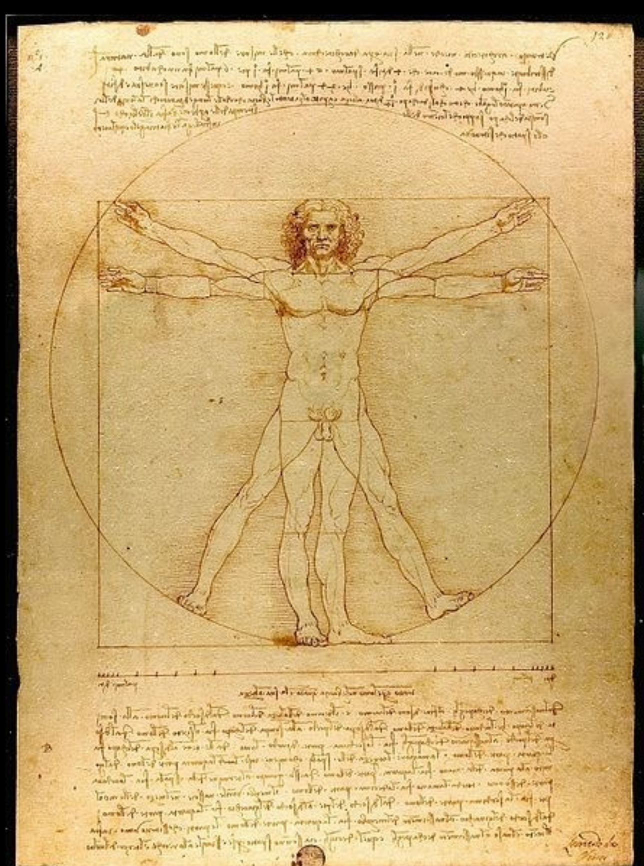
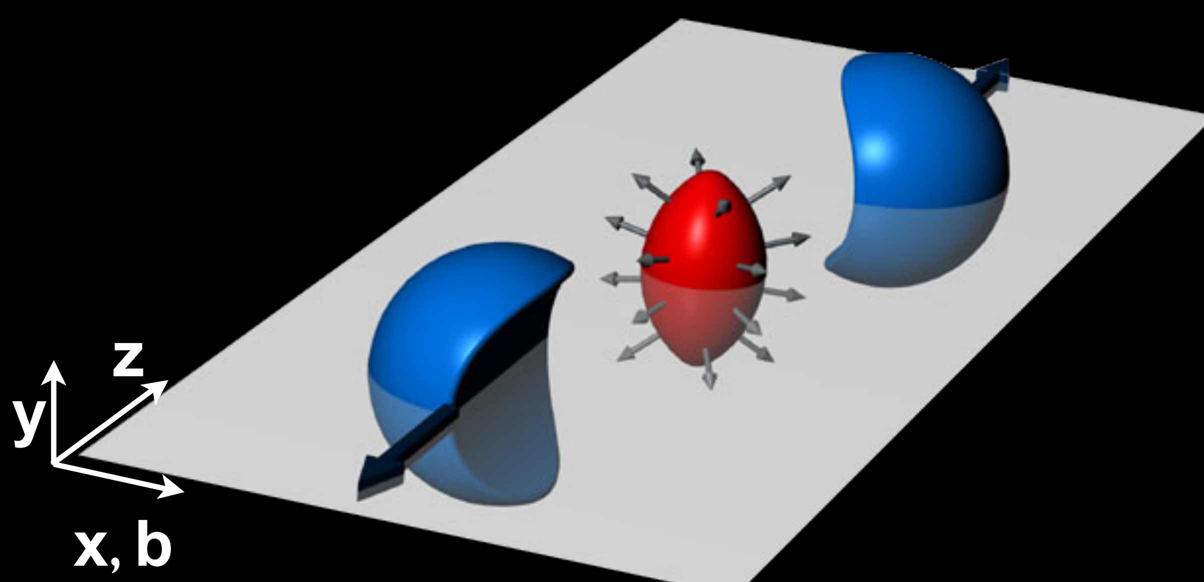
Anisotropic Flow: past, present and future (ideal shapes and symmetries)

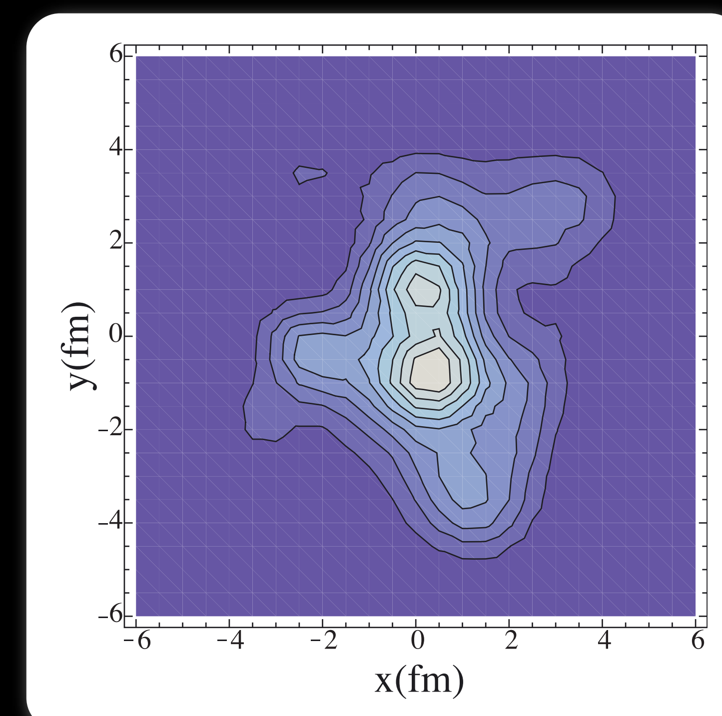
Raimond Snellings

WPCF 2013

05-11-2013



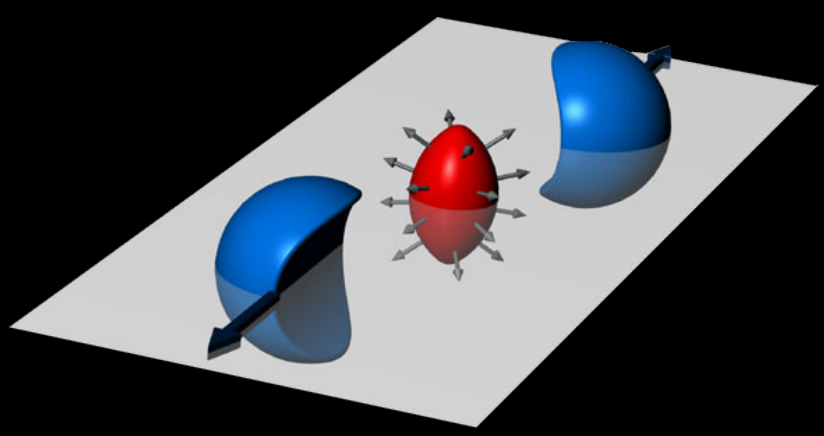




Collective Flow in Heavy Ion Collisions

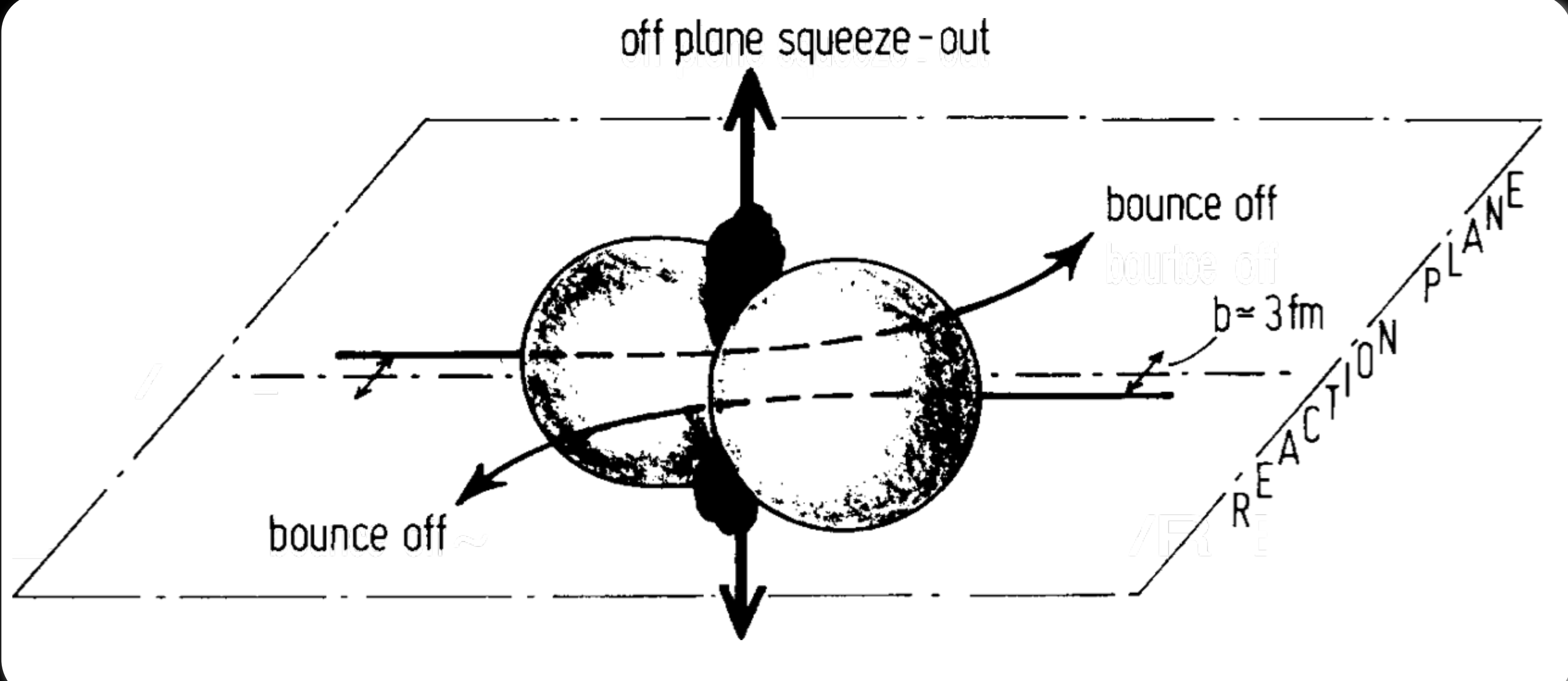
- Originating from the expansion of the hot and compressed reaction zone
- Sensitive to the equation of state, the transport coefficients (e.g. viscosity or elementary collisions scattering cross sections) and initial energy density distribution of the created system
- Studied for many decades from the MeV to TeV scale

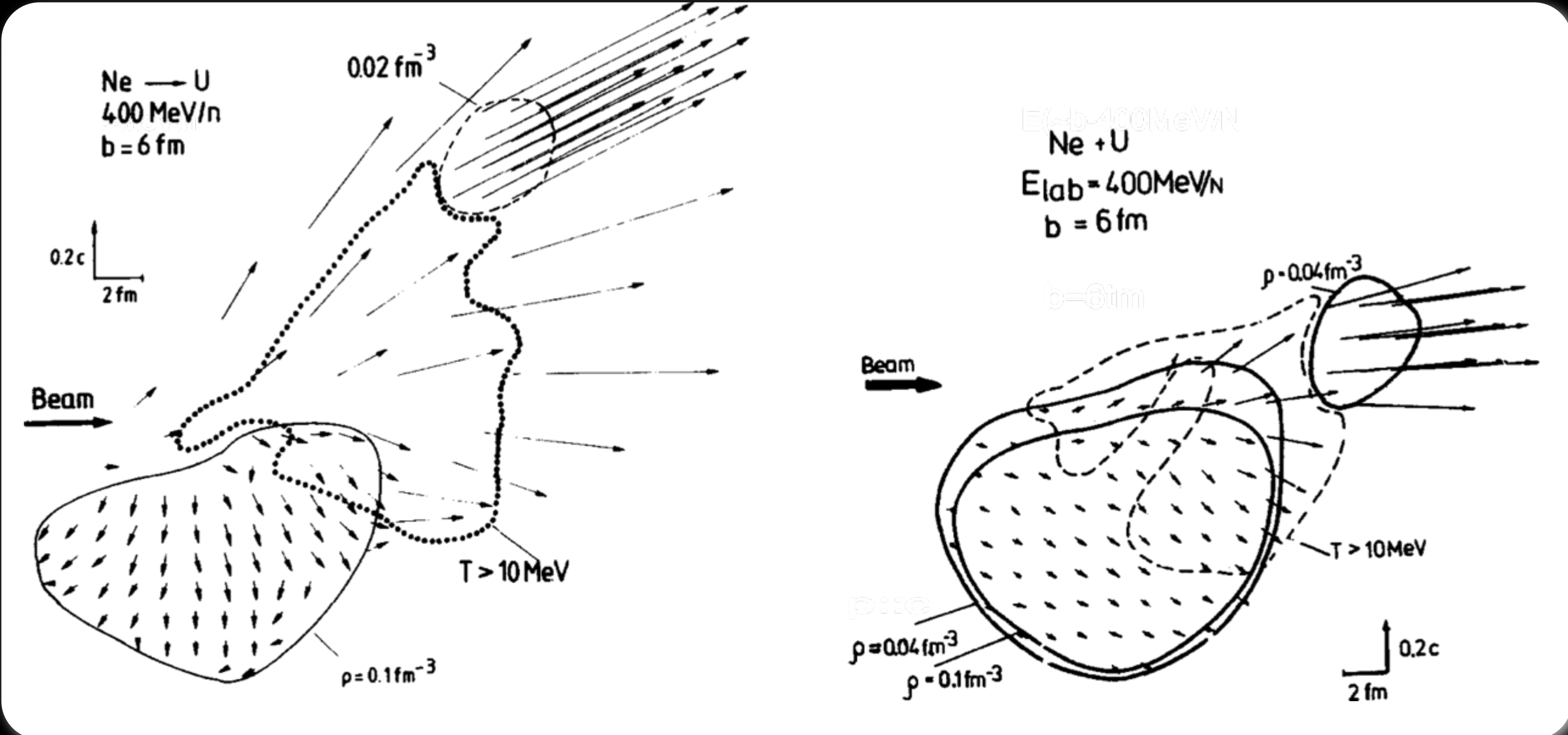
Collective Flow



H. Stöcker and W. Greiner,
Phys. Rep. 137 (1986) 277

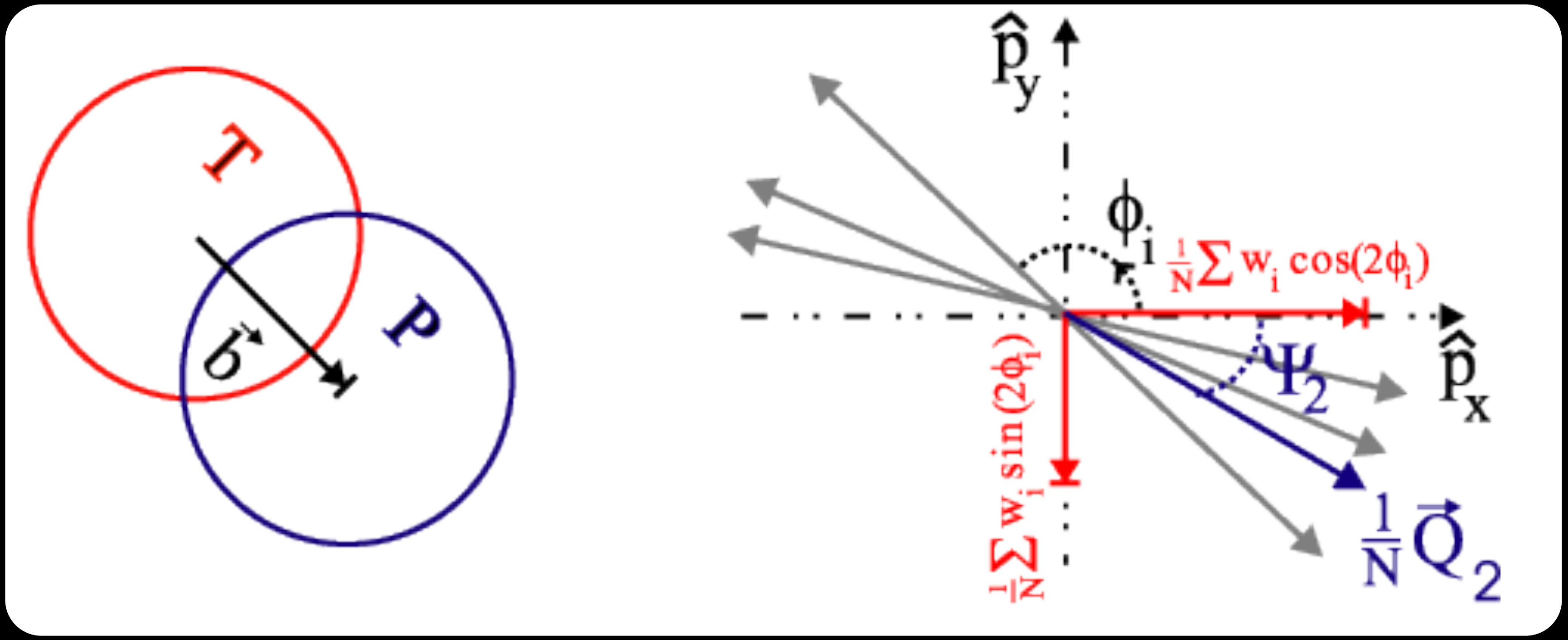
quickly recognized as important probe





Event Plane

the event plane is an experimental estimate of the reaction plane



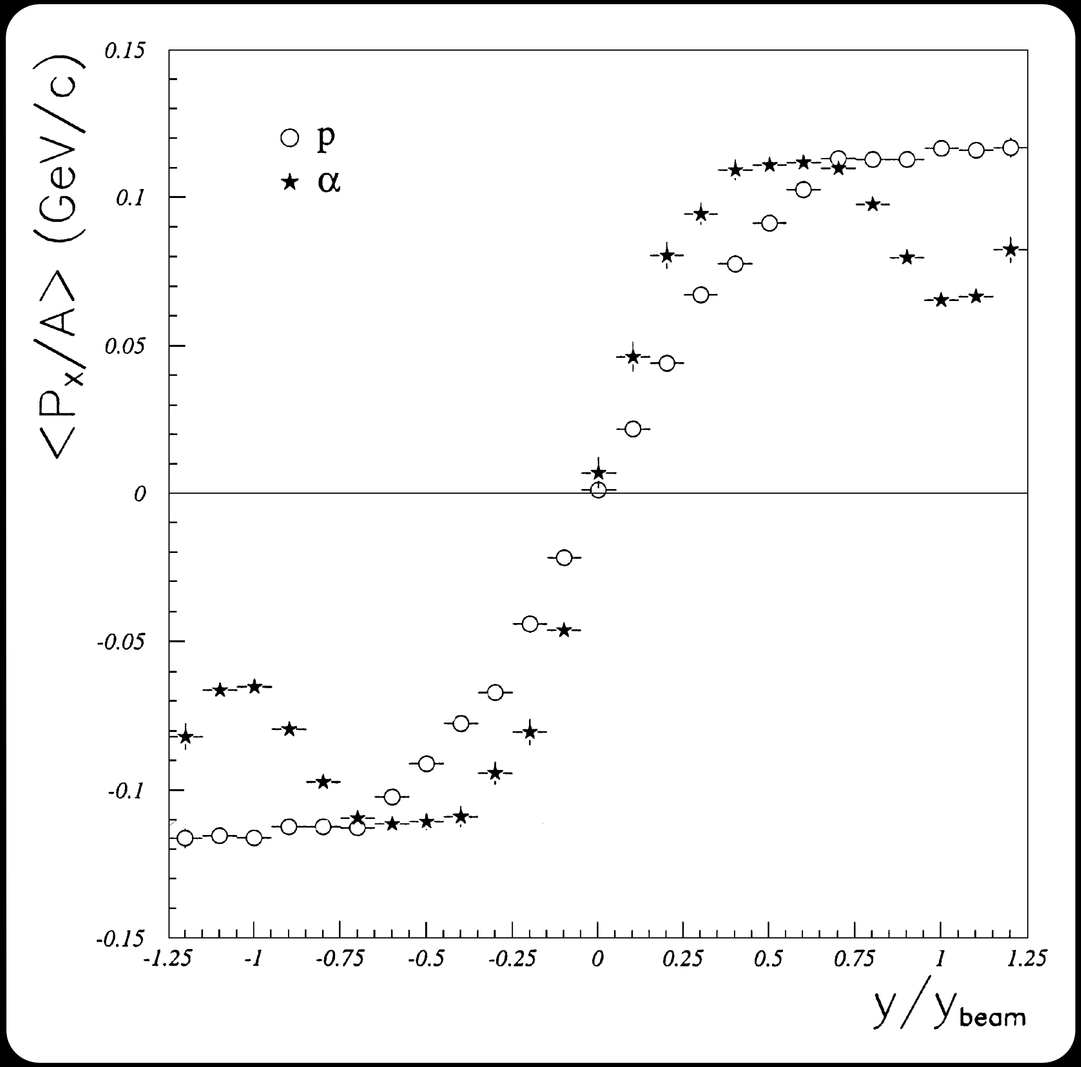
$$Q_{nx} = \sum_i w_i \cos(n\phi_i)$$

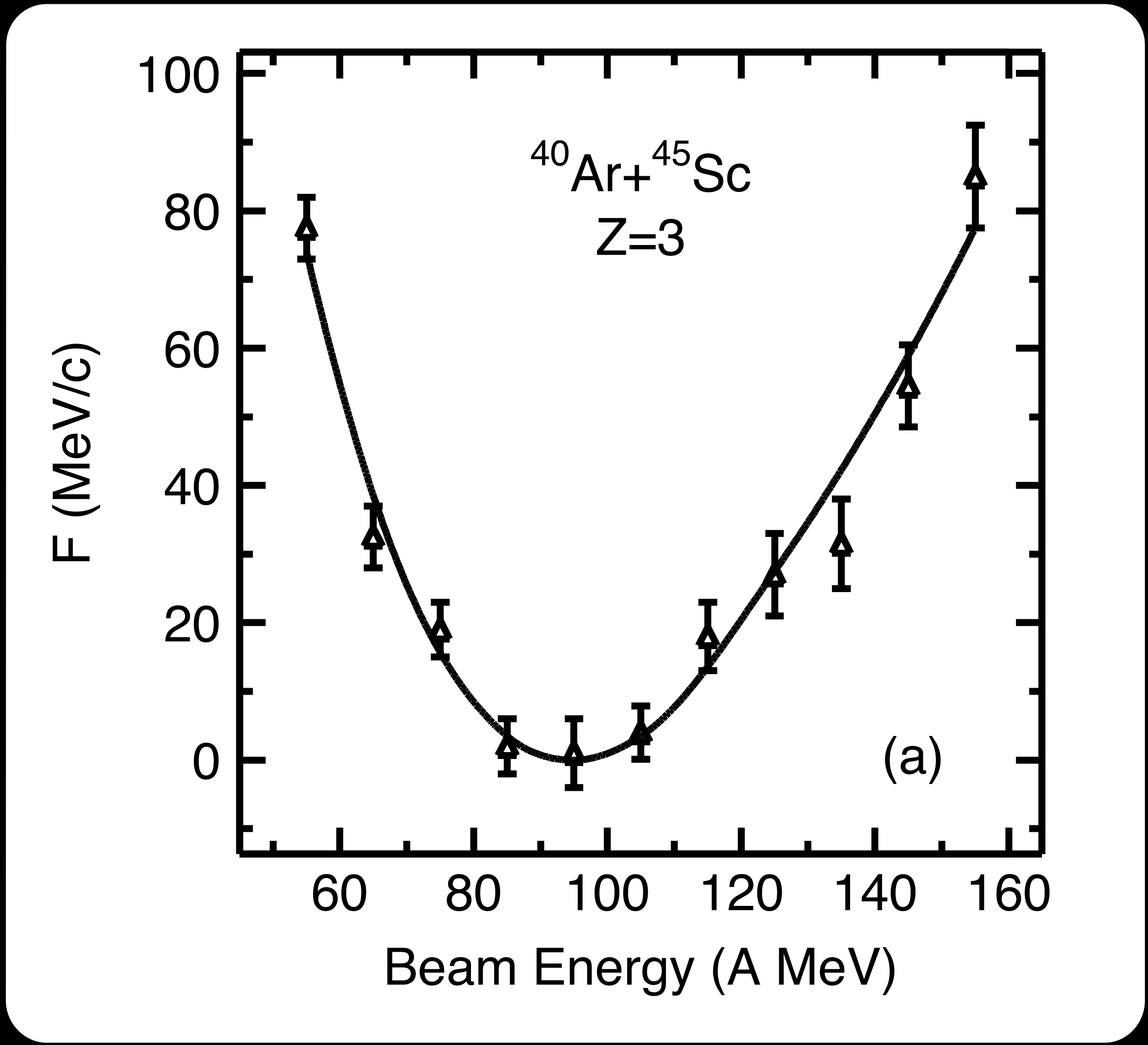
Danielewicz and Odyniec '85

$$Q_{ny} = \sum_i w_i \sin(n\phi_i)$$

$$\Psi_n^{EP} = \frac{1}{n}\tan^{-1}\left(\frac{Q_{ny}}{Q_{nx}}\right)$$

Directed Flow (in-plane flow)





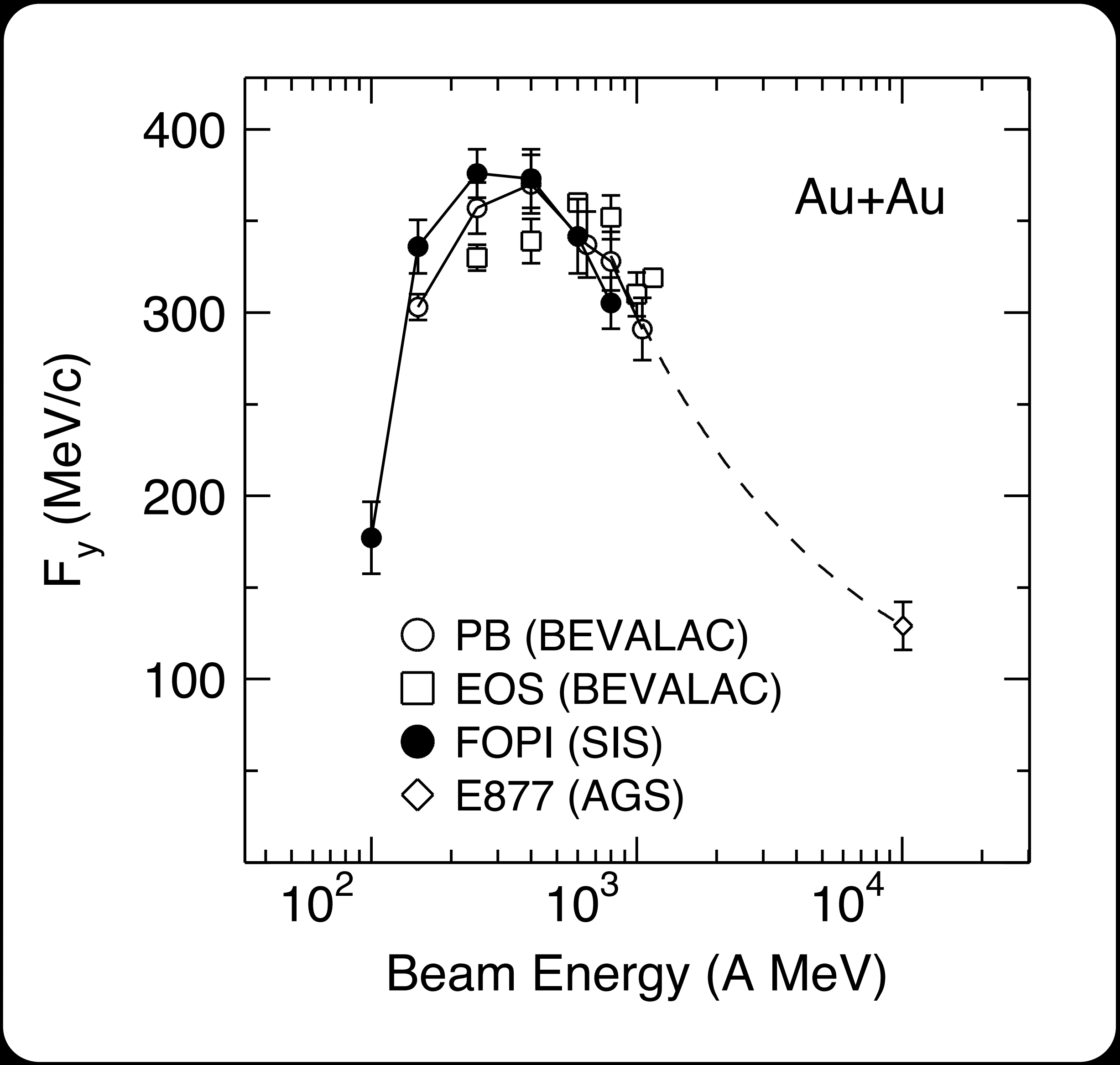
$$F = d\langle p_x/A\rangle/dy_n$$

average transverse momentum in the reaction plane

balancing energy; transition from attractive to repulsive interaction

for review see Reisdorf and Ritter '97

Directed Flow (in-plane flow)

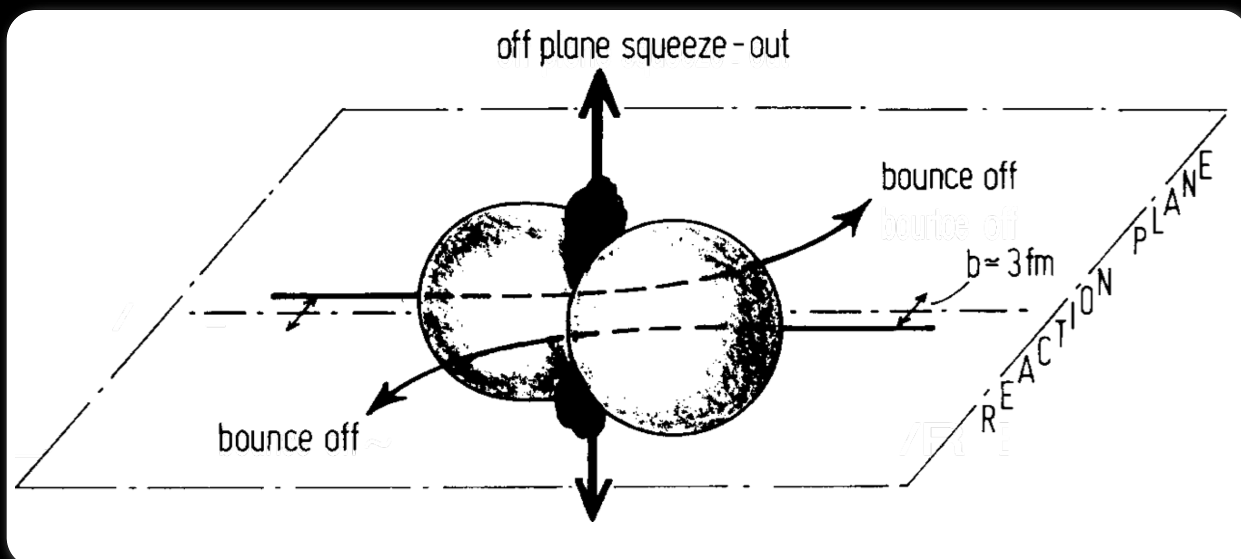


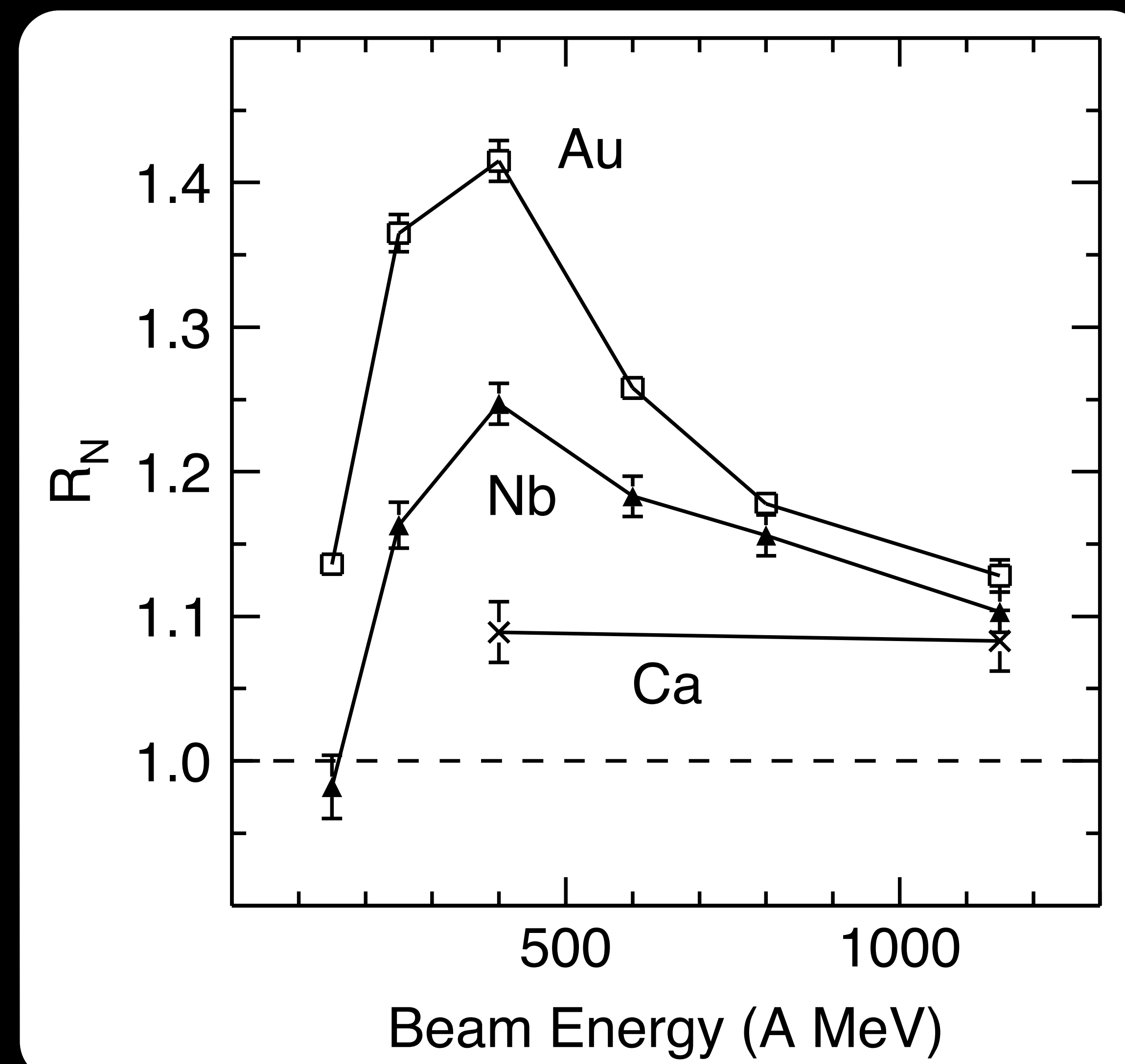
Directed flow does not continue to increase with increasing beam energy, interpreted as a softening of the EoS

for higher energies see talk M. Lisa and I. Selyuzhenkov

for review see Reisdorf and Ritter '97

Squeeze Out (out of plane flow)





R_N = ratio of particles emitted out of plane versus in plane

$$R_N = \frac{dN/d\varphi(90) + dN/d\Phi(-90)}{dN/d\varphi(0) + dN/d\varphi(180)} = \frac{1-a_2}{1+a_2}$$

for review see Reisdorf and Ritter '97

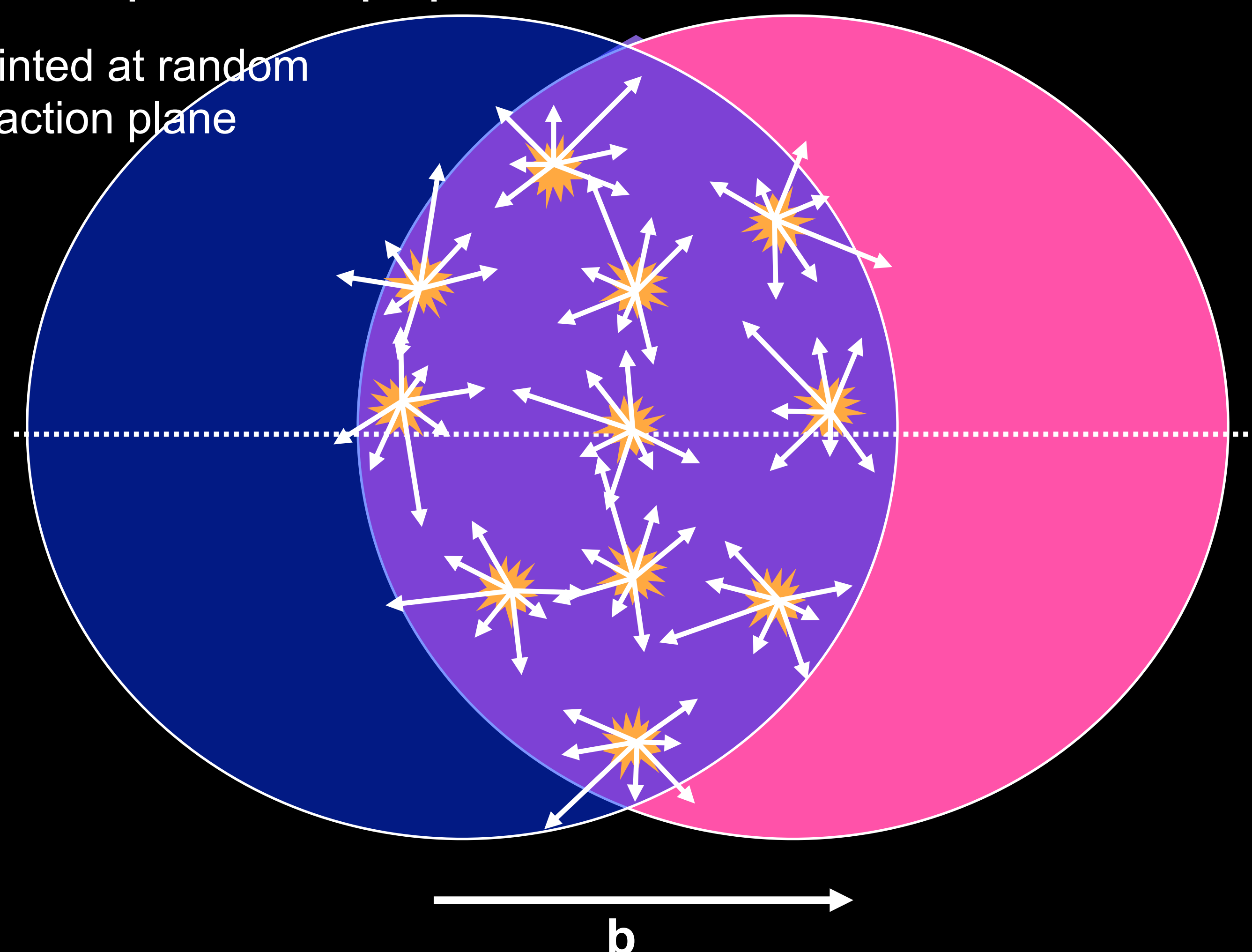
Elliptic Flow

Animation: Mike Lisa

1) Superposition of independent p+p:

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

momenta pointed at random
relative to reaction plane



Ollitrault '92

Elliptic Flow

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

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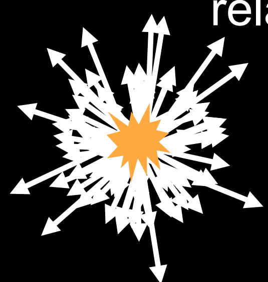
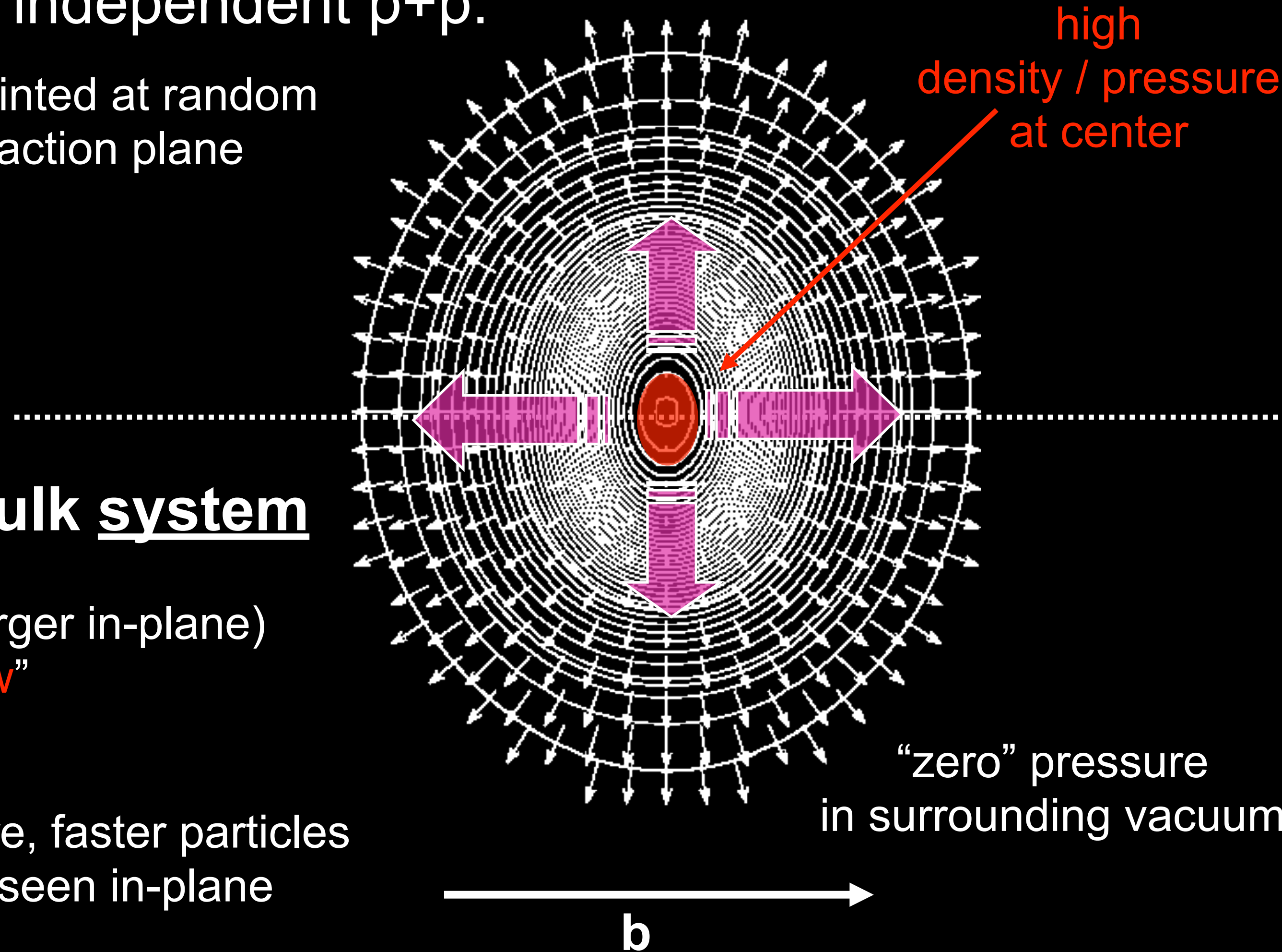
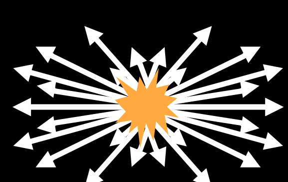




2) Evolution as a **bulk <u>system</u>**

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

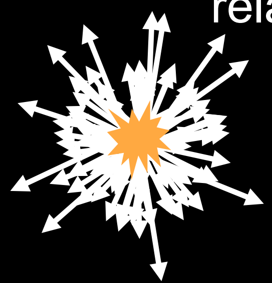


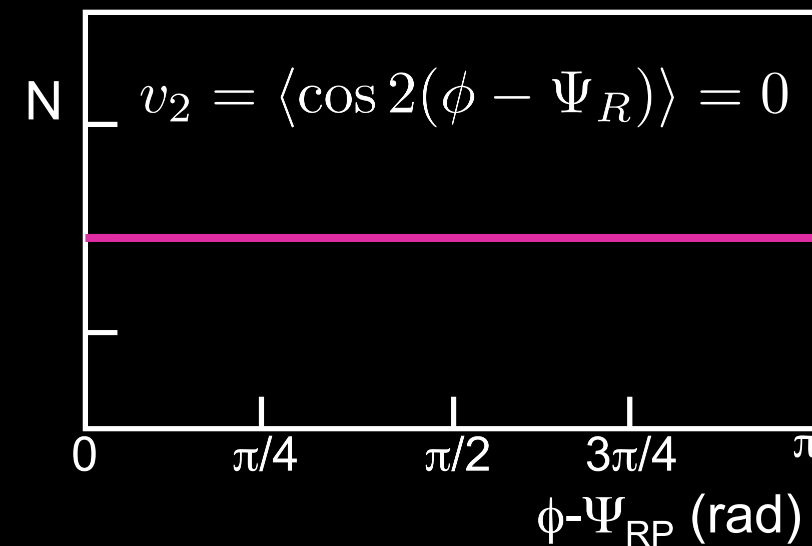
more, faster particles
seen in-plane

Elliptic Flow

1) Superposition of independent p+p:

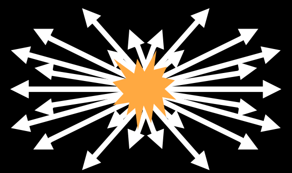
momenta pointed at random relative to reaction plane



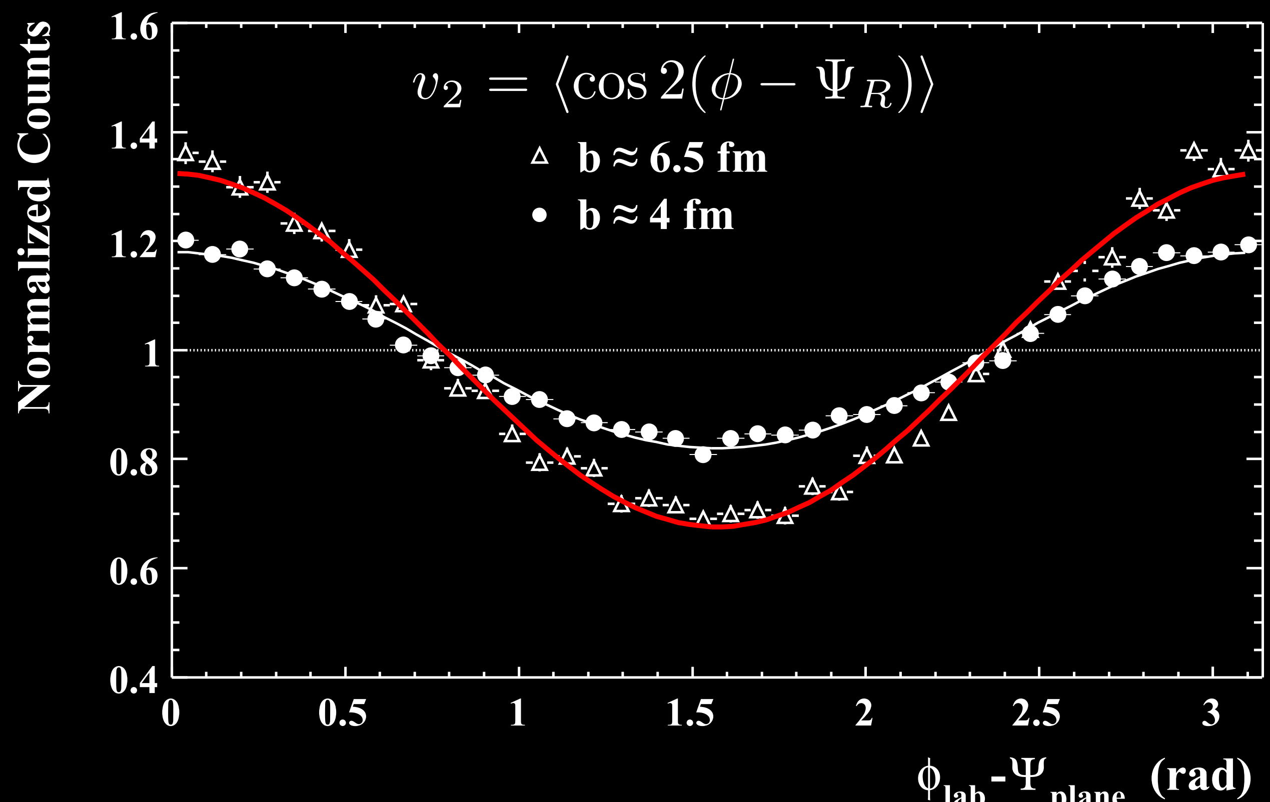


2) Evolution as a **bulk system**

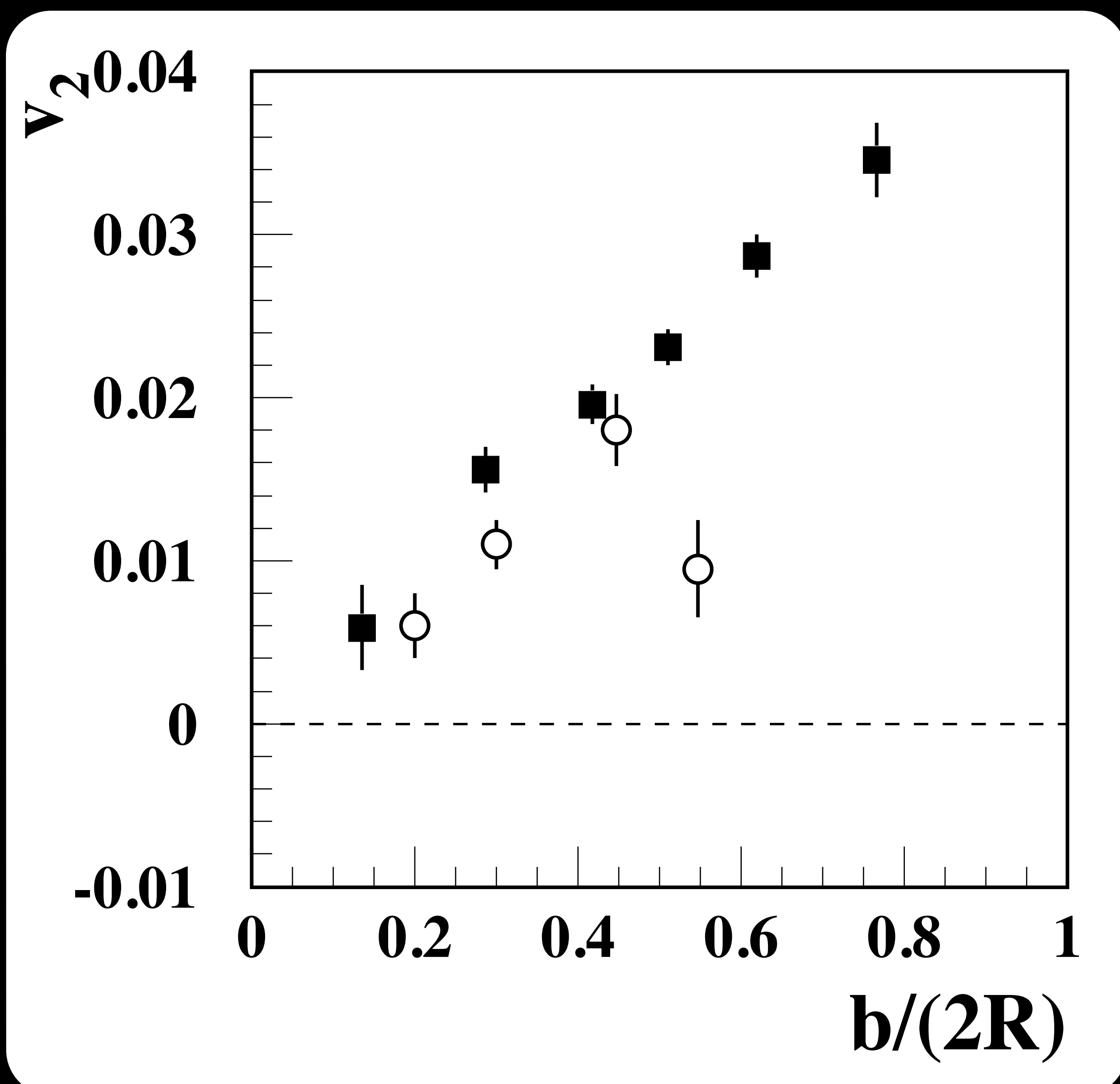
Pressure gradients (larger in-plane) push bulk "out" → "flow"



more, faster particles seen in-plane

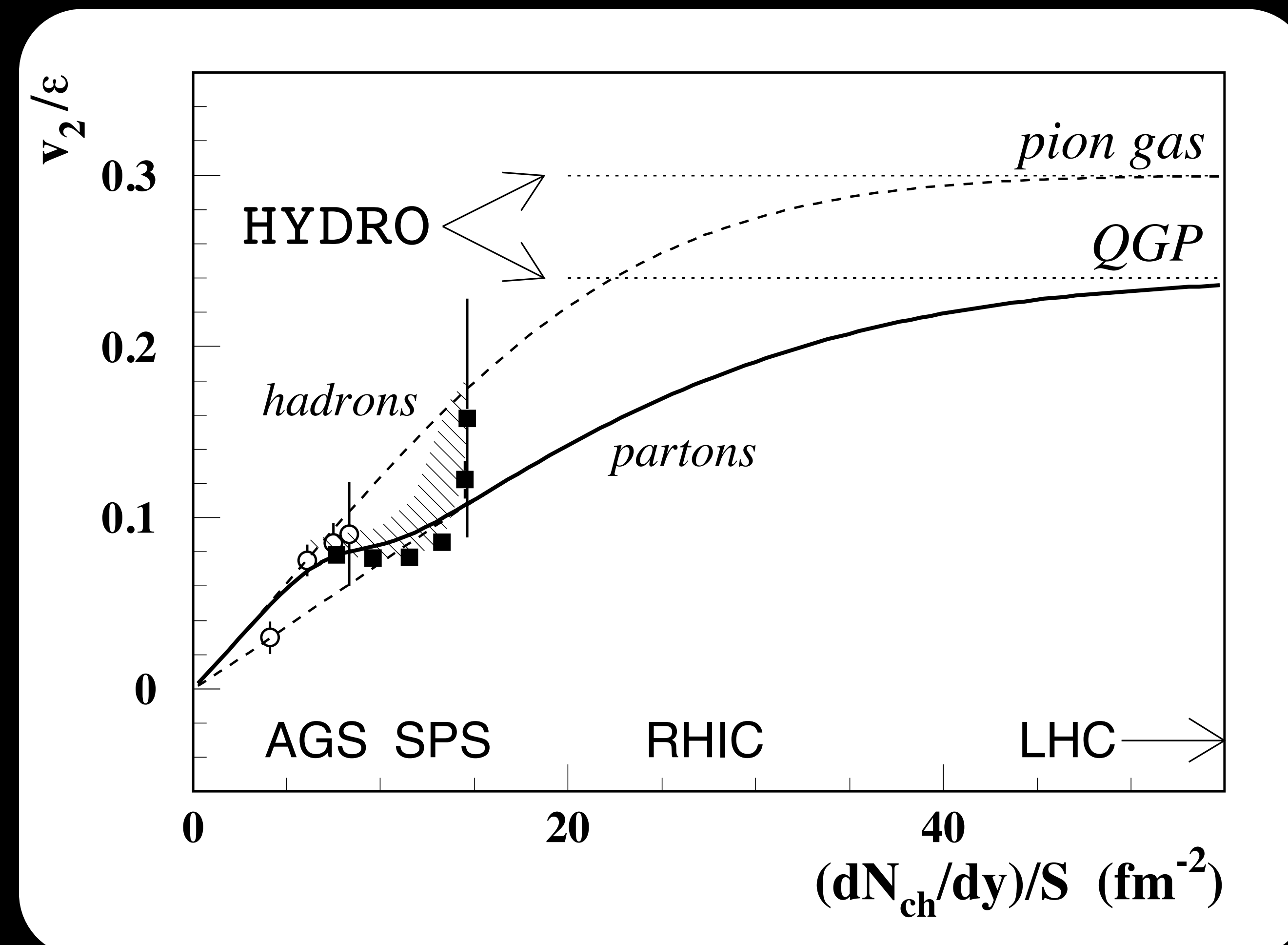


Elliptic Flow (AGS and SPS)



in-plane elliptic flow observed at AGS and SPS (increasing as function of energy)

Voloshin and Poskanzer '99



from peripheral to central collisions
change of EoS at SPS energies?
(currently much better understood!)
for ideal fluid elliptic flow will continue to increase for RHIC and LHC energies

Pre-RHIC Prejudice

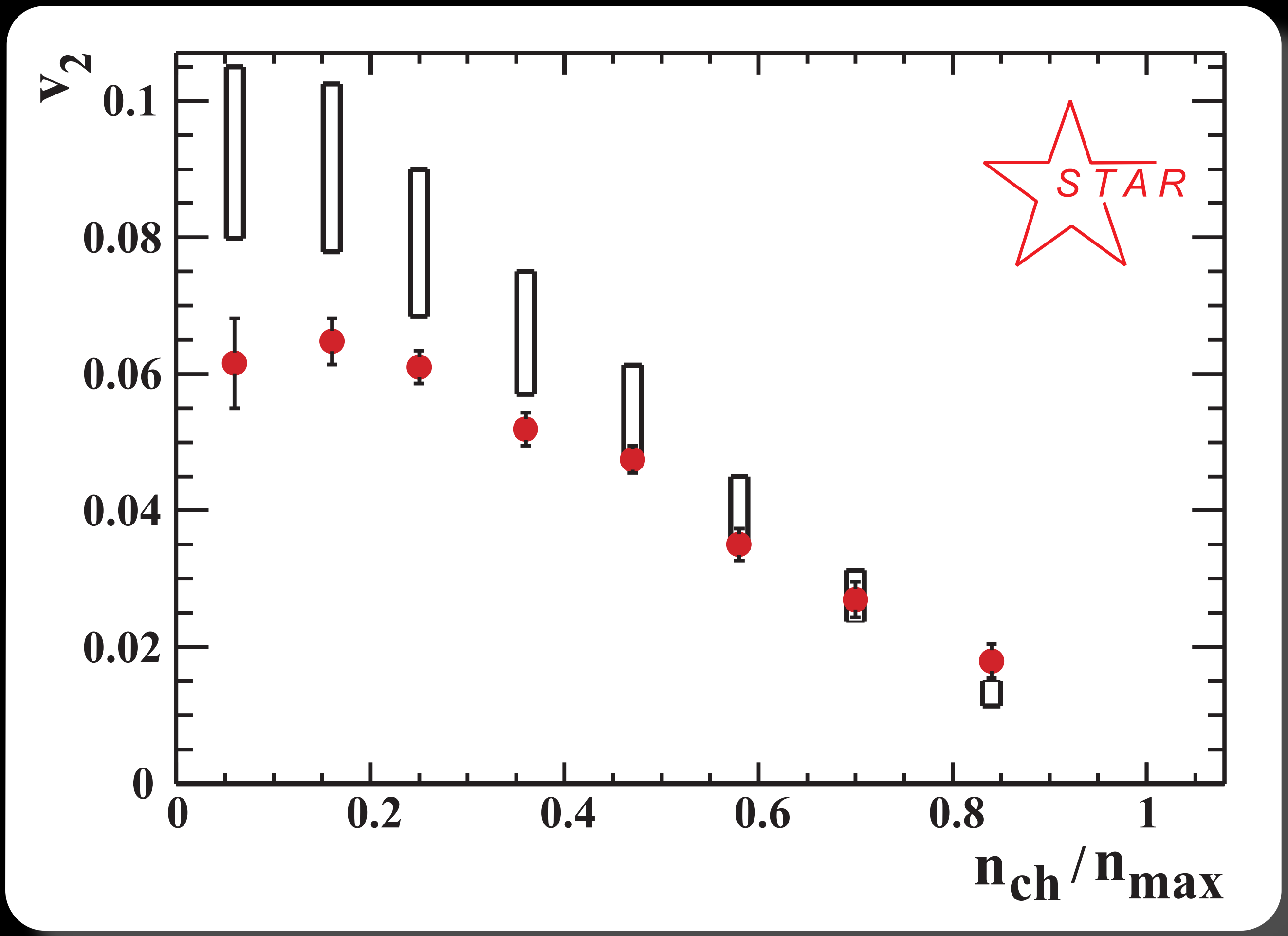
Flow

- **Radial:**
  - Will (continue to) be a very large effect
  - Essential component to understanding spectra at RHIC.
- **Directed:**
  - Already small at SPS
  - Almost irrelevant at RHIC
- **Elliptic:**
  - Zero for truly central events (at any energy)
  - Is it
    - A necessary evil for understanding events with non-zero impact parameter?

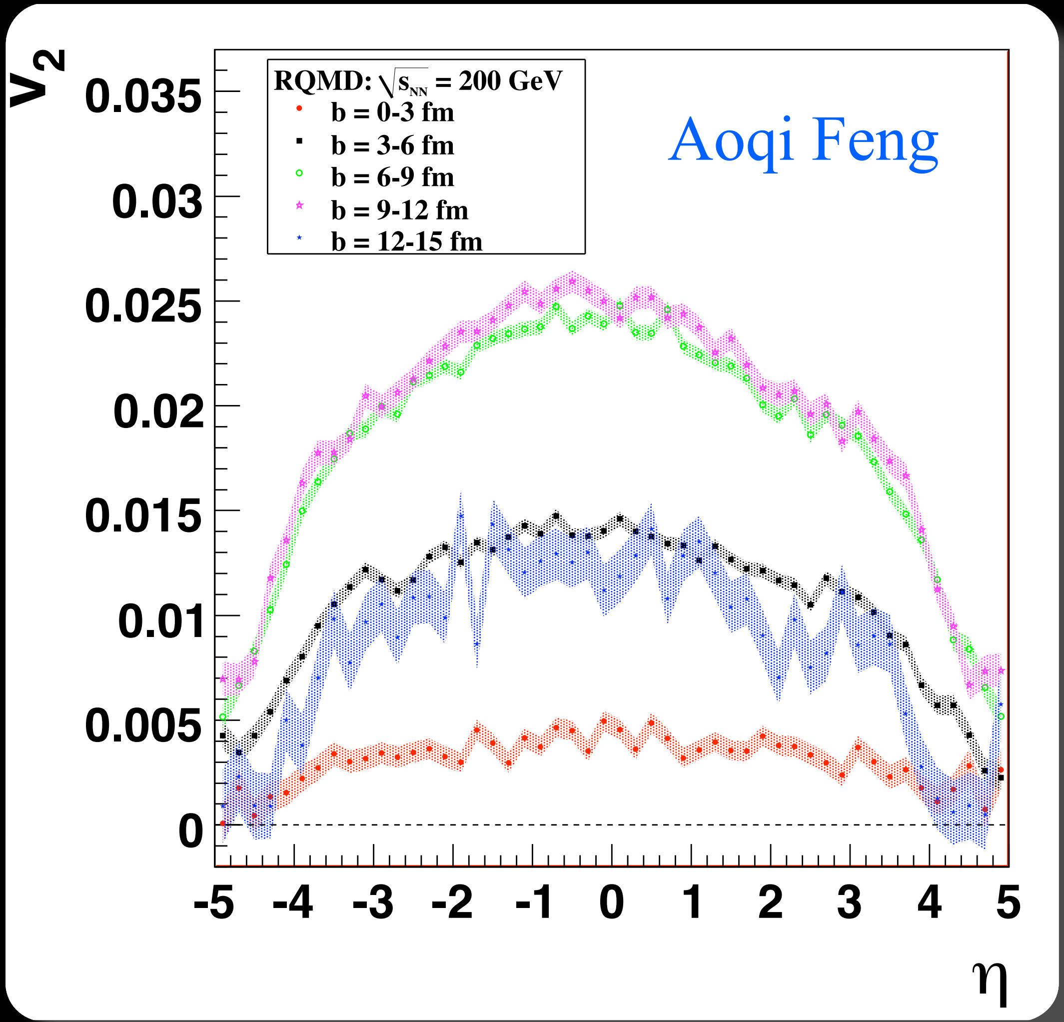
    Or
    - An essential tool to our understanding of EoS+(time evolution) of (non-isotropic) initial conditions?
  - My *prejudice:*
    Effects of elliptic flow will be small at RHIC

09-Jan-98 *W.A. Zajc*

Flow at RHIC



STAR Phys. Rev. Lett. 86, 402–407 (2001)



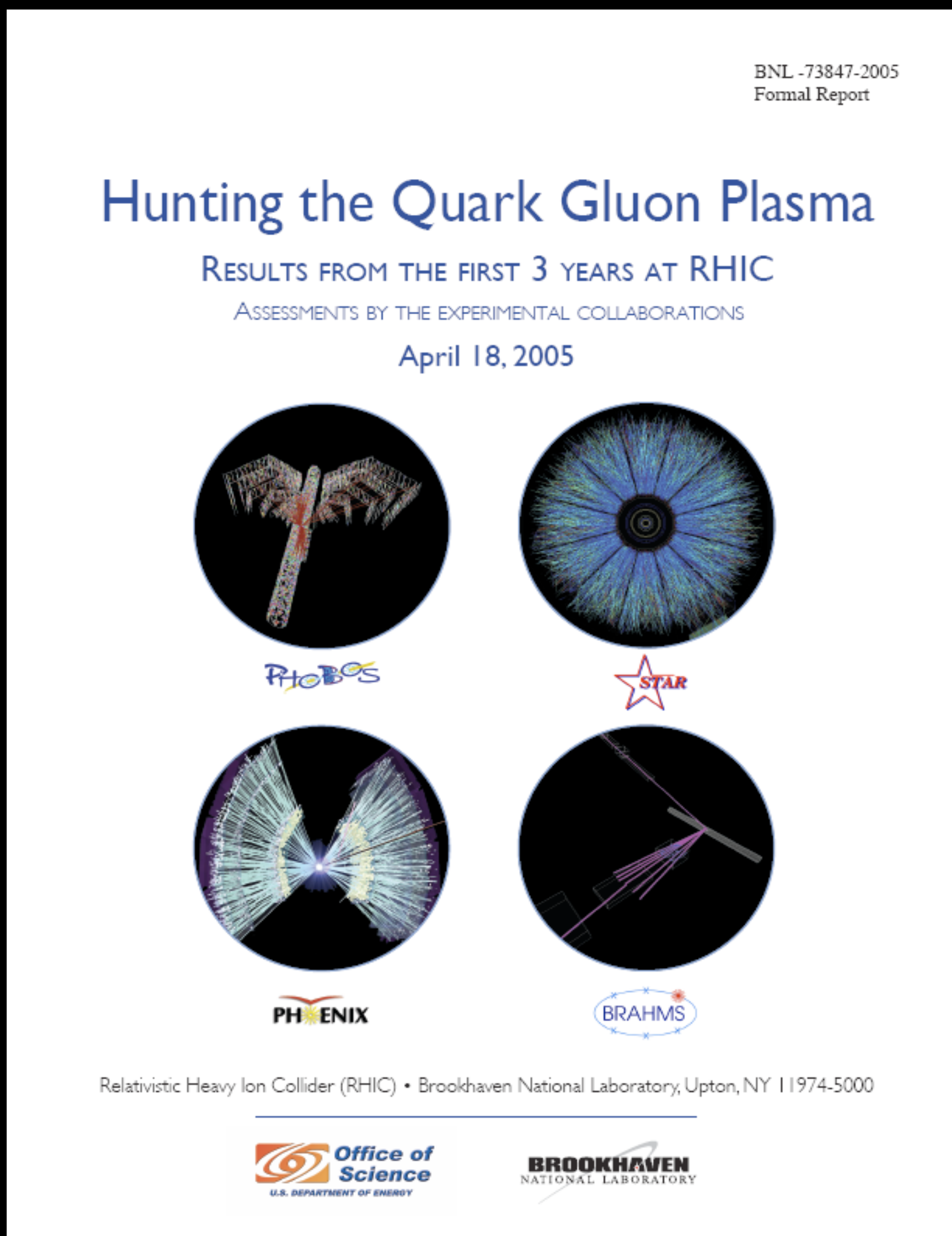
Ideal hydro gets the magnitude for more central collisions

Hadron cascade calculations are factors 2-3 off

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005



BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

Results from the first 3 years at RHIC

Assessments by the experimental collaborations

April 18, 2005

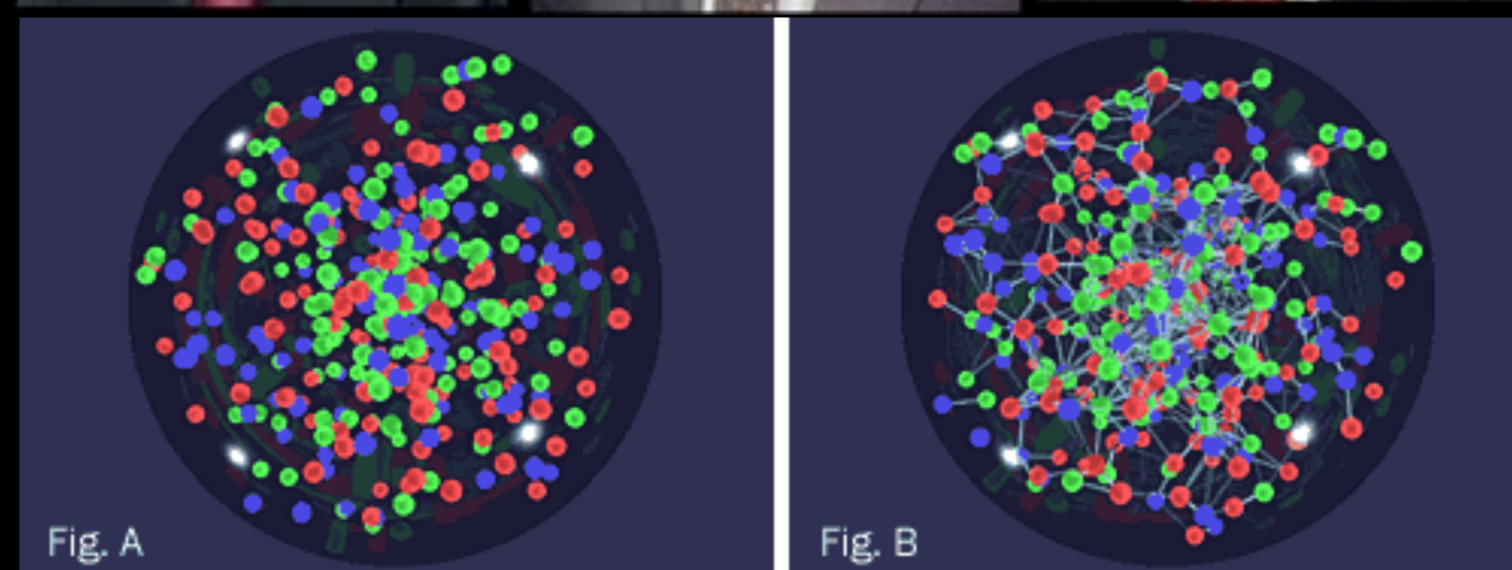
PHOBOS STAR

PHENIX BRAHMS

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Office of Science U.S. Department of Energy

Brookhaven National Laboratory



change description from a weakly coupled to strongly coupled system

Early Universe Went With the Flow

Posted April 18, 2005 5:57PM

Between 2000 and 2003 the lab's Relativistic Heavy Ion Collider repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last prevailed in the universe less than 100 millionths of a second after the big bang.

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

Mark Peplow

nature

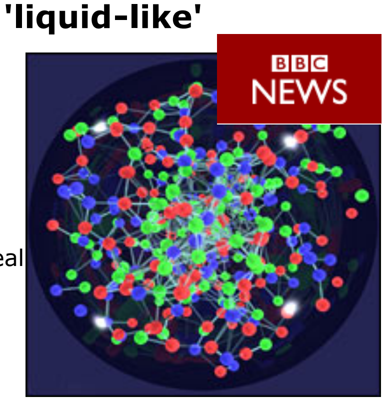
The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".



The impression is of matter that is more strongly interacting than predicted

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

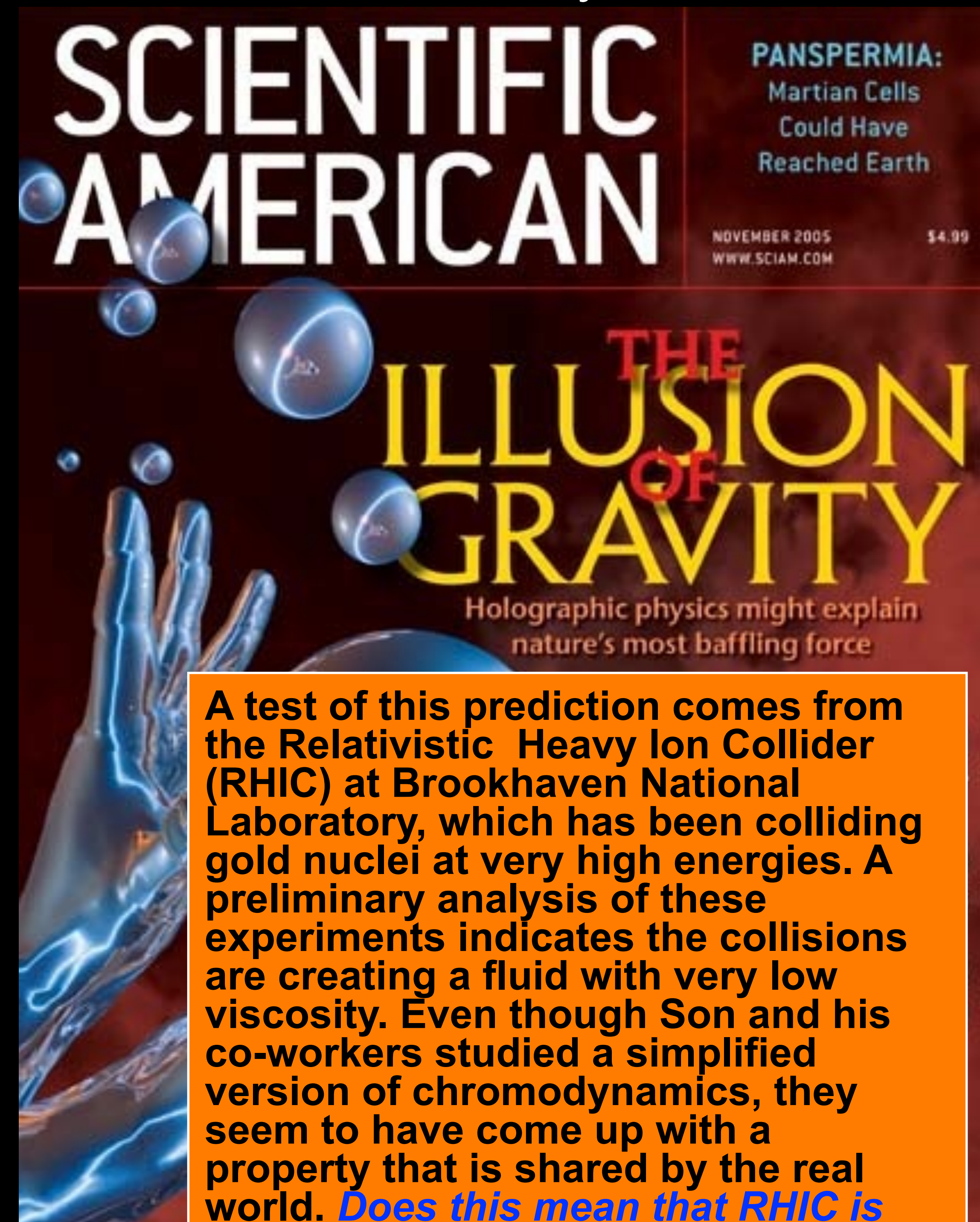
The Washington Post

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

Allows for using 'AdS/CFT'-correspondence to calculate transport properties like the specific shear viscosity

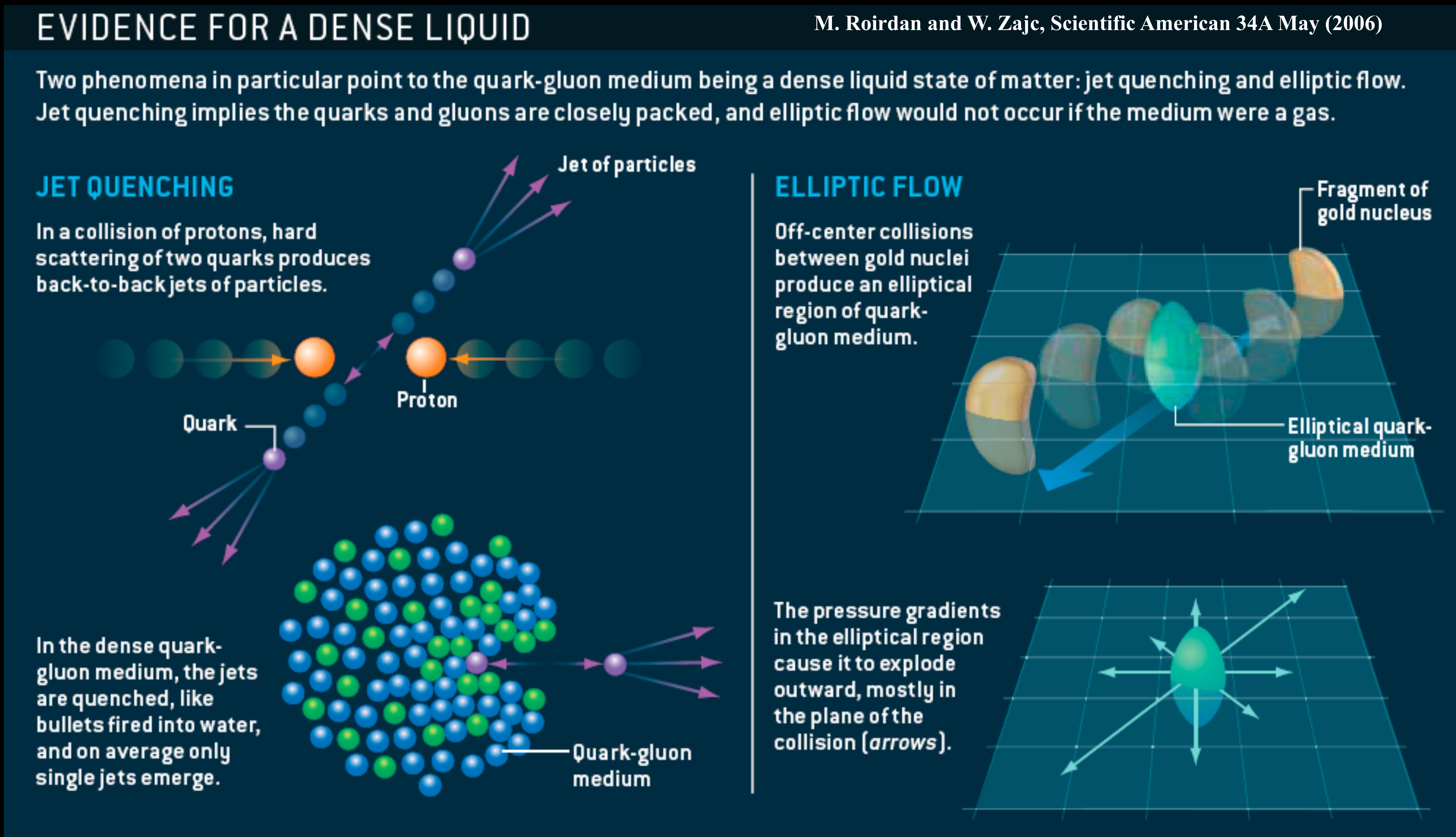
AdS/CFT calculations established a strong coupling lower limits to the specific shear viscosity which seem to be very close to the maximum allowed by the elliptic flow data

"The Illusion of Gravity" J. Maldacena



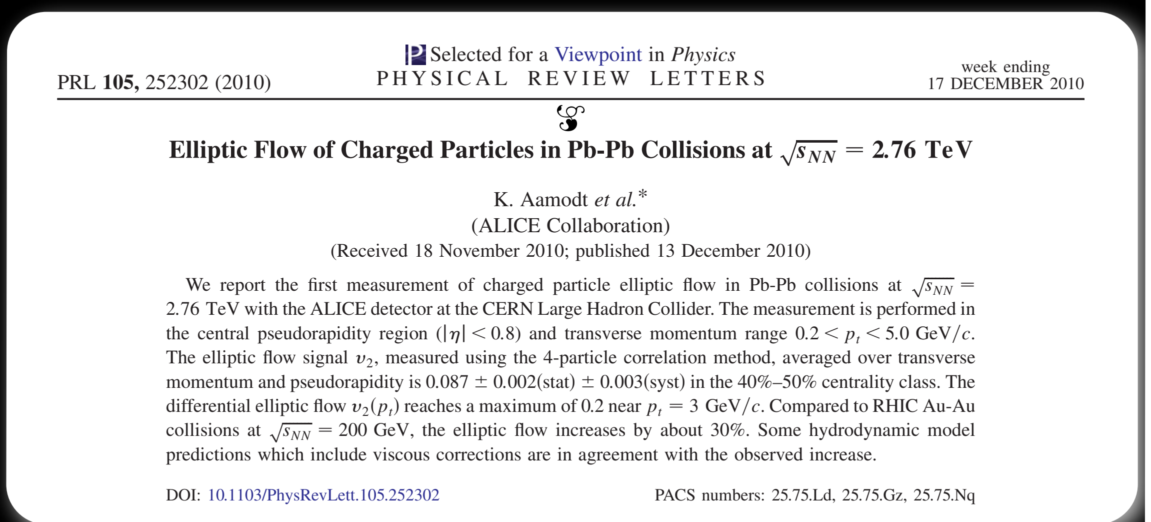
A test of this prediction comes from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, which has been colliding gold nuclei at very high energies. A preliminary analysis of these experiments indicates the collisions are creating a fluid with very low viscosity. Even though Son and his co-workers studied a simplified version of chromodynamics, they seem to have come up with a property that is shared by the real world. *Does this mean that RHIC is creating small five-dimensional black holes? It is really too early to tell,* both experimentally and theoretically.

Highlights at RHIC



perfect liquid

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

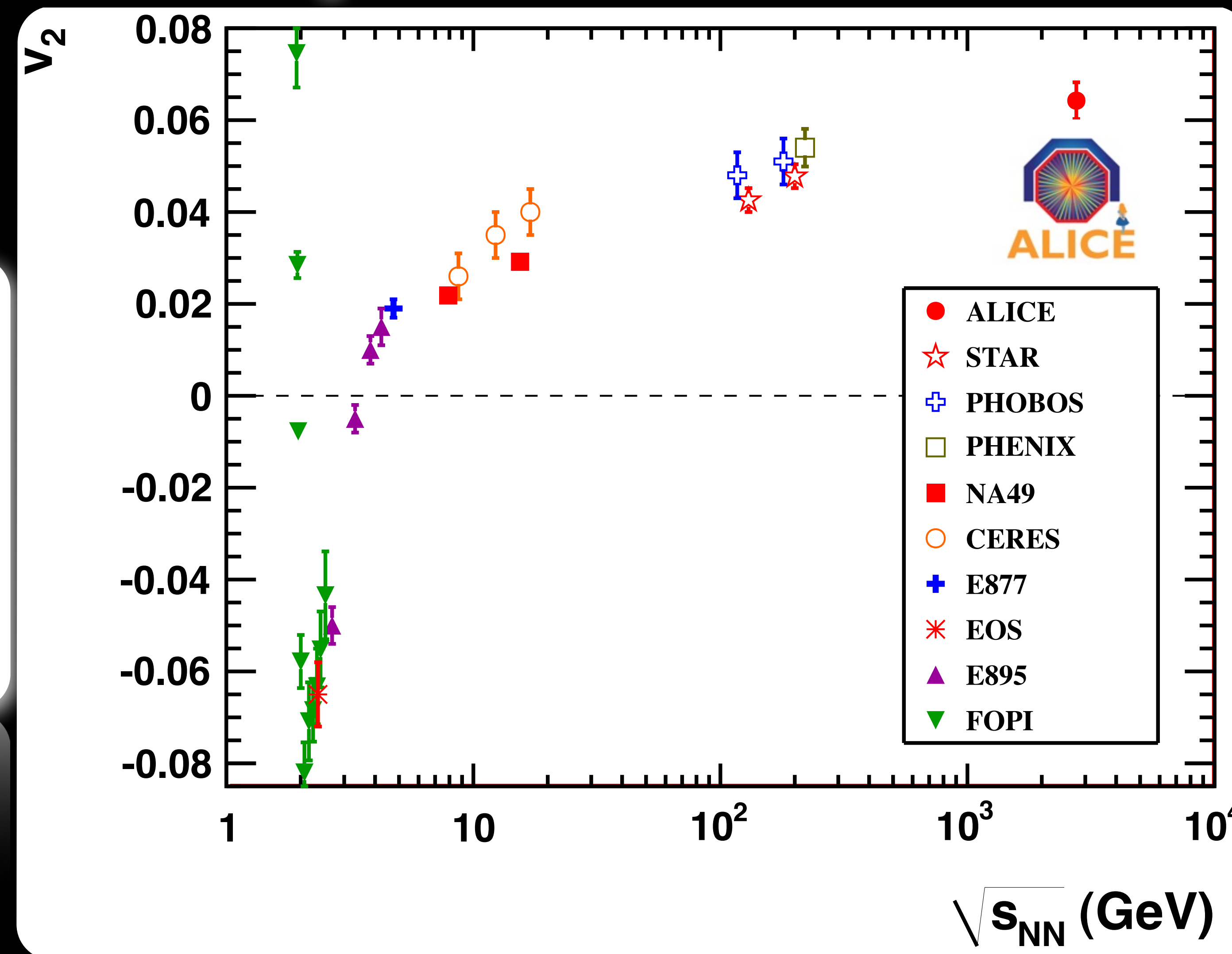

PRL **105,** 252302 (2010) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

K. Aamodt *et al.**
(ALICE Collaboration)
(Received 18 November 2010; published 13 December 2010)

We report the first measurement of charged particle elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} =$ 2.76 TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.2 < p_t < 5.0$ GeV/c. The elliptic flow signal v_2, measured using the 4-particle correlation method, averaged over transverse momentum and pseudorapidity is 0.087 ± 0.002(stat) $\pm$ 0.003(syst) in the 40%–50% centrality class. The differential elliptic flow $v_2(p_t)$ reaches a maximum of 0.2 near $p_t = 3$ GeV/c. Compared to RHIC Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the elliptic flow increases by about 30%. Some hydrodynamic model predictions which include viscous corrections are in agreement with the observed increase.

DOI: 10.1103/PhysRevLett.105.252302 PACS numbers: 25.75.Ld, 25.75.Gz, 25.75.Nq



First LHC heavy-ion physics paper <10 days after first collisions

CERN, November 26, 2010:
'the much hotter plasma produced at the LHC behaves as a very low viscosity liquid.'

Hydro Motivated Fit

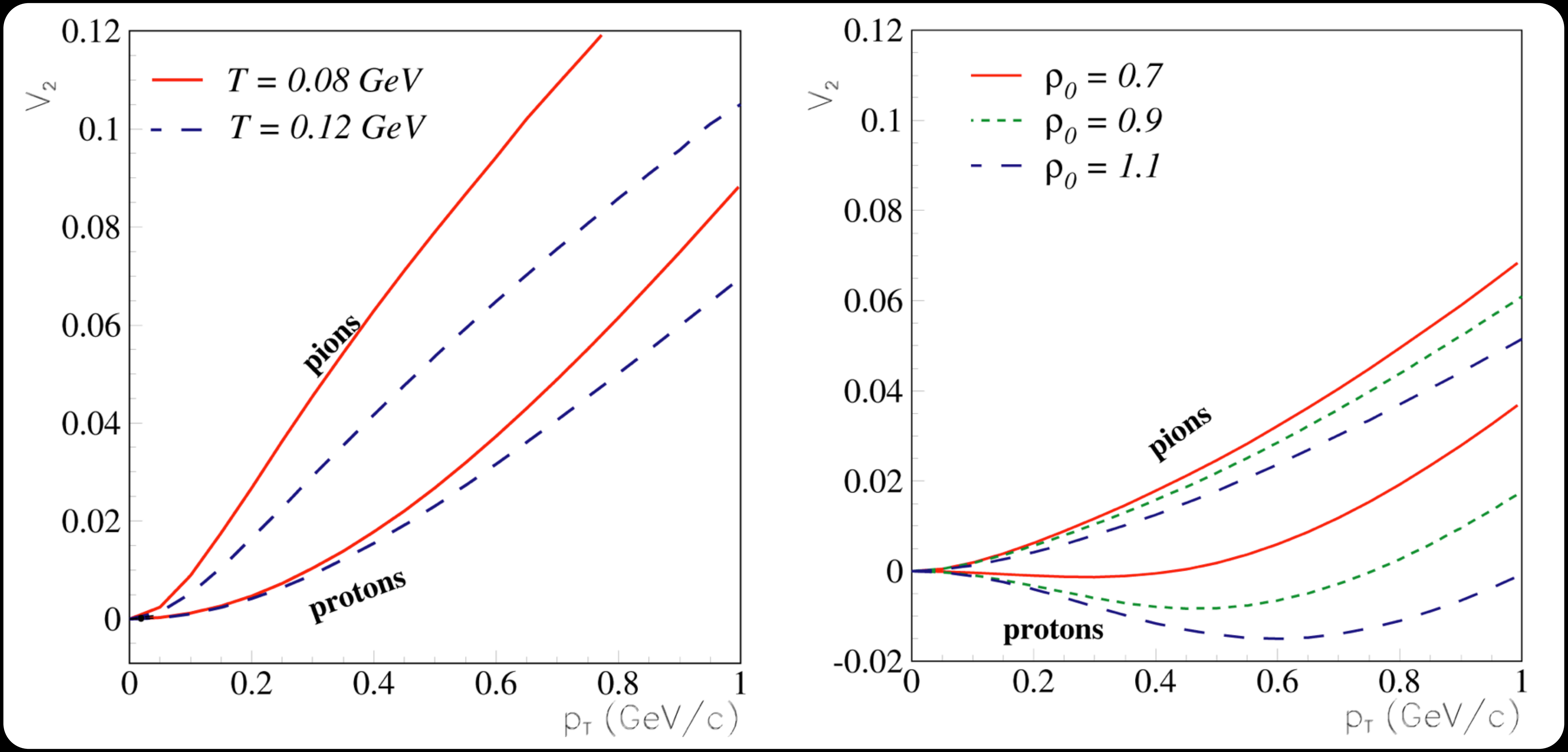
$$v_2(p_t) = \frac{\int_0^{2\pi} d\phi_b \cos(2\phi_b) I_2(\alpha_t) K_1(\beta_t)(1 + 2s_2 \cos(2\phi_b))}{\int_0^{2\pi} d\phi_b I_0(\alpha_t) K_1(\beta_t)(1 + 2s_2 \cos(2\phi_b))}$$

$$\alpha_t(\phi_b) = \left(\frac{p_t}{T_f}\right) \sinh(\rho(\phi_b)) \qquad \beta_t(\phi_b) = \left(\frac{m_t}{T_f}\right) \cosh(\rho(\phi_b))$$

$$\rho(\phi_b) = \rho_0 + \rho_a \cos(2\phi_b)$$

STAR Phys. Rev. Lett. 87, 182301 (2001)

The effect of freeze-out temperature and radial flow on v_2

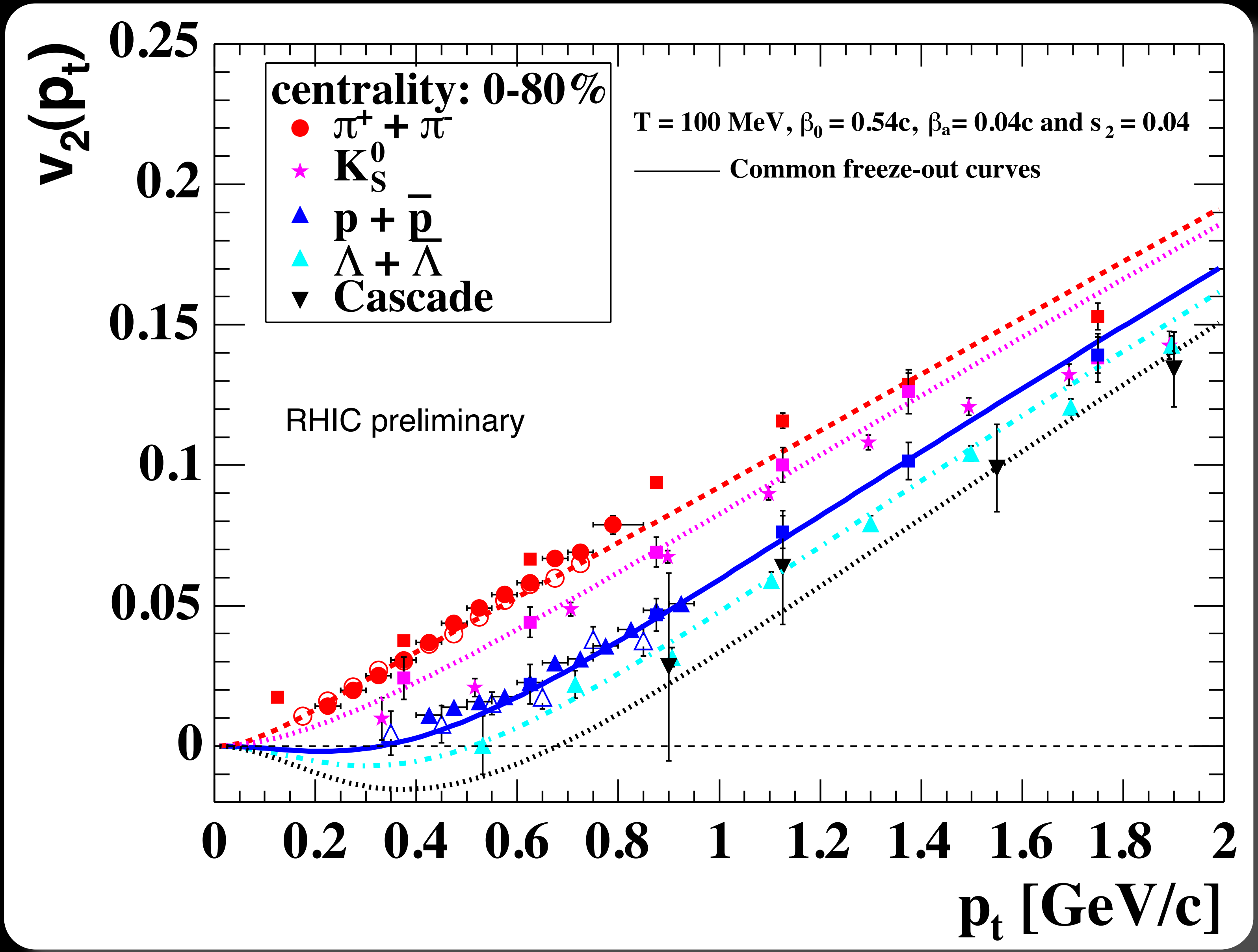


F. Retiere and M.A. Lisa, Phys.Rev.C70:044907,2004

- light particle $v_2(p_t)$ very sensitive to temperature
- heavier particles $v_2(p_t)$ more sensitive to transverse flow

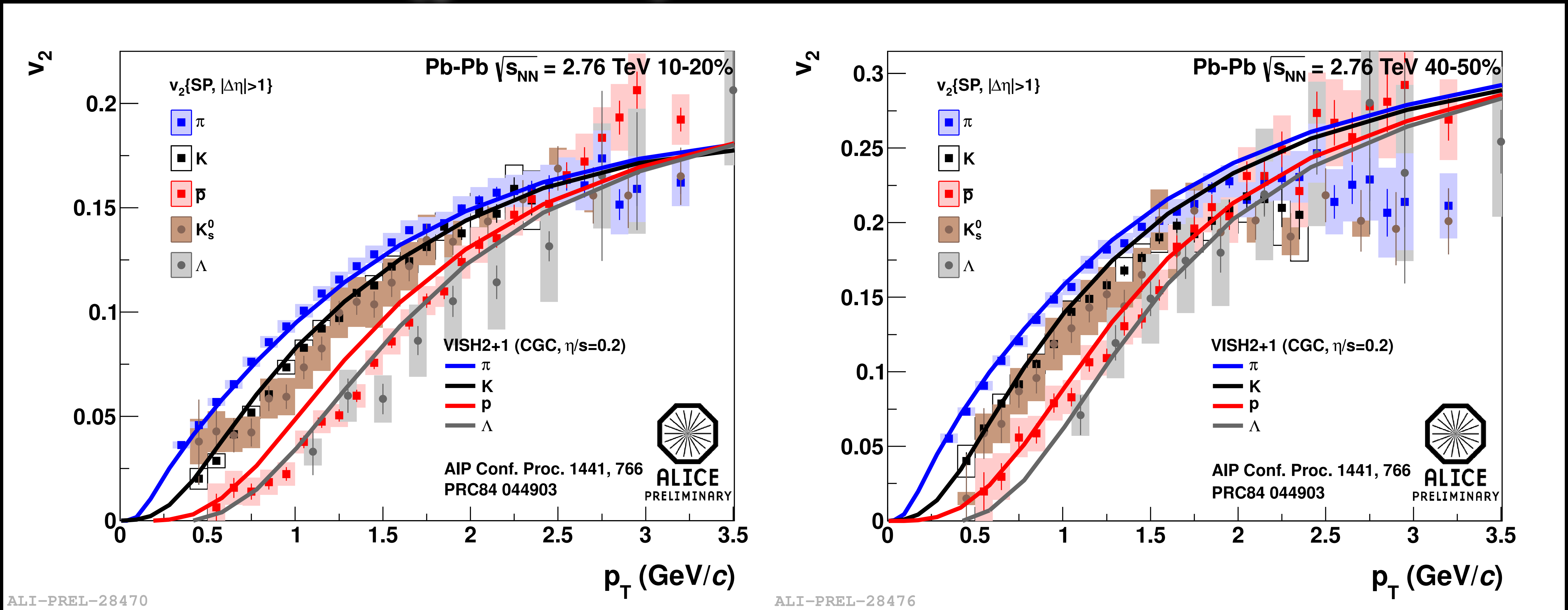
boosted thermal spectra

the observed particles are characterized by a single freeze-out temperature and a common azimuthal dependent boost velocity



Fits from STAR Phys. Rev. Lett. 87, 182301 (2001)

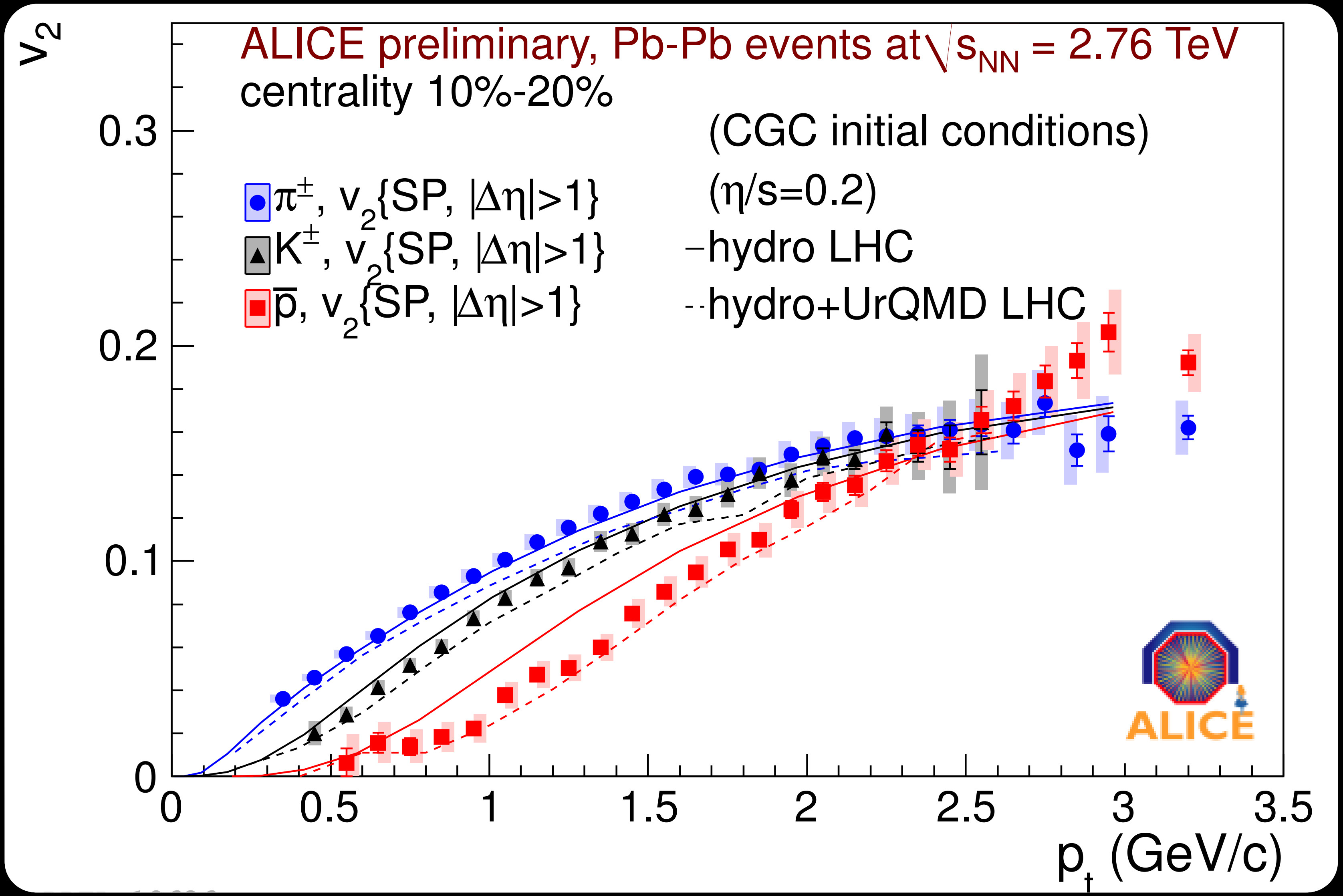
v_2 (p_t,m) at the LHC



see talk F. Noferini

Stronger radial flow but pure hydro calculations do not describe well the most central collisions

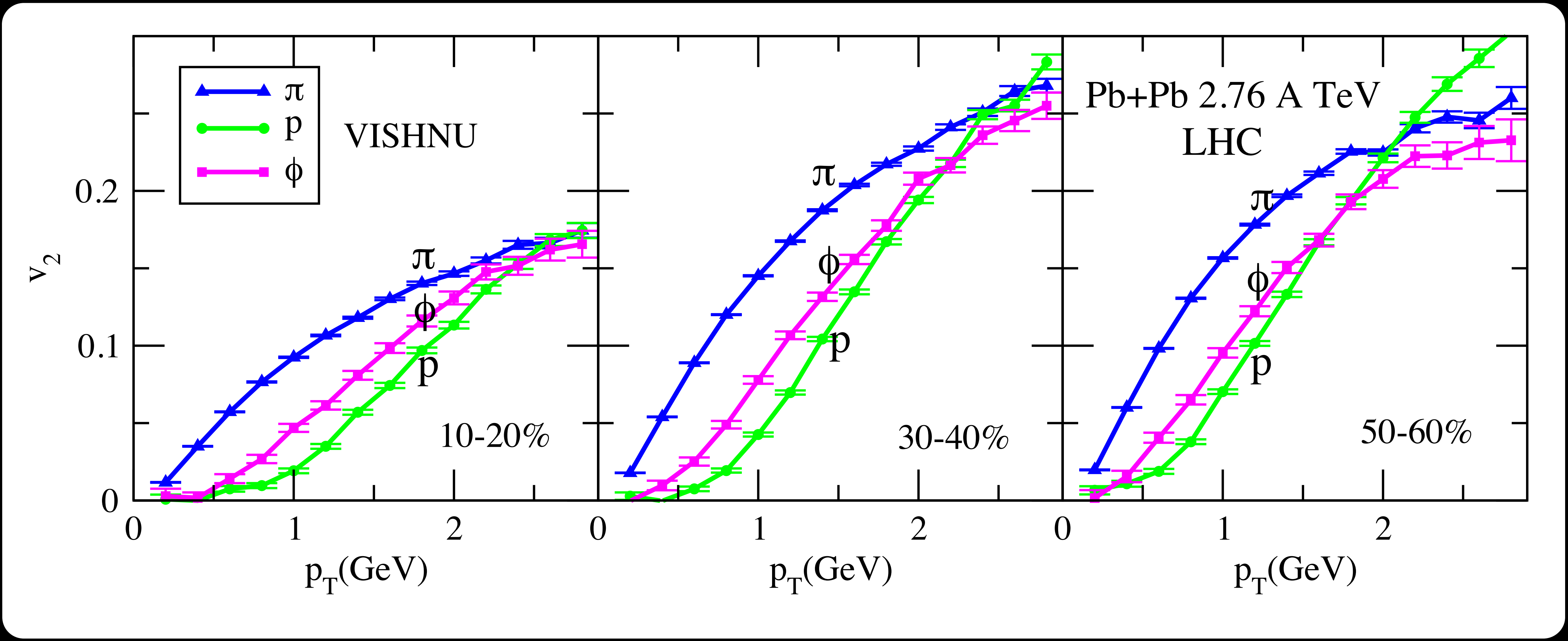
v_2 (p_t,m) at the LHC



Radial flow build up in the hadronic phase has to be taken into account, models have to be more sophisticated

v_2 (p_t,m) at the LHC

Song, Bass and Heinz: arXiv:1311.0157



phi meson ideal probe of hadronic phase contribution
(assuming interaction cross sections are known)

initial conditions

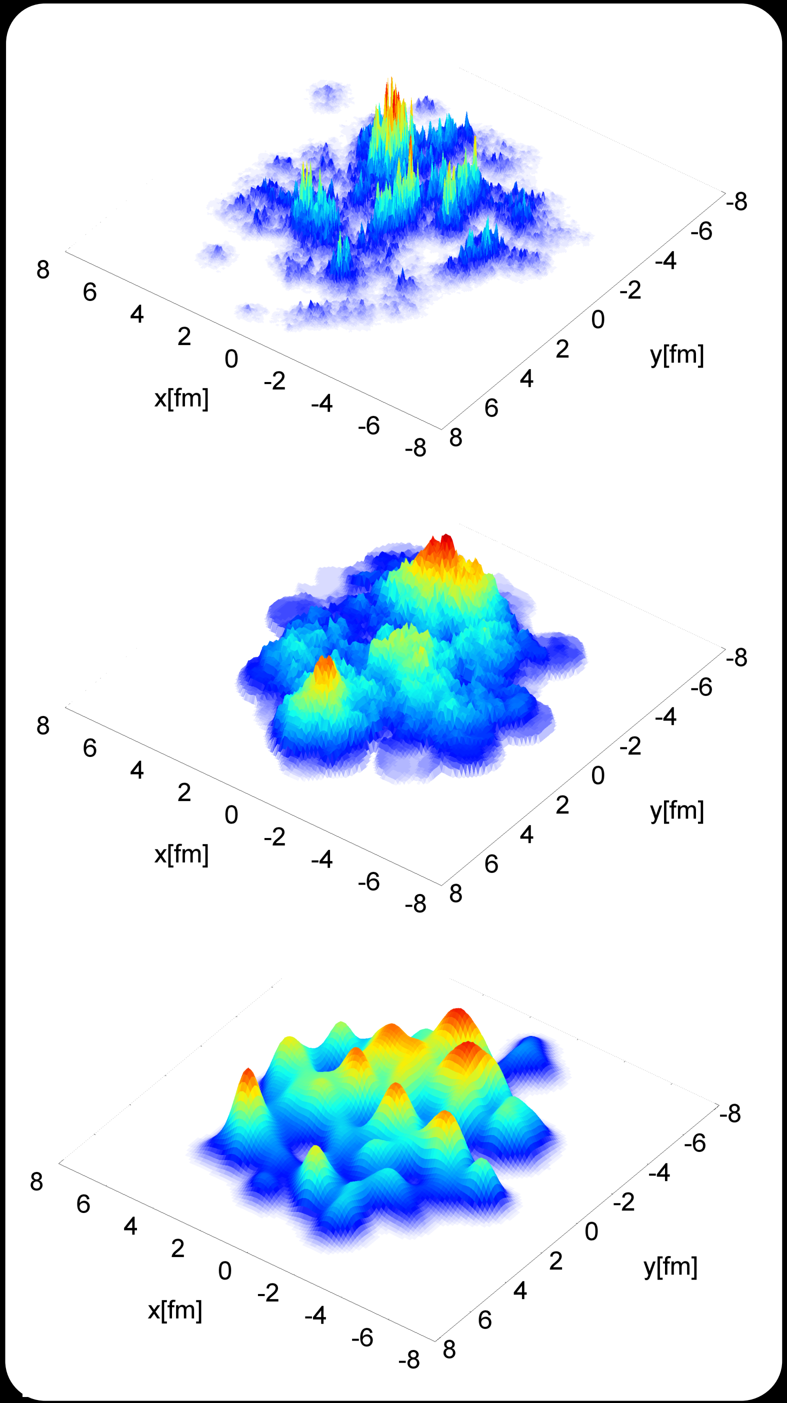
IP-Glasma

gluons + fluctuations

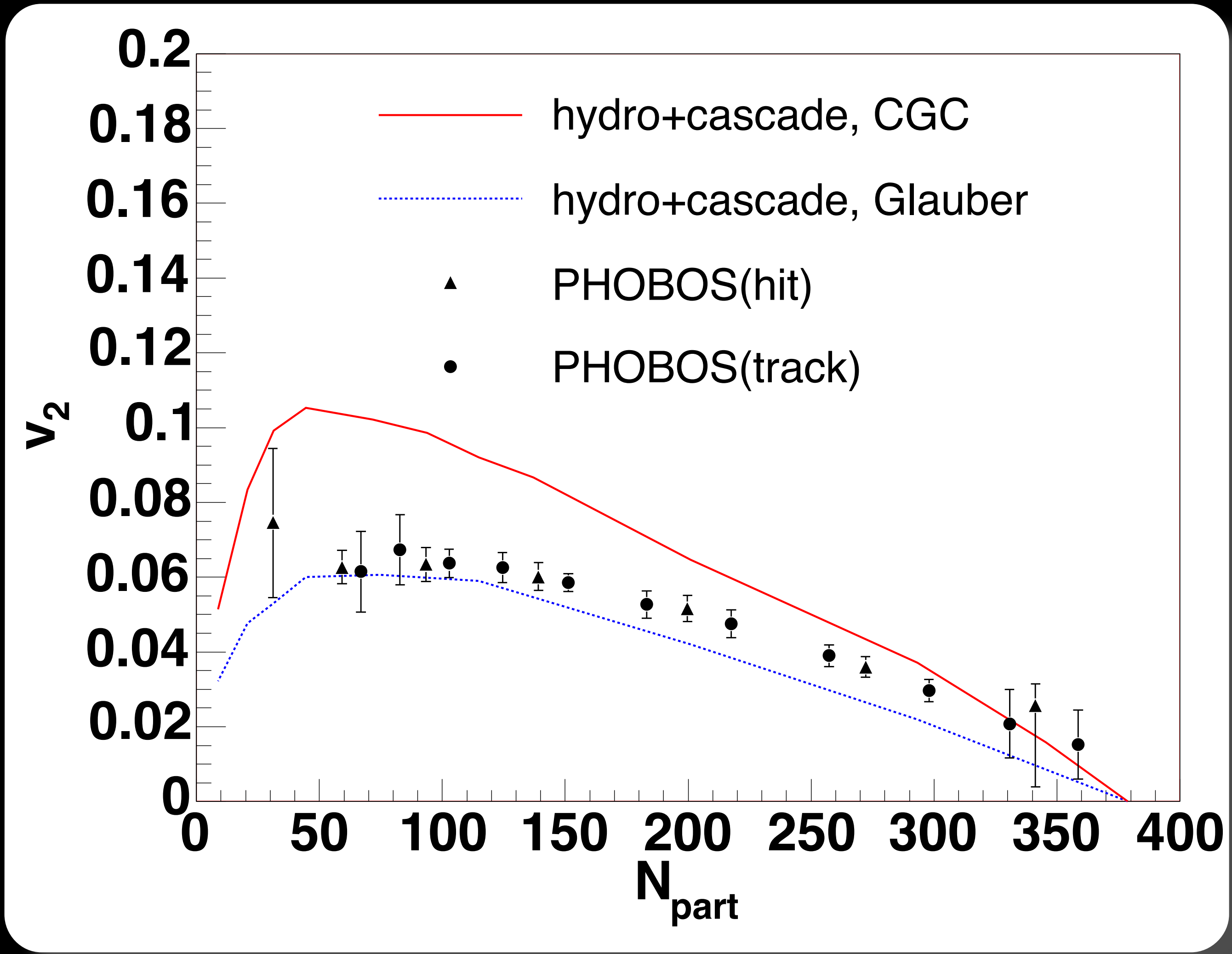
MC-KLN

gluons

MC-Glauber



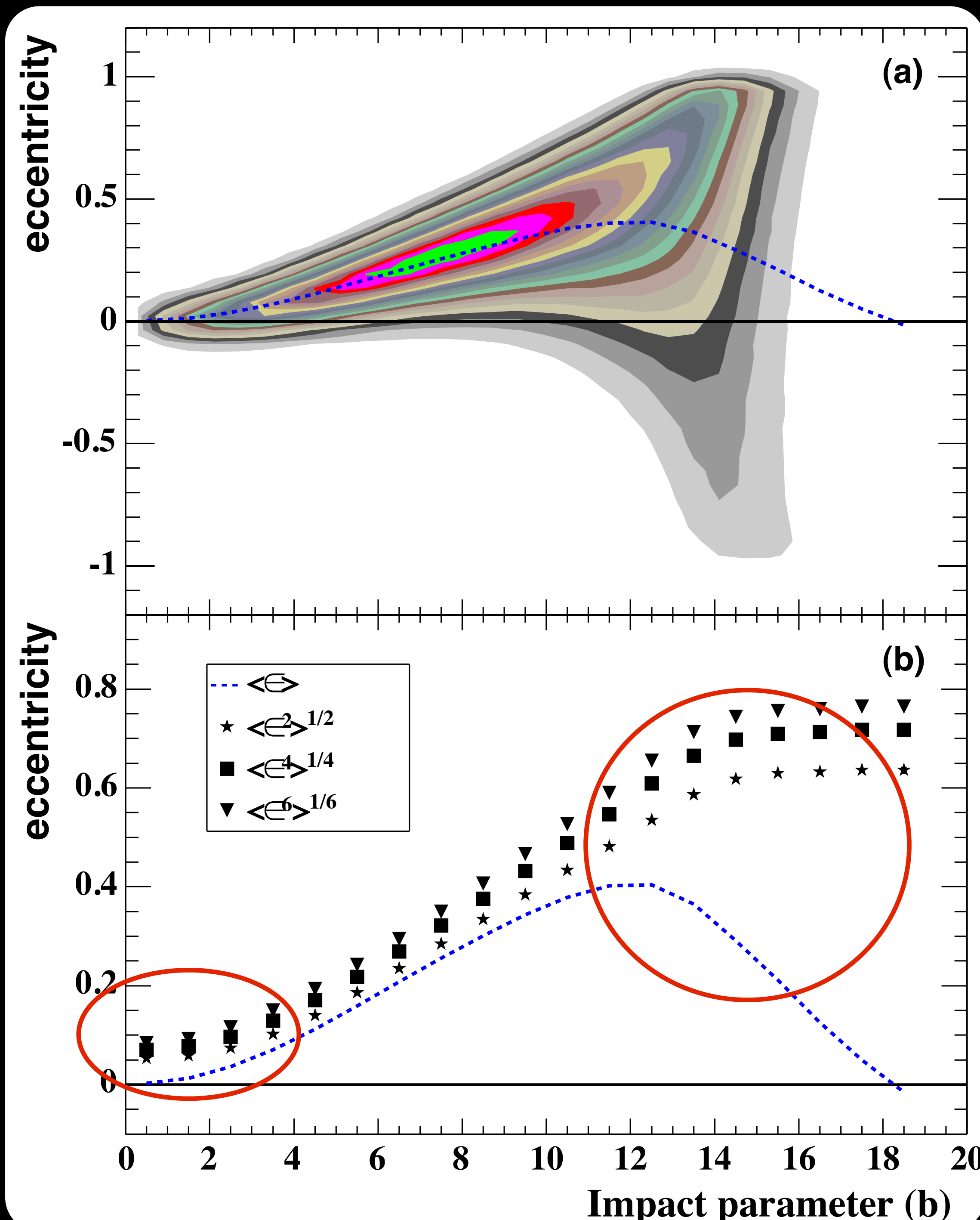
$$v_2 \propto \varepsilon$$



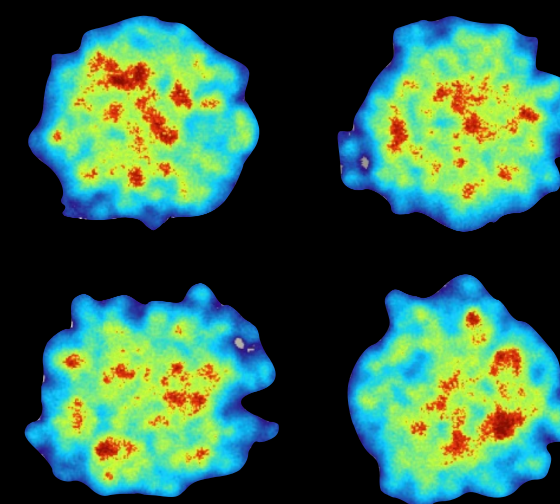
T. Hirano et al., Phys. Lett. B 636 299 (2006)
T. Hirano et al., J.Phys.G34:S879-882,2007

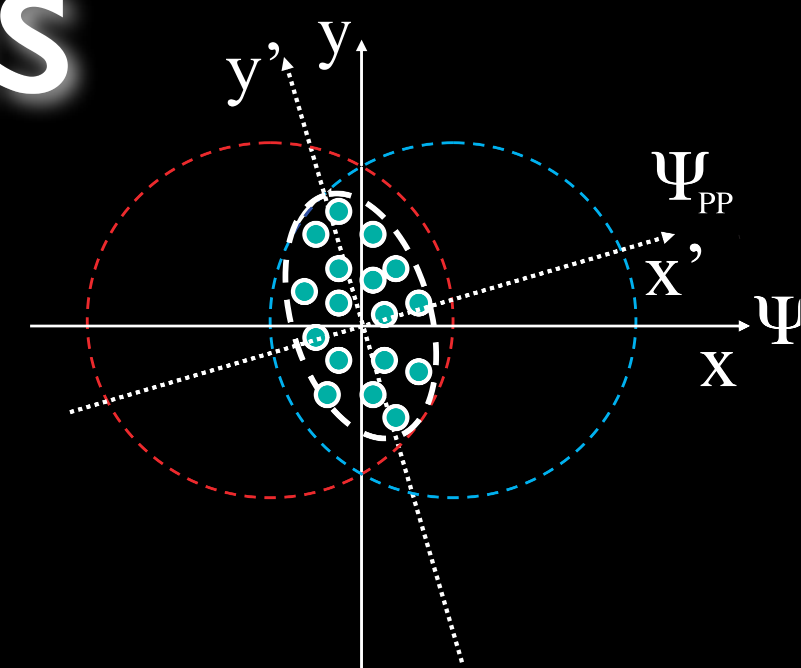
limit on how "non-ideal" the system is allowed to be depends on our understanding of the initial conditions!

v_2 fluctuations



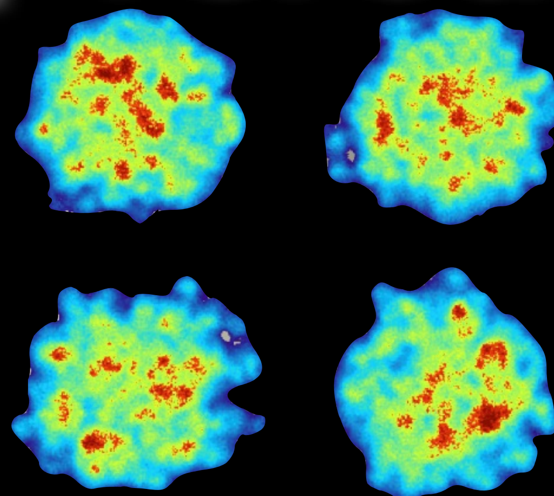
M. Miller and RS, arXiv:nucl-ex/0312008





- measured: $v_2\{2\} = \sqrt{(\langle v_2 \rangle^2 + \sigma_v^2 + \delta)}$
- using: $v_2 \propto \varepsilon$
- If the eccentricity fluctuates
$$\langle \varepsilon^2 \rangle - \langle \varepsilon \rangle^2 \neq 0$$
$$\langle v_2 \rangle \neq \sqrt{\langle (v_2)^2 \rangle}$$
- fluctuations change v_2 estimate significantly!

v_2 versus centrality in ALICE

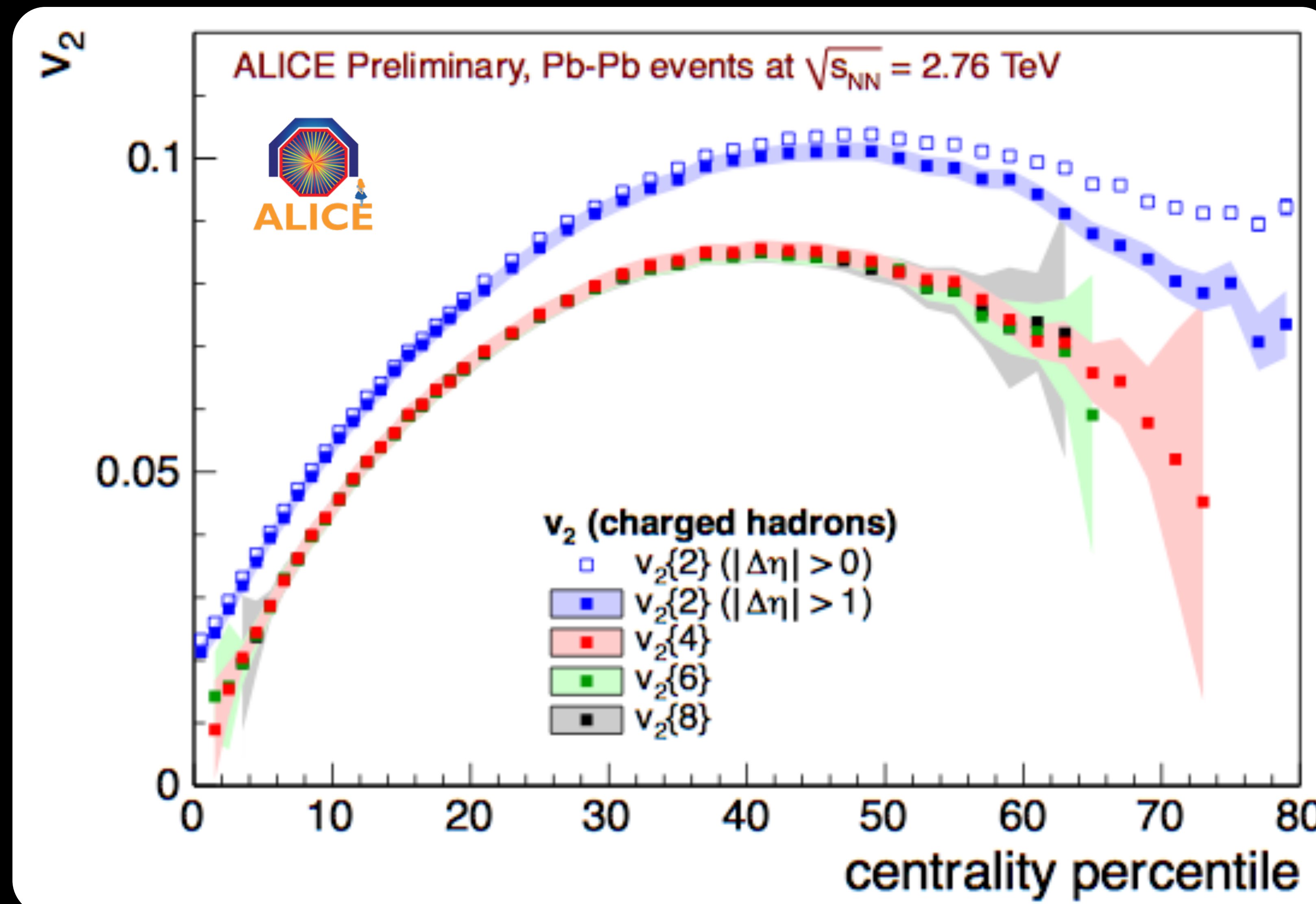


$$v\{2\} = \langle v\rangle + \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle}$$

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

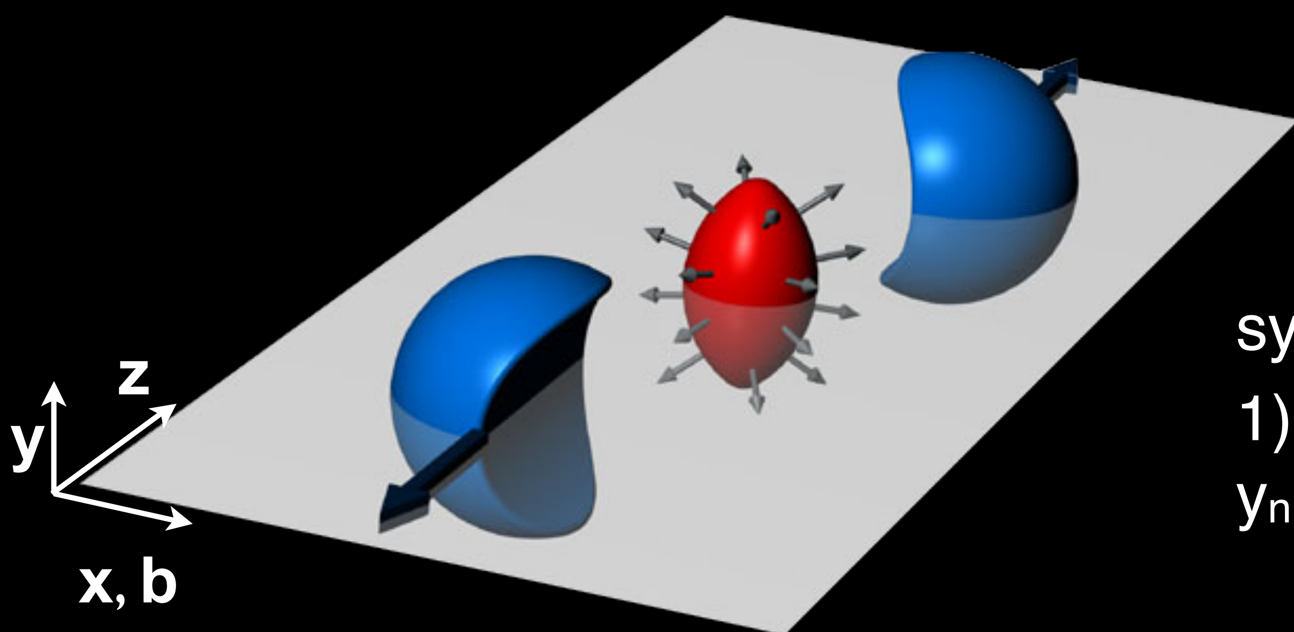
$$v\{6\} = \langle v\rangle - \frac{1}{2}\frac{\sigma_v^2}{\langle v\rangle}$$

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



Clear separation between $v_2\{2\}$ and higher order cumulants
Higher order cumulant v_2 estimates are consistent within uncertainties

Azimuthal distributions



$$r(\varphi) = \frac{x_0}{2\pi} + \frac{1}{\pi}\sum_{n=1}^{\infty}[x_n \cos(n\varphi) + y_n \sin(n\varphi)]$$

symmetries reduce the number of parameters

1) particle yield at ϕ and -ϕ should be equal -> $y_n = 0$ (no sin terms)

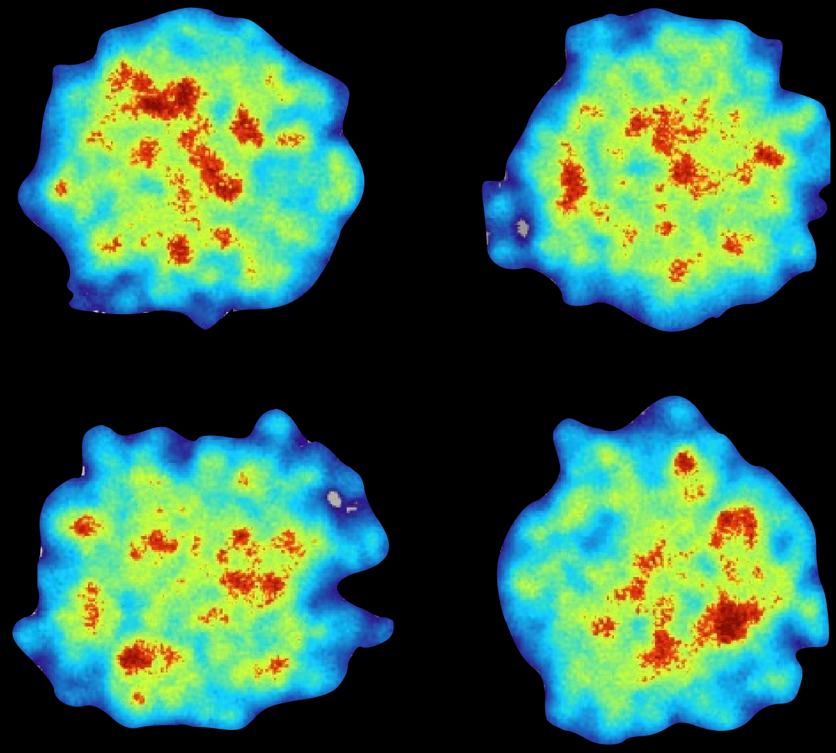
$$\frac{dN}{d\varphi} = \frac{1}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_R)]\right]$$

2) particle yield at ϕ and ϕ+π should be equal -> cos(nϕ) = 0 for odd n

only even harmonics at mid-rapidity, v_2, v_4, v_6, etc

$$v_n = \langle \cos[n(\varphi - \Psi_R)] \rangle$$

Azimuthal distributions



$$r(\varphi) = \frac{x_0}{2\pi} + \frac{1}{\pi}\sum_{n=1}^{\infty}[x_n\cos(n\varphi) + y_n\sin(n\varphi)]$$

in general can be written as:

$$r(\varphi) = \frac{v_0}{2\pi} + \frac{1}{\pi}\sum_{n=1}^{\infty}[v_n\cos(n\varphi - \Psi_n)]$$

all harmonics at mid-rapidity; v_1, v_2, v_3, v_4, v_5, v_6, etc

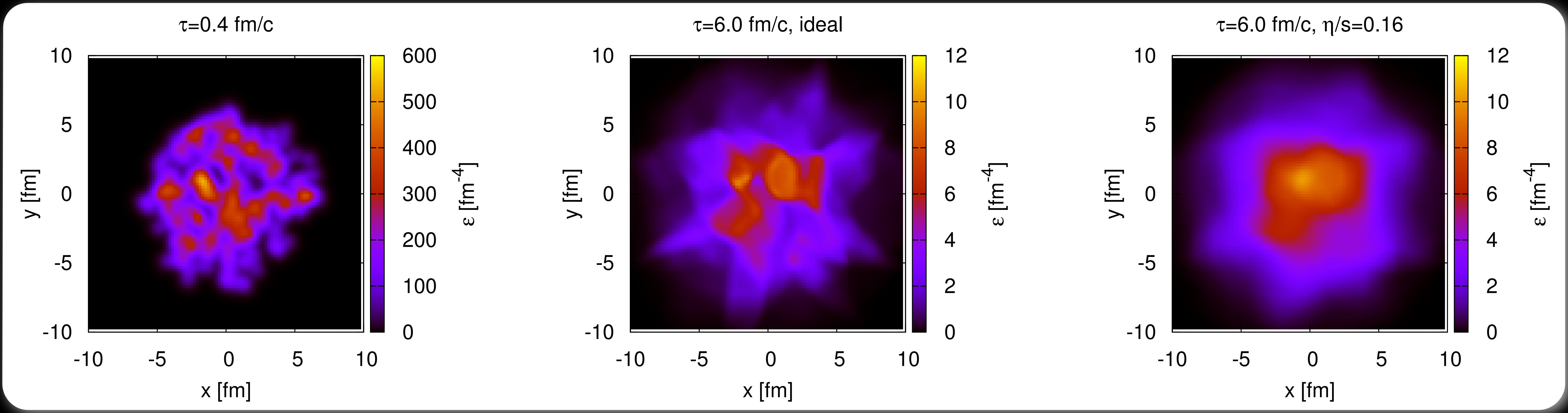
$$v_n = \langle\cos[n(\varphi - \Psi_n)]\rangle$$

in addition; ψ_1, ψ_2, ψ_3, ψ_4, ψ_5, ψ_6, etc

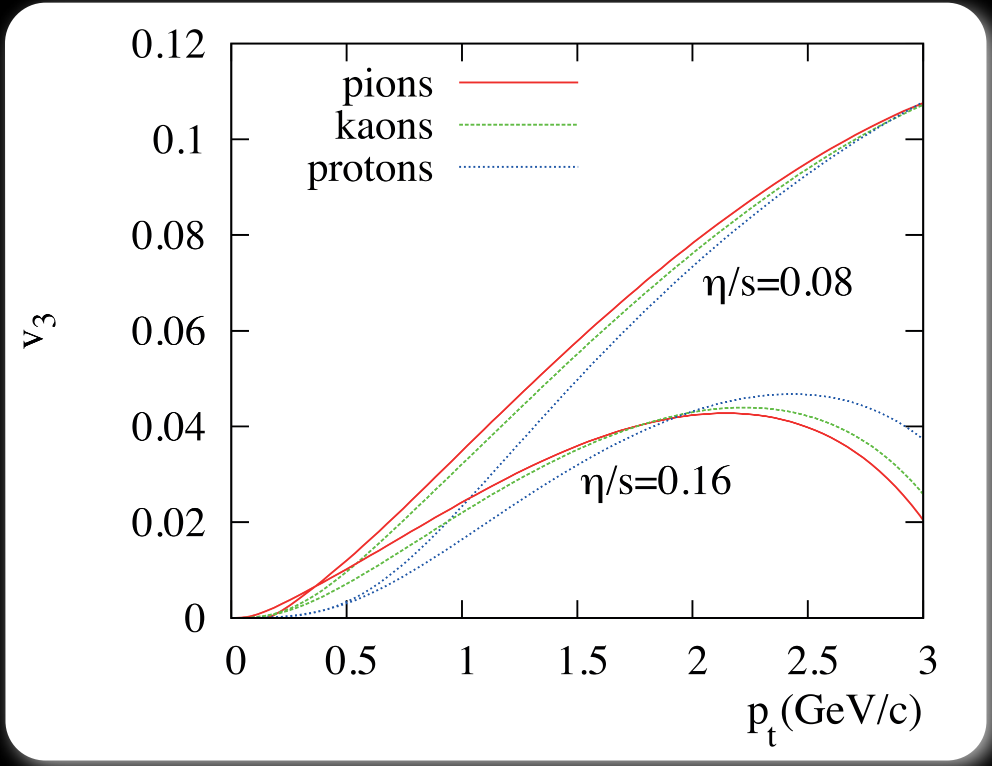
The higher harmonics and planes give detailed constraints on the initial conditions and shear viscosity of the system

shear viscosity

Music, Sangyong Jeon



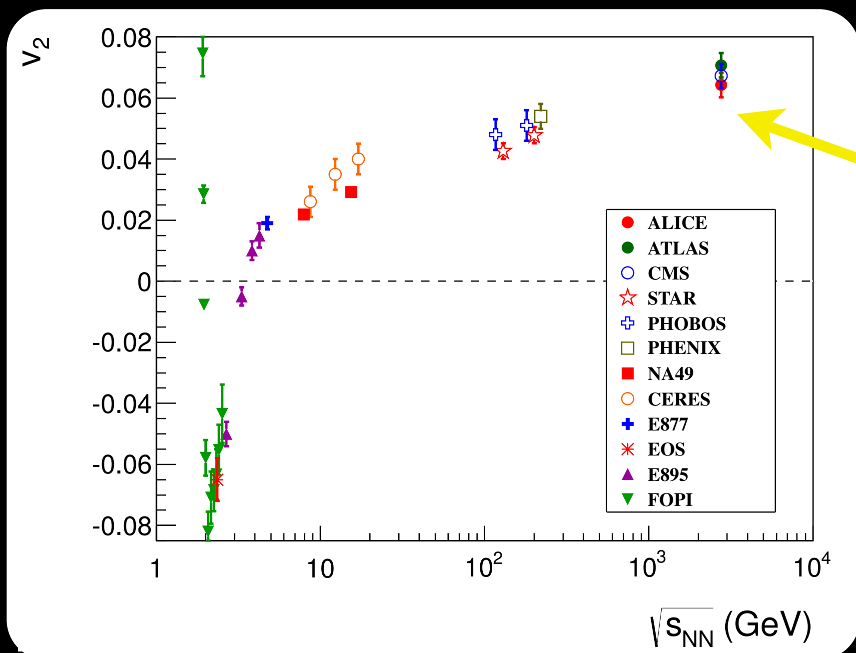
initial conditions ideal hydro η/s=0 viscous hydro η/s=0.16

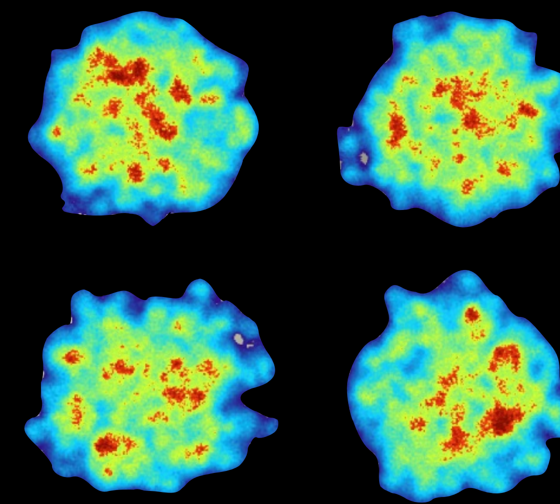


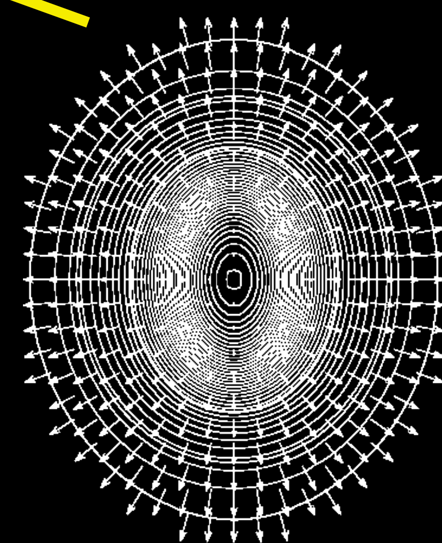
larger η/s clearly smoothes the distributions and suppresses the higher harmonics (e.g. v_3)

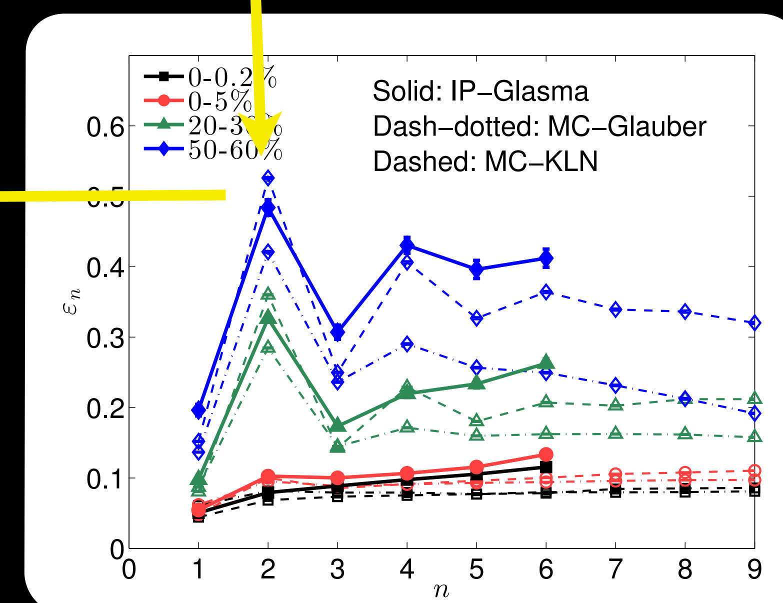
Hydro: Alver, Gombeaud, Luzum & Ollitrault, Phys. Rev. C82 (2010)

Fluctuating Initial Conditions



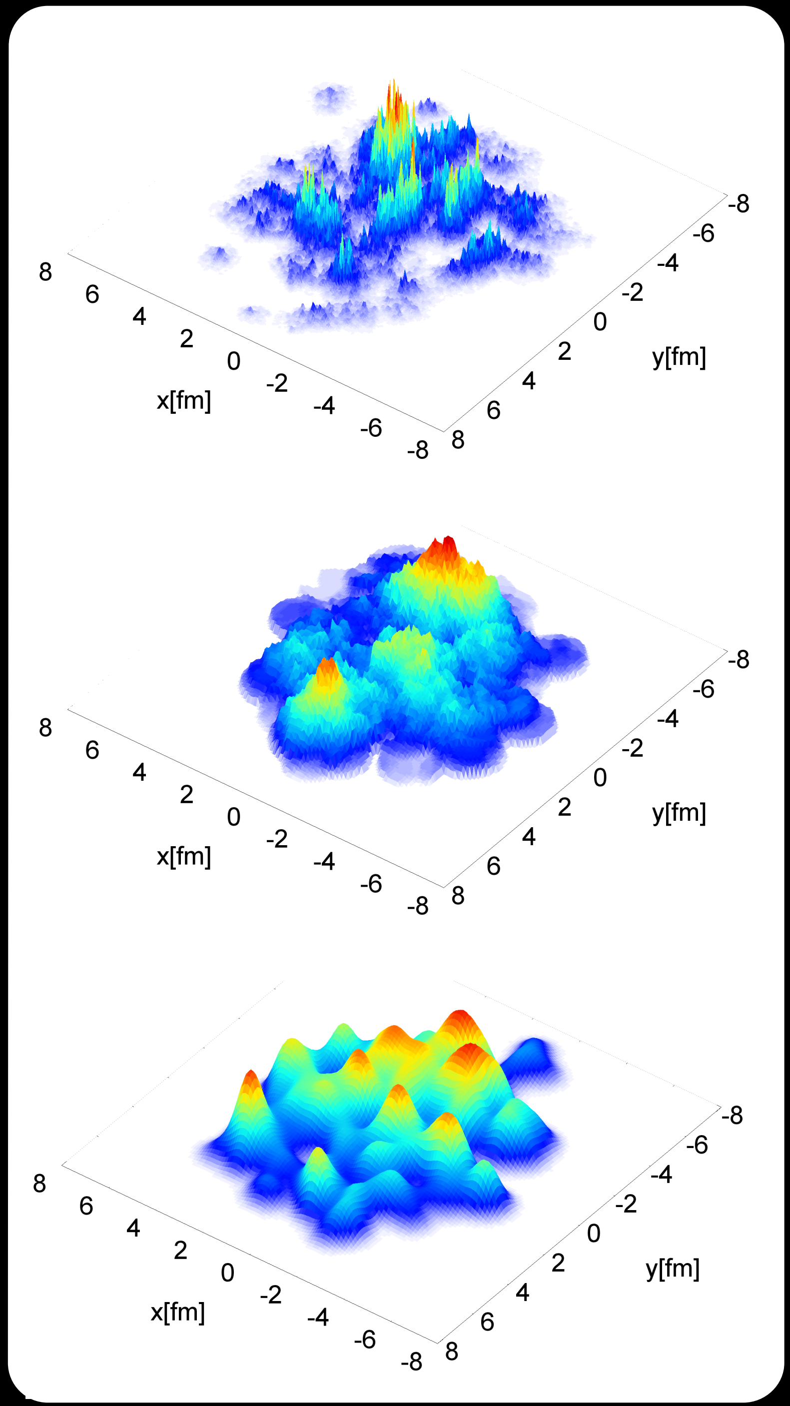


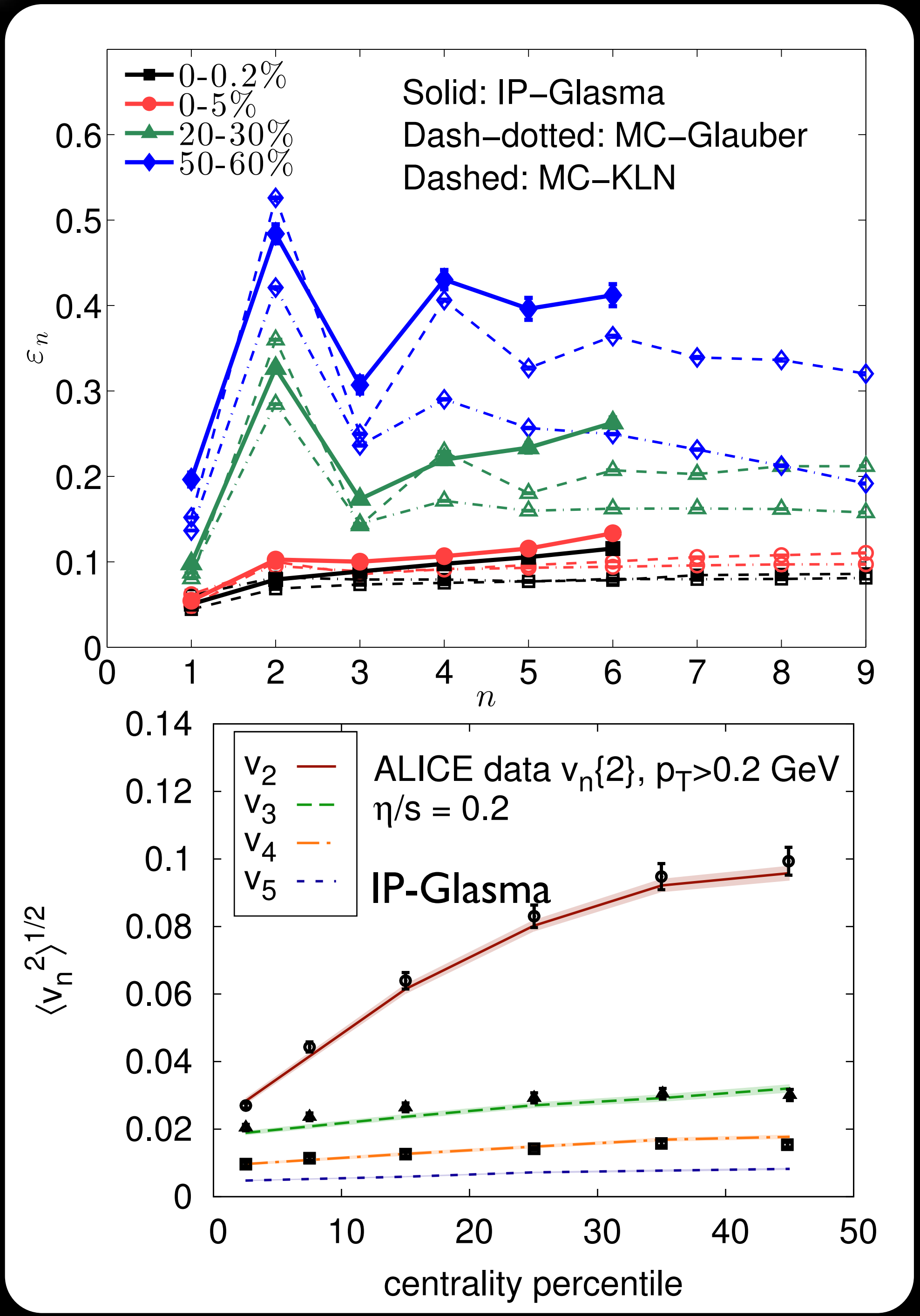




Fluctuating initial conditions generate power spectrum of harmonics which are different for different collision centralities.
Central collisions dominated by fluctuations resulting in a flat power spectrum
peripheral collisions dominated by the 2nd order coefficient.
Measurements of the power spectrum allows us to disentangle the various initial state models

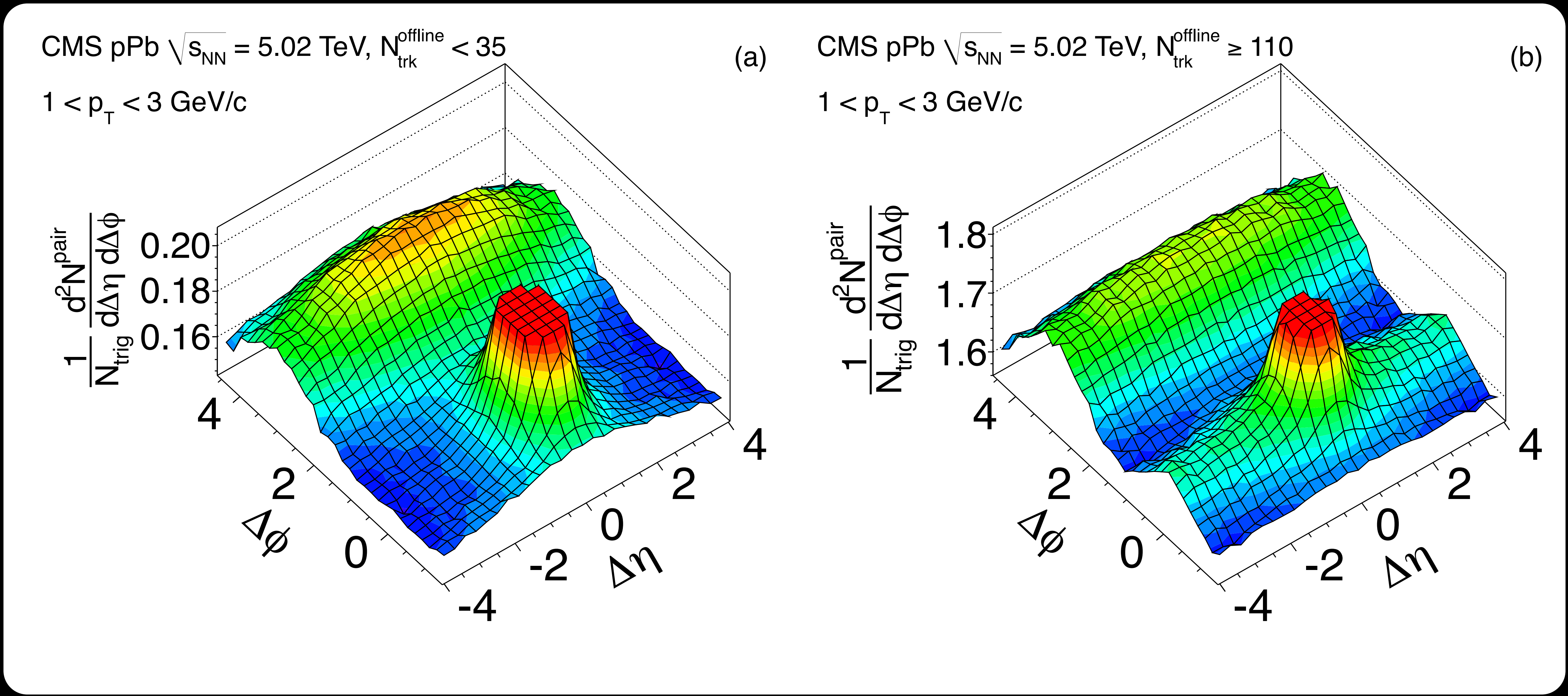
Power Spectrum





Currently only the IP-Glasma initial conditions provide a consistent description of the measurements

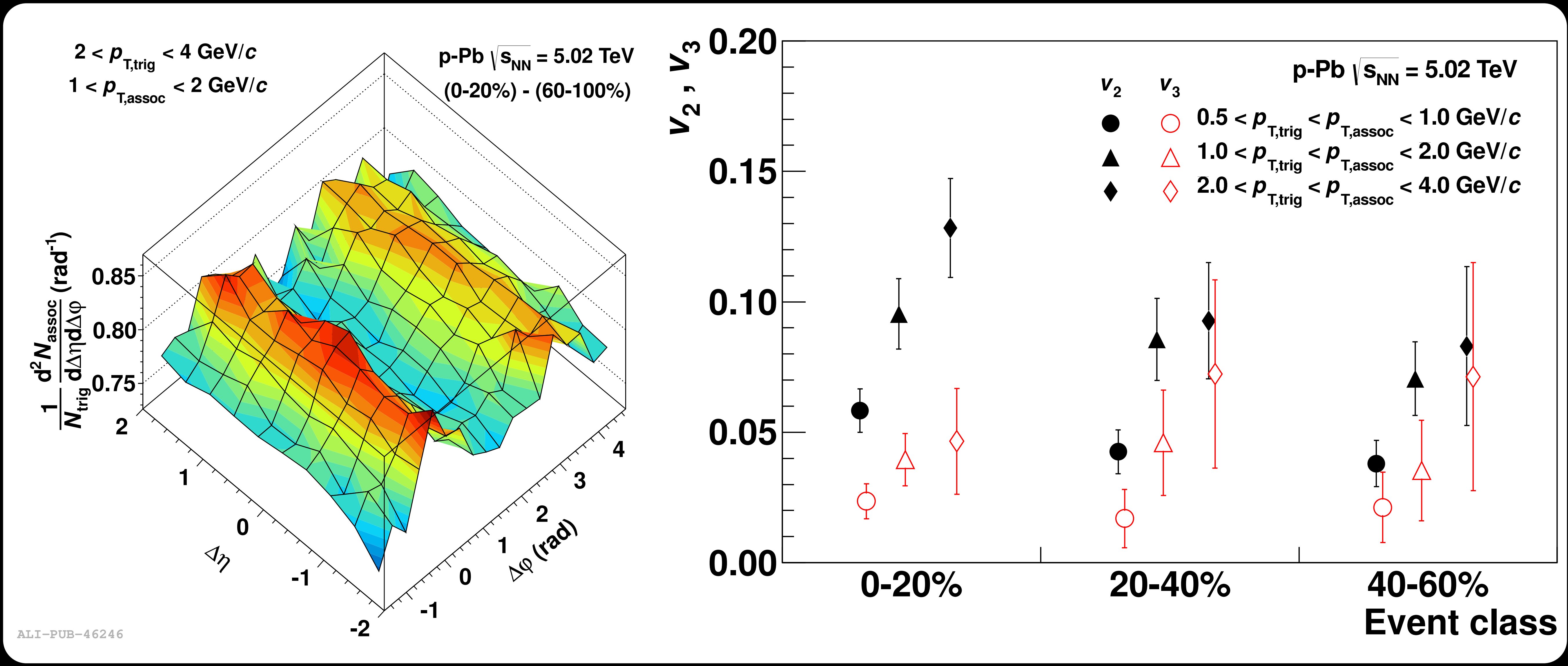
correlations pA



high-multiplicty pA collisions show in addition to the jet correlations also a ridge structure

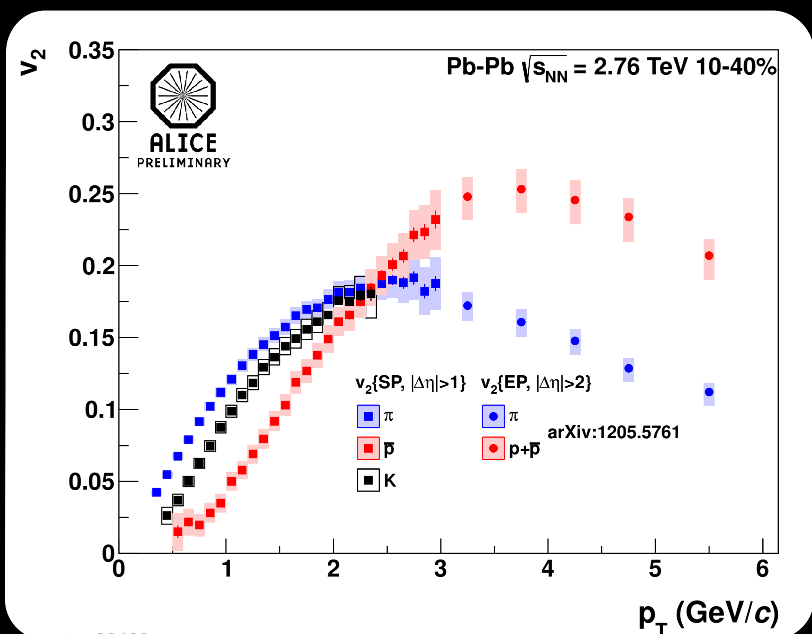
is this collective flow?

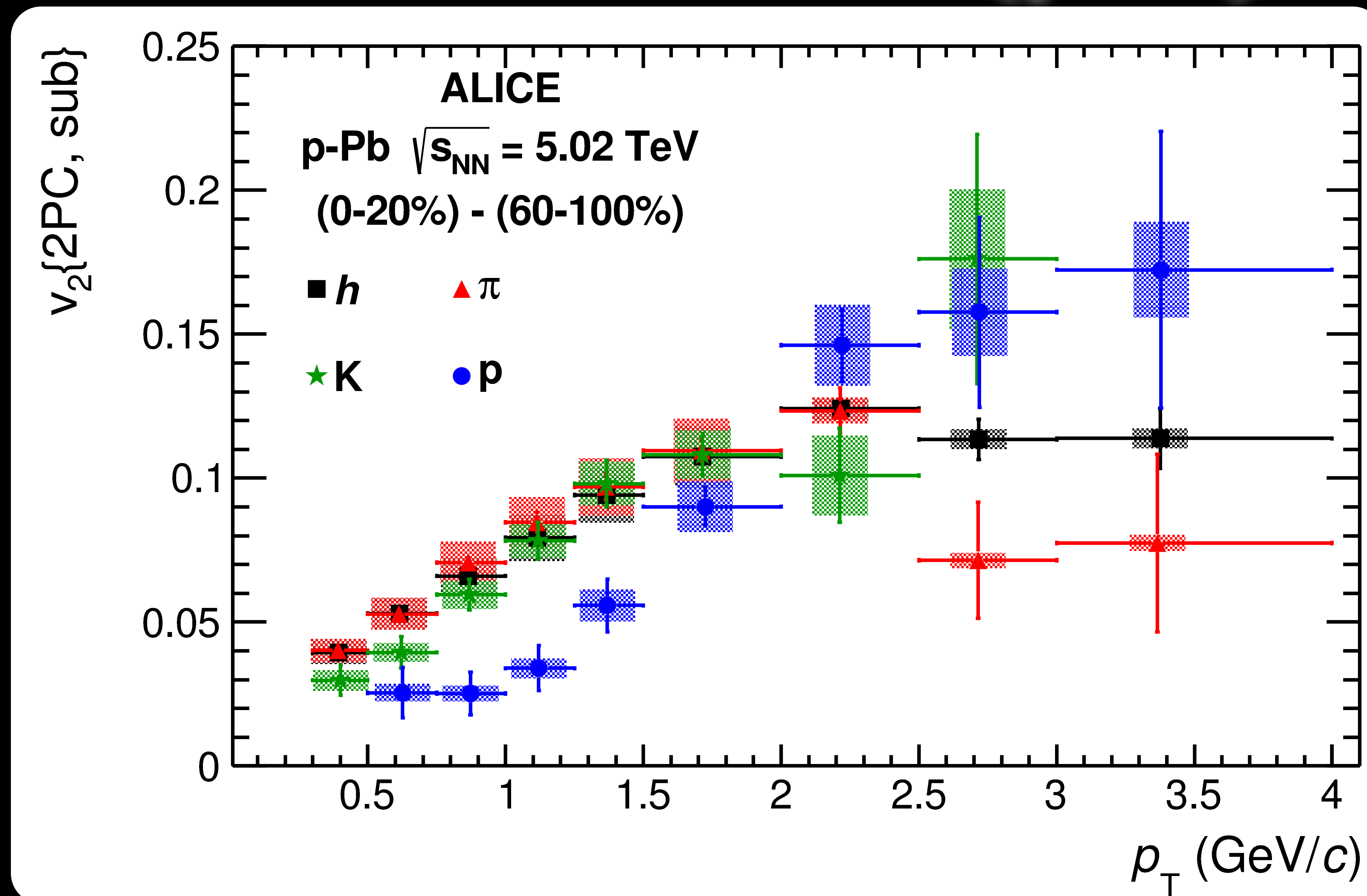
correlations



- large v_2 and v_3 components measured in pA collisions as well
- does it behave as collective flow?

Angular Correlations (pid)





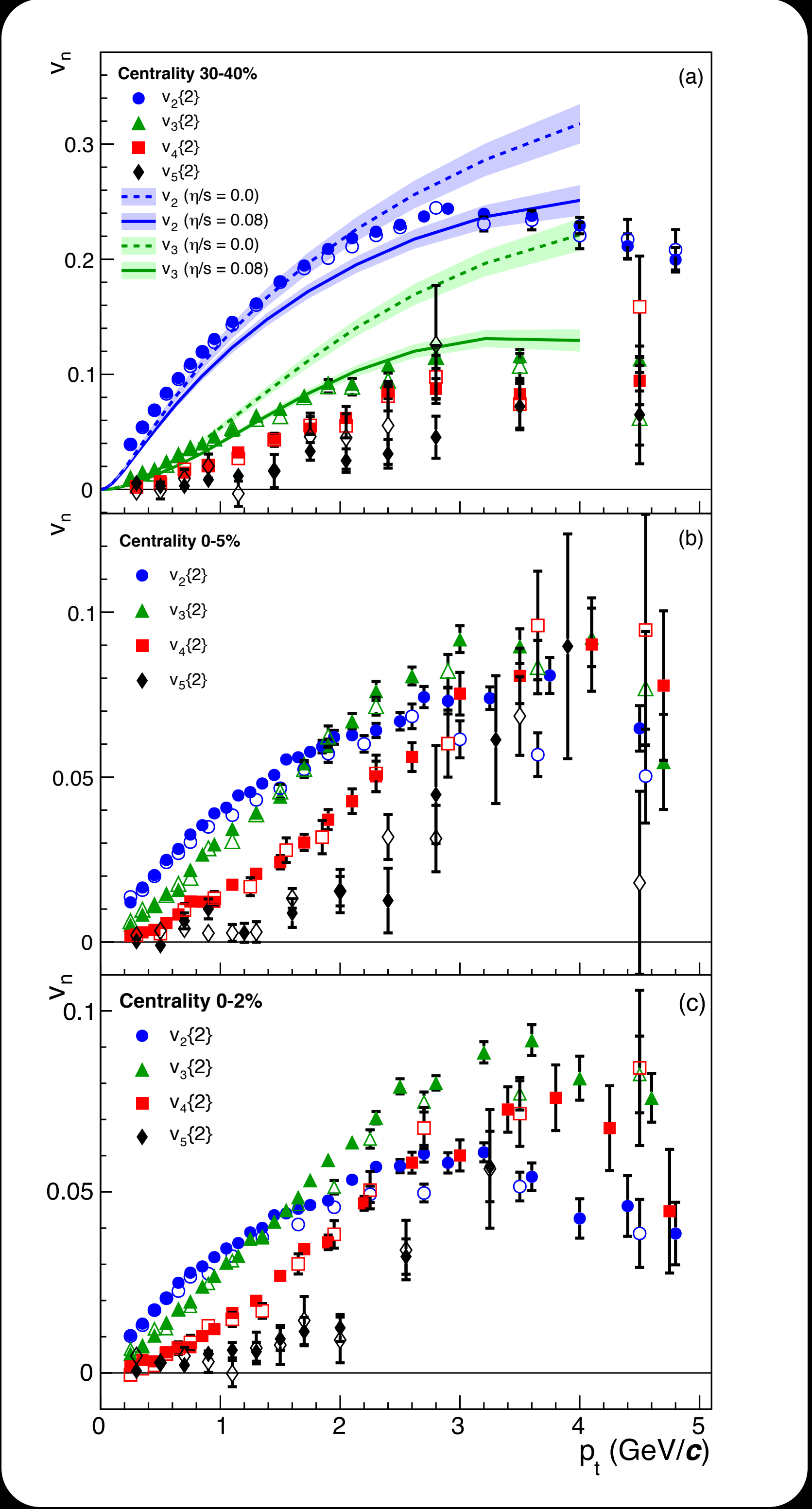
very similar trends as observed in AA collisions!

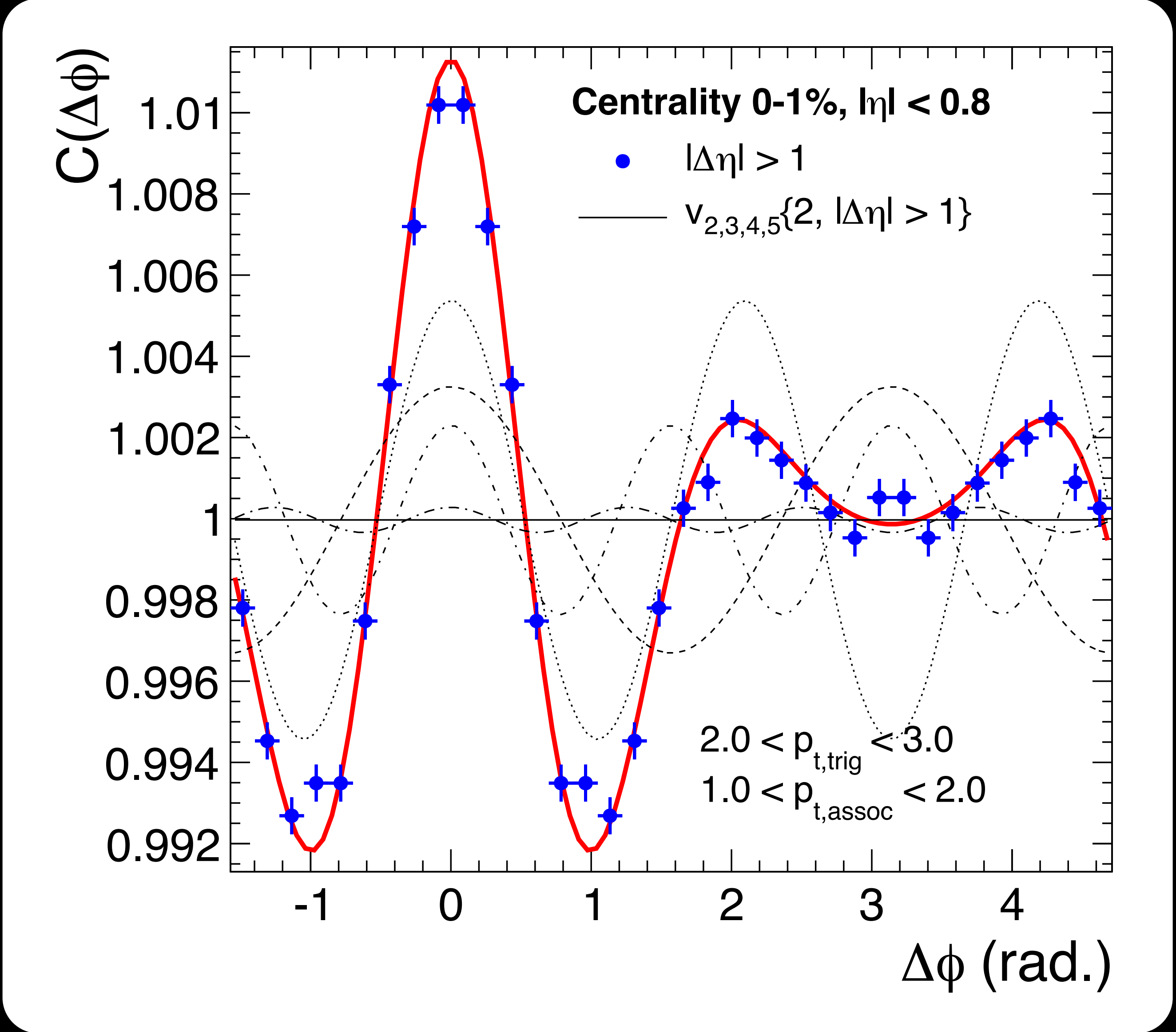
Summary

- Anisotropic Flow was studied over huge beam energy range were it was used to constrain EoS, transport coefficients and initial conditions
- clear connection to the geometry of the collision (and fluctuations in the initial geometry, provide strong constraints on initial state models)
- at high energies, in (rare) pp and pA collisions, "surprising" similarities with AA are observed (see for details following talks)
  - also final state effects? or initial state, e.g. CGC?
- pp and pA much more interesting than just "boring" reference for hard probes
  - geometrical picture in pp and pA theoretically rather unconstrained

Thanks

Angular Correlations





understood from initial eccentricities followed by a hydrodynamical evolution