Heavy ion collisions: Initial state fluctuations and higher harmonics flow

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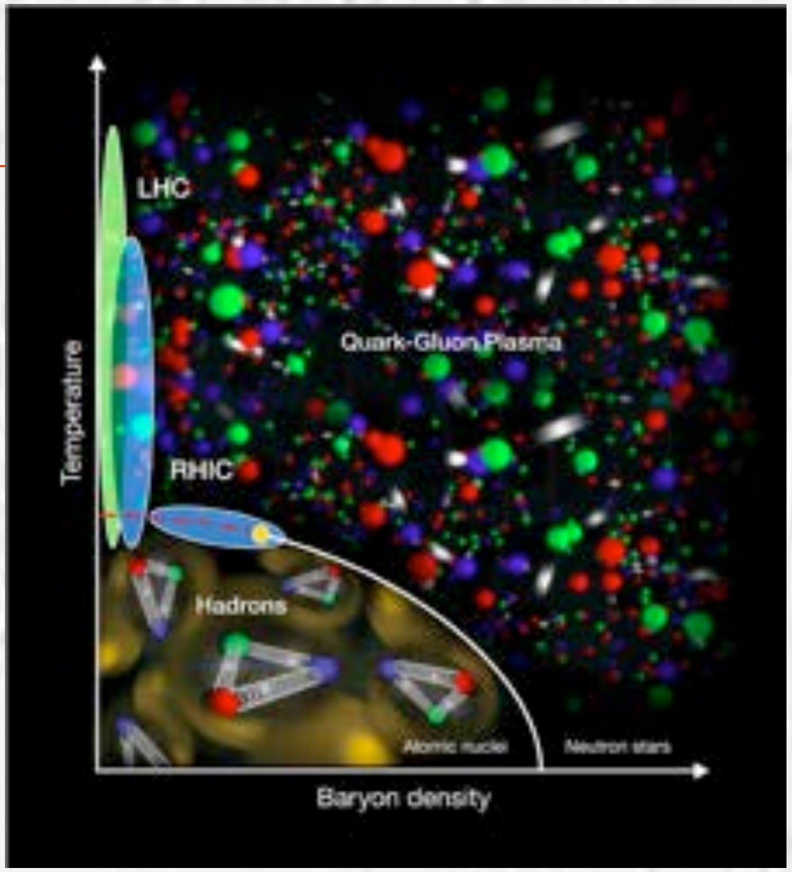
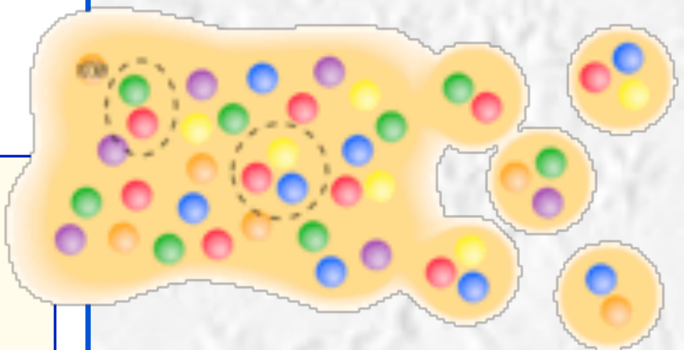
Outline:

- ✦ Introduction: why do we care?
- ✦ Can we observe ISFs?
  - Higher harmonics anisotropic flow
  - dipole flow (“where do spectators flow”?)
  - azHBT
- ✦ Event Shape Engineering
- ✦ Background study in the CME search
- ✦ Conclusions

Ultrarelativistic nuclear collisions

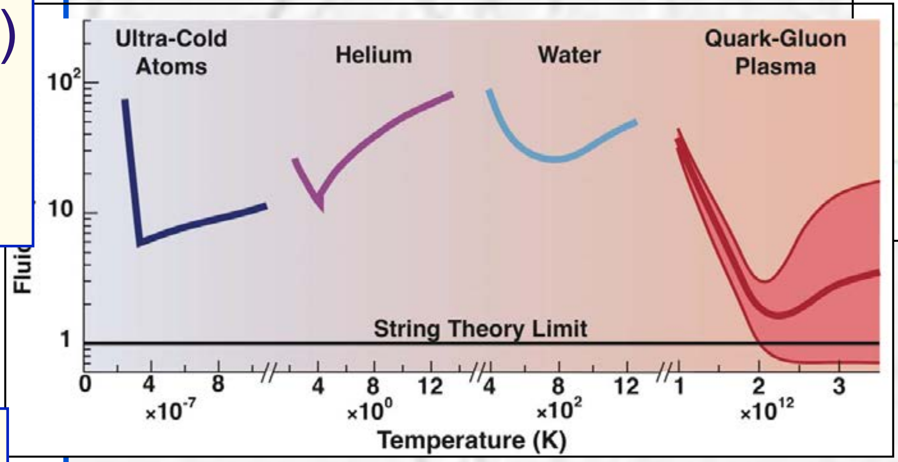


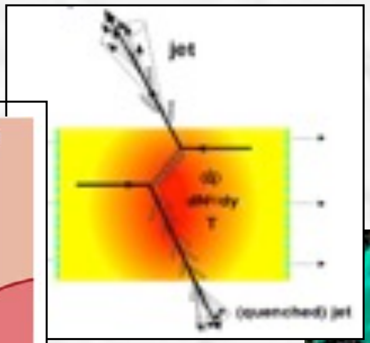
Goal: strongly interacting (QCD) matter

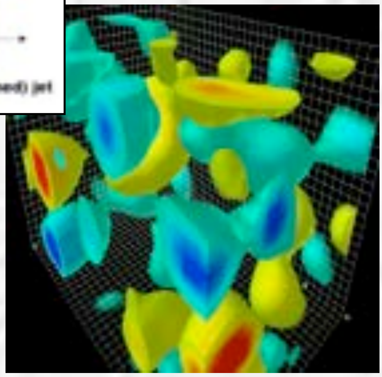


Physics of :

- hadronization (more generally: physics of multiparticle production)
- properties of the QCD vacuum (e.g. CME)
- transport properties of QCD matter
- ...

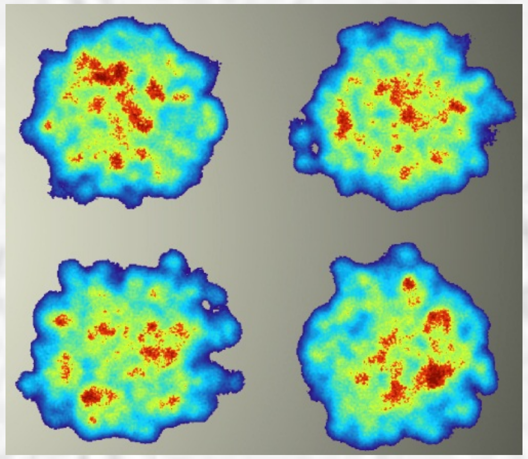




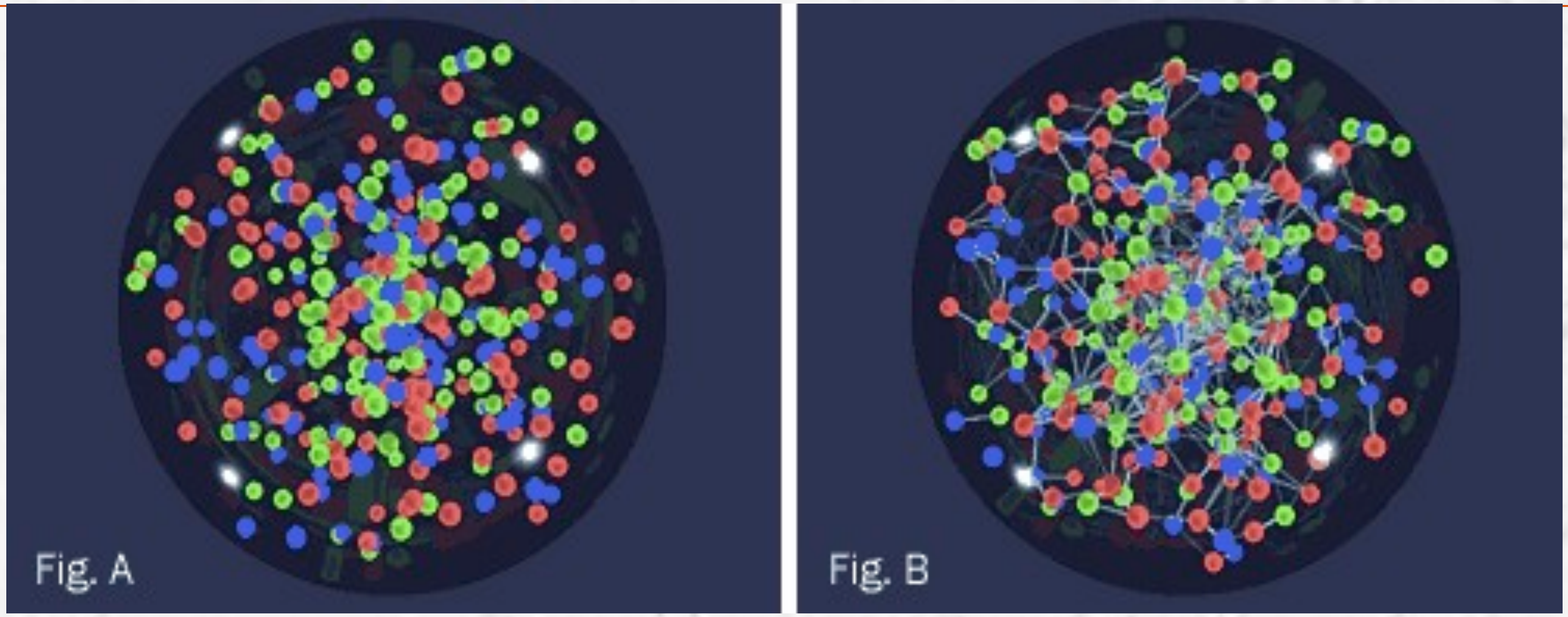


Most analyses involve two- and/or many particle correlations.

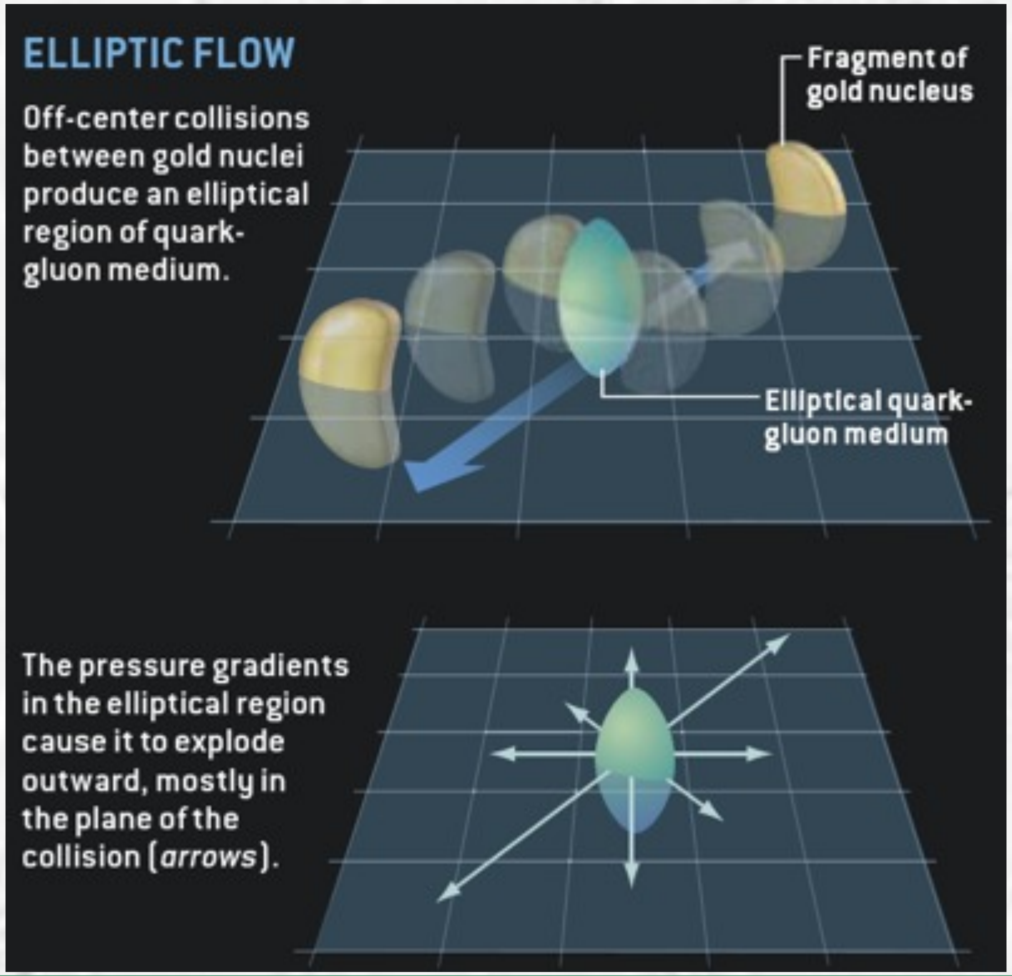
Understanding the initial conditions and their role/contribution to the final state particle distributions/correlations becomes very important.



(one of pre-RHIC questions:) QGP - Gas or Liquid?



Anisotropic flow: system response to the anisotropic initial conditions.



Elliptic flow

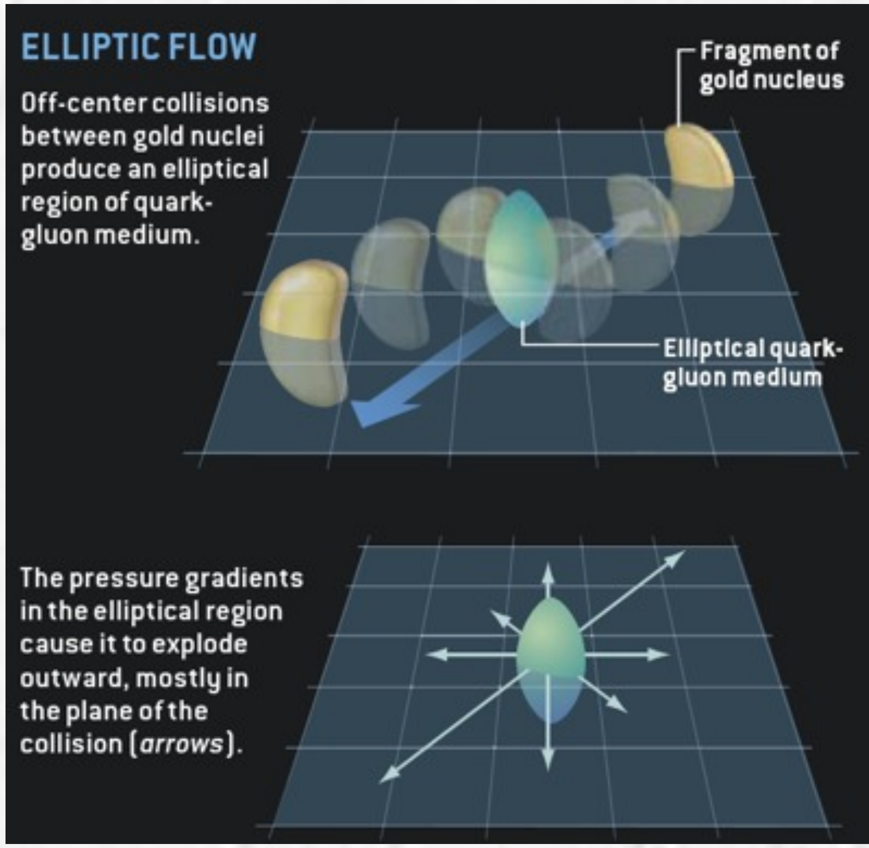
$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2v_1 \cos(\Delta\phi) + 2v_2 \cos(2\Delta\phi) + \ldots$$

$$\Delta\phi = \phi - \Psi_{RP}$$

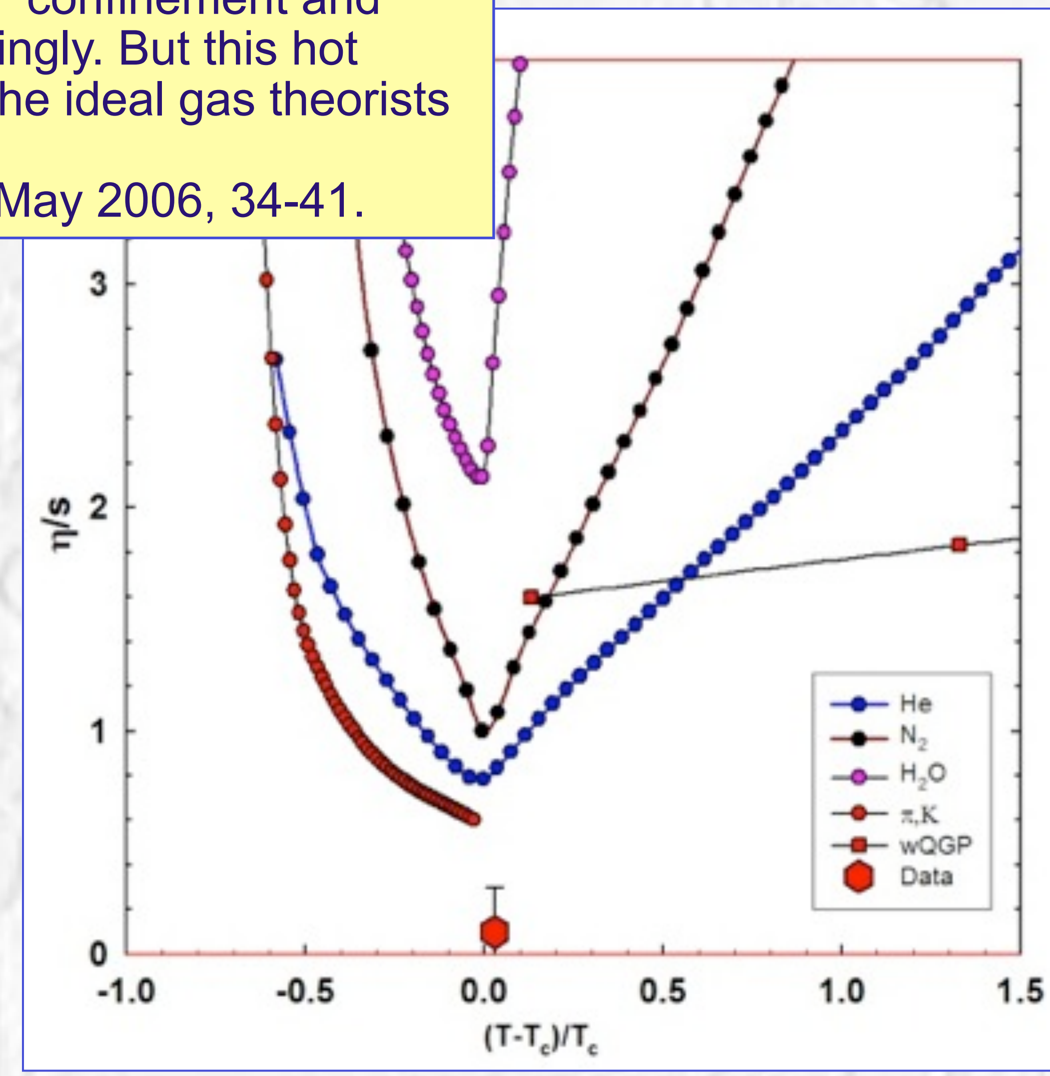
First RHIC "Au+Au" paper: > 500 citations

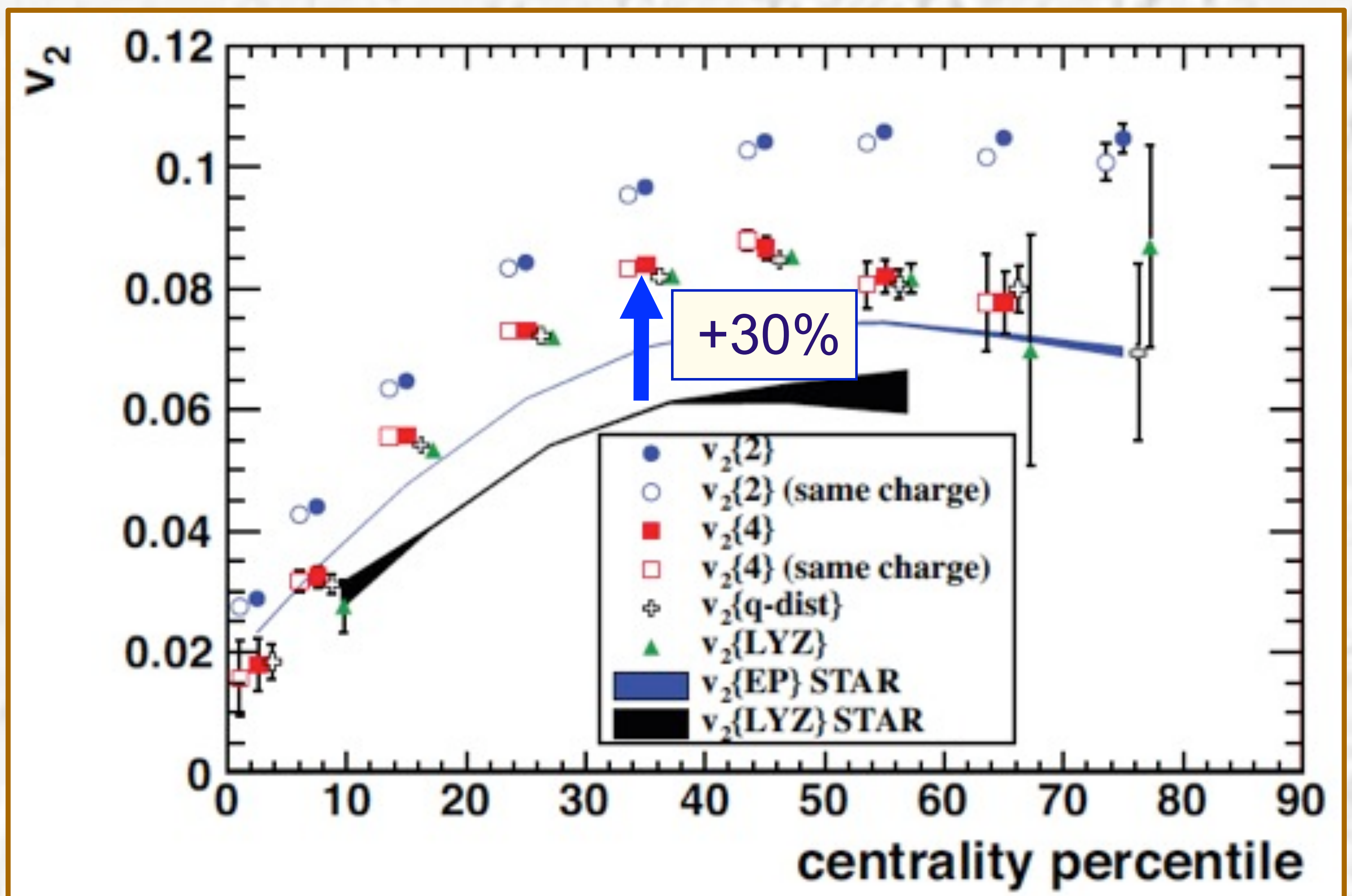
First LHC "Pb+Pb" paper: > 300 citations

Elliptic flow at RHIC and LHC



"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.

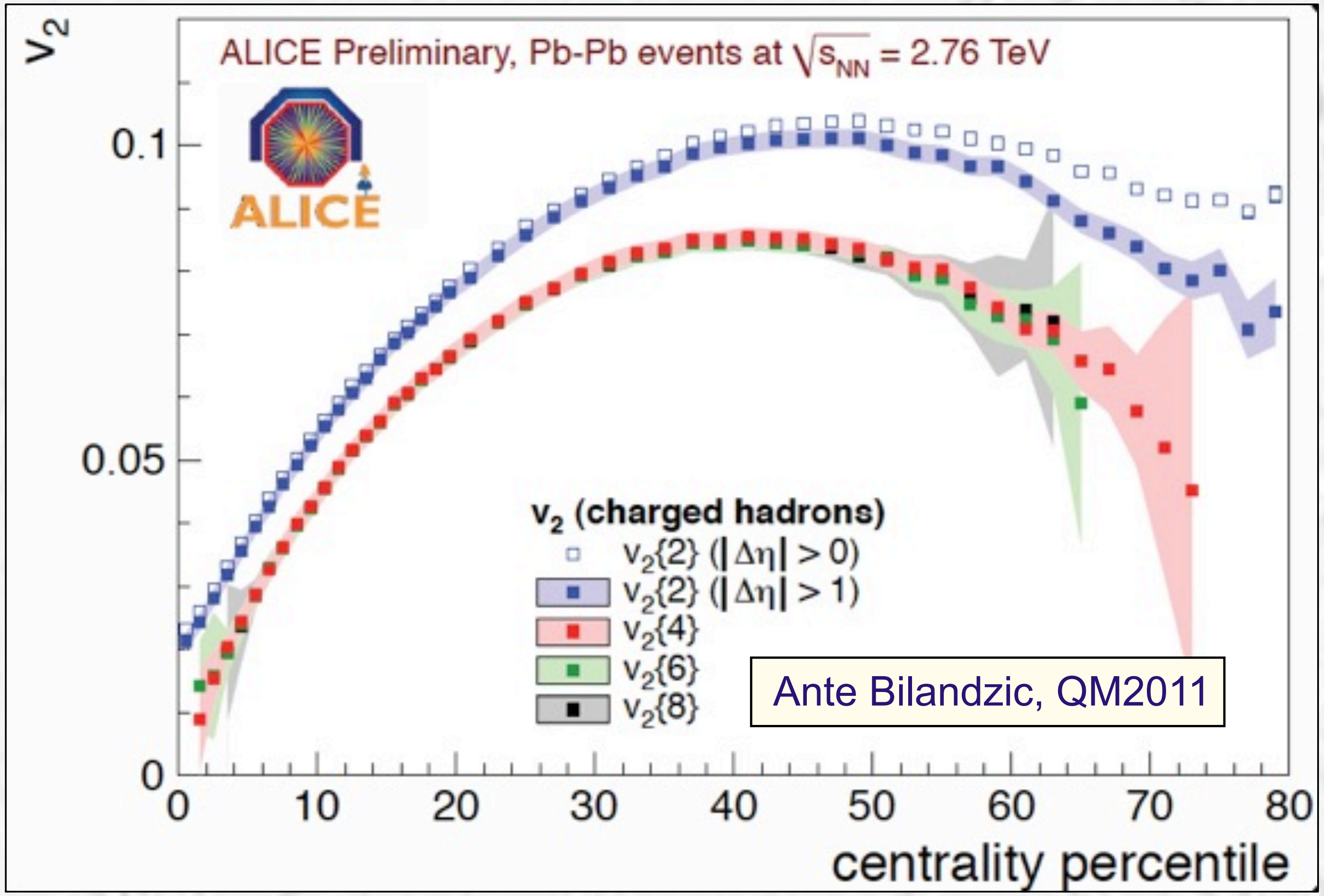




LHC: Increase in elliptic flow ~30%, in agreement with hydrodynamics

CERN Press release, November 26, 2010:
'confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..'

v2{2} vs v2{4} flow fluctuations or nonflow?



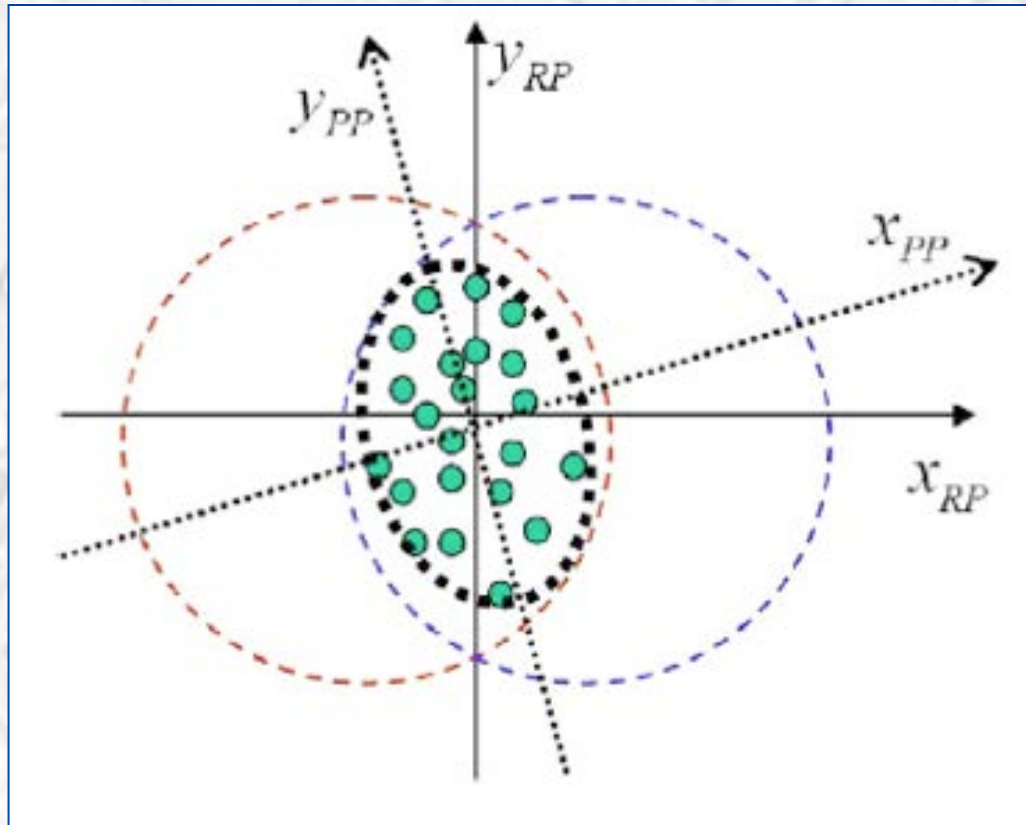


Fig. 1. The definitions of the *RP* and *PP* coordinate systems.

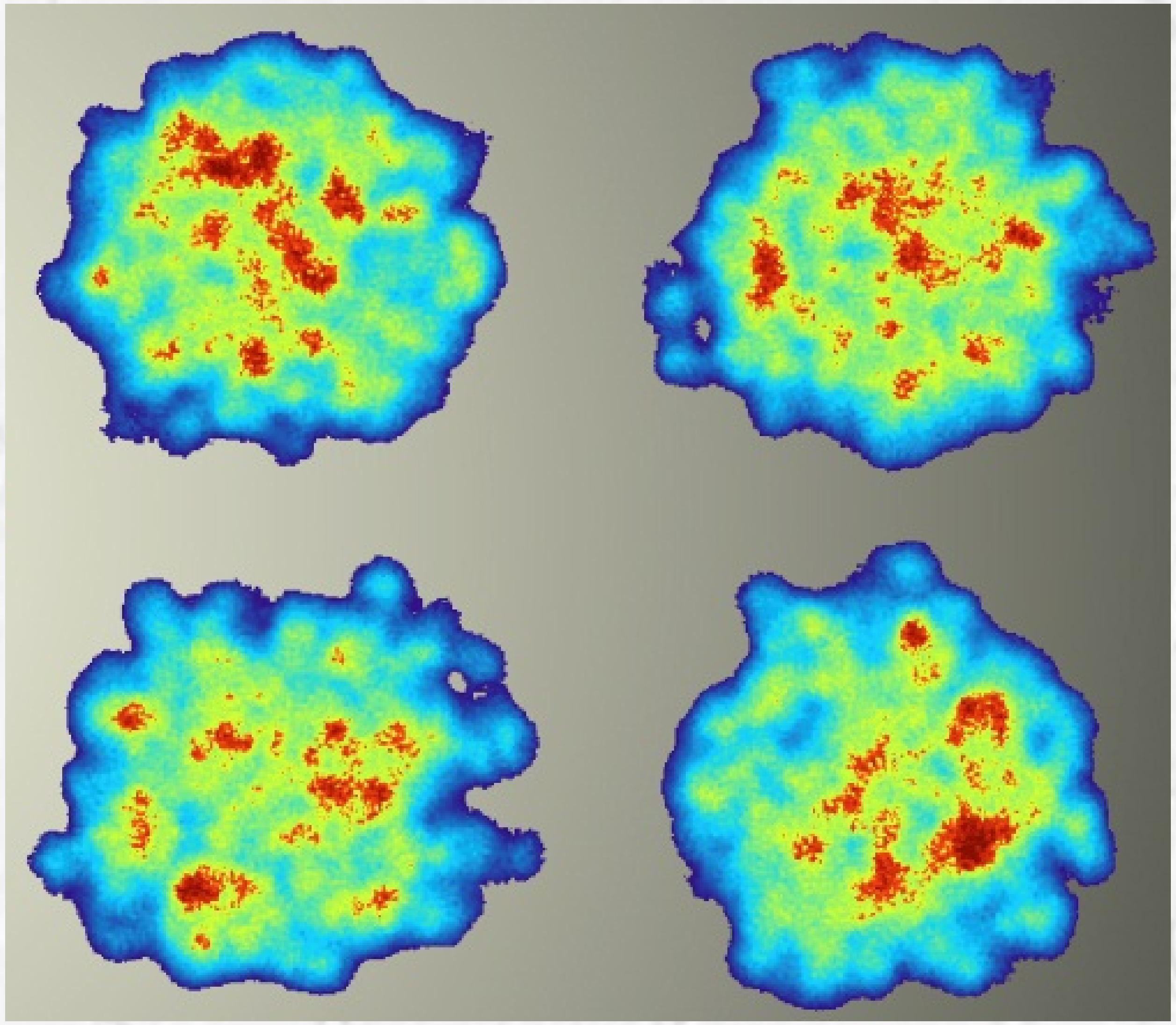
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

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

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

Current understanding: The dominant contribution to the difference between v2{2} and v2[4] is due to flow (initial state) fluctuations

Initial state fluctuations

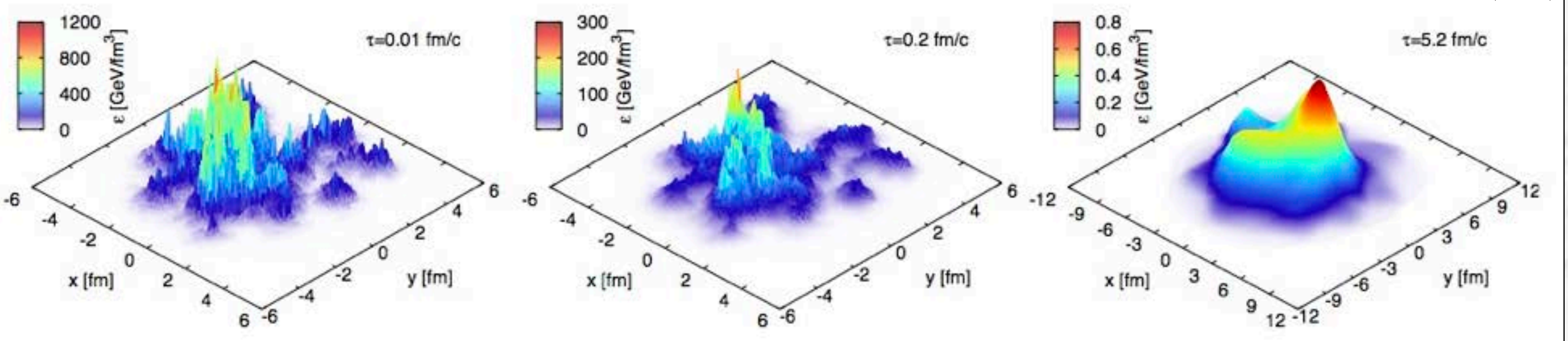


Initial state fluctuations (energy/entropy,...) what do they lead to in the final state?

Can we “observe” them?

Friend or foe? (Only unwelcome background or we can utilize them to study properties of the medium?)

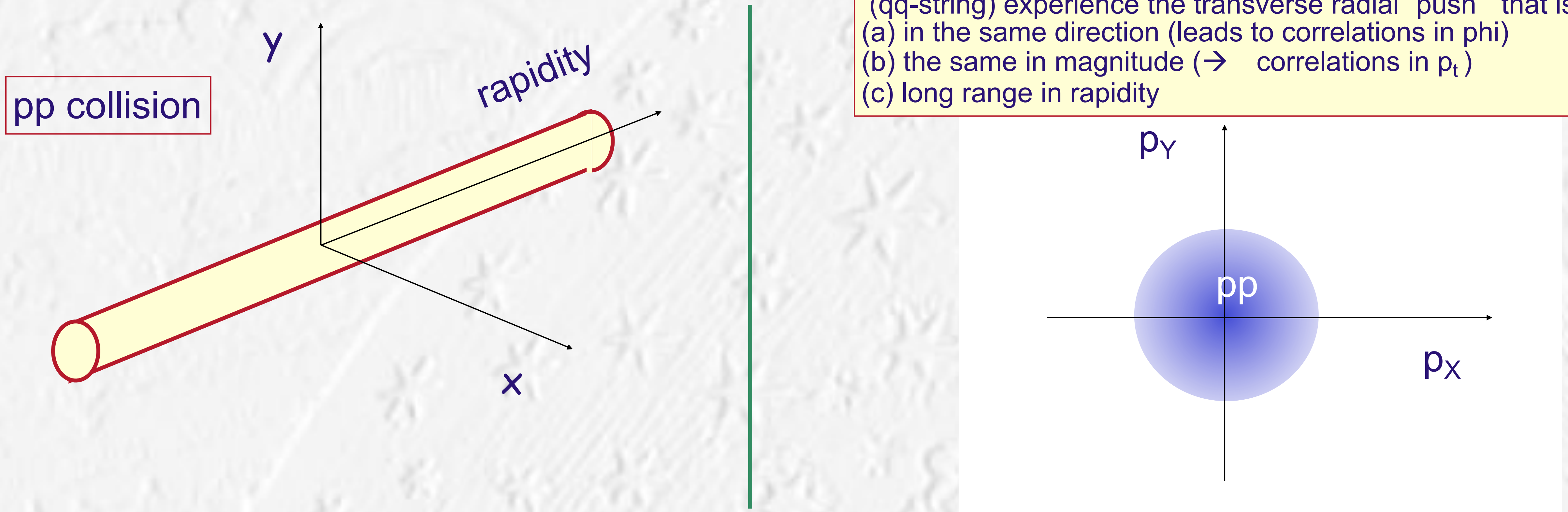
Schenke B, Tribedy P, Venugopalan R. *Phys. Rev. Lett.* 108:252301 (2012)

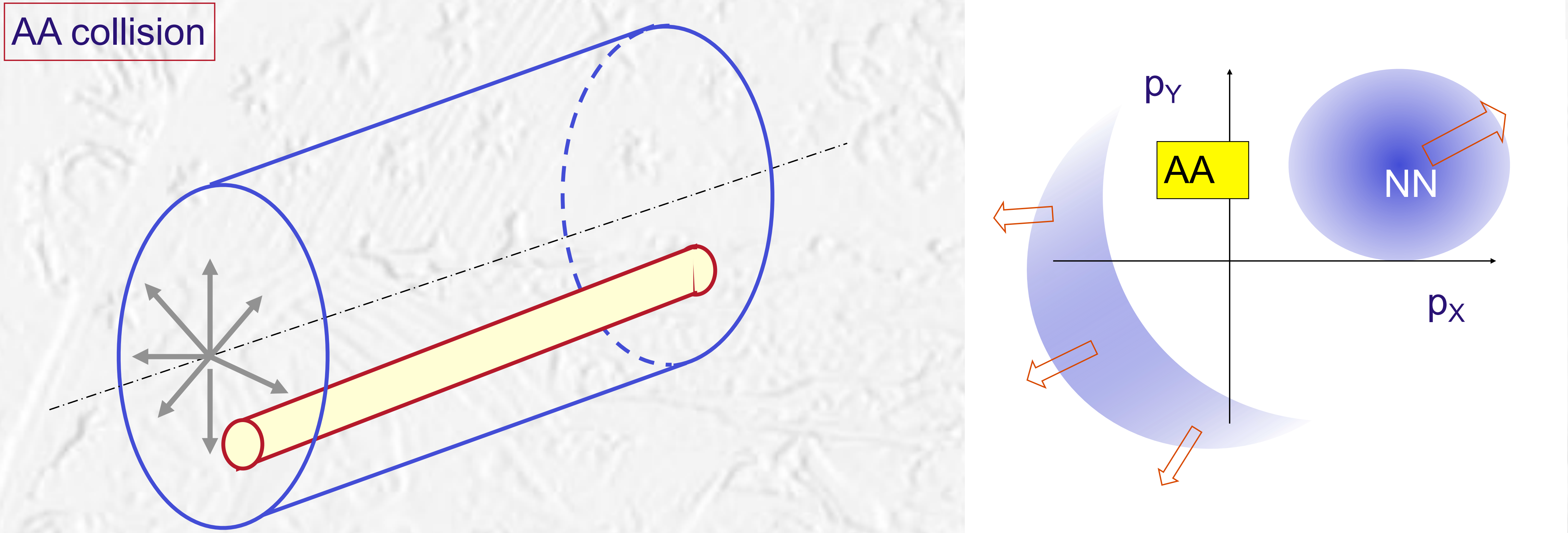


Radial expansion → 2-part azimuthal correlations

[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)
(c) long range in rapidity





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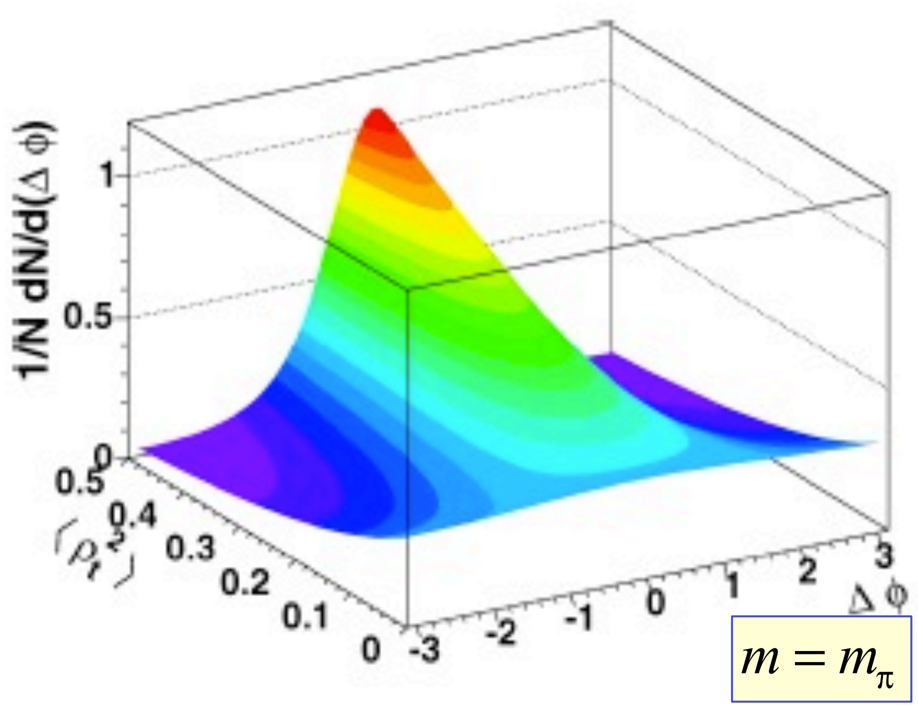
Radial expansion ➔ 2-part azimuthal correlations

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



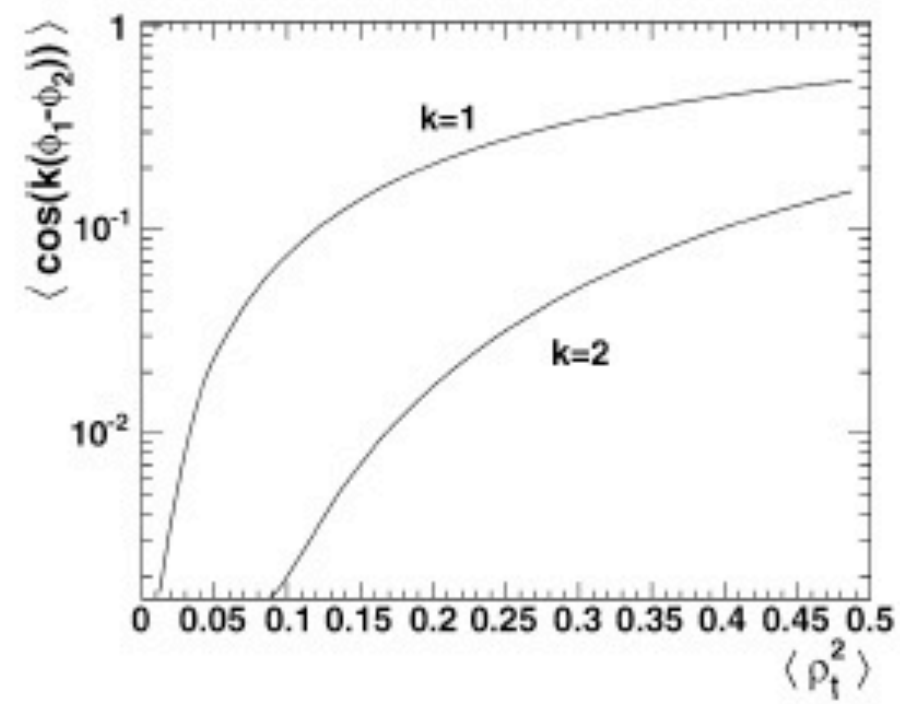


Fig. 3. (Color online.) Two pion $\Delta\phi$ distribution as function of $\langle \rho_t^2 \rangle$ in the blast wave model. Linear velocity profile and $T = 110$ MeV have been assumed.

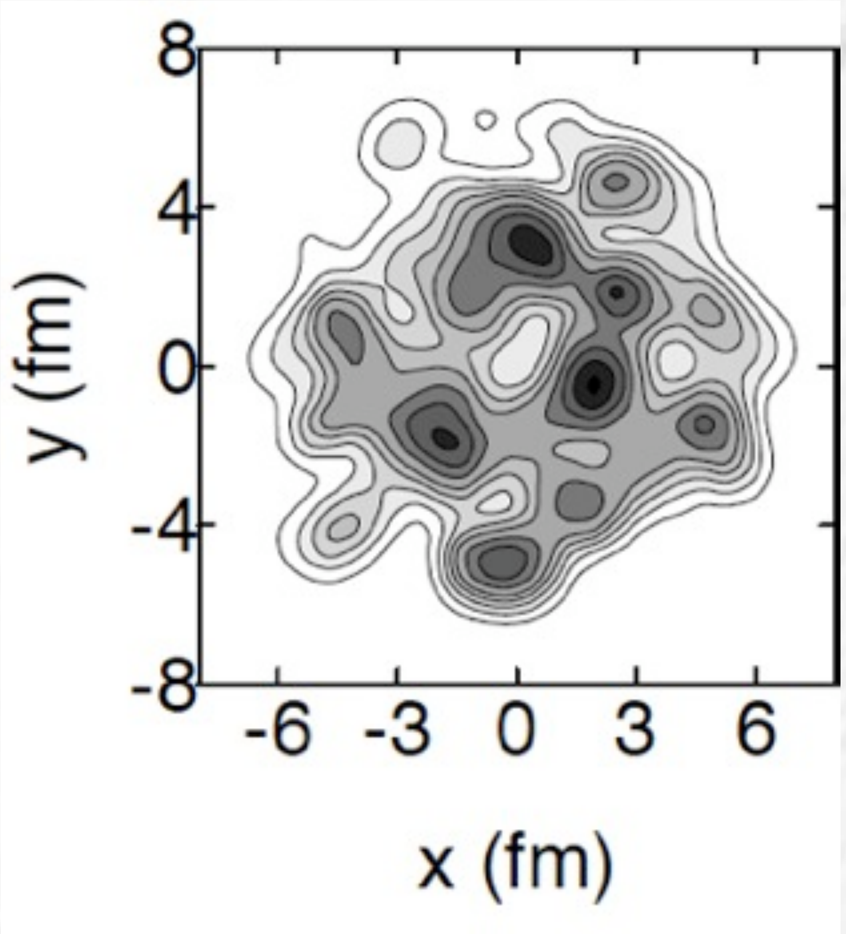
Fig. 4. The average values of $\cos(\Delta\phi)$ and $\cos(2\Delta\phi)$ for the distribution shown in Fig. 3.

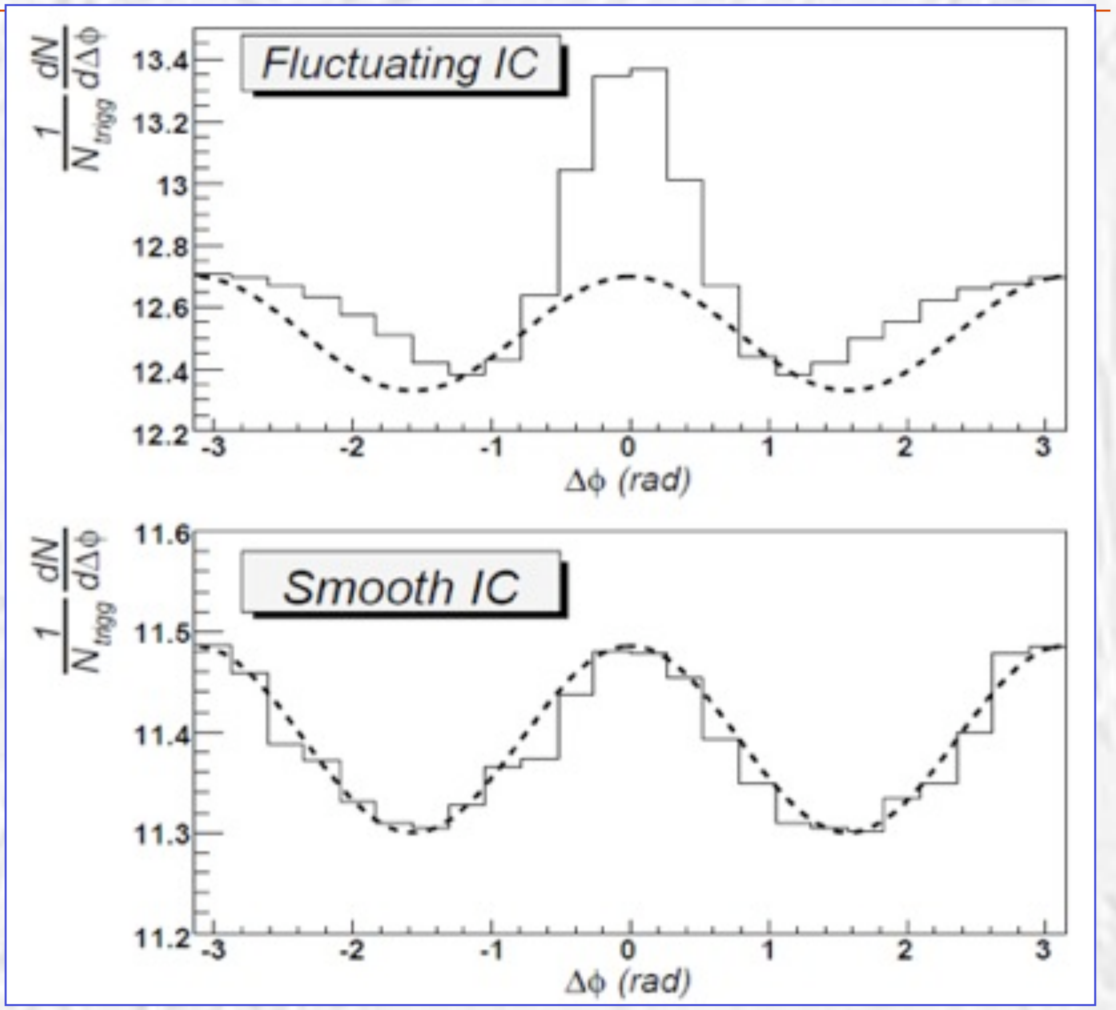
Figures are shown for particles from the same NN collision.
Dilution factor to be applied!

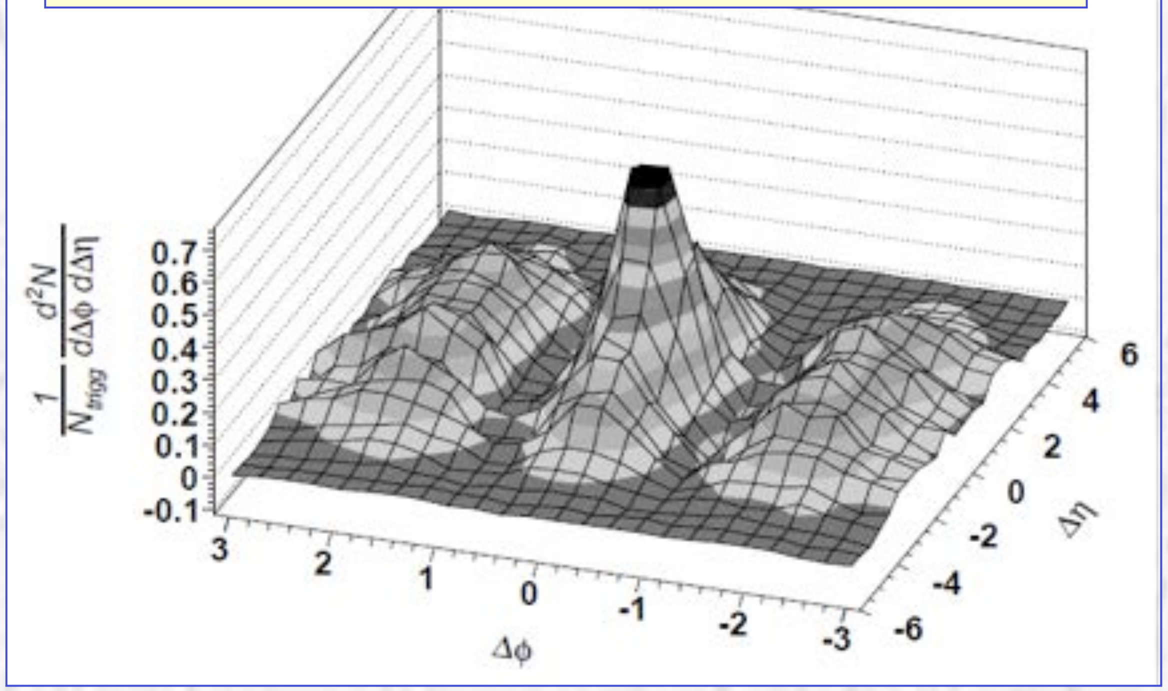
!!! - the large values of transverse flow, (average transverse rapidity squared) $\langle \rho_t^2 \rangle > 0.25$, would contradict elliptic flow measurements (nonflow contribution).

Correlation function. Pure hydro.

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







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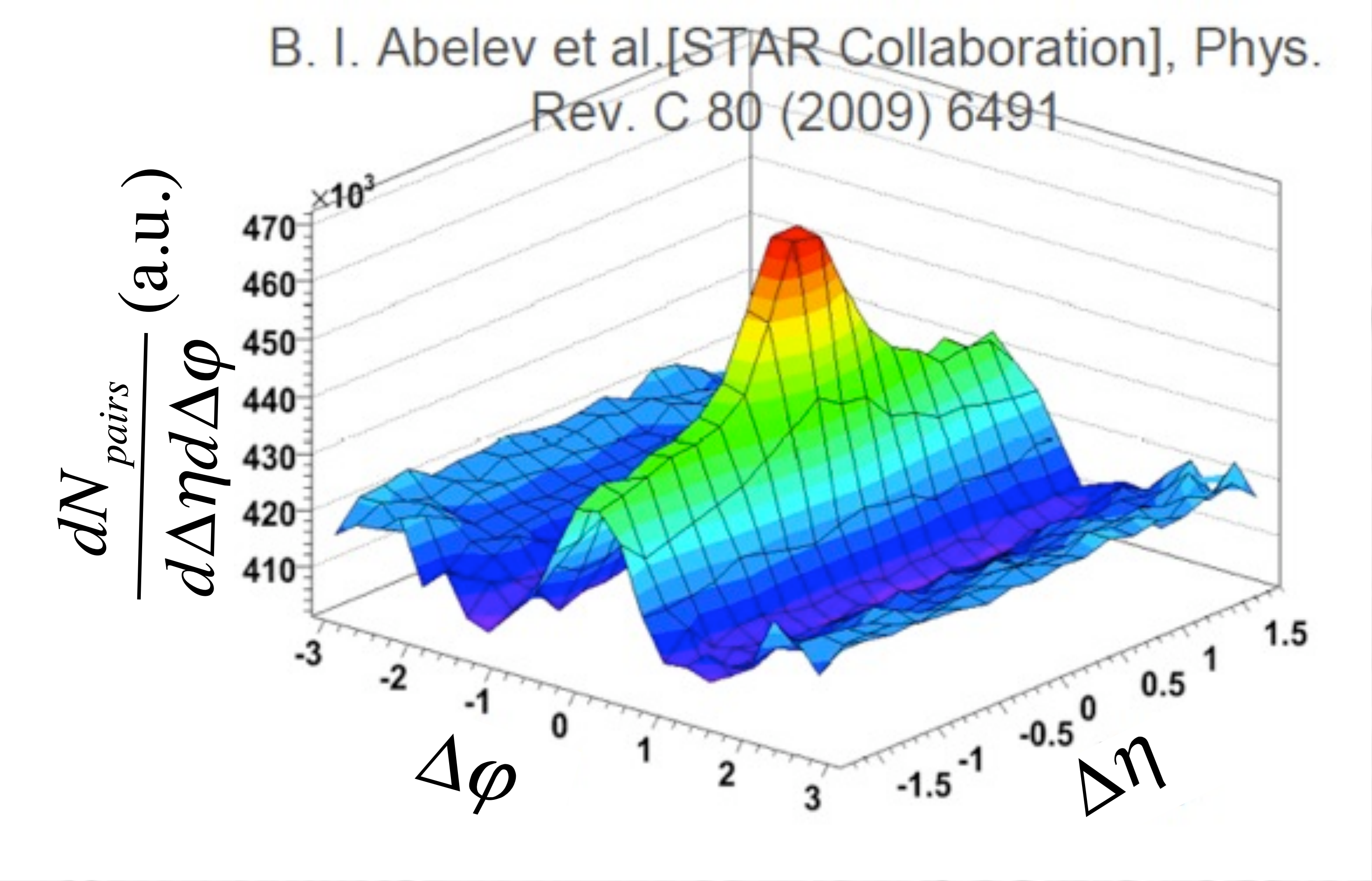
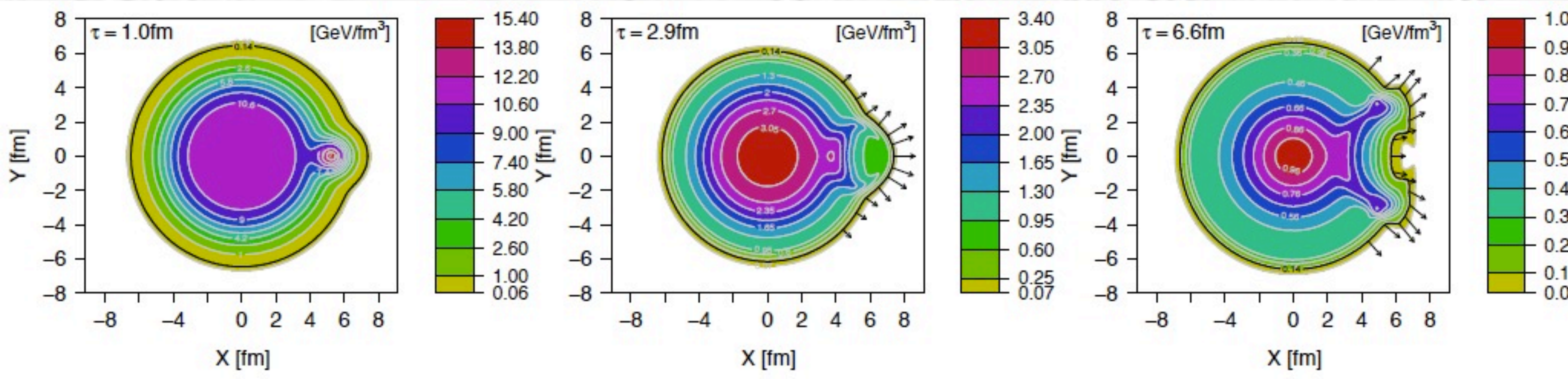
"Ridge". (Nonflow?)



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

Single "hot spot"

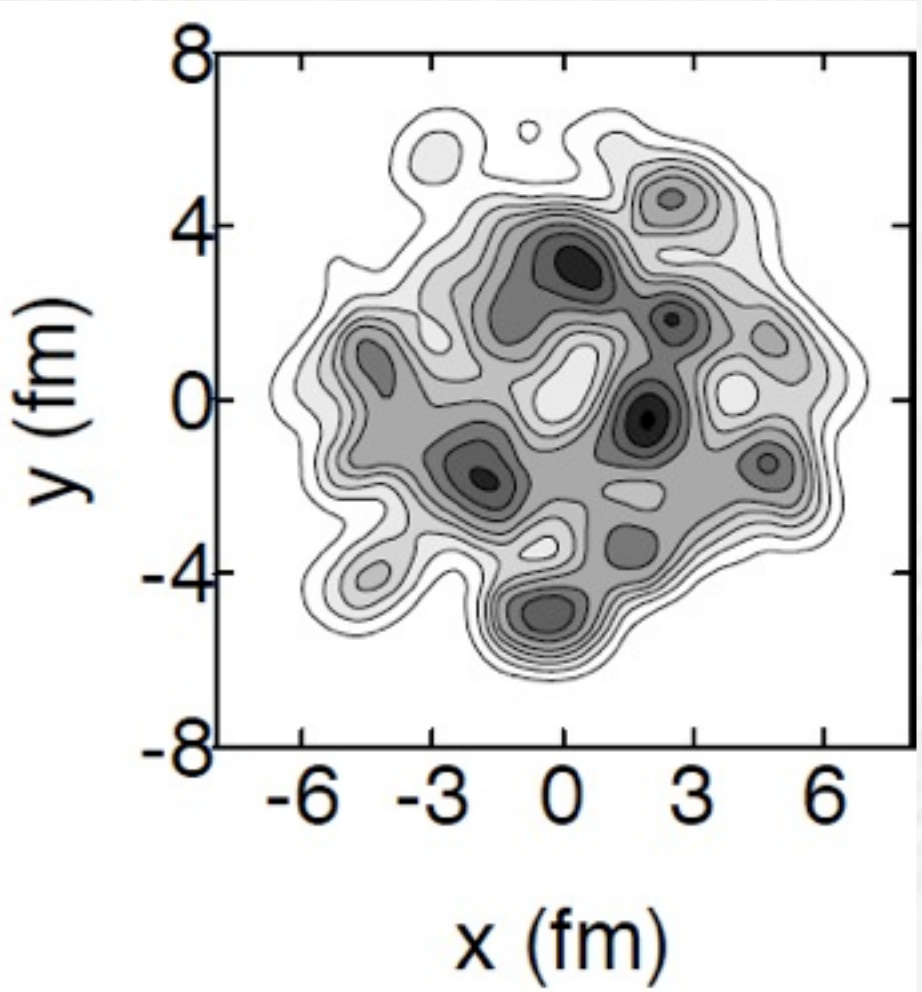
R. P. G. Andrade, F. Grassi, Y. Hama, W. -L. Qian, Nucl. Phys. **A854**, 81-88 (2011).



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) are different.

Density decomposition



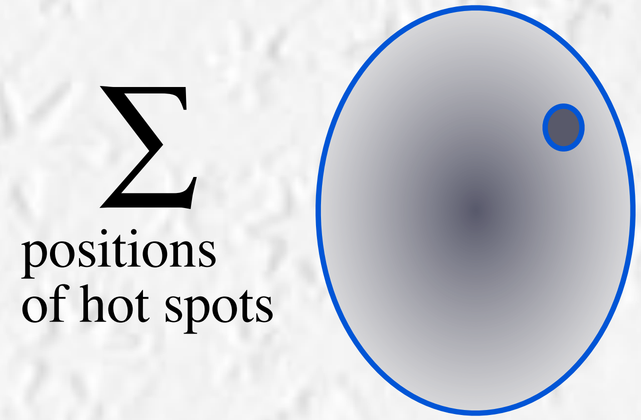
Yogiro Hama,[1] Rone Peterson G. Andrade,[1] Frédérique Grassi,[1] Wei-Liang Qian,[1] Takeshi Osada,[2] Carlos Eduardo Aguiar,[3] and Takeshi Kodama[3]

=

"Nonflow" description

In the linear approximation one can study the effects of density fluctuations **either** like this ("nonflow")

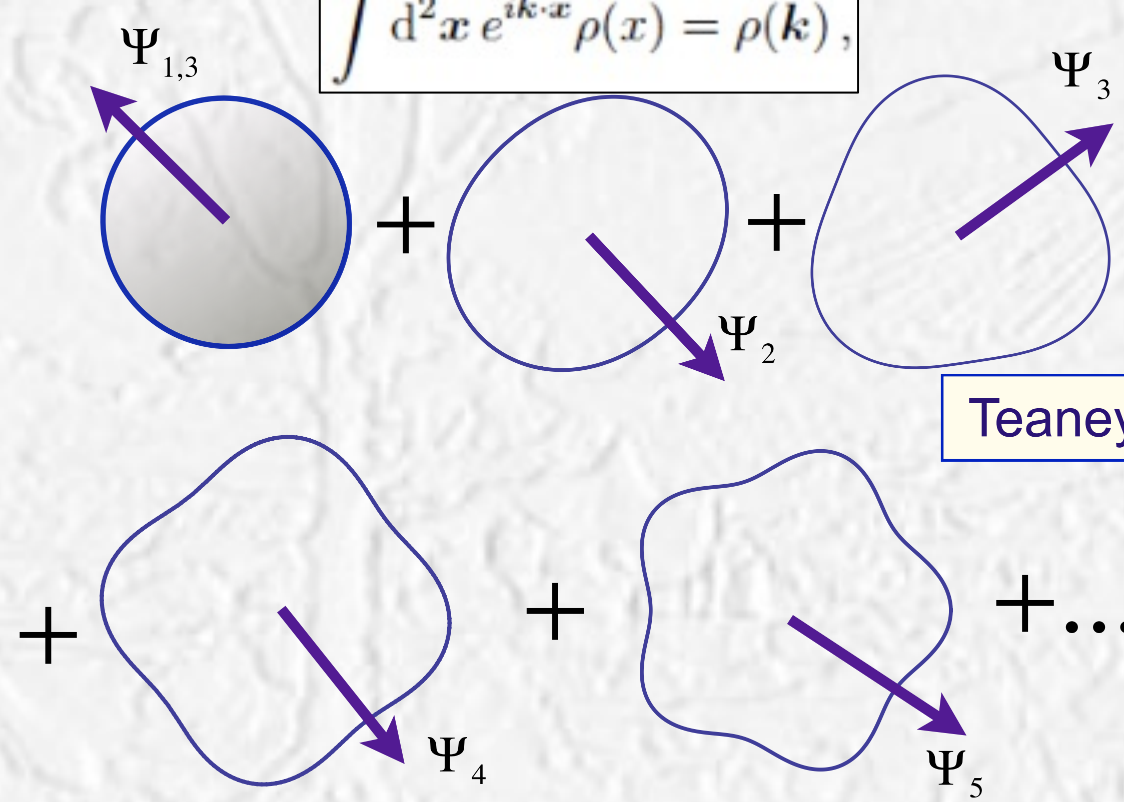
Shuryak et al.



... **or** via 2d Fourier decomposition ('higher harmonic flow")

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

Higher harmonics flow

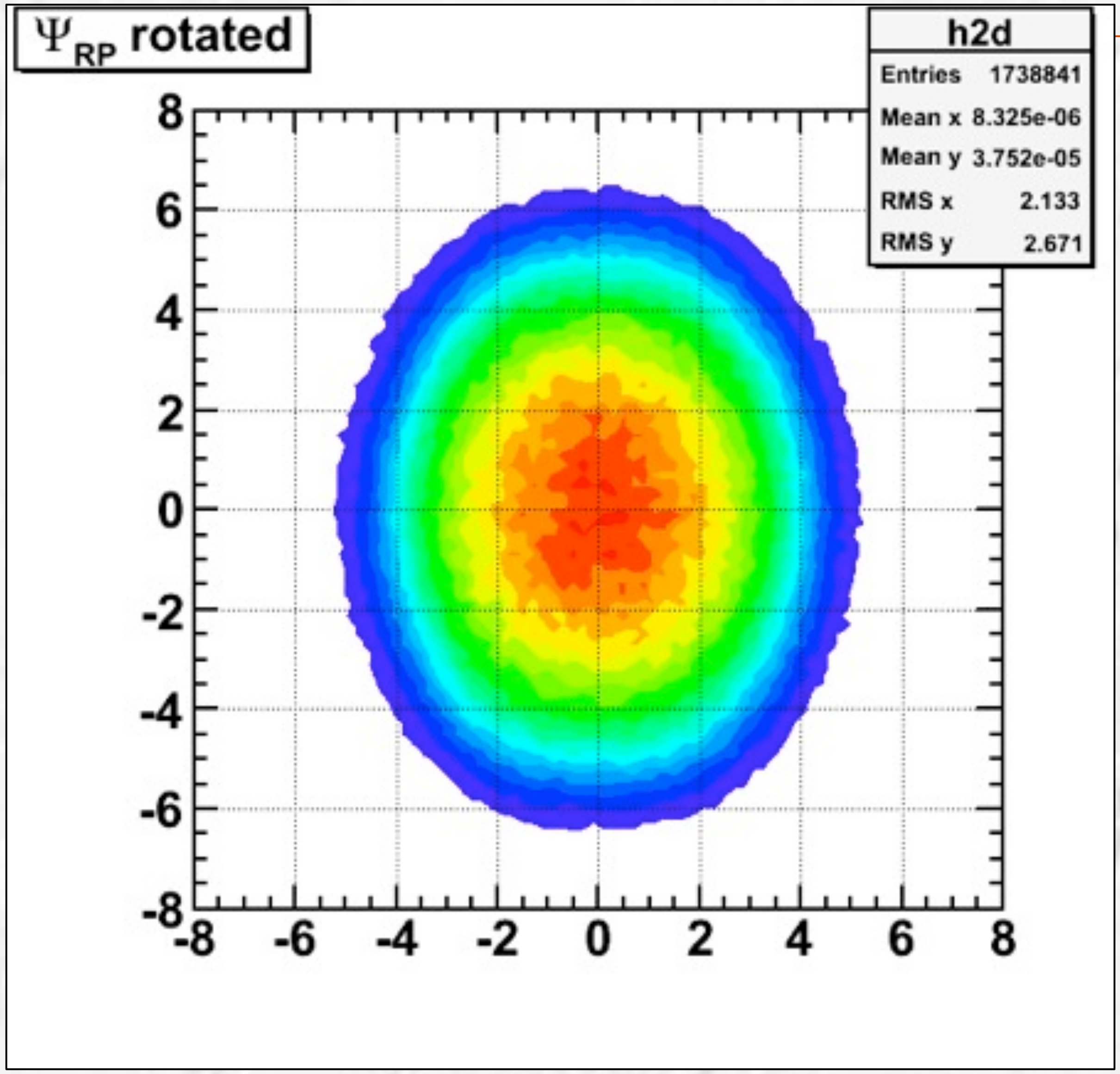


Teaney and Yan

$$\varepsilon_n e^{in\Phi_n} \equiv -\frac{\int r\,dr\,d\phi\, r^n e^{in\phi}\, e(r,\phi)}{\int r\,dr\,d\phi\, r^n e(r,\phi)} \quad (n>1),$$

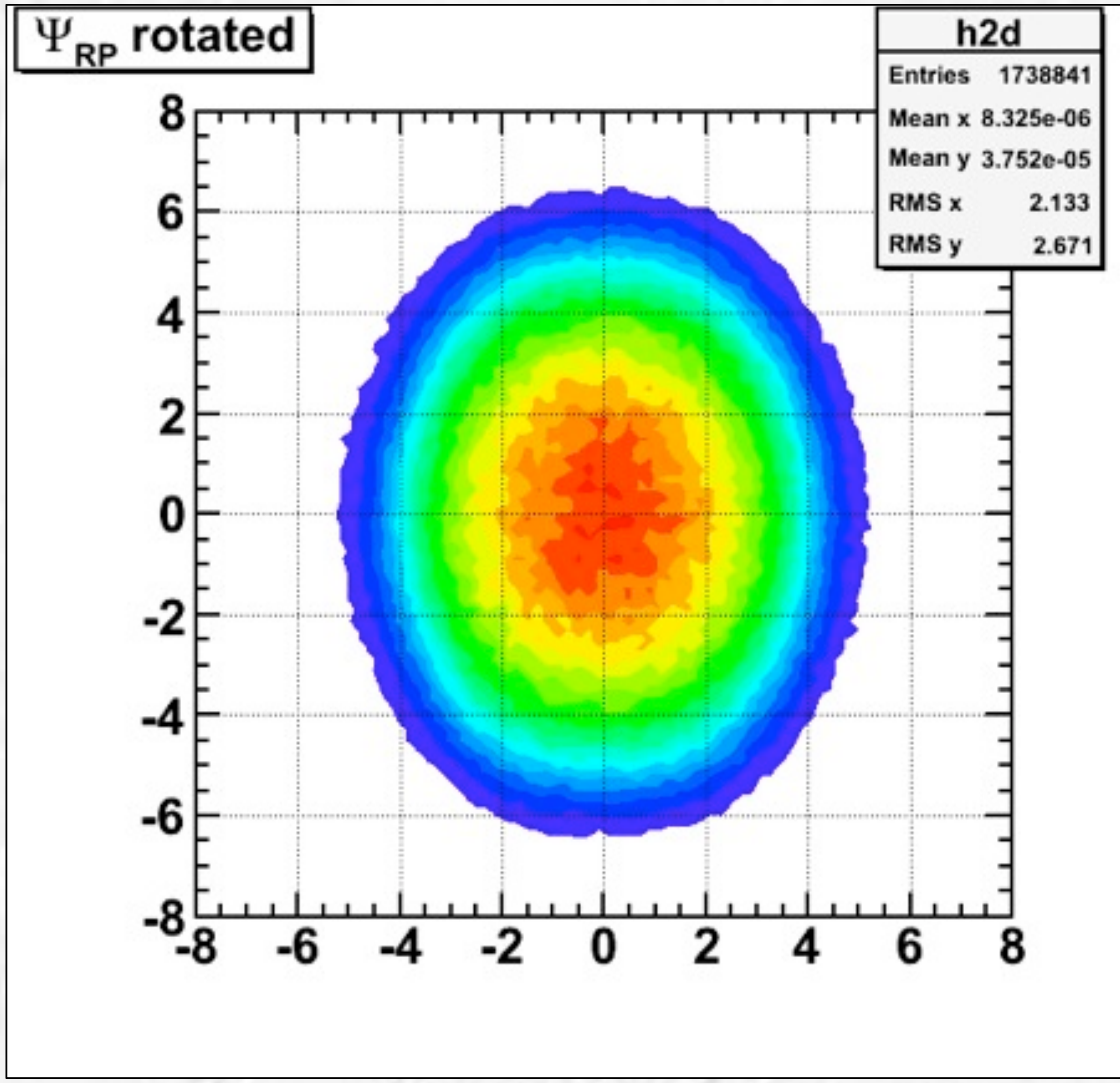
$$\varepsilon_1 e^{i\Phi_1} \equiv -\frac{\int r\,dr\,d\phi\, r^3 e^{i\phi}\, e(r,\phi)}{\int r\,dr\,d\phi\, r^3 e(r,\phi)}$$

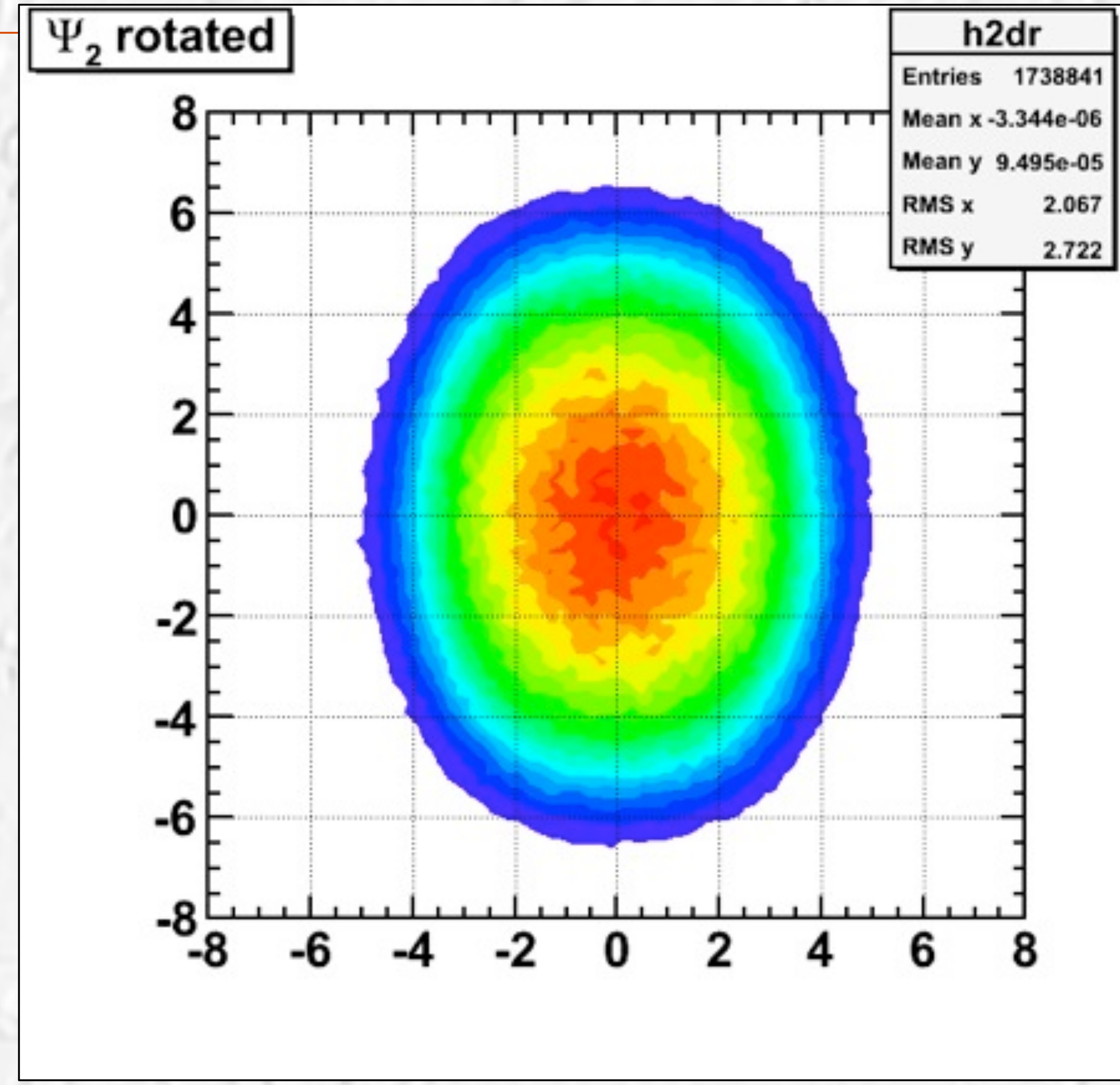
Density distributions



10k Pb+Pb events, b=8 fm

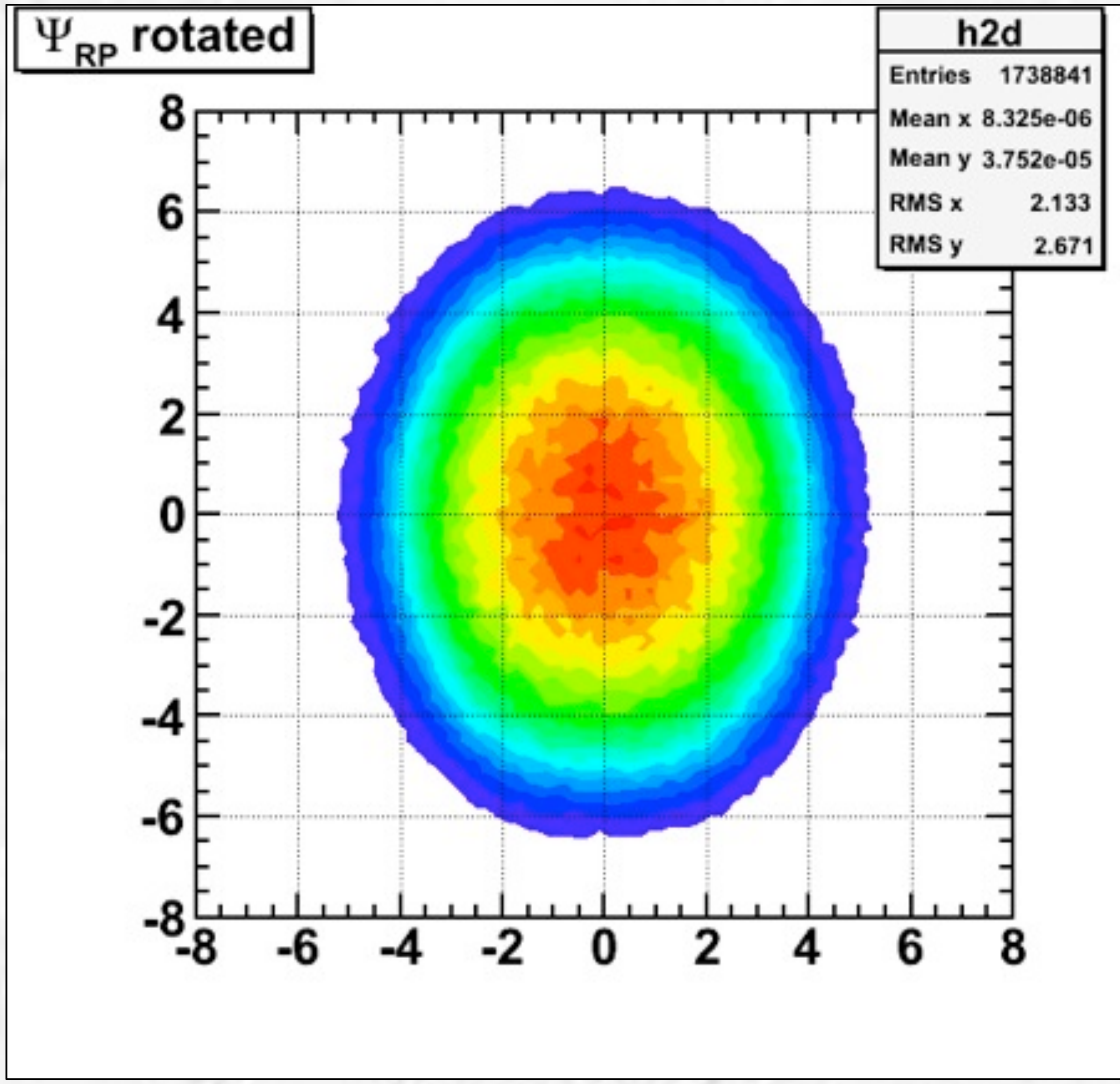
Density distributions

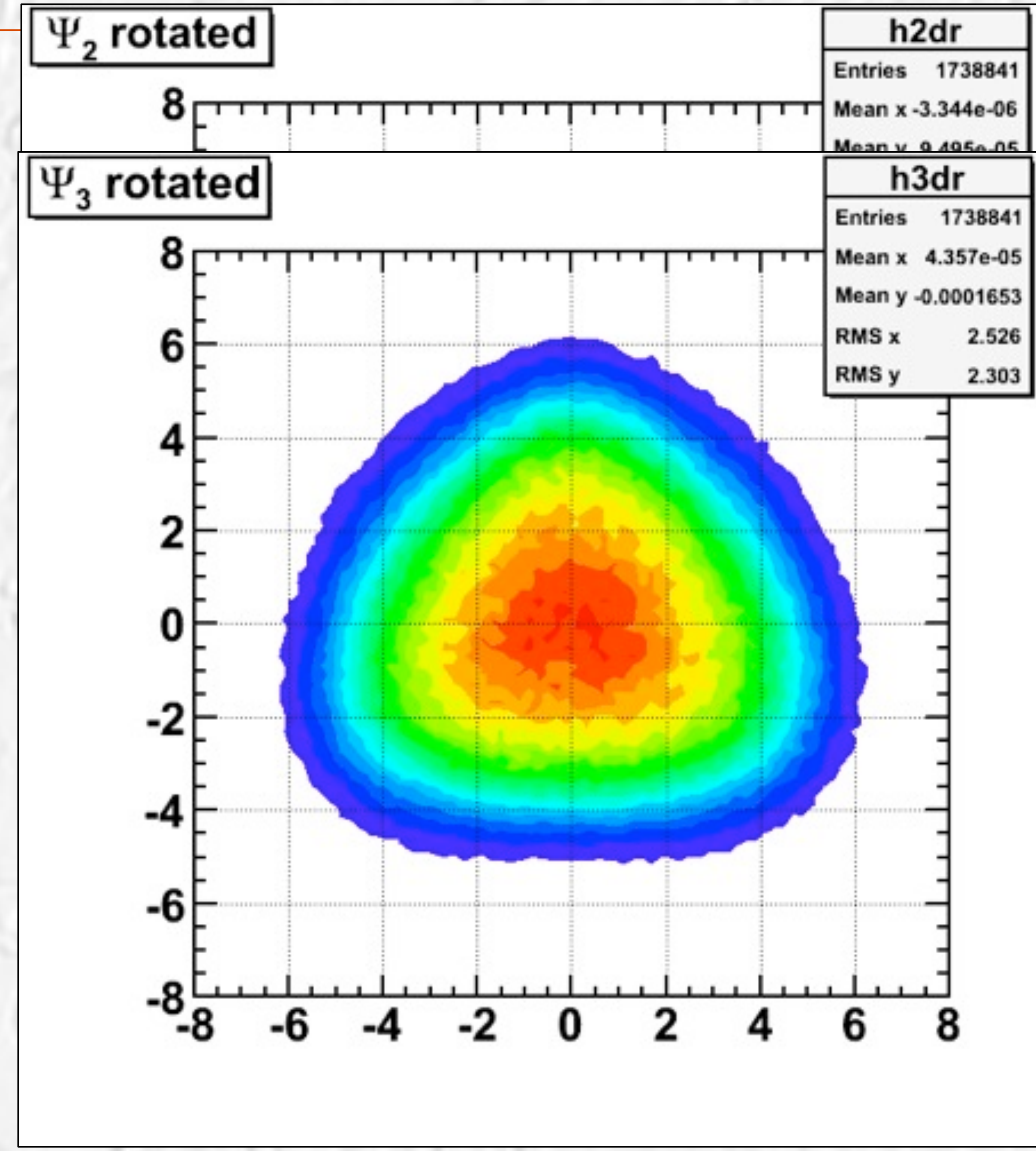




10k Pb+Pb events, b=8 fm

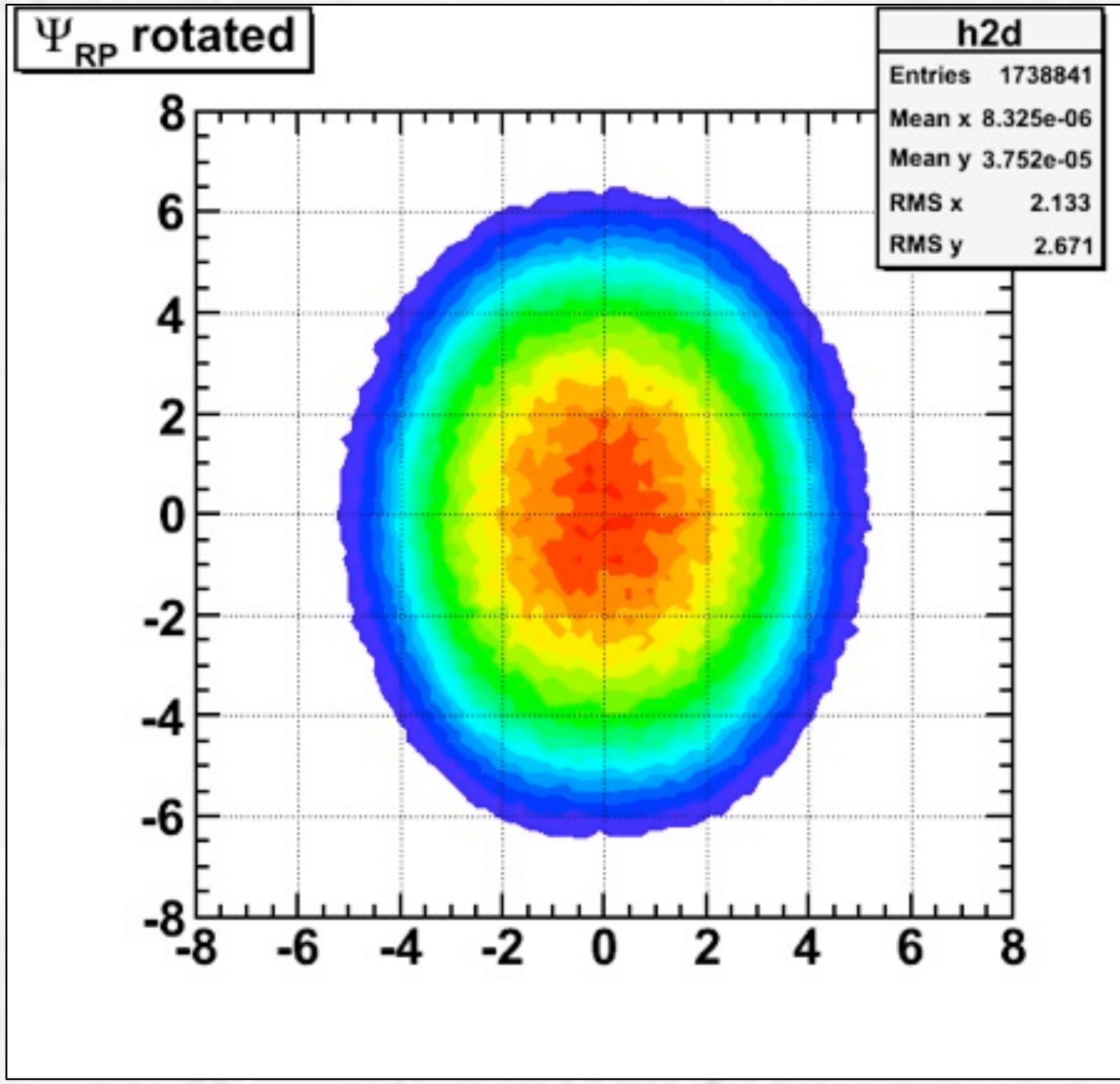
Density distributions

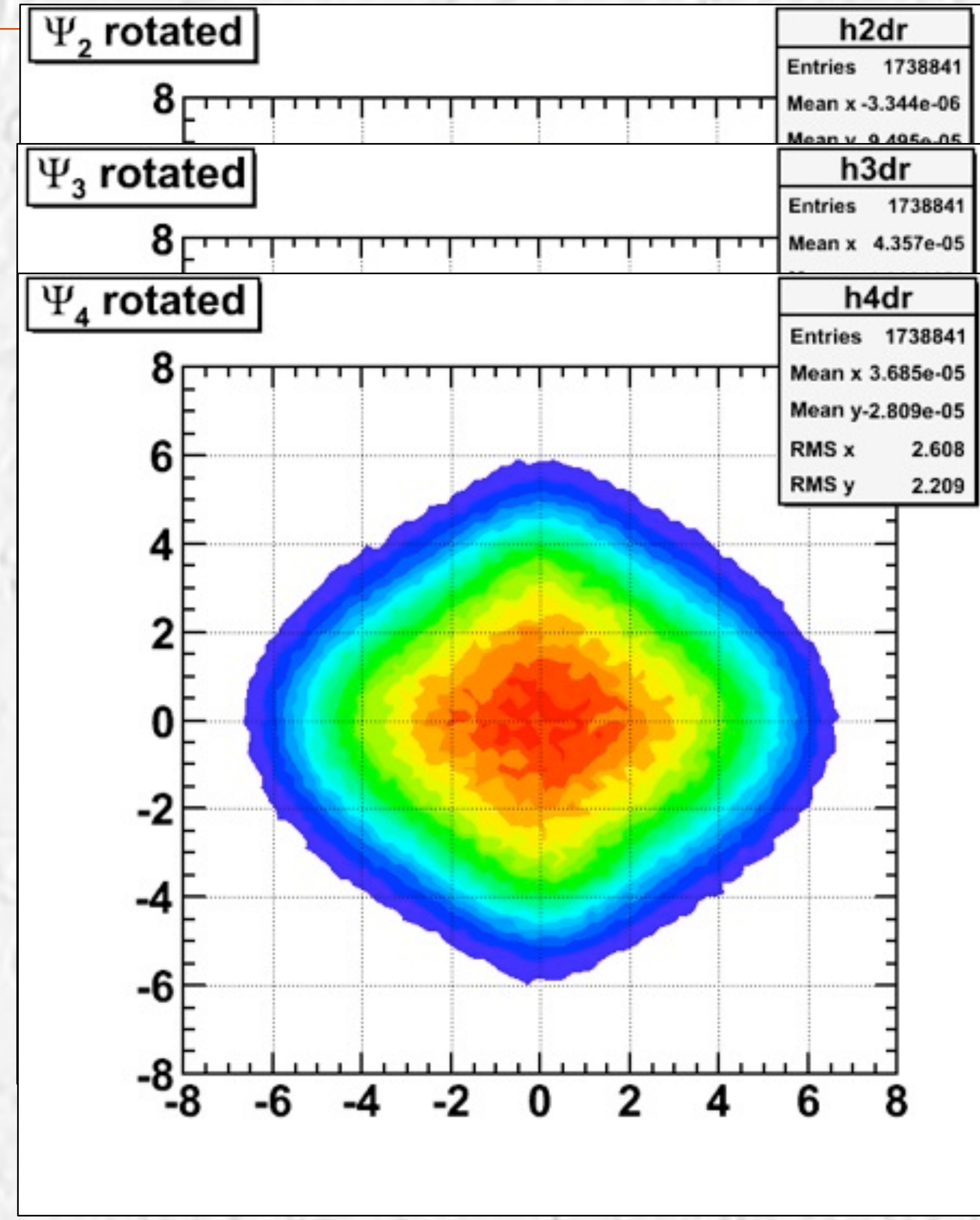




10k Pb+Pb events, b=8 fm

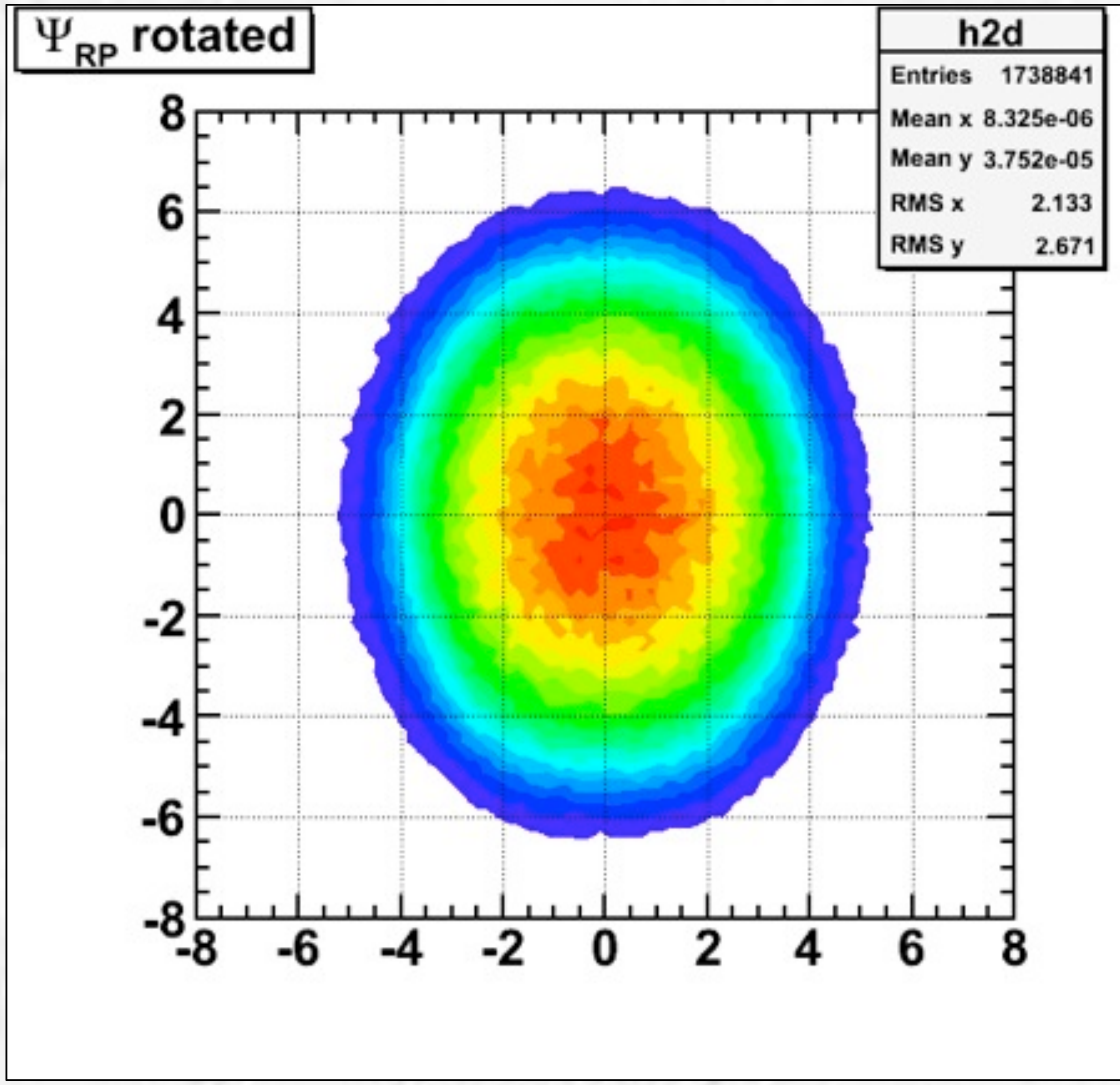
Density distributions

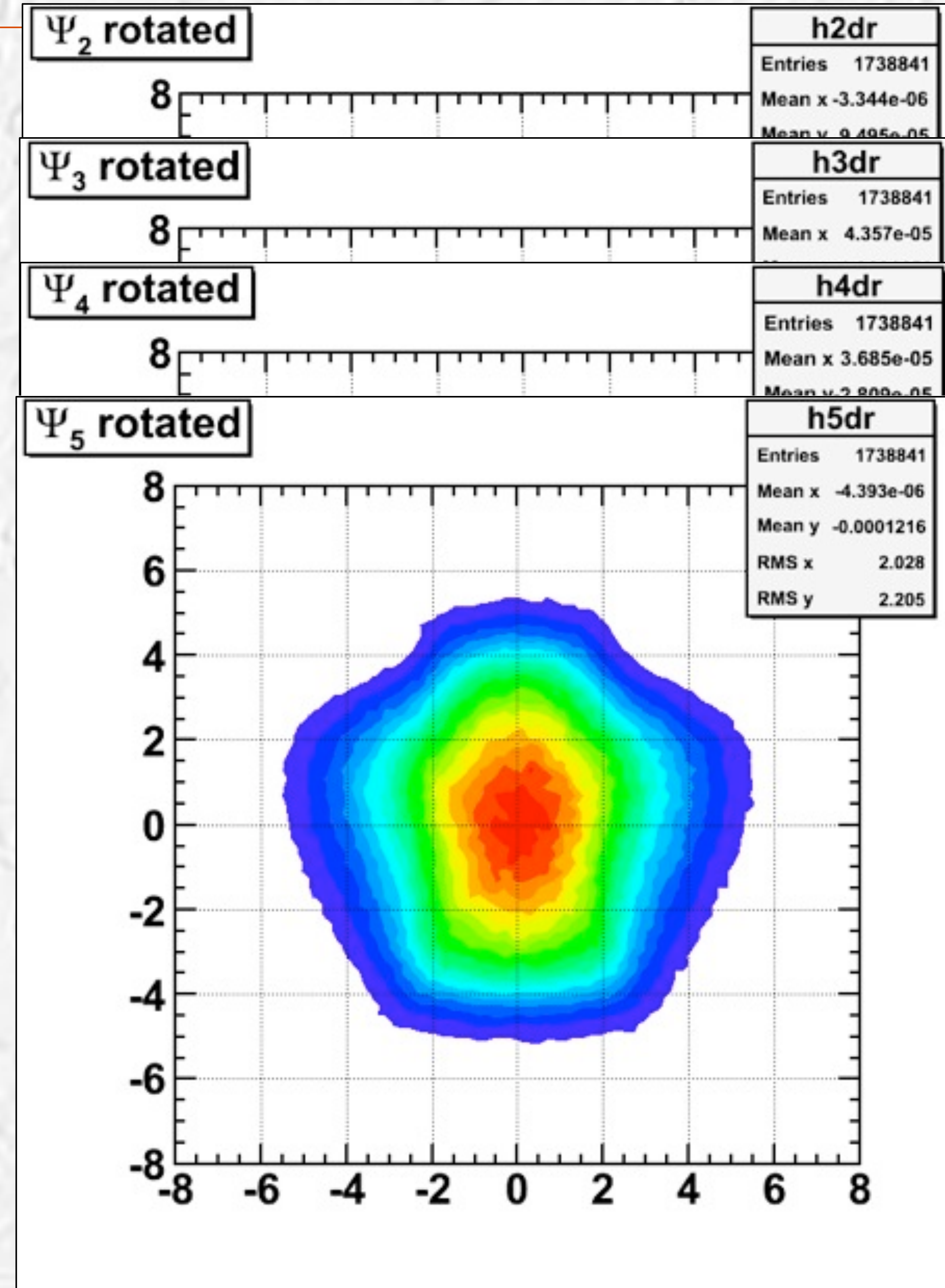




10k Pb+Pb events, b=8 fm

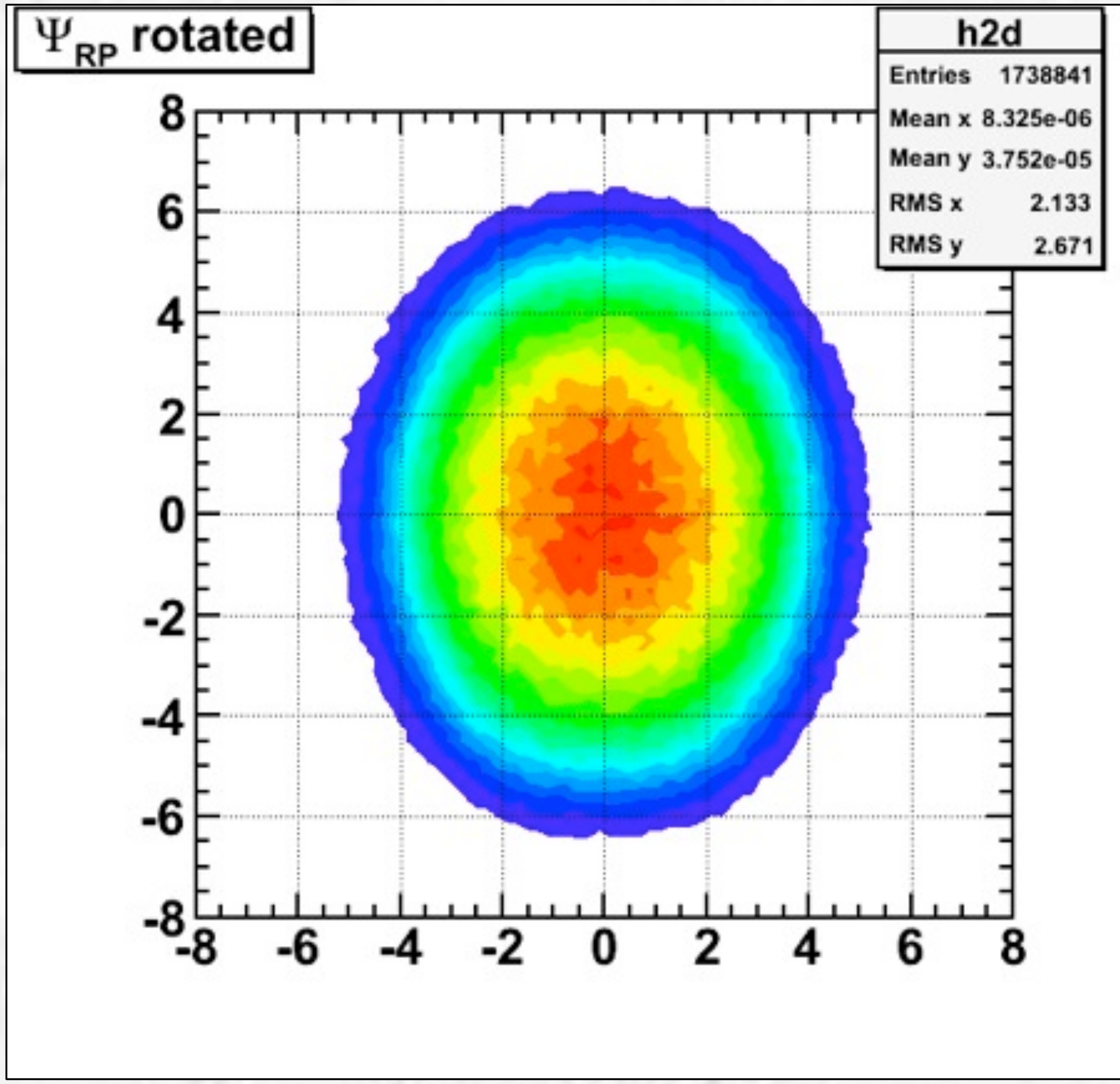
Density distributions

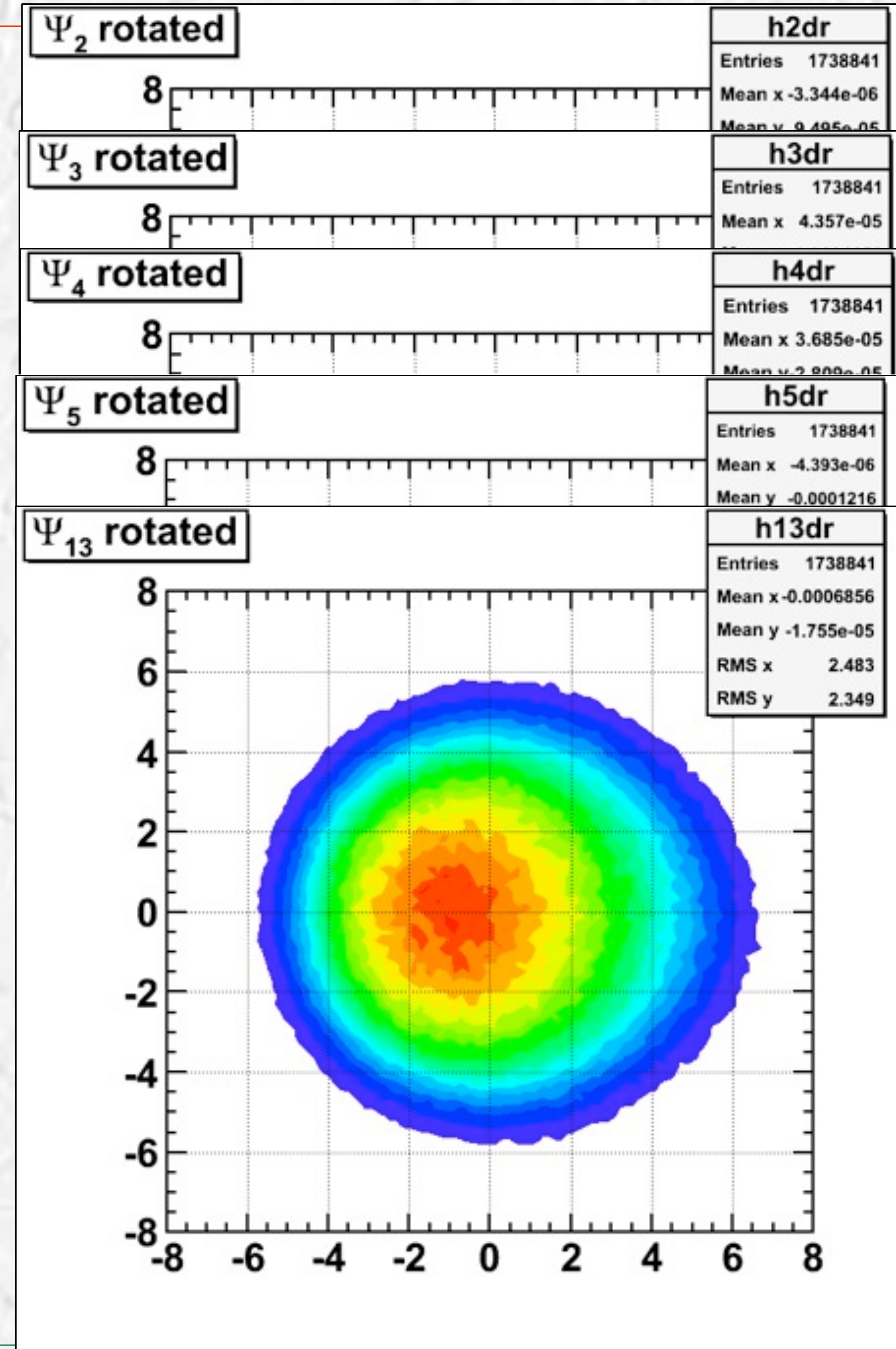




10k Pb+Pb events, b=8 fm

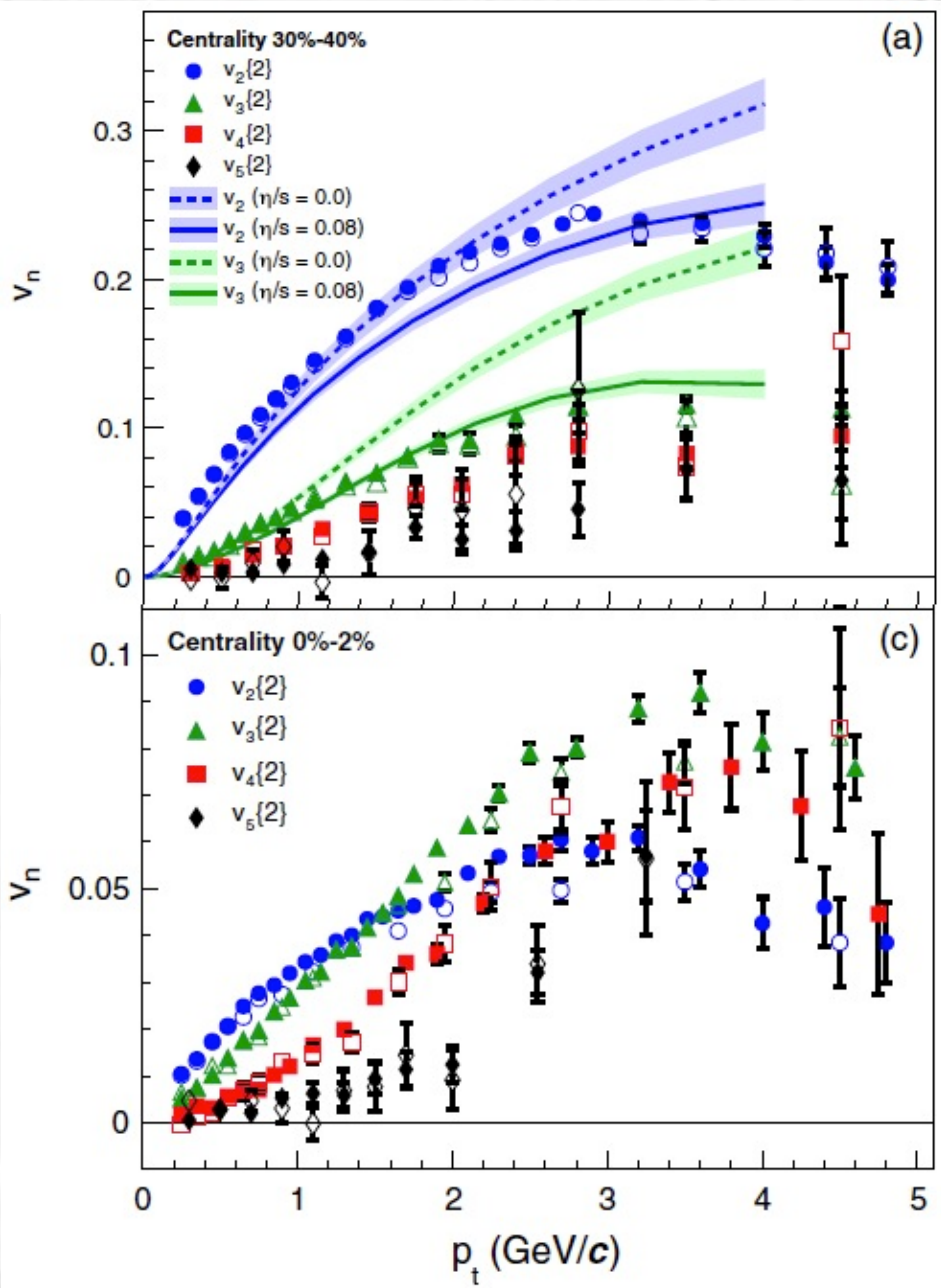
Density distributions





10k Pb+Pb events, b=8 fm

ALICE: flow fluctuations - “ridge” duality



PRL **107**, 032301 (2011)

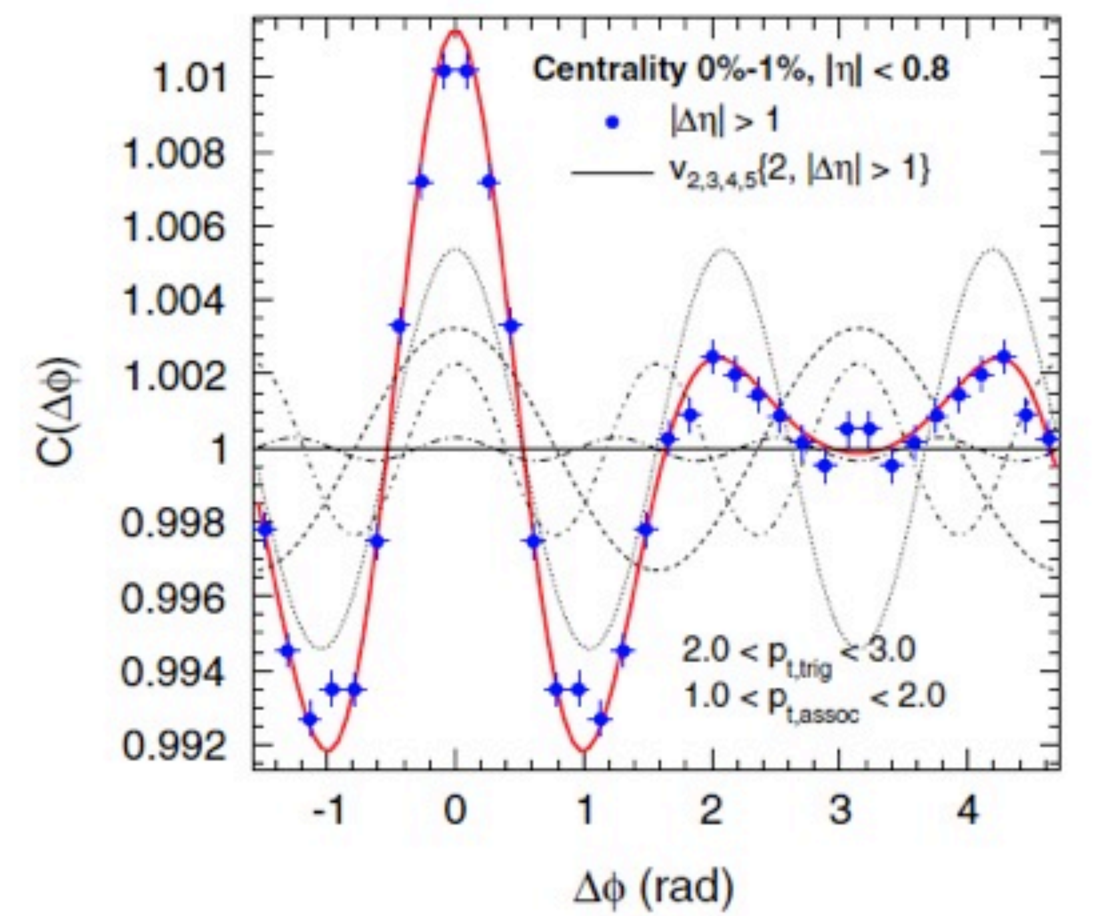


FIG. 4 (color online). The two-particle azimuthal correlation, measured in $0 < \Delta\phi < \pi$ and shown symmetrized over 2π, between a trigger particle with $2 < p_t < 3$ GeV/c and an associated particle with $1 < p_t < 2$ GeV/c for the 0%–1% centrality class. The solid red line shows the sum of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

$$C(\Delta\phi) \equiv \frac{N_{\mathrm{mixed}}}{N_{\mathrm{same}}} \frac{dN_{\mathrm{same}}/d\Delta\phi}{dN_{\mathrm{mixed}}/d\Delta\phi},$$

Similar results by ATLAS

arXiv:1107.1468v2 [nucl-ex] 13 Jul 2011

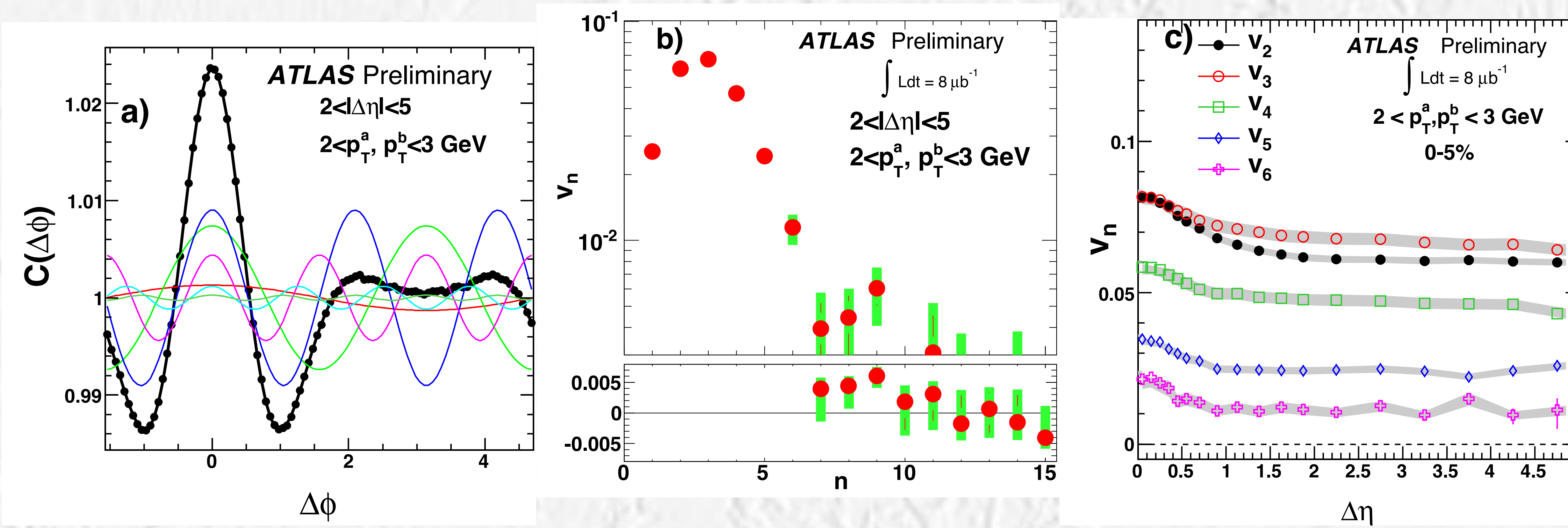
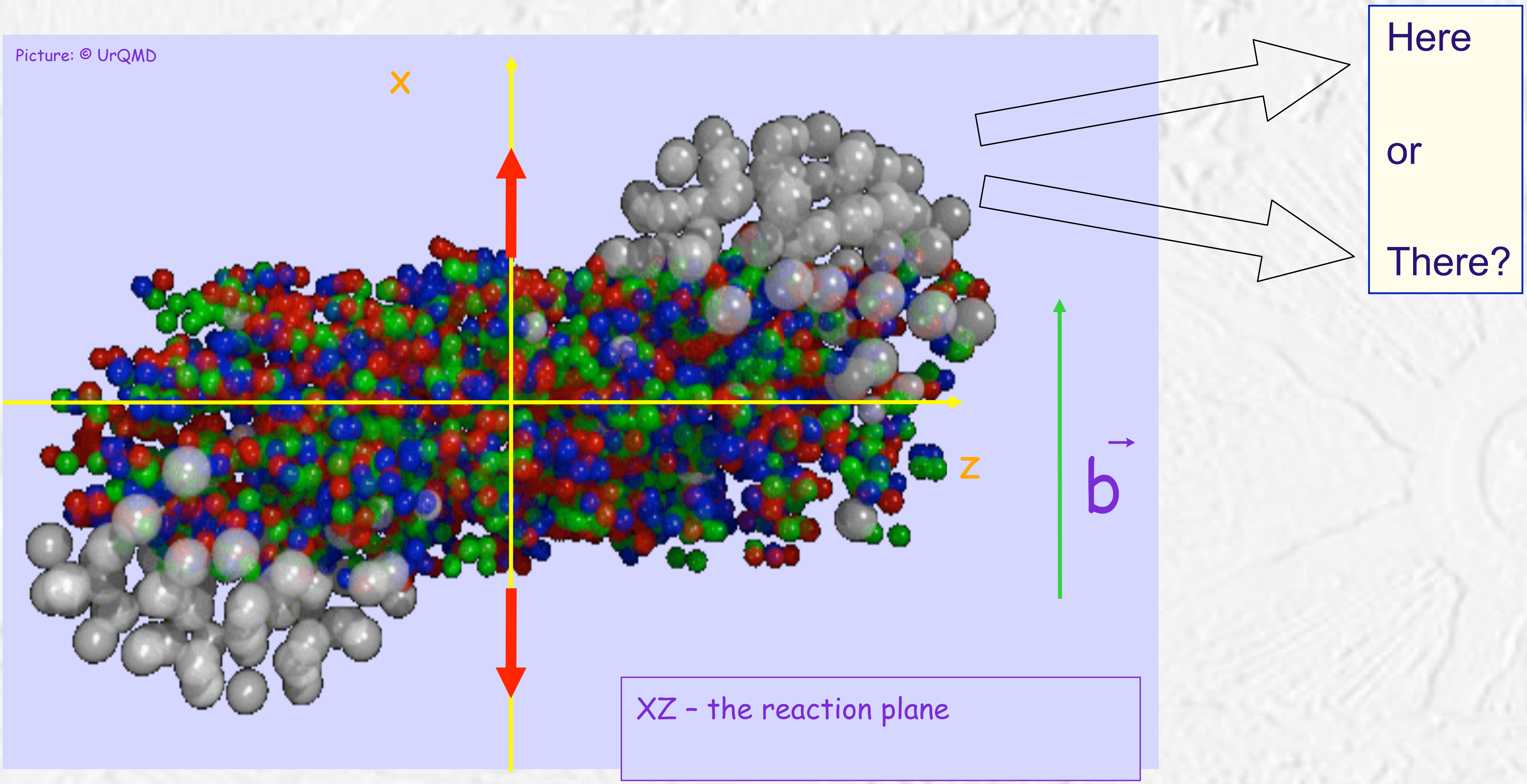


Figure 4. The steps involved in the extraction of the v_n (2-3 GeV fixed-$p_{\rm T}$ correlation in 0-5% centrality): a) $\Delta\phi$ correlation function for $2 < |\Delta\eta| < 5$, overlaid with contributions from individual Fourier components and the sum, b) Fourier coefficient v_n vs n, and c) $v_2 - v_6$ vs $\Delta\eta$.

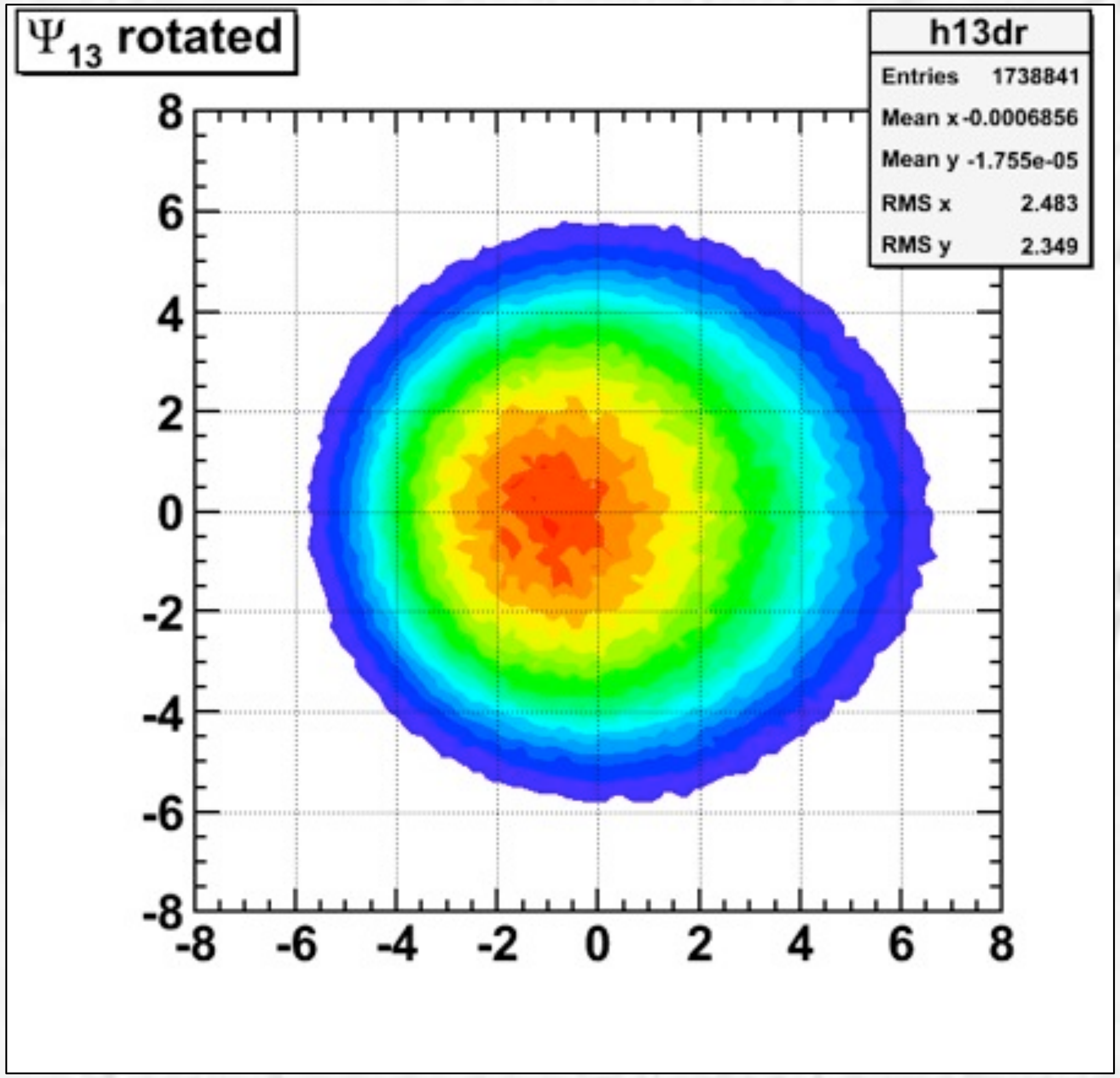
Where do spectators flow?

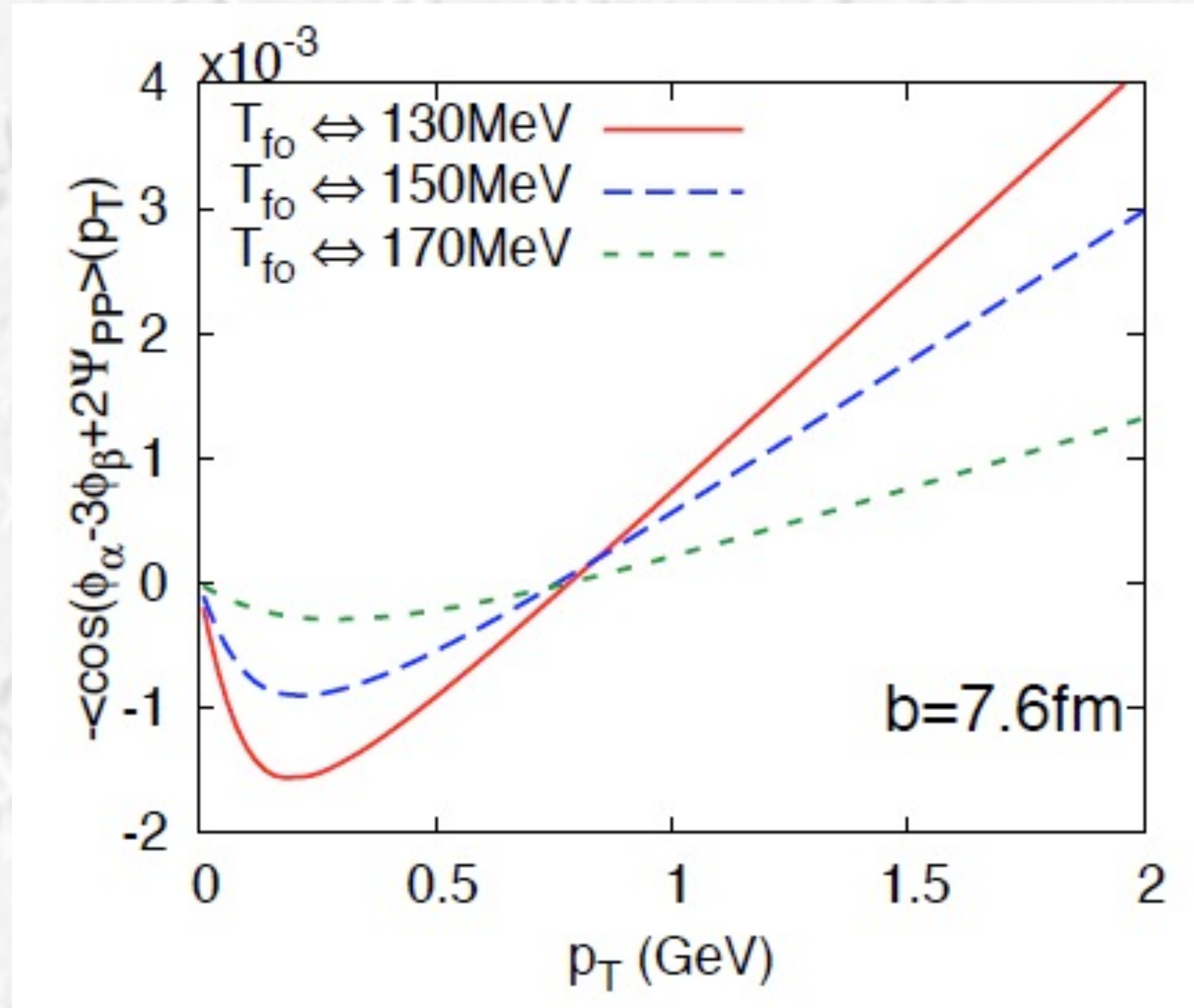


$v_1(p_t)$

Triangularity and Dipole Asymmetry in Heavy Ion Collisions

Derek Teaney and Li Yan





$$\varepsilon_n e^{in\Phi_n} \equiv -\frac{\int r\,dr\,d\phi\, r^n e^{in\phi}\, e(r,\phi)}{\int r\,dr\,d\phi\, r^n e(r,\phi)} \quad (n>1),$$

$$\varepsilon_1 e^{i\Phi_1} \equiv -\frac{\int r\,dr\,d\phi\, r^3 e^{i\phi}\, e(r,\phi)}{\int r\,dr\,d\phi\, r^3 e(r,\phi)}$$

Dipole flow, circa 2004

arXiv:nucl-th/0403044v1 15 Mar 2004

Rapidity dependent momentum anisotropy at RHIC

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† Department of Physics, The Ohio State University, Columbus, OH 43210, USA
‡ Physik Department, TU München, D-85747 Garching, Germany

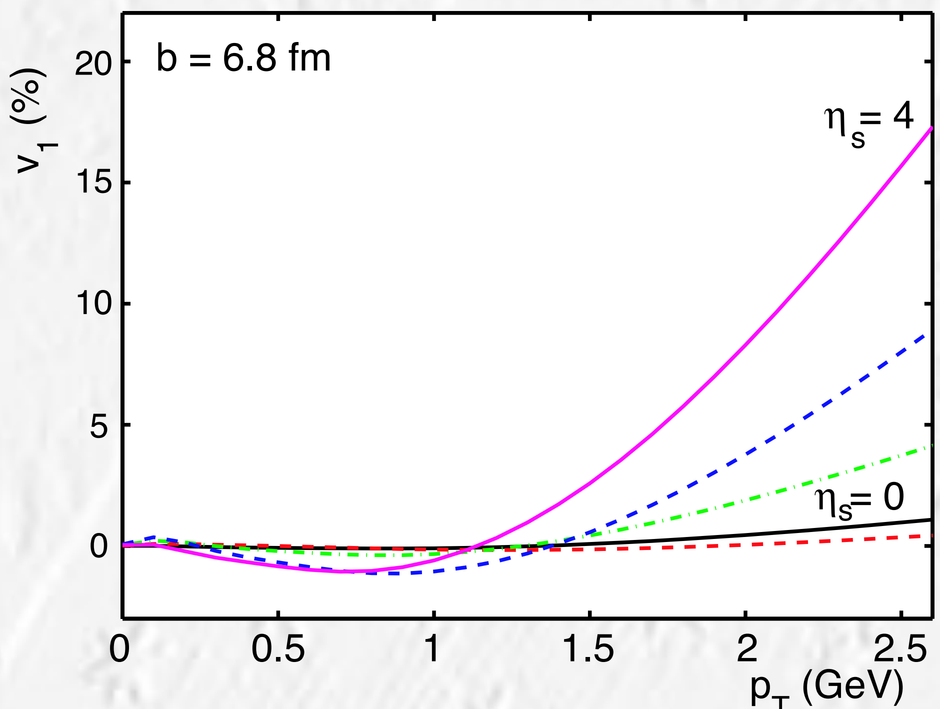
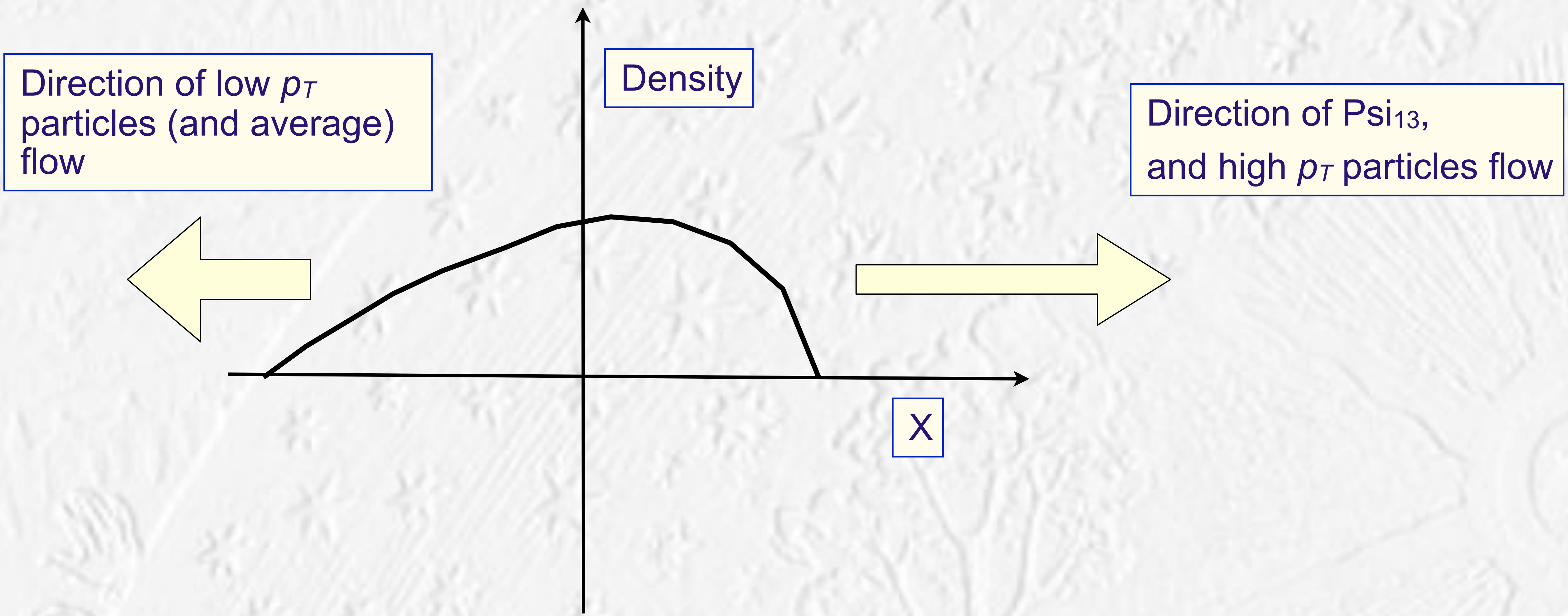


Figure 2. *Left:* Differential directed flow $v_1(p_\perp)$ of directly emitted pions (no resonance decays) for $\eta_s = y = 0, 1, 2, 3, 4$. Except for a region of positive v_1 at $0 < p_\perp < 0.5\,\mathrm{GeV}$ and a shift of the rest of the curves by about 0.5 GeV to larger $p_\perp$, the curves for direct protons look similar. *Right:* $p_\perp$-integrated elliptic flow

Similar observations has been made later by Teaney and Yan, Retinskaya et.al., in relation to effects of initial density fluctuations

At forward rapidities the transverse overlap region becomes asymmetric and is shifted sidewards in the x (or impact parameter) direction. This turns out to give rise to a non-zero directed flow signal $v_1(p_\perp)$ which increases with $|\eta_s|$ (left panel in Fig. 2). Of course, since the colliding matter receives no overall transverse kick, the $p_\perp$-integrated directed flow is zero.

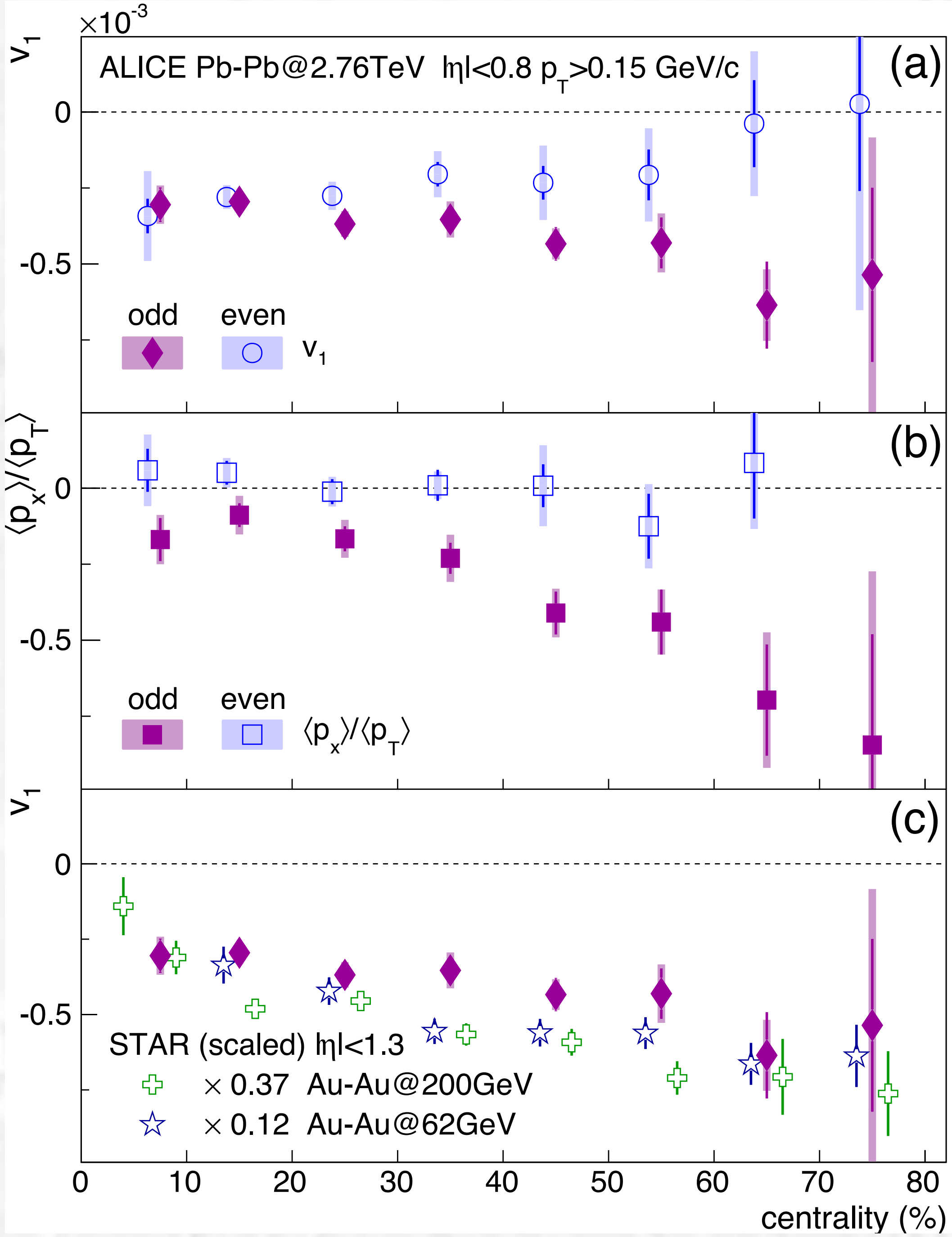
Dipole flow direction

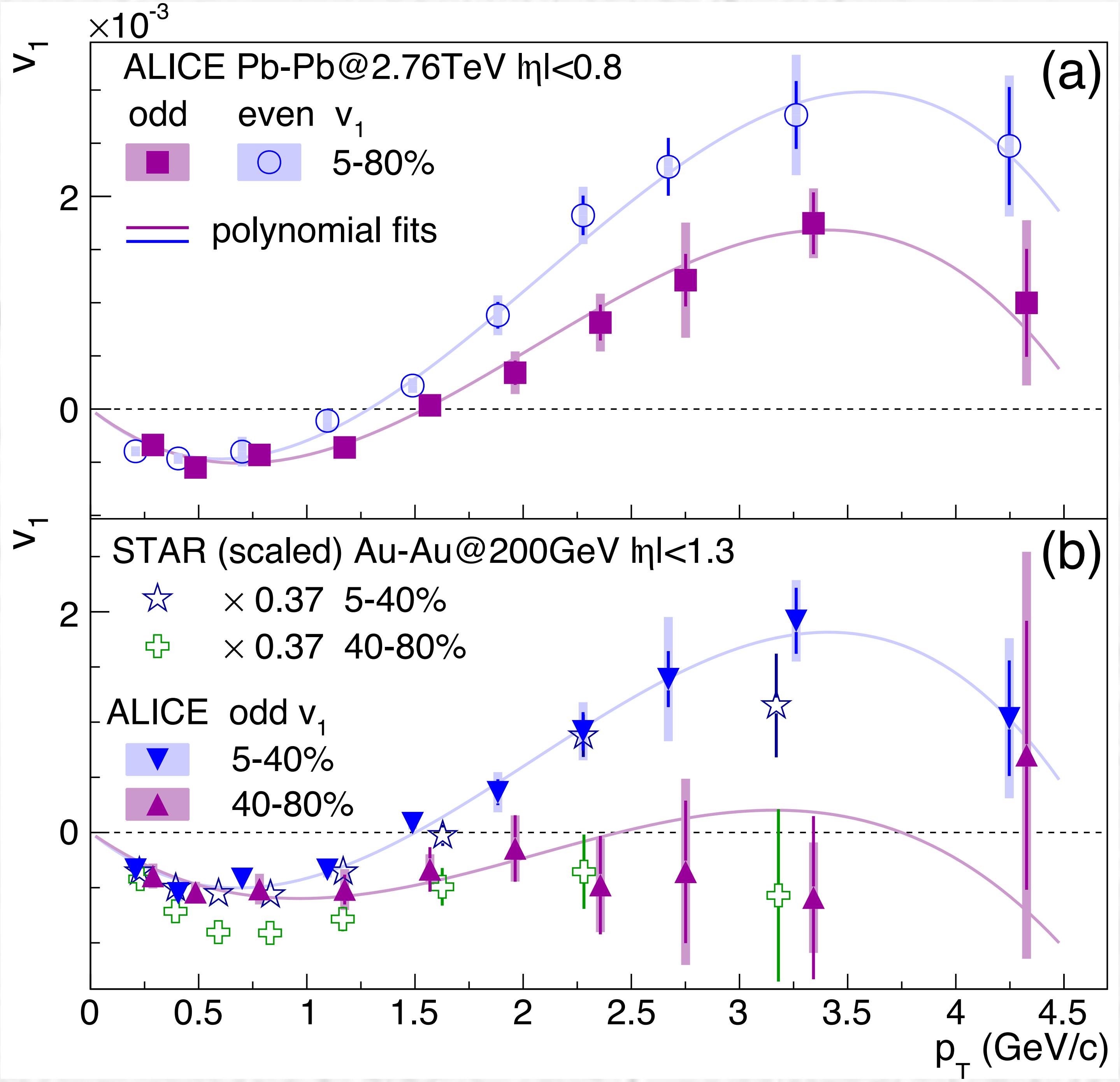


$$\langle x \rangle = 0, \quad \langle x^3 \rangle < 0$$

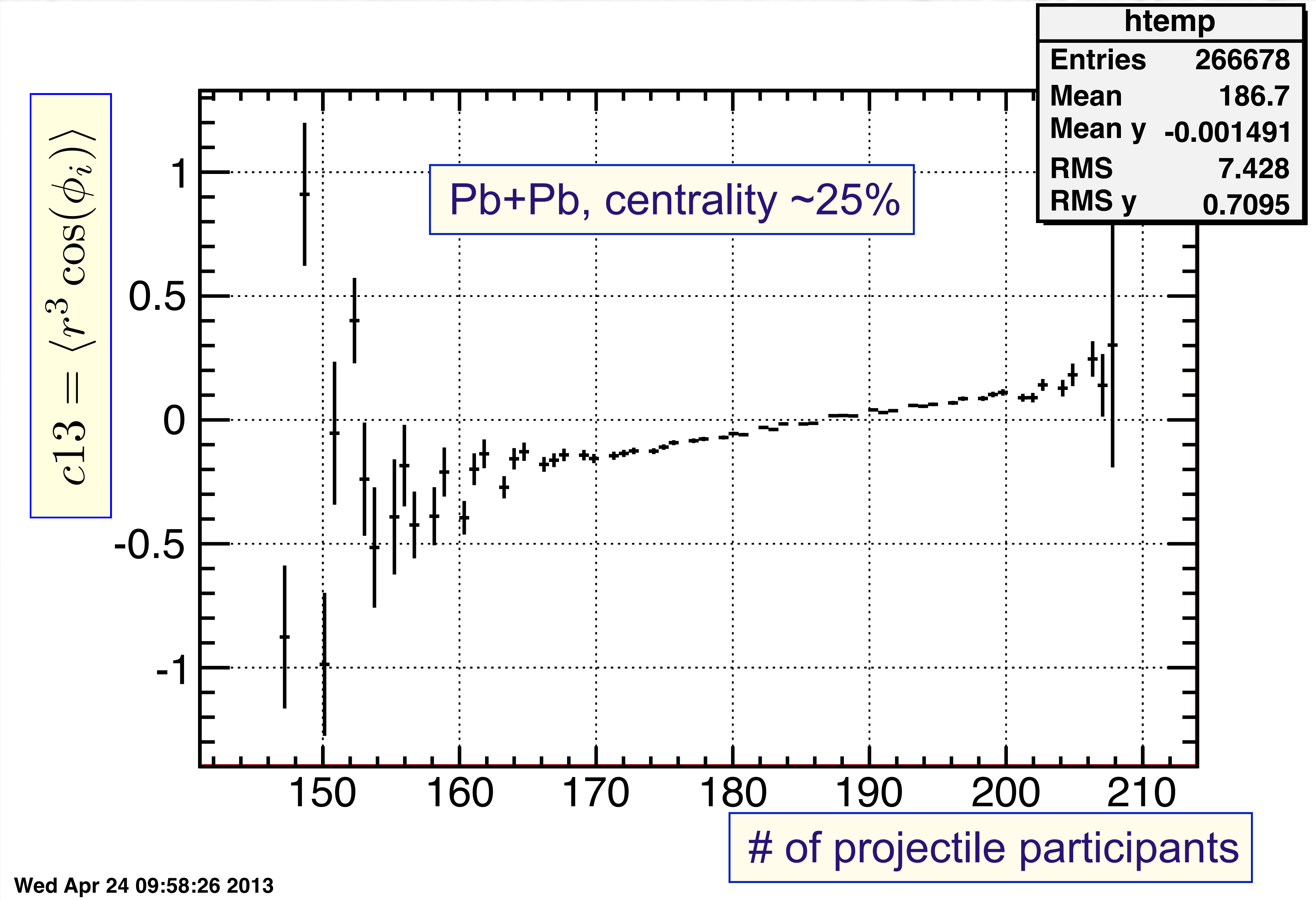
ALICE: Directed/"dipole" flow (wrt spectators flow)

arXiv:1306.4145v1 [nucl-ex] 18 Jun 2013





MC Glauber model



More projectile spectators ⟷ More projectile participants

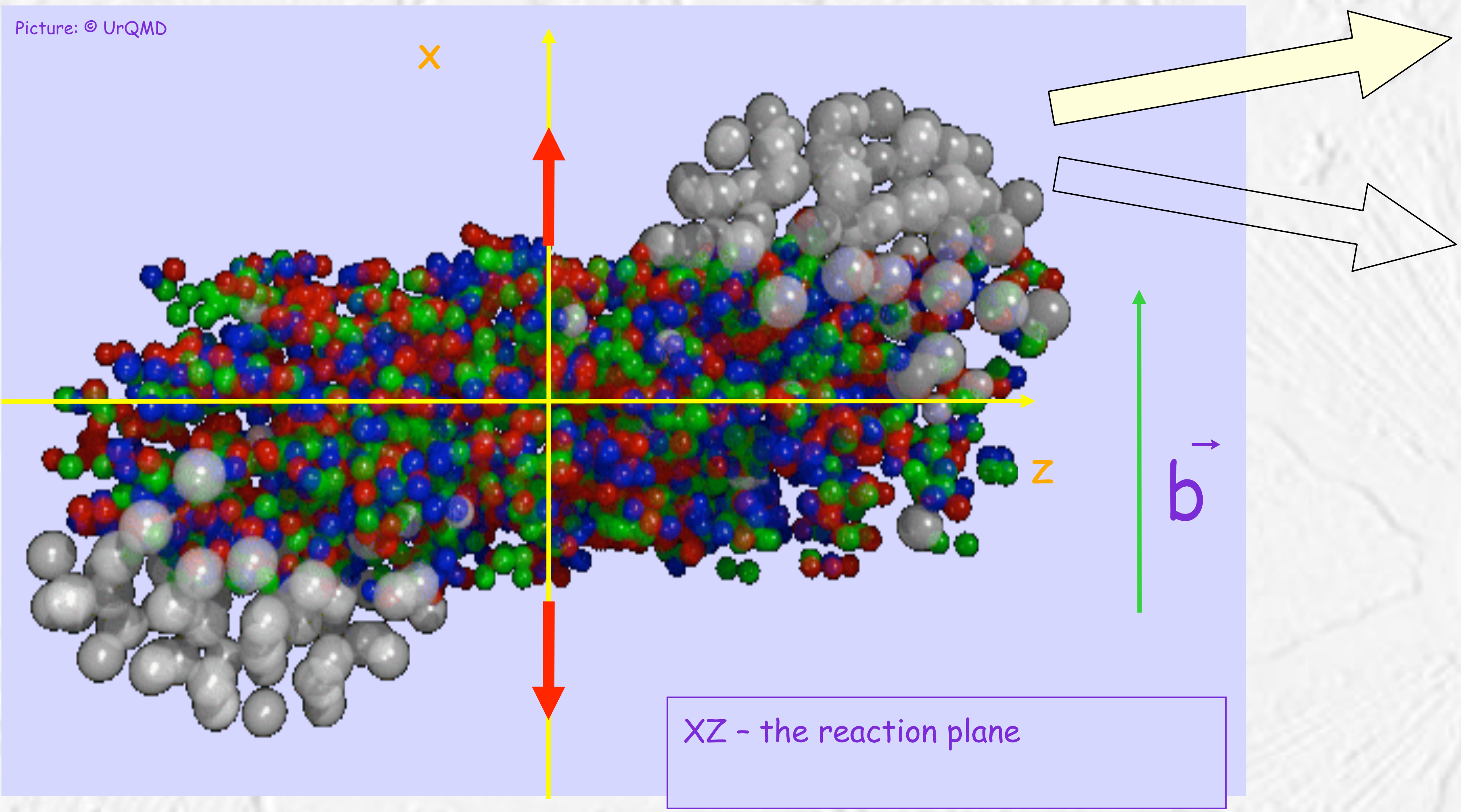
↓

c13 < 0

↓

v1<0

Where spectators flow



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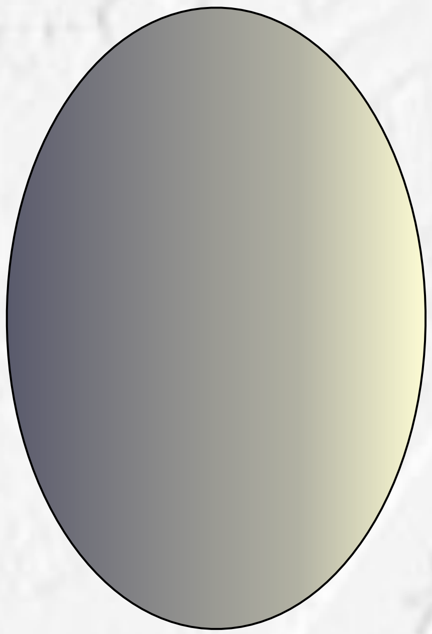
azFemto (azimuthally sensitive ...)

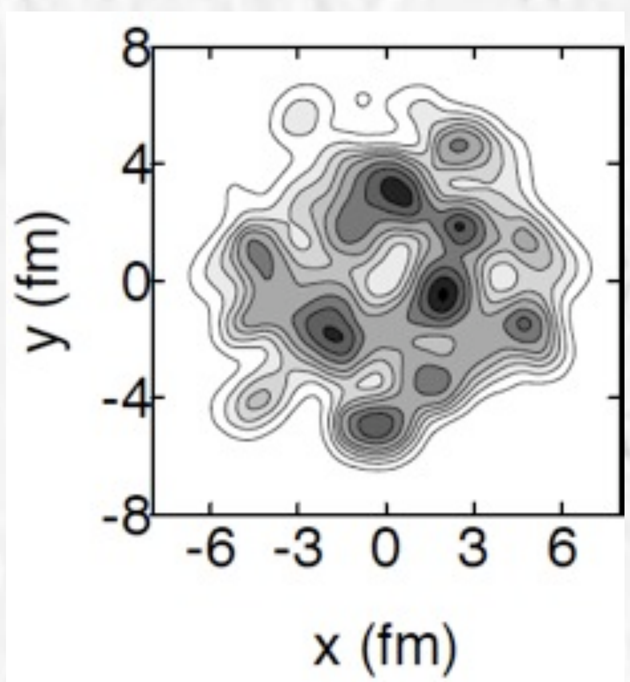
S. A. Voloshin and W. E. Cleland, Phys. Rev. C **53**, 896 (1996) [arXiv:nucl-th/9509025];Phys. Rev. C **54**, 3212 (1996) [arXiv:nucl-th/9606033].



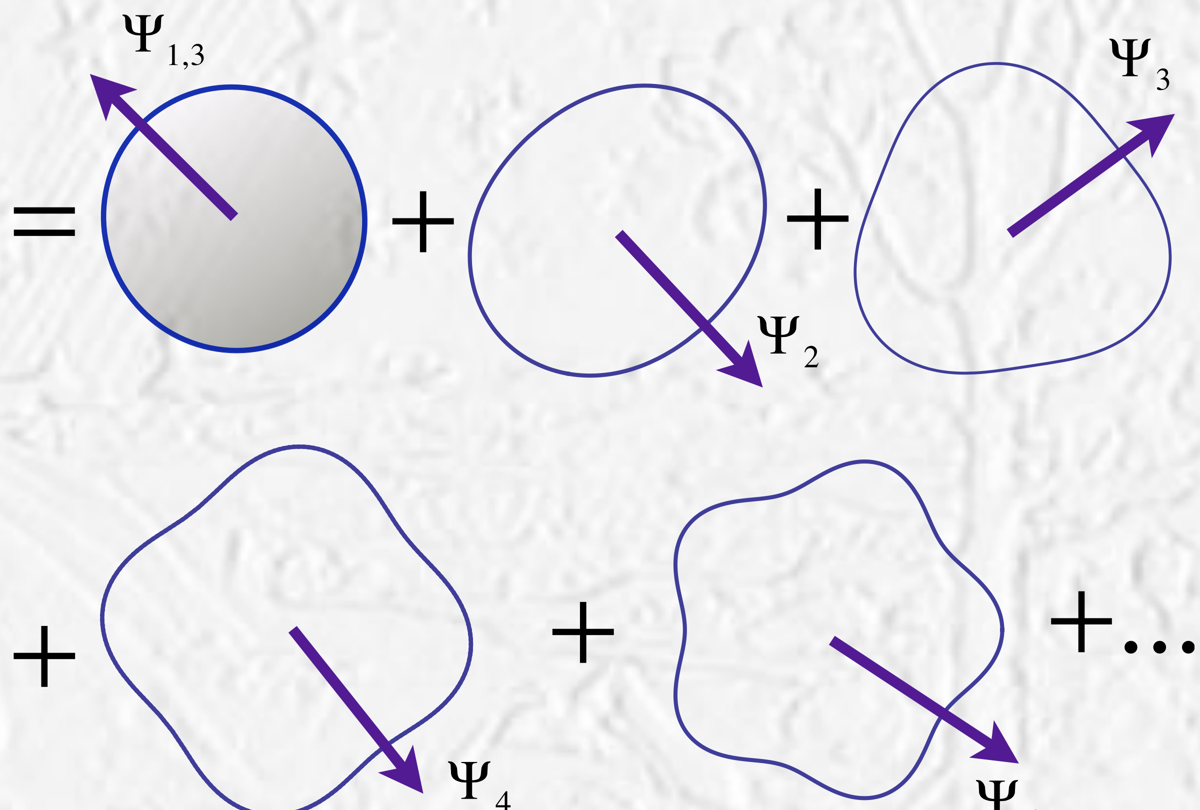
HBT radii:

$$R_{ij}^2 = \left\langle \left(\Delta x_i - V_i \Delta t\right)\left(\Delta x_j - V_j \Delta t\right) \right\rangle$$

	R_x^2	R_y^2	R_z^2	R_{xy}^2	R_{xz}^2	R_{yz}^2
$x+$	16.9	19.1	12.6	0.8	-1.5	-1.0
$x-$	25.3	16.6	11.8	-1.1	3.3	1.2
$y+$	17.6	24.0	12.9	-1.9	2.7	0.6
$y-$	15.8	24.8	14.7	2.8	1.2	-0.2



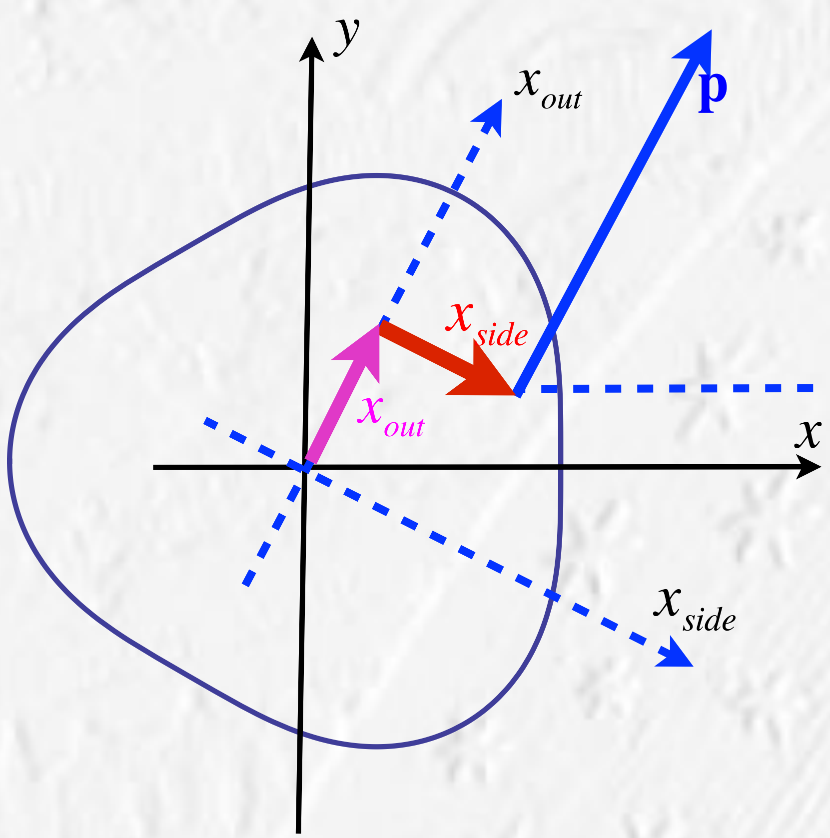
Yogiro Hama,[1] Rone Peterson G. Andrade,[1] Frédérique Grassi,[1] Wei-Liang Qian,[1] Takeshi Osada,[2] Carlos Eduardo Aguiar,[3] and Takeshi Kodama[3]



Can we resolve individual shapes?

azHBT. Stationary and expanding sources

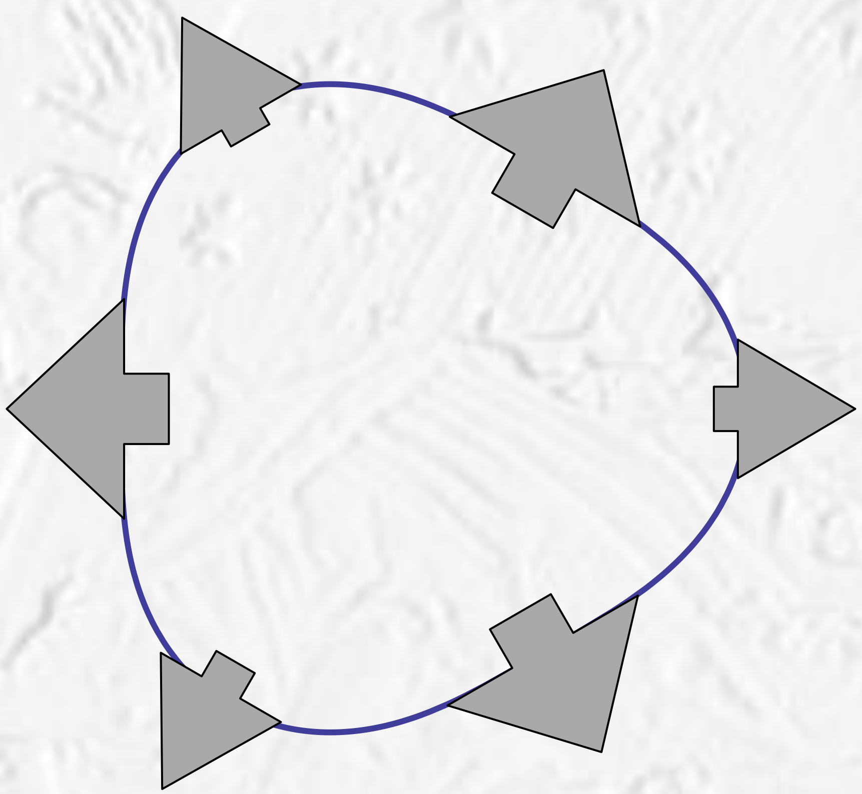
S. A. Voloshin, Quark Matter 2011, J. Phys. G **38**, 124097 (2011)



Stationary source: no higher order anisotropy in the leading order

$$\langle x_{side}^2 \rangle = \langle x^2 \rangle \sin^2\phi + \langle y^2 \rangle \cos^2\phi - \langle xy \rangle \sin 2\phi$$

Expansion leads to nontrivial *R(ϕ)* dependence:
- variation in the "blast wave" velocity
- variation in velocity gradients in the "side" direction

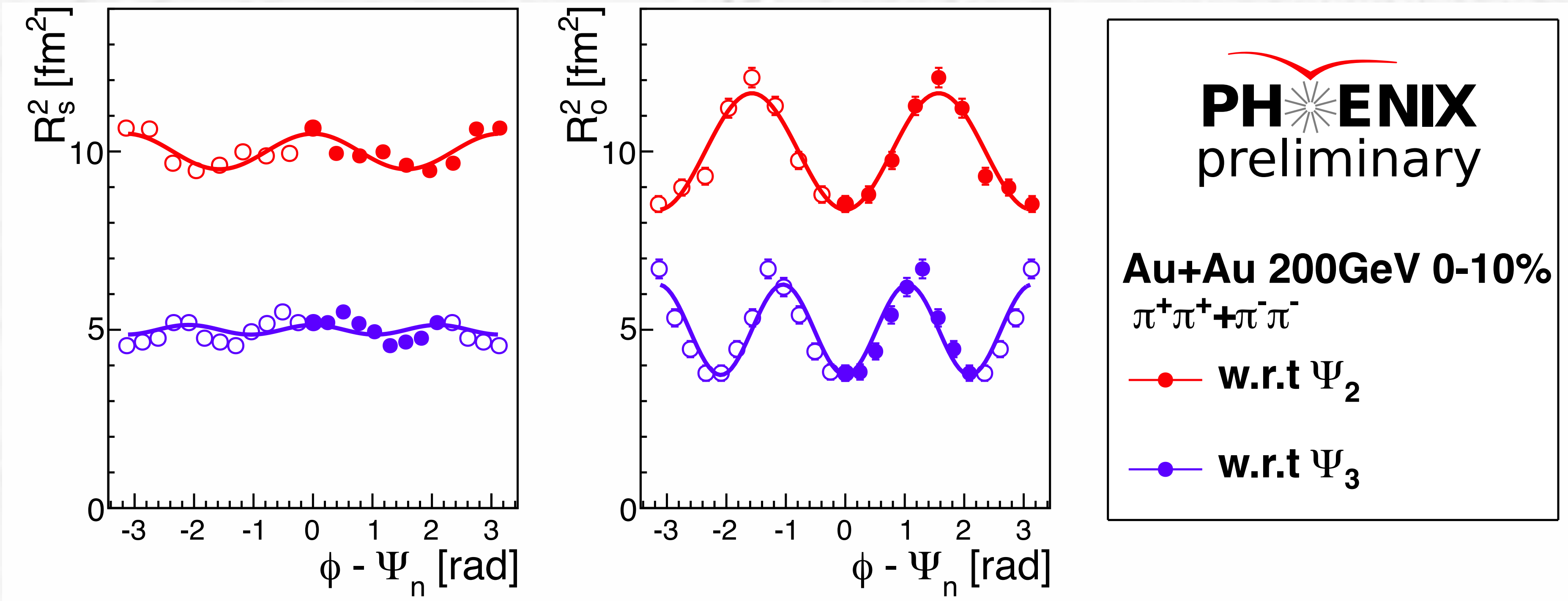


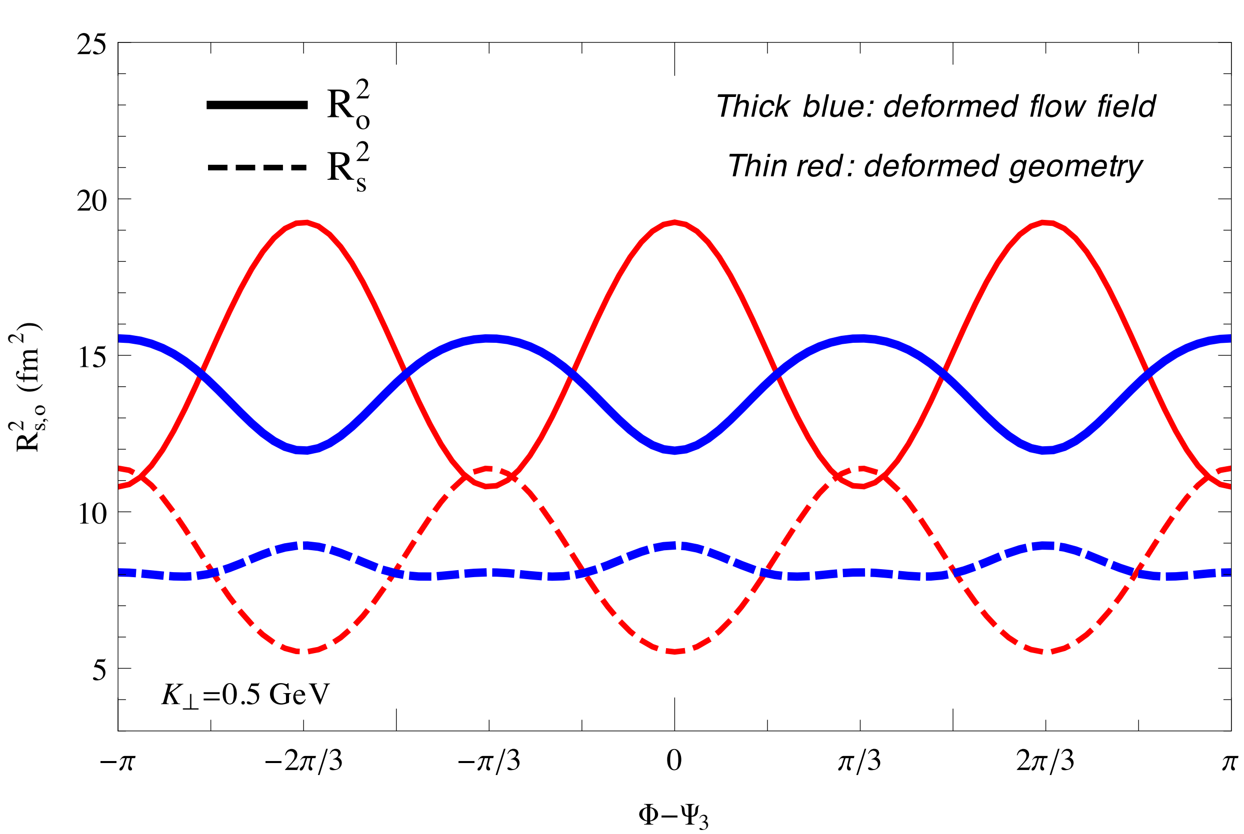
$$R_{out}^2 = \left\langle \left(\Delta x_{out} - V_t \Delta t \right)^2 \right\rangle$$

$$R_{long} \propto \frac{v_{therm}}{dv_z / dz}$$

PHENIX results and hydro calculations

arXiv:1304.2876v1 [nucl-ex] 10 Apr 2013





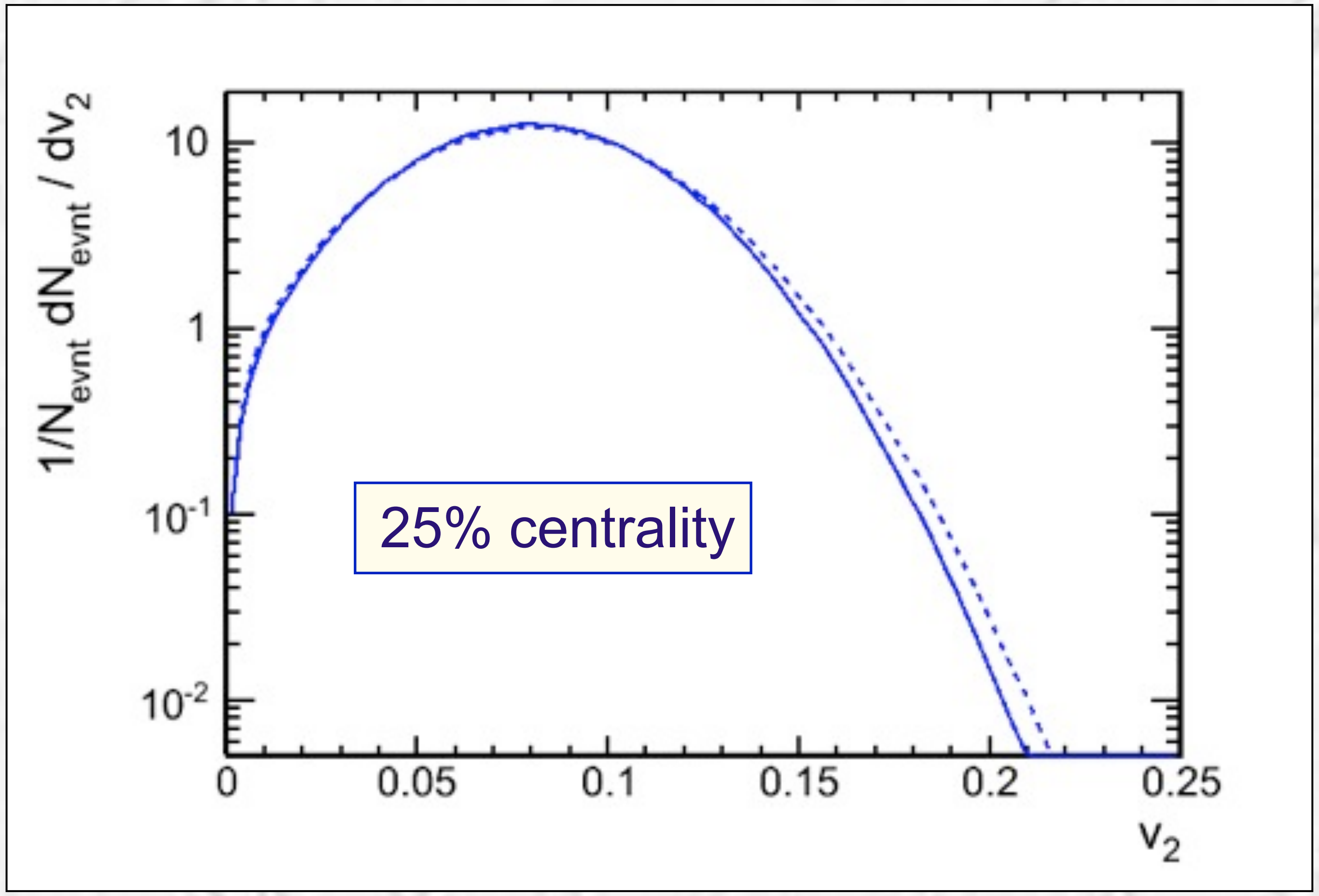
Christopher J. Plumberg, Chun Shen, and Ulrich Heinz

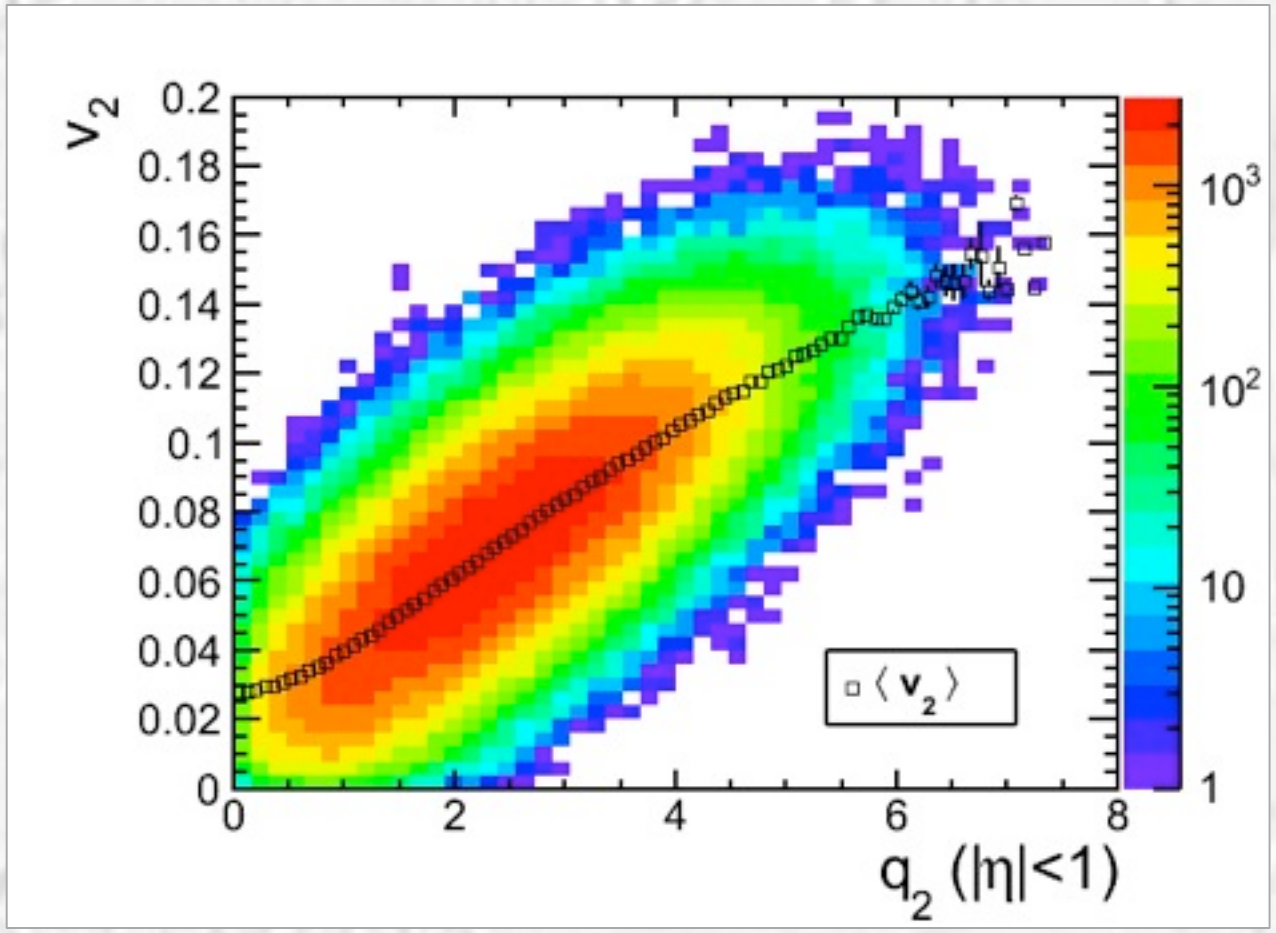
arXiv:1306.1485v1 [nucl-th] 6 Jun 2013

FIG. 3: (Color online) Triangular oscillations of R_s^2 (dashed) and R_o^2 (solid) for pion pairs with momentum $K_\perp = 0.5$ GeV, as a function of emission angle Φ relative to the triangular flow direction Ψ_3. Shown are results for two model scenarios: A deformed flow field ($\bar{v}_3 = 0.25$) in a spatially isotropic ($\bar{\epsilon}_3 = 0$) density distribution (thick blue lines), and a source with triangular geometric deformation ($\bar{\epsilon}_3 = 0.25$) expanding with radially symmetric ($\bar{v}_3 = 0$) flow (thin red lines). For the two scenarios the oscillations of both R_s^2 and $R_o^2$are seen to be out of phase by $\pi/3$.

Event shape engineering

J. Schukraft, A. Timmins and *S. A. Voloshin*, Phys. Lett. B **719**, 394 (2013)





Based on the use of flow vector as discussed in *S. A. Voloshin*, Phys. Rev. Lett. **105**, 172301 (2010)

$$Q_{n,X} = \sum_{i=1}^{M} \cos(n\phi_i)$$

$$Q_{n,Y} = \sum_{i=1}^{M} \sin(n\phi_i)$$

$$q_n = Q_n/\sqrt{M}$$

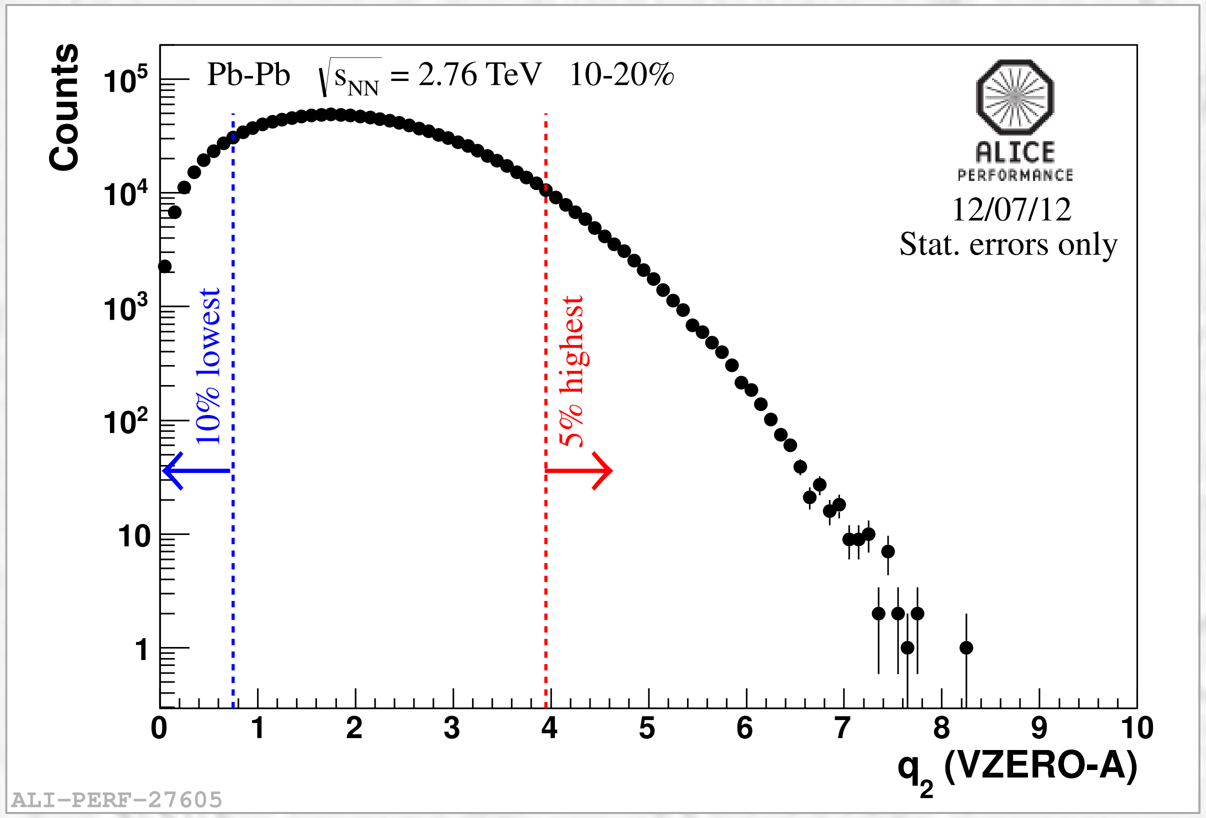
Event shape engineering (ESE) - selection of events corresponding to either large or small flow

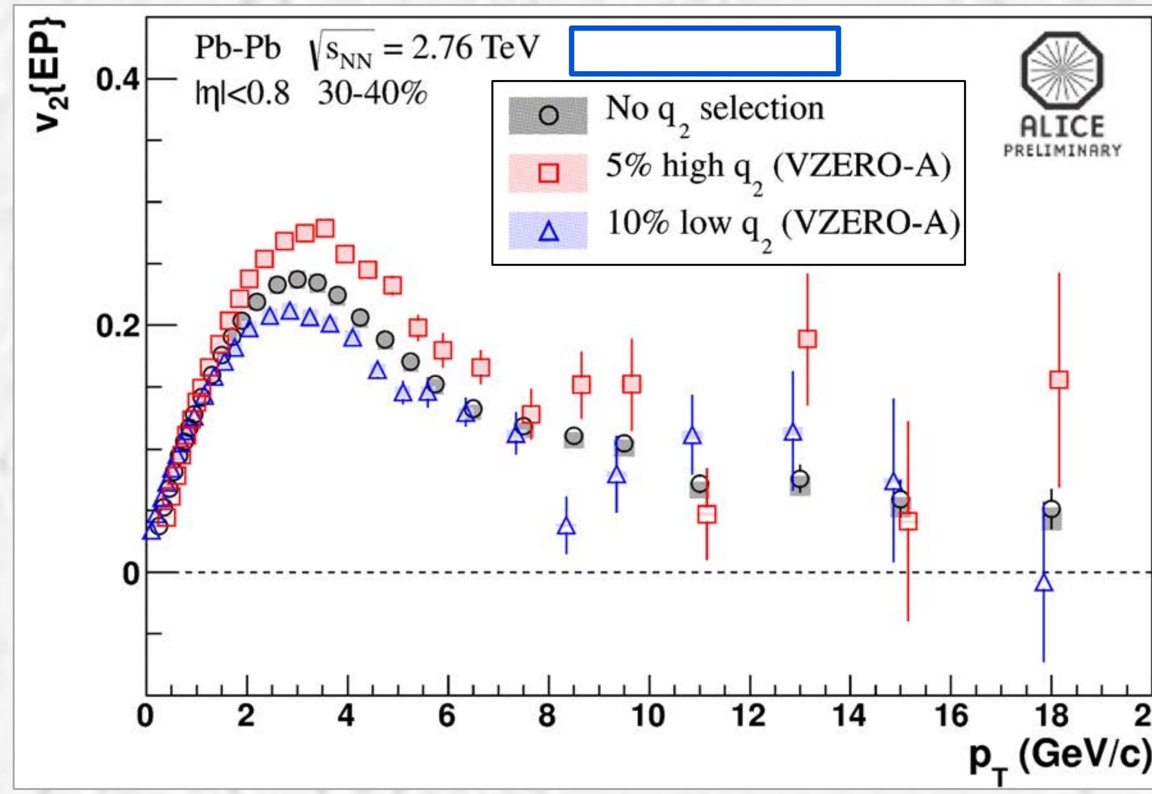
Flow in SE events: p_T dependence

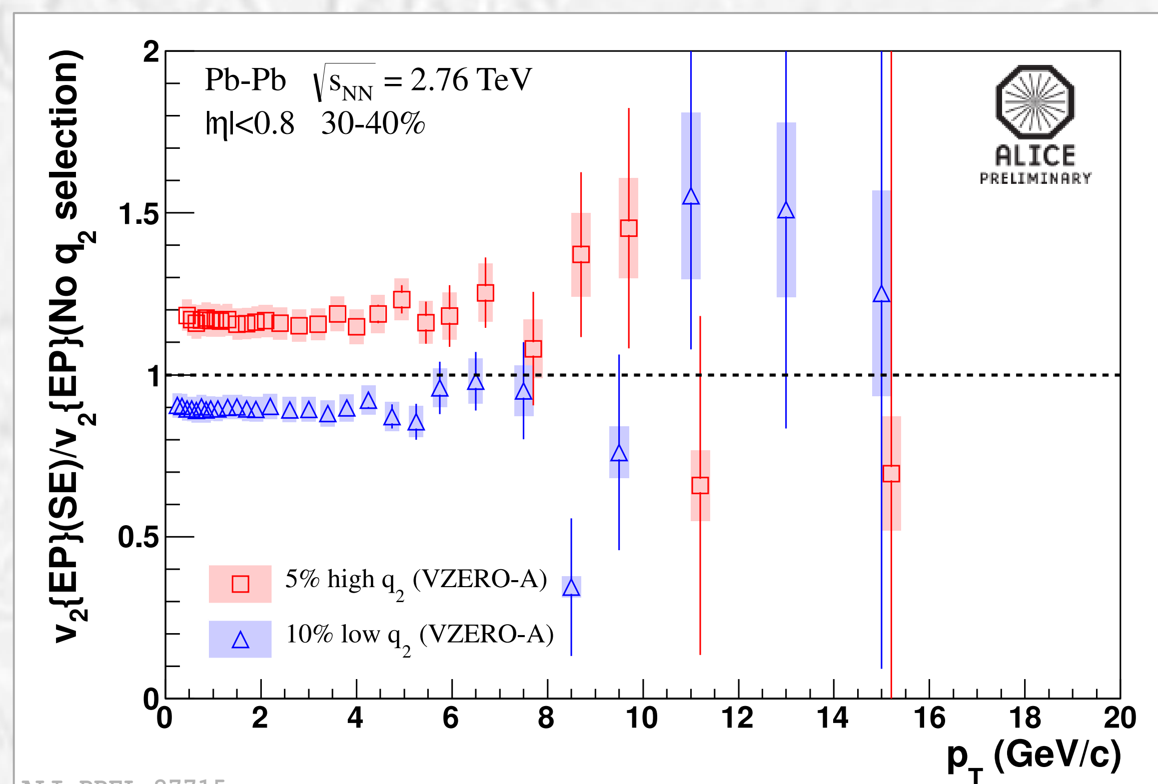
A. Dobrin [ALICE], Quark Matter 2012, Washington DC, August 2012.

event selection q_2 vector: $2.8 < \eta < 5.1$

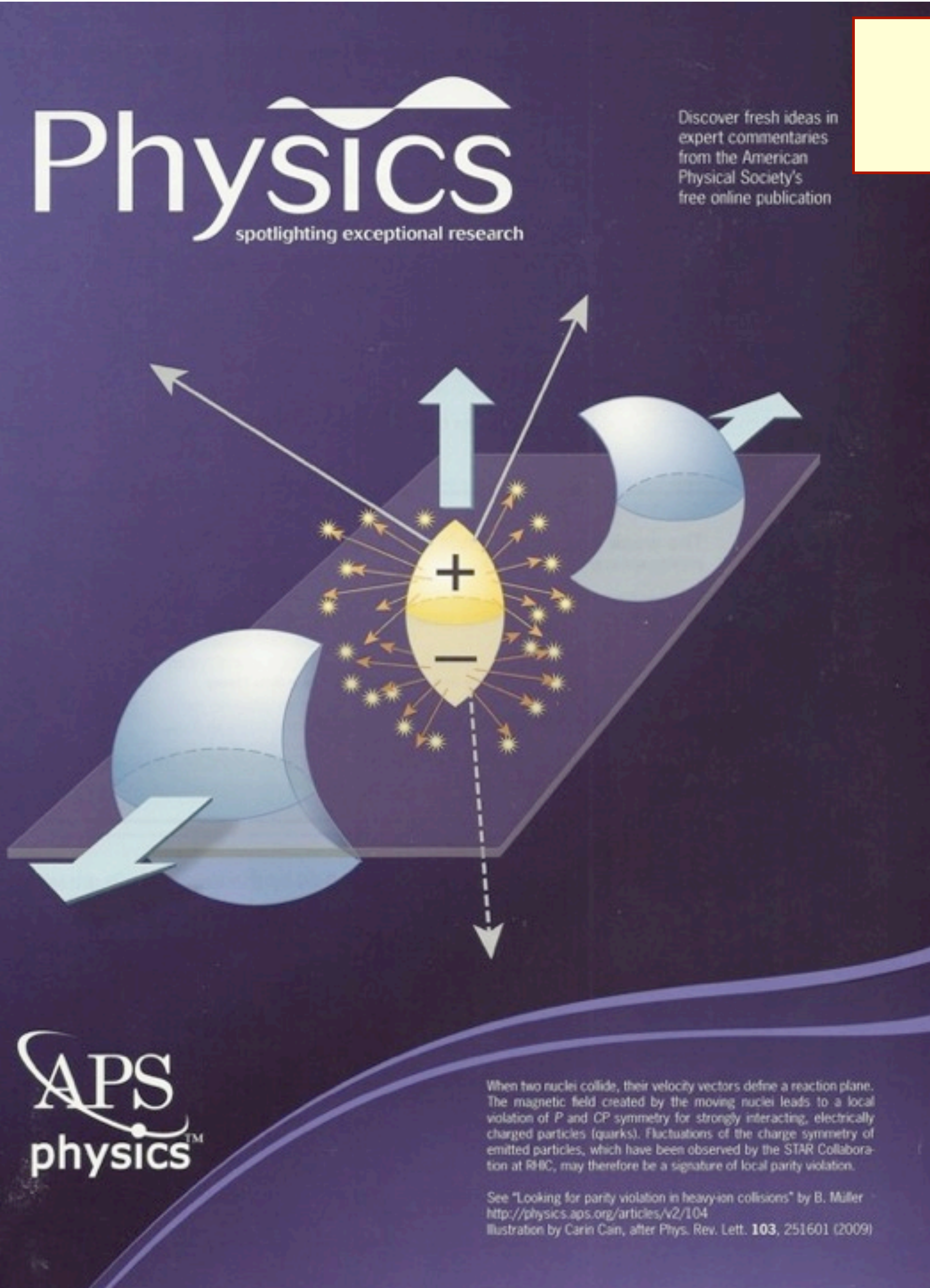
analysis: $|\eta| < 0.8$







Initial shape fluctuation effect is very similar up to $p_T \sim 6$ GeV/c



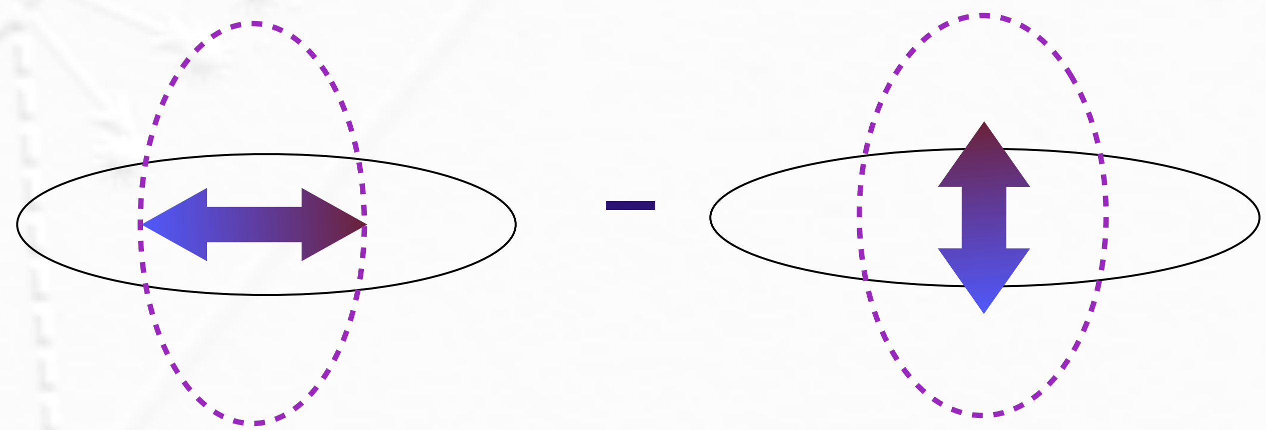
Search for the local parity violation (CME) in HIC

Effective particle distribution

$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2v_1\cos(\Delta\phi) + 2v_2\cos(2\Delta\phi) + \ldots + 2a_{1,\pm}\sin(\Delta\phi) + \ldots, \quad \Delta\phi = \phi - \Psi_{RP}$$

S.A. Voloshin, Phys. Rev. C 70 (2004) 057901

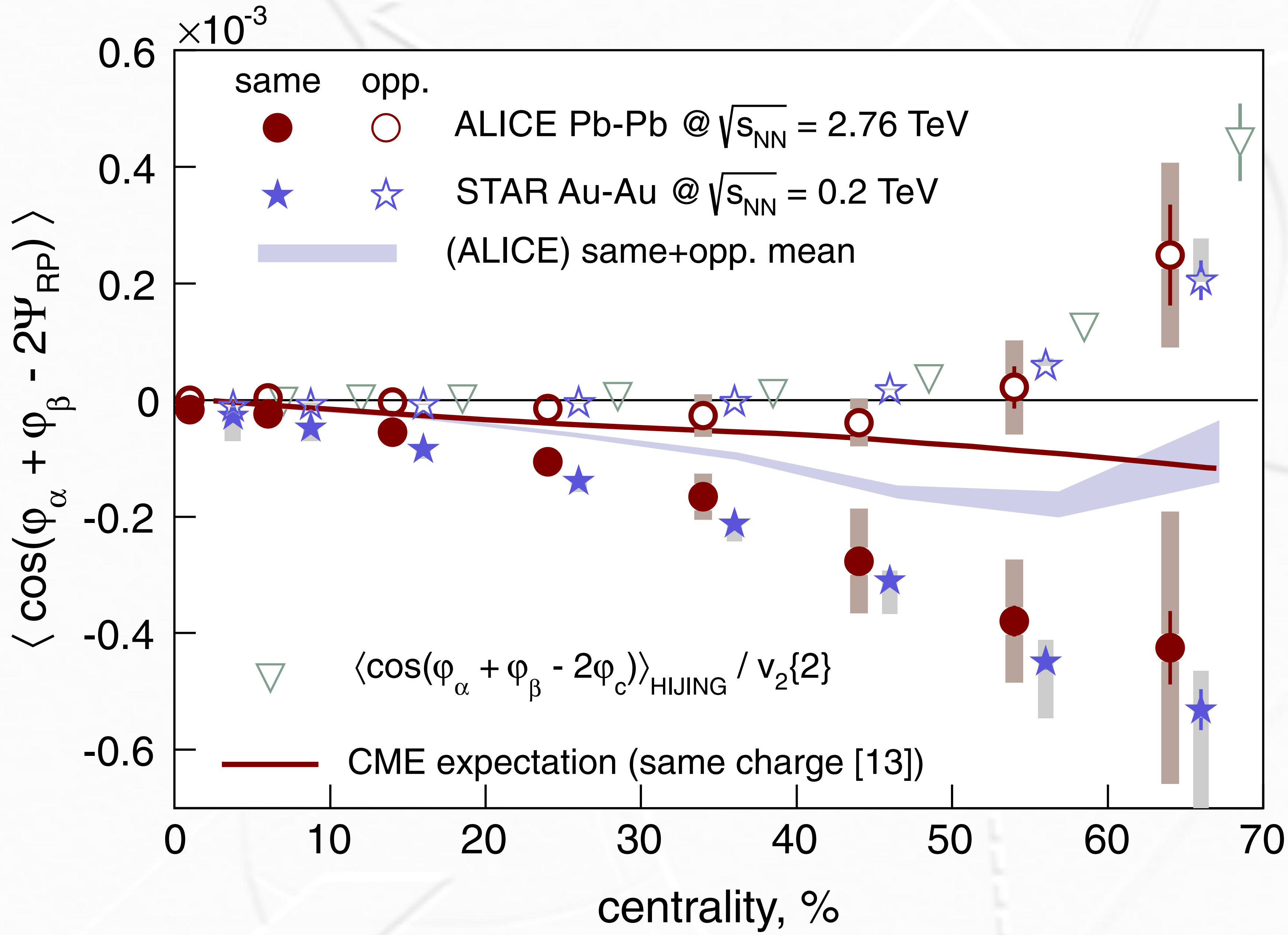
$$\begin{aligned}\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP})\rangle &= \langle\cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle - \langle\sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle \\ &= [\langle v_{1,\alpha}v_{1,\beta}\rangle + B_{in}] - [\langle a_\alpha a_\beta\rangle + B_{\rm out}],\end{aligned}$$



The sign of the correlations is sensitive to the "direction" (in- or out-of-plane), the background is suppressed (B_{in}-B_{out}) at least by a factor of $v_2 < 10^{-1}$.

LHC vs RHIC

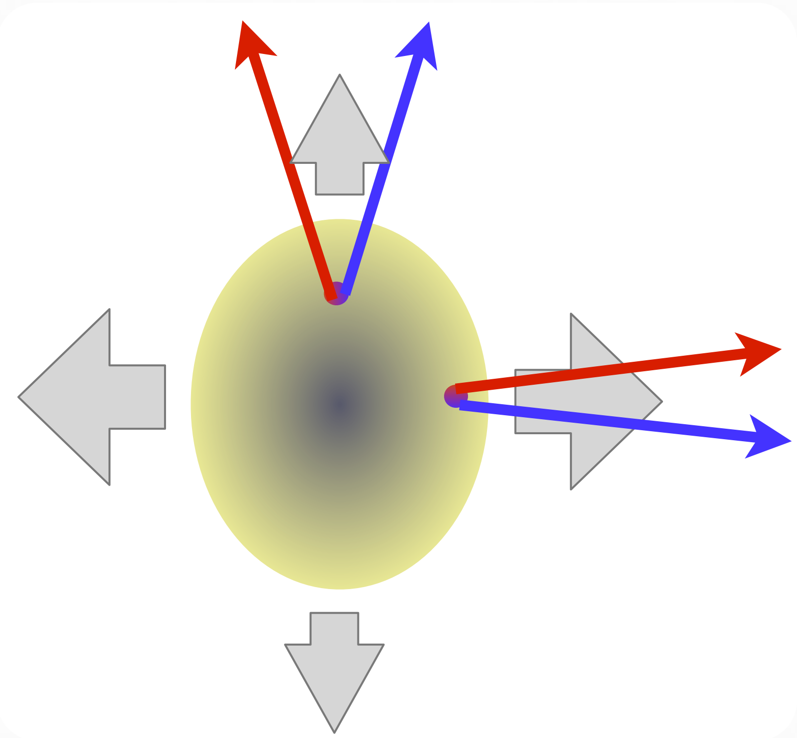
ALICE Collaboration PRL **110,** 012301 (2013)



RHIC and LHC results -- surprisingly close!

- no effect of change in magnetic field lifetime (?)
- no effect of almost 3 times higher multiplicity density (?)

CME background: "flowing clusters"



The only possible background ~ v_2

Voloshin, PRC70 057901 (2004)

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

One of the "strong" candidates: Local Charge Conservation at freeze-out + Radial + Elliptic Flow. Blast wave model:

Pratt, arXiv:1002.1758v1[nucl-th]

Schlichting and Pratt, PRC83 014913 (2011)

Hori, Gunji, Hamagaki, Schlichting, arXiv:1208.0603

- Correlations only between opposite charges
- To be consistent with data must be combined with (negative) charge independent correlations (e.g. momentum conservation).
- No event generator exhibits such strong correlations as predicted by Blast wave model

CME vs background. U+U

S. A. Voloshin, Phys. Rev. Lett. **105**, 172301 (2010)

Gang Wang (for the STAR Collaboration)
arXiv:1210.5498v2 [nucl-ex] 15 Nov 2012

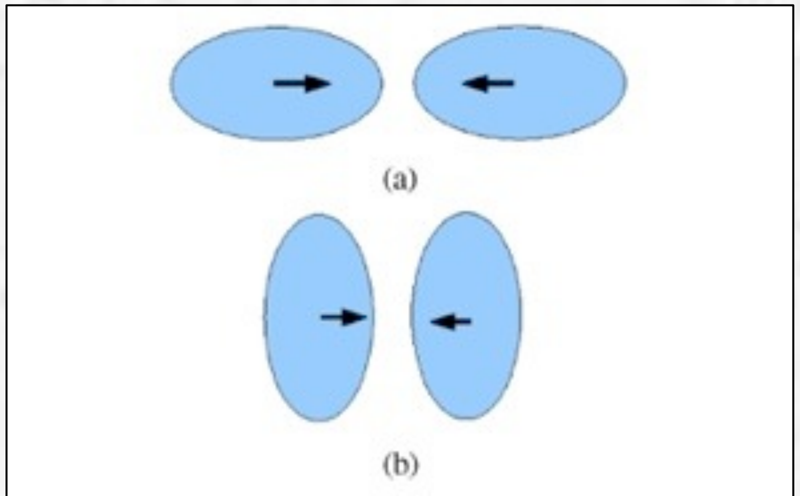


FIG. 1 (color online). Schematic view of central $U + U$ collisions: (a) tip-tip and (b) body-body.

In both cases the magnetic field is small, but elliptic flow is large in body-body.
A way to disentangle two effects!

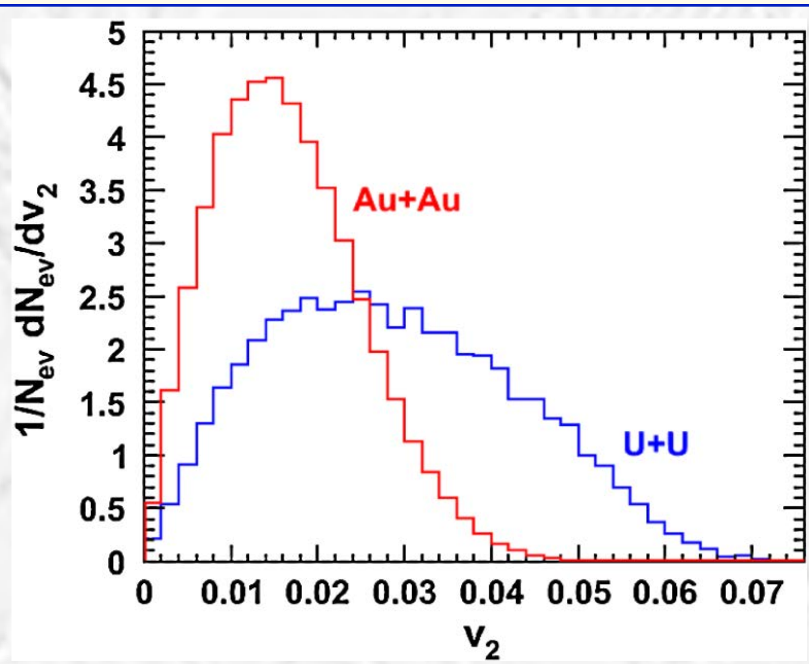
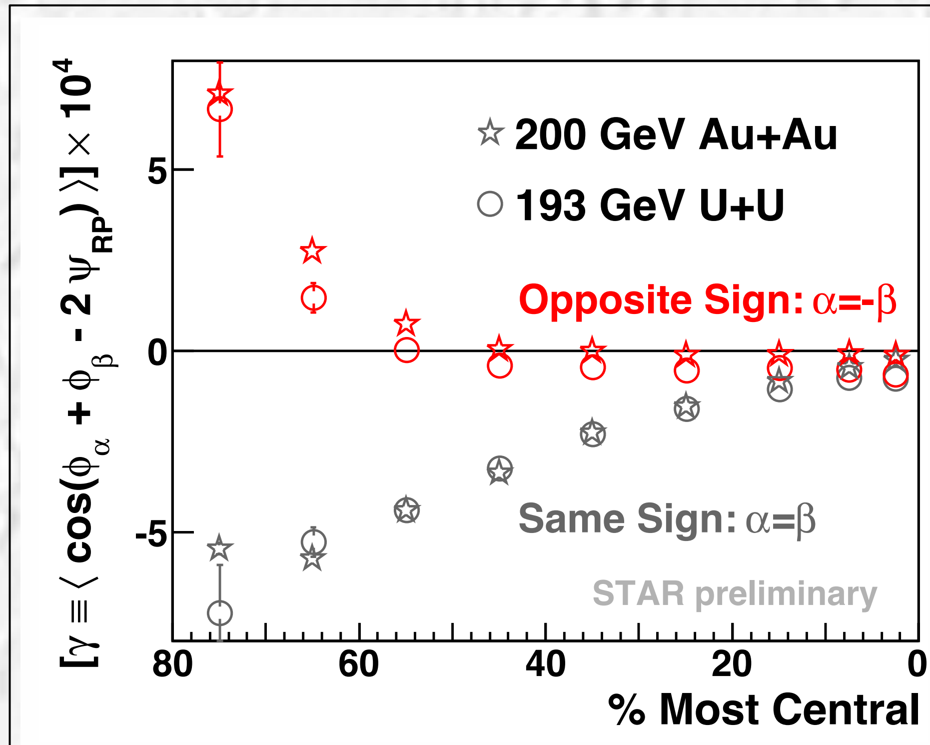
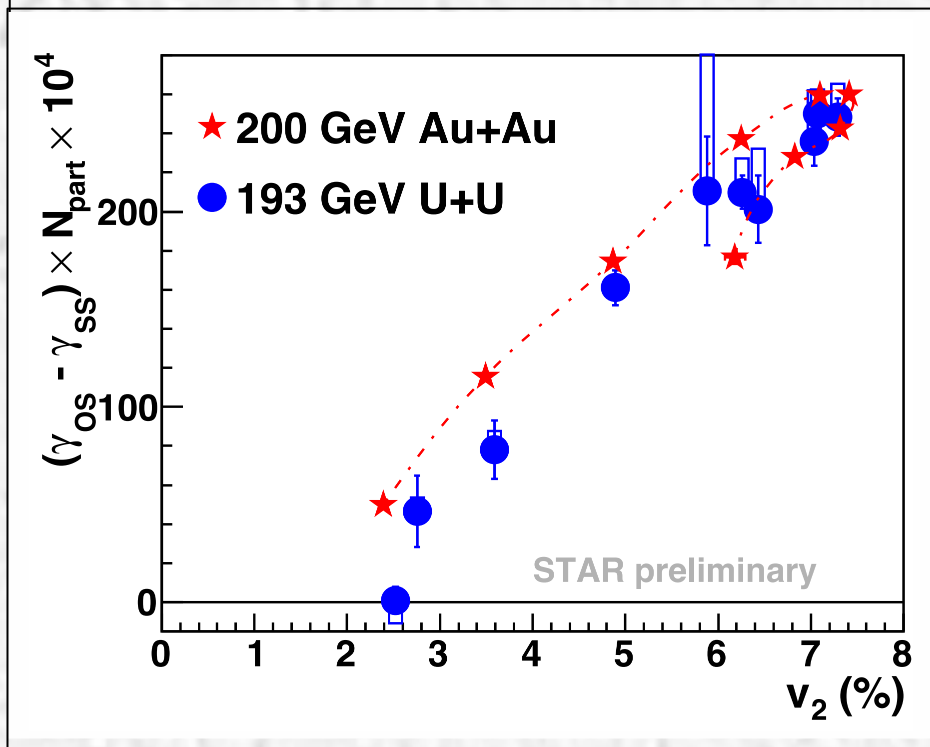


FIG. 2 (color online). Event distributions in v_2 for Au + Au and $U + U$ collisions in event samples with the number of spectators $N_{sp} < 20$.





(Preliminary) STAR results point to the signal in excess of background proportional to v_2

CME vs background. "Double harmonics"

Voloshin, Prog.Part.Nucl.Phys. **67** 541 (2012)

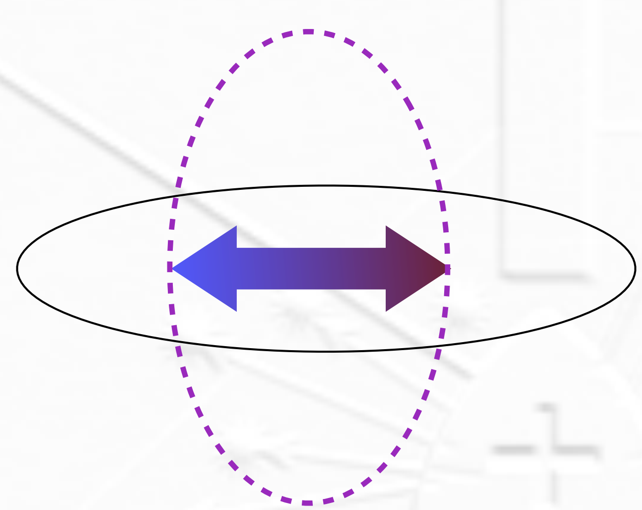
$$\langle\cos(\phi_a+\phi_b-2\Psi_2)\rangle = \langle\cos(\phi_a-\Psi_2)\cos(\phi_b-\Psi_2)\rangle - \langle\sin(\phi_a-\Psi_2)\sin(\phi_b-\Psi_2)\rangle$$

Charge independent part:

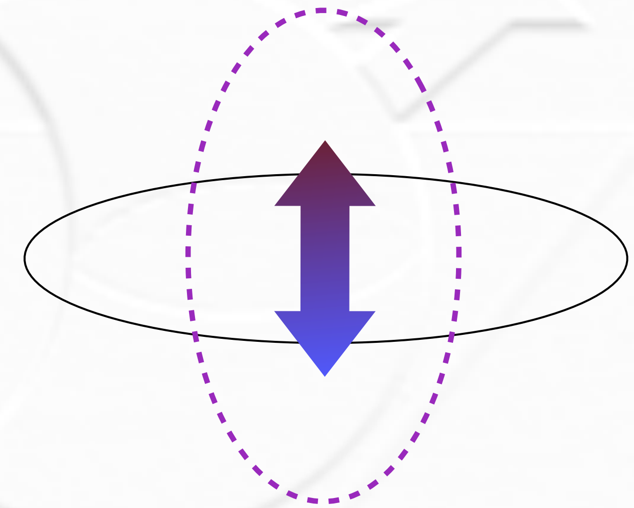
- directed flow fluctuations "in-plane" vs "out-of-plane"

Charge dependent part:

- contribution from CME
- "flowing cluster" background



positive



negative

"Directed flow" fluctuations relative to the elliptic flow plane

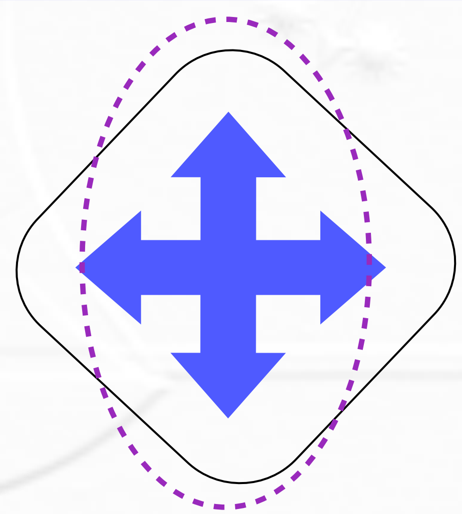
$$\langle\cos(2\phi_a+2\phi_b-4\Psi_4)\rangle = \langle\cos(2\phi_a-2\Psi_4)\cos(2\phi_b-2\Psi_4)\rangle - \langle\sin(2\phi_a-2\Psi_4)\sin(2\phi_b-2\Psi_4)\rangle$$

Charge independent part:

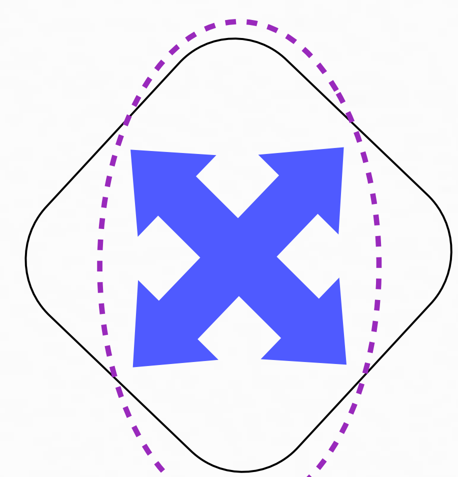
- Elliptic flow fluctuations "in-phase" vs "out-of-phase" with 4-th harmonic flow

Charge dependent version:

- NO contribution from CME.
- "flowing cluster" background (~ v_4 instead of ~v_2)



positive

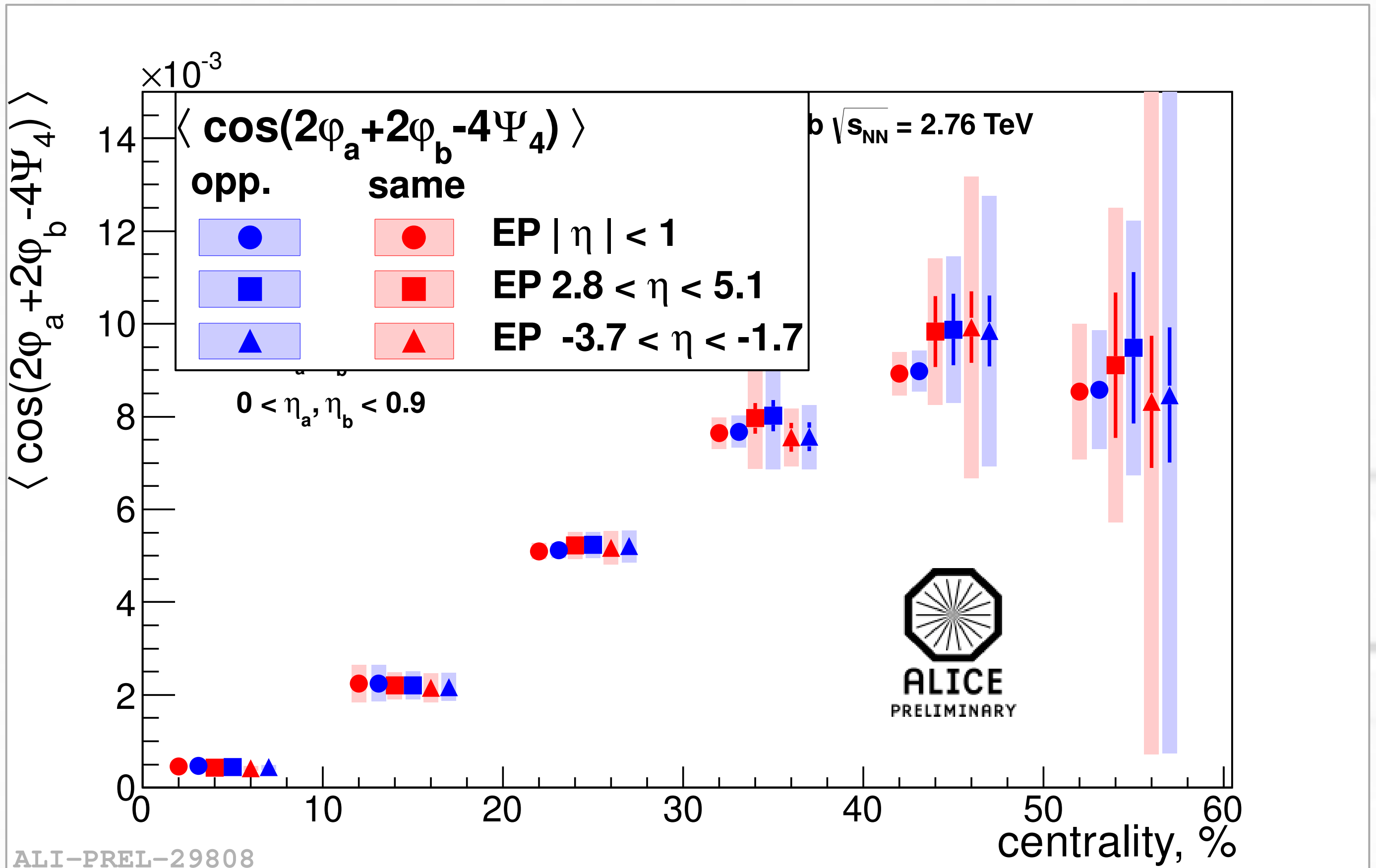


negative

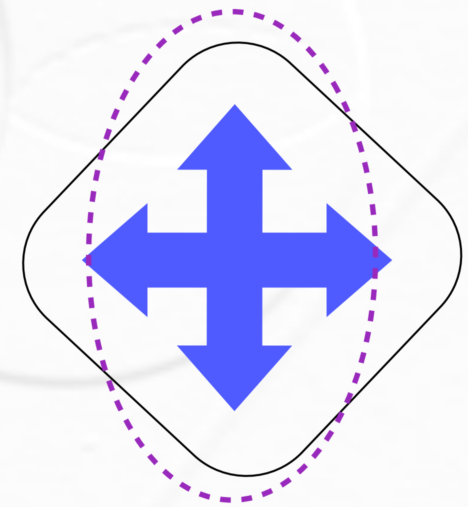
Elliptic flow fluctuations relative to the quadrangular flow plane

“Double harmonics” correlator. Exp.

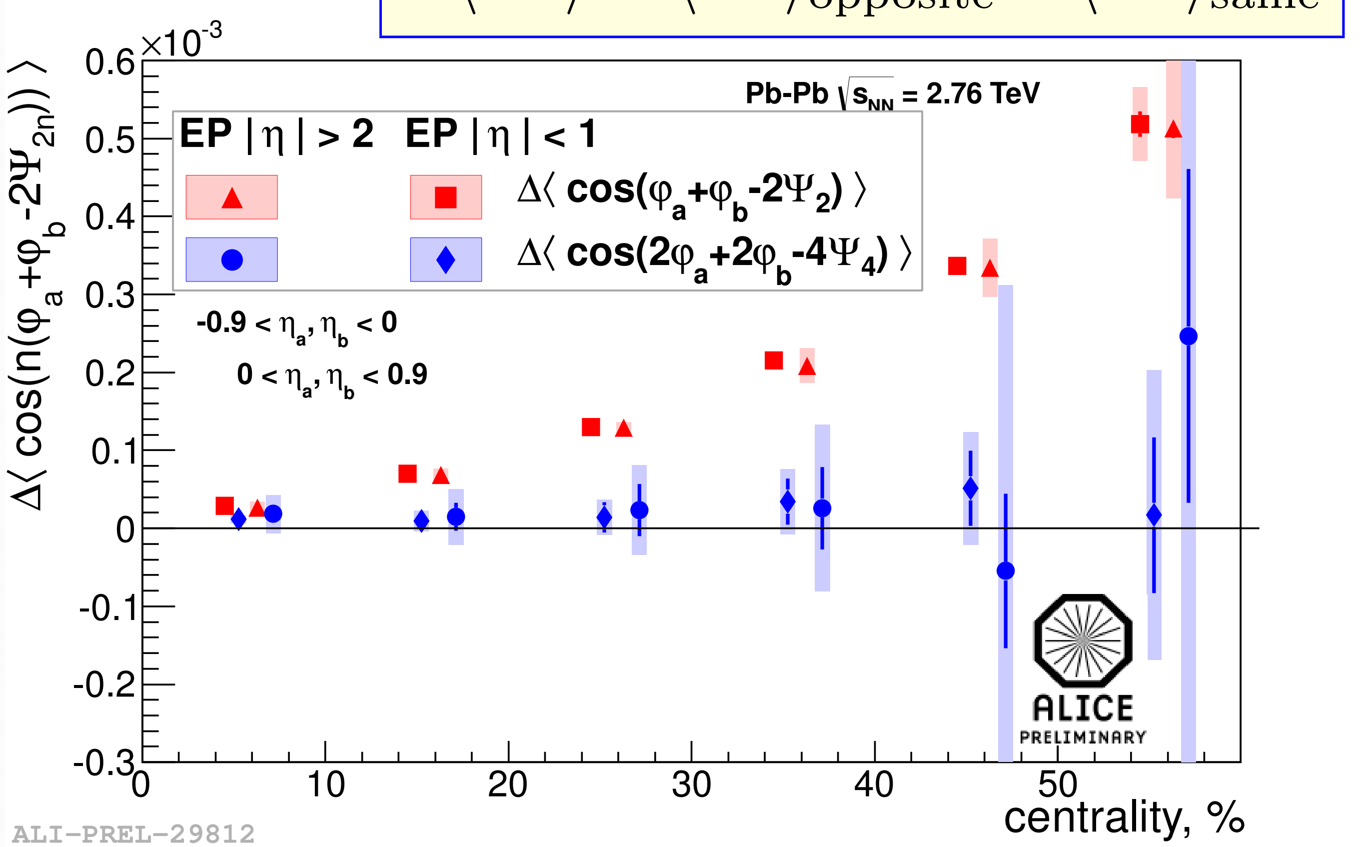
ALICE @ QM2012: talk by
Y. Hori, poster by J. Mlynarz



Strong positive correlations between Ψ_2 and Ψ_4



$$\Delta\langle\ldots\rangle = \langle\ldots\rangle_{\text{opposite}} - \langle\ldots\rangle_{\text{same}}$$



No indication of significant contribution from the effect of local charge conservation
⊕ radial flow

Requires theoretical modeling

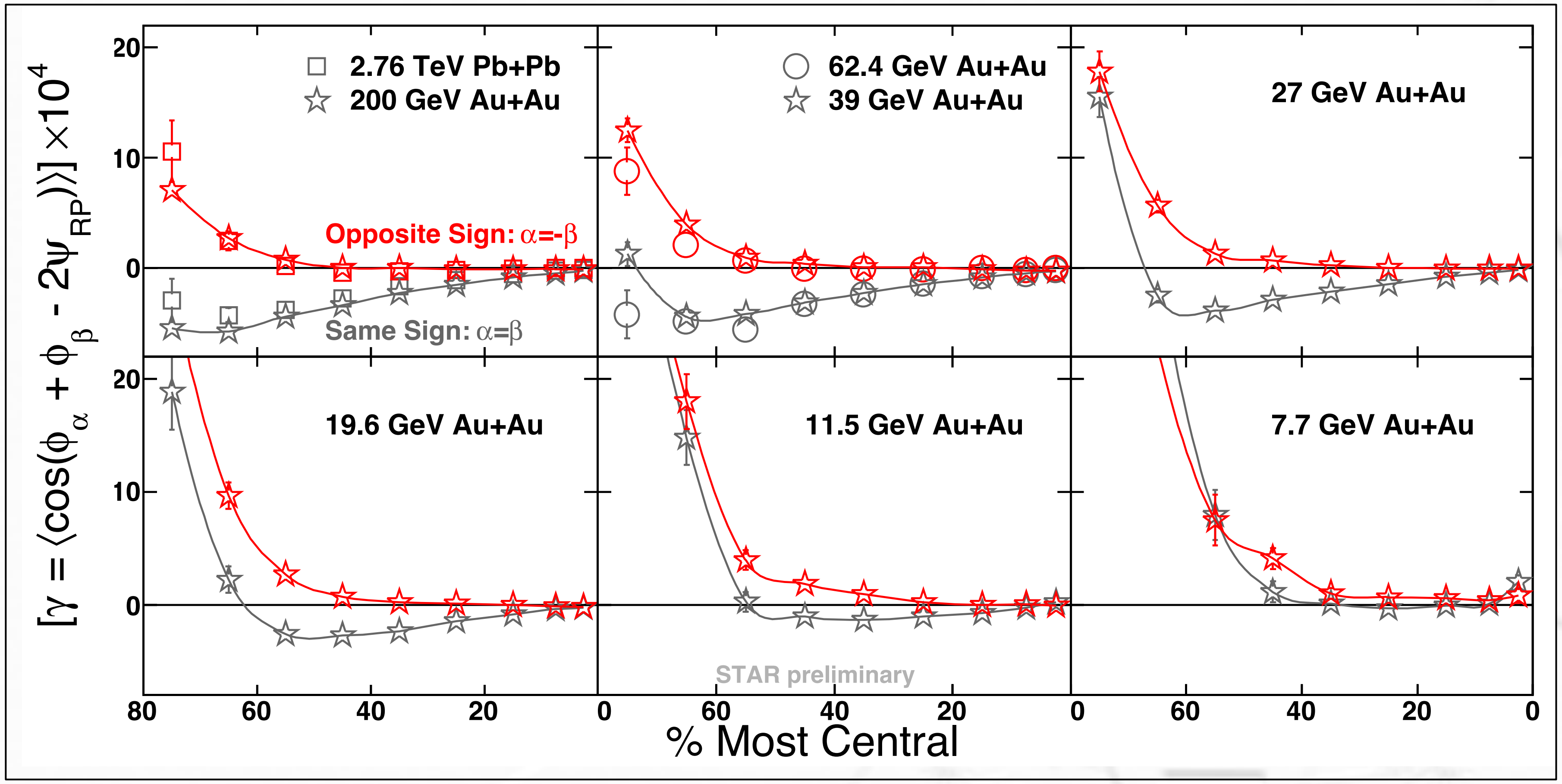
Conclusions

Initial state geometry fluctuations in heavy ion collisions play an important role in formation of the particle correlations.

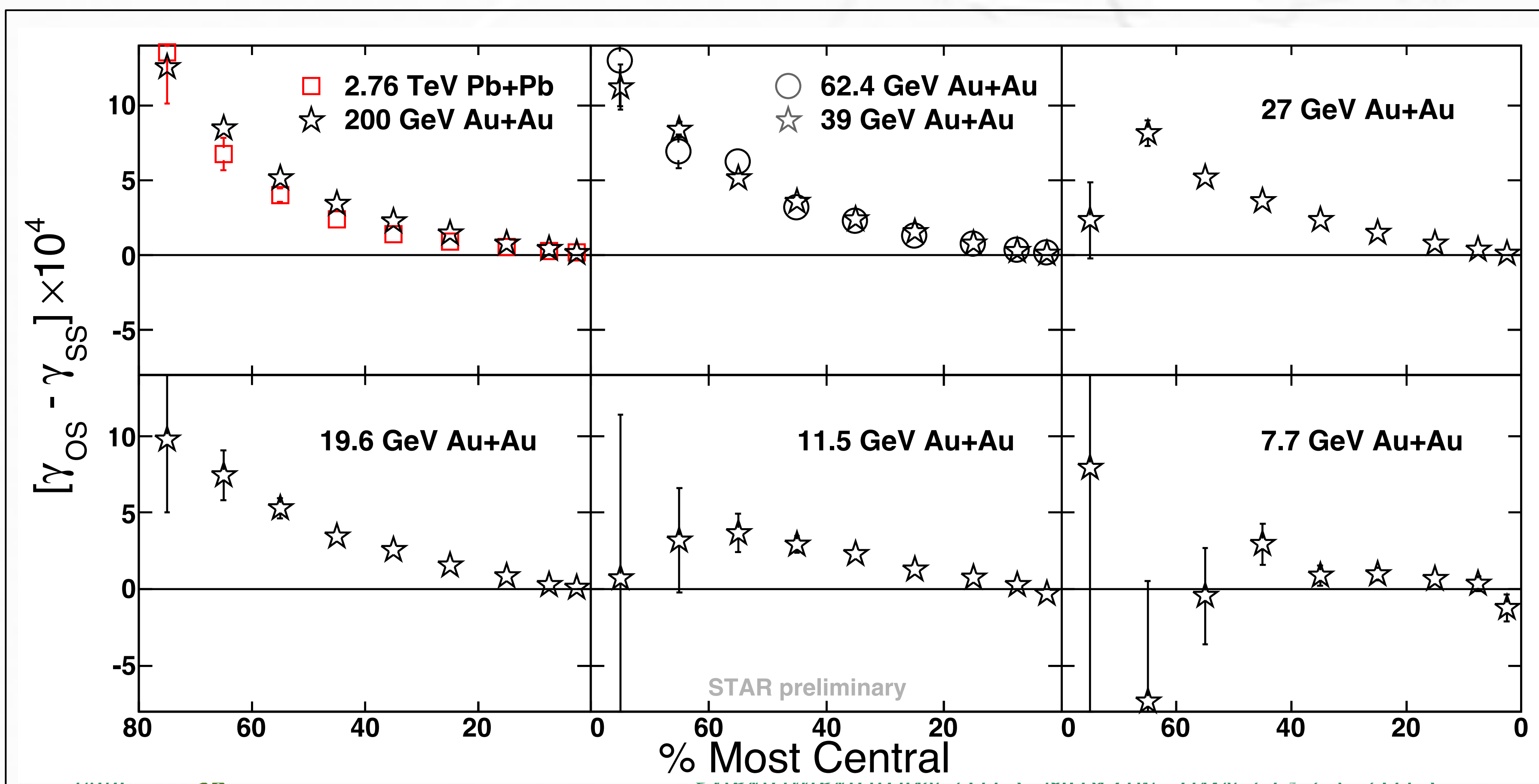
Utilizing them properly one can get an important and unique tool to study particle production, the properties of the created system and its evolution.

EXTRA SLIDES

RHIC BES results

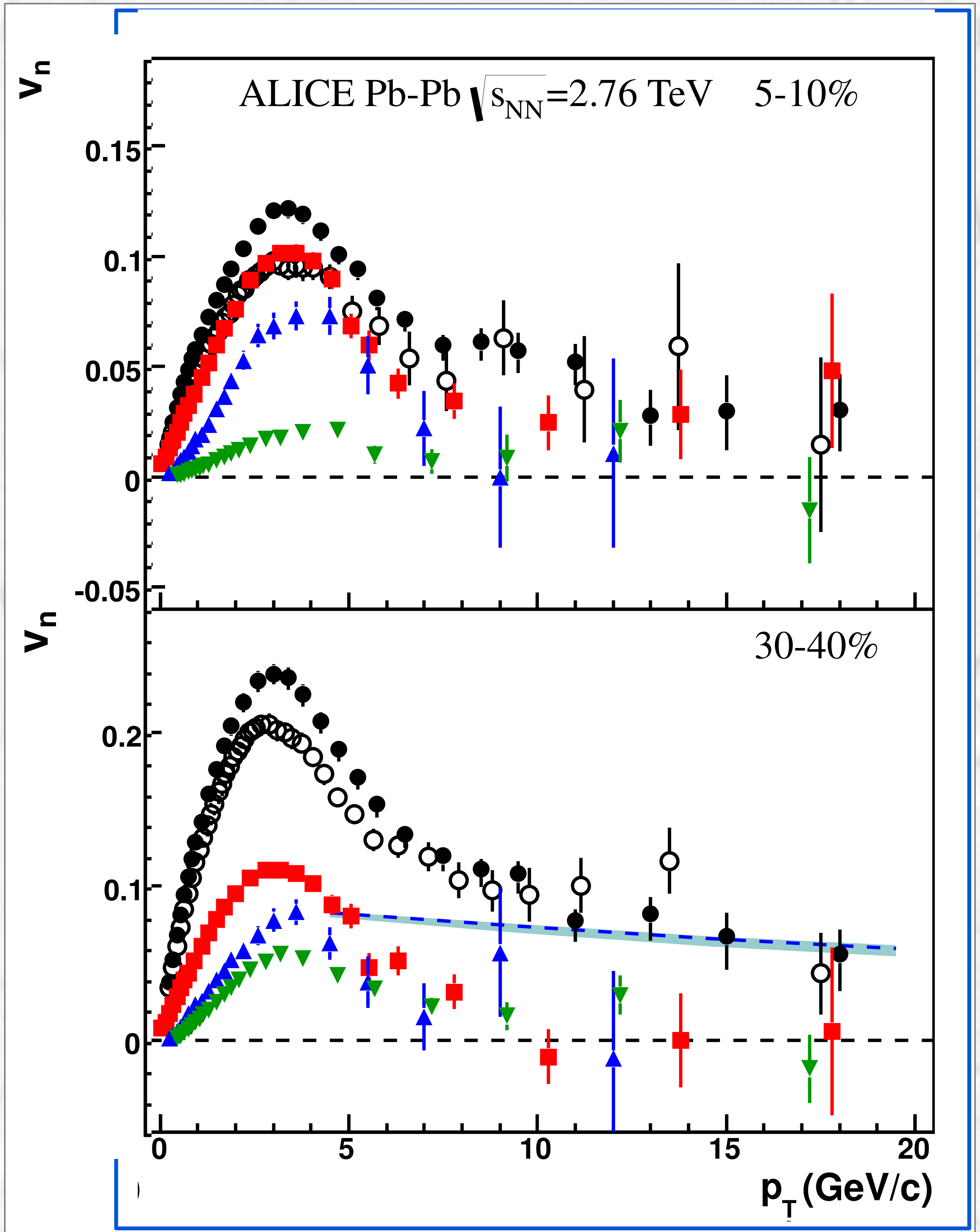


- Again, the signal is surprisingly “stable” over the wide range of energies
- Disappears at 7 GeV?



v_2, v_3 and v_4 for p_T up to 20 GeV/c

ALICE: arXiv:1205.5761



$v_n(p_T)$ up to p_T=20 GeV/c, where flow is dominated by jet quenching mechanism

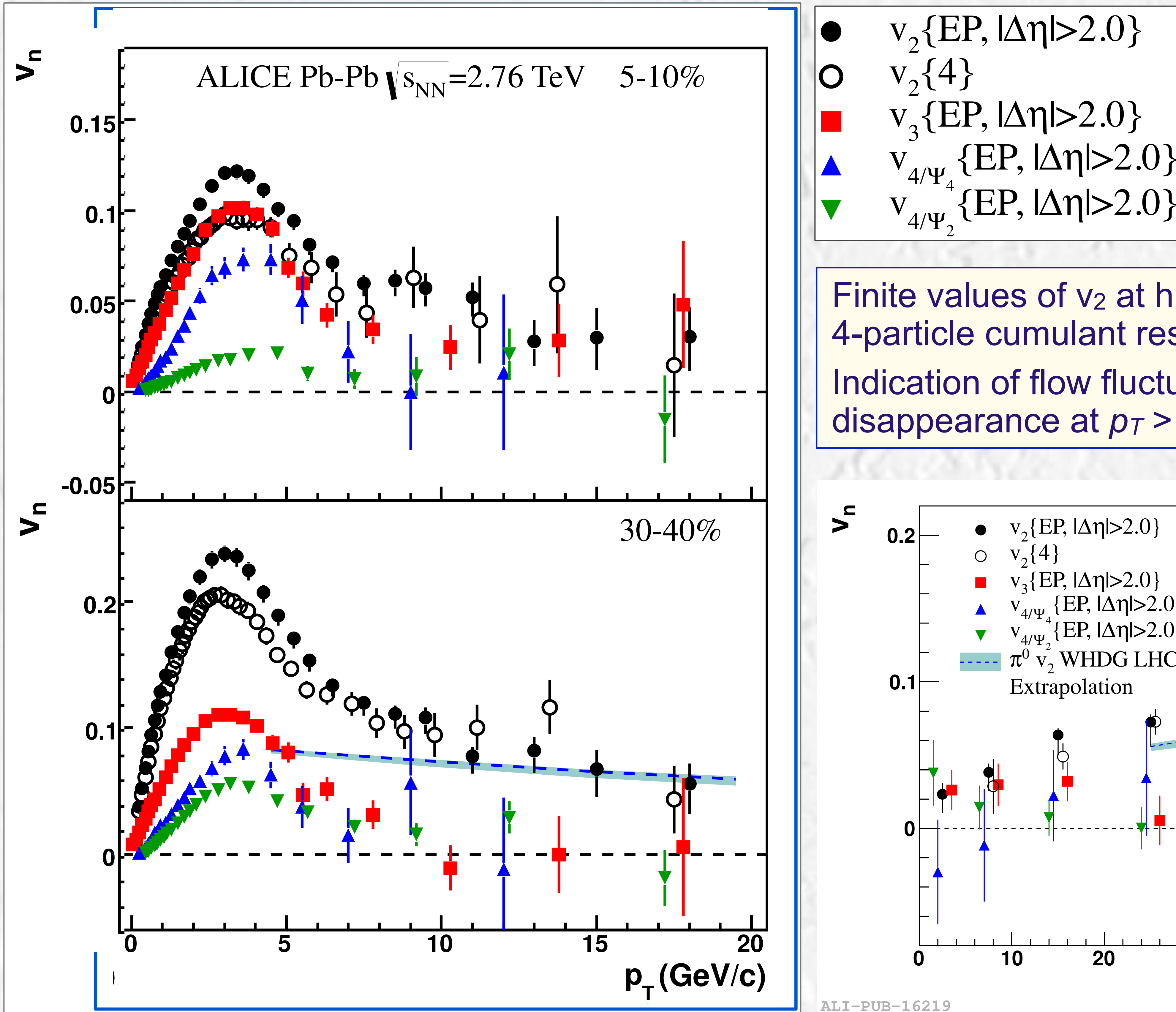
Nonflow suppressed either by rapidity gap or using 4-particle cumulans

v_4 measured wrt Ψ_2 and Ψ_4

Horowitz, Gyulassy, JPhys G 38 124114 (2011)

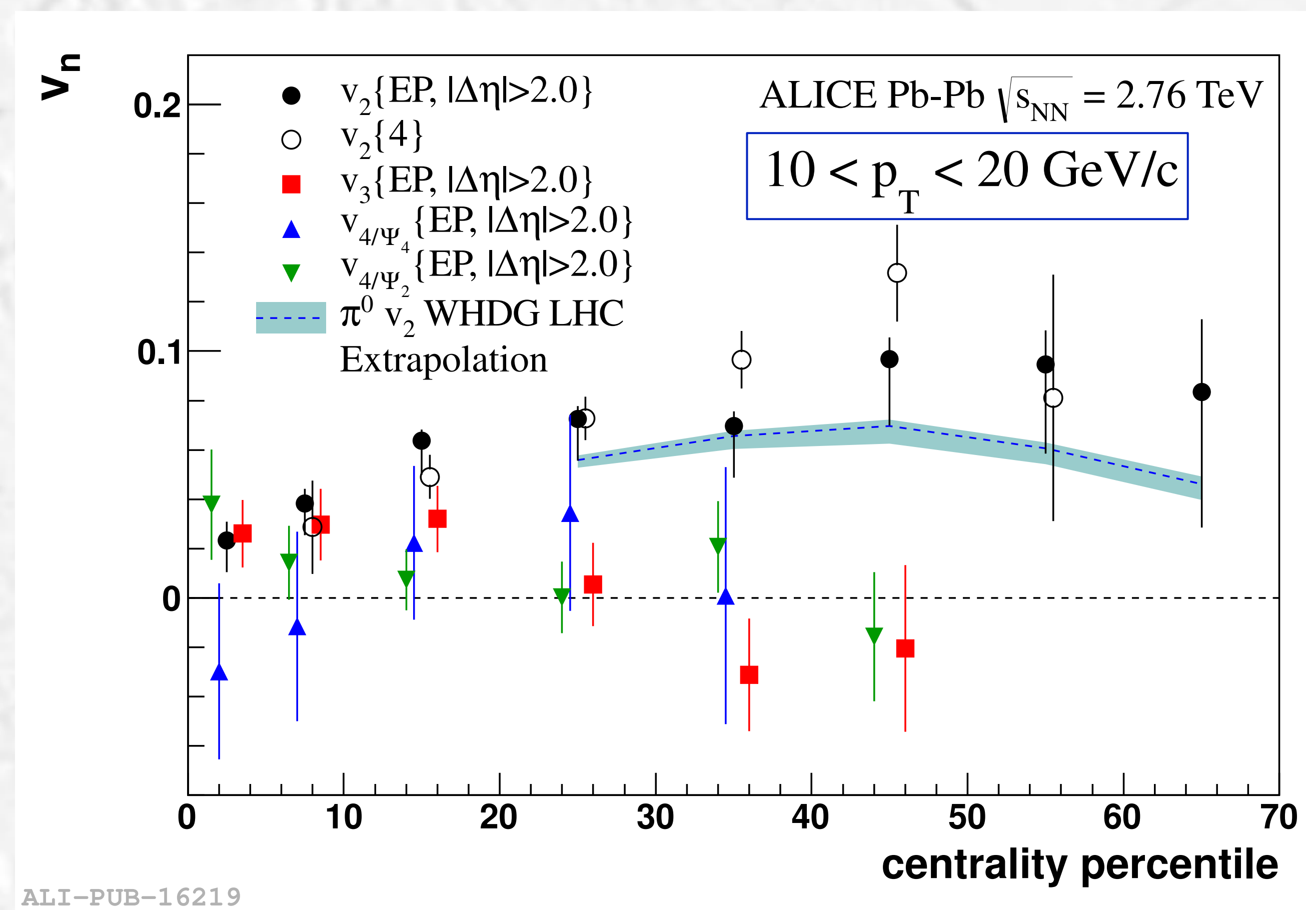
v_2, v_3 and v_4 for p_T up to 20 GeV/c

ALICE: arXiv:1205.5761



Finite values of v_2 at high p_T, including 4-particle cumulant results

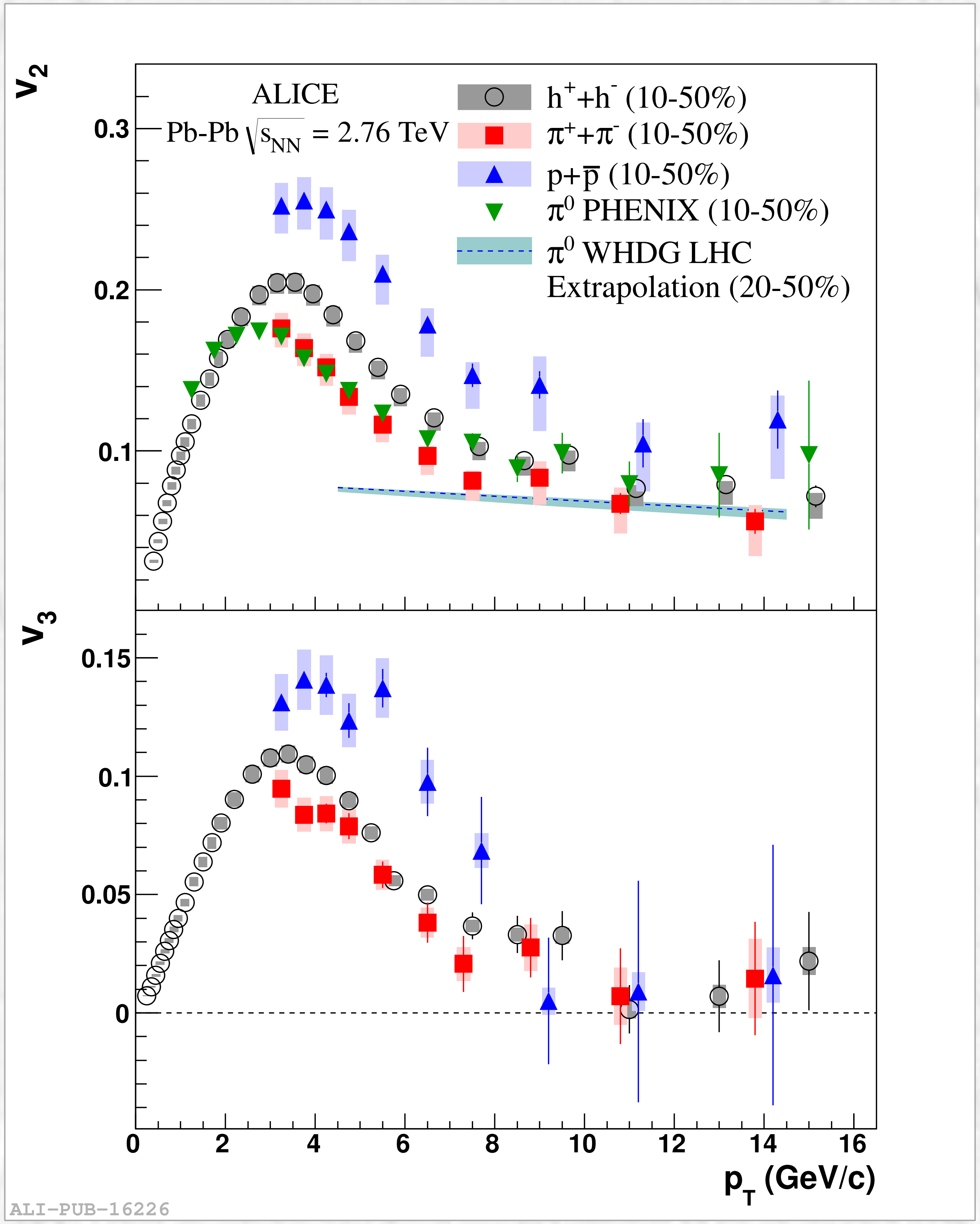
Indication of flow fluctuation effect disappearance at p_T > 10 GeV/c



WAYNE STATE UNIVERSITY

Proton and pion v_2 and v_3 at high p_T

ALICE: arXiv:1205.5761

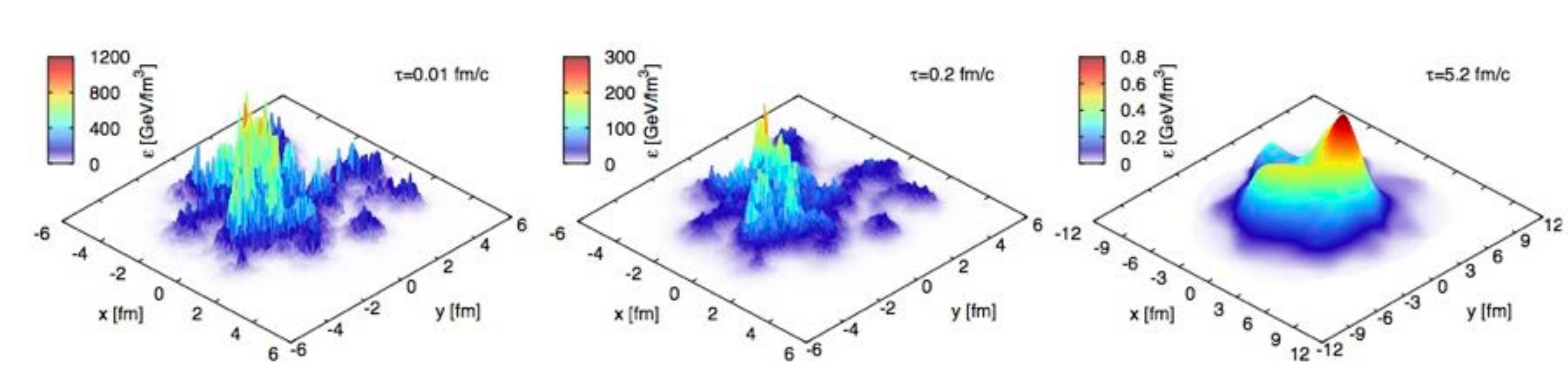


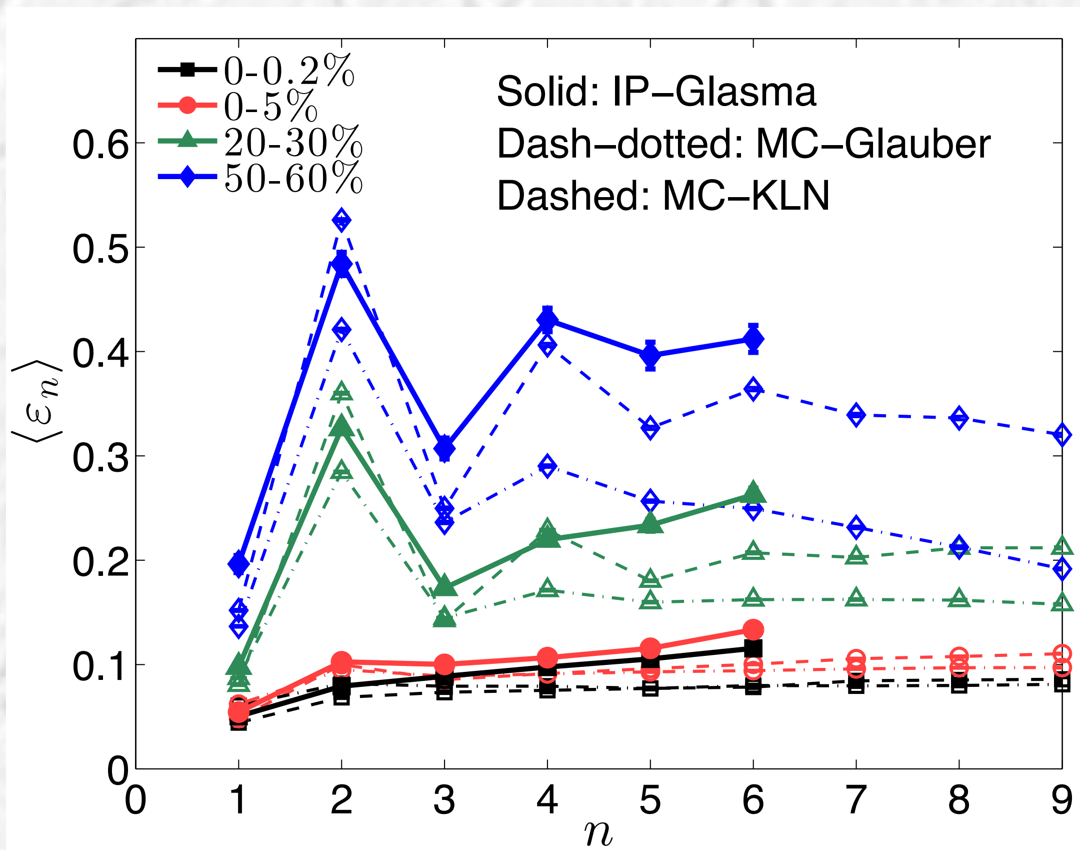
proton/pion splitting extends up to p_T ≃ 10 GeV/c

v_3 approaches zero for all particle species

WAYNE STATE UNIVERSITY

Eccentricities

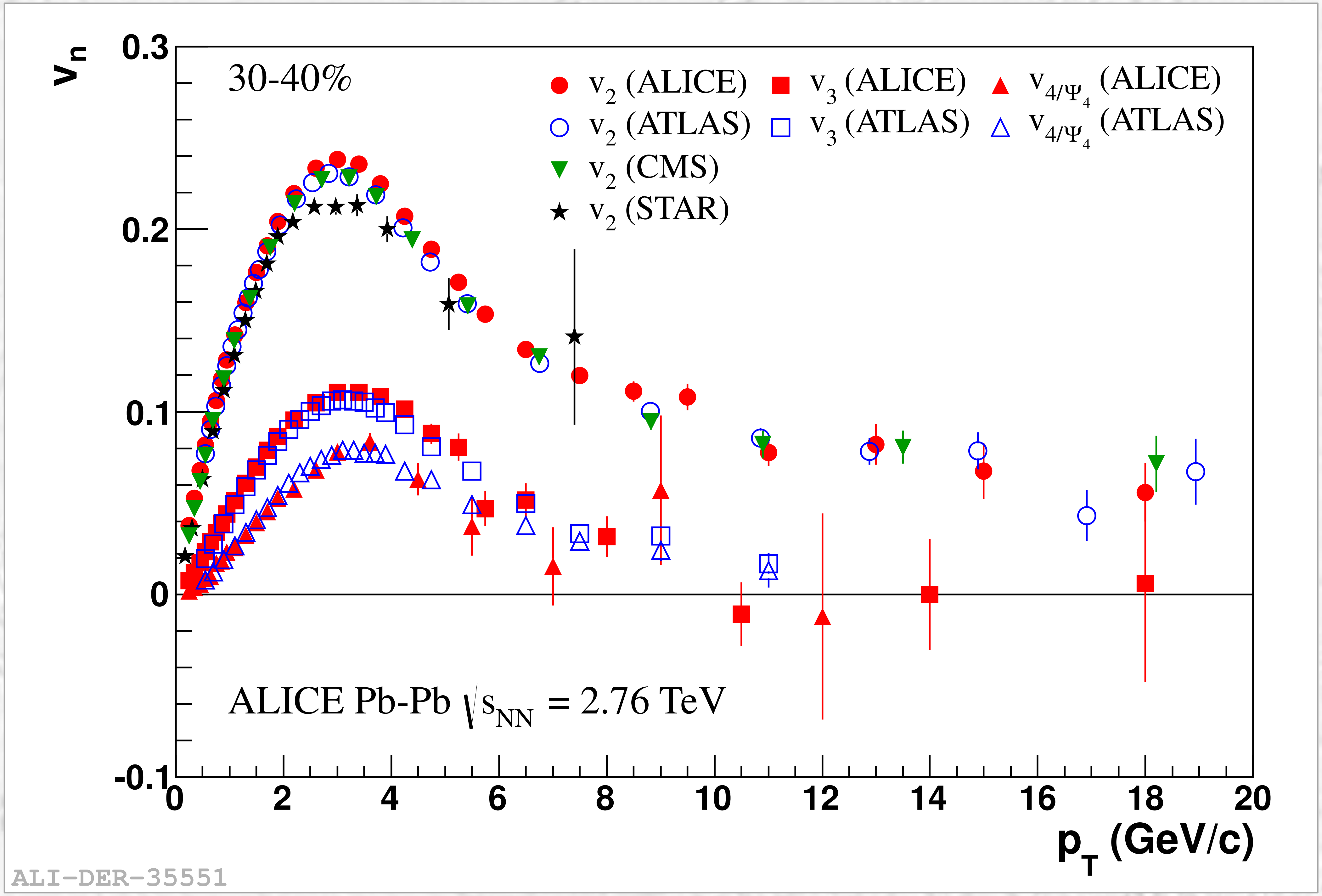




$$\varepsilon_1 e^{i\Phi_1} \equiv -\frac{\int r\,dr\,d\phi\, r^3 e^{i\phi}\, e(r,\phi)}{\int r\,dr\,d\phi\, r^3 e(r,\phi)}, \quad \varepsilon_n e^{in\Phi_n} \equiv -\frac{\int r\,dr\,d\phi\, r^n e^{in\phi}\, e(r,\phi)}{\int r\,dr\,d\phi\, r^n e(r,\phi)} \; (n>1),$$

$v_n(p_T)$, comparison with other experiments

ALICE: arXiv:1205.5761



Good agreement with other experiments

Blast wave results

Schlichting and Pratt, PRC83 014913 (2011)

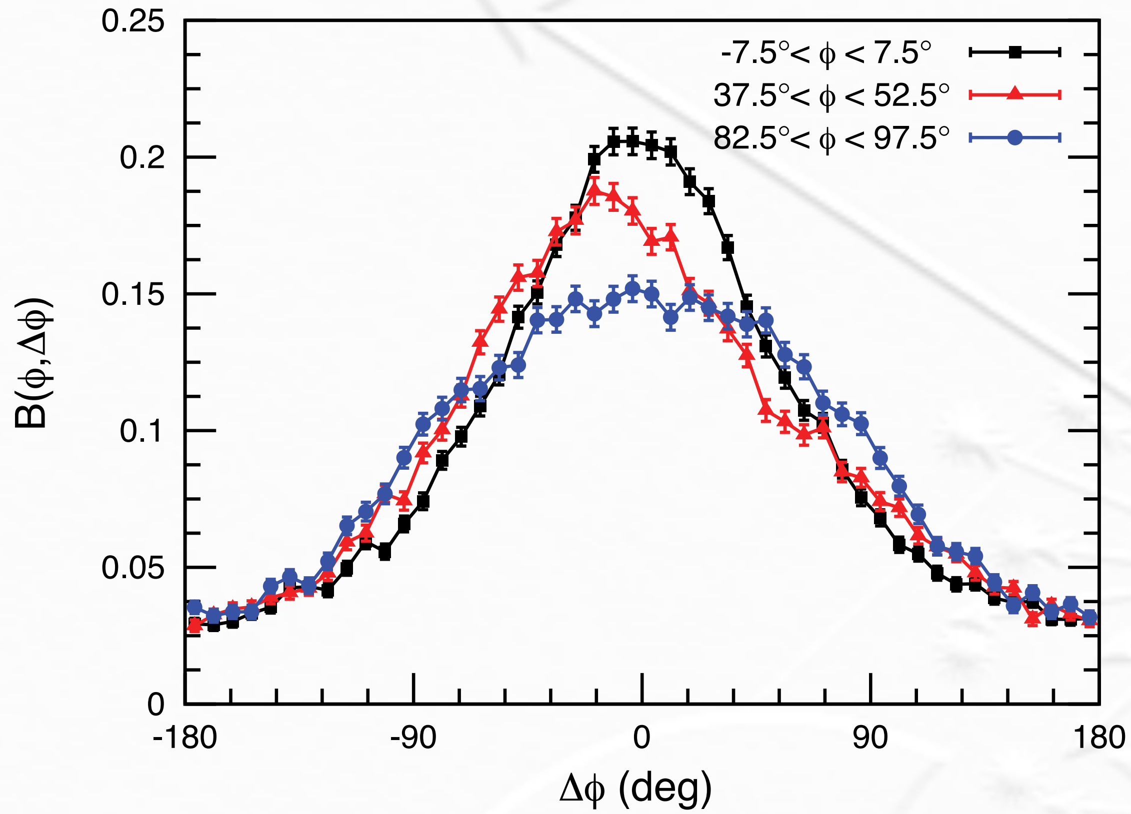
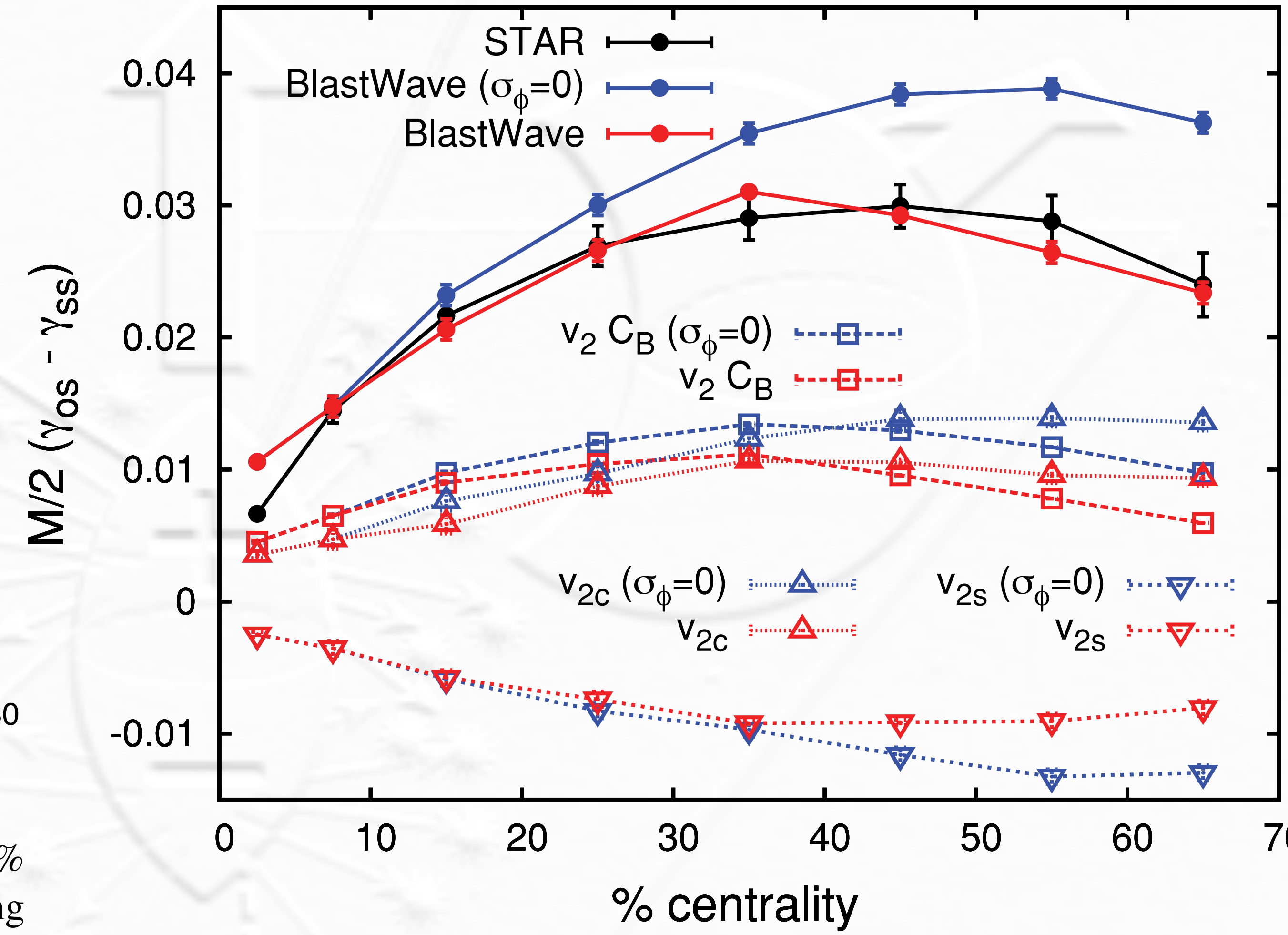


FIG. 7. (Color online) Balance function $B(\phi, \Delta\phi)$ for 40–50% centrality as function of the relative angle included by balancing partners for $\phi = 0°$ (black squares), 45° (red triangles), and 90° (blue circles). The balance function is narrower for in-plane pairs than for out-of-plane pairs. For intermediate angles, the balance function is biased toward negative angles.

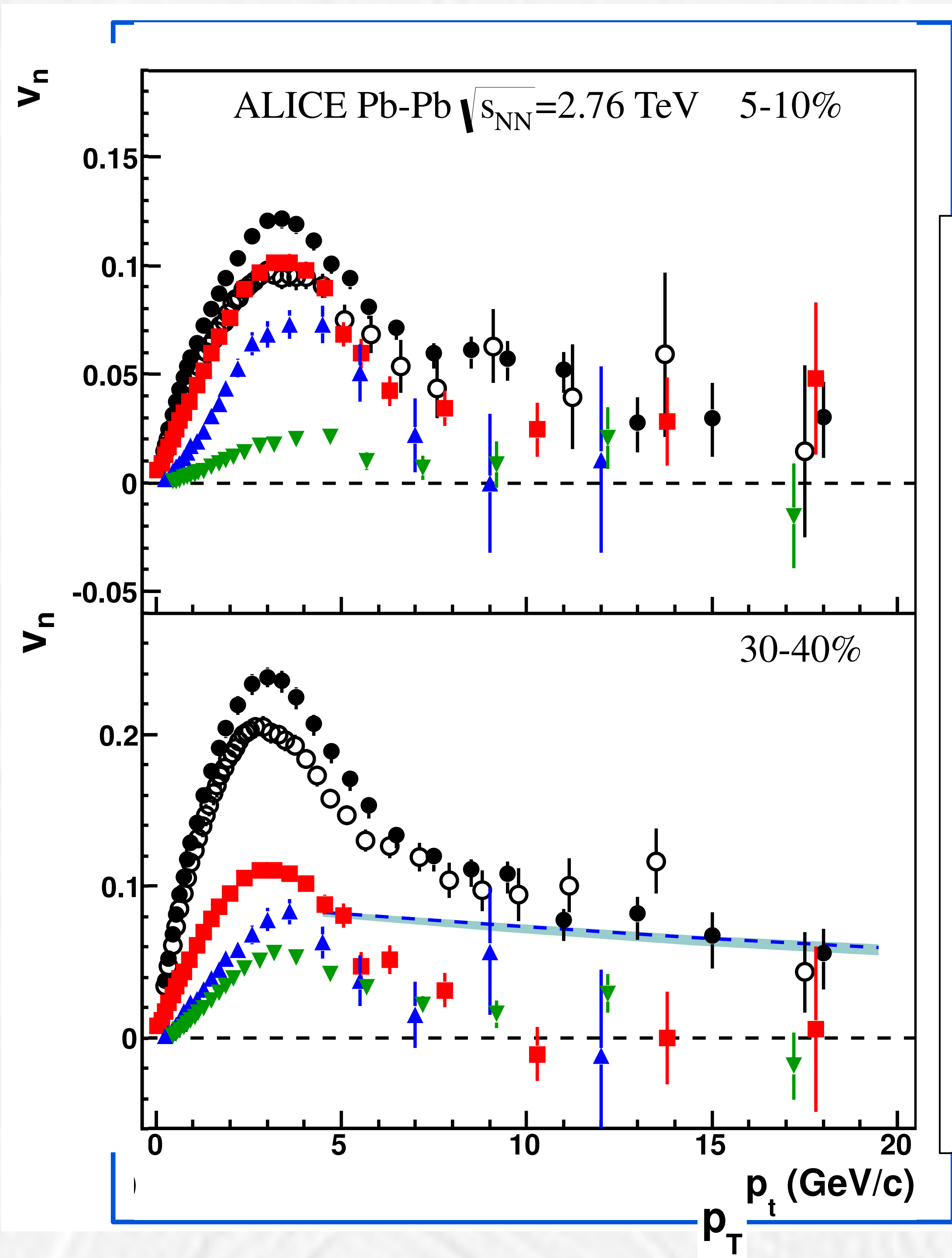


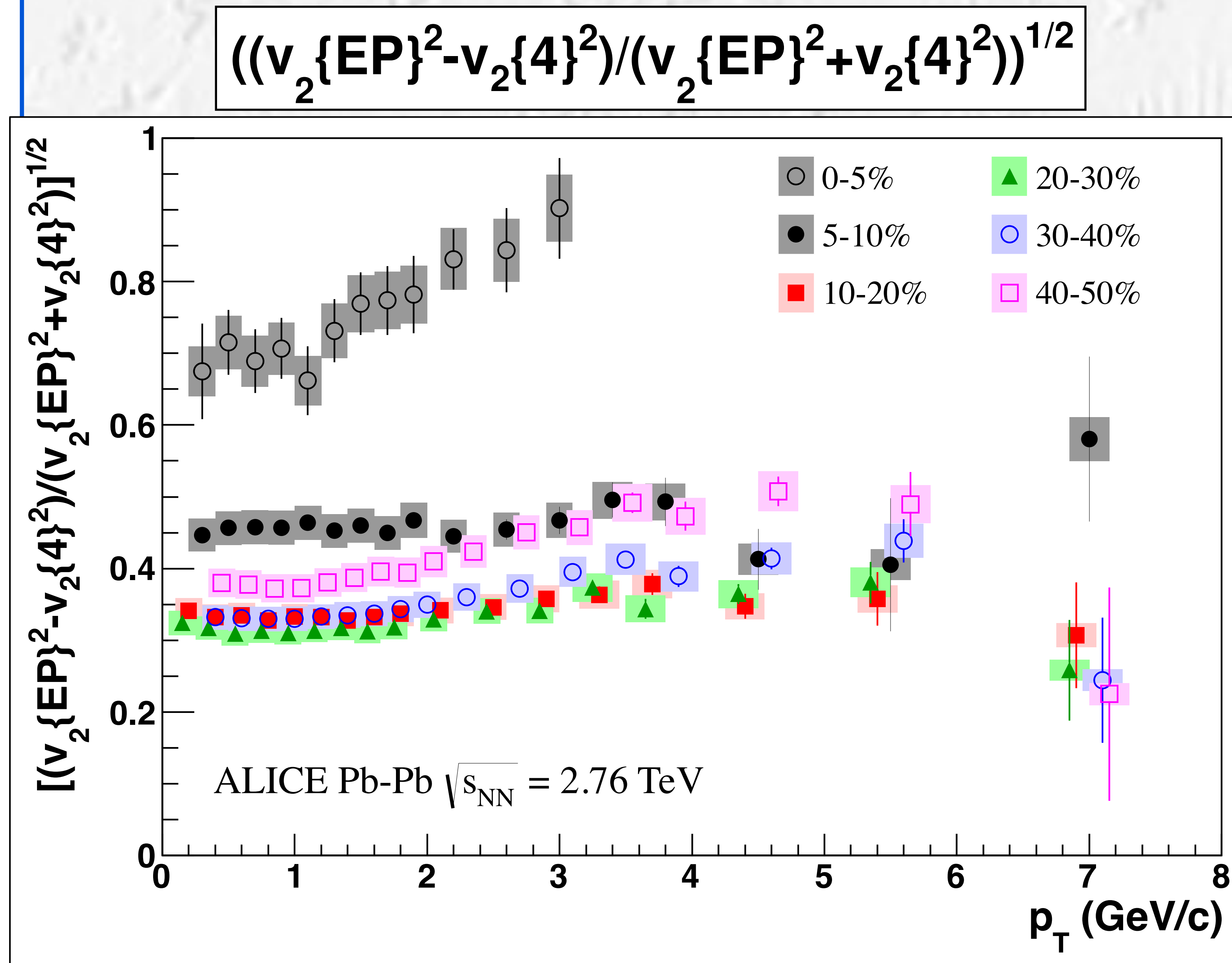
$$\frac{\langle M^2 \gamma_P \rangle}{\langle M \rangle} = \frac{2}{\langle M \rangle} \int d\phi \, d\Delta\phi \langle \frac{dM}{d\phi} \rangle \, B(\phi, \Delta\phi) \times [\cos(2\phi)\cos(\Delta\phi) - \sin(2\phi)\sin(\Delta\phi)],$$

- With some "adjustments" can describe the data (diff "opp" - "same").
- Note that the correlator is inversely proportional to multiplicity

Fluctuations vs p_T

ALICE: arXiv:1205.5761





Fluctuations extend up to $p_T \sim 8$ GeV/c with very similar magnitude

Note that v_4 measured wrt Ψ_2 and Ψ_4 becomes very similar at the same p_T