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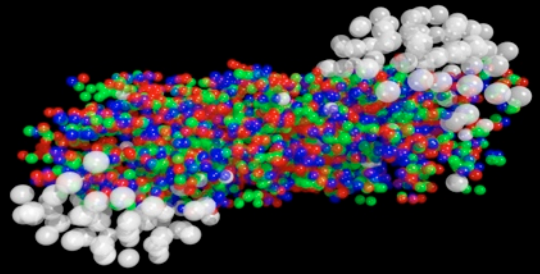


Heavy Ion Collisions II

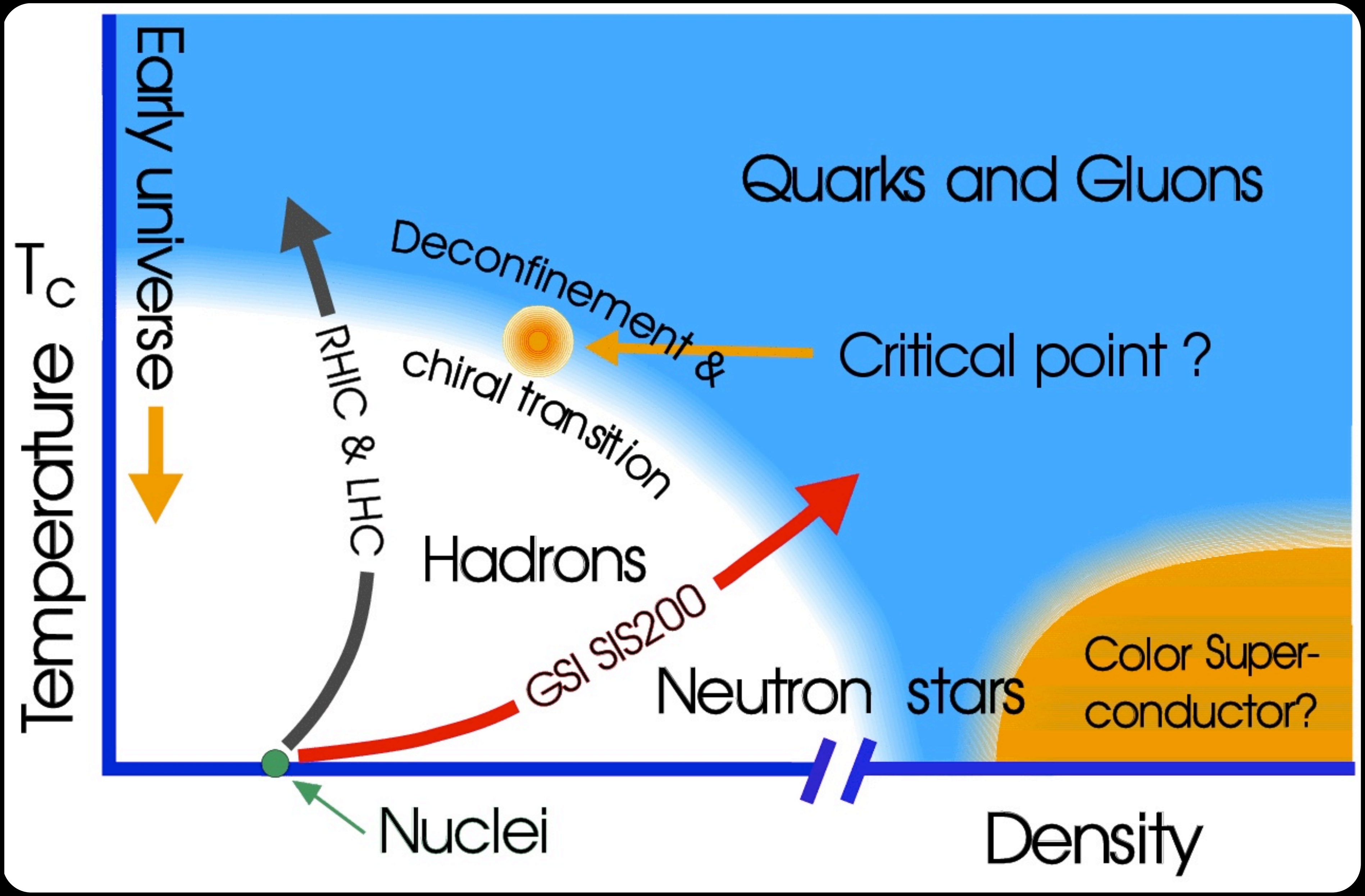
Student Lecture
Raimond Snellings

ICFP Kolymbari, Crete 2012

Content

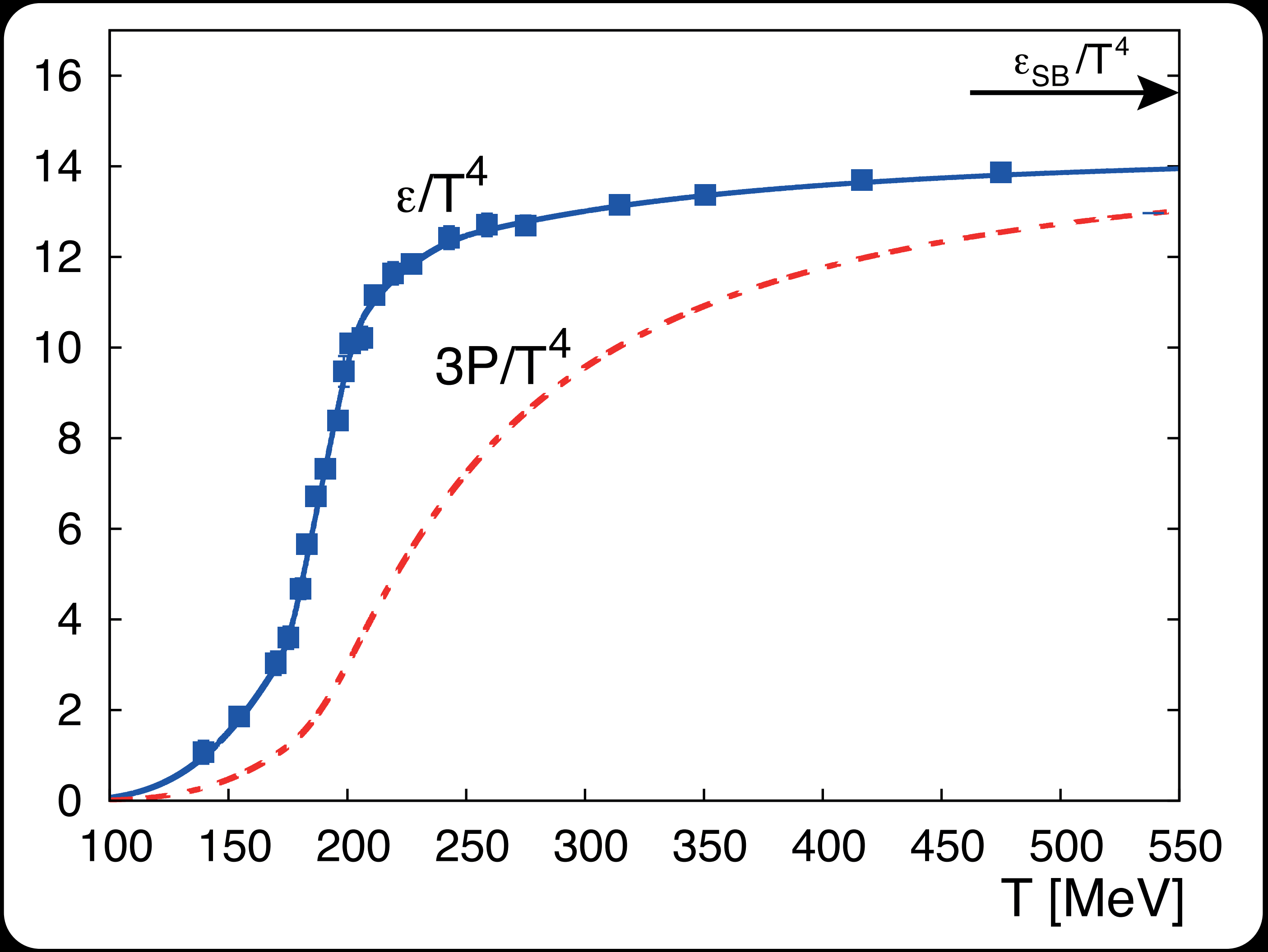
1) Why measure anisotropic flow?
2) How do we measure flow?
3) Current results on anisotropic flow

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



Based on Krishna Rajagopal and Frank Wilczek: Handbook of QCD

QCD on the Latice



T ~ 190 MeV, ε ~ 1 GeV/fm^3

at the critical temperature a strong increase in the degrees of freedom

✓ gluons, quarks & color!

not an ideal massless gas!

✓ what are the properties?

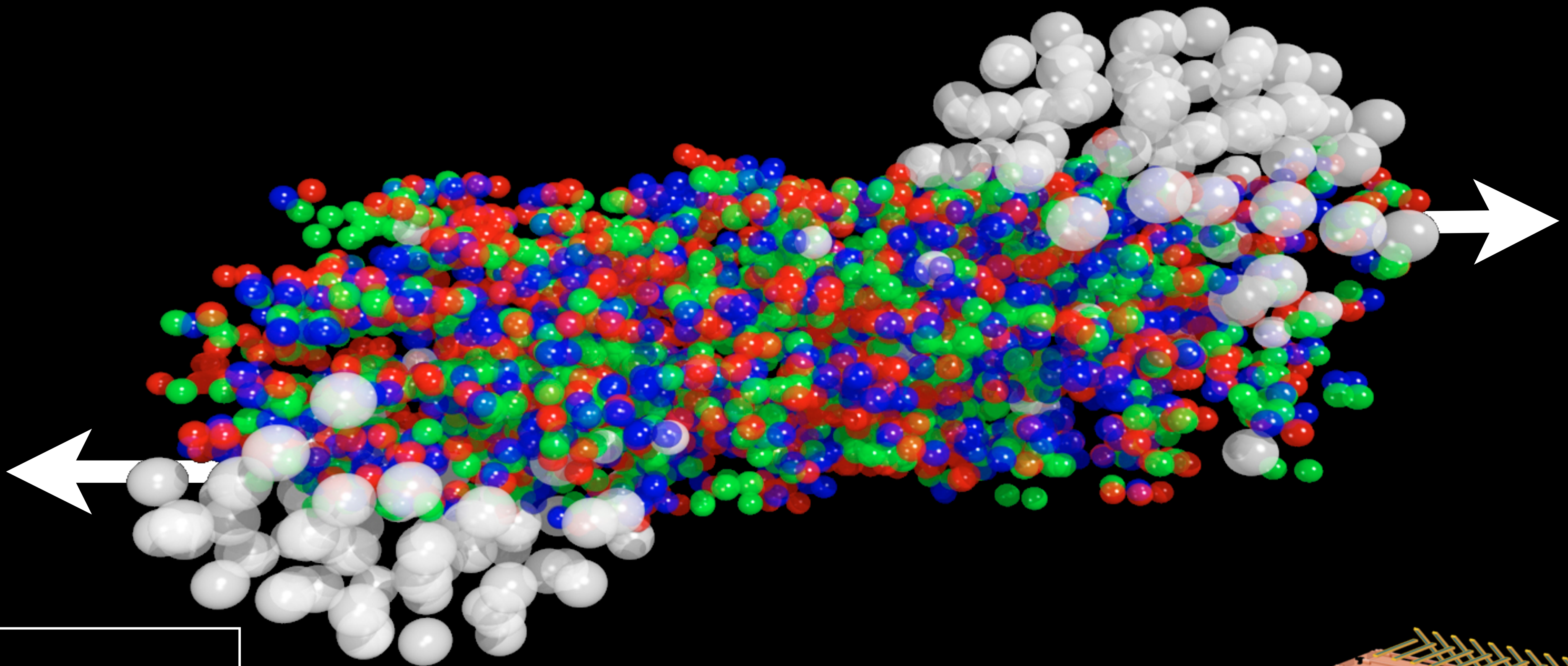
at the phase transition dp/dε decreases rapidly

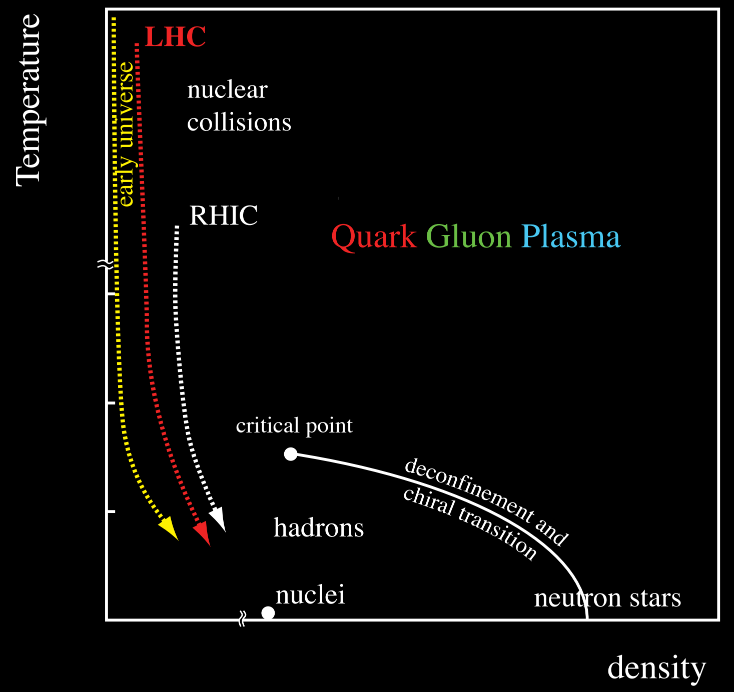
$$p = \frac{1}{3}\epsilon = g\frac{\pi^2}{90}T^4$$

$$g_{\mathrm{H}} \approx 3 \quad g_{\mathrm{QGP}} \approx 37$$

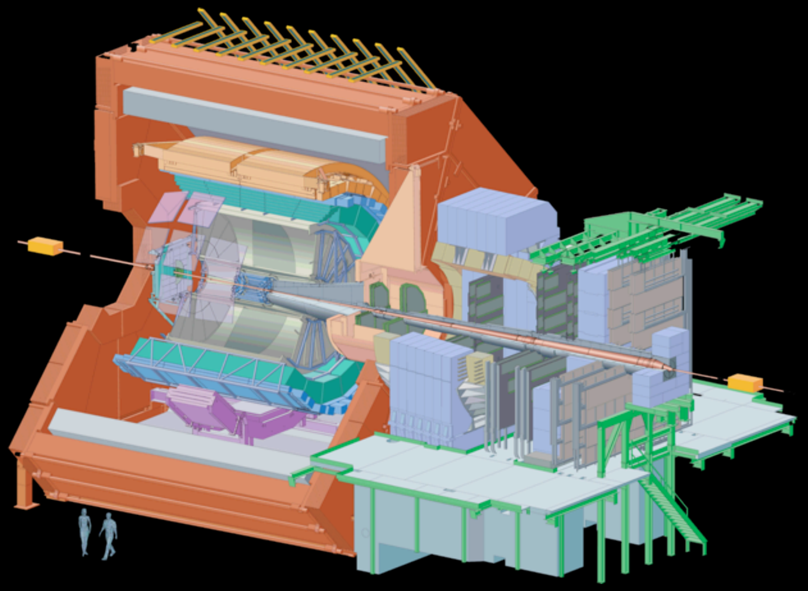
$$g = 2_{\mathrm{spin}} \times 8_{\mathrm{gluons}} + \frac{7}{8} \times 2_{\mathrm{flavors}} \times 2_{q\bar{q}} \times 2_{\mathrm{spin}} \times 3_{\mathrm{color}}$$

Experiment?

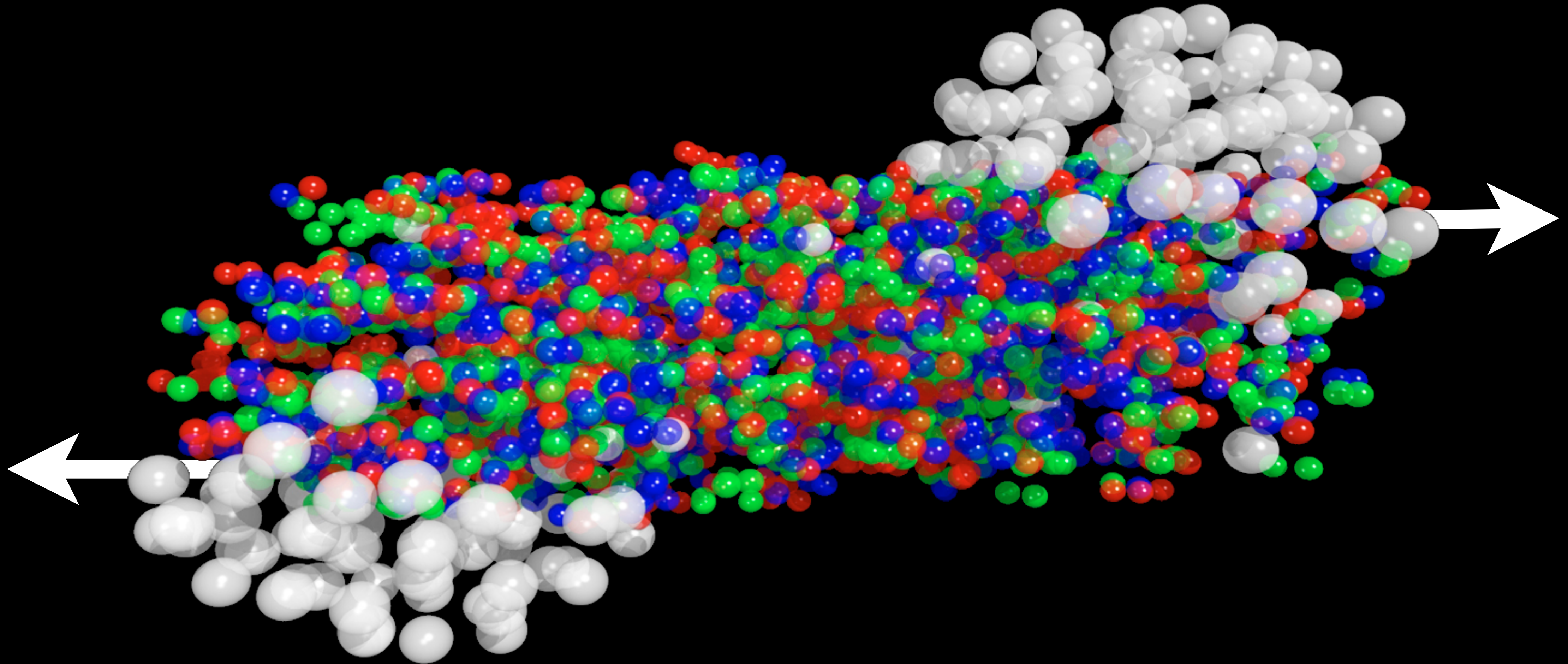




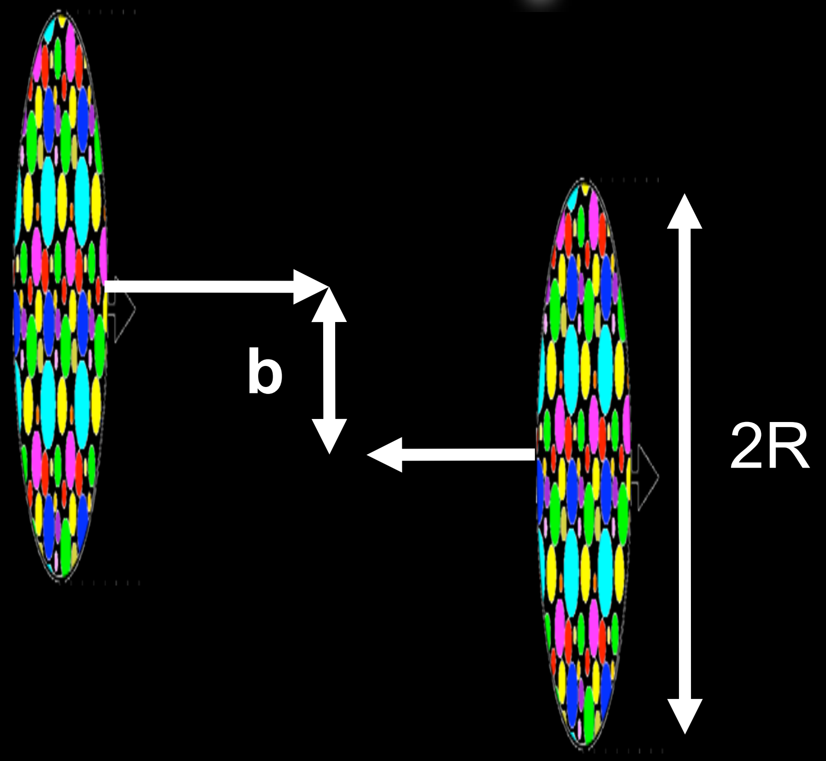
study phase transition in controlled lab conditions by colliding heavy-ions



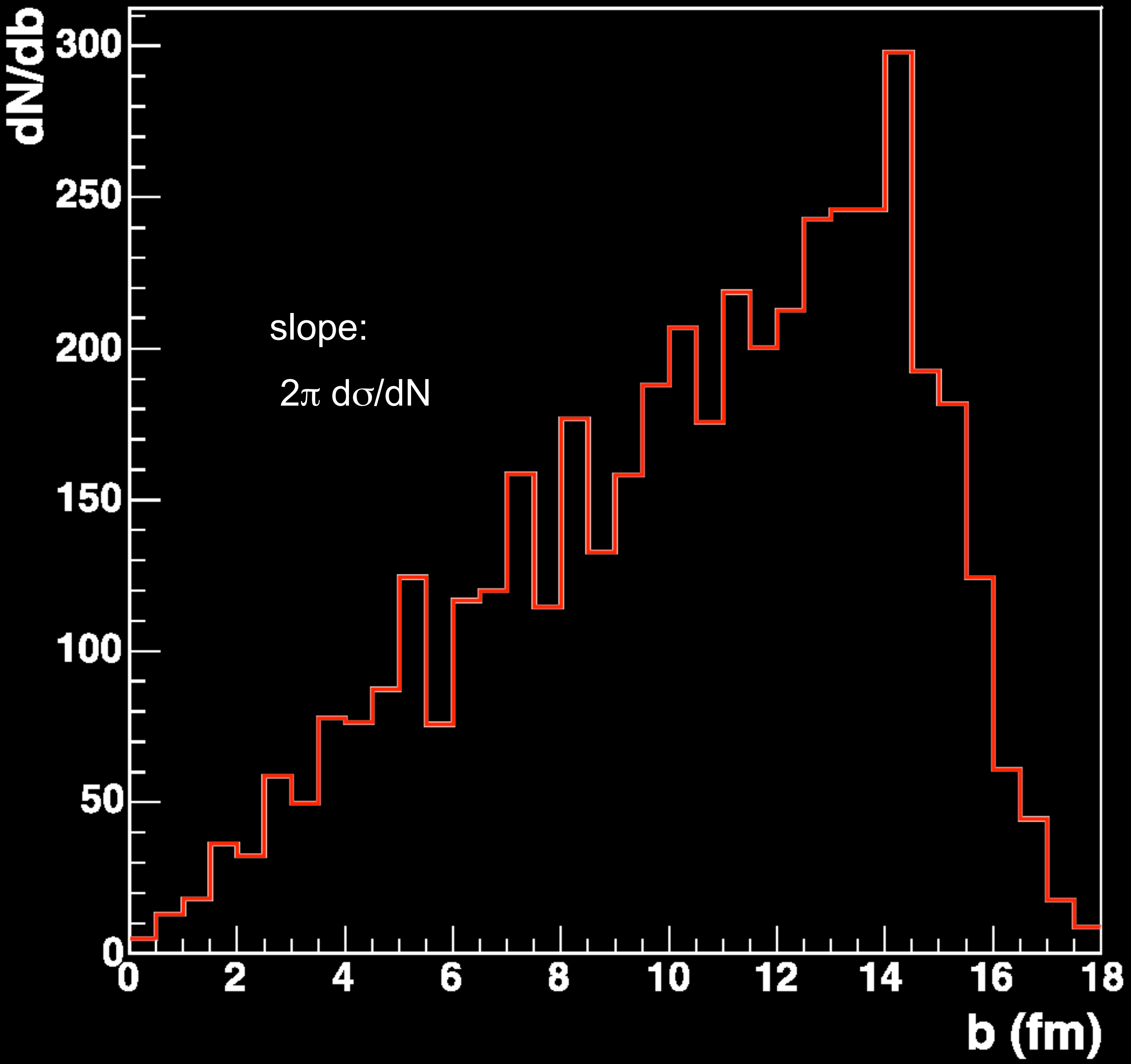
Event Characterization



Impact Parameter



- impact parameter **b**
  - perpendicular to beam direction
  - connects centers of the colliding ions

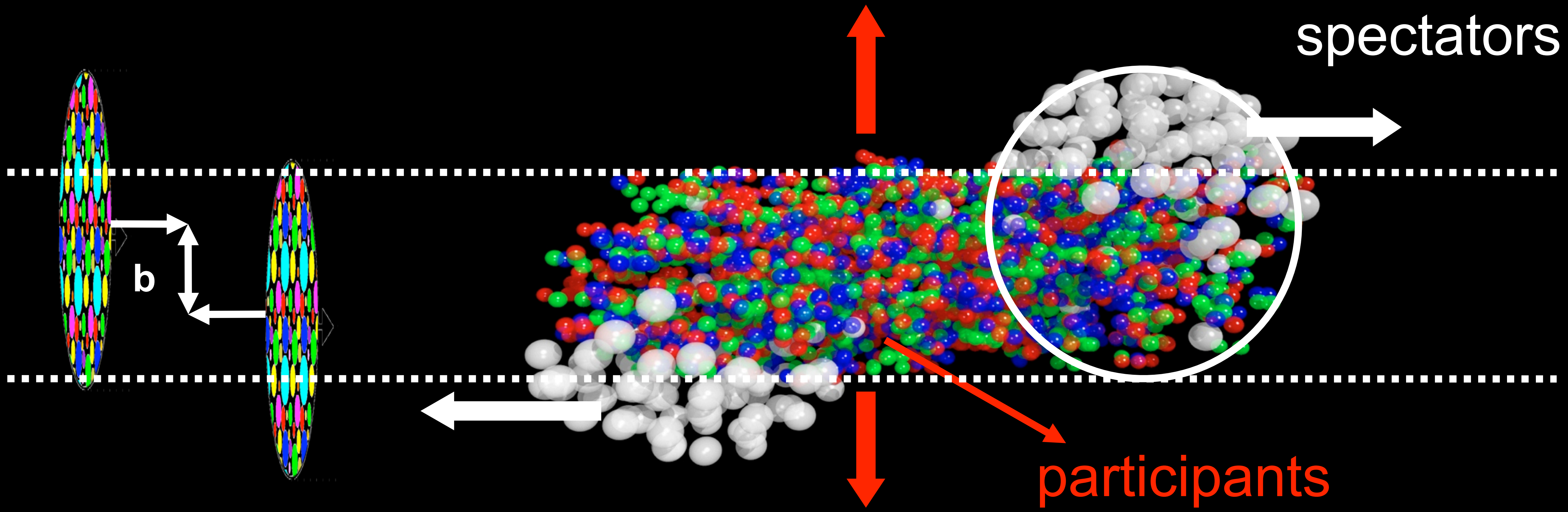


slope:

$2\pi\ d\sigma/dN$

$$d\sigma = 2\pi b\, db$$

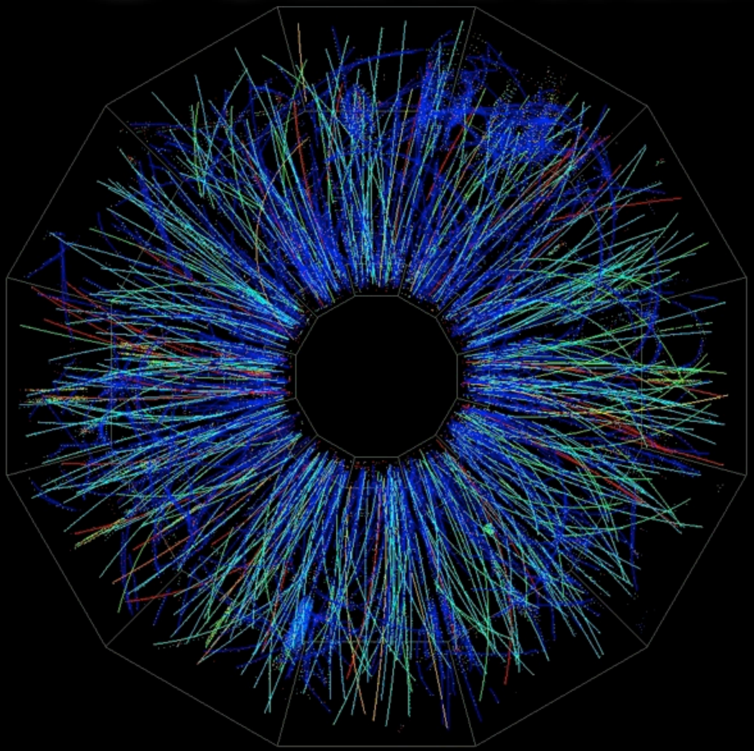
Centrality Determination (I)



centrality characterized by:

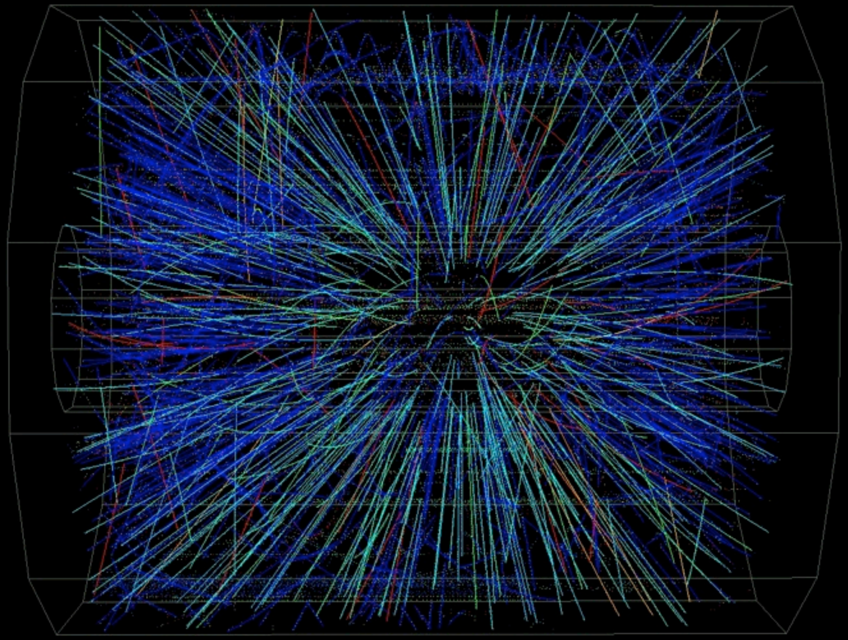
1. N_{part}, $N_{wounded}$: number of nucleons which suffered at least one inelastic nucleon-nucleon collision
2. N_{coll}, N_{bin}: number of inelastic nucleon-nucleon collisions

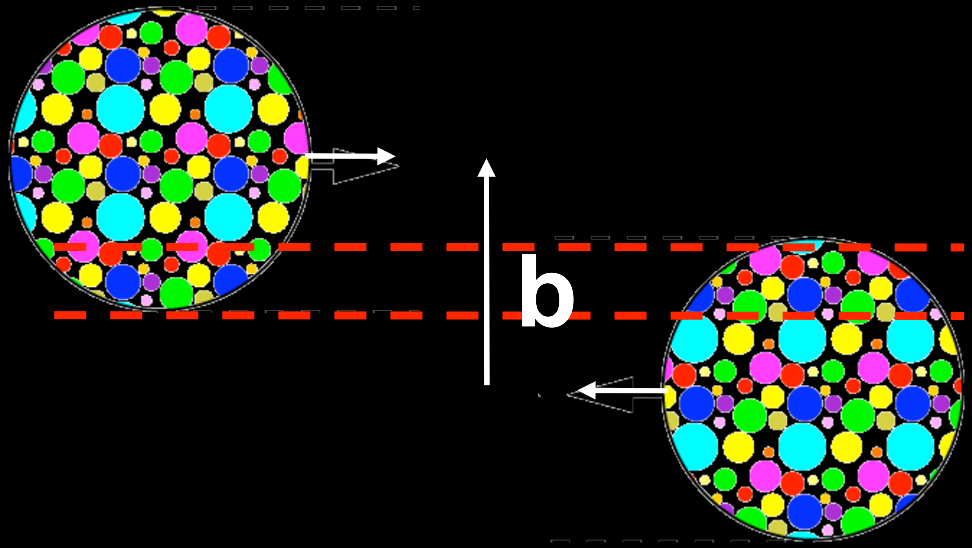
Centrality determination (III)



Peripheral Event

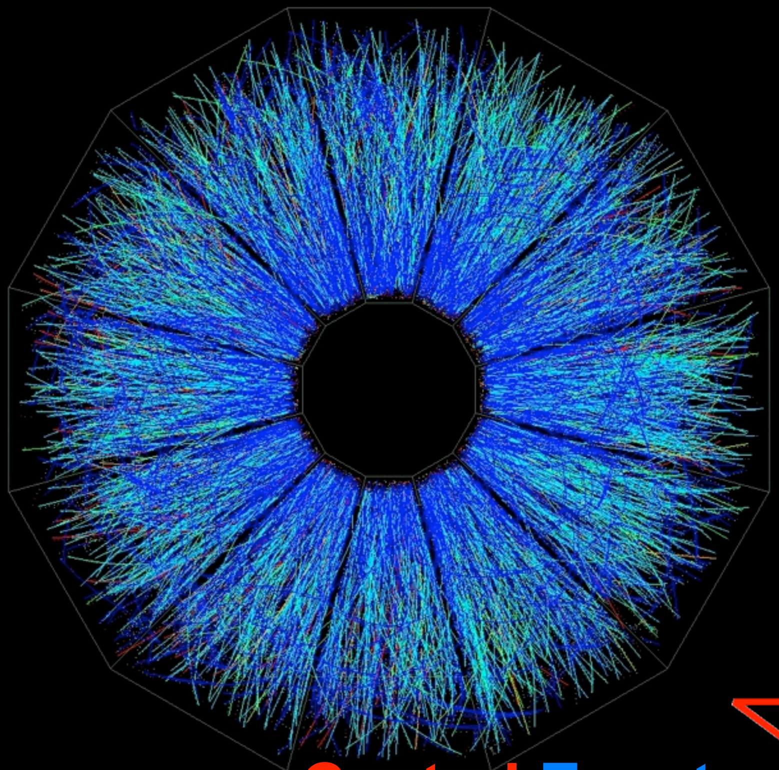
From real-time Level 3 display





- ✓ peripheral collisions, largest fraction cross section
- ✓ many spectators
- ✓ “few” particles produced

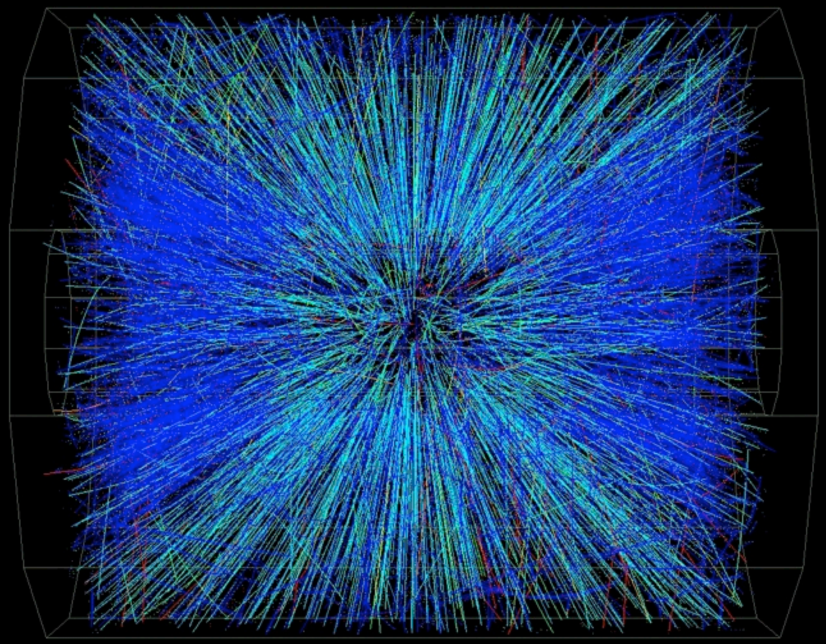
Centrality determination (IV)

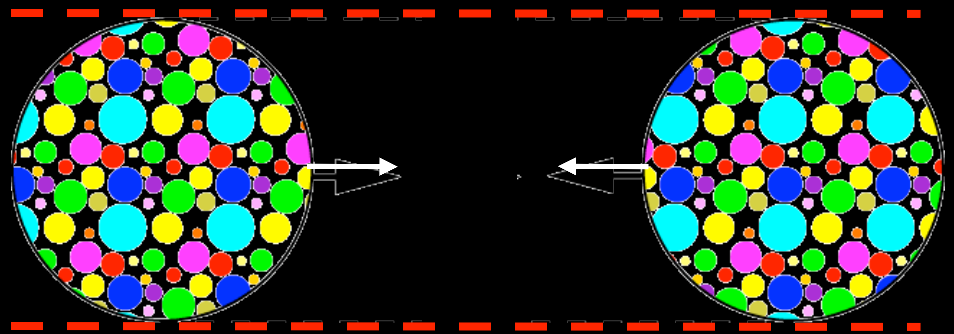


Central Event

STAR

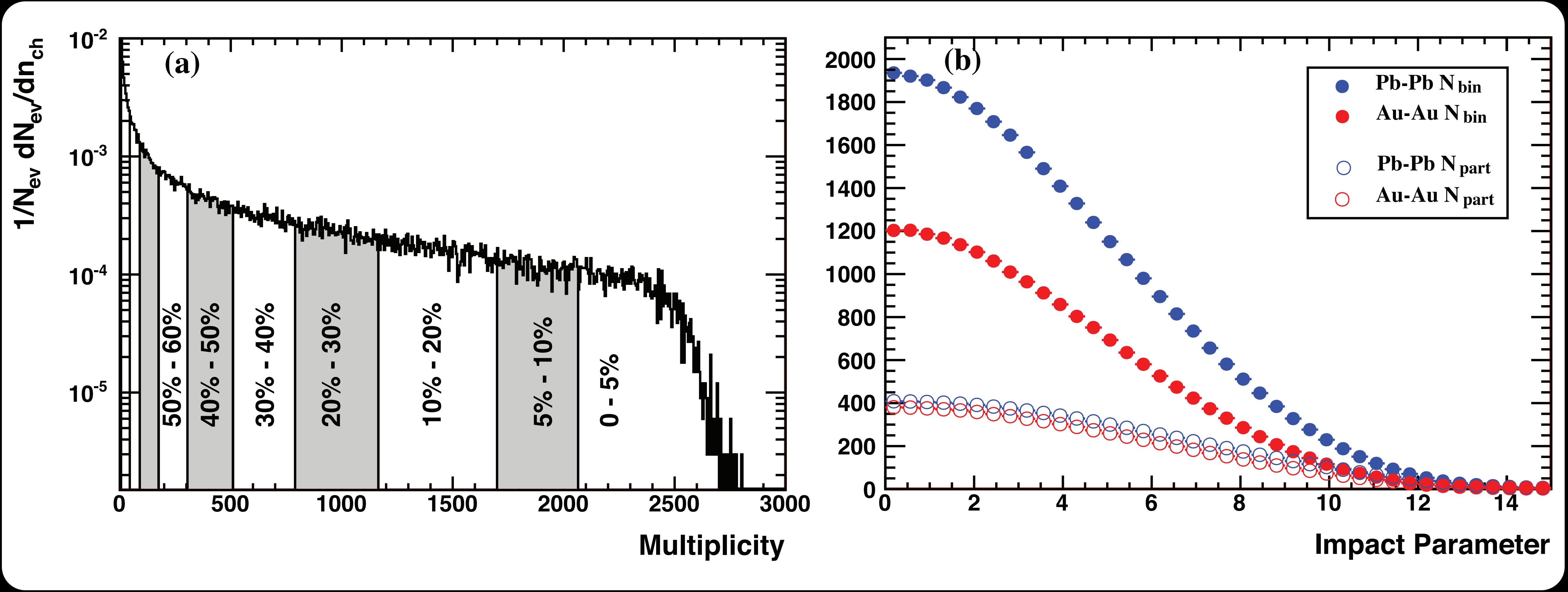
From real-time Level 3 display





- ✓ impact parameter **b** = 0
- ✓ central collisions, small cross section
- ✓ no spectators
- ✓ many particles produced

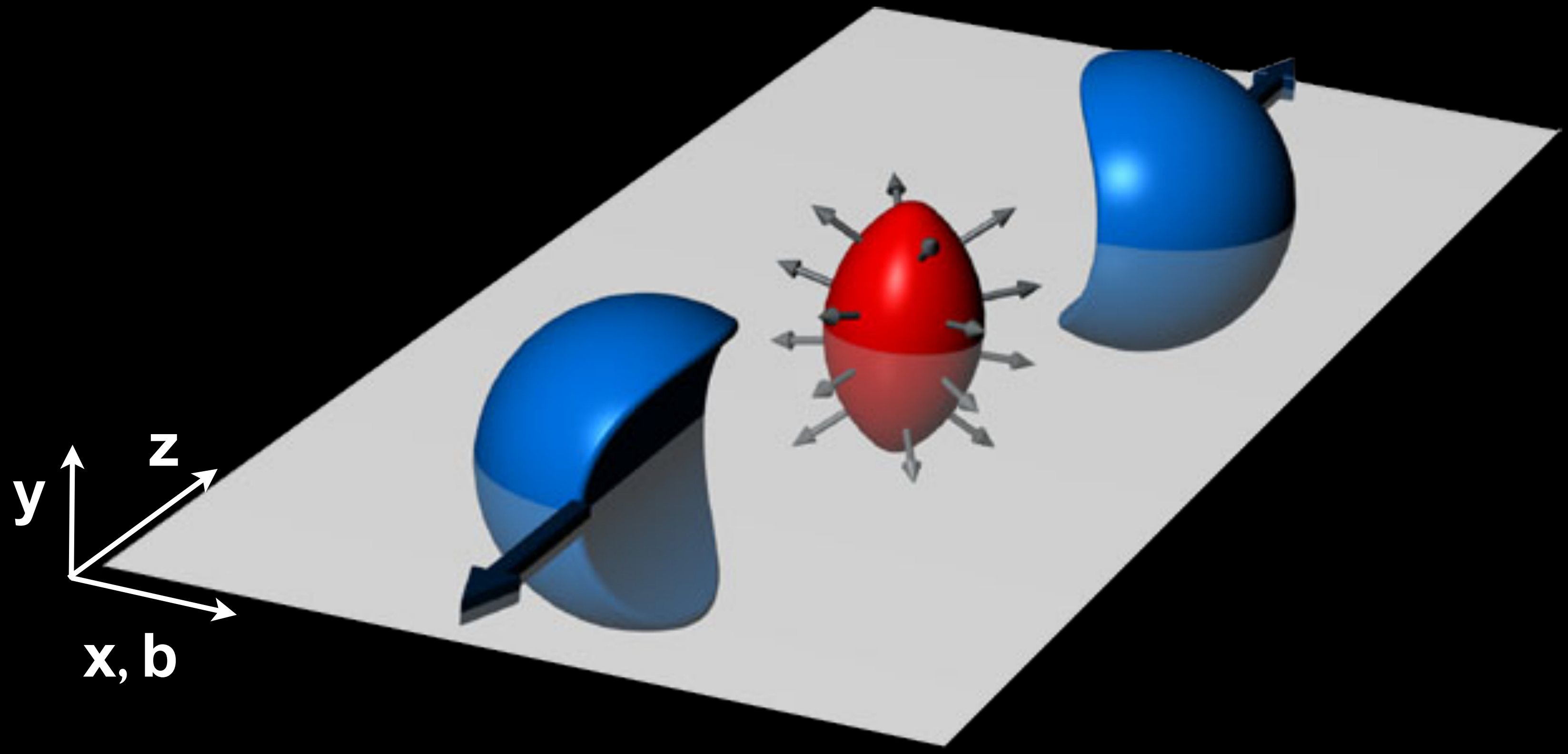
Centrality determination (ALICE)

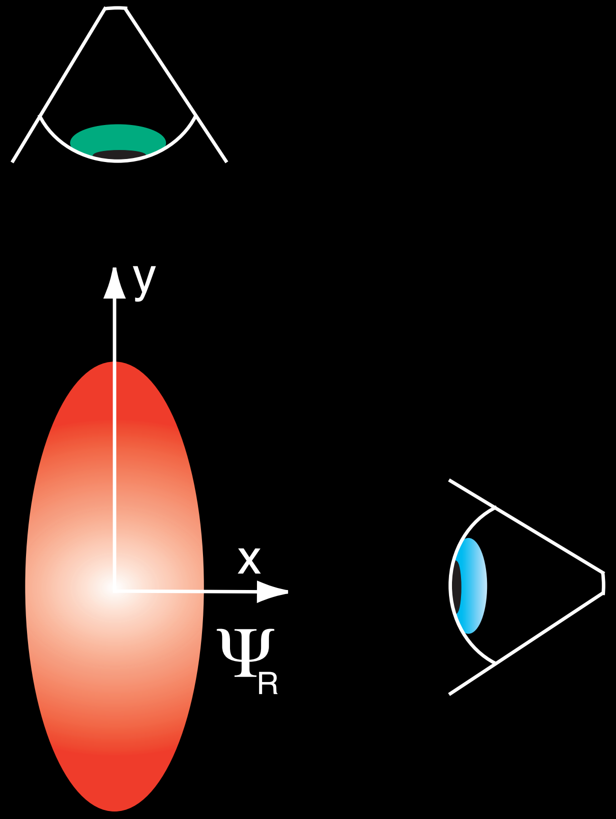


- ✓ Determines the magnitude of the impact parameter

$\%\sigma_{tot}$	$\langle N_{part} \rangle$	$\langle b \rangle$
0-5	386	2.48
20-30	177	7.85
60-70	25	12.66

The Reaction Plane

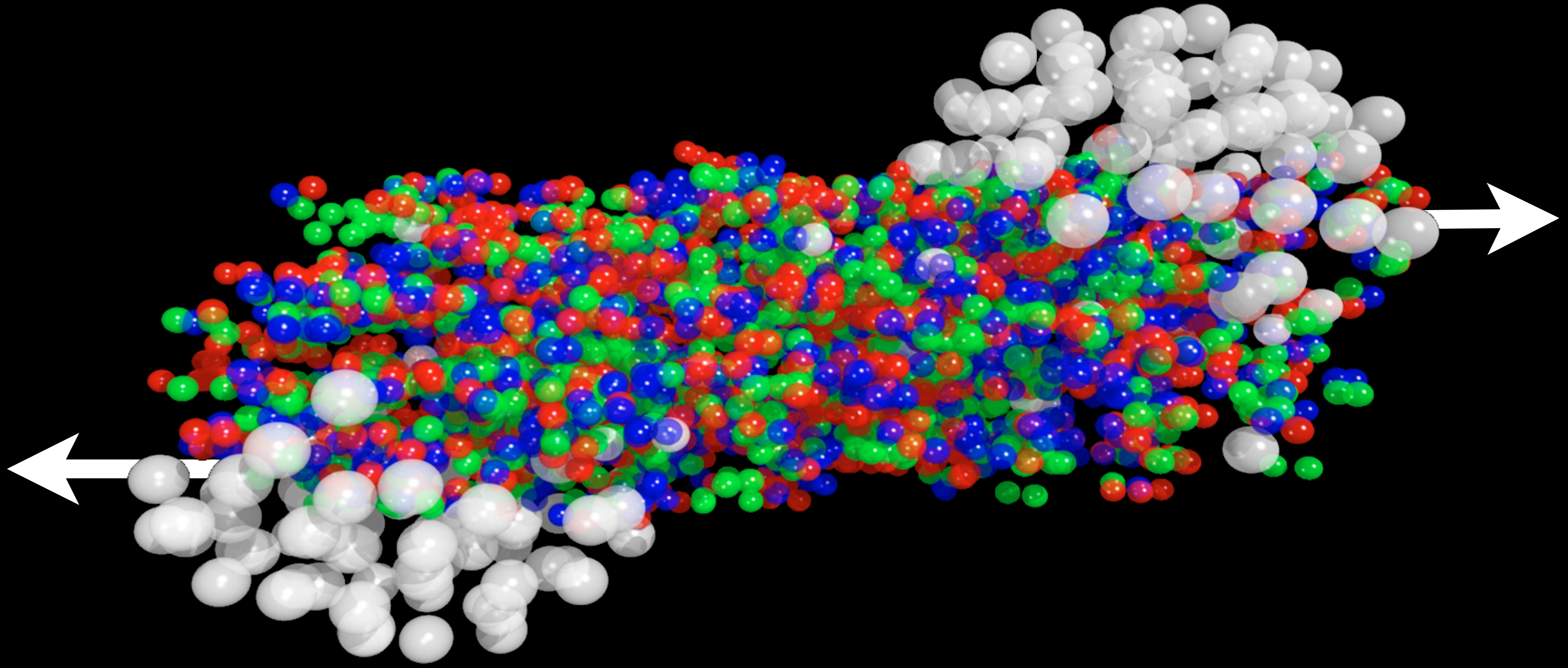


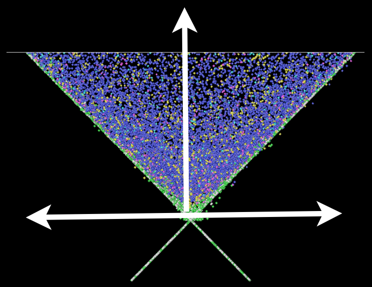


$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{\mathrm{d}^3N}{p_t \mathrm{d}p_t \mathrm{d}y \mathrm{d}(\phi - \Psi_R)}$$

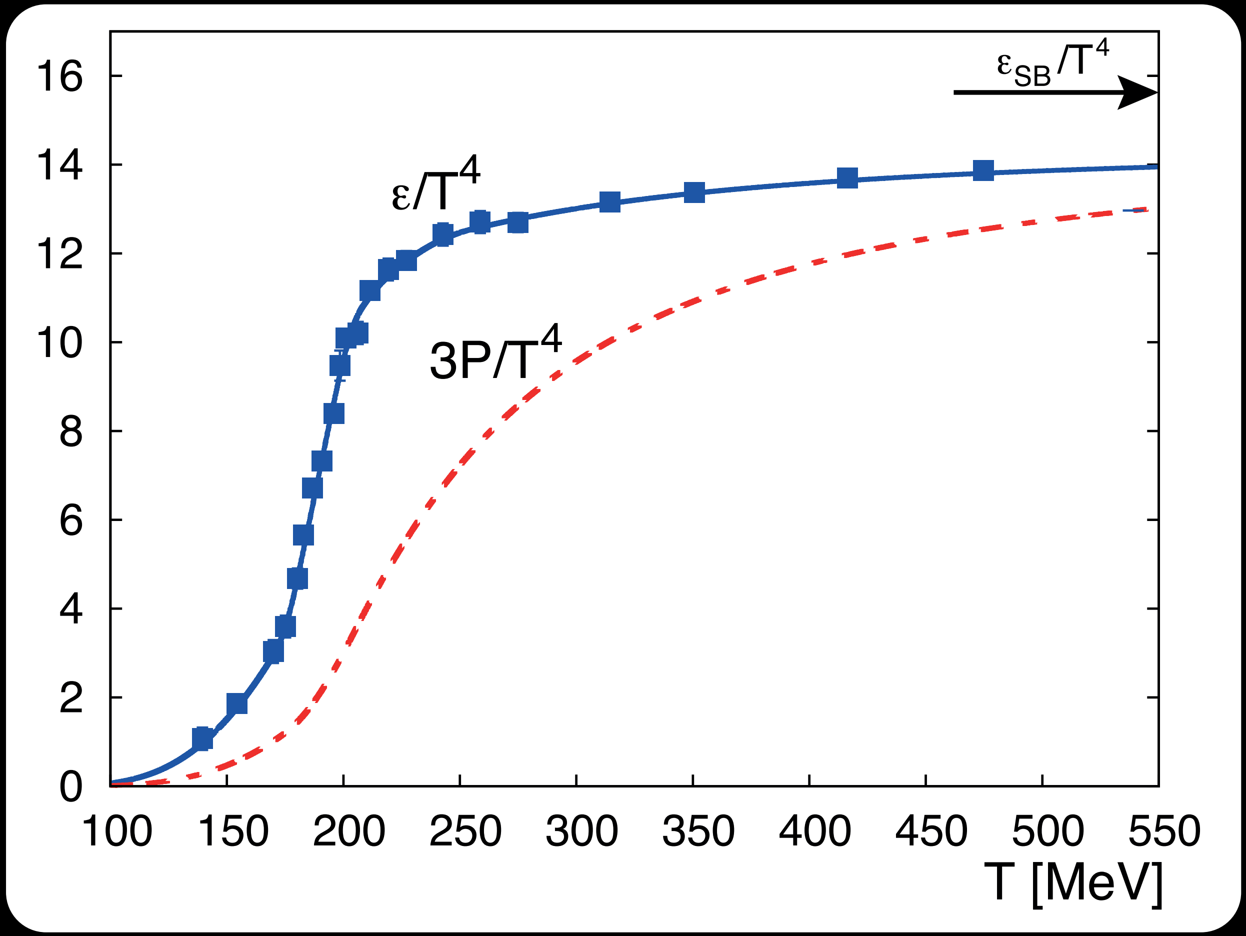
determine the angle of the reaction plane ψ_R

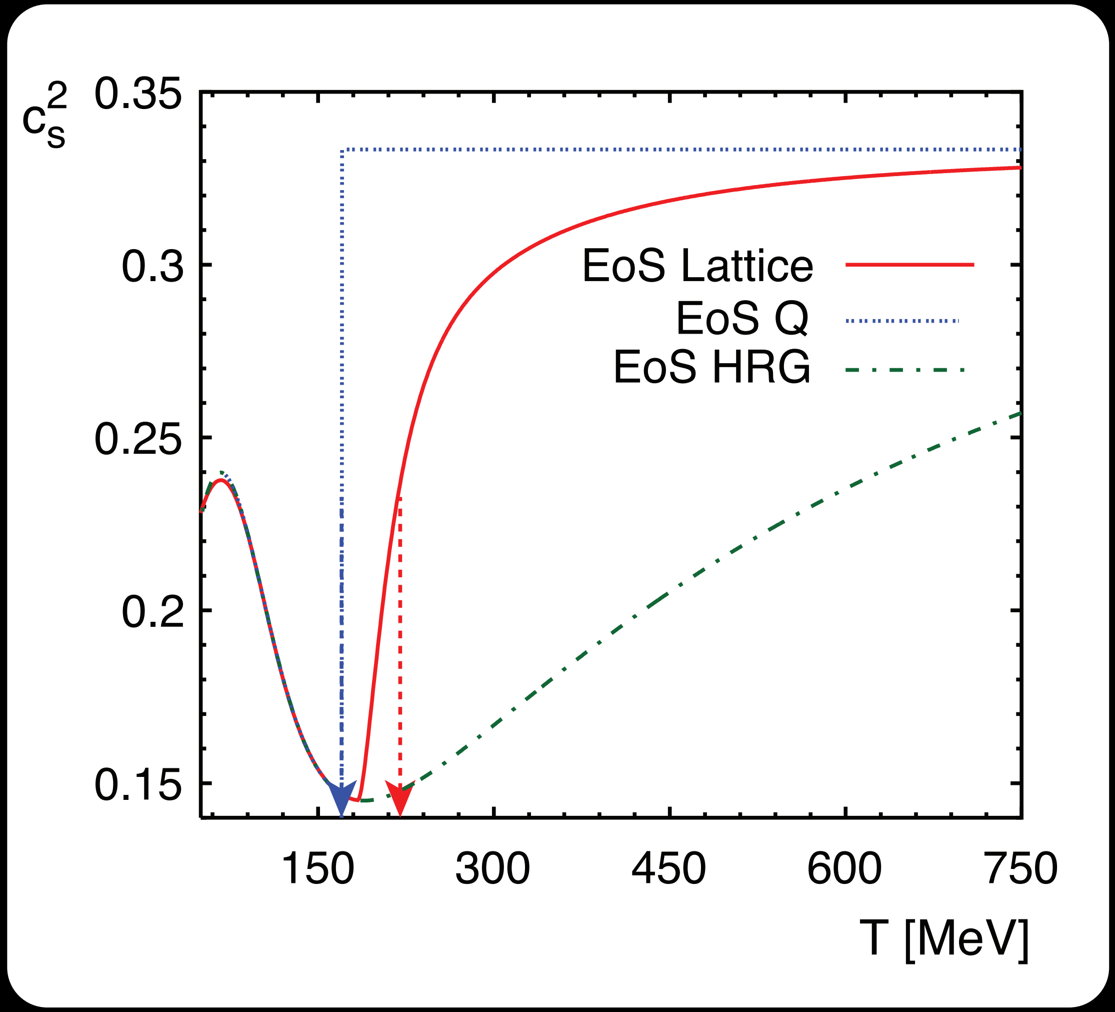
Collective Flow





Velocity of Sound



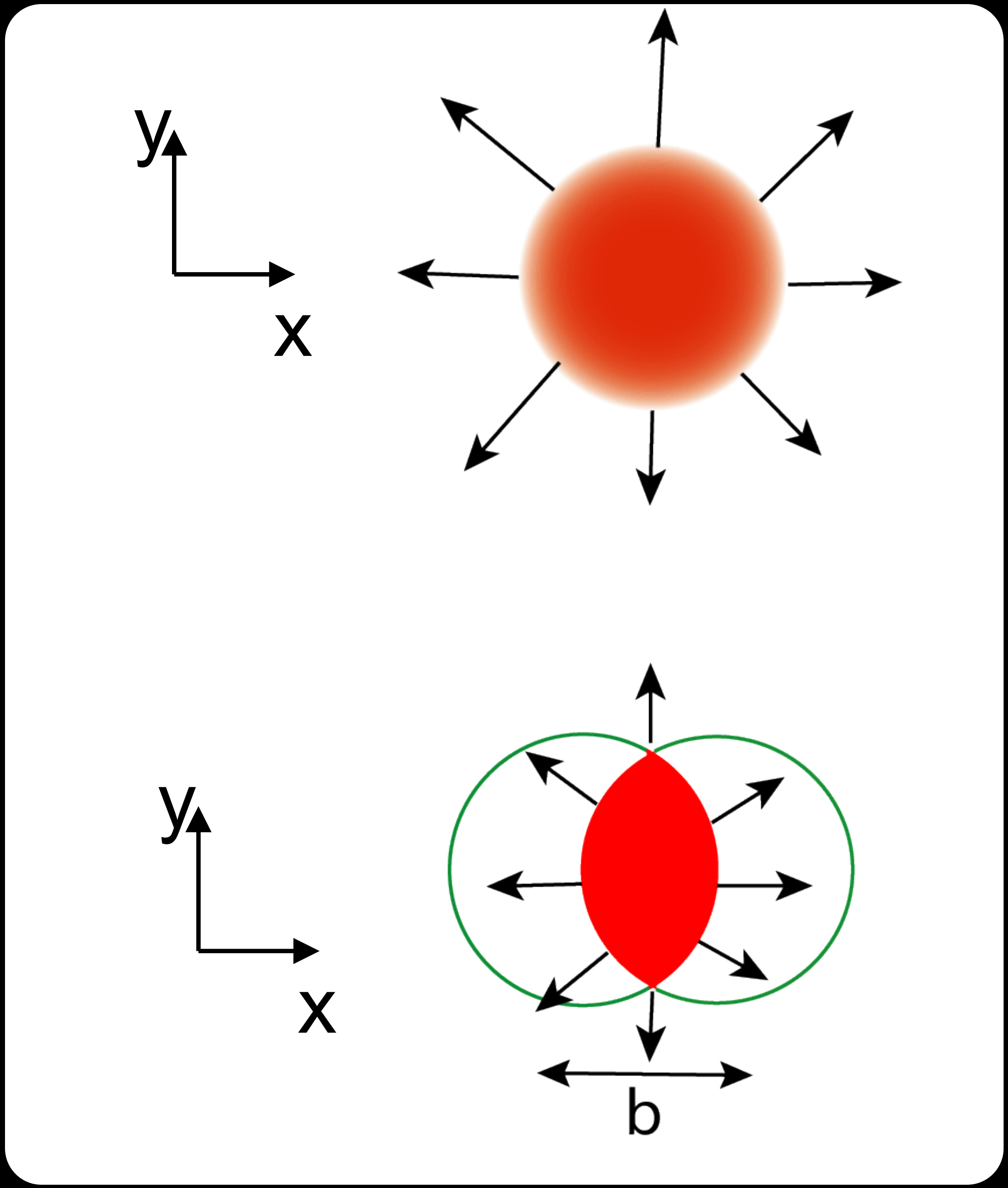


$$P_{\mathrm{QGP}} = \frac{1}{3}\varepsilon_{\mathrm{QGP}} = g\frac{\pi^2}{90}T^4$$

velocity of sound $C_s = \sqrt{\dfrac{dP}{d\varepsilon}}$

the magnitude of the collective motion is proportional to the velocity of sound

Collective Motion

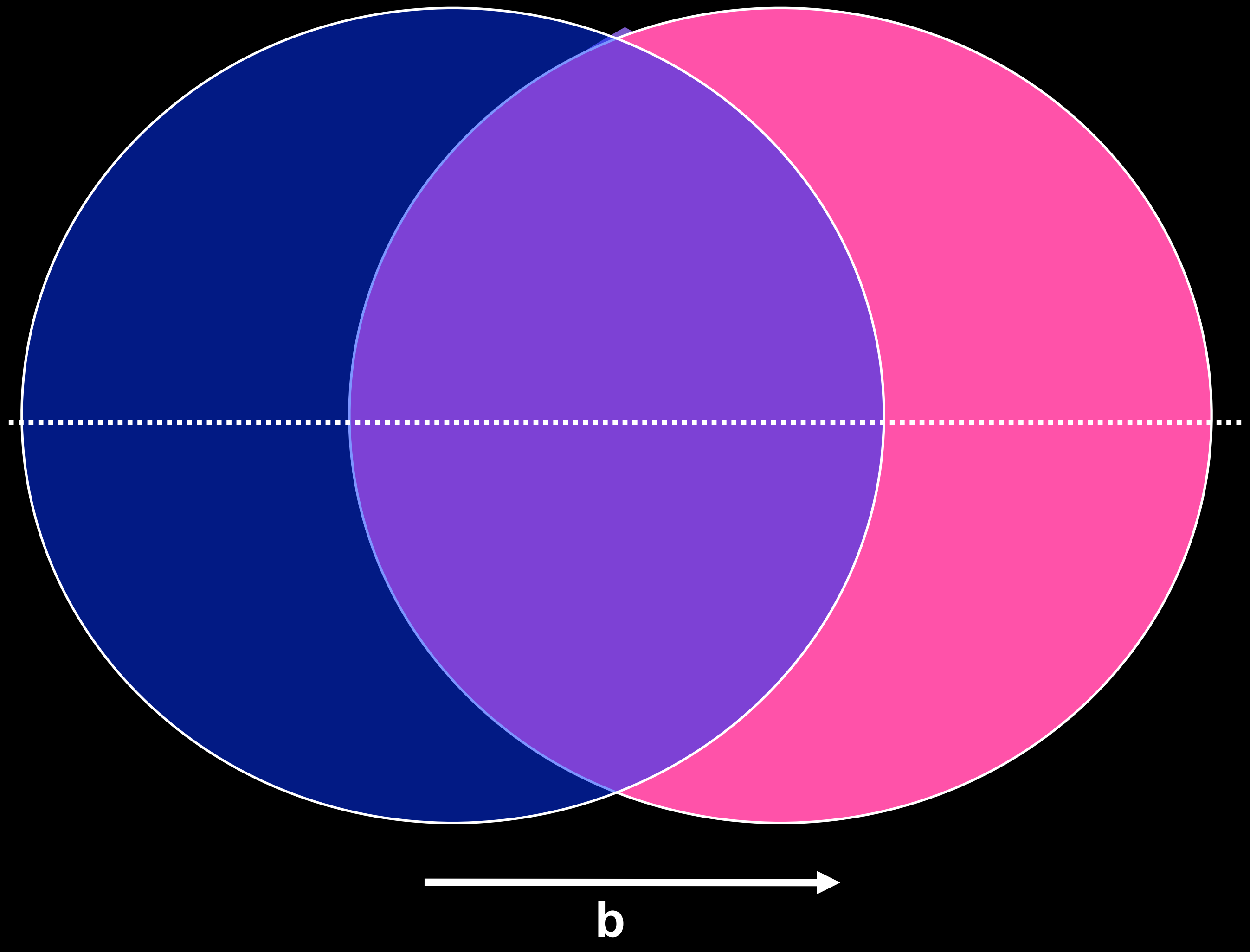


main type of transverse flow in central collision (b=0) is radial flow Integrates pressure history over complete expansion phase

elliptic flow v_2 caused by anisotropic initial overlap region (b > 0) more weight towards early stage of expansion

Elliptic Flow

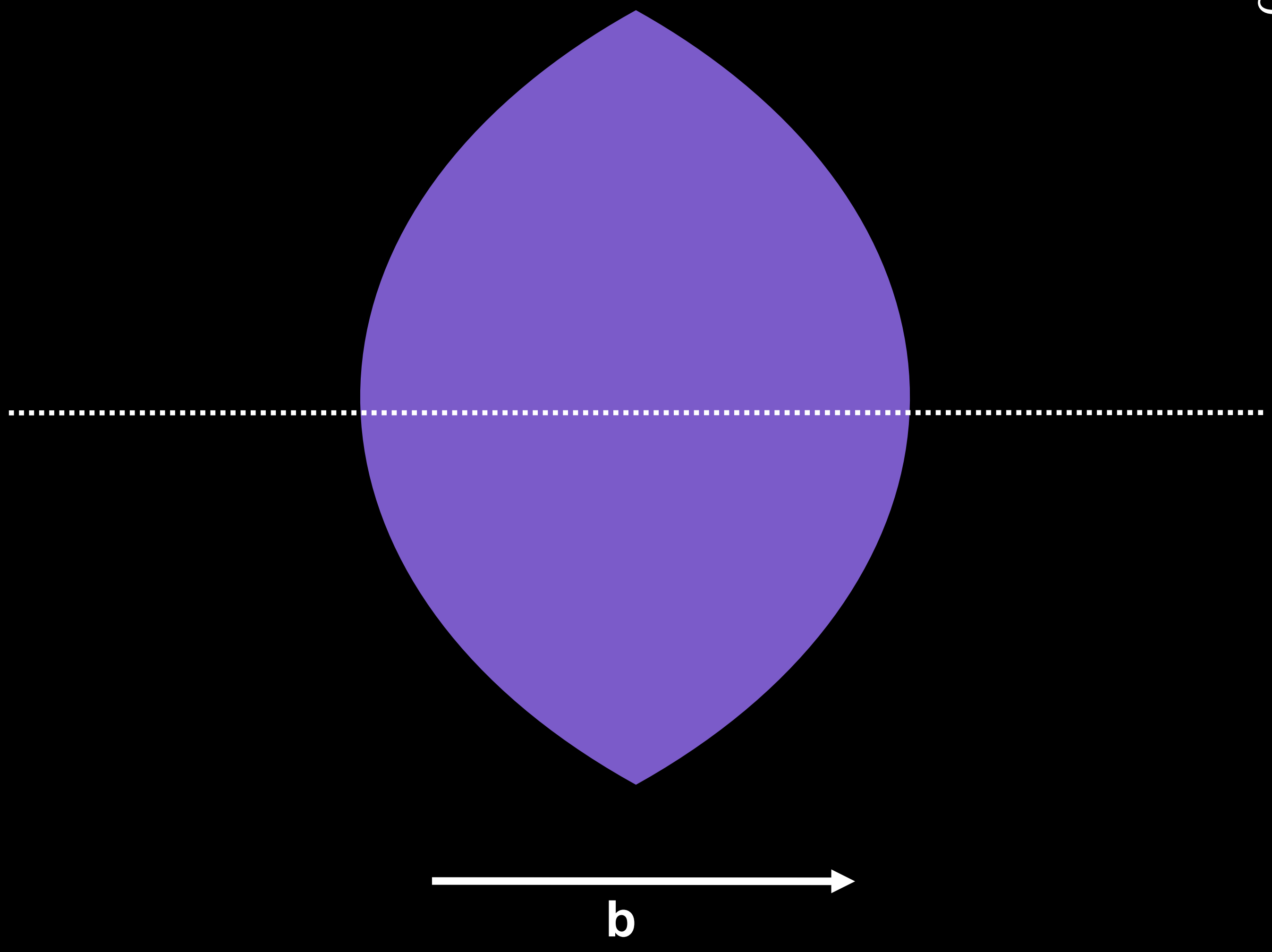
Animation: Mike Lisa



Elliptic Flow

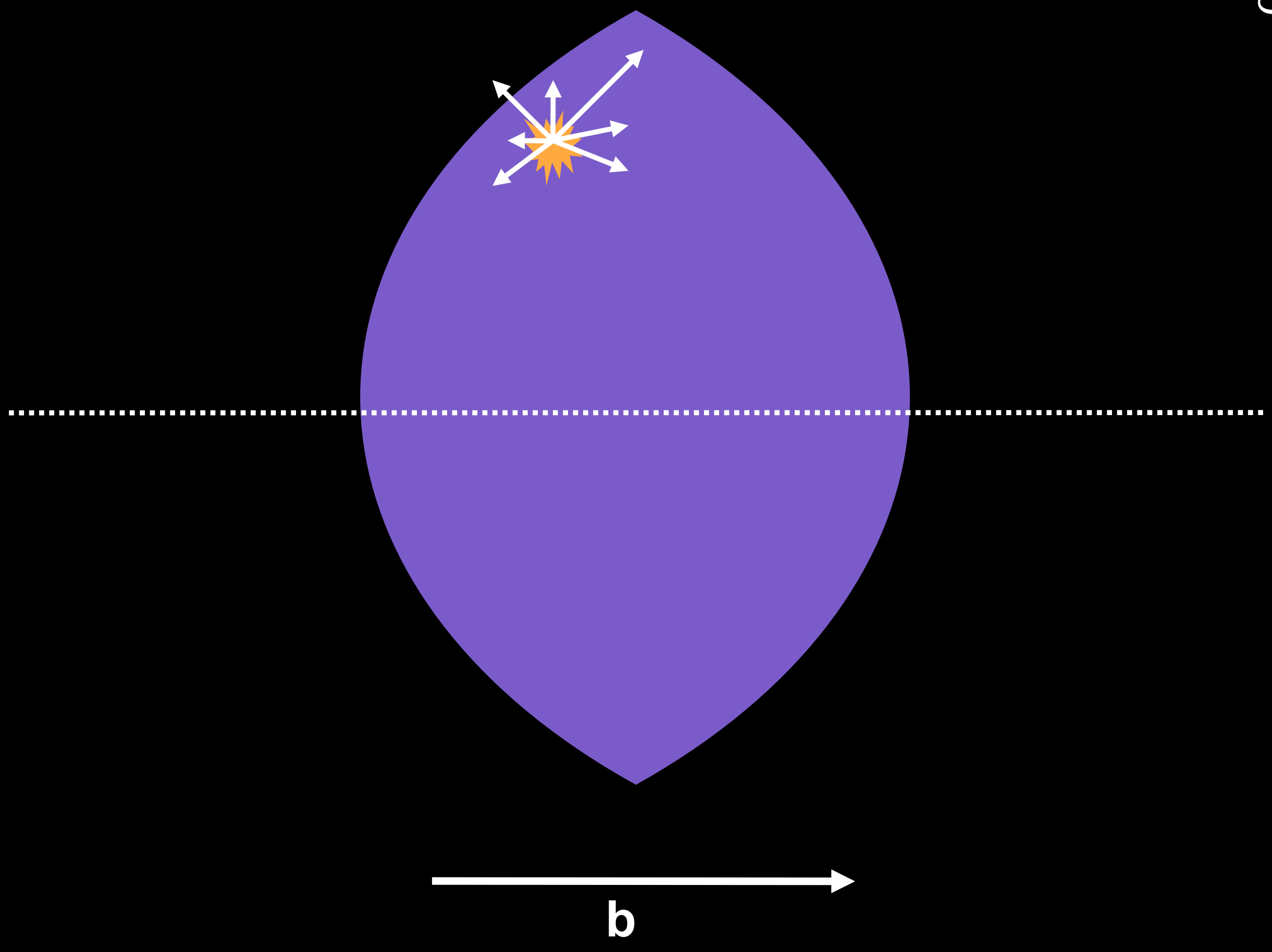
Animation: Mike Lisa

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



Elliptic Flow

1) superposition of independent p+p:



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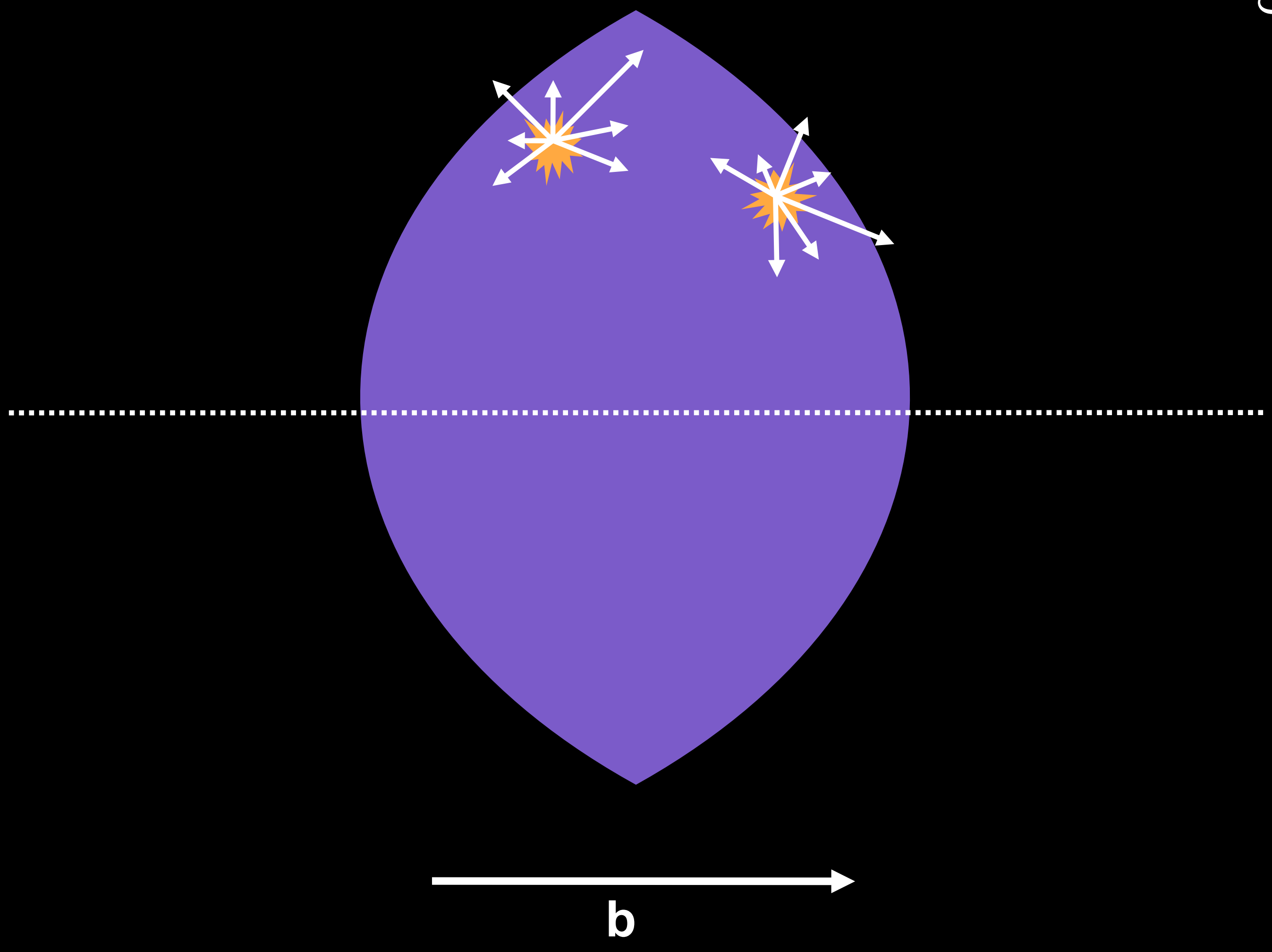

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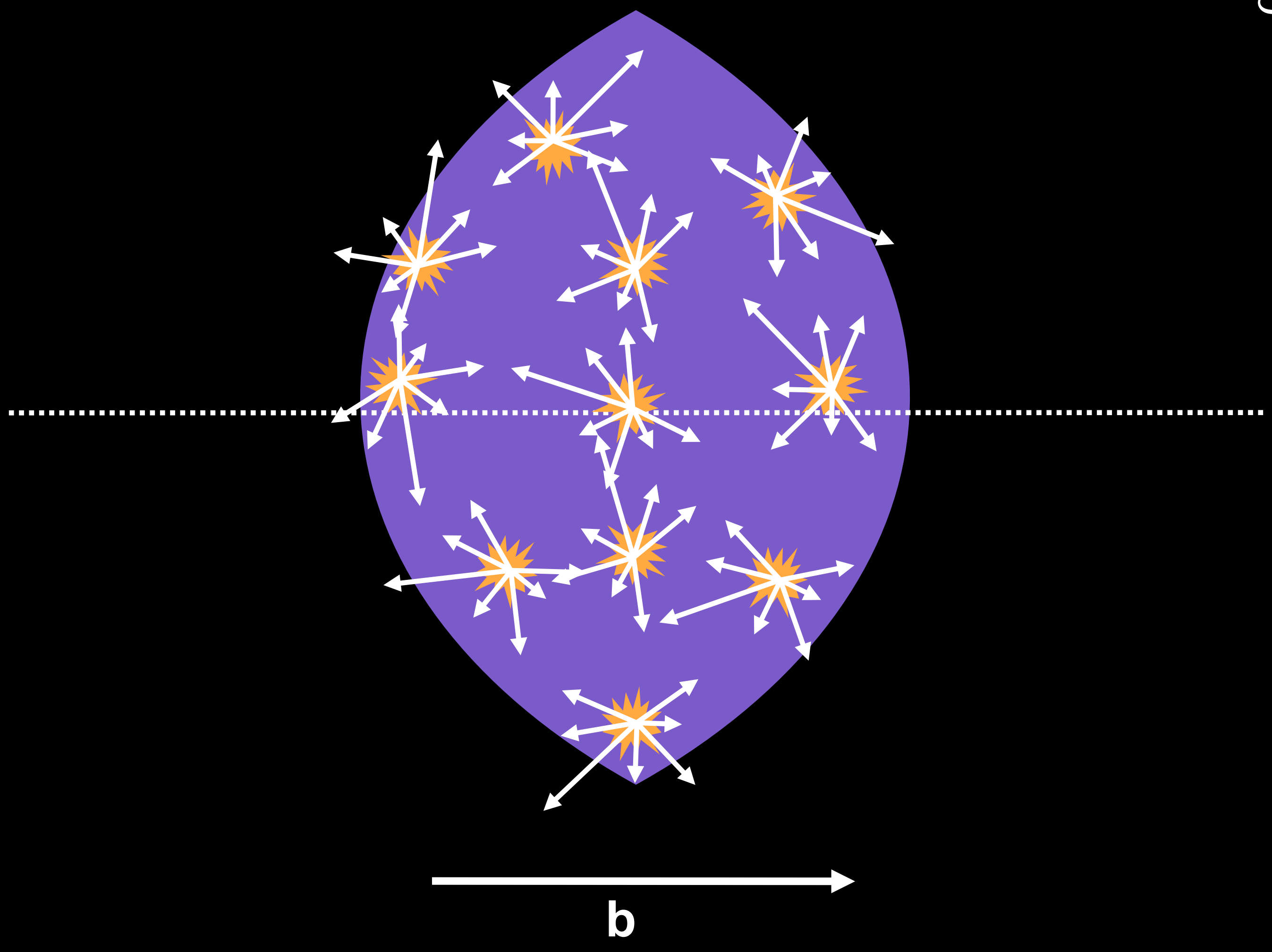


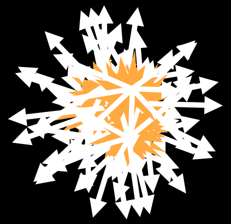
Elliptic Flow

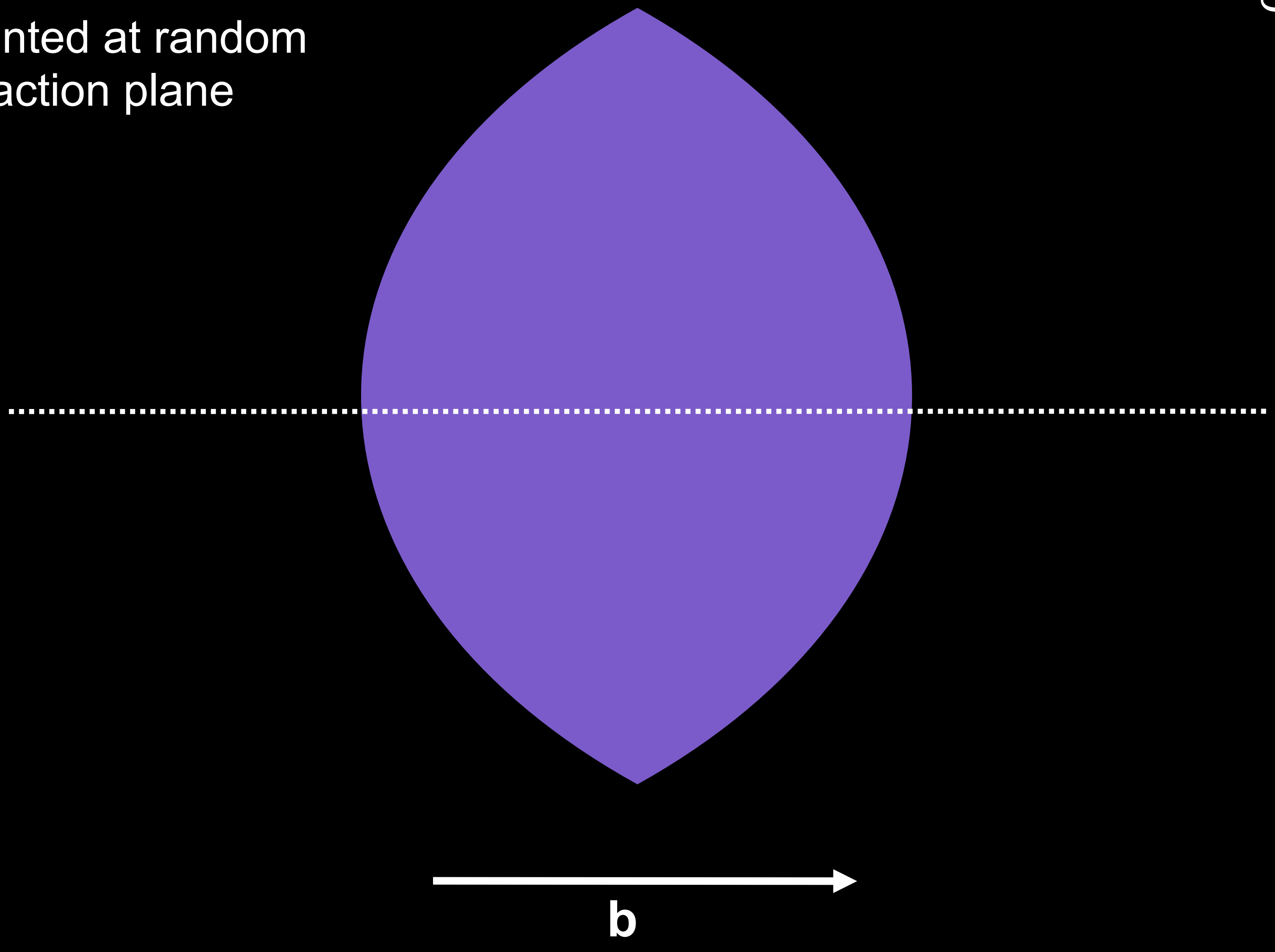
Animation: Mike Lisa

1) superposition of independent p+p:

momenta pointed at random
relative to reaction plane

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





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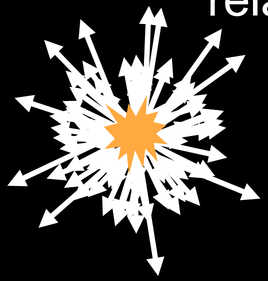
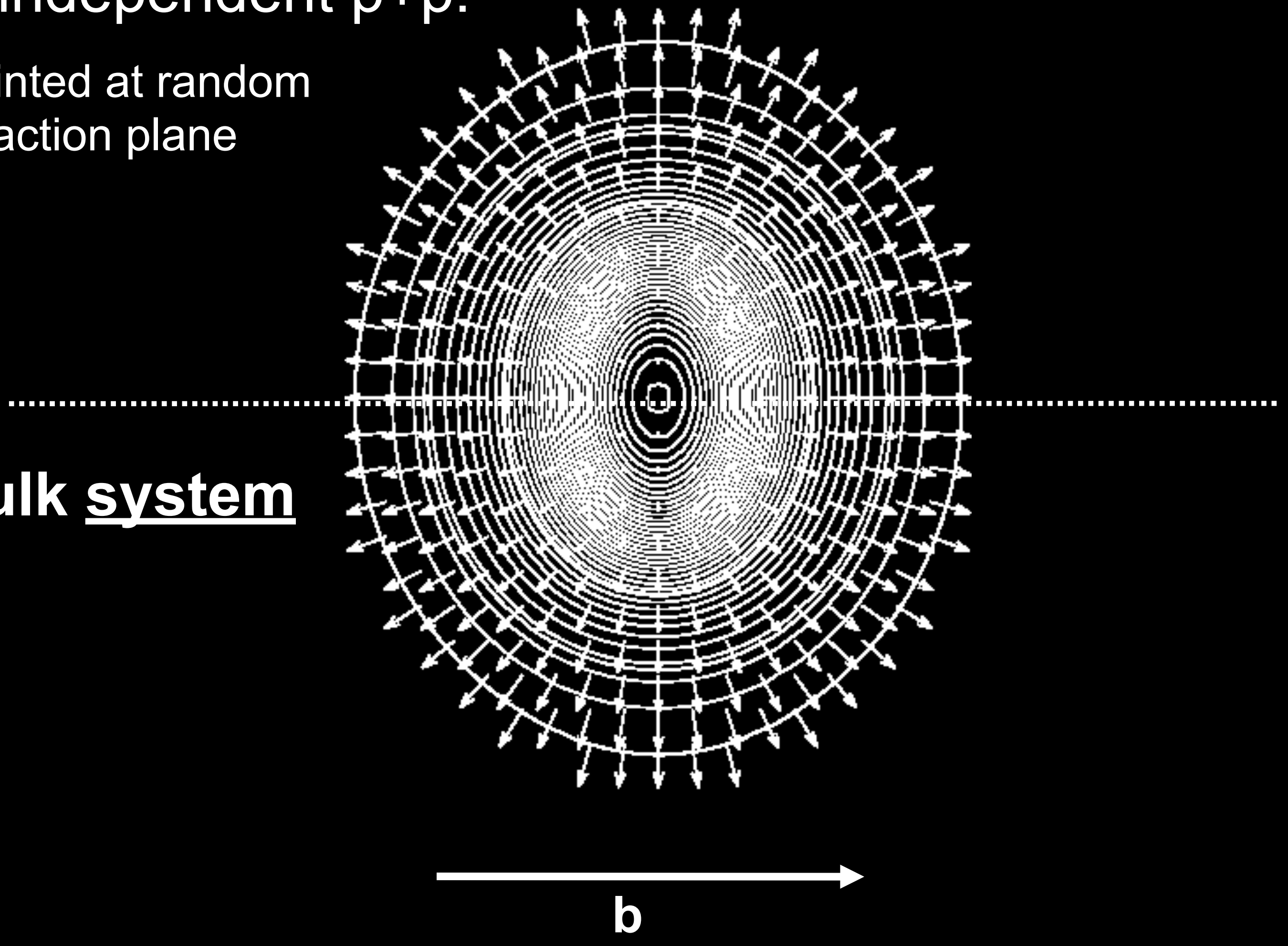


2) evolution as a **bulk** **<u>system</u>**



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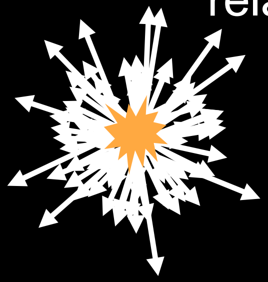

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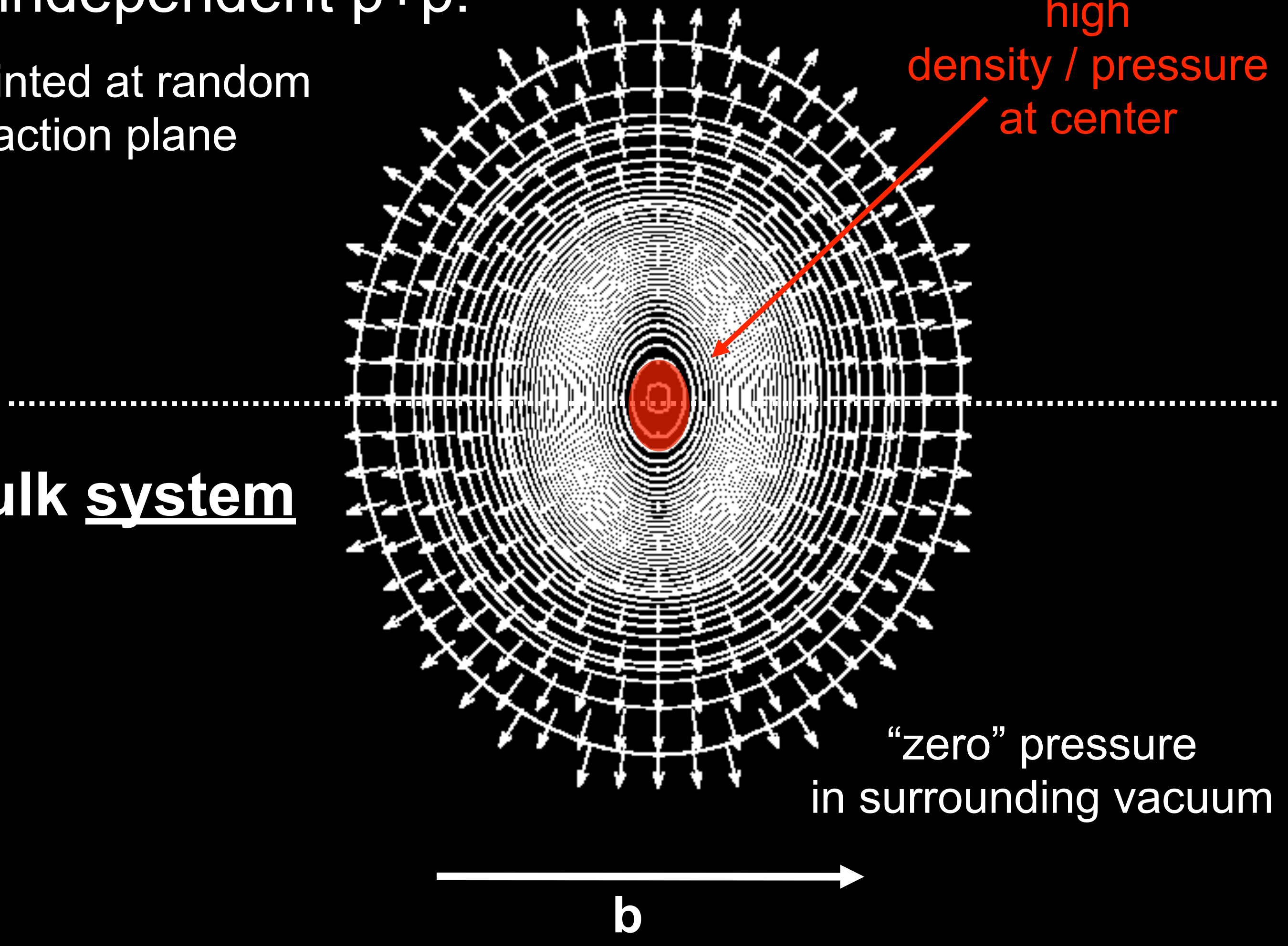


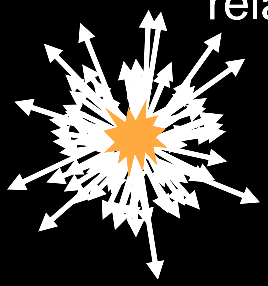
high
density / pressure
at center

"zero" pressure
in surrounding vacuum

Elliptic Flow

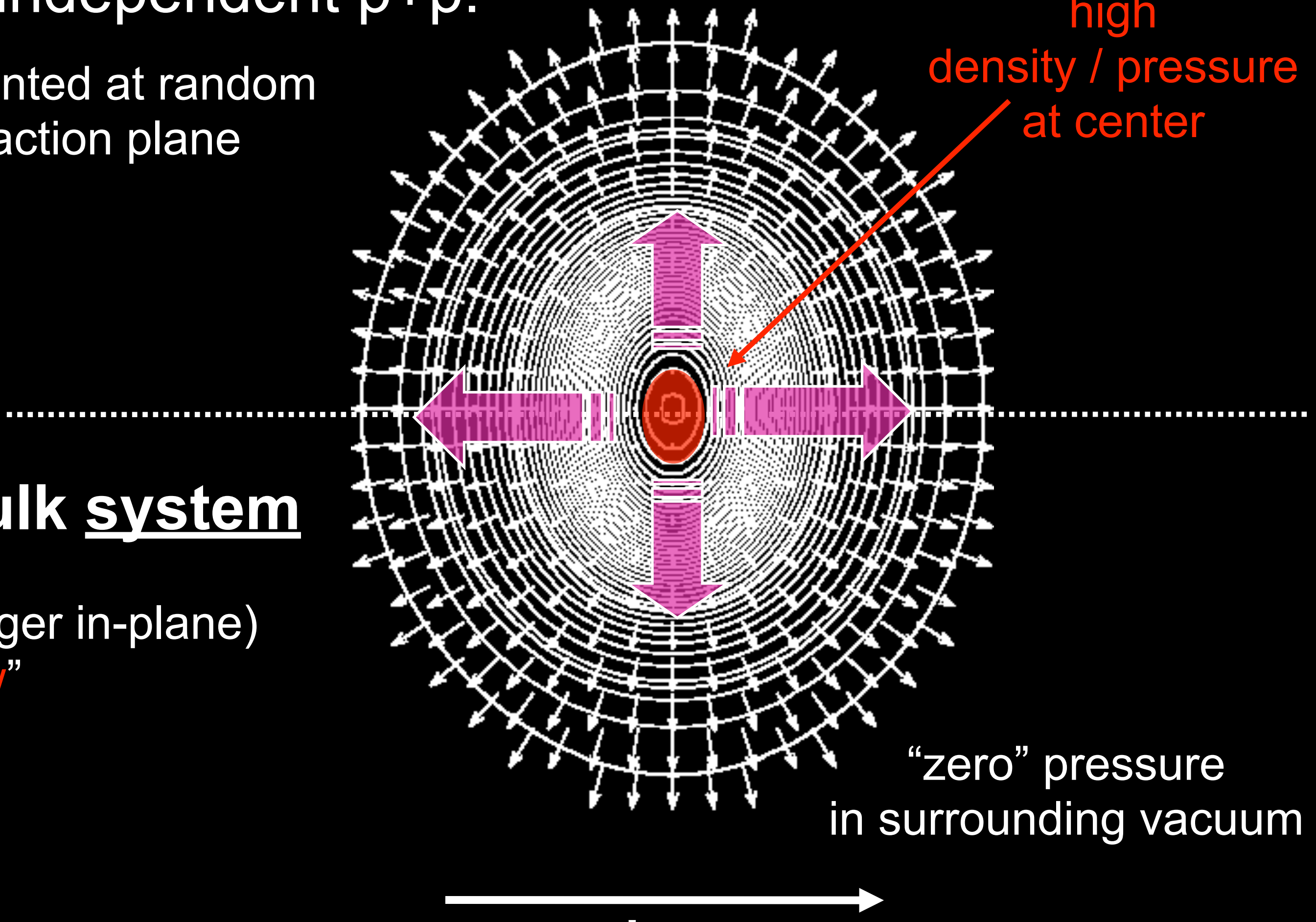
1) superposition of independent p+p:

momenta pointed at random
relative to reaction plane



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

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



high
density / pressure
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“zero” pressure
in surrounding vacuum

b

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

Elliptic Flow

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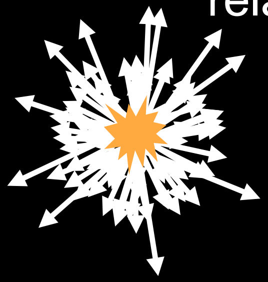

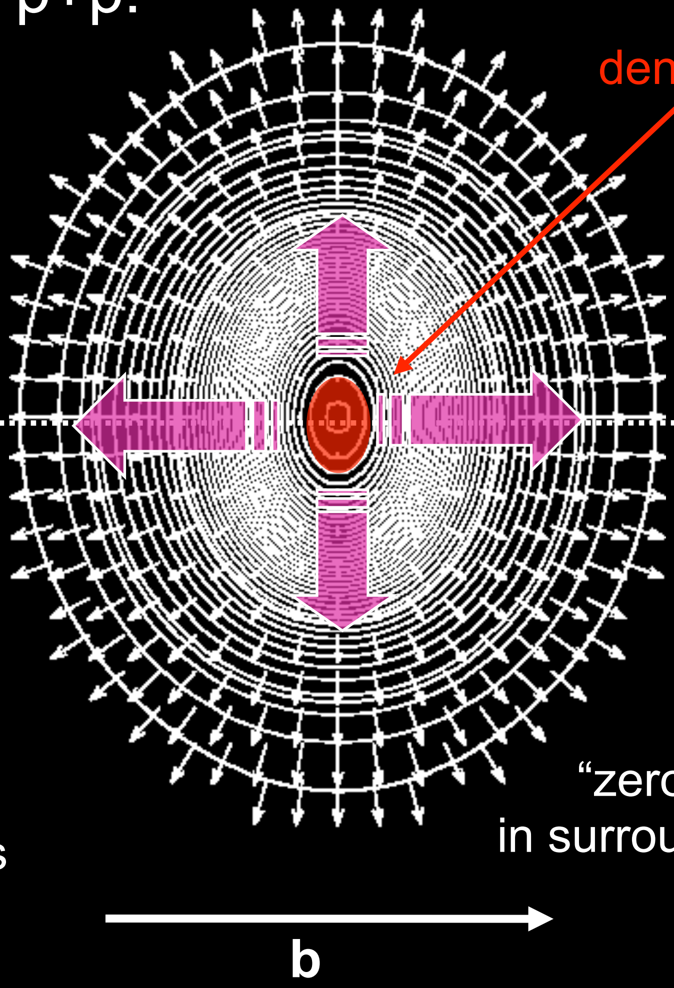

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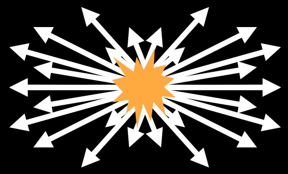
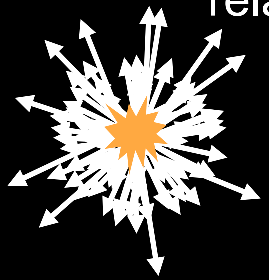


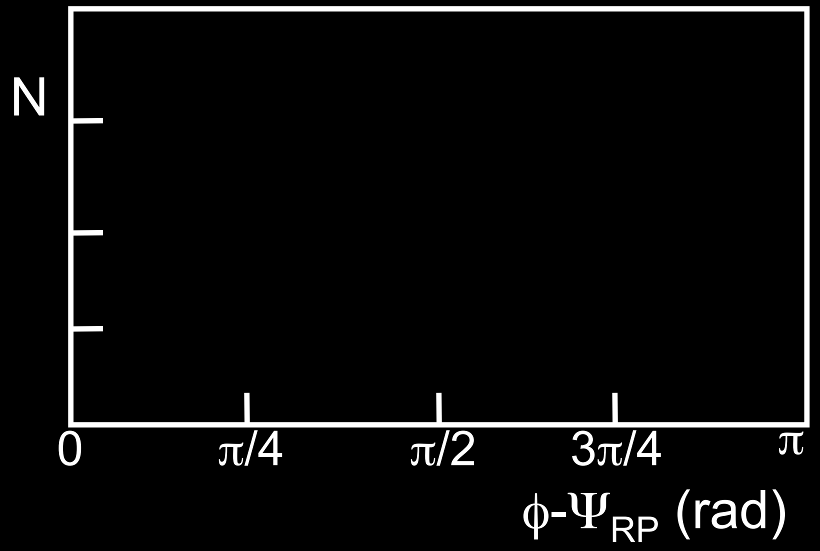
more, faster particles
seen in-plane

Elliptic Flow

1) superposition of independent p+p:



momenta pointed at random
relative to reaction plane



Elliptic Flow

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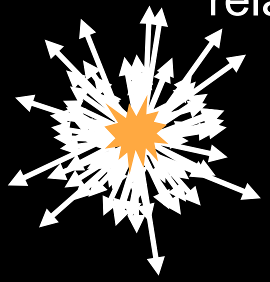
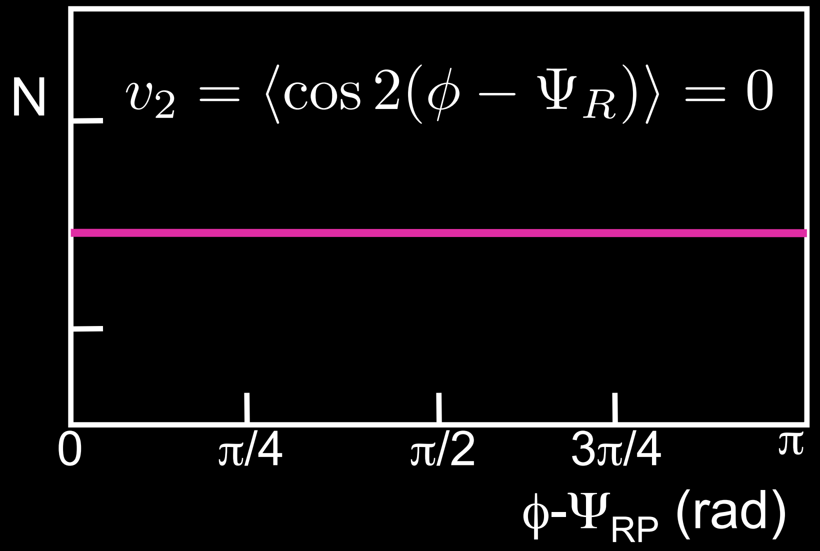


momenta pointed at random relative to reaction plane



Elliptic Flow

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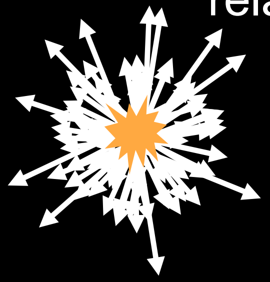

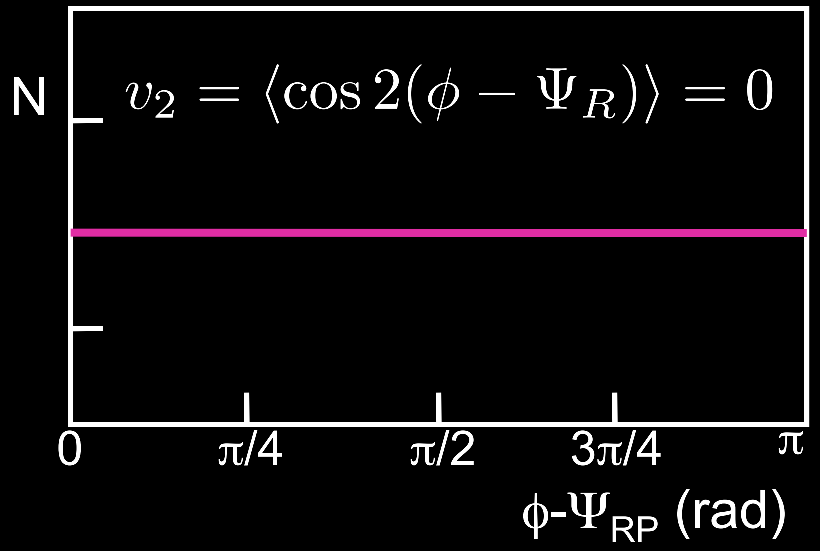

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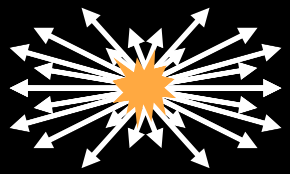
pressure gradients (larger in-plane)
push bulk "out" → "flow"

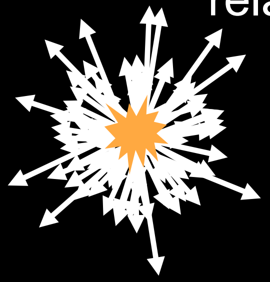


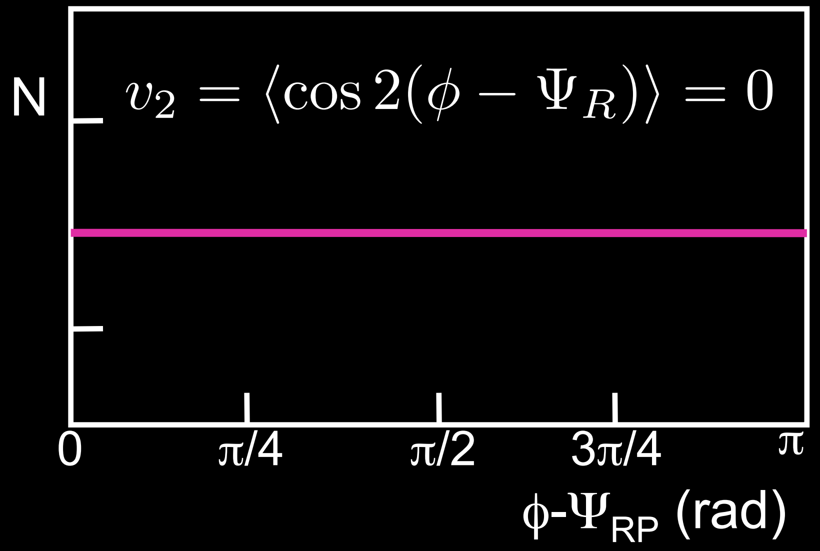
more, faster particles
seen in-plane

Elliptic Flow

1) superposition of independent p+p:

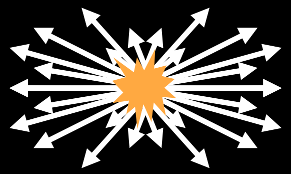
momenta pointed at random
relative to reaction plane





2) evolution as a **bulk system**

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



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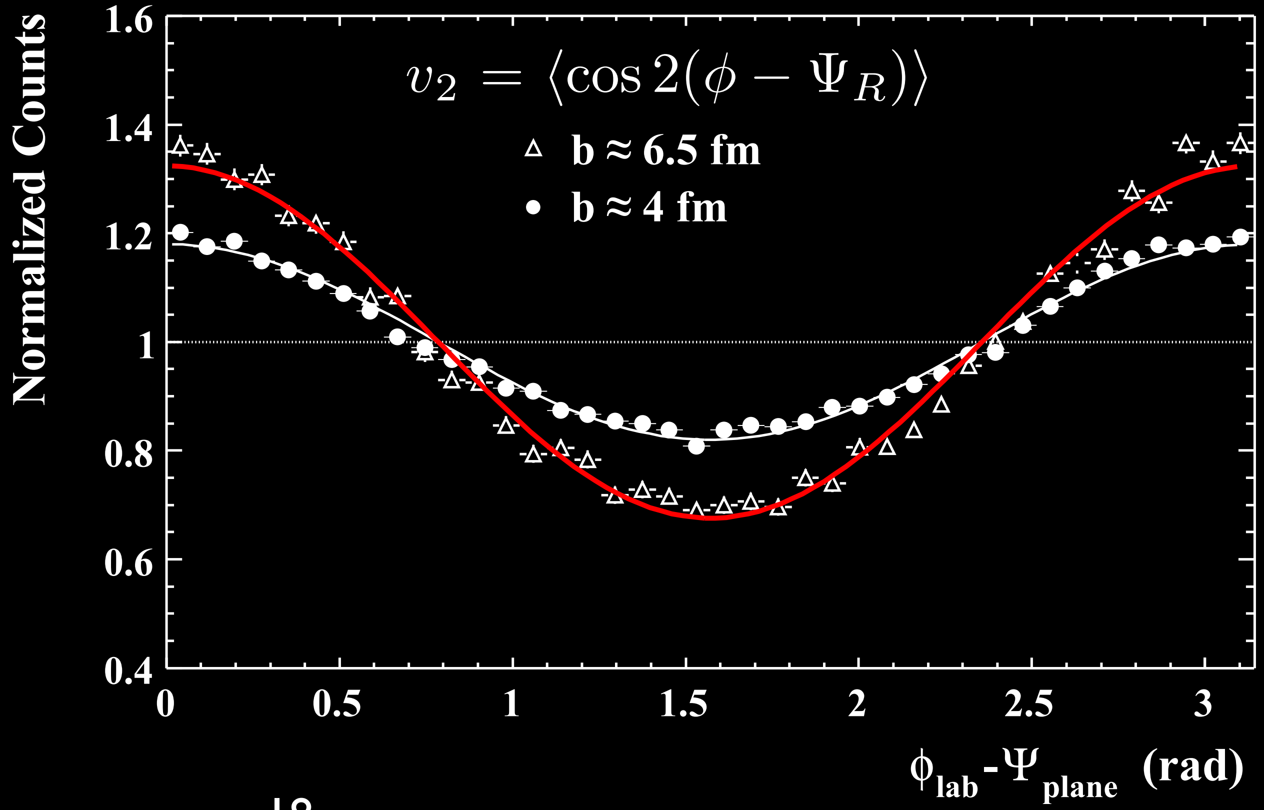


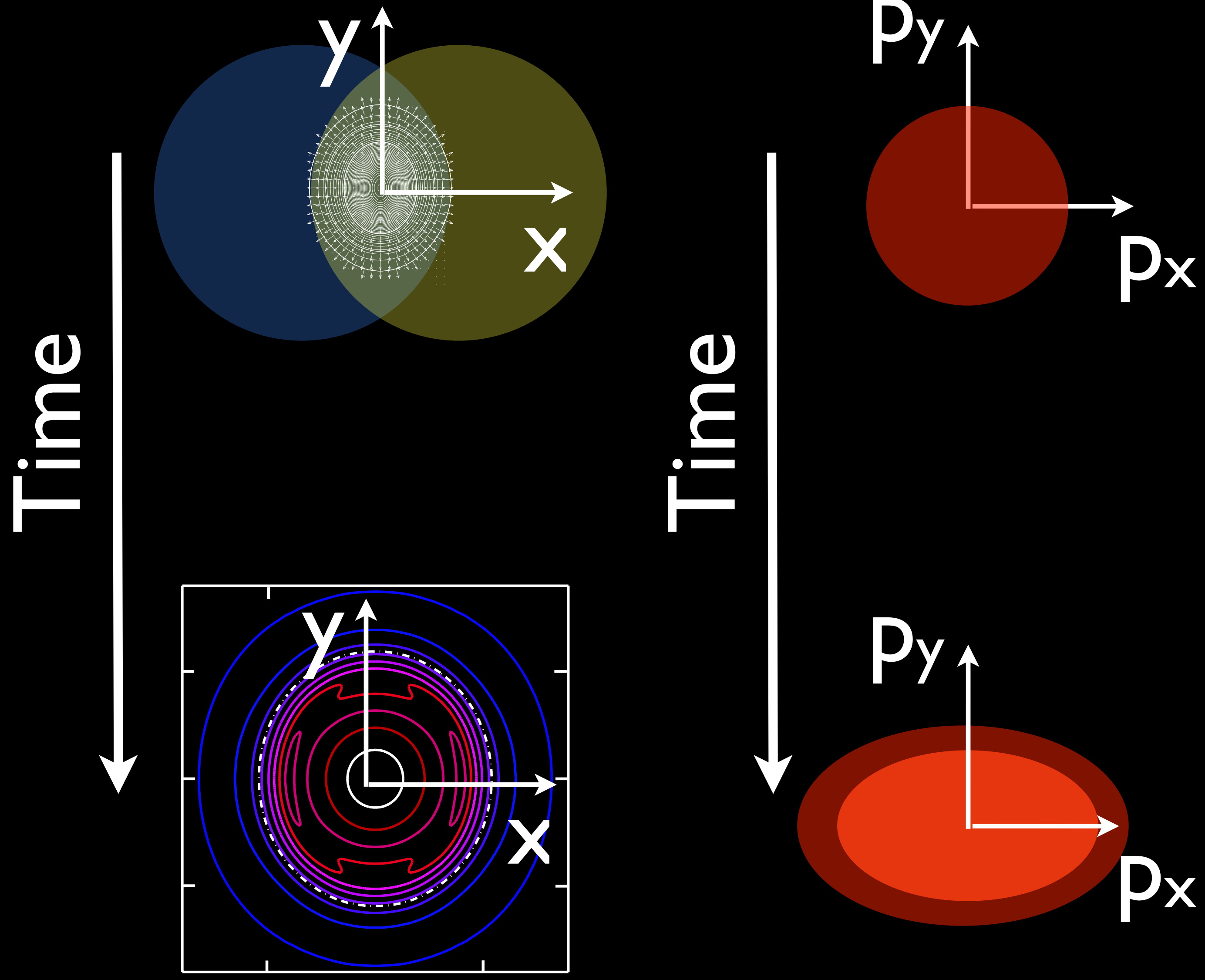
Elliptic Flow

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\phi \rangle$$

- in non central collisions coordinate space configuration is anisotropic (almond shape). However, initial momentum distribution isotropic (spherically symmetric)

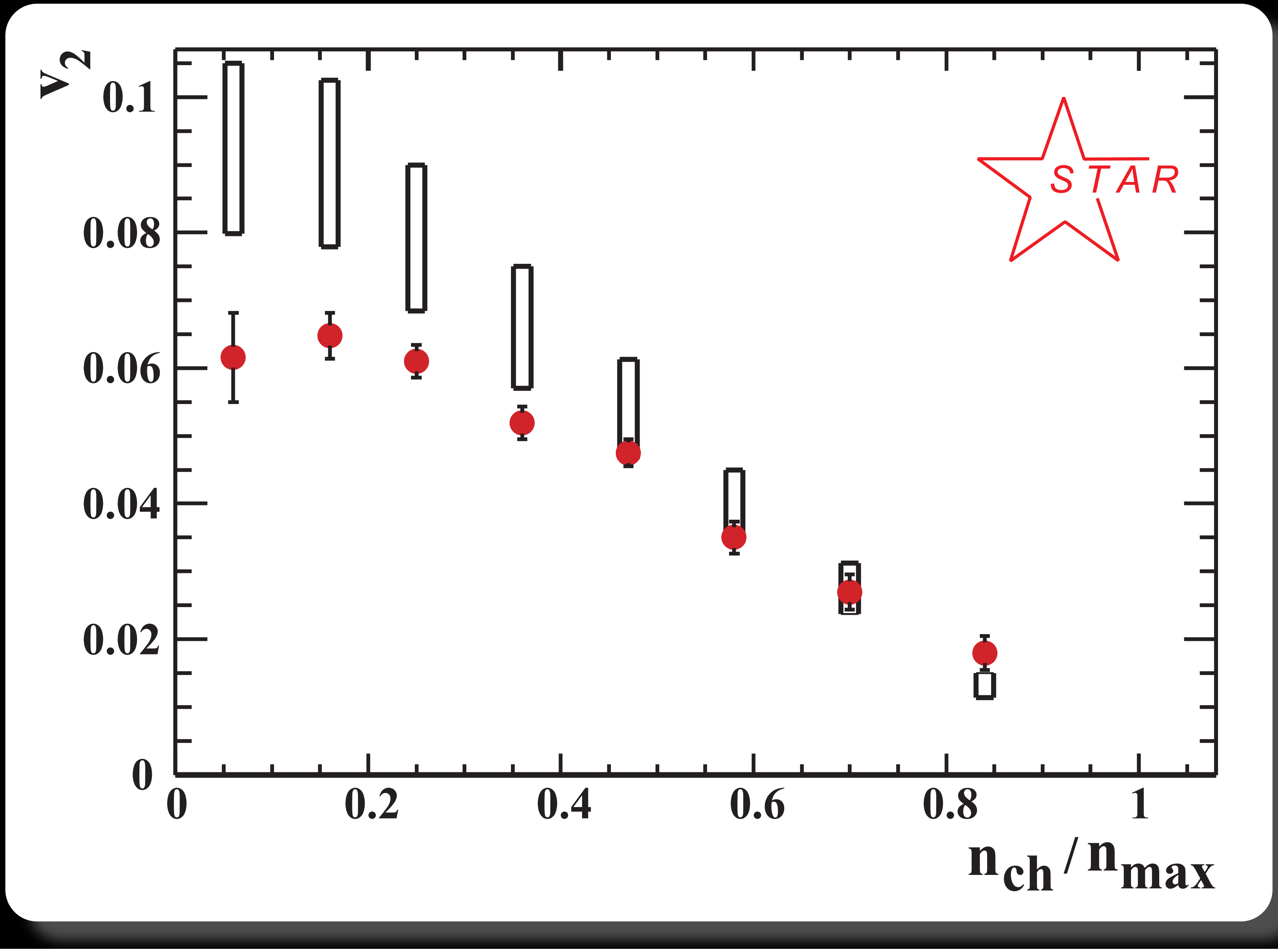
- interactions among constituents generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy → anisotropic flow

- self-quenching → sensitive to early stage



Flow at RHIC

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



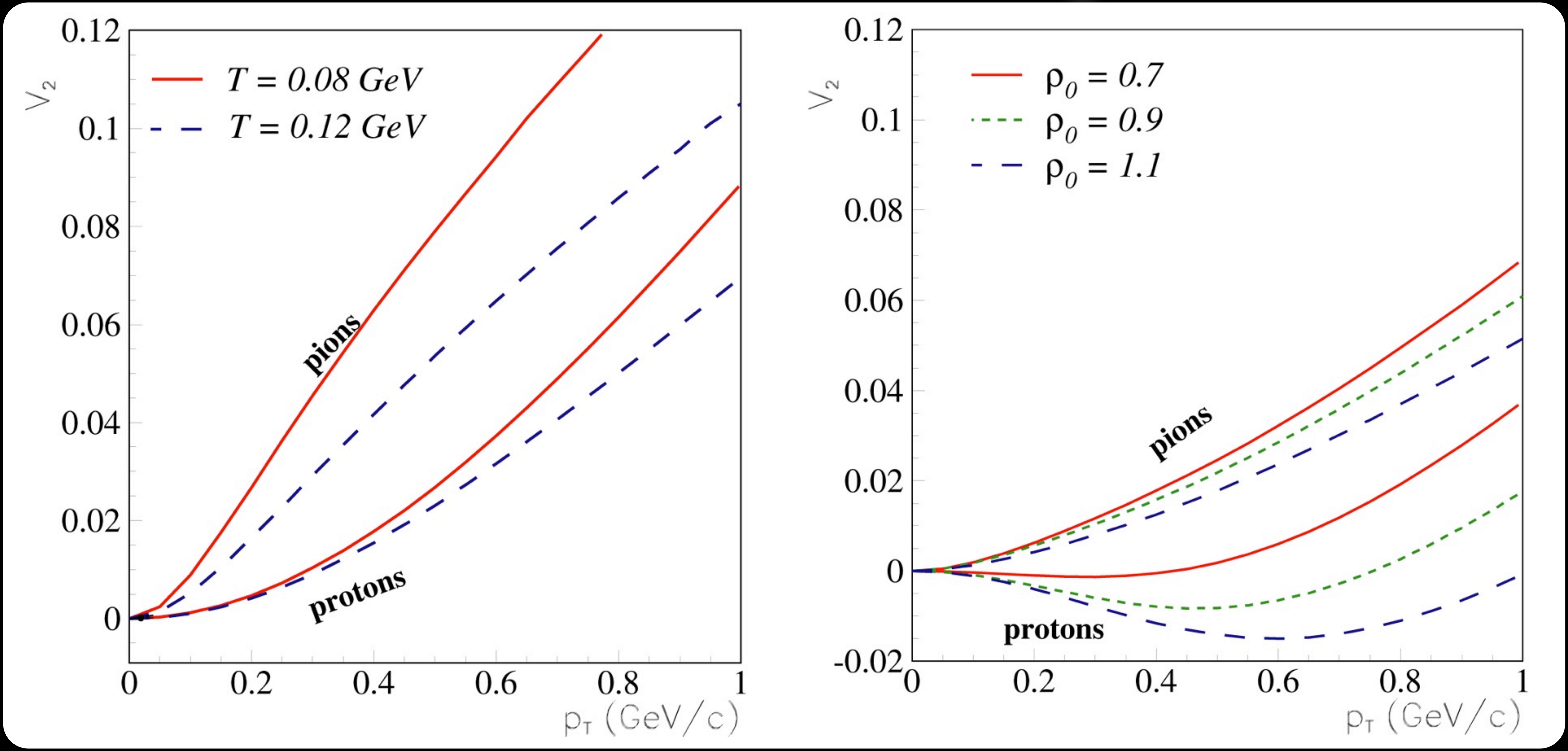
ideal hydro gets the magnitude for more central collisions

flow as large as it possibly can be?

$v_2(p_t)$ and particle mass

- on what freeze-out variables does it depend (simplification)?
  - the average velocity difference in and out of plane (due to Δp)
  - but also
    - the average freeze-out temperature
    - the average transverse flow

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

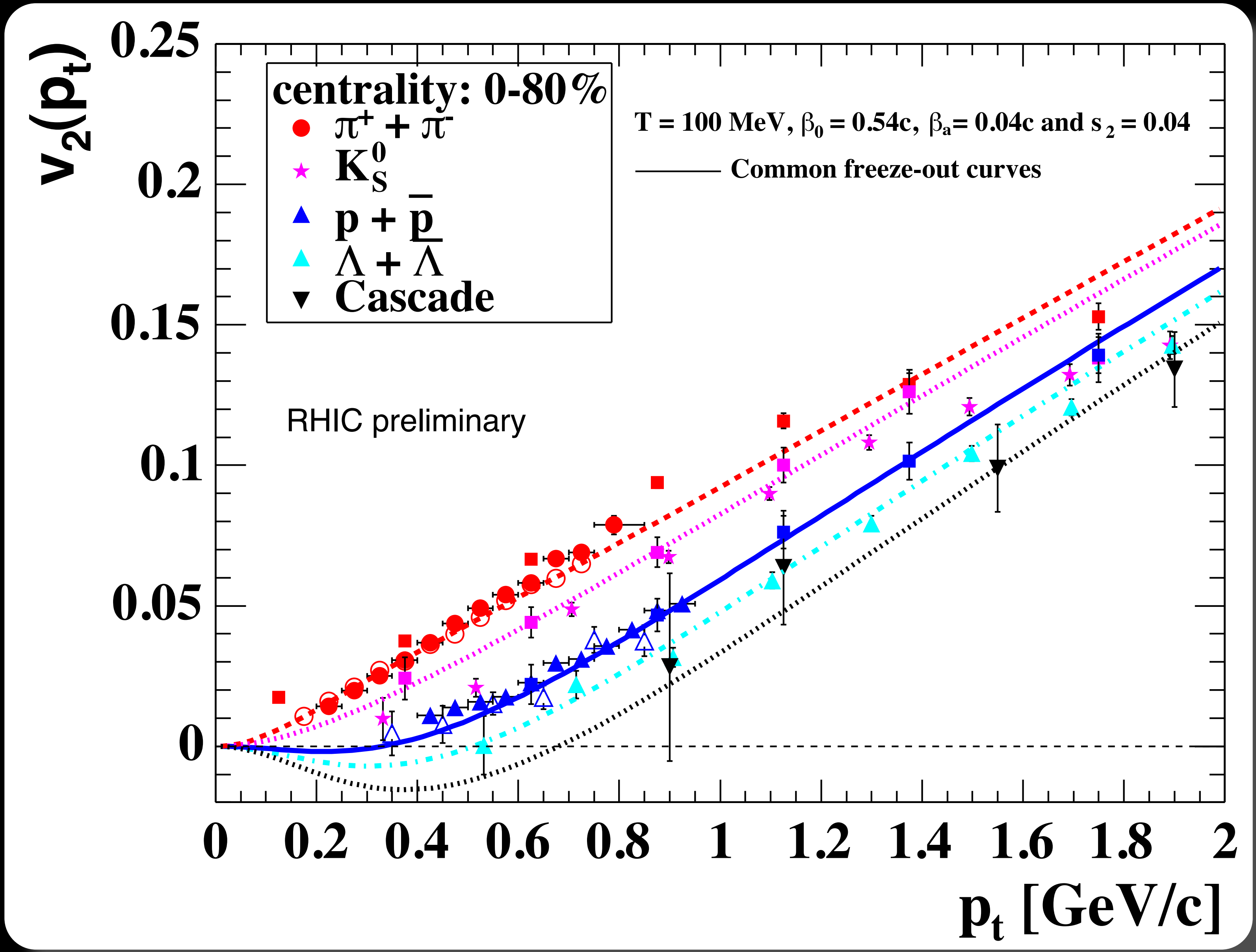


F. Retiere and M.A. Lisa, Phys.Rev.C70:044907,2004

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

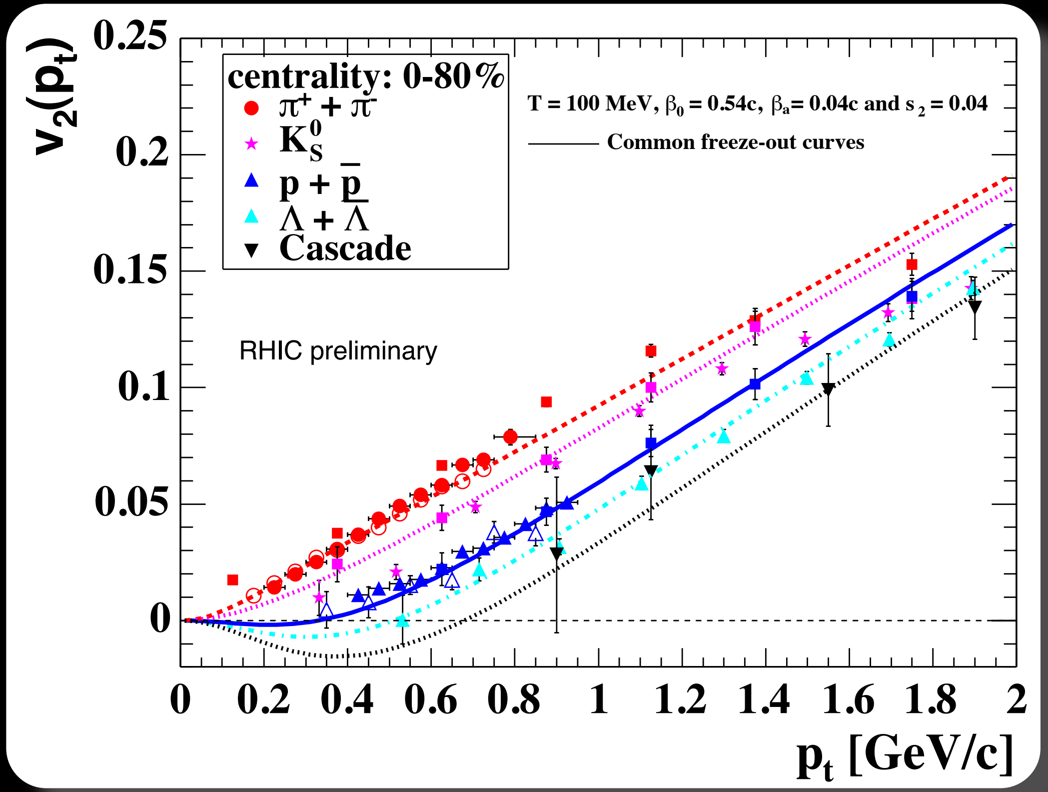
boosted thermal spectra

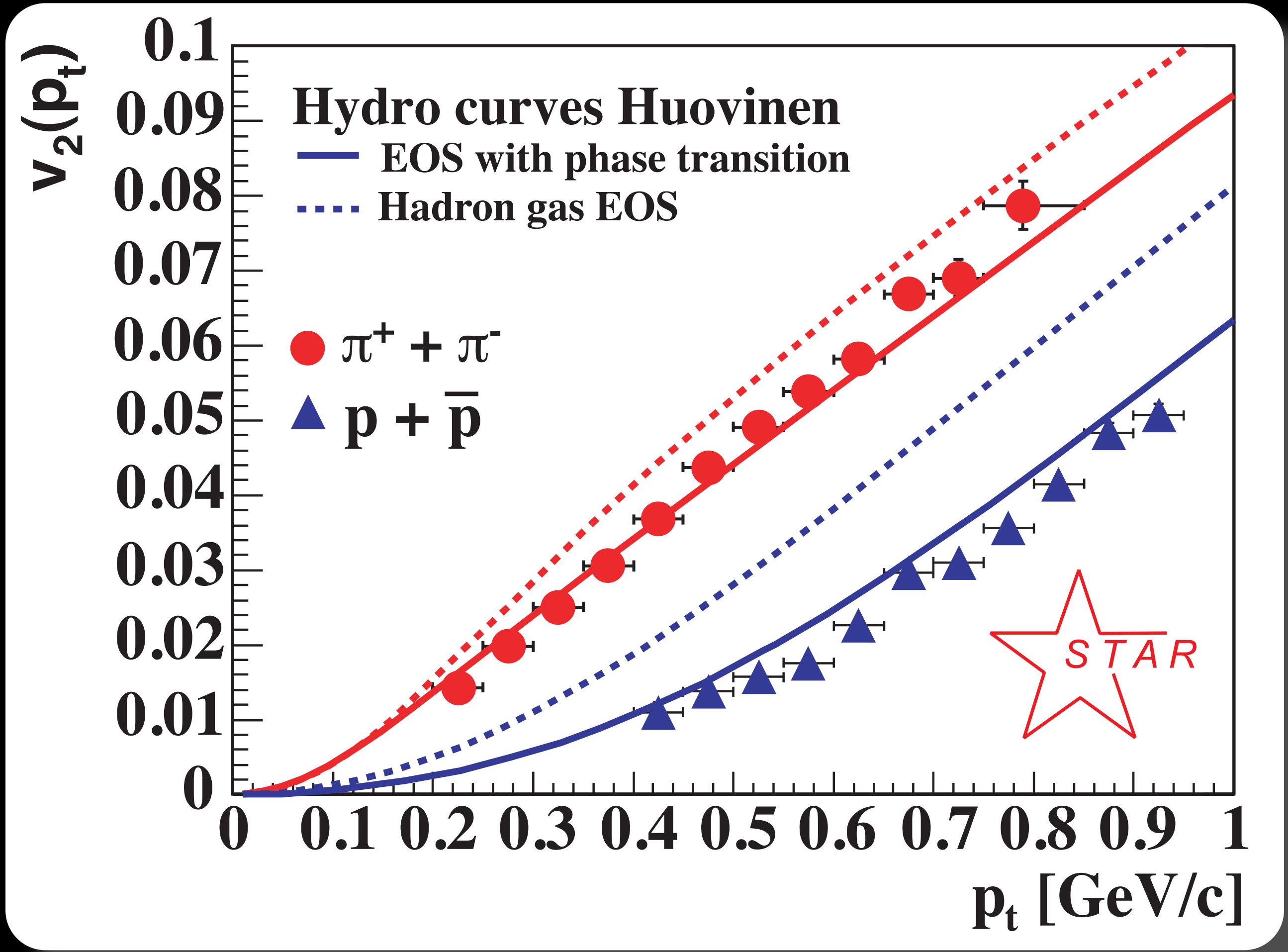
the observed particles are characterized by a single freeze-out temperature and a common azimuthal dependent boost velocity



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

The EoS





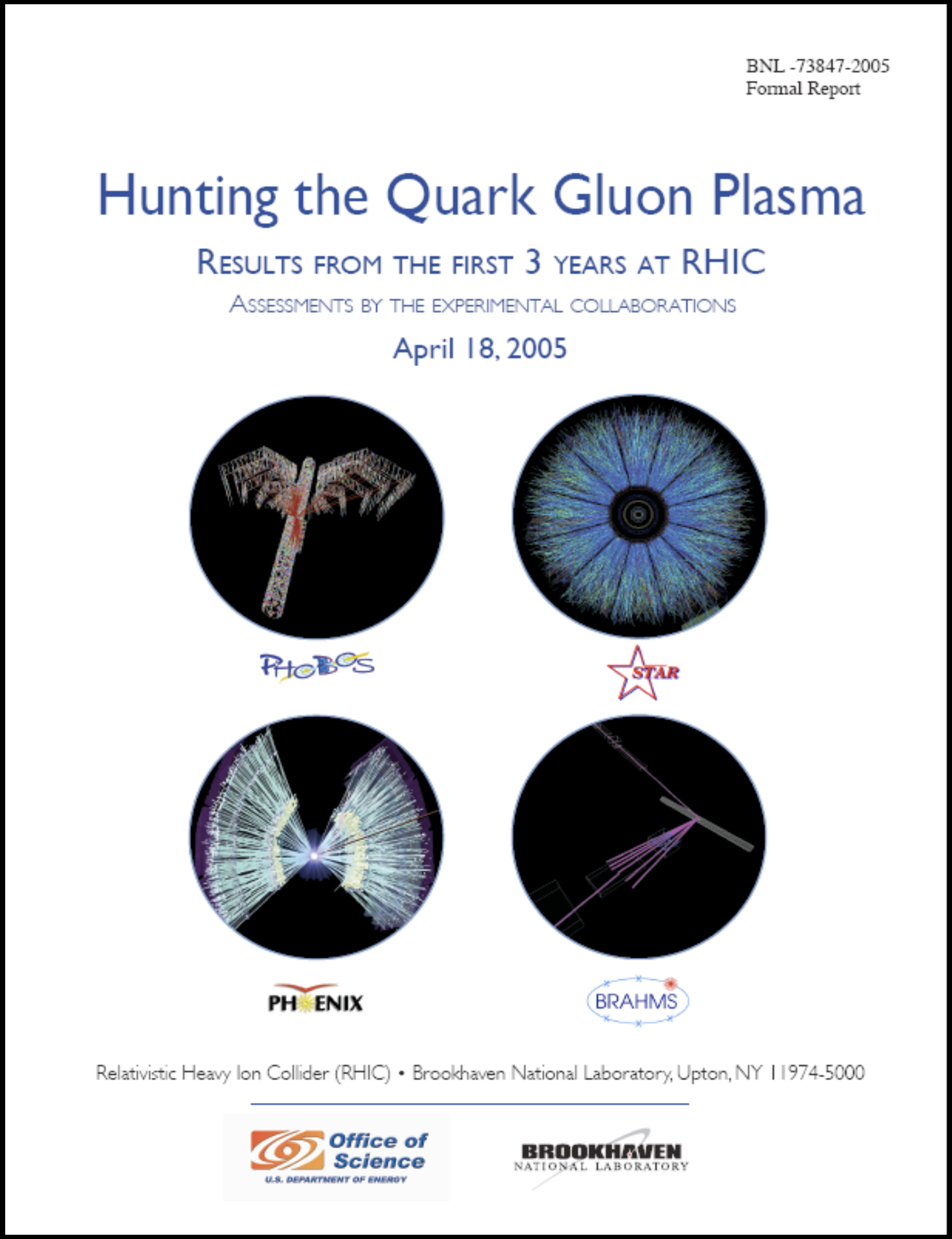
Data: STAR Phys. Rev. Lett. 87, 182301 (2001)

The species dependence is sensitive to the EoS

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

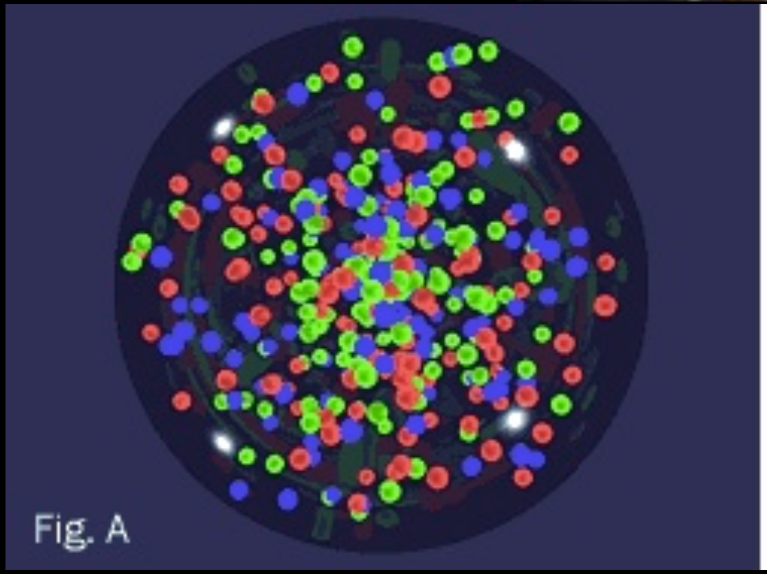


Fig. A

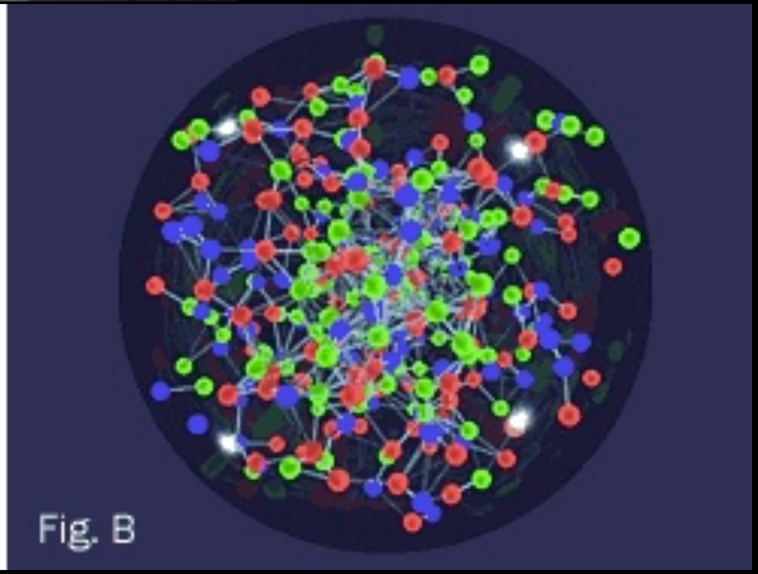
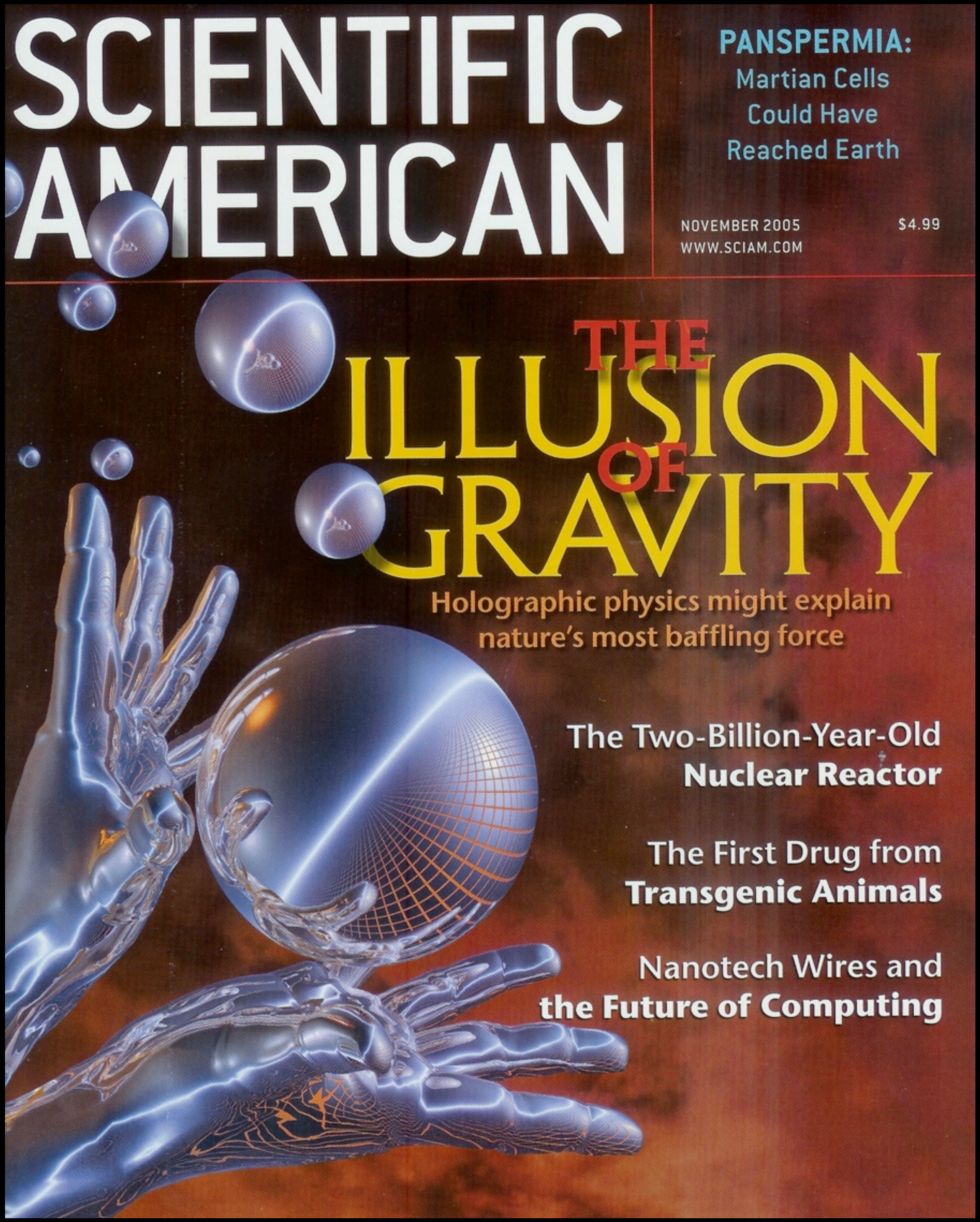


Fig. B

AdS/CFT



SCIENTIFIC AMERICAN

PANSPERMIA:
Martian Cells
Could Have
Reached Earth

NOVEMBER 2005
WWW.SCIAM.COM
$4.99

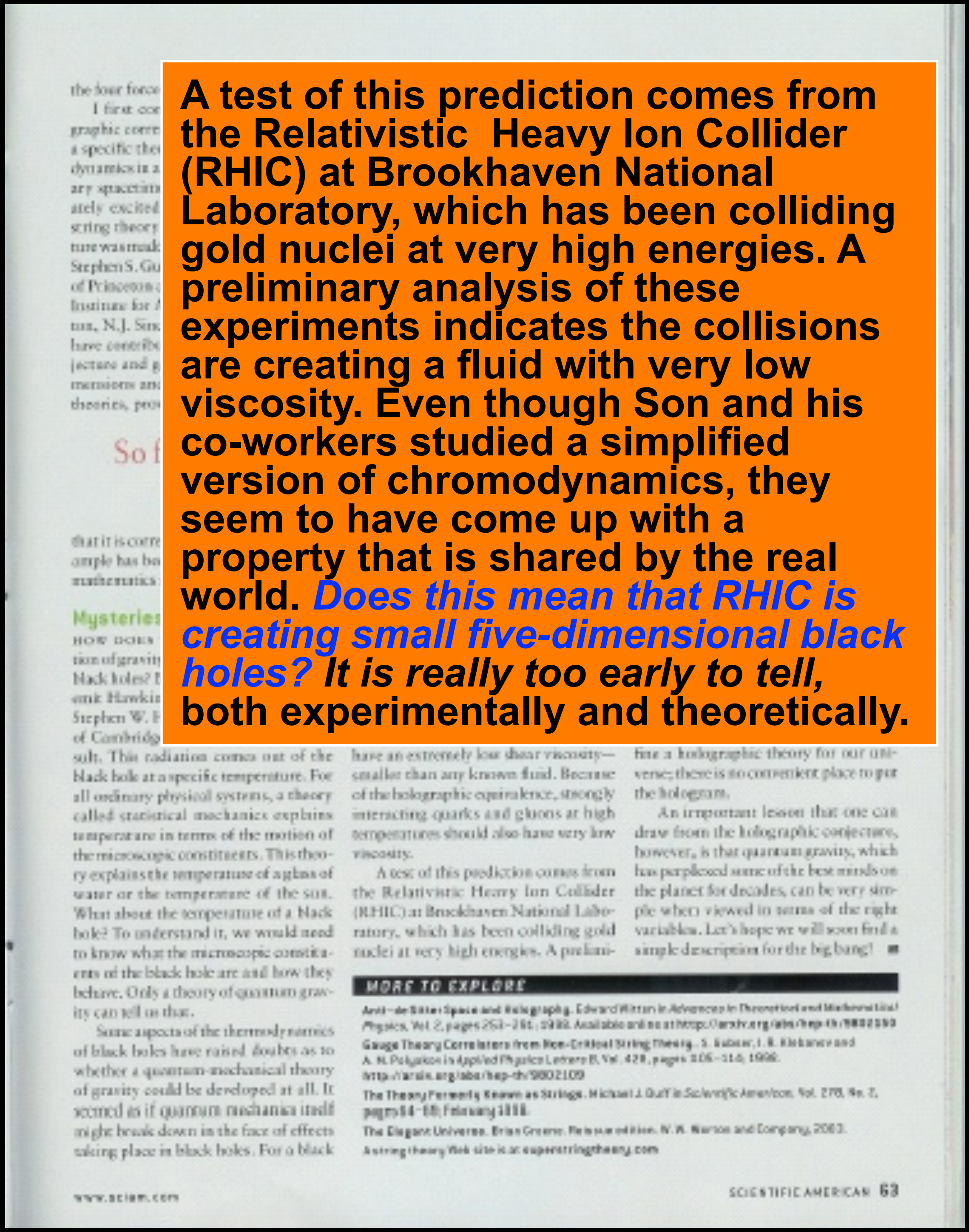
THE ILLUSION OF GRAVITY

Holographic physics might explain nature's most baffling force

The Two-Billion-Year-Old Nuclear Reactor

The First Drug from Transgenic Animals

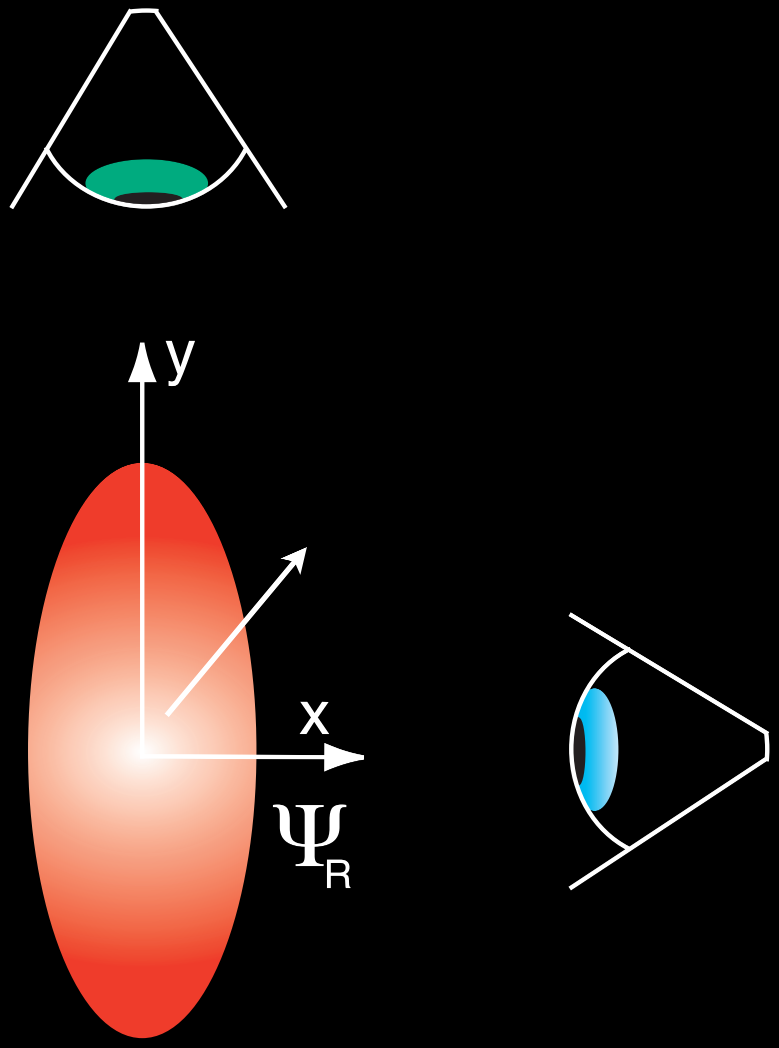
Nanotech Wires and the Future of Computing



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.

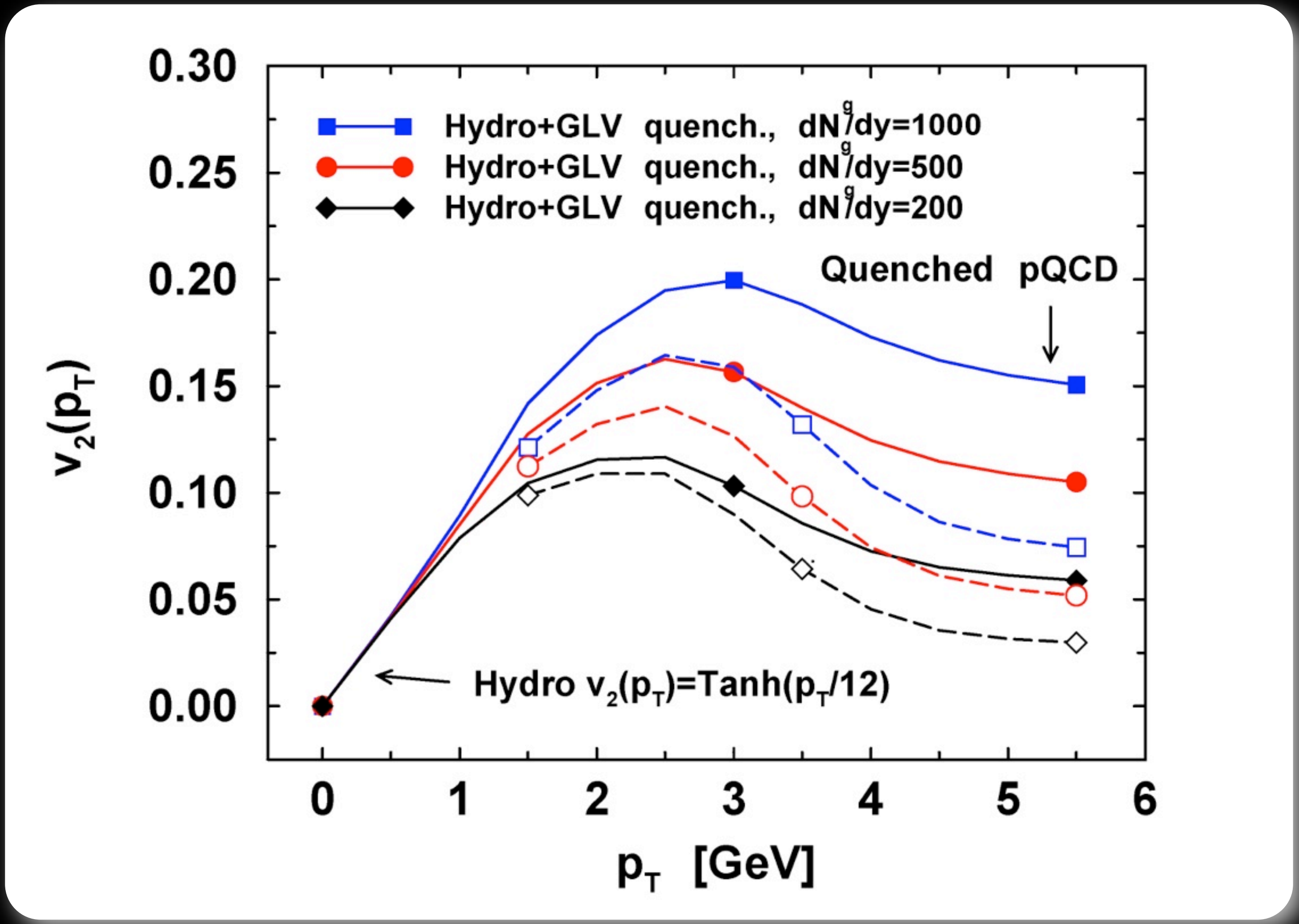
November, 2005 Scientific American "The Illusion of Gravity" J. Maldacena

parton energy loss



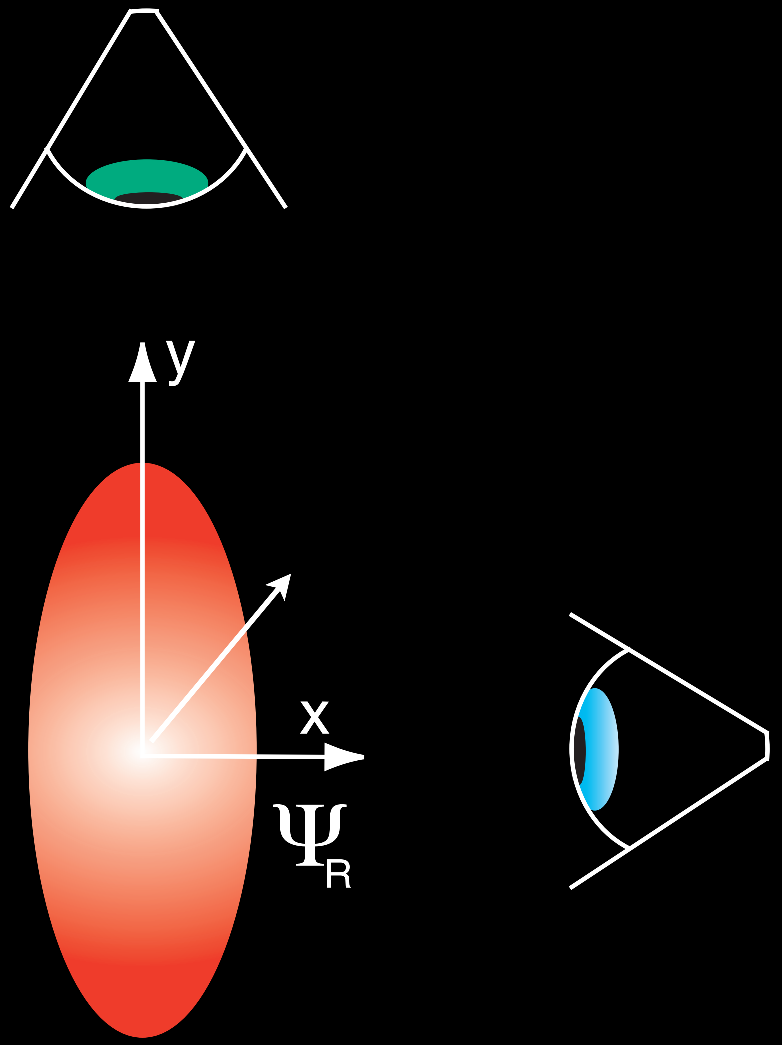
$$v_2 = \langle \cos 2(\phi - \Psi_R) \rangle$$

R.S, A.M. Poskanzer, S.A. Voloshin,
nucl-ex/9904003

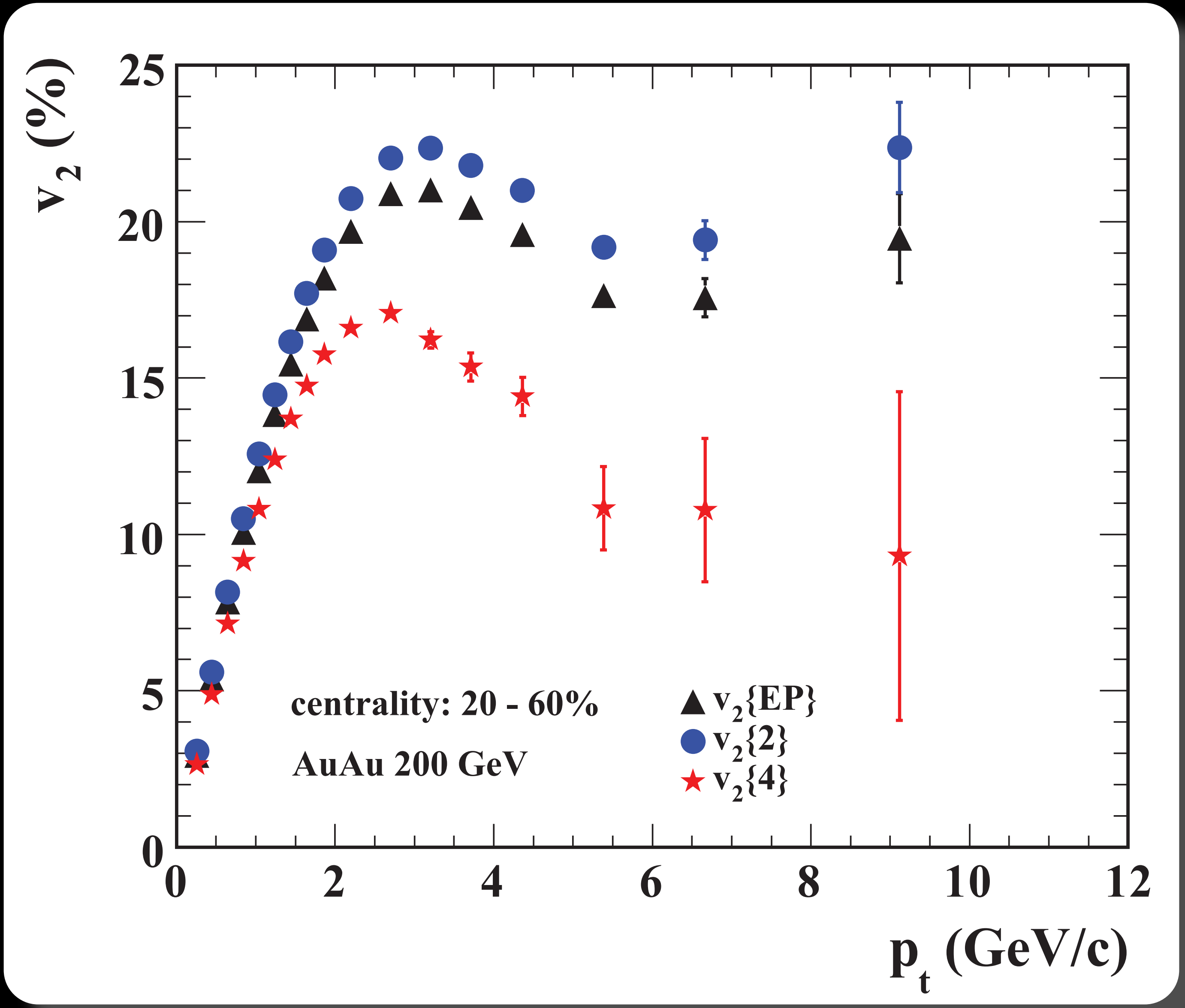


M. Gyulassy, I. Vitev and X.N. Wang
PRL 86 (2001) 2537

parton energy loss



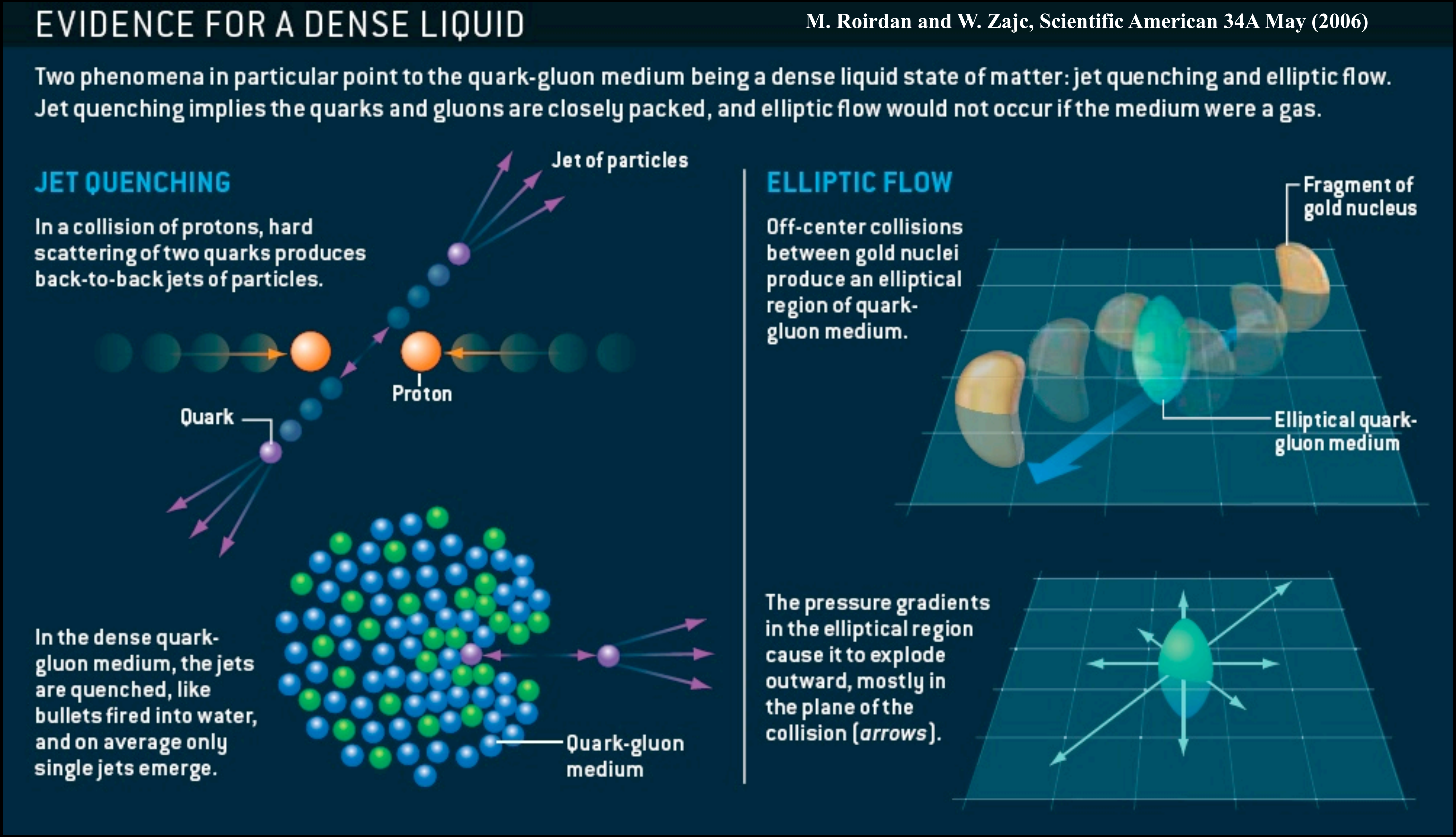
$$v_2 = \langle \cos 2(\phi - \Psi_R) \rangle$$



Yuting Bai, Nikhef PhD thesis

strong path length dependence observed!

highlights at RHIC



EVIDENCE FOR A DENSE LIQUID

M. Roirdan and W. Zajc, Scientific American 34A May (2006)

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.

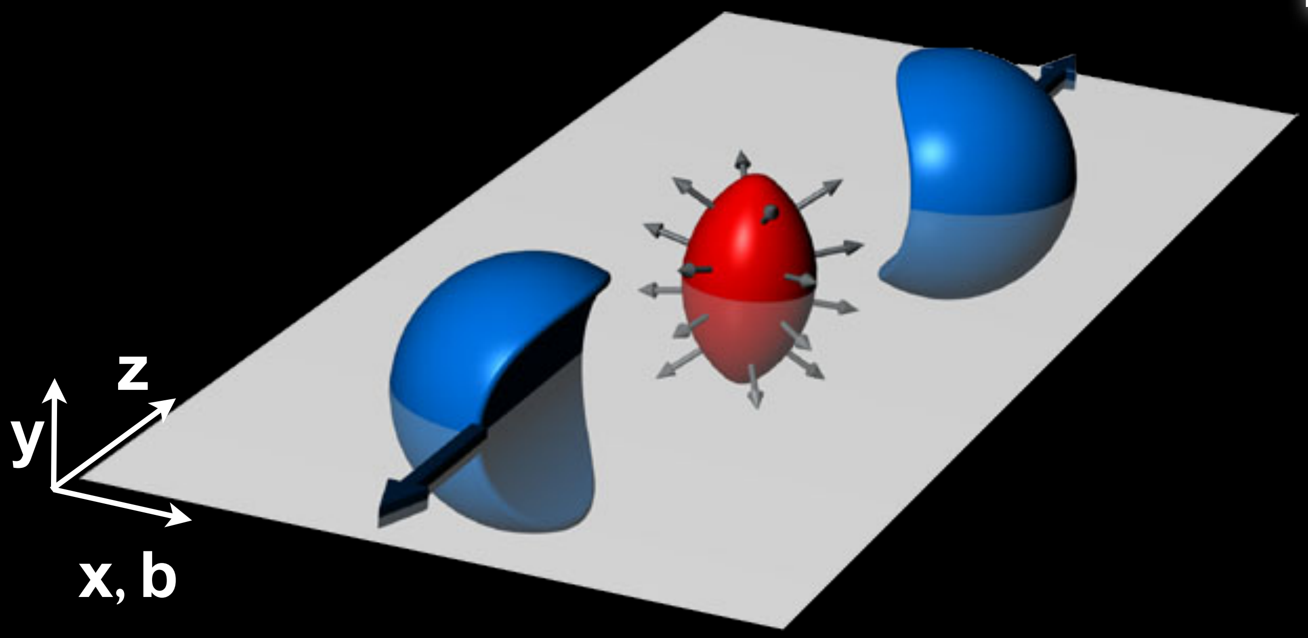
In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

ELLIPTIC FLOW

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).

How to Measure Anisotropic Flow?



Azimuthal distributions of particles measured with respect to the reaction plane (spanned by impact parameter vector and beam axis) are not isotropic.

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

$$v_n = \langle\cos n(\phi-\Psi_{\mathrm{RP}})\rangle$$

harmonics v_n quantify anisotropic flow

S. Voloshin and Y. Zhang (1996)

measure anisotropic flow

- since reaction plane cannot be measured event-by-event, consider quantities which do not depend on it’s orientation: multi-particle azimuthal correlations

$$\left\langle e^{in(\phi_1-\phi_2)}\right\rangle = \left\langle e^{\underset{\uparrow}{in\phi_1}}\right\rangle \left\langle e^{\underset{\uparrow}{-in\phi_2}}\right\rangle + \left\langle e^{in(\phi_1-\phi_2)}\right\rangle_{\mathrm{corr}}$$

zero for symmetric detector when averaged over many events

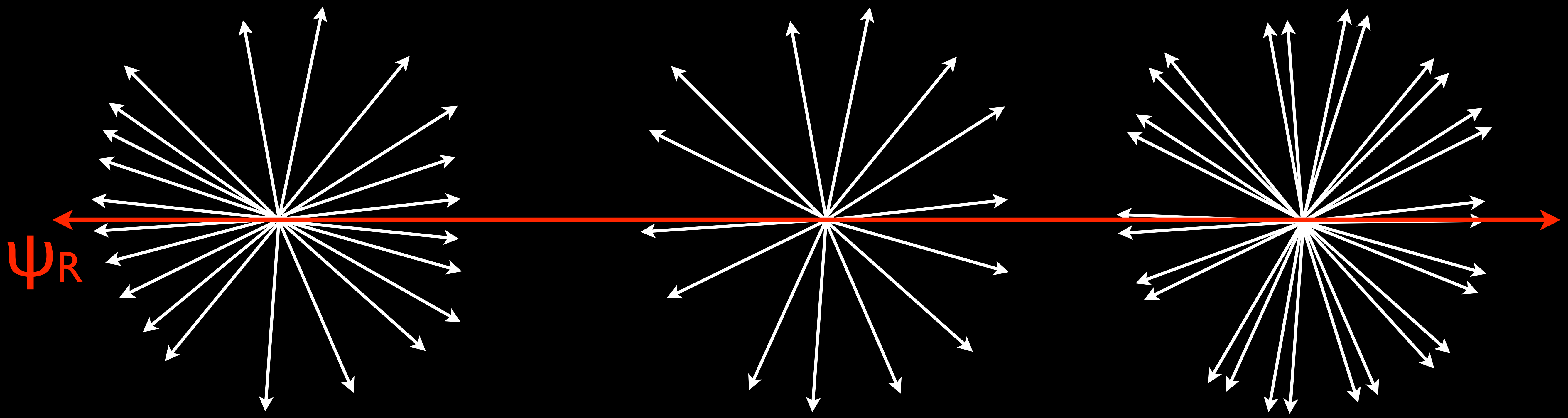
$$\begin{aligned}\langle\langle 2\rangle\rangle \equiv \left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle &= \left\langle\left\langle e^{in(\phi_1-\Psi_{\mathrm{RP}}-(\phi_2-\Psi_{\mathrm{RP}}))}\right\rangle\right\rangle \\ &= \left\langle\left\langle e^{in(\phi_1-\Psi_{\mathrm{RP}})}\right\rangle\left\langle e^{-in(\phi_2-\Psi_{\mathrm{RP}})}\right\rangle\right\rangle \\ &= \left\langle v_n^2\right\rangle\end{aligned}$$

- assuming that only correlations with the reaction plane are present

nonflow

- however, there are other sources of correlations between the particles which are not related to the reaction plane which break the factorization, lets call those δ_2 for two particle correlations

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



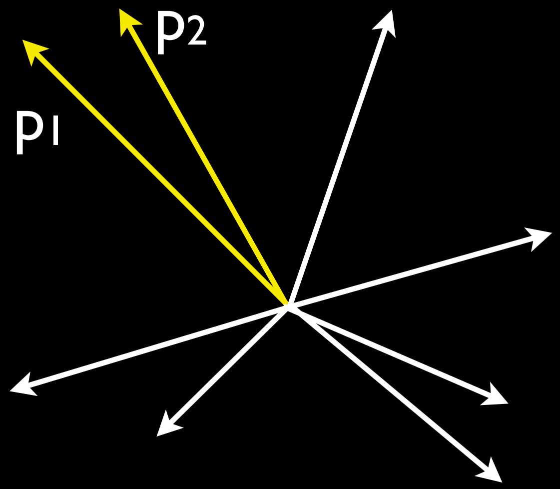
$v_2 > 0$, $v_2\{2\} > 0$

$v_2 = 0$, $v_2\{2\} = 0$

$v_2 = 0$, $v_2\{2\} > 0$

nonflow

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



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

can we do better?

- use the fact that flow is a correlation between all particles: use multi-particle correlations

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

$$\left\langle\!\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle\!\right\rangle = v_n^4 + 4v_n^2\delta_2 + 2\delta_2^2 + \delta_4$$

- not so clear if we gained something

Can we do better?

- build cumulants with the multi-particle correlations

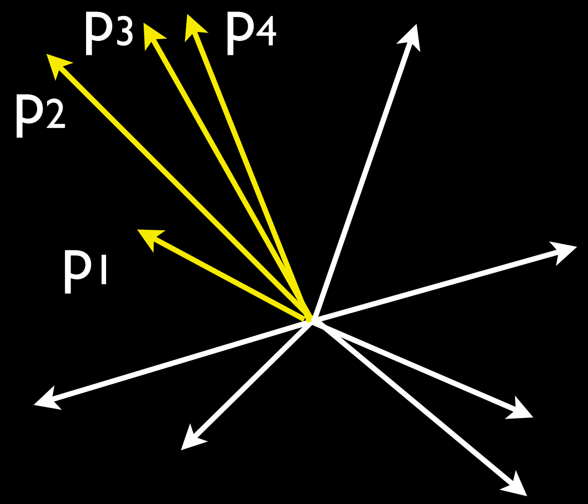
Ollitrault and Borghini

- for detectors with uniform acceptance 2nd and 4th cumulant are given by:

$$\begin{aligned} c_n\{2\} &\equiv \left\langle\!\left\langle e^{in(\phi_1-\phi_2)} \right\rangle\!\right\rangle = v_n^2 + \delta_2 \\ c_n\{4\} &\equiv \left\langle\!\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle\!\right\rangle - 2\left\langle\!\left\langle e^{in(\phi_1-\phi_2)} \right\rangle\!\right\rangle^2 \\ &= v_n^4 + 4v_n^2\delta_2 + 2\delta_2^2 - 2(v_n^2+\delta_2)^2 + \delta_4 \\ &= -v_n^4 + \delta_4 \end{aligned}$$

- got rid of two particle non-flow correlations!

Can we do better?



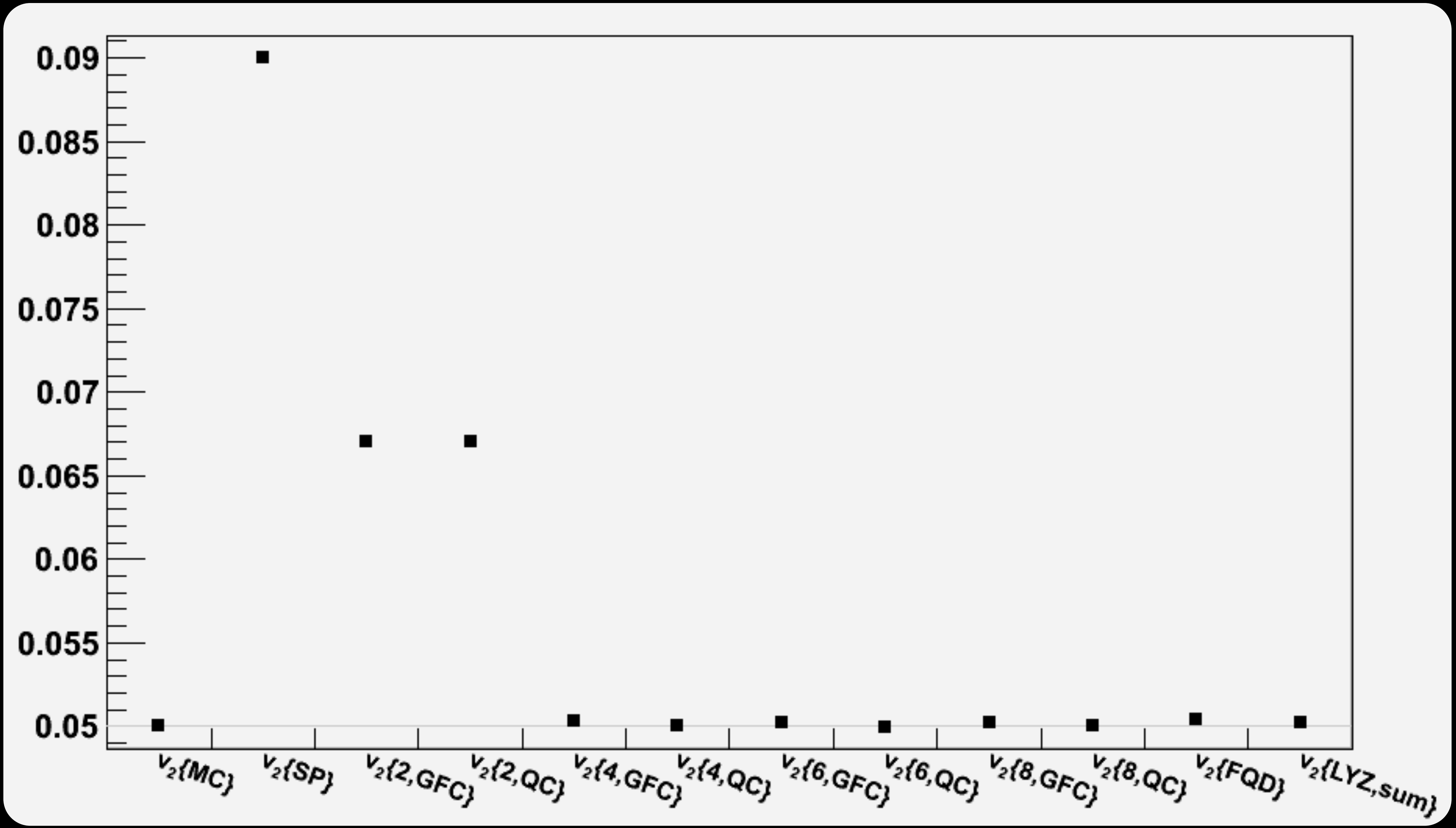
Particle 1 coming from the mini-jet. To select particle 2 we can make a choice out of remaining M-1 particles; once particle 2 is selected we can select particle 3 out of remaining M-2 particles and finally we can select particle 4 out of remaining M-3 particles. Hence the probability that we will select randomly four particles coming from the same resonance is 1/(M-1)(M-2)(M-3). From this we can draw a conclusion that for large multiplicity: $\delta_2 \sim 1/M, \qquad \delta_4 \sim 1/M^3$

- therefore to reliably measure flow:

$$v_n^2 \gg 1/M \quad \Rightarrow \quad v_n \gg 1/M^{1/2}$$
$$v_n^4 \gg 1/M^3 \quad \Rightarrow \quad v_n \gg 1/M^{3/4}$$

nonflow example

Example: input $v_2 = 0.05$, $M = 500$, $N = 5 \times 10^6$ and simulate nonflow by taking each particle twice



as expected only two particle methods are biased

Flow Fluctuations

Both two and multi-particle correlations have an extra feature one has to keep in mind!

- By using multi-particle correlations to estimate flow we are actually estimating the averages of various powers of flow

$$\begin{aligned} \langle\langle 2\rangle\rangle &= \left\langle v^2\right\rangle , \quad \langle\langle 6\rangle\rangle = \left\langle v^6\right\rangle \\ \langle\langle 4\rangle\rangle &= \left\langle v^4\right\rangle , \quad \langle\langle 8\rangle\rangle = \left\langle v^8\right\rangle \end{aligned}$$

- But what we are after is: $\langle v\rangle$

Flow Fluctuations

- in general: take a random variable x with mean μ_x and spread σ_x . The the expectation value of some function of a random variable x, E[h(x)], is to leading order given by

$$\langle h(x)\rangle \equiv E[h(x)] = h(\mu_x) + \frac{\sigma_x^2}{2} h''(\mu_x)$$

- using this for the flow results:

$$\begin{aligned}
\left\langle v^2 \right\rangle &= \langle v\rangle^2 + \sigma_v^2 \\
\left\langle v^4 \right\rangle &= \langle v\rangle^4 + 6\sigma_v^2 \langle v\rangle^2 \\
\left\langle v^6 \right\rangle &= \langle v\rangle^6 + 15\sigma_v^2 \langle v\rangle^4 \\
\left\langle v^8 \right\rangle &= \langle v\rangle^8 + 28\sigma_v^2 \langle v\rangle^6
\end{aligned}$$

- remember cumulants are combinations of these quantities

Flow Fluctuations

- flow estimates from cumulants can be written as:

$$\begin{aligned} v\{2\} &= \left\langle v^2 \right\rangle^{1/2} \\ v\{4\} &= \left(-\left\langle v^4\right\rangle + 2\left\langle v^2\right\rangle^2\right)^{1/4} \\ v\{6\} &= \left[\frac{1}{4}\left(\left\langle v^6\right\rangle - 9\left\langle v^2\right\rangle\left\langle v^4\right\rangle + 12\left\langle v^2\right\rangle^3\right)\right]^{1/6} \\ v\{8\} &= \left[-\frac{1}{33}\left[\left\langle v^8\right\rangle - 16\left\langle v^6\right\rangle\left\langle v^2\right\rangle - 18\left\langle v^4\right\rangle^2\right.\right. \\ &\qquad \left.\left. +144\left\langle v^4\right\rangle\left\langle v^2\right\rangle^2 - 144\left\langle v^2\right\rangle^4\right]\right]^{1/8} \end{aligned}$$

- take the expression from previous slide and use:

$$\sigma_v \ll \langle v \rangle$$

- take up to order σ^2, the surprisingly simple result is:

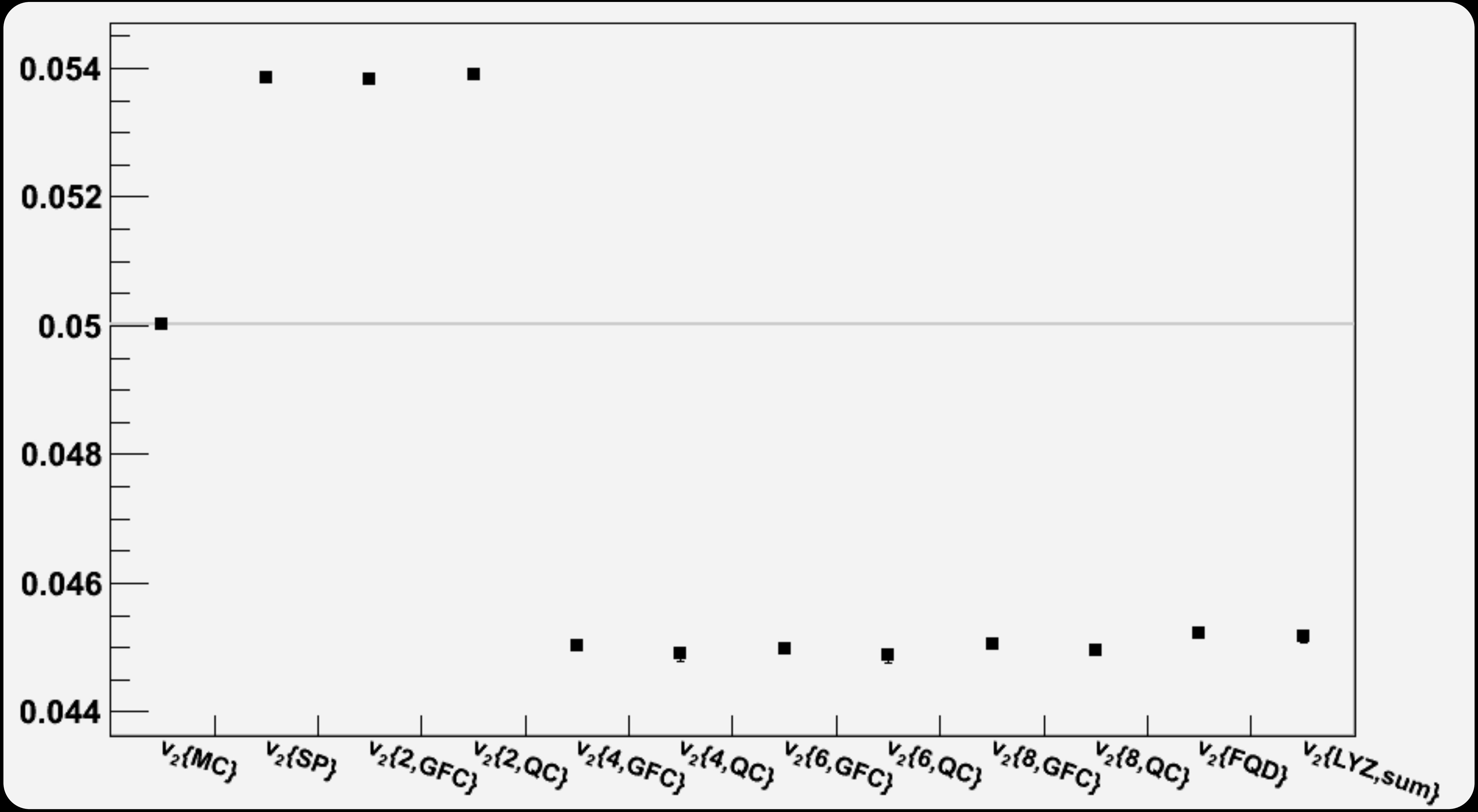
Flow Fluctuations

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

- for $\sigma_v << <v>$ this is a general result to order σ^2

Flow Fluctuations

Example: input v_2 = 0.05 +/- 0.02 (Gausian), M = 500, $N = 1 \times 10^6$

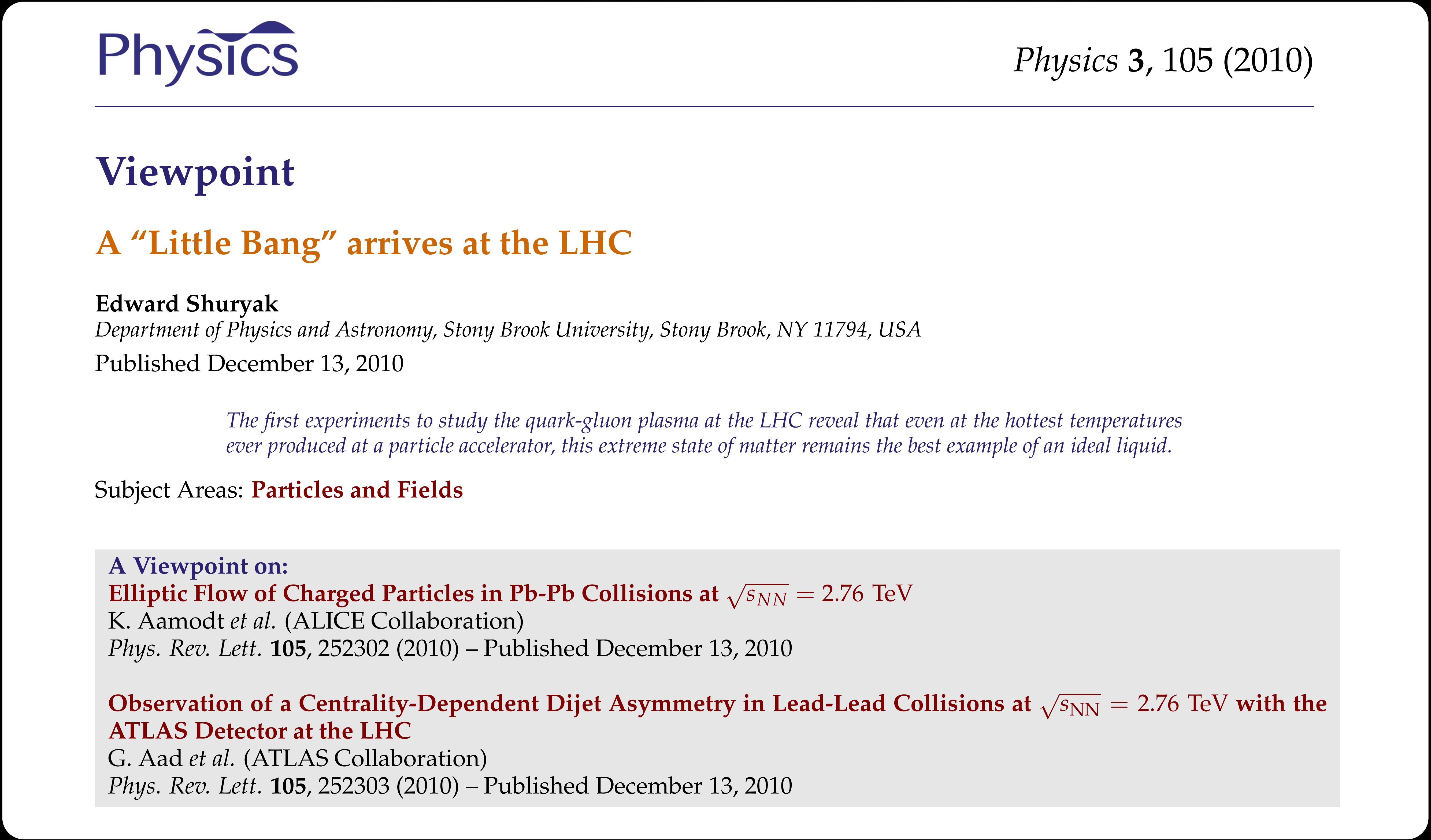


Gaussian fluctuation behave as predicted also for Lee Yang Zeroes and fitting Q distribution (more on that later)

Summary Methods

- two particle methods are sensitive to nonflow
- all methods are effected by event-by-event fluctuations of the flow
    - but for most cases this happens in a controlled way (although we can not disentangle nonflow and fluctuations unambiguously)

Current Results



Physics

Physics **3**, 105 (2010)

Viewpoint

A "Little Bang" arrives at the LHC

Edward Shuryak
Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA

Published December 13, 2010

The first experiments to study the quark-gluon plasma at the LHC reveal that even at the hottest temperatures ever produced at a particle accelerator, this extreme state of matter remains the best example of an ideal liquid.

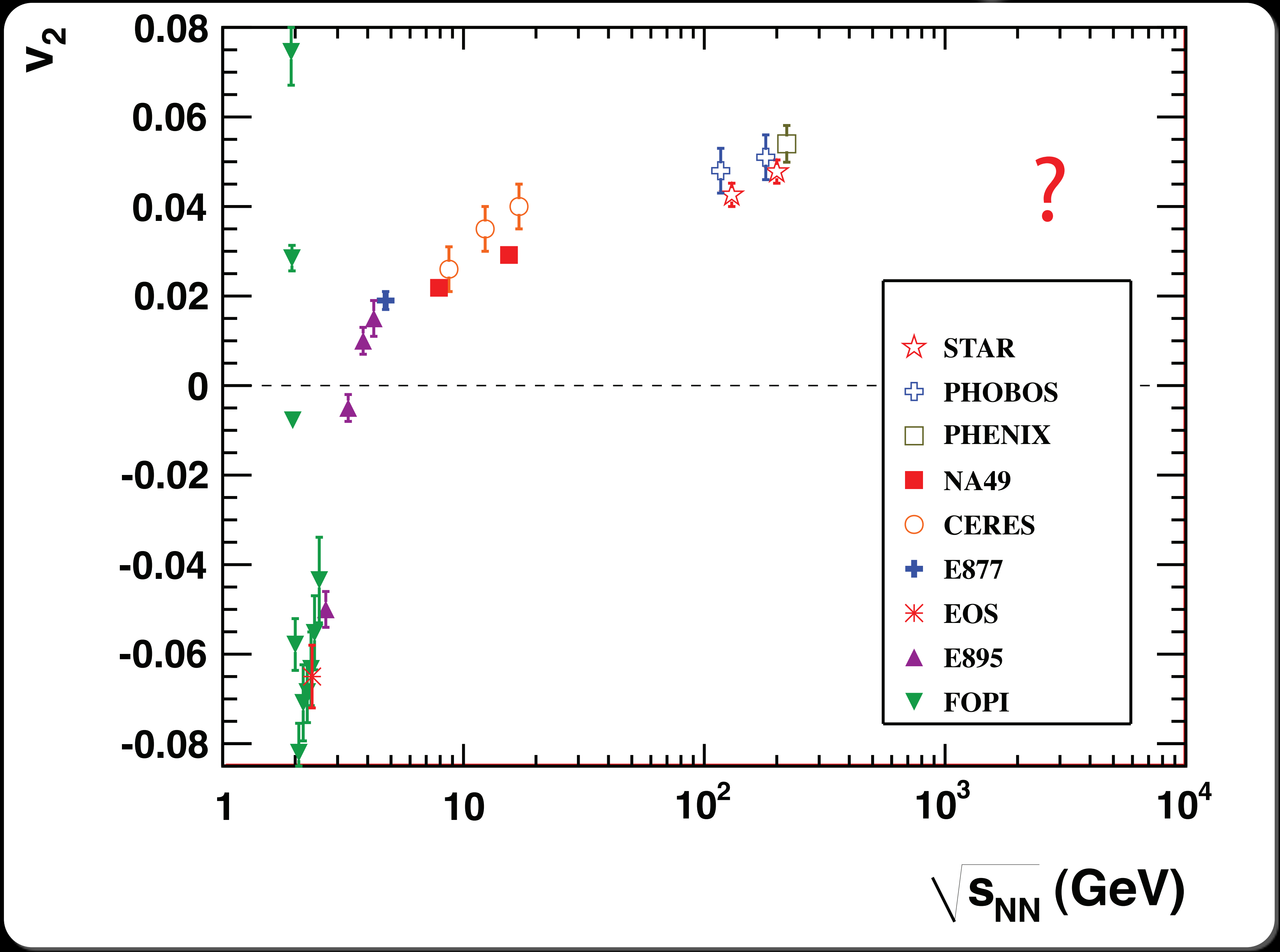
Subject Areas: **Particles and Fields**

A Viewpoint on:
Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV
K. Aamodt *et al.* (ALICE Collaboration)
Phys. Rev. Lett. **105**, 252302 (2010) – Published December 13, 2010

Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV **with the ATLAS Detector at the LHC**
G. Aad *et al.* (ATLAS Collaboration)
Phys. Rev. Lett. **105**, 252303 (2010) – Published December 13, 2010

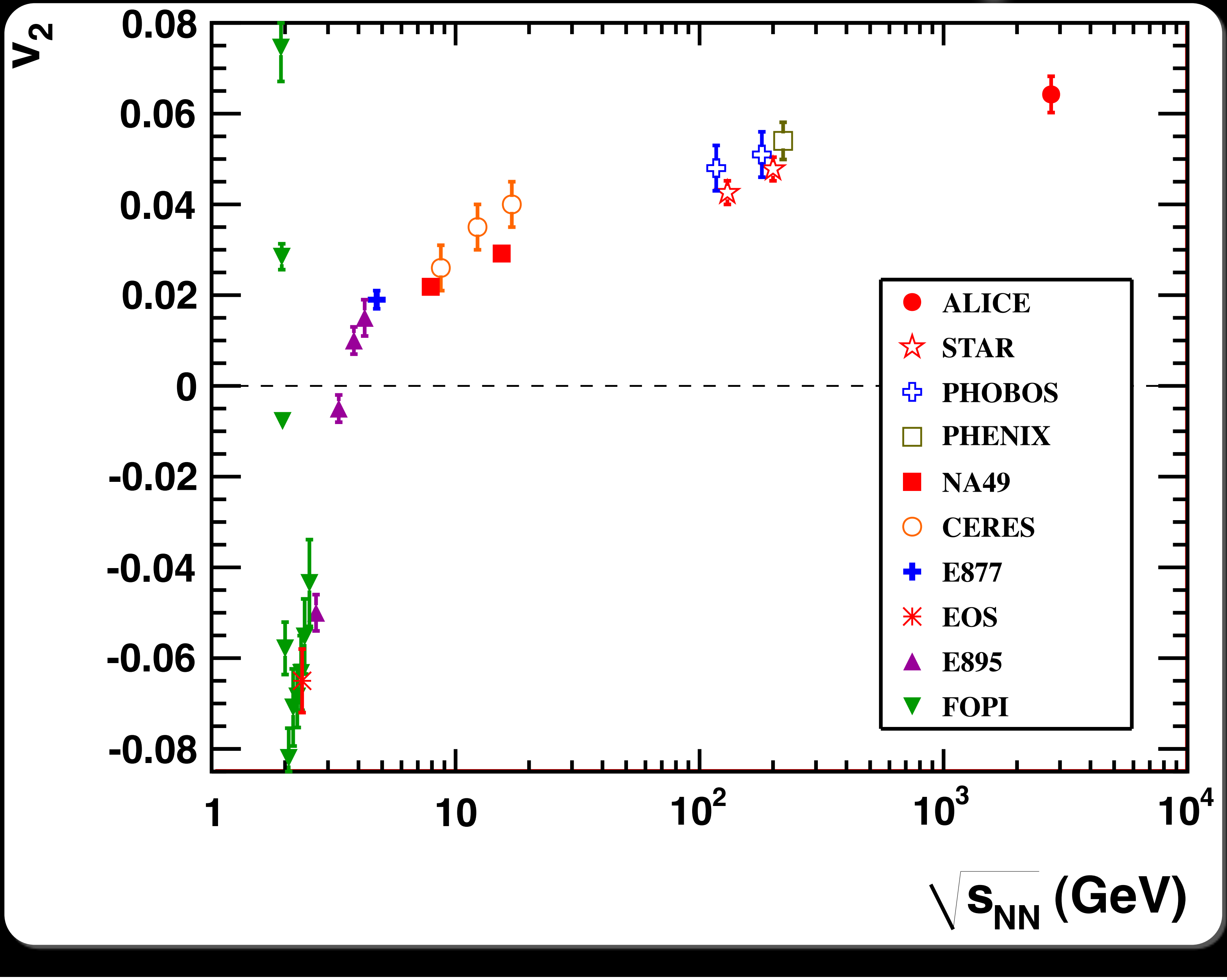
more in the conference

The Perfect Liquid?



What to expect at the LHC: still the perfect liquid or approaching a viscous ideal gas?

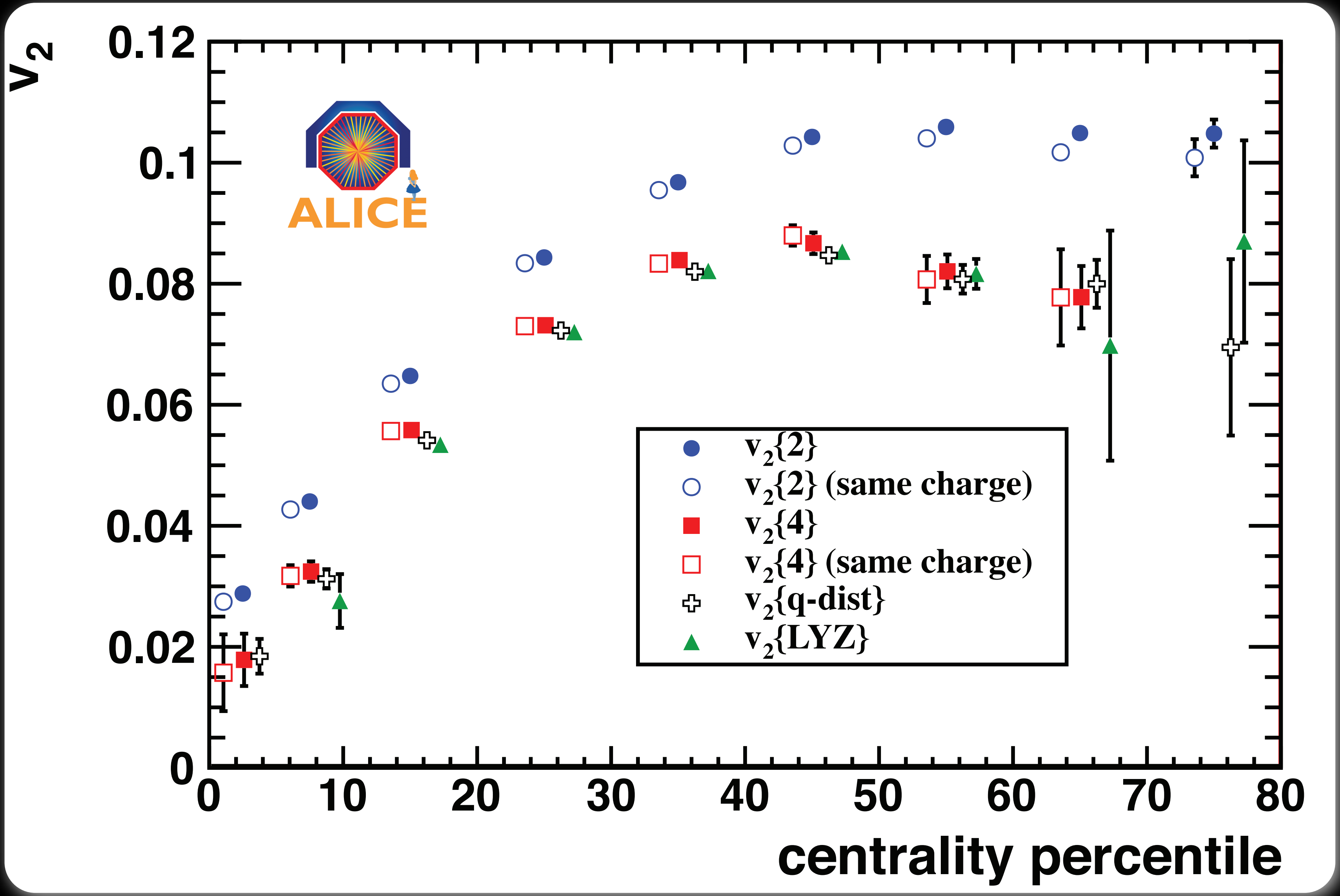
The Perfect Liquid?



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

CERN, November 26, 2010:
‘the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..’

v_2 in ALICE



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

expected difference between two and multi-particle estimates

multi-particle estimates agree within uncertainties as is expected for collective flow!

Flow Fluctuations

when nonflow is negligible!

in limit of small (not necessarily Gaussian) fluctuations

$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2$$

$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$

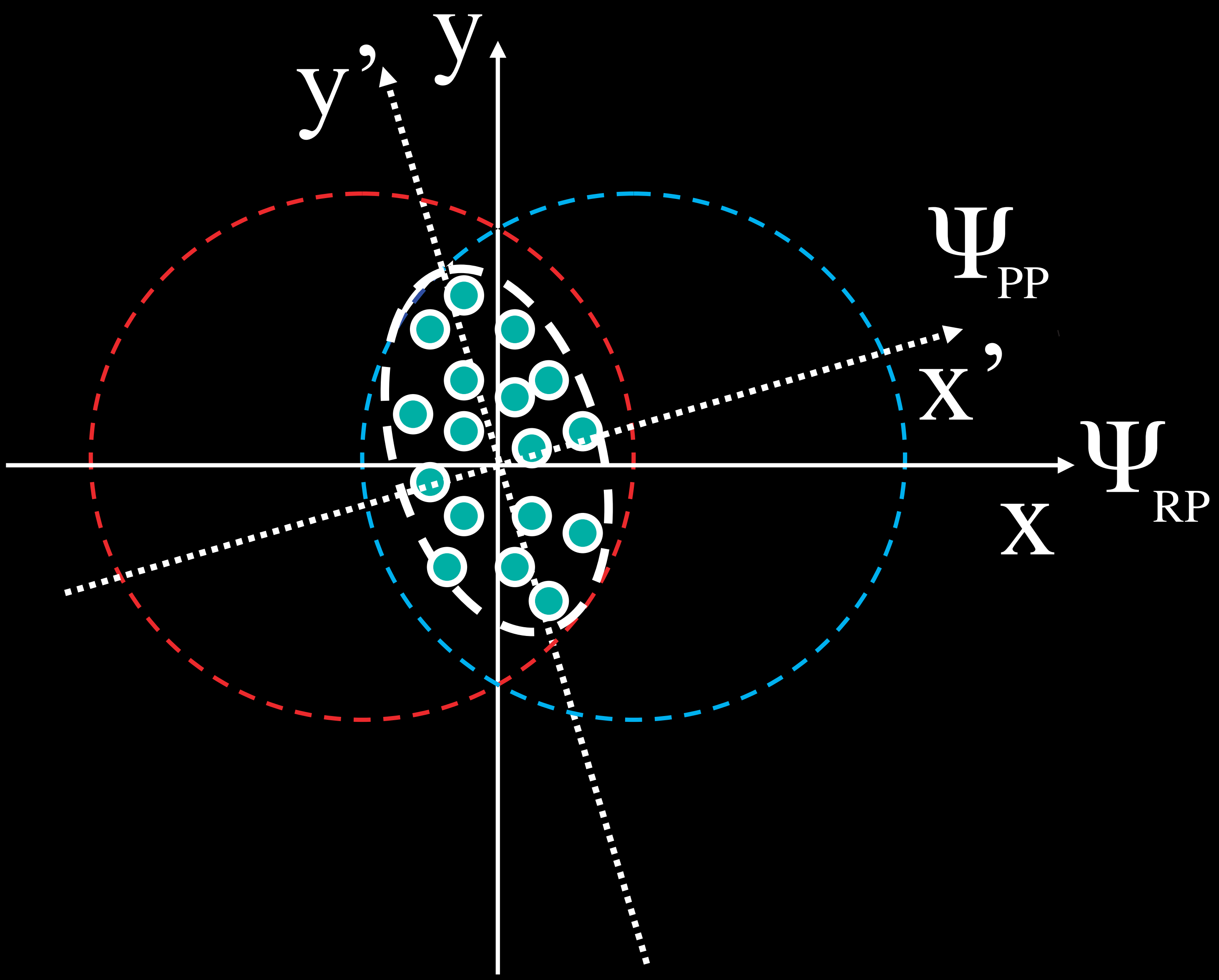
$$v_n^2\{2\} + v_n^2\{4\} = 2\bar{v}_n^2$$

$$v_n^2\{2\} - v_n^2\{4\} = 2\sigma_v^2$$

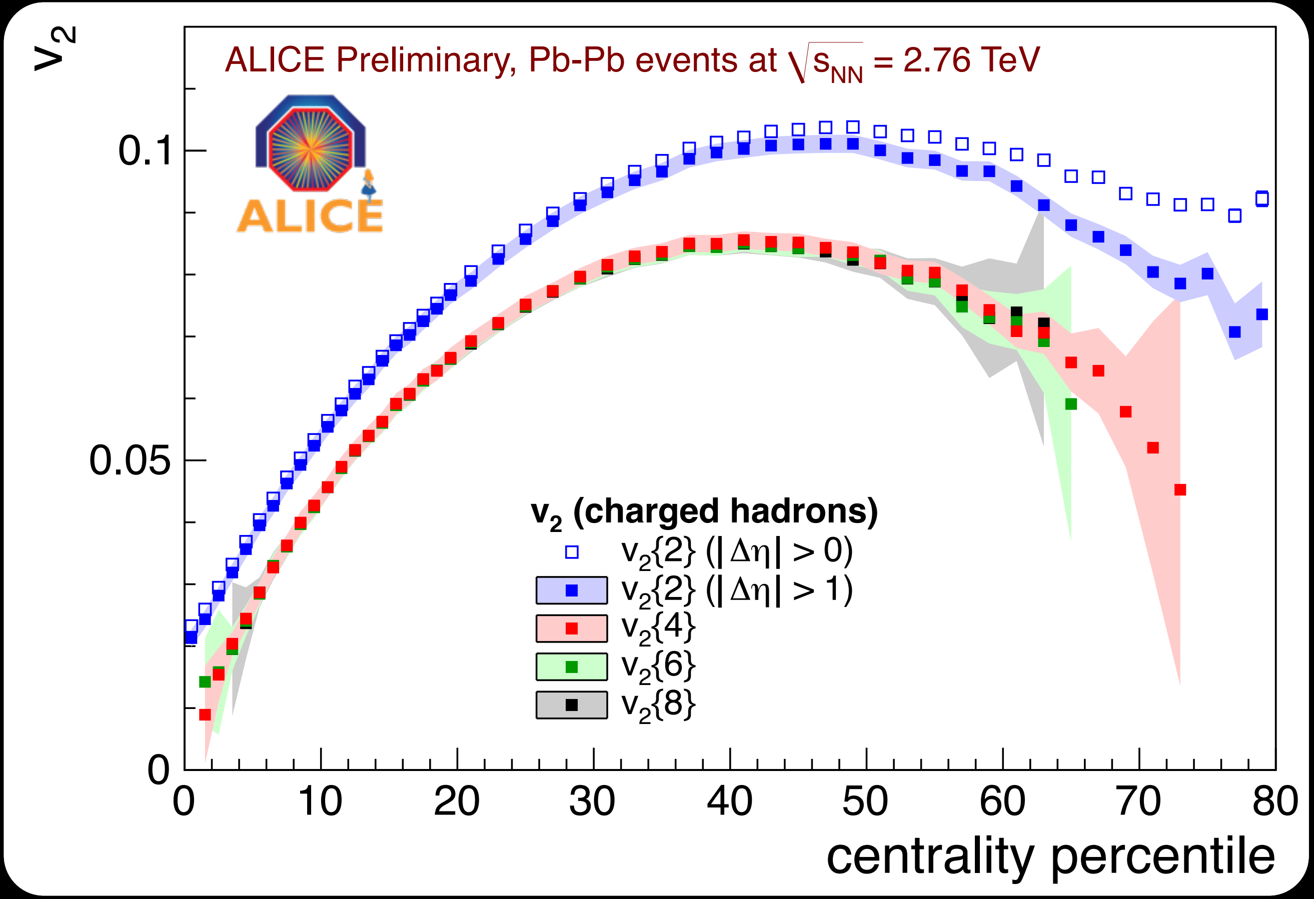
in limit of only (Gaussian)fluctuations

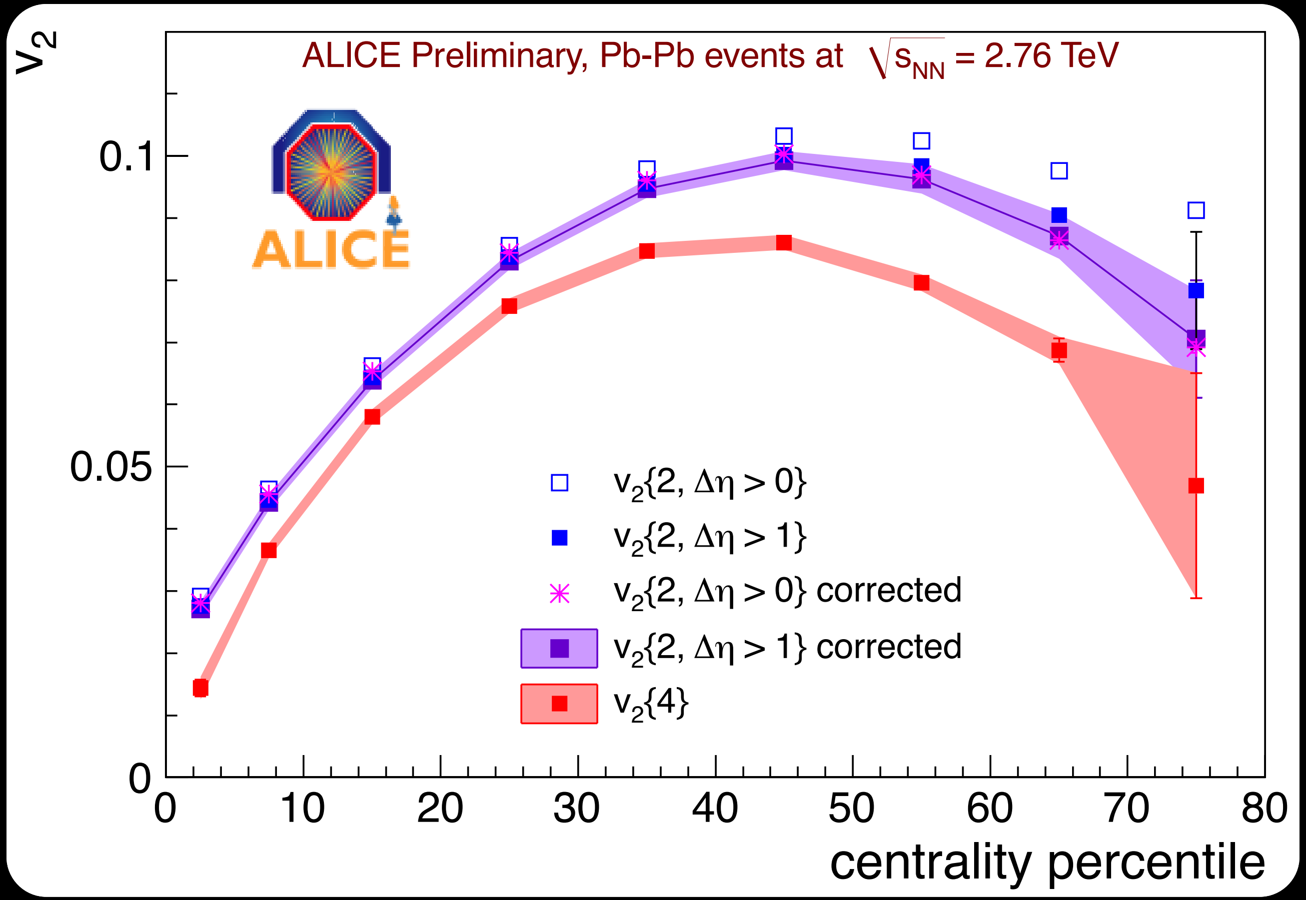
$$v_n\{4\} = 0$$

$$v_n\{2\} = \frac{2}{\sqrt{\pi}}\bar{v}_n$$



v_2 versus centrality in ALICE





see presentation A. Bilandzic

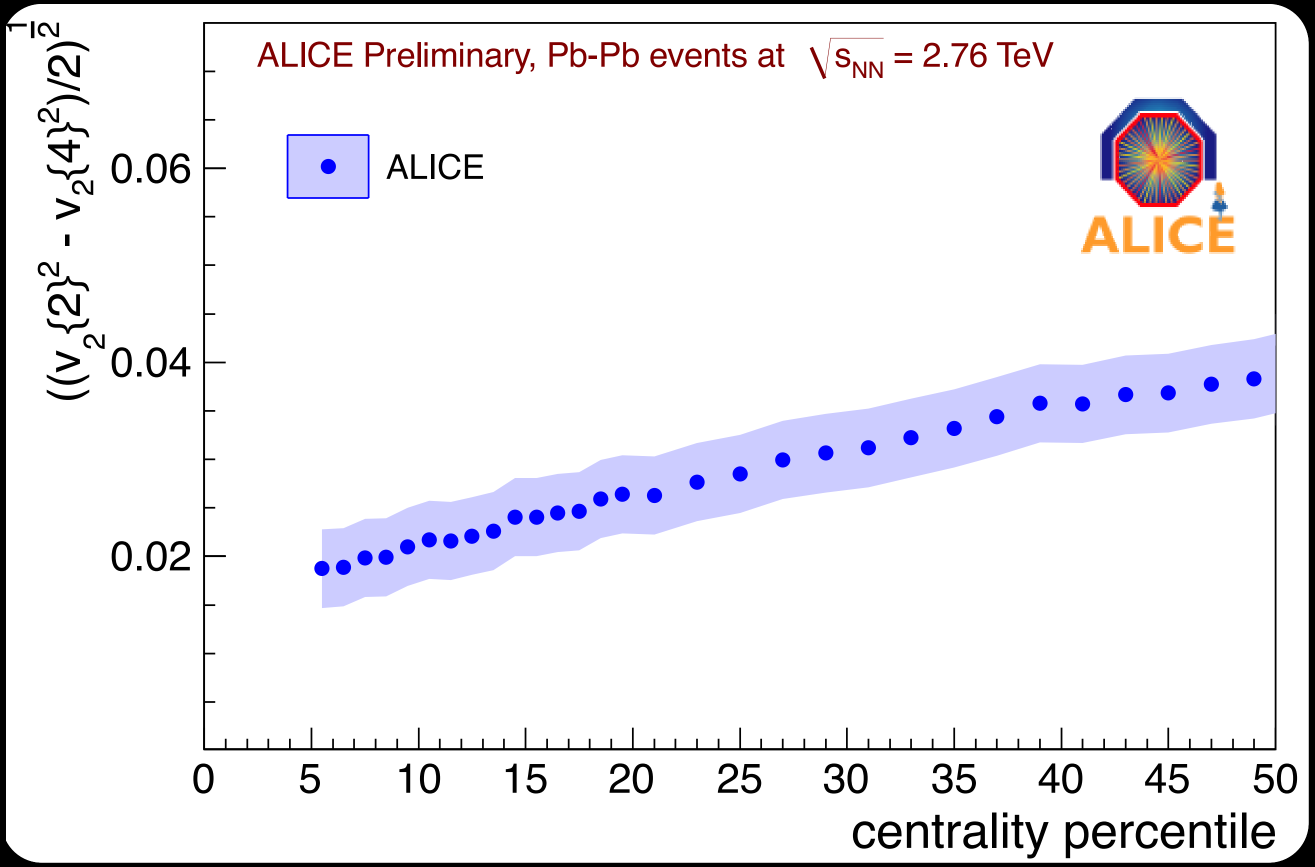
Two particle v_2 estimates depend on $\Delta\eta$

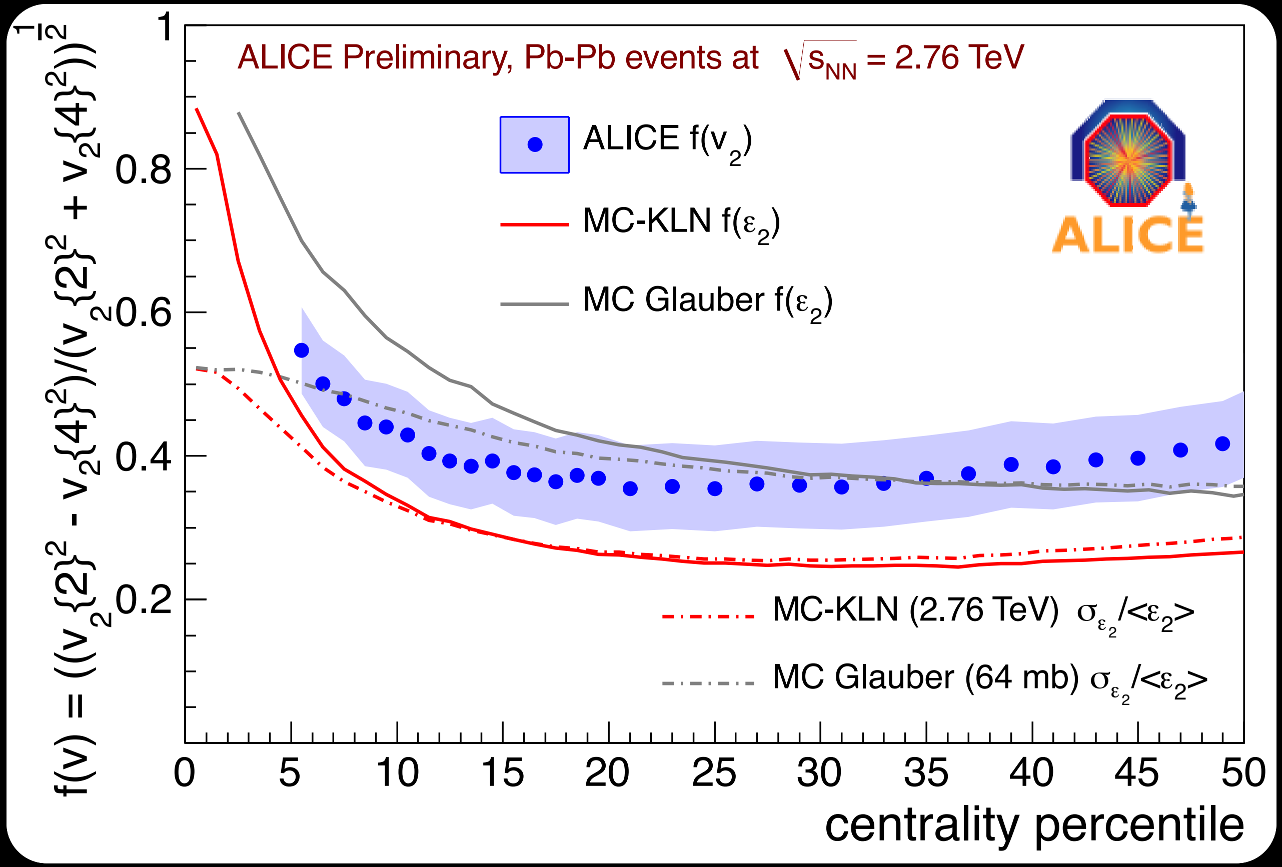
Higher order cumulant v_2 estimates are consistent within uncertainties

Two particle v_2 estimates are corrected for nonflow based on HIJING

The estimated nonflow correction for $\Delta\eta > 1$ is included in the systematic uncertainty

v_2 Fluctuations





$$\sigma_{v_n} \simeq [\frac{1}{2}(v_n^2\{2\} - v_n^2\{4\})]^{\frac{1}{2}}$$

$$\frac{\sigma_{v_n}}{v_n} \simeq \left(\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}\right)^{\frac{1}{2}}$$

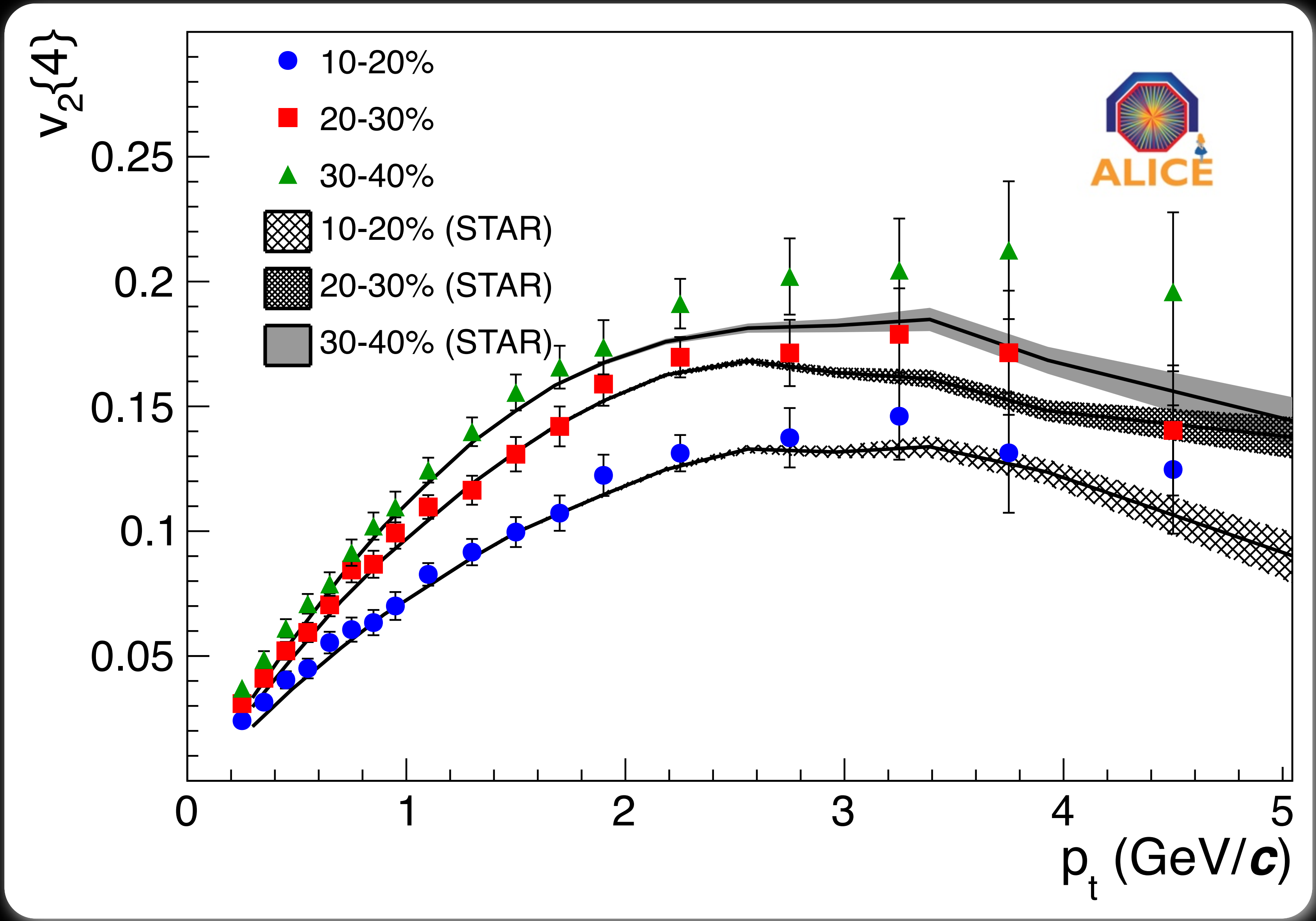
For more central collisions the data is between MC Glauber and MC-KLN CGC

Summary

- Anisotropic flow measurements provides strong constraints on the properties of hot and dense matter produced at RHIC and LHC energies and have lead to the new paradigm of the QGP as the so called perfect liquid
  - At the LHC we observe even stronger flow than at RHIC which is expected for almost perfect fluid behavior
  - More in the conference!

v_2 as function of p_t

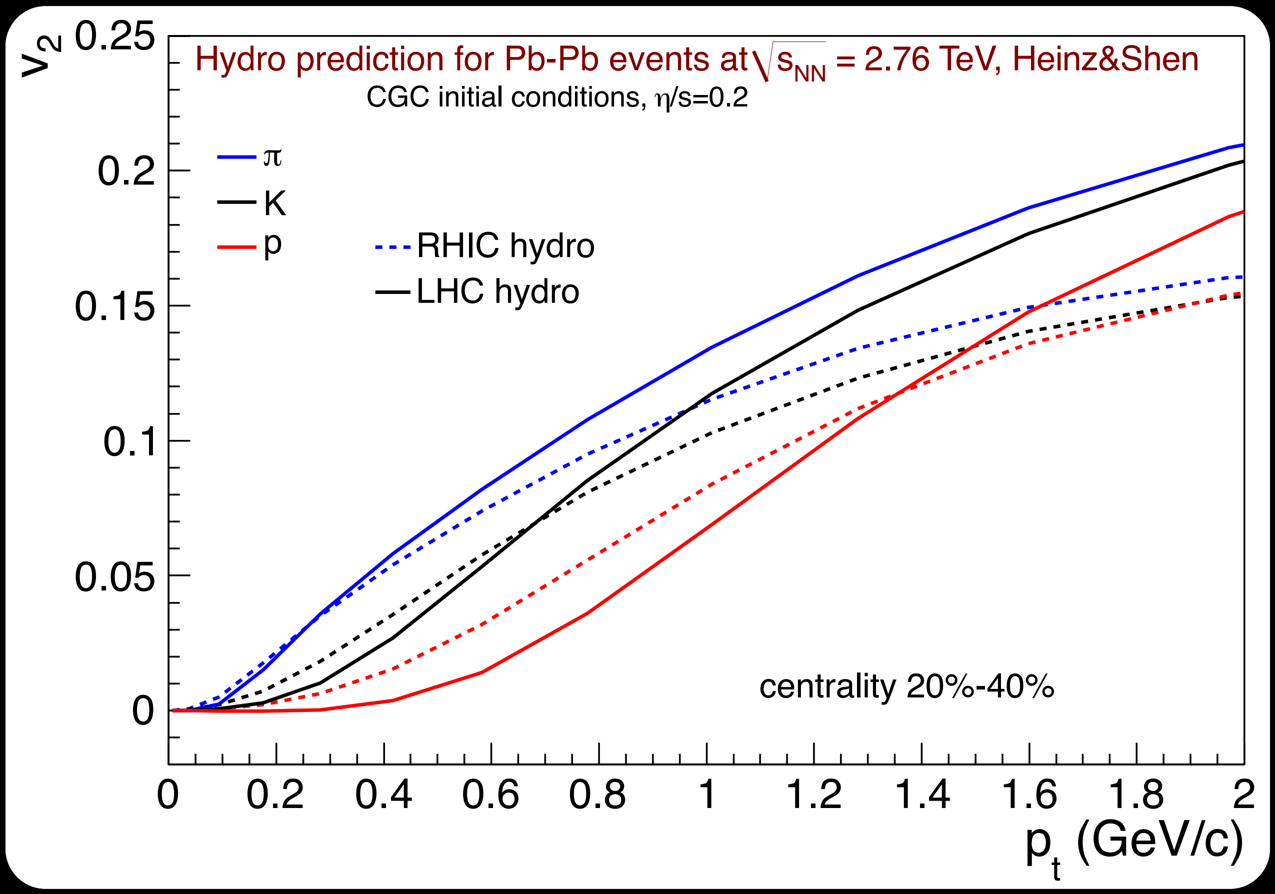
K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)



Elliptic flow as function of transverse momentum does not change much from RHIC to LHC energies, can we understand that?

v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

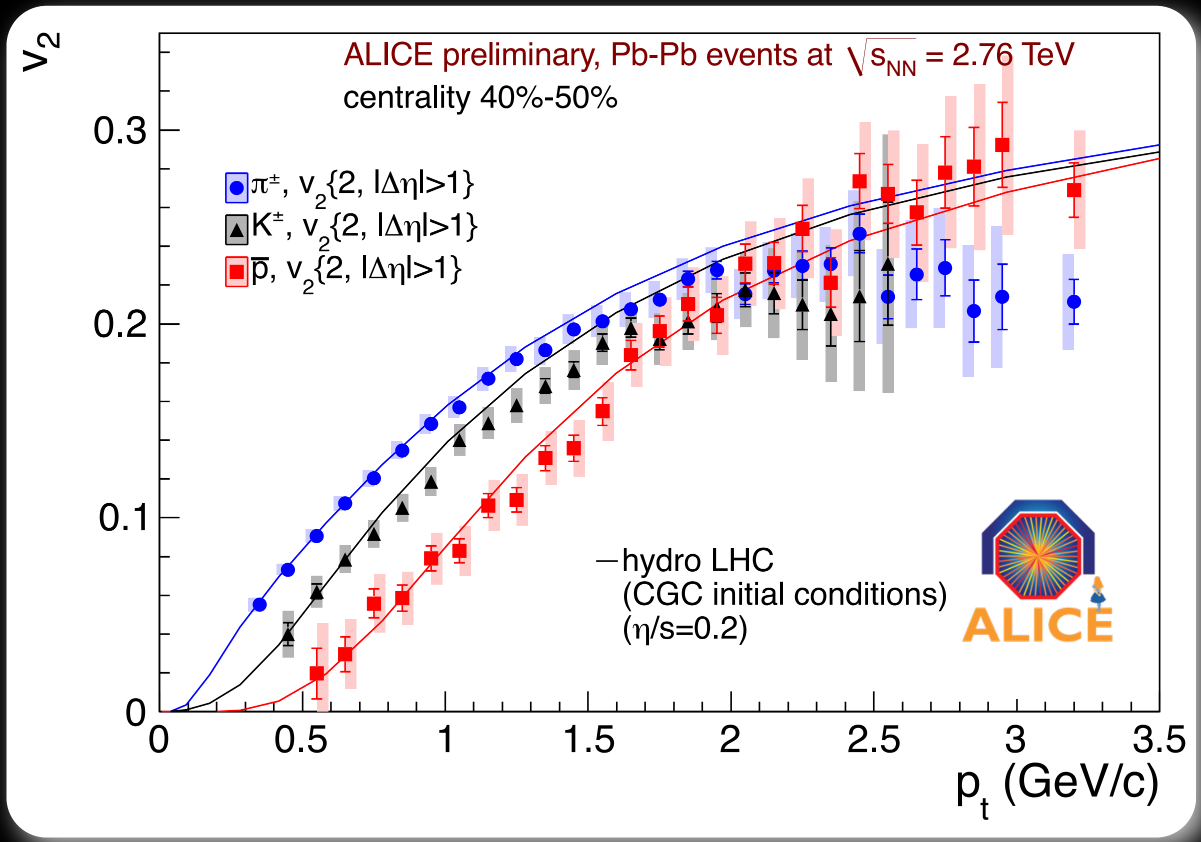


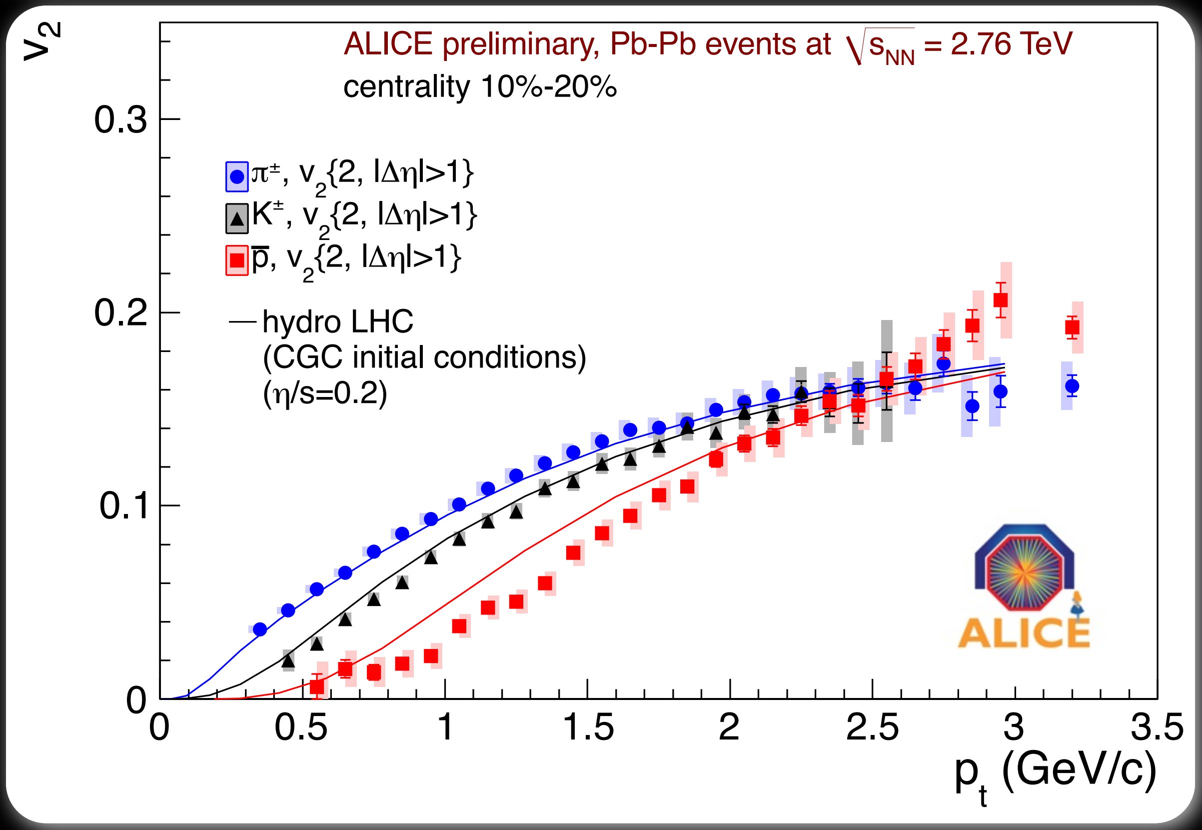
hydro models predict larger mass splitting

data shows mass splitting and agrees well with hydro predictions for mid-central collisions

for more central collisions the anti-proton flow is not described by the same calculations

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

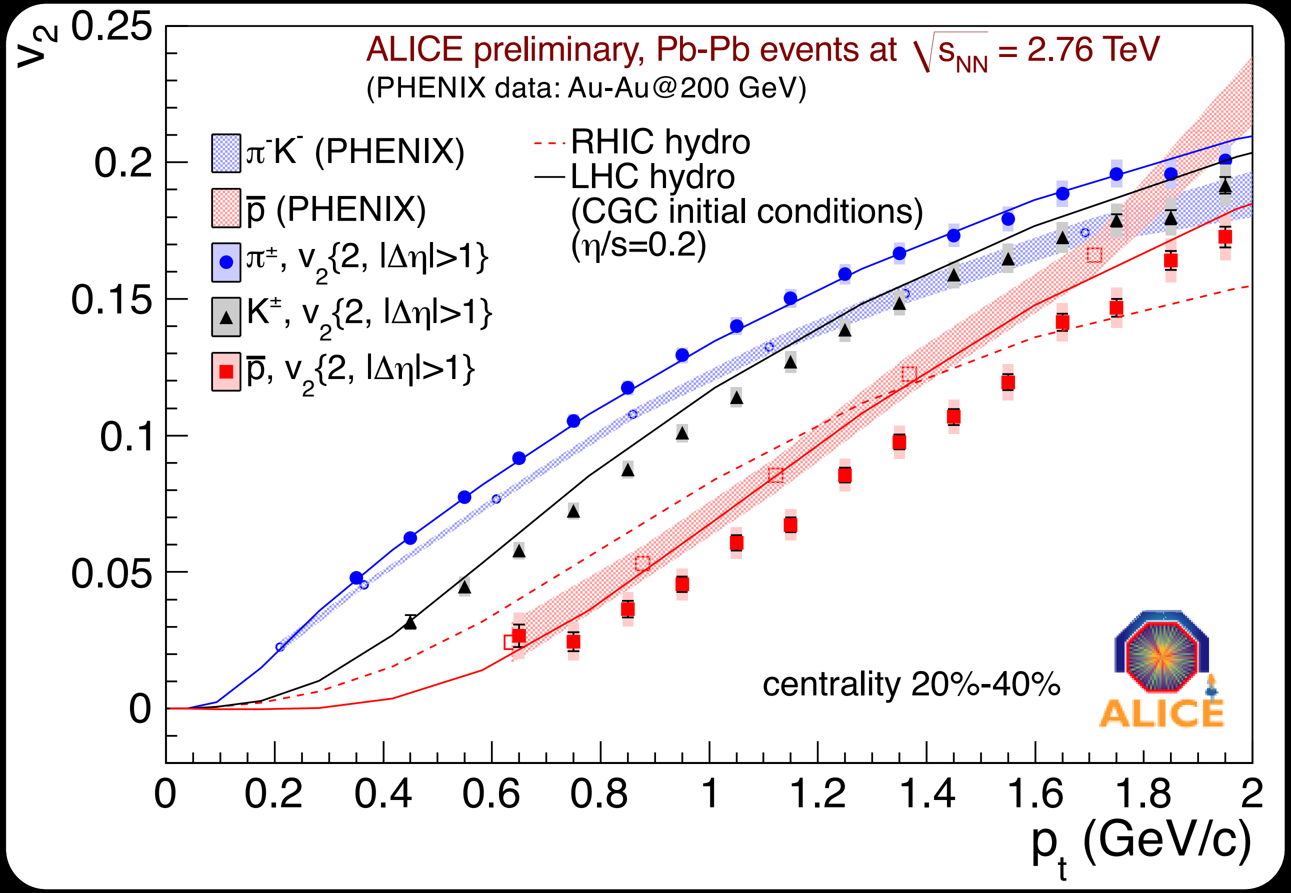


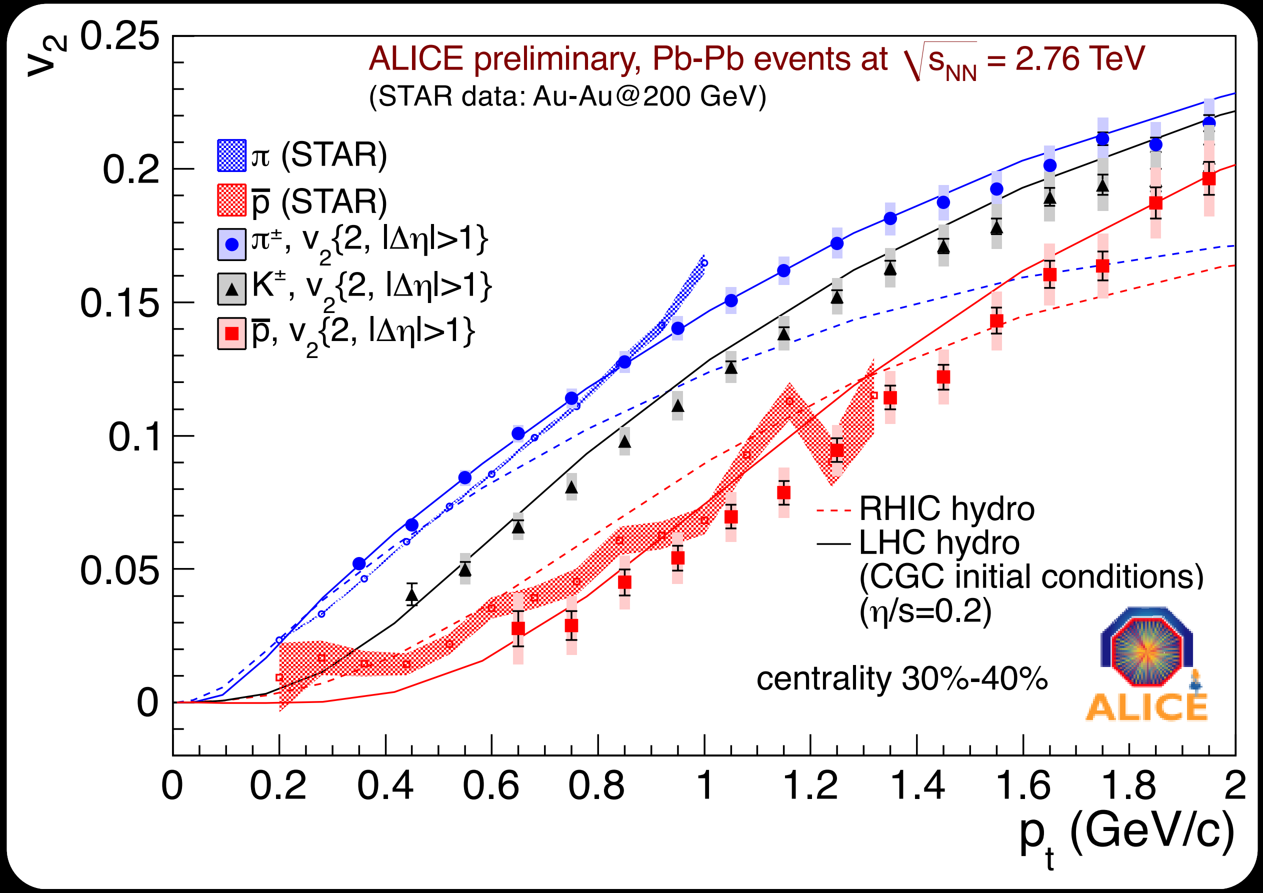


see presentation M. Krzewicki

v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226





see presentation M. Krzewicki

the mass splitting increased compared to RHIC energies

pion and Kaon v_2 are described well with hydrodynamic predictions using MC-KLN CGC initial conditions and $\eta/s = 0.2$