Quark Gluon Plasma; in AA, pA and pp collisions?

what can we learn from that?

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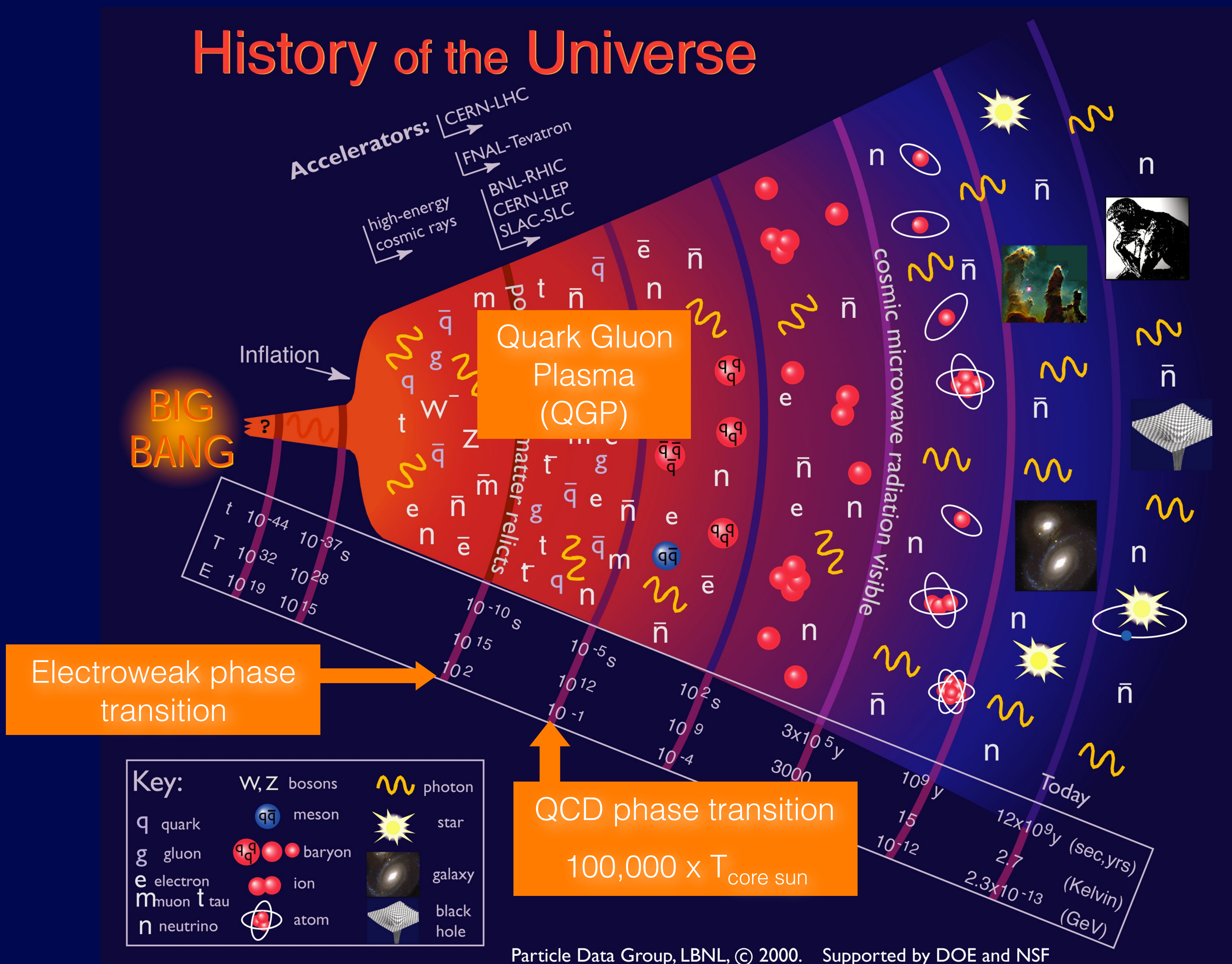
NIKHEF

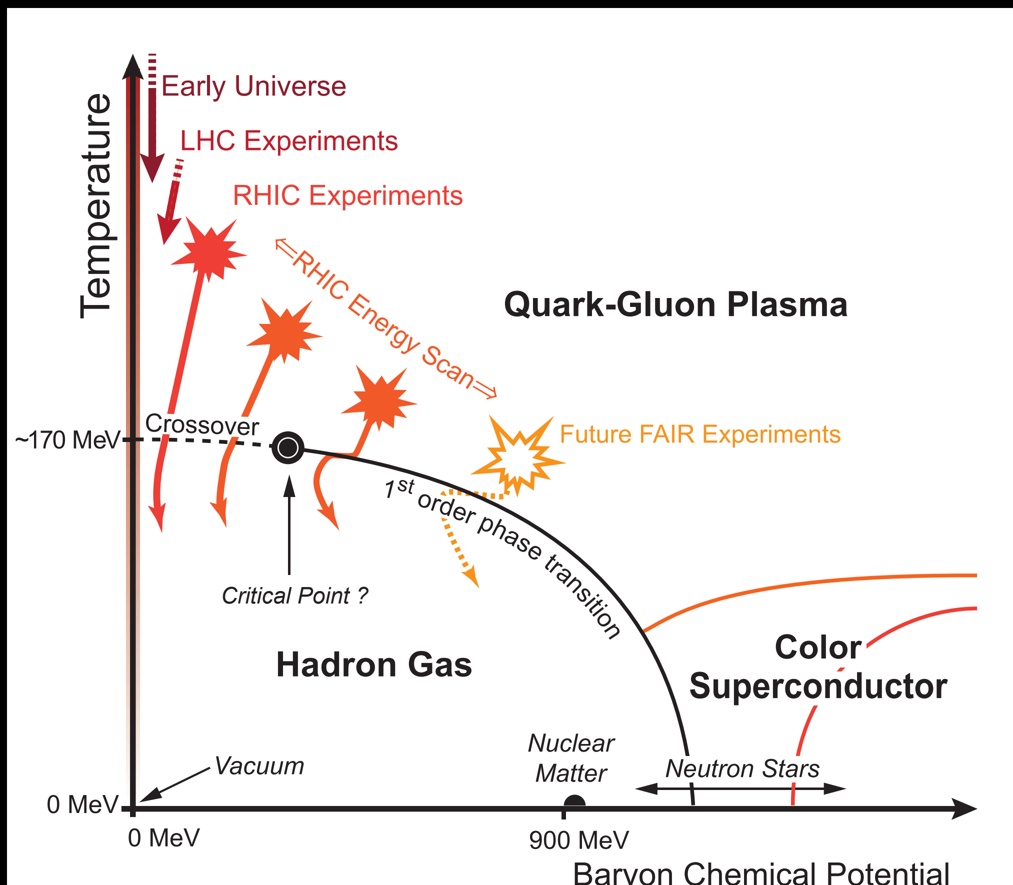
Nikhef colloquium 2016

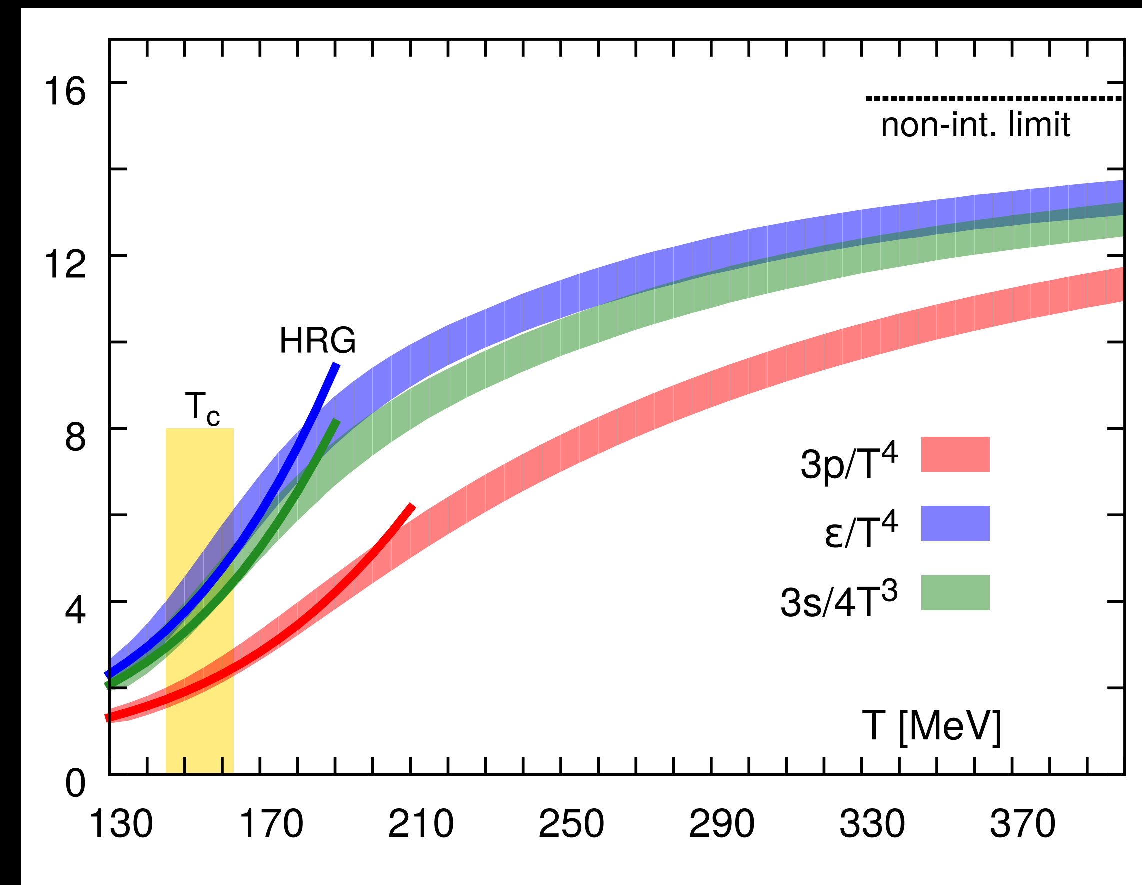
What happens when you heat and compress matter to very high temperatures and densities?

Do we understand what QCD tells us?



Lattice QCD and the Phase Diagram





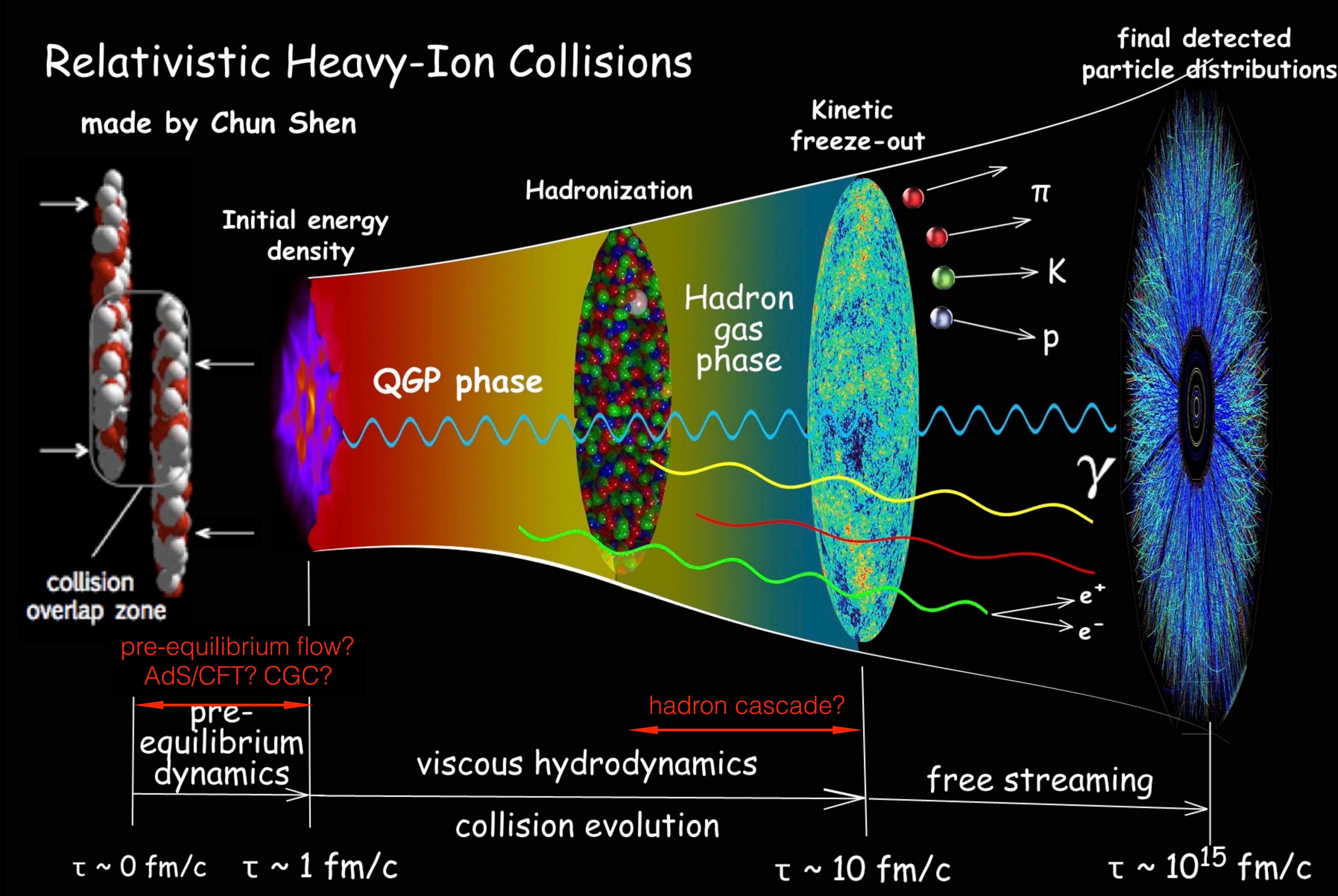
hotQCD collab: arXiv:1407.6387

- at μ_B=0 we have rather reliable calculations from the lattice
- at larger μ_B conflicting results from the lattice
- for all cases the lattice calculations tell us (currently) very little about the (transport) properties of the matter
    - in case of a strongly interacting system, using e.g. the AdS/CFT correspondence, the energy density over T^4 reaches about 70% of the non-interacting limit, not so different from lattice QCD!
    - what are the relevant degrees of freedom?

How to connect observables to lattice QCD predictions?

- try to create a large hot and dense system for which thermodynamics/hydrodynamics can be applied
  - collide heavy-ions at the highest energies possible

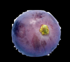
Our current picture



How to connect observables to lattice QCD predictions?

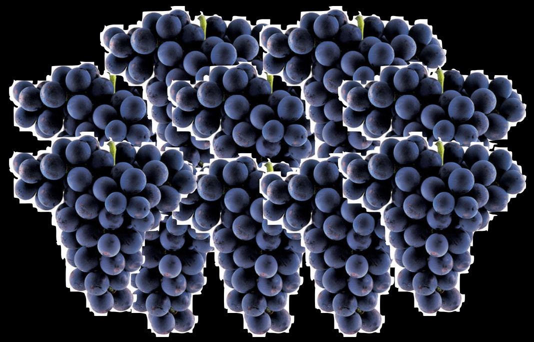
- many of the quantities calculable on the lattice are difficult/impossible to measure directly from the observed particle distributions
  - not well constrained contributions of e.g. initial conditions, different phases, hadronization, ….
- need some extra reference of other well understood control parameters
  - pp collisions and pA collisions as reference?

How to connect observables to lattice QCD predictions?

 $\neq$ 

$\neq$ 

pp pA AA

 $\neq$ 

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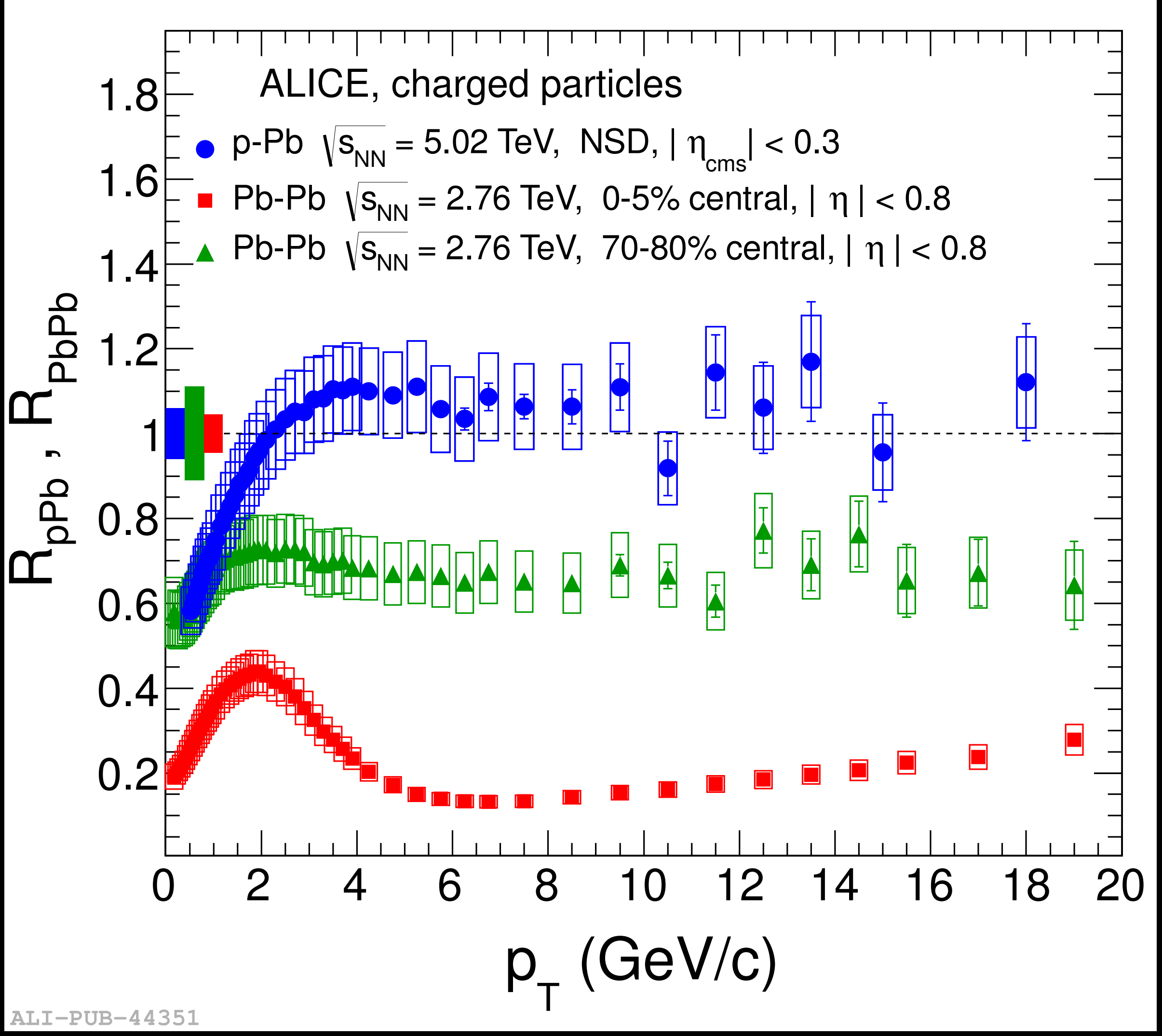
The ratio of scaled pp, pA and AA

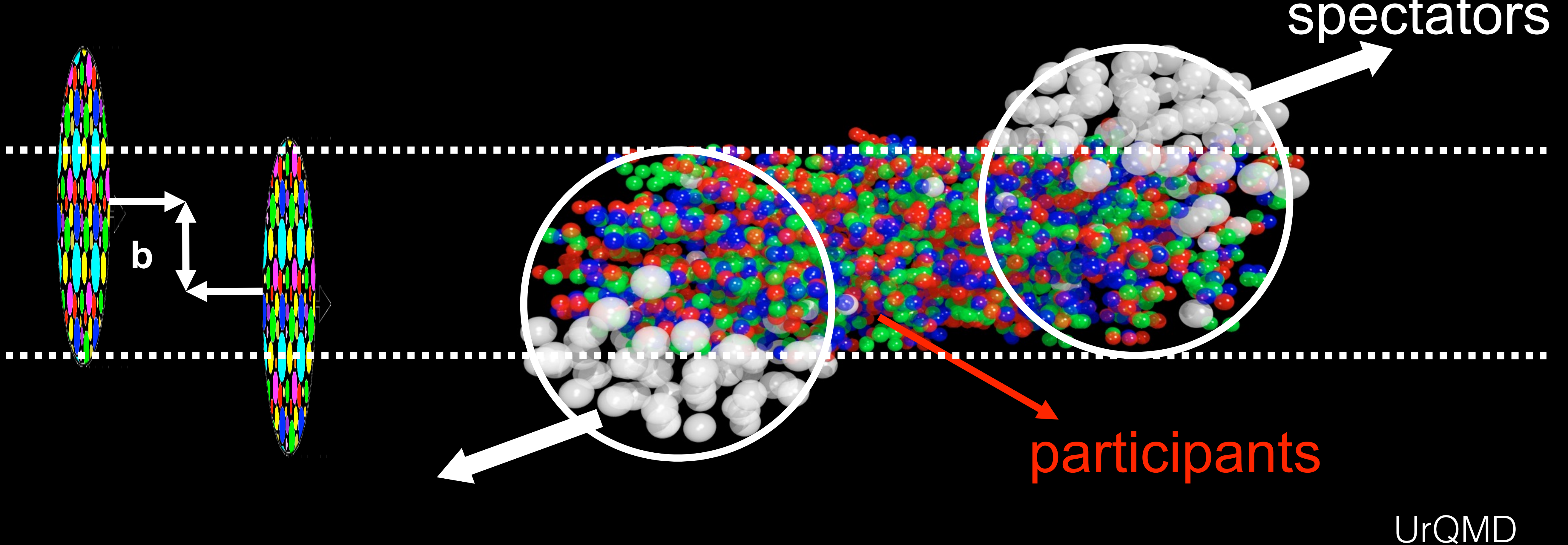


The Jack fruit is much heavier than a comparable amount of grapes or mixed fruit

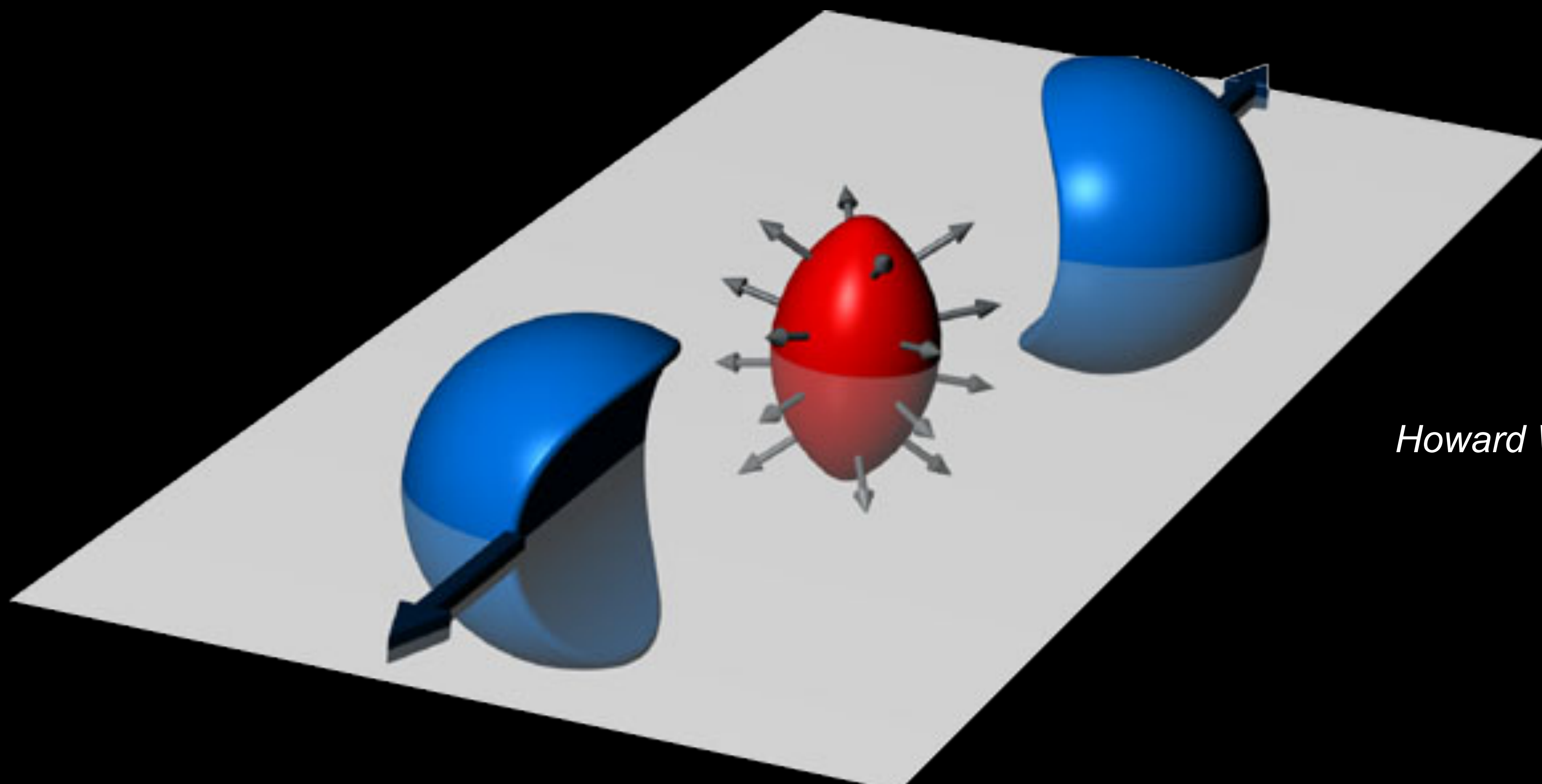
How to connect observables to lattice QCD predictions?

- many of the quantities calculable on the lattice are difficult/ impossible to measure directly from the observed particle distributions
  - not well constrained contributions of e.g. different phases, hadronization, ….
- need some extra reference of other well understood control parameters
  - pp collisions as reference, pA collisions as reference?
  - **geometry as a control parameter?**

A Heavy-Ion Collision



The transverse plane



Howard Wieman

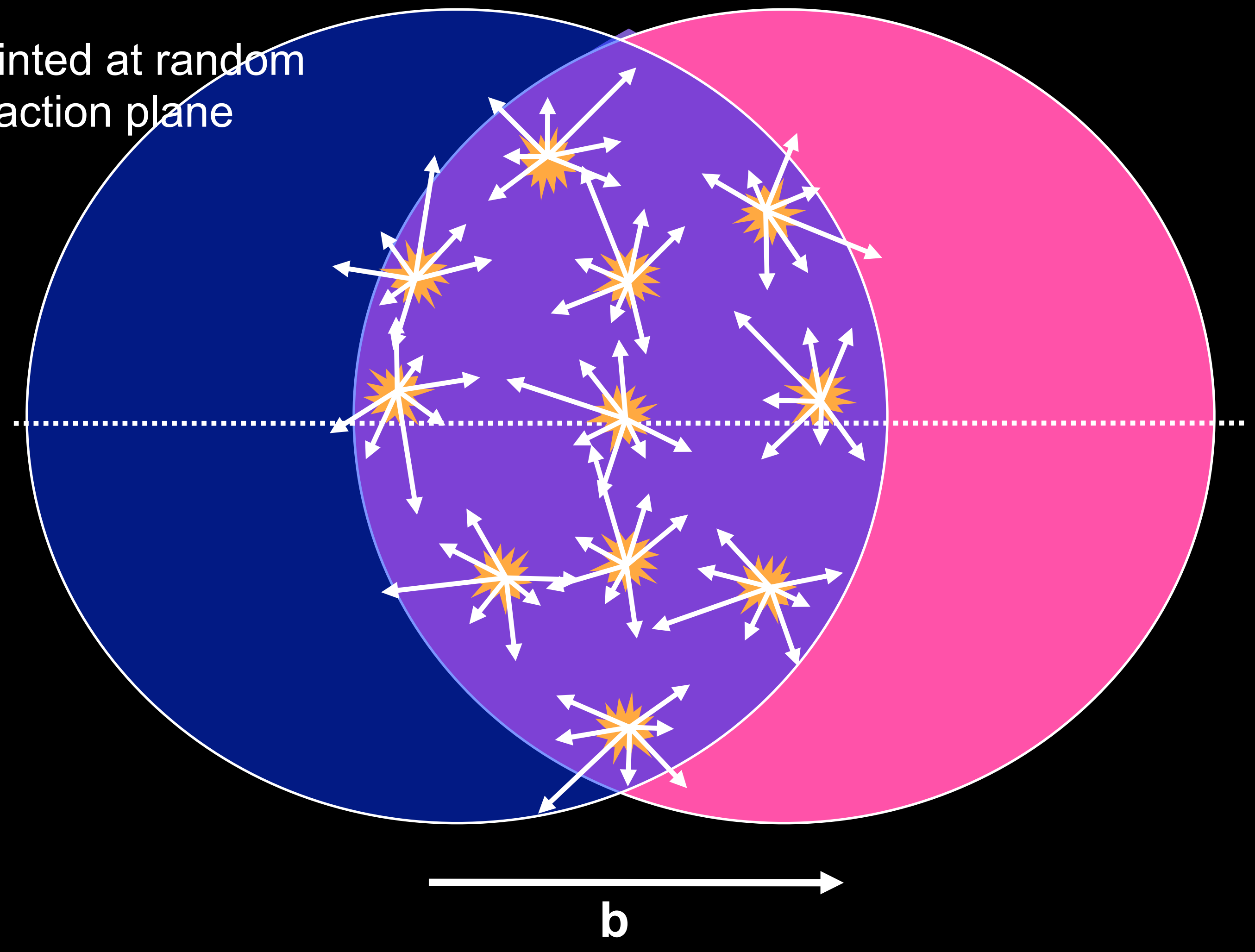
Elliptic Flow

Ollitrault 1992

Animation: Mike Lisa

1) superposition of independent p+p:

momenta pointed at random
relative to reaction plane



Elliptic Flow

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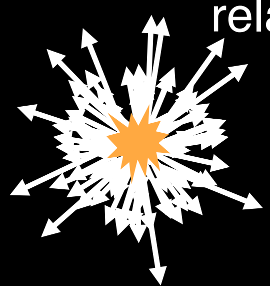
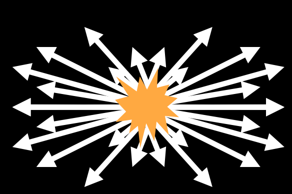
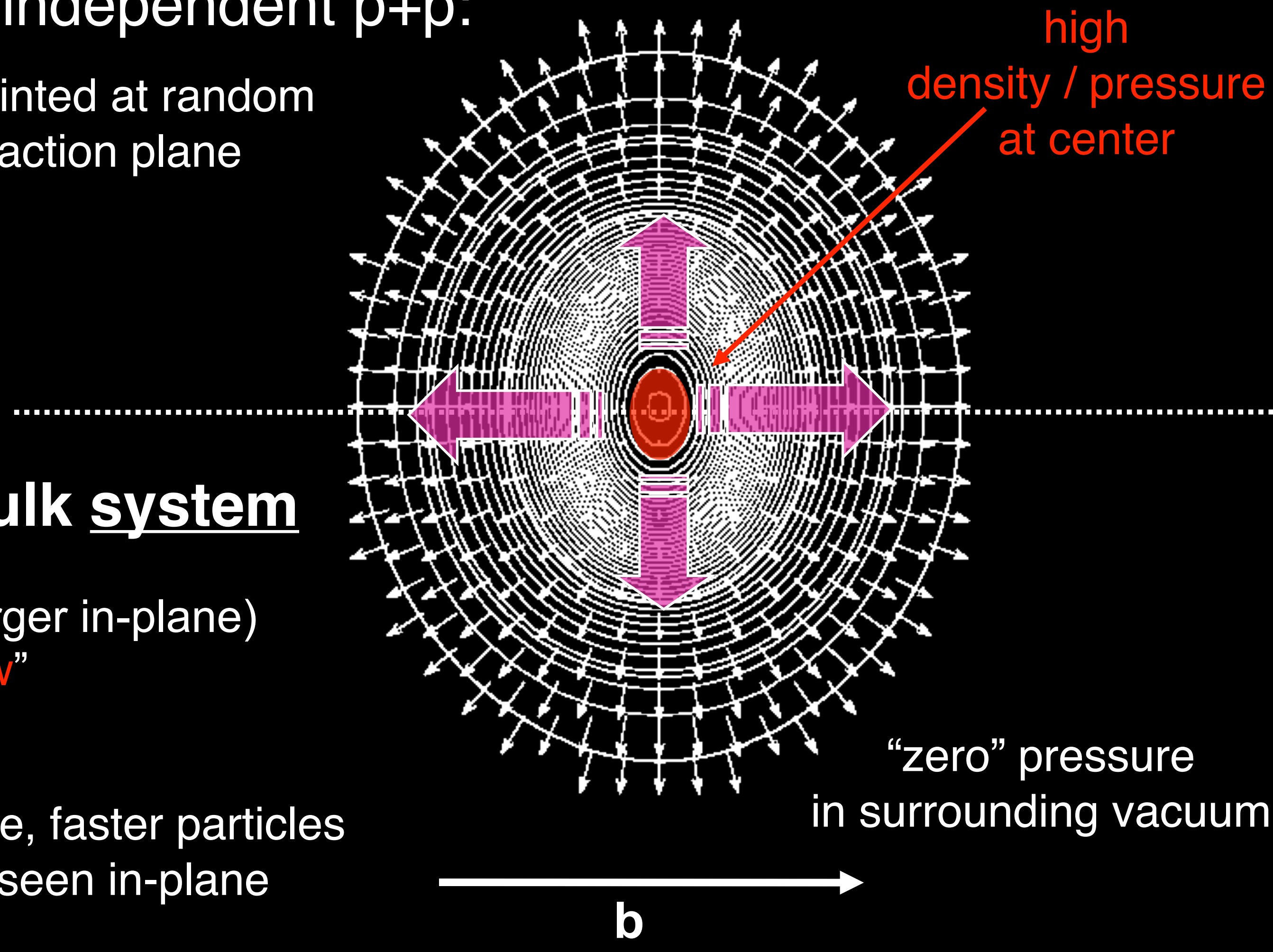


2) evolution as a **bulk <u>system</u>**

pressure gradients (larger in-plane)
push bulk “out” → “flow”



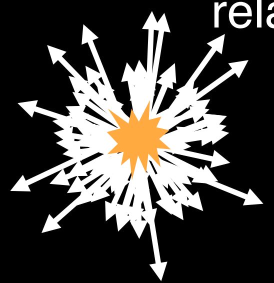
more, faster particles
seen in-plane

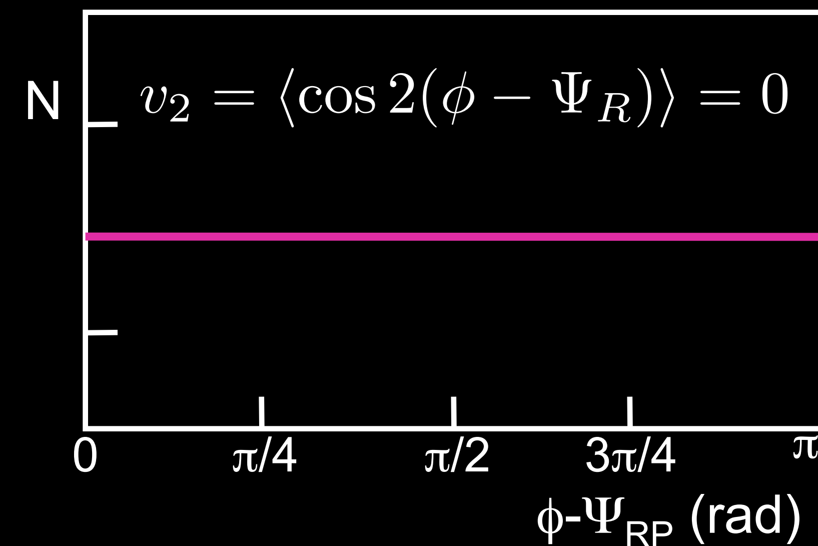


Elliptic Flow

1) superposition of independent p+p:

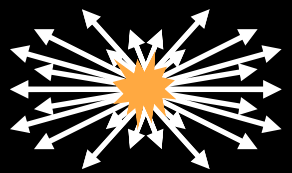
momenta pointed at random relative to reaction plane



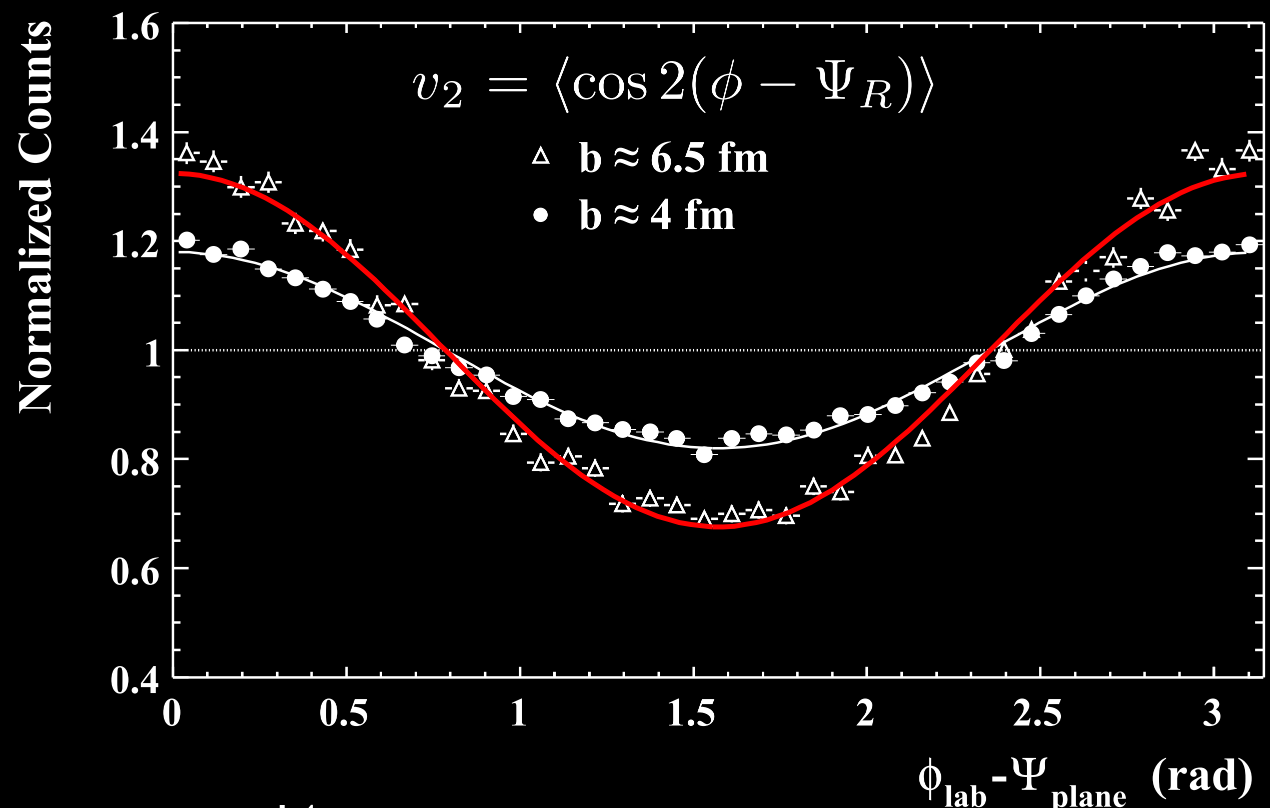


2) evolution as a **bulk** **system**

pressure gradients (larger in-plane) push bulk "out" → "flow"



more, faster particles seen in-plane



What do we measure?

We do not know the reaction plane ψ_R or in more general ψ_n

$$v_n \equiv \langle e^{in(\varphi - \Psi_n)} \rangle$$

We can calculate these observables only using correlations

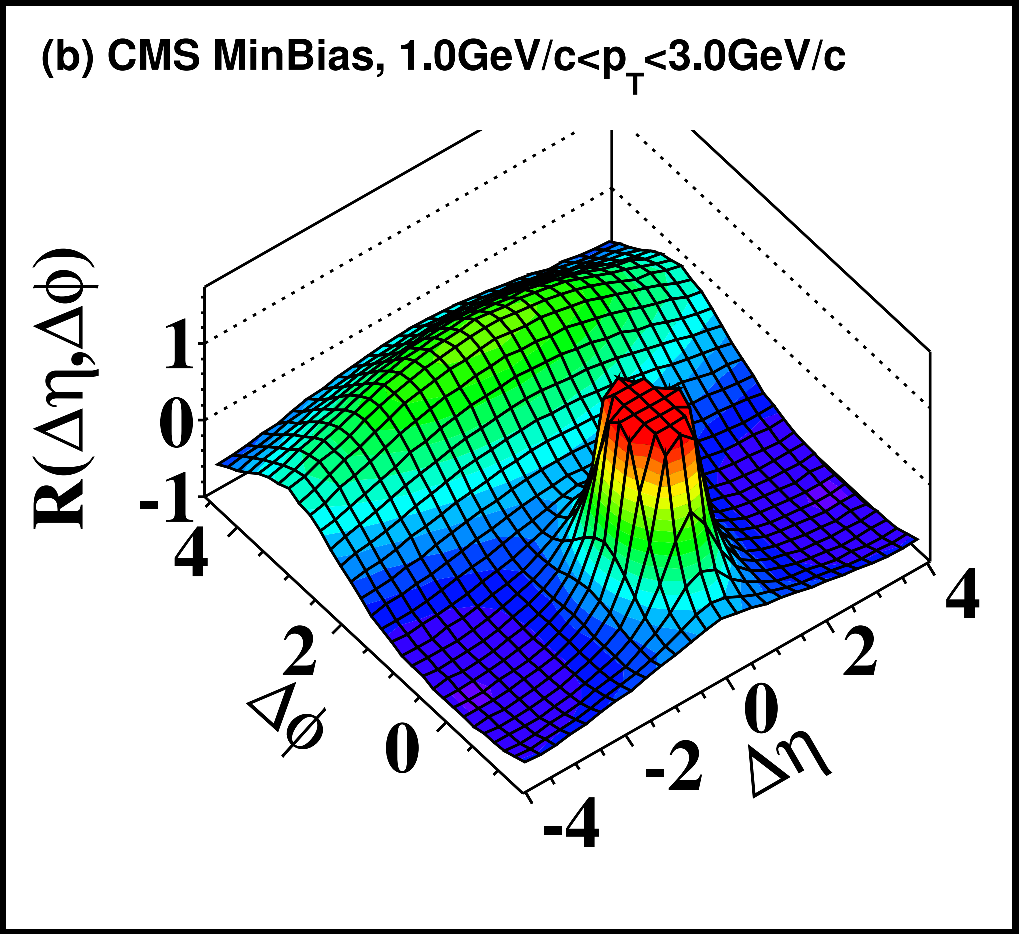
$$\langle\langle e^{in(\varphi_1 - \varphi_2)} \rangle\rangle = \langle\langle e^{in(\varphi_1)} \rangle\rangle \langle\langle e^{in(\varphi_2)} \rangle\rangle + \langle\langle e^{in(\varphi_1 - \varphi_2)} \rangle_c \rangle$$

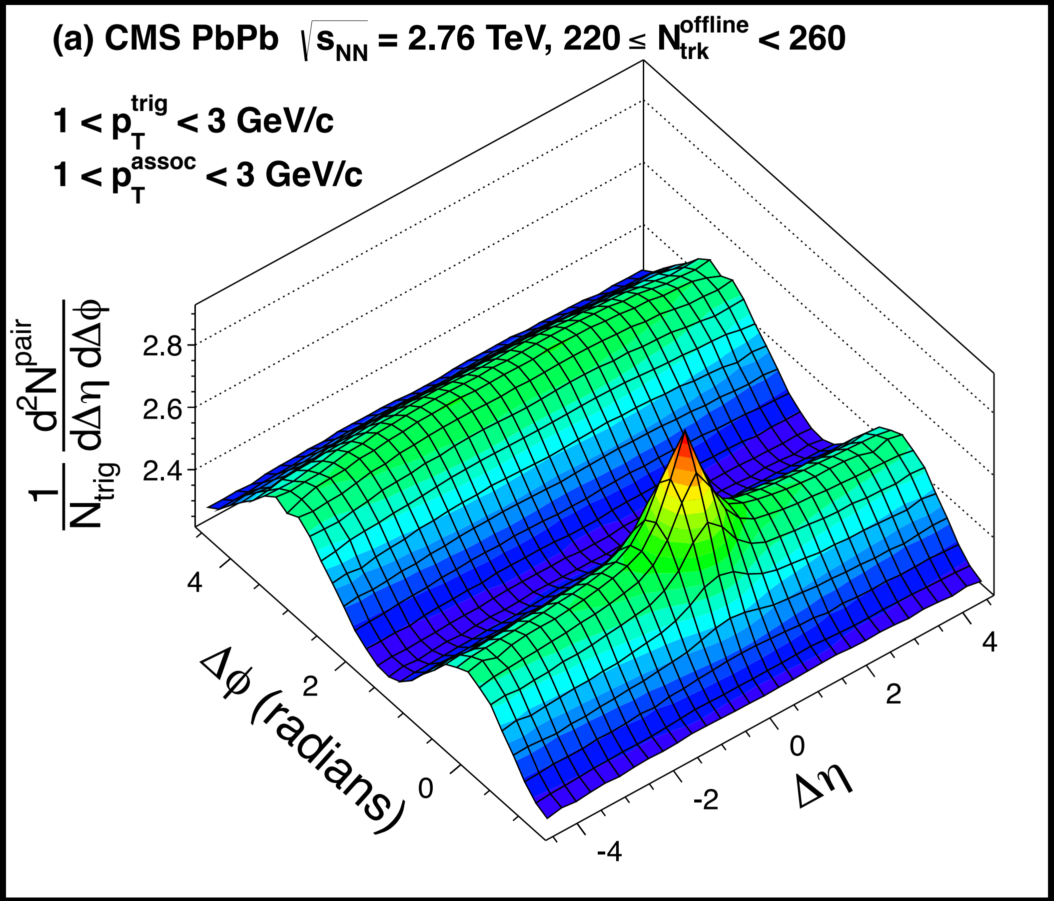
zero for symmetric detector when averaged over many events

$$\begin{aligned} \langle\langle e^{in(\varphi_1 - \varphi_2)} \rangle\rangle &= \langle\langle e^{in(\varphi_1 - \Psi_n - (\varphi_2 - \Psi_n))} \rangle\rangle \\ &= \langle\langle e^{in(\varphi_1 - \Psi_n)} \rangle \langle e^{-in(\varphi_2 - \Psi_n)} \rangle\rangle \\ &= \langle v_n^2 \rangle \end{aligned}$$

when only ψ_n correlations are present

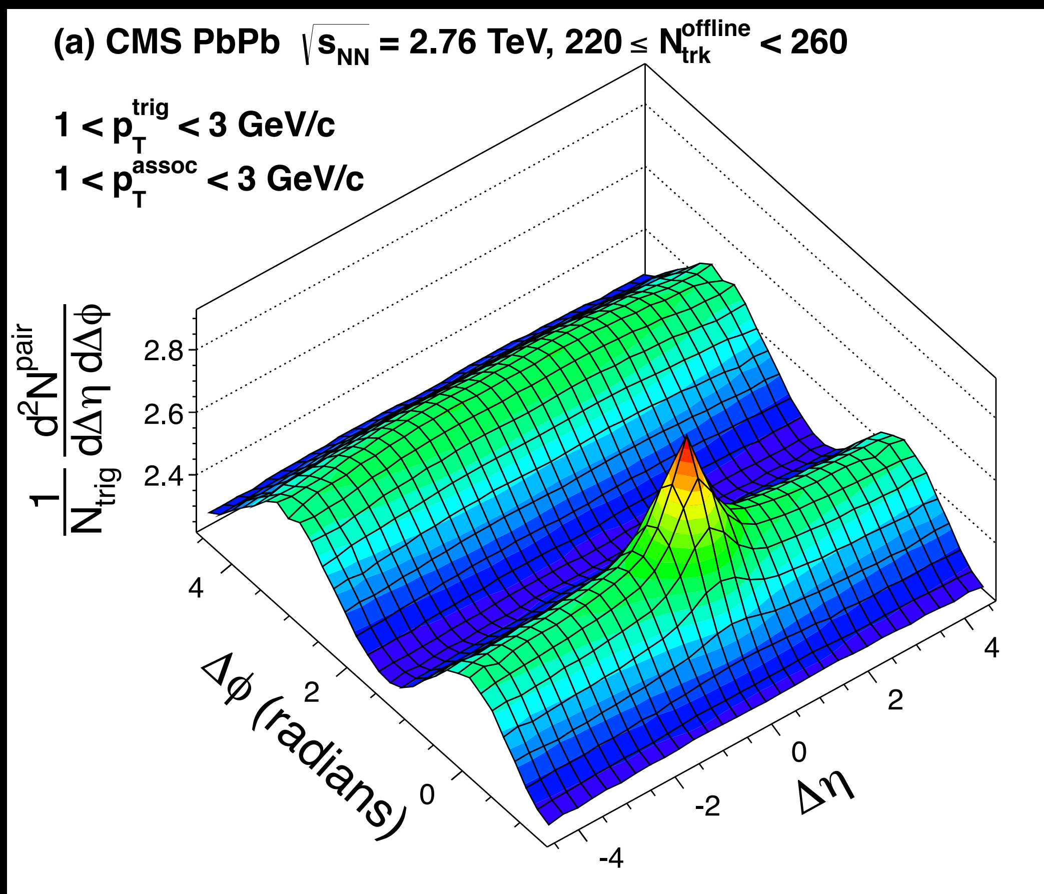
What do we measure?





In minimum bias pp collisions clear jet near and away side peak
In PbPb long ridge structures on near and away side
Signatures of correlations due to the initial stage (geometry) and in PbPb final state interactions (which translate spatial geometry into momentum space)

How do we quantify these ridges?

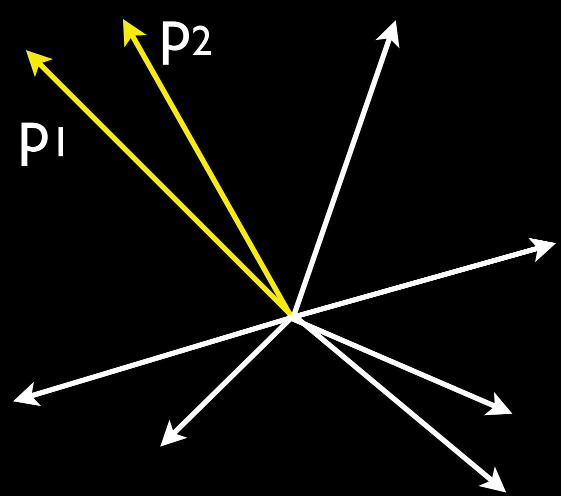


The long range correlations can be characterised by the flow Fourier harmonics such as v_2, which is the most dominant

$$\frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{dN^{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}[1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi)]$$

Collective motion

$$\left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle = \langle v_n^2 \rangle + \delta_2$$



particle 1 coming from the resonance. Out of remaining M-1 particles there is only one which is coming from the same resonance, particle 2. Hence a probability that out of M particles we will select two coming from the same resonance is ~ 1/(M-1). From this we can draw a conclusion that for large multiplicity: $\delta_2 \sim 1/M$

- therefore to reliably measure flow:

$$v_n^2 \gg 1/M \quad \Rightarrow \quad v_n \gg 1/M^{1/2}$$

- not easily satisfied: M=200 v_n >> 0.07

Collective motion

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Generalized Cumulant Expansion Method*

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Department of Physics, University of Tokyo

(Received April 11, 1962)

The moment generating function of a set of stochastic variables defines the cumulants or the semi-invariants and the cumulant function. It is possible, simply by formal properties of exponential functions, to generalize to a great extent the concepts of cumulants and cumulant function. The stochastic variables to be considered need not be ordinary c-numbers but they may be q-numbers such as used in quantum mechanics. The exponential function which defines a moment generating function may be any kind of generalized exponential, for example an ordered exponential with a certain prescription for ordering q-number variables. The definition of average may be greatly generalized as far as the condition is fulfilled that the average of unity is unity. After statements of a few basic theorems these generalizations are discussed here with certain examples of application. This generalized cumulant expansion provides us with a point of view from which many existent methods in quantum mechanics and statistical mechanics can be unified.

$$\begin{aligned}
&\langle X_j\rangle_c=\langle X_j\rangle\\
&\langle X_j^2\rangle_c=\langle X_j^2\rangle-\langle X_j\rangle^2\\
&\langle X_jX_l\rangle_c=\langle X_jX_l\rangle-\langle X_j\rangle\langle X_l\rangle\\
&\langle X_jX_kX_l\rangle_c=\langle X_jX_kX_l\rangle\\
&\qquad-\{\langle X_j\rangle\langle X_kX_l\rangle+\langle X_k\rangle\langle X_lX_j\rangle+\langle X_l\rangle\langle X_jX_k\rangle\}\\
&\qquad+2\langle X_j\rangle\langle X_k\rangle\langle X_l\rangle\\
&\langle X_jX_kX_lX_m\rangle_c=\langle X_jX_kX_lX_m\rangle\\
&\quad-\{\langle X_j\rangle\langle X_kX_lX_m\rangle+\langle X_k\rangle\langle X_jX_lX_m\rangle+\langle X_l\rangle\langle X_jX_kX_m\rangle+\langle X_m\rangle\langle X_jX_kX_l\rangle\}\\
&\quad-\{\langle X_jX_k\rangle\langle X_lX_m\rangle+\langle X_jX_l\rangle\langle X_kX_m\rangle+\langle X_jX_m\rangle\langle X_kX_l\rangle\}\\
&\quad+2\{\langle X_j\rangle\langle X_k\rangle\langle X_lX_m\rangle+\langle X_j\rangle\langle X_l\rangle\langle X_kX_m\rangle+\langle X_j\rangle\langle X_m\rangle\langle X_kX_l\rangle\\
&\qquad+\langle X_jX_k\rangle\langle X_l\rangle\langle X_m\rangle+\langle X_jX_l\rangle\langle X_k\rangle\langle X_m\rangle+\langle X_jX_m\rangle\langle X_k\rangle\langle X_l\rangle\}\\
&\quad-6\langle X_j\rangle\langle X_k\rangle\langle X_l\rangle\langle X_m\rangle
\end{aligned}\tag{2.8}$$

cumulants allow us to see if there are multi-particle correlations in the system (cumulants nonzero only mathematical proof)

What do we measure?

Build cumulants with multi-particle correlations (Ollitrault and Borghini, 2000)

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

got rid of 2-particle correlations not related to collective flow however now we measure higher moment moments of the distribution

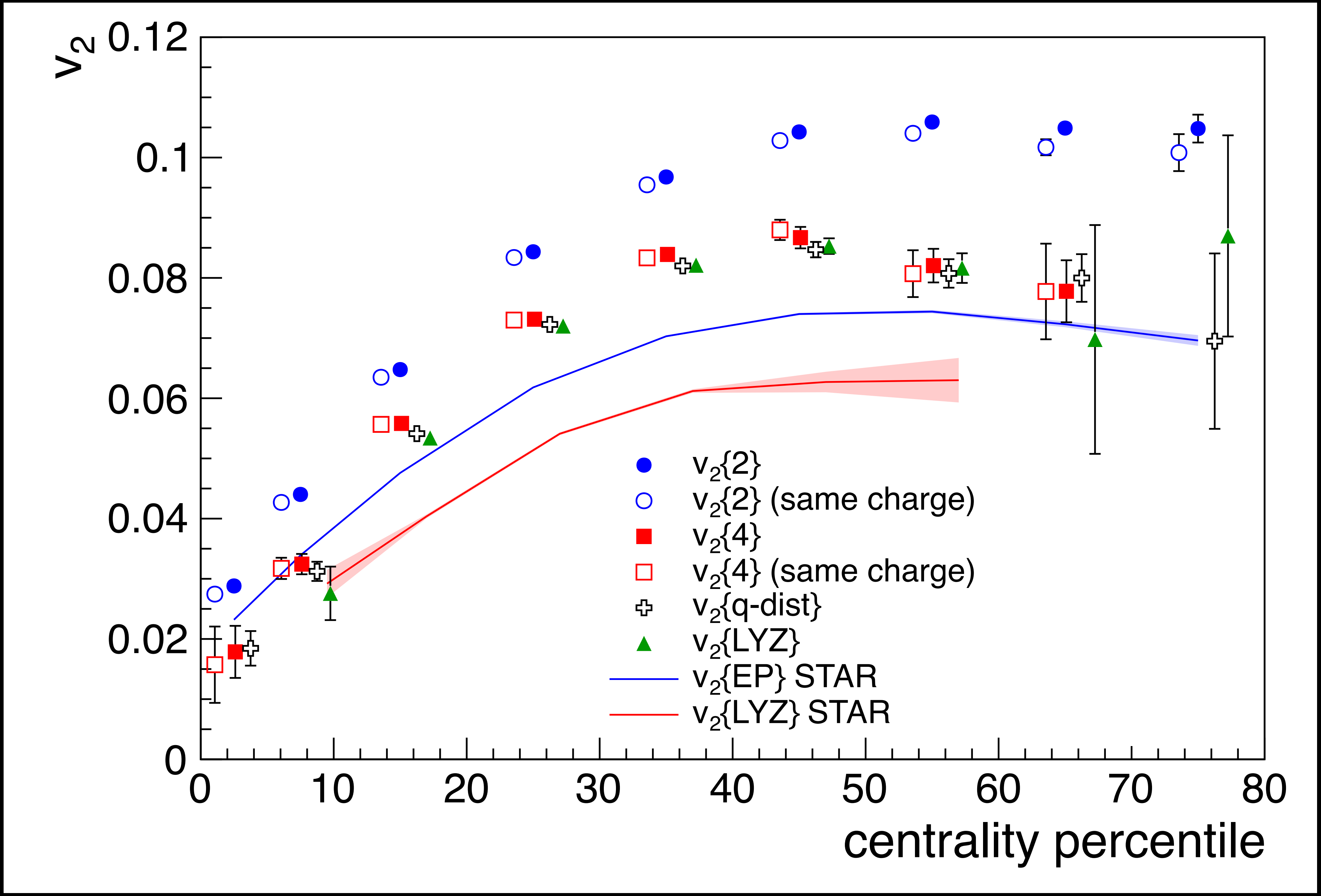
mathematical framework to calculate these analytically developed at Nikhef and used by all RHIC and LHC experiments

What do we measure?

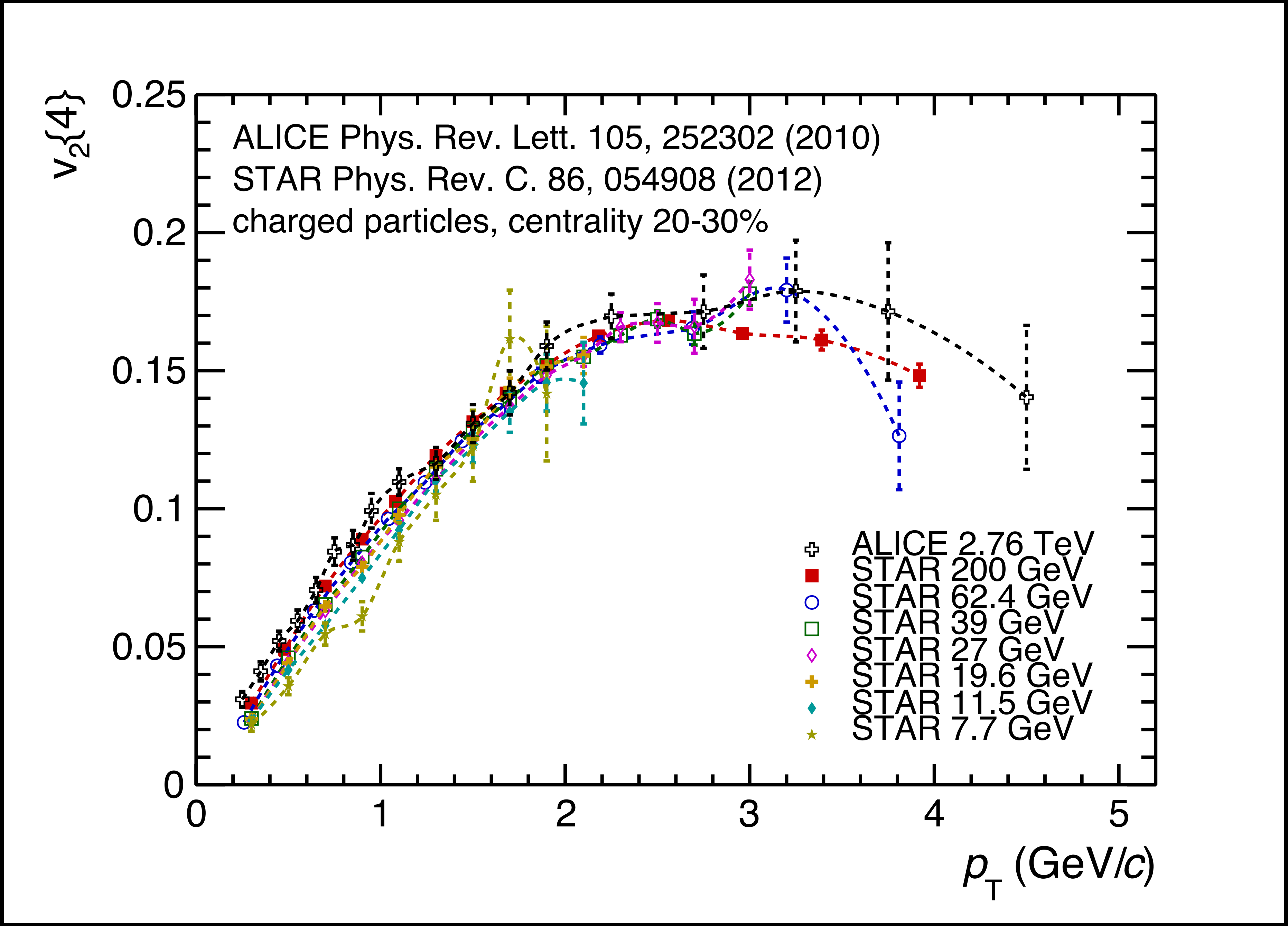
if the fluctuations are small or for a special pdf we can say for any distributions that the various flow estimates follow:

$$
\begin{aligned}
v\{2\} &= \langle v \rangle + \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle} \\
v\{4\} &= \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle} \\
v\{6\} &= \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle} \\
v\{8\} &= \langle v \rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v \rangle}
\end{aligned}
$$

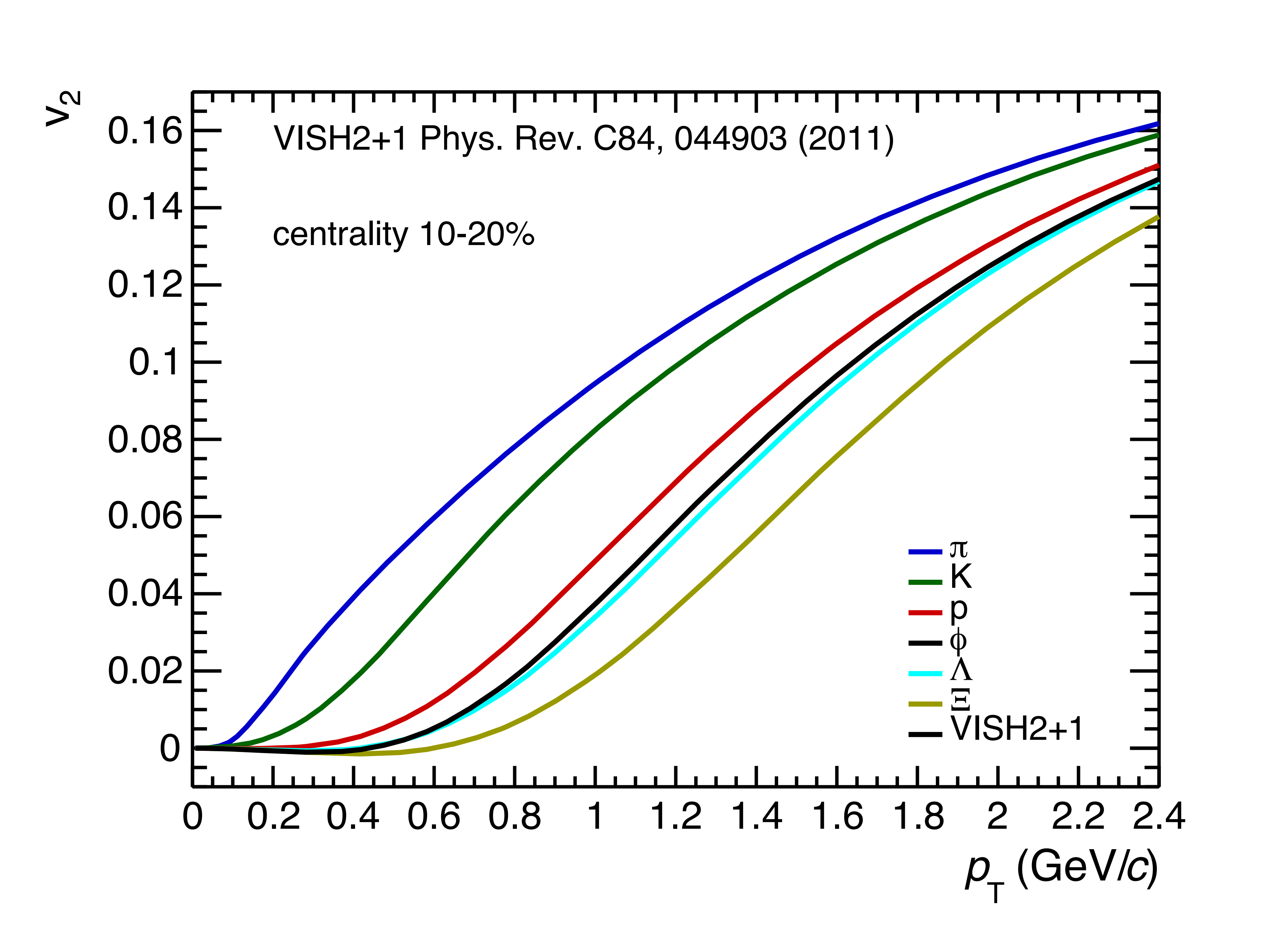
Integrated v_2



Collision energy dependence of elliptic flow as function of transverse momentum

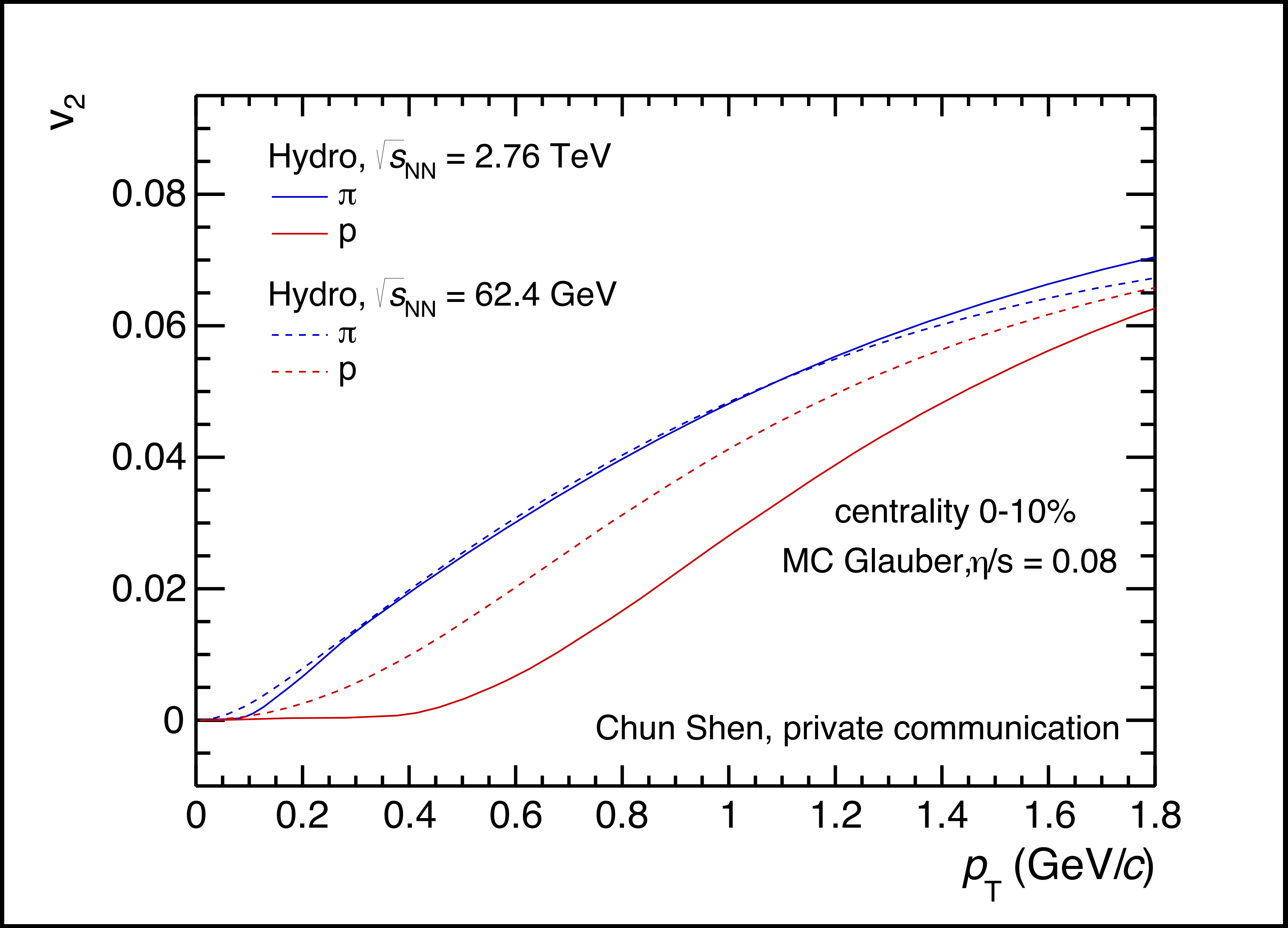


Collective behaviour



In a 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

Hydrodynamic behaviour



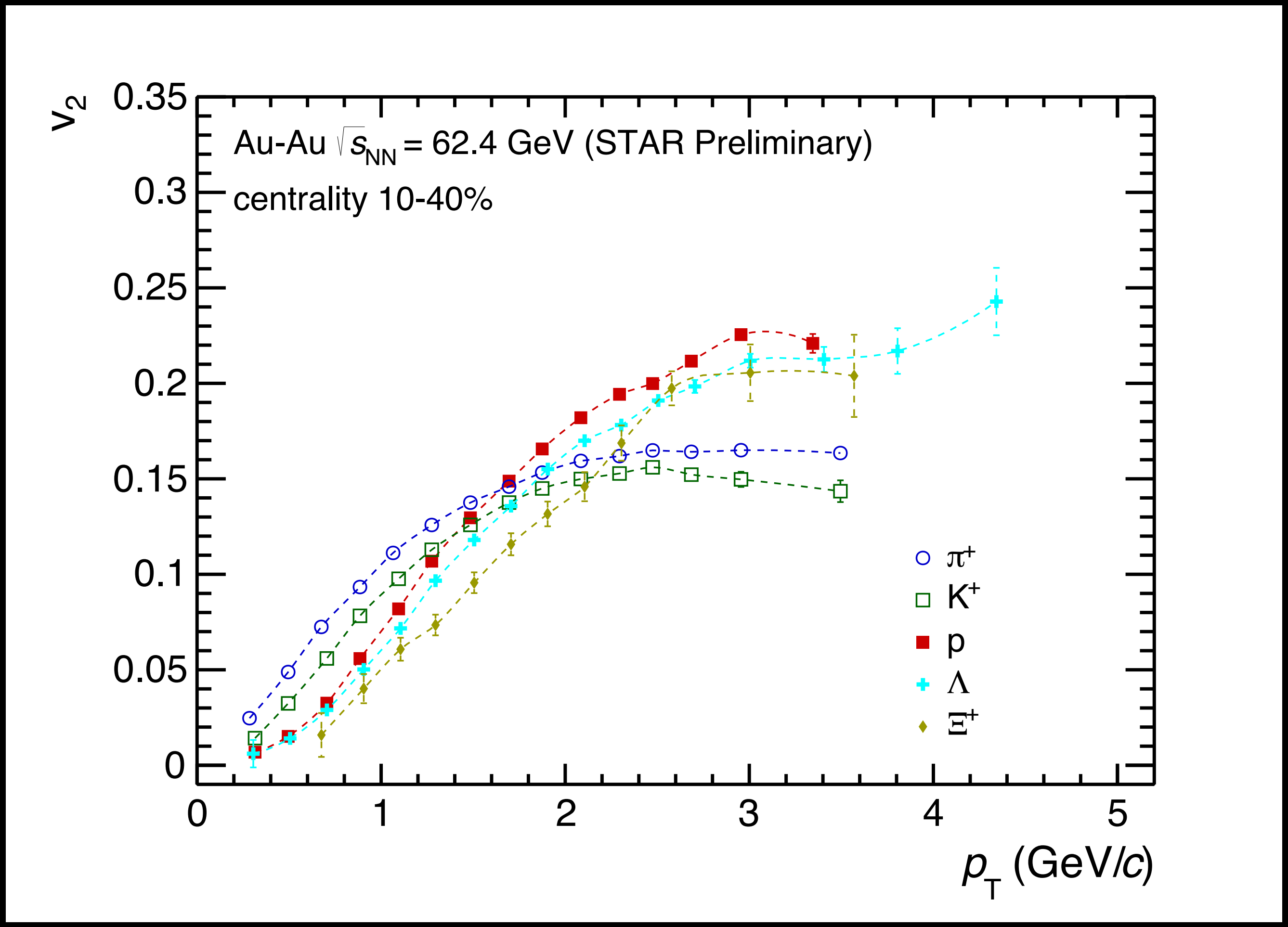
hydro picture

particles have a common temperature and flow velocity

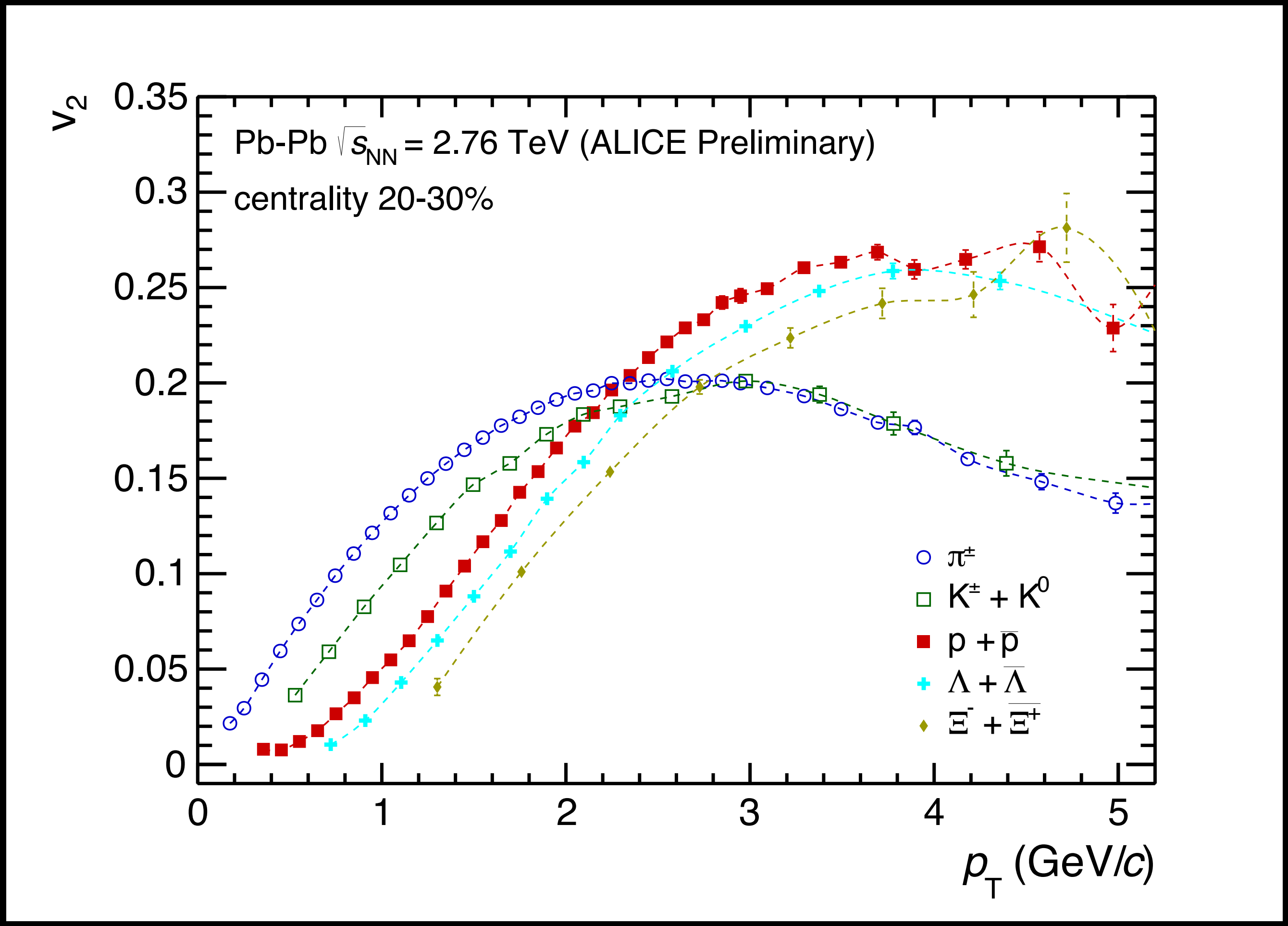
larger radial flow increases mass splitting

Collision energy dependence of elliptic flow for particles with different masses

STAR QM2014



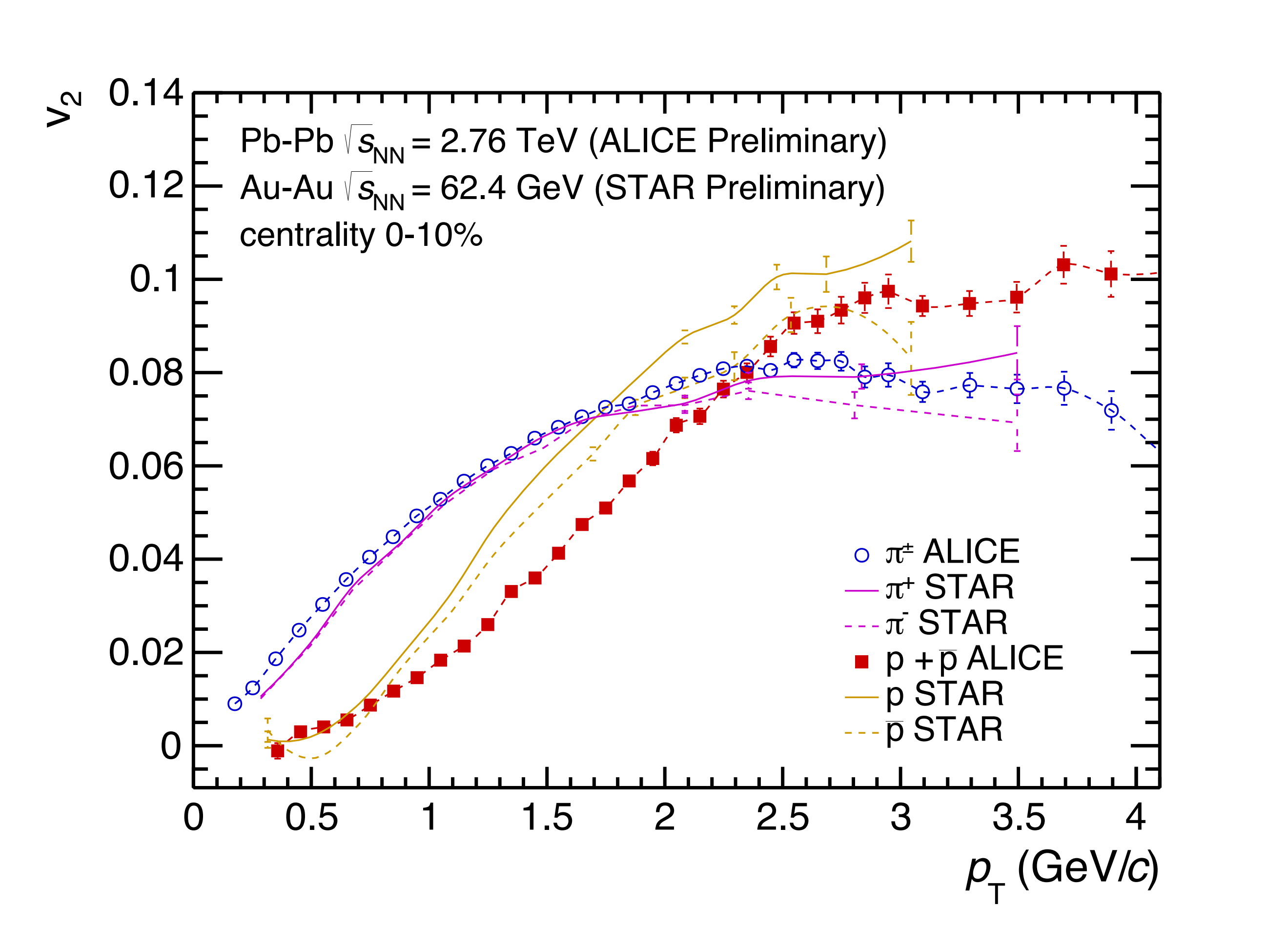
ALICE arXiv:1405.4632



mass hierarchy follows hydrodynamic picture at low p_T!

Collision energy dependence of elliptic flow as function of transverse momentum

ALICE arXiv:1405.4632 STAR QM2014



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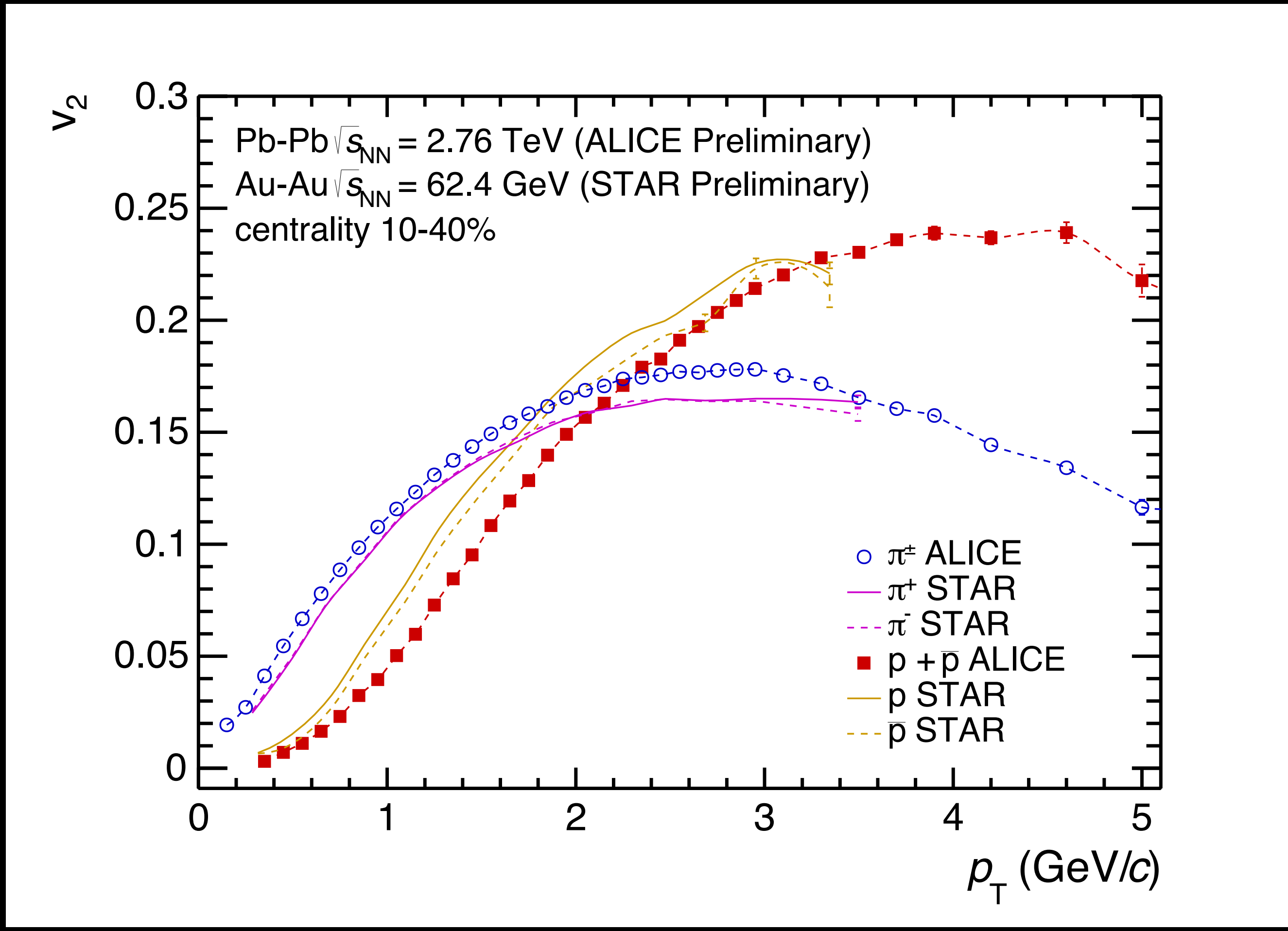
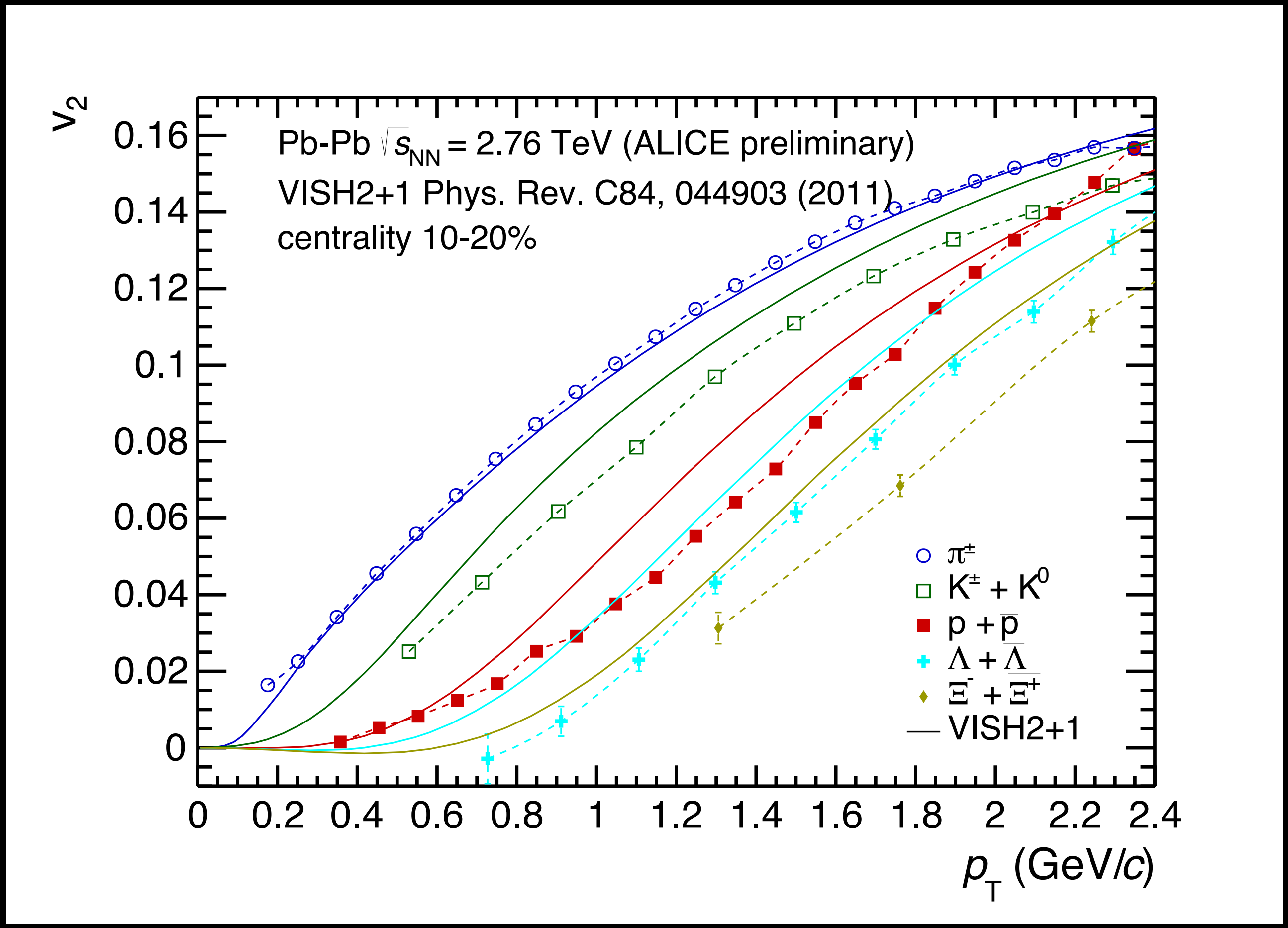


while the p_T-differential charged particle v_2 changes very little over two orders of magnitude the v_2 of heavier particles clearly shows the effect of the larger collective flow at higher collision energies

Compared to viscous hydrodynamics

ALICE arXiv:1405.4632



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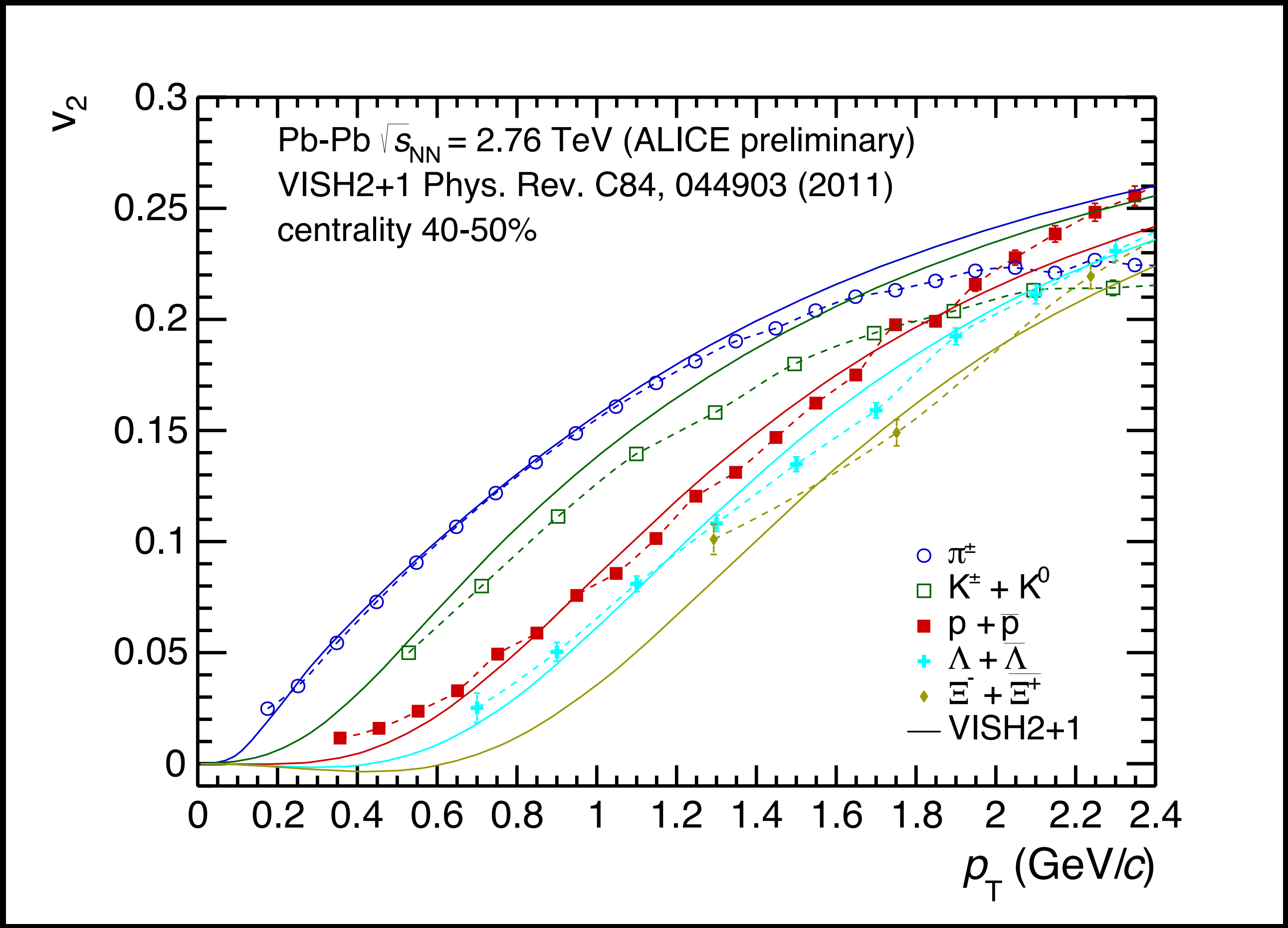
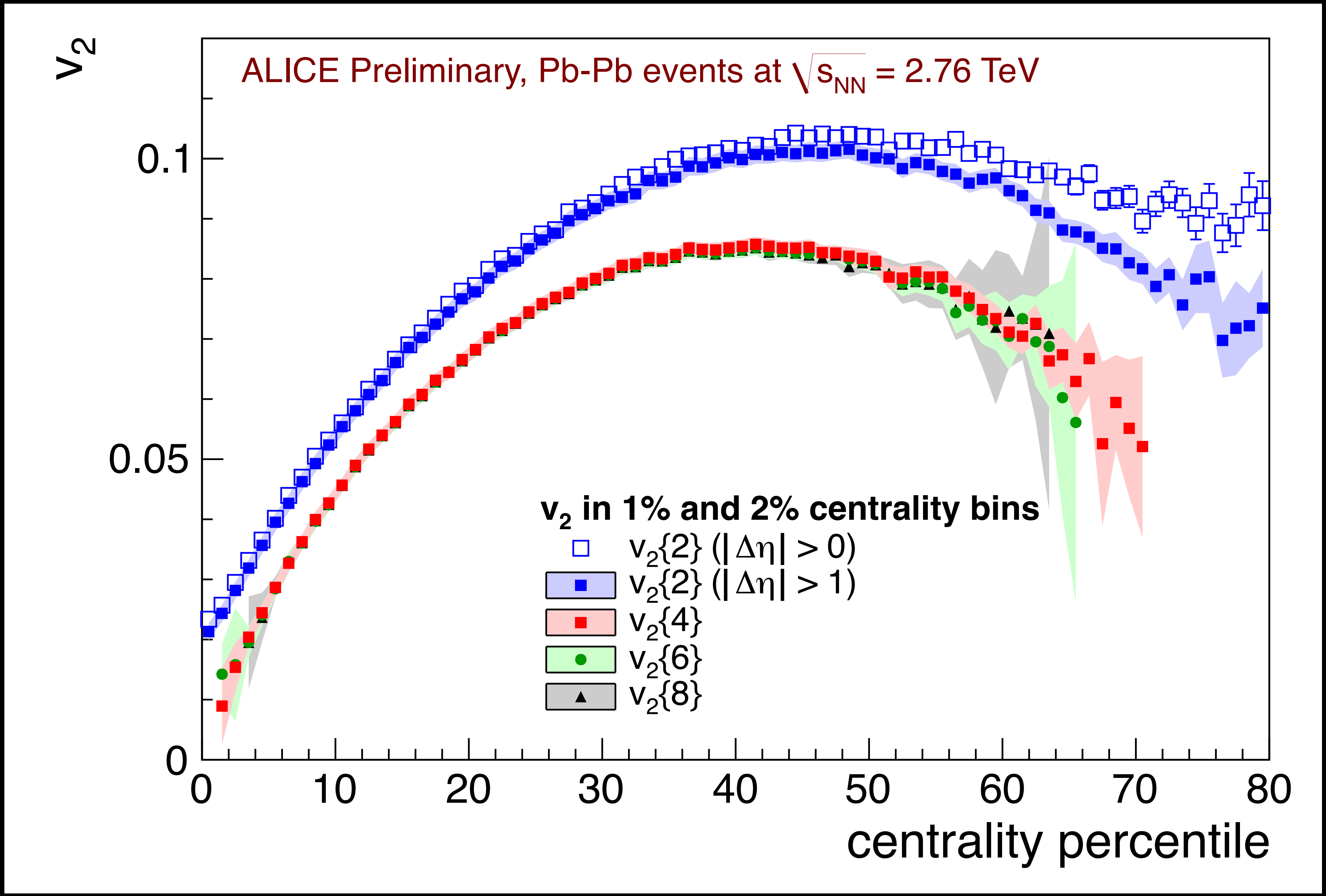


pure viscous hydrodynamics VISH2+1, status at QM2011

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

Fluctuations



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

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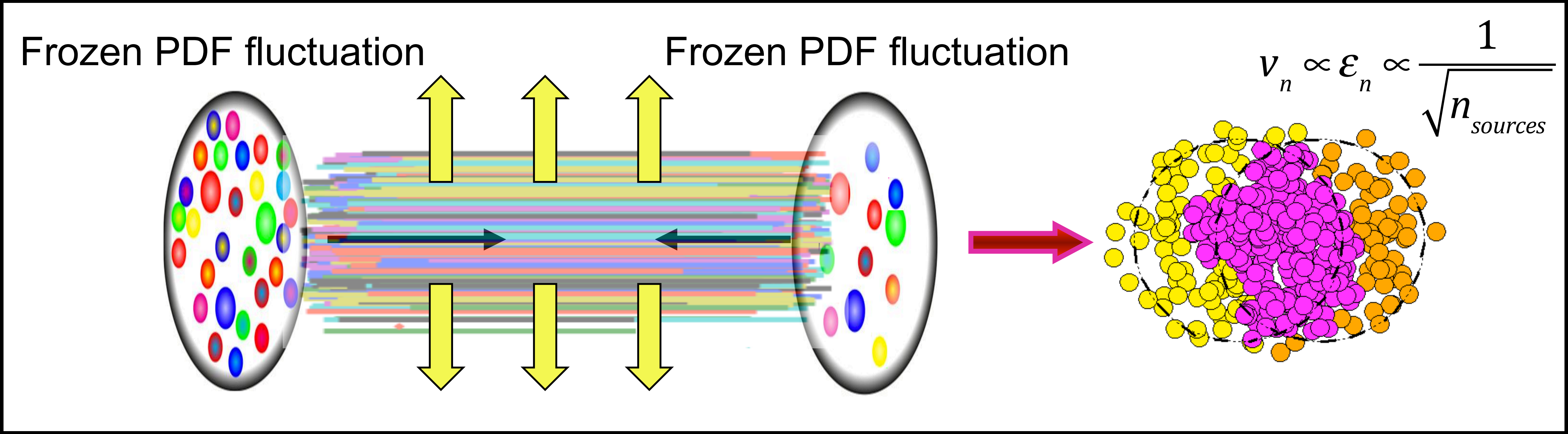
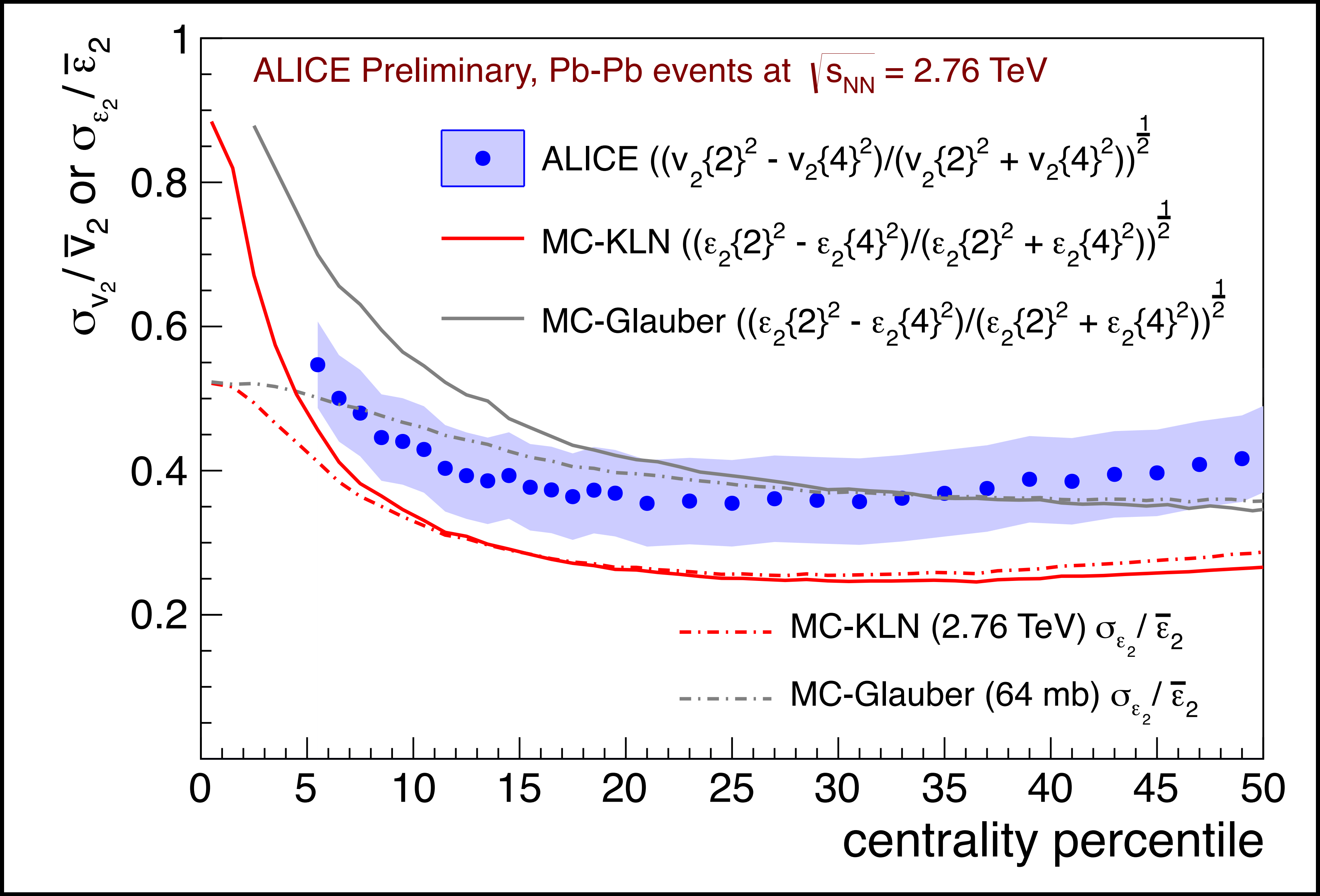
for small fluctuations or specific pdf

Fluctuations



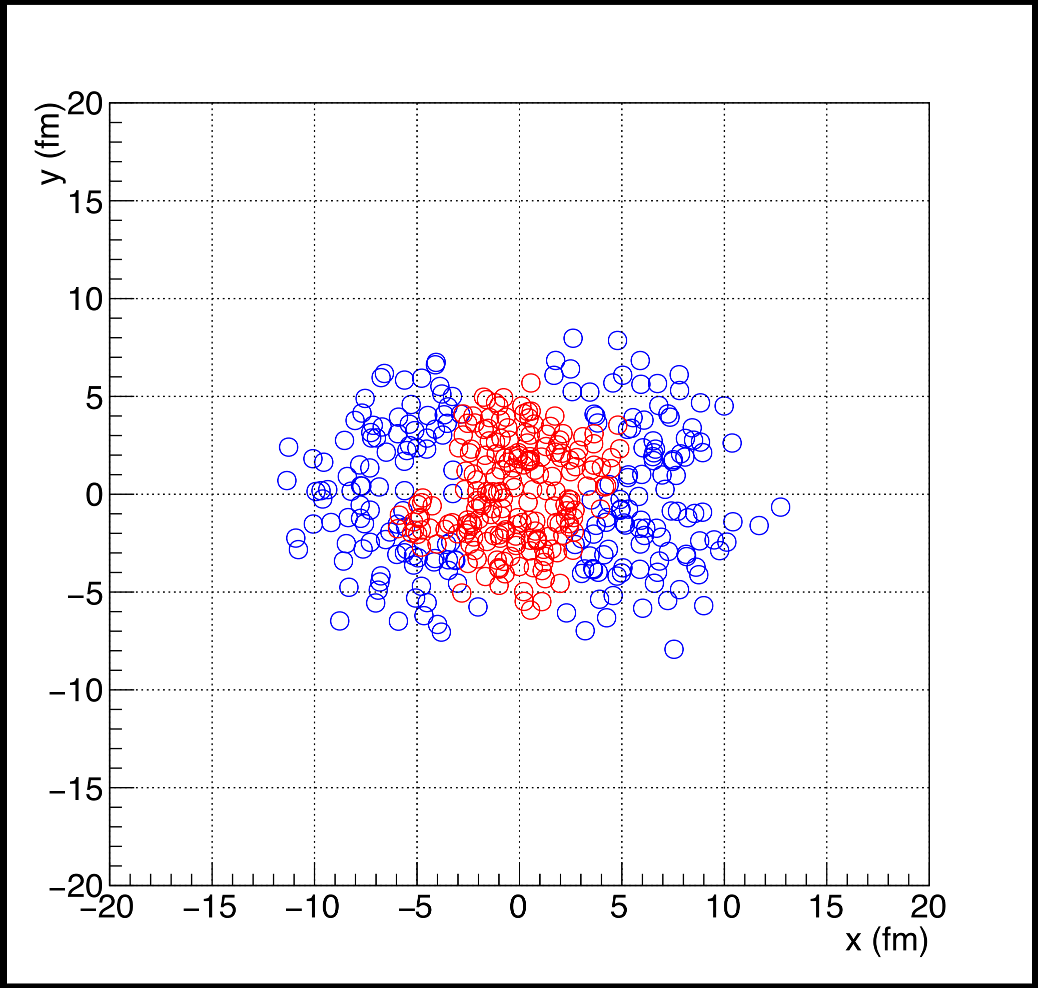
flow fluctuations scale with the number of sources
good tool to constrain initial conditions!

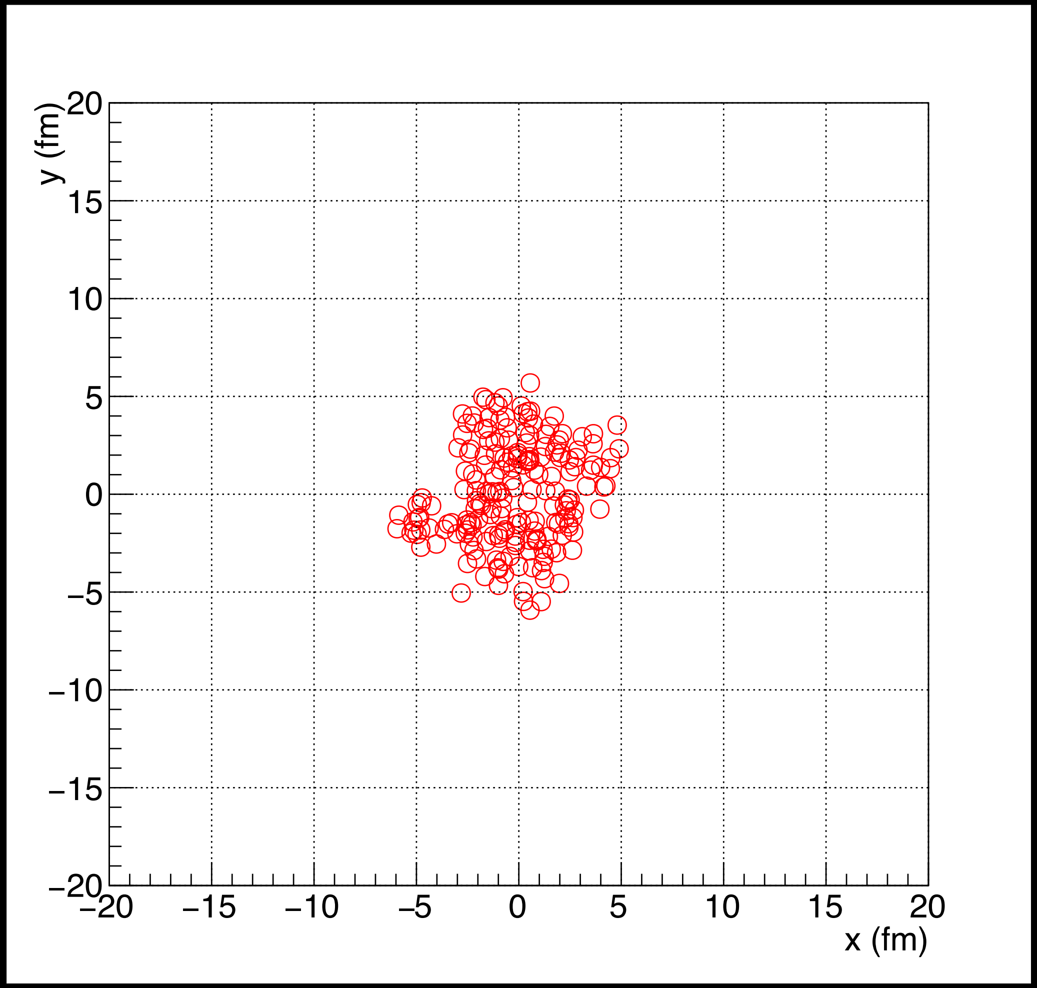
Fluctuations



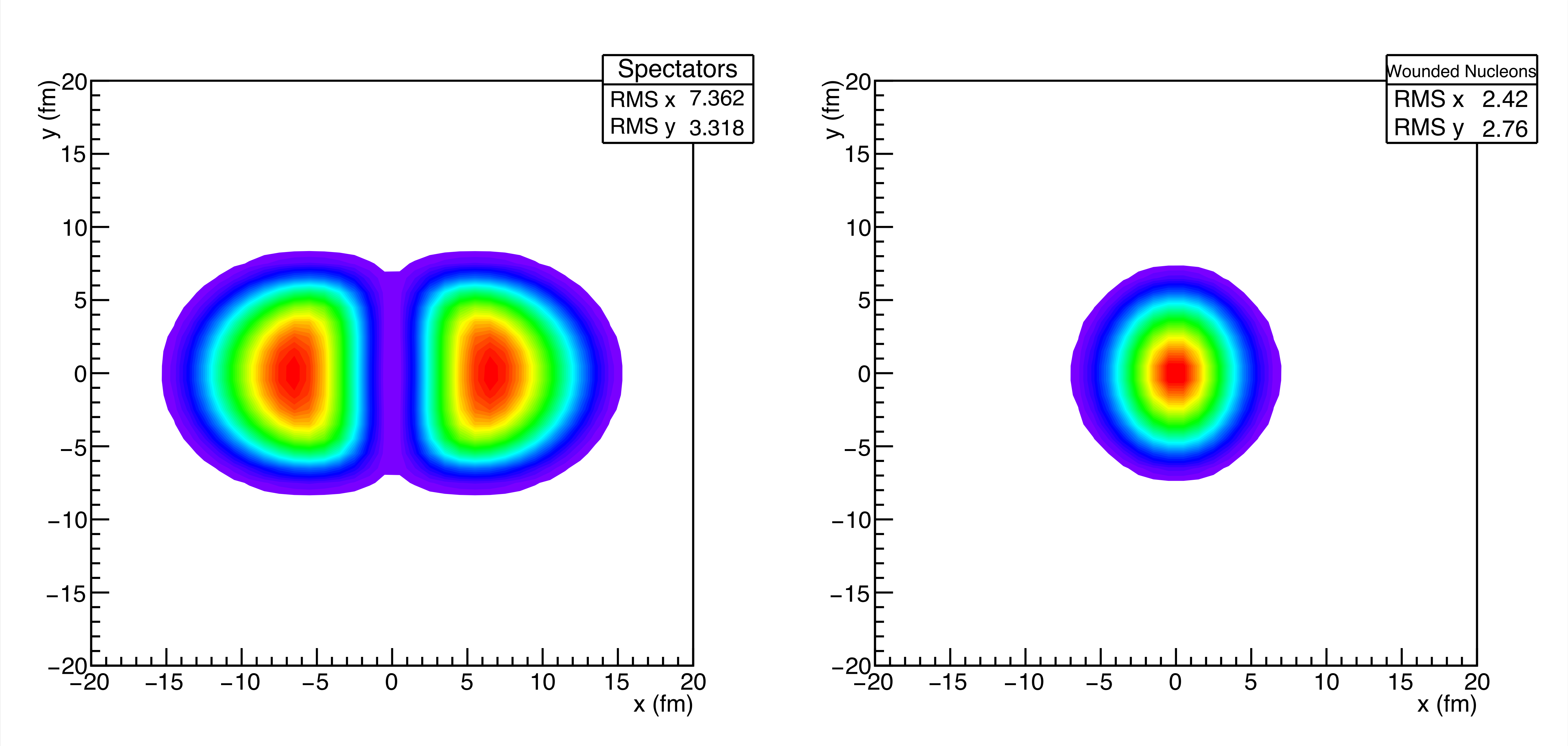
Various initial state models do capture the trend but fail on the details

A Single Collision

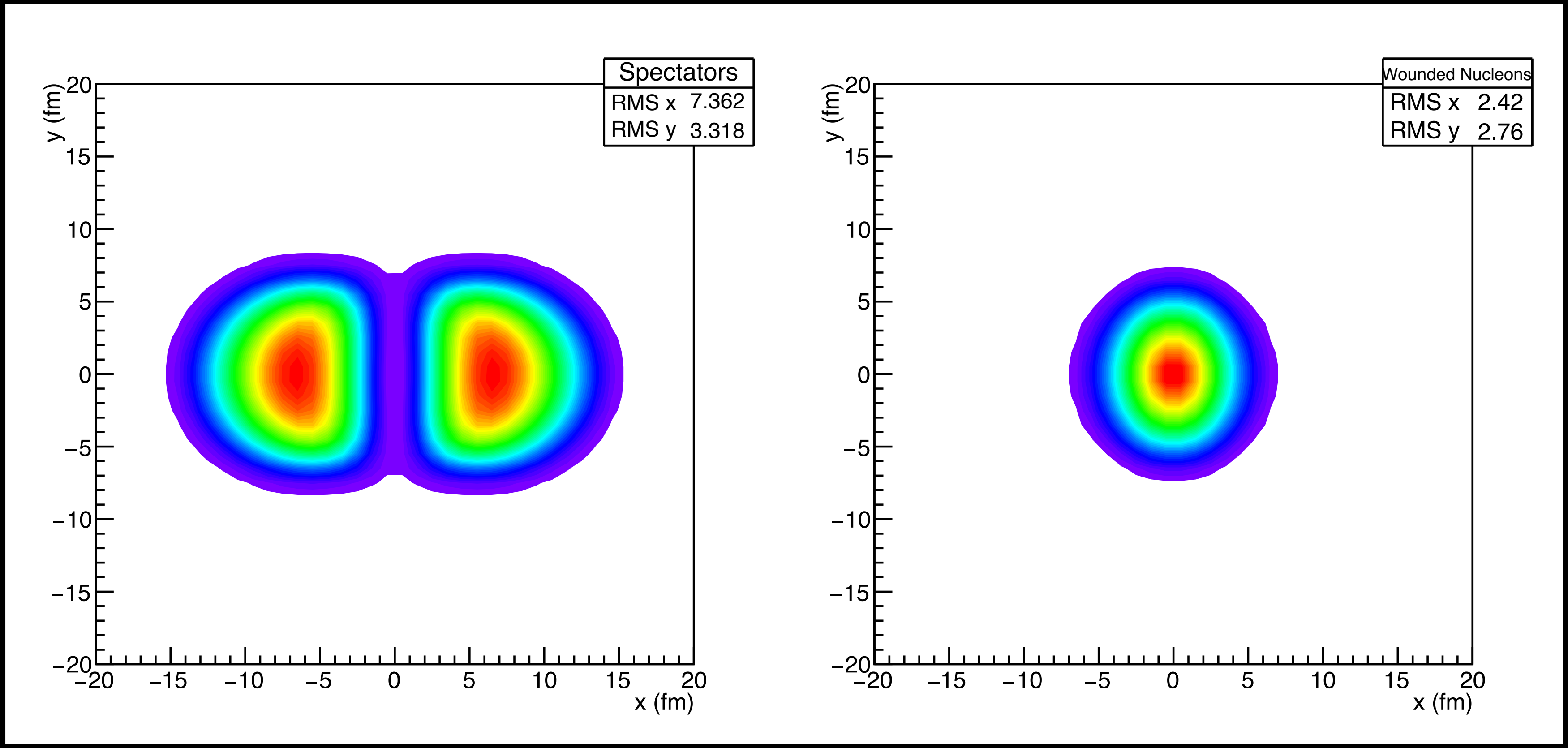


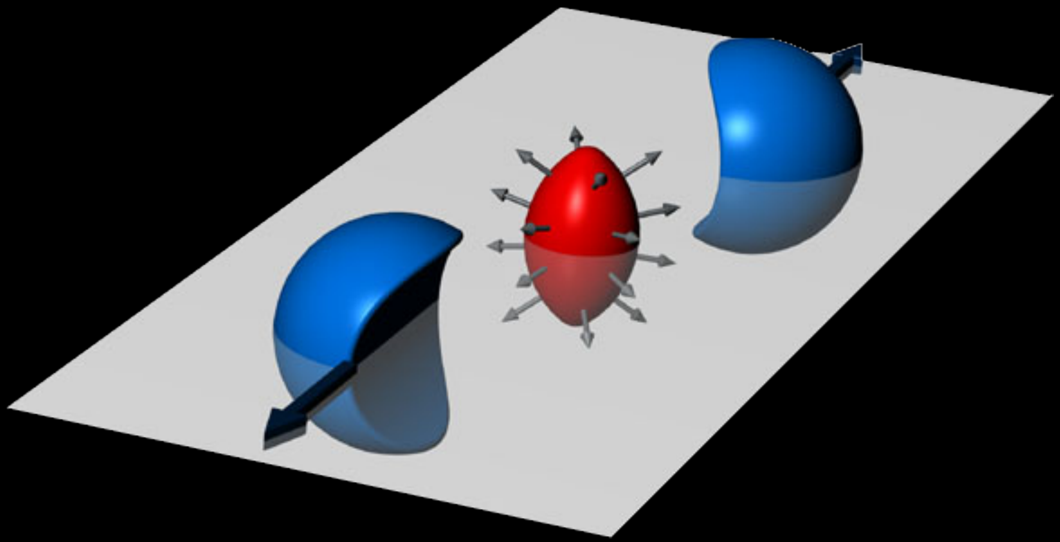


Many Collisions versus the Reaction Plane

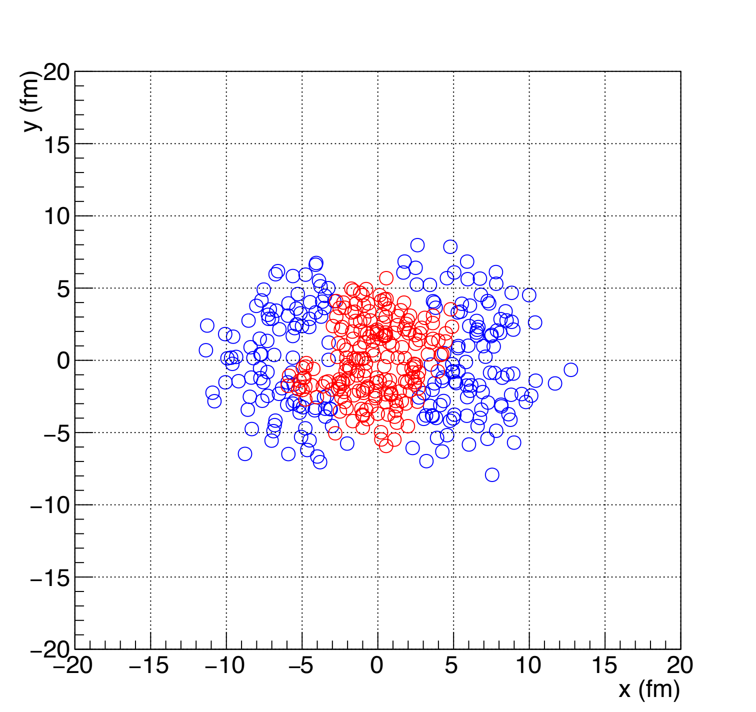


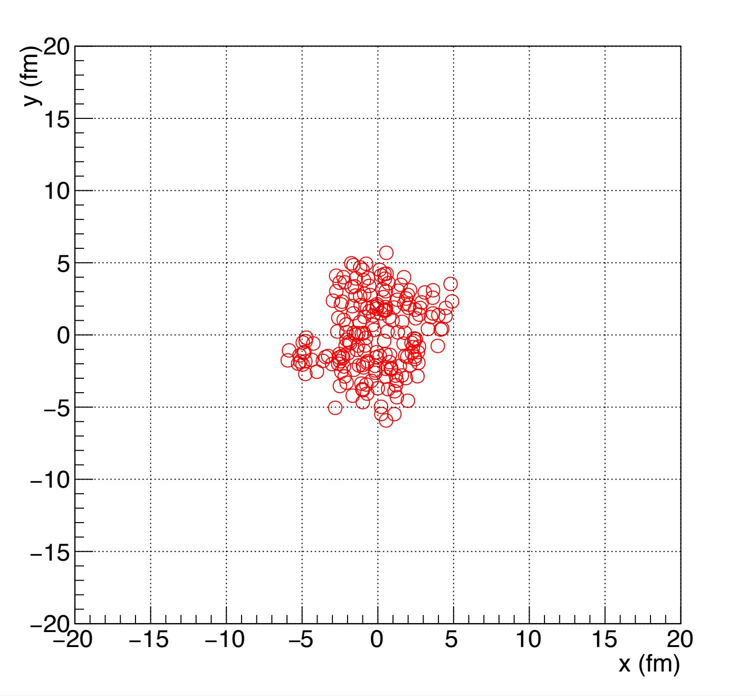
The original picture

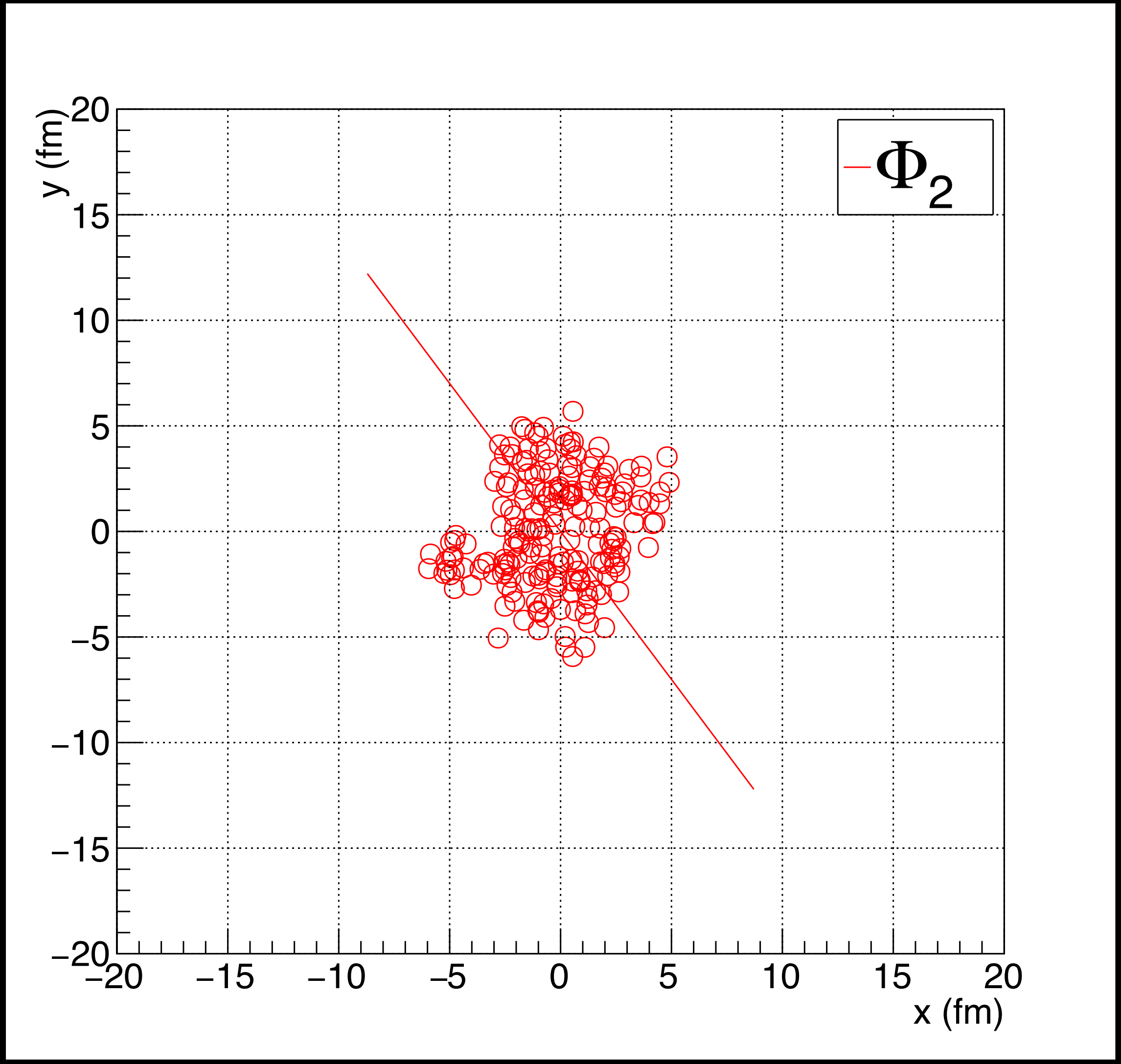




Symmetry Plane

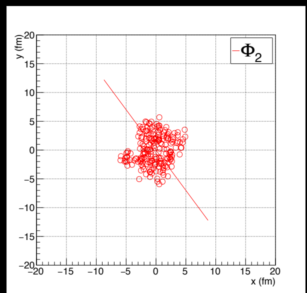




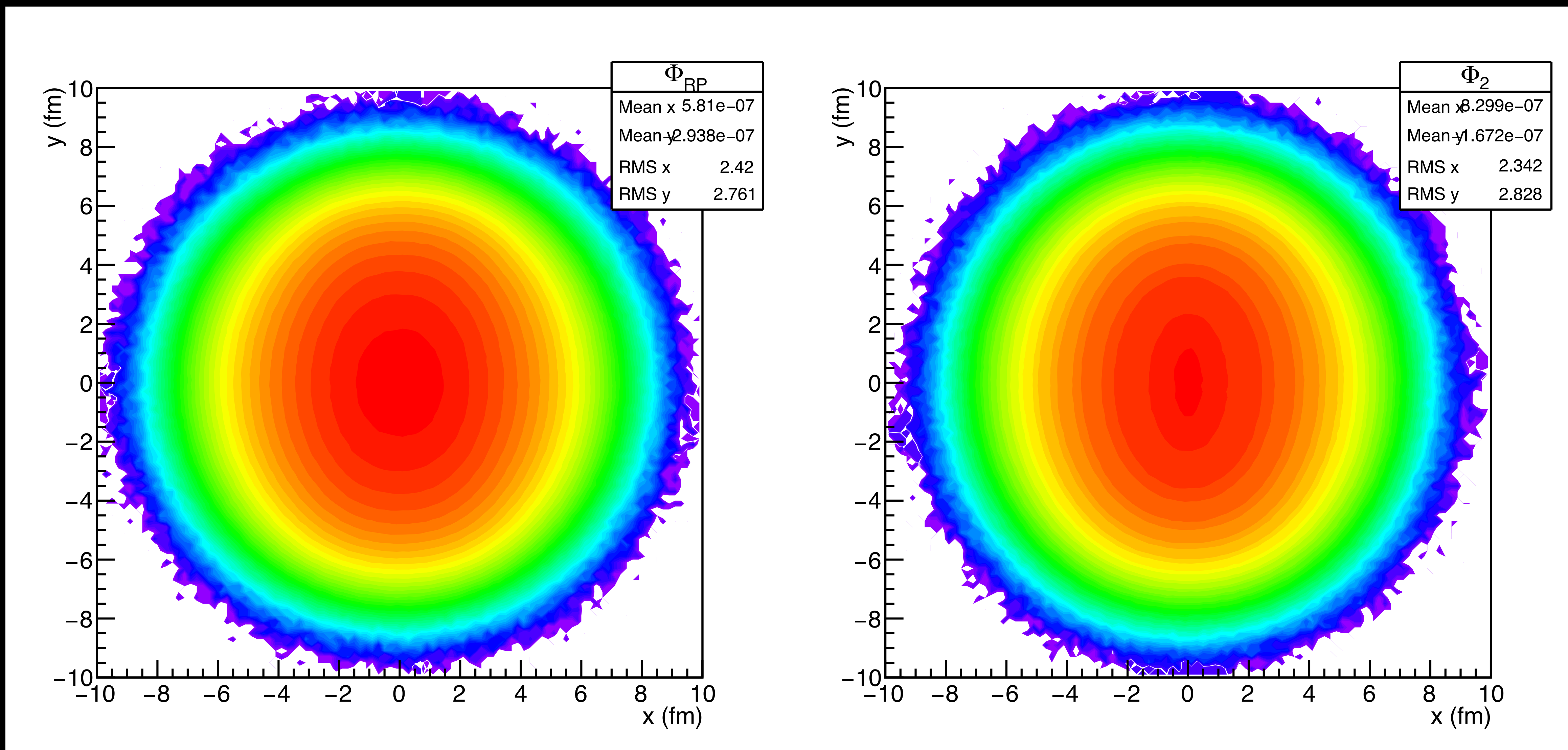


Using the particles produced we (experimentalists) determine, due to the fluctuations, a symmetry plane which is different than the Reaction Plane

$$v_n \propto \varepsilon_n$$



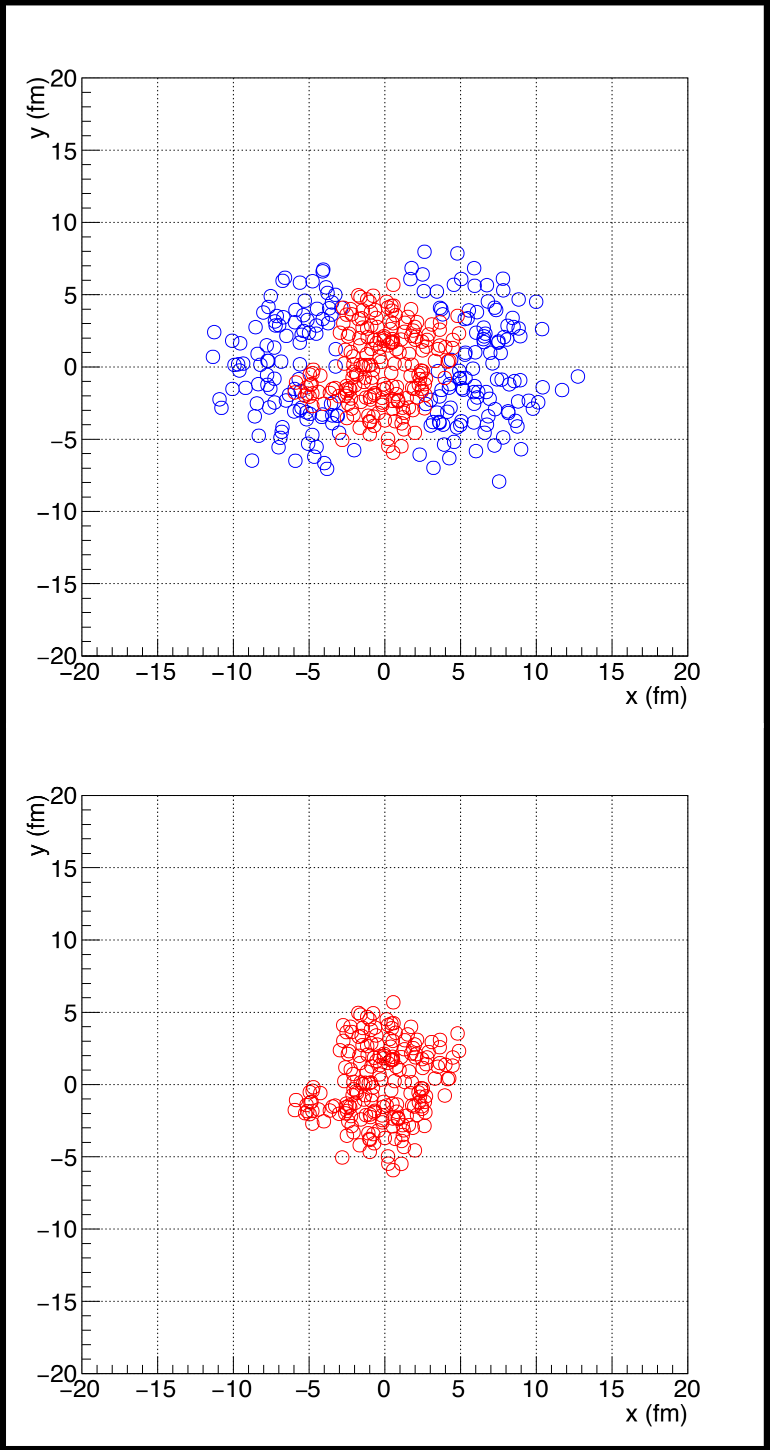
Symmetry Planes

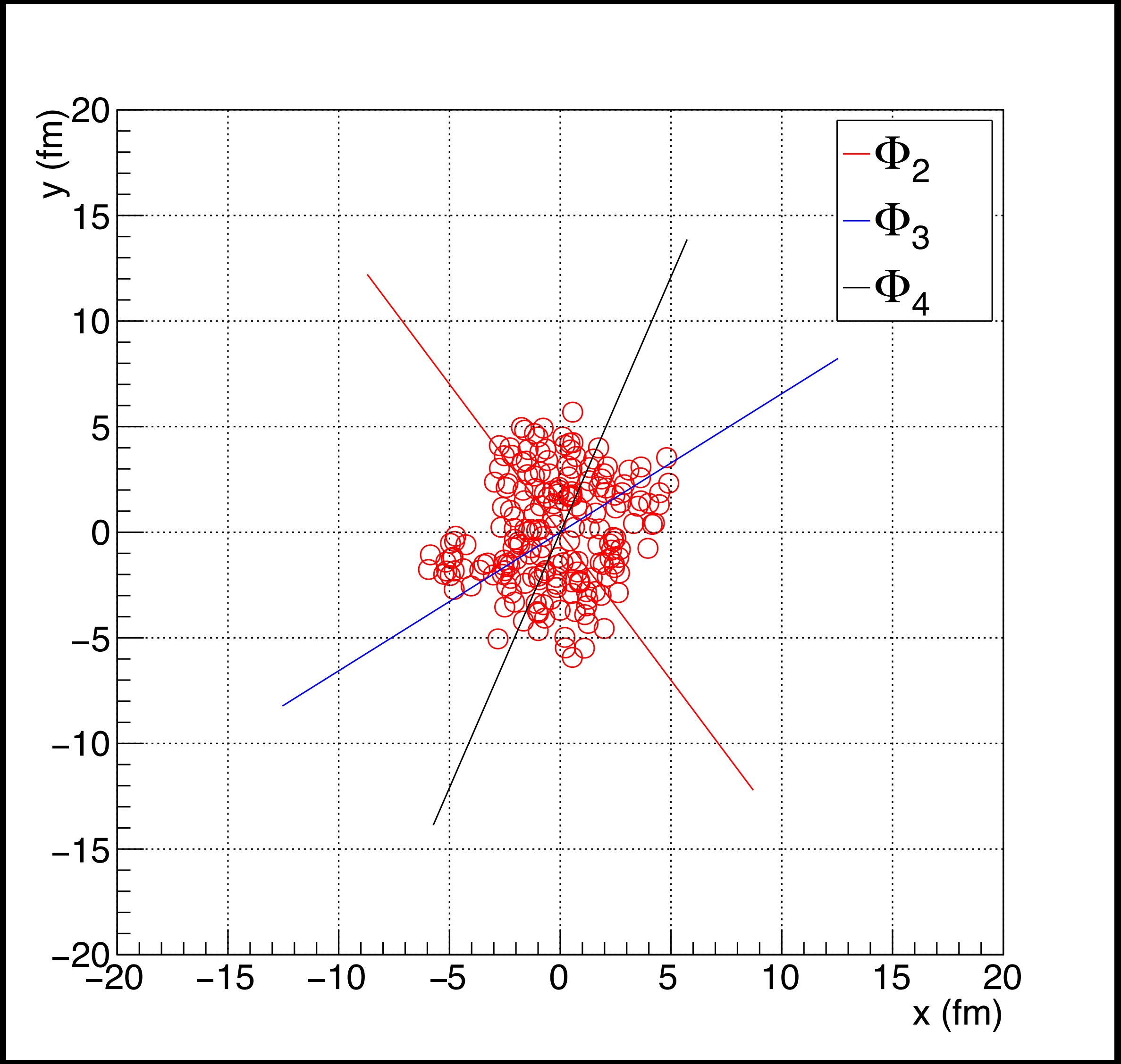


The asymmetry of the system is larger versus this symmetry plane

$$v_n \propto \varepsilon_n$$

Symmetry Planes

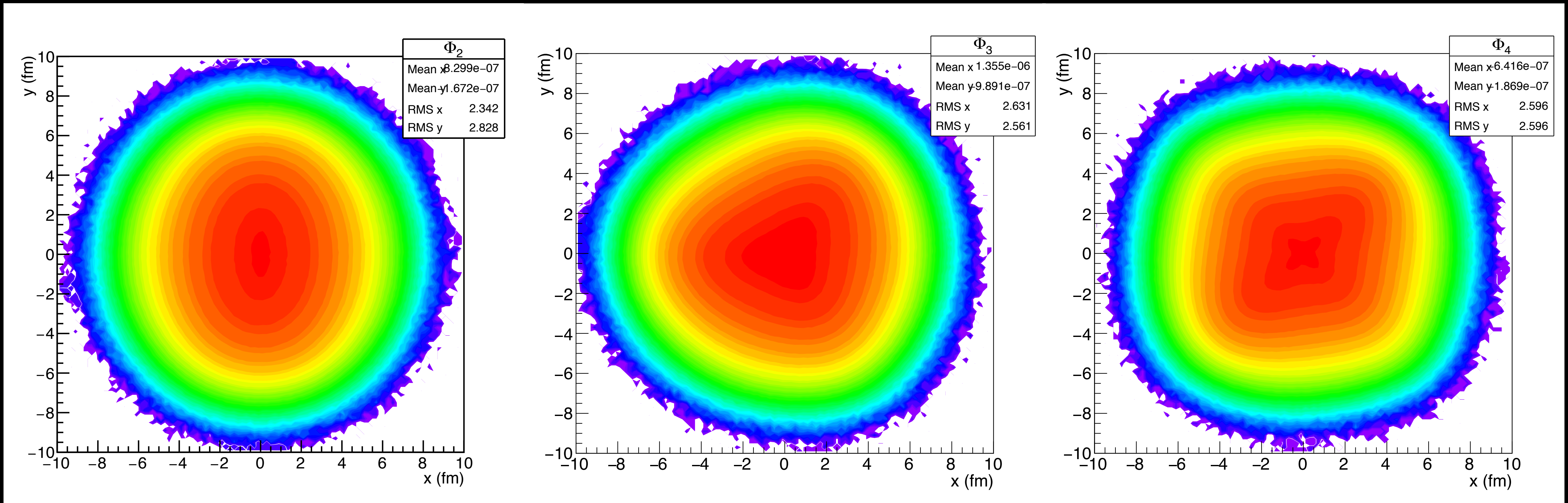




There are many more symmetry planes

$$v_n \propto \varepsilon_n$$

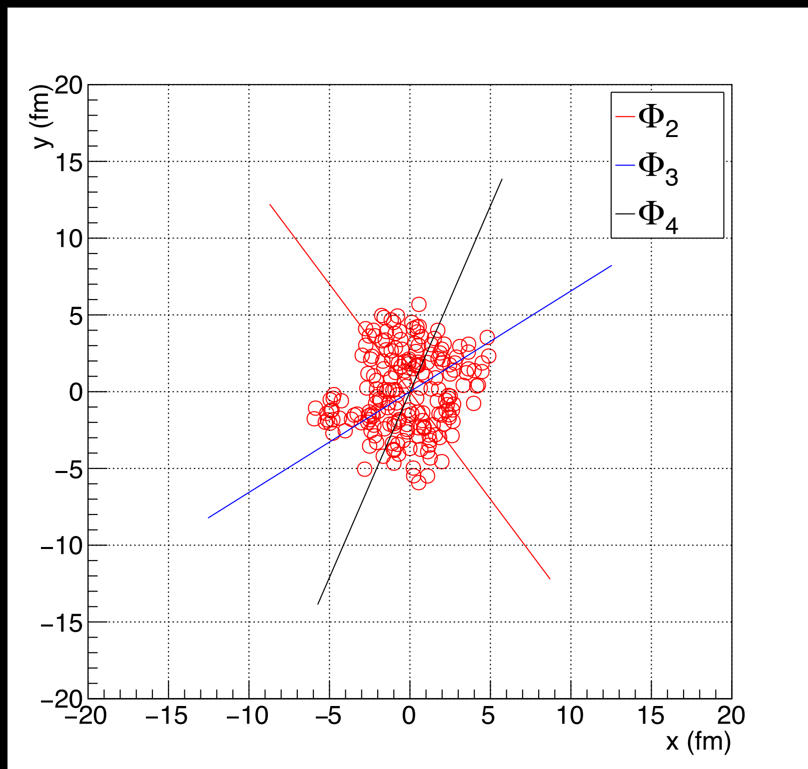
Symmetry Planes



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

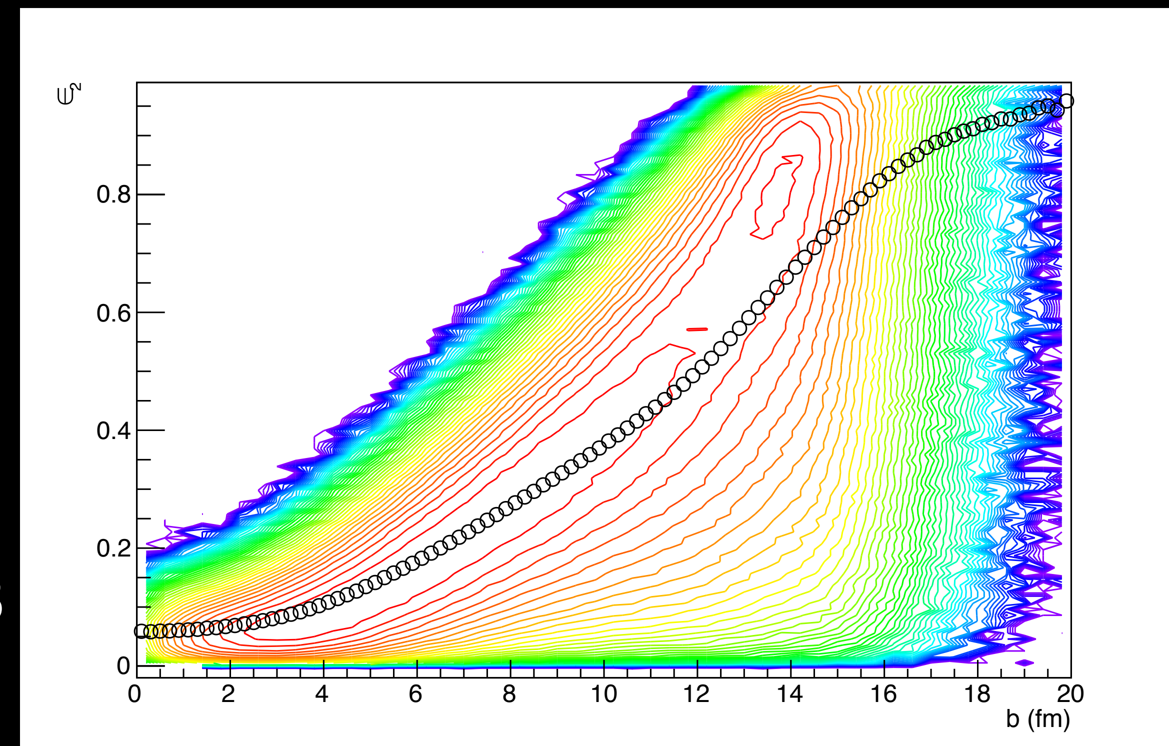
$$v_n \propto \varepsilon_n$$

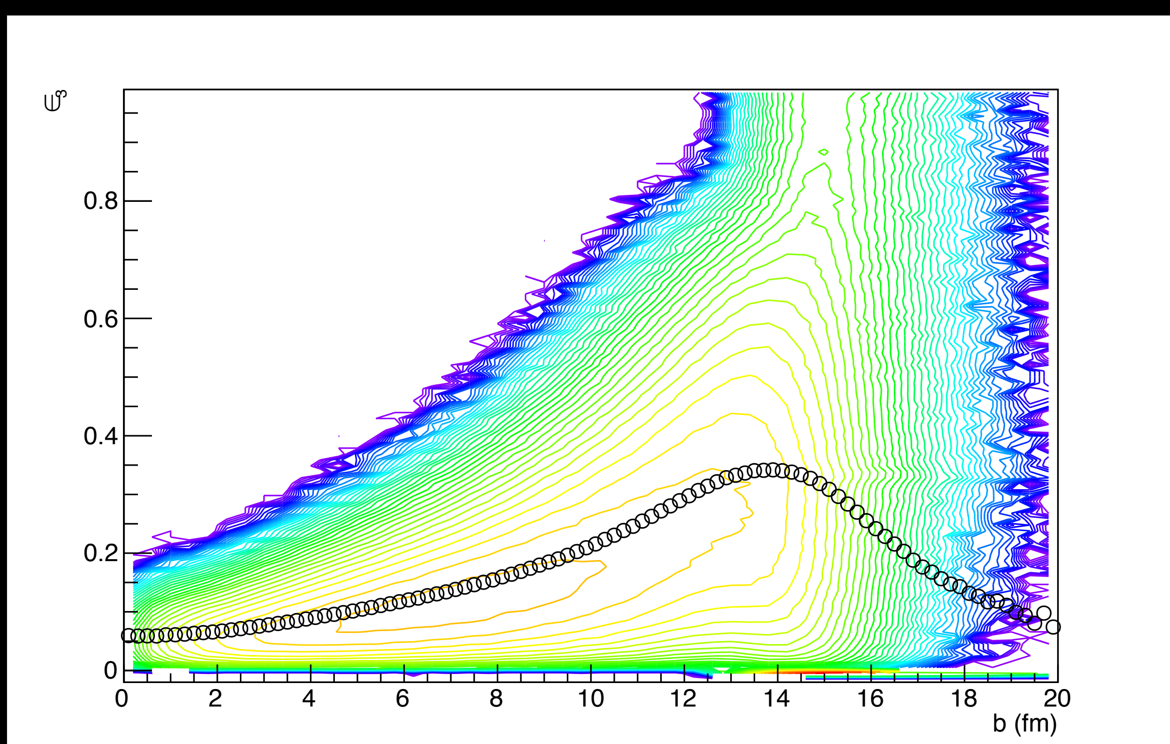
Eccentricities

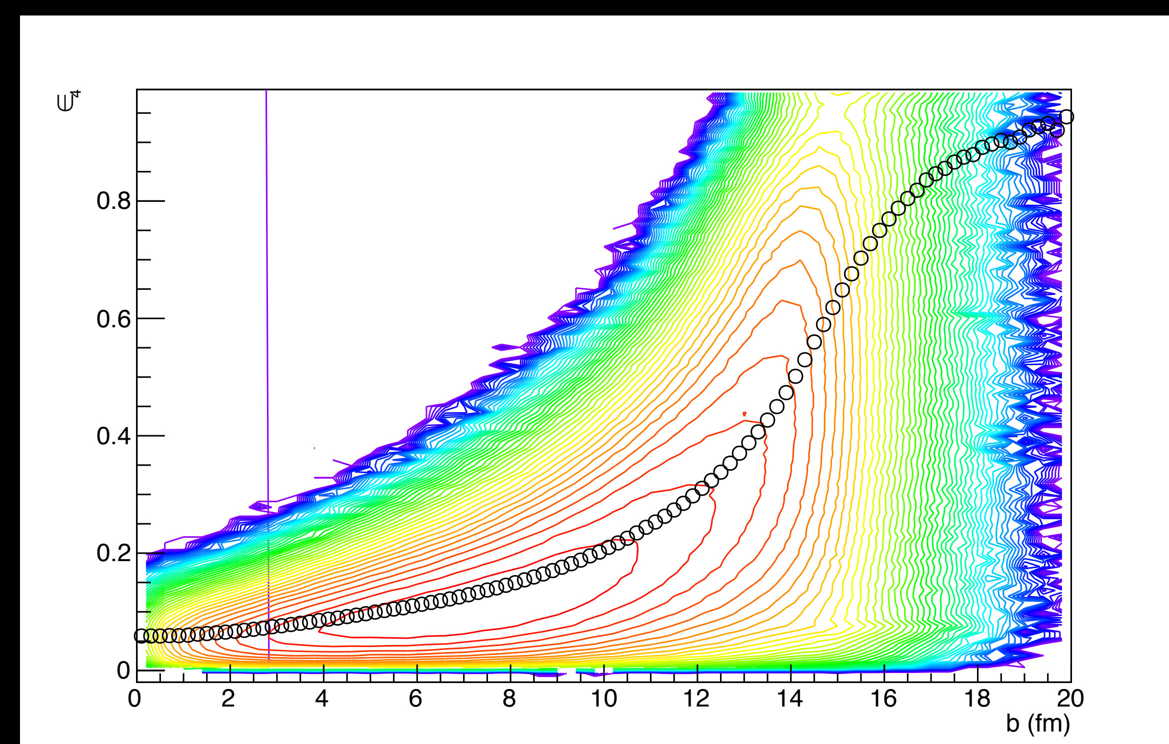


$$v_n \propto \varepsilon_n$$

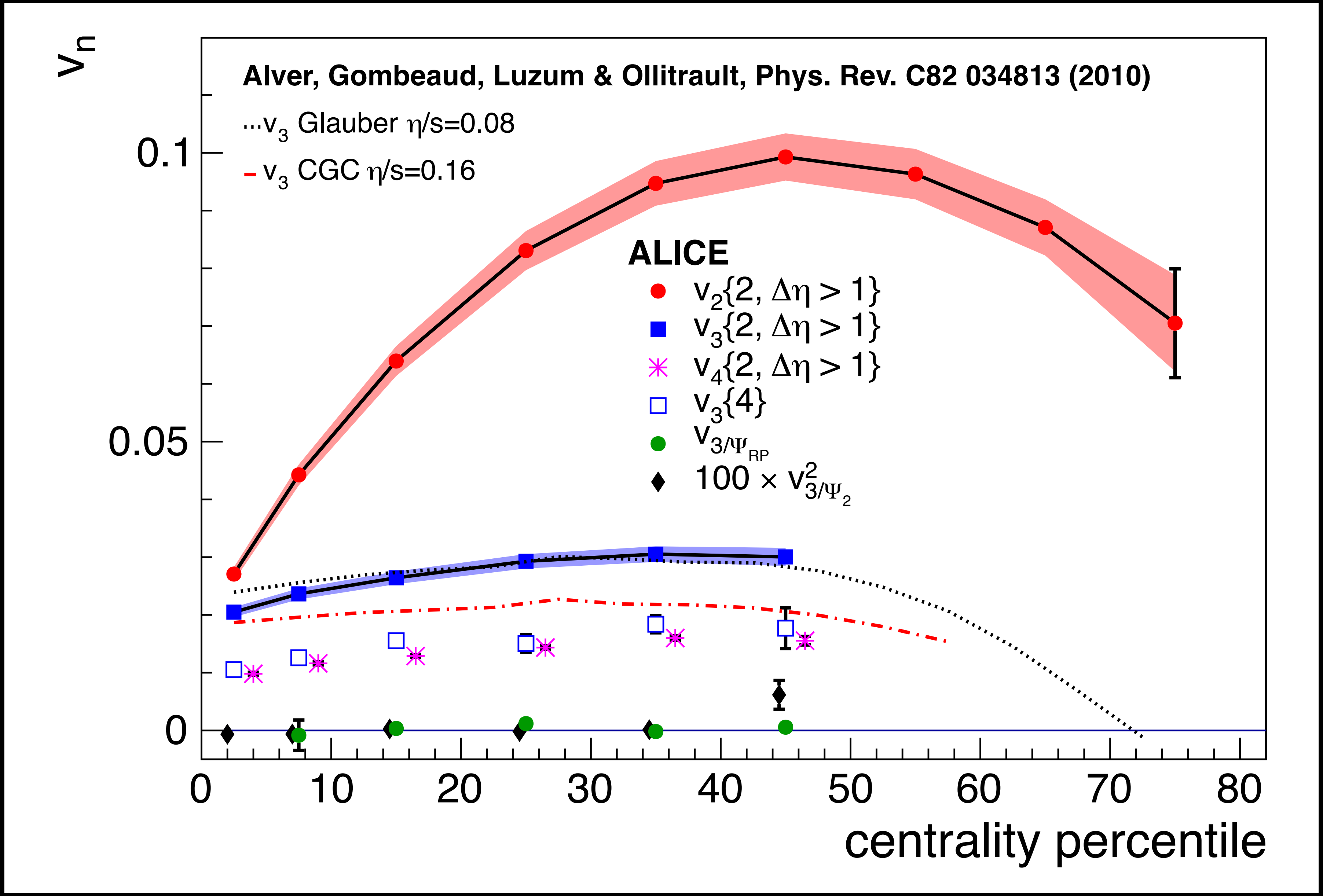
for n=2 and 3





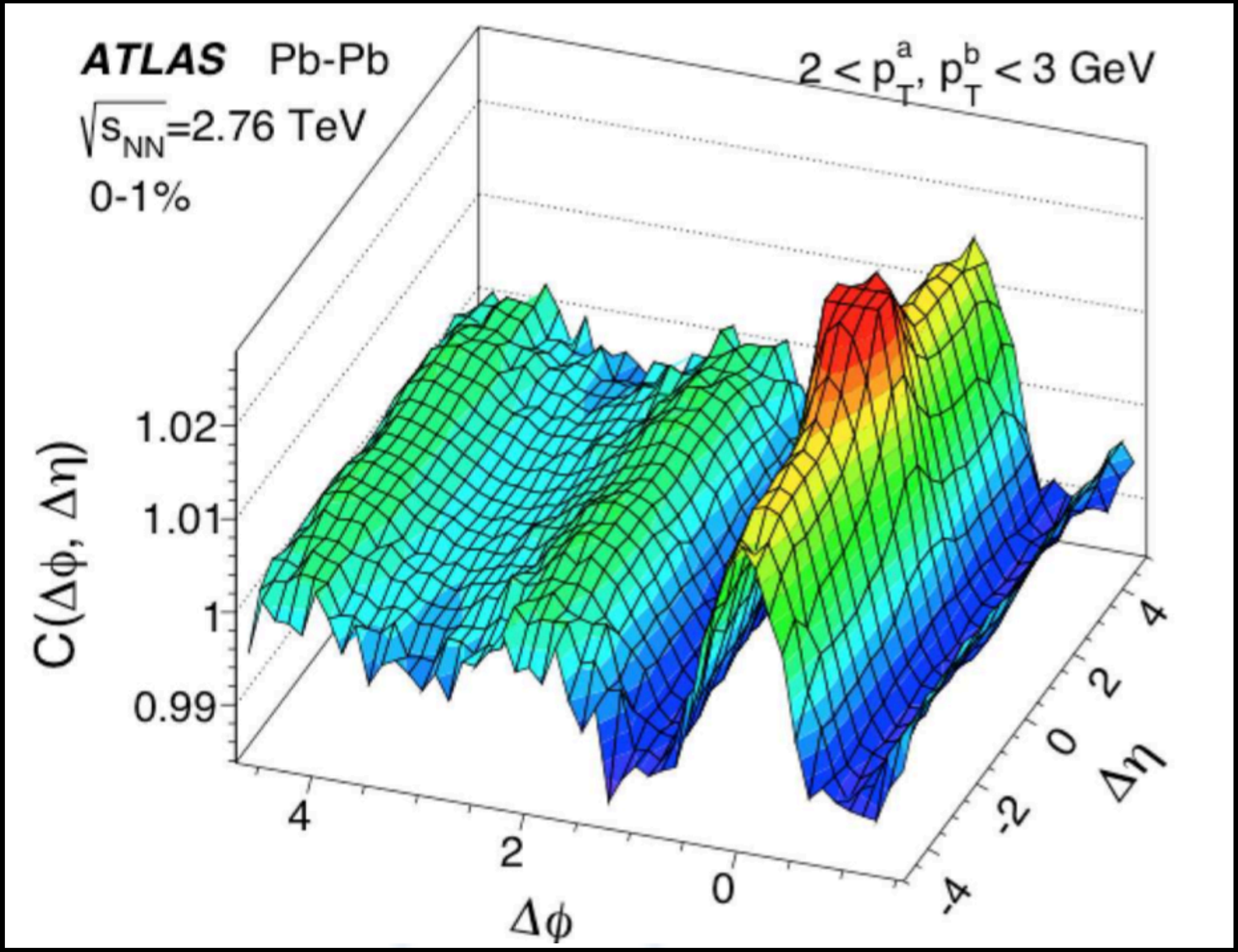


Higher harmonics



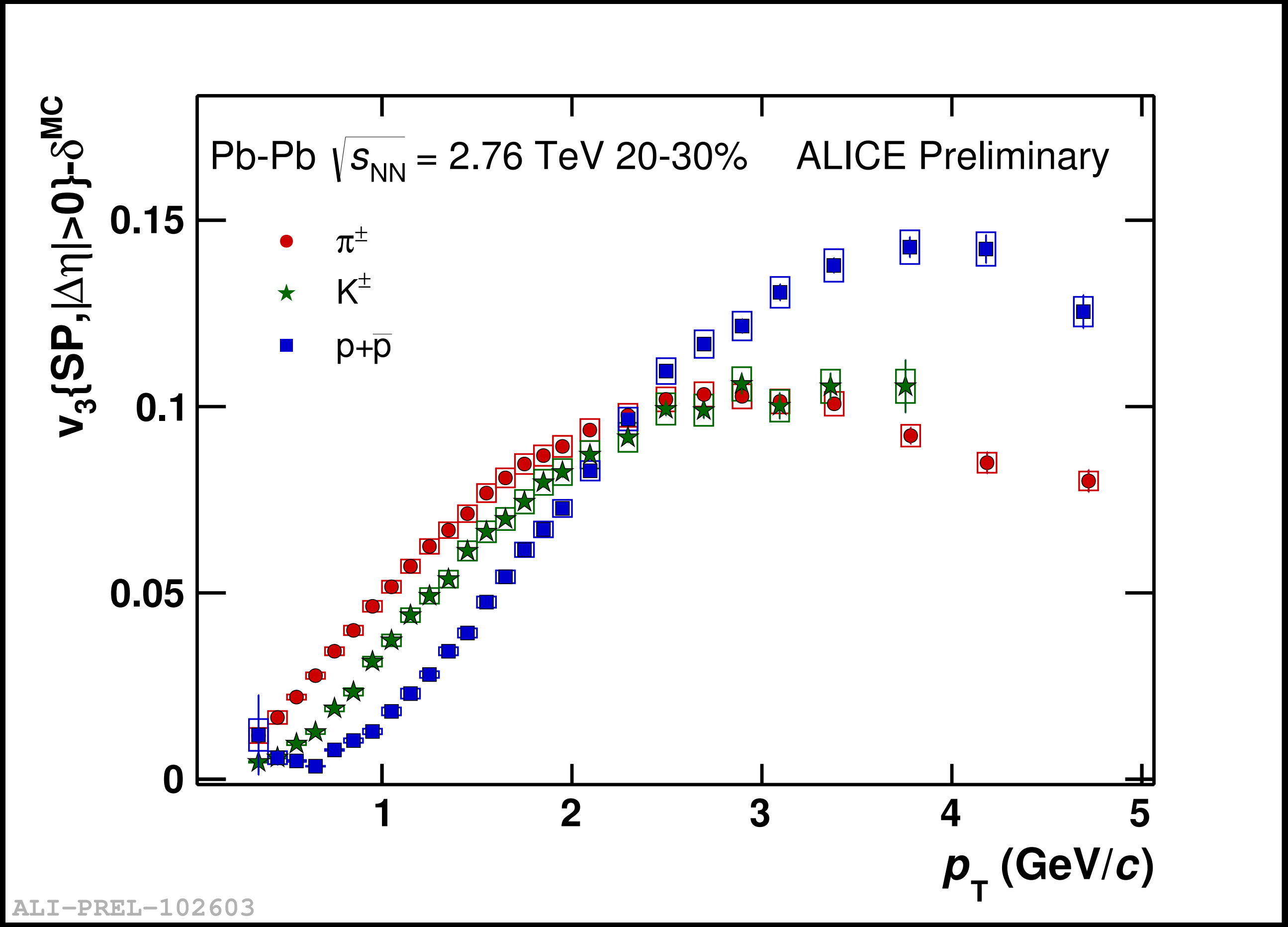
higher harmonics very sensitive to fluctuations and transport parameters such as viscosity

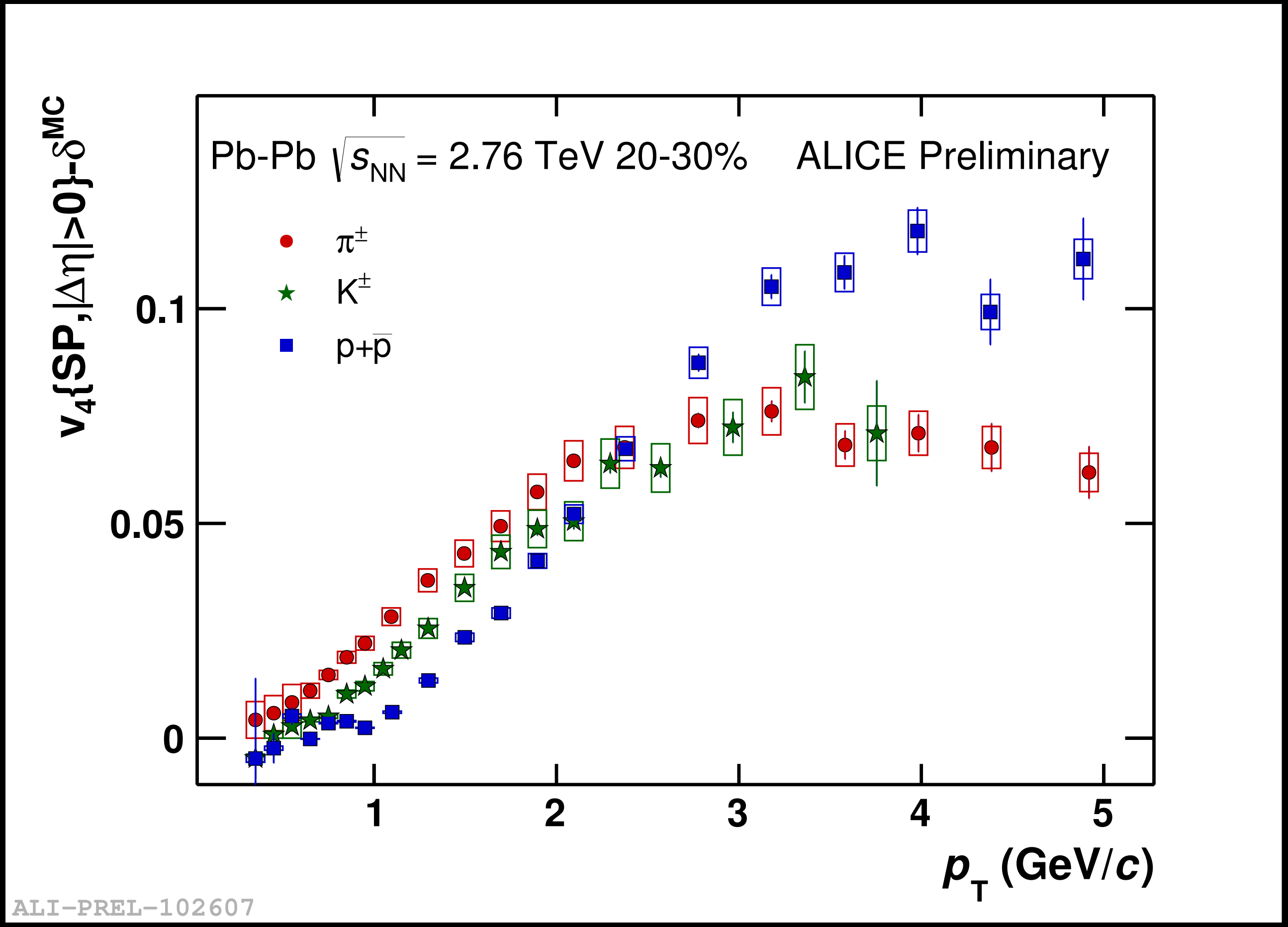
Higher harmonics



Higher harmonics clearly seen by eye in correlation function

Higher harmonics

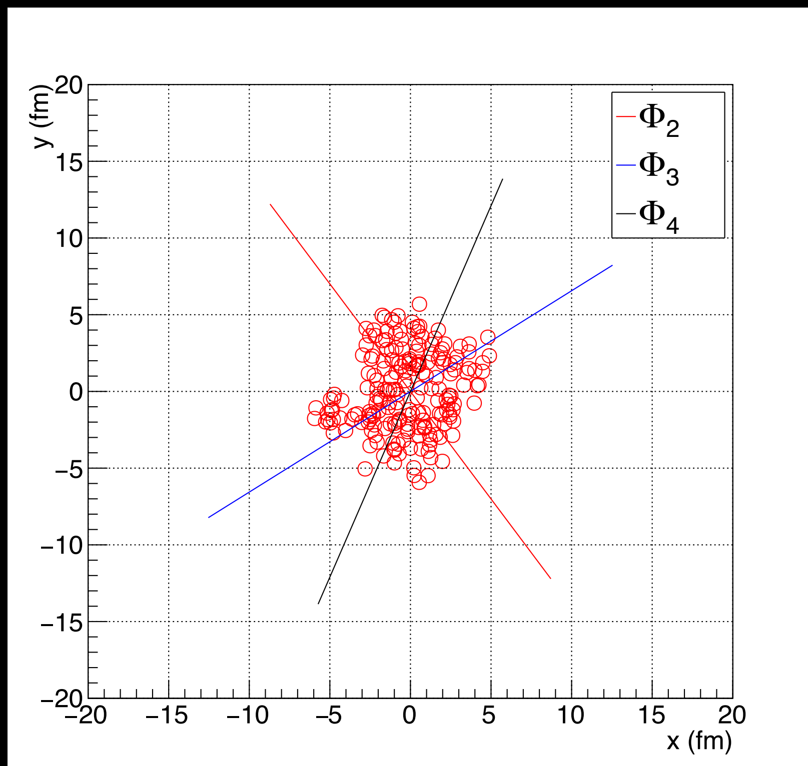


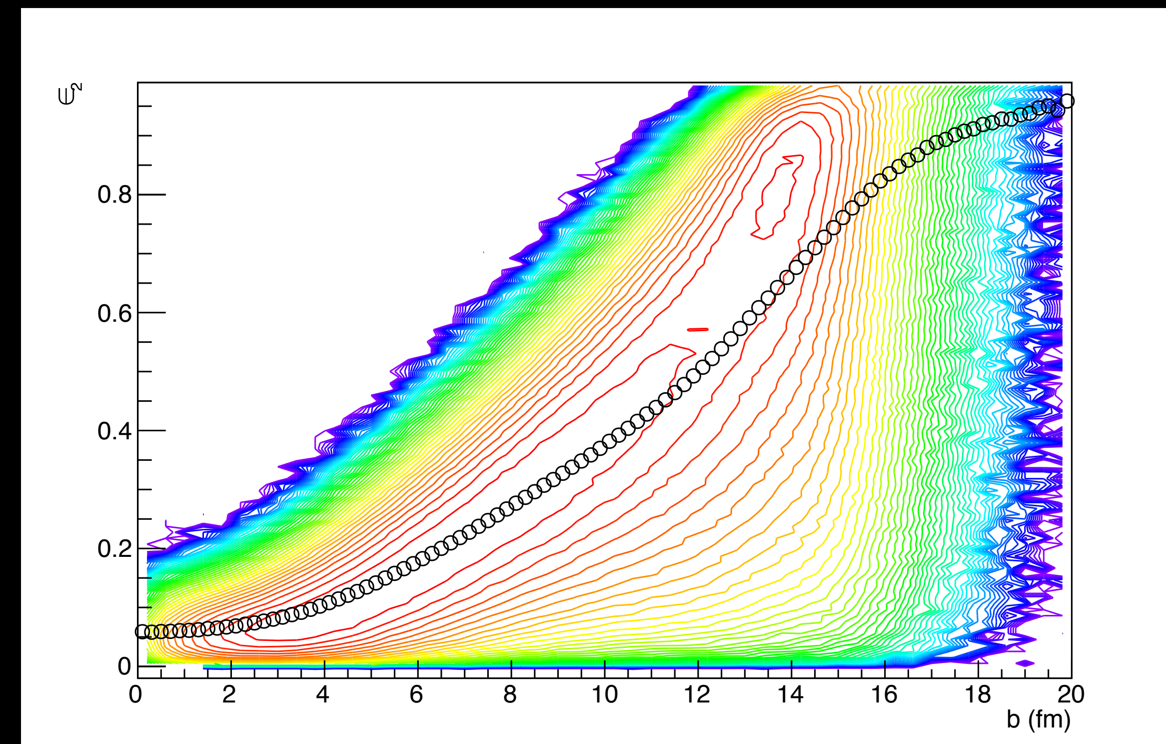


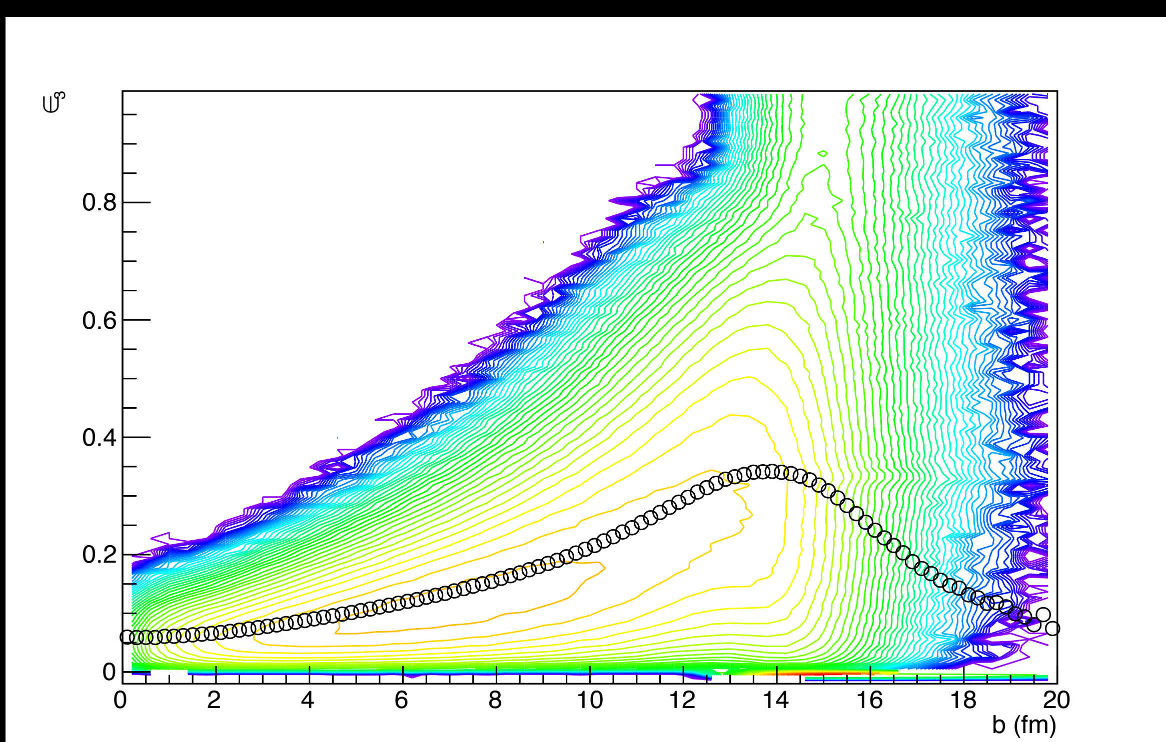
the mass ordering is also observed for higher harmonics

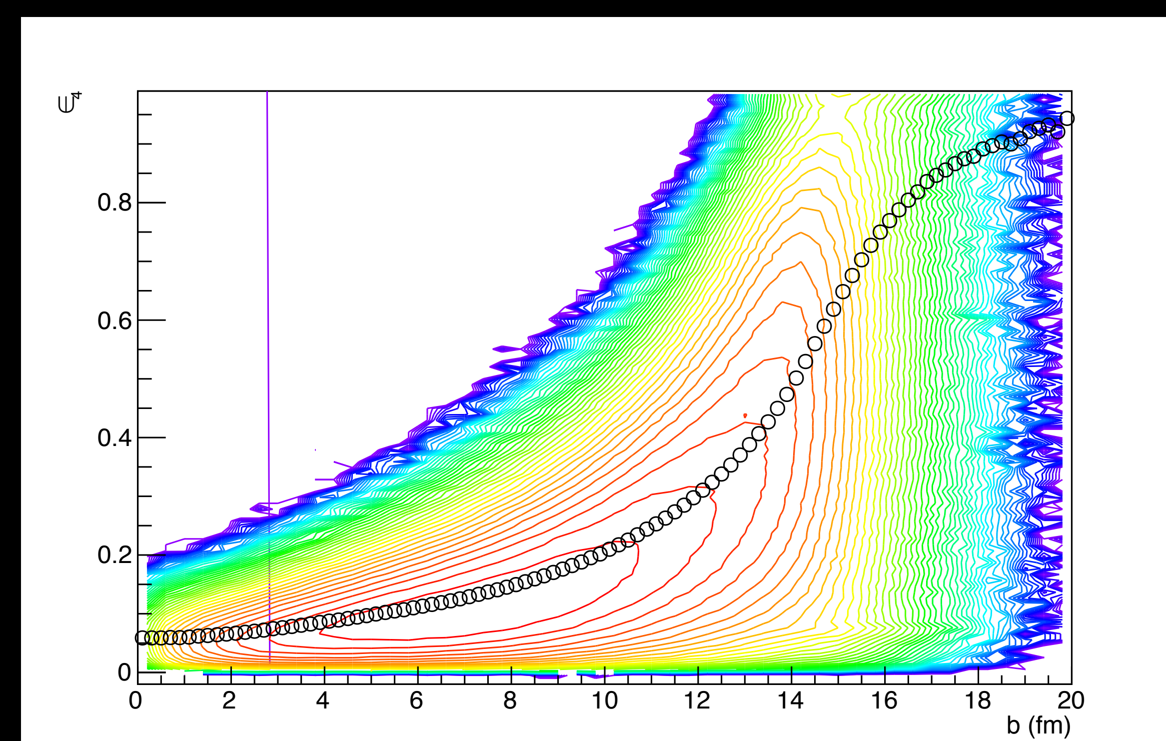
Naghmeh Mohammadi

Fluctuations









What do the fluctuations tell us?

- small fluctuations easy but do not provide much information
- in our case fluctuations are large and can give a lot of information about the initial stage of the collision and the evolution of the system
- constrain the underlying pdf!

Fluctuations

Bessel-Gaussian

$$p(\varepsilon_n) = \frac{\varepsilon_n}{\sigma^2} I_0\left(\frac{\varepsilon_n \varepsilon_n}{\sigma^2}\right) \exp\left(-\frac{\varepsilon_0^2 + \varepsilon_n^2}{2\sigma^2}\right)$$

ε_0 is the anisotropy versus the reaction plane and σ the fluctuations.
Works for mid-central collisions, not expected to work for peripheral collisions because not constraint to 1
this distribution predict that $v_3\{4\}=0$

Power-law distribution

$$p(\varepsilon_n) = 2\alpha\, \varepsilon_n \left(1 - \varepsilon_n^2\right)^{\alpha - 1}$$

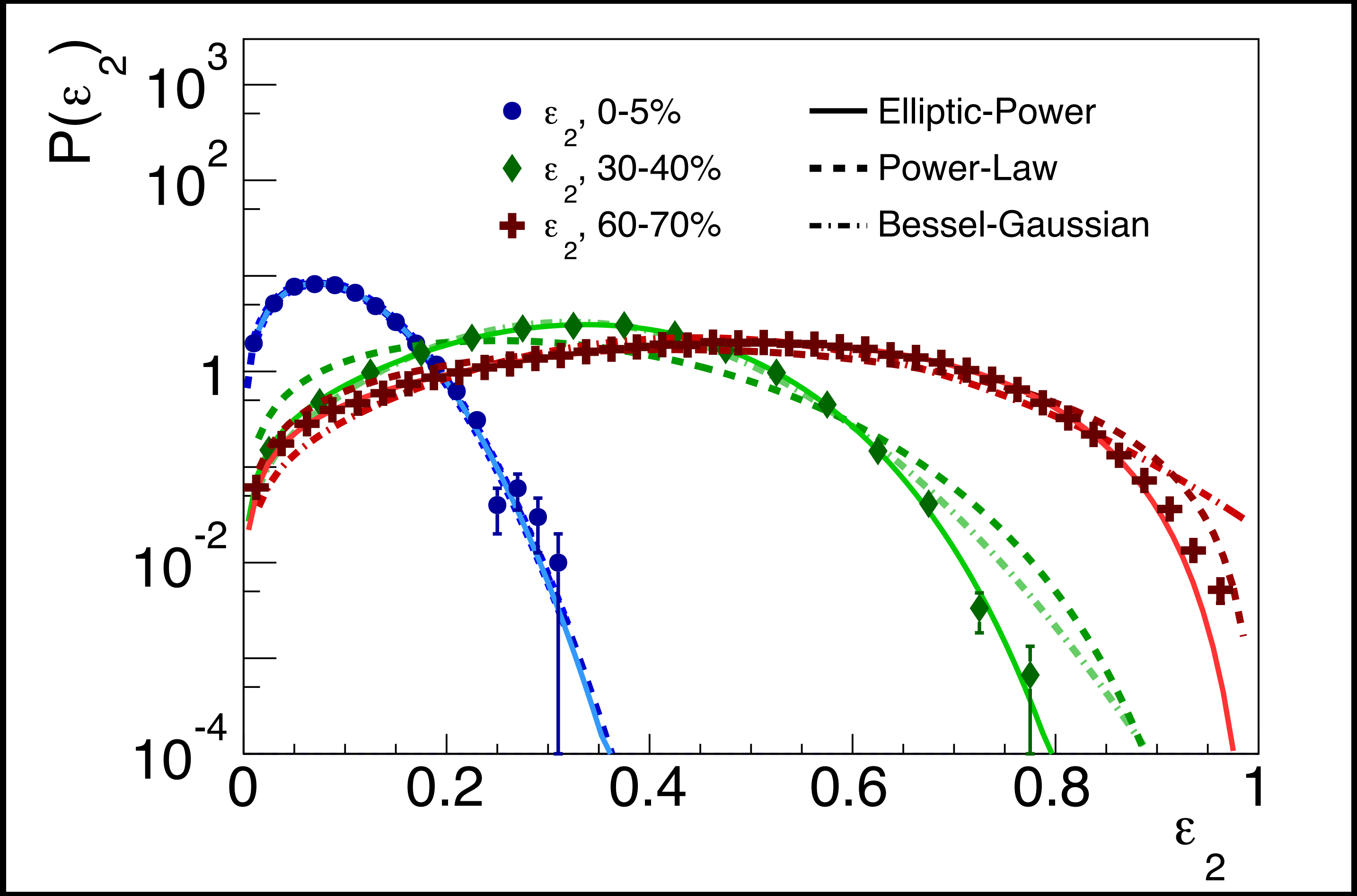
α quantifies the fluctuations, this function has no ε_0 therefore only describes the response due to fluctuations

Elliptic Power distribution

$$p(\varepsilon_n) = \frac{\alpha\, \varepsilon_n}{\pi} \left(1 - \varepsilon_0^2\right)^{\alpha + \frac{1}{2}} \int_0^{2\pi} \frac{\left(1 - \varepsilon_n^2\right)^{\alpha - 1} \mathrm{d}\phi}{\left(1 - \varepsilon_0\, \varepsilon_n \cos\phi\right)^{2\alpha + 1}}$$

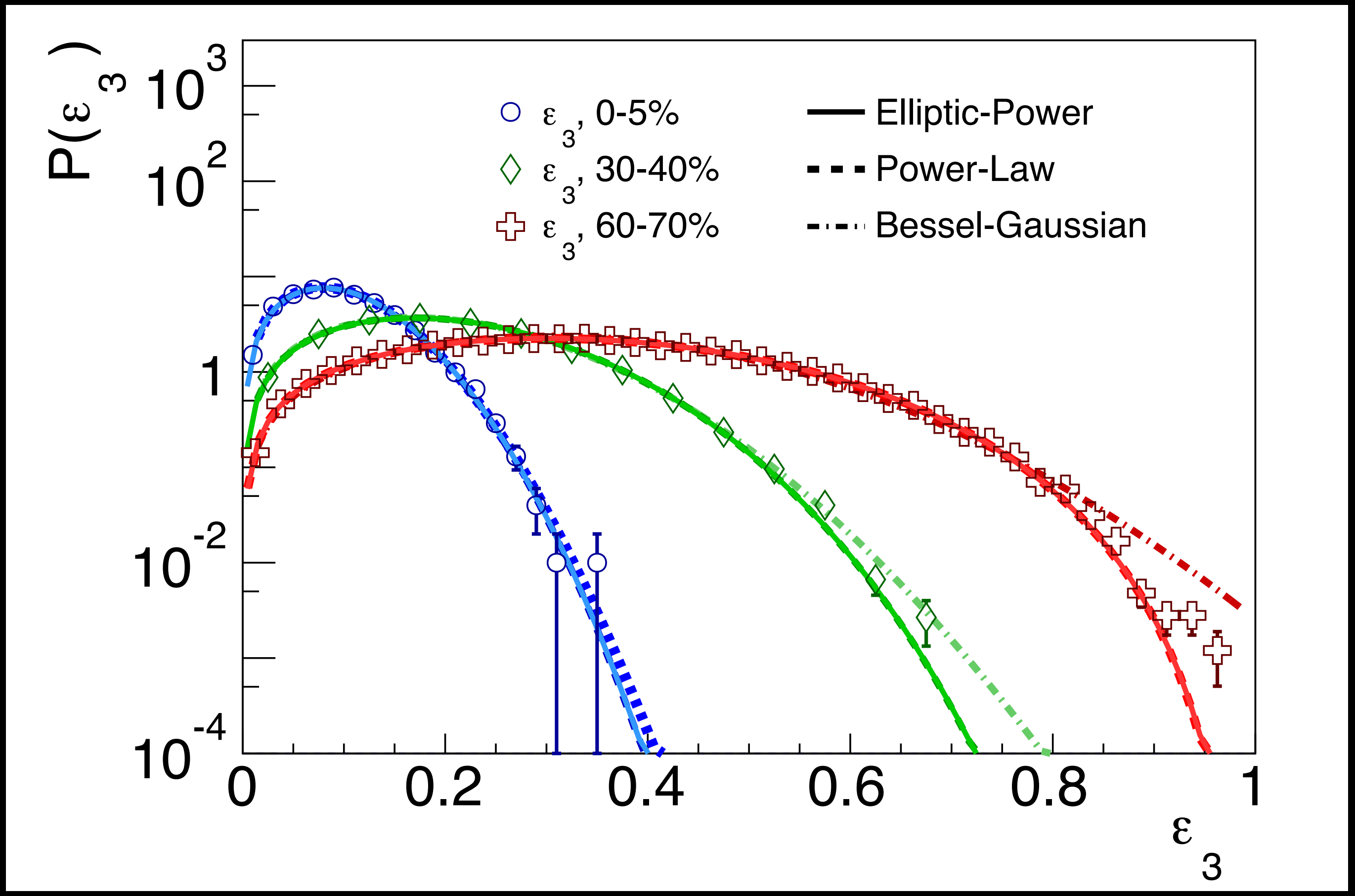
α and ε_0 are the ingredients with same definition as in previous distributions

Fluctuations



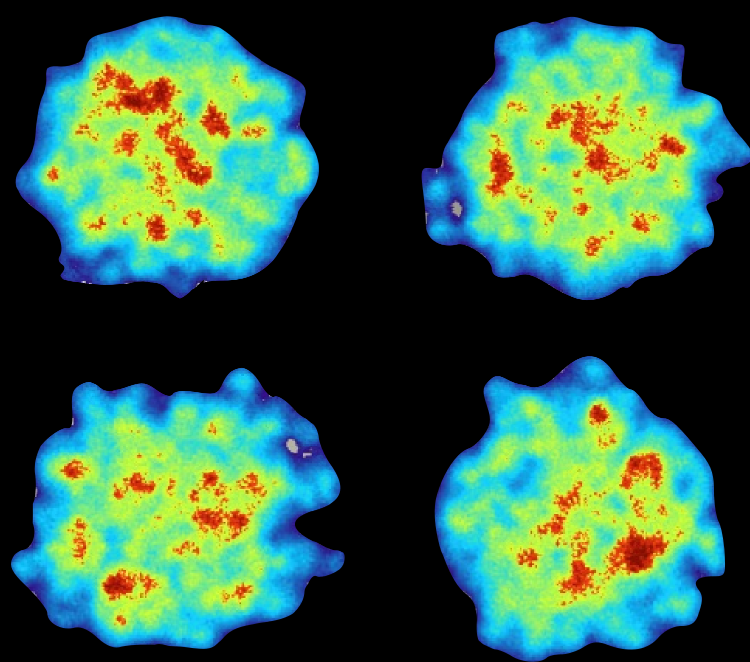
In 0-5% all three functions work rather well. This is understood, ε_0 is small and α is large. Elliptic Power turns into a Bessel Gaussian and with ε_0 small the anisotropy versus the reaction plane and power law also works. For more peripheral collisions the Elliptic Power is the only distributions which works well

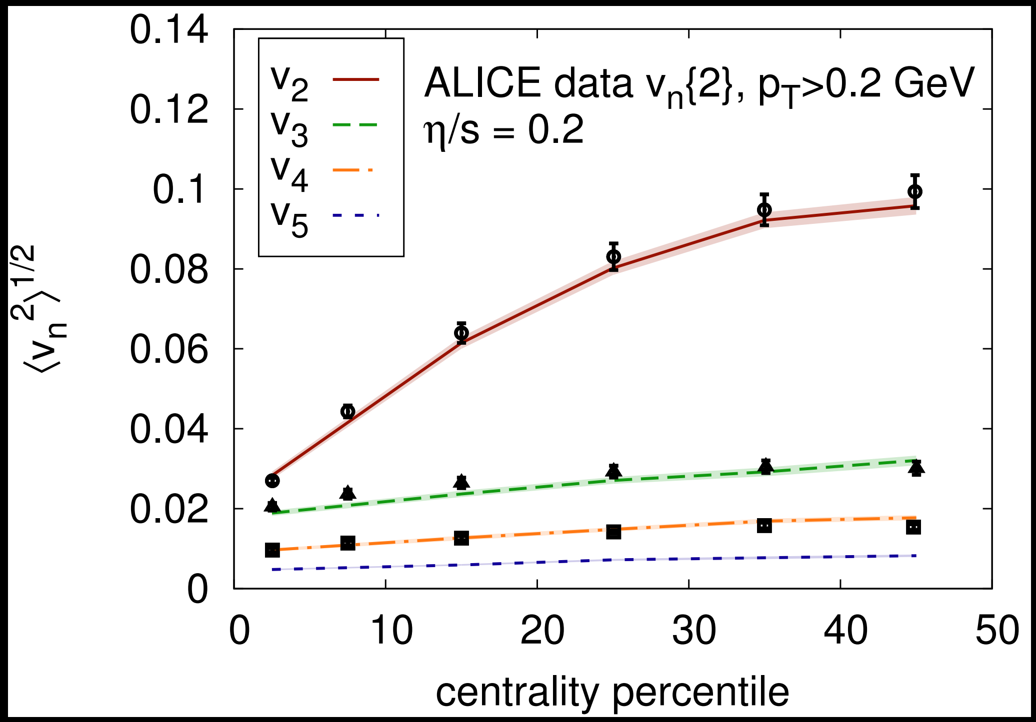
Fluctuations

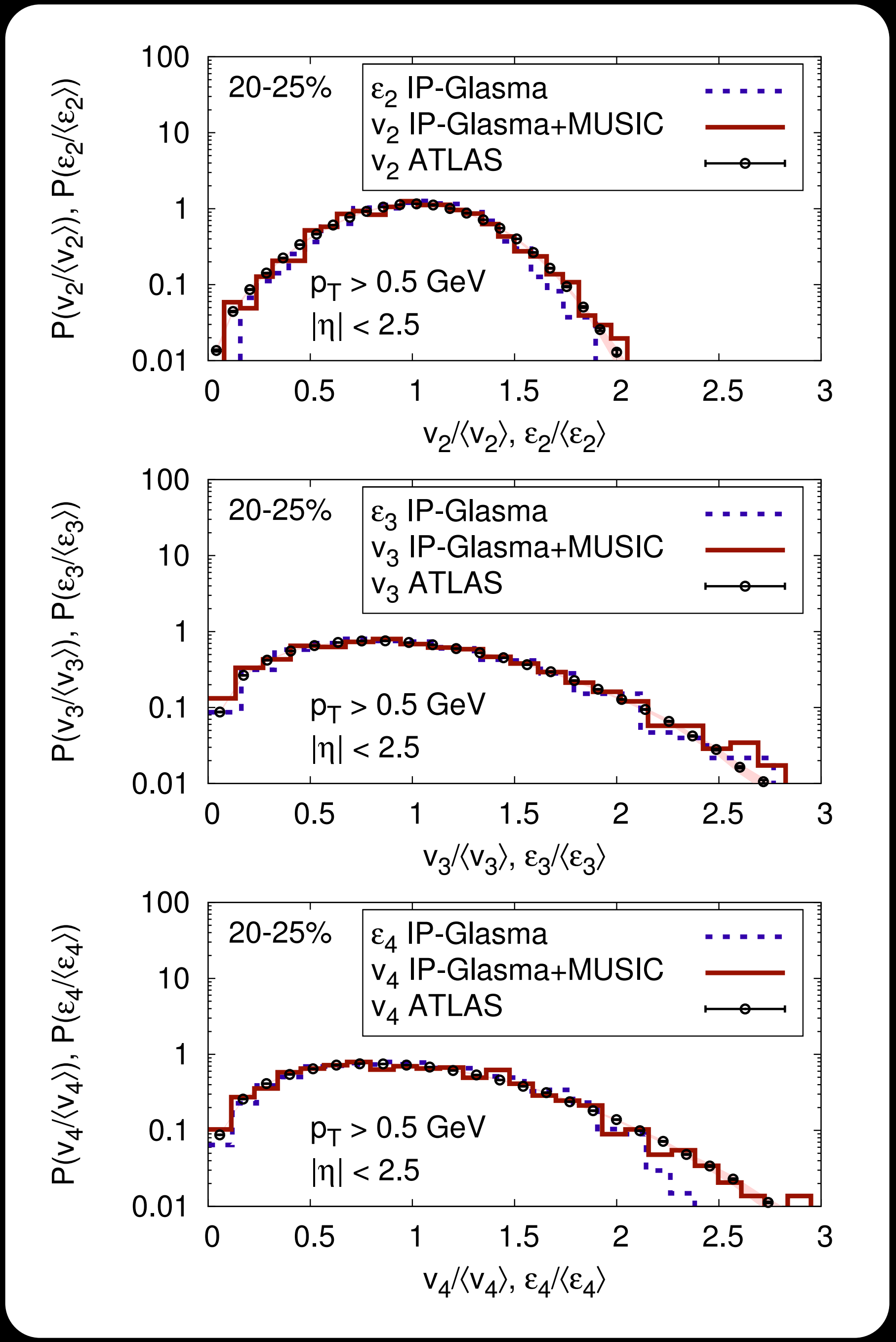


ε_3, v_3 dominated by fluctuations. For more central collisions all three functions work rather well. Again this is understood Bessel Gaussian fails for more peripheral due to lack of constraint < 1. The fact that $\varepsilon_3\{4\}$ and $v_3\{4\}$ are non-zero completely excluded the Bessel Gaussian

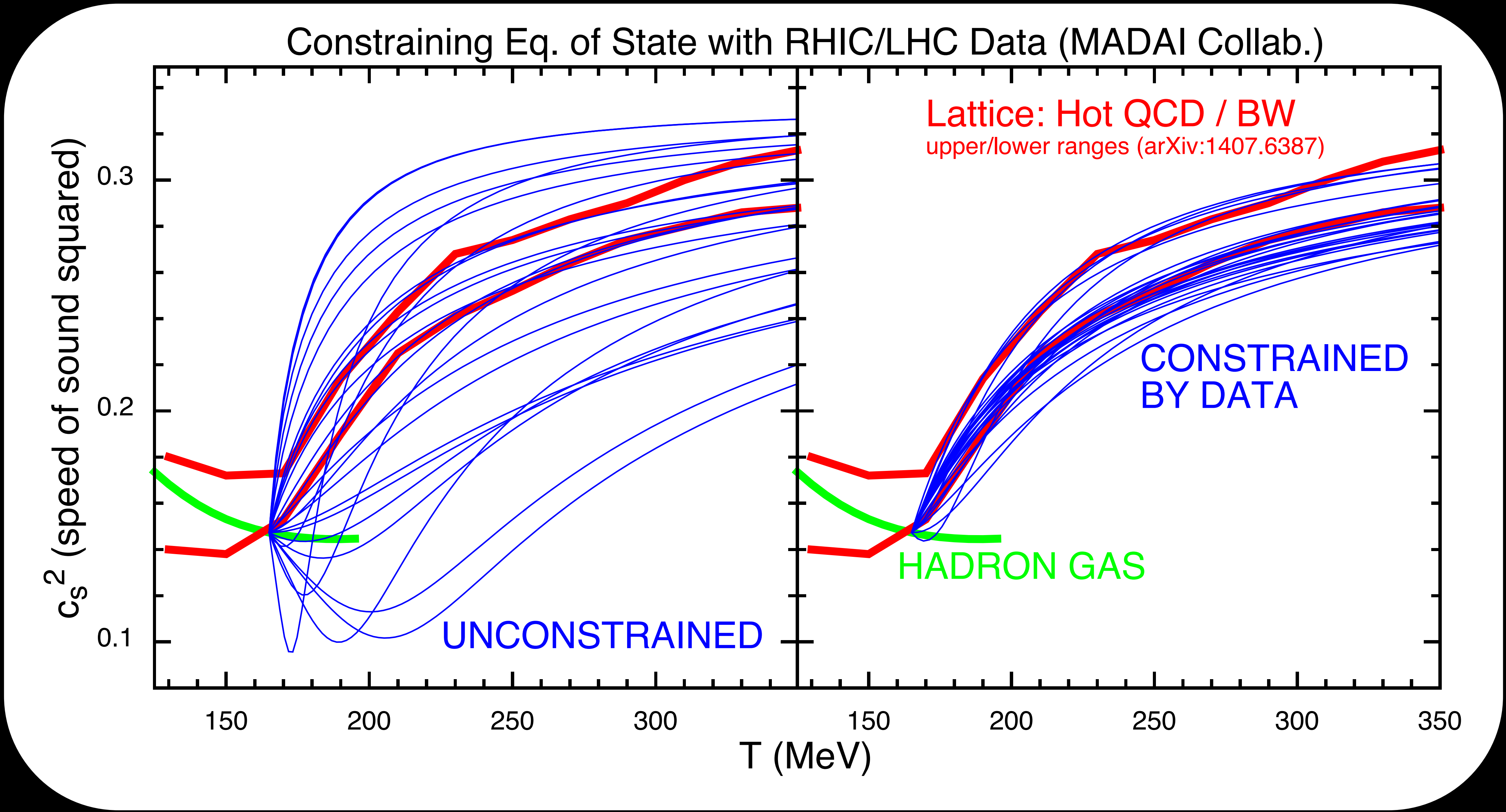
The Standard Model for QGP Evolution (fluctuations)







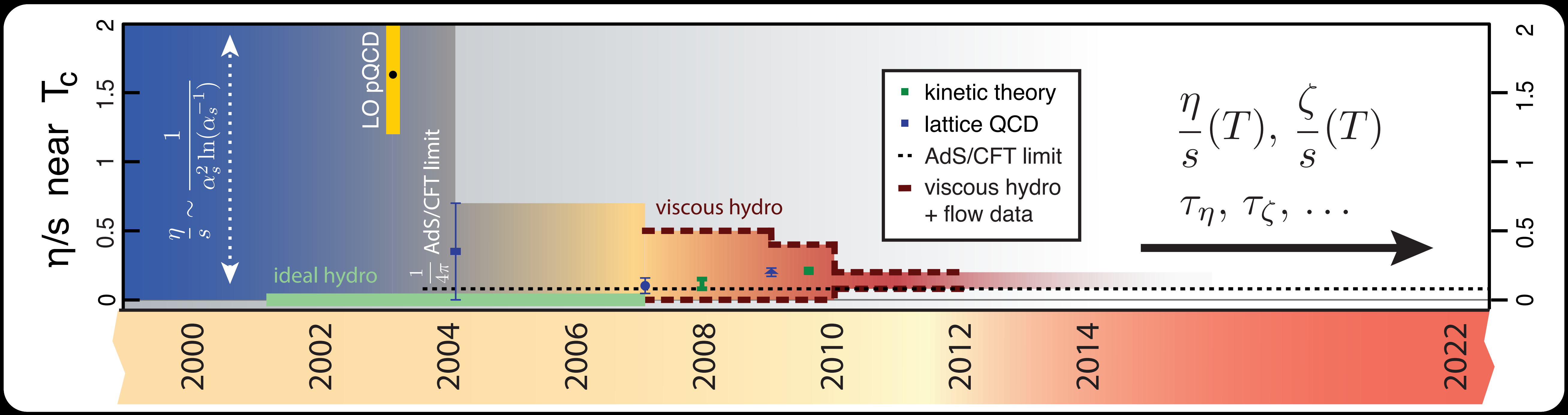
Equation of State



Constraints from RHIC and LHC data

We start to answer the question how well we can constrain the EoS

The Standard Model for QGP Evolution



Correlations between harmonics (magnitude)

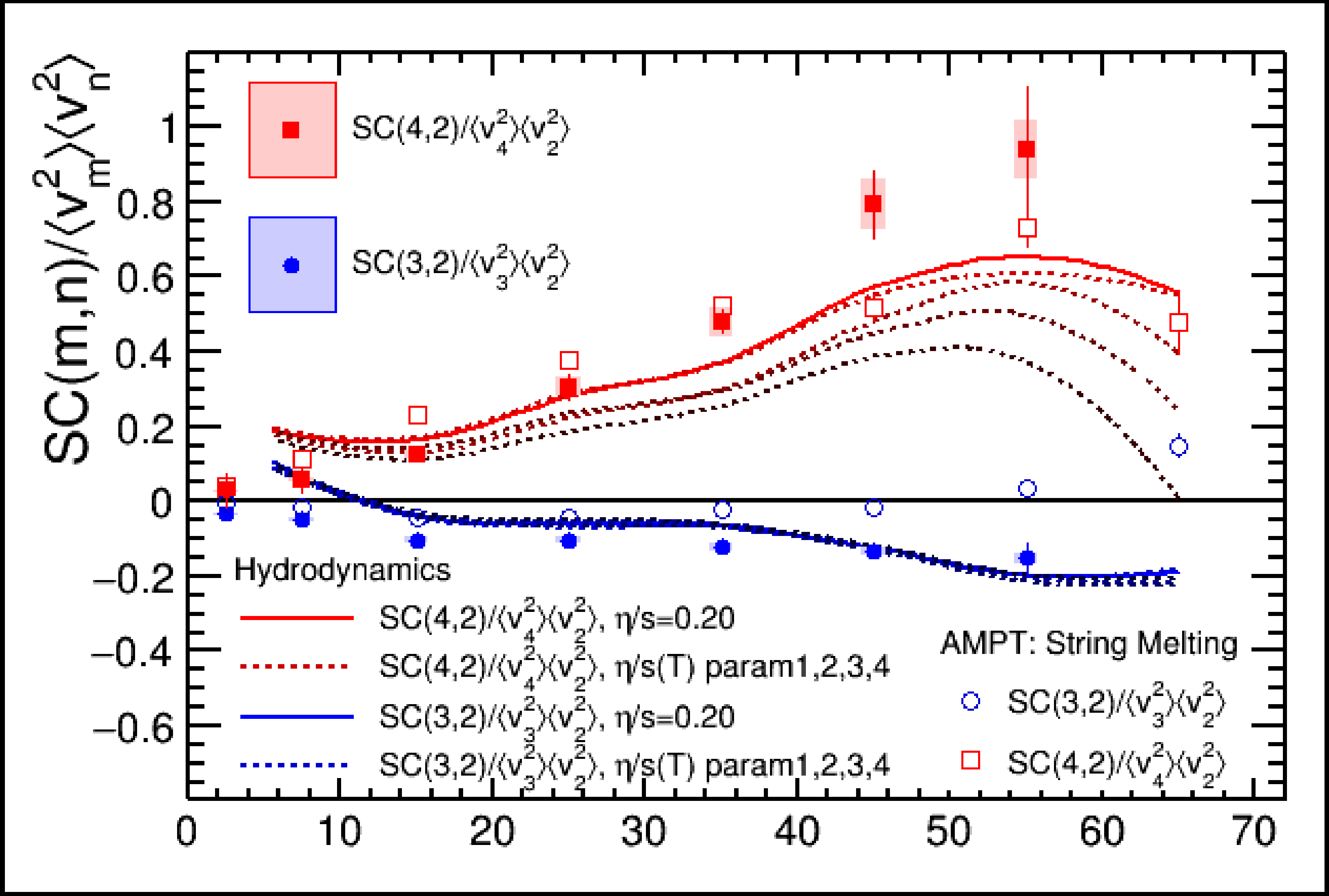
- one can define a symmetric cumulant

$$
\begin{aligned}
\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle_c &= \langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle \\
&\quad -\langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\,\langle\langle\cos[n(\varphi \\
&= \left\langle v_m^2 v_n^2\right\rangle-\left\langle v_m^2\right\rangle\left\langle v_n^2\right\rangle
\end{aligned}
$$

- if nonzero there is no factorisation and the magnitude of the harmonics is correlated

Correlations between harmonics (magnitude)

ALICE: 1604.07663, submitted to PRL

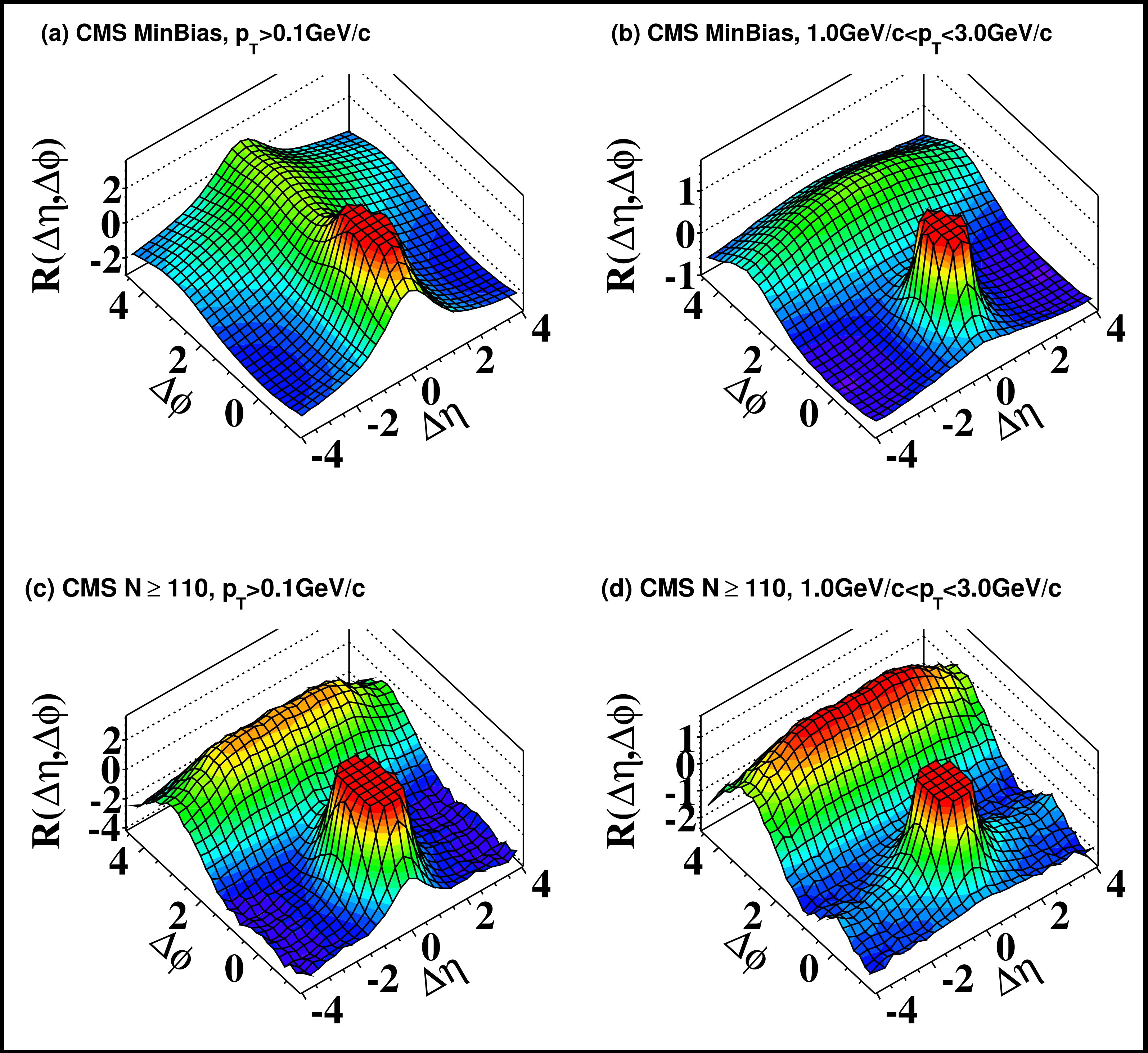


clear correlations and anti-correlations between the harmonics, some which are non-trivial from initial conditions, generated during expansion of the system

Small systems; pp and pA collisions

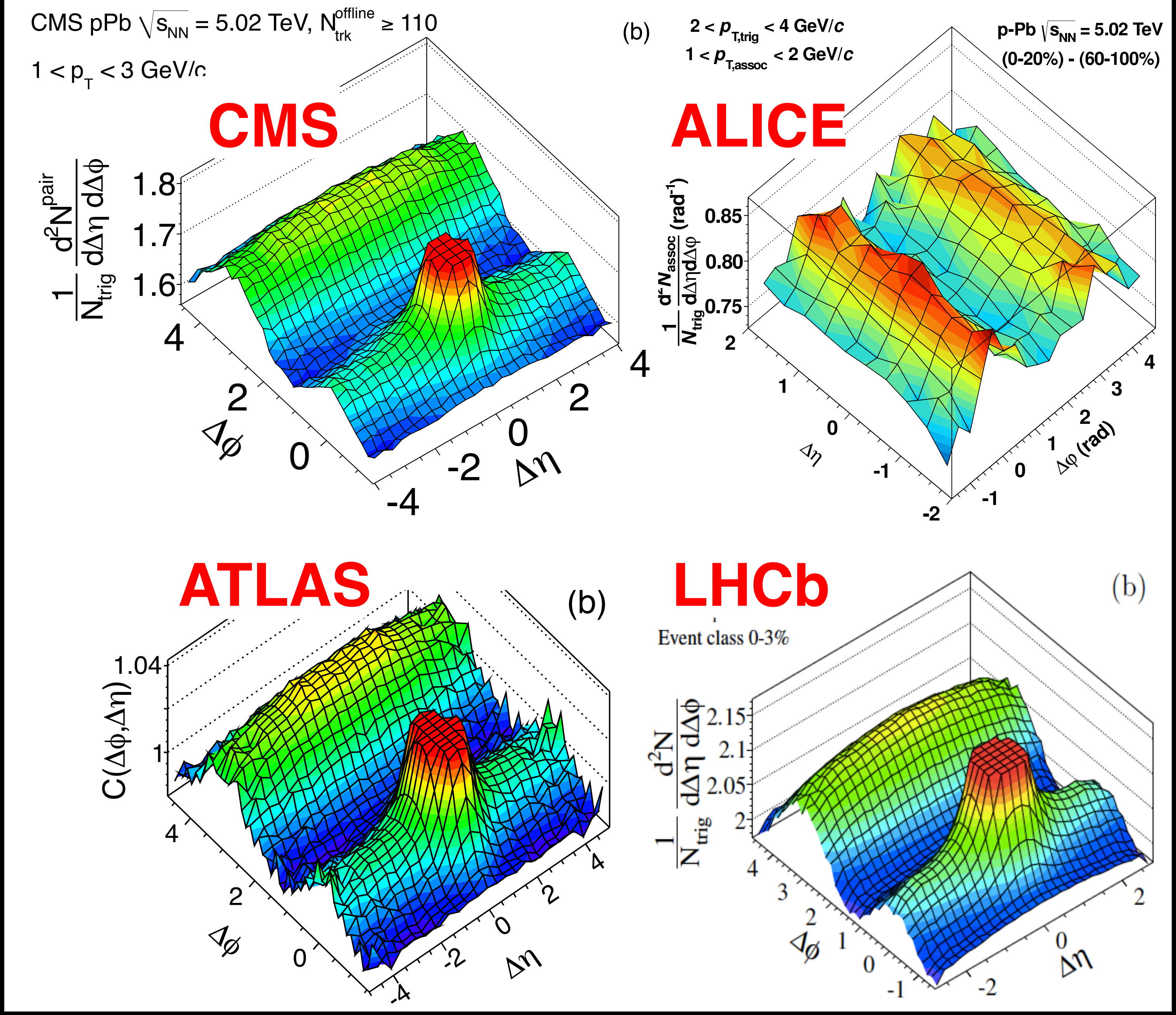
- a reference for AA (pA cold nuclear matter effects)
- good systems for studies of the parton distributions (e.g. CGC) if there are no final state effects

Small systems; pp



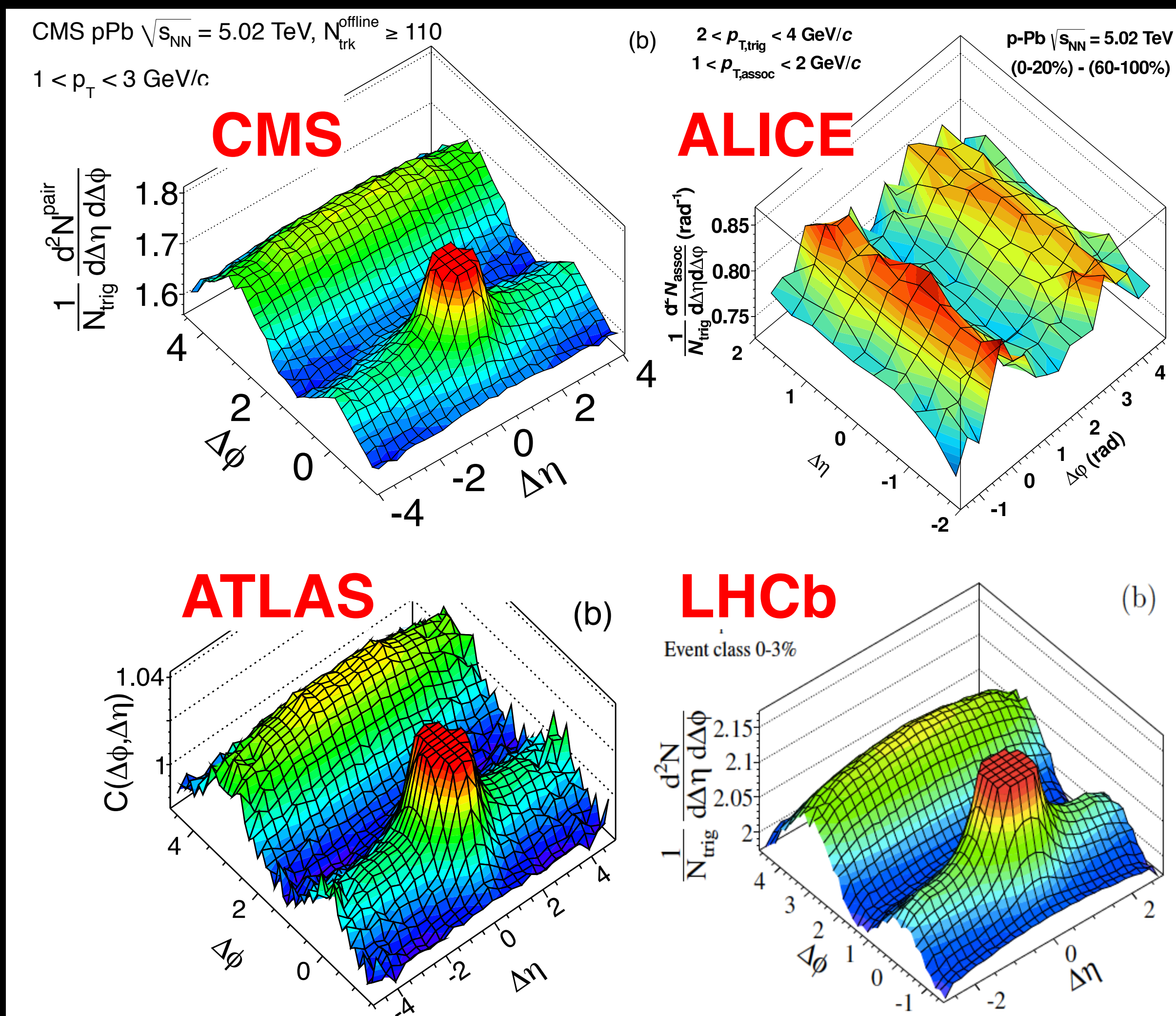
2010 CMS observed near side ridge in pp!

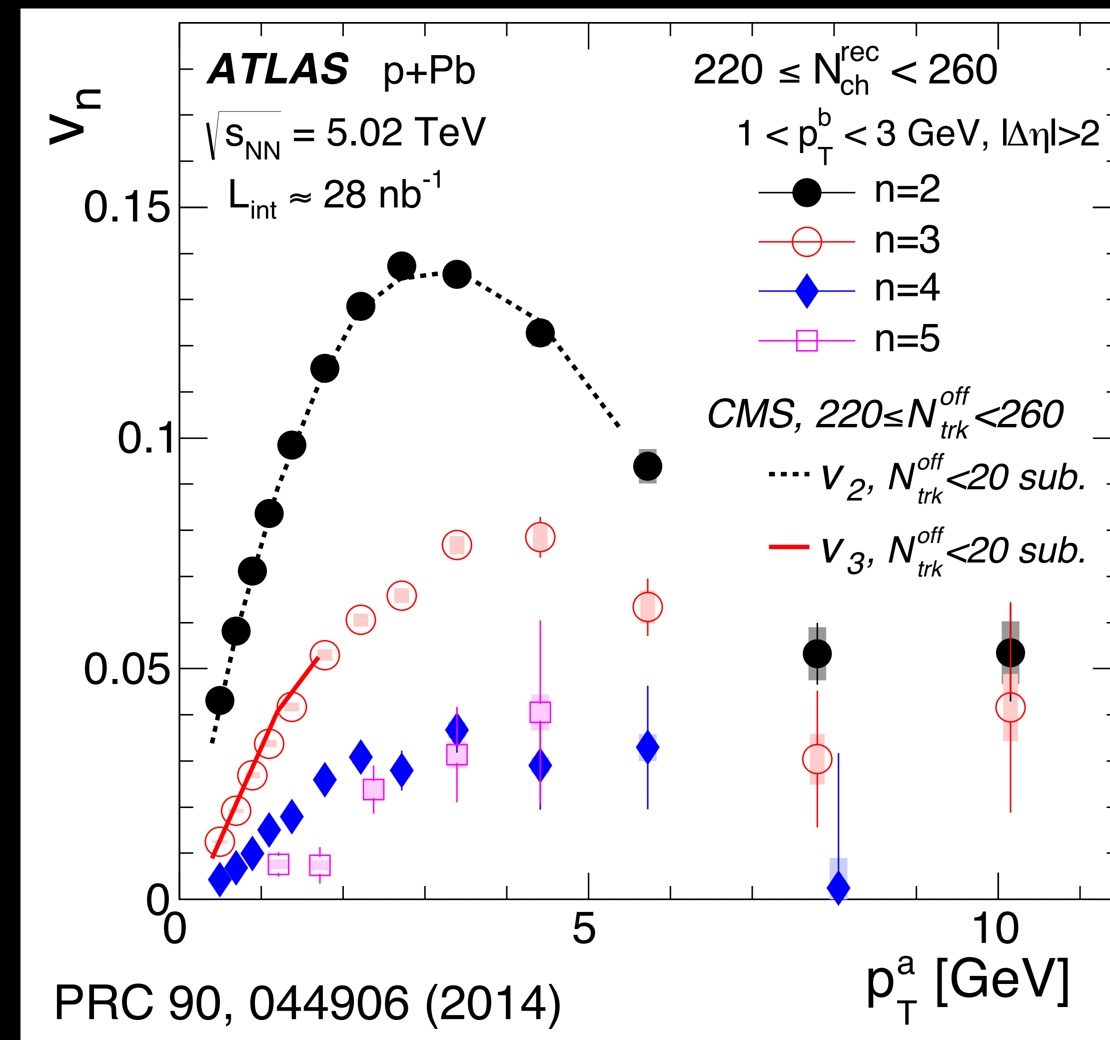
Small systems; pA



pA collisions near and away-side ridge observed by all LHC experiments

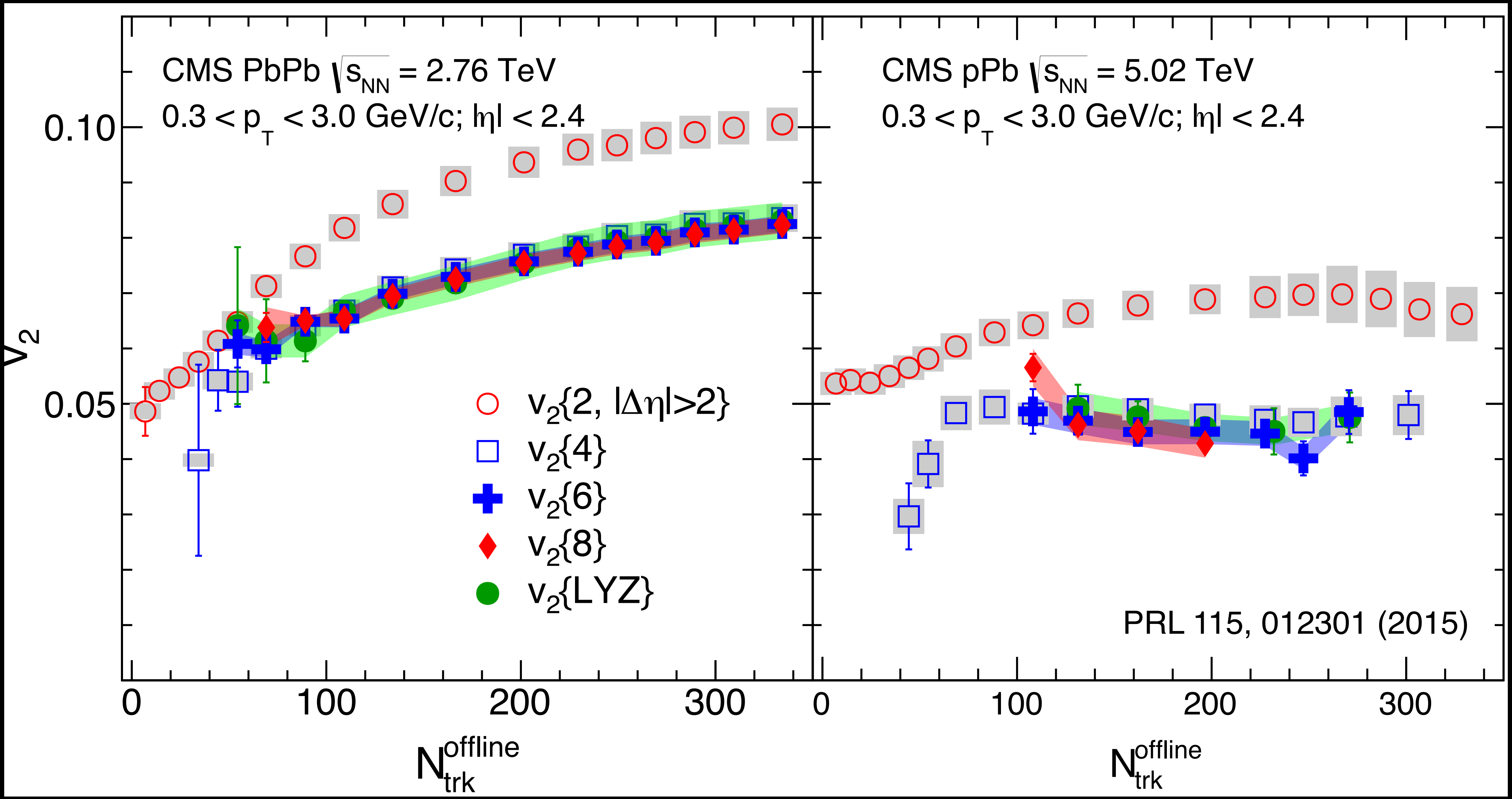
Small systems; pA





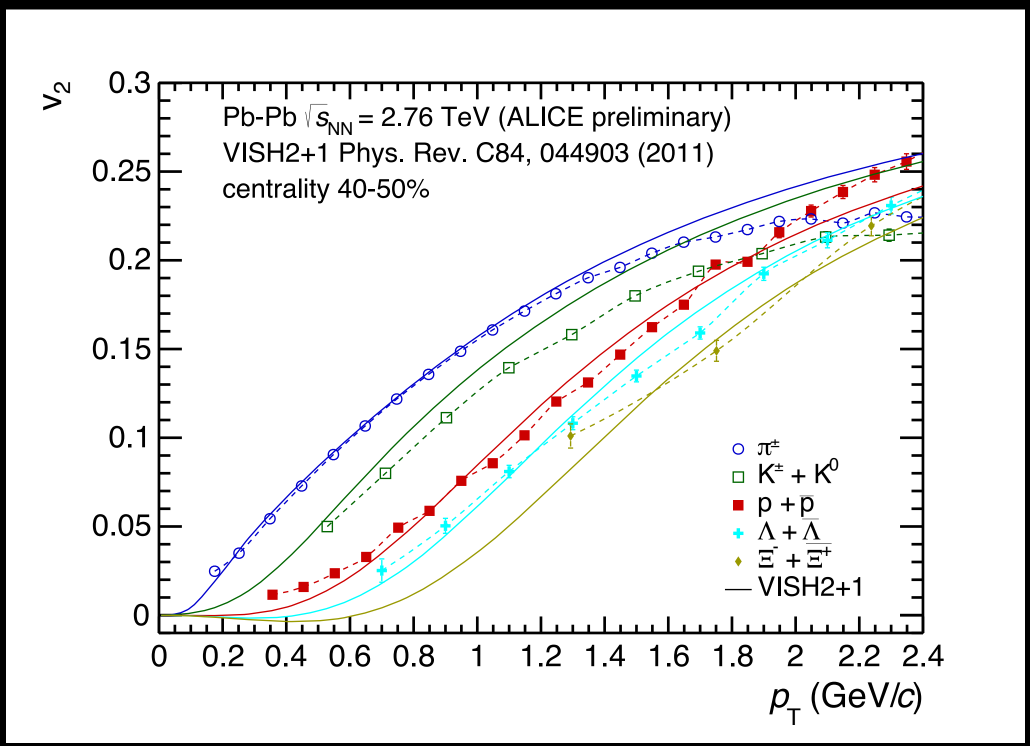
pA collisions near and away-side ridge observed by all LHC experiments
and characterised by significant flow Fourier harmonics

pA true collectivity?

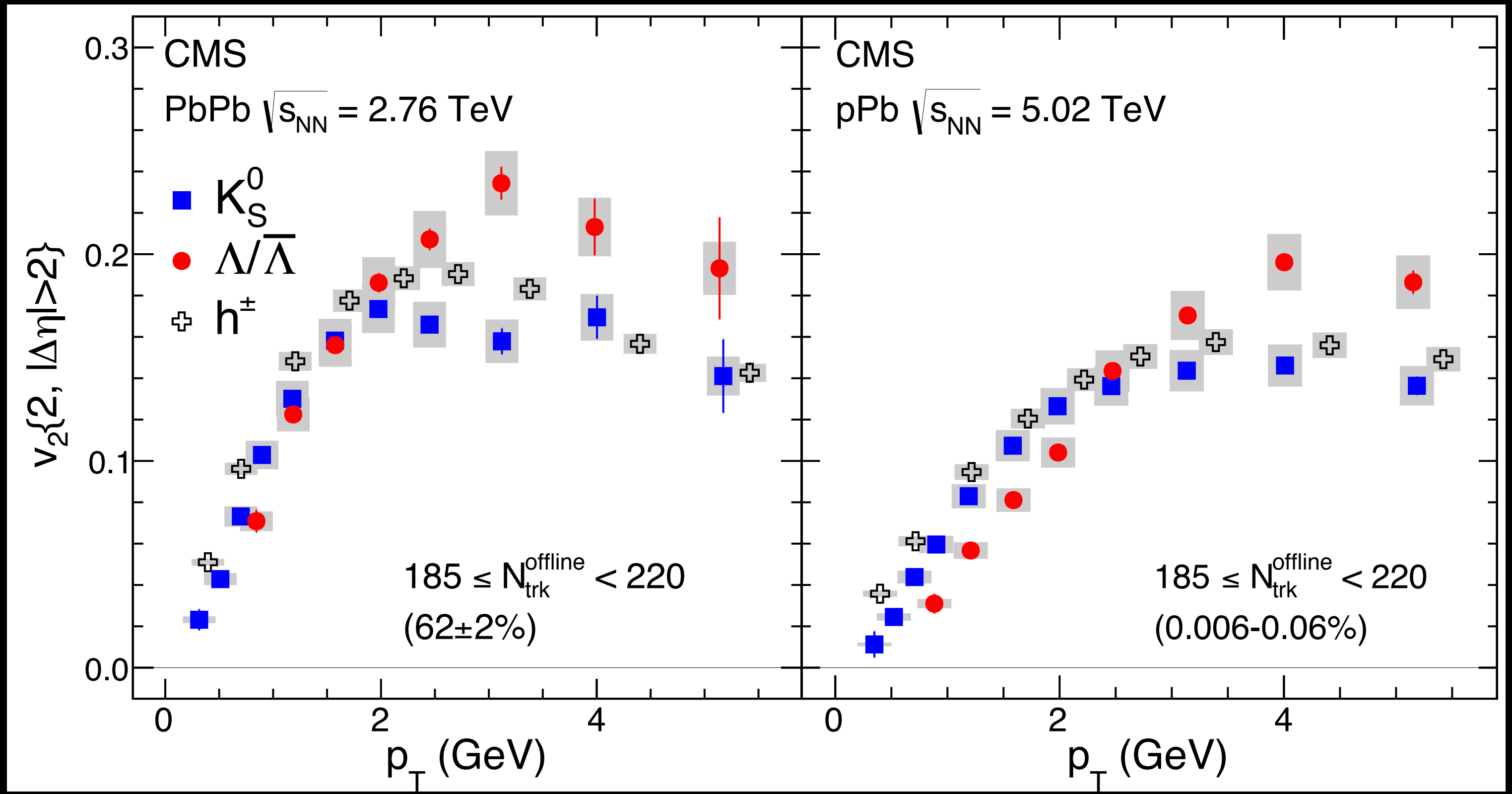


also multi-particle correlations using cumulants show clear evidence for collectivity in small systems

pA true collectivity?



PLB 742 (2015) 200

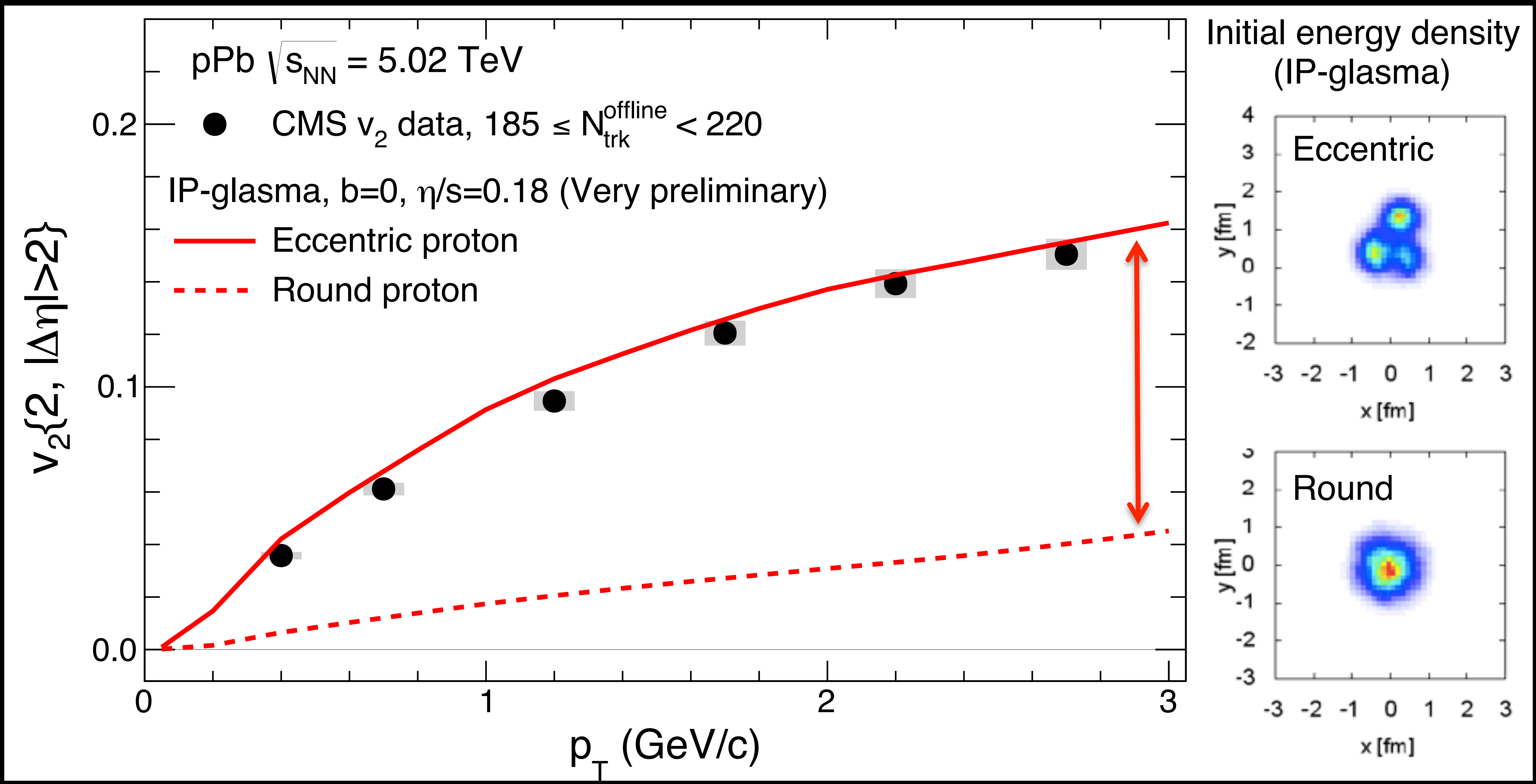


mass scaling observed in AA also observed in pA and at similar event multiplicity even stronger in pA

Small systems; pp and pA collisions

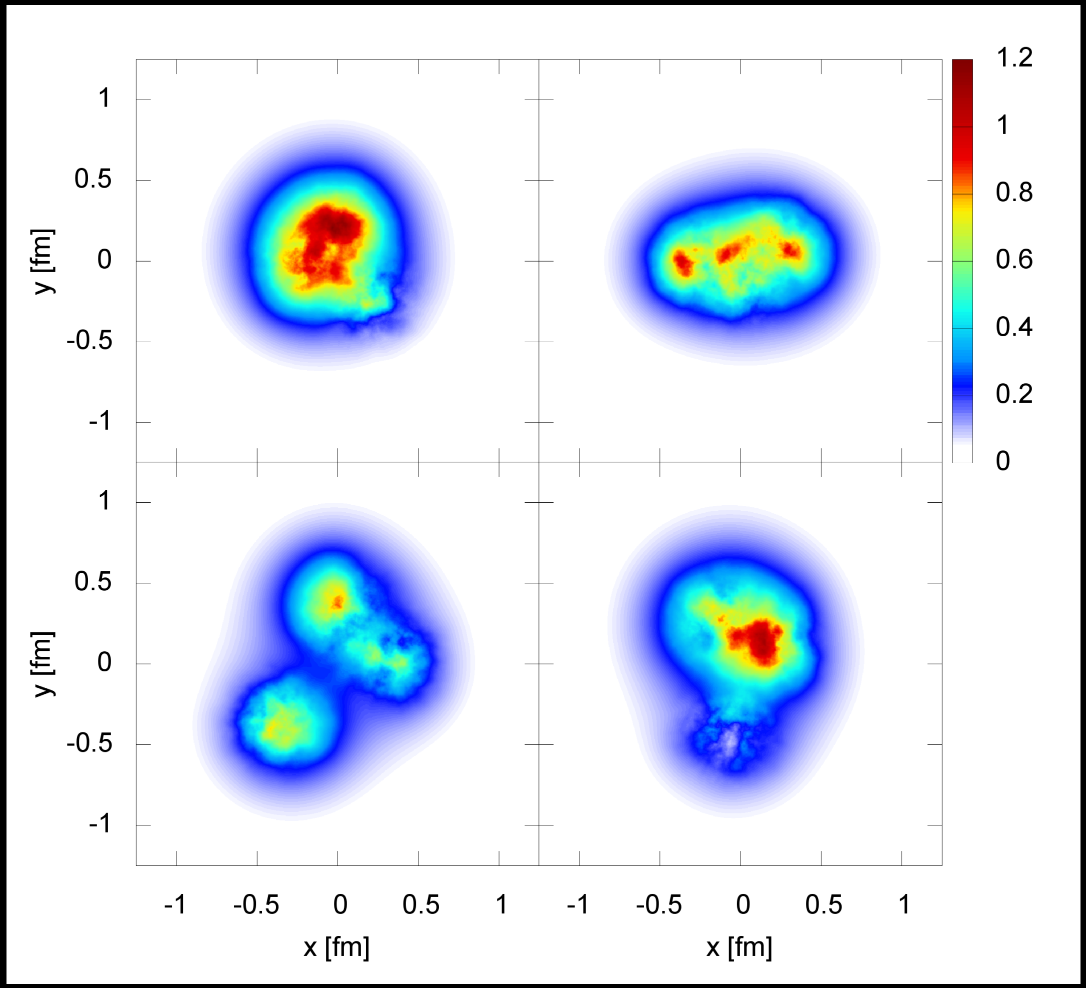
- is it strong final state interactions (hydro like behaviour) in small systems for high multiplicity events as in AA collisions?
  - data consistent with “hydro” scenario
  - small and large fluids should have similar properties (EoS, transport parameters), viscous corrections are larger though
  - biggest uncertainty the initial conditions (the “shape”)

What is the shape of the proton?

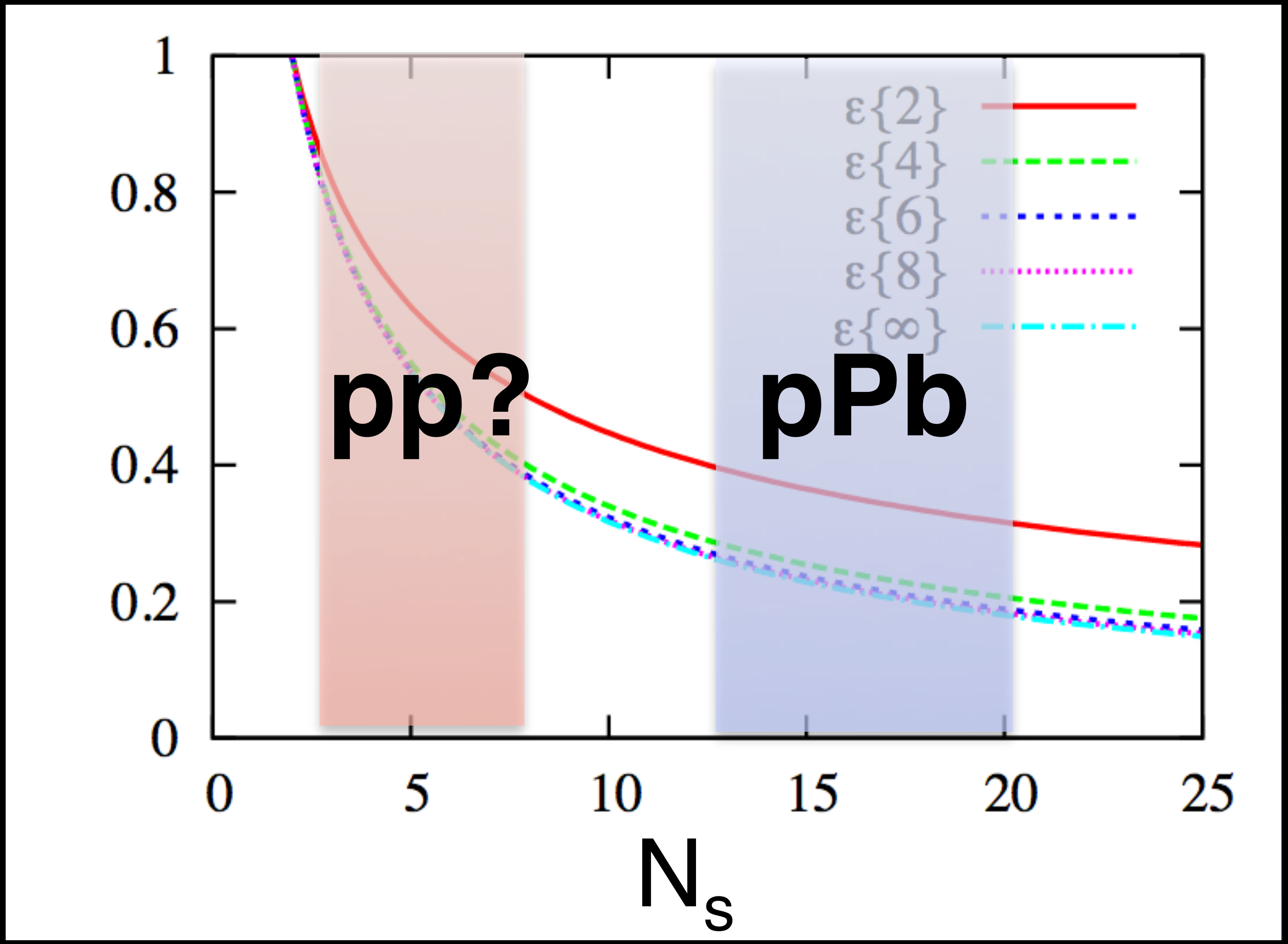


What are the sources of particle production?

Mantysaasri, Schenke, arXiv:1603.04349



Yan, Ollitrault, PRL 112, 082301 (2014)



$$\frac{v_n\{4\}}{v_n\{2\}} = \frac{\epsilon_n\{4\}}{\epsilon_n\{2\}} = \frac{2}{1 + N_s/2}$$

Summary

- In AA collisions clear evidence of the importance of the initial spatial distribution (in all gory details) in all the correlations
  - naturally explained if the constituents have strong final state interactions which translate them in an almost perfect liquid to momentum space
  - some depend non-trivially on the evolution (which is well captures in models with final state interactions)
  - very rich playground for theorist and experimentalist!
- In pp and pA collisions similar experimental evidence found in correlations
  - again naturally explained with “strong” final state interactions (other models fail so far) for a system very similar to the QGP in AA
  - not as well tested as in AA
    - large uncertainties in initial conditions
  - could provide new ways of determining number of sources in particle production in pA and pp and the geometrical structure of the proton