Collective motion in ALICE

can we constrain transport parameters?

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November 03, 2016

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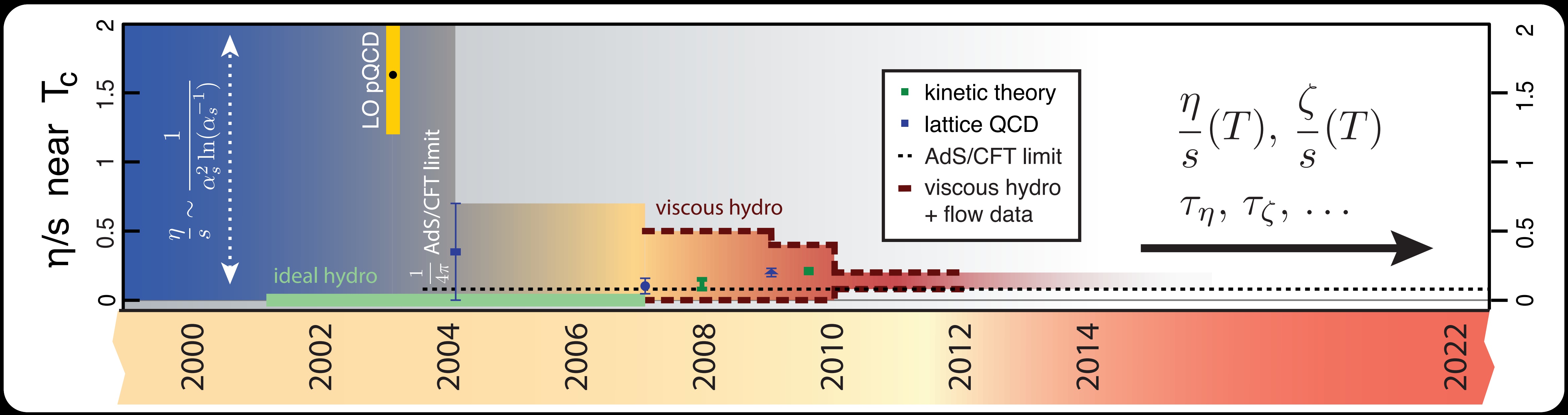
The nearly perfect liquid paradigm

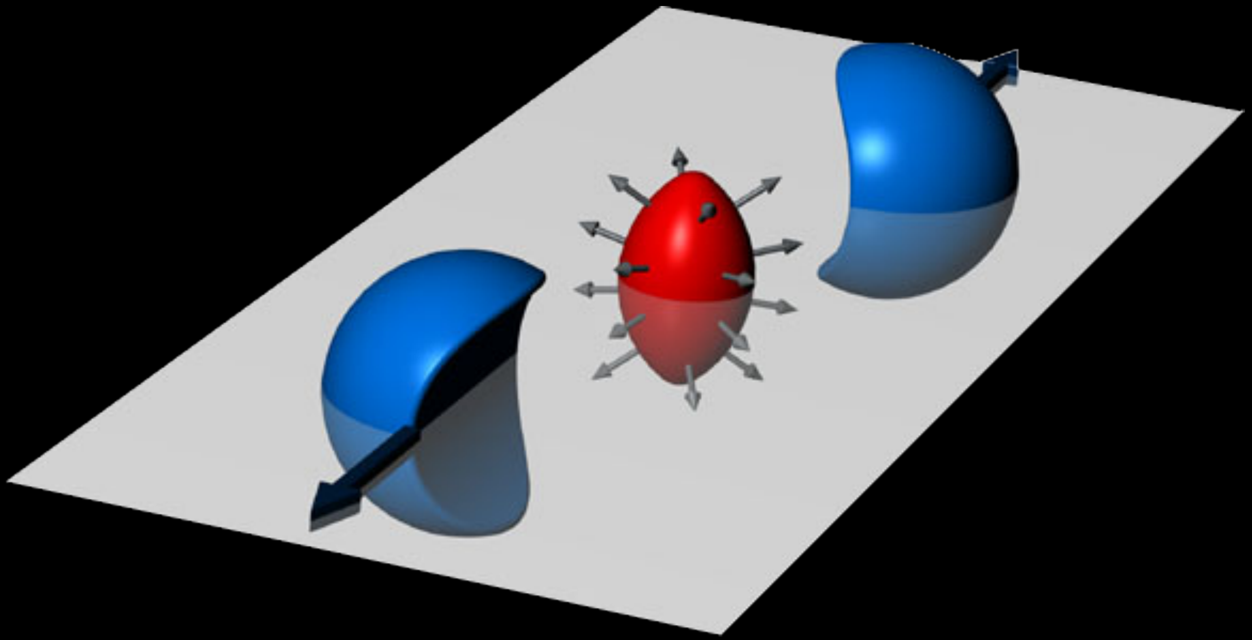
- a large amount, if not most, of the observables in the soft sector can be interpreted in terms of collective behaviour in AA collisions
- viscous hydrodynamics very successful in describing, and even predicting semi-qualitative, simultaneously these observables

The nearly perfect liquid paradigm

- many open questions still
  - how well do we know the initial conditions?
  - if, when and how does the system thermalize?
  - what is the hadronization mechanism?
  - hadronic interactions and their contribution to observables?
  - ……
- would like to answer what is the magnitude of transport coefficients and how do they depend on e.g. T and what the relevant degrees of freedom are
- Are we able to do this now?

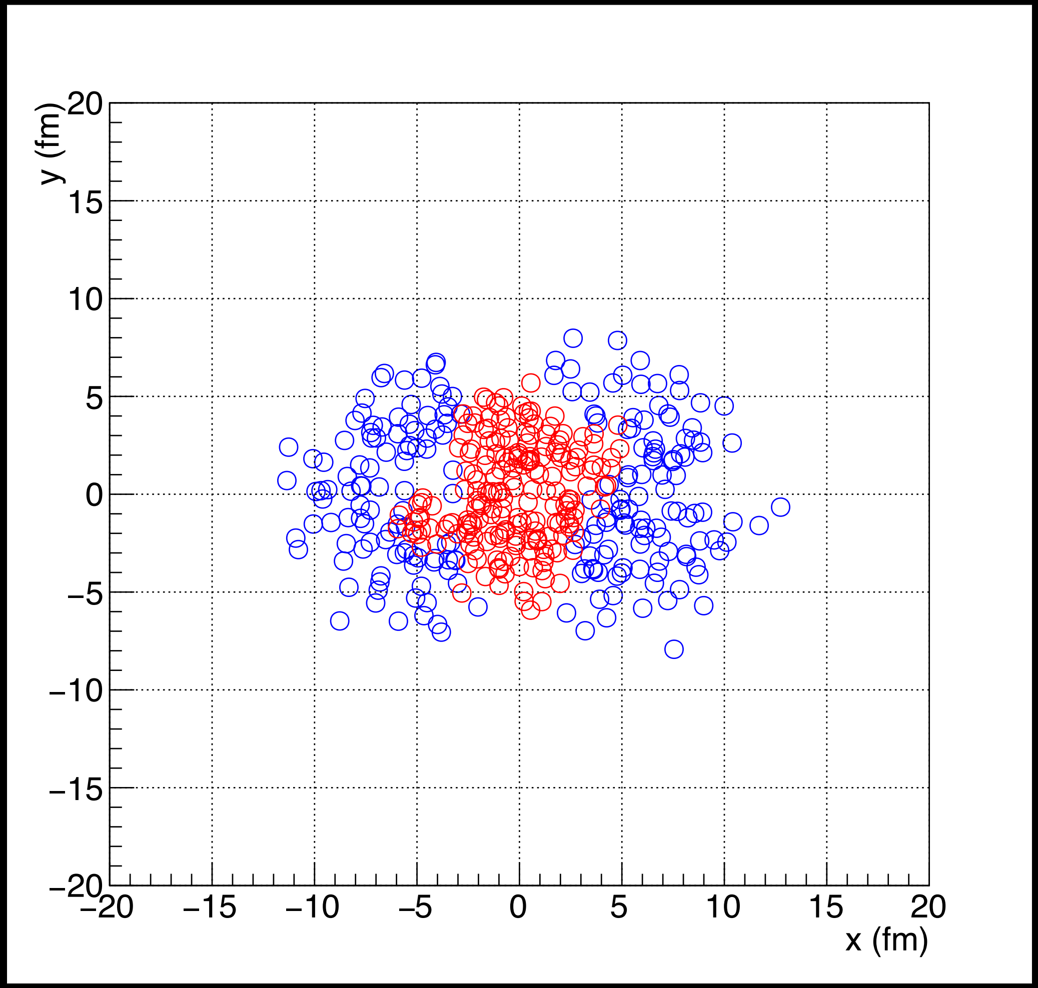
The nearly perfect liquid paradigm

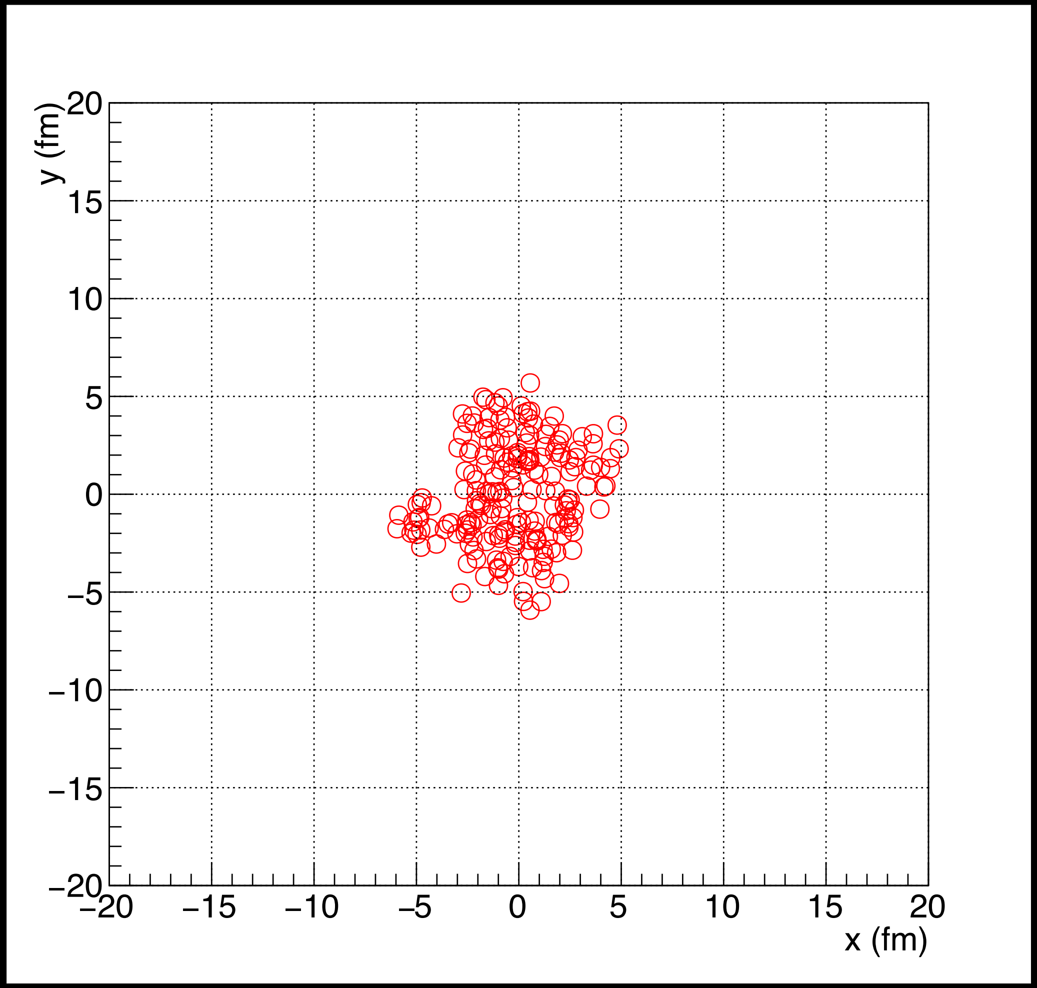


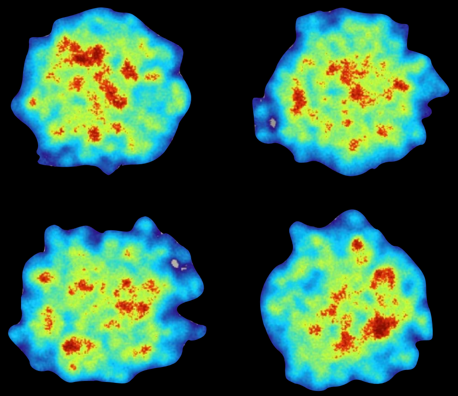


Howard Wieman

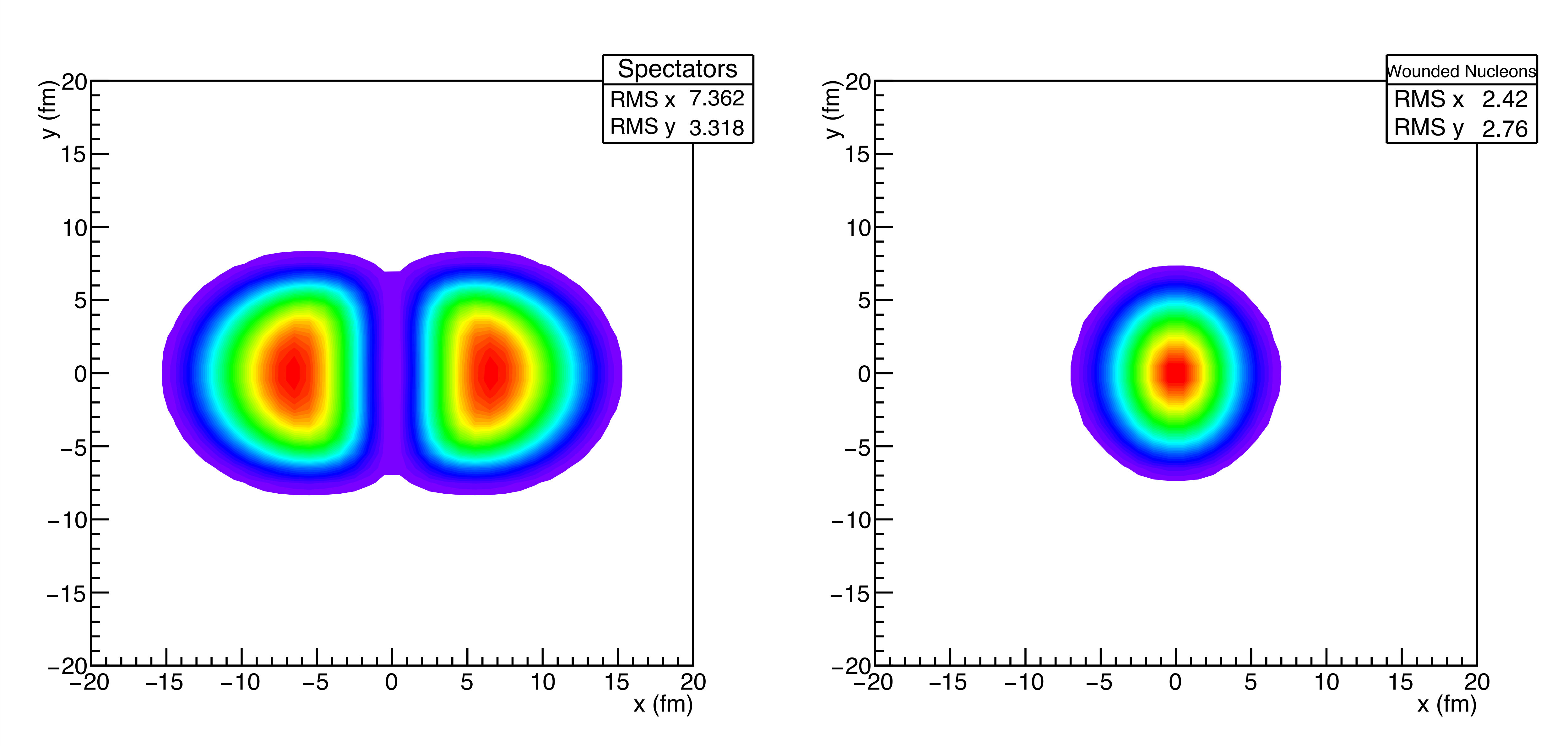
A Single Collision



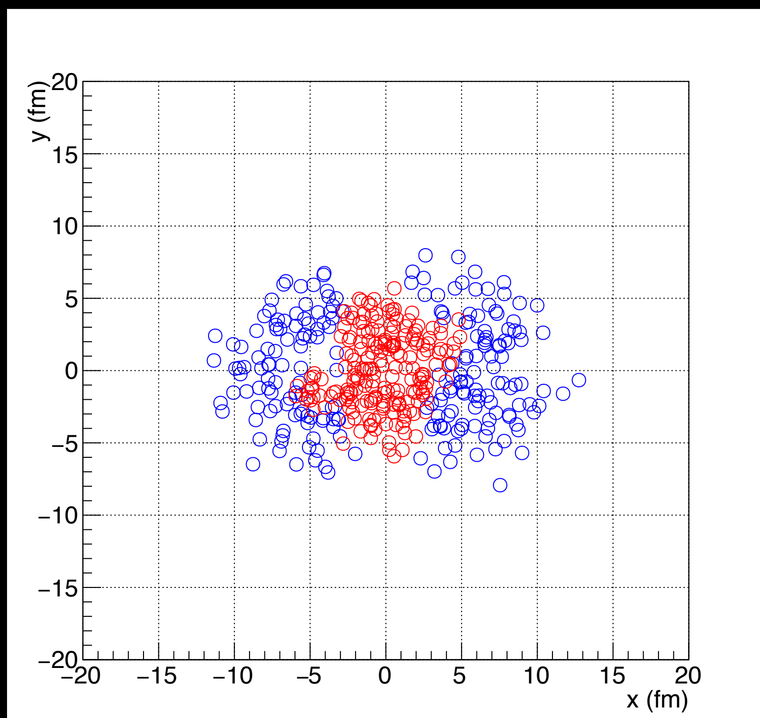


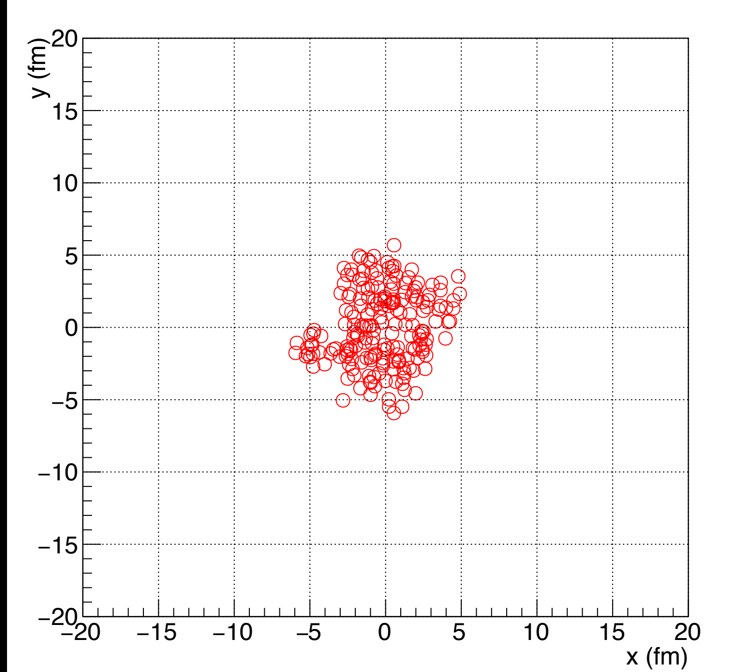


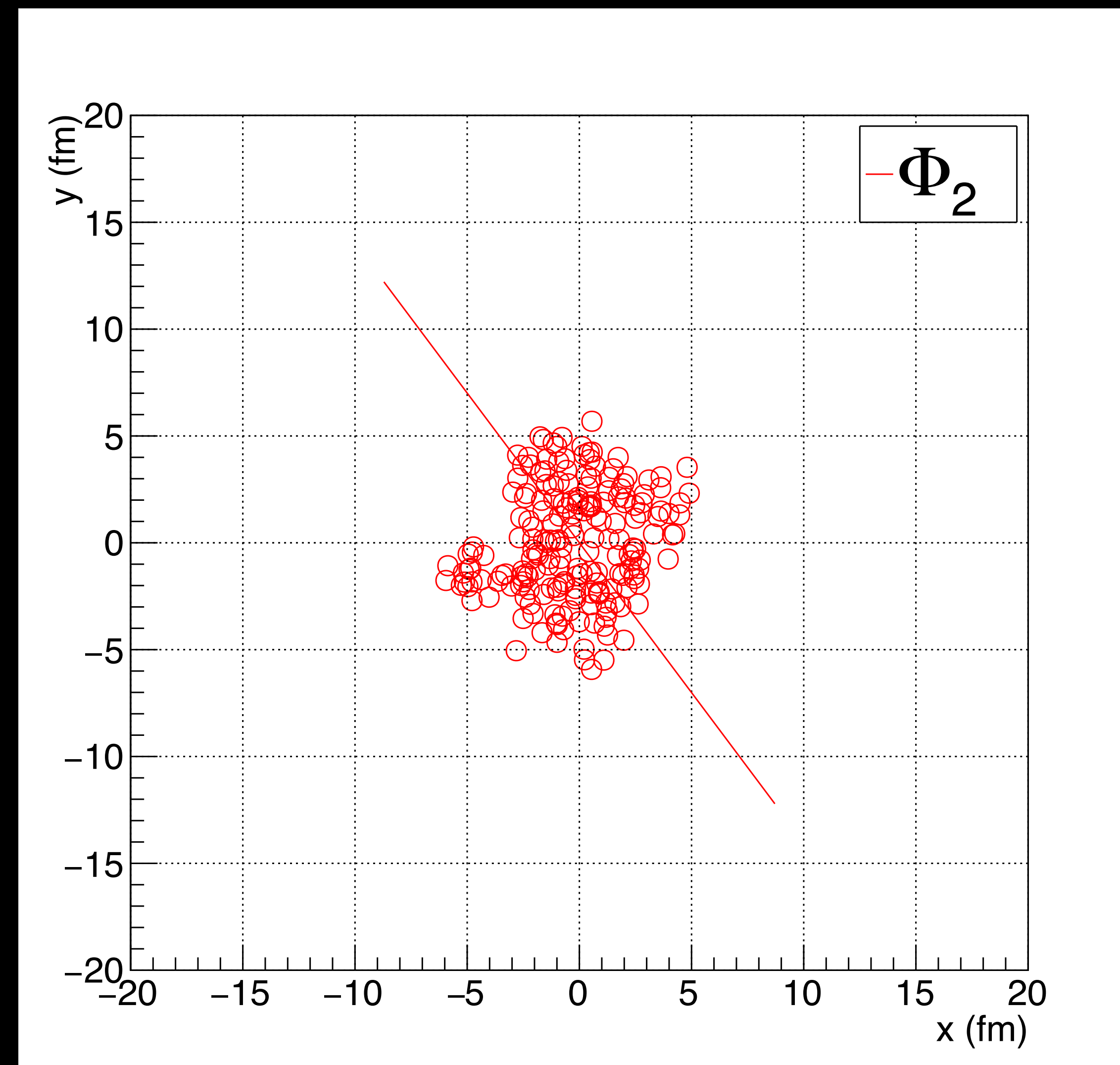
Many Collisions versus the Reaction Plane



Symmetry Plane

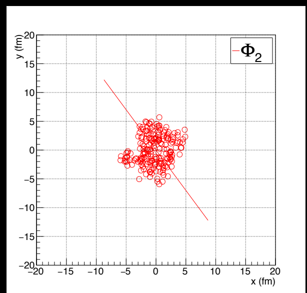




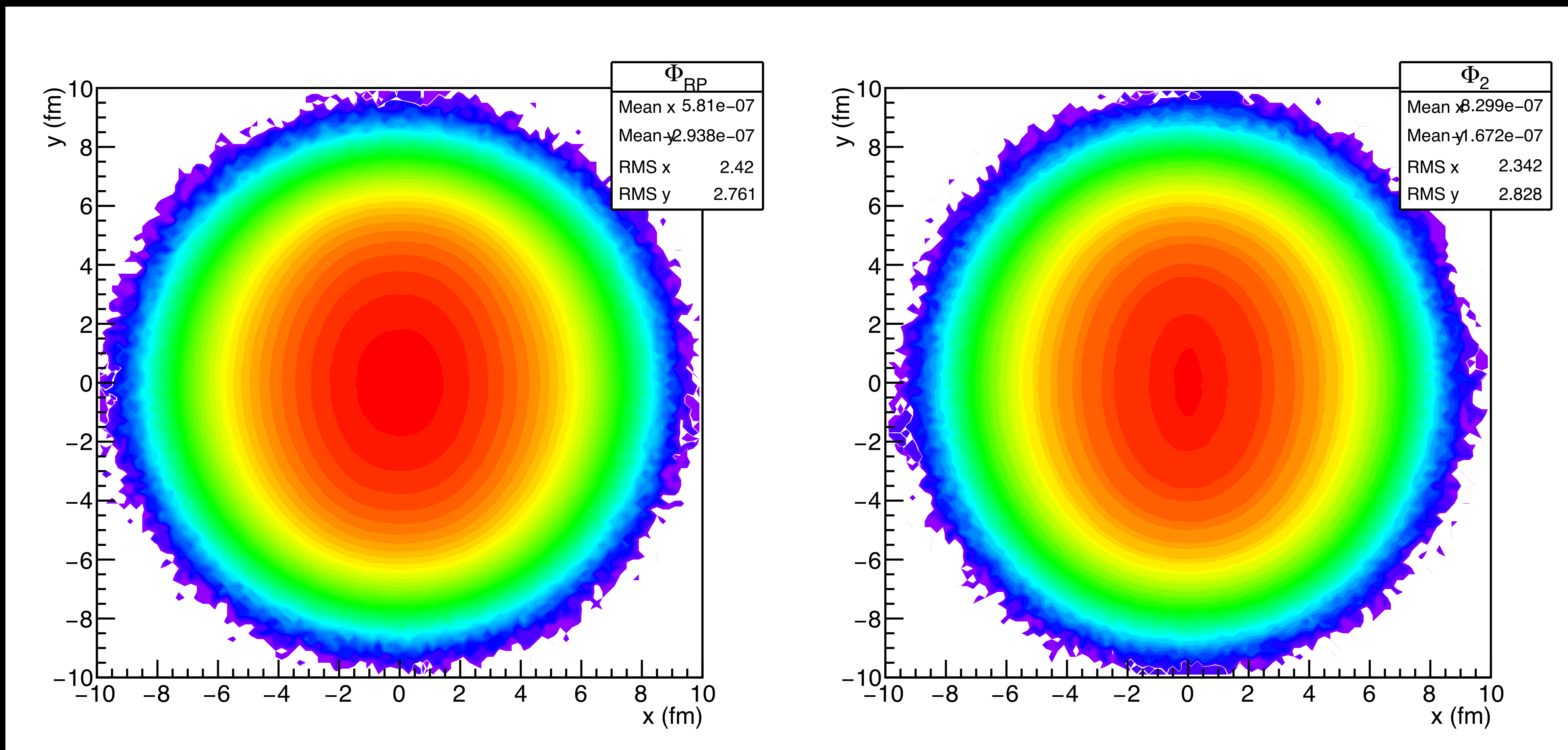


Using the particles produced we (experimentalists) determine, due to the fluctuations, a symmetry plane which is different than the Reaction Plane

$v_n \propto \varepsilon_n$ for n=2 and 3

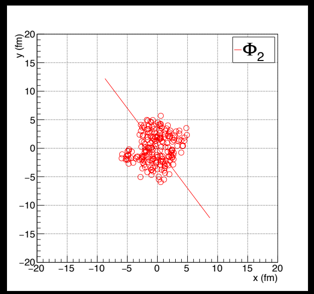


Symmetry Planes



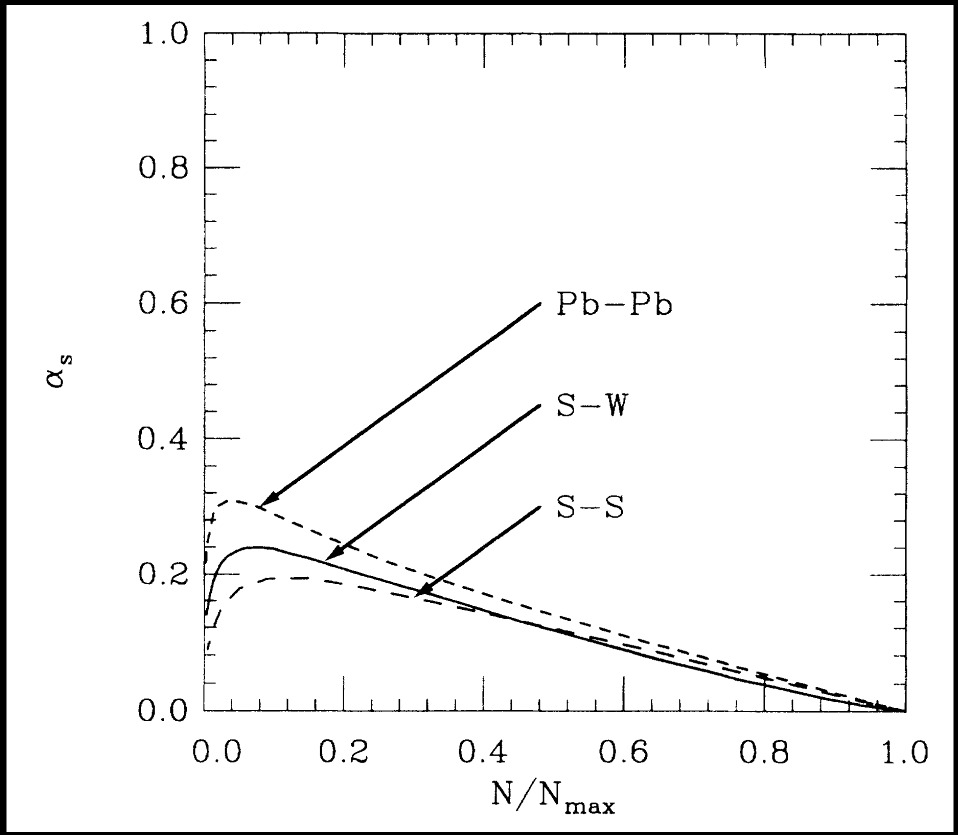
The asymmetry of the system is larger versus this symmetry plane

$v_n \propto \varepsilon_n$ for n=2 and 3

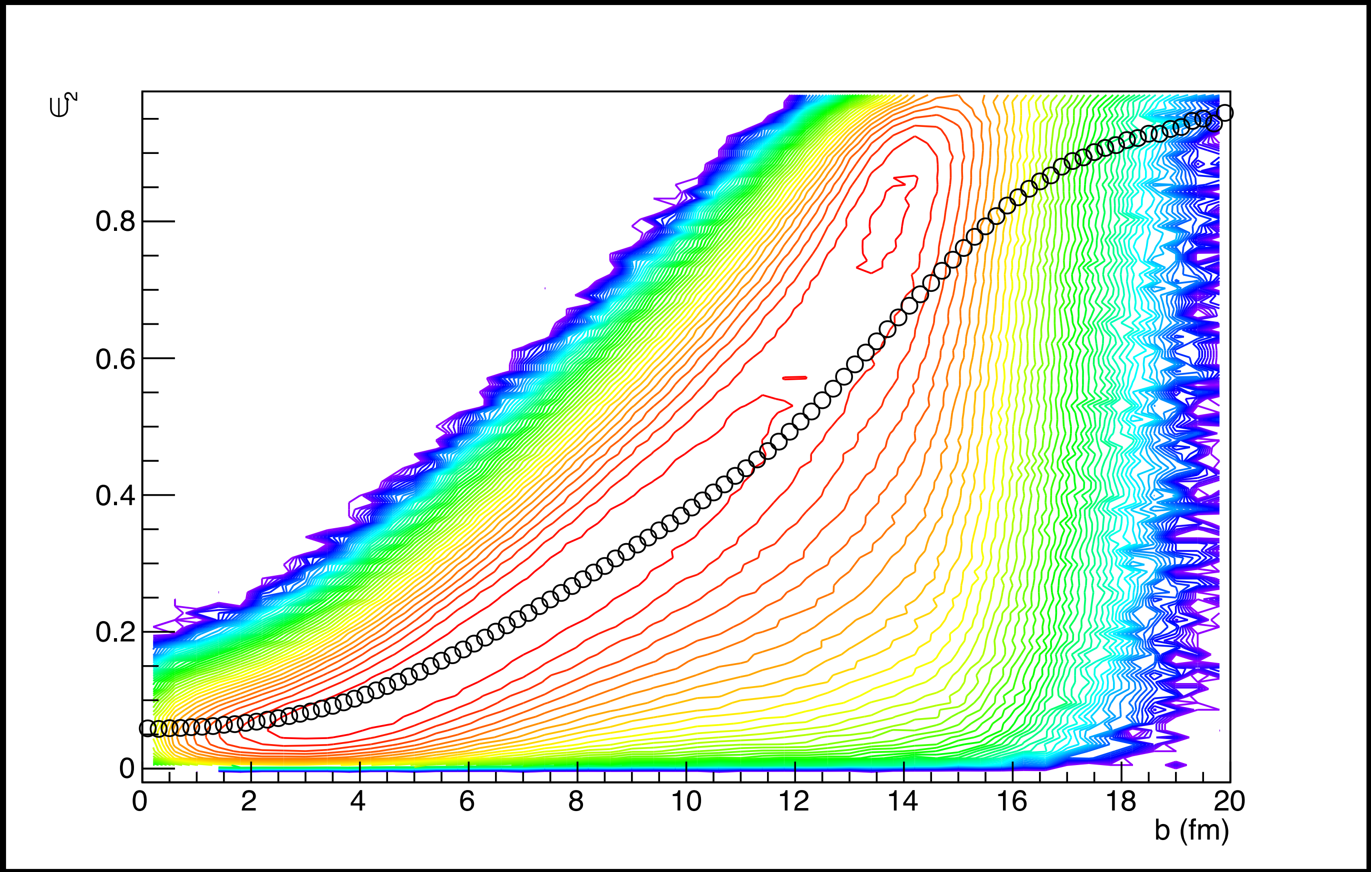


Fluctuations

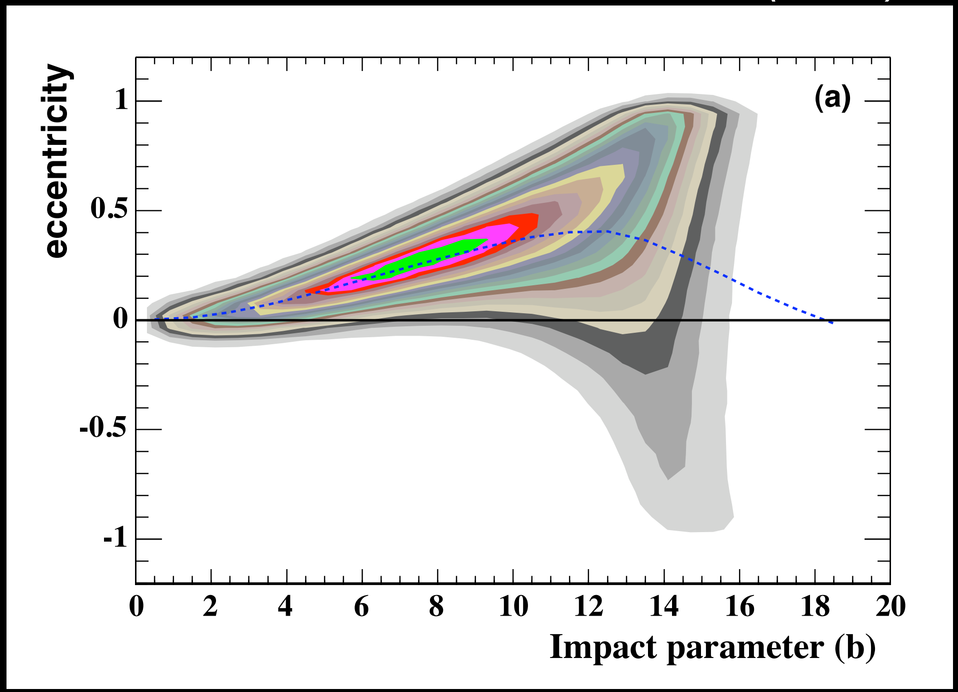
Jean-Yves Ollitrault; PRD 46 (1992)



PHOBOS (2005)



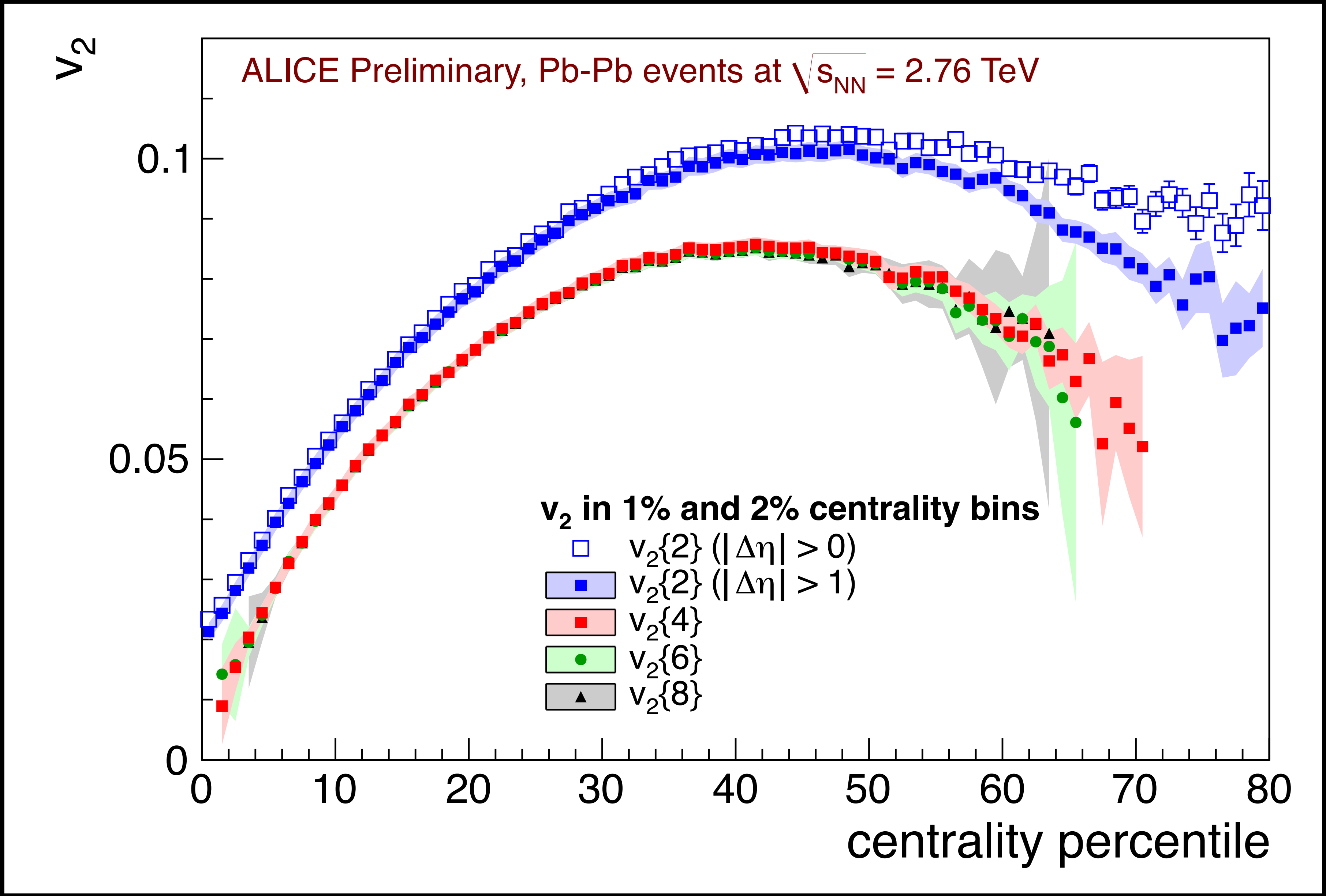
Mike Miller, RS nucl-ex/0312008 (2003)



The asymmetry is larger and even non-zero for perfectly central collisions
This asymmetry in coordinate space is though to be responsible, due to e.g. final state interactions, for the observed anisotropy in particle production

$v_n \propto \varepsilon_n$ for n=2 and 3

Fluctuations



$$v\{2\} = \langle v \rangle + \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle}$$

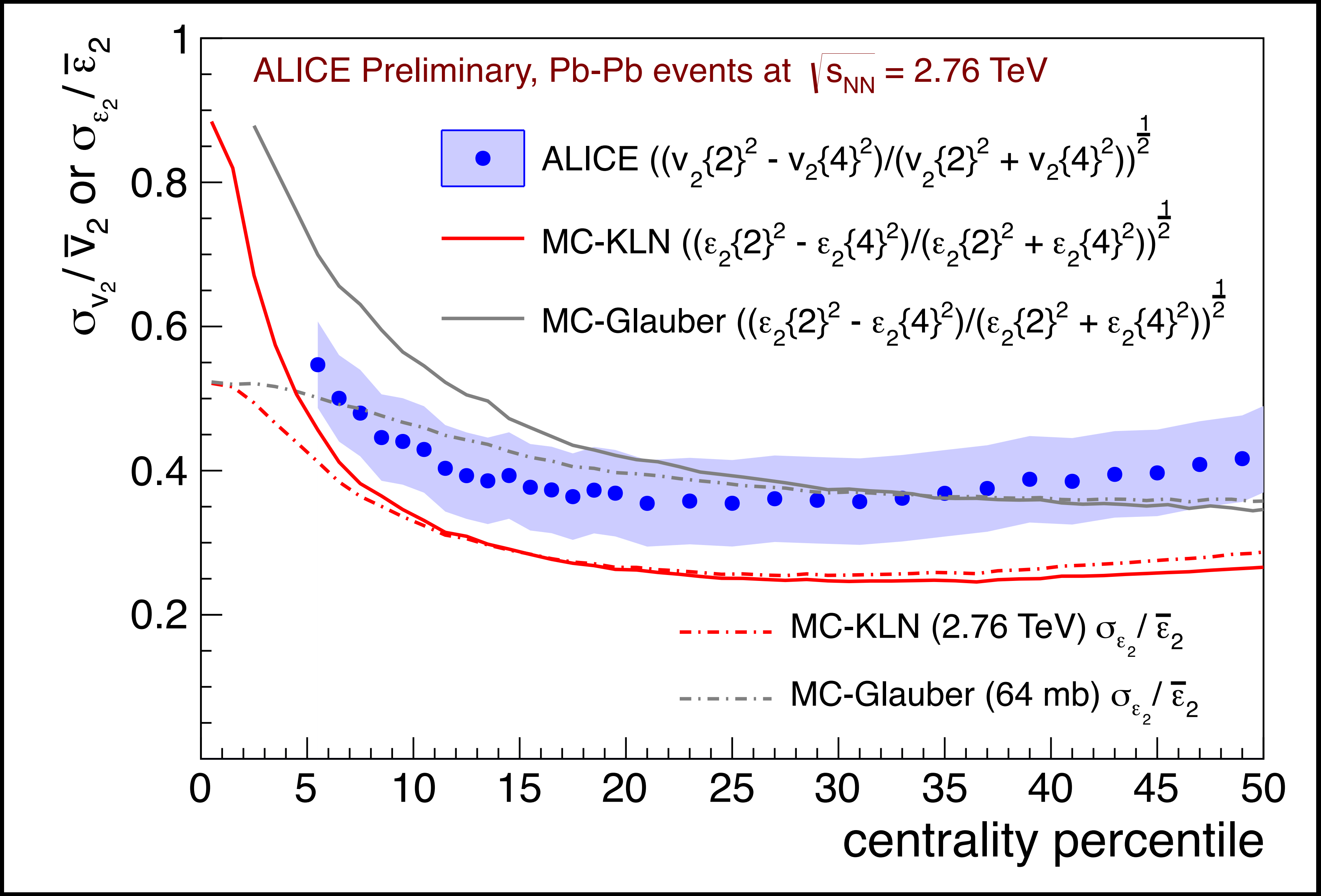
$$v\{4\} = \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle}$$

$$v\{6\} = \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle}$$

$$v\{8\} = \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle}$$

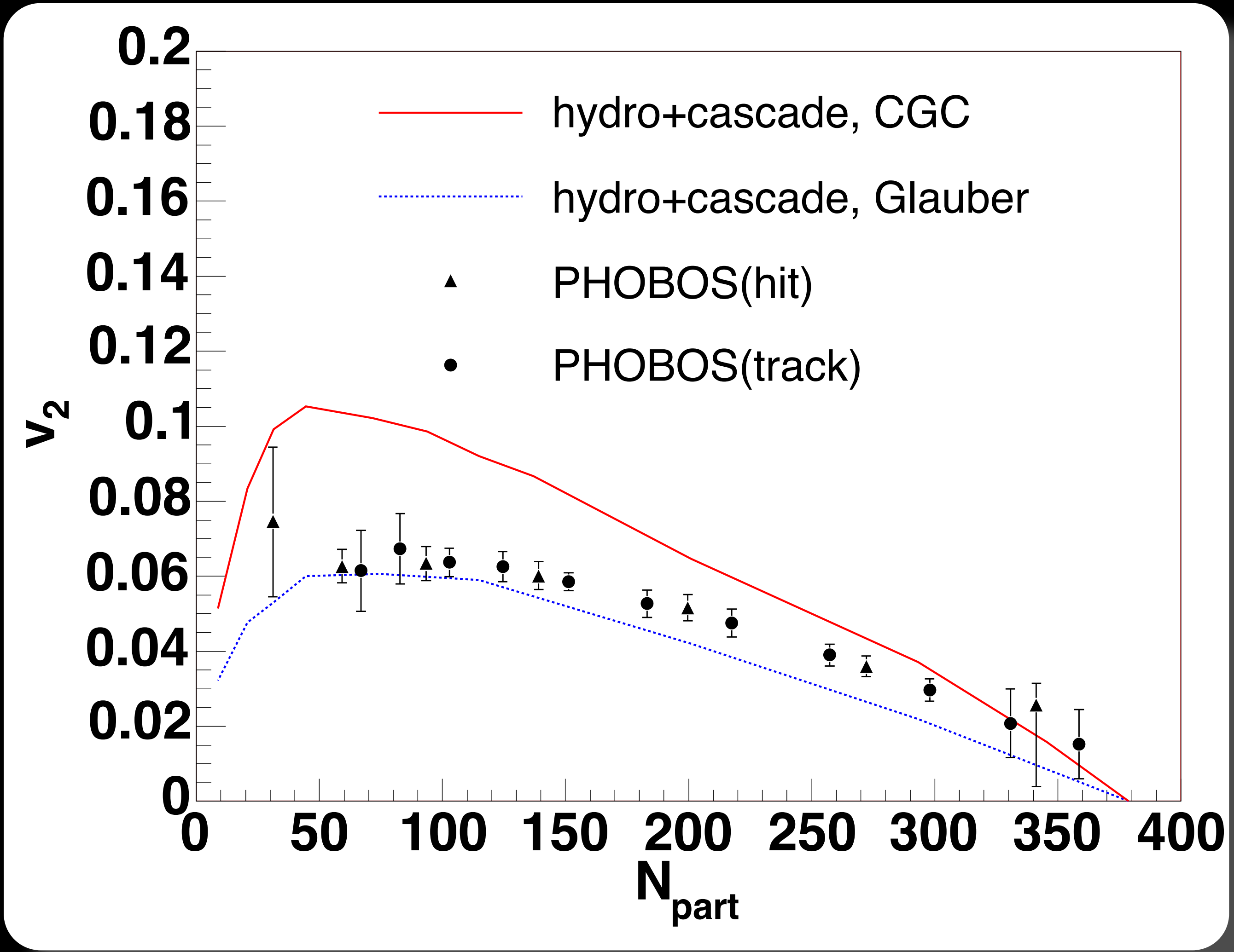
for small fluctuations or specific pdf

Fluctuations



Various initial state models do capture the trend but fail on the details

the initial spatial distributions

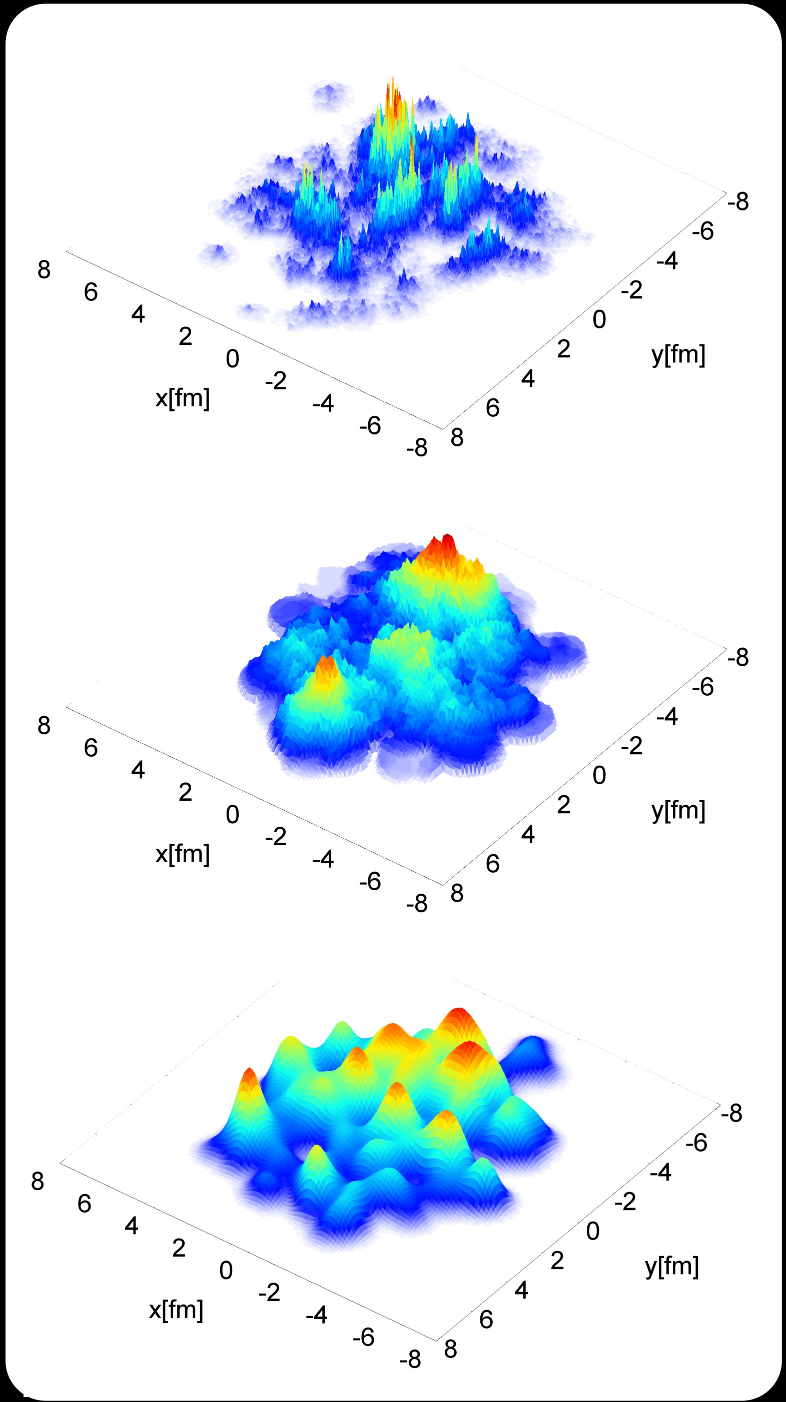


T. Hirano et al., Phys. Lett. B 636 299 (2006)
T. Hirano et al., J.Phys.G34:S879-882,2007

IP-Glasma
gluons + fluctuations

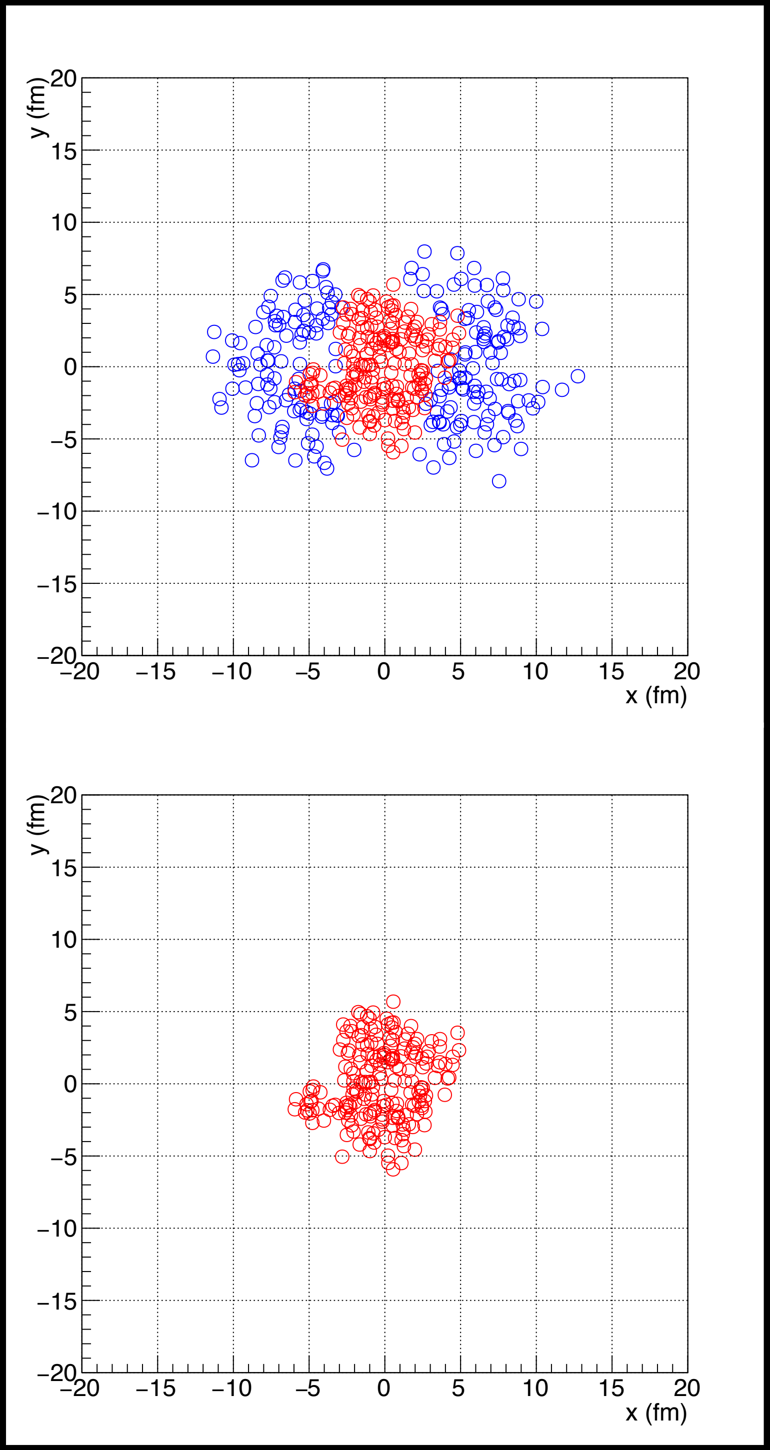
MC-KLN
gluons

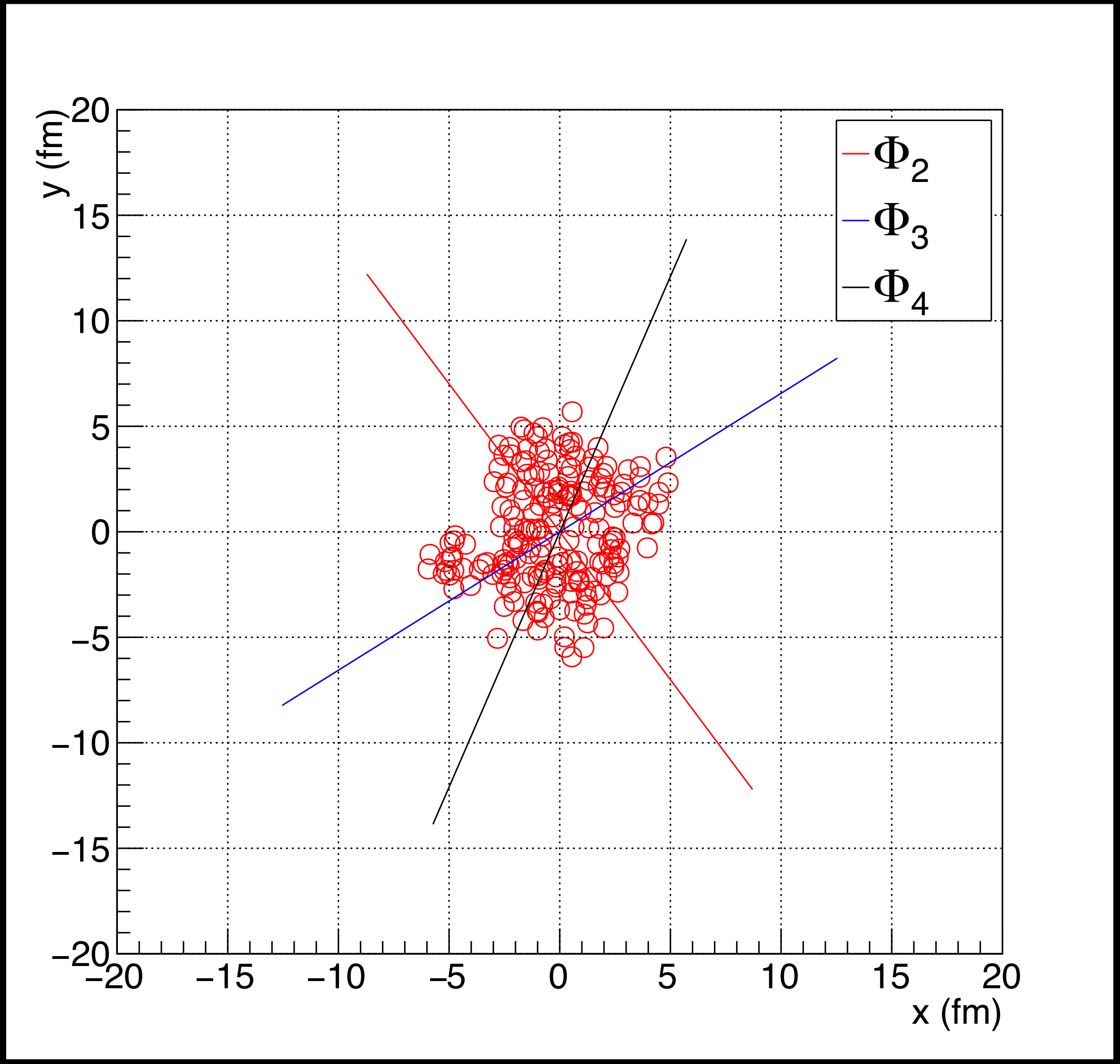
MC-Glauber



- Important input for determining response of the system are the initial conditions

Symmetry Planes



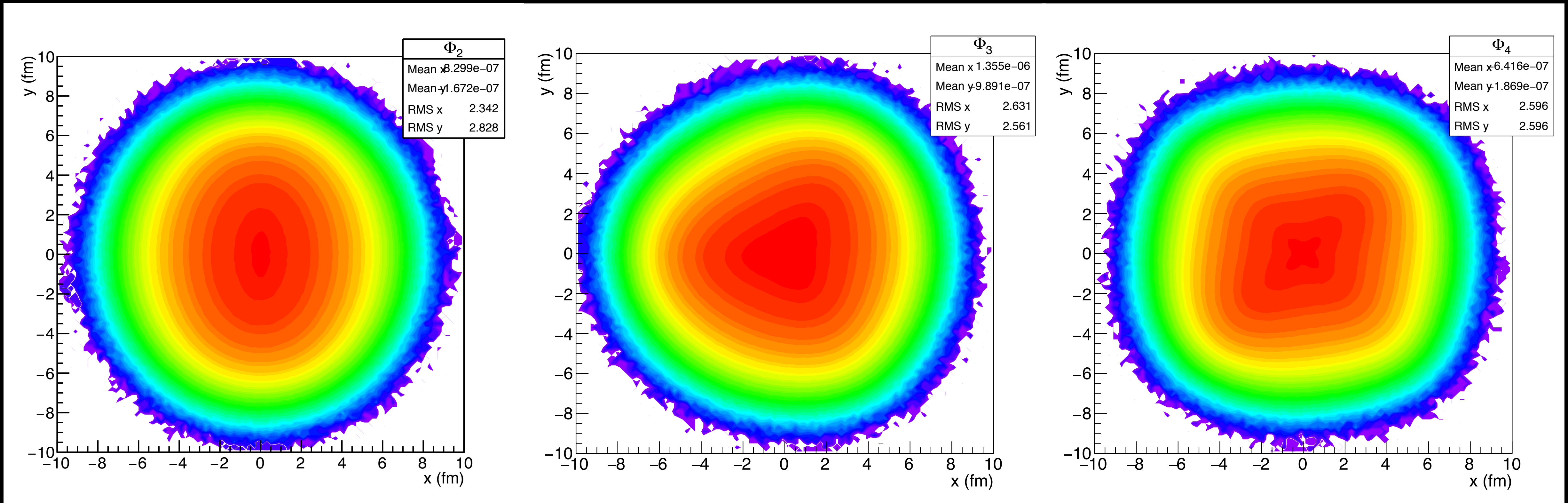


There are many more symmetry planes

$$v_n \propto \varepsilon_n$$

for n=2 and 3

Symmetry Planes

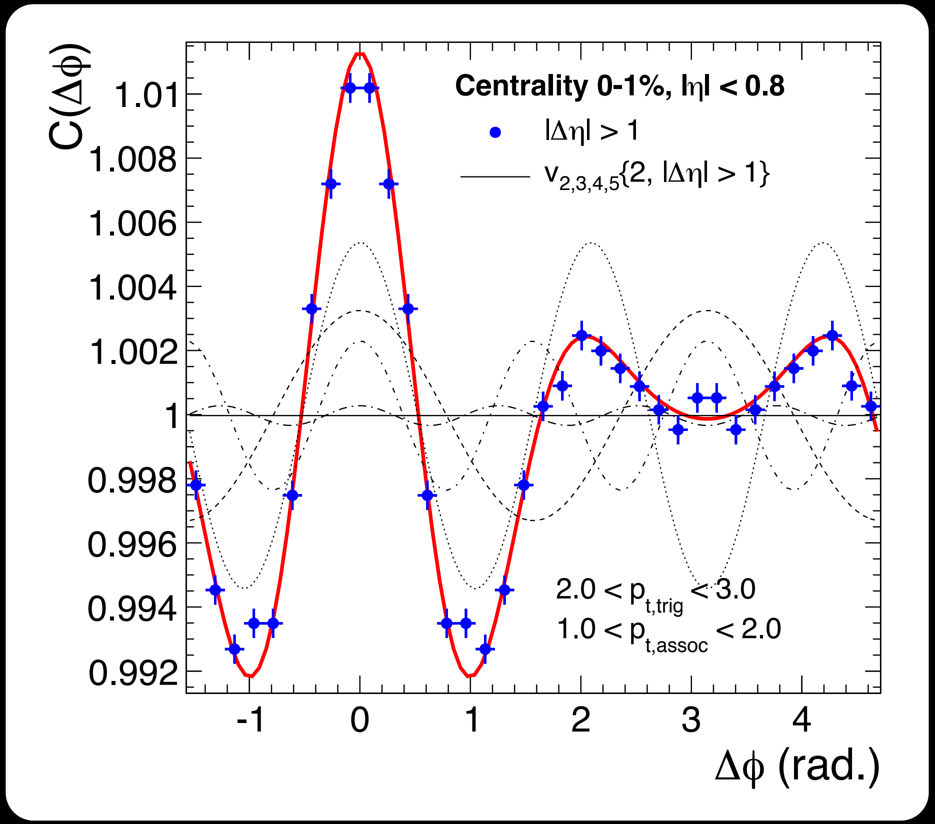


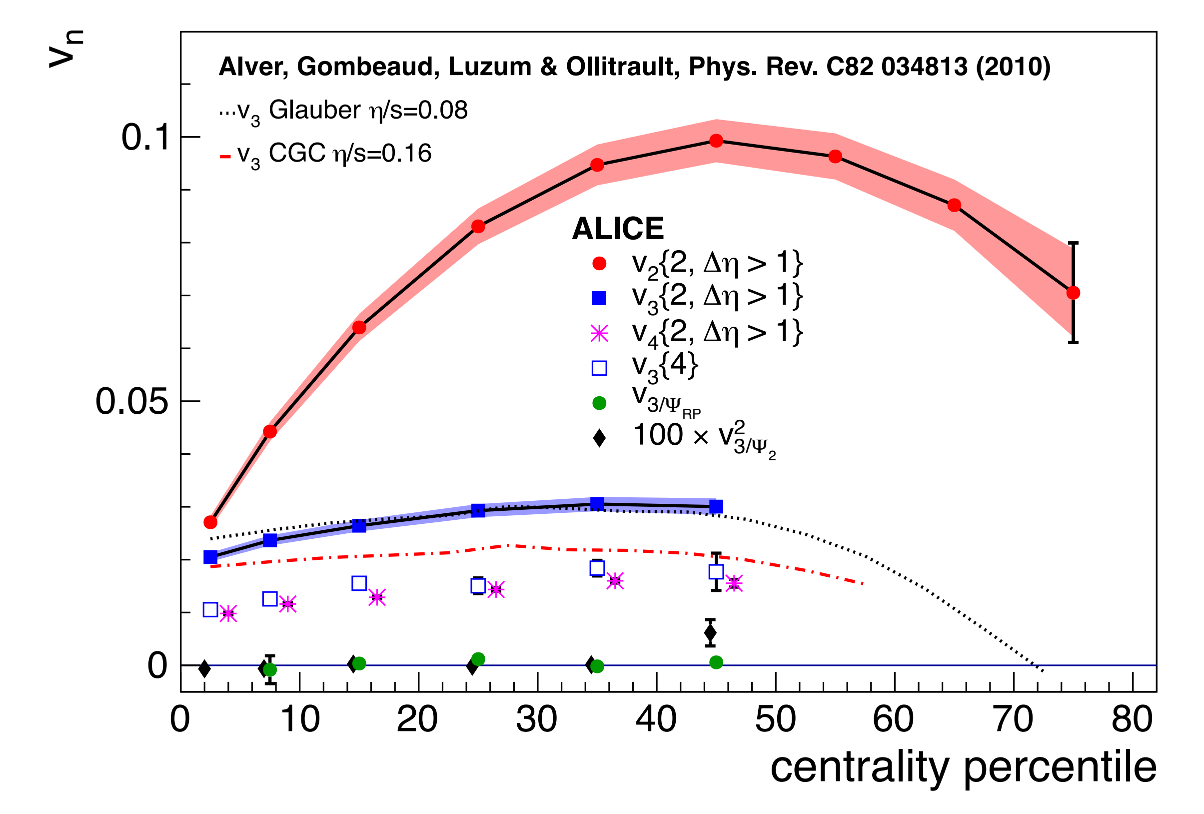
rotated to the planes of symmetry we clearly see the different harmonics

$$v_n \propto \varepsilon_n$$

for n=2 and 3

Higher harmonics



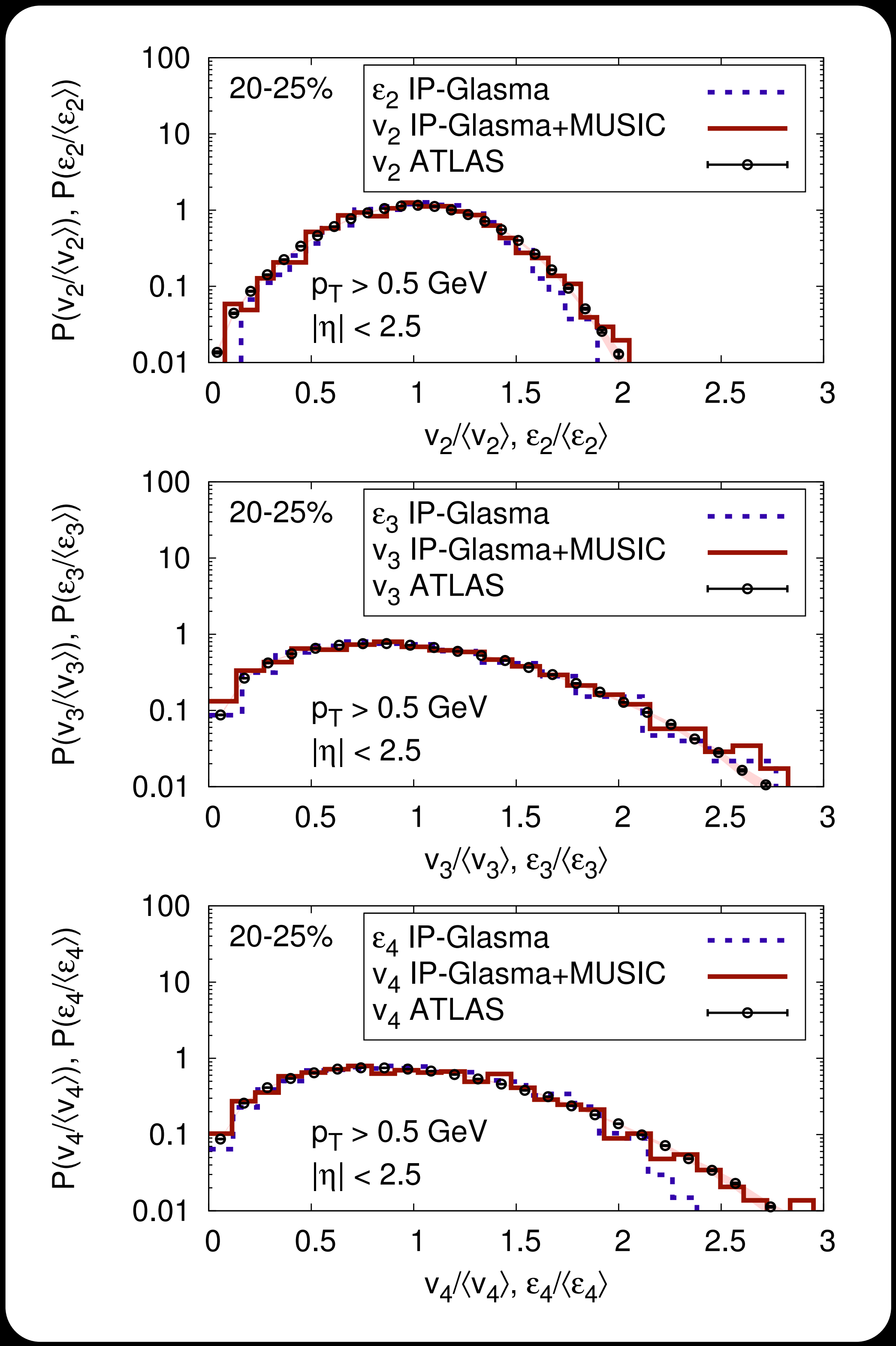


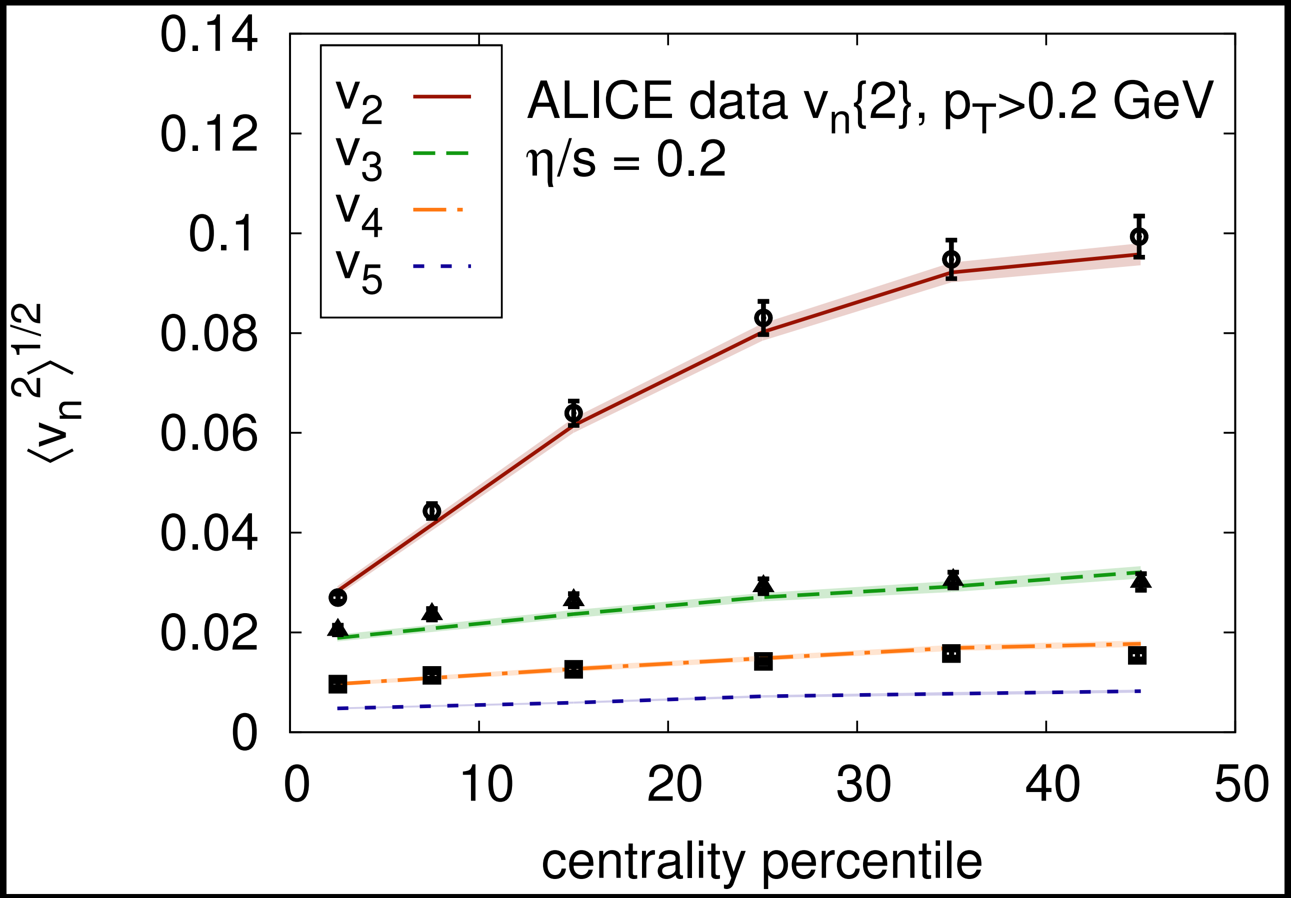
ALICE arXiv:1105.3865 (2011)

ALICE published the first results on higher harmonics showing that for very central collisions the azimuthal correlations showed clear evidence for higher order harmonics without having to do any subtraction

It also showed for the first time that $v_3\{4\}$ is unequal to zero, a signature of the collective effect and the non gaussian fluctuations!

Higher harmonics





- The observables we have are determined by the full probability distribution function!
    - important to constrain this

The nearly perfect liquid paradigm

J. Bernhard, J. Scott Moreland, S. Bass, J. Liu, U. Heinz, arXiv:1605.03954

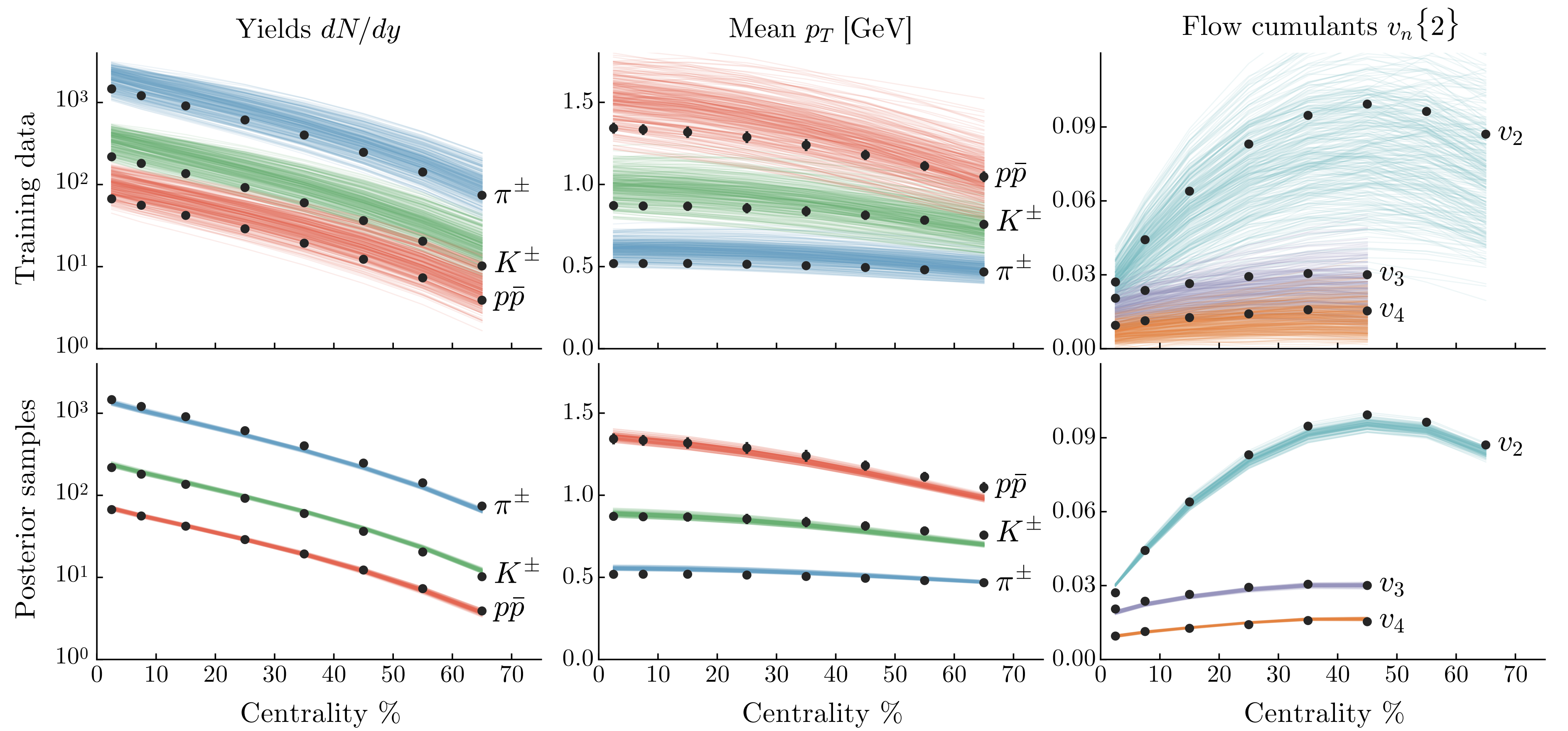


FIG. 8. Simulated observables compared to experimental data from the ALICE experiment [108, 109]. Top row: explicit model calculations for each of the 300 design points, bottom: emulator predictions of 100 random samples drawn from the posterior distribution. Left column: identified particle yields dN/dy, middle: mean transverse momenta $\langle p_T \rangle$, right: flow cumulants $v_n\{2\}$.

Using the Hydro paradigm to constrain parameters

The nearly perfect liquid paradigm

J. Bernhard, J. Scott Moreland, S. Bass, J. Liu, U. Heinz, arXiv:1605.03954

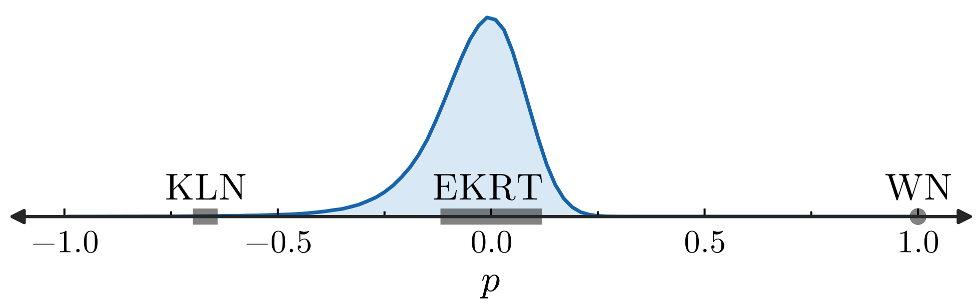


FIG. 9. Posterior distribution of the TRENTo entropy deposition parameter p introduced in Eq. (14). Approximate p-values are annotated for the KLN ($p \approx 0.67 \pm 0.01$), EKRT ($p \approx 0.0 \pm 0.1$), and wounded nucleon ($p = 1$) models.

see talk Kari Eskola

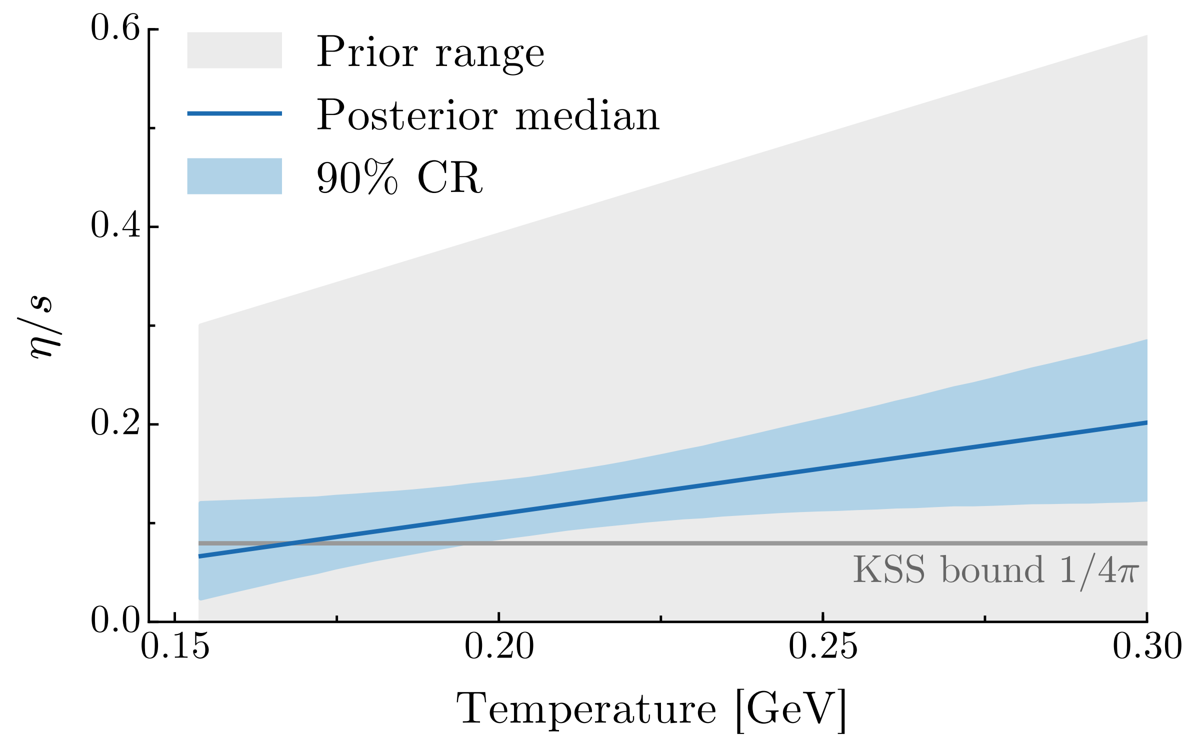
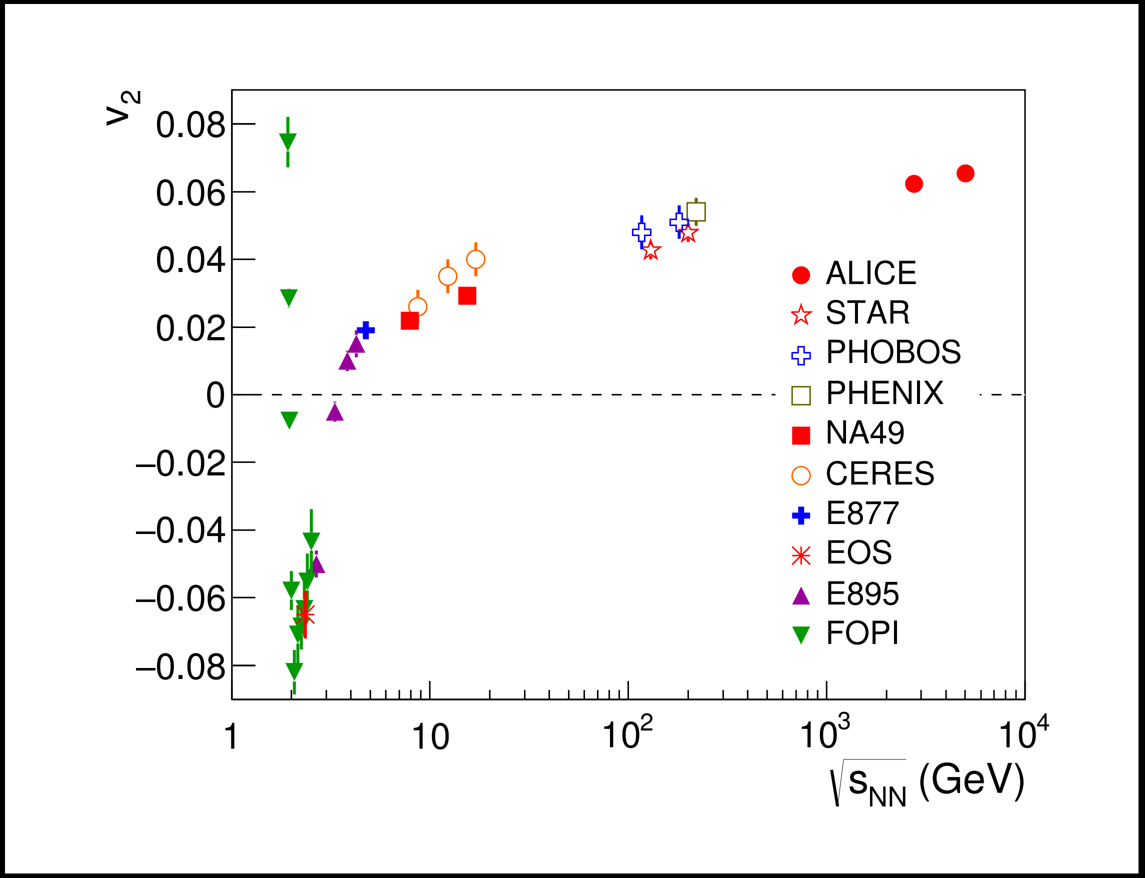
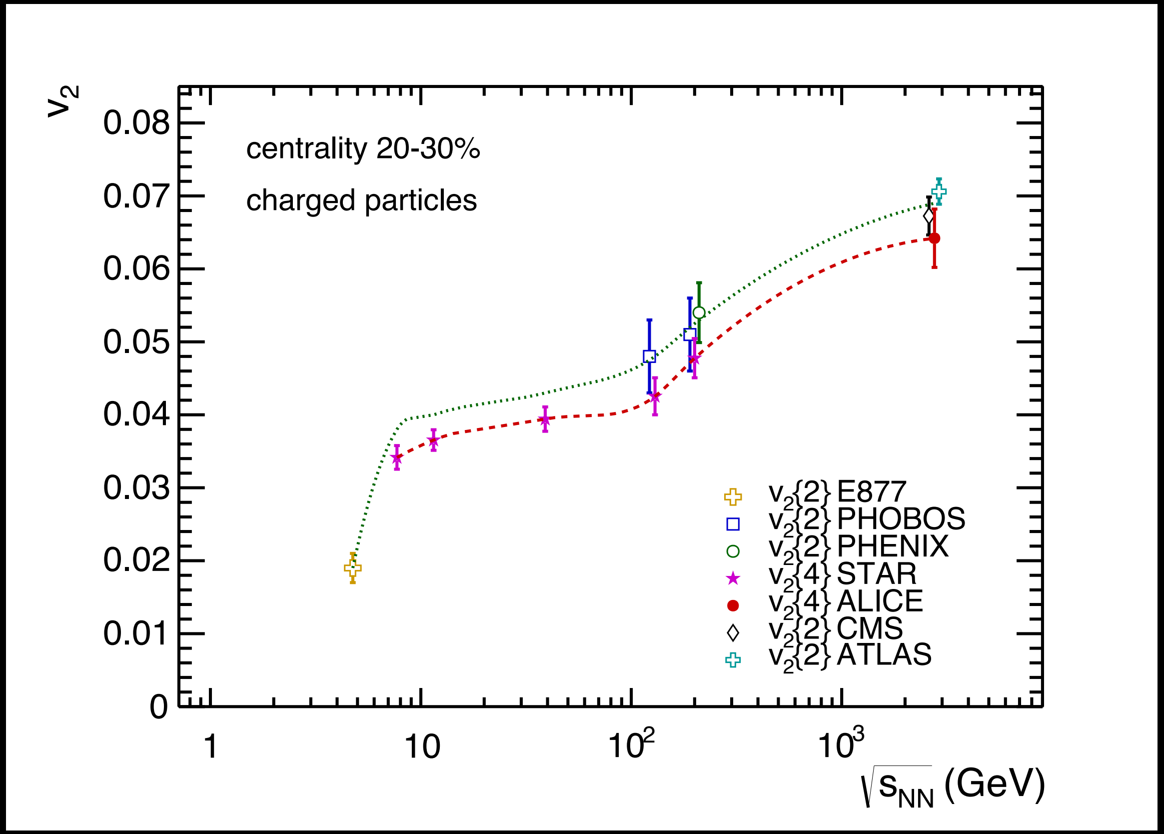


FIG. 10. Estimated temperature dependence of the shear viscosity $(\eta/s)(T)$ for $T > T_c = 0.154$ GeV. The gray shaded region indicates the prior range for the linear $(\eta/s)(T)$ parametrization Eq. (31), the blue line is the median from the posterior distribution, and the blue band is a 90% credible region. The horizontal gray line indicates the KSS bound $\eta/s \geq 1/4\pi$ [12–14].

smallest uncertainties at temperatures which determine the anisotropic flow at the LHC

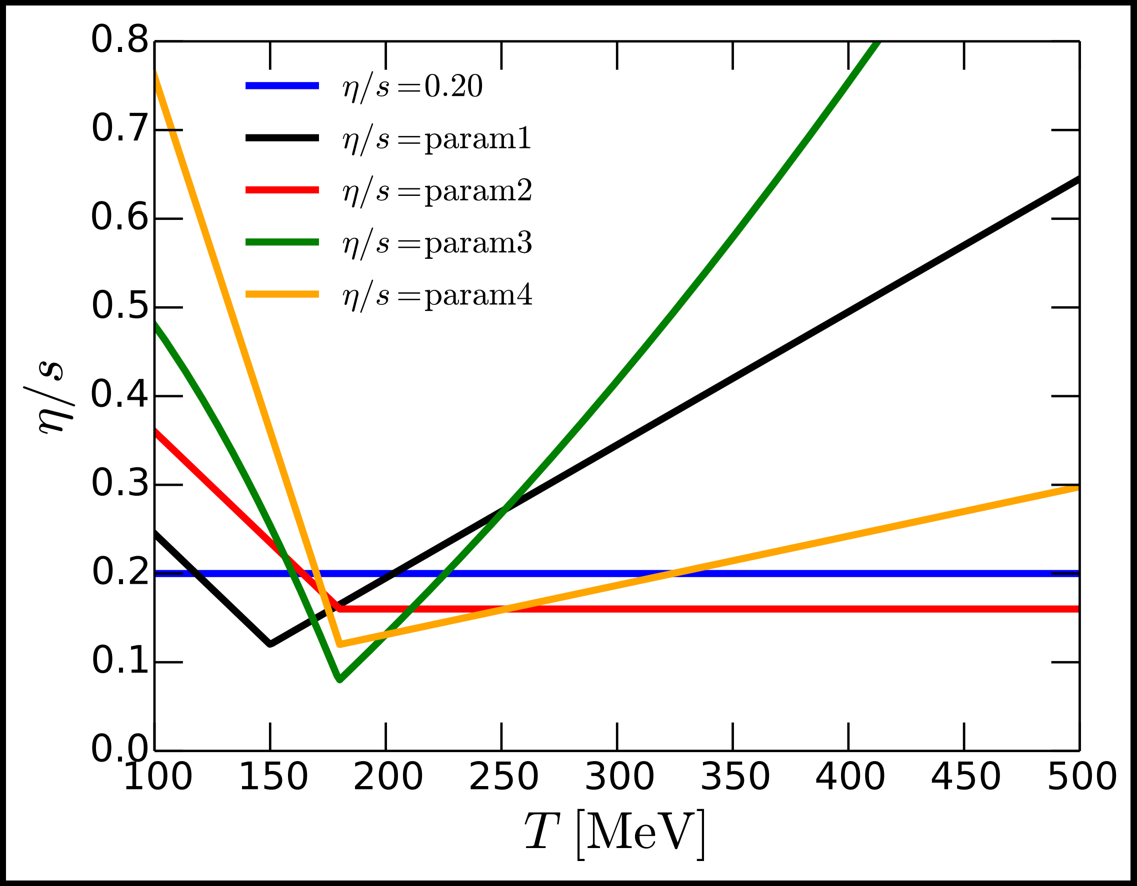
The nearly perfect liquid paradigm
how to improve our knowledge?



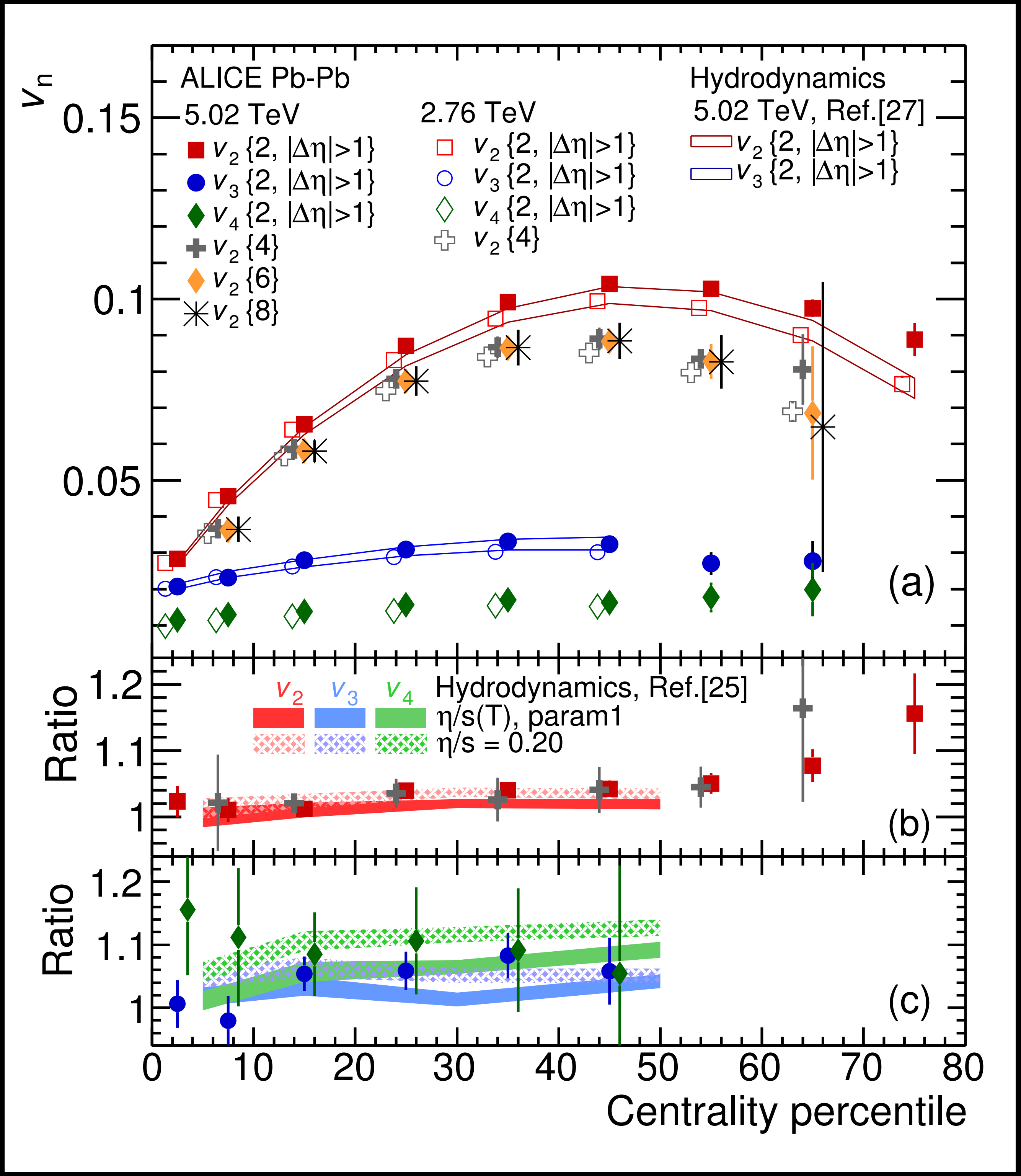


can be improved by using data from RHIC and the LHC at the different energies

The nearly perfect liquid paradigm how to improve



arXiv:1505.02677



detailed calculations for LHC at different energies

constraints will improve when full dataset is analysed

The nearly perfect liquid paradigm

Is our picture correct??

J. Bernhard, J. Scott Moreland, S. Bas[illegible], J. L[illegible], U. [illegible]einz, arXiv:1605.03954

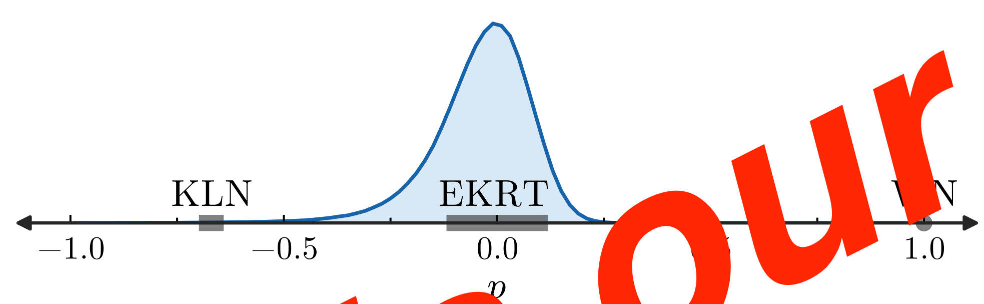
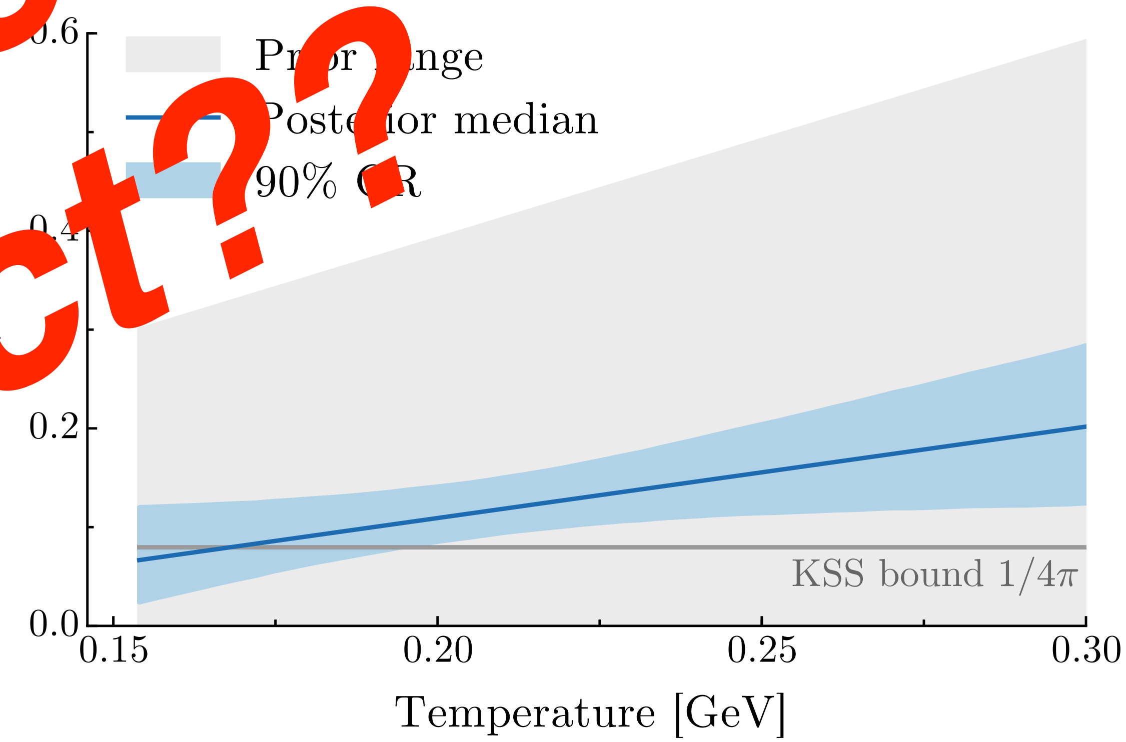


FIG. 9. Posterior d[illegible]ributio[illegible] of the $\mathrm{T_RENTo}$ entropy de[illegible] position parameter p [illegible]tr[illegible]ced in Eq. (14). Appr[illegible]ima[illegible] p-values are annotated for the KLN ($p \approx 0.67 \pm$ [illegible]), EKRT ($p \approx 0.0 \pm 0.1$), and wounded [illegible] (p [illegible] 1) models.

see talk Kari Eskola

smallest uncertainties at temperatures which determine the anisotropic flow at the LHC



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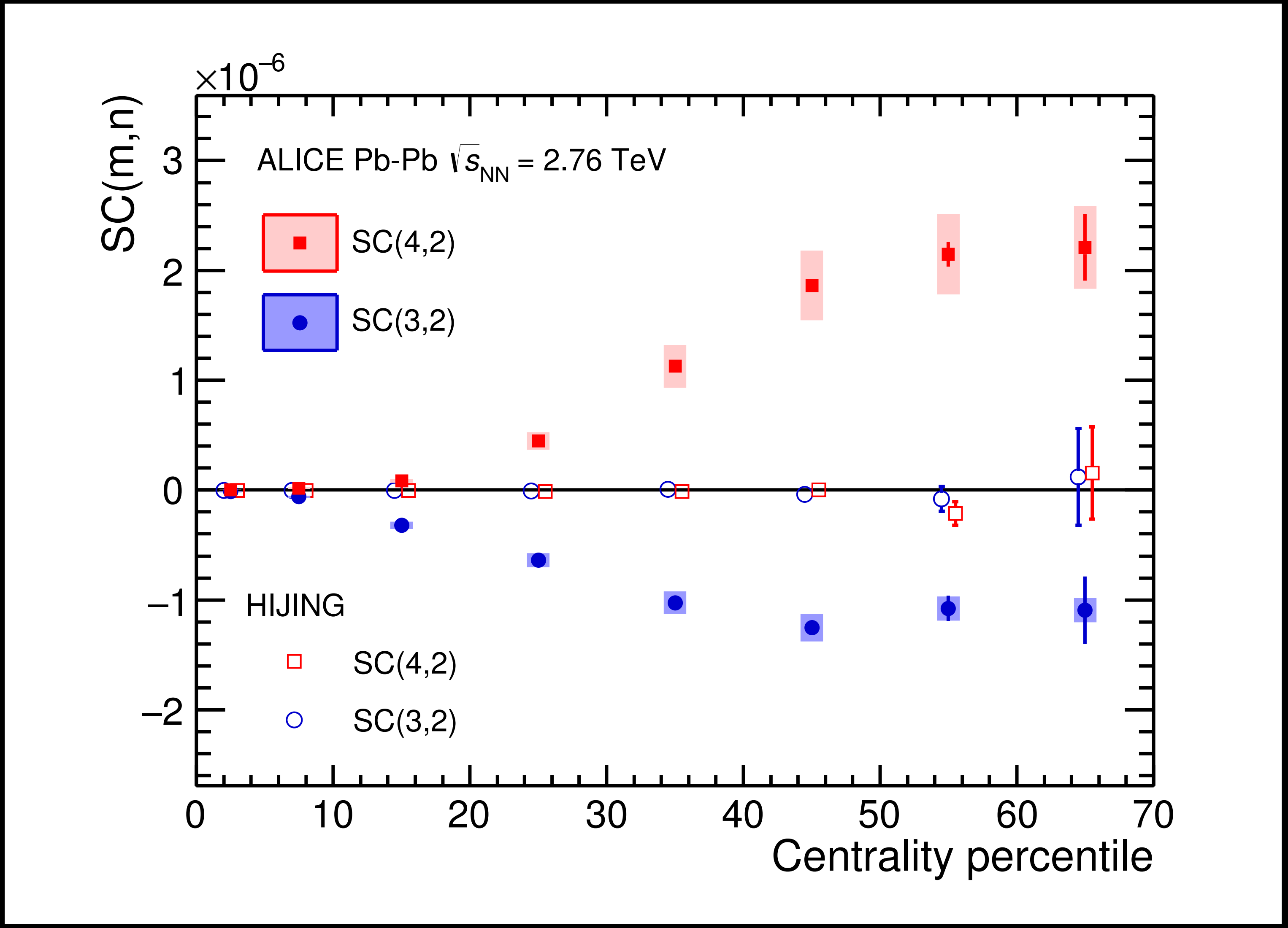
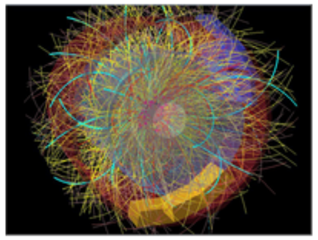
How well do we understand the dynamics?

- $SC(m,n) = \langle v^2_m v^2_n \rangle - \langle v^2_m \rangle \langle v^2_n \rangle$ measures correlations between magnitudes of v_n and v_m
- while both terms are nonzero in most models, the SC are zero in HIJING this illustrates that they are nearly insensitive to nonflow
- a clear correlations between v_2 and v_4 and anti-correlation between v_2 and v_3 are measured by ALICE



ALICE arXiv:1604.07663



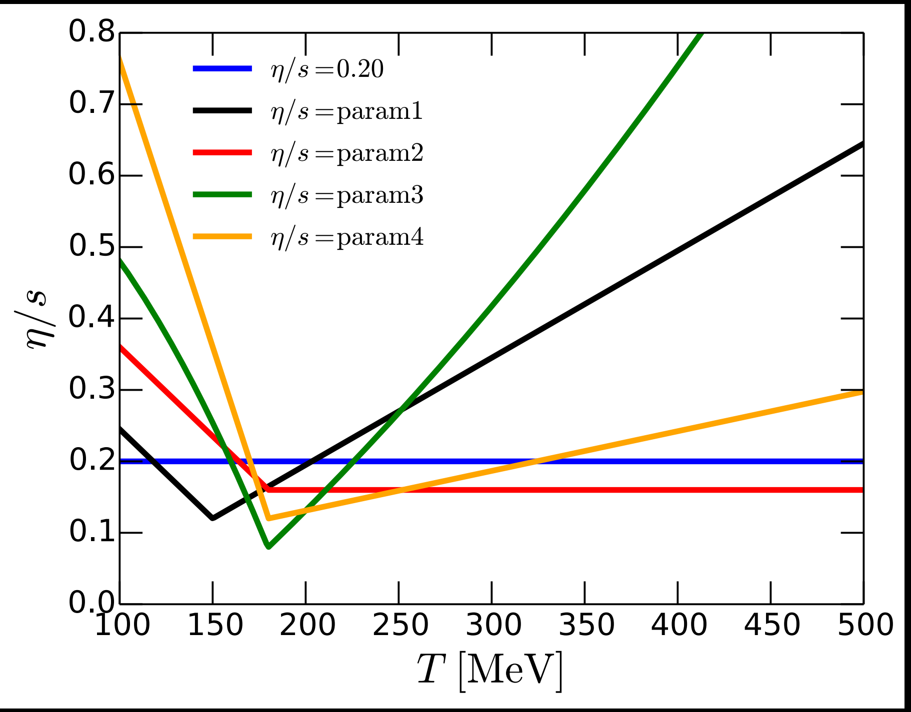
Correlated event-by-event fluctuations of flow harmonics in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

J. Adam *et al.* (ALICE Collaboration)

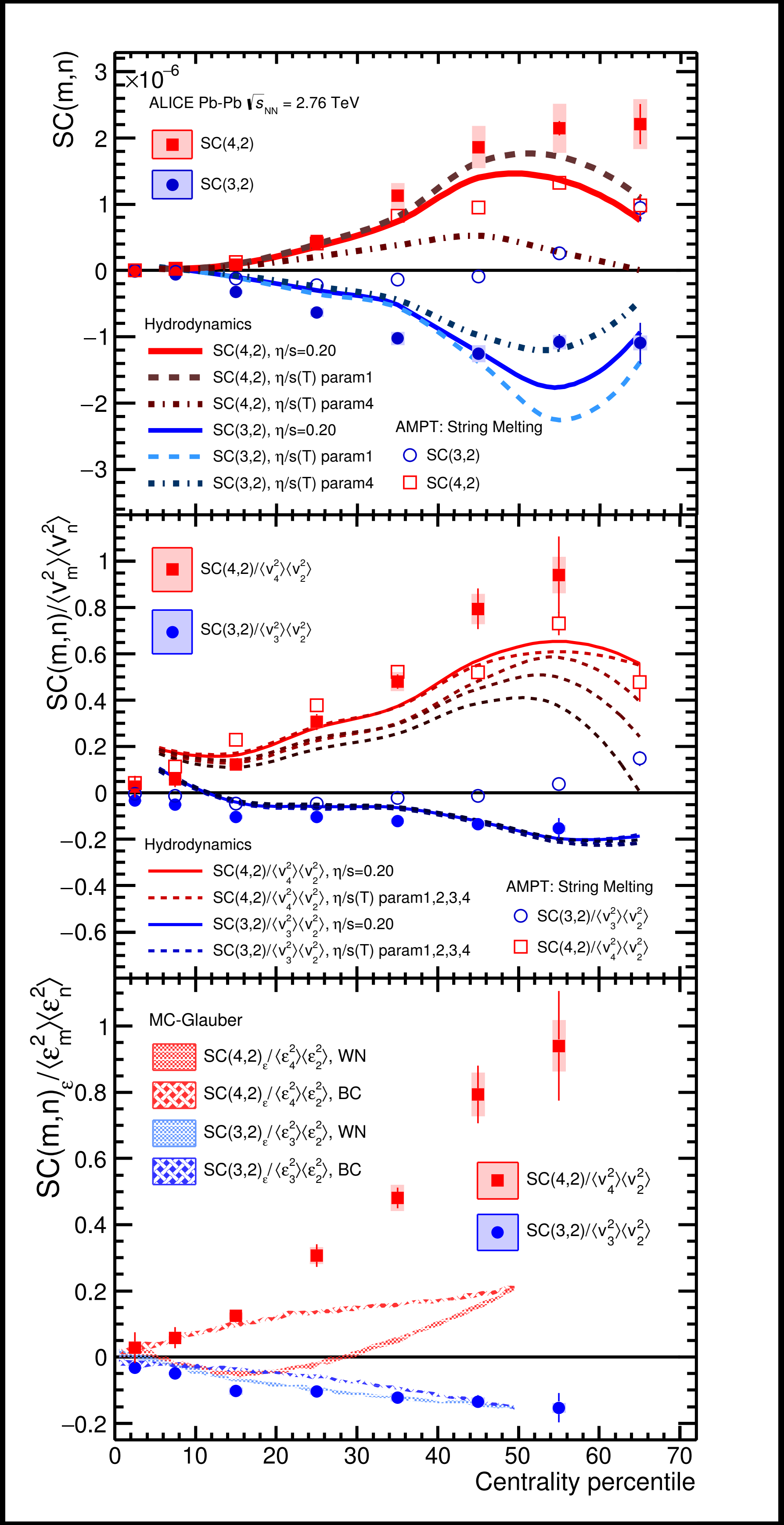
Phys. Rev. Lett. **117**, 182301 (2016)

Published 28 October 2016

How well do we understand the dynamics?



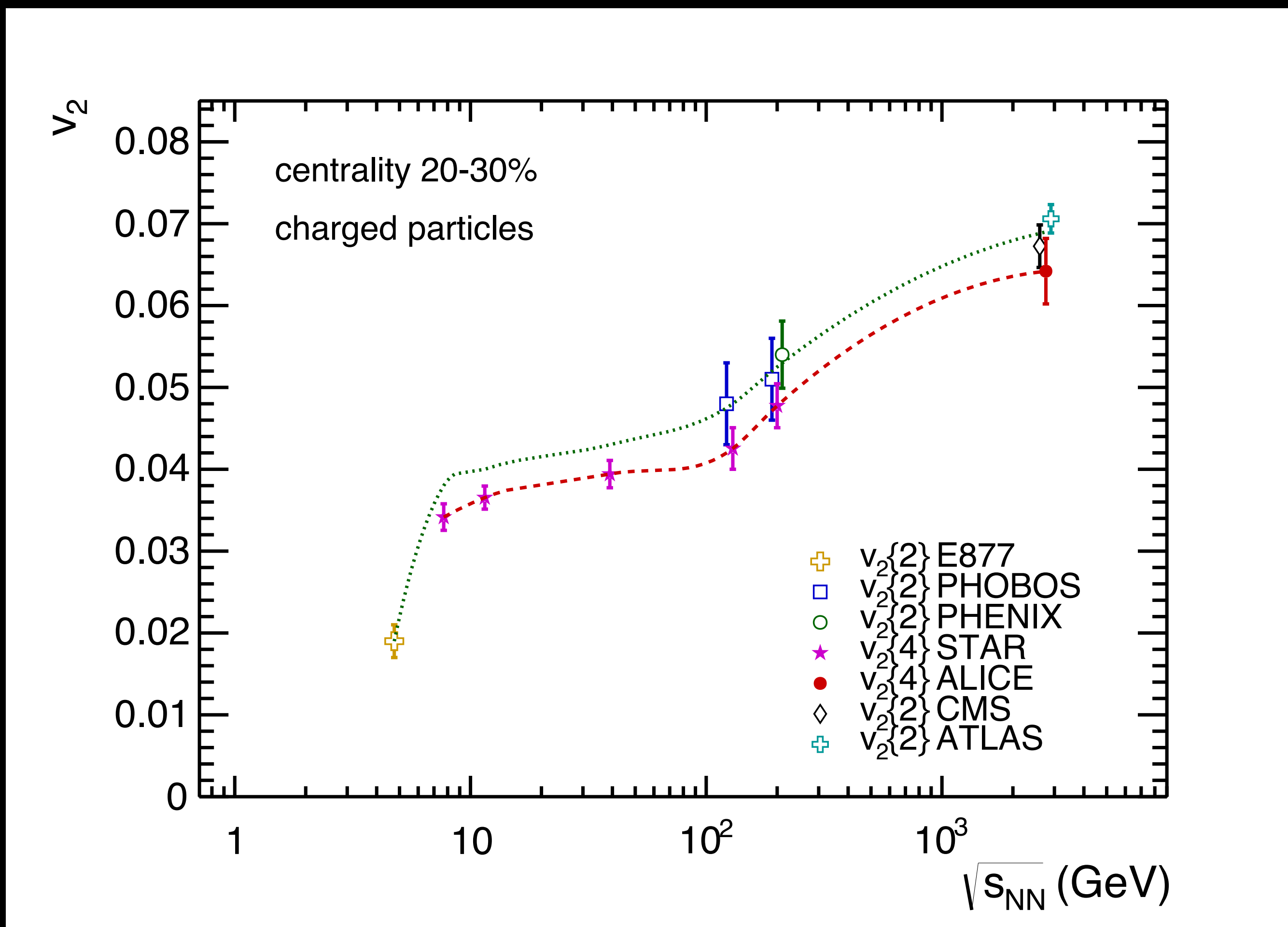
arXiv:1505.02677

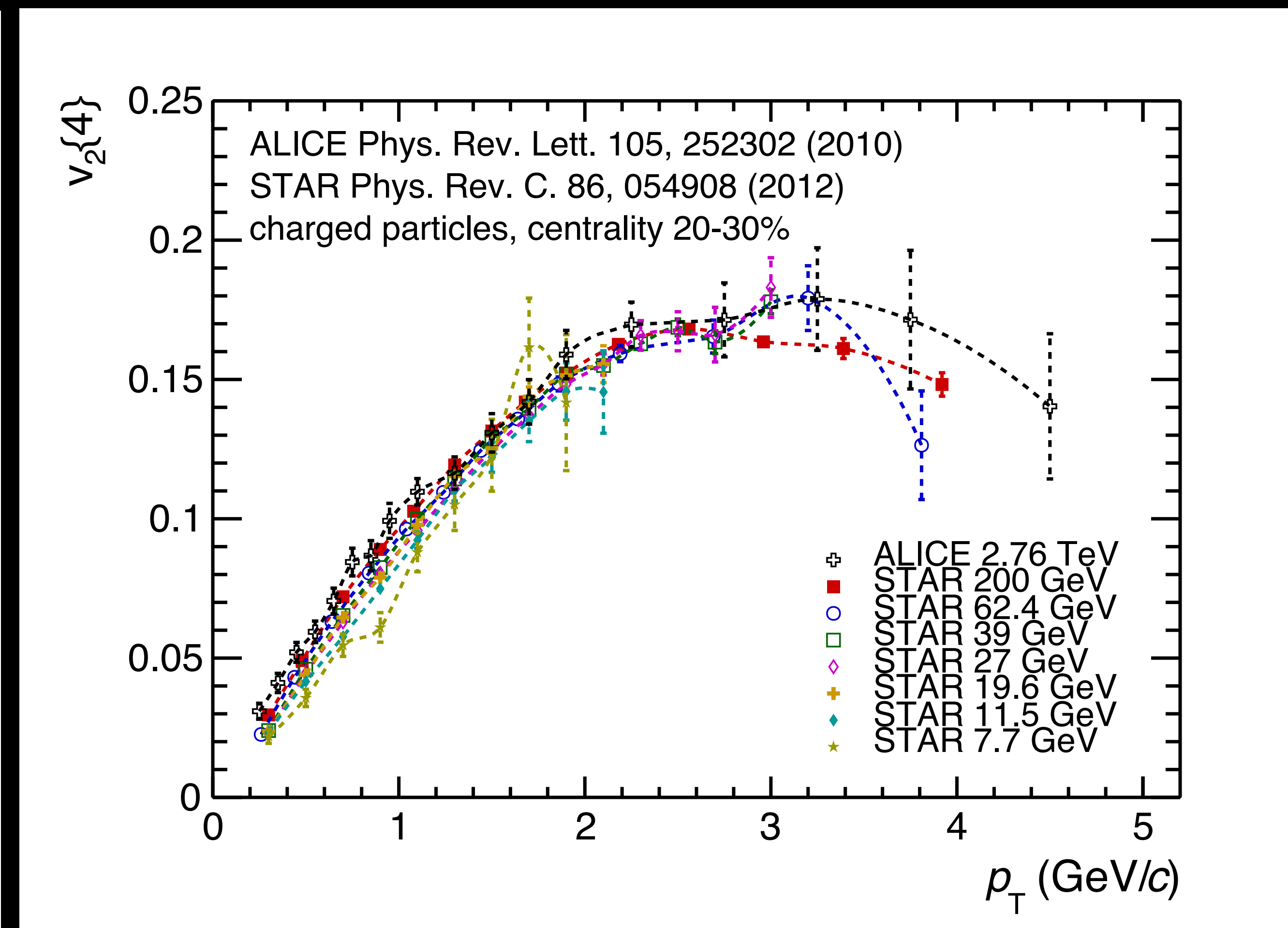


- Hydrodynamics describes the trend in the correlation, however does not describe quantitatively the magnitude

ALICE arXiv:1604.07663

How well do we understand the dynamics?

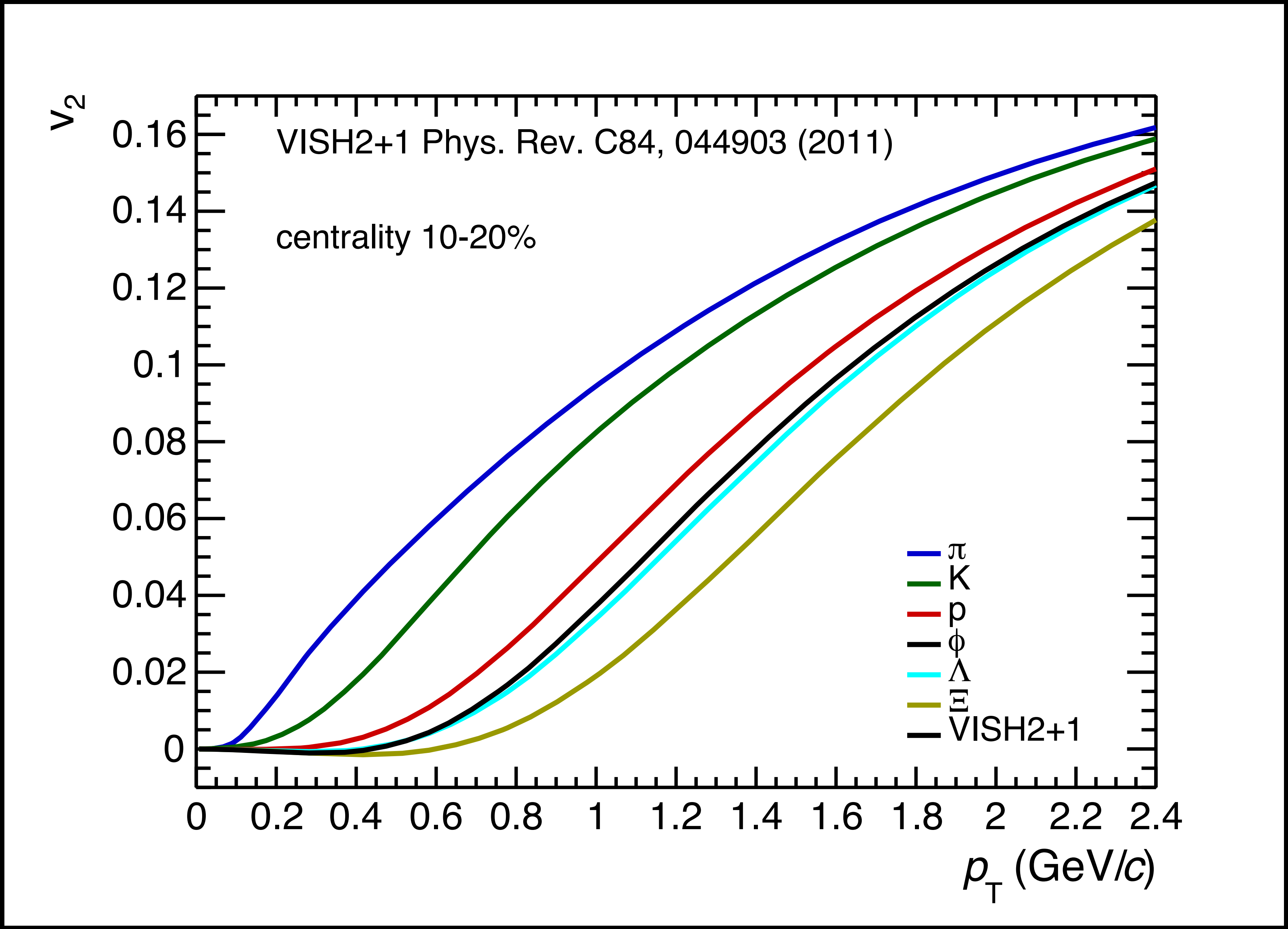




Elliptic flow increases from RHIC to LHC collision energies about 30%
Detailed measurements of $v_2\{4\}$ at RHIC in the beam energy scan combined with the LHC measurements show tantalising evidence for a change in slope.

The p_T-differential elliptic flow also increases with collision energy but difference is small over two orders of magnitude
Is this expected/understood?

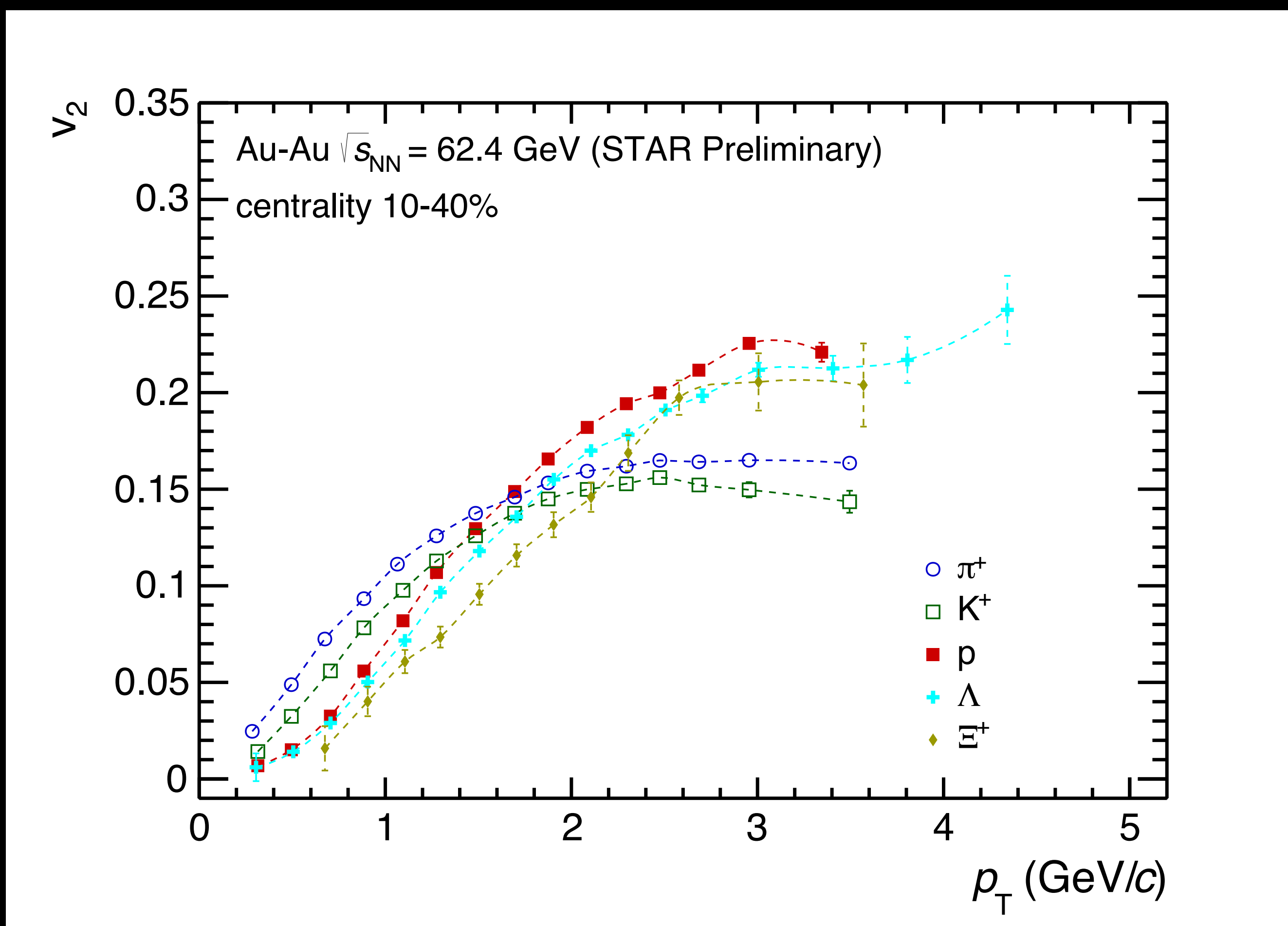
How well do we understand the dynamics?



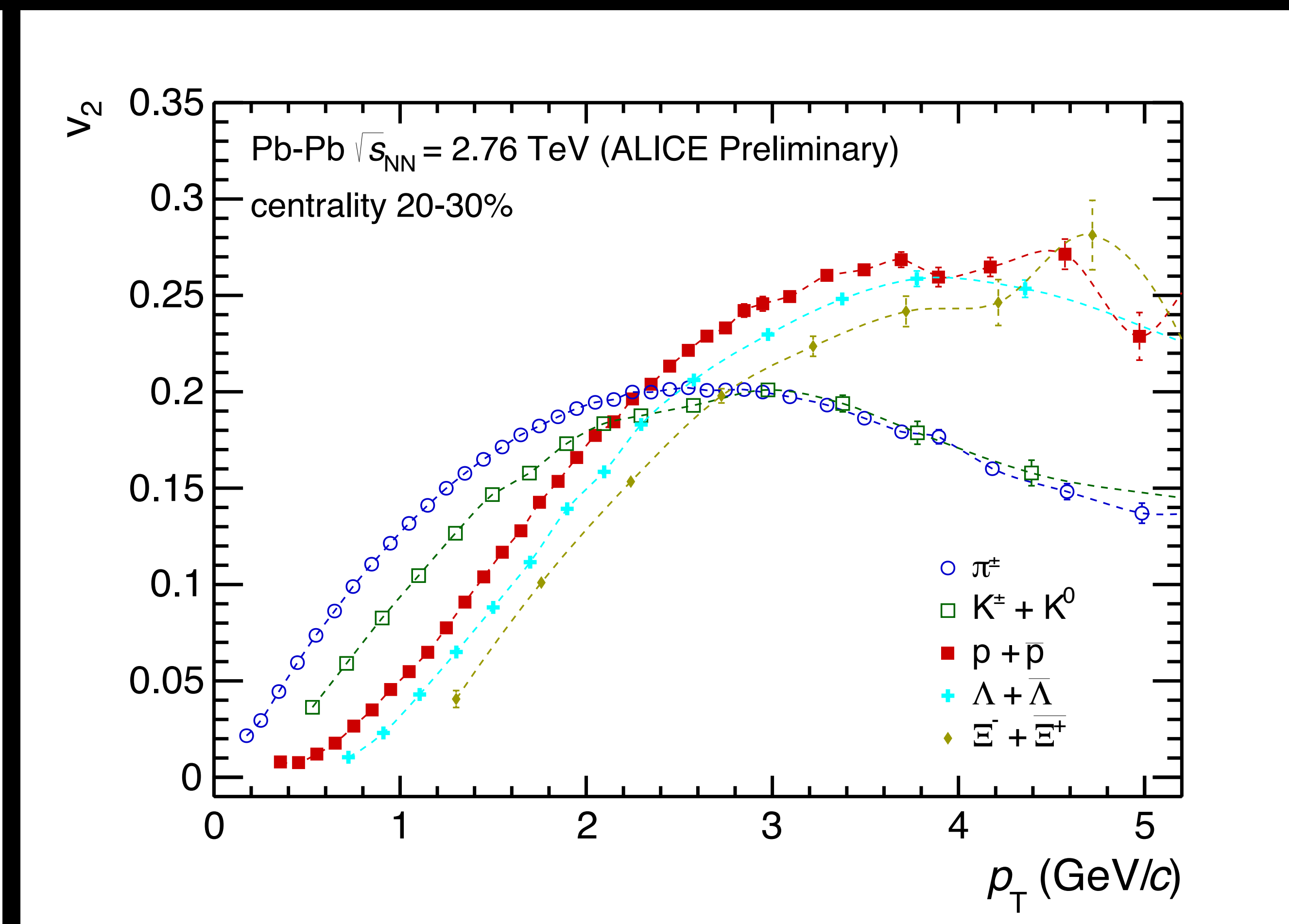
In the hydro picture particles have a common temperature and flow velocity at freeze-out. The difference in p_T-differential elliptic flow depends mainly on one parameter: the mass of the particle and changes with the magnitude of the radial flow

Collision energy dependence of elliptic flow for particles with different masses

STAR QM2014

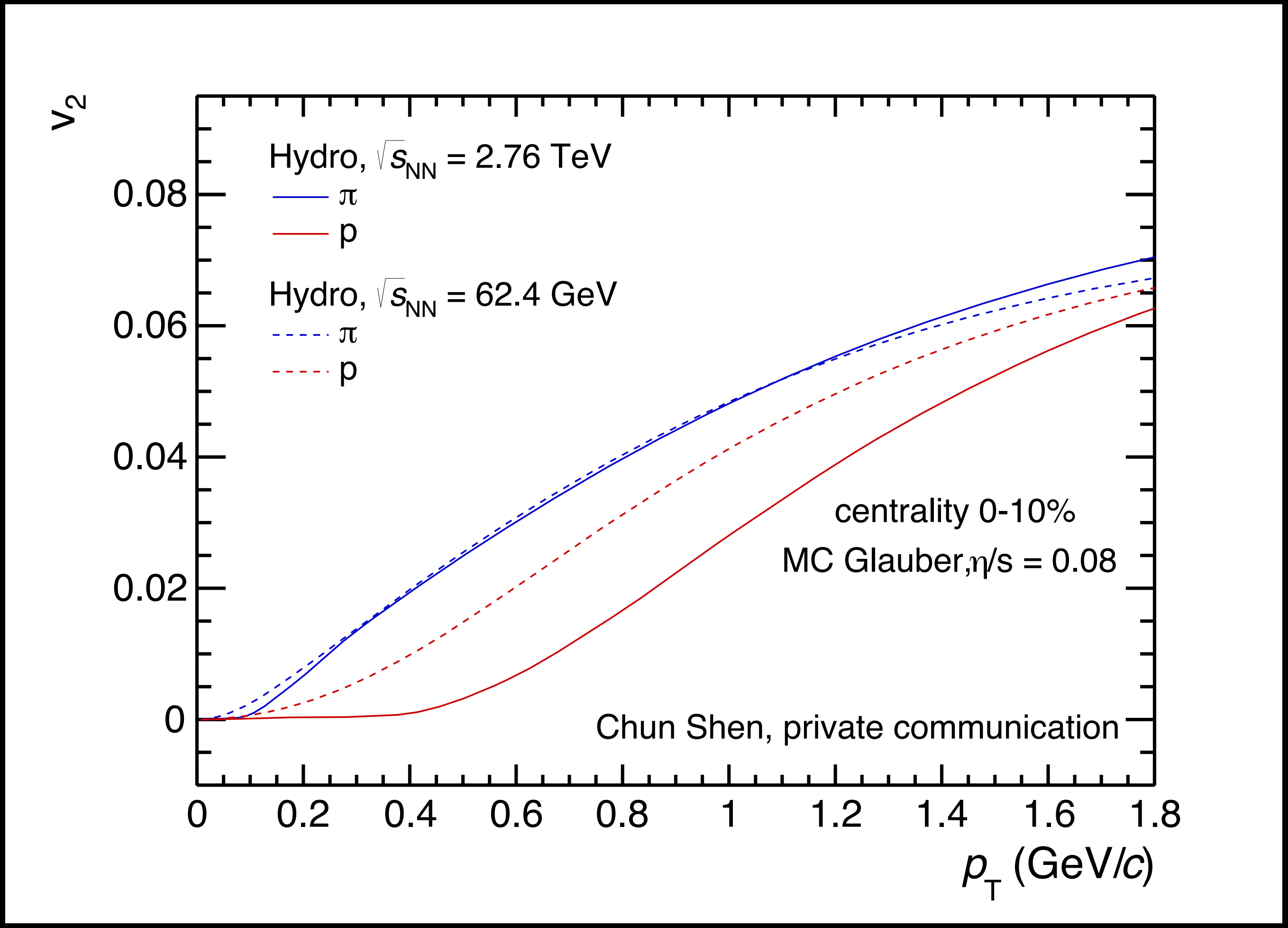


ALICE arXiv:1405.4632



mass hierarchy follows hydrodynamics at low p_T

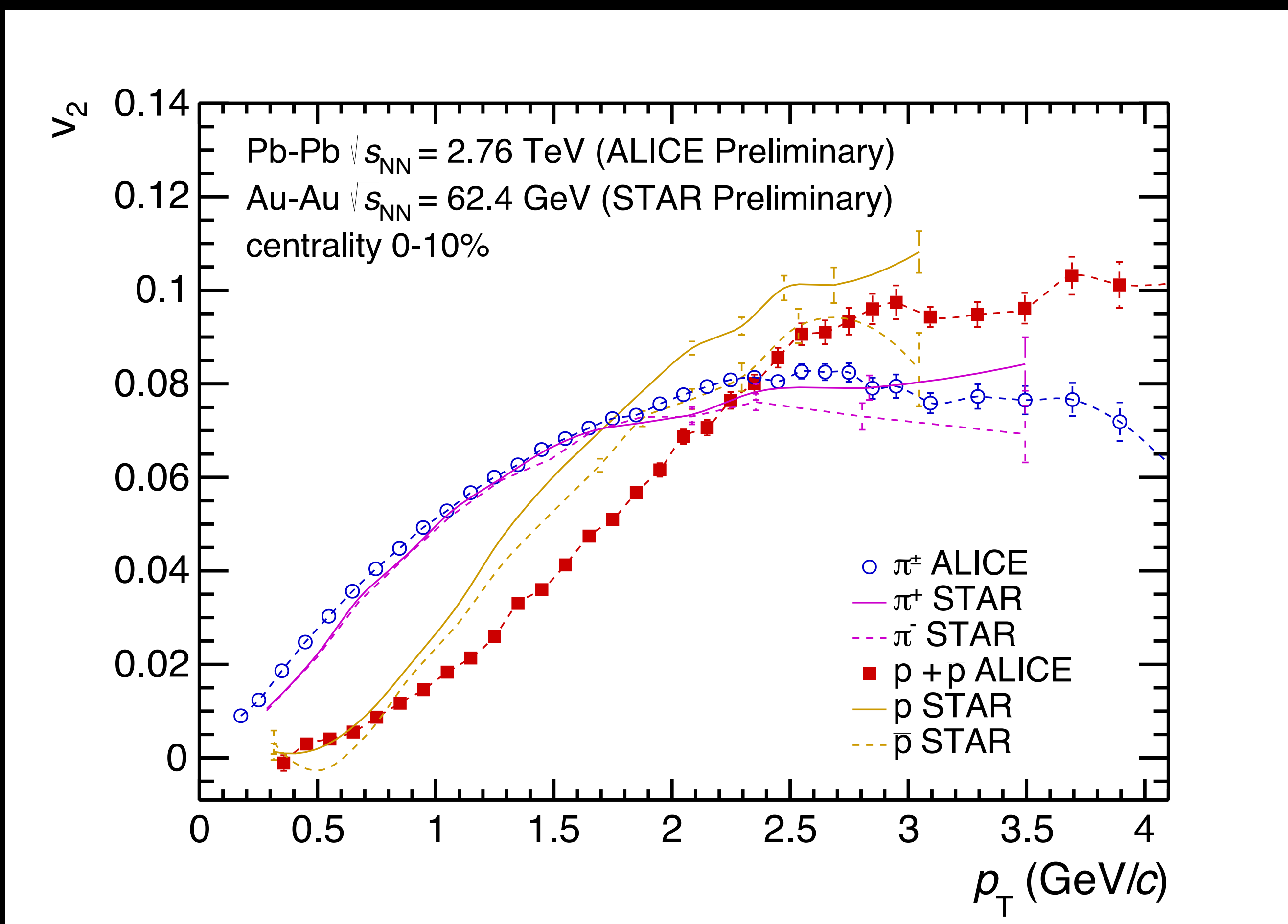
Hydrodynamic behaviour



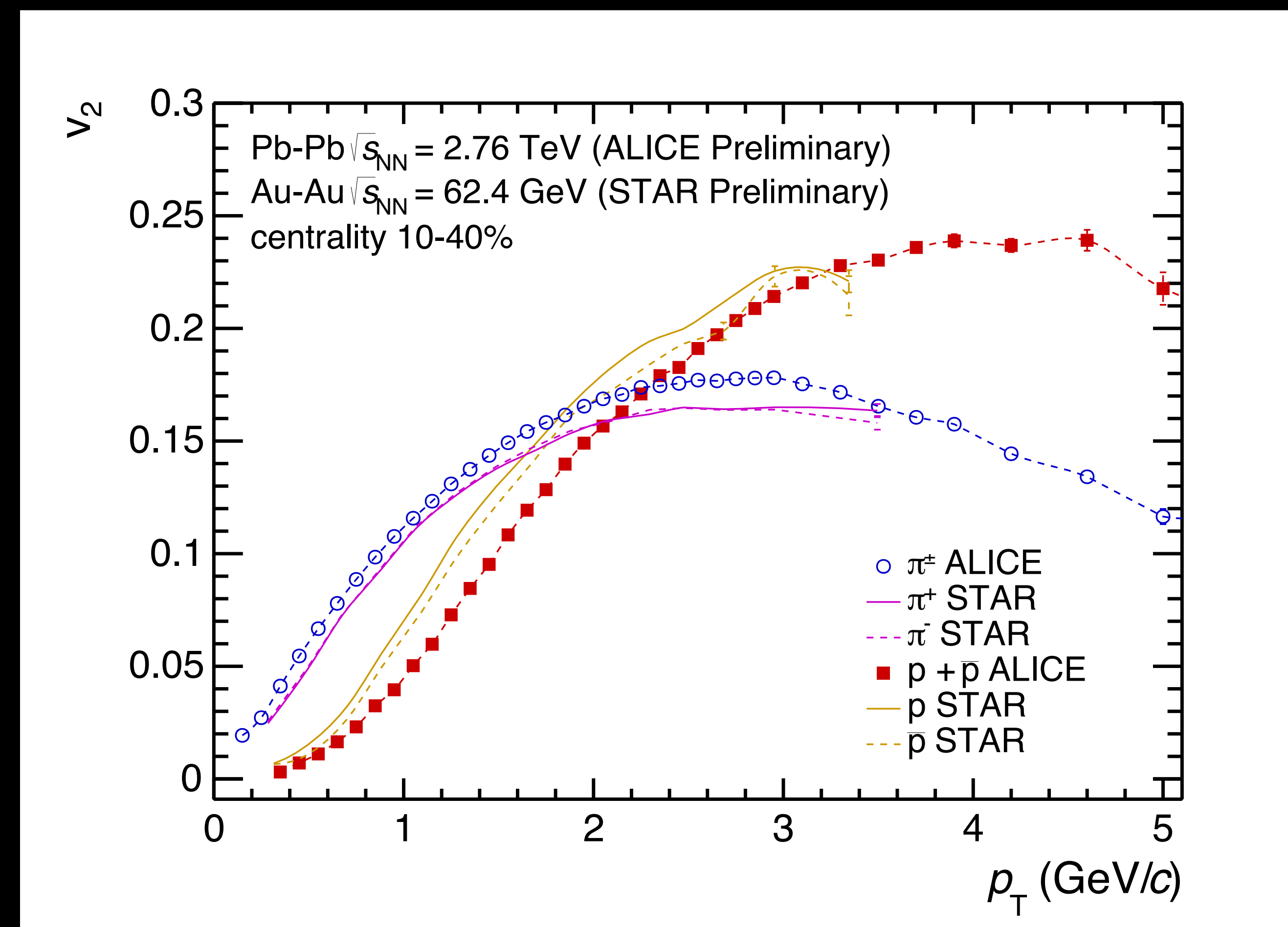
hydro picture
particles have a common temperature and flow velocity
larger radial flow increases mass splitting

Collision energy dependence of elliptic flow as function of transverse momentum

ALICE arXiv:1405.4632 STAR QM2014



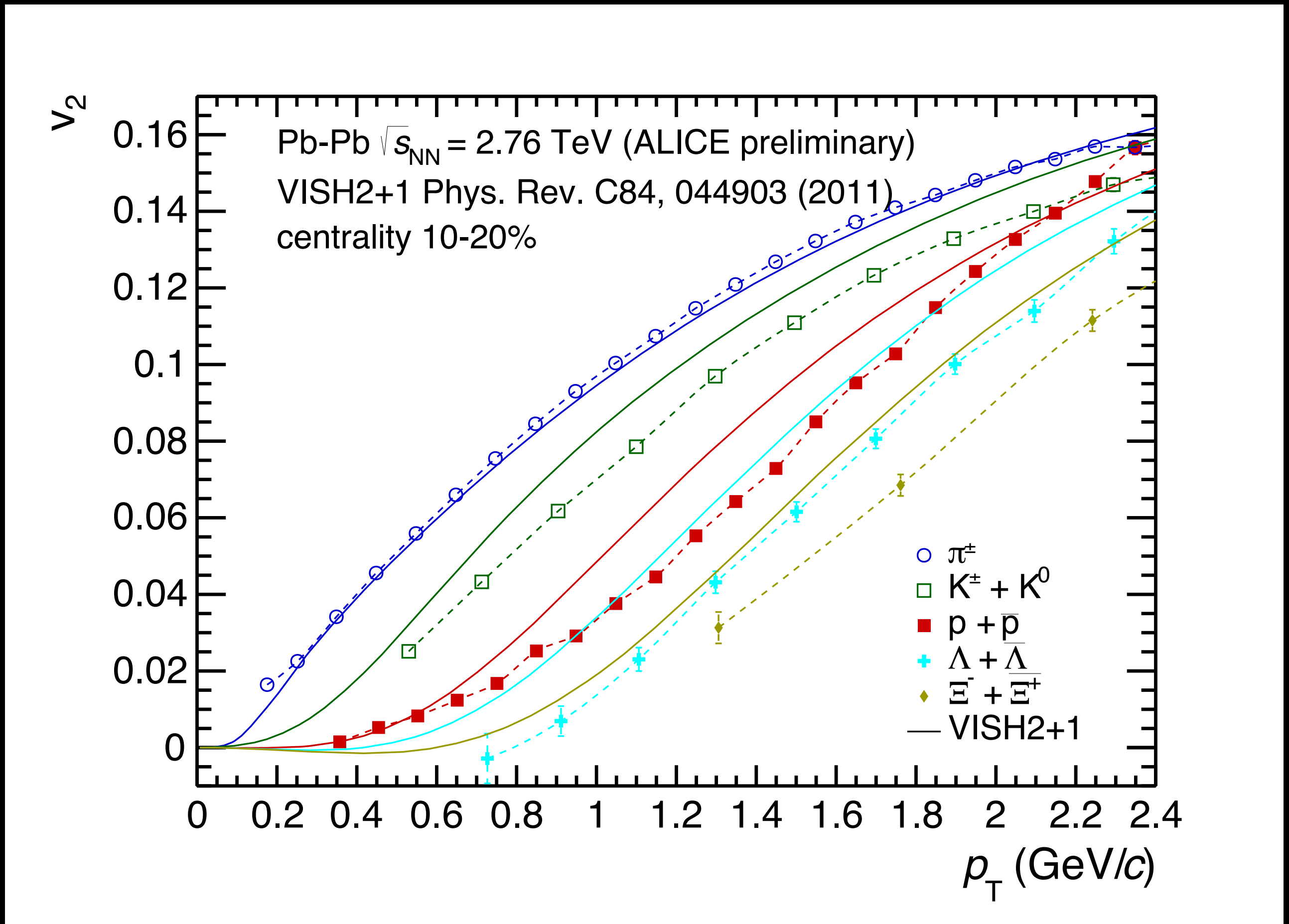
ALICE arXiv:1405.4632 STAR QM2014



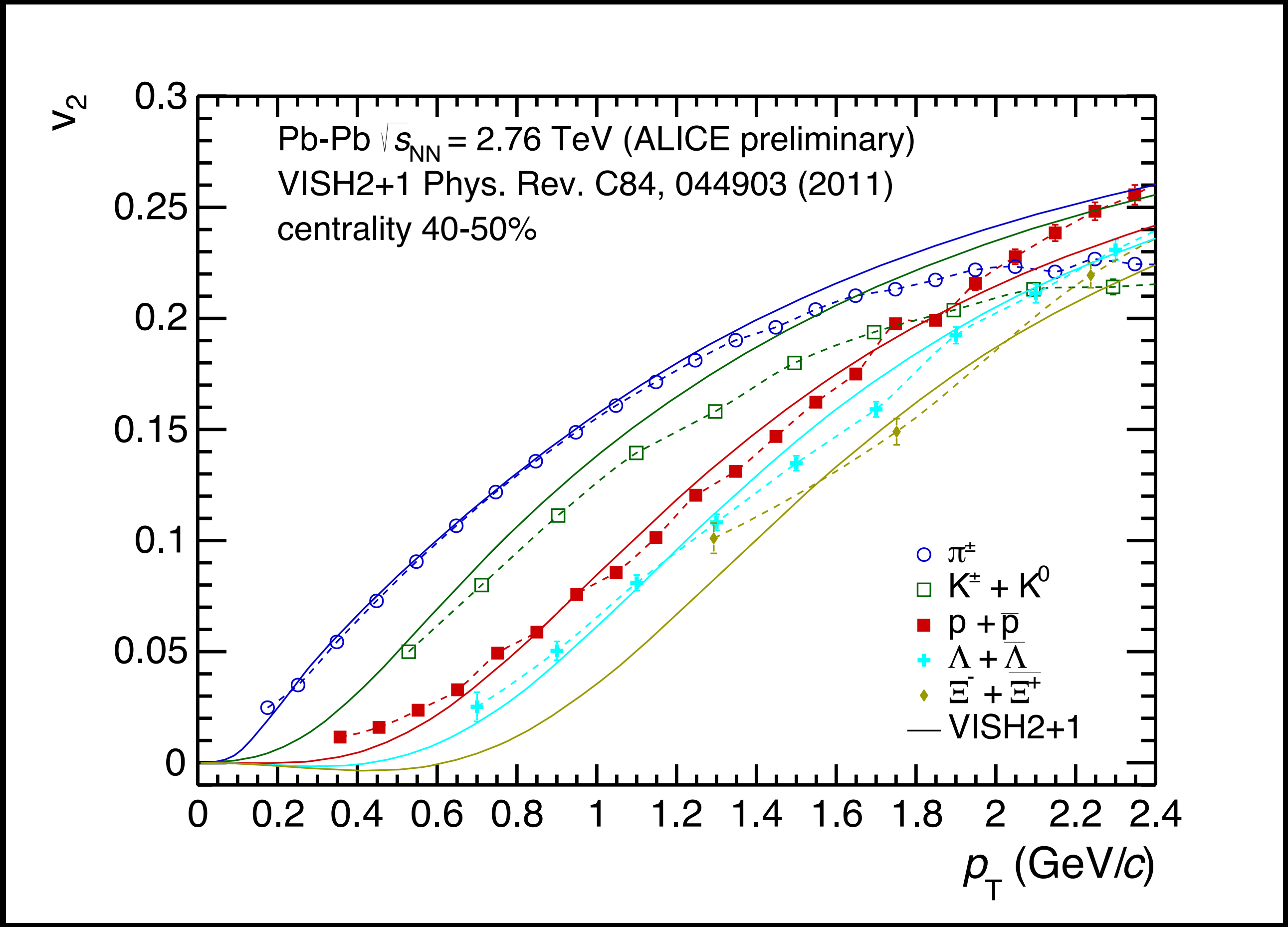
while the p_T-differential charged particle v_2 changes very little over two orders of magnitude the v_2 of heavier particles clearly shows the effect of the larger collective flow at higher collision energies

Compared to viscous hydrodynamics

ALICE arXiv:1405.4632



ALICE arXiv:1405.4632



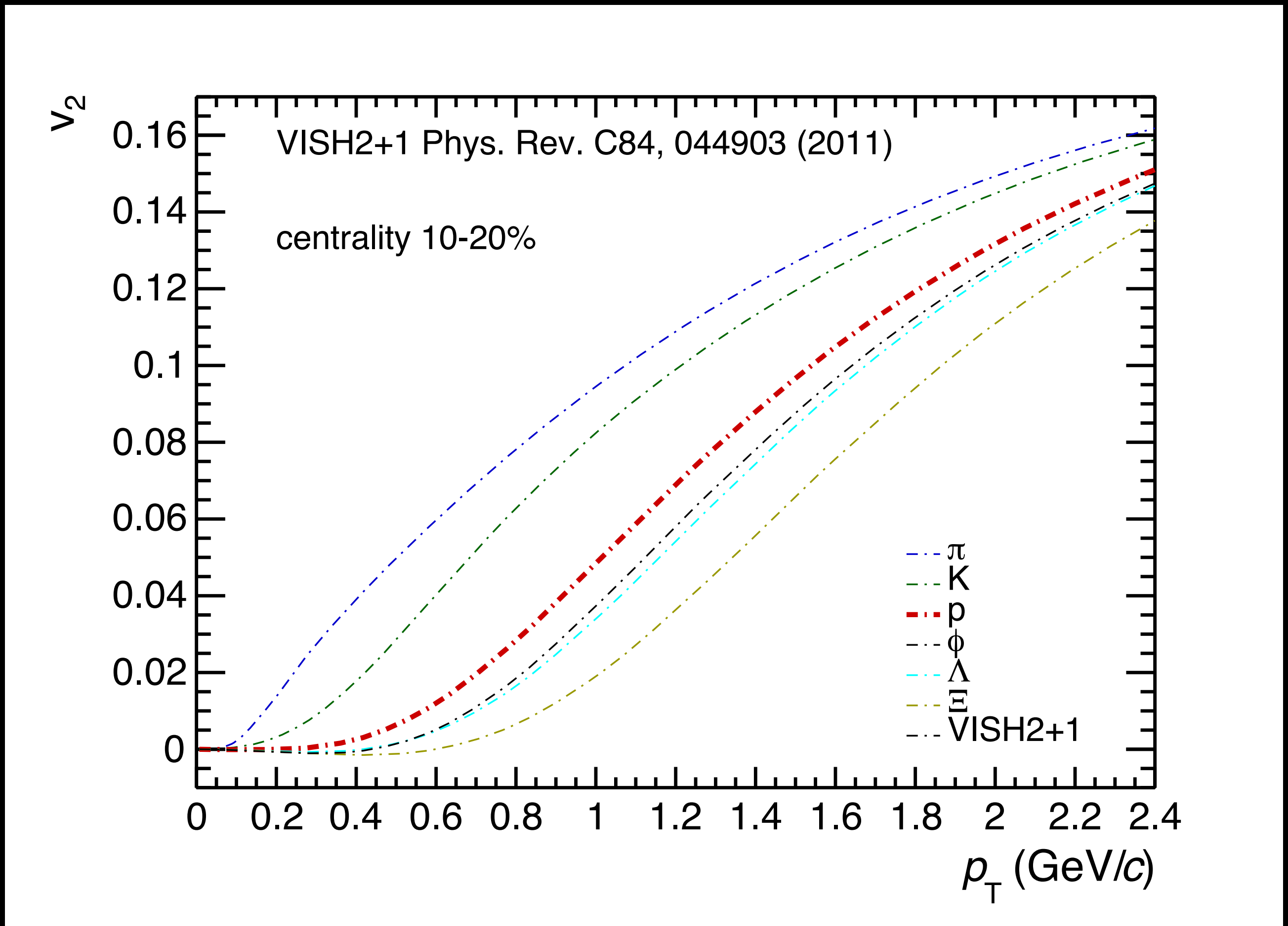
pure viscous hydrodynamics VISH2+1, status at QM2011

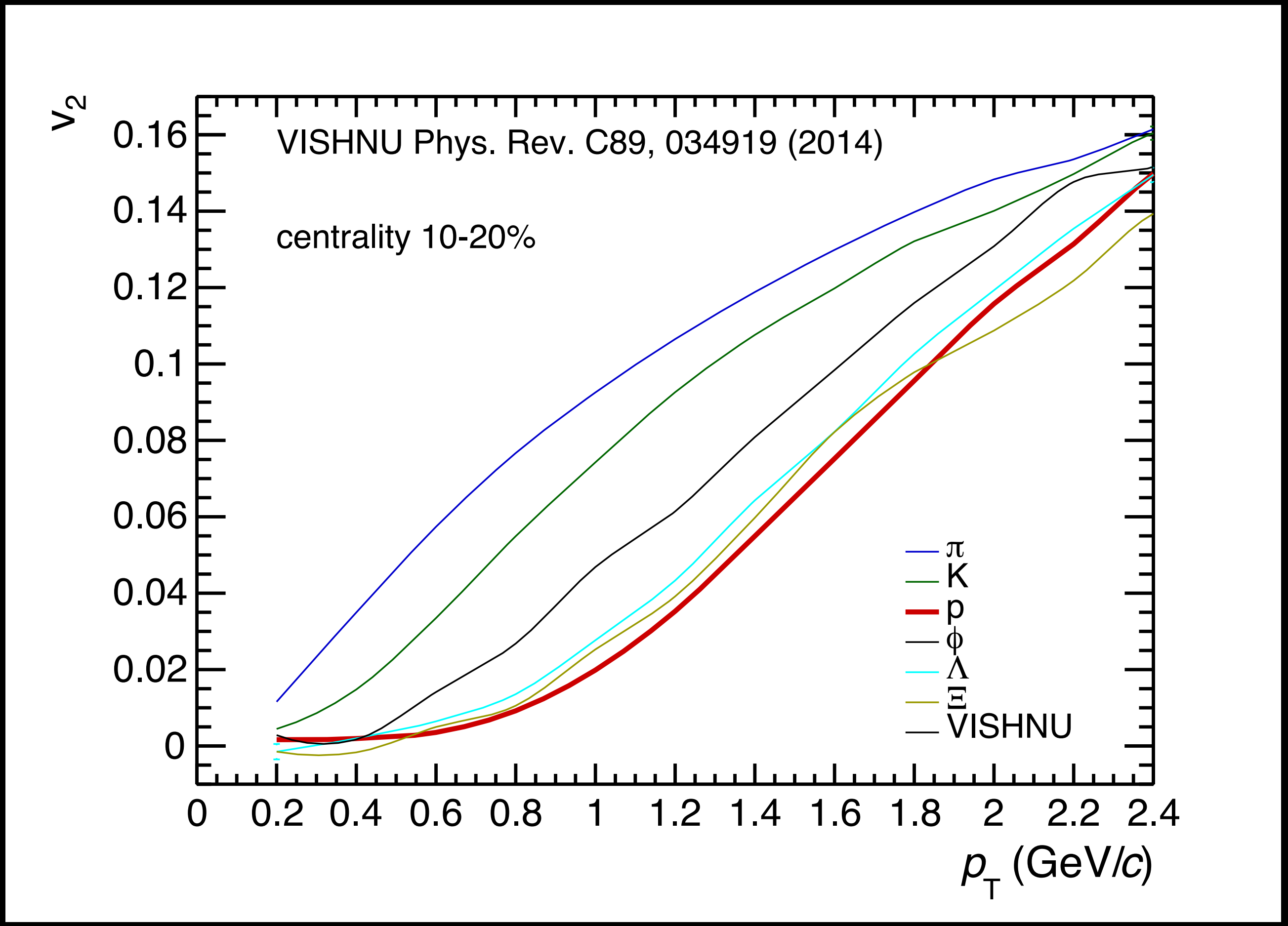
Viscous hydrodynamics predictions worked reasonably well for more peripheral collisions 40-50%

For more central collisions, 10-20%, the radial flow seems to be under-predicted as the protons deviate a lot and this was part of the proton puzzle (the data plotted here shows this is not just for protons but all heavy particles)

can this be understood by a more dissipative hadronic phase (model with a hadron cascade)?

Viscous hydrodynamics and the effect of the hadronic cascade

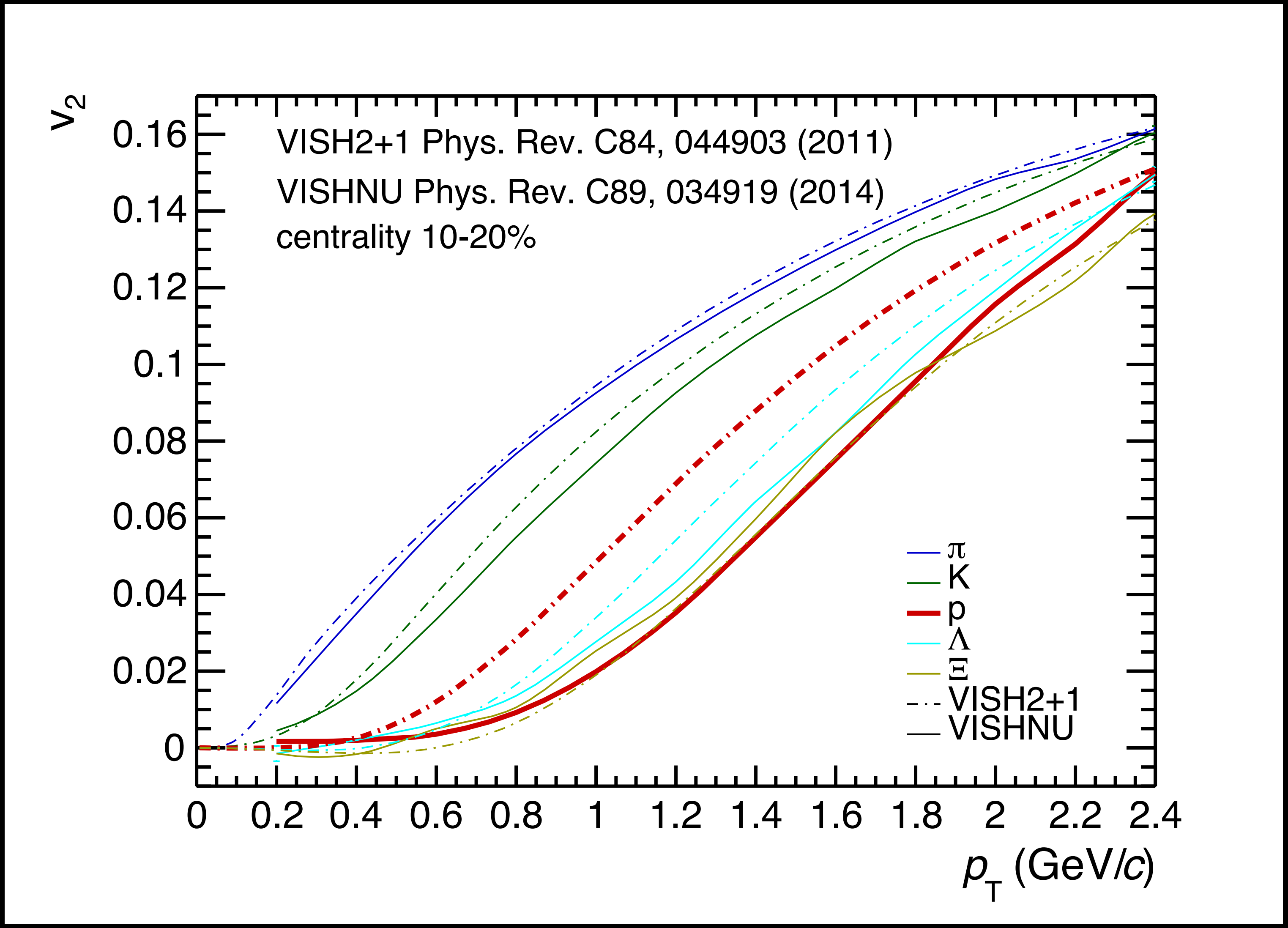




VISH2+1 viscous hydrodynamics
"standard" mass scaling

VISHNU viscous hydrodynamics + hadron cascade
mass scaling broken,
depending on individual hadronic re-interaction cross sections (pion wind pushing the protons)

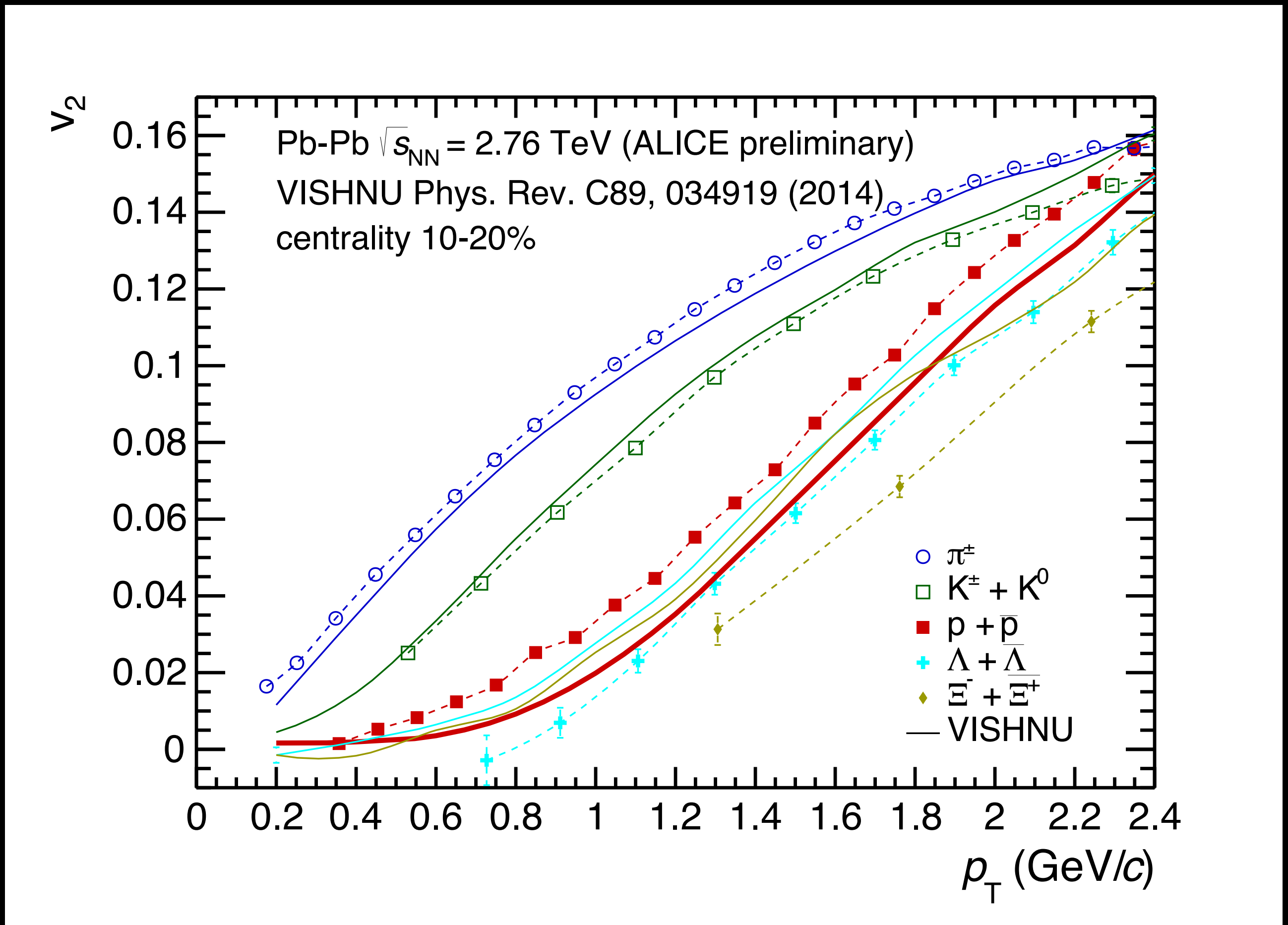
Viscous hydrodynamics and the effect of the hadronic phase



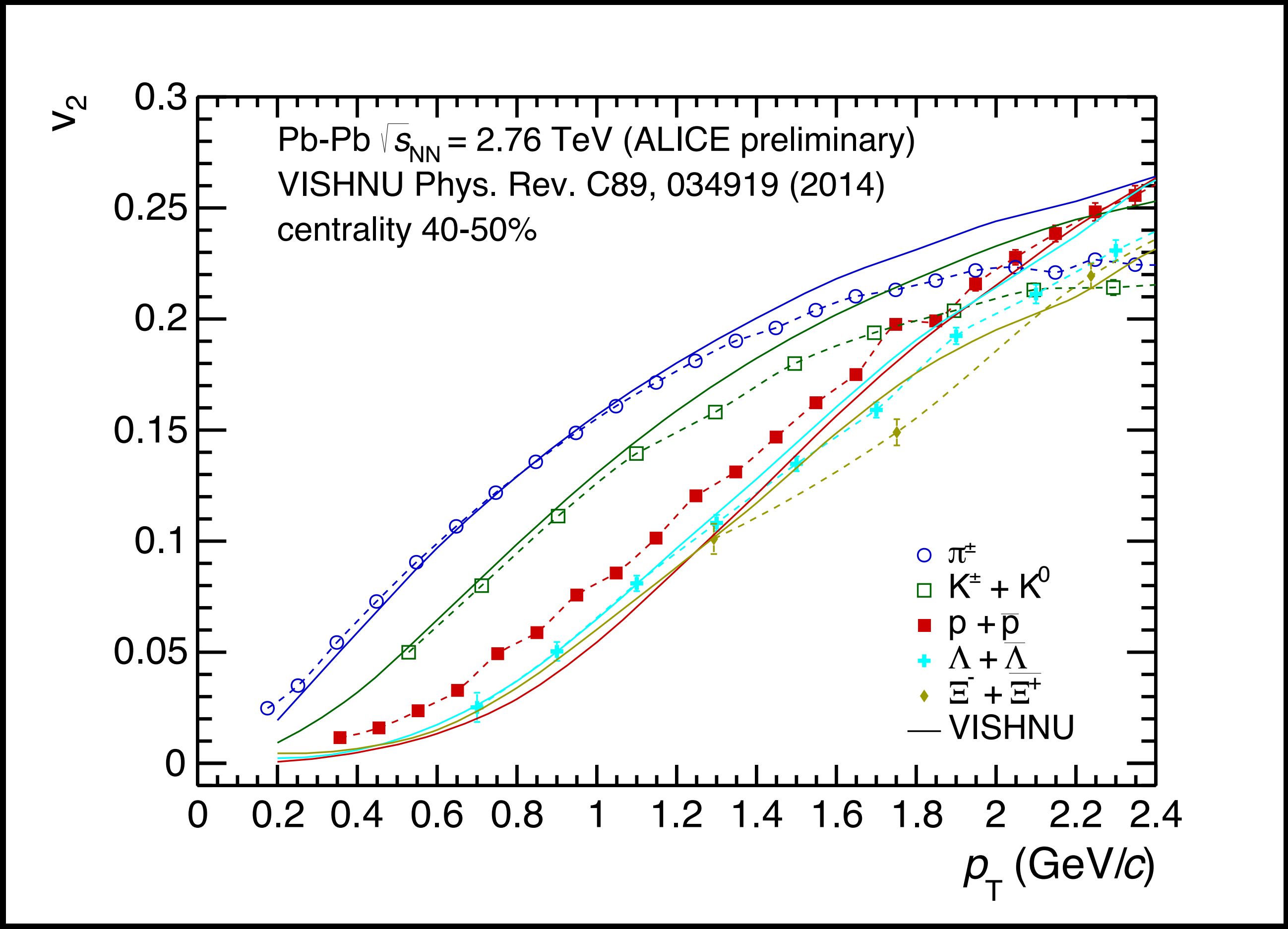
VISHNU viscous hydrodynamics + hadron cascade
big effect for the protons!
mass scaling broken,
depending on individual hadron-hadron re-interaction cross sections

Viscous hydrodynamics + hadron cascade

ALICE arXiv:1405.4632



ALICE arXiv:1405.4632

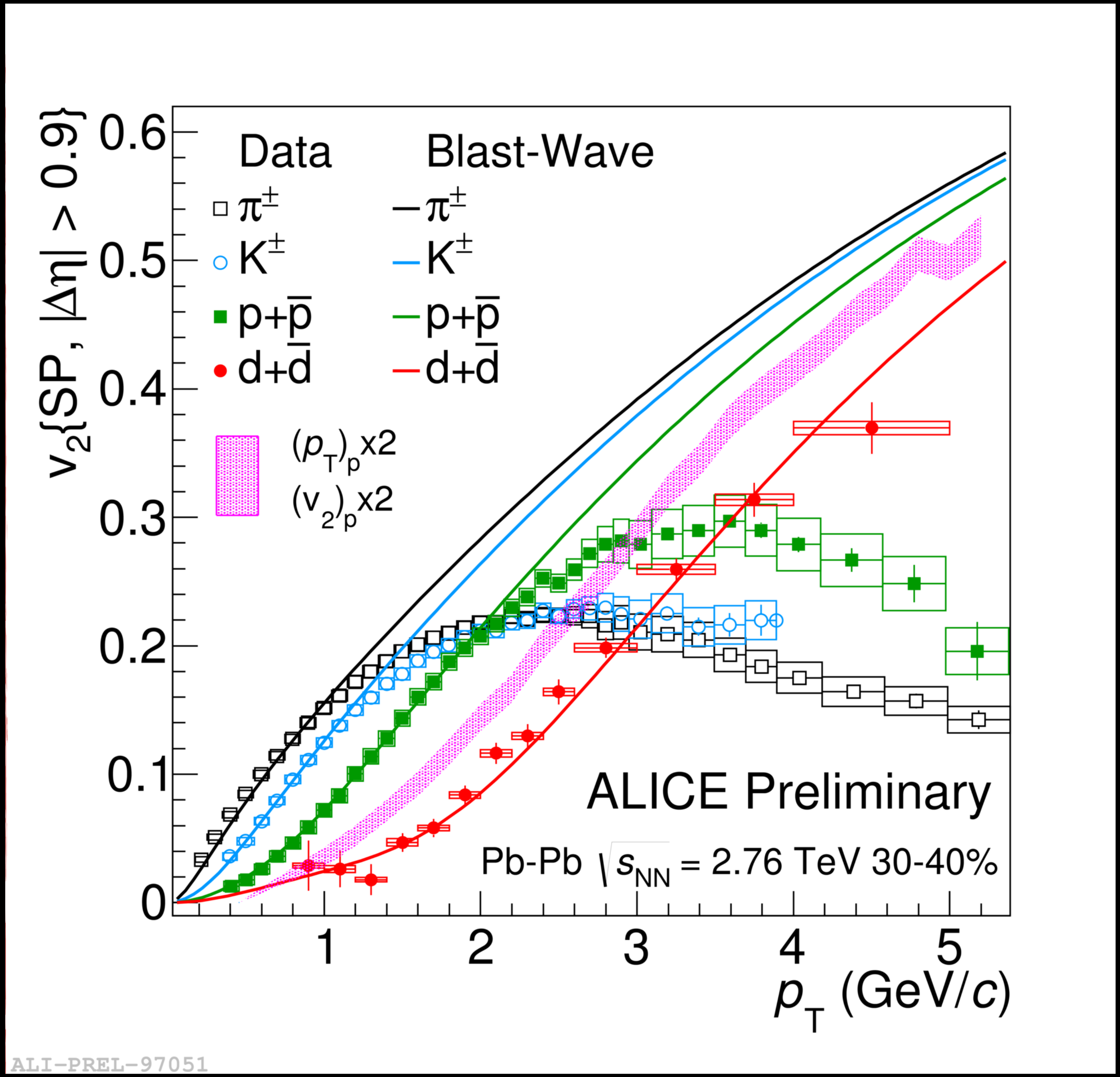


Viscous hydro +hadron cascade improves the Kaon v_2
It increases the push for the protons but actually over does it
It breaks the mass scaling and is incompatible with the data
It does a worse job than “simple” viscous hydrodynamics!!

over estimating effect of hadronic cascade?
or is the model lacking pre-equilibrium flow?

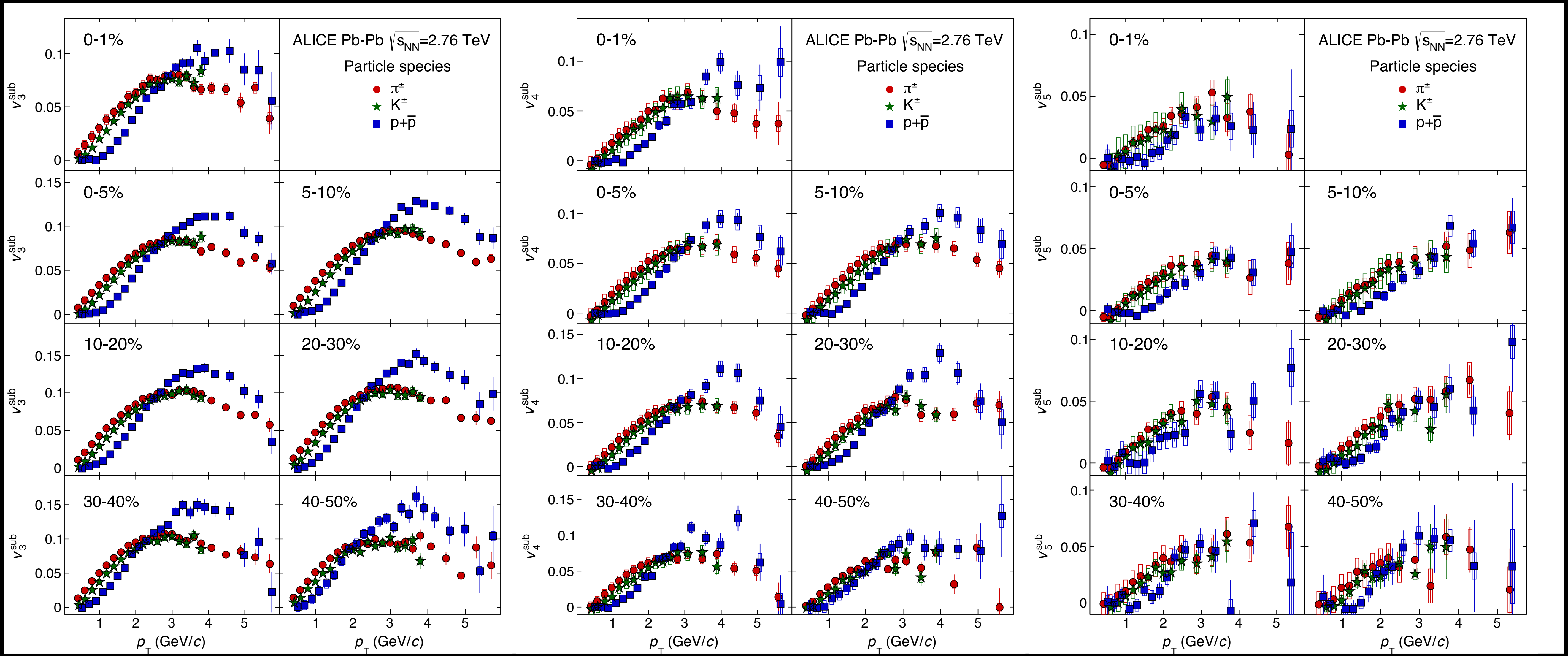
How well do we understand the dynamics?

even deuteron v_2 follows mass scaling other particles, described by common freeze-out temperature and flow velocity



How well do we understand the dynamics?

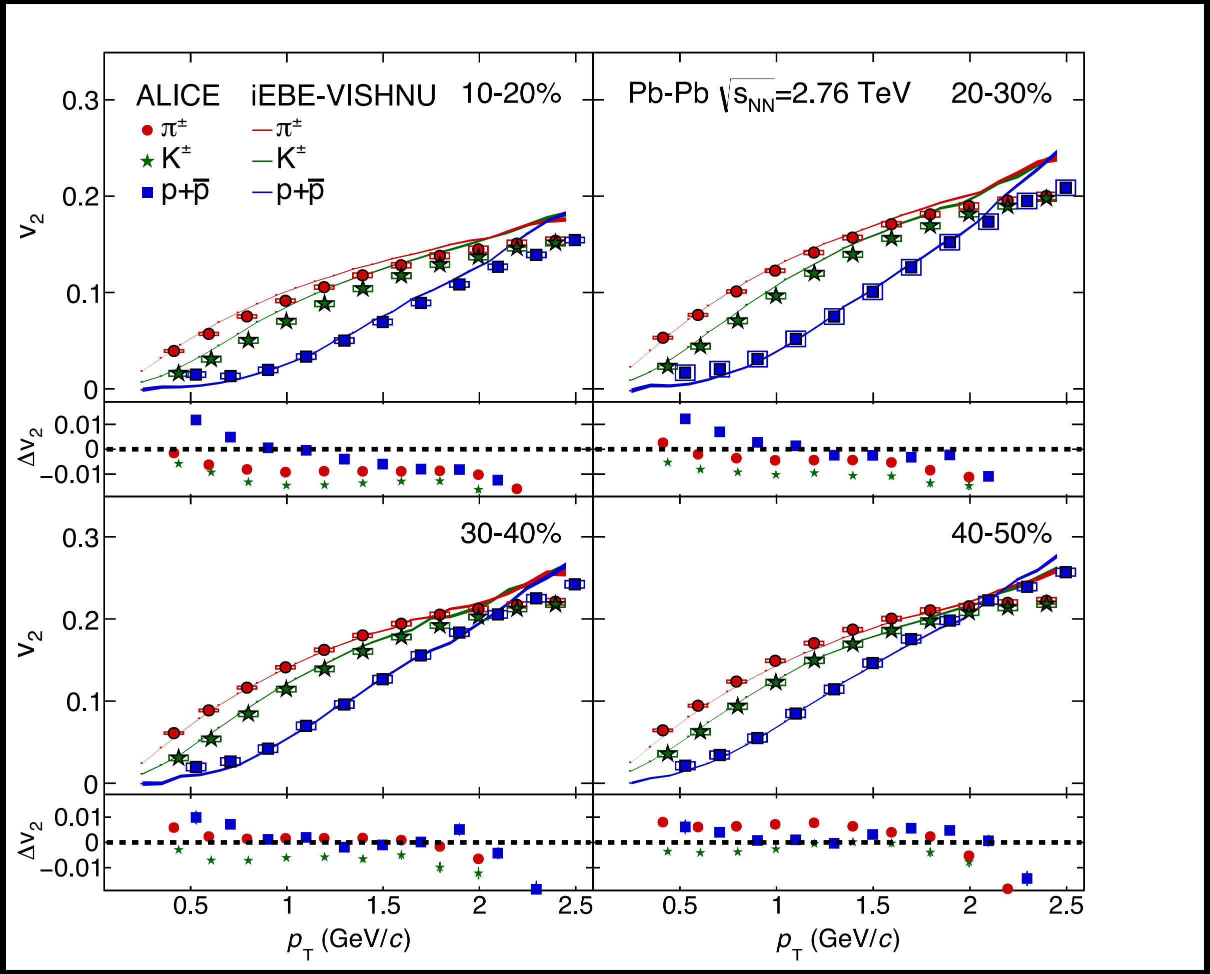
arXiv:1606.06057 accepted by JHEP



v_3, v_4, v_5, follow mass scaling as expected for boosted system

How well do we understand the dynamics?

arXiv:1606.06057 accepted by JHEP



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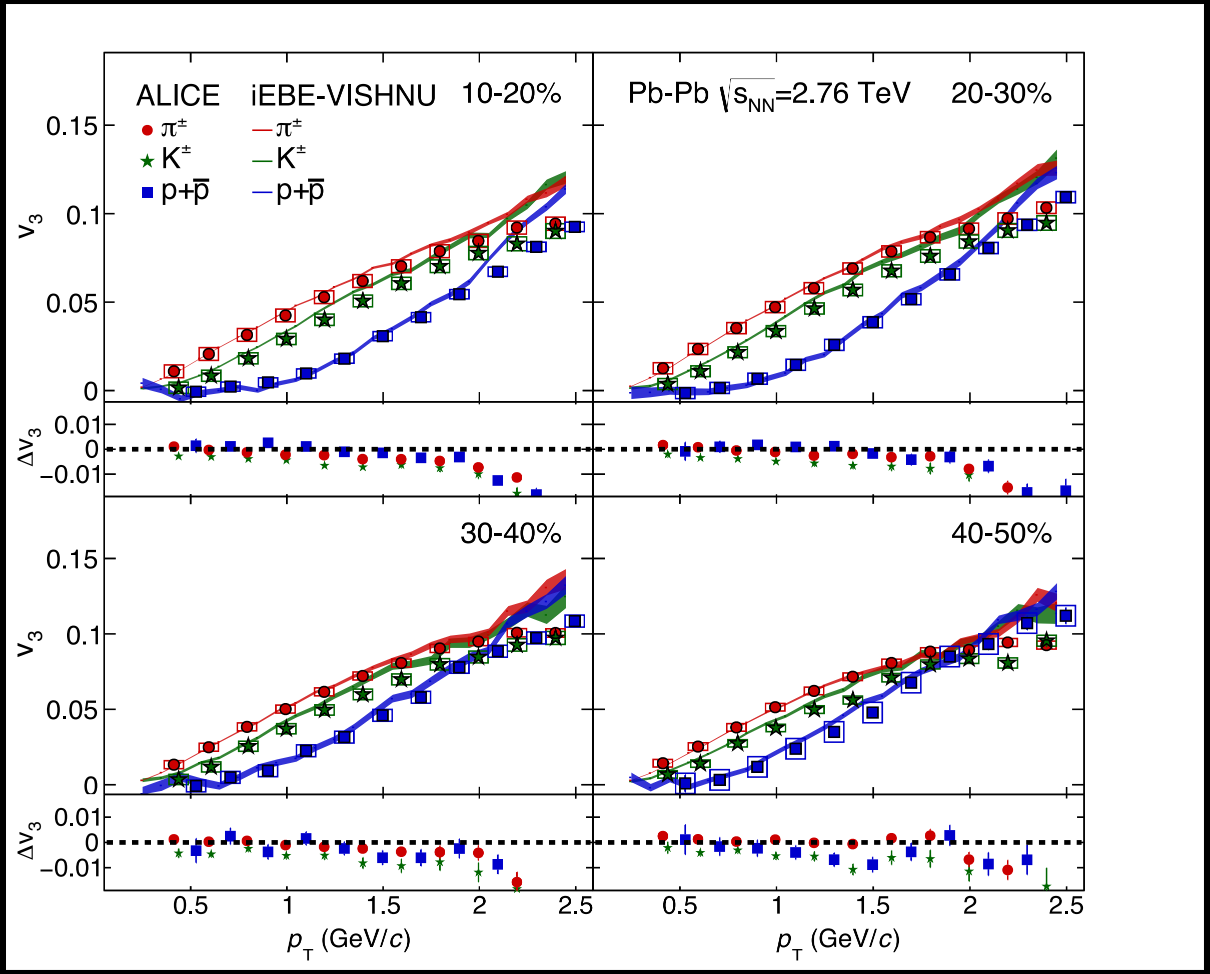
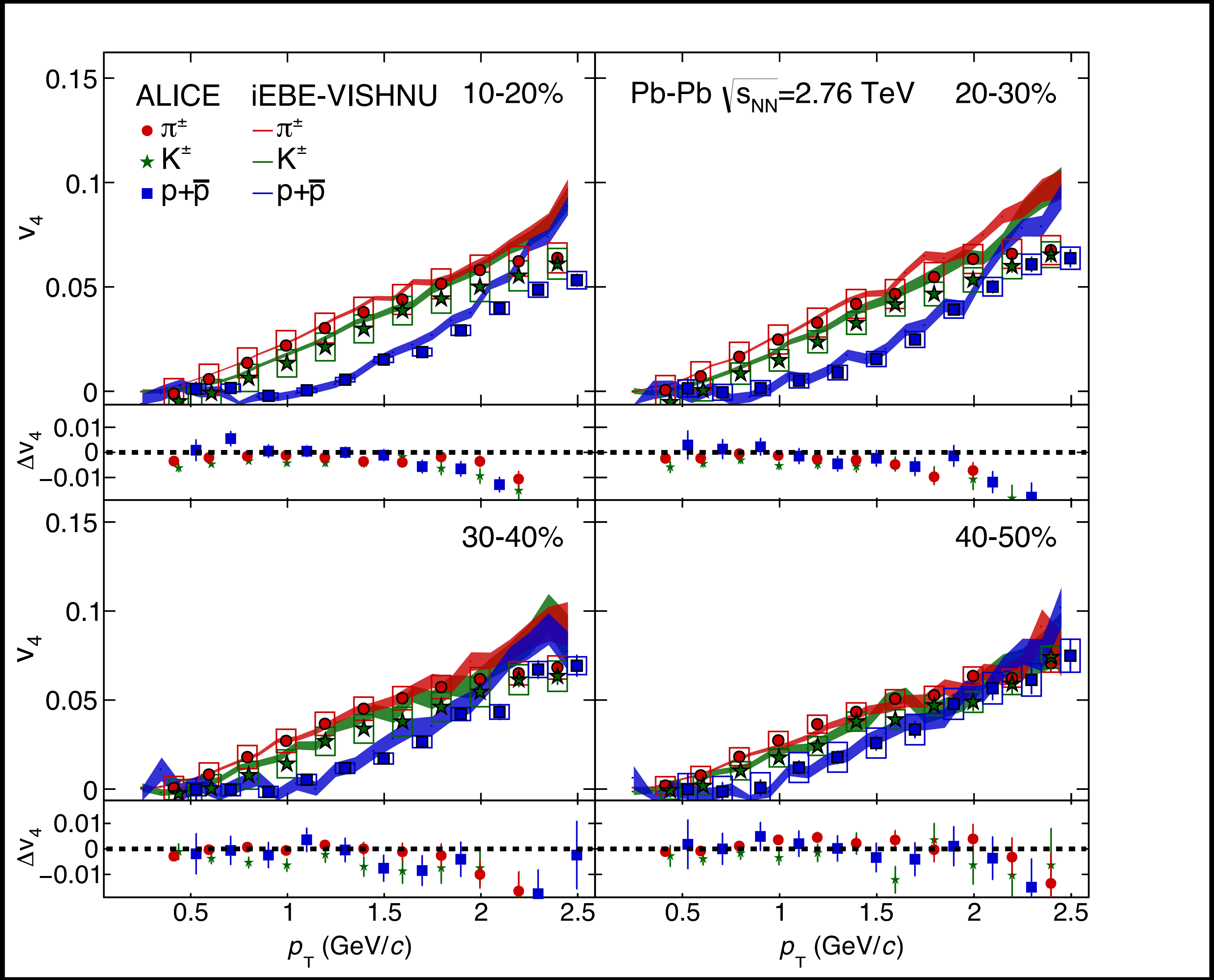


Hydro describes v_n well for pions, kaons and protons, however probably same problem as in v_2 for heavier strange particles

How well do we understand the dynamics?

arXiv:1606.06057 accepted by JHEP



even v_4, which is not only a response to ε_4 is described well

How well do we understand the dynamics?

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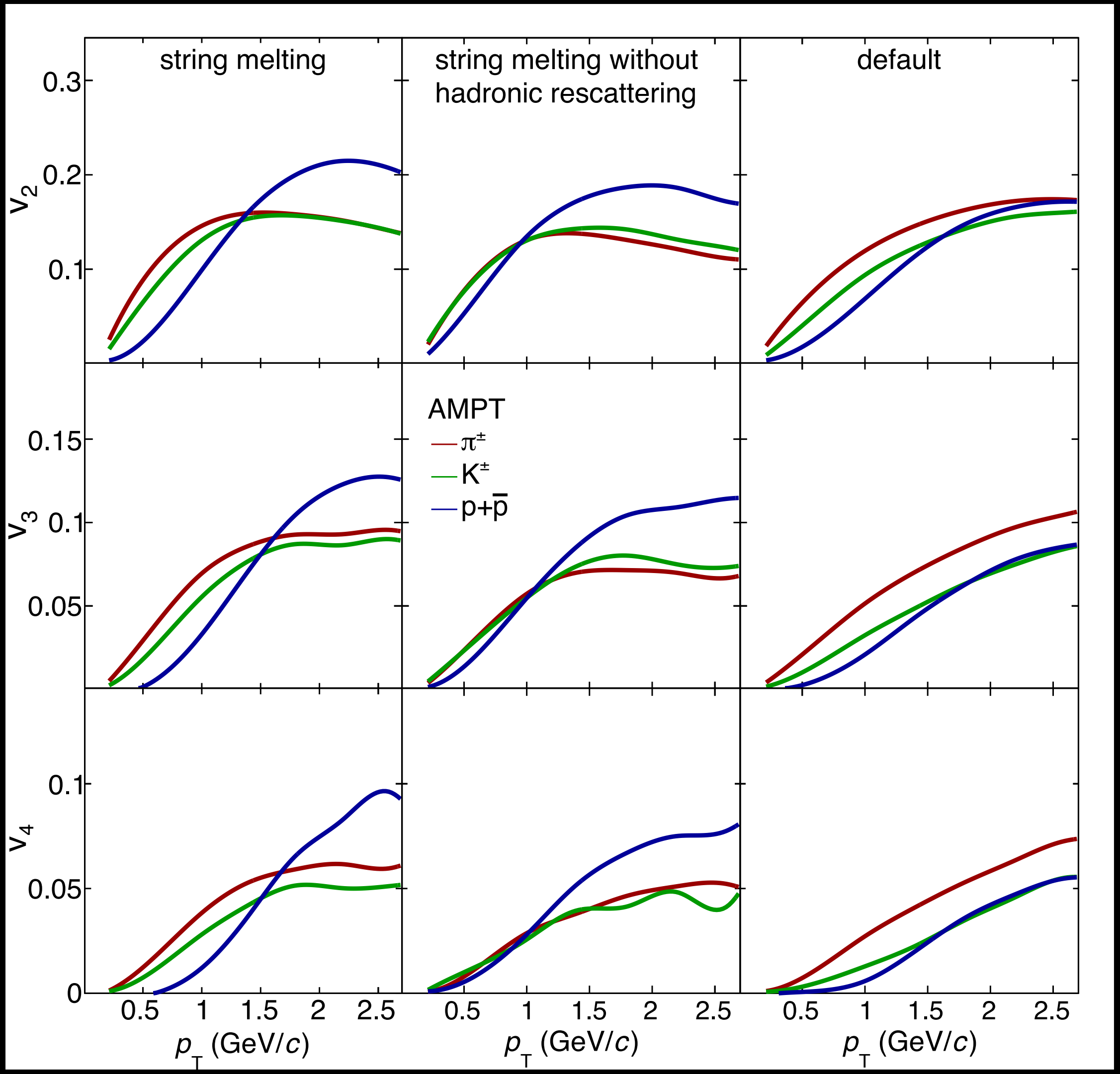

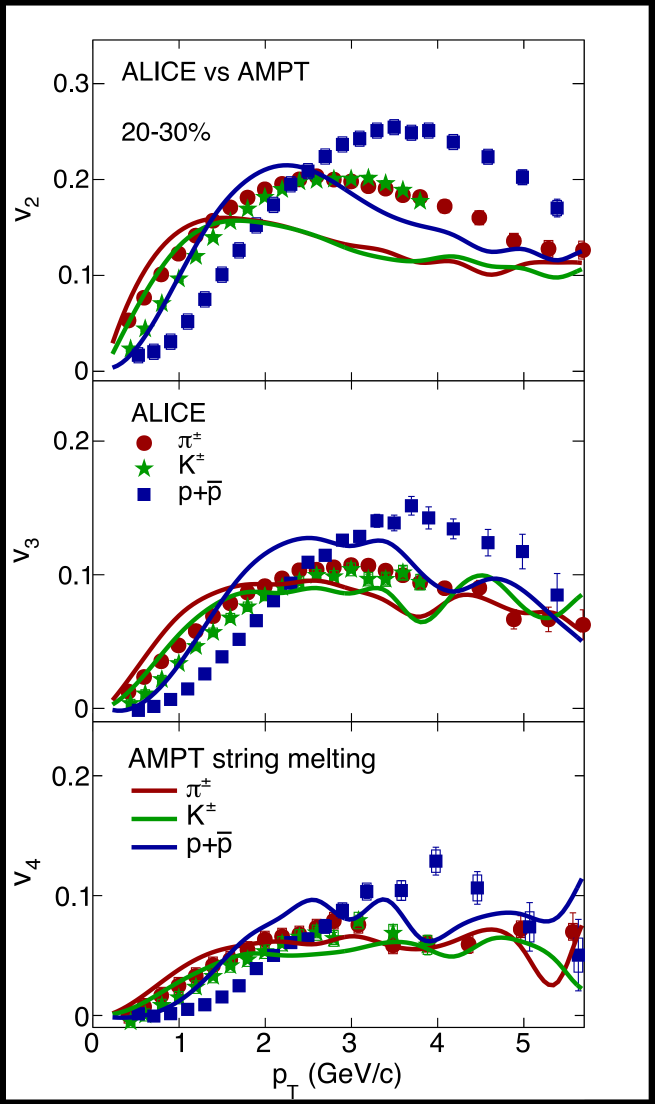

sensitive to dynamics in AMPT, in this model radial flow is underestimated.
different mechanism for anisotropic and radial flow

Summary?

- large fraction observables understood in nearly perfect liquid paradigm
  - used to constrain EoS and transport parameters
- Important question still are all ingredients already in place?
  - pre-equilibrium phase, hadronization, hadronic phase, …