Collective phenomena in ultrarelativistic nuclear collisions - Anisotropic flow and more

Sergei A. Voloshin

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International School of Nuclear Physics
33rd Course
From Quarks and Gluons to Hadrons and Nuclei
Erice-Sicily
September 16-24, 2011

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Sergei A. Voloshin Wayne State University

- Introduction. High energy heavy ion collisions.
  - Anisotropic flow: Number of constituent quark (NCQ) scaling
  - Tests of the chiral magnetic effect
- Anisotropic flow: system response to anisotropic initial conditions.
  - Flow fluctuations and nonflow
  - Fluctuation in the initial conditions → (all) harmonics flow
- Conclusions

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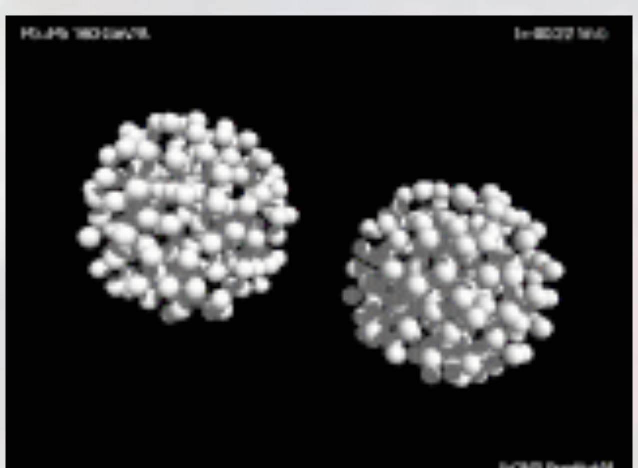
Ultrarelativistic nuclear collisions

	BNL AGS	CERN SPS	BNL RHIC	CERN LHC
$\sqrt{s_{NN}}$	~5 GeV	~ 17 GeV	up to 200 GeV	~2760 (5500) GeV



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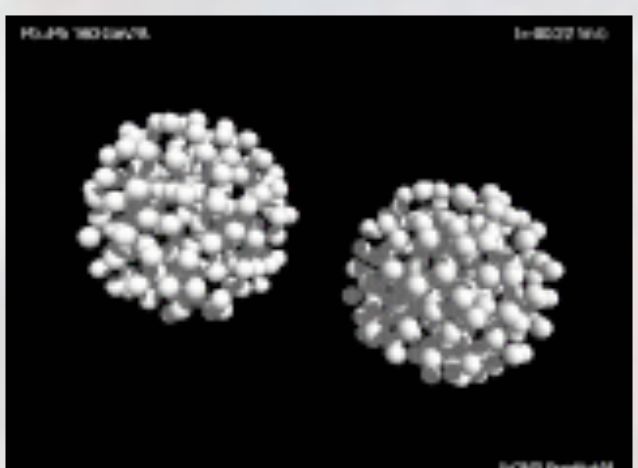

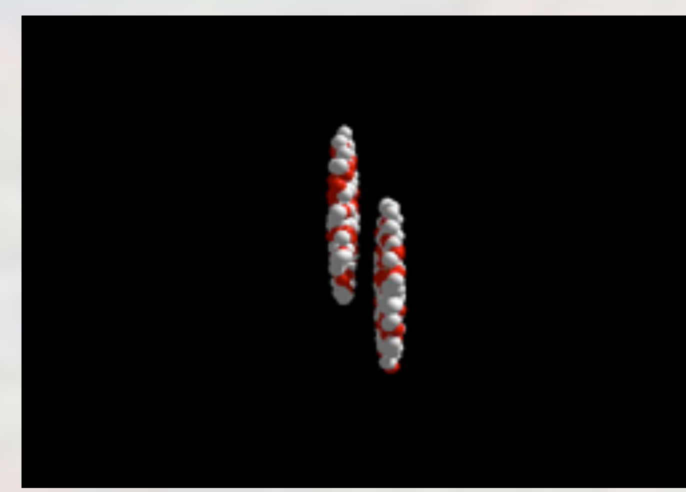

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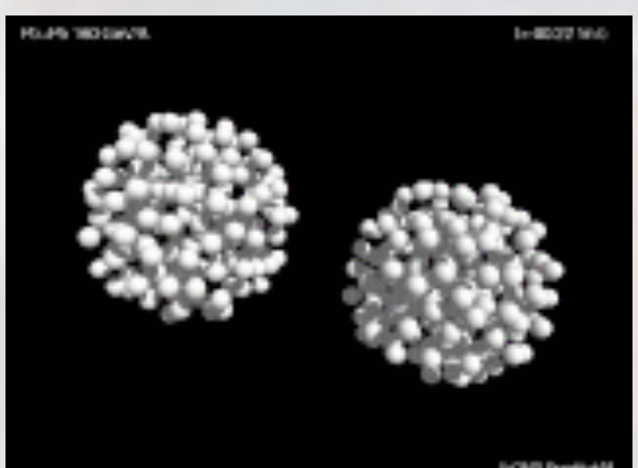

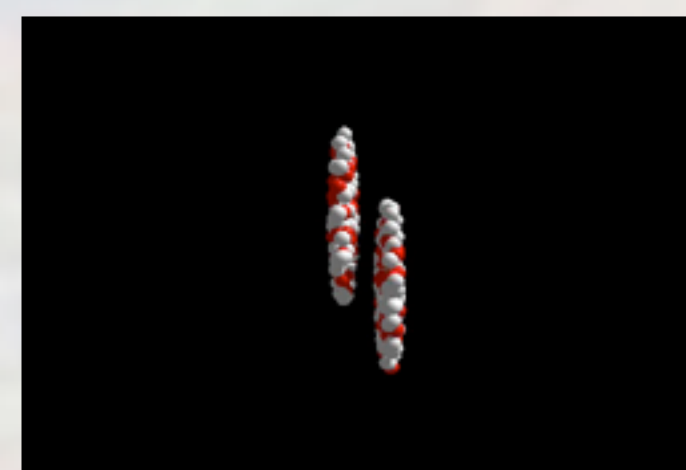

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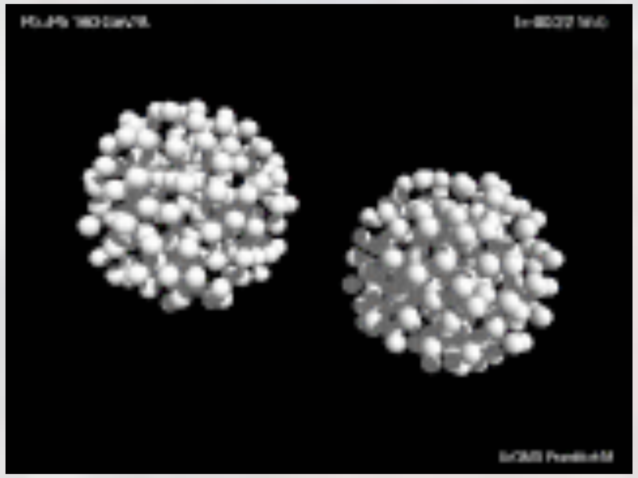

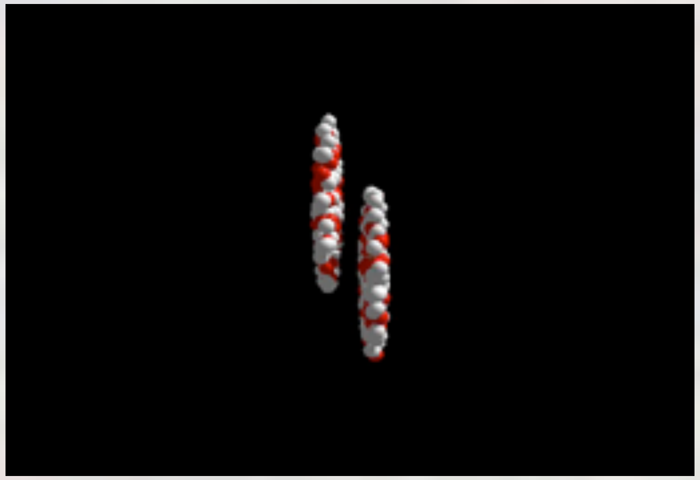

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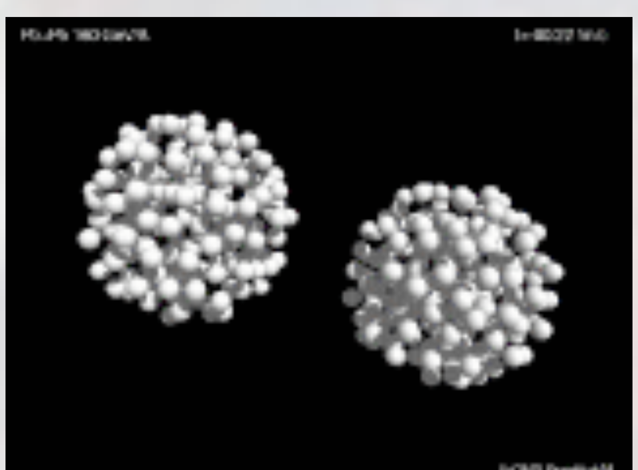

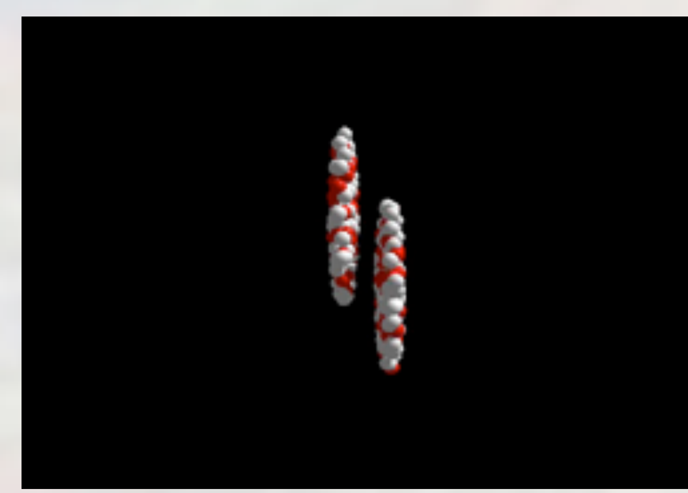

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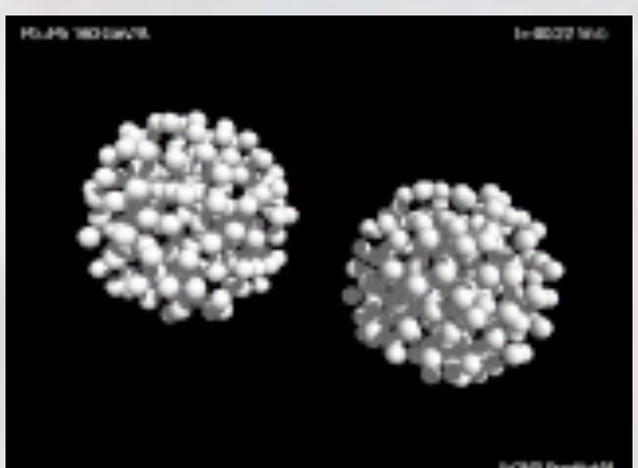

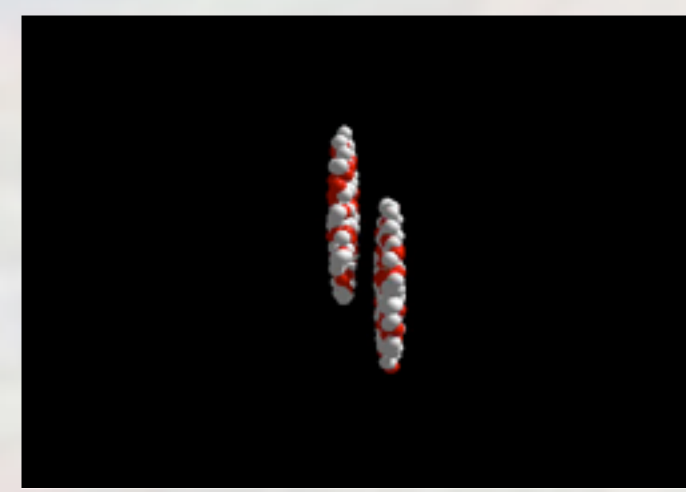

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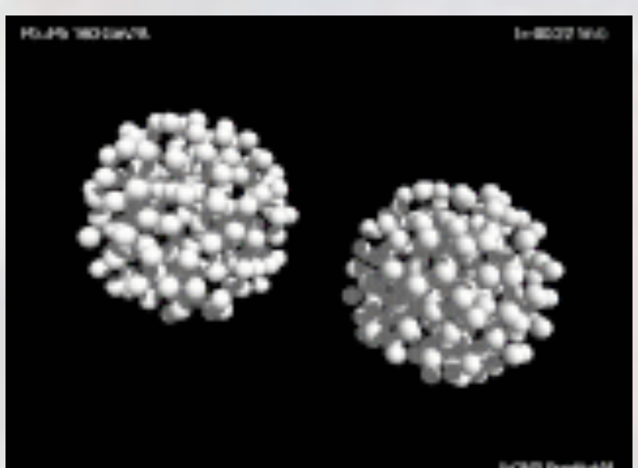
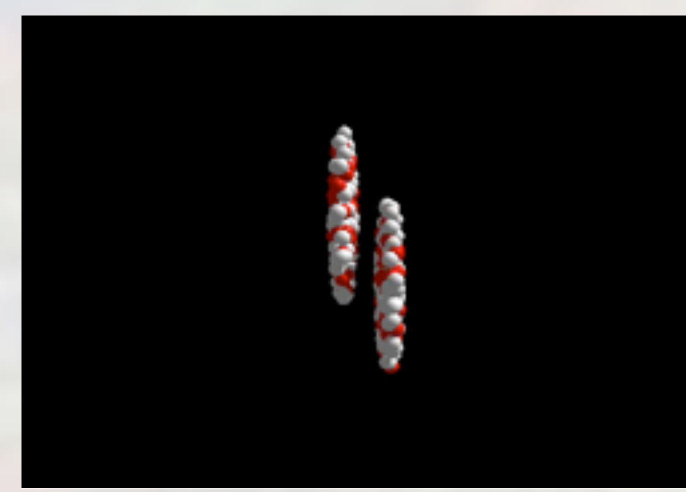
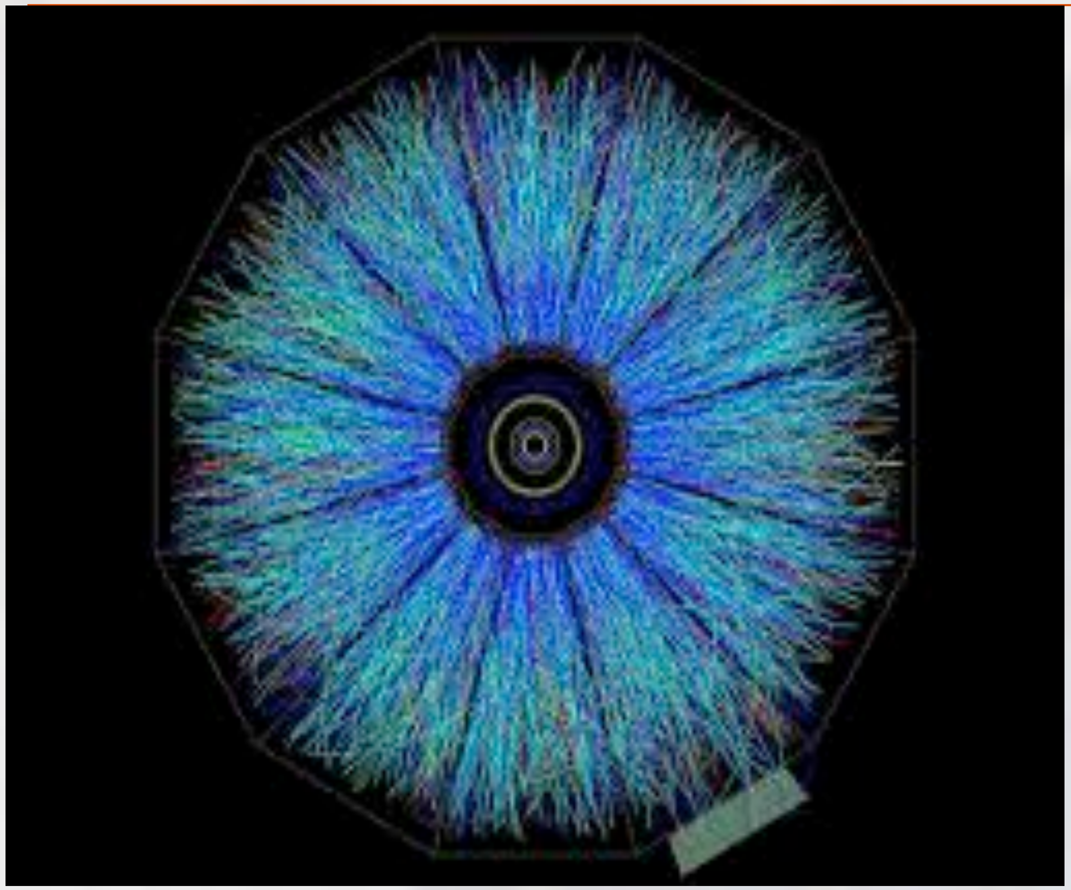


x (A=208) ➡

LHC Pb+Pb central collision: ~ 0.2 mJ !!!



From Quarks and Gluons to Hadrons and Nuclei



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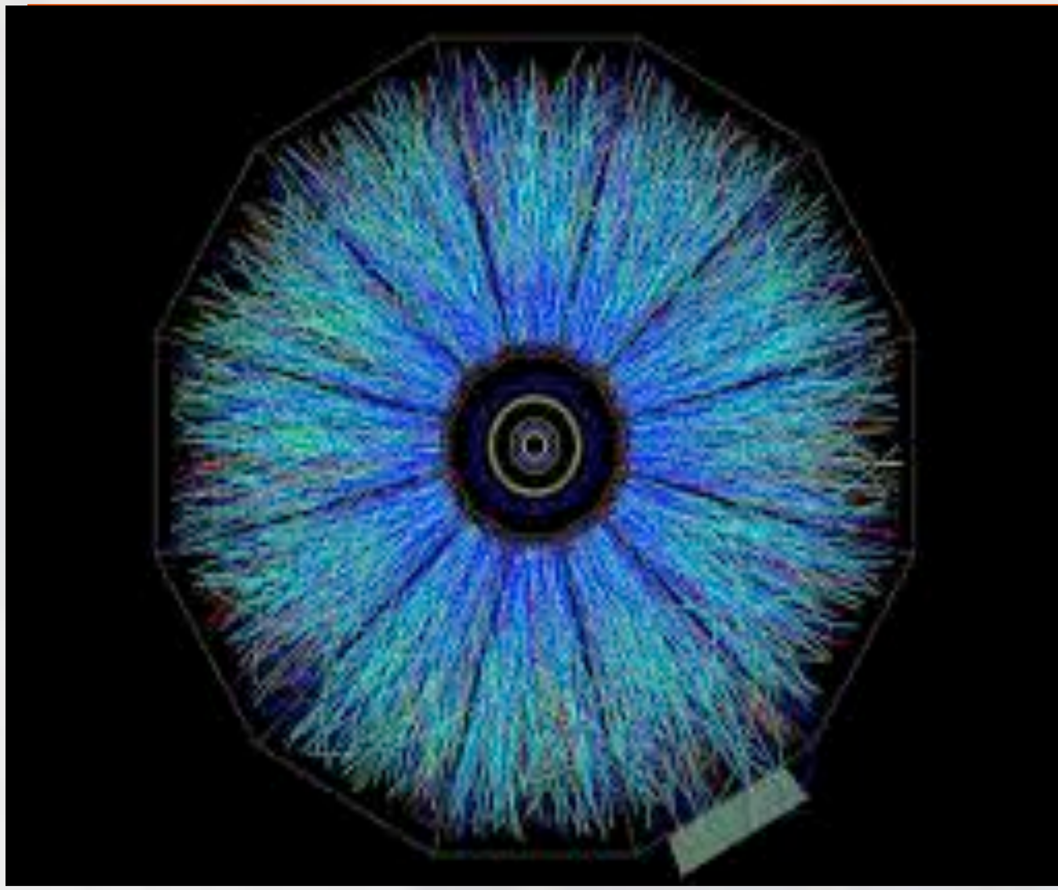
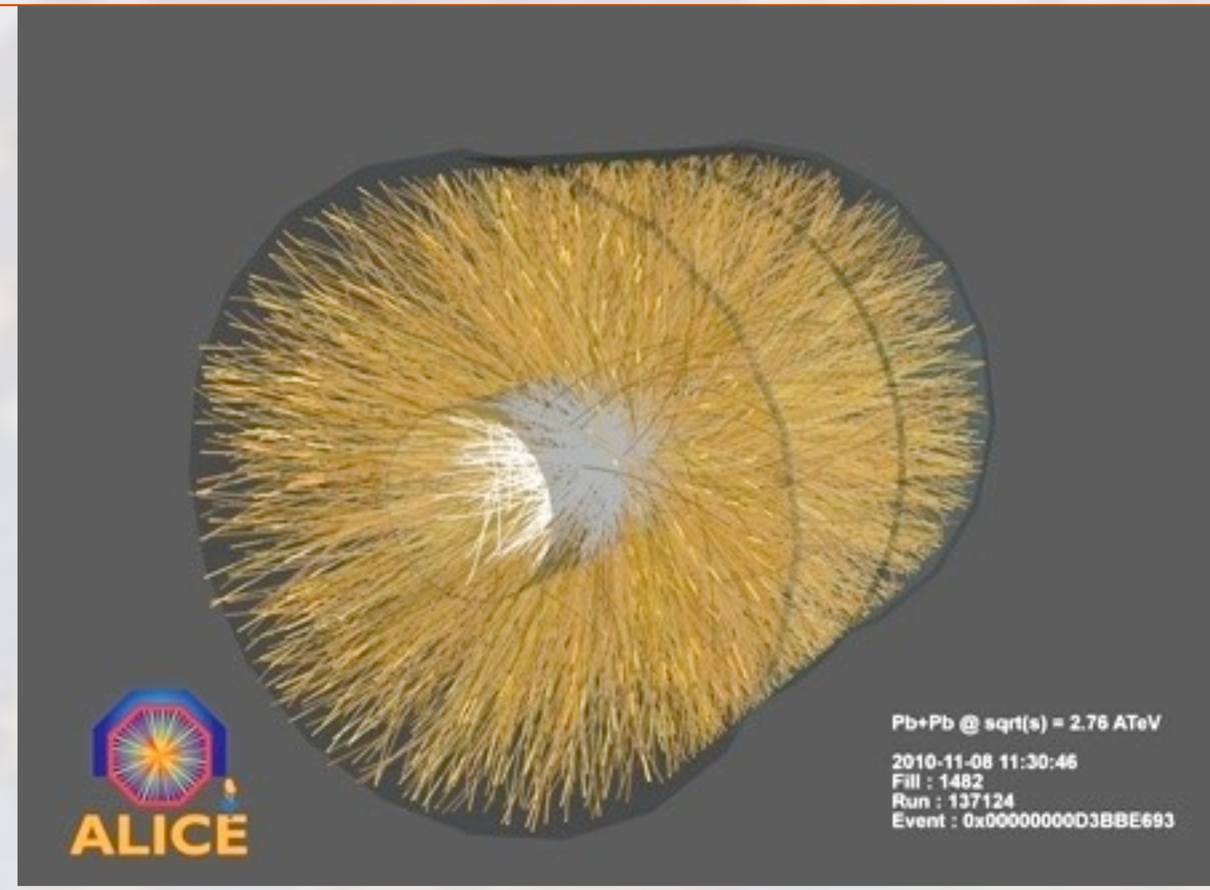
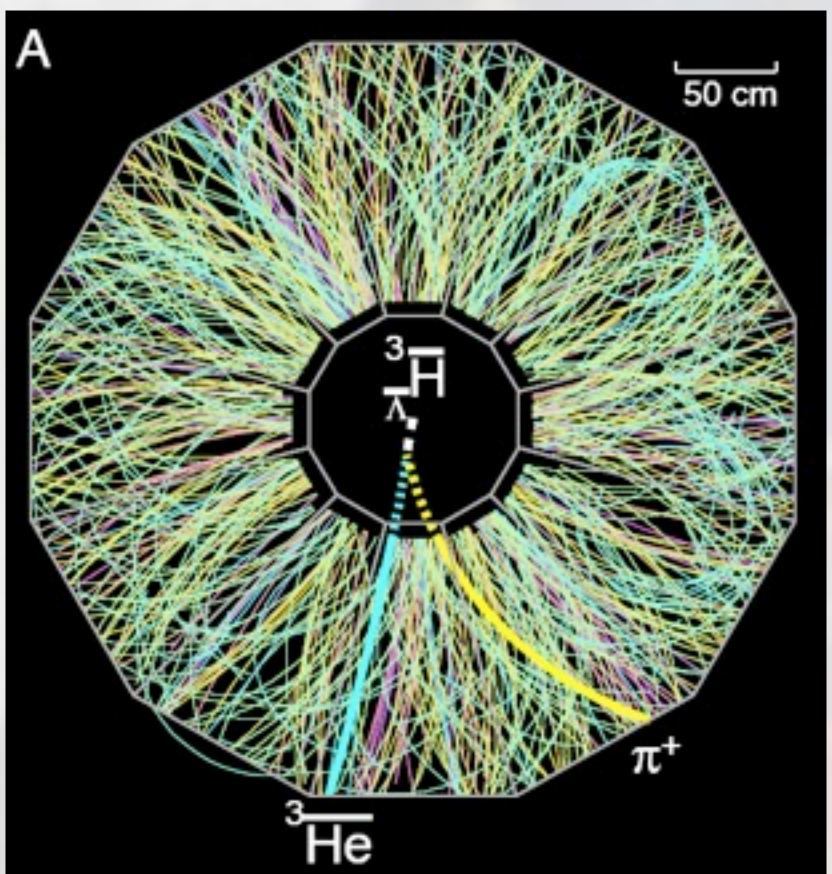
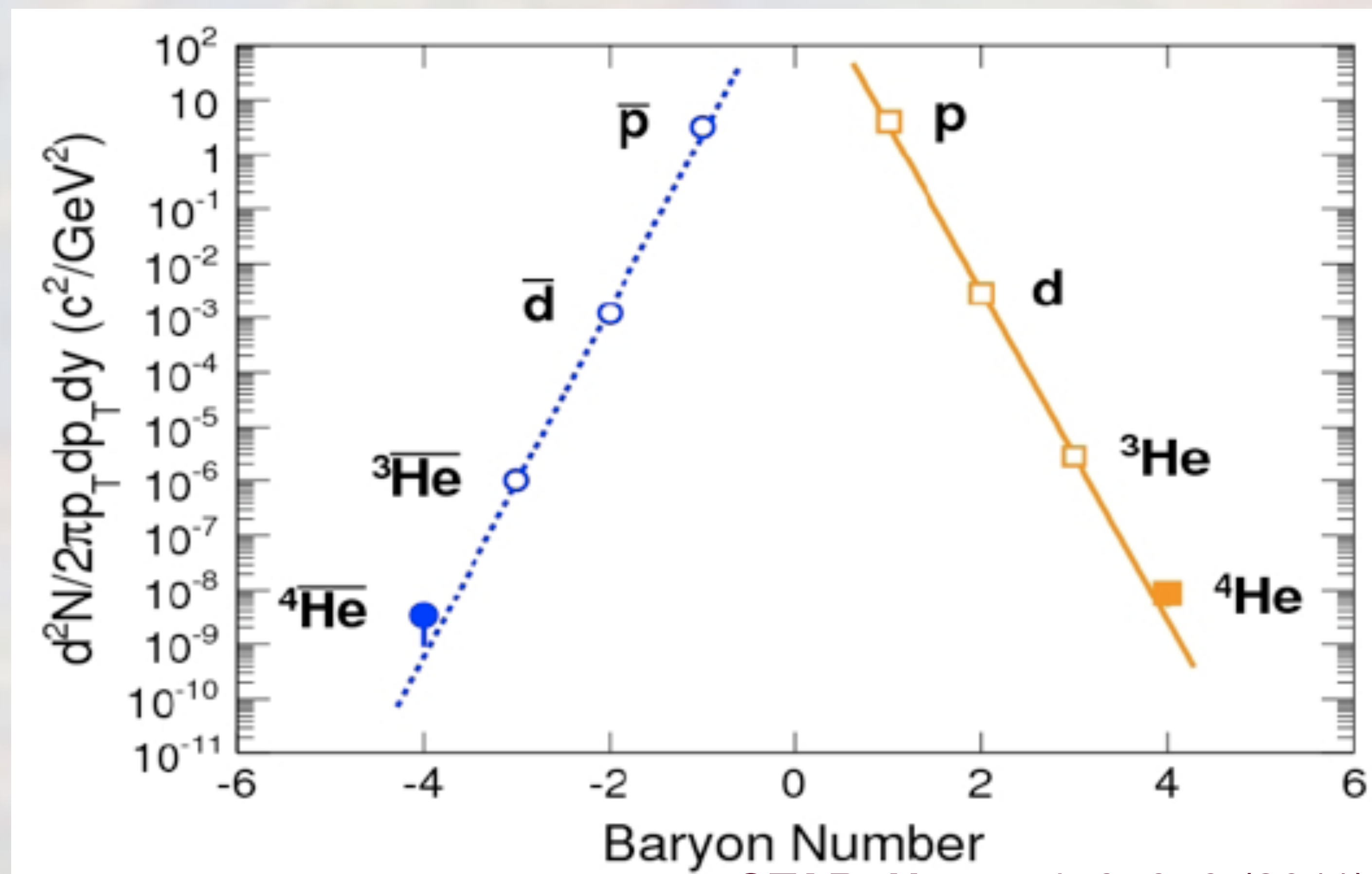






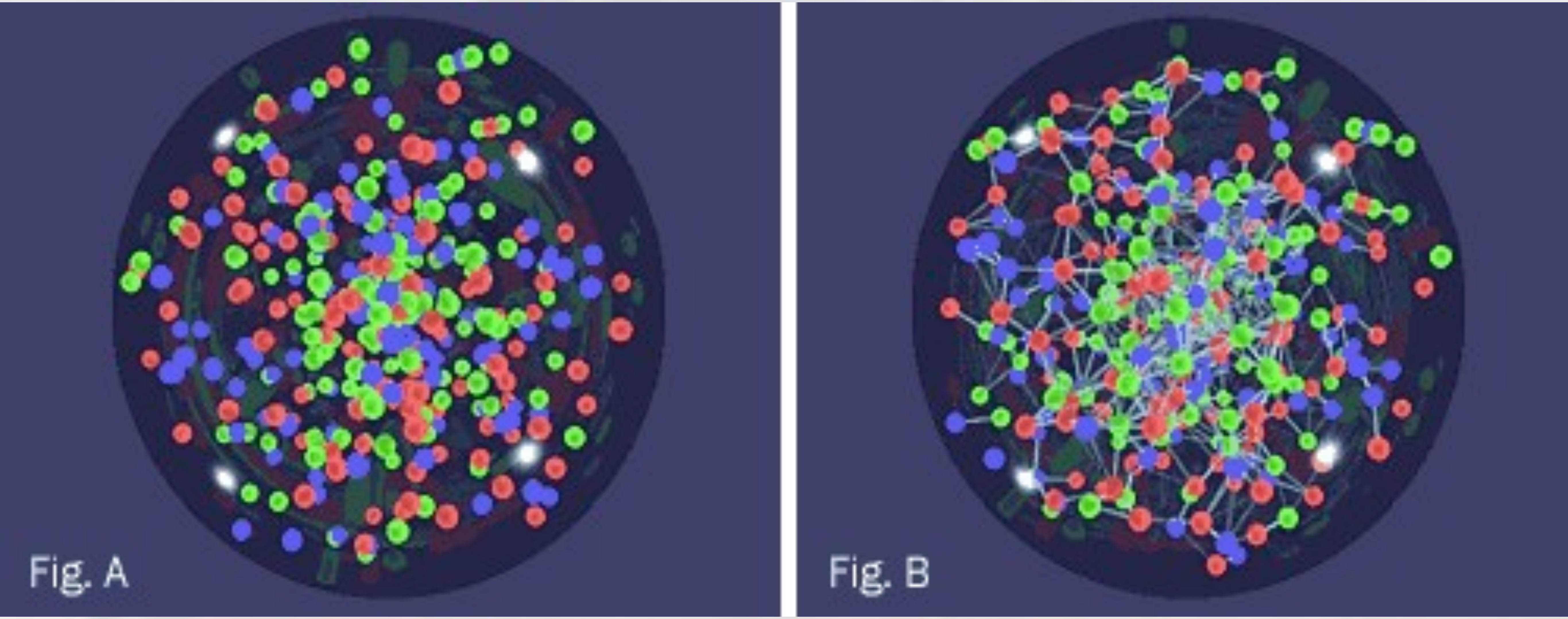


STAR, Science 328, 58 (2010)

STAR, Nature 473, 353 (2011)

QGP@RHIC: Gas or Liquid?

Quark-Gluon Plasma = color deconfinement
+ thermalization + ?



Local color screening ➔ deconfinement = "free" color propagation over large (>> 1 fm) distances

RHIC answer in the news

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 per…

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

by Mark Peplow
news@nature.com

nature

The Universe consisted of a perfect liquid in its first mo… results from an atom-smashing experiment.

New State of Matter Is 'Nearly Perfect' Liquid

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings--which could provide new insight into the composition of the universe just moments after the big bang--today in Florida at a meeting of the American Physical Society.

SCIENTIFIC AMERICAN

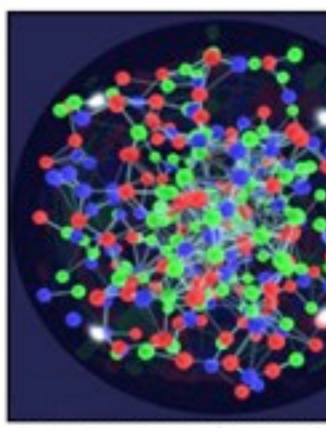

Image: BNL

There are four collaborations, dubbed BRAHMS, PHENIX, PHOBOS and STAR, working at Brookhaven's Relativistic Heavy Ion Collider (RHIC). All of them study what happens when two interacting beams of gold ions smash into one another at great velocities, resulting in thousands of subatomic collisions every second. When the researchers analyzed the… found that the particles produ…

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.

BBC NEWS


The impression is of matter th… more strongly interacting than… pred…

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 p…

社会 asahi.comトップ > 社会 > その他・話題

宇宙の始まりはしずく？　「クオークは液体」と発表

2005年04月18日23時34分

宇宙誕生の大爆発「ビッグバン」直後に相当する超高温・高密度の状態を再現する実験をしてきた日米などの国際チームは１８日、物質を形づく… が、気体のよ… 態にあったと… 宇宙や物質の… ある。

Science — Iran Daily — April 20, 2005 — 4

…Universe Liquid-Lik…

…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.

Everything was so hot then that quarks and gluons, which are now almost inextricably bound into the protons and neutrons inside atomic nuclei, were thought to have flown around like BBs in a blender.

But by reproducing the conditions of the early universe, RHIC has shown that unconstrained quarks and gluons don't fly away in all directions so much as squirt out in streams.

"The matter that we've formed behaves like a very nearly perfect liquid," Aronson said.

When physicists talk about a perfect liquid, they don't mean the best glass of champagne they ever tasted. The word "perfect" refers to the liquid's viscosity, a friction-like property that …

…sions.

Theoretical physicists have recently proposed that material swallowed … happens in a black hole and what goes on when two gold nuclei collide at RHIC.

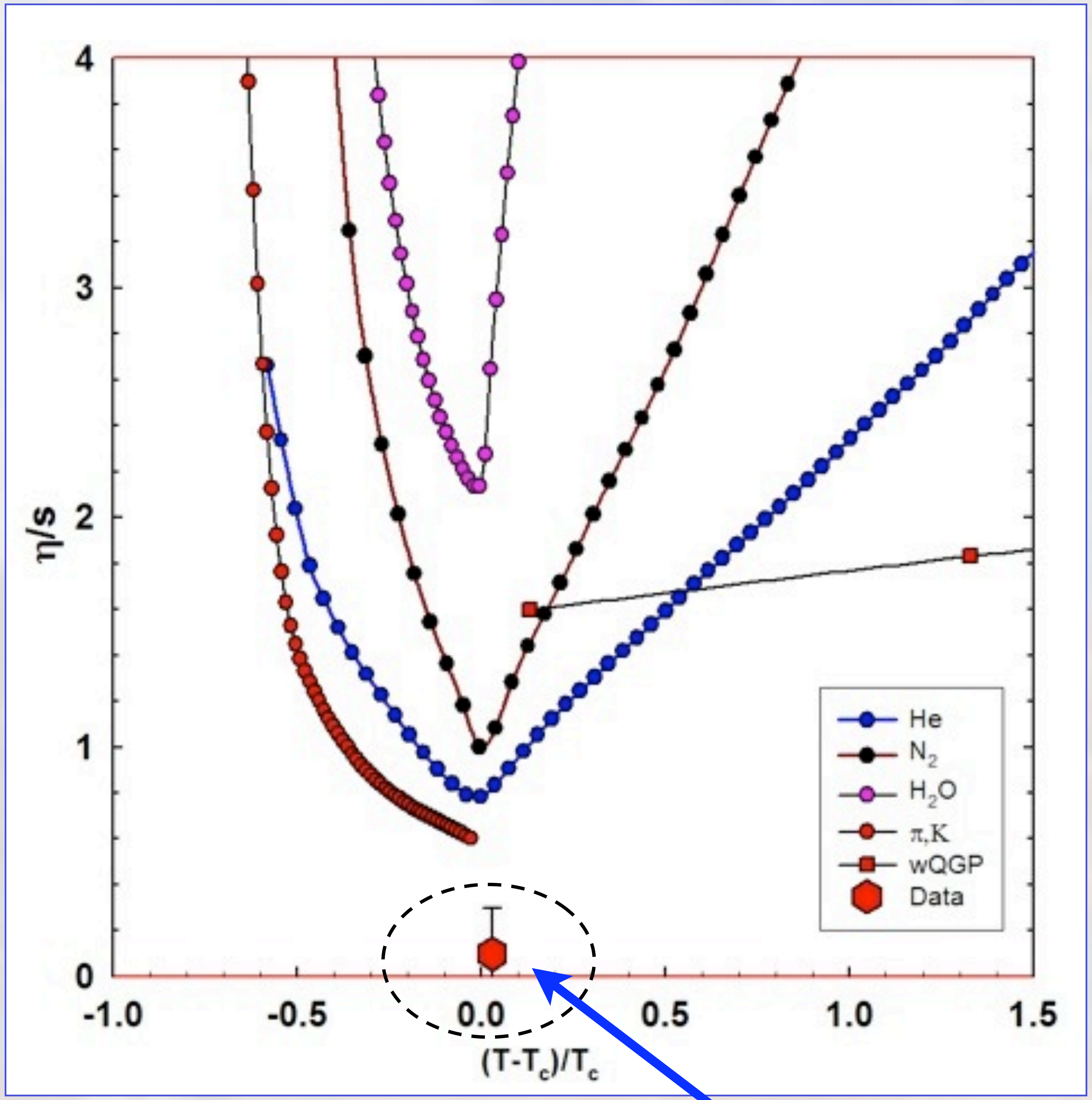
…offers opportunities to exciting questions," said … smashed the nuclei of…

Early Universe Went With the Flow

Posted April 18, 2005 5:57PM

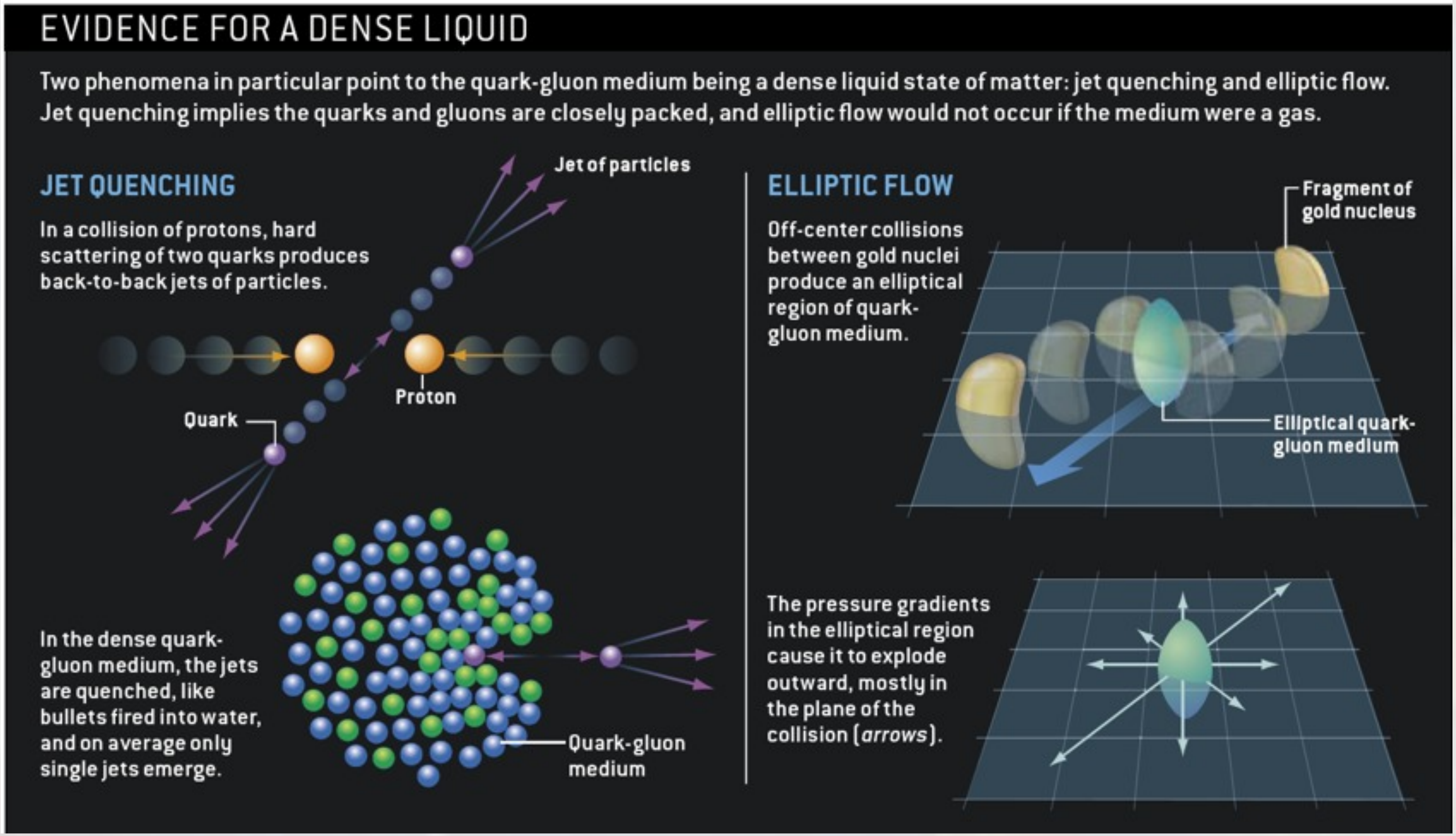
Between 2000 and 2003 the lab's Relativistic Heavy Ion Collider repeatedly smashed the nuclei of gold atoms together with such force that their energy briefly generated trillion-degree temperatures. Physicists think of the collider as a time machine, because those extreme temperature conditions last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

Shear viscosity / entropy density



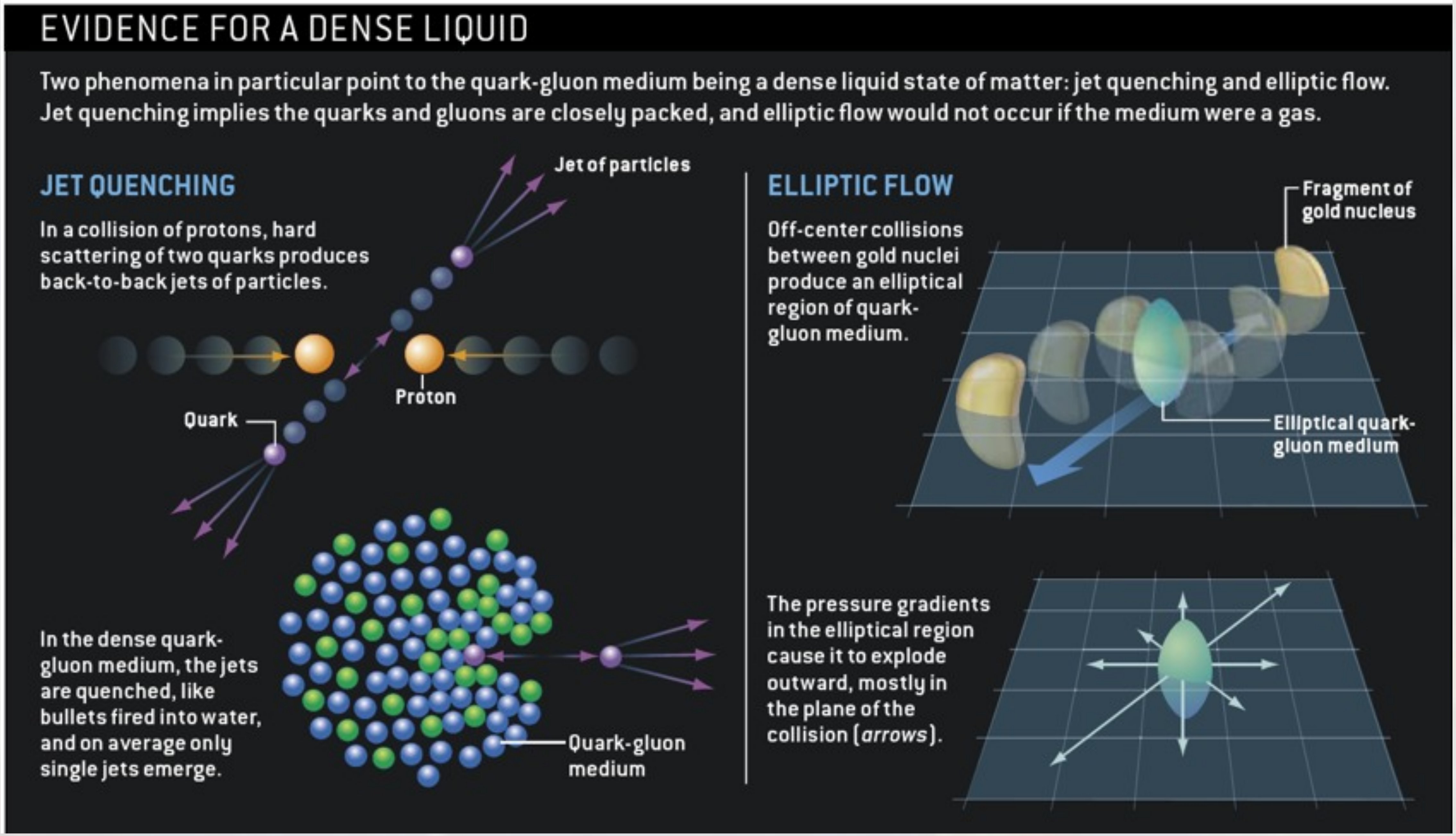
$$\frac{\eta}{s} \sim \frac{1}{4\pi}$$

Major RHIC discoveries



"The physical picture emerging from the four (RHIC) experiments is consistent and surprising. The quarks and gluons indeed break out of confinement and behave collectively, if only fleetingly. But this hot mélange acts like a liquid, not the ideal gas theorists had anticipated."
M. Riordan, W. Zajc, Sci. Am., May 2006, 34-41.

Major RHIC discoveries



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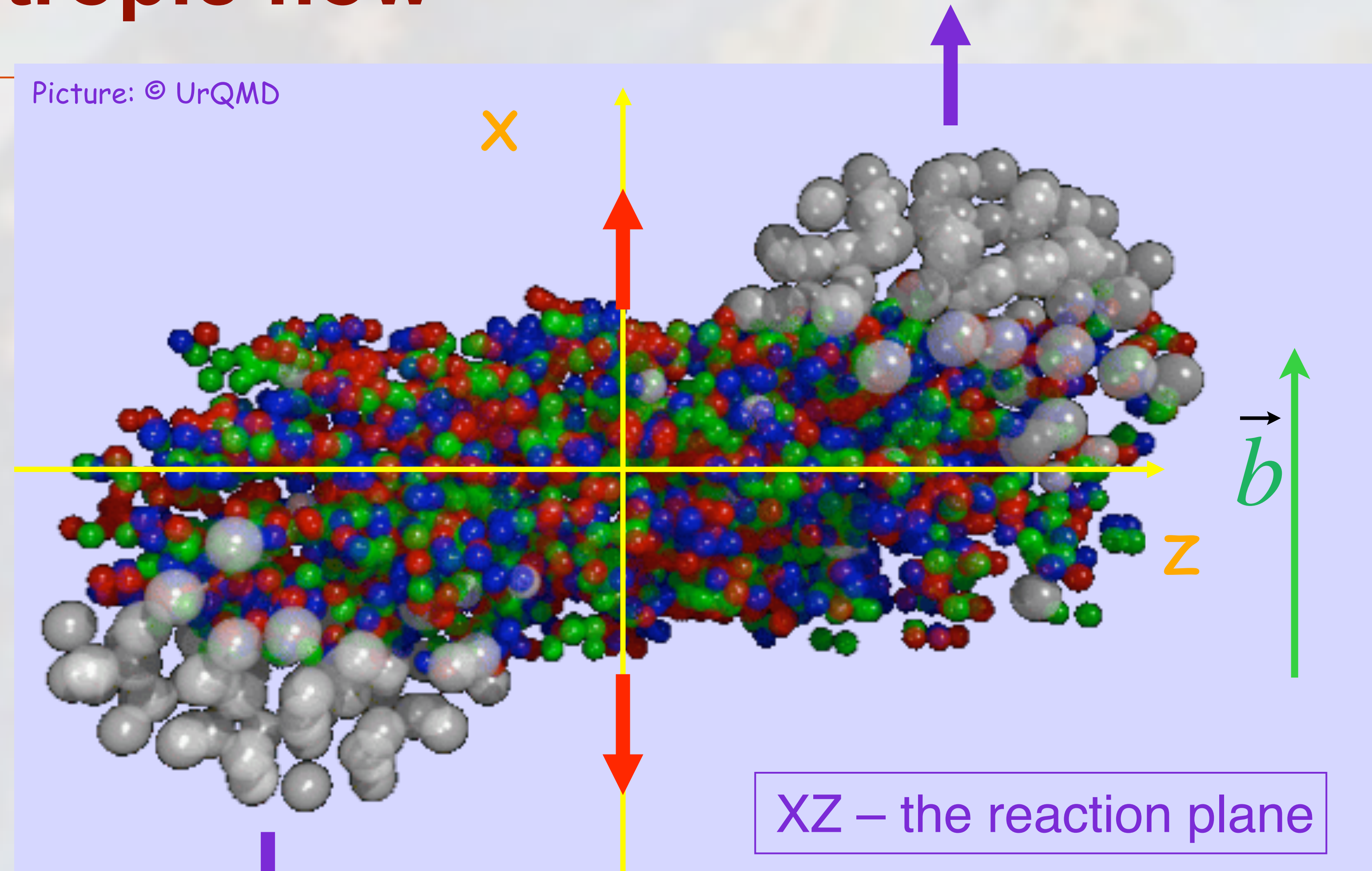
Three major RHIC discoveries (my "count"):
1. Large elliptic flow
2. Jet quenching
3. Constituent quark number scaling

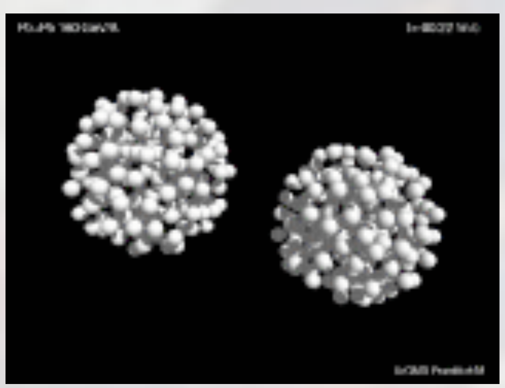
Anisotropic flow

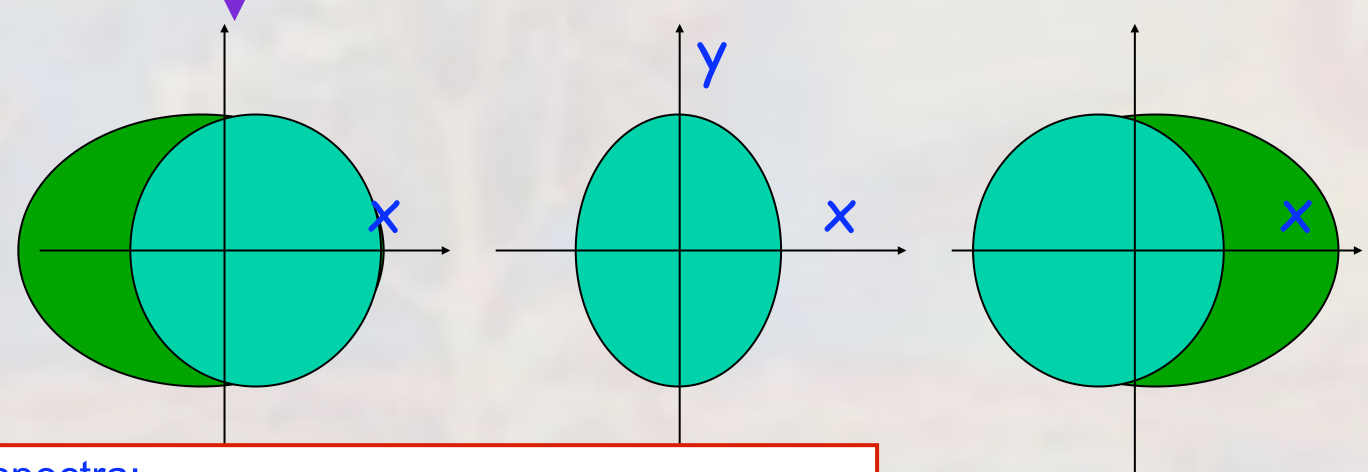
Anisotropic flow ≡ correlations with respect to the reaction plane (more general definition later)



Term "flow" does not mean necessarily "hydro" flow – used only to emphasize the collective behavior ←→ multiparticle azimuthal correlation.

Note large orbital angular momentum in the system and strong electric and magnetic fields!





Fourier decomposition of single particle (semi) inclusive spectra:

$$\frac{d^3N}{dp_t\,dy\,d\Delta\varphi} = \frac{d^2N}{dp_t\,dy}\frac{1}{2\pi}\left(1 + 2v_1\cos(\Delta\varphi) + 2v_2\cos(2\Delta\varphi) + \ldots\right)$$

Directed flow

Elliptic flow

S.V., Y. Zhang
hep-ph/9407282
Z.Phys. C70 (1996) 665

Constituent quark coalescence

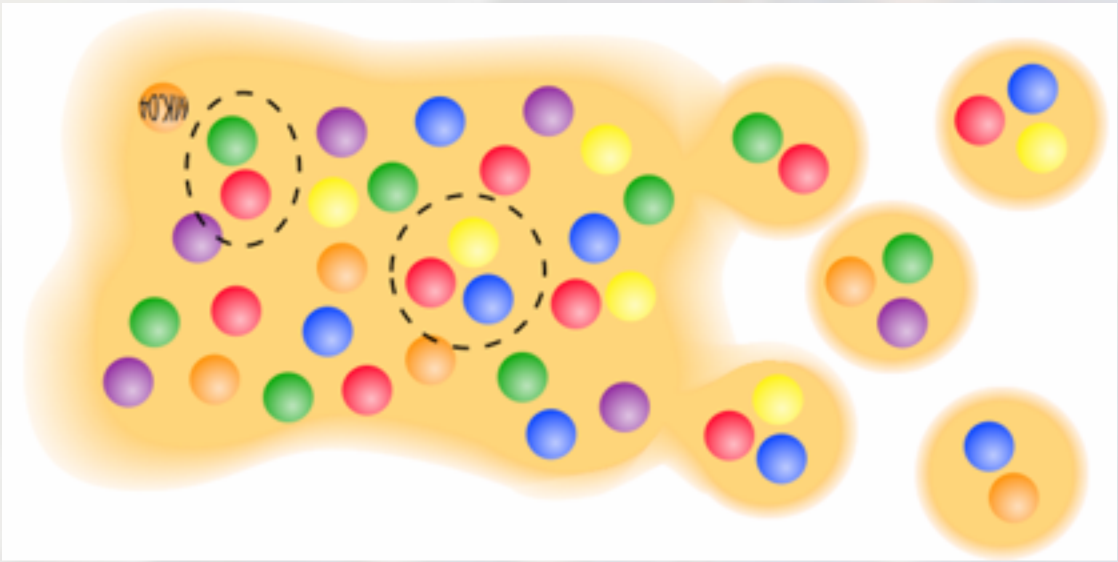
S.V., QM2002
D. Molnar, S.V., PRL 2003

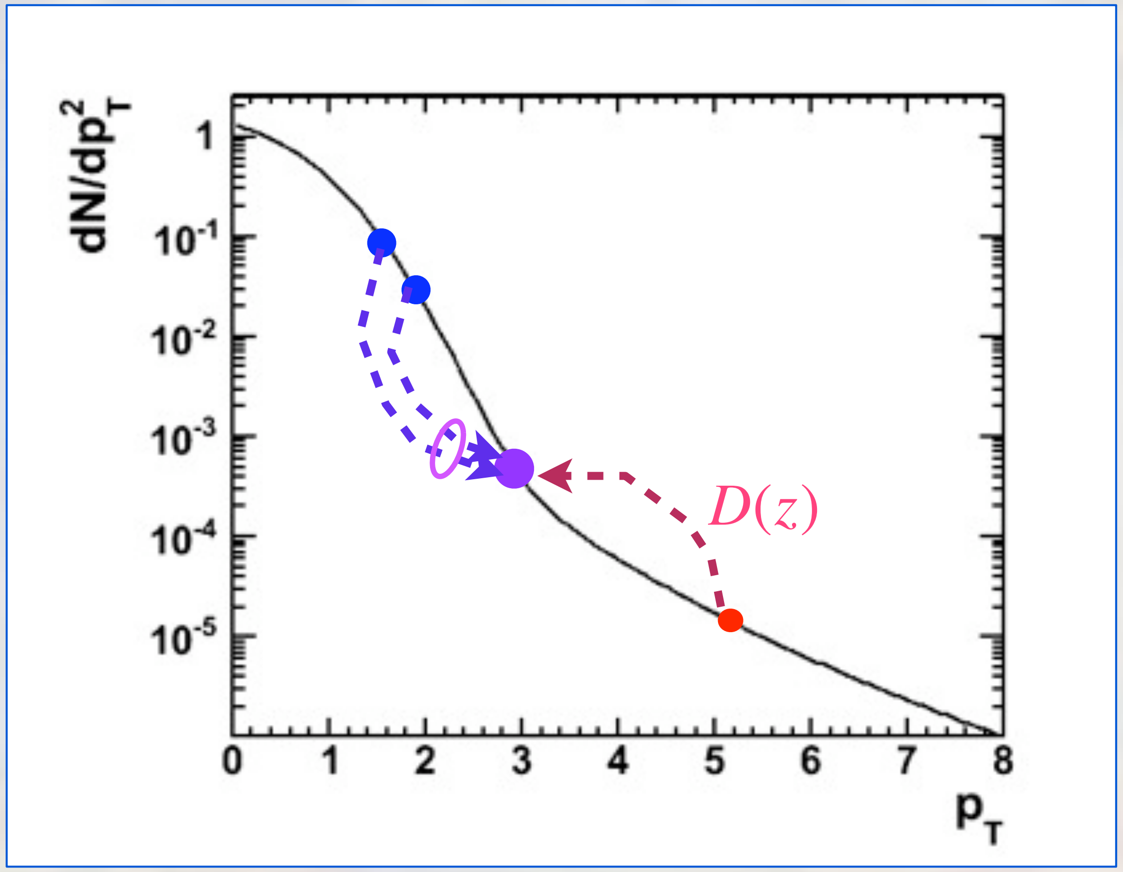
coalescence — **fragmentation**

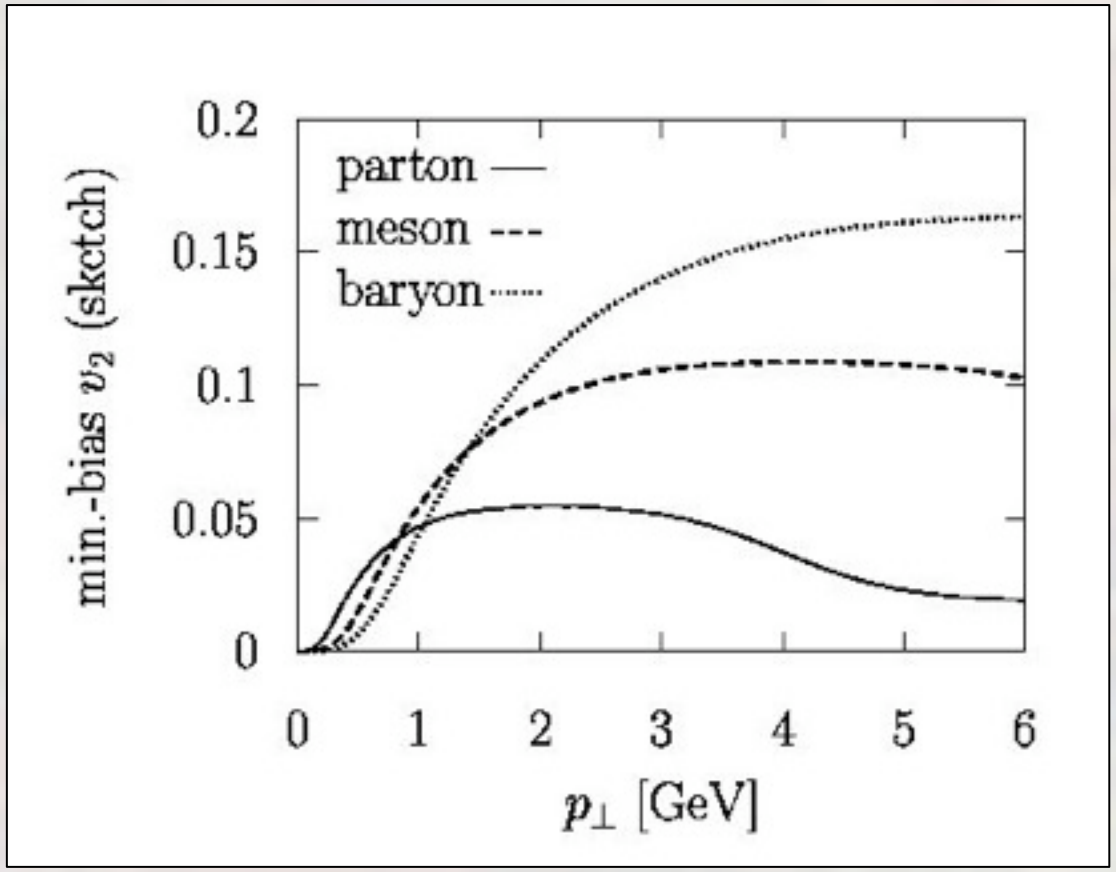
Low p_t quarks — High p_t quarks

In the intermediate region coalescence can be described by:

$$\frac{d^3 n_M}{d^3 p_M} \propto \left[\frac{d^3 n_q}{d^3 p_q}\left(p_q \approx p_M/2\right)\right]^2 \rightarrow \begin{array}{l} v_{2,M}(p_t) \approx 2 v_{2,q}(p_t/2) \\ v_{2,B}(p_t) \approx 3 v_{2,q}(p_t/3) \end{array}$$







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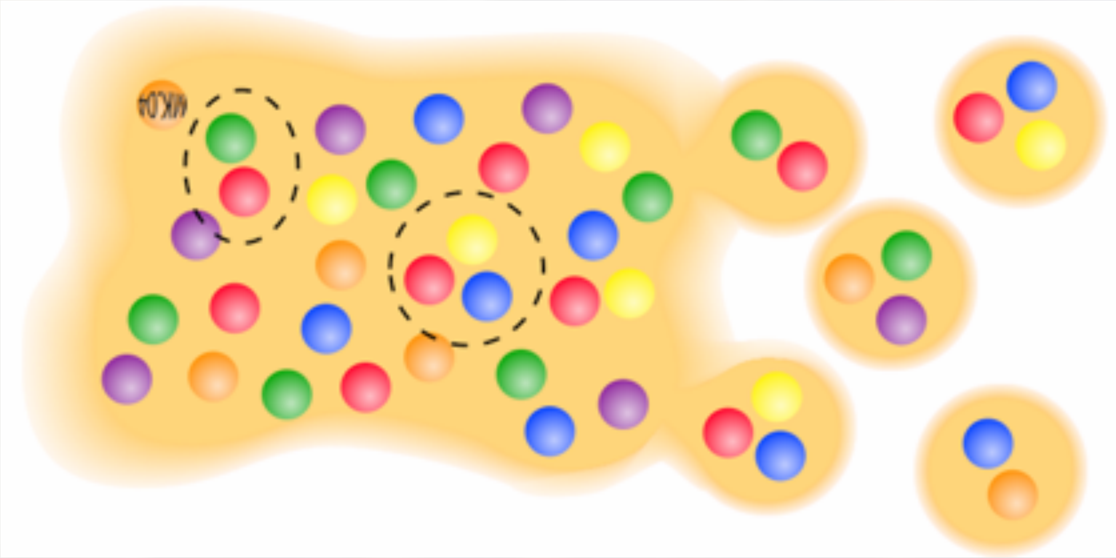
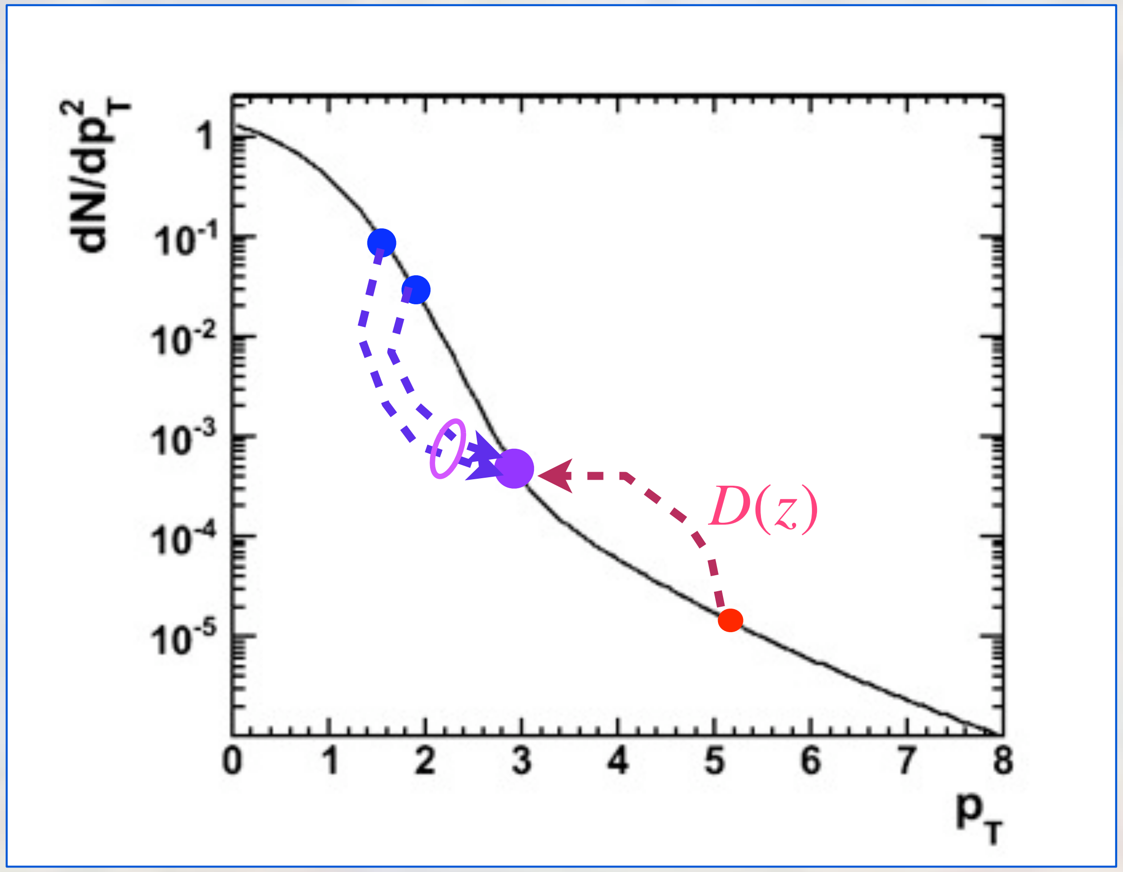
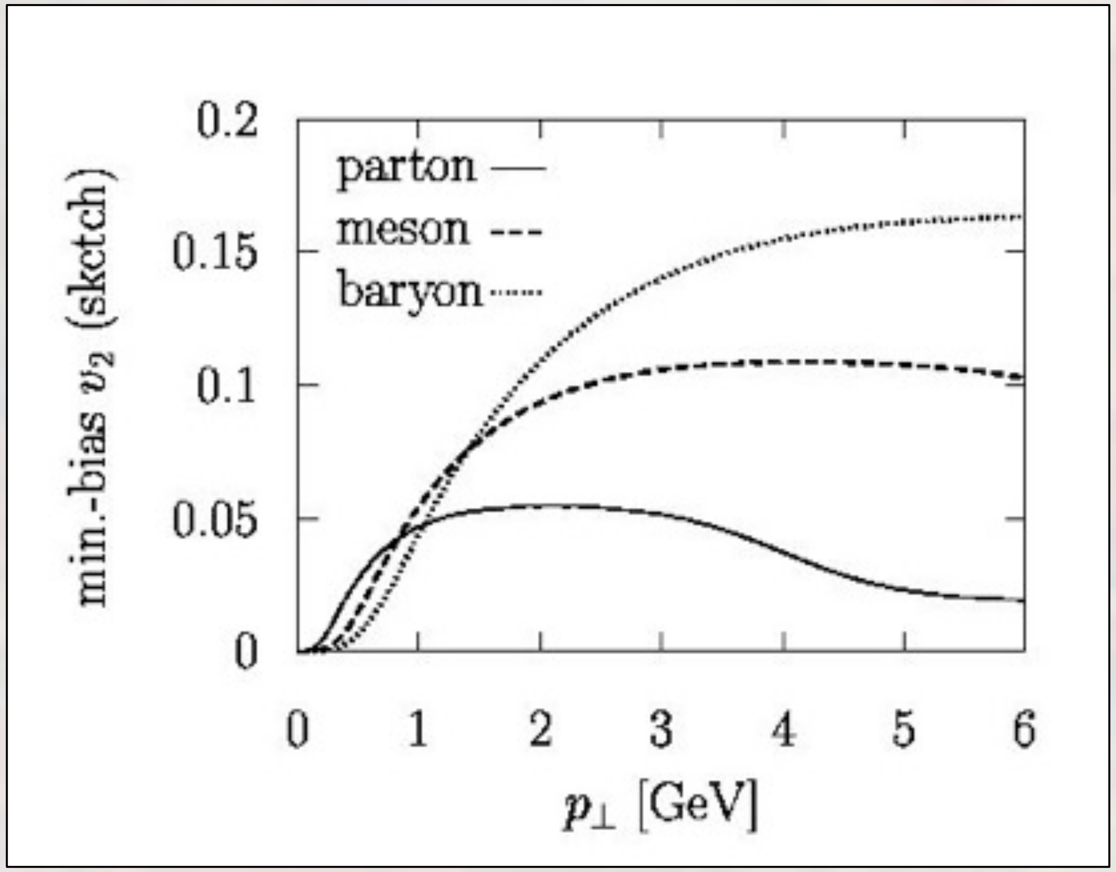
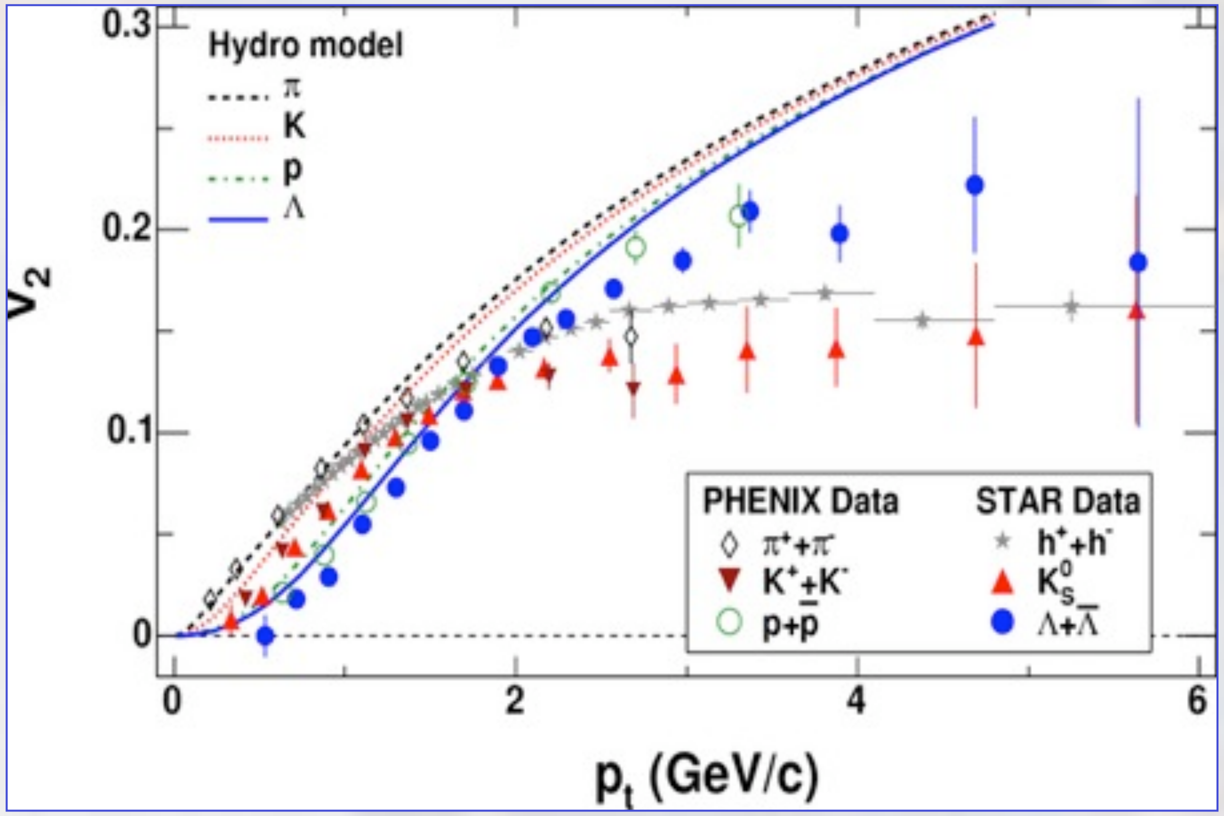


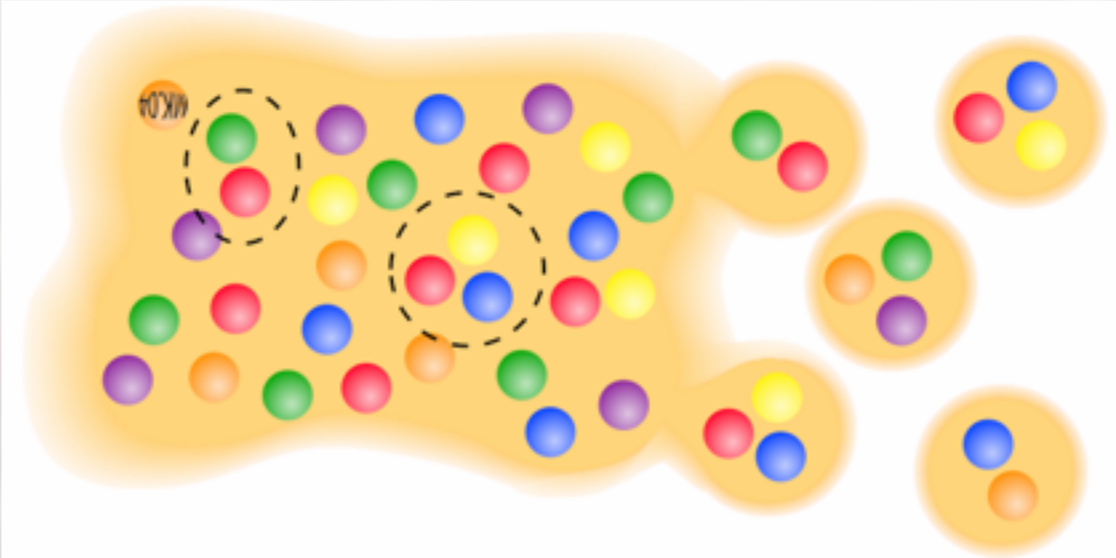
Gas of constituent quarks – deconfinement ?

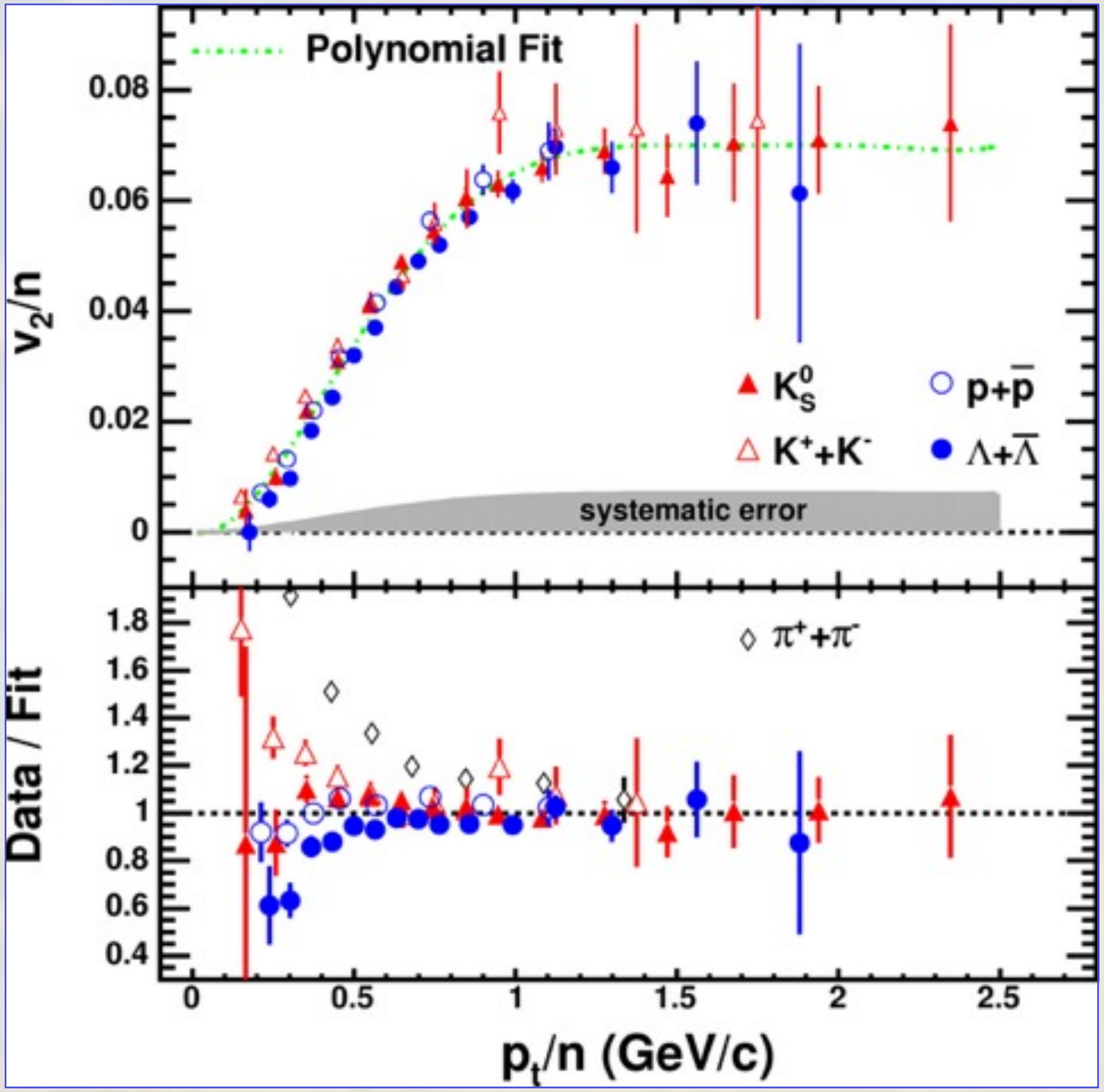




Elliptic flow: Quark scaling







STAR PRL 92(2004)052302

STAR, Phys Rev C (72), 014904 (2005)

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- Elliptic flow saturates at p_t~ 1 GeV, just at constituent quark scale. An accident?

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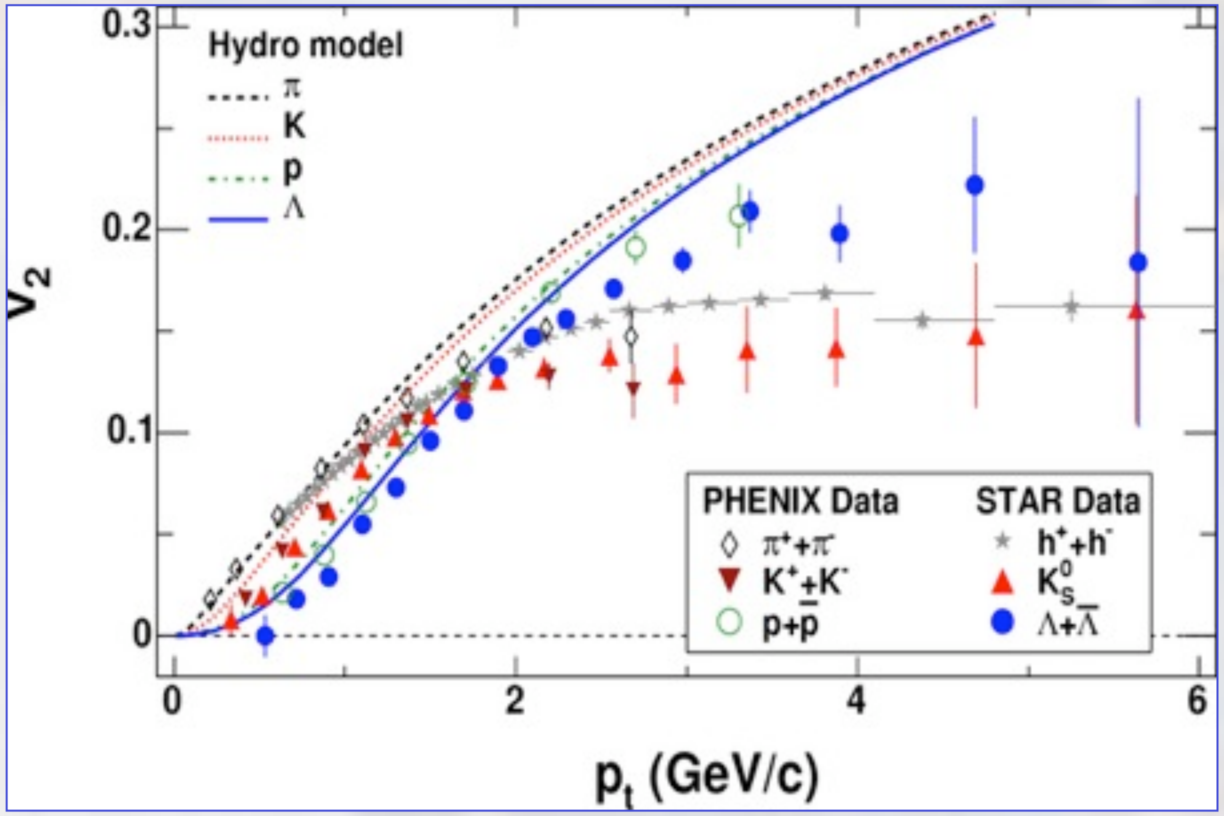

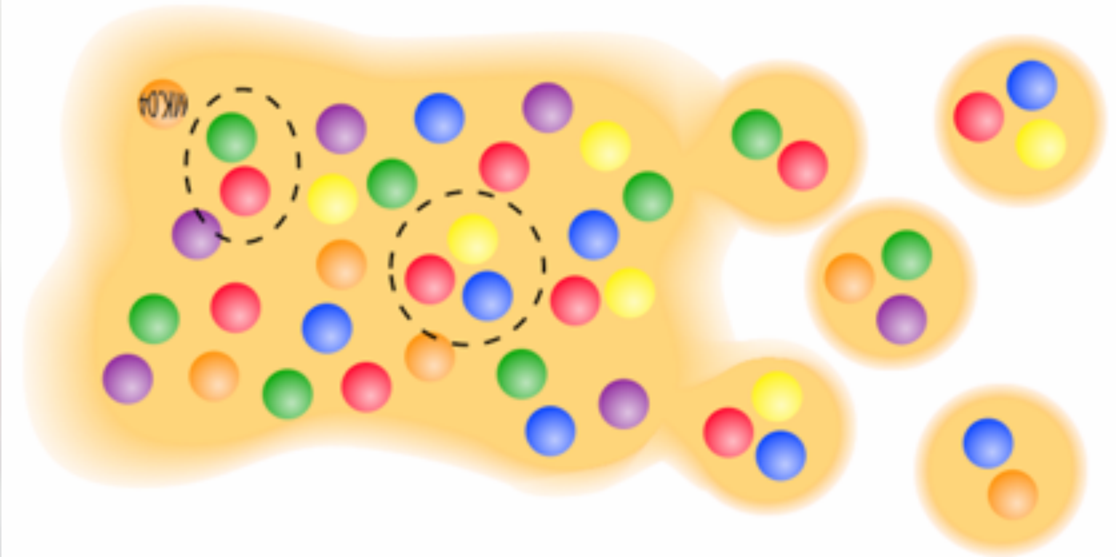

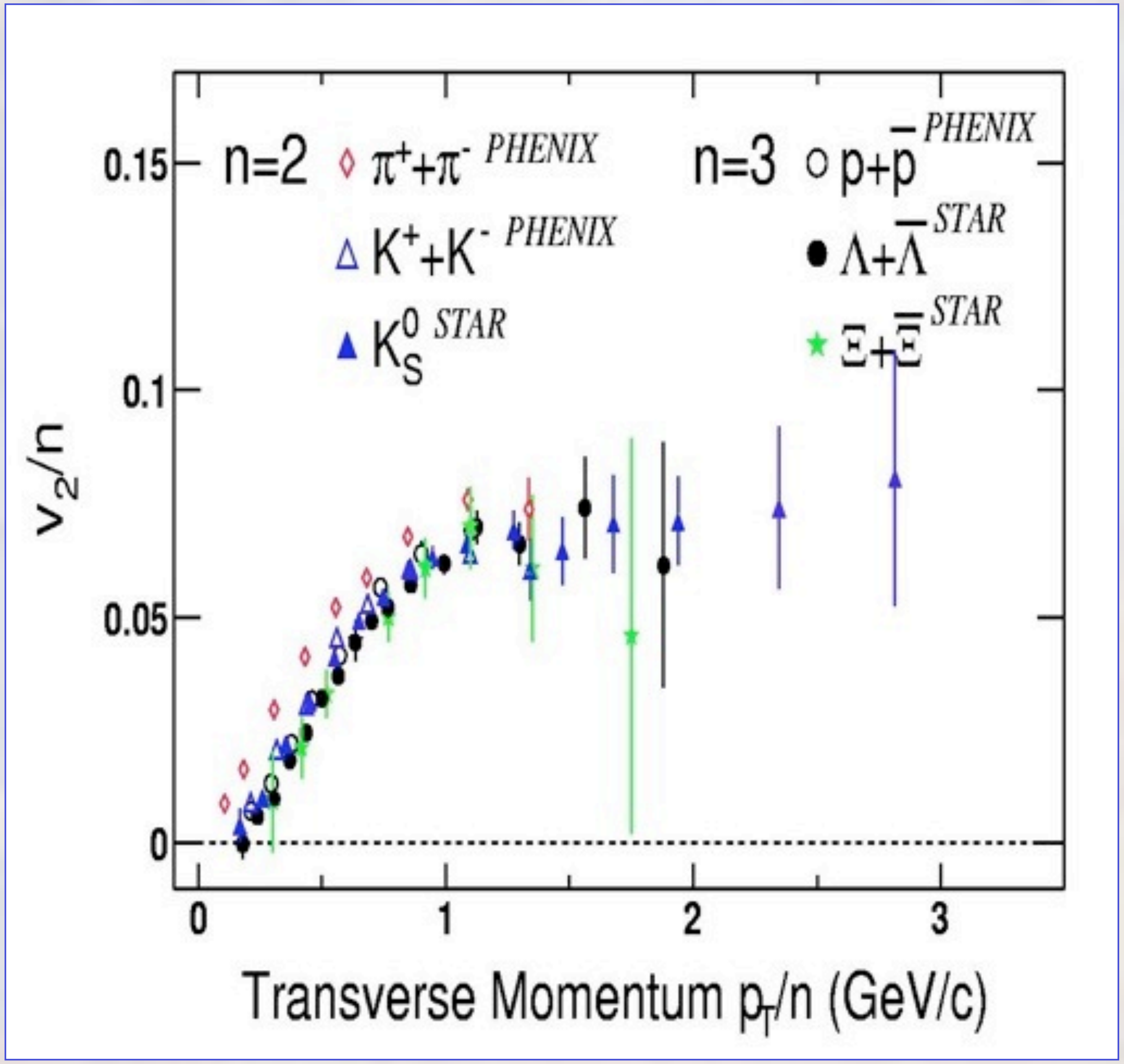

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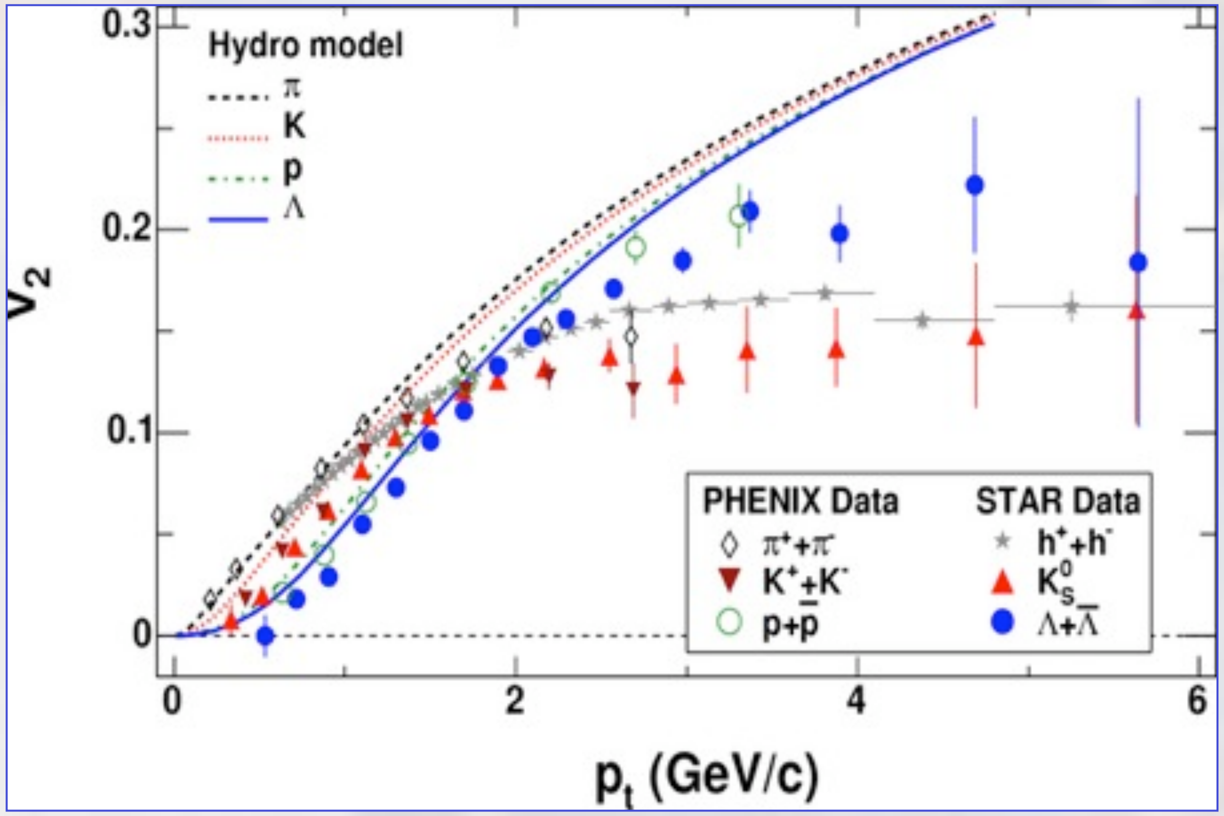

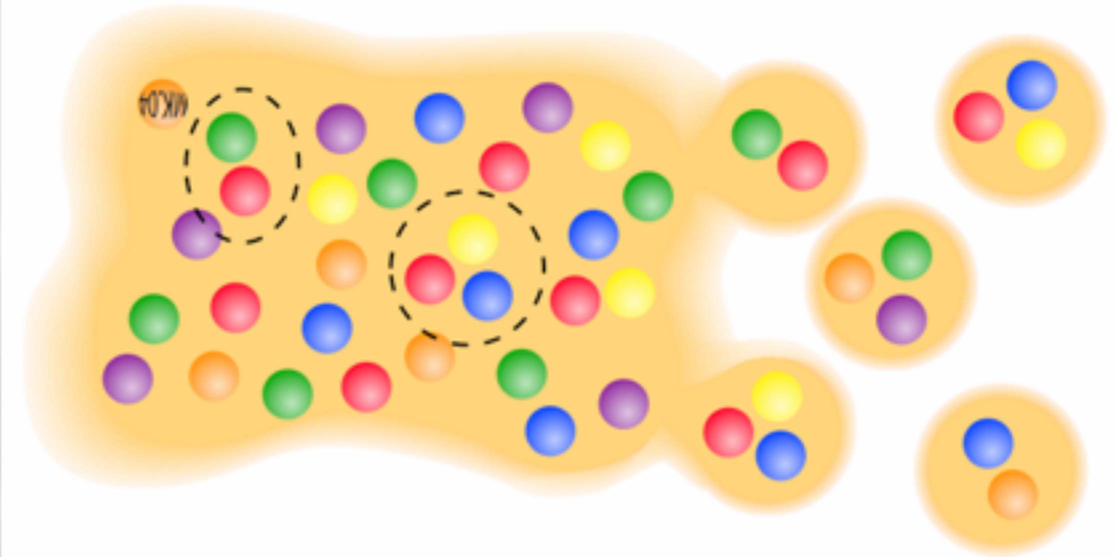

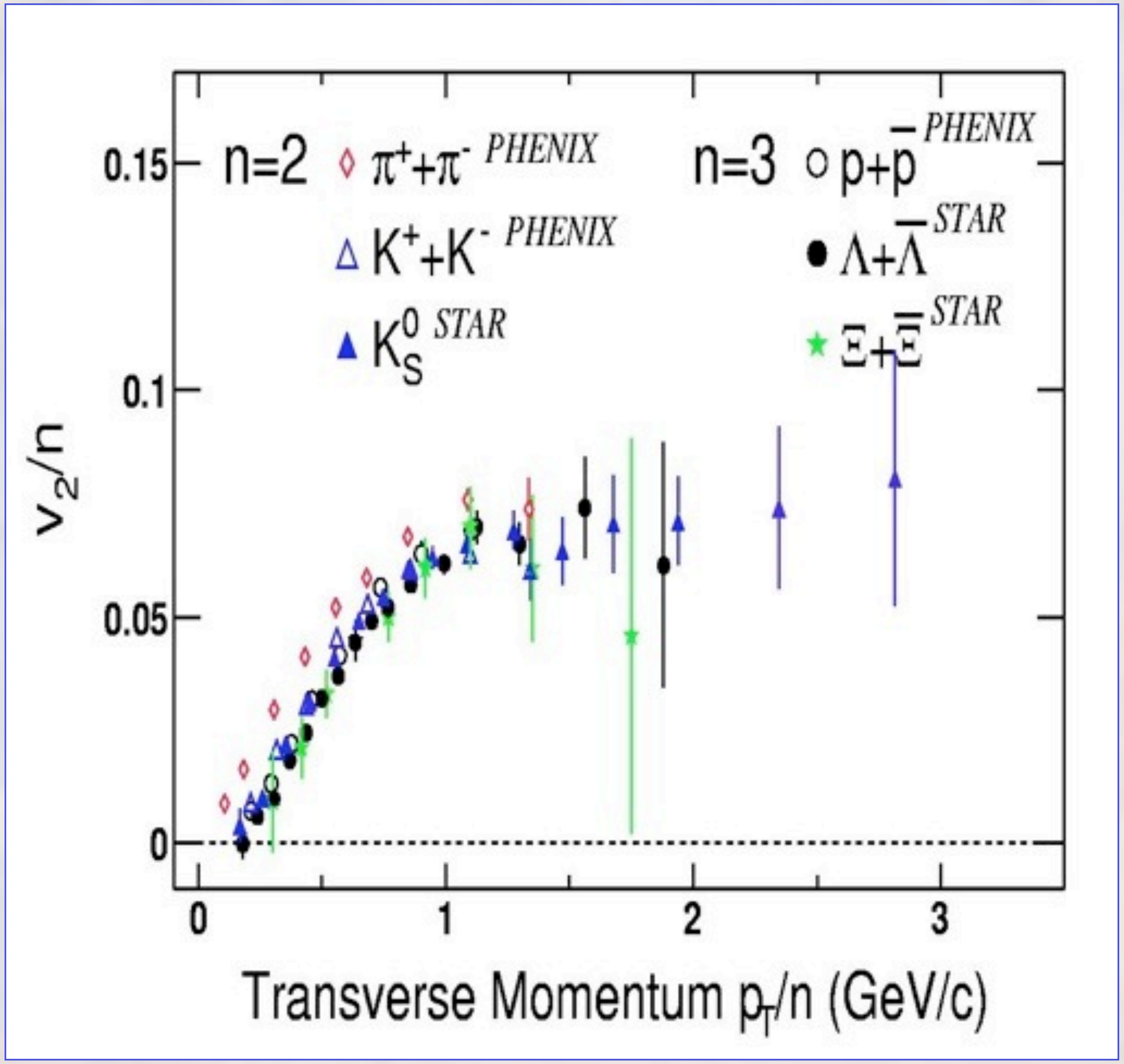

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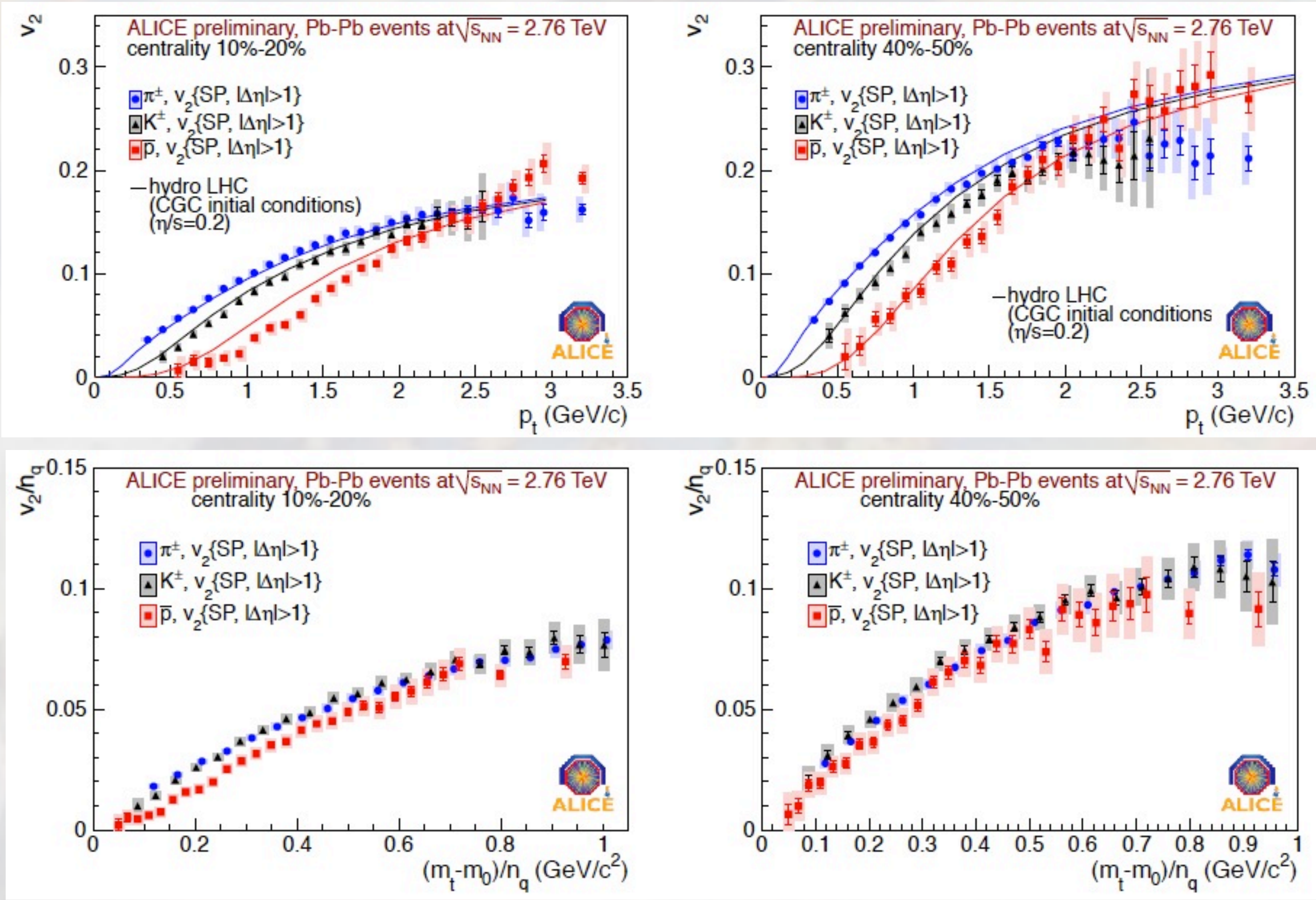
Gas of constituent quarks – deconfinement !

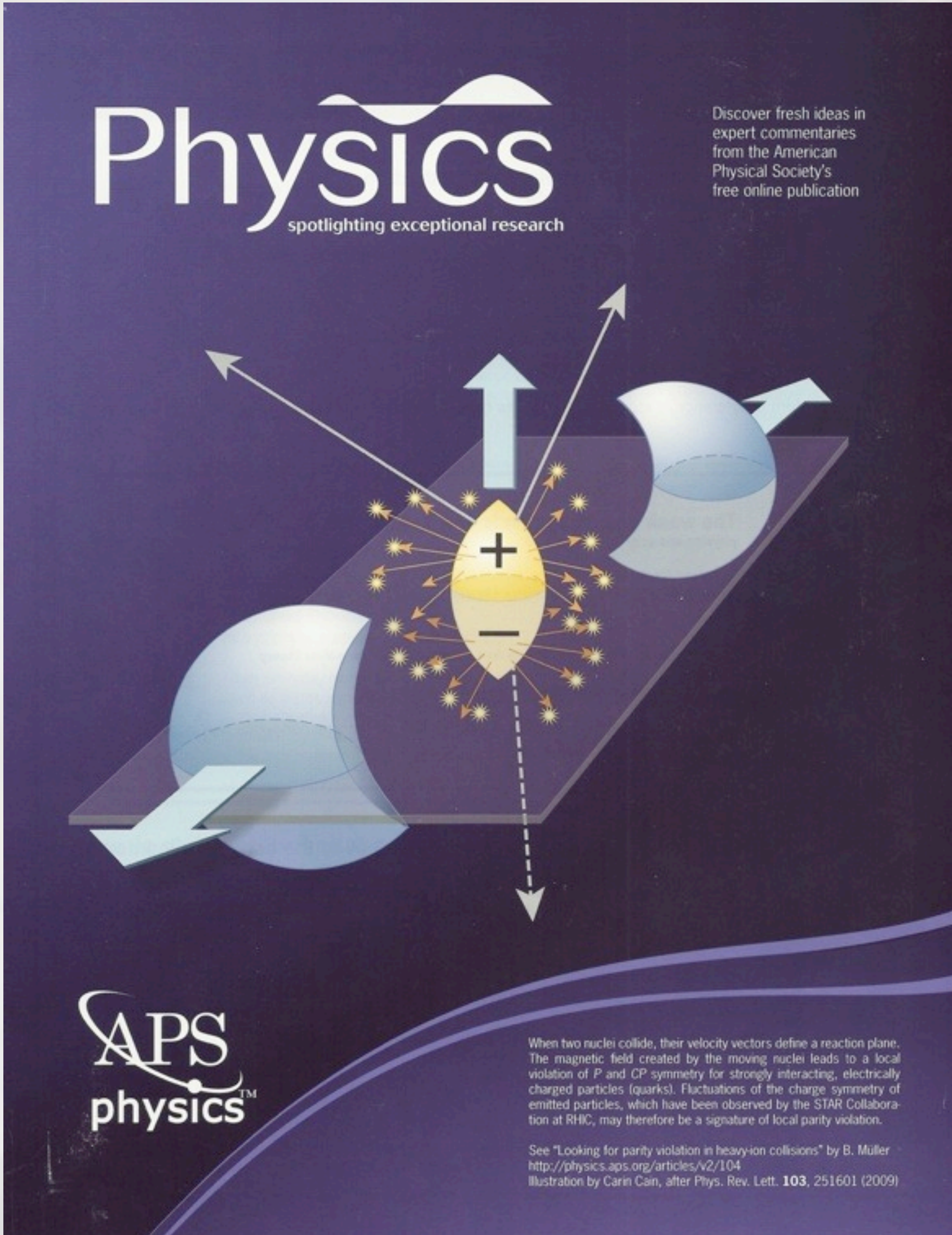
LHC



Similarly at LHC, final analysis in progress.

WAYNE STATE UNIVERSITY

Chiral Magnetic Effect



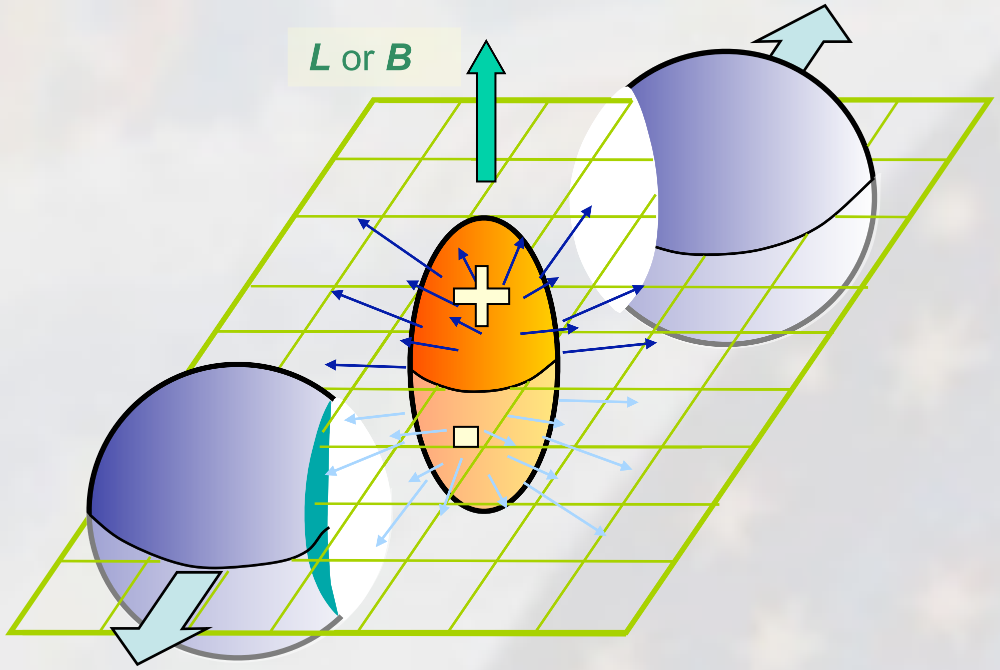
Charge separation along the magnetic field would manifest violation of parity (mirror symmetry)

Kharzeev, PLB633:260 (2006)
Kharzeev, Zhitnitsky, NPA797:67 (2007)
Kharzeev, McLerran, Warringa, NPA803:227 (2008)
Fukushima, Kharzeev, Waringa, PRD 78:074033 (2008)

Voloshin PRC70:057901 (2004)

B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **103**, 251601 (2009).
B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **81**, 054908 (2010).

Chiral magnetic effect. EDM of QCD matter.



D. Kharzeev / Physics Letters B 633 (2006) 260–264

M. Giovannini[(b)] and M. E. Shaposhnikov[(a)1]

Phys.Rev.D57:2186-2206,1998.

Charge separation along the orbital momentum:
EDM of the QCD matter (~ the neutron EDM)
(Local Parity Violation)

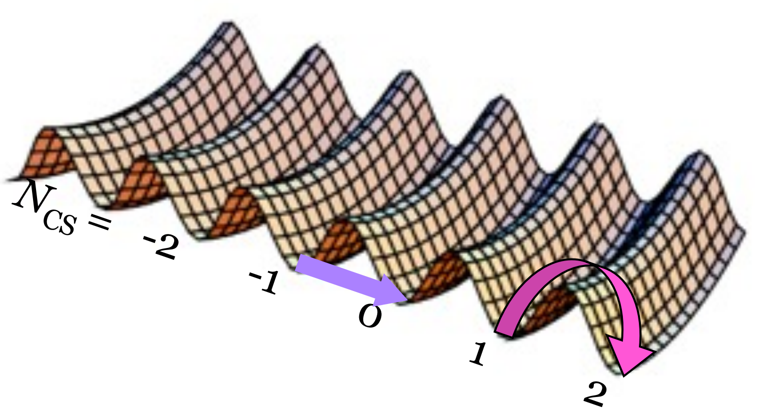
Chiral magnetic effect:
quark interactions with topologically nontrivial gluonic field configurations ⇨ $N_L \neq N_R$

⊕ magnetic field ⇨ charge separation

or

Induction of the electric field parallel to the (static) magnetic field

Energy of gluonic field is periodic in N_{cs} direction (~ a generalized coordinate)



Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or go-over-barrier

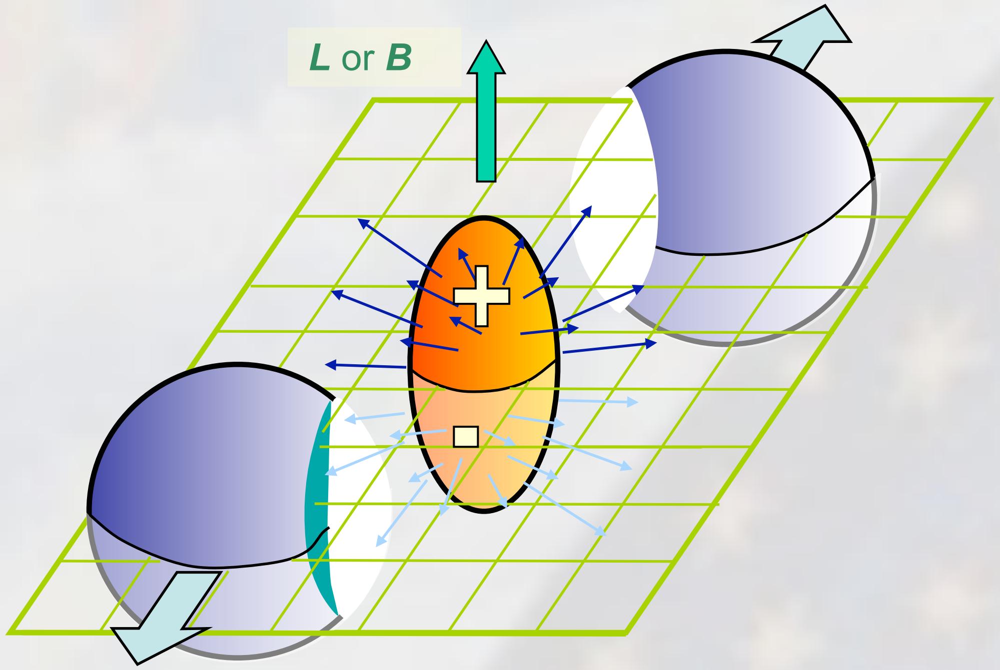
$$N_R - N_L = Q$$

$$A_u = \frac{N_R - N_L}{N_R + N_L}$$

$$A_{\pi^+} = -A_{\pi^-} \simeq \frac{Q}{N_{\pi^+}}$$

The asymmetry is too small to observe in a single event, but is measurable by correlation techniques

Chiral magnetic effect. EDM of QCD matter.



D. Kharzeev / Physics Letters B 633 (2006) 260–264

M. Giovannini[(b)] and M. E. Shaposhnikov[(a)1]

Phys.Rev.D57:2186-2206,1998.

Charge separation along the orbital momentum:
EDM of the QCD matter (~ the neutron EDM)
(Local Parity Violation)

Chiral magnetic effect:
quark interactions with topologically nontrivial gluonic field configurations ⇨ $N_L \neq N_R$

⊕ magnetic field ⇨ charge separation

or

Induction of the electric field parallel to the (static) magnetic field

$$N_R - N_L = Q$$

$$A_u = \frac{N_R - N_L}{N_R + N_L}$$

$$A_{\pi^+} = -A_{\pi^-} \simeq \frac{Q}{N_{\pi^+}}$$

The asymmetry is too small to observe in a single event, but is measurable by correlation techniques

Observable. Backgrounds

Voloshin PRC70:057901 (2004)

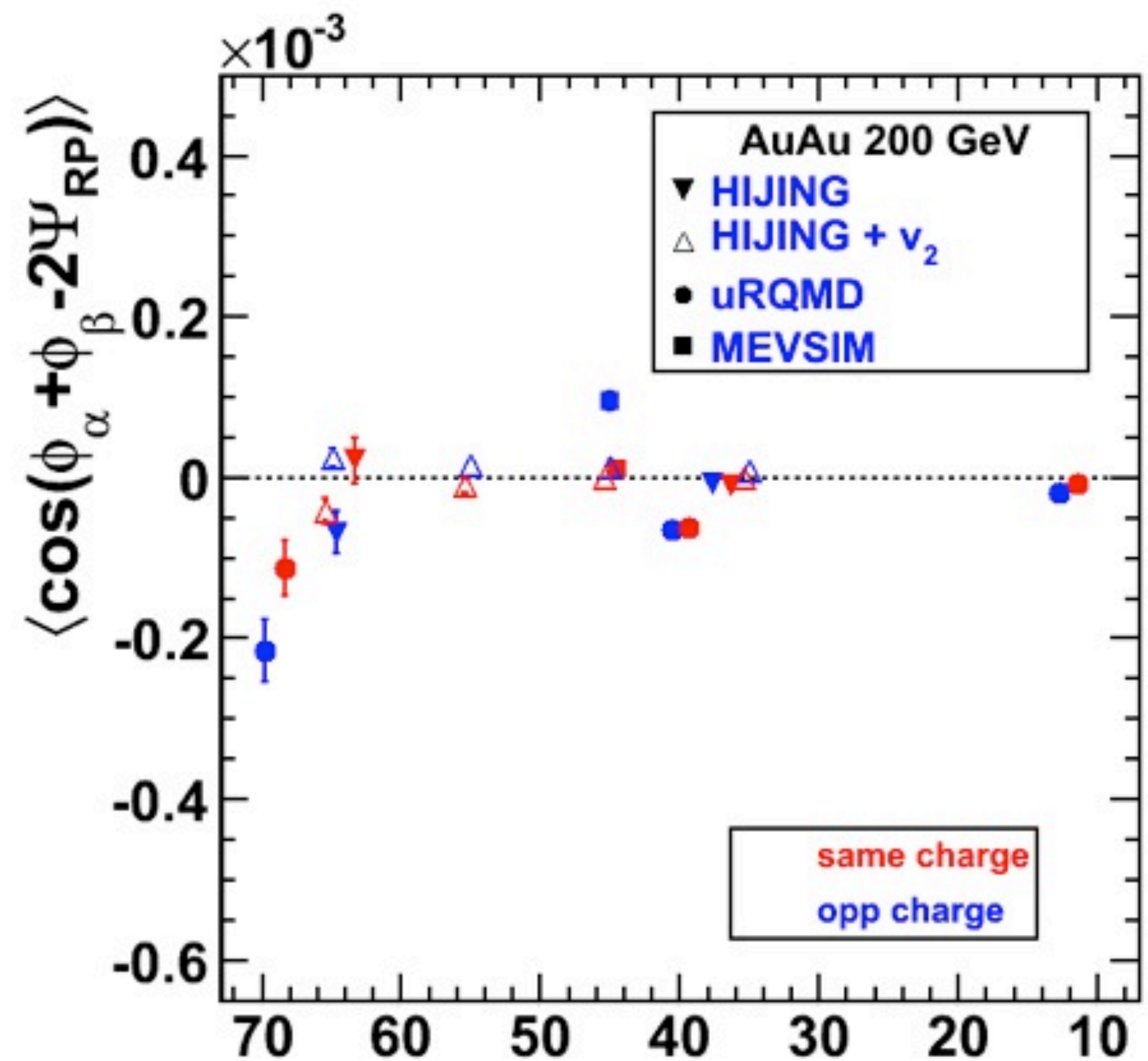
I. Physical background (RP dependent).
Can not be suppressed

$$\langle\cos(\phi_\alpha+\phi_\beta-2\Psi_{RP})\rangle =$$
$$= \langle\cos\Delta\phi_\alpha\,\cos\Delta\phi_\beta\rangle - \langle\sin\Delta\phi_\alpha\,\sin\Delta\phi_\beta\rangle$$
$$= [\langle v_{1,\alpha}v_{1,\beta}\rangle + B^{in}] - [\langle a_\alpha a_\beta\rangle + B^{out}].$$

- "Flowing clusters"/RP dependent fragmentation

$$\langle\cos(\phi_\alpha+\phi_\beta-2\Psi_{RP})\rangle =$$
$$= A_{clust}\,\langle\cos(\phi_\alpha+\phi_\beta-2\phi_{clust})\rangle_{clust}\, v_{2,clust}$$

- Global polarization, v_1 fluctuations, …



B. I. Abelev et al. [STAR Collaboration], Phys. Rev. Lett. 103, 251601 (2009).
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(+,+) and (-,-) results are combined as "same charge"
HIJING+v2 = added "afterburner" to generate flow
MEVSIM: flow as in experiment, number of resonances maximum what is consistent with experiment

II. RP independent. (depends on method and in general can be greatly reduced)

$$\langle\cos(\phi_a+\phi_\beta-2\phi_c)\rangle \stackrel{?}{=} \langle\cos(\phi_a+\phi_\beta-2\Psi_{RP})\rangle\, v_{2,c}$$

Event generators: the signal is not zero, but different from expectations (e.g. same charge ~ opp. charge)

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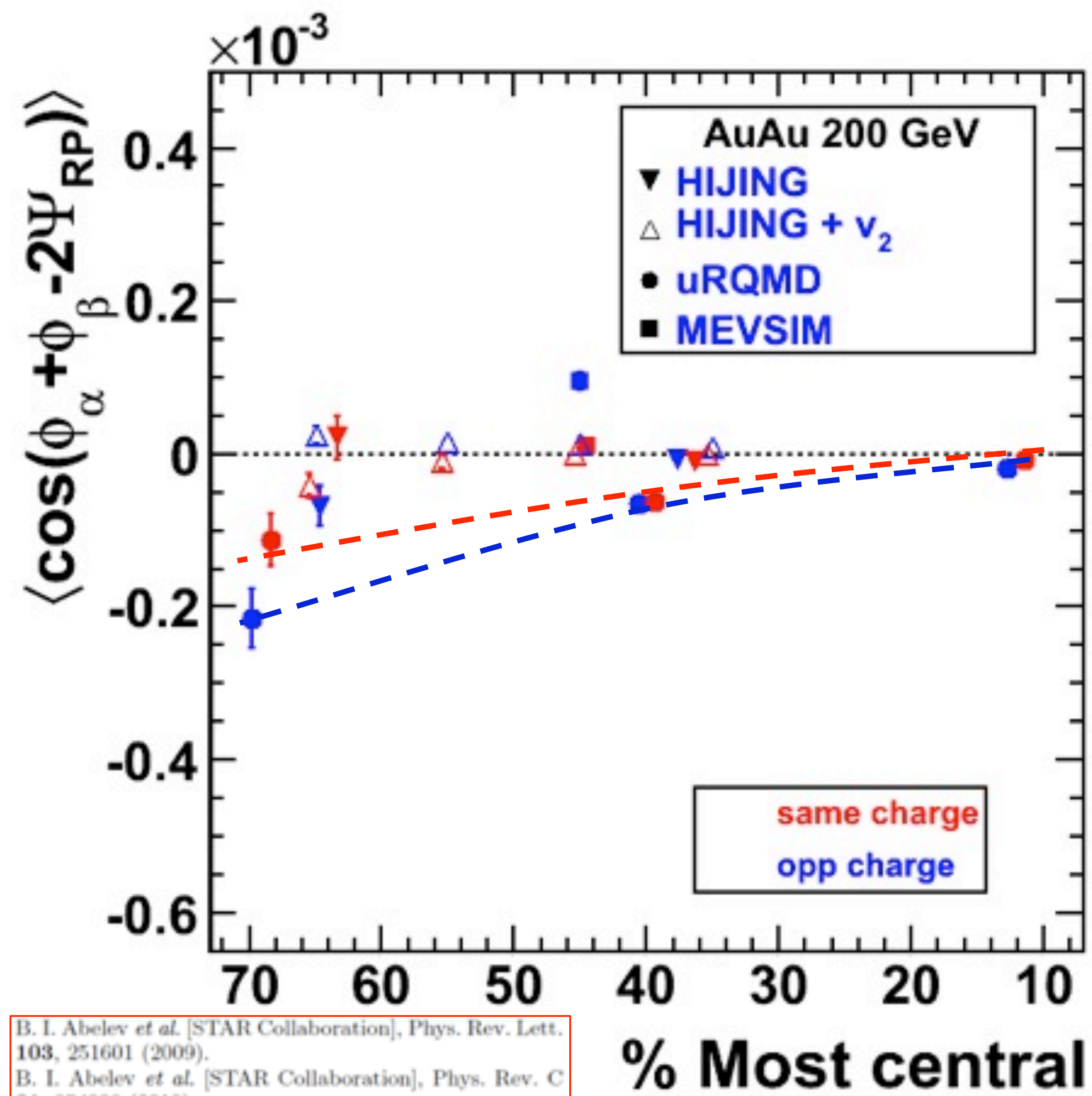

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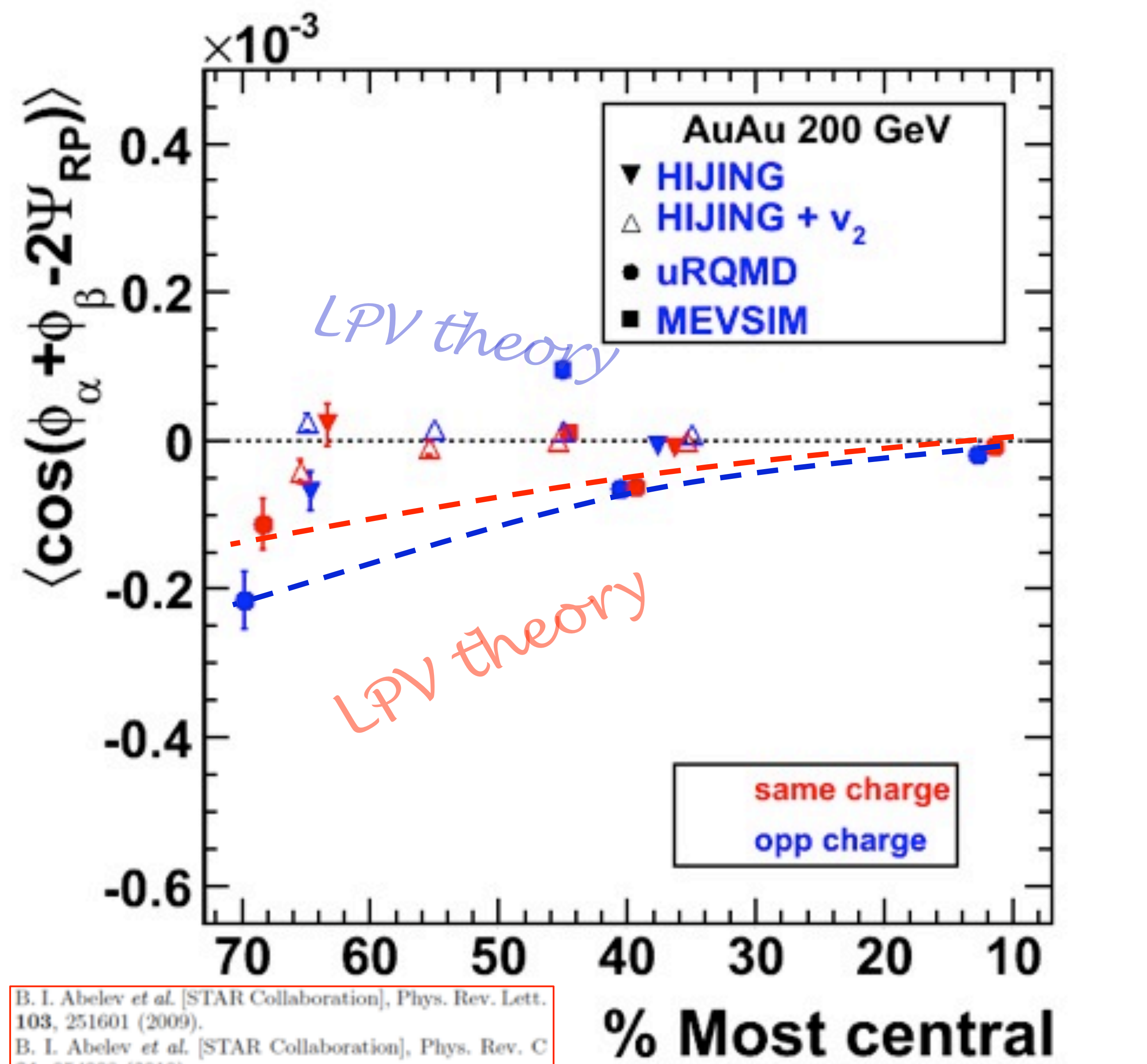

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RHIC (STAR) Data vs models

B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **103**, 251601 (2009).
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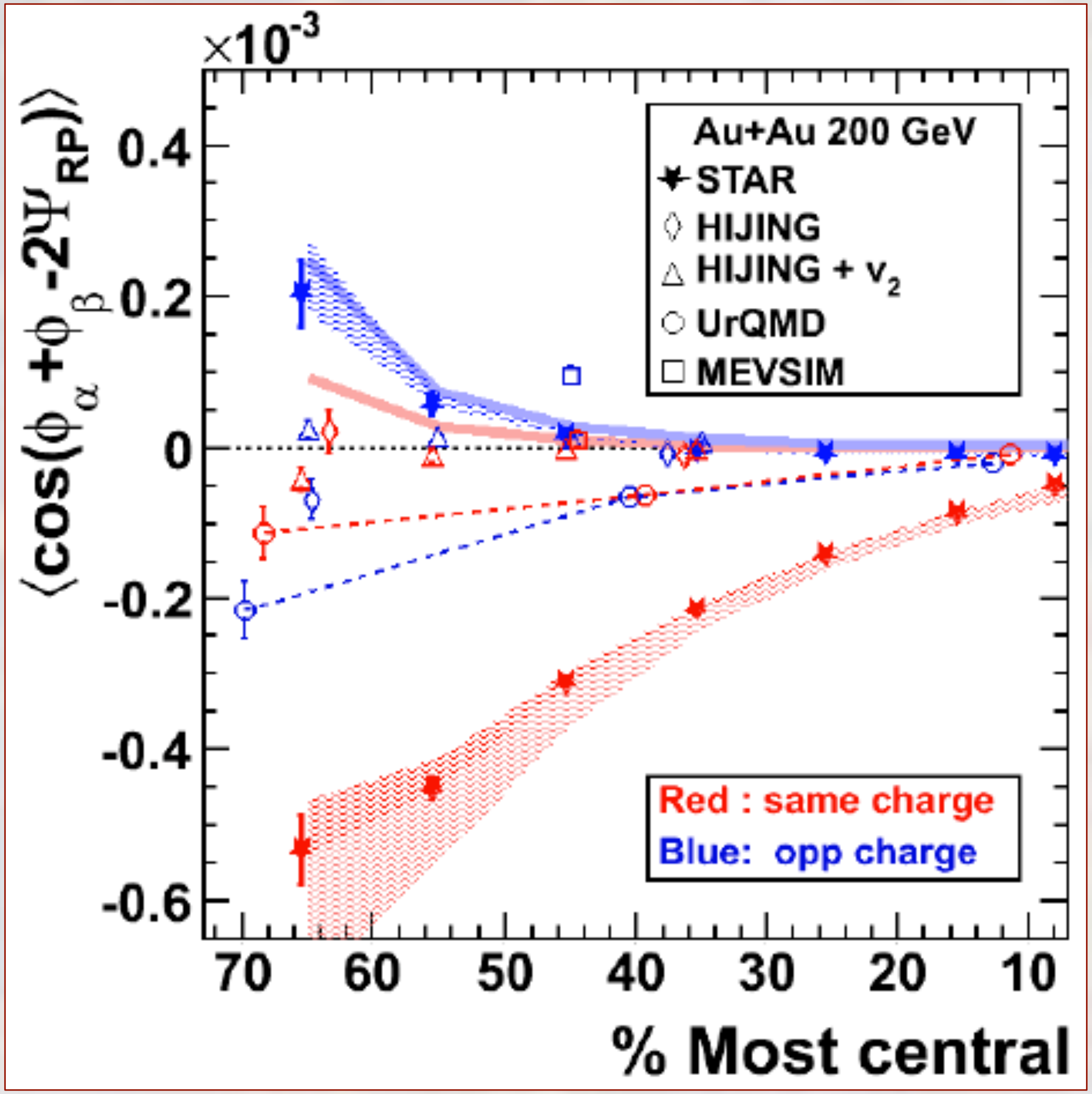
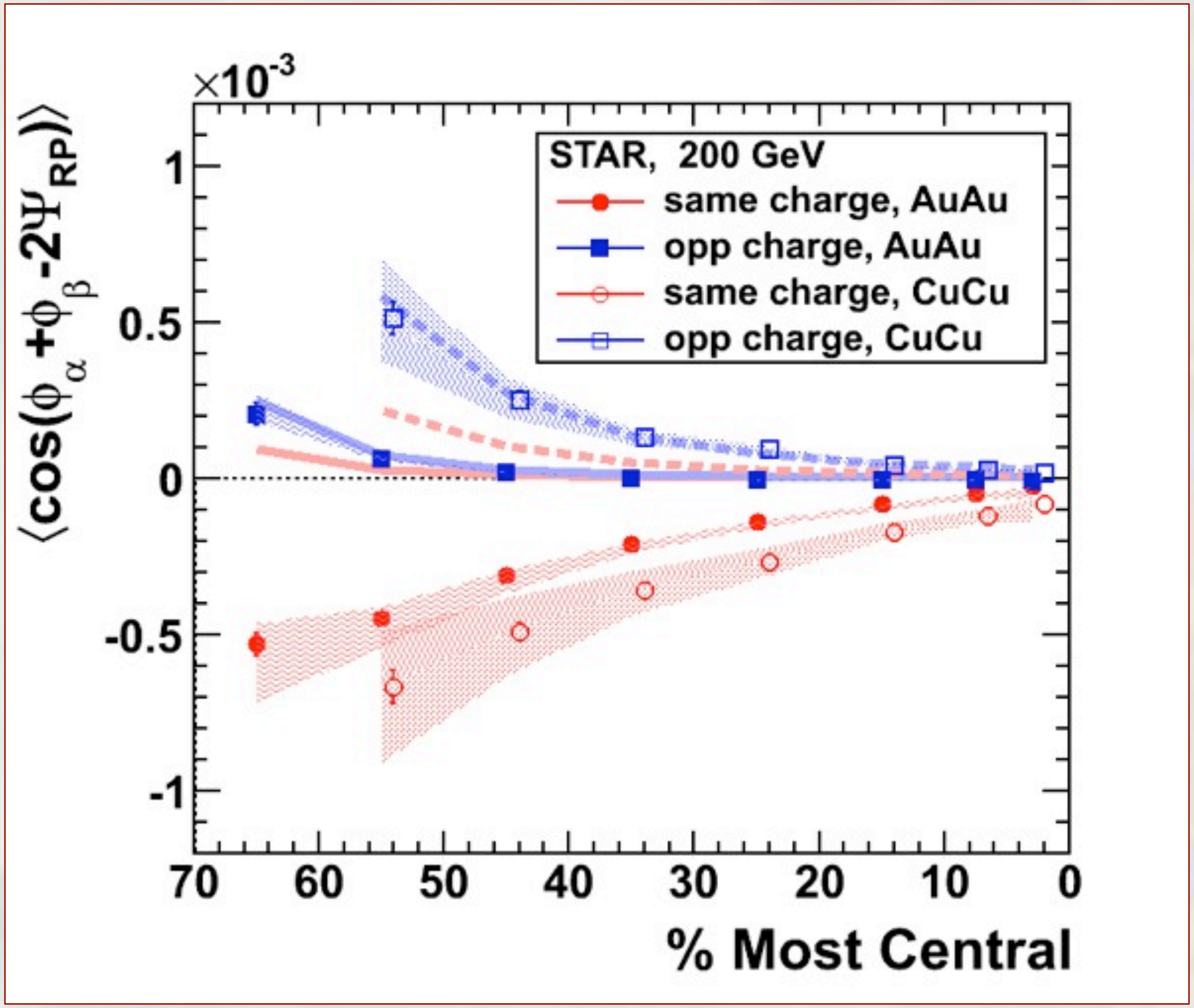
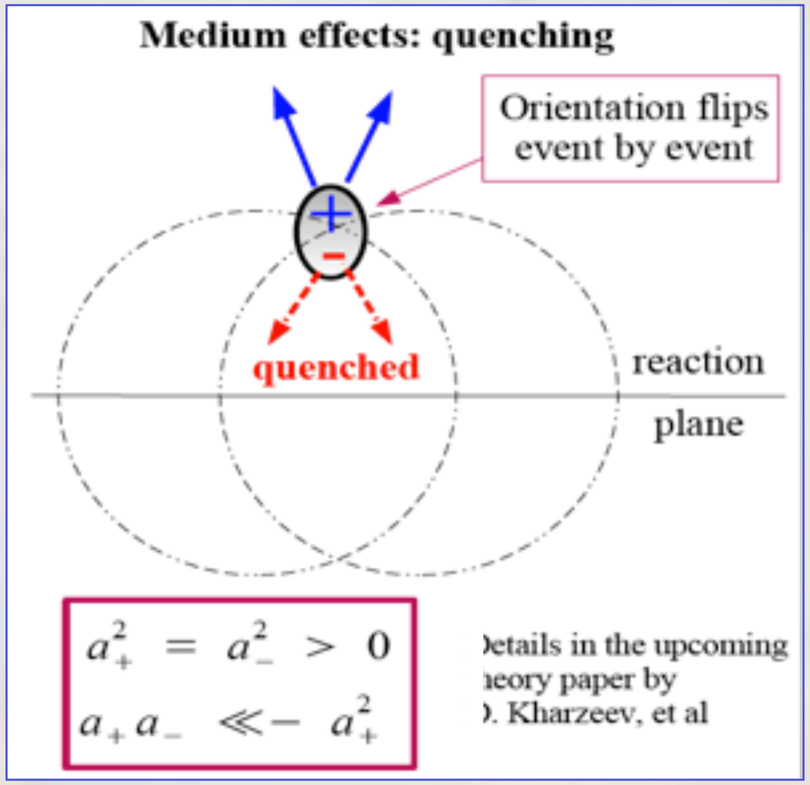
- Large difference in like-sign vs unlike-sign correlations in the data compared to models.
- Bigger amplitude in like-sign correlations compared to unlike-sign.
- Like-sign and unlike-sign correlations are consistent with theoretical expectations
- … but the unlike-sign correlations are small, might have significant contribution effects not related to the RP orientation.
- The "base line" can be shifted from zero.



⟨+,+⟩ and ⟨–,–⟩ results agree within errors and are combined in this plot and all plots below.

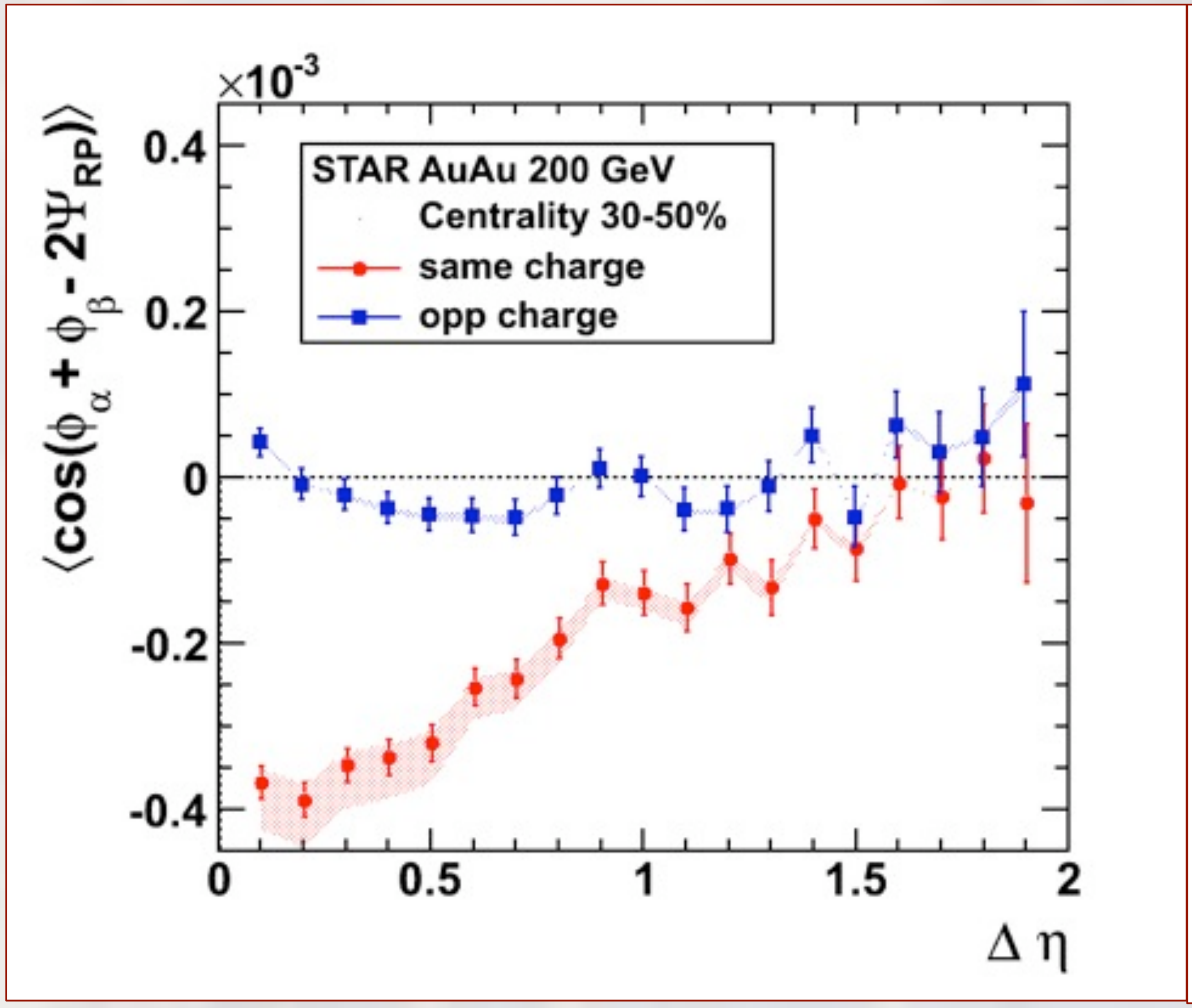
Au+Au and Cu+Cu @ 200 GeV

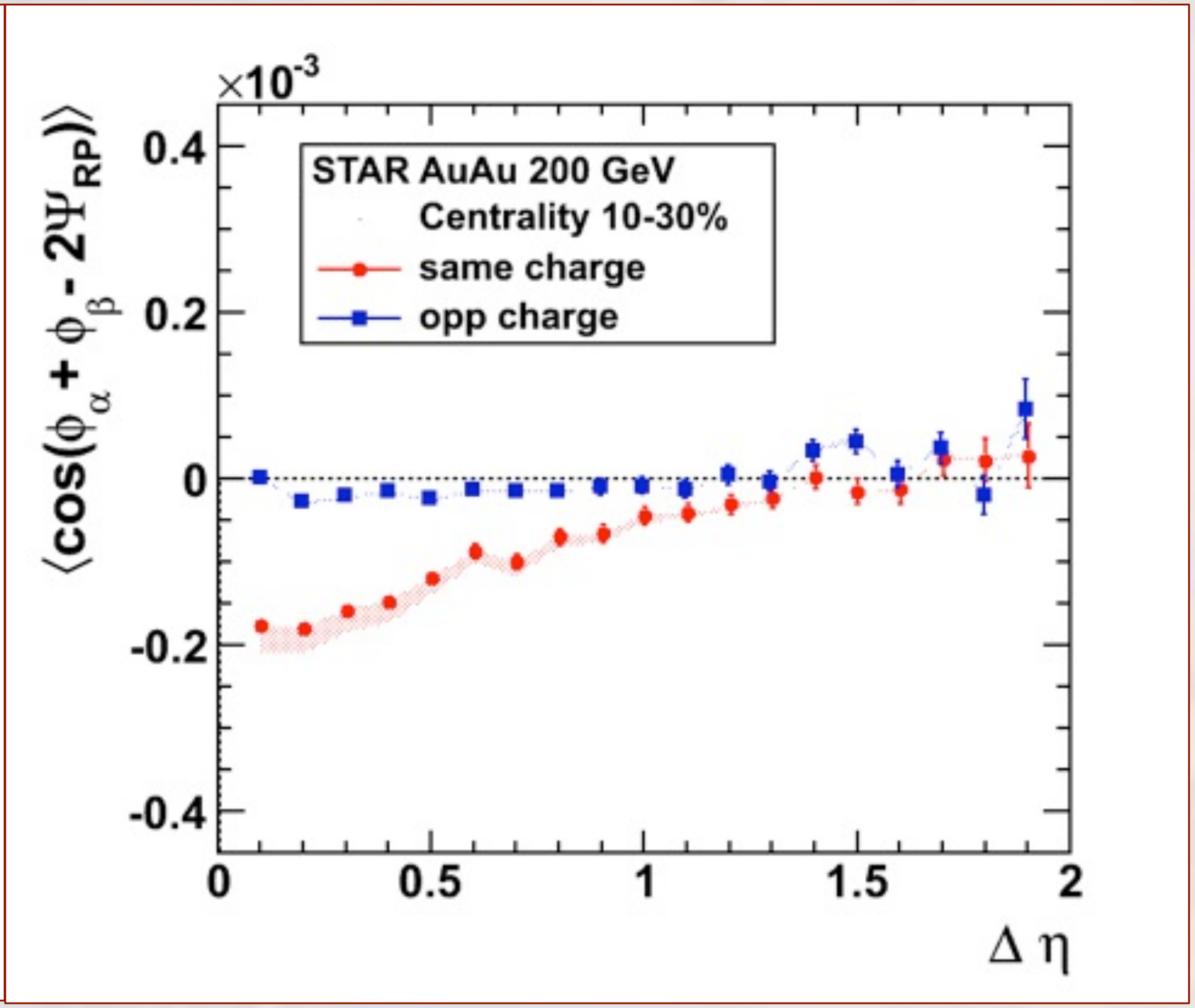




+/– signal in Cu+Cu is stronger, qualitatively in agreement with "theory", but keep in mind large uncertainties due to correlations not related to RP

$\Delta\eta$ dependences (AuAu200).



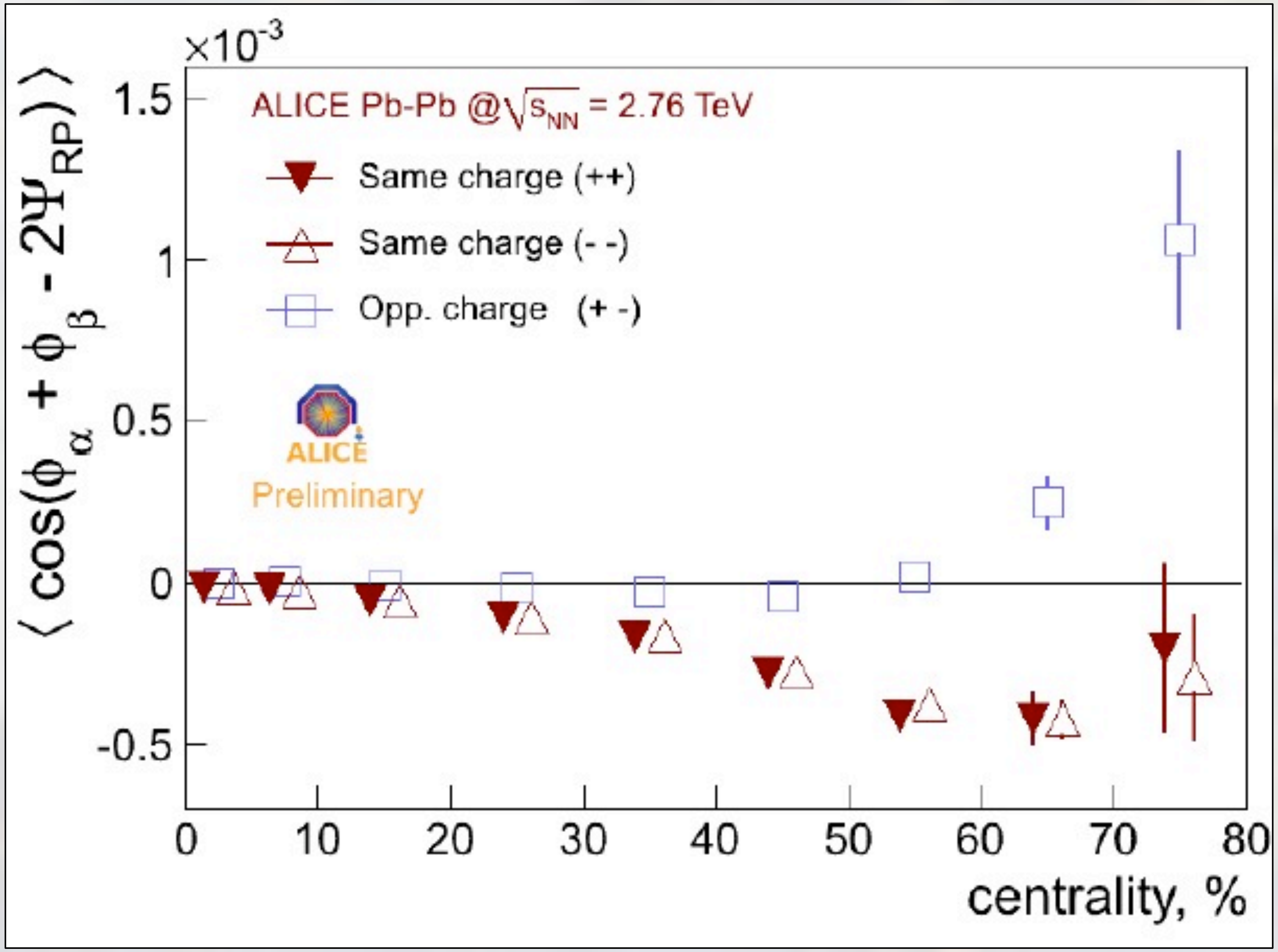


Typical “hadronic” width, consistent with “theory”.

Not color flux tubes?

Correlations at large $\Delta\eta$ (and large Δpt, see next slide) -- it is not HBT or Coulomb.

LHC



ALICE: the signal is very similar to that observed by STAR.

Further (future) tests

Sergei A. Voloshin PRL 105, 172301 (2010)

U+U very central collisions

All ("physics") background effects
scale with elliptic flow.

Correlations due to chiral magnetic effect
scale with (square of) the magnetic field.

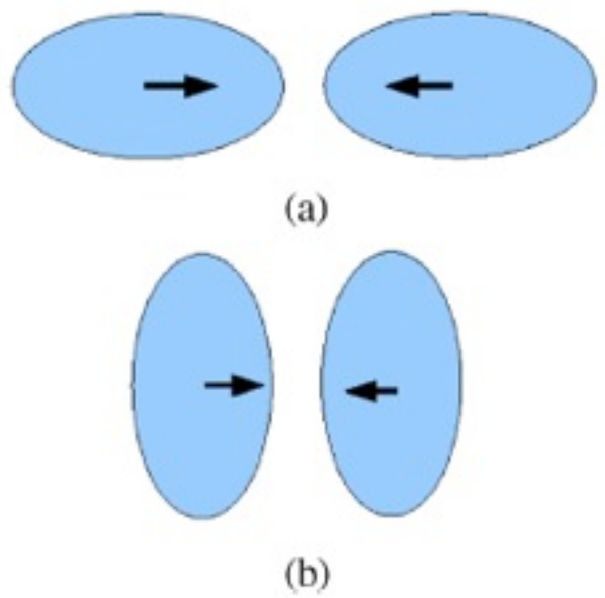


FIG. 1 (color online). Schematic view of central $U + U$ collisions: (a) tip-tip and (b) body-body.

In both cases the magnetic field is small,
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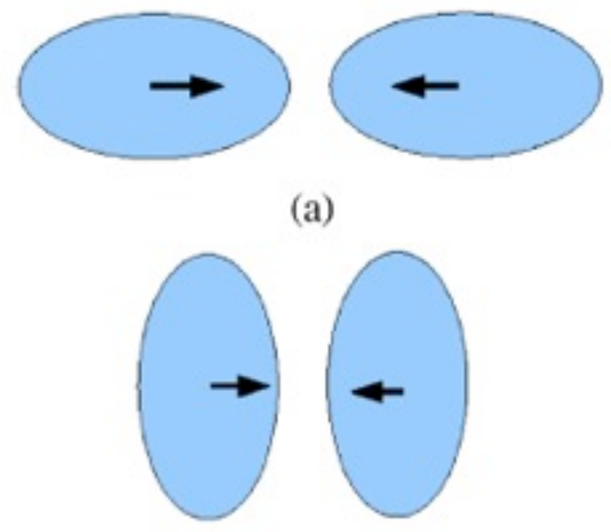

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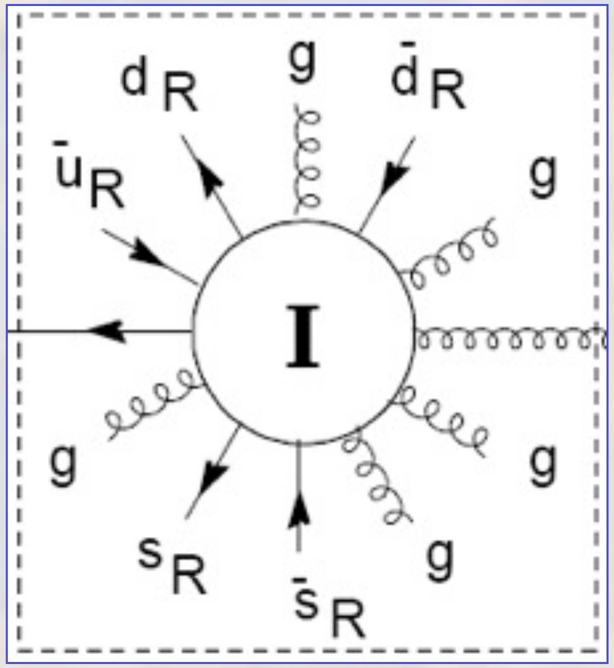
Try to identify other features of the "topological bubbles", e.g. instanton "bubble"

- decays isotropically,
- into equal number of q-qbar pairs of all flavors.

t'Hooft's interaction

Instanton subprocess:

Δ chirality = 2 n_f



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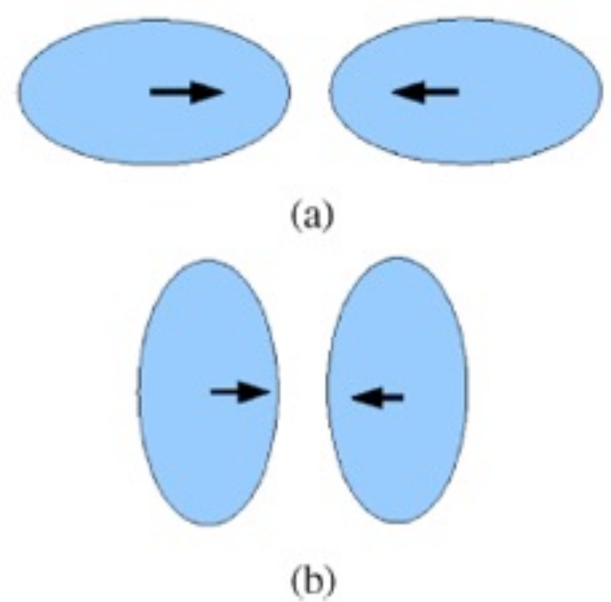

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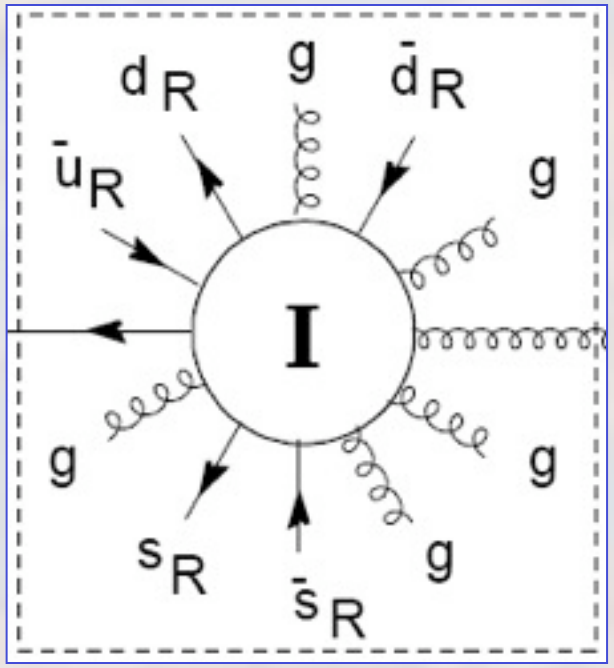
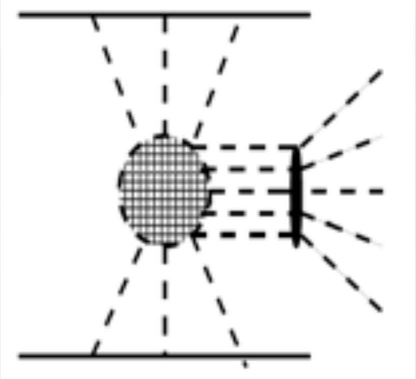


Nonperturbative Phenomena and Phases of QCD

Edward V. Shuryak



$$M_{sph} \approx \frac{30}{g^2(\rho)\rho} \sim 2.5\, GeV$$

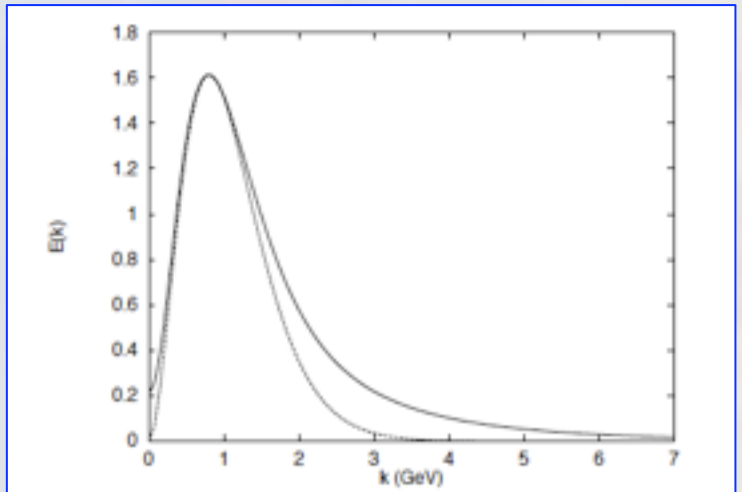


FIG. 14. Energy spectrum of prompt gluons (solid line), obtained from the numerical solution, and a thermal distribution with $T = 285$ MeV (dashed line).

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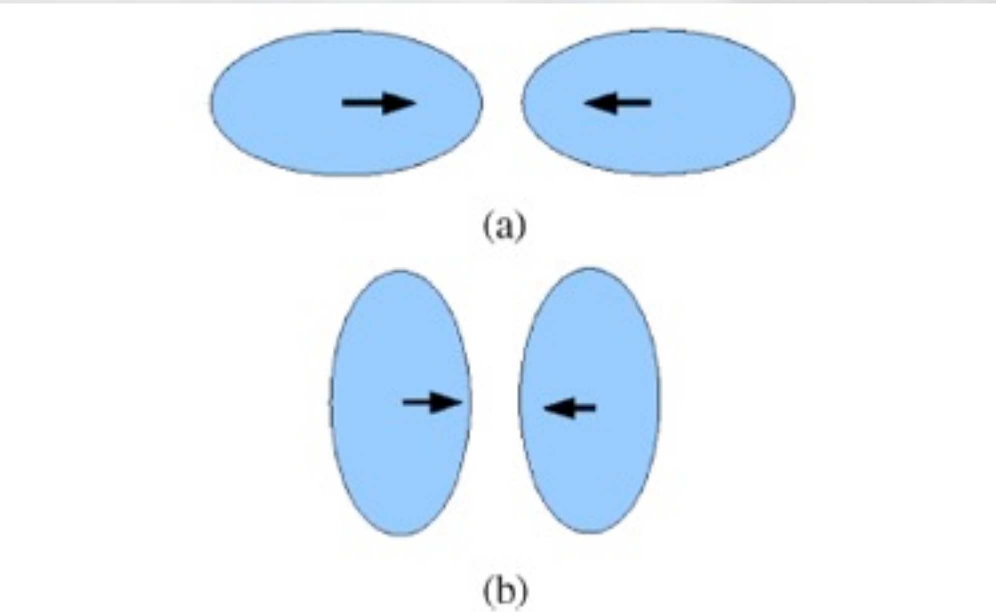

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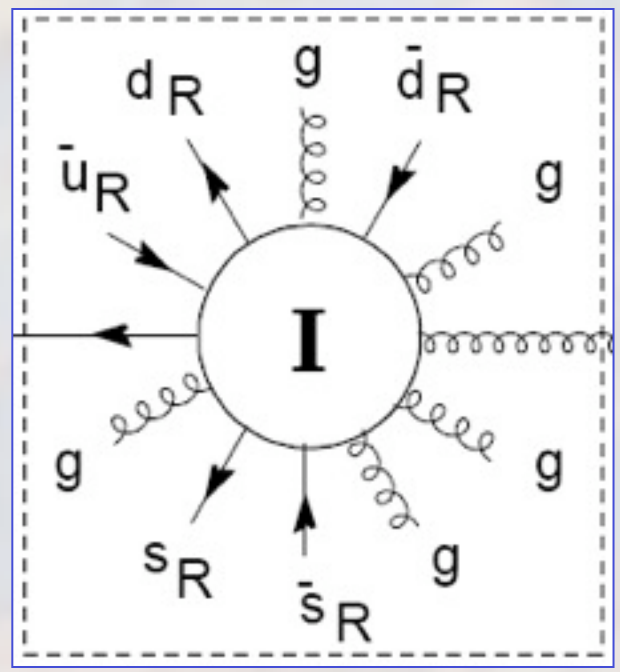

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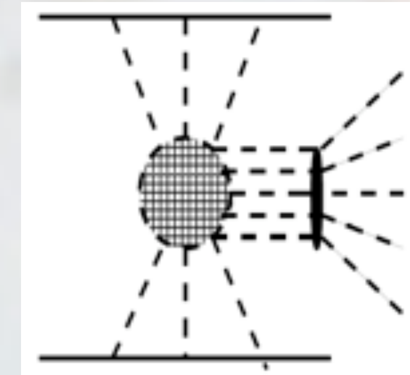

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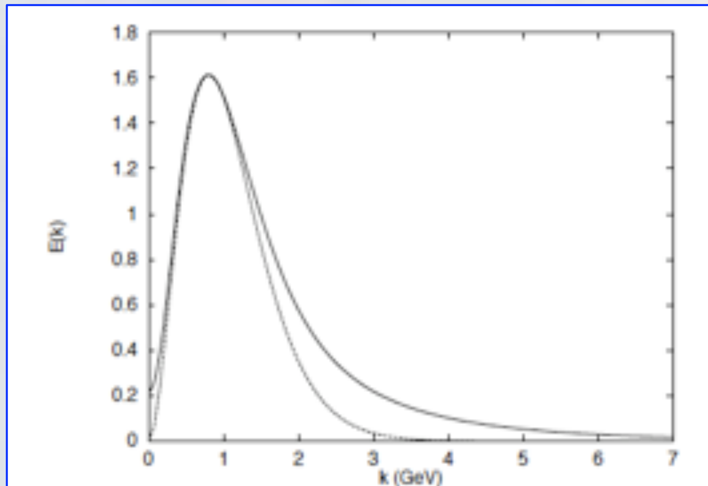

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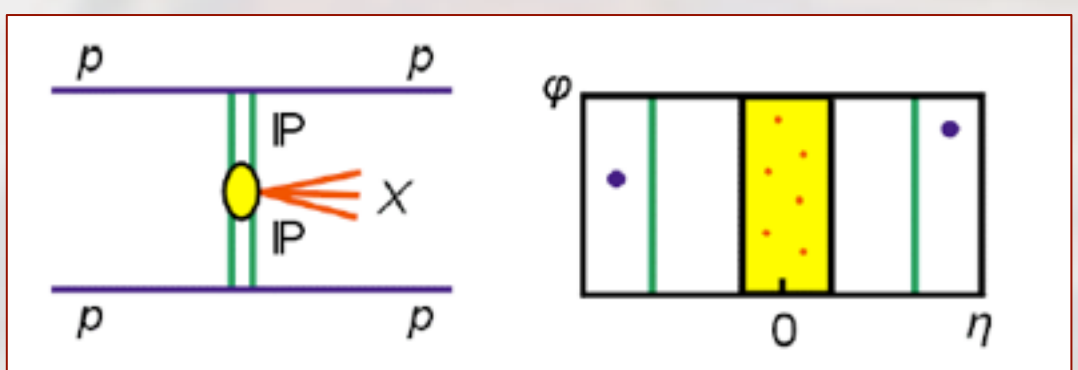
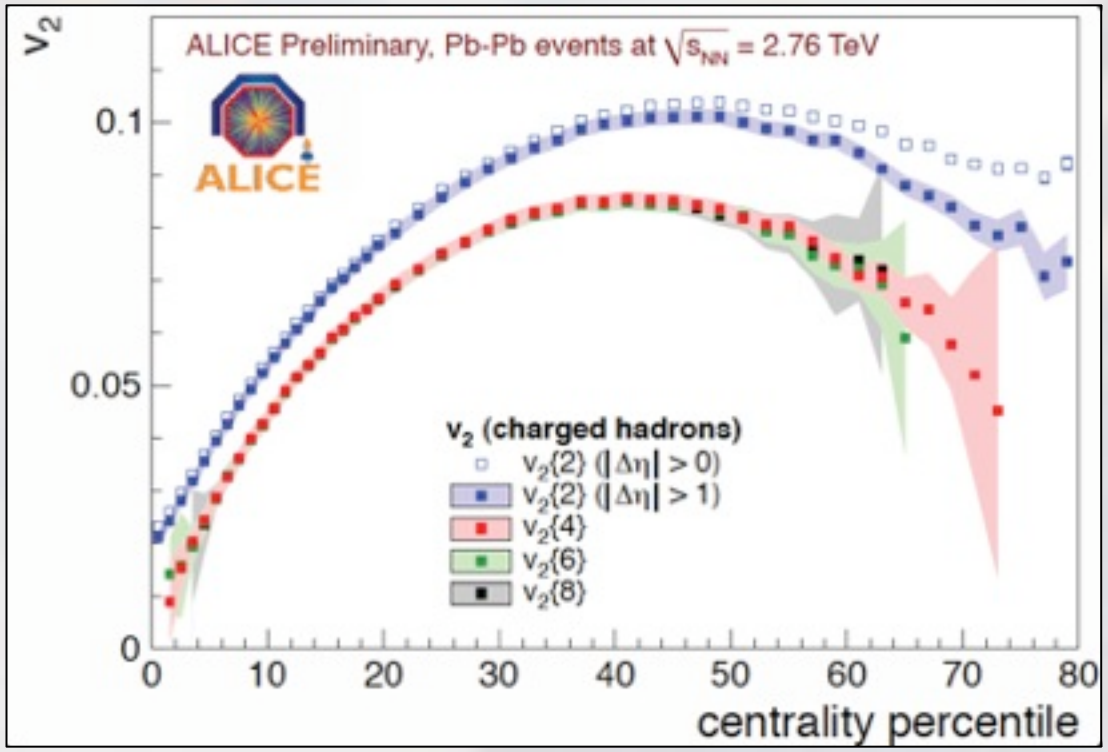


STAR, pp2pp, phase II

Look for: Mass distribution, multiplicities, quark flavor content of the clusters (PID correlations, KKπ vs πππ, etc.), angular distributions, unusual behavior in HBT parameters (production by coherent field)

Flow fluctuations. "Nonflow"



$$v_2\{2\}^2 \equiv \left\langle \cos\left(2\left(\varphi_1-\varphi_2\right)\right)\right\rangle = \left\langle v_2^2\right\rangle + \delta = \left\langle v_2\right\rangle^2 + \sigma_v^2 + \delta$$

$$v_2\{4\}^4 \equiv 2\left\langle \cos\left(2\left(\varphi_1-\varphi_2\right)\right)\right\rangle^2 - \left\langle \cos\left(2\left(\varphi_1+\varphi_2-\varphi_3-\varphi_4\right)\right)\right\rangle \approx 2\left\langle v_2^2\right\rangle^2 - \left\langle v_2^4\right\rangle$$

The difference between two-particle and many-particle correlation results are due to flow fluctuations and nonflow.

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

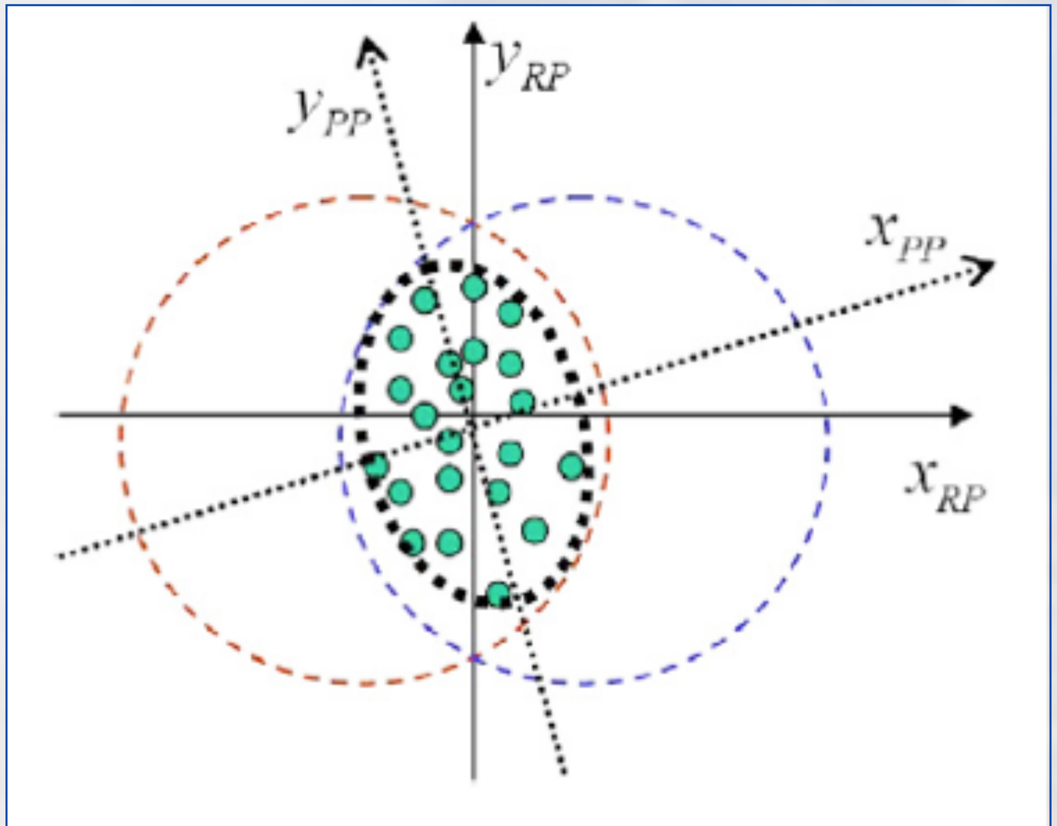
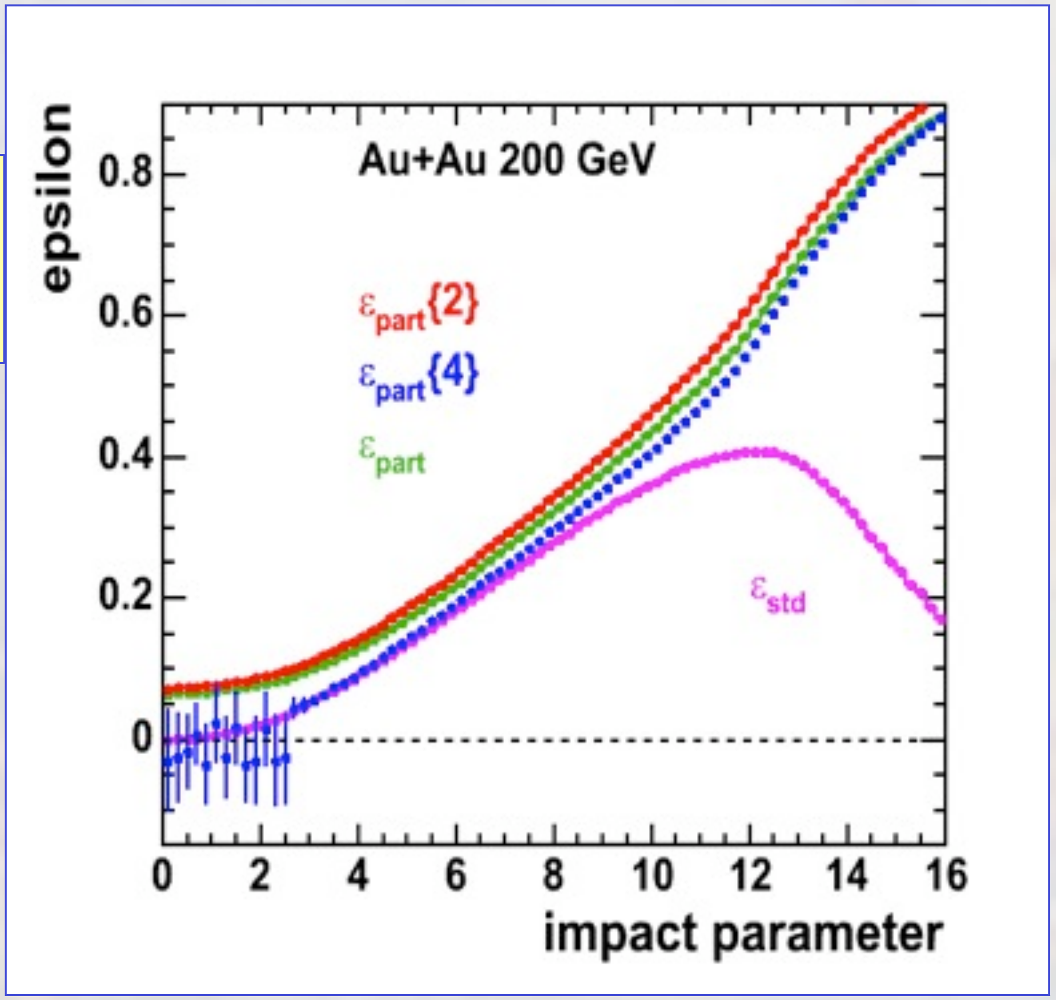
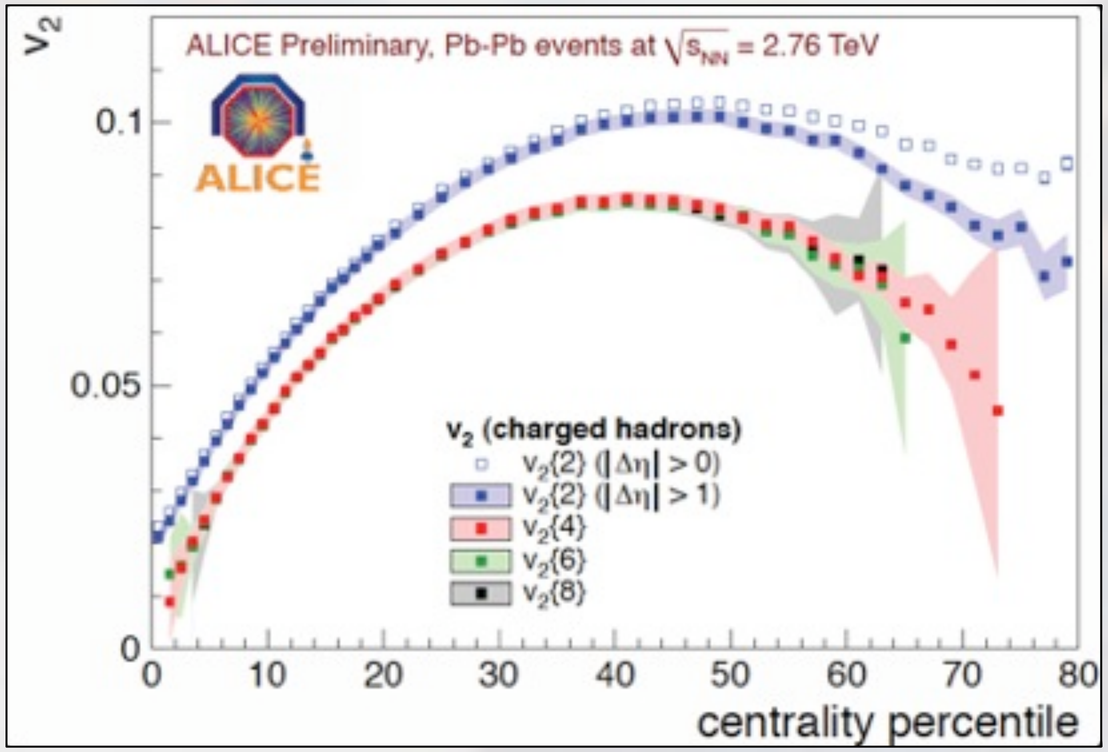


Fig. 1. The definitions of the *RP* and *PP* coordinate systems.



WAYNE STATE UNIVERSITY

Flow fluctuations. “Nonflow”



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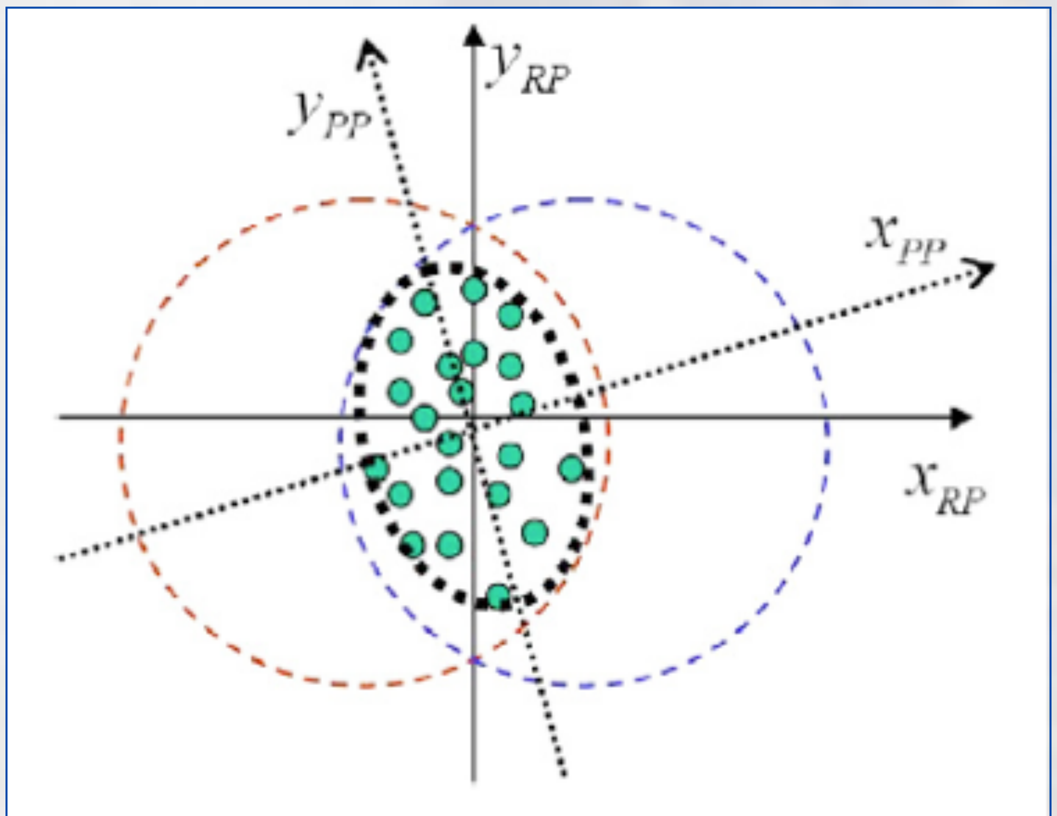

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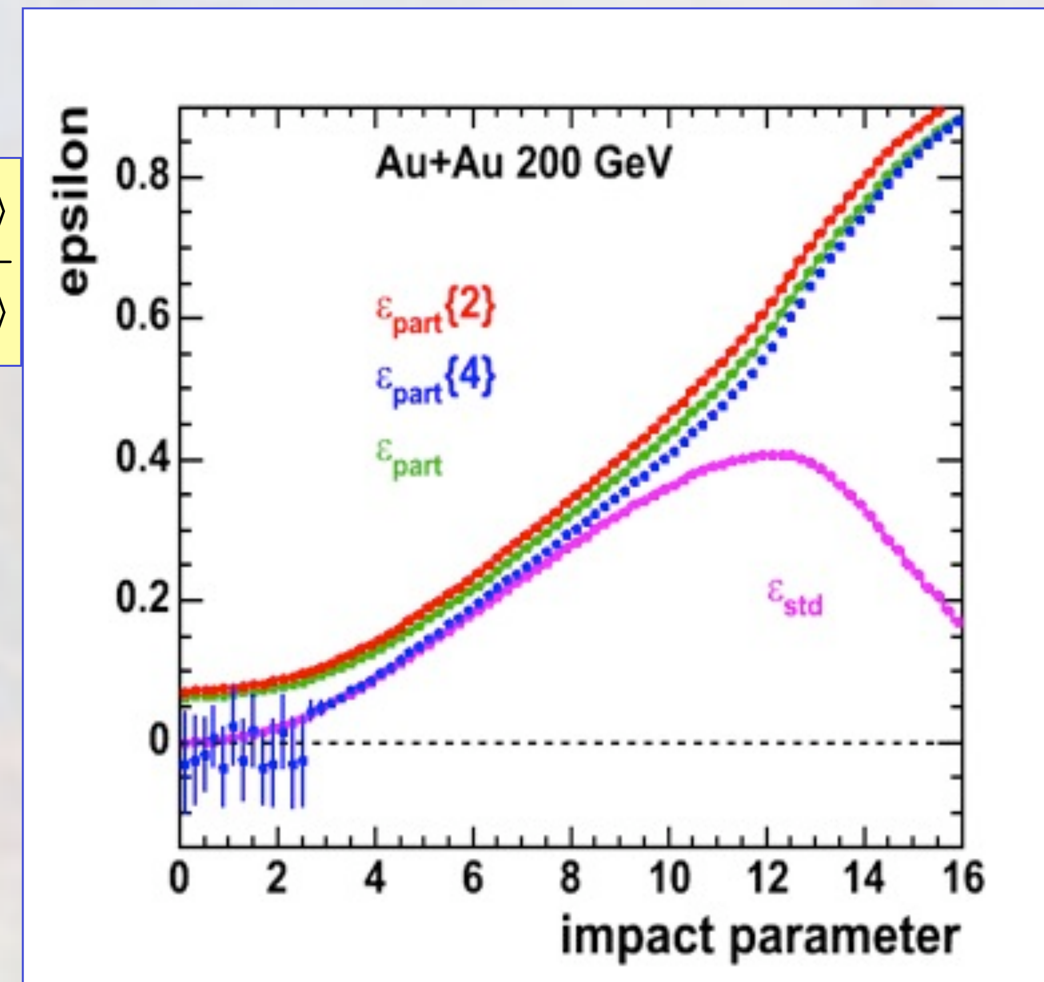
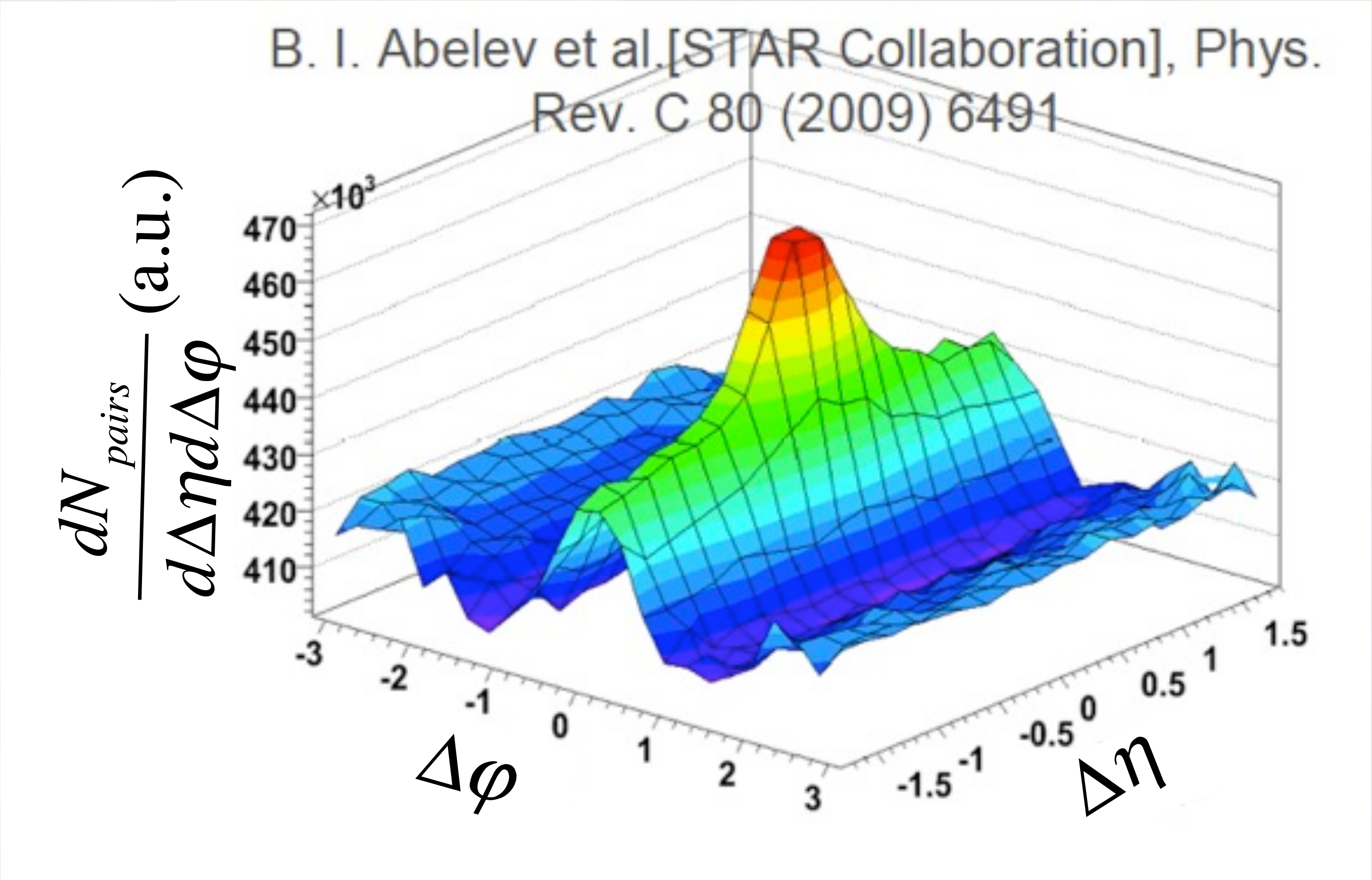


The difference between v2[2] qnd v2[4} is almost
fully saturated by eccentricity fluctuations according to nucleon participant Glauber MC.

“Ridge”. (Nonflow?)



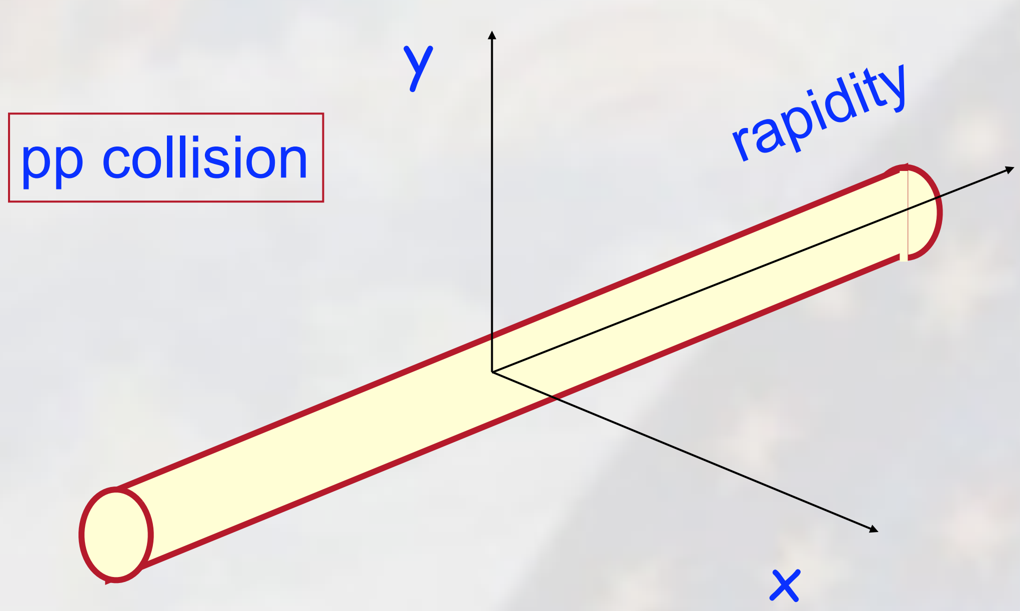
$$\frac{dN_{pairs}}{d\Delta\eta d\Delta\varphi} \text{ (a.u.)}$$

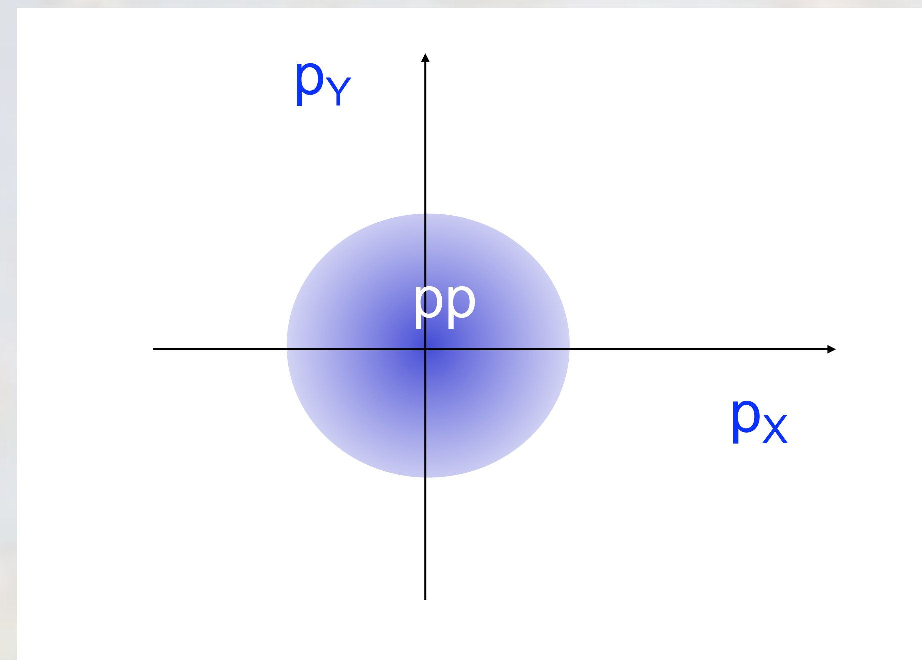
Long range in rapidity and localized in azimuth correlations have been observed in semi-central and central collisions.

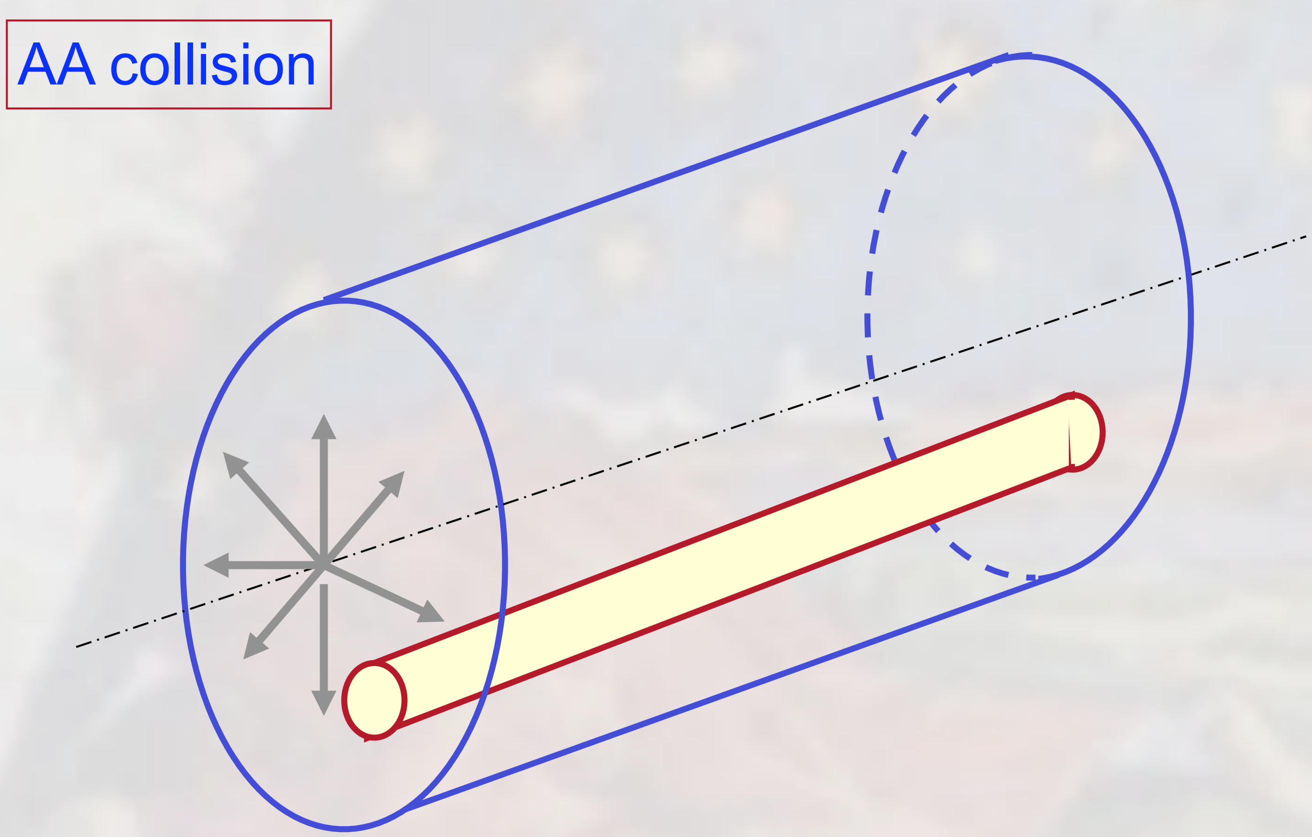
Radial expansion → 2-part azimuthal correlations

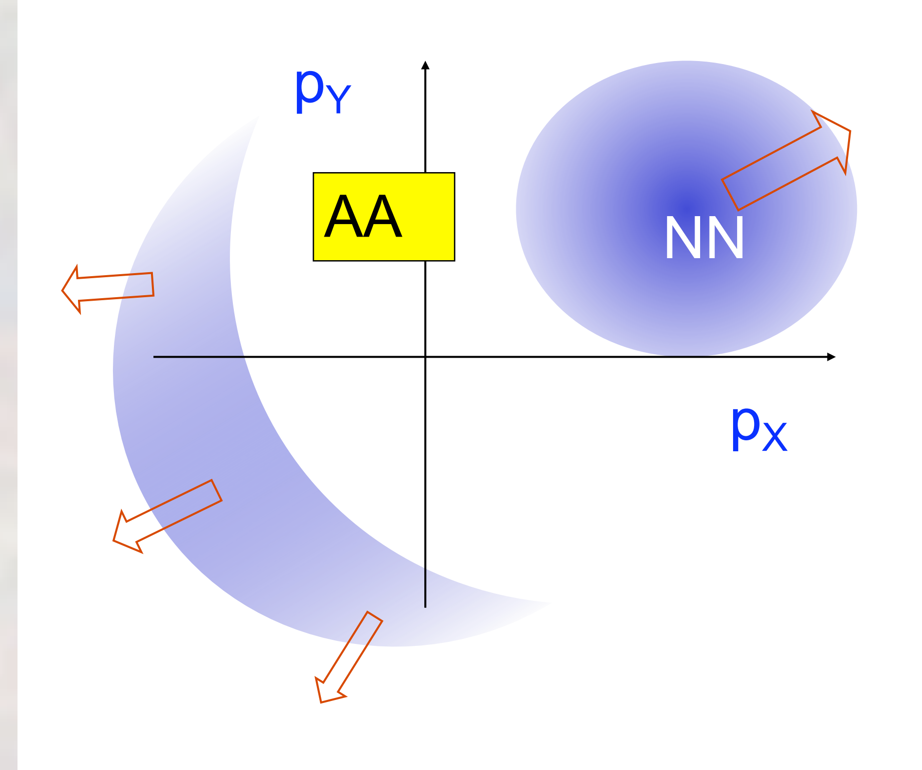
[arXiv:nucl-th/0312065]

All particles produced in the same NN-collision (qq-string) experience the transverse radial "push" that is
(a) in the same direction (leads to correlations in phi)
(b) the same in magnitude (→ correlations in p_t)



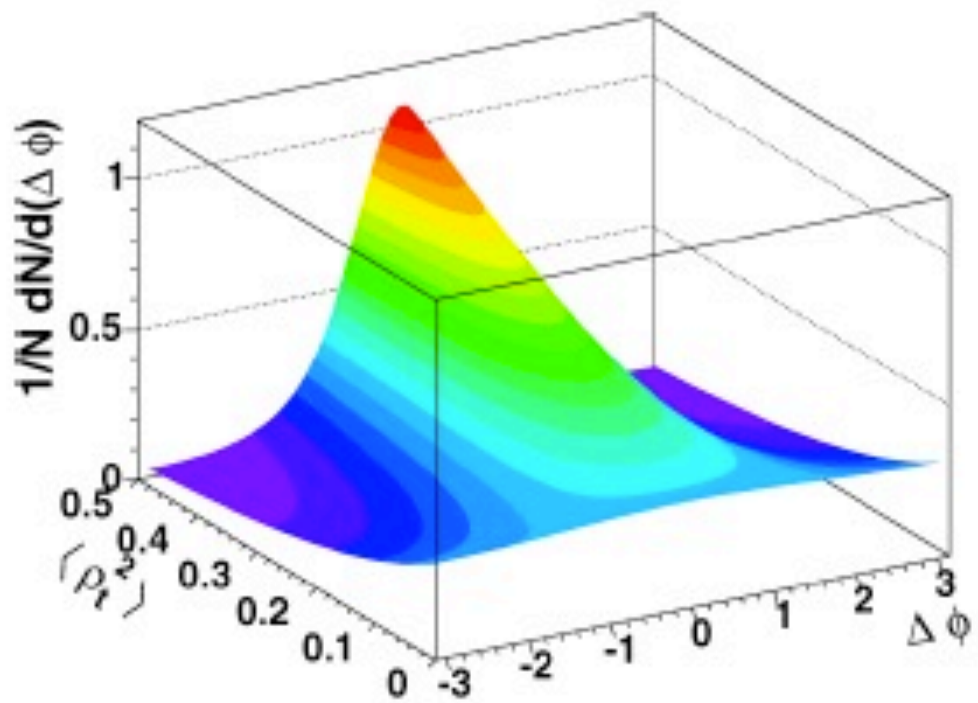






Radial expansion ➔ 2-part azimuthal correlations

[arXiv:nucl-th/0312065] S.A. Voloshin / Physics Letters B 632 (2006) 490–494 493



$m = m_\pi$

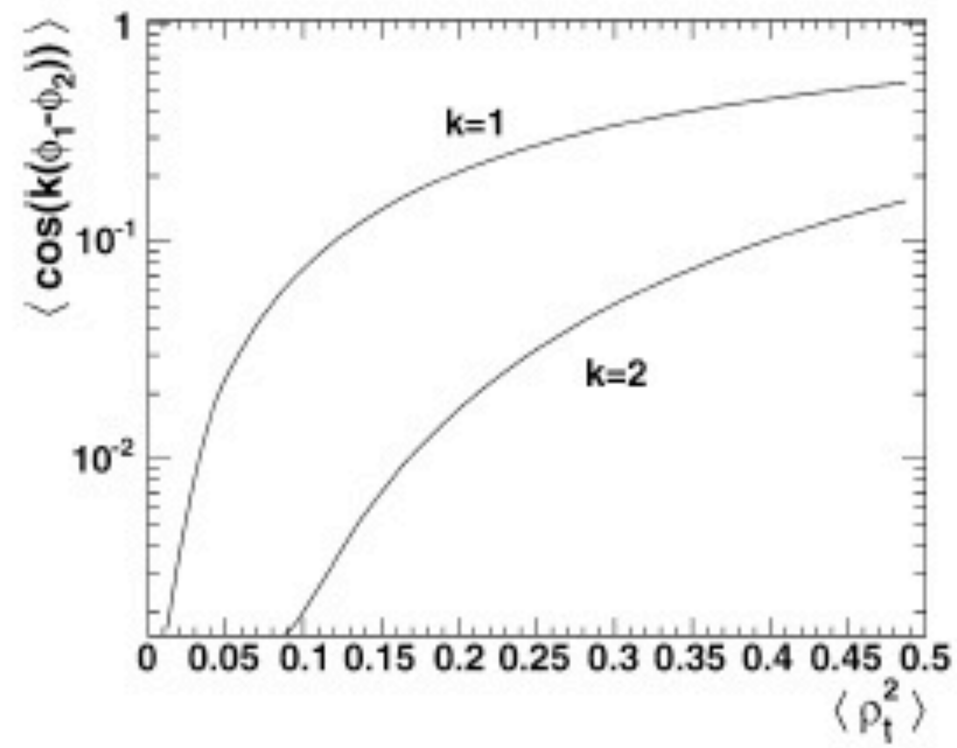


Fig. 3. (Color online.) Two pion $\Delta\phi$ distribution as function of $\langle \rho_t^2 \rangle$ in the blast wave model. Linear velocity profile and $T = 110$ MeV have been assumed.

Fig. 4. The average values of $\cos(\Delta\phi)$ and $\cos(2\Delta\phi)$ for the distribution shown in Fig. 3.

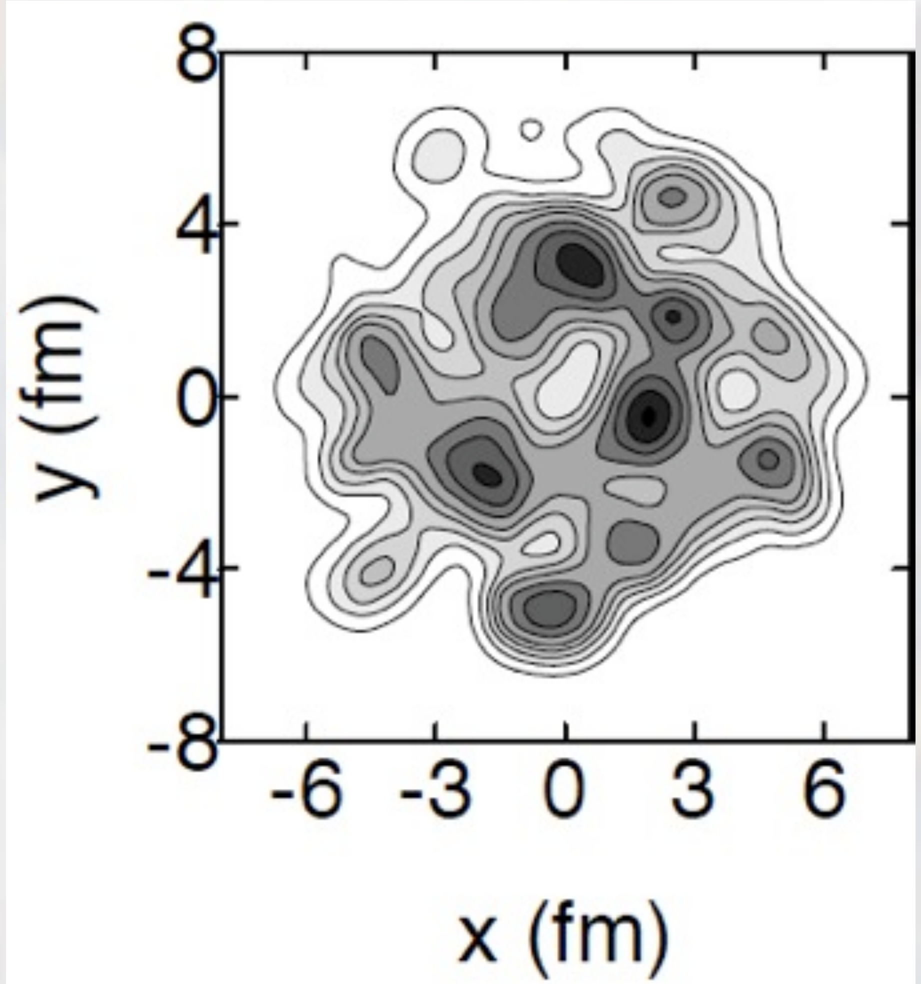
Figures are shown for particles from the same NN collision.
Dilution factor to be applied!

$$\left\langle uQ^* \right\rangle = M\left\langle uu^* \right\rangle = M(v^2 + \delta) = Mv^2 + \tilde{\delta}$$

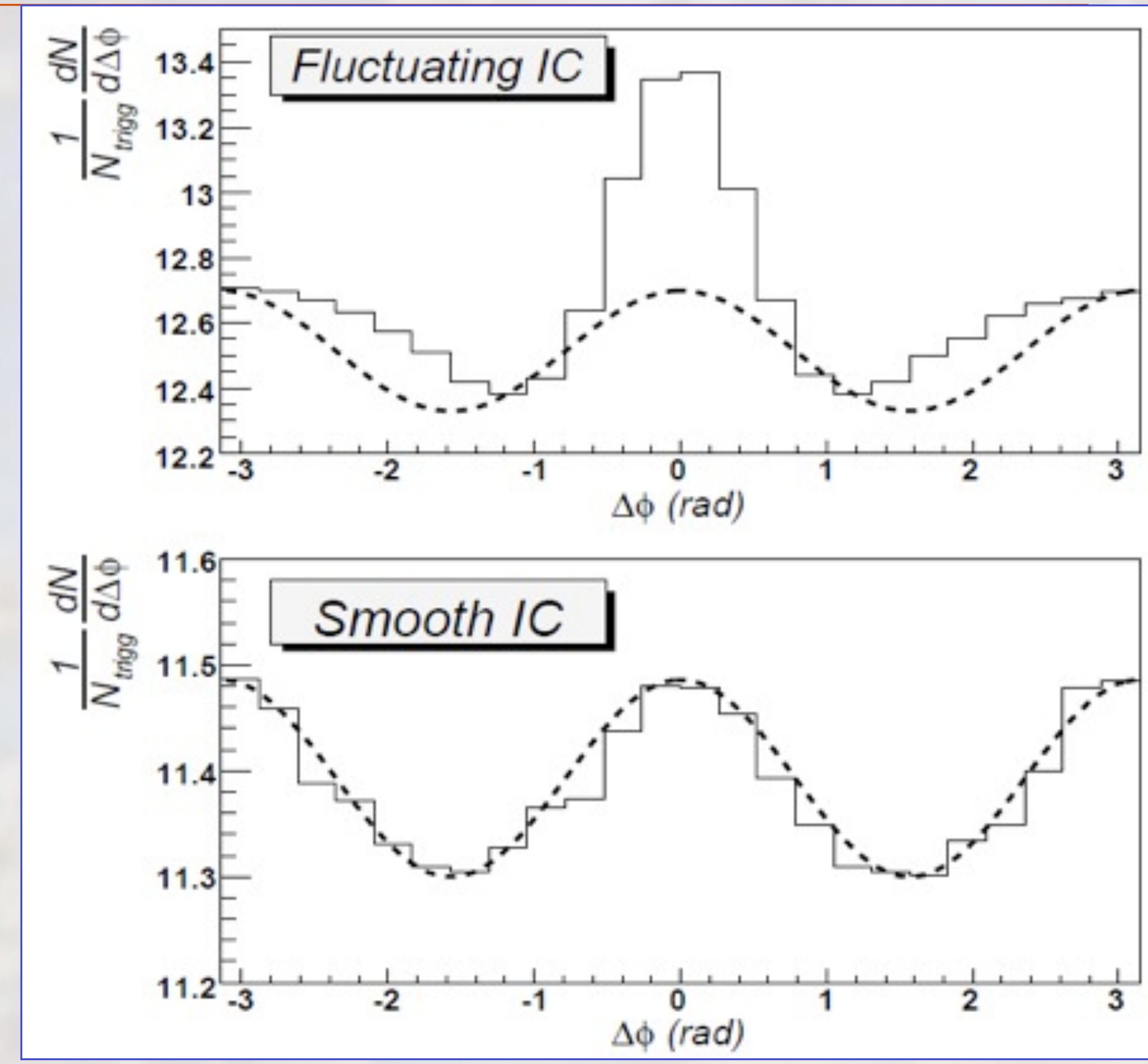
!!! - the large values of transverse flow, $\rho_t^2 > 0.25$, would contradict "non-flow" estimates in elliptic flow measurements

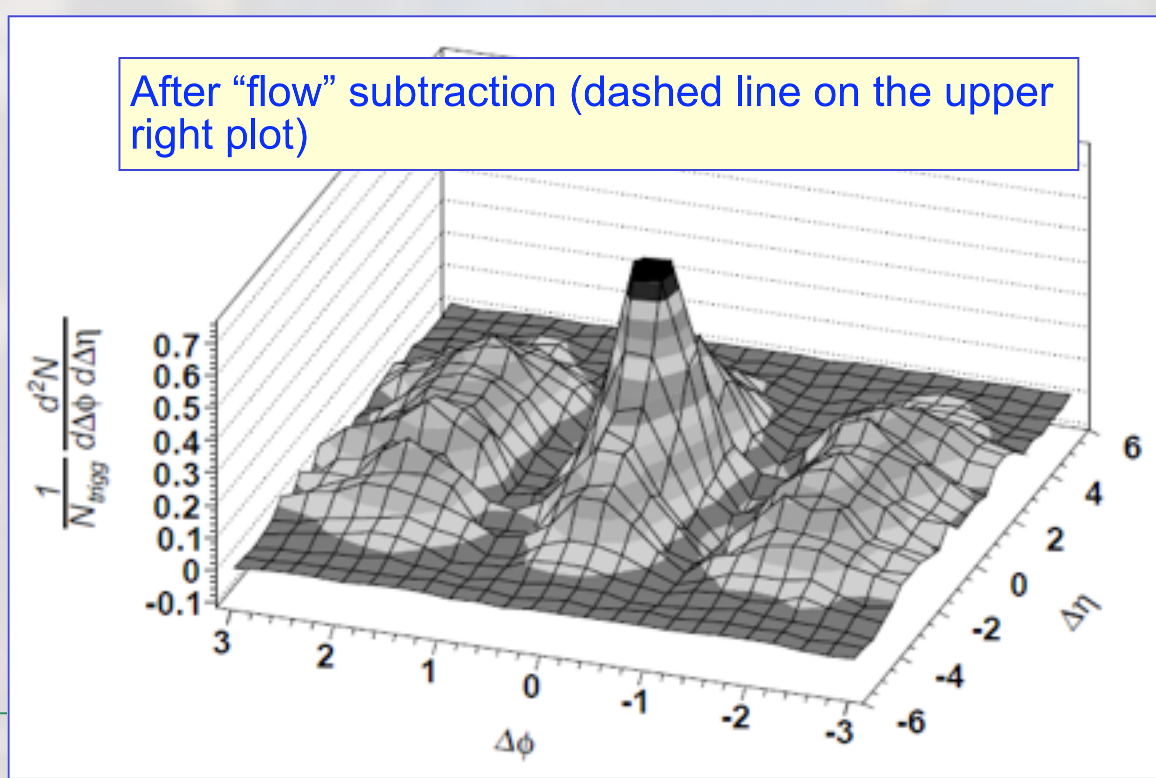
Correlation function. Pure hydro.

J. Takahashi *et al.*,arXiv:0902.4870v1

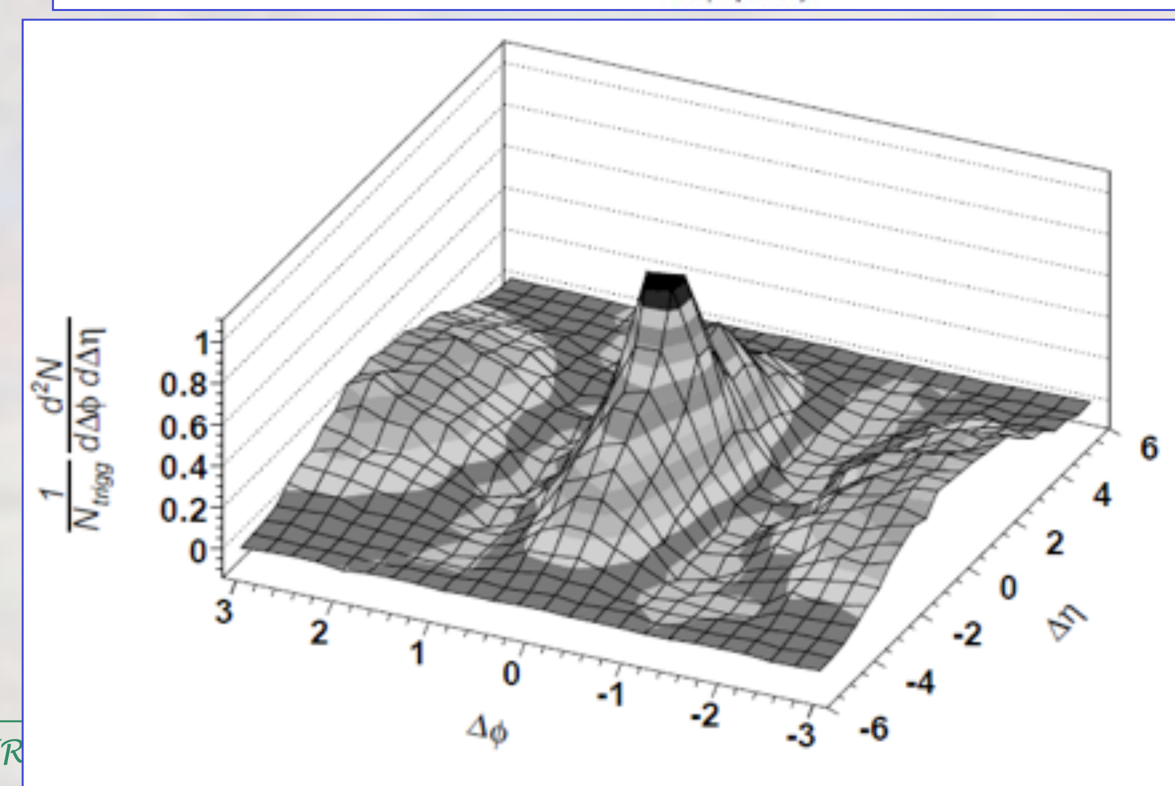


Yogiro Hama,[1] Rone Peterson G. Andrade,[1] Frédérique Grassi,[1] Wei-Liang Qian,[1] Takeshi Osada,[2] Carlos Eduardo Aguiar,[3] and Takeshi Kodama[3]



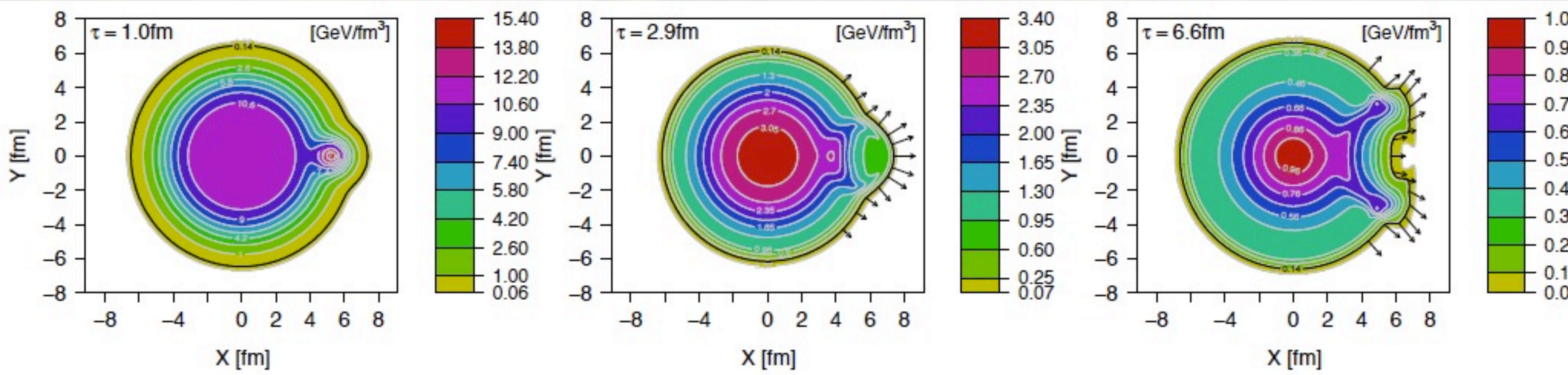


After “flow” subtraction (dashed line on the upper right plot)



Single “hot spot”

R. P. G. Andrade, F. Grassi, Y. Hama, W. -L. Qian, Nucl. Phys. **A854**, 81-88 (2011).

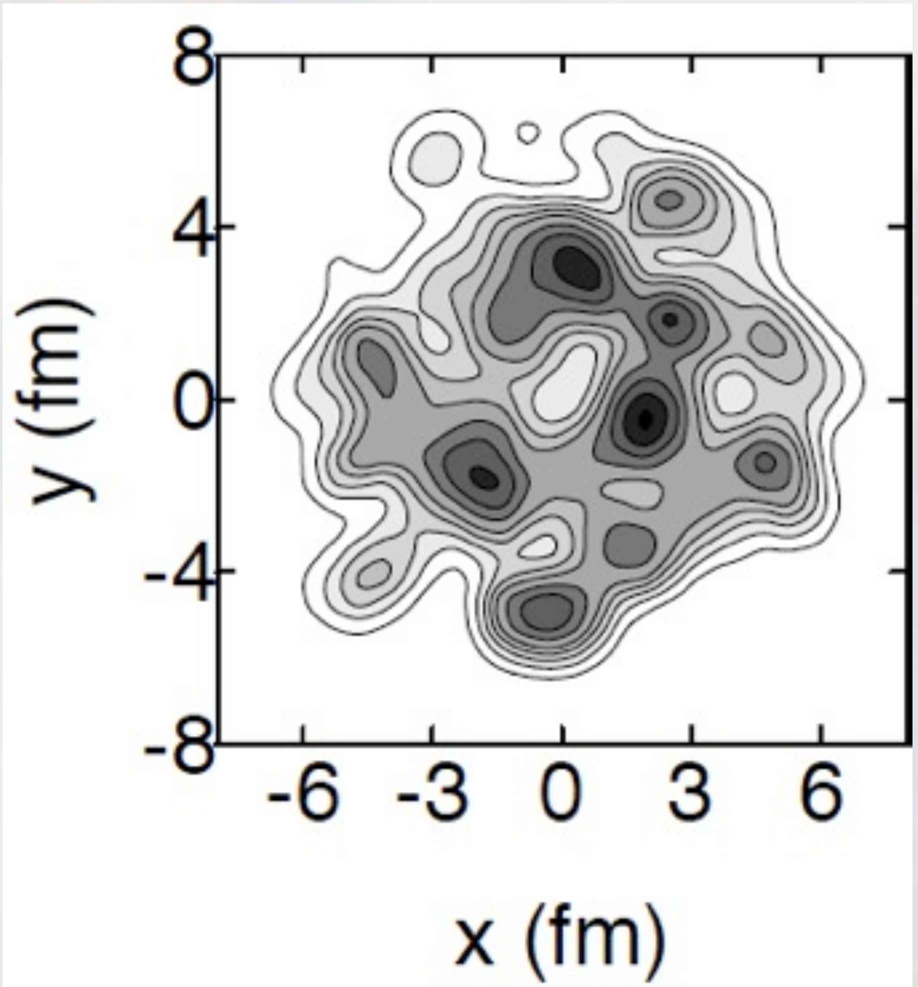


Instead of a “bump” due to a push-out of a “hot spot” by radial flow, it appears that the high density region actually “blocks” the development of radial flow in this direction, leading to a dip with two “side-splashes”.

Note that the “dip” and the “bump” lead to _positive_ correlations, the “ridge”, but the details (e.g. harmonic decomposition of the correlation function is different)

Density decomposition

Shuryak et al.

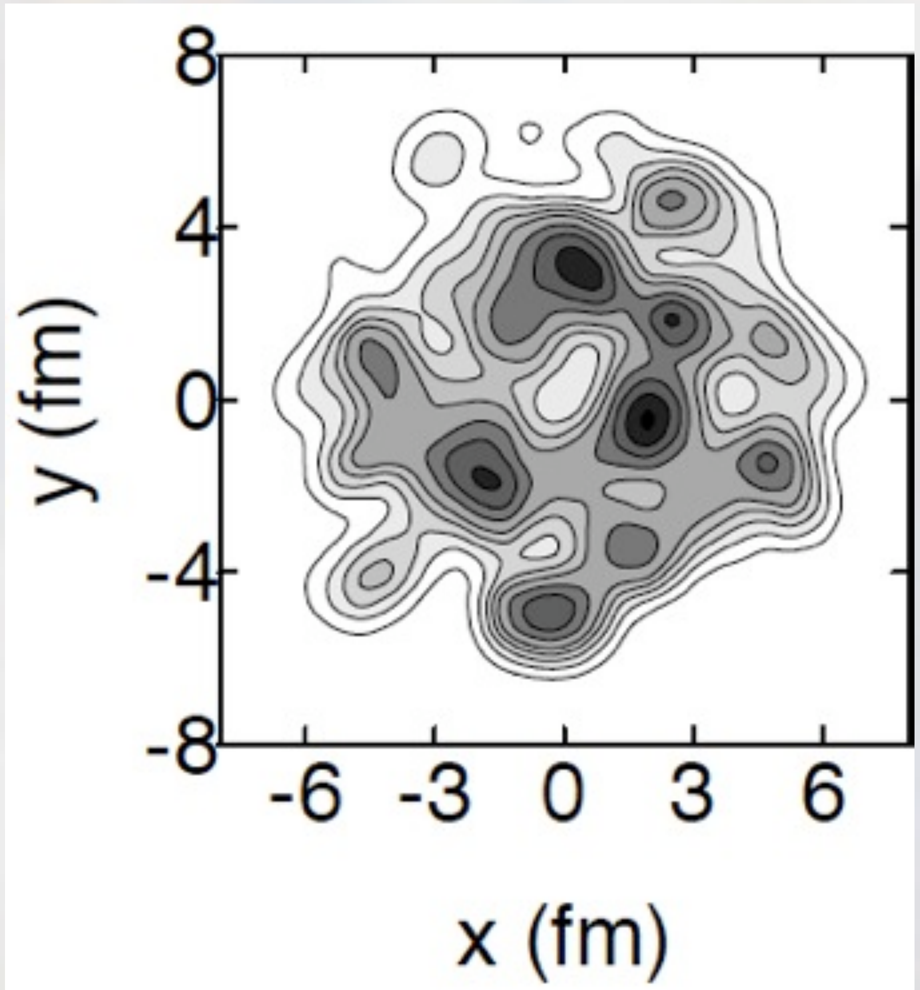


Yogiro Hama,[1] Rone Peterson G. Andrade,[1] Frédérique Grassi,[1] Wei-Liang Qian,[1] Takeshi Osada,[2] Carlos Eduardo Aguiar,[3] and Takeshi Kodama[3]

$$= \sum_{\text{positions of hot spots}}$$

It is difficult to select events with (only) one hot spot at a given position ==> we will proceed in a different direction.

Density decomposition



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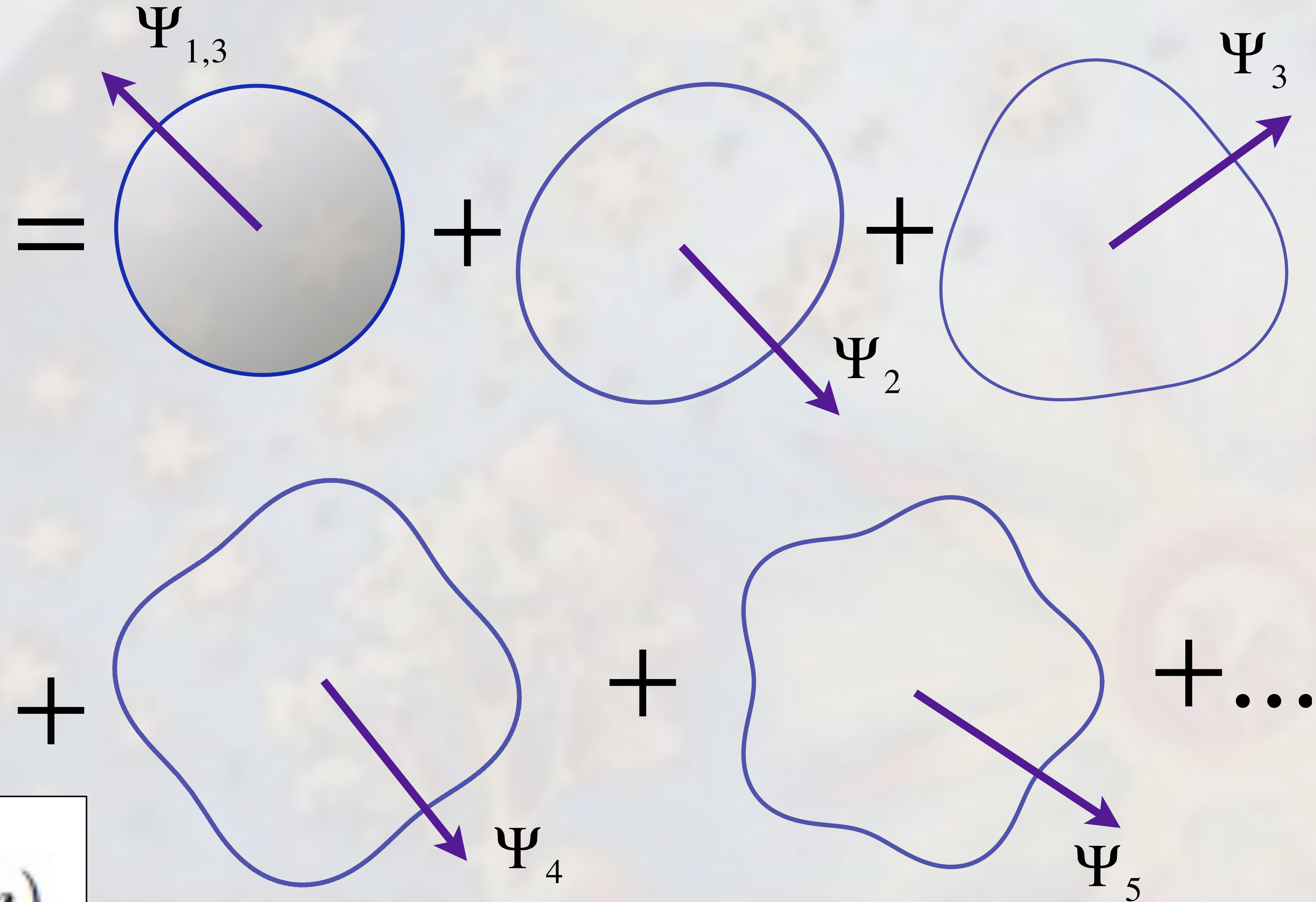


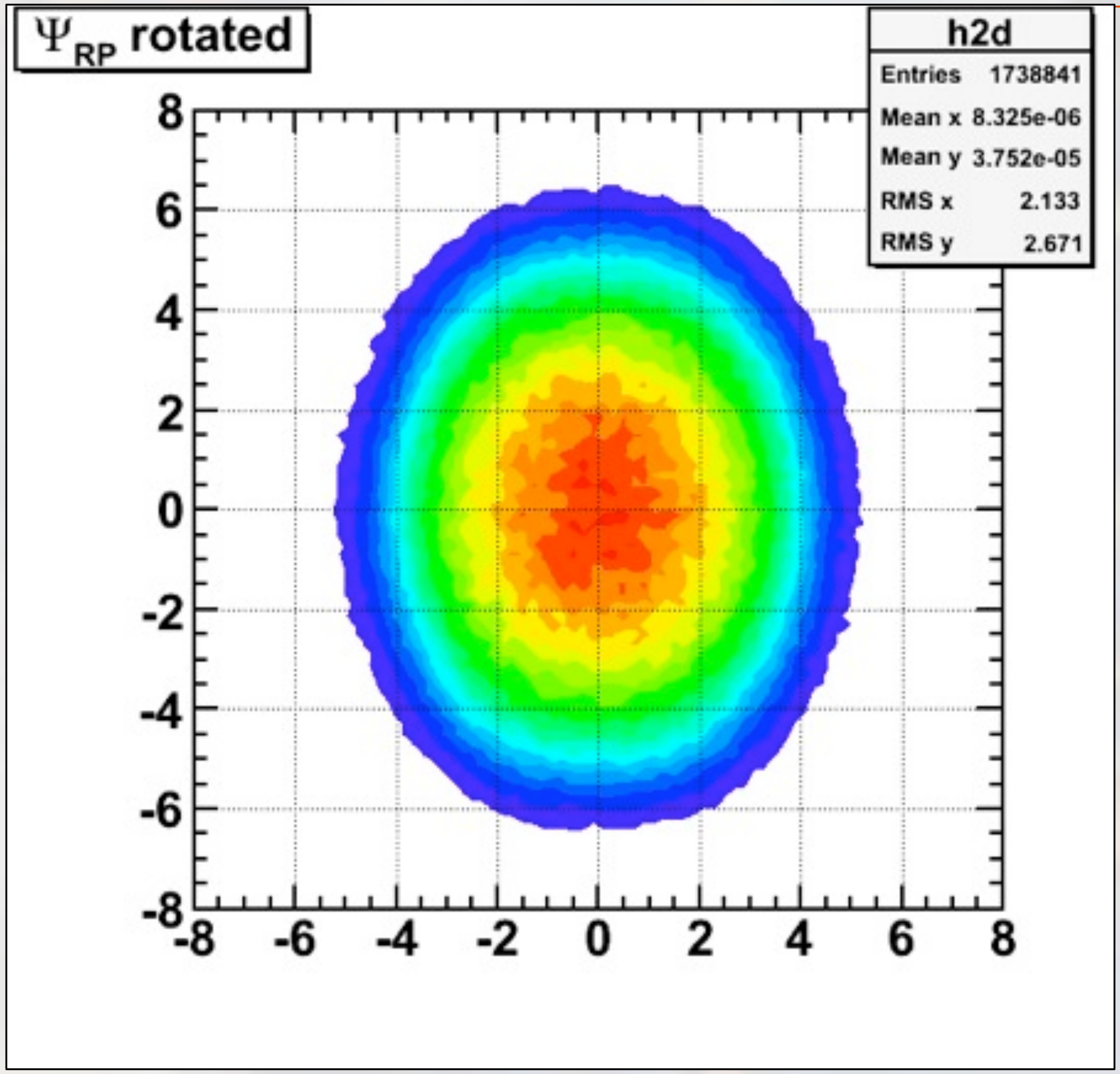
$$\int d^2x \, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \rho(\boldsymbol{x}) = \rho(\boldsymbol{k}) \,,$$

arXiv:1010.1876v1 [nucl-th] 9 Oct 2010

Derek Teaney and Li Yan

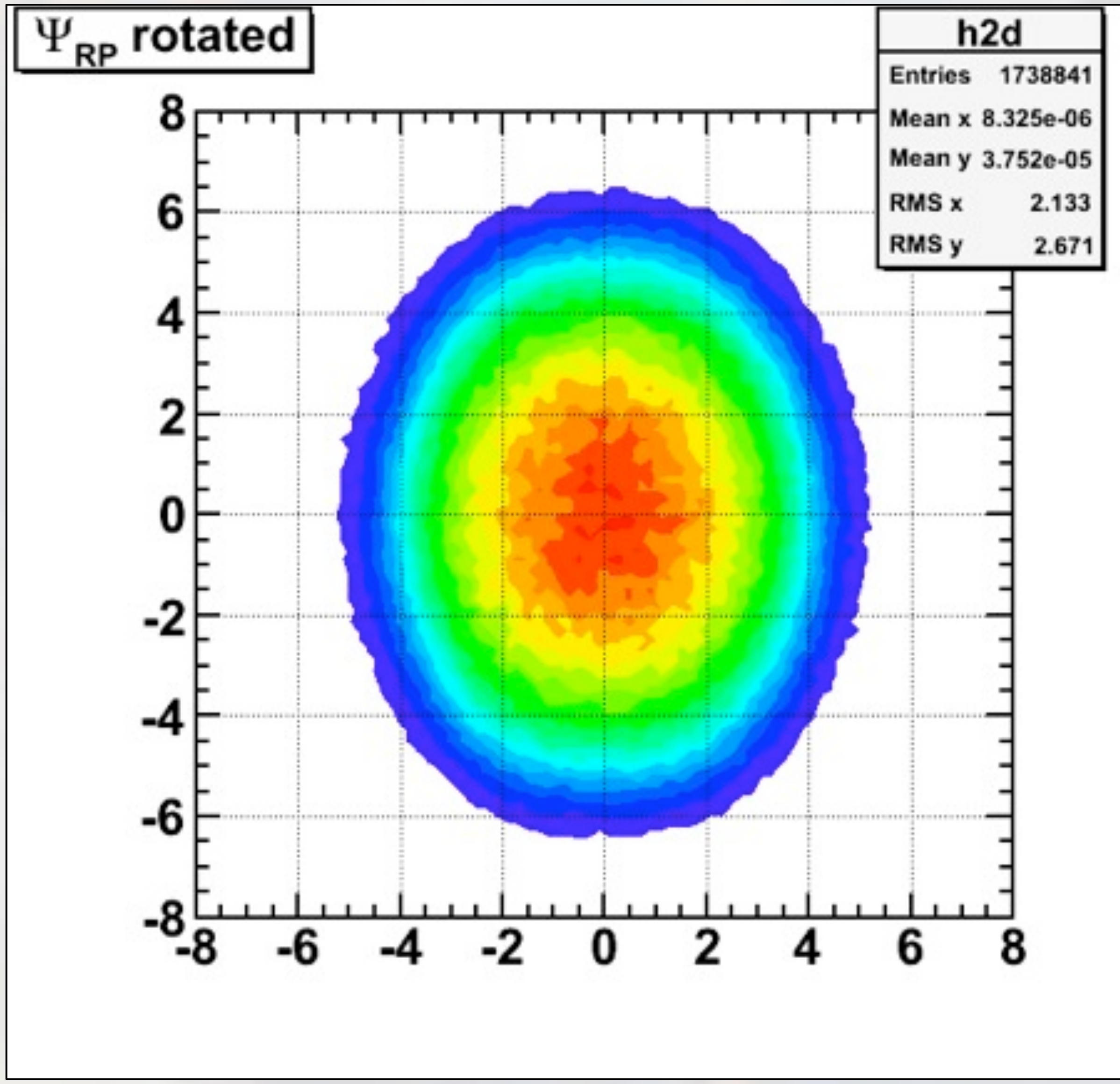
$$e^{ikr\cos\phi} = 1 + ikr\cos\phi - \frac{1}{2}k^2r^2\cos^2\phi - \frac{1}{6}ik^3r^3\cos^3\phi + \ldots$$

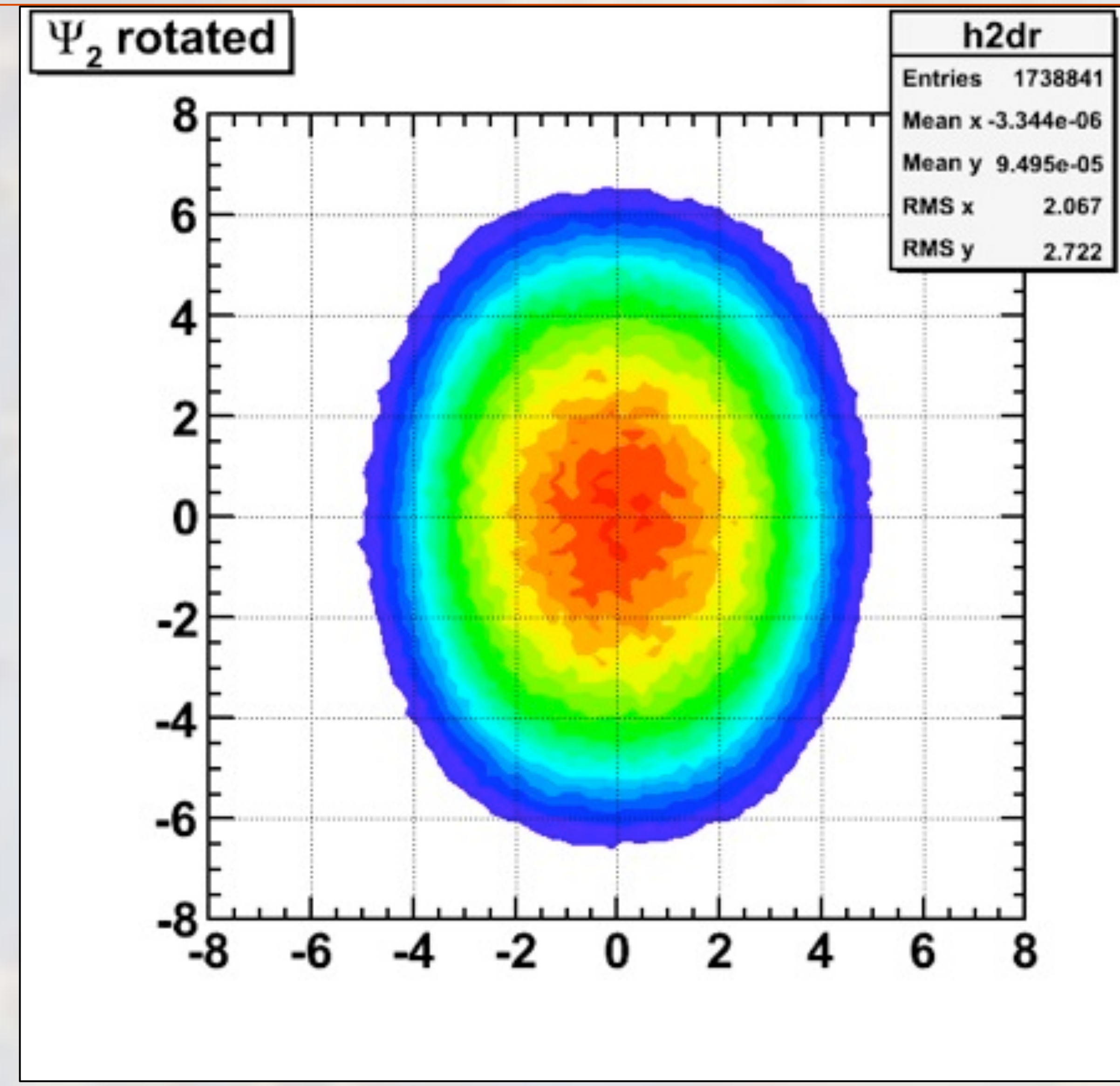
Density distributions



10k Pb+Pb events, b=8 fm

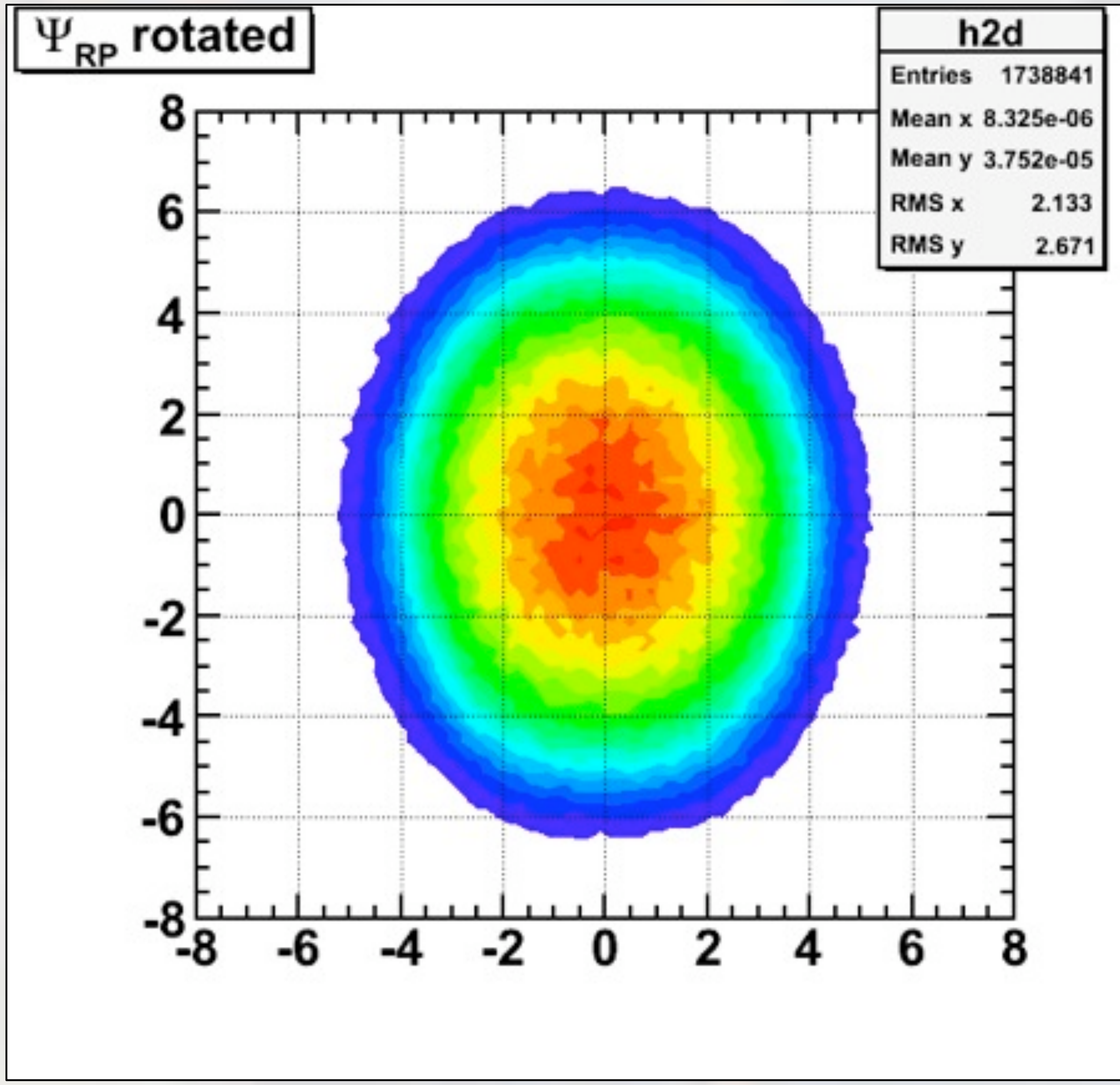
Density distributions

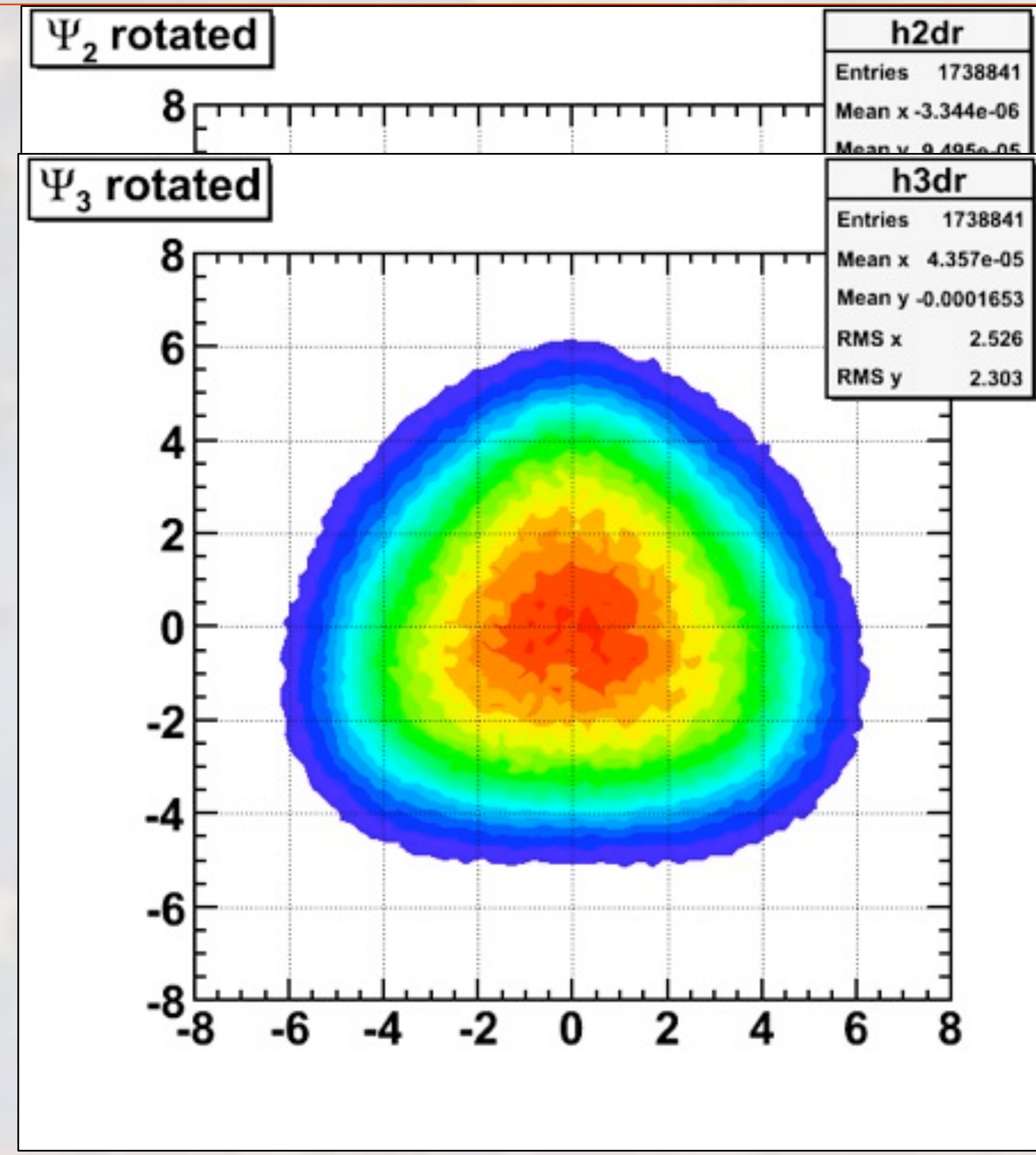




10k Pb+Pb events, b=8 fm

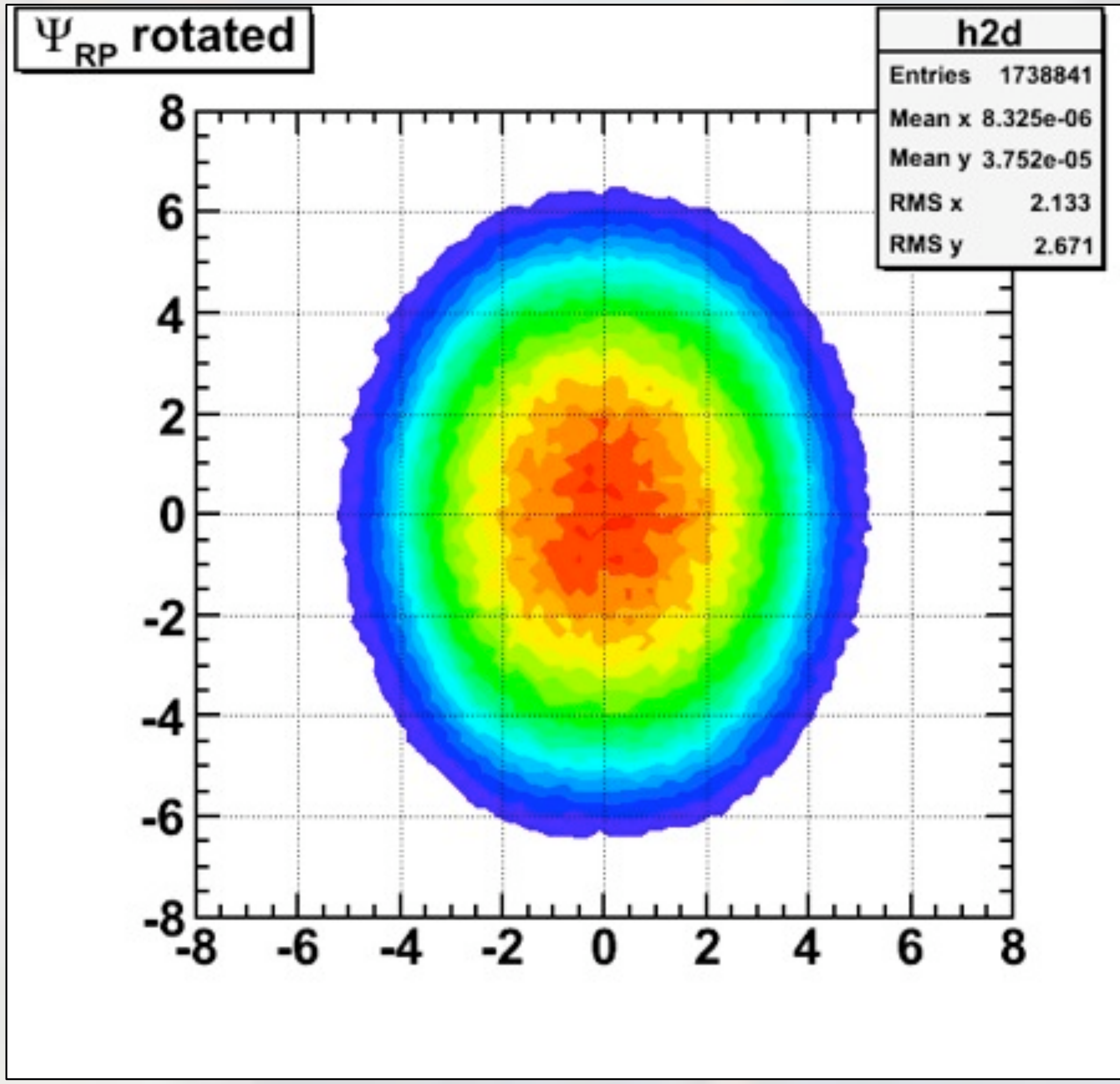
Density distributions

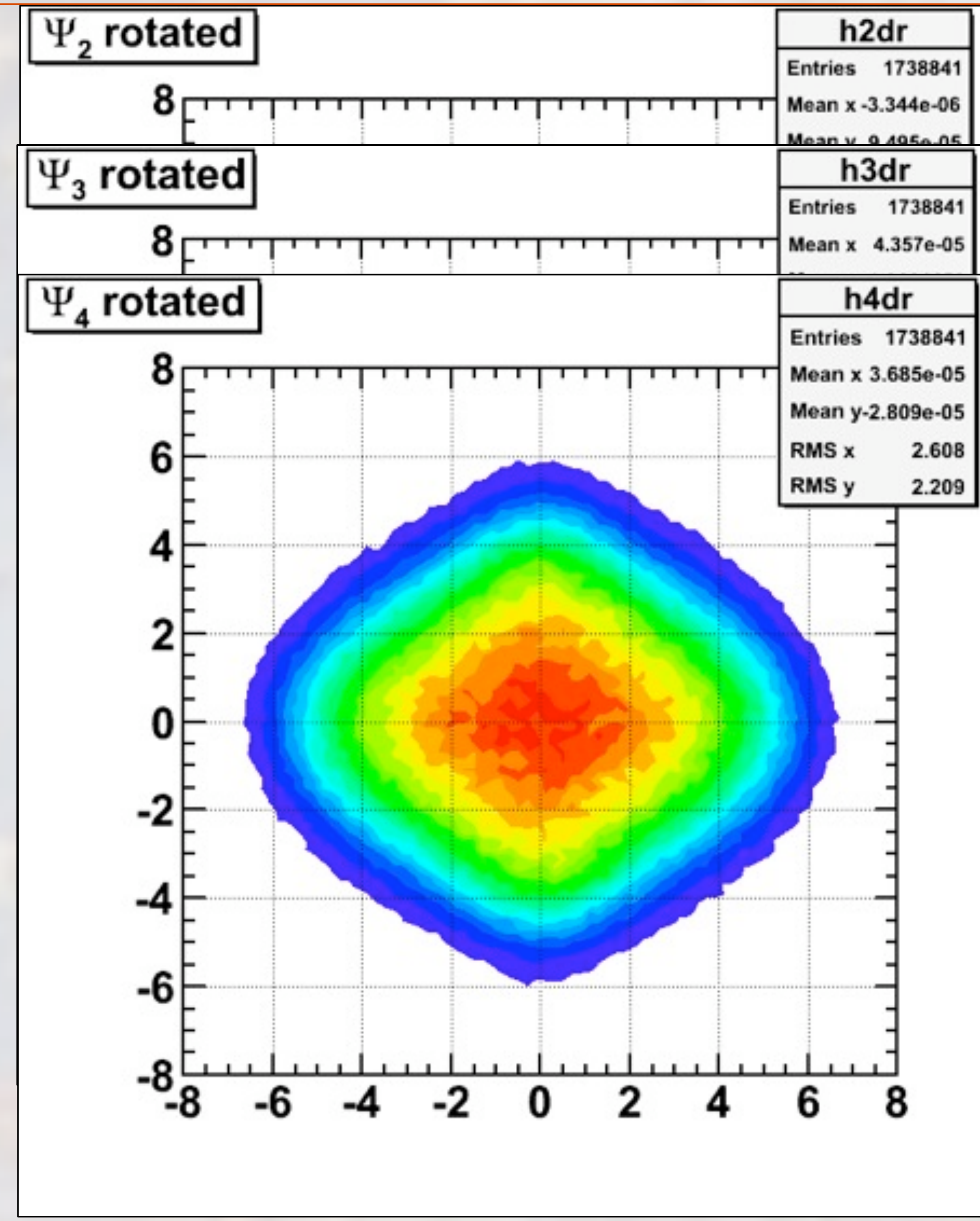




10k Pb+Pb events, b=8 fm

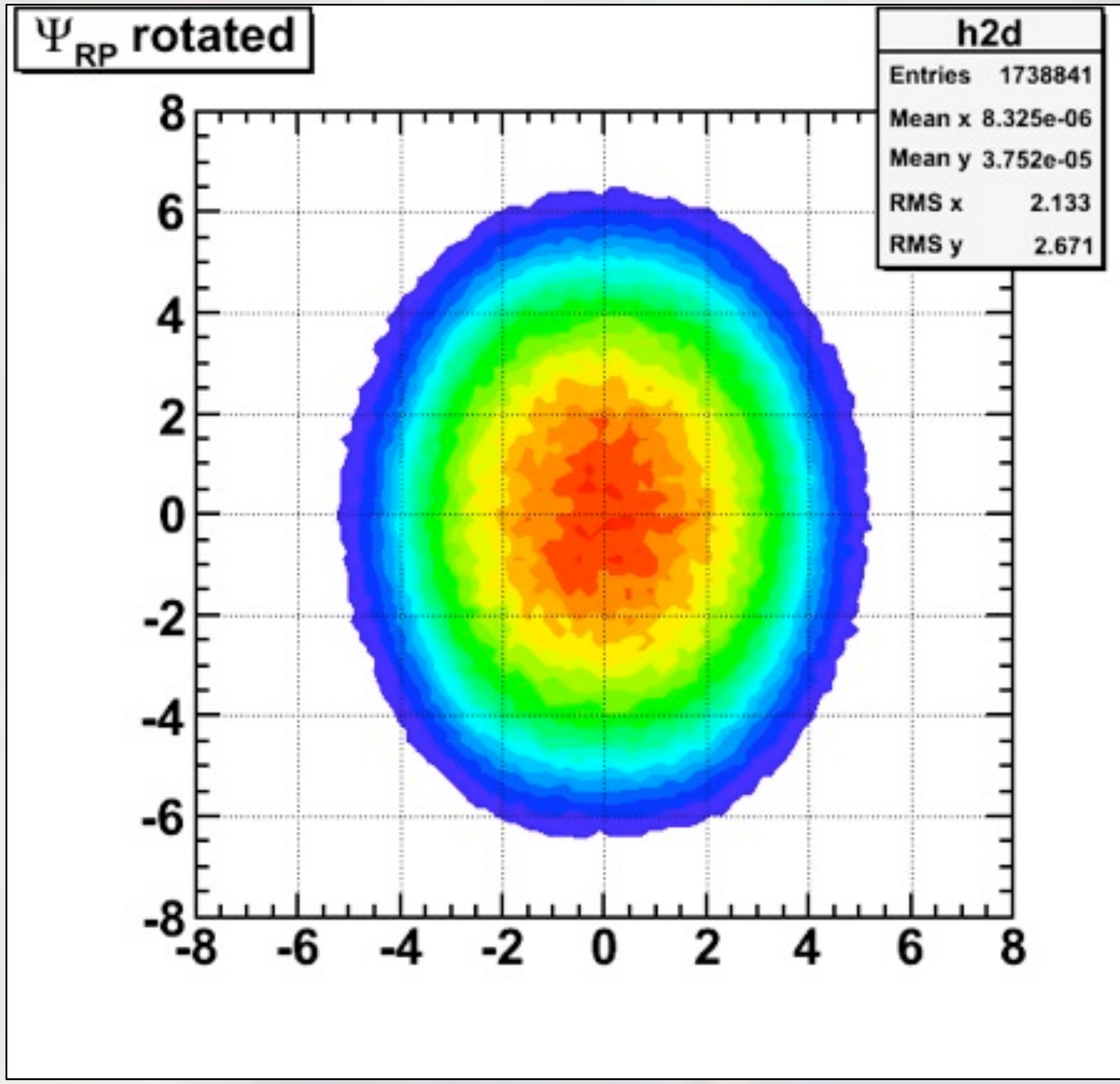
Density distributions

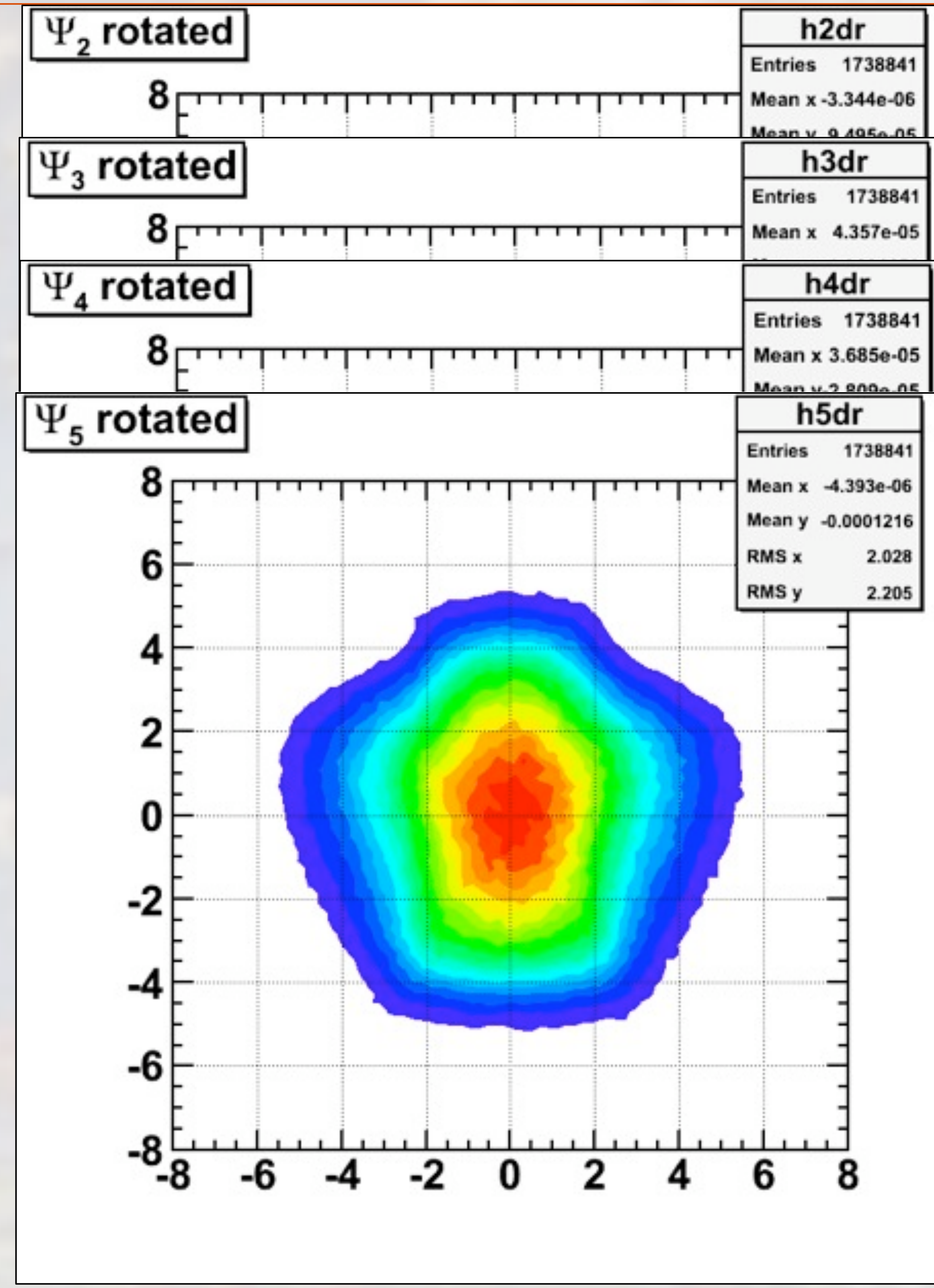




10k Pb+Pb events, b=8 fm

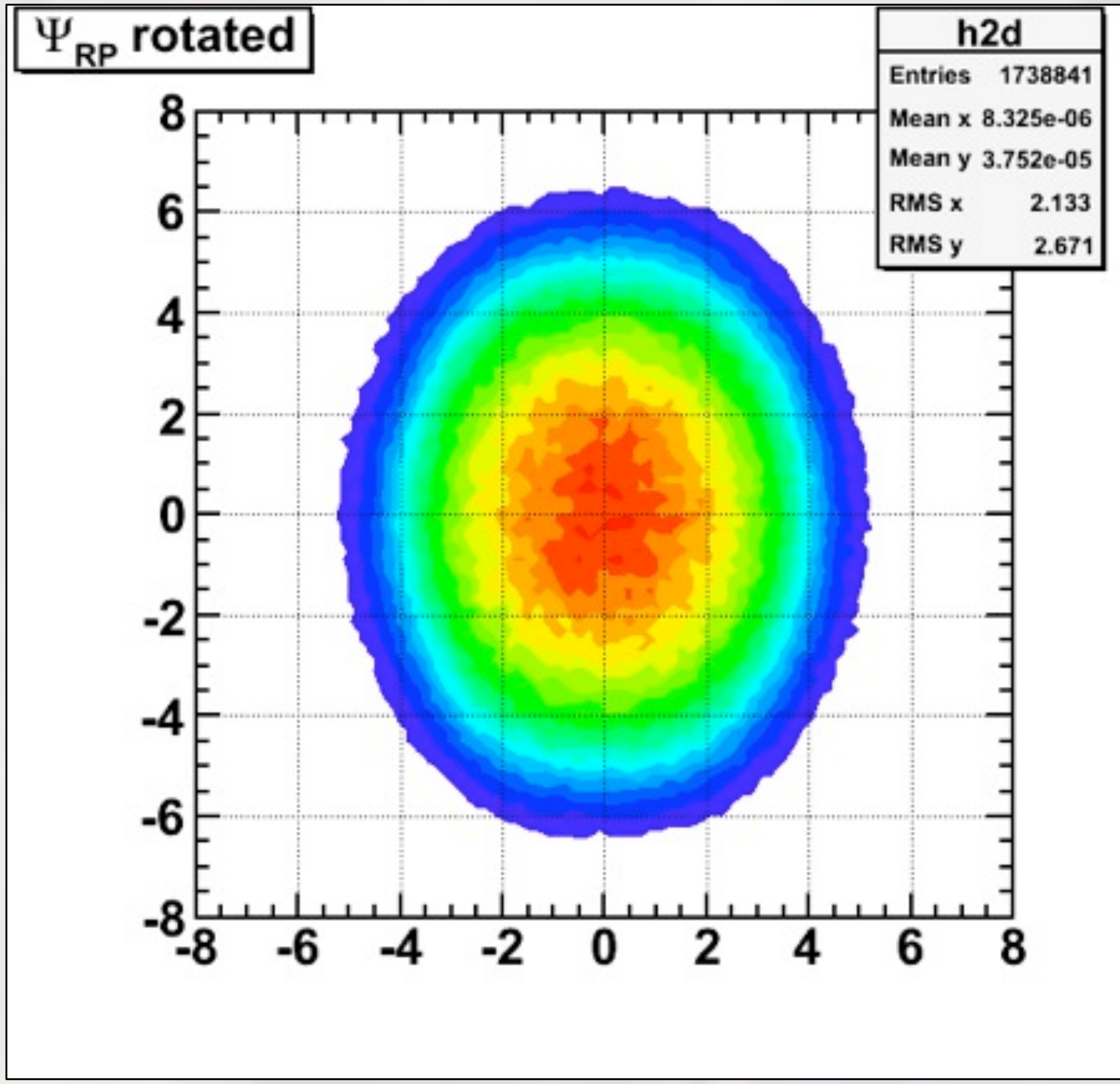
Density distributions

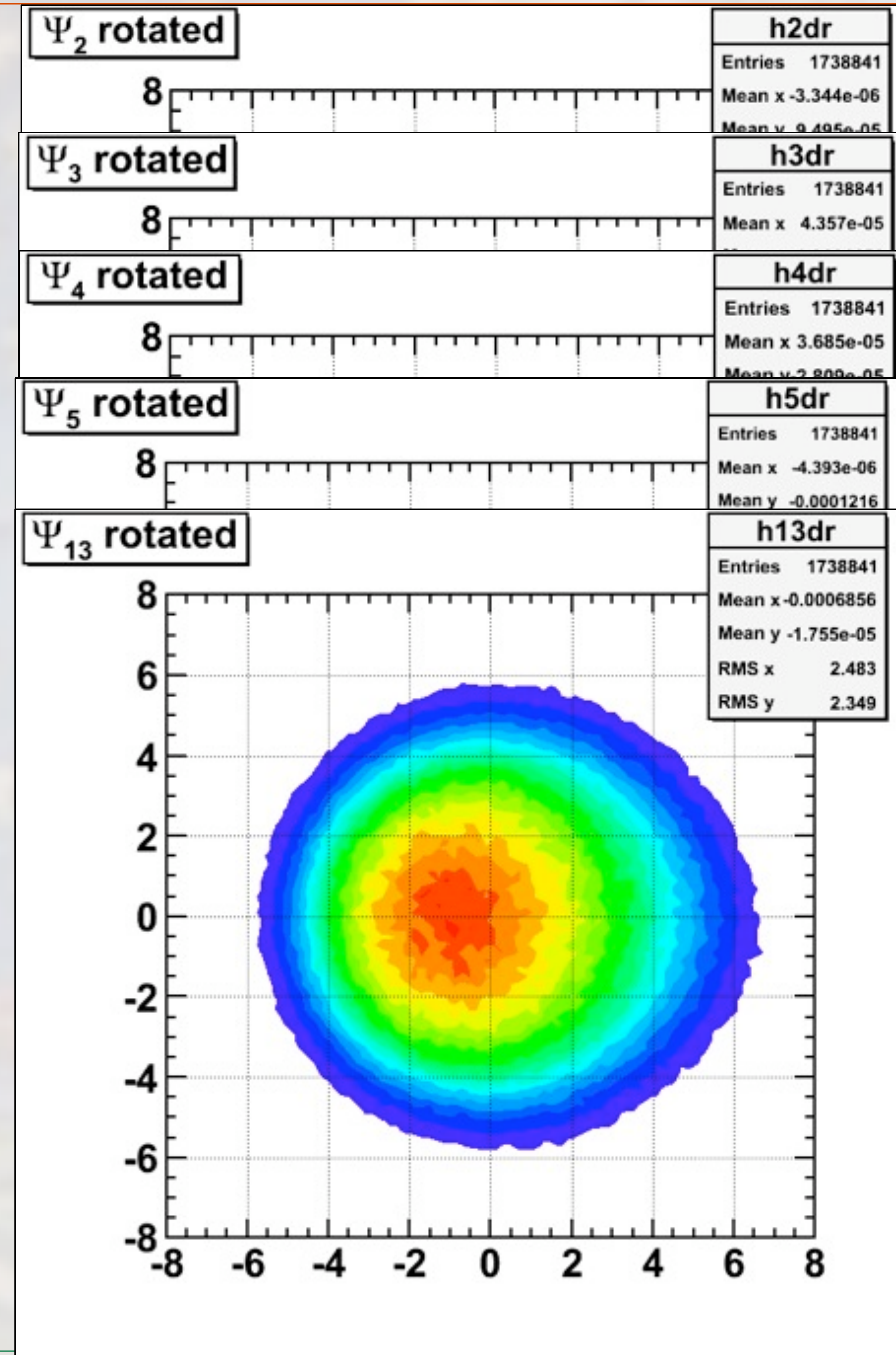




10k Pb+Pb events, b=8 fm

Density distributions

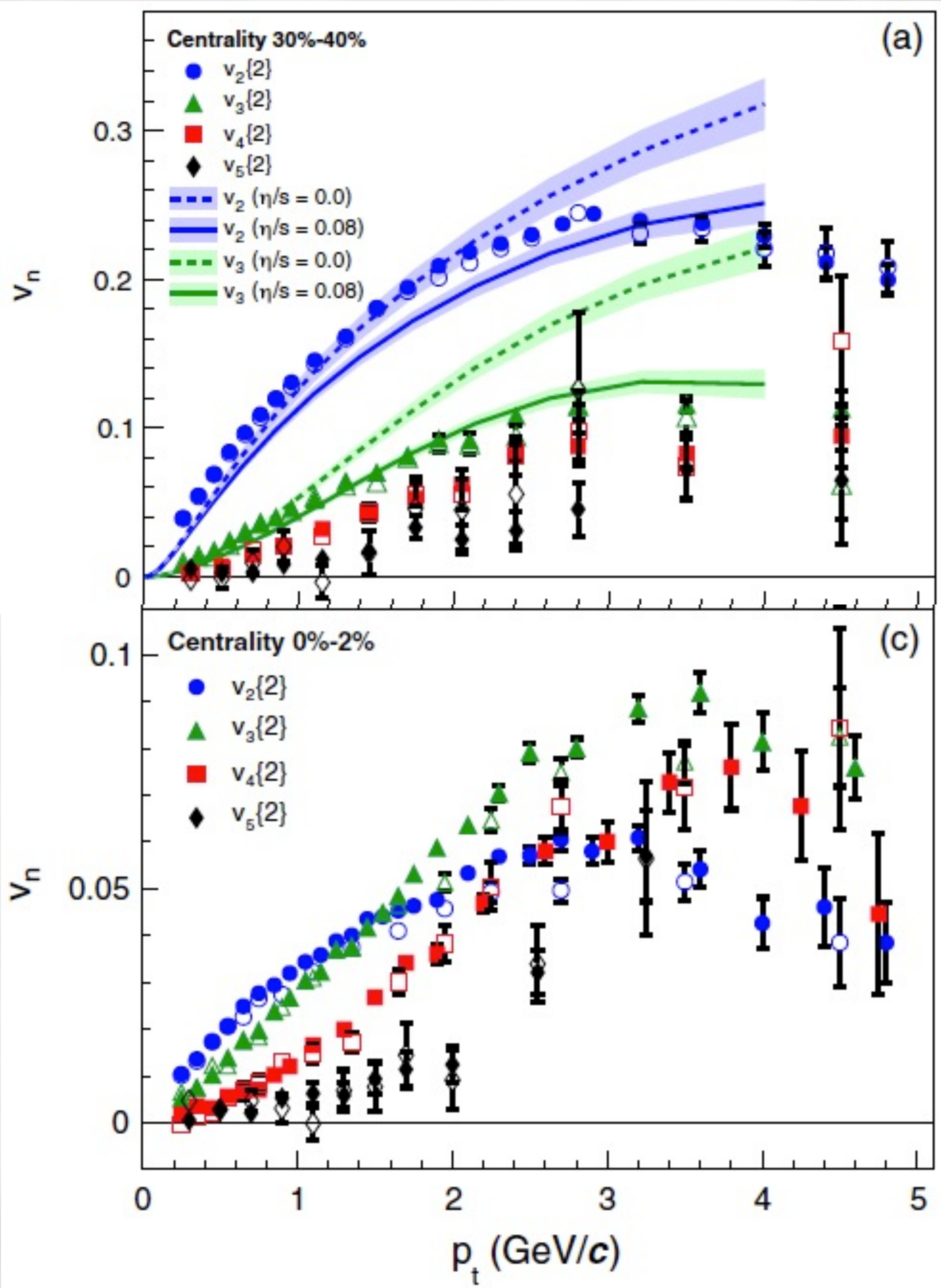




10k Pb+Pb events, b=8 fm

ALICE

PRL **107**, 032301 (2011)



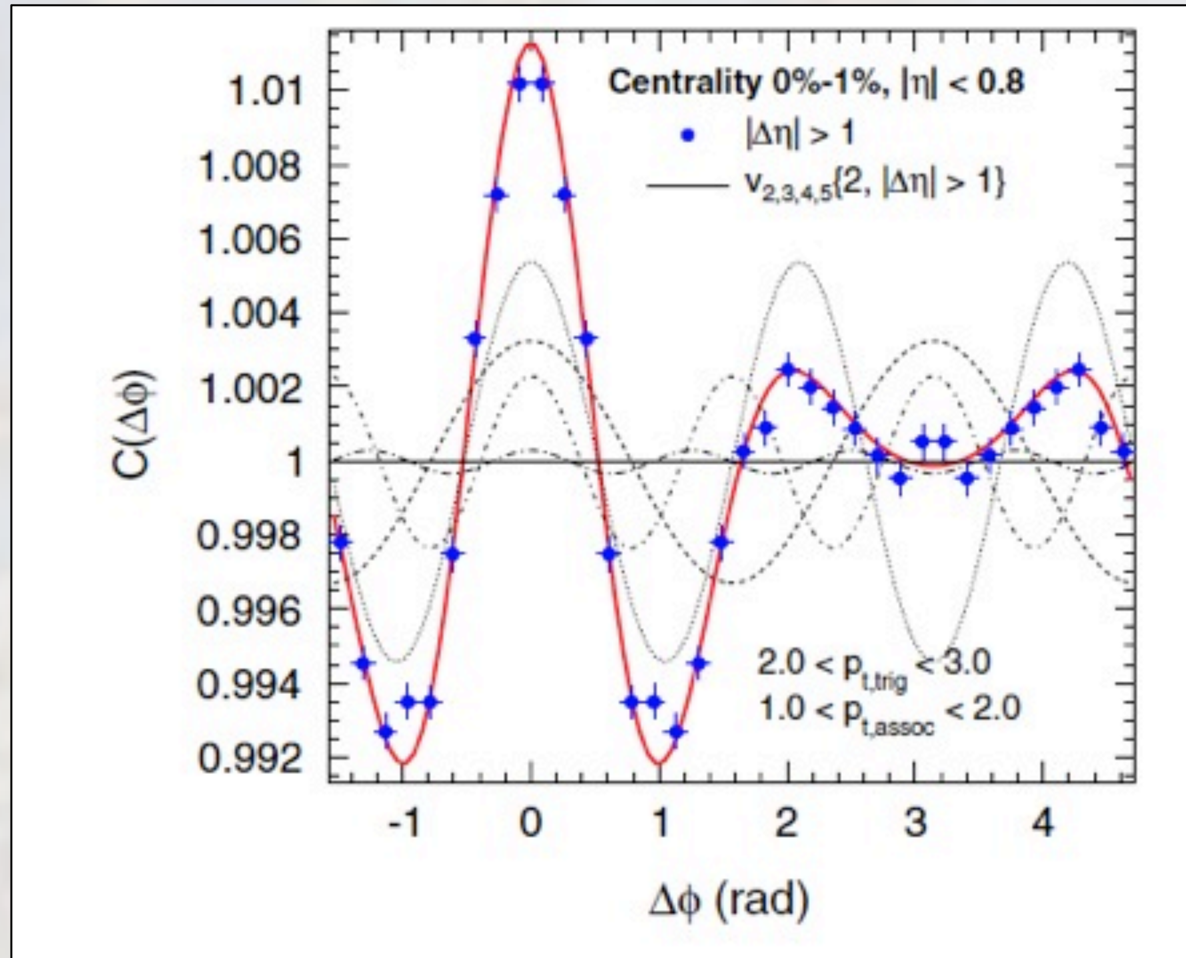
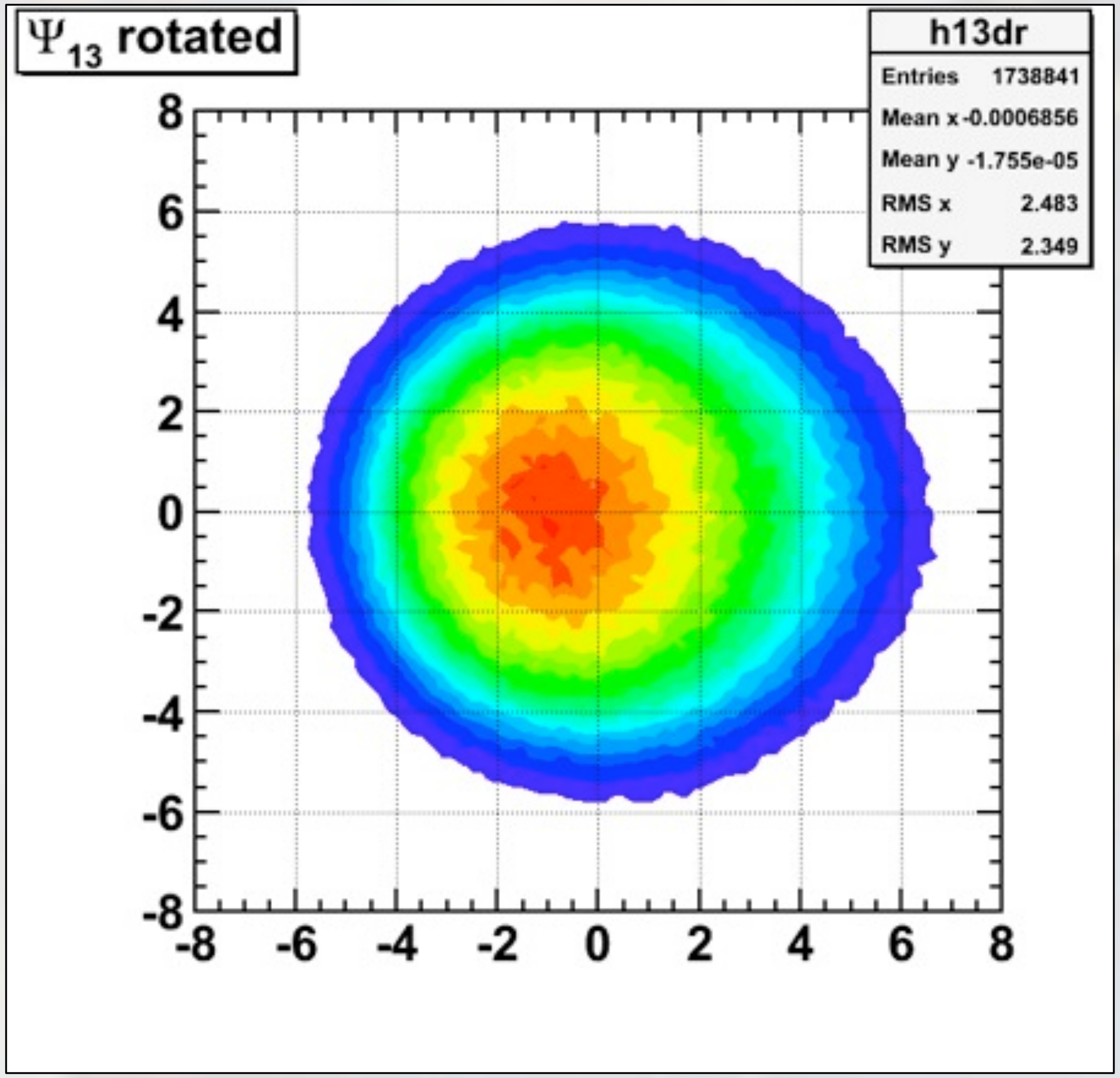
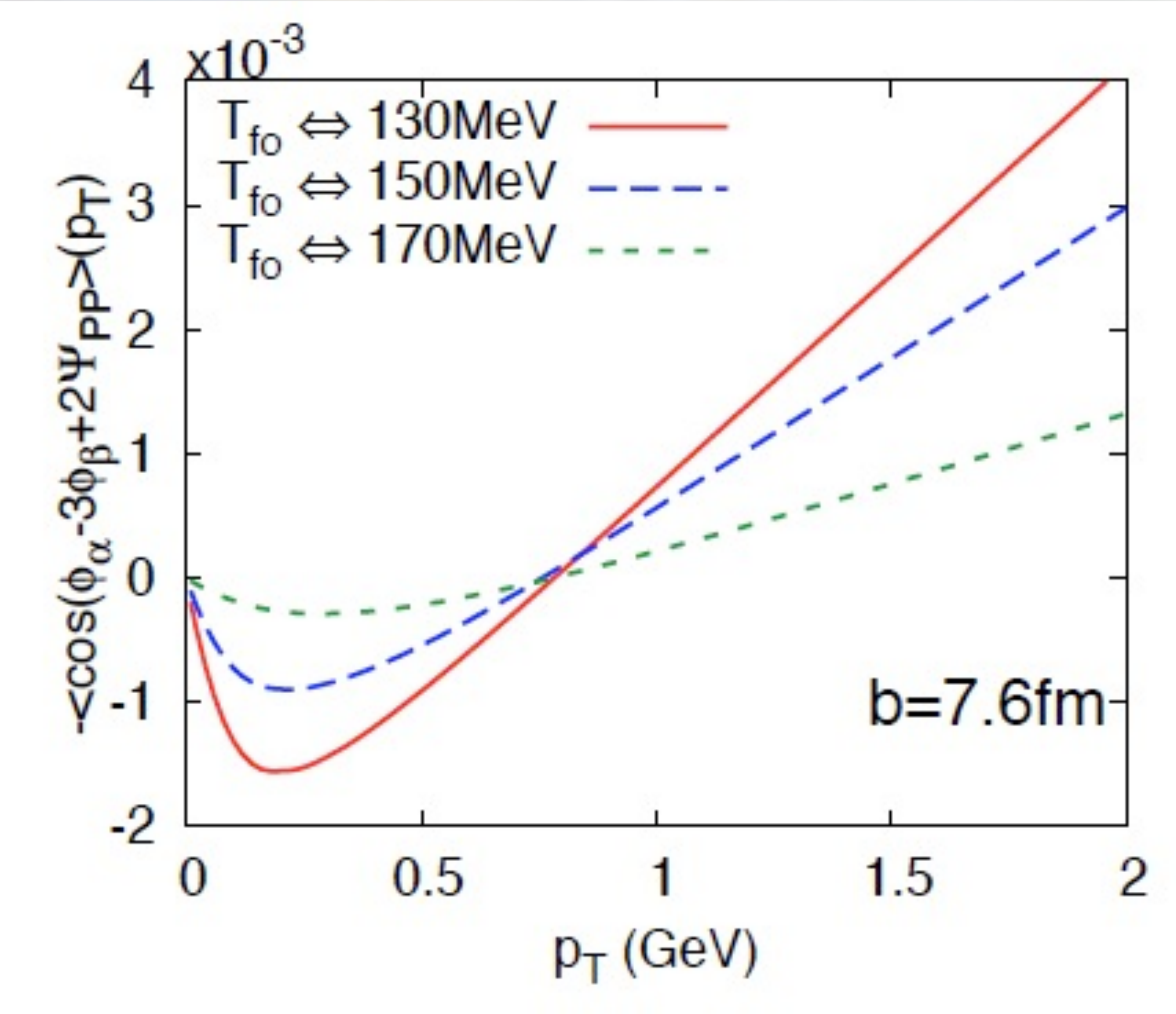


FIG. 4 (color online). The two-particle azimuthal correlation, measured in $0 < \Delta\phi < \pi$ and shown symmetrized over 2π, between a trigger particle with $2 < p_t < 3$ GeV/c and an associated particle with $1 < p_t < 2$ GeV/c for the 0%–1% centrality class. The solid red line shows the sum of the measured anisotropic flow Fourier coefficients v_2, v_3, v_4, and v_5 (dashed lines).

$v_1(p_t)$





Triangularity and Dipole Asymmetry in Heavy Ion Collisions

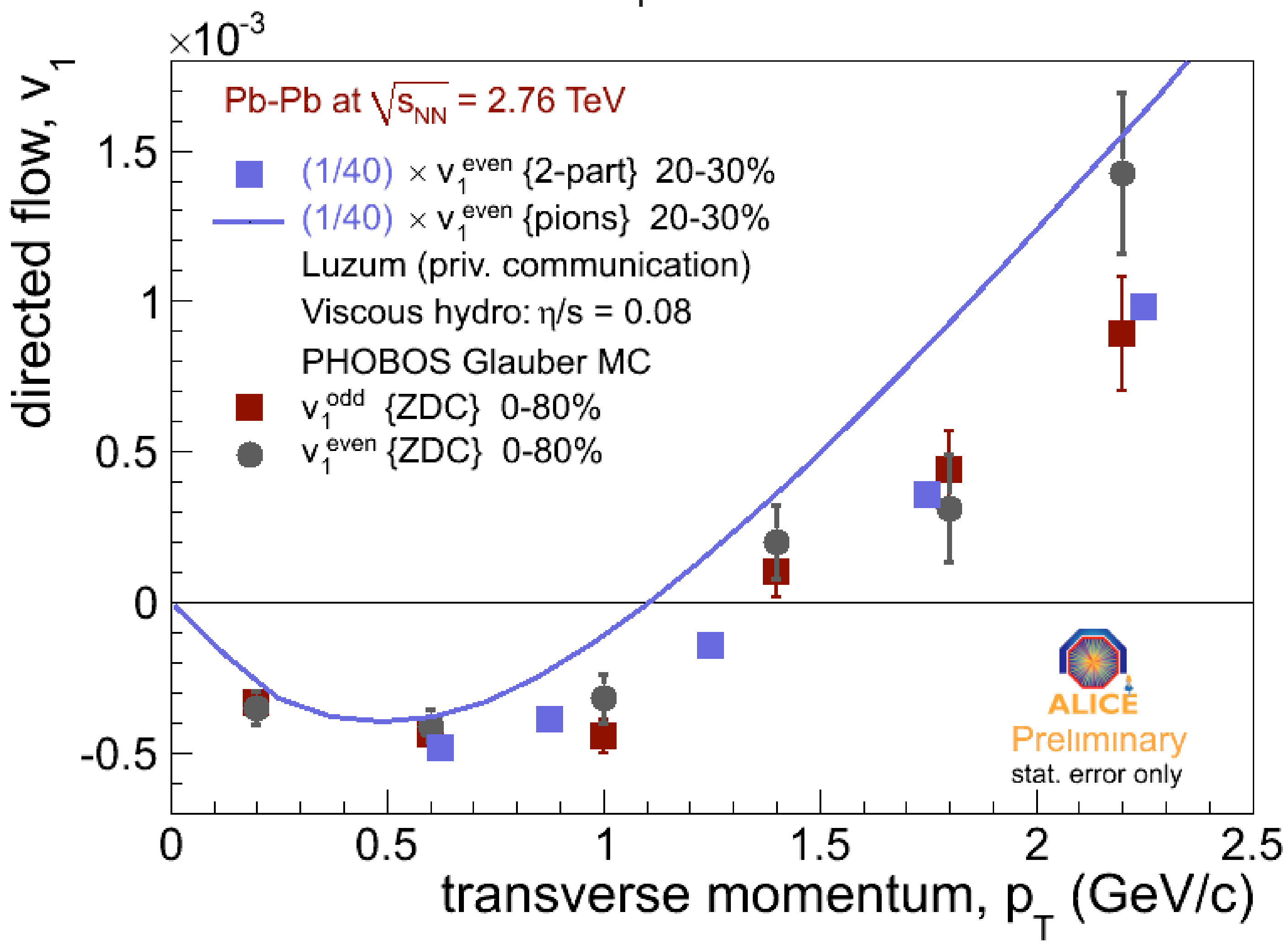
Derek Teaney and Li Yan

p_t dependence of "odd" and "even" v_1

15

EMMI

Even and odd v_1 with spectators and flow fluctuations



Viscous hydrodynamic calculations for pions:
M. Luzum (private. com.)
Method:
B. Alver, *et.al.*
arXiv:1007.5469 (2011)

2-particle correlation fits:
talk #560 by A. Adare

- Similar p_T shape of even and odd v_1{ZDC} and v_1 extracted from Fourier fits of two particles correlations
- Much smaller signal with spectators (~1/40)

ALICE

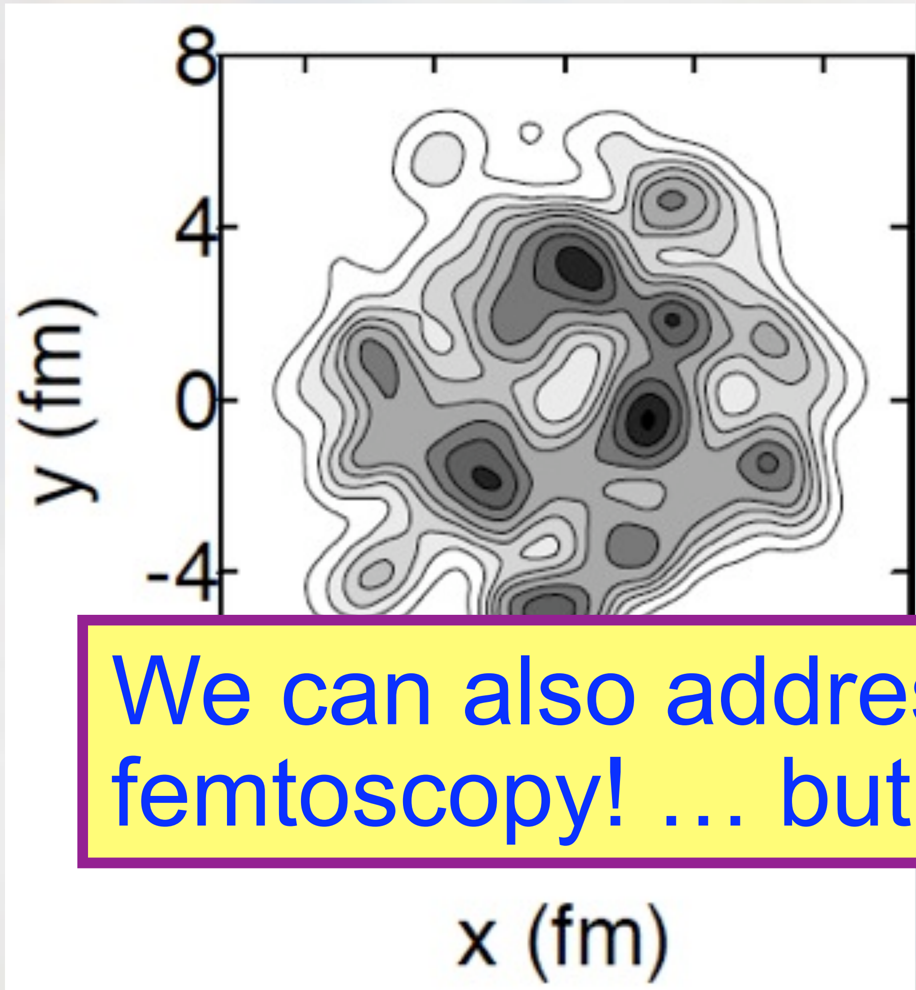
Ilya Selyuzhenkov 27/05/2011

QUARK MATTER ANNECY 2011

The origin of both is the same -- density gradients

WAYNE STATE UNIVERSITY

Density decomposition



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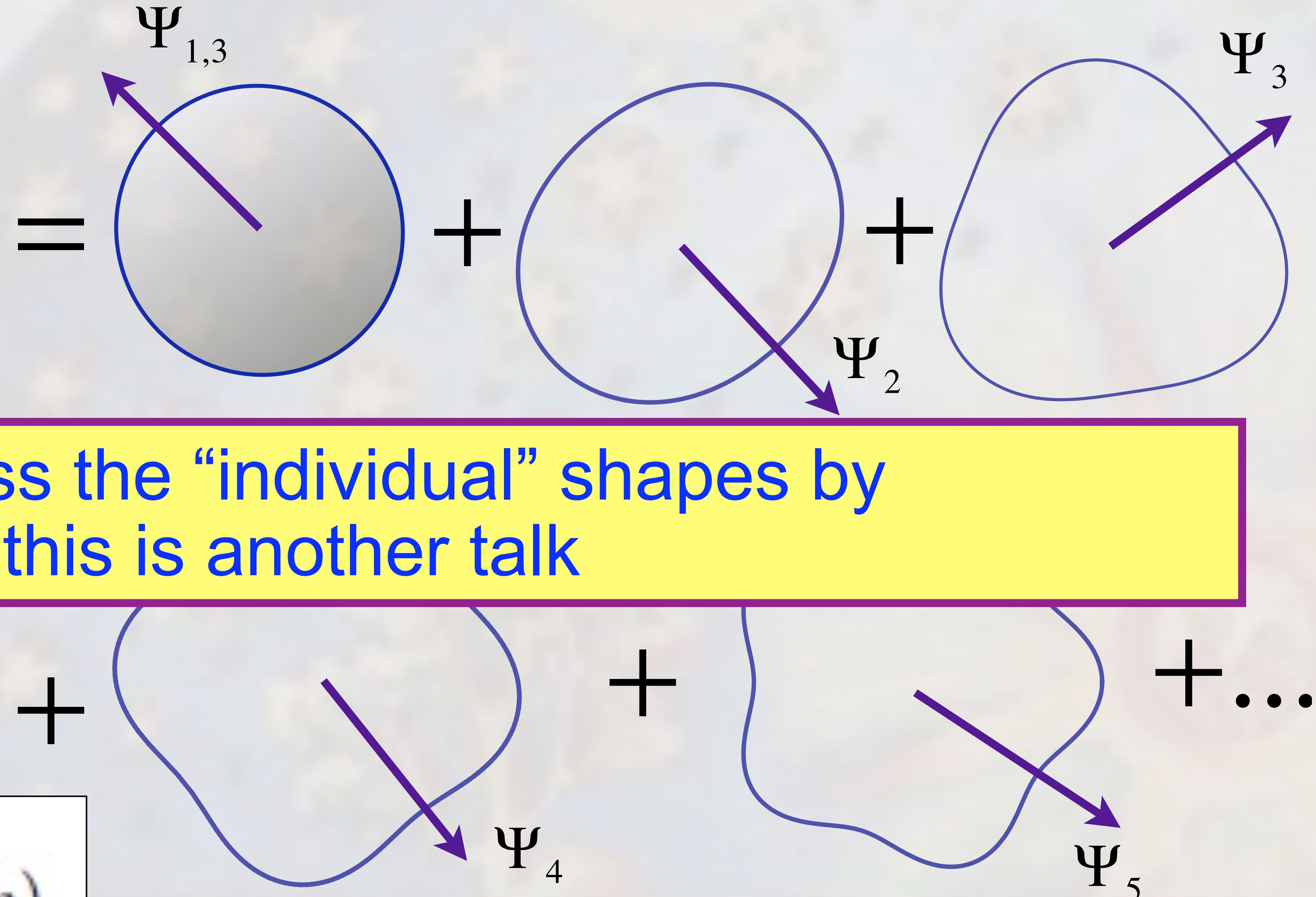

We can also address the “individual” shapes by femtoscopy! … but this is another talk

$$\int \mathrm{d}^2\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \rho(\boldsymbol{x}) = \rho(\boldsymbol{k}),$$

arXiv:1010.1876v1 [nucl-th] 9 Oct 2010

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Summary

- Heavy ion collisions is a unique laboratory to study QCD, including physics of hadronization, properties of QCD vacuum.
- Anisotropies in particle production appear to be a very sensitive tool for such studies.

✦ Constituent quark number scaling -- an important observation which might reveal the dynamics of hadronization.

✦ Anisotropies in particle production in a very strong magnetic field of colliding nuclei could provide a unique "playground" for direct experimental studies of nonperturbative QCD effects.

✦ Flow fluctuations, quite accurately measurable experimentally, provide another observable very sensitive to the initial state of the system evolution / wave function of the fast nucleus.

✦ "Nonflow" due to interplay of "hot spots" and radial flow, and flow fluctuations due to fluctuations in in the "shape" are different descriptions of the same phenomena.