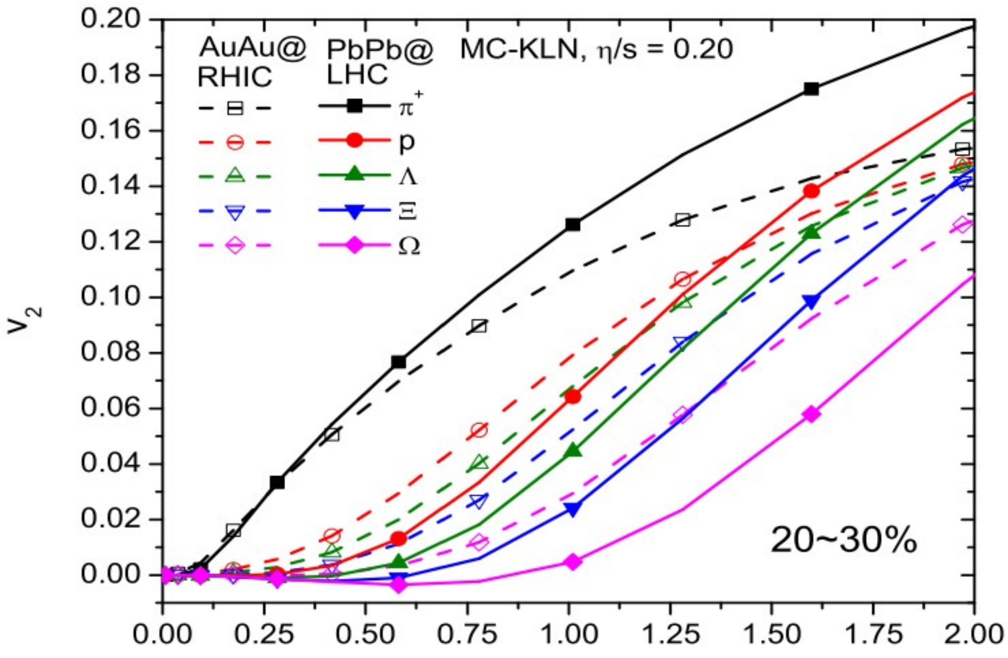


arXiv:1009.3244

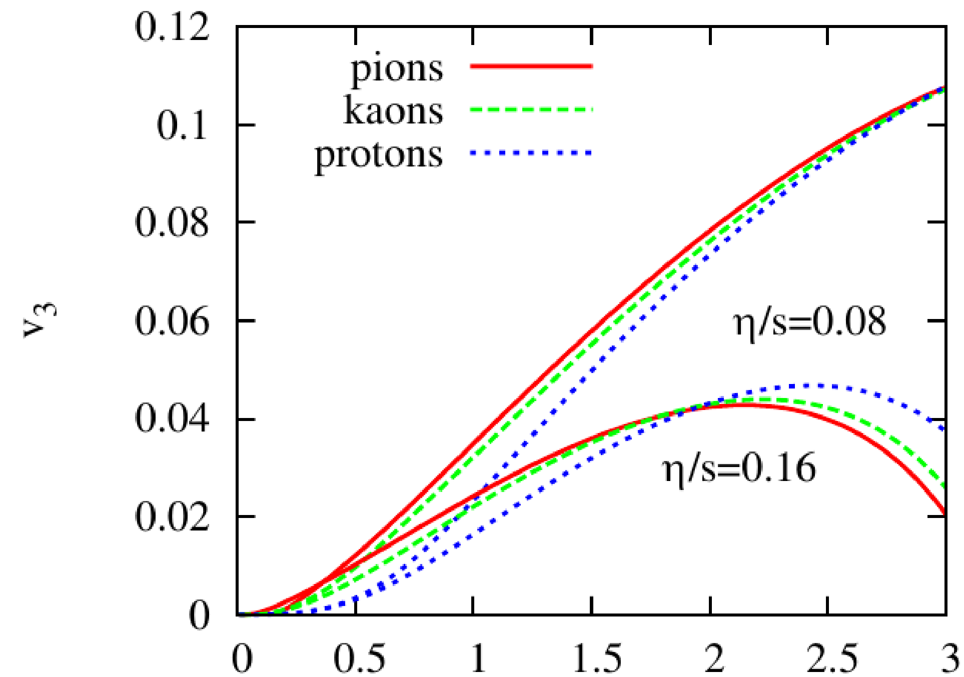
viscous, η/s=0.16

- Fluctuations in the initial shape damped by η/s.

Probing the medium properties



arXiv:1108:5323



Phys.Rev.C 82, 034913 (2010)

Sensitive probes of η/s:

- Elliptic flow of identified particles;
- Higher flow harmonics.

- *probe of radial flow*: mass dependence.

Flow measurement

- Cannot exactly know Ψ_n in: $v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$
- ... correlate particle pairs:

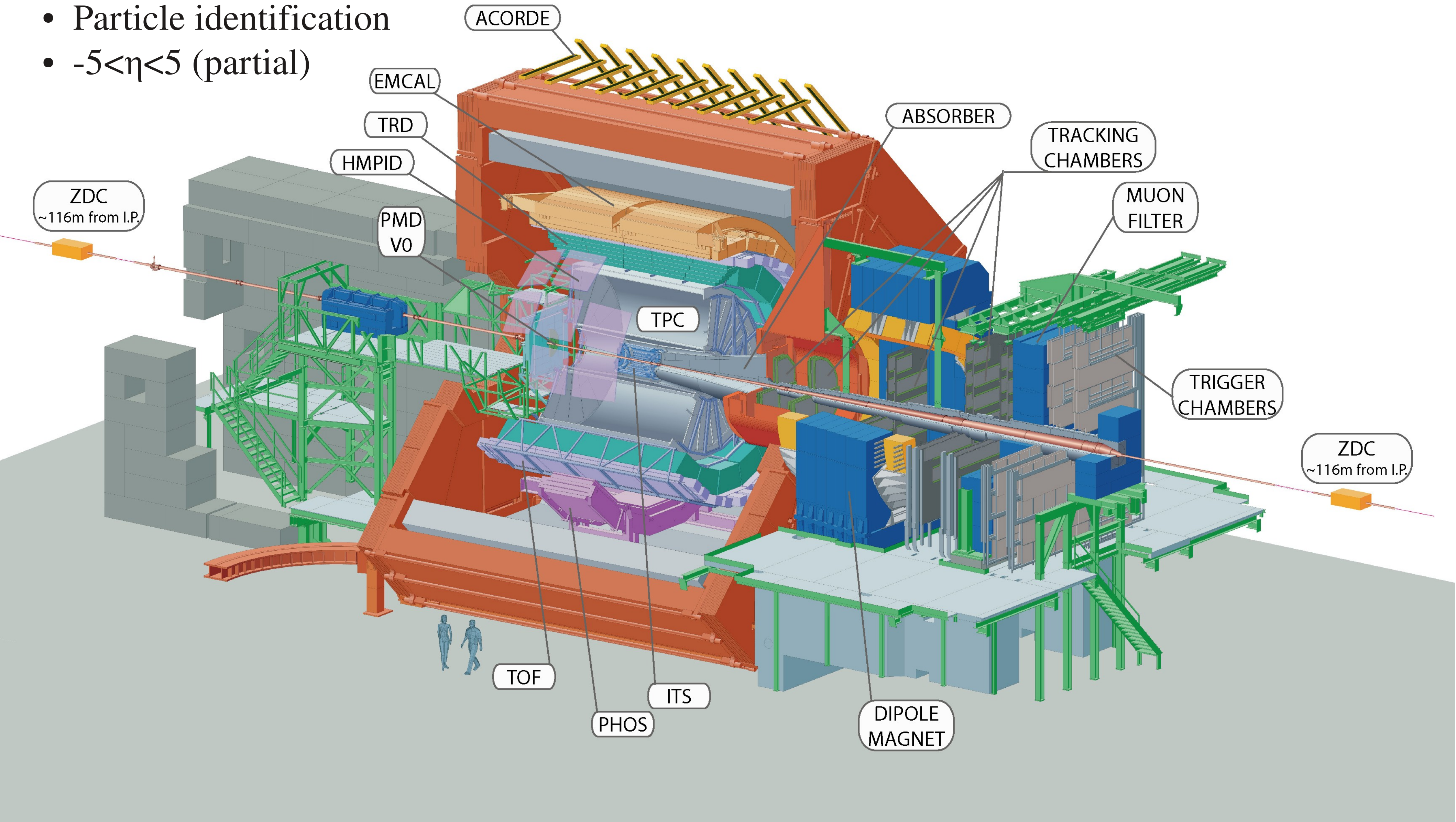
$$\langle\langle \cos(n(\phi_1 - \phi_2)) \rangle\rangle = \langle v_n^2 \rangle + \delta_n$$

  - δ_n is a correlation not related to the collective behaviour: *non-flow* (e.g. resonance decays, jet fragmentation,...)
  - Non-flow can be suppressed in 2-particle correlators by e.g. requiring η separation or correlating like-sign particles.

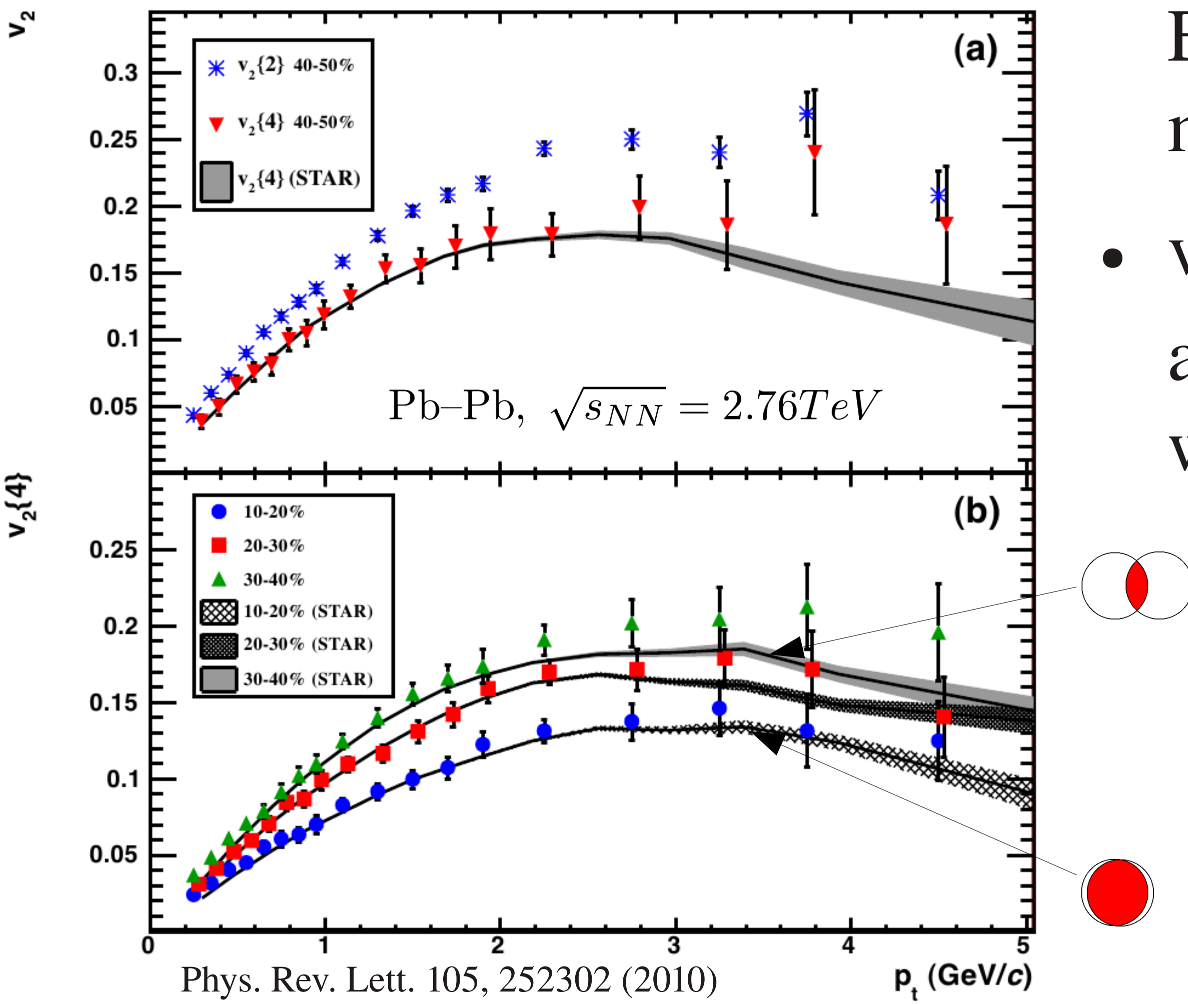
- ... or correlate more particles, e.g. a 4-particle cumulant is not sensitive to 2-particle non-flow.

The ALICE detector

- Full azimuthal coverage
- ~100MeV< p_T<~100GeV
- Particle identification
- -5<η<5 (partial)



First results

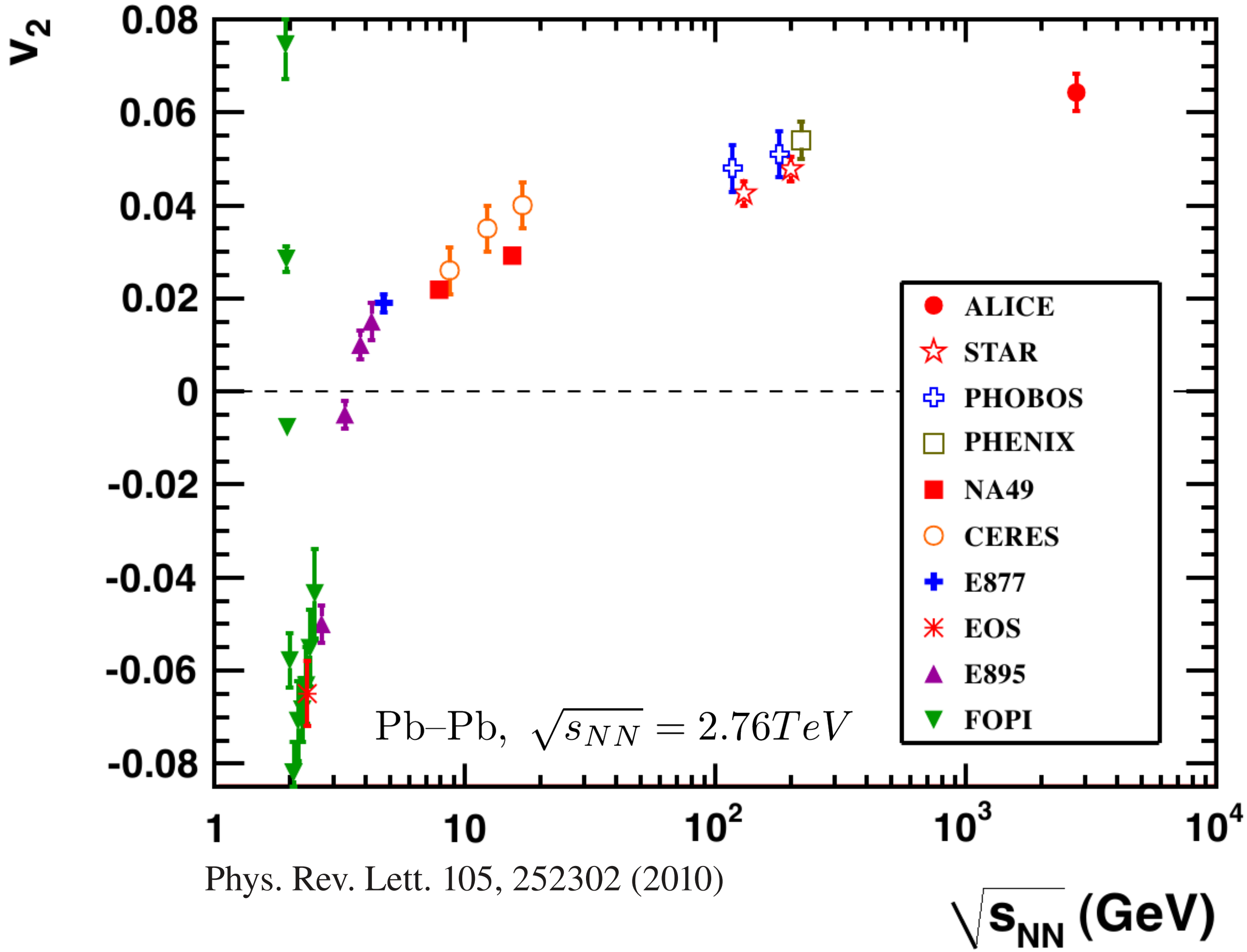


Phys. Rev. Lett. 105, 252302 (2010)

Elliptic flow vs. transverse momentum

- v_2 at LHC systematically above RHIC data, difference within uncertainties.

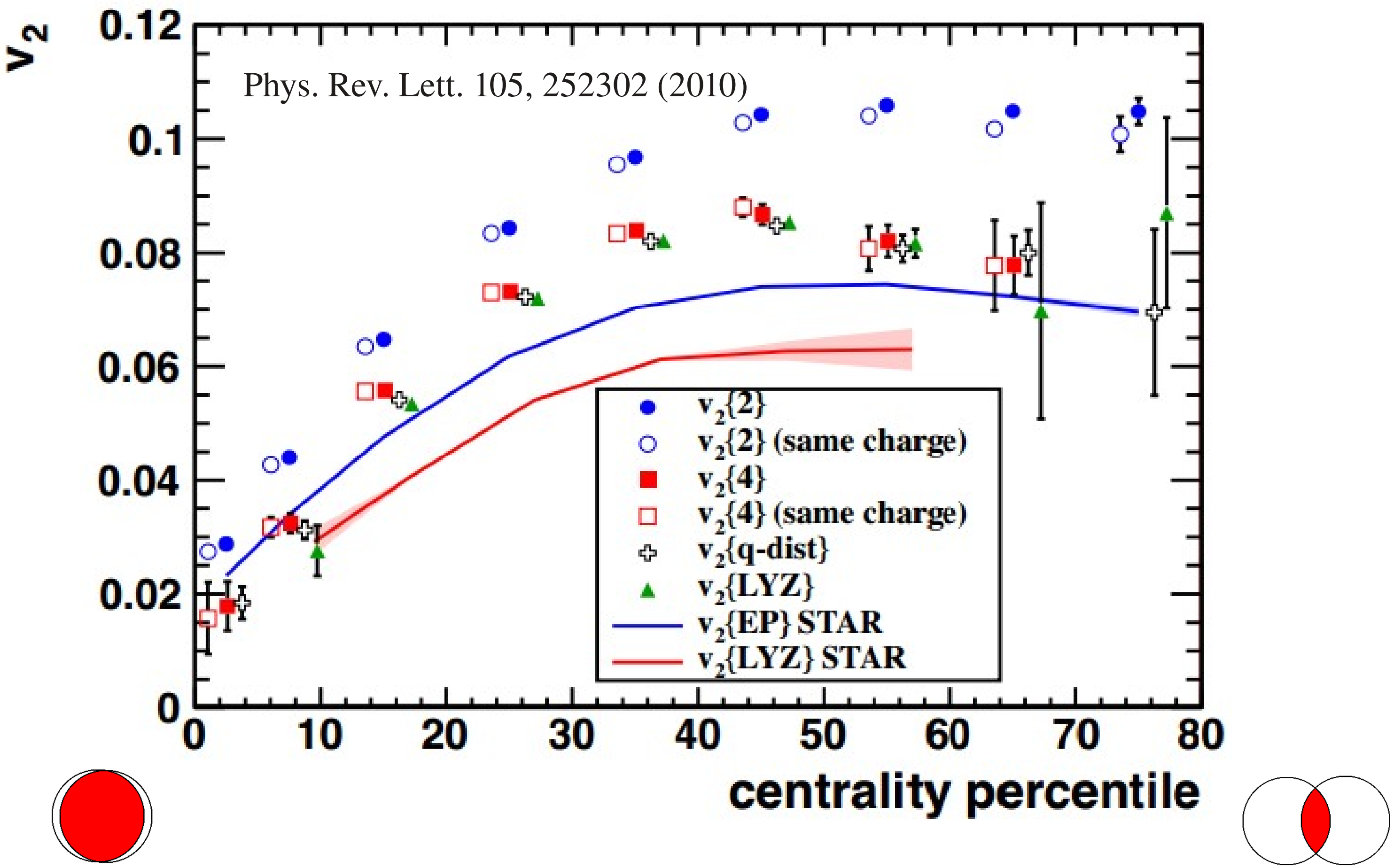
First results



Phys. Rev. Lett. 105, 252302 (2010)

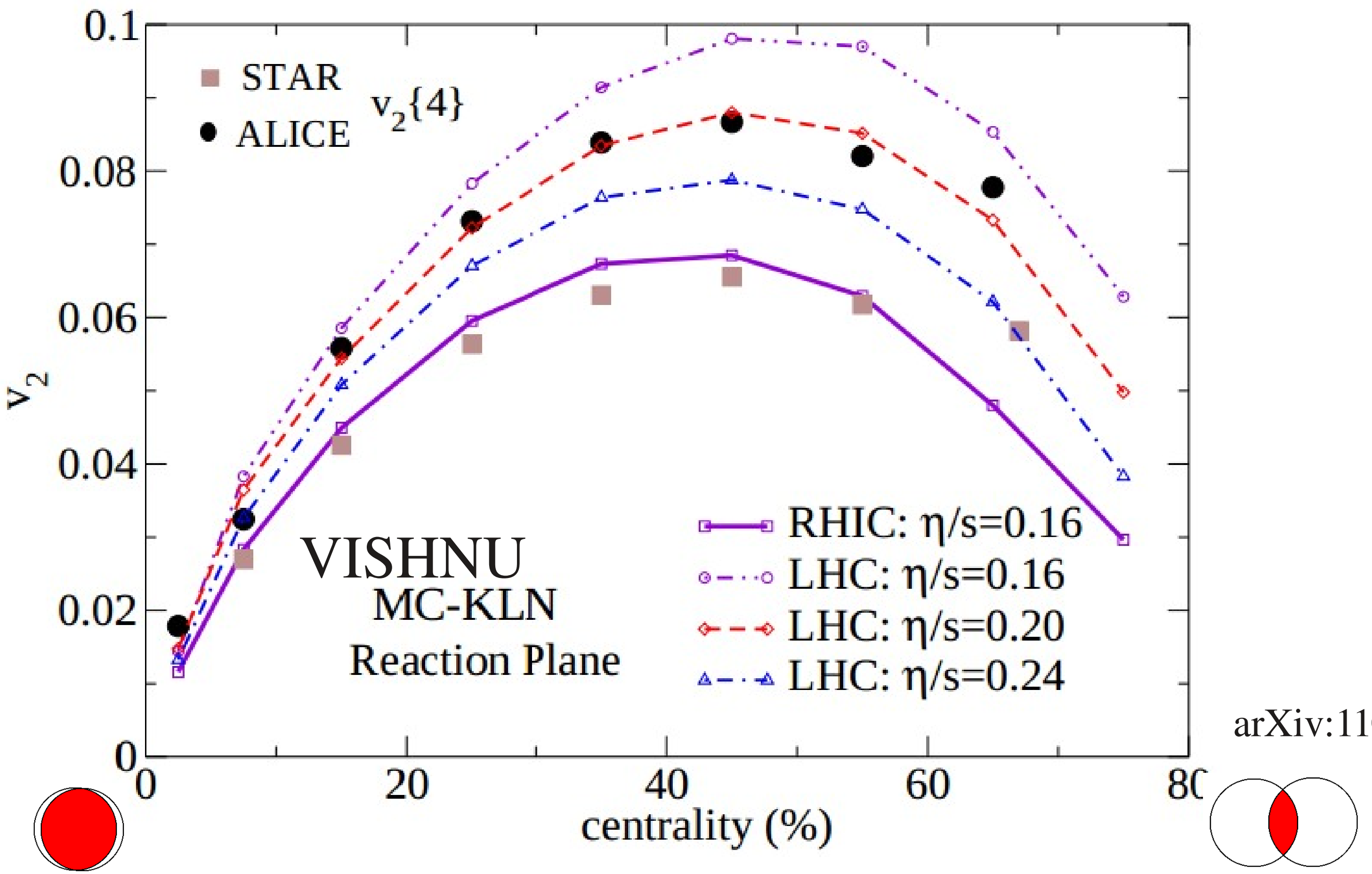
- Integrated flow at LHC 30% larger than at RHIC.
  - Rise driven by change in the mean p_T of the particles (since the differential flow did not change significantly).

First results



- Integrated elliptic flow vs. centrality estimated with various methods
- 2-particle methods depend weakly on charge combination due to non-flow.
- Multi-particle methods agree within uncertainties.

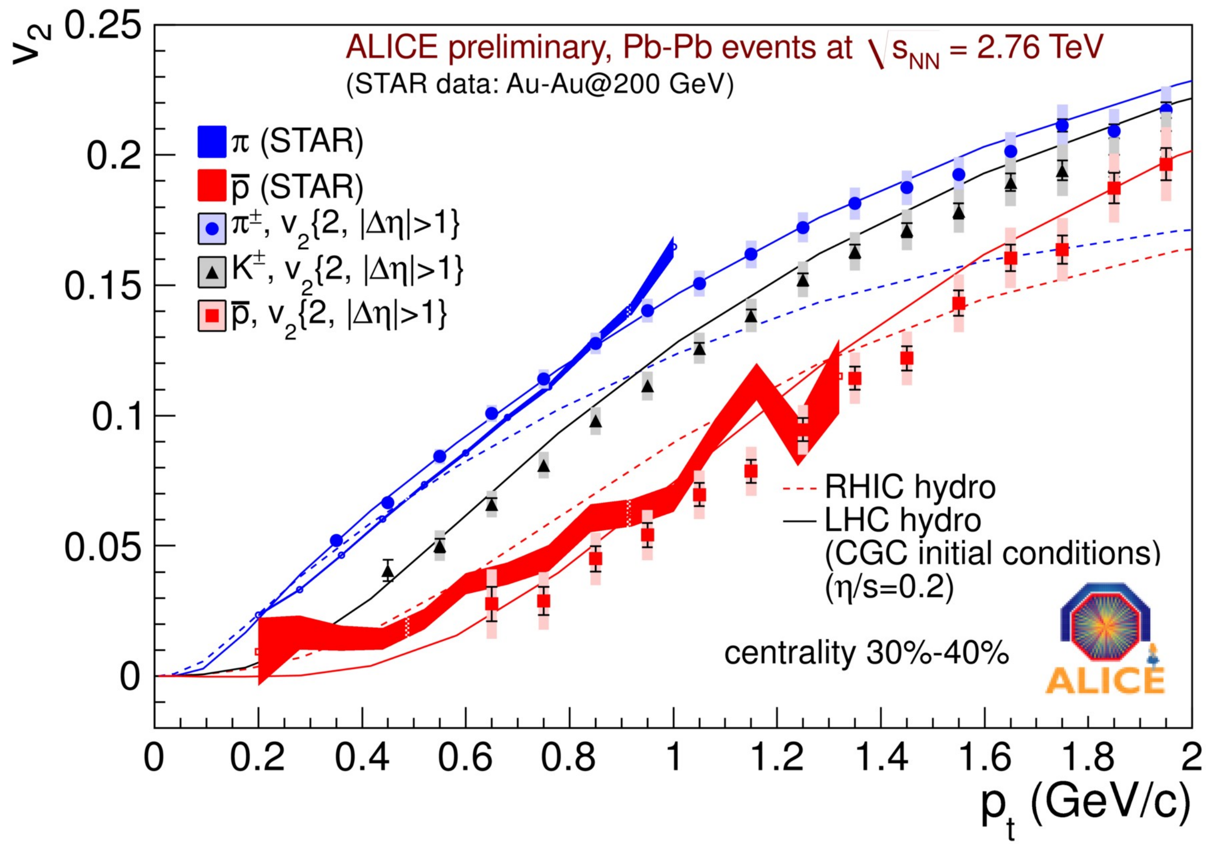
Hydrodynamic description of v_2

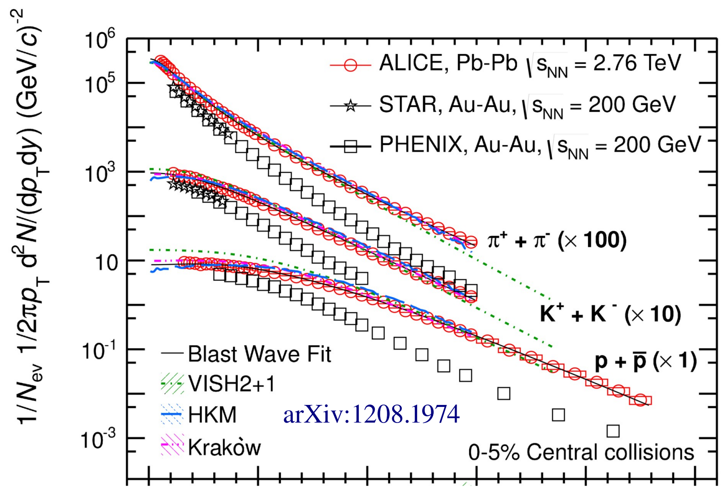


arXiv:1108:5323

- Hydrodynamic models seem to favour a low value of η/s at both RHIC and LHC energies.
- There are, however, many other parameters in the model, studies ongoing.

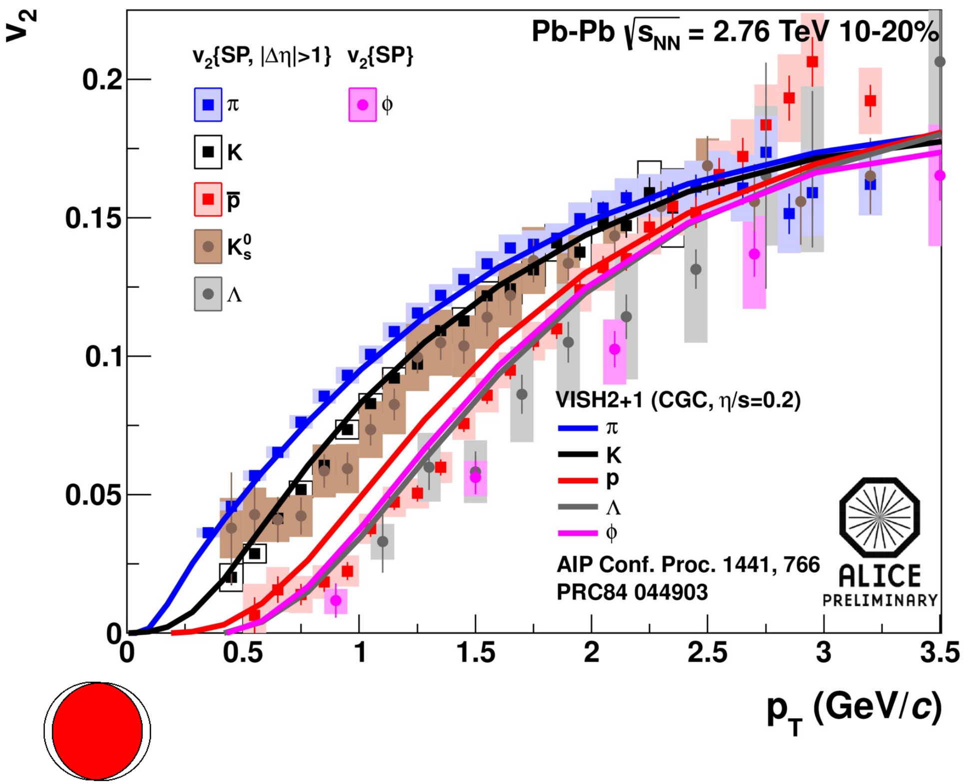
Radial flow at LHC – identified particle flow

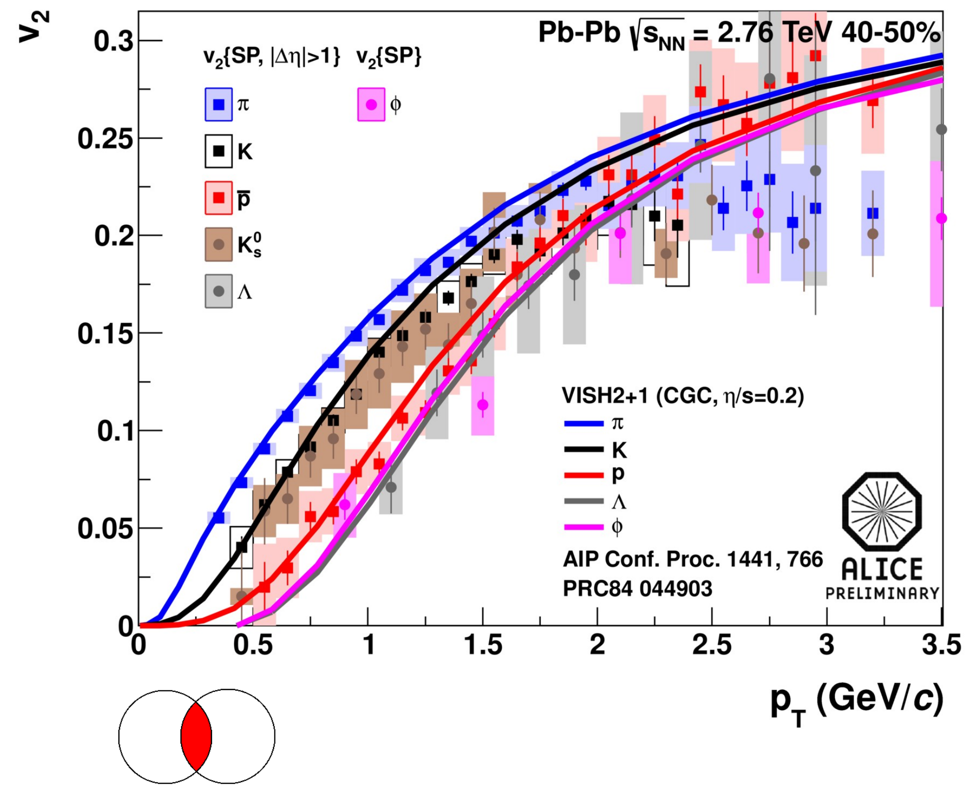




- Mass splitting at LHC is larger than at RHIC, as expected from hydrodynamics.
- Consistent with larger radial flow (attributed to larger particle densities).
- Blast wave fits of spectra show an increase of radial flow from RHIC to LHC.

Flow of identified particles

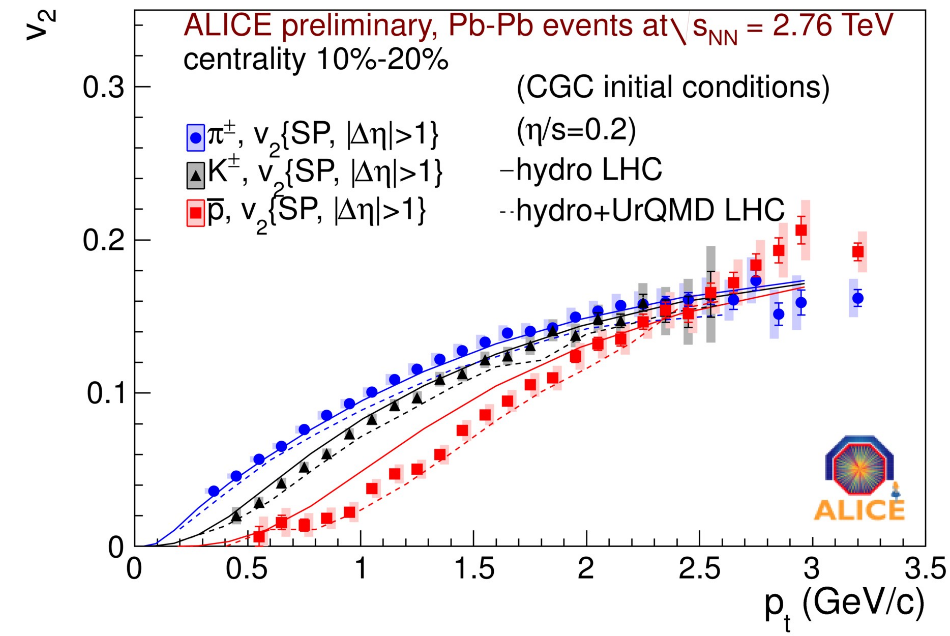


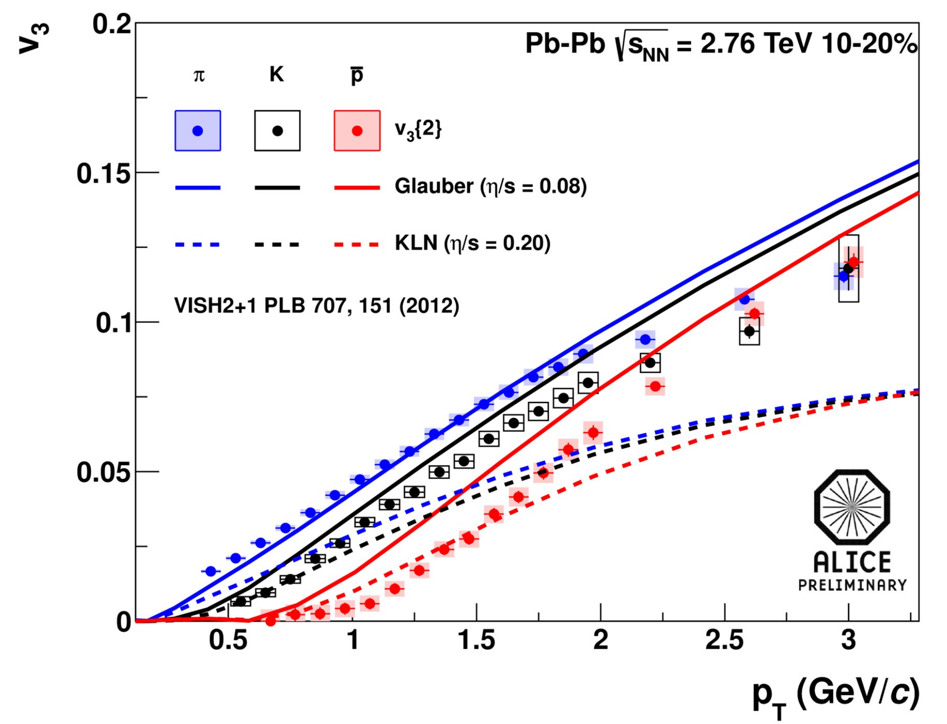


- Viscous hydrodynamics (VISH2+1) model does not describe heavier particles well, especially in more central collisions.

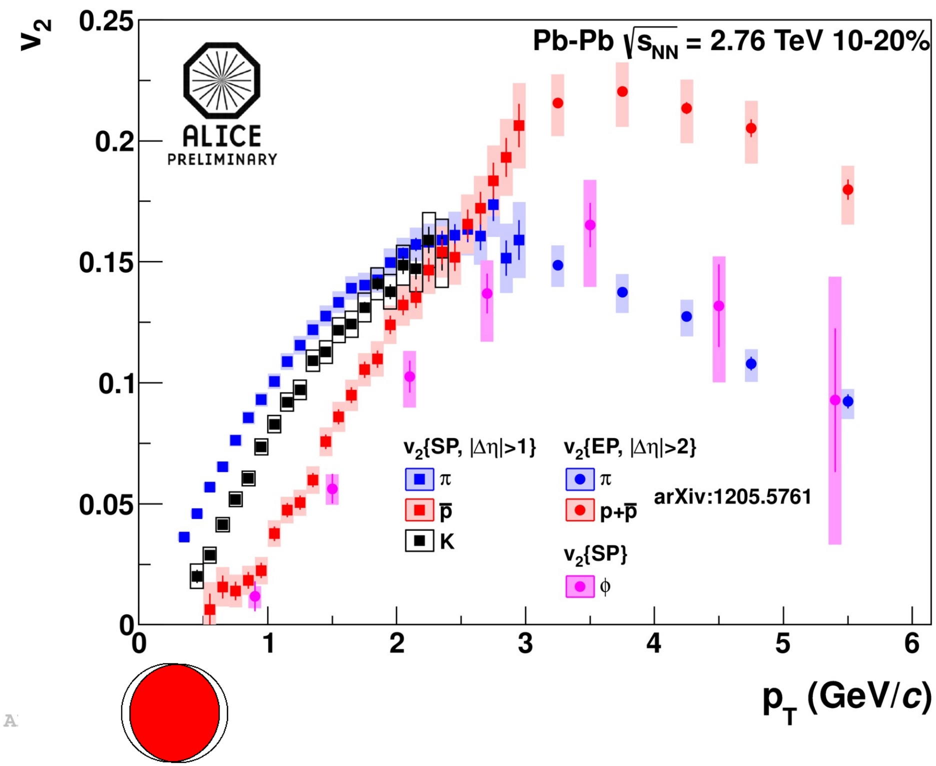
v_2,v_3 vs. hydro + transport model

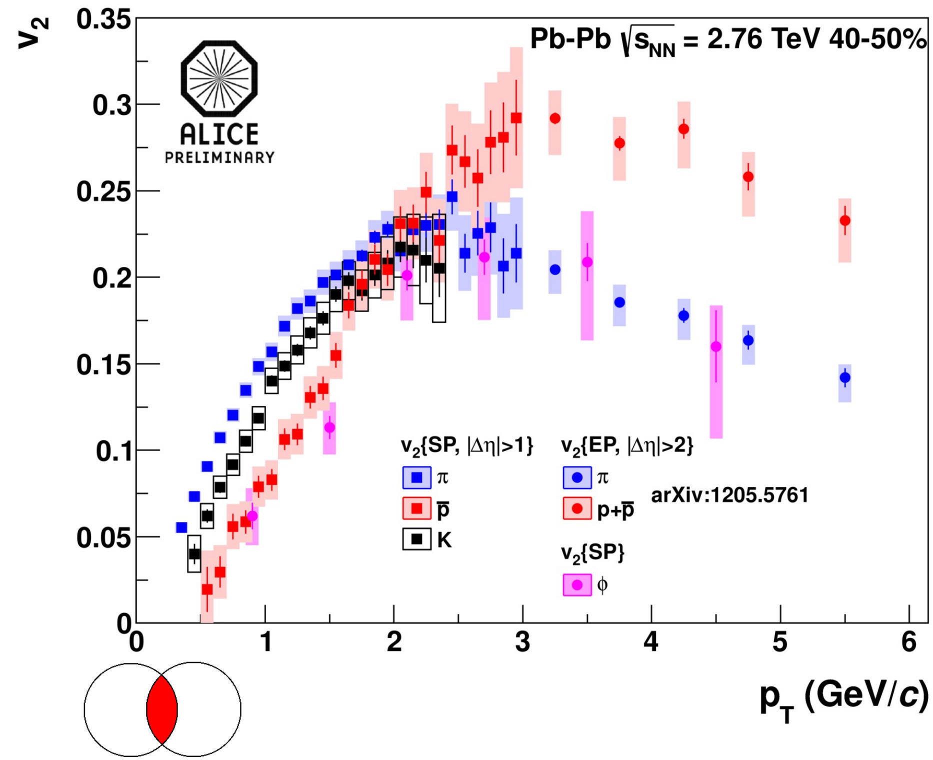
- VISH2+1 overestimates v_2 for heavier particles in more central collisions.
- Adding hadronic rescattering (UrQMD) after the hydrodynamic stage in the model reproduces the v_2. (VISHNU, arXiv:1108:5323).
- Additional constraints from triangular flow: model favours low η/s.





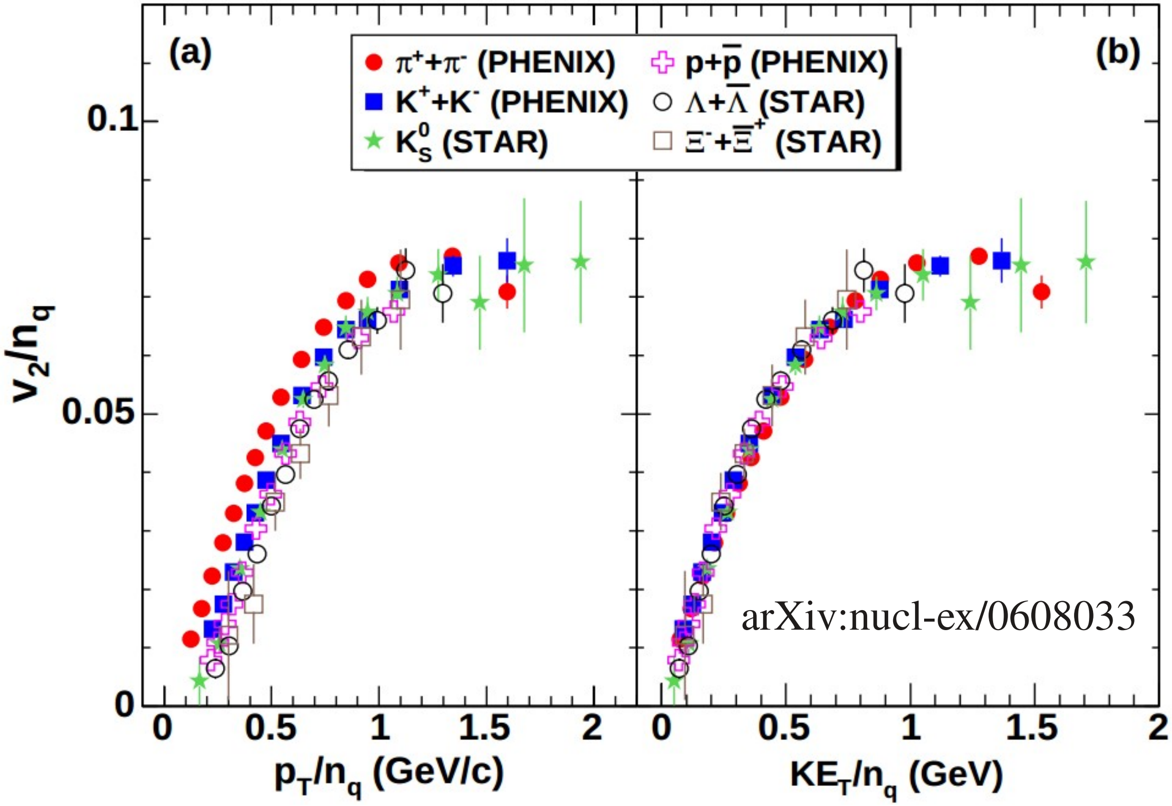
Flow of identified particles





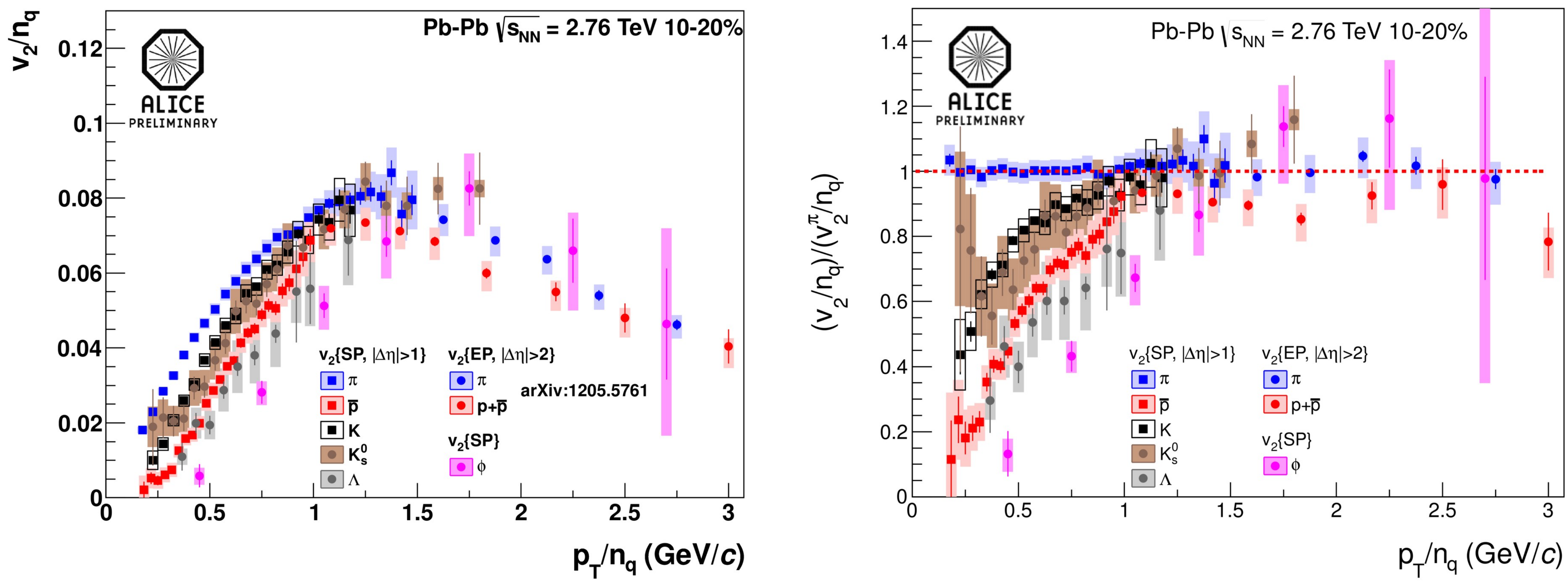
- Strong centrality dependence: v_2 is ~0.15 for more central, ~0.25 for more peripheral (at 2.5GeV/c)
- Crossing point around p_T=2.5GeV/c.
- Clear mass dependence.
- Above the crossing point phi meson v_2 is compatible with flow of pions – quark number scaling?

Elliptic flow scaling at RHIC



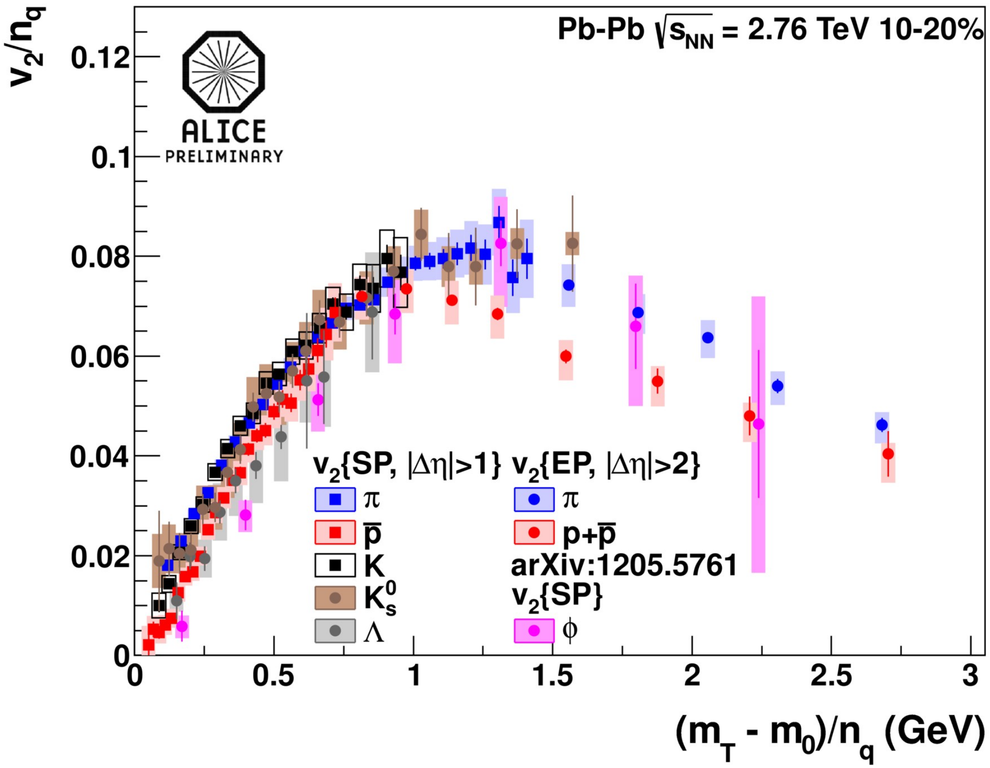
- Two types of scaling:
  - Number of quarks scaling motivated by the quark coalescence picture.
  - Scaling of flow per valence quark vs the transverse kinetic energy (KE_T=$\sqrt{m^2 + p_t^2} - m_0$) per quark.
- KE_T/n_q scaling at lower p_T was observed at top RHIC energy.

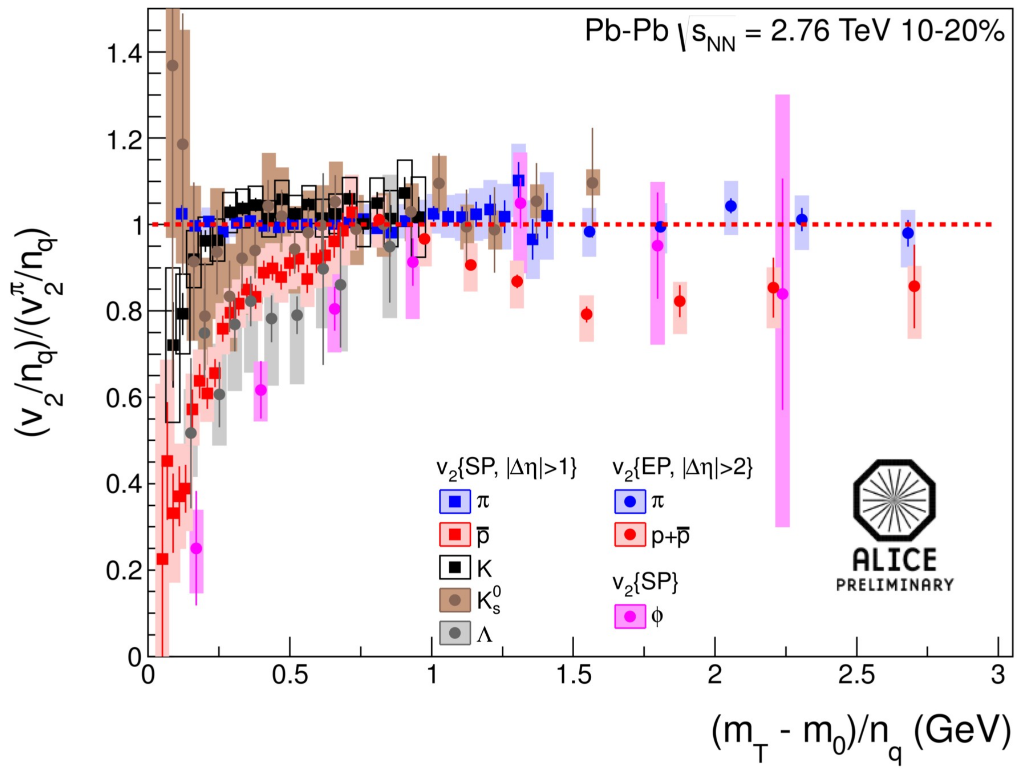
Quark number scaling at LHC



- For $3<p_T<6$ v_2 can be used to test the model of hadron production by coalescence.
- We see only an approximate scaling.

KE_T scaling at LHC





- Scaling of flow per valence quark versus kinetic transverse energy KE_T per valence quark does not hold at LHC (for KE_T<1).

Flow fluctuations

- From correlations we measure $\left\langle v_2^2 \right\rangle$:

$$\langle\langle\cos(n(\phi_1 - \phi_2))\rangle\rangle = \left\langle v_n^2 \right\rangle$$

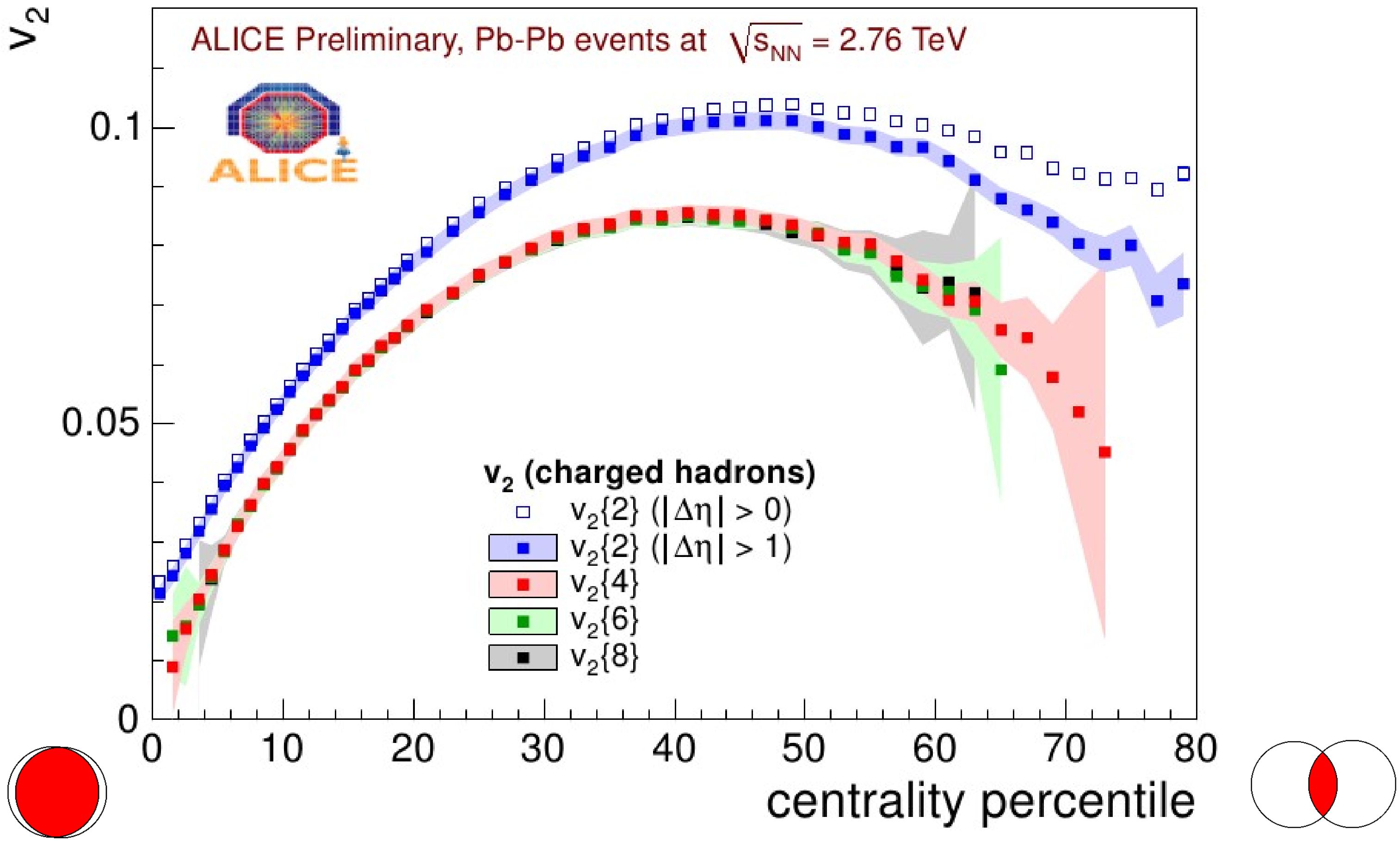
- Contribution from event-by-event fluctuations:

$$\langle v_2^2 \rangle \quad = \quad \langle v_2 \rangle^2 + \sigma^2$$

- 2- and multi-particle estmates have a different sensitivity to fluctuations (for small σ):

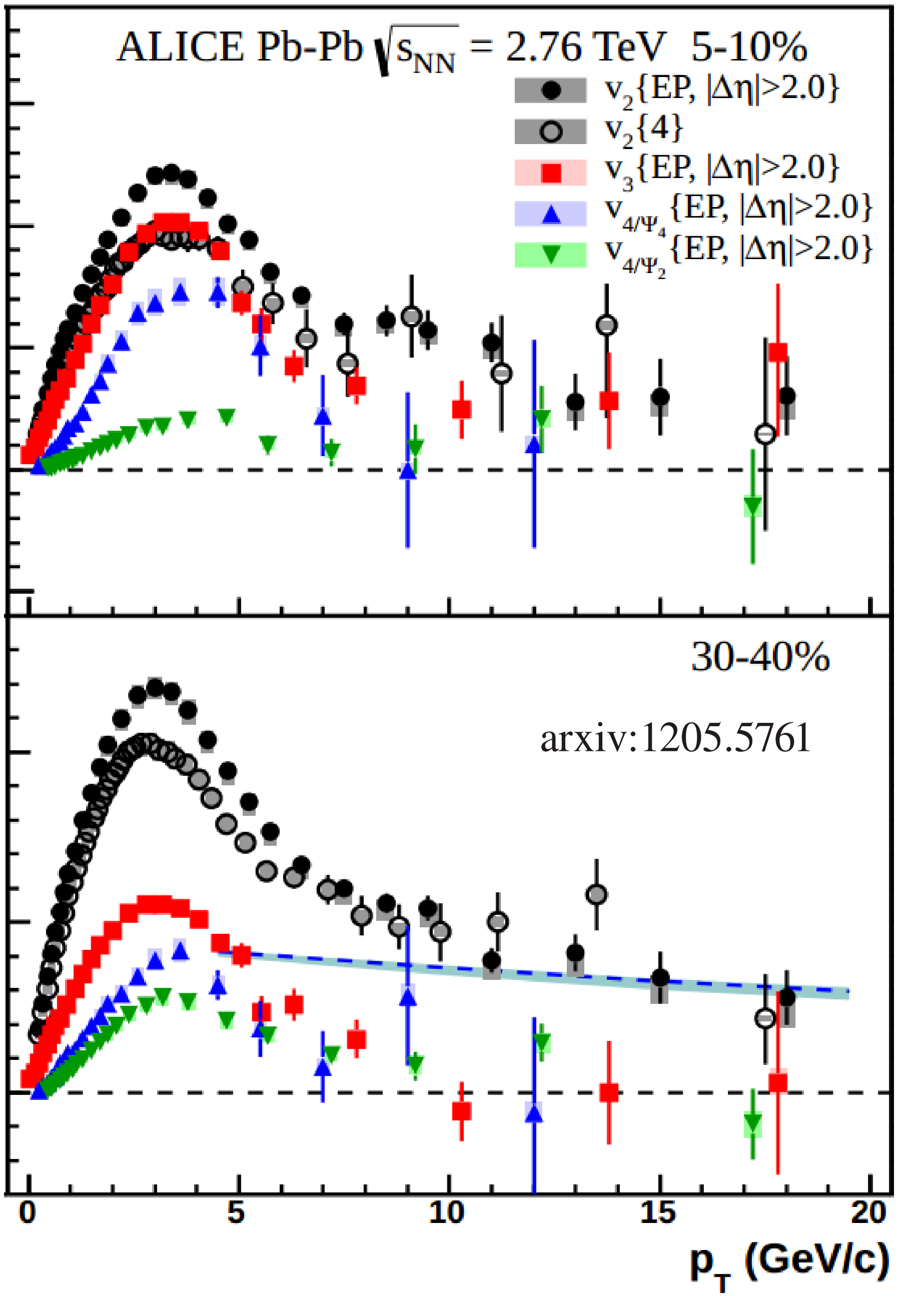
$$v_2\{2\} \quad = \quad \langle v_2 \rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}$$
$$v_2\{4\} \quad = \quad \langle v_2 \rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2 \rangle}$$

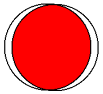
Flow, non-flow, fluctuations



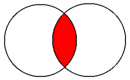
- Difference between 2- and multi-particle estimators due to event-by-event fluctuations.
- 2-particle methods sensitive to non-flow correlations, can be suppressed by introducing separation between particles (e.g. η-gap).

Flow at high transverse momentum

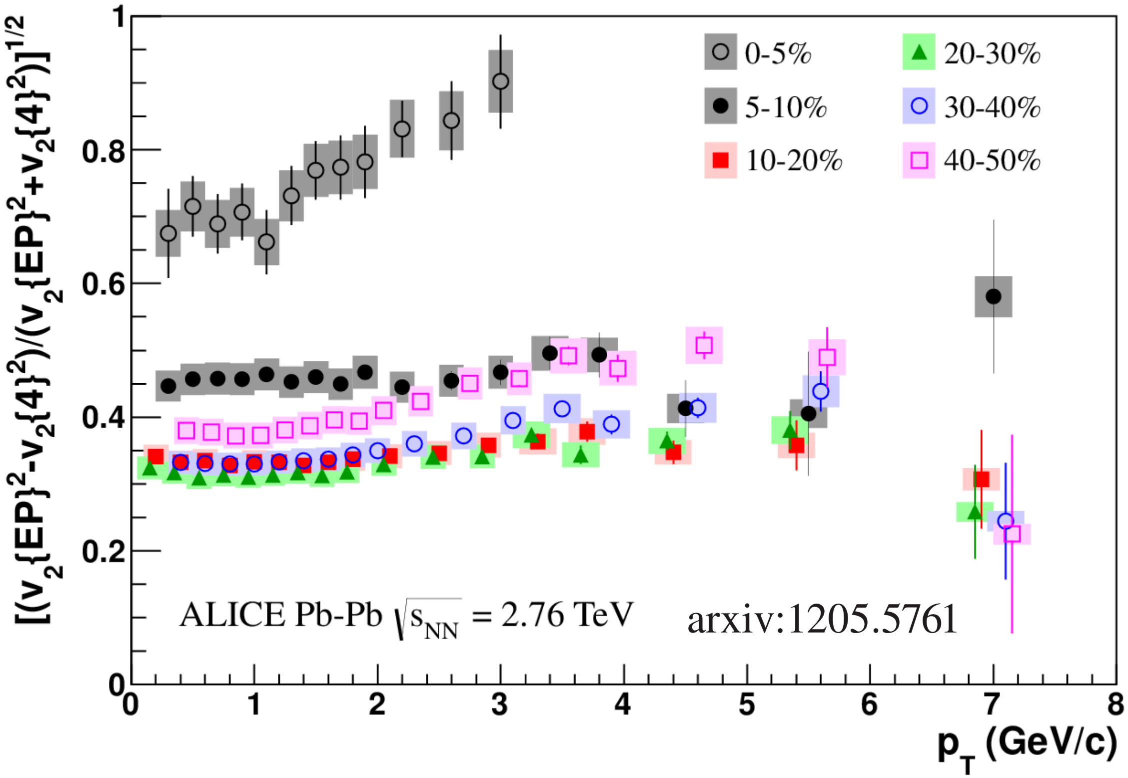




- Finite value of v_2 at high p_T, both 2- and 4- particle estimate.
- Flow at high p_T dominated by the jet interaction with the medium.
- Fluctuation dominated higher harmonics may disappear at p_T>10GeV/c, more statistics needed.

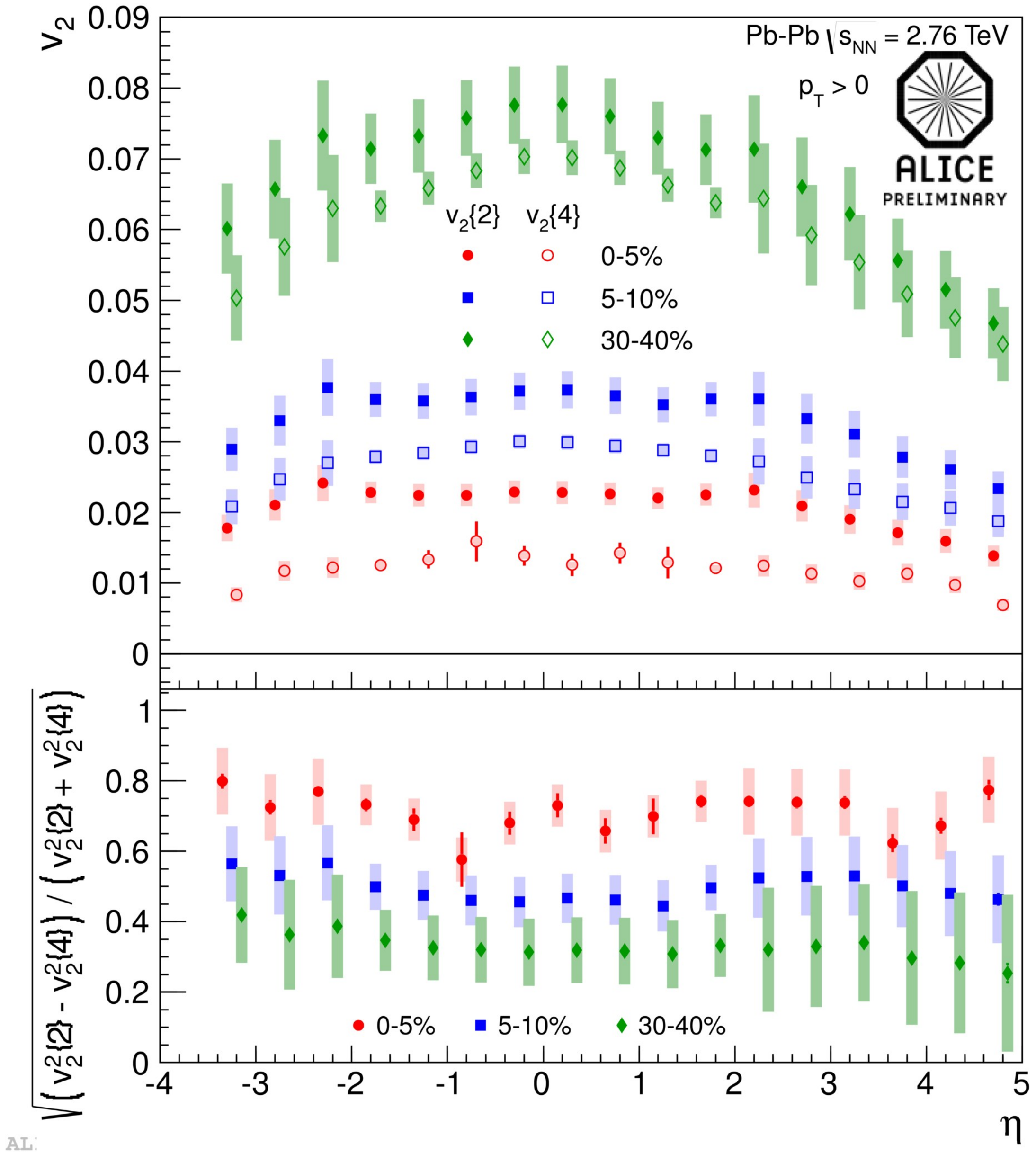


Fluctuations (vs. p_T)



- Magnitude of v_2 fluctuations varies only little up to p_T~6GeV/c except most central collisions.
- For very central events and very peripheral events non-flow contribution is expected to be large.

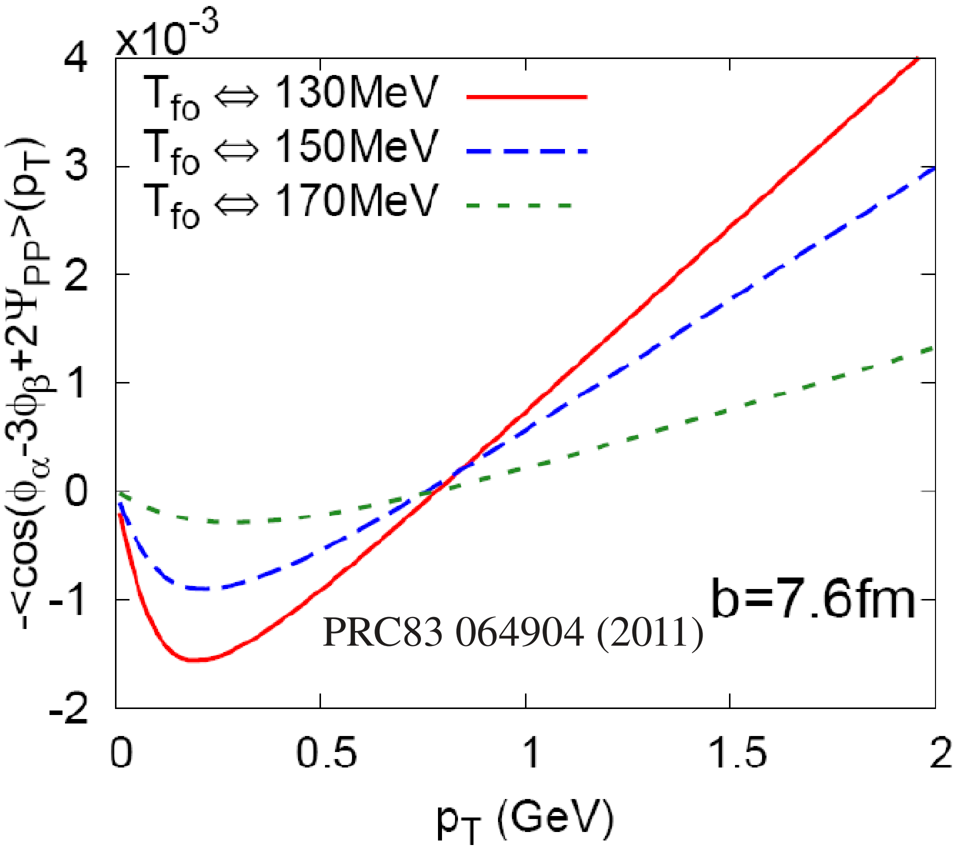
Fluctuations (vs. η)

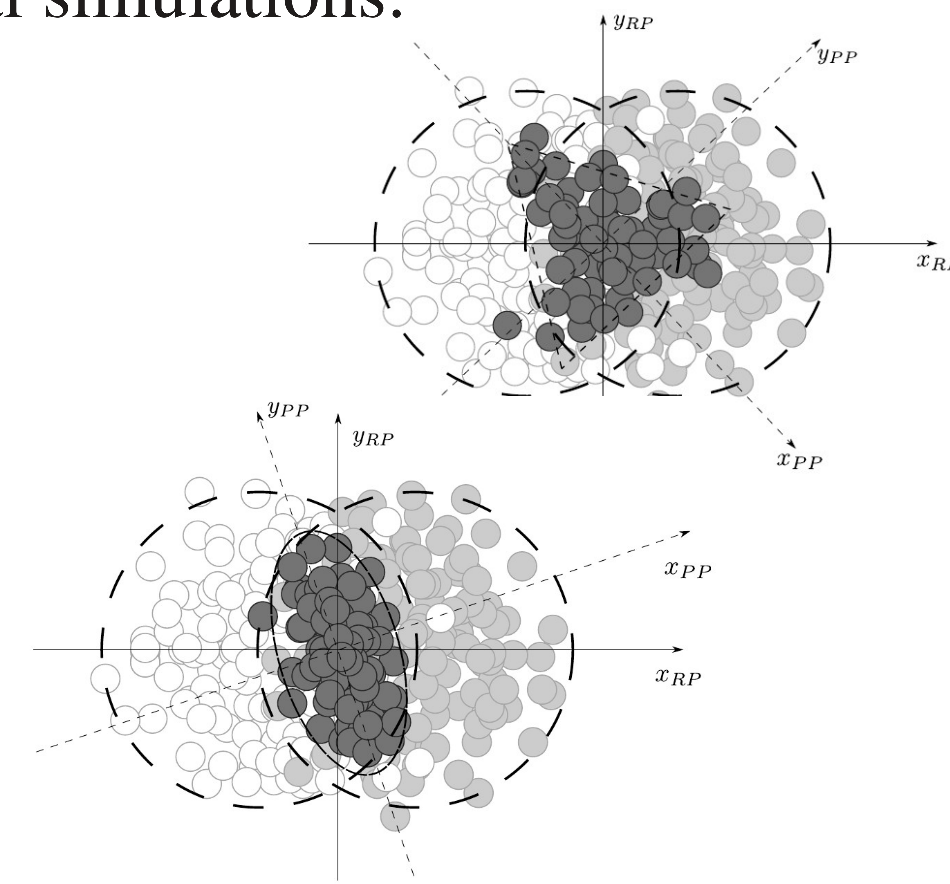


- Dependence of v_2 on psudo-rapidity for different centralities.
- Magnitude of relative flow fluctuations at midrapidity very similar to the forward region (up to η~5) for different centralities.

Correlations between symmetry planes

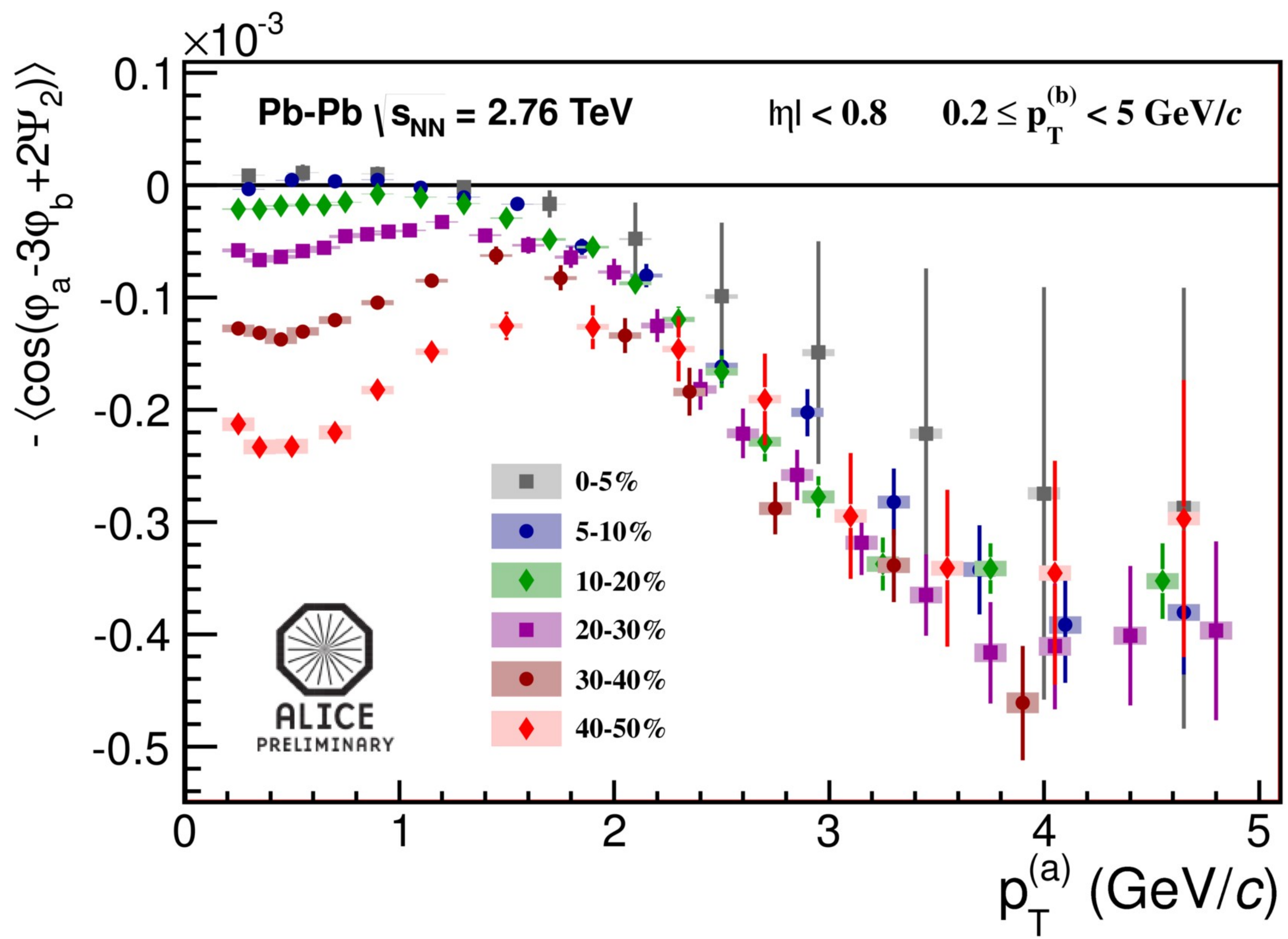
- Teaney & Yan proposed: $\langle\langle \cos(\phi_\alpha - 3\phi_\beta + 2\Psi_2)\rangle\rangle$
- Three particle mixed harmonic correlation;
  - correlates the dipole, elliptic and triangular event planes.
- Expectation from hydrodynamical simulations:

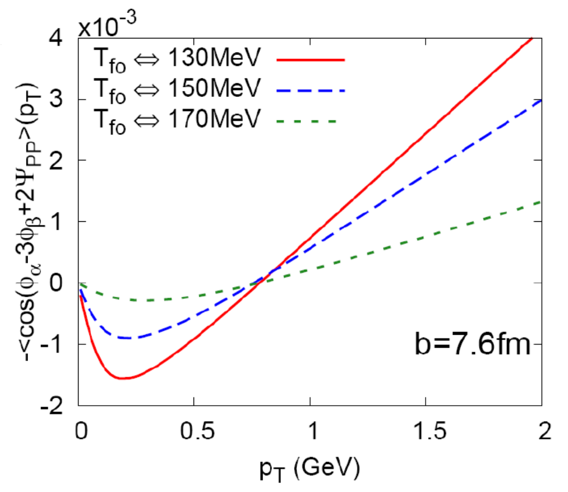




Correlations between symmetry planes

- Measurement deviates substantially from the theory expectation at higher p_T:

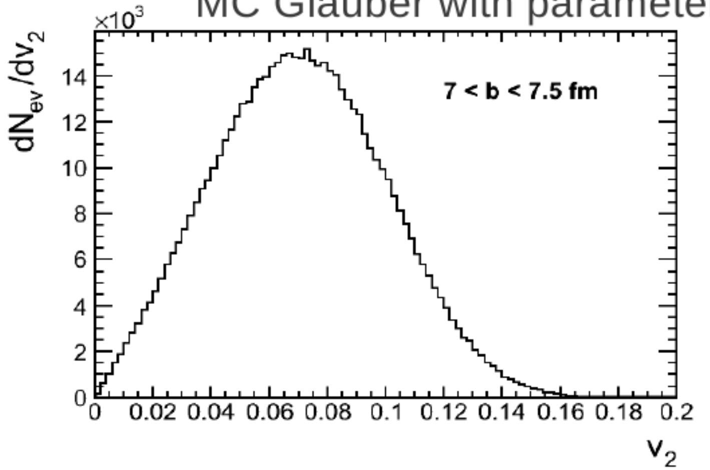


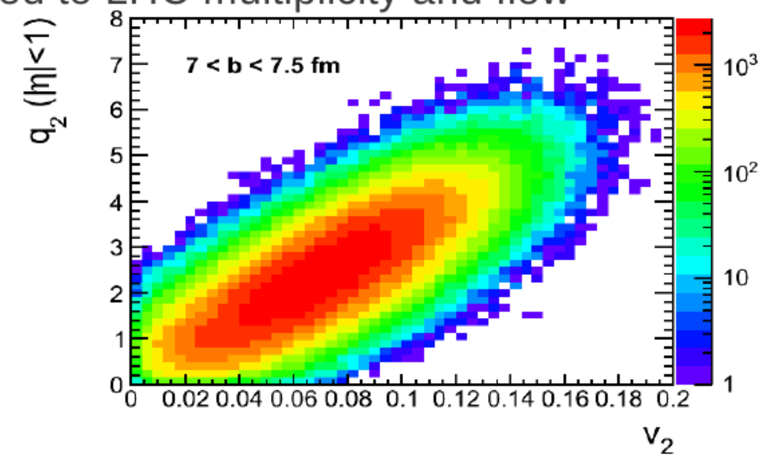


Event shape engineering

- Study the effect of fluctuations on various observables by selecting event classes with different shapes (in azimuth).

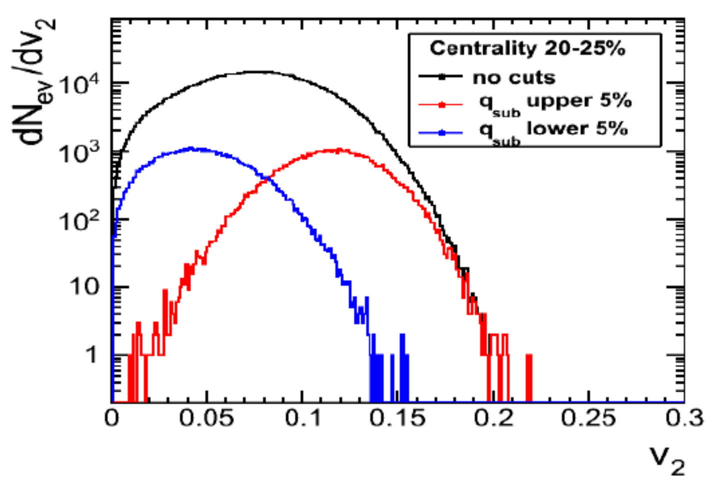
MC Glauber with parameters tuned to LHC multiplicity and flow





For fixed centrality, flow fluctuates. Can we select events with given flow value?

Yes, based on the length of flow vector



Flow vector → q-distributions

$$Q_{n,x} = \sum_i \cos(n\phi_i) \qquad Q_n = \{Q_{n,x}, iQ_{n,y}\}$$
$$Q_{n,y} = \sum_i \sin(n\phi_i) \longrightarrow q_n = |Q_n|/\sqrt{M}$$

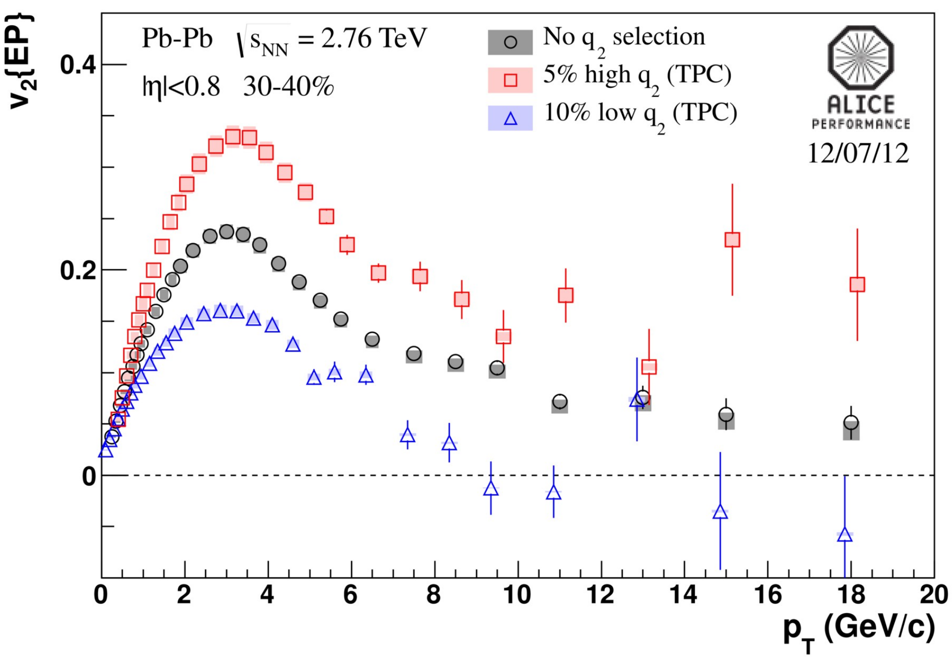
Cutting on q_2 in one pseudo-rapidity window and measure v_2 in another window:

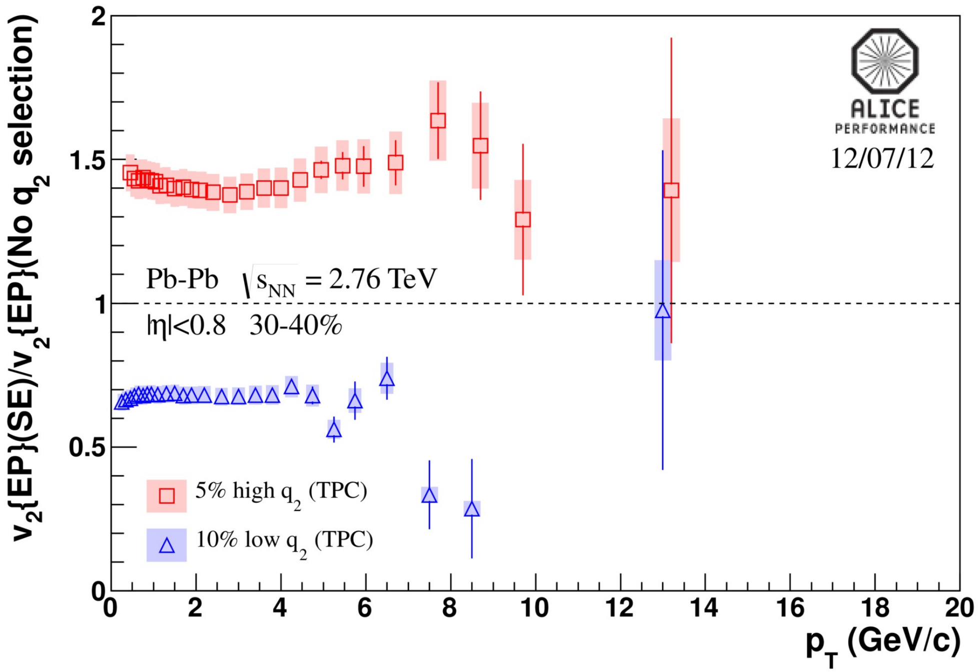
- Width of v_2 distribution for shape engineered (SE) events smaller than unbiased results
- Variation of v_2 up to factor of 2-3

Quark Matter 2012

A.Dobrin

Event shape engineering





- For a fixed centrality select 5% highest q_2 and 10% lowest q_2.
- Similar contributions from fluctuations up to p_T~6GeV/c.
- p_T dependence of the ratio may come from remaining non-flow contributions.
- New tool for studying the effects of the event shape on many physics observables.

Summary

- Flow is sensitive to the evolution and properties of the medium created in heavy-ion collisions.
- Elliptic flow of charged and identified particles indicates a strong rise of the expansion velocity of the medium (radial flow).
- All harmonics are sensitive to η/s
  - hydro and hybrid models indicate a strongly coupled phase with a low η/s.
- Relative flow fluctuations have a similar magnitude up to p_T~6GeV/c and η~5, and may be different for the high p_T region where particle production from hard processes dominates.
- Correlations between symmetry planes in data differ from the expectation.
- New tools being deployed, e.g. event shape selection which allows to study effects of initial fluctuations on many physics observables.
- Many more results available (heavy flavour flow, search for the chiral magnetic effect, see e.g. QM2012 proceedings).

dankie