The Art of the Flow

Sergei A. Voloshin
Wayne State University

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Flow and:
- Centrality/energy dependence, and ideal fluid
- Constituent Quark Scaling, and deconfinement
- Nonflow/fluctuations, and “ridge”, initial geometry
- azHBT, and proof of collective expansion
- Velocity fields, vorticity, and polarization

Exploring the secrets of the universe

Art Poskanzer

1 Color by Roberta Weir

BERKELEY LAB

Coauthored with Art: 7 phenomenology, PAs: 2 NA49 and 9 STAR

QM ’95, NA49 and flow at SPS

Quark Matter '95

Y. Zhang (E877) – technique, first flow measurements at AGS
J-Y. Ollitrault - ‘non-flow”

S.Voloshin, Y. Zhang arXiv:hep-ph/9407282v1 12 Jul 1994

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$$v_n = \langle \cos[n(\phi_i - \Psi_{RP})] \rangle$$

Event plane resolution correction made for each harmonic

Unfiltered theory can be compared to experiment!

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QM ’97

Directed and Elliptic Flow in 158 GeV/Nucleon Pb + Pb Collisions

A.M. Poskanzer[a] for the NA49 Collaboration

VOLUME 80, NUMBER 19 PHYSICAL REVIEW LETTERS 11 MAY 1998

(Received 10 November 1997)

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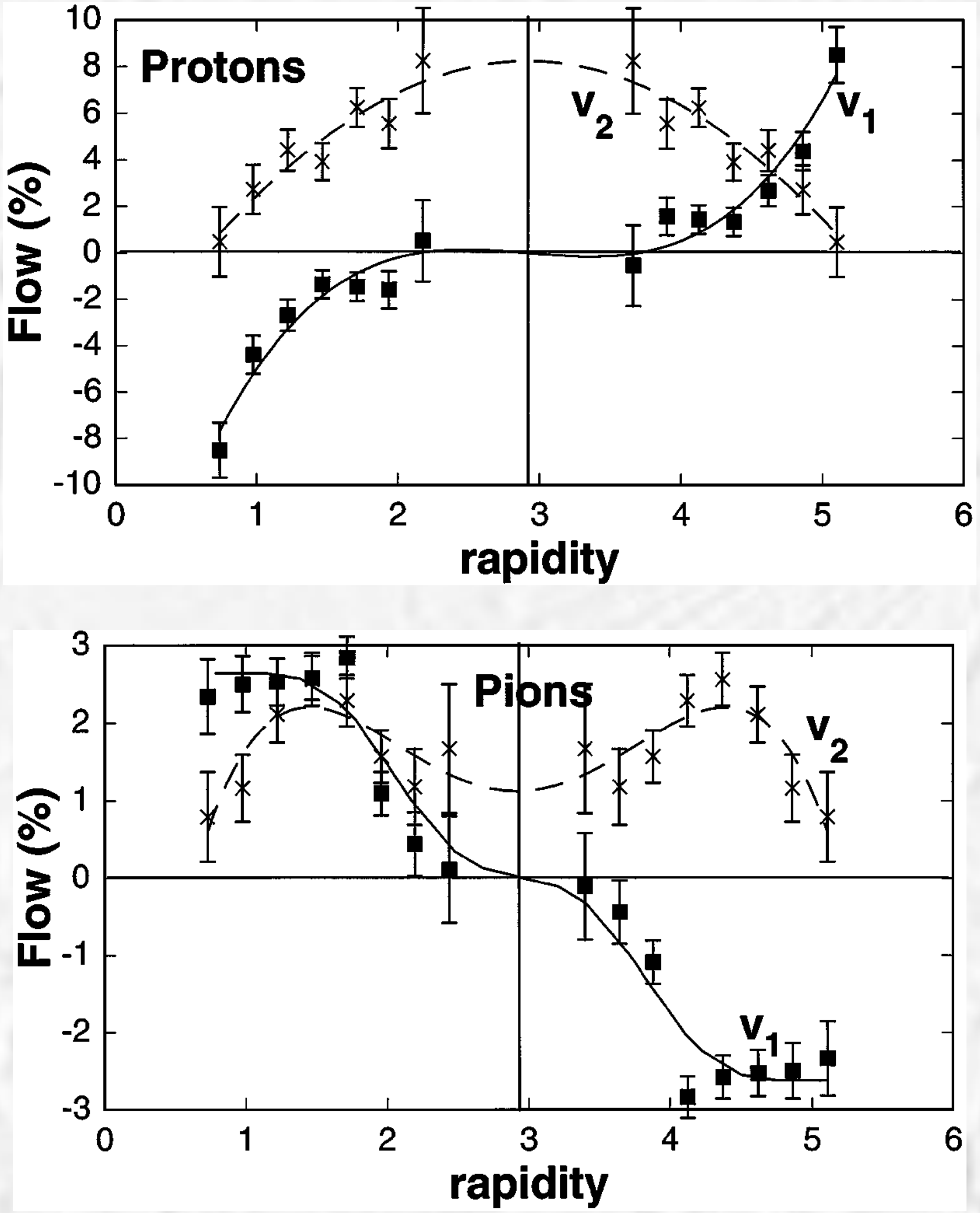

FIG. 2. The rapidity dependence of the directed (v_1) and elliptic (v_2) flow for the protons ($0.6 < p_t < 2.0$ GeV/c) and pions ($0.05 < p_t < 0.35$ GeV/c). The points below midrapidity ($y = 2.92$) have been reflected from the measurements in the forward hemisphere. The curves are to guide the eye.

Flow “method paper”

PHYSICAL REVIEW C VOLUME 58, NUMBER 3 SEPTEMBER 1998

Methods for analyzing anisotropic flow in relativistic nuclear collisions

A. M. Poskanzer[1] and S. A. Voloshin[2,*]

[1]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*

[2]*Physikalisches Institut der Universität Heidelberg, Heidelberg, Germany*

(Received 20 May 1998)

The strategy and techniques for analyzing anisotropic flow (directed, elliptic, etc.) in relativistic nuclear collisions are presented. The emphasis is on the use of the Fourier expansion of azimuthal distributions. We present formulas relevant for this approach, and in particular, show how the event multiplicity enters into the event plane resolution. We also discuss the role of nonflow correlations and a method for introducing flow into a simulation. [S0556-2813(98)04109-0]

Physical Review C 50th Anniversary Milestones

50 YEARS PHYSICAL REVIEW C

Citations: Google Scholar/inSPIRE 2157/1410

Flow proponent

Art: Flow proponent, advocate, supporter

Promoted and developed flow methods, codes, analyses, helped to test ALICE codes…

Was happy to see how flow draws attention at the conferences

Notations, $v_2\{\mathrm{EP}\}$

FlowStyle in ROOT

FlowEvent

"little" q flow vector

v_2^2/v_4 physics

```
//////////////////////////////////////////////////////////////////////
//
// $Id: StFlowEvent.cxx,v 1.7 2000/06/01 18:26:35 posk Exp $
//
// Author: Raimond Snellings and Art Poskanzer
//////////////////////////////////////////////////////////////////////
//
// Description: A subset of StEvent
//
//////////////////////////////////////////////////////////////////////
//
// $Log: StFlowEvent.cxx,v $
// Revision 1.7  2000/06/01 18:26:35  posk
// Increased precision of Track integer data members.
//
// Revision 1.6  2000/05/20 00:55:13  posk
// Condensed flownanoevent.root somewhat.
//
...vision 1.5  2000/05/16 20:59:29  posk
...oshin's flownanoevent.root added.
//
...vision 1.4  2000/05/12 22:42:04  snelling
...itions for persistency and minor fix
```

DIRECTED AND ELLIPTIC FLOW OF CHARGED PIONS . . . PHYSICAL REVIEW C 68, 034903 (2003)

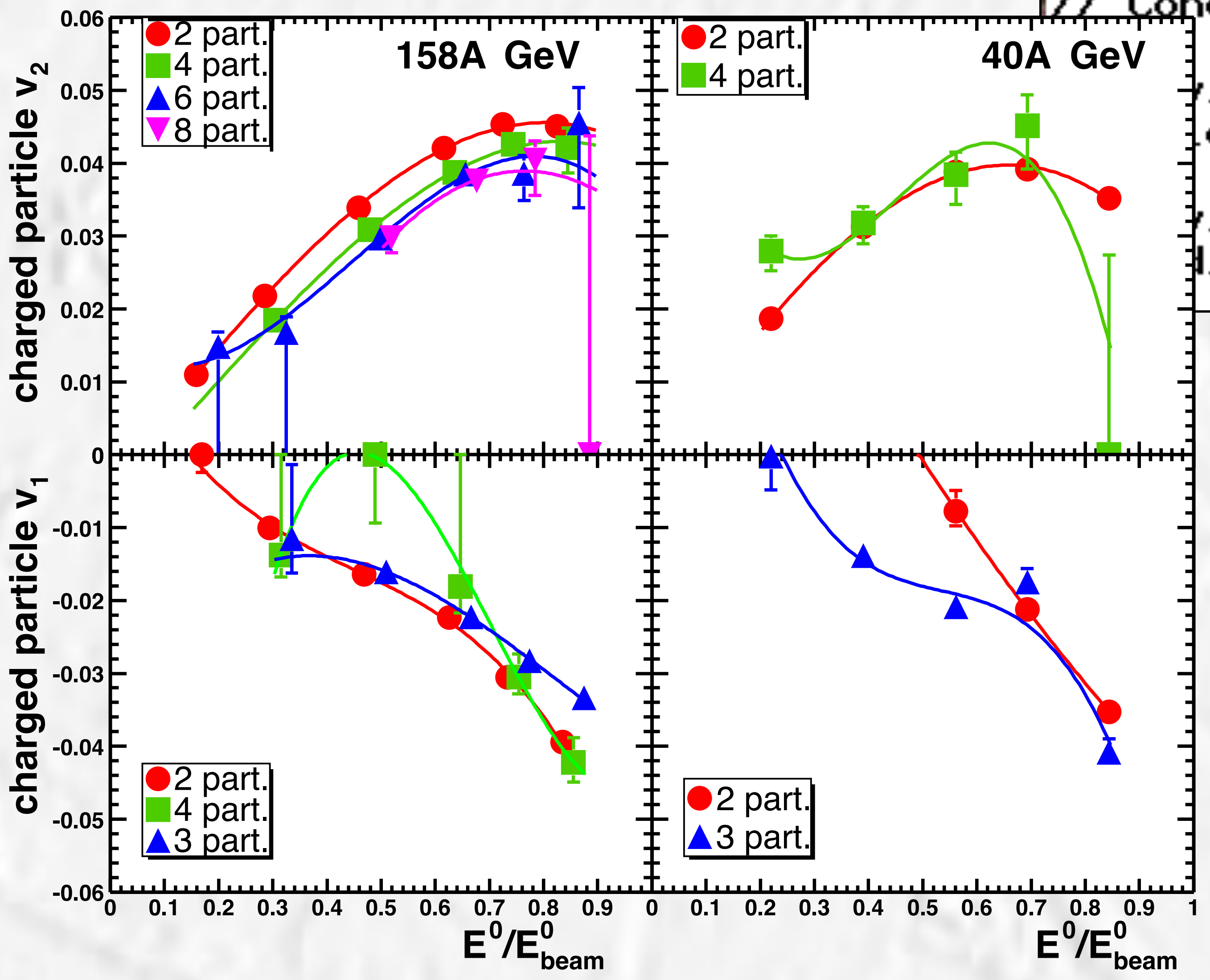

FIG. 21. (Color online) Weighted flow $\langle w_n e^{in(\phi-\Phi_{RP})}\rangle/\sqrt{\langle w_n^2\rangle}$, Eq. (13), with $w_1=y$ in the center of mass frame and $w_2=p_t$, from the

```
//////////////////////////////////////////////////////////////////////
//
// $Id: StFlowNanoEvent.cxx,v 1.6 2000/05/26 21:29:30 posk Exp $
//
// Author: Sergei Voloshin and Raimond Snellings, March 2000
//
// Description:  A persistent Flow nano DST
//
//  The StFlowNanoEvent class has a simple event structure:
//        TClonesArray     *fTracks;
//
//        Int_t            mNtrack;                    // track number
//        Int_t            mEventID;                   // event ID
//        UInt_t           mOrigMult;                  // number of StEvent tracks
//        UInt_t           mCentrality;                // centrality bin
//        StThreeVectorF   mVertexPos;                 // primary vertex position
//
//   The StFlowNanoEvent data member fTracks is a pointer to a TClonesArray.
//   It is an array of a variable number of tracks per event.
//   Each element of the array is an object of class StFlowTrack
//
//////////////////////////////////////////////////////////////////////
//
// $Log: StFlowNanoEvent.cxx,v $
// Revision 1.6  2000/05/26 21:29:30  posk
// Protected Track data members from overflow.
//
```

Elliptic flow centrality/energy dependence

The physics of the centrality dependence of elliptic flow

S.A. Voloshin [a,b], A.M. Poskanzer [a]

[a] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[b] *Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA*

Received 30 September 1999; received in revised form 13 December 1999; accepted 29 December 1999
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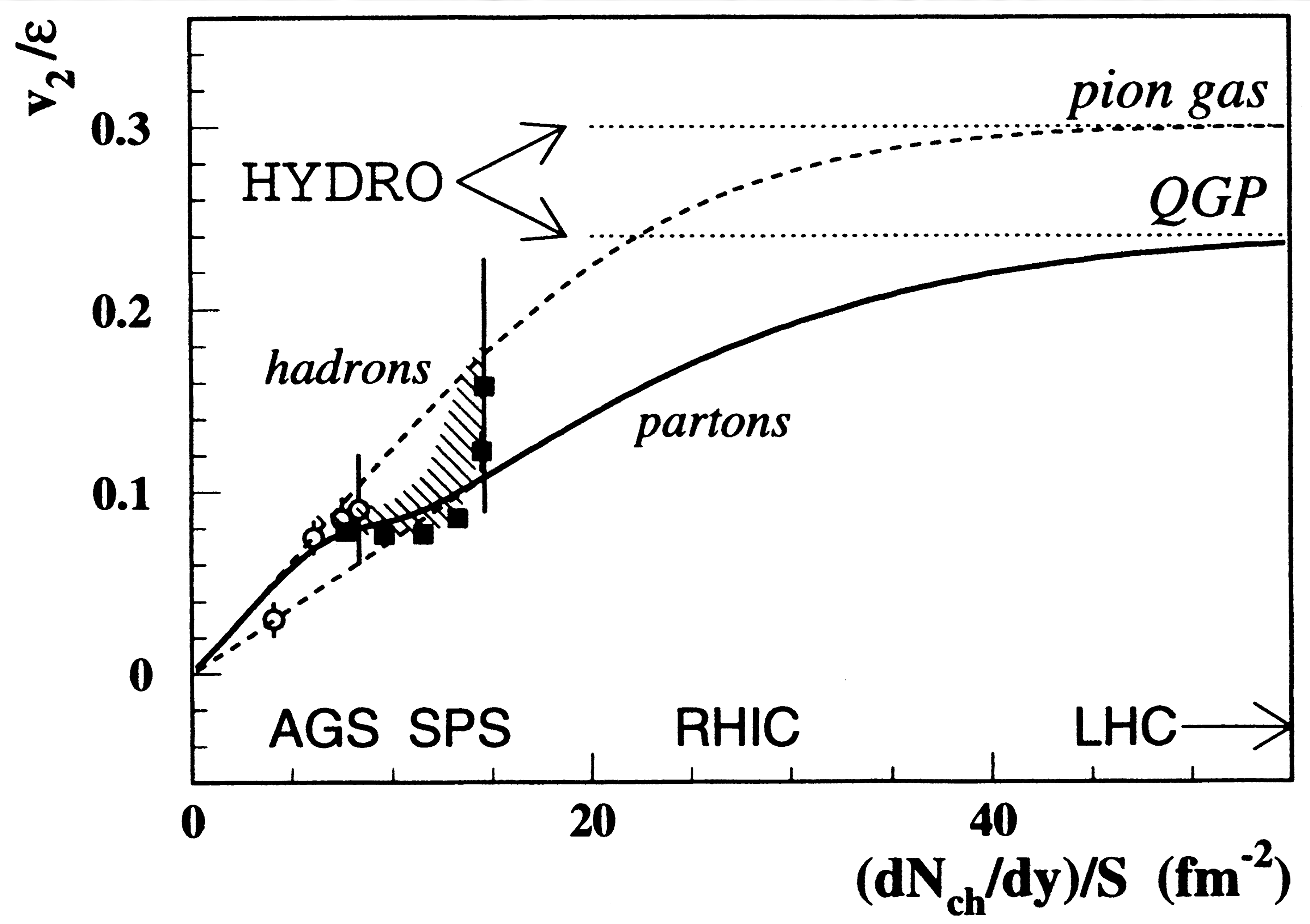

Fig. 3. Elliptic flow divided by the initial space elliptic anisotropy at the AGS (open circles) and the SPS (filled squares). The shaded area shows the uncertainty in the SPS experimental data due to the uncertainty in the centrality determination. See text and footnote for the description of the curves and hydro limits.

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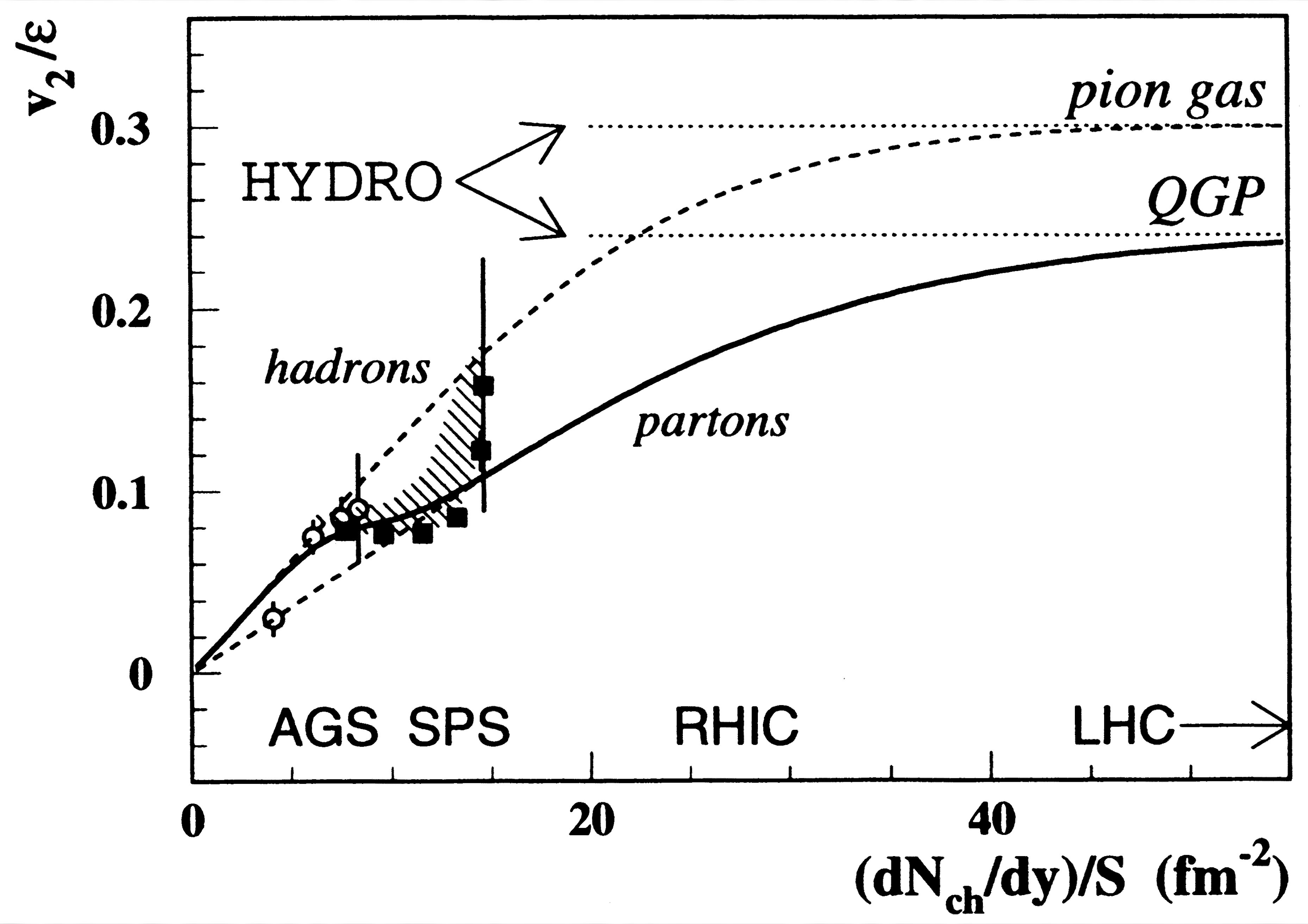

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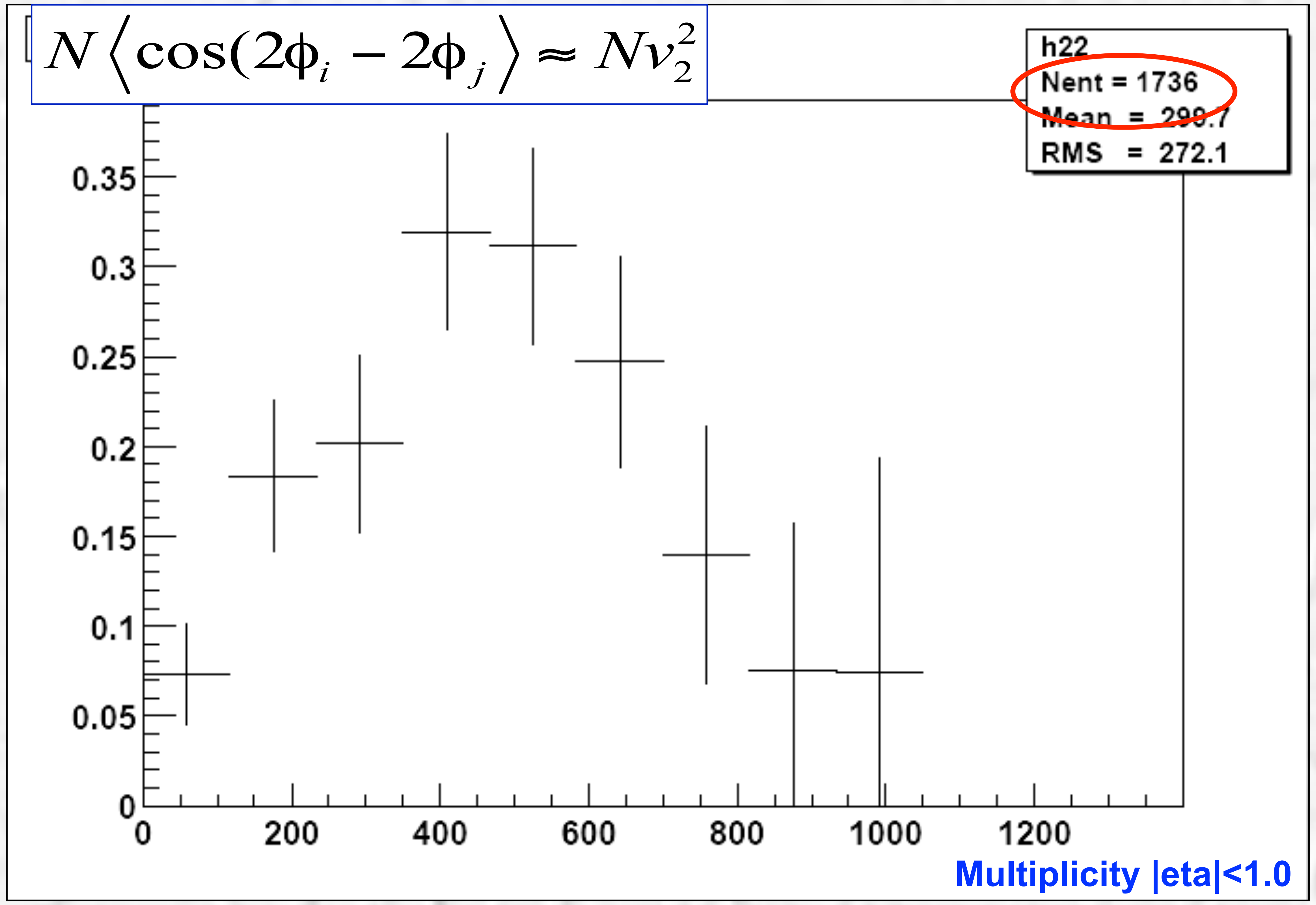
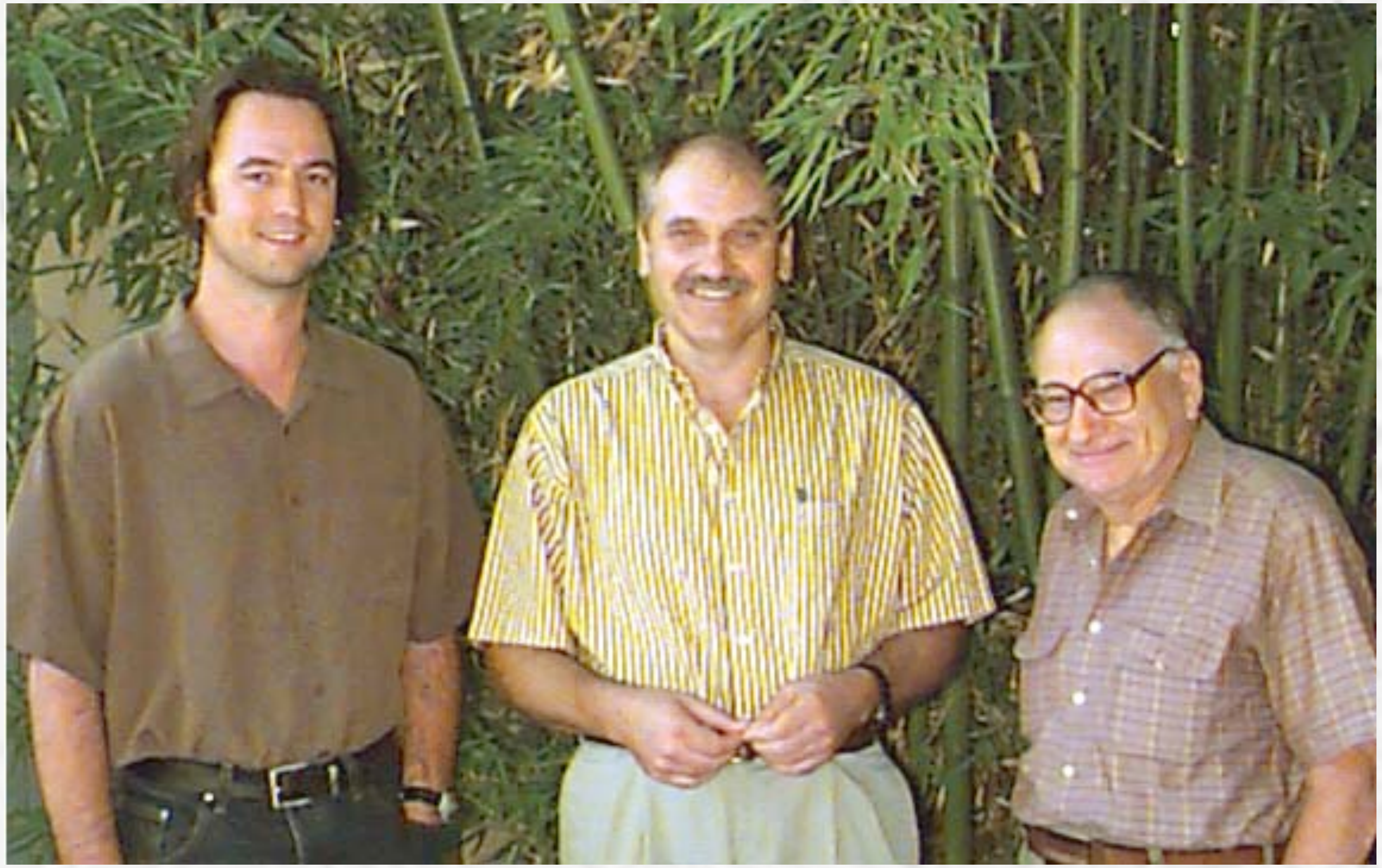
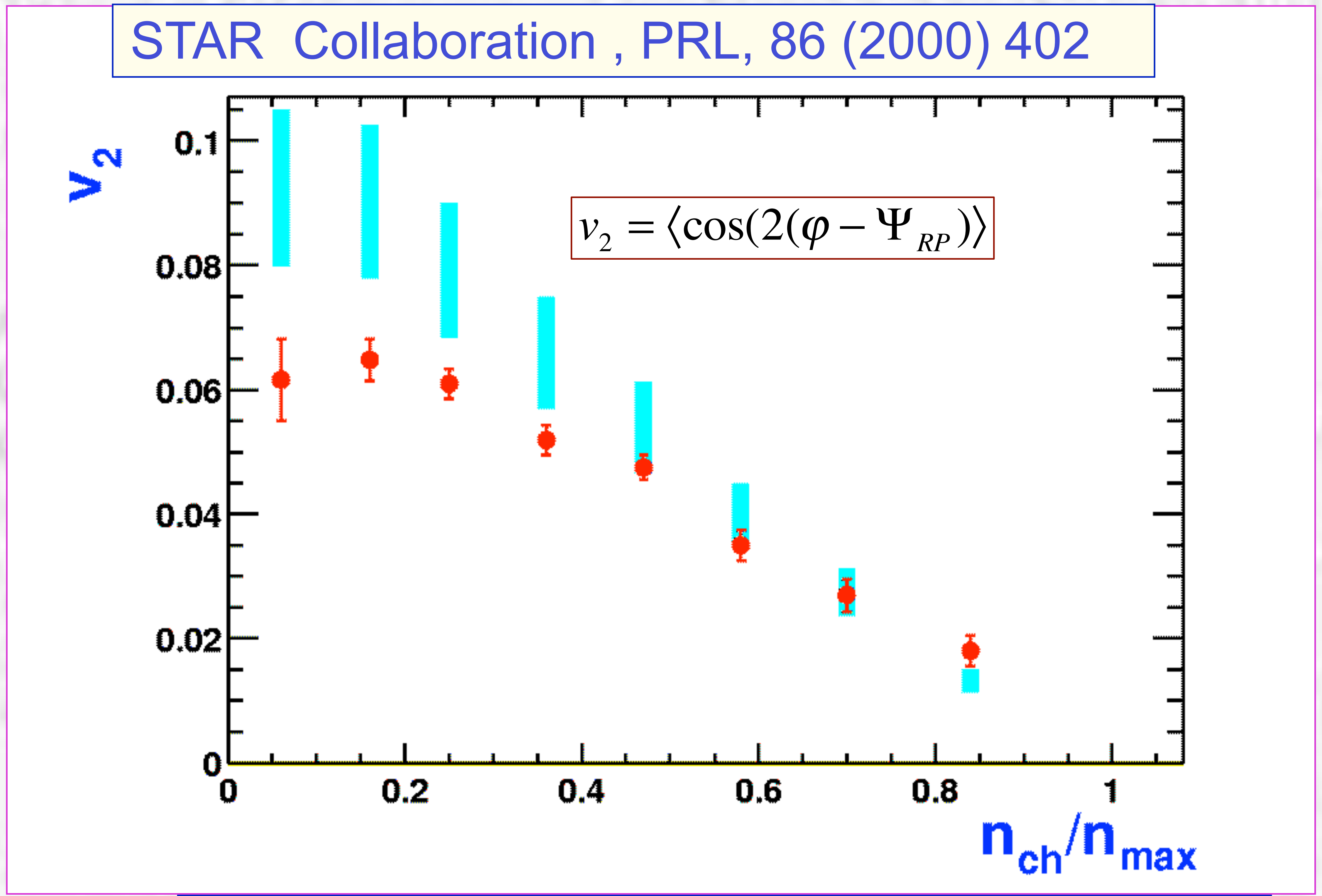
2-particle azimuthal correlations



Results from data taken during the first three hours of RHIC operation

First observation of elliptic flow at RHIC (STAR)





For the first time in Heavy-Ion Collisions the flow measurements are in quantitative agreement with hydrodynamic model predictions up to mid-central collisions

Dense and (likely) thermalized matter

Elliptic flow centrality/energy dependence

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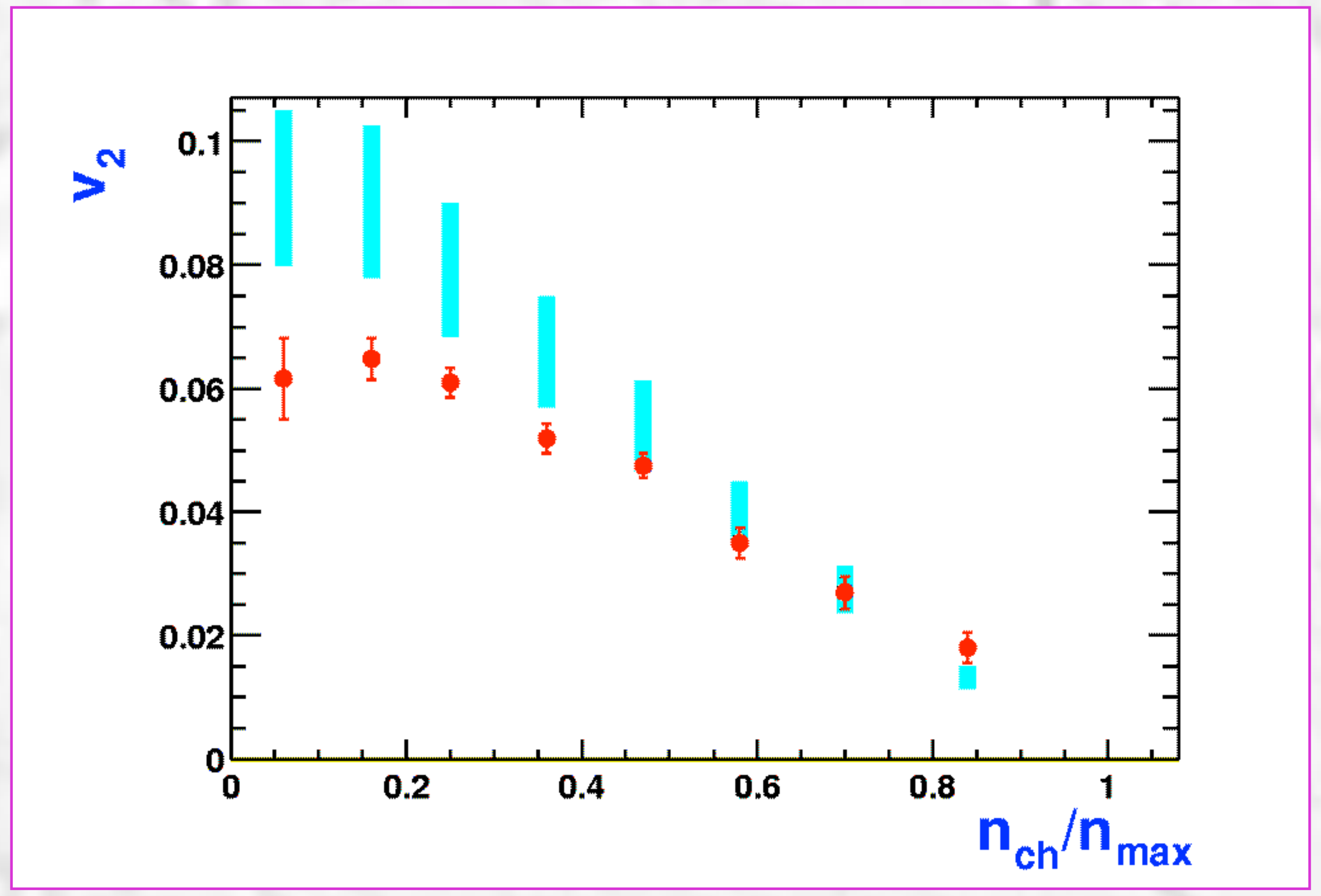

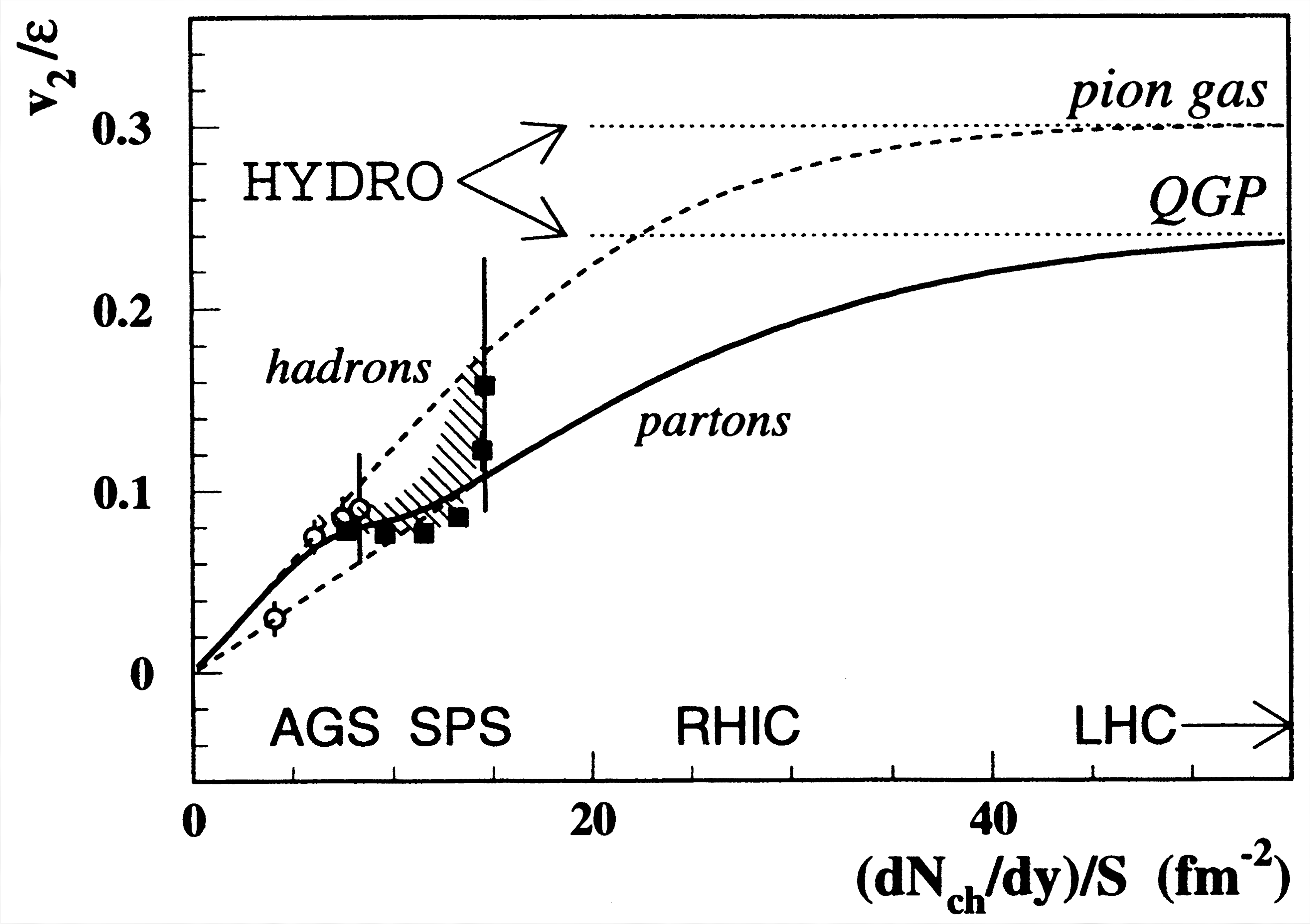

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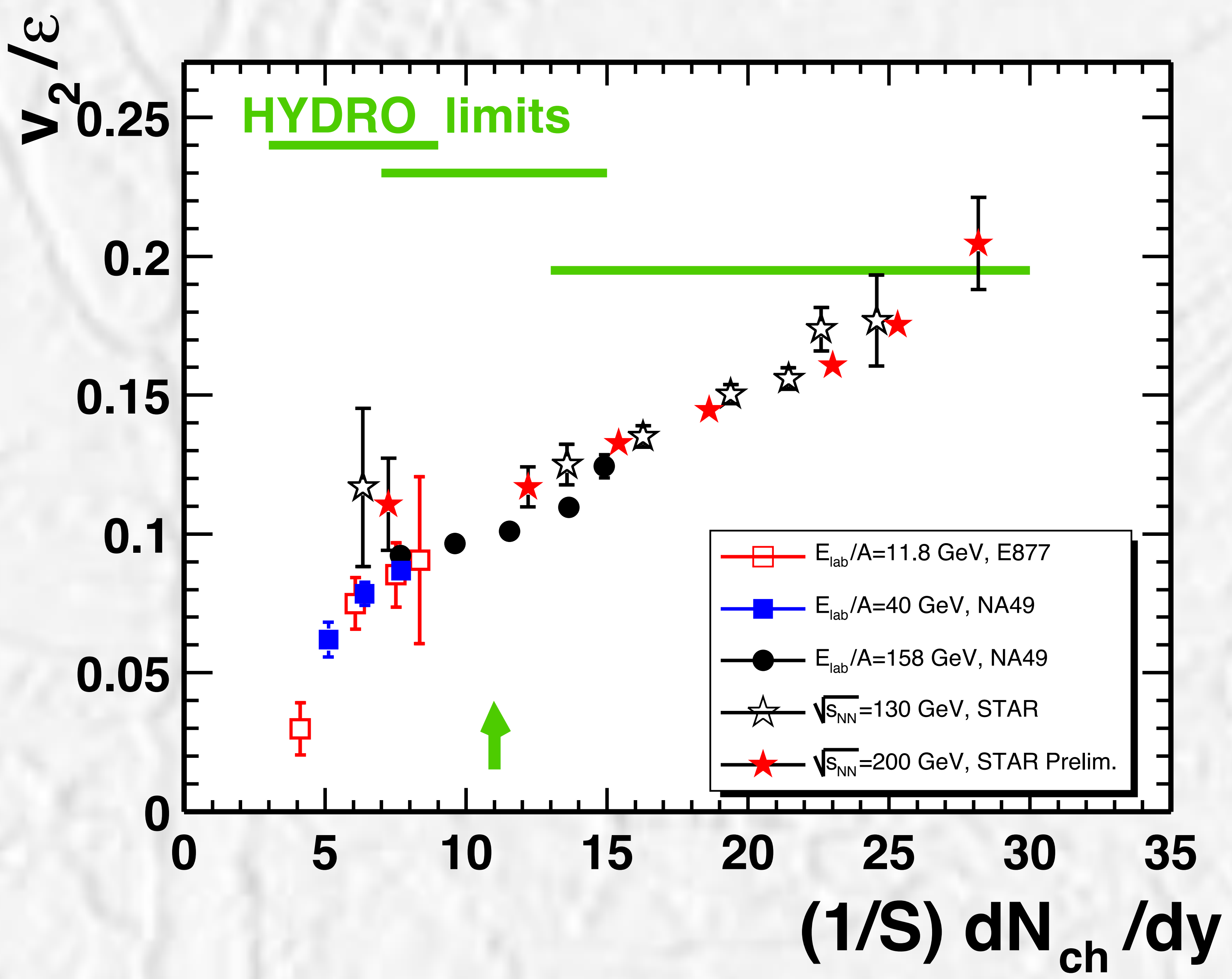


FIG. 25. (Color online) v_2/ϵ as a function of particle density. The v_2 values are for near midrapidity ($0<y<0.6$ for 40*A* GeV and $0<y<0.8$ for 158*A* GeV). The results of NA49 pion v_2 are compared to charged particle v_2 measured by E877 and STAR. The meaning of the horizontal lines (hydro limits) and of the arrow will be discussed in Sec. VI.

QGP - The Perfect fluid

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 perva

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 momen
results from an atom-smashing experiment.

New State of Matter Is 'Nearly Perfect' Liquid

Image: BNL

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.

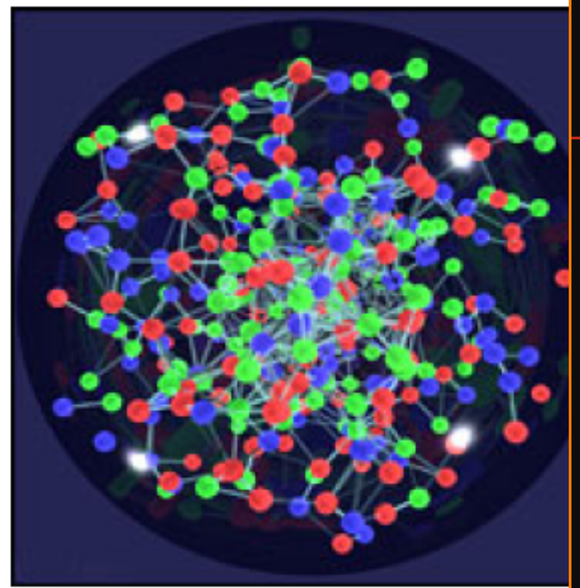
SCIENTIFIC AMERICAN

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 patterns of the atoms' trajectories after these collisions, they

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 that is more strongly interacting than predicted

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

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

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

05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
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、
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、気体のように自由に跳び回る
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基本粒子クオークとそれらをく

Science　Iran Daily　April 20, 2005　4

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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 affects a flui flow and th to objects try through it. high viscos viscosity is fect liquid ha ity at all, wh sible in reali for theoreti sions.

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Early Universe Went With the Flow

Posted April 18, 2005 5:57PM

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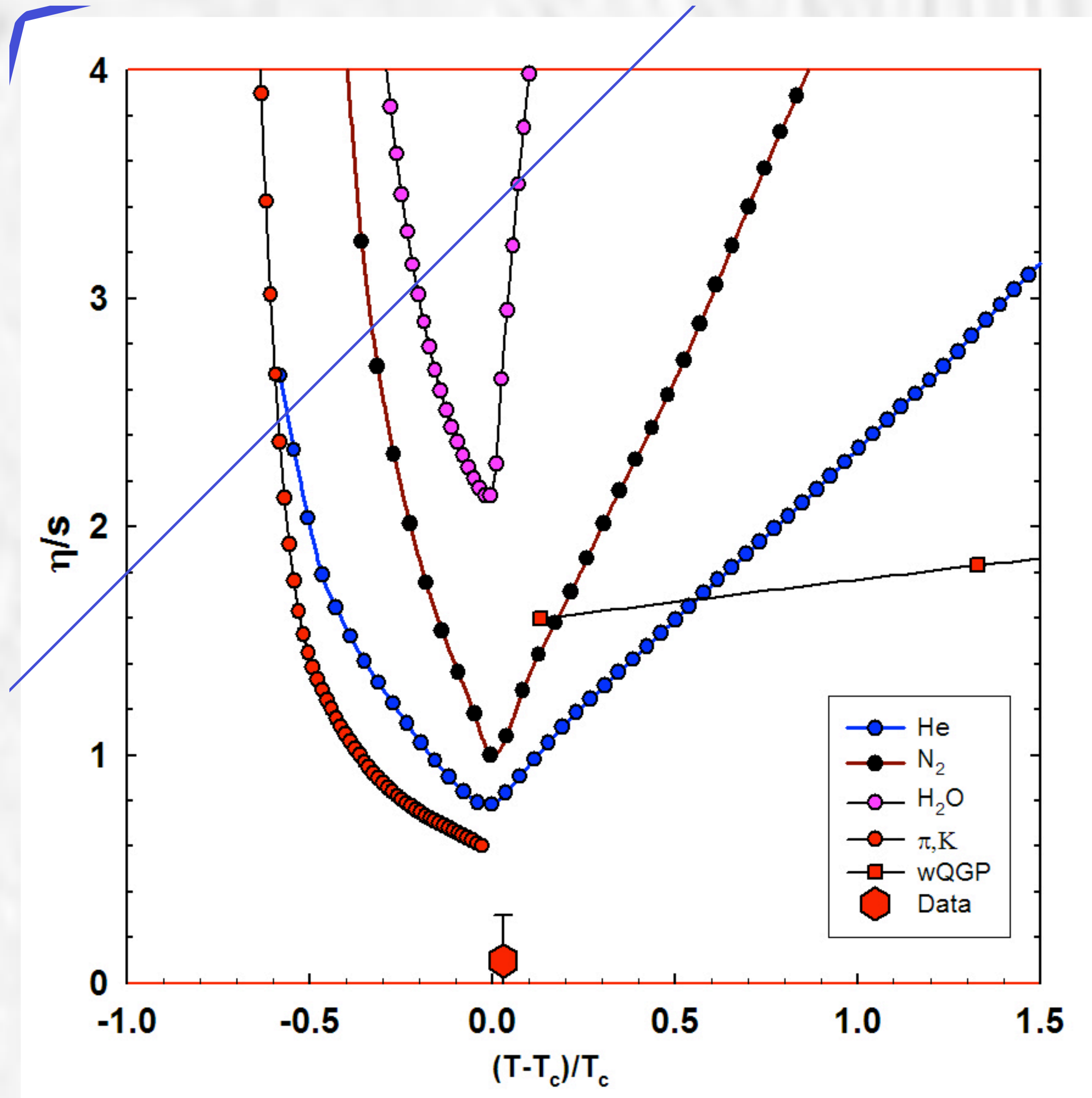

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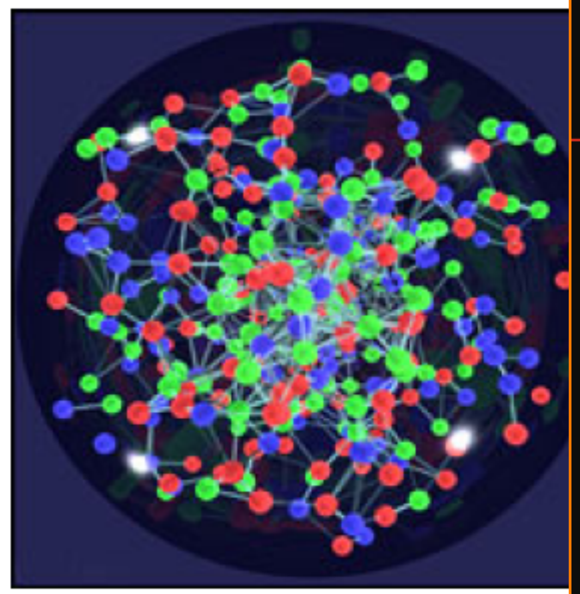

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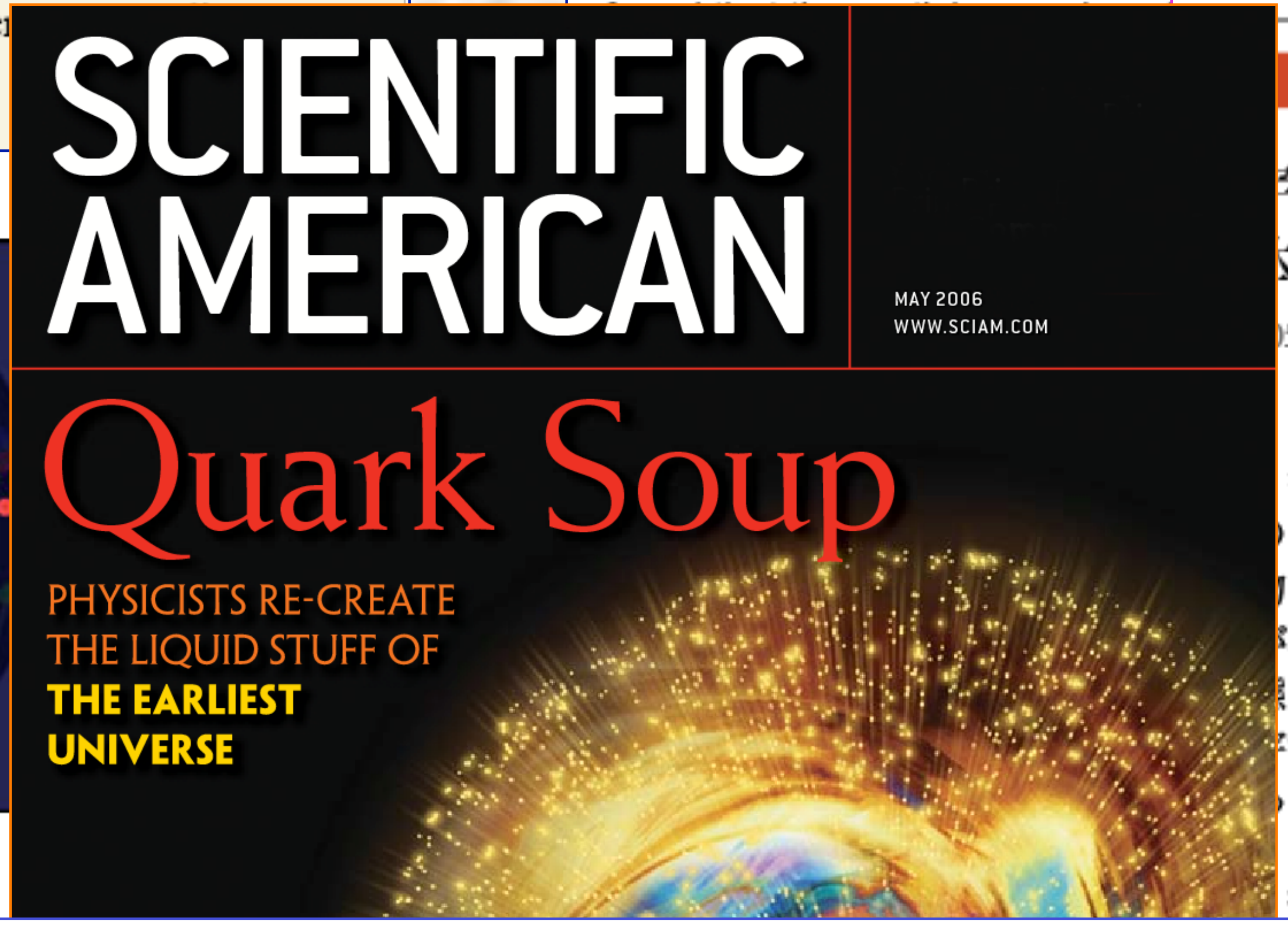

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Energy dependence: AGS-SPS-RHIC-LHC

version 7, November 7, 2010. Text: new, old, questions

Elliptic flow of charged particles in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

de M. Michel Nostradamus

We report the first measurement of charged particle elliptic flow in Pb+Pb collisions at $\sqrt{s_{NN}}=$ 2.76 TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.25 < p_t < 5$ GeV/c. The elliptic flow signal, v_2, averaged over transverse momentum and pseudorapidity, reaches values of 0.085 for relatively peripheral collisions (40–50% most central). The differential elliptic flow $v_2(p_t)$ reaches a maximum of 0.25 around $p_t = 3$ GeV/c. Compared to RHIC Au+Au collisions at $\sqrt{s_{NN}}=$ 200 GeV, the elliptic flow increases by about 15% in agreement with hydrodynamical model predictions.

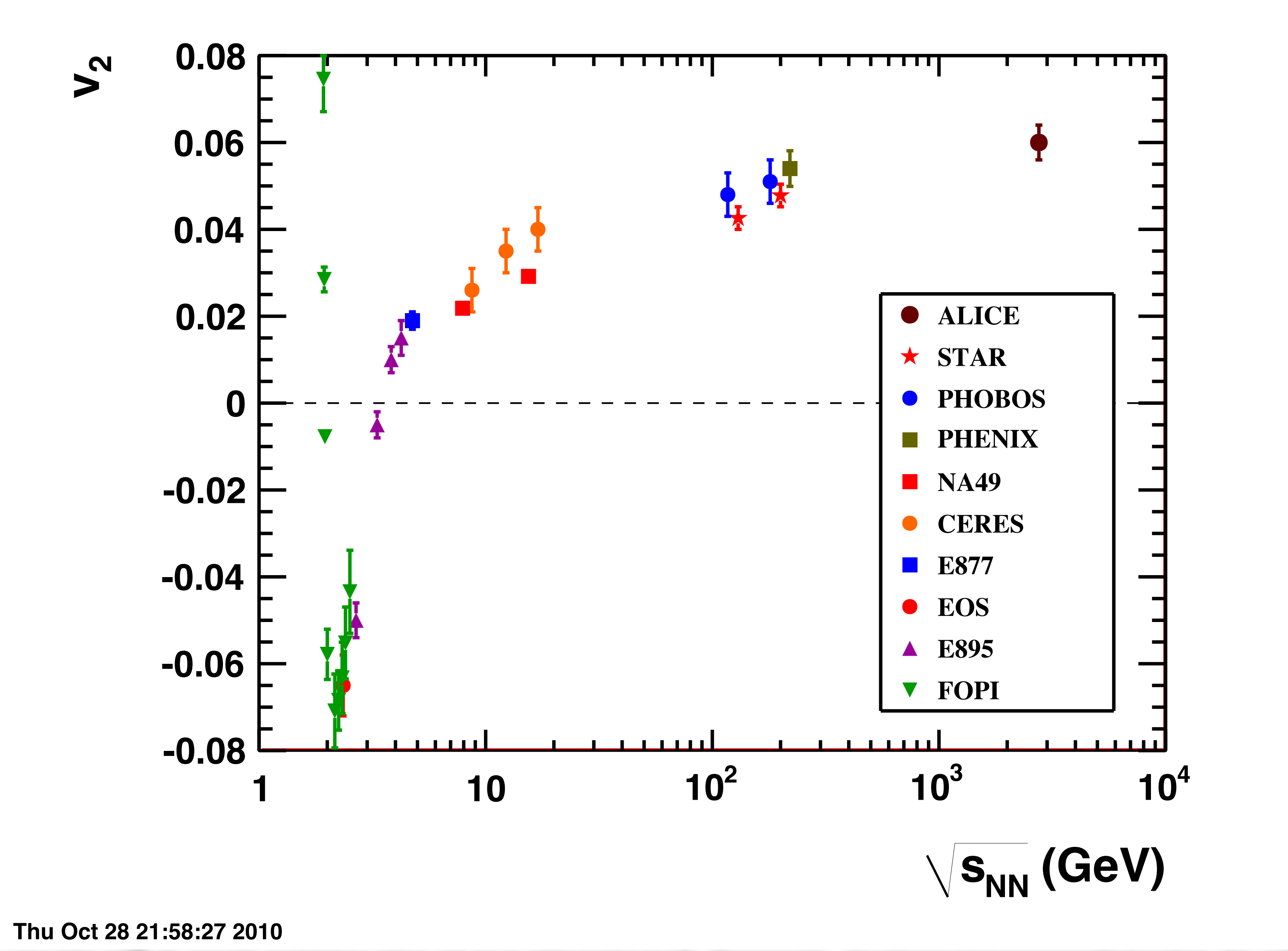

FIG. 4. Integrated elliptic flow in Pb+Pb 20–30% centrality collisions at 2.76 TeV compared with results from lower energies taken at similar centralities. The compilation is taken from [26].

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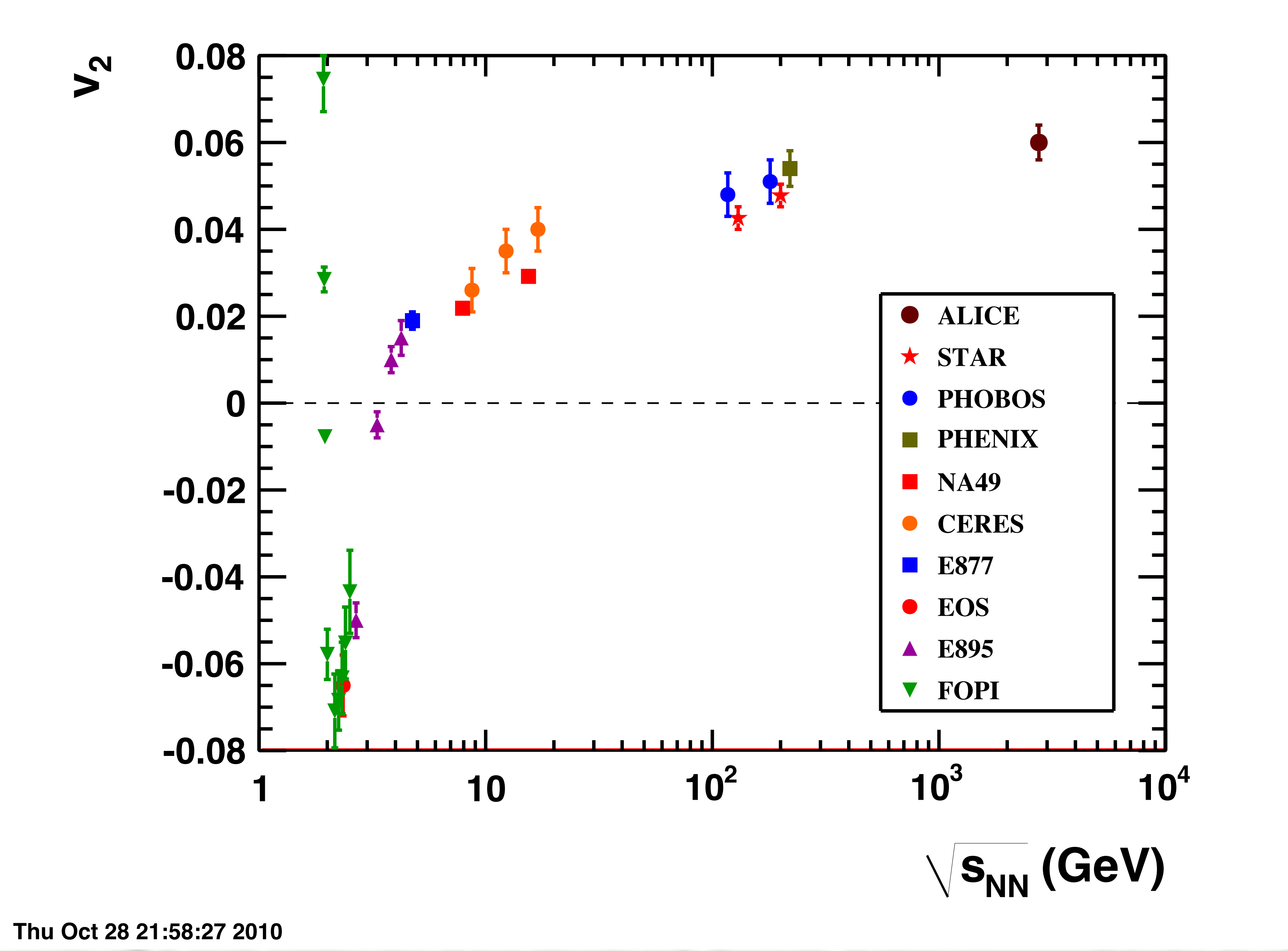

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Selected for a Viewpoint in *Physics*
PRL **105,** 252302 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

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K. Aamodt *et al.**
(ALICE Collaboration)

(Received 18 November 2010; published 13 December 2010)

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

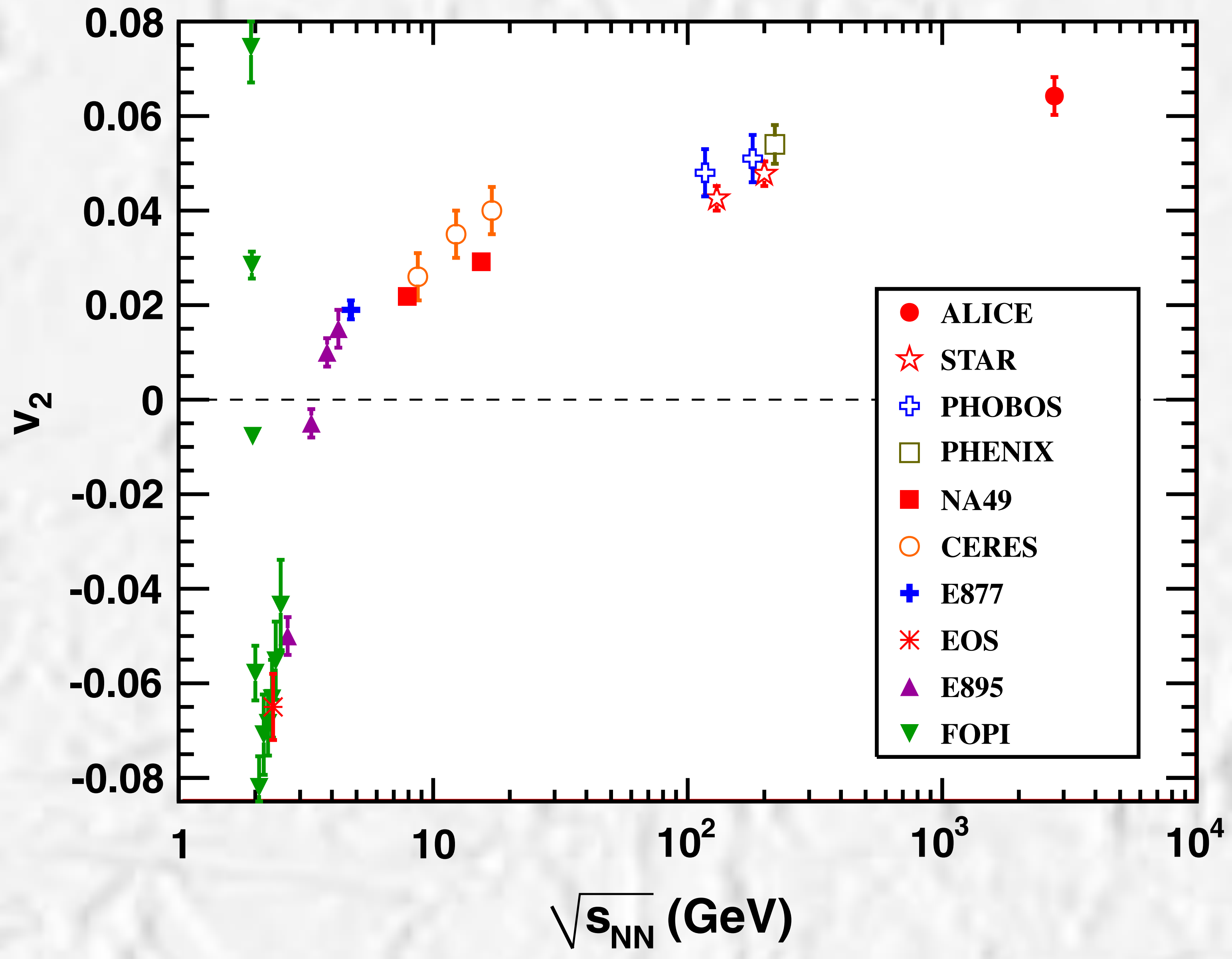

FIG. 4 (color online). Integrated elliptic flow at 2.76 TeV in Pb-Pb 20%–30% centrality class compared with results from lower energies taken at similar centralities [40,43].

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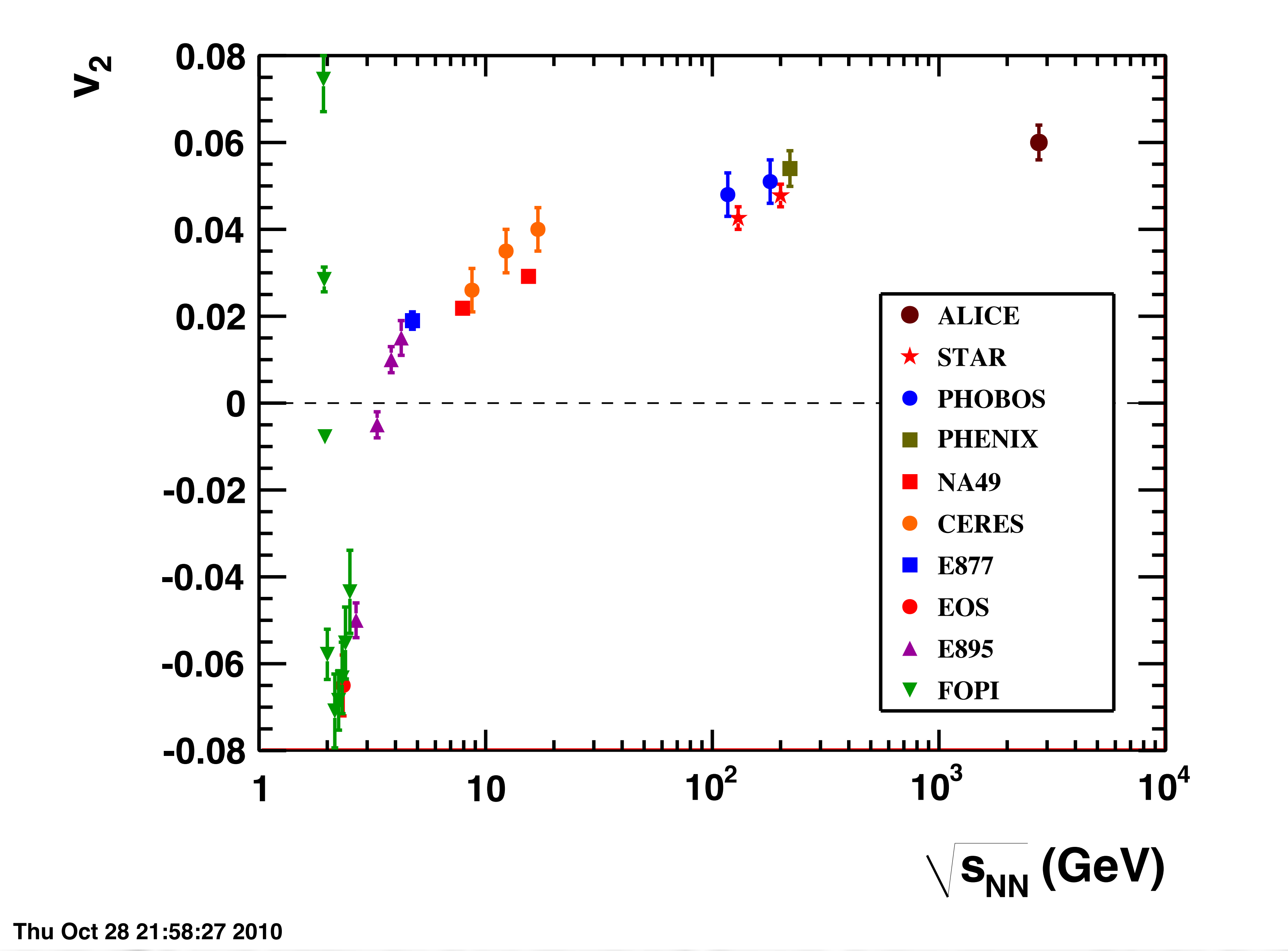

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(ALICE Collaboration)

(Received 18 November 2010; published 13 December 2010)

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

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

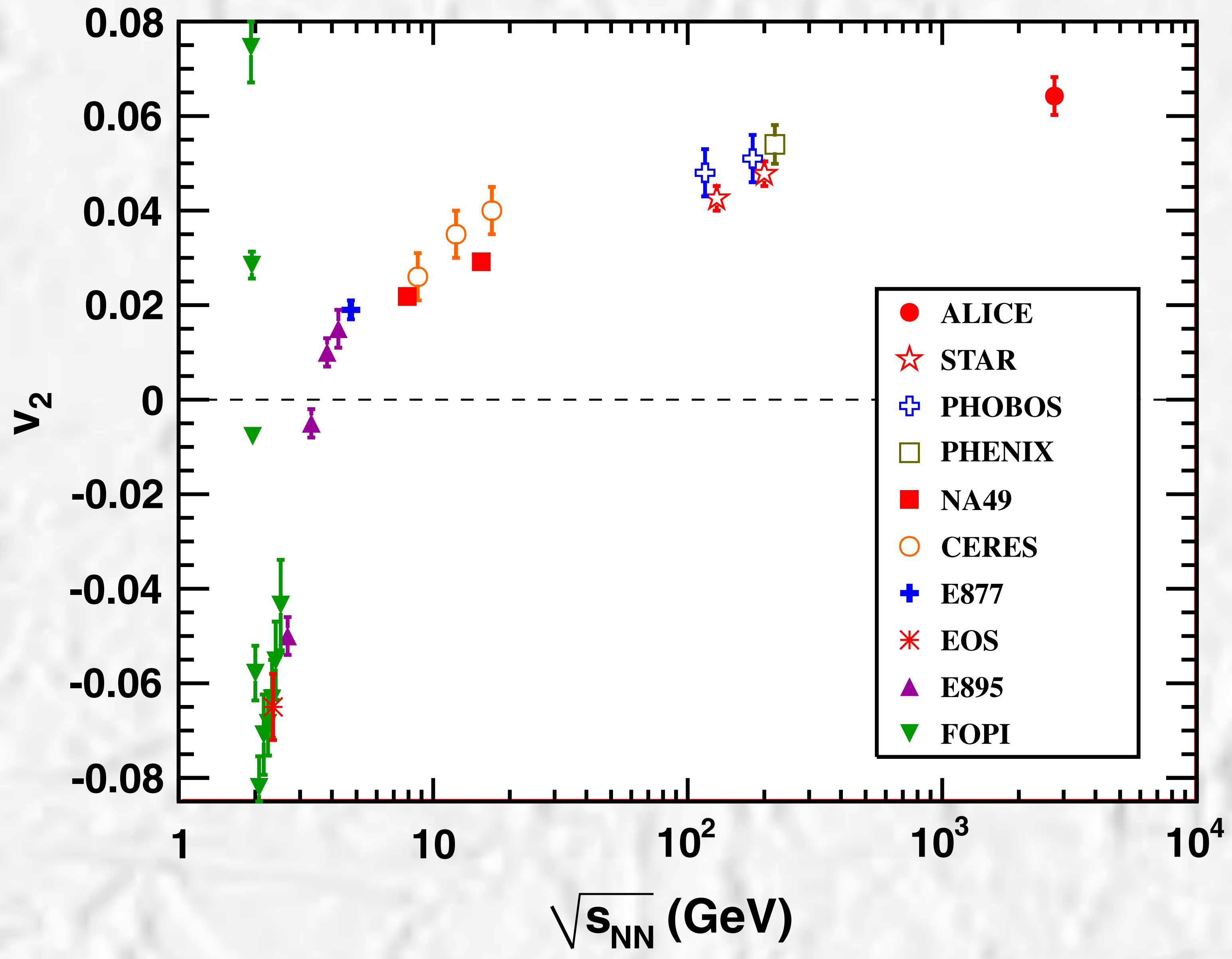
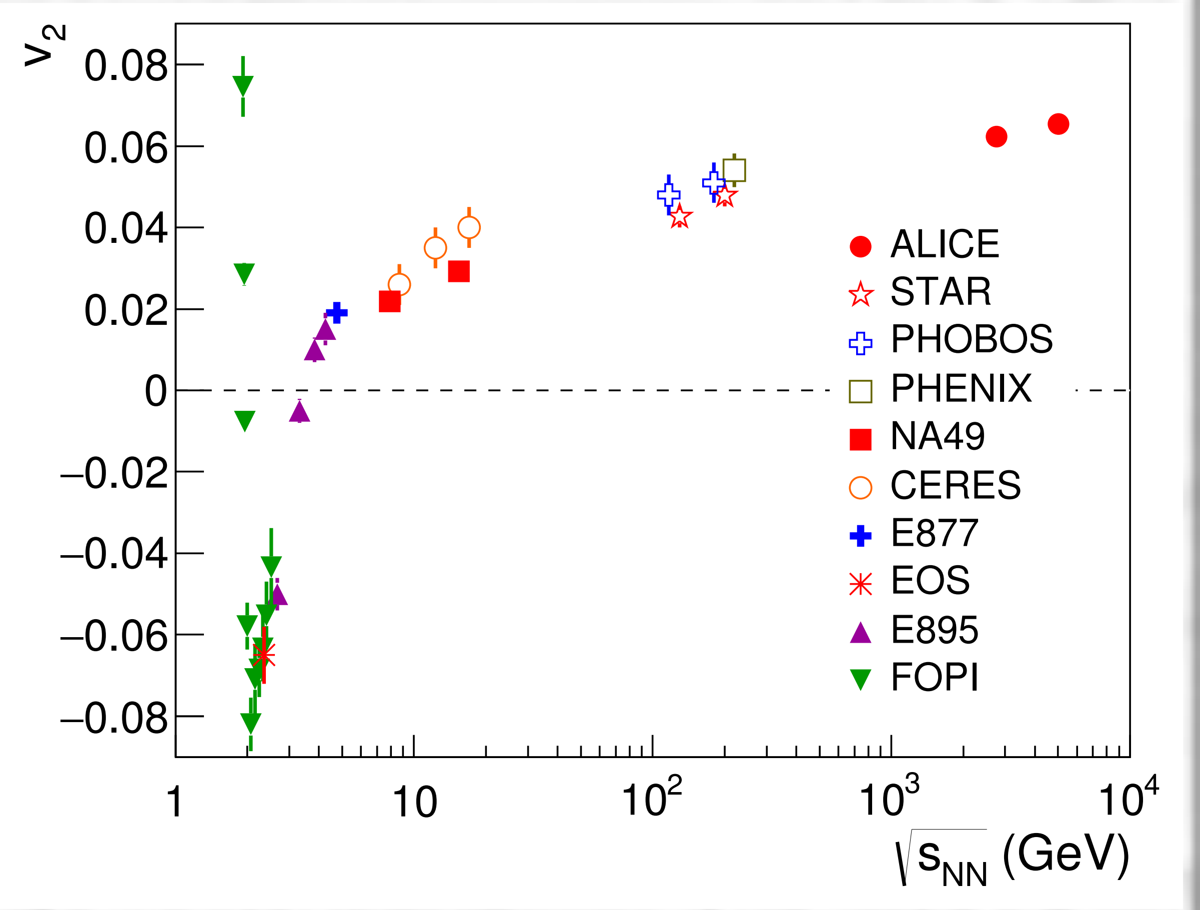
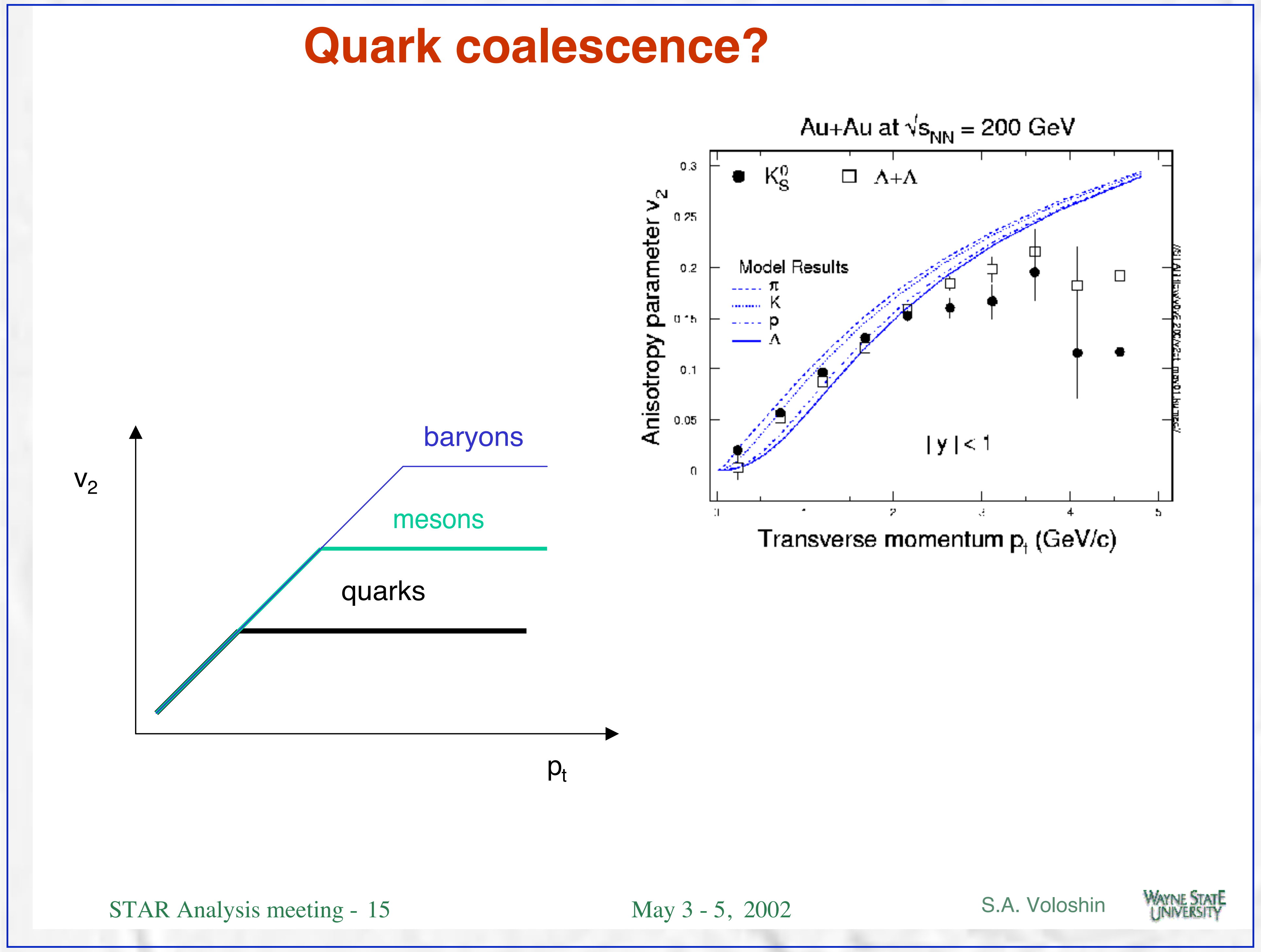


FIG. 4 (color online). Integrated elliptic flow at 2.76 TeV in Pb-Pb 20%–30% centrality class compared with results from lower energies taken at similar centralities [40,43].

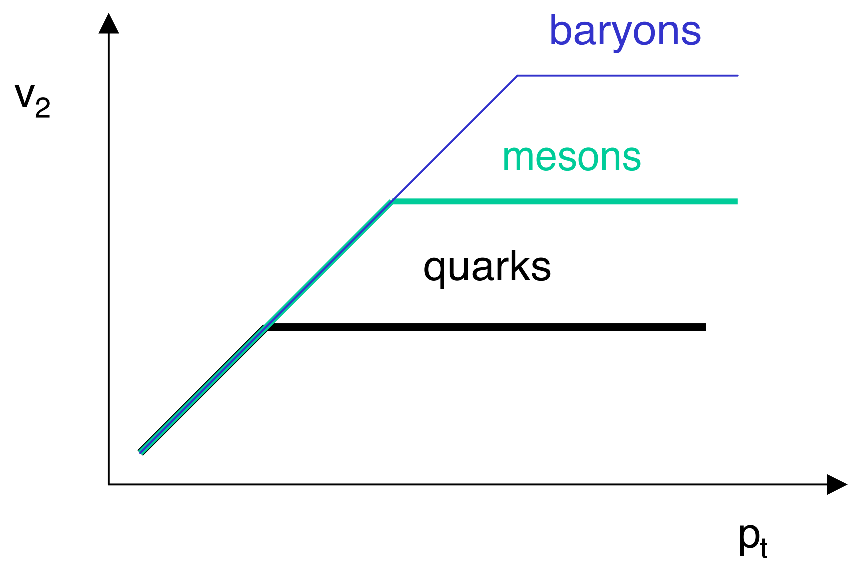


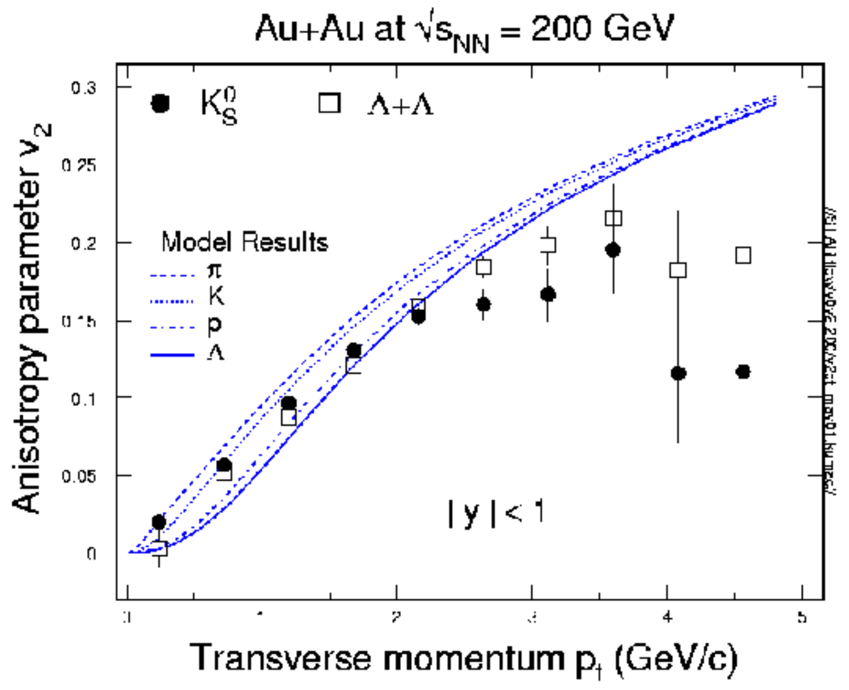
Constituent quark scaling



Constituent quark scaling

Quark coalescence?



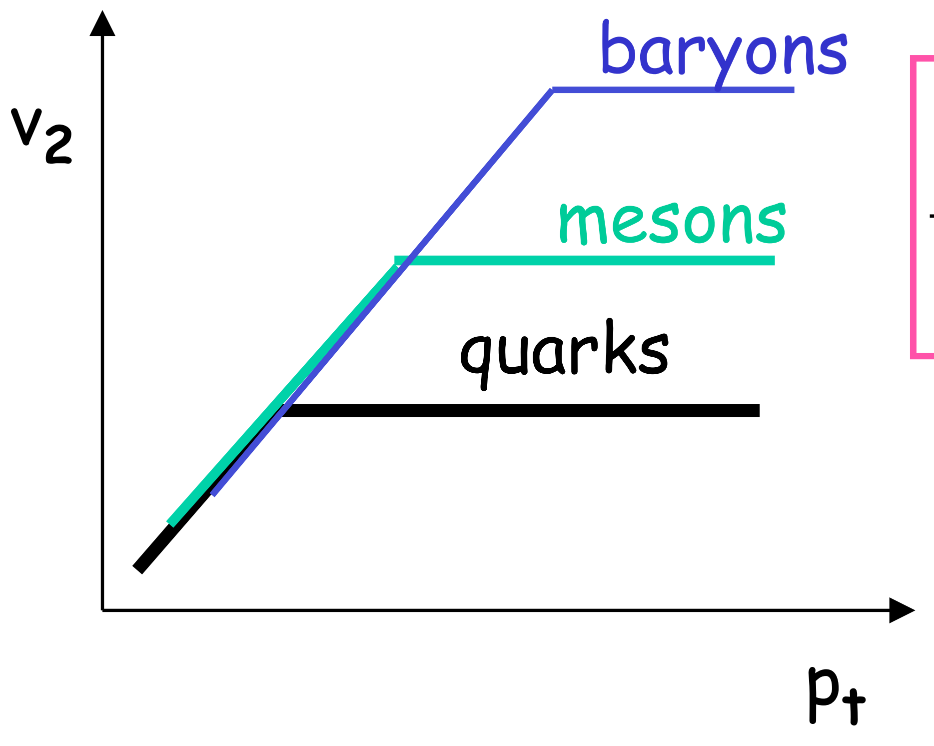


Constituent quark model + coalescence

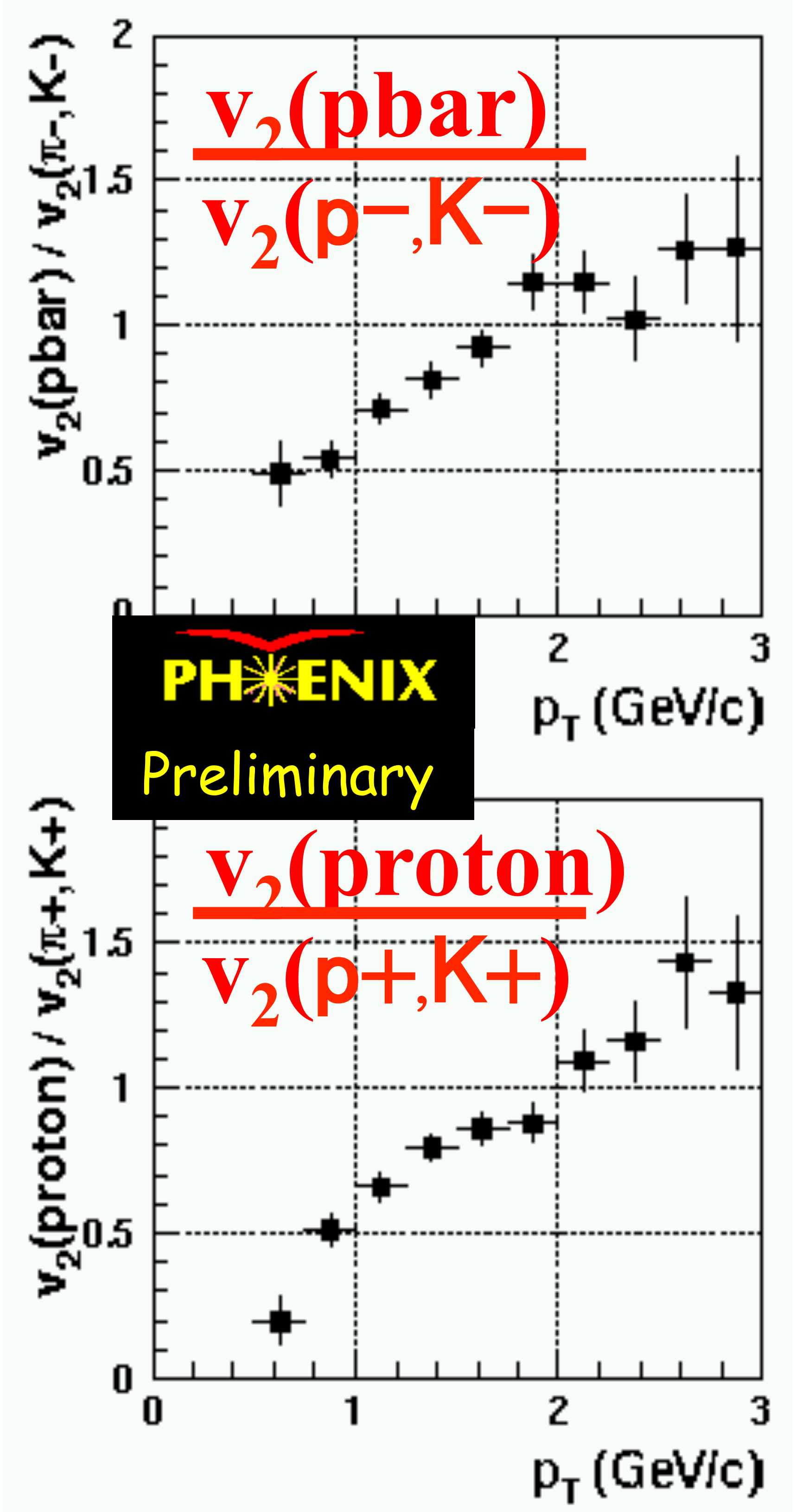
coalescence — fragmentation

Low p_t quarks — High p_t quarks

Coalescence in the intermediate region (rare products):



$$\frac{d^3 n_M}{d^3 p_M} \propto \left[\frac{d^3 n_q}{d^3 p_q}\left(p_q \approx p_M / 2\right)\right]^2$$



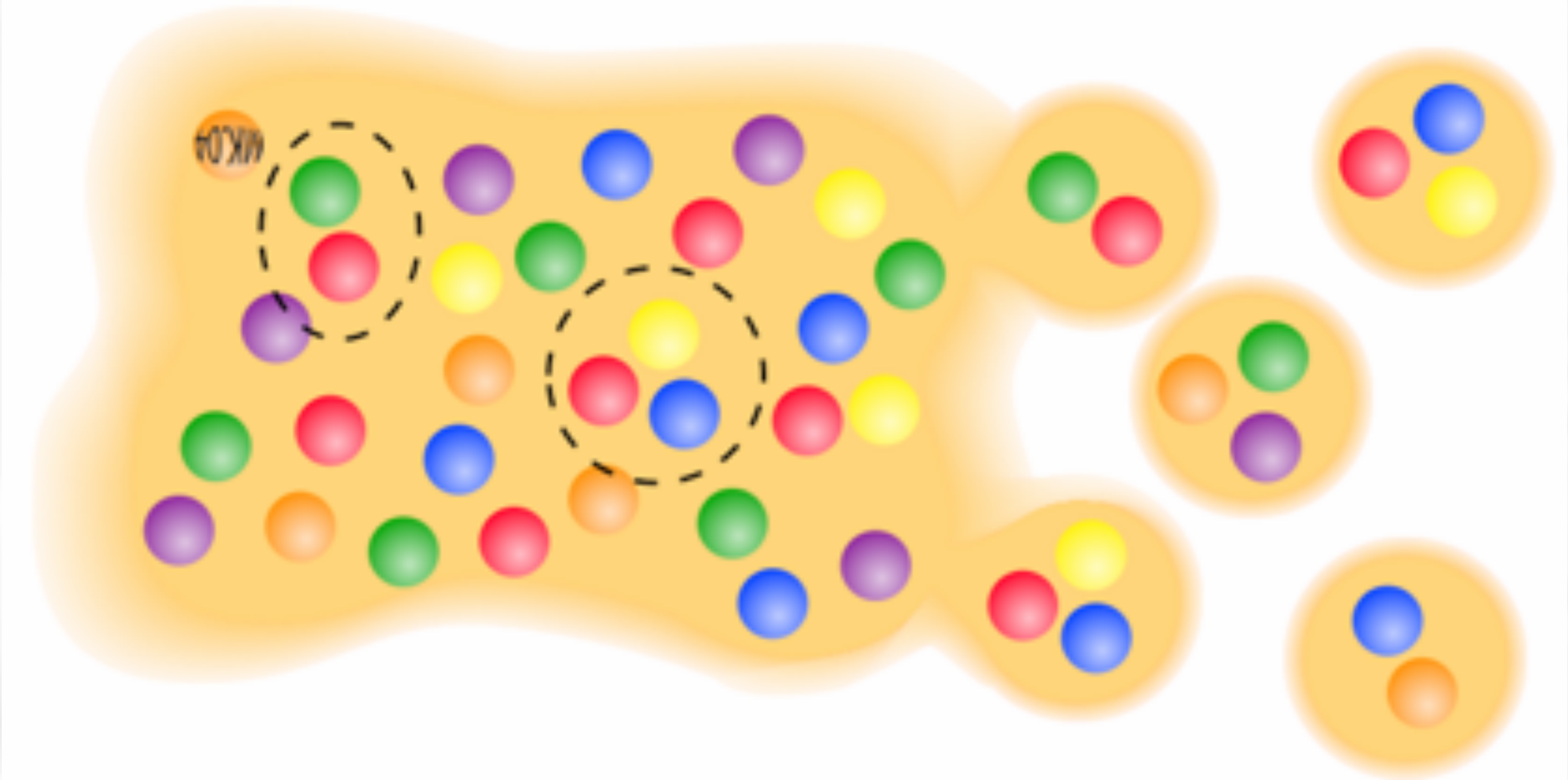
Side-notes:
a) more particles produced via coalescence vs parton fragmentation ➔ larger mean p_t...
b) ➔ higher baryon/meson ratio

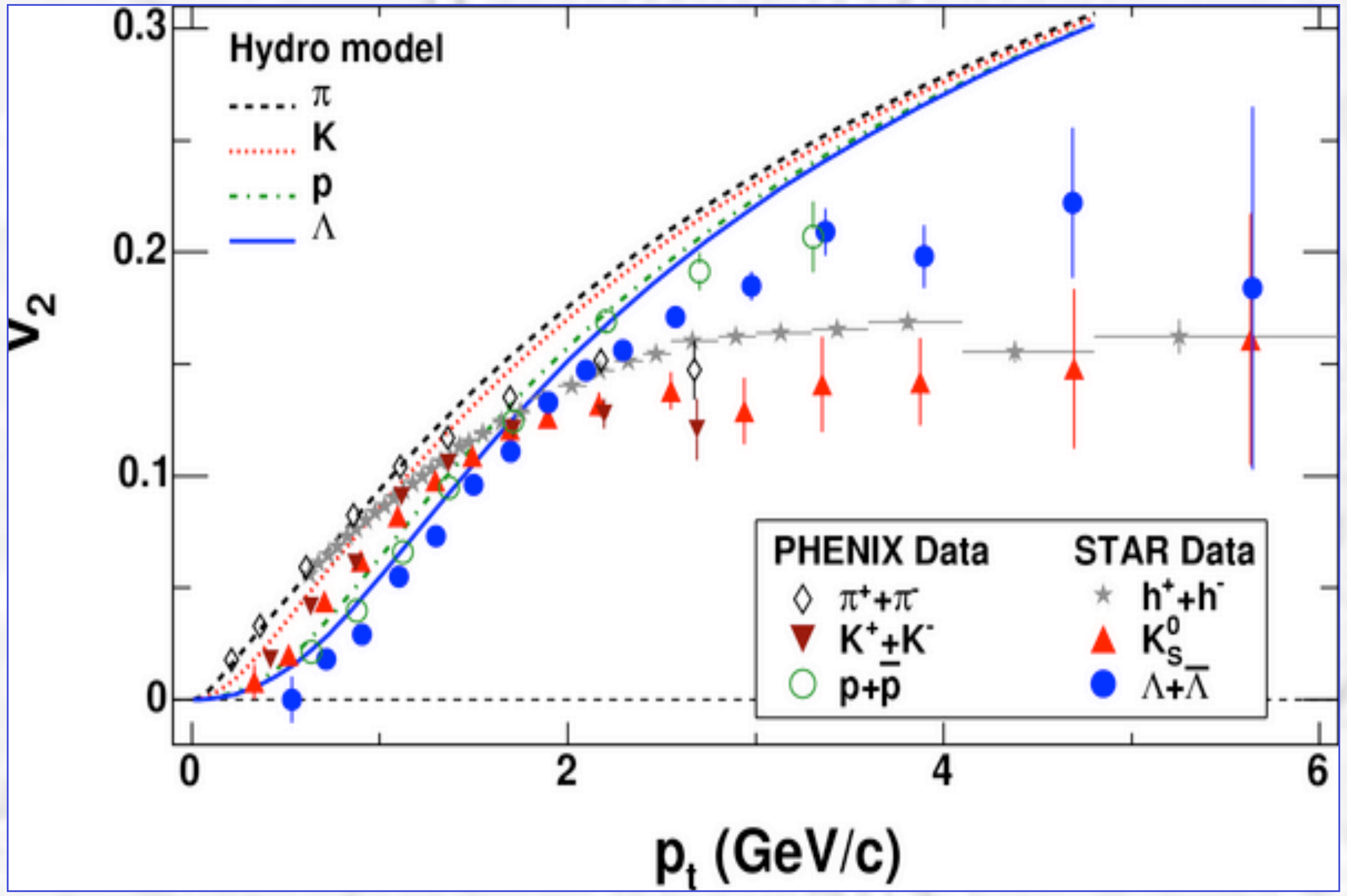
- What is the centrality dependence of the effect?

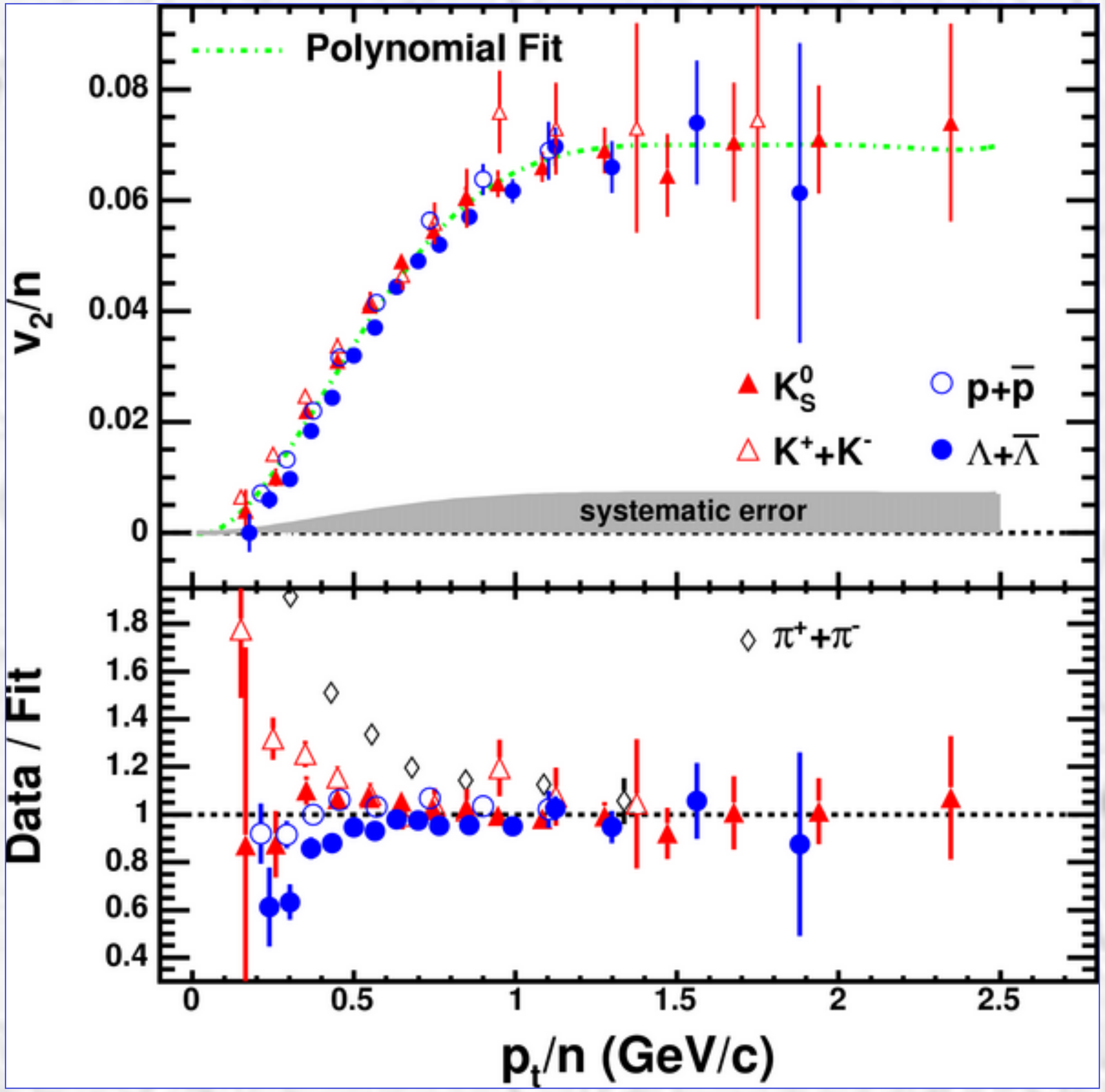
Quarks flow - deconfinement

STAR PRL 92(2004)052302

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



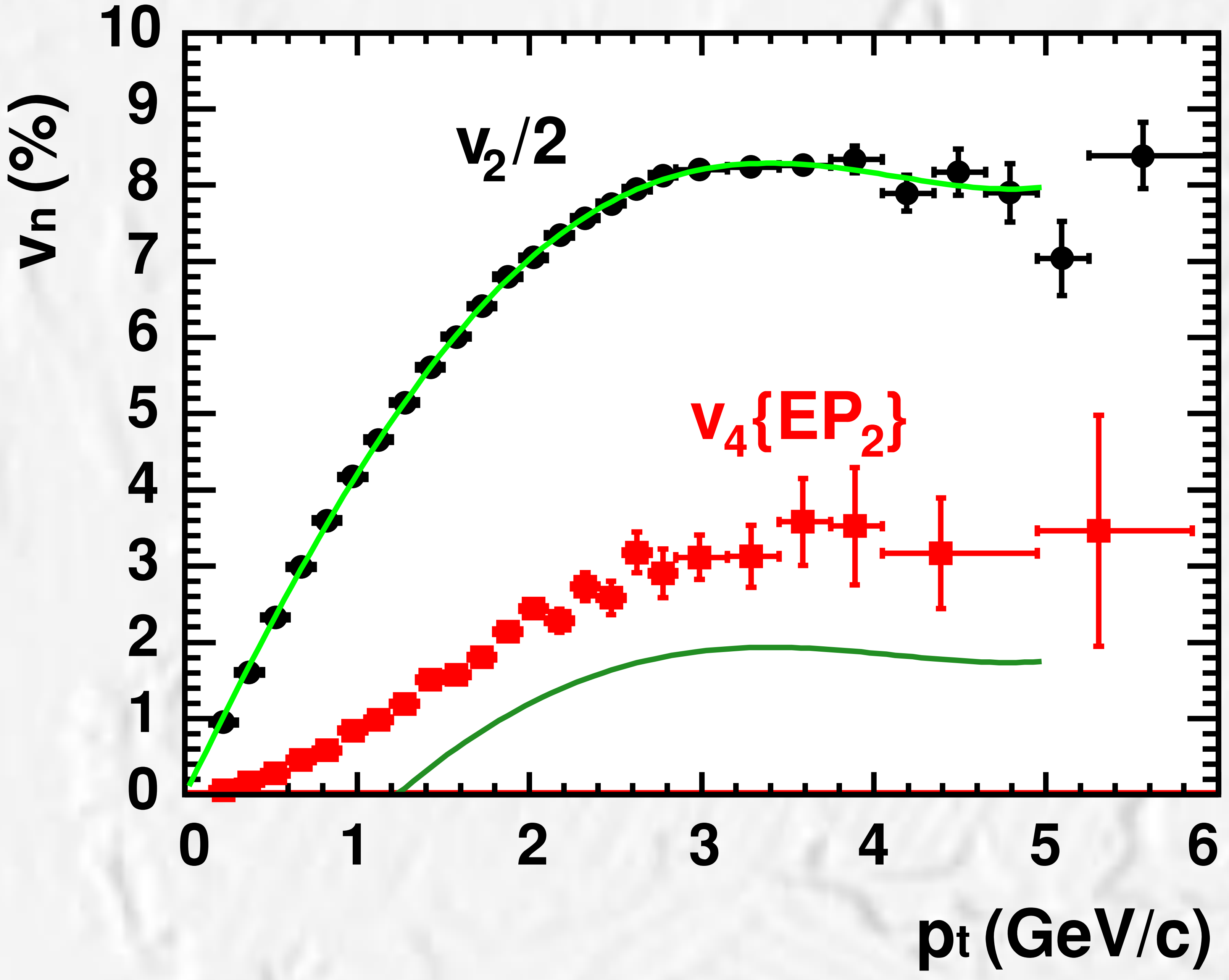


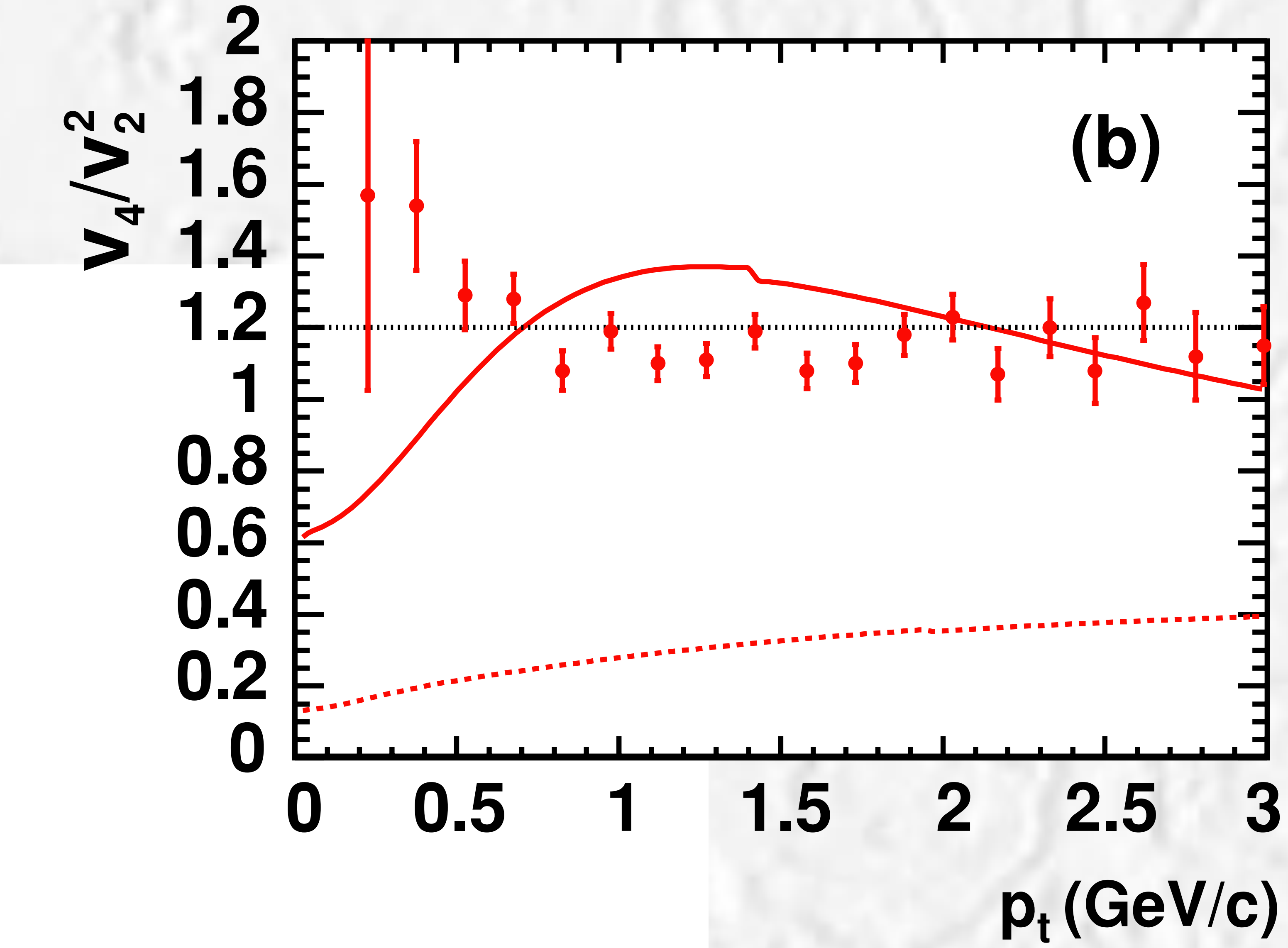


v_2 and v_4

PHYSICAL REVIEW C **72**, 014904 (2005)

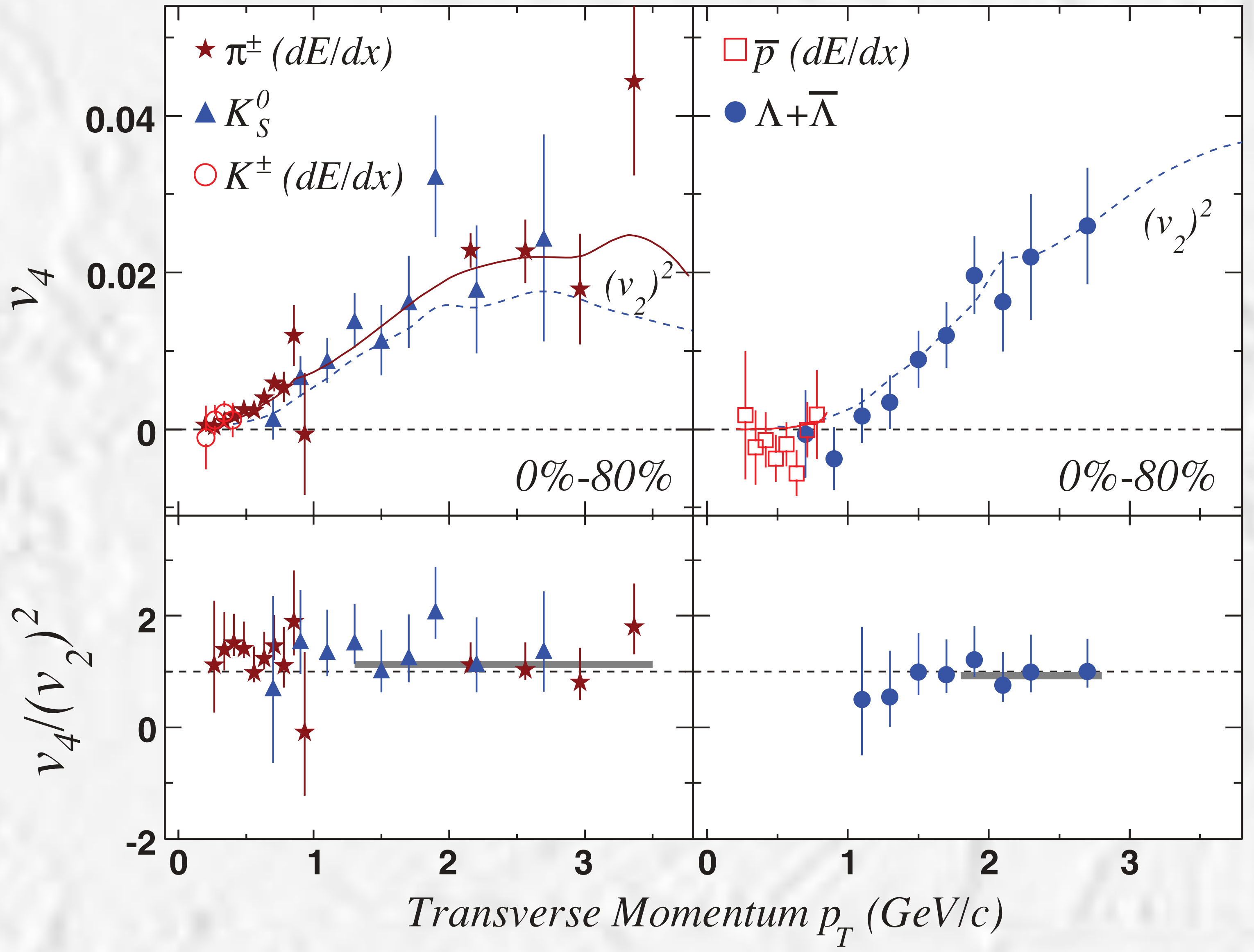
Azimuthal anisotropy in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV





PHYSICAL REVIEW C **75**, 054906 (2007)

Mass, quark-number, and $\sqrt{s_{NN}}$ dependence of the second and fourth flow harmonics in ultrarelativistic nucleus-nucleus collisions



Physical Review C 50th Anniversary Milestones

PHYSICAL REVIEW C

NCQ scaling in nonlinear flow modes

JHEP

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RECEIVED: *February 10, 2020*
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PUBLISHED: *June 24, 2020*

Non-linear flow modes of identified particles in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

ALICE
The ALICE collaboration

$$V_{\mathrm{n}} = v_{\mathrm{n}} e^{i\mathrm{n}\Psi_{\mathrm{n}}}$$

$$V_4 = V_4^{\mathrm{L}} + V_4^{\mathrm{NL}} = V_4^{\mathrm{L}} + \chi_{4,22}(V_2)^2,$$

Does the ratio of baryon and meson flow in nonlinear modes equals to the square or first power of that in linear parts?

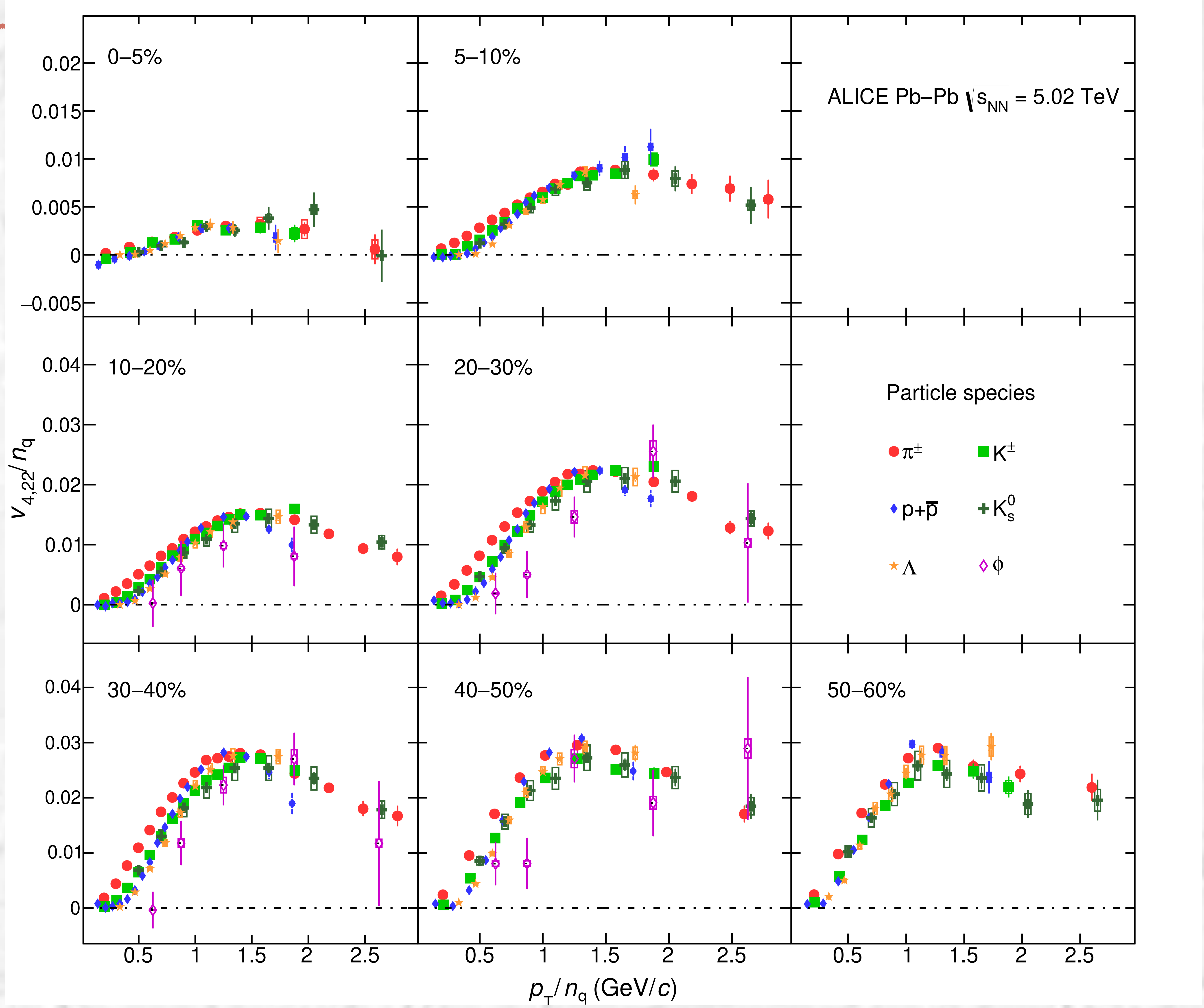


Figure 10. The p_{T}/n_q-dependence of $v_{4,22}/n_q$ for different particle species grouped into different centrality intervals of Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Statistical and systematic uncertainties are shown as bars and boxes, respectively.

Flow and Non-flow

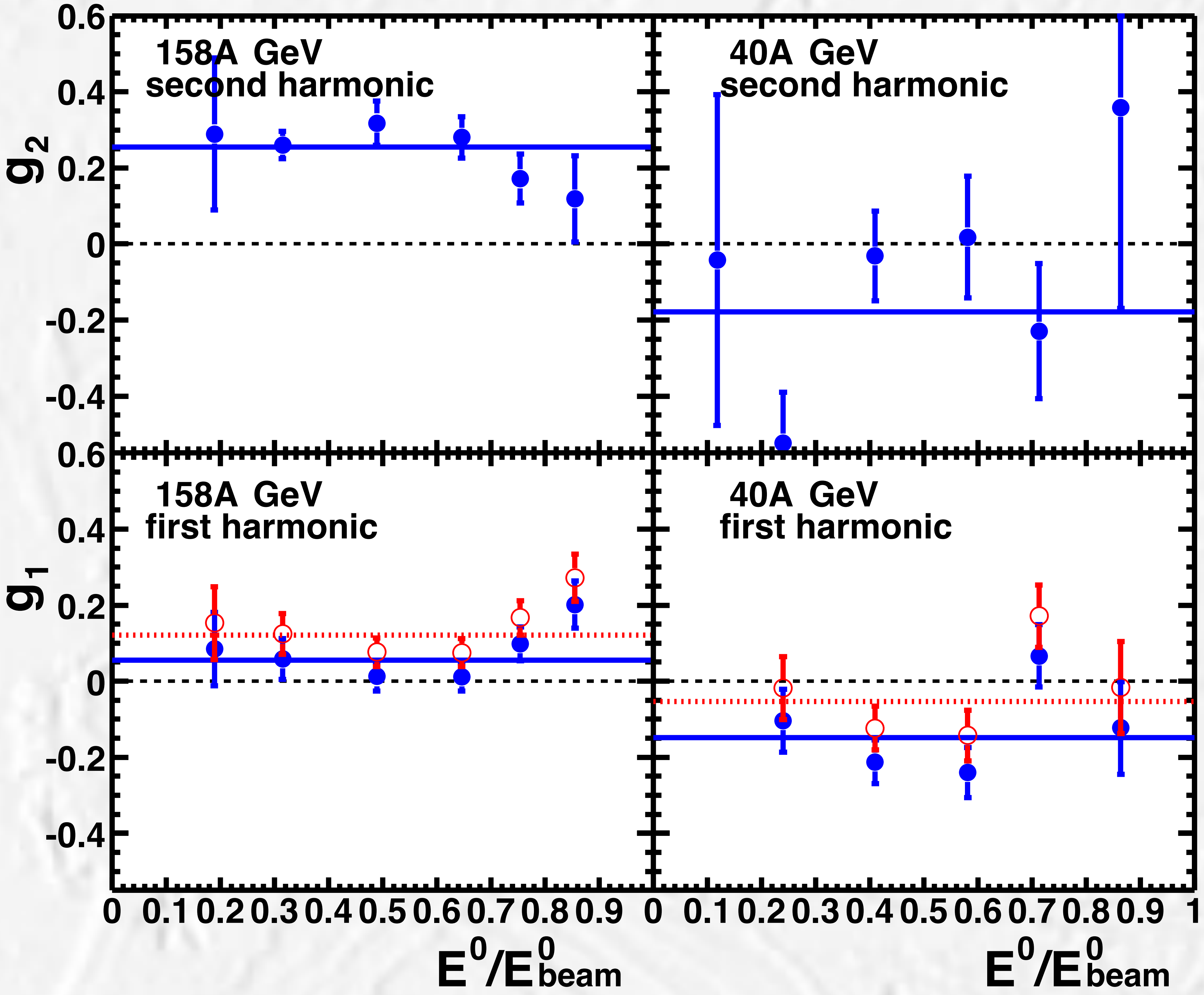


FIG. 22. (Color online) Nonflow azimuthal correlations from Eq. (16), for the first, g_1, (bottom) and second, g_2, (top) Fourier harmonics, from 158A GeV (left) and 40A GeV (right) Pb+Pb collisions. For g_1, the solid points represent all nonflow effects, while the open points are corrected for momentum conservation. The horizontal lines are at the mean values.

$$\langle v_2^2 \rangle = \langle v_2 \rangle^2 + \sigma_{v_2}^2 + g_2/N$$

PHYSICAL REVIEW C **72**, 014904 (2005)

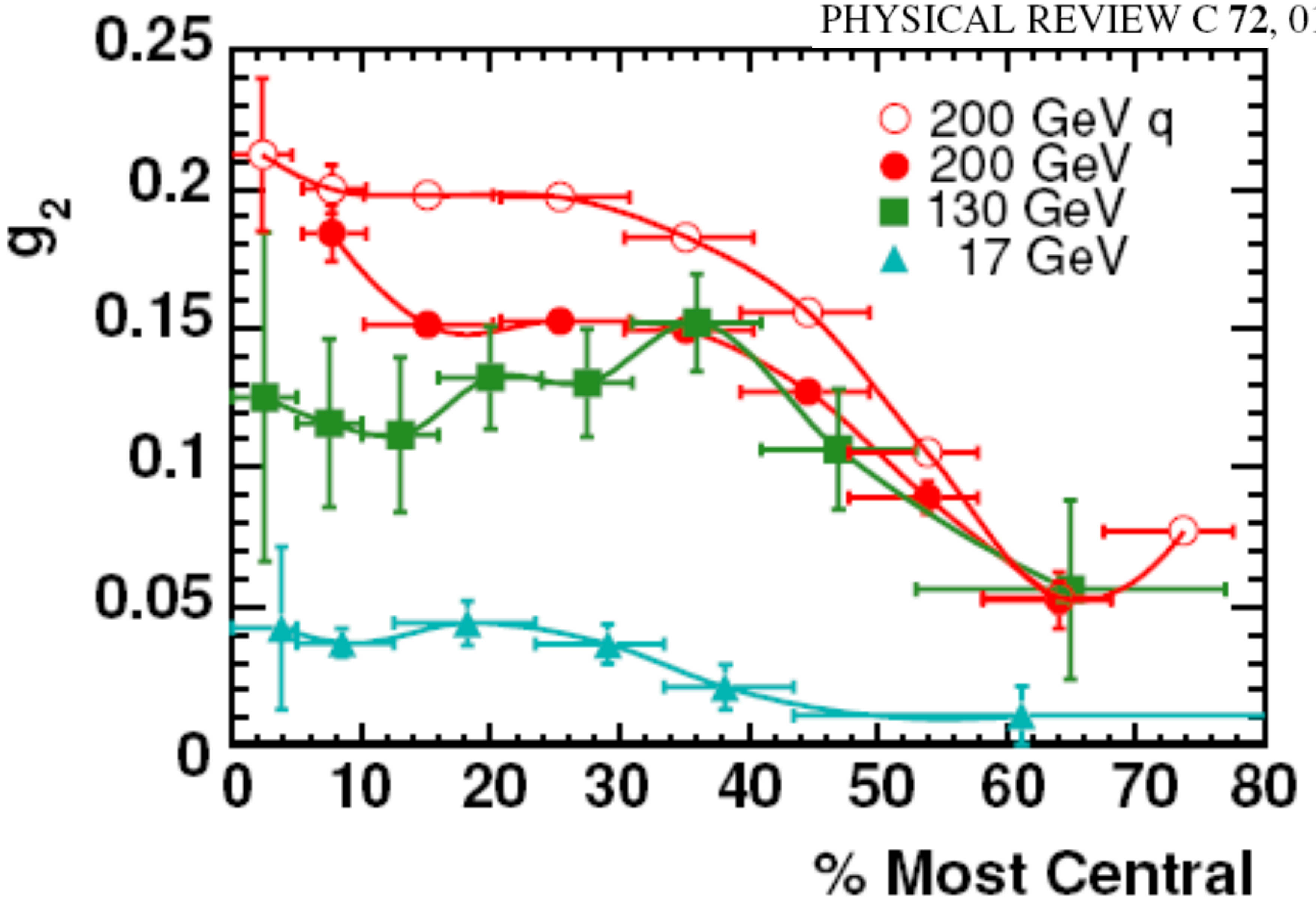
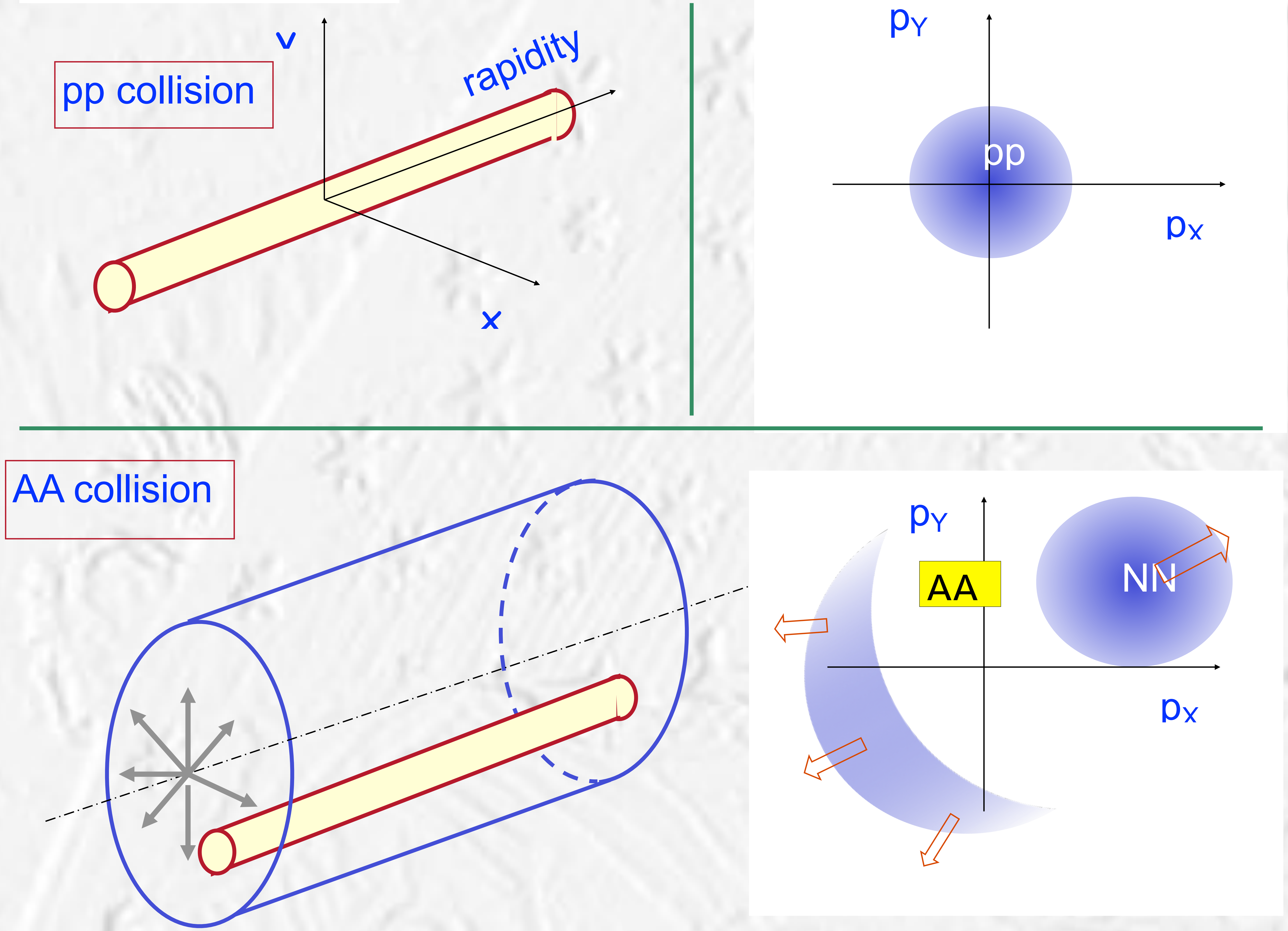


FIG. 31. (Color online) The nonflow parameter, g_2, as a function of centrality. The solid points are from the cumulant method. The open circles are from the q distribution method.

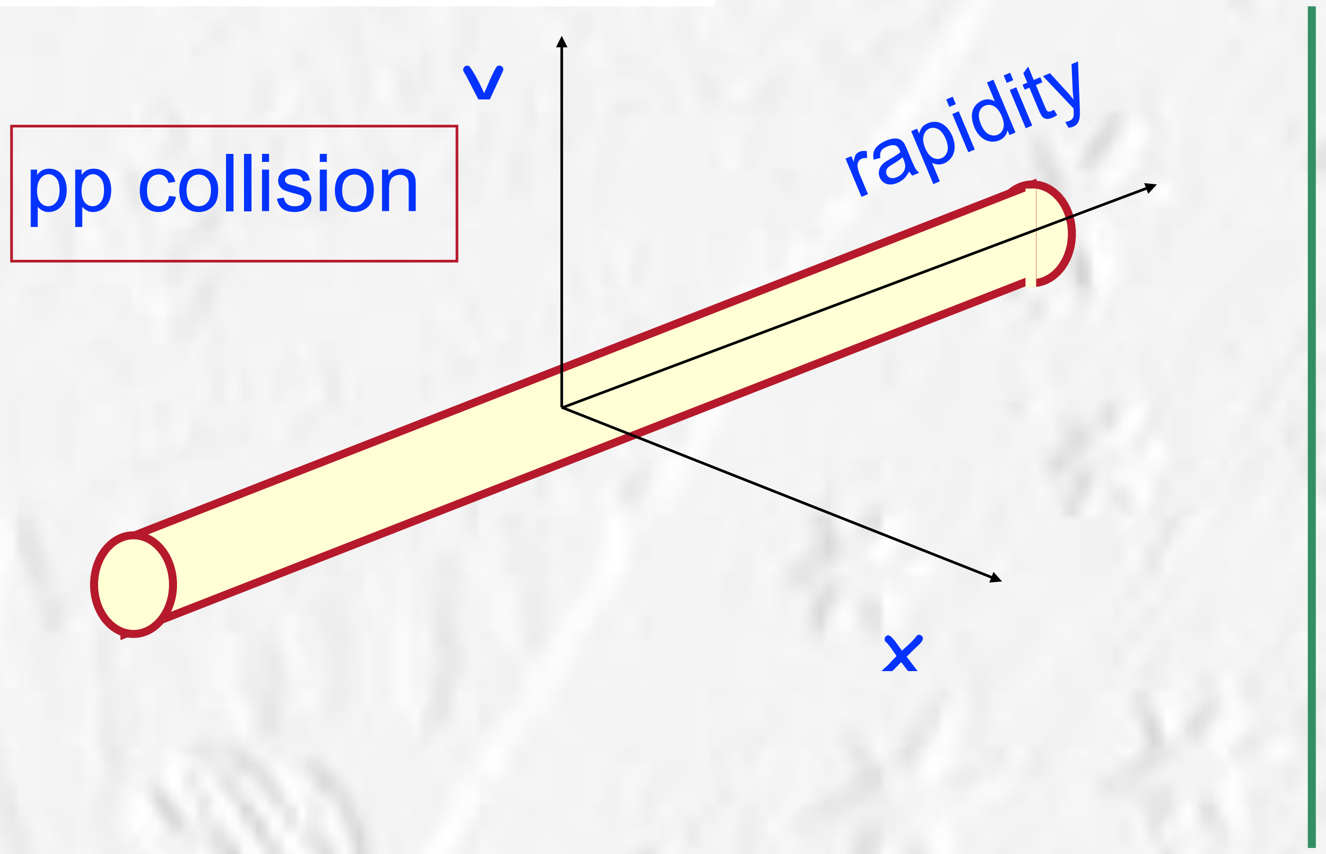
Radial expansion → nonflow

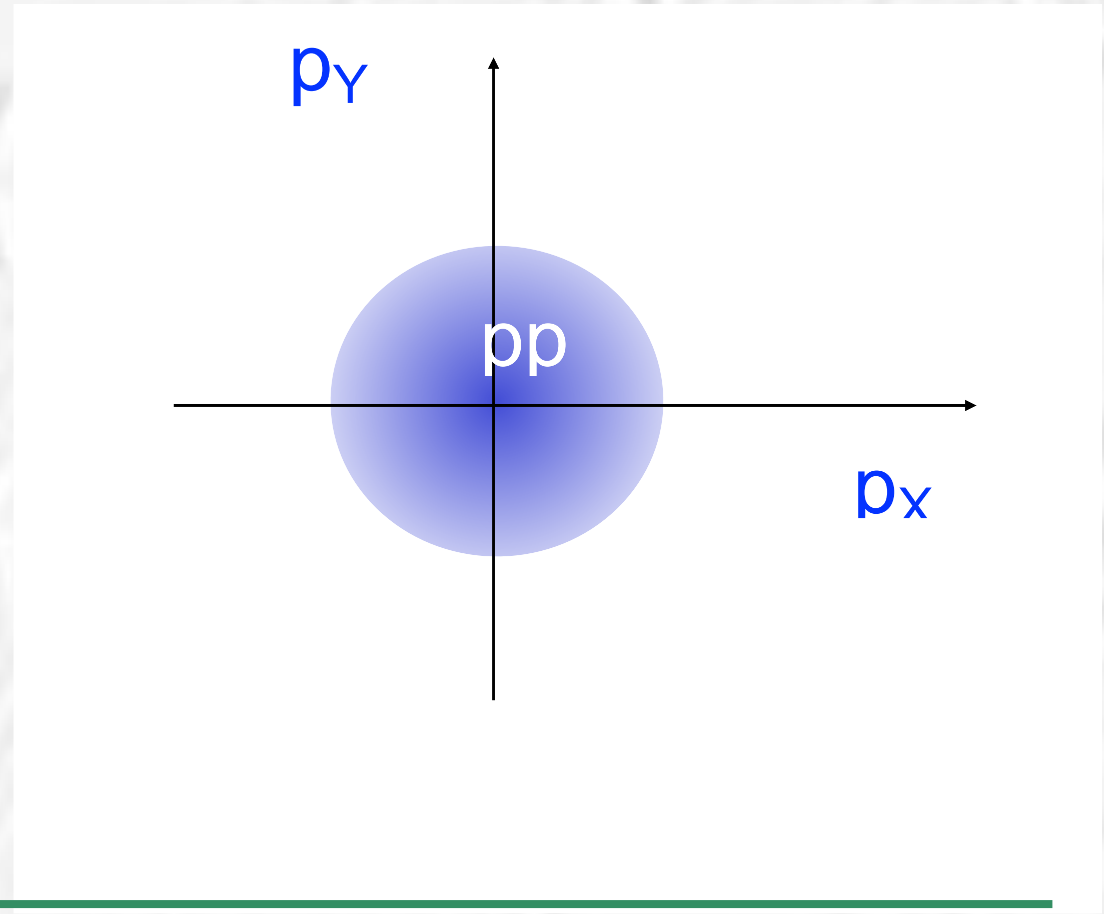
[arXiv:nucl-th/0312065]

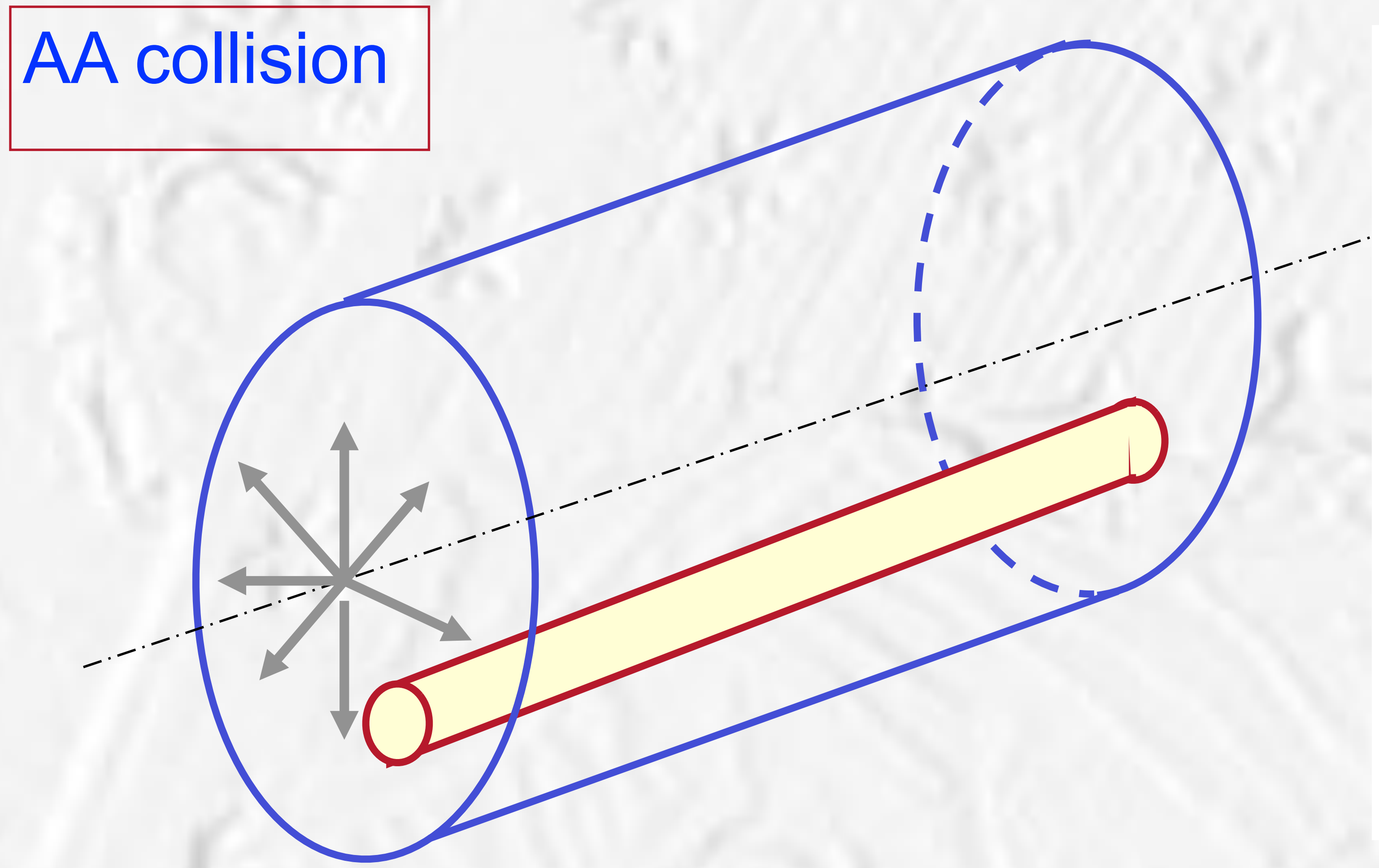


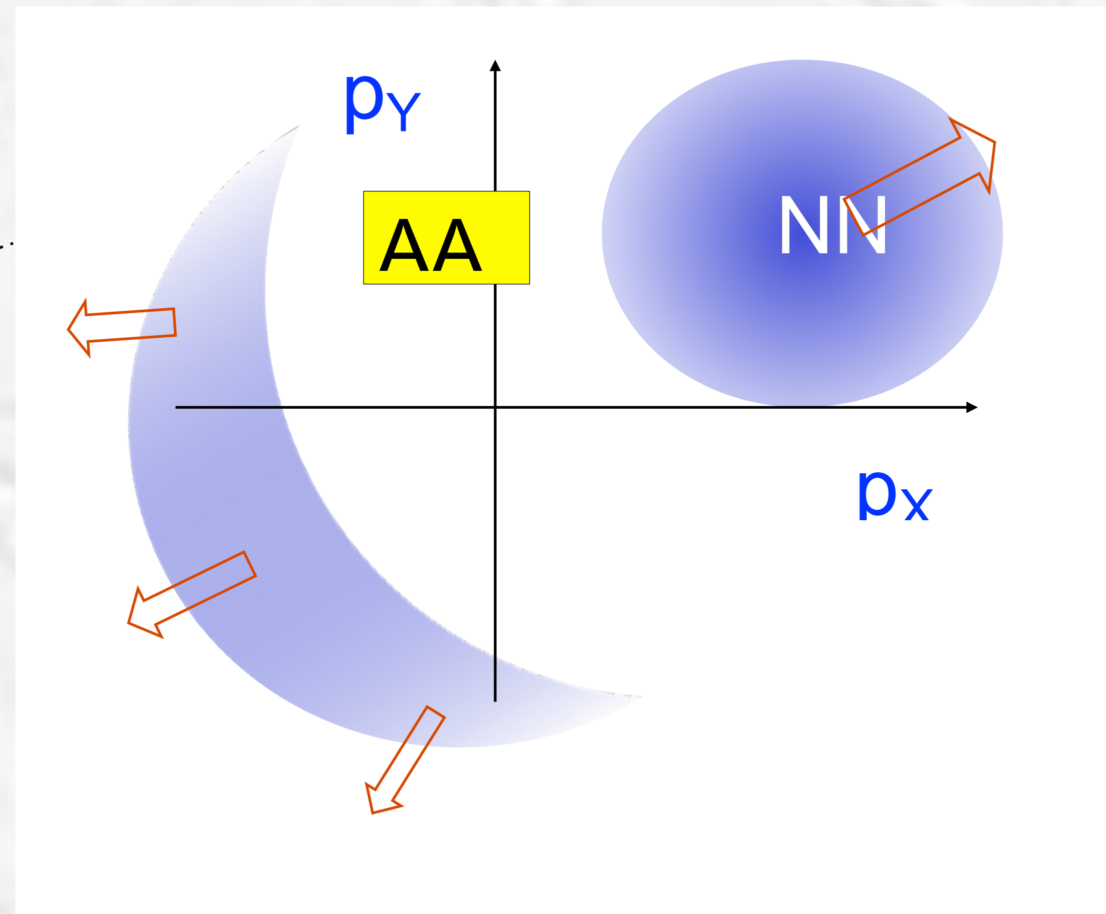
Radial expansion → nonflow

[arXiv:nucl-th/0312065]

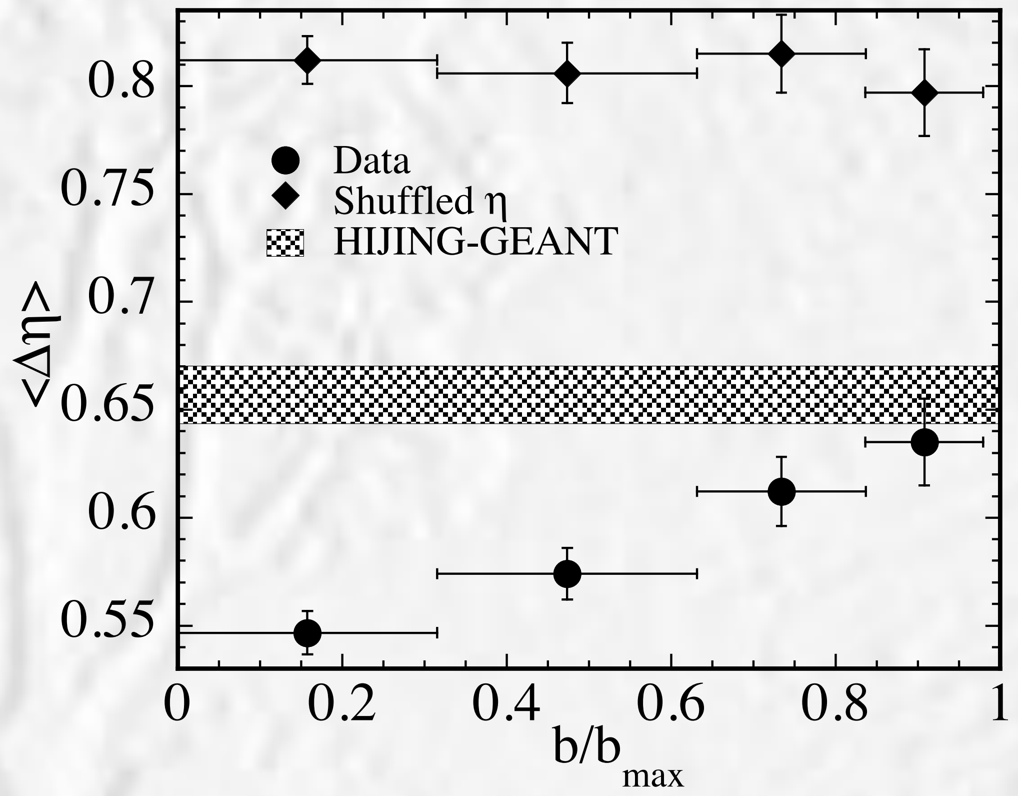






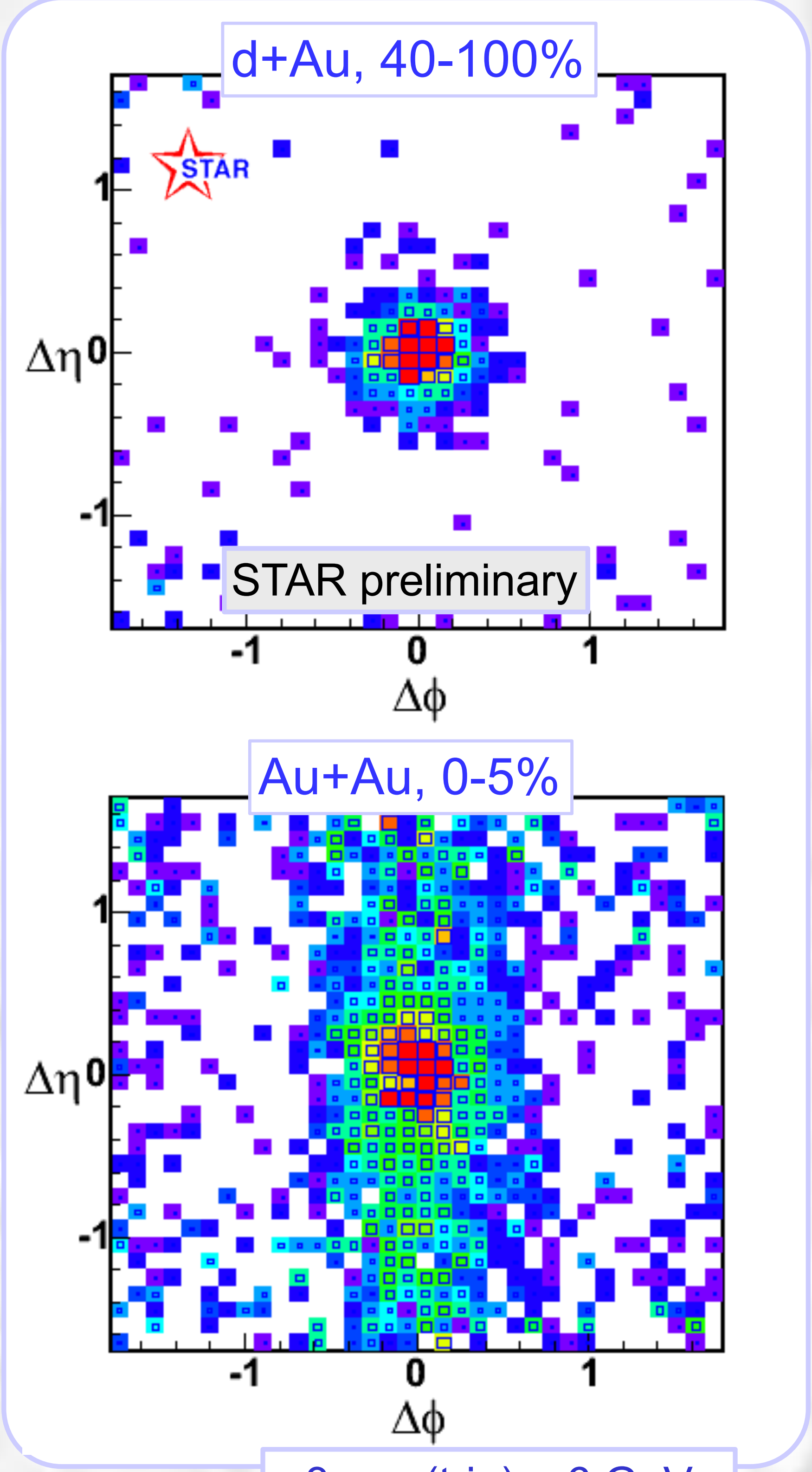


arXiv:nucl-ex/0301014v1 24 Jan 2003



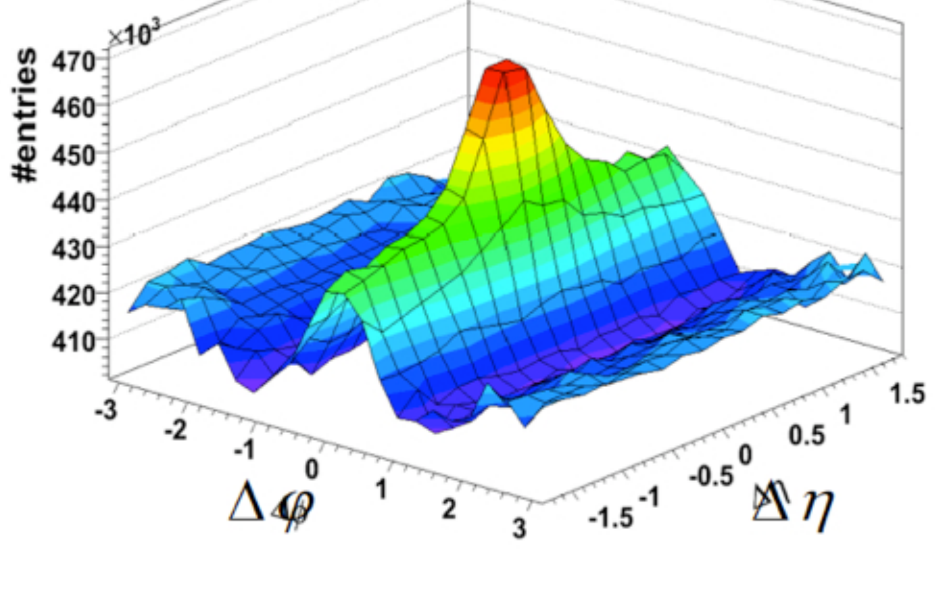
IG. 2: The width of the balance function for charged par-icles, $\langle\Delta\eta\rangle$, as a function of normalized impact parameter b/b_{max}). Error bars shown are statistical. The width of he balance function from HIJING events is shown as a band hose height reflects the statistical uncertainty. Also shown re the widths from the shuffled pseudorapidity events.

D. Magestro (STAR) – Hard Probes 2004



$3 < p_T(trig) < 6$ GeV
$2 < p_T(assoc) < p_T(trig)$

B. I. Abelev et al.[STAR Collaboration], Phys. Rev. C 80 (2009) 6491



Radial expansion → nonflow, cont'd

S.A. Voloshin / Physics Letters B 632 (2006) 490–494 493

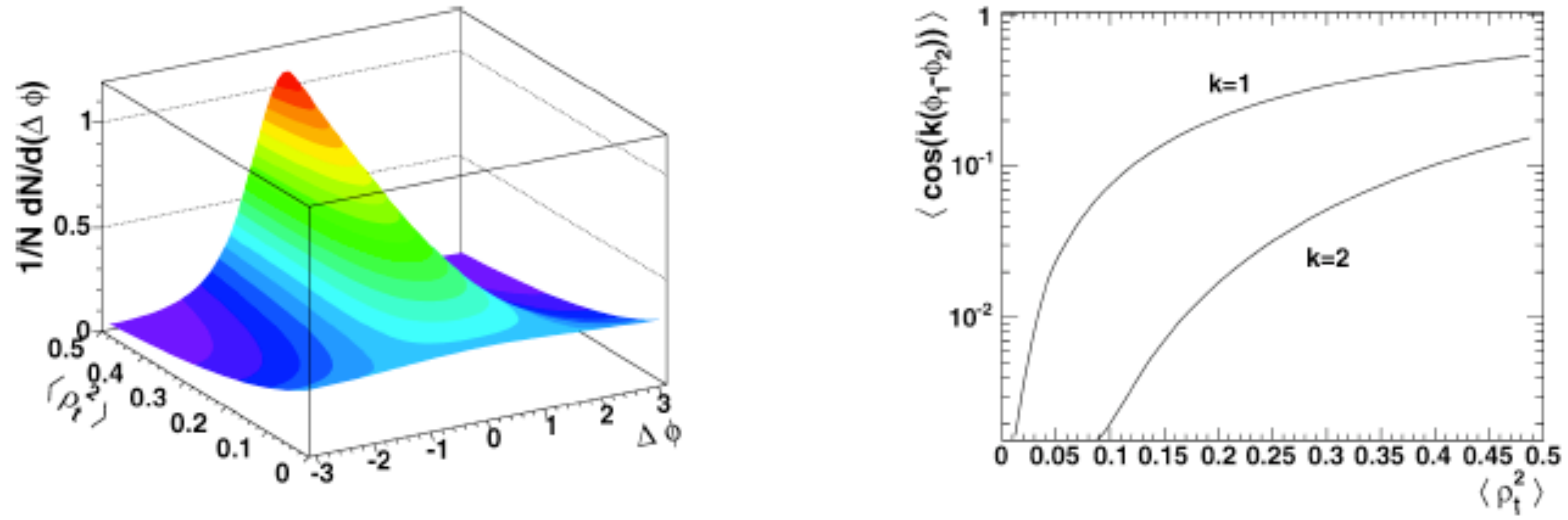


Fig. 3. (Color online.) Two pion $\Delta\phi$ distribution as function of $\langle \rho_t^2 \rangle$ in the blast wave model. Linear velocity profile and $T = 110$ MeV have been assumed.

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

PHYSICAL REVIEW C **72**, 014904 (2005)

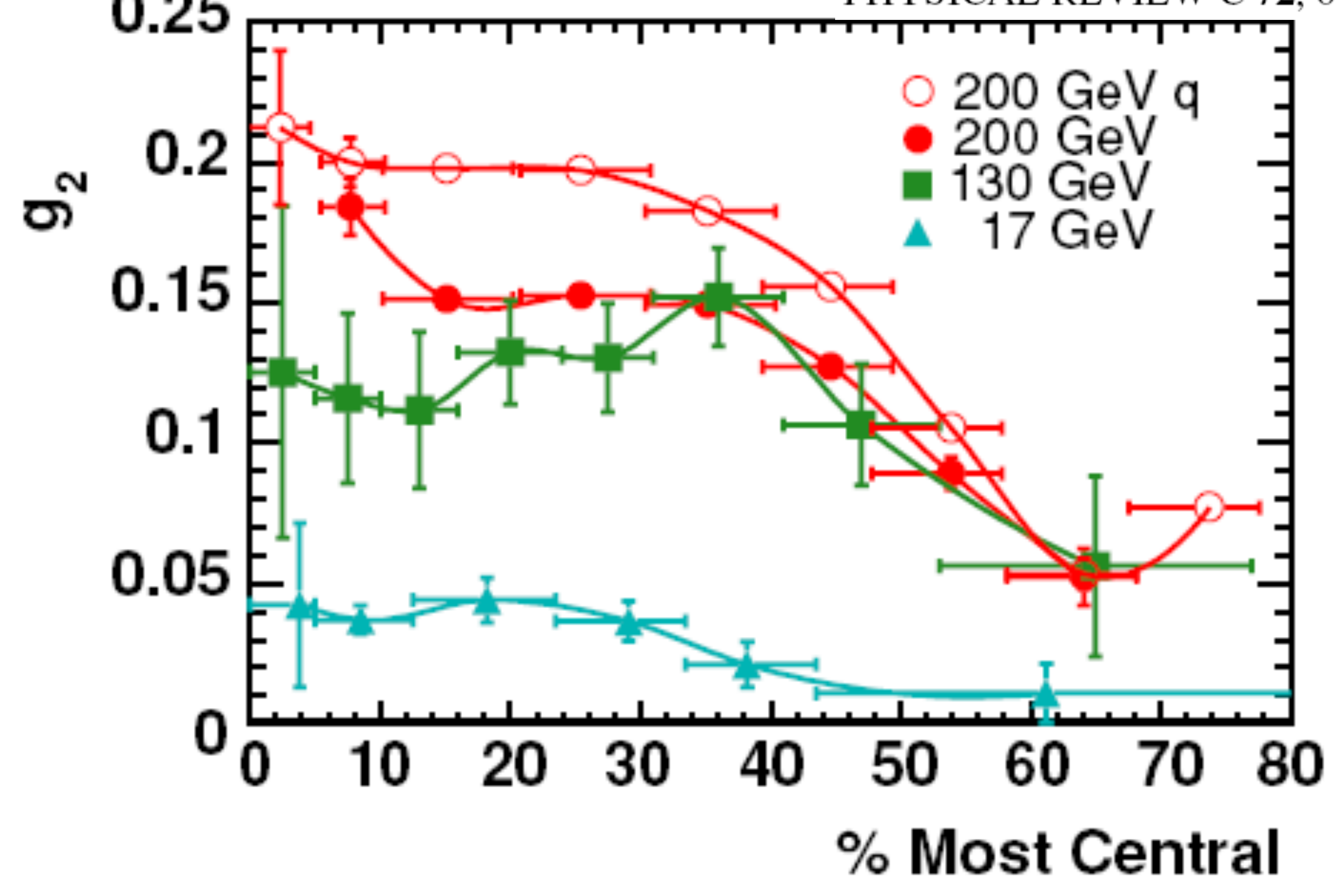
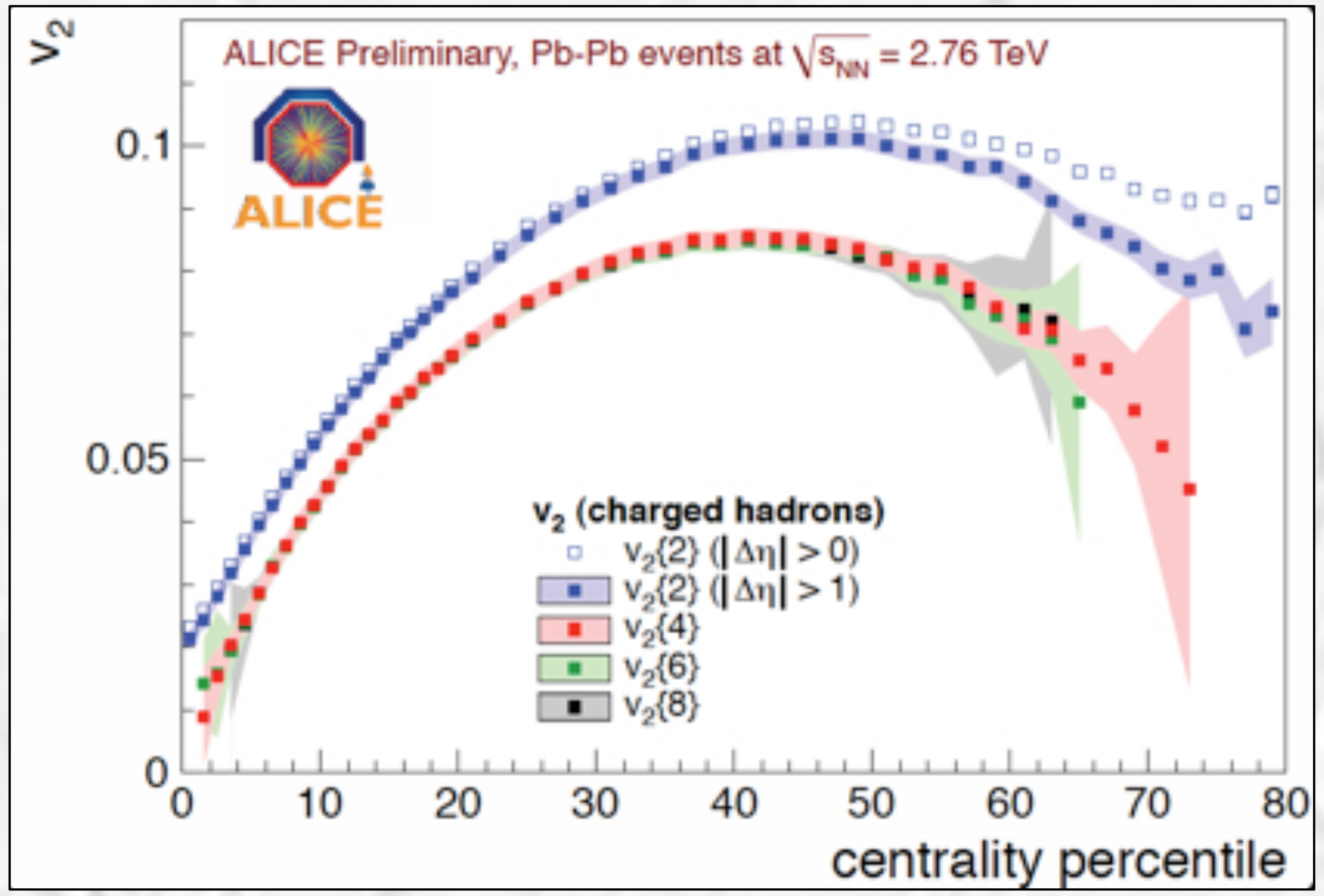


FIG. 31. (Color online) The nonflow parameter, g_2, as a function of centrality. The solid points are from the cumulant method. The open circles are from the q distribution method.

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

Flow fluctuations



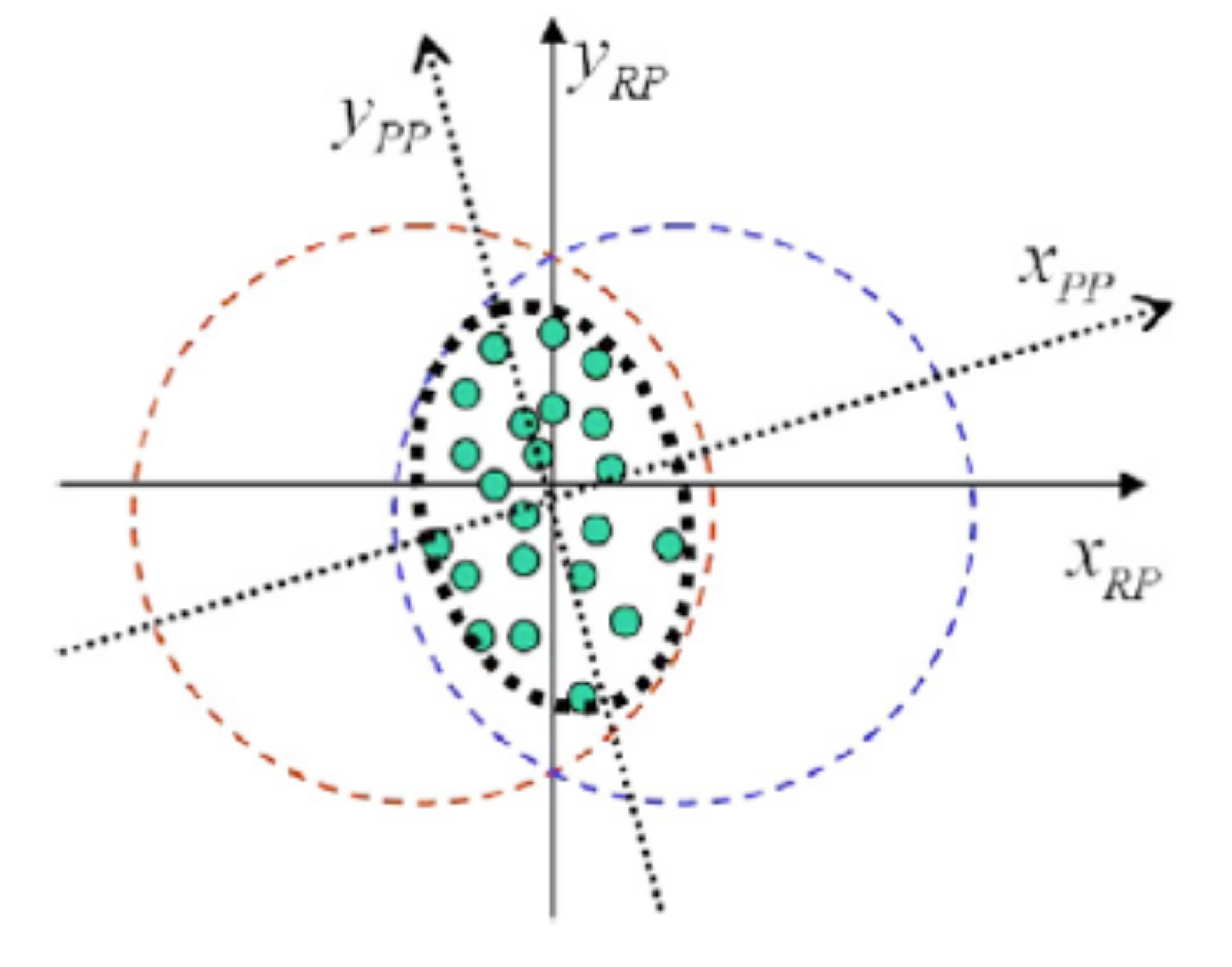


Fig. 1. The definitions of the *RP* and *PP* coordinate systems.

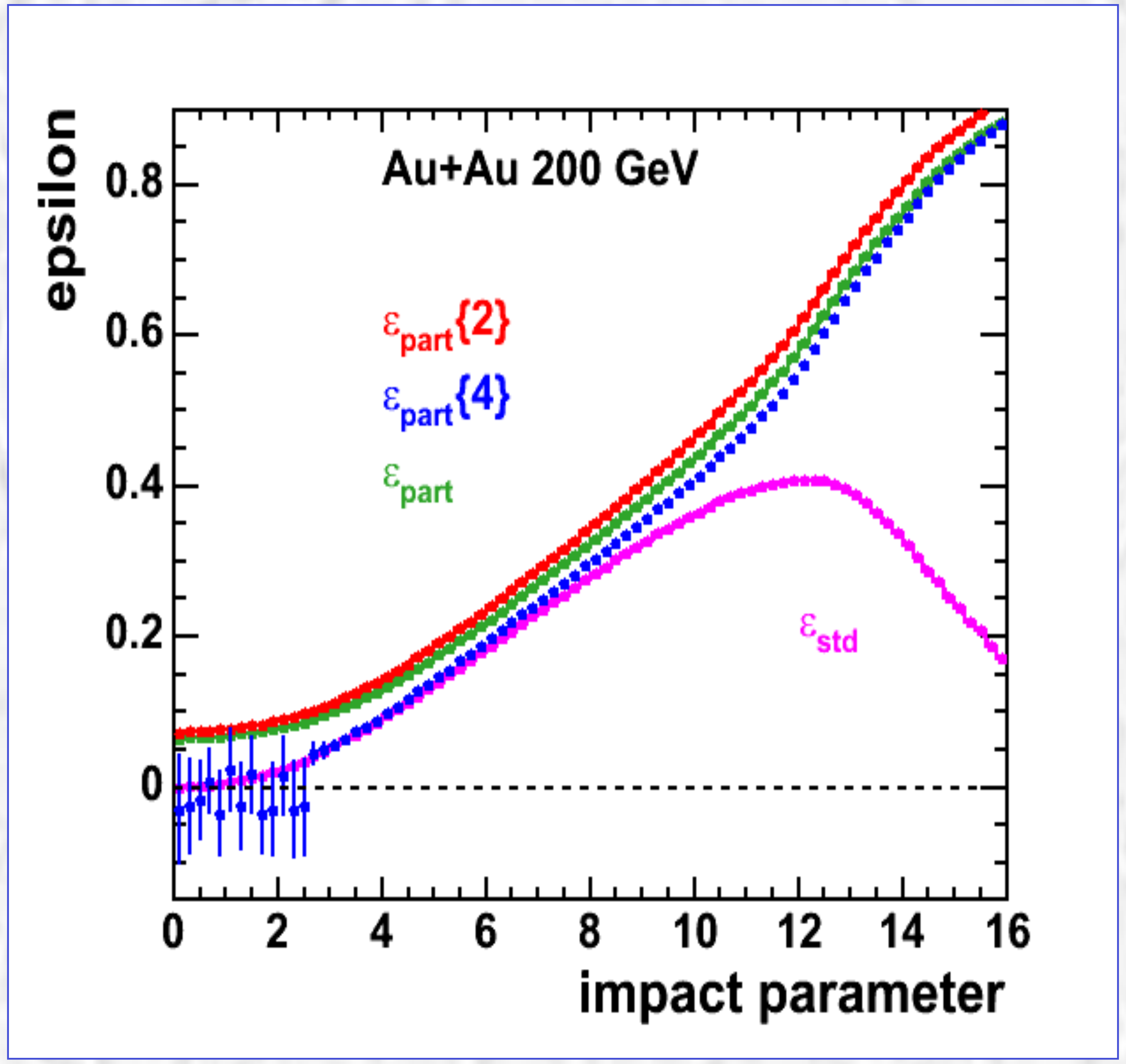
Elliptic flow in the Gaussian model of eccentricity fluctuations *Physics Letters B 659 (2008) 537–541*

Sergei A. Voloshin[a,*], Arthur M. Poskanzer[b], Aihong Tang[c], Gang Wang[d]

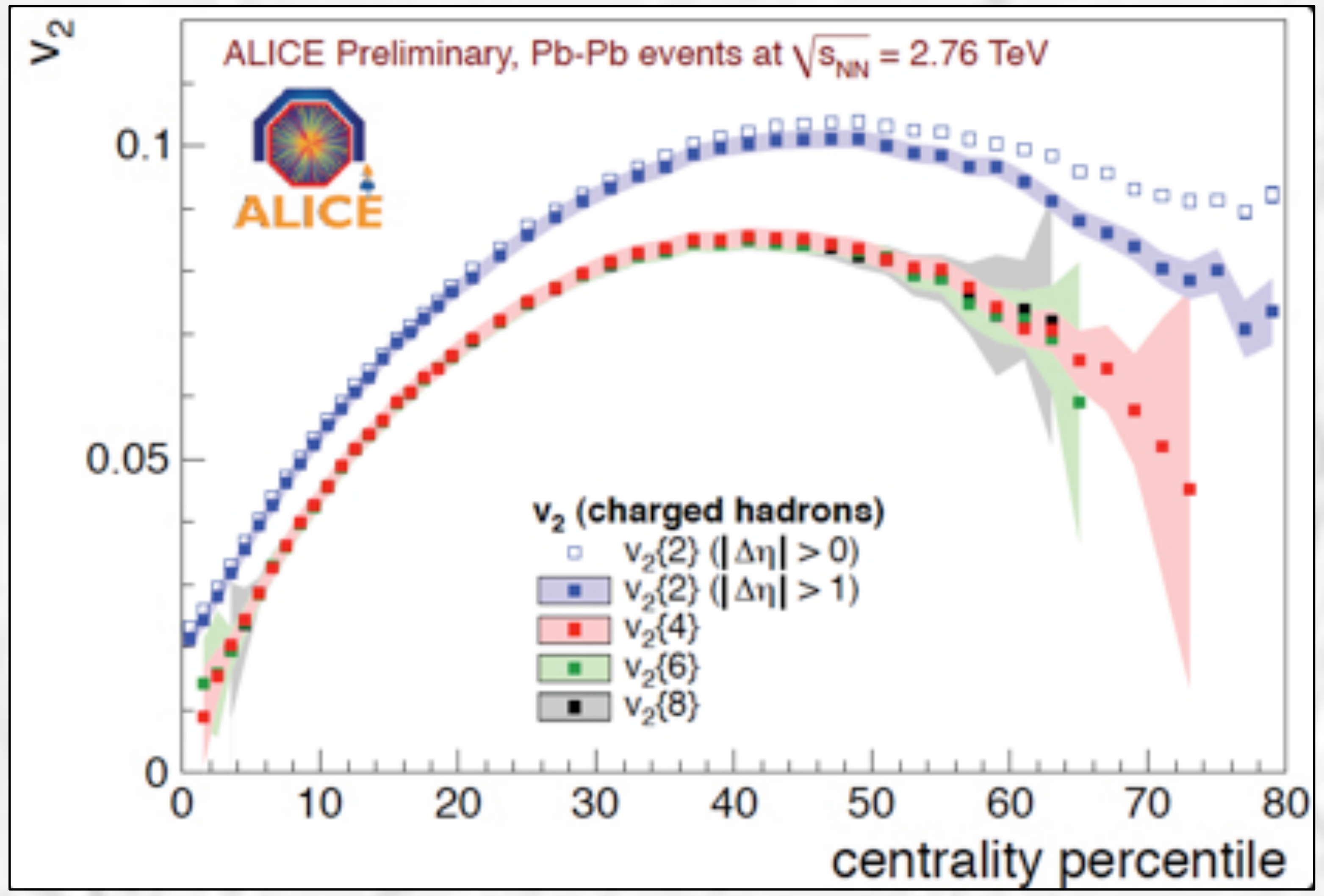
$$\langle v_2^2 \rangle = \langle v_2 \rangle^2 + \sigma_{v_2}^2 + g_2/N$$

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

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



Flow fluctuations



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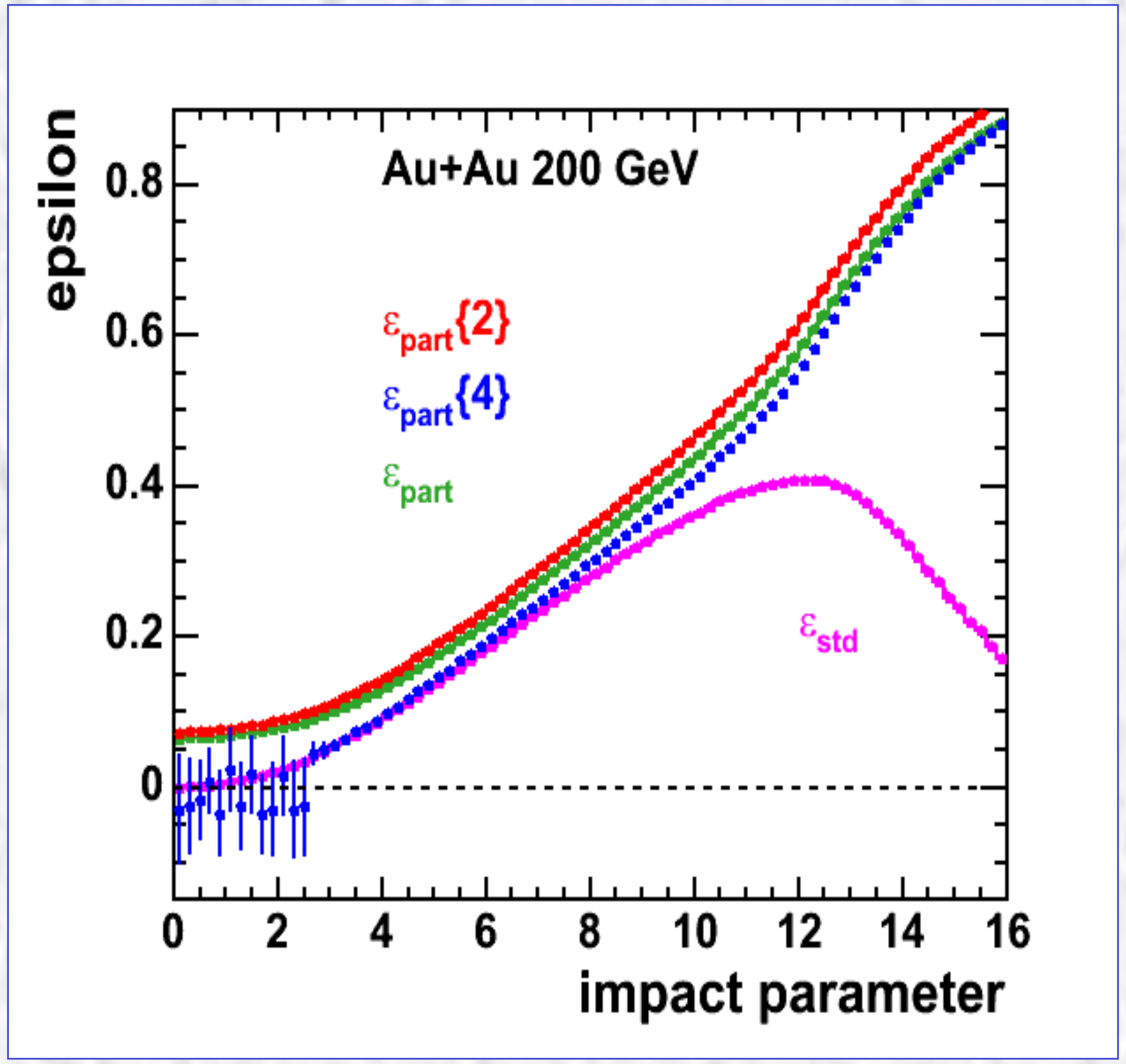


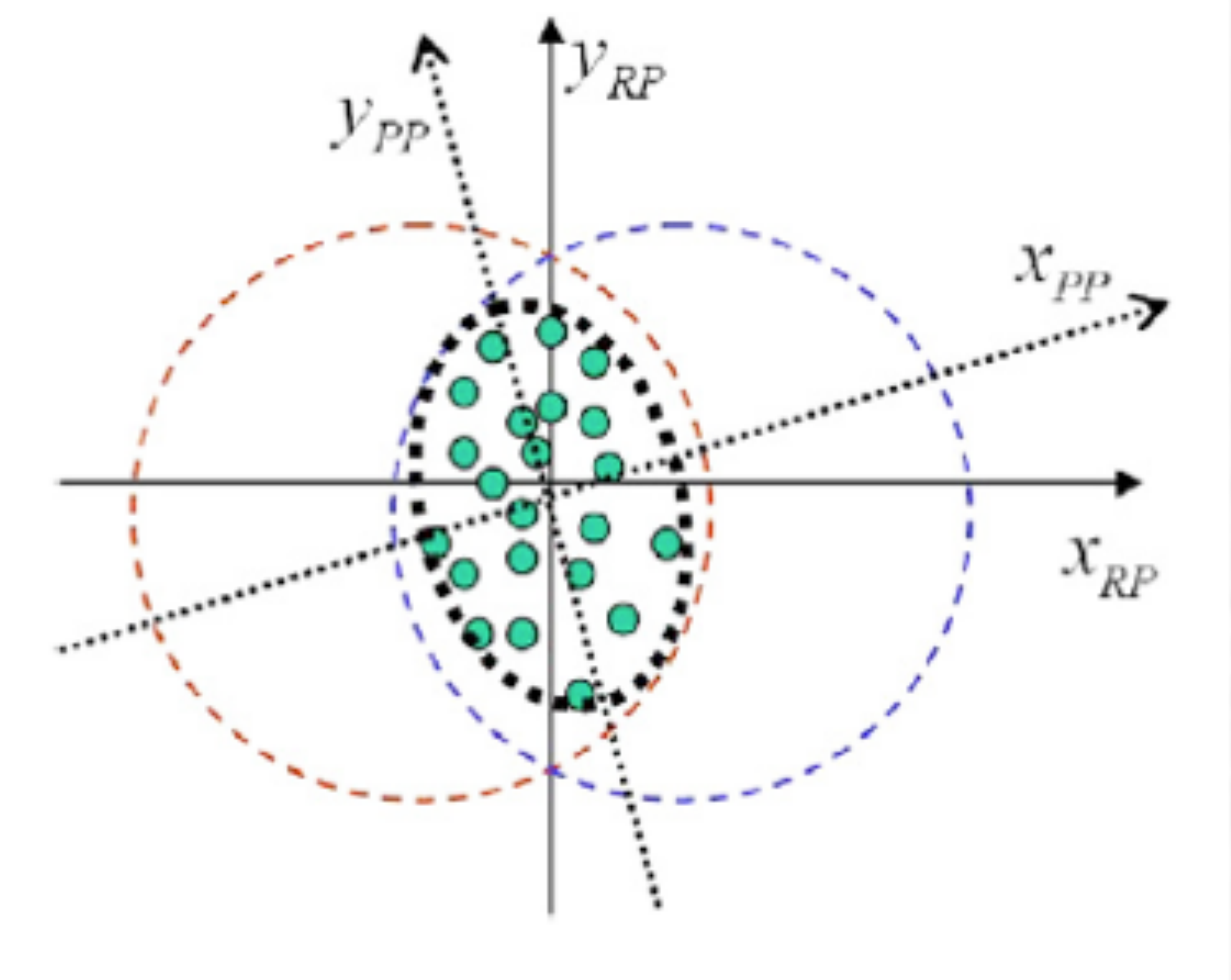


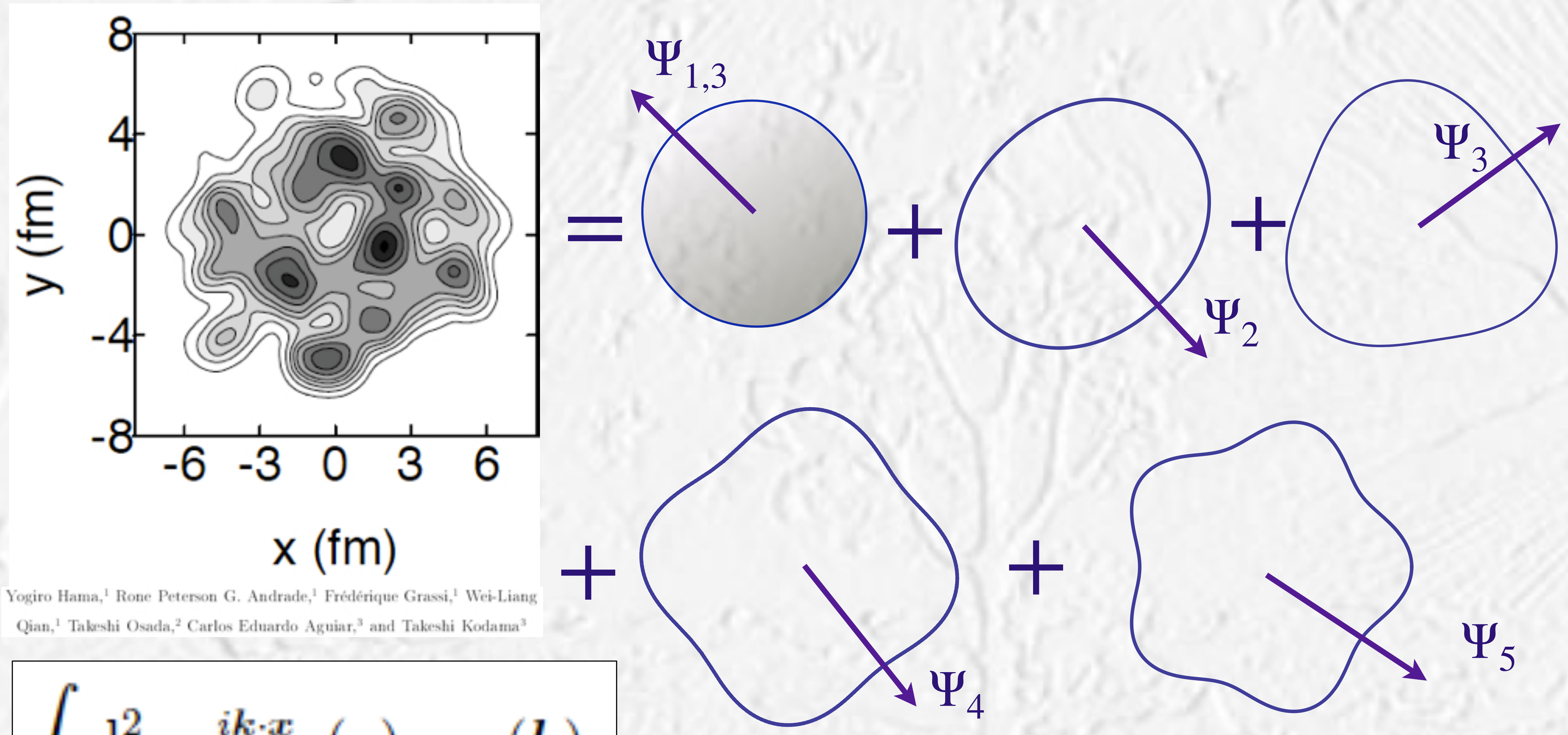
Fig. 1. The definitions of the *RP* and *PP* coordinate systems.

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

Elliptic flow in the Gaussian model of eccentricity fluctuations *Physics Letters B 659 (2008) 537–541*

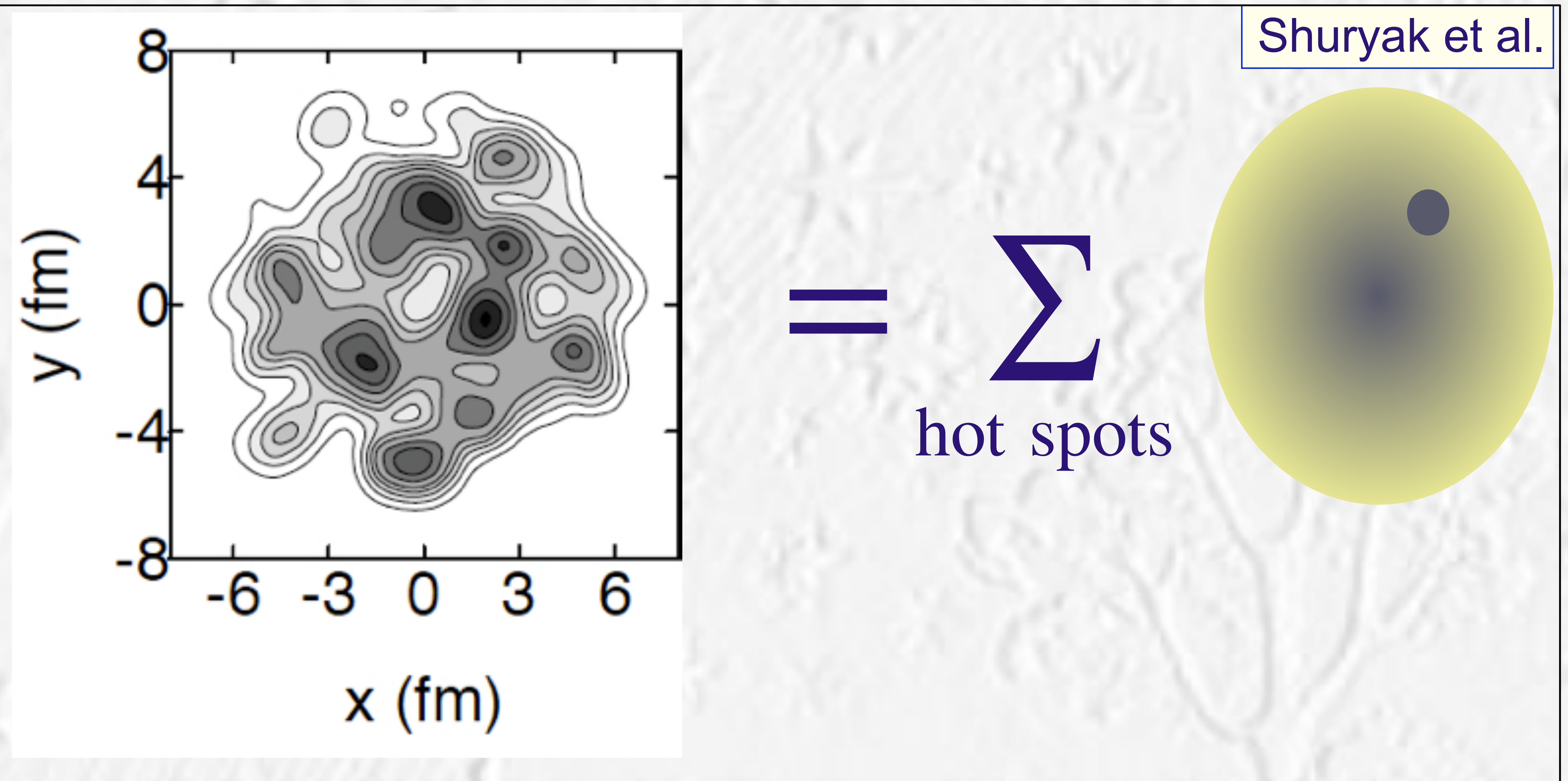
Sergei A. Voloshin [a,*], Arthur M. Poskanzer [b], Aihong Tang [c], Gang Wang [d]

Flow fluctuations = nonflow (radial expansion)



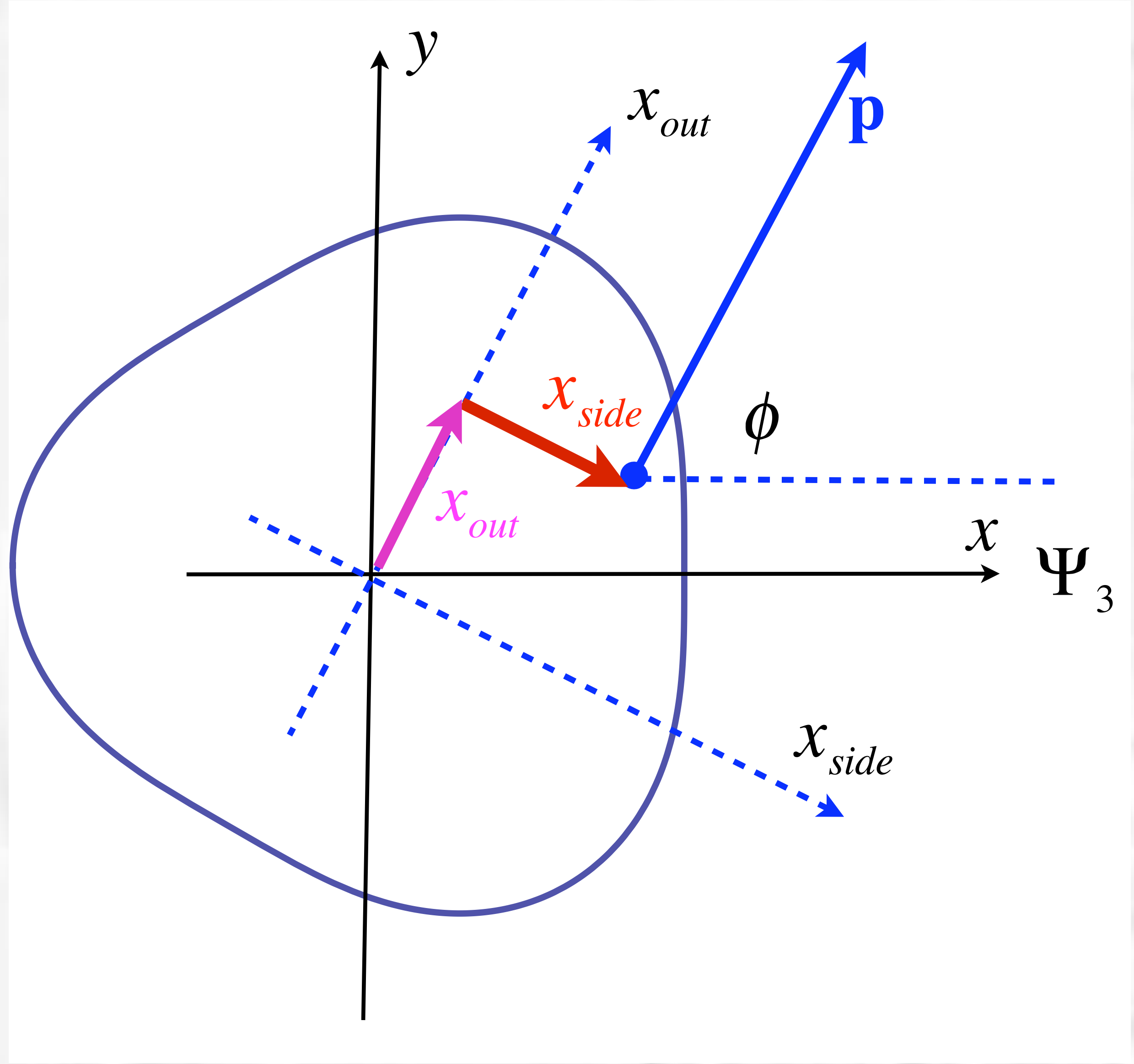
$$\int d^2\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \rho(\boldsymbol{x}) = \rho(\boldsymbol{k}),$$

Triangularity and Dipole Asymmetry in Heavy Ion Collisions
arXiv:1010.1876v1 [nucl-th] 9 Oct 2010
Derek Teaney and Li Yan



$v_n\{RP\}$ - “hot spots” correlations = nonflow
$v_n\{PP\}$ - flow vs “participant planes” - “hot spot” correlations = part of flow fluctuations

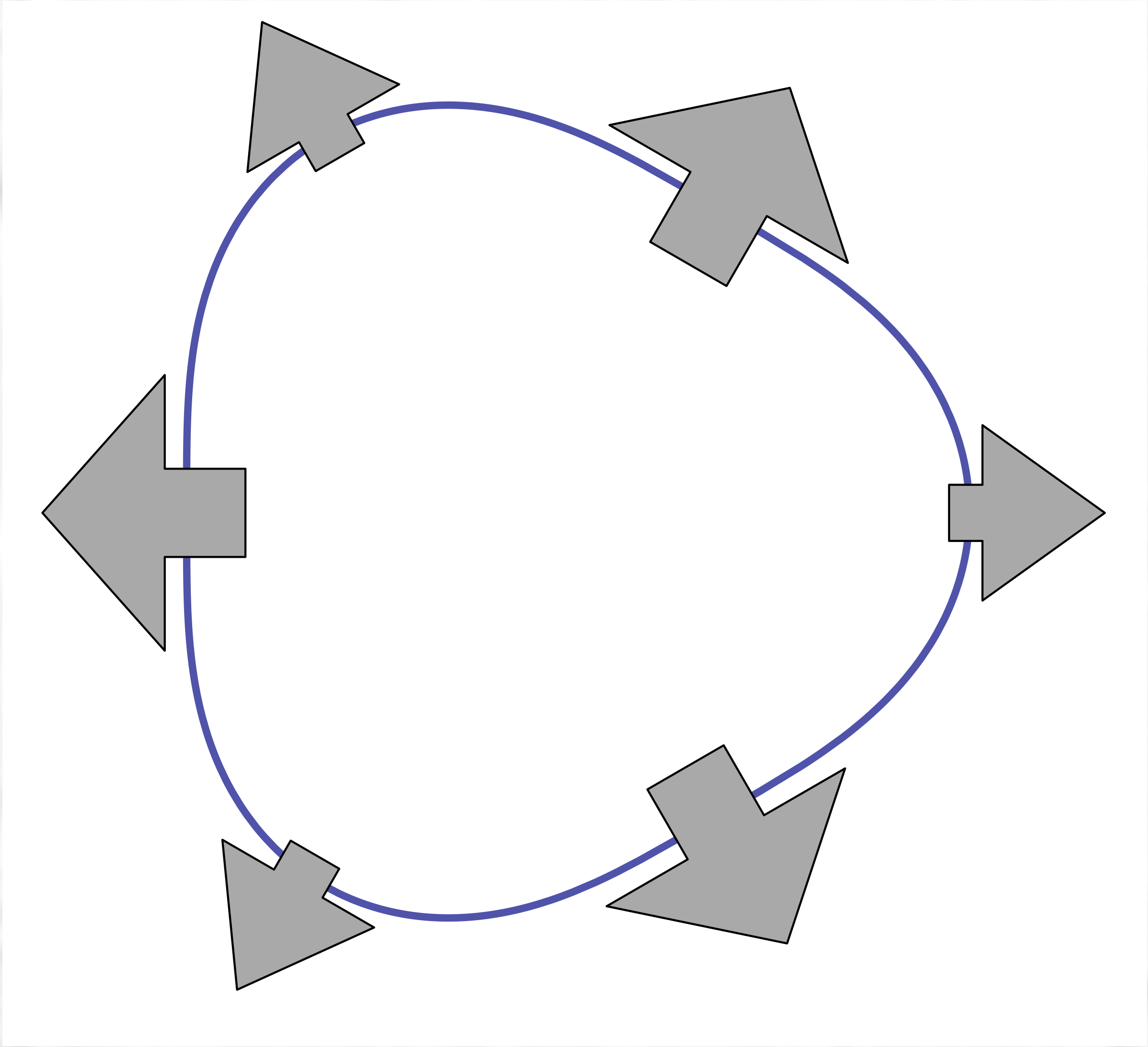
Stationary and expanding sources



Rotation of the coordinate system:

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

Stationary source:
no higher order anisotropy in the Gaussian approximation
4-th harmonic modulations appears only in $\langle x^4 \rangle$
3-rd harmonic modulations appears only in $\langle x^6 \rangle$



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

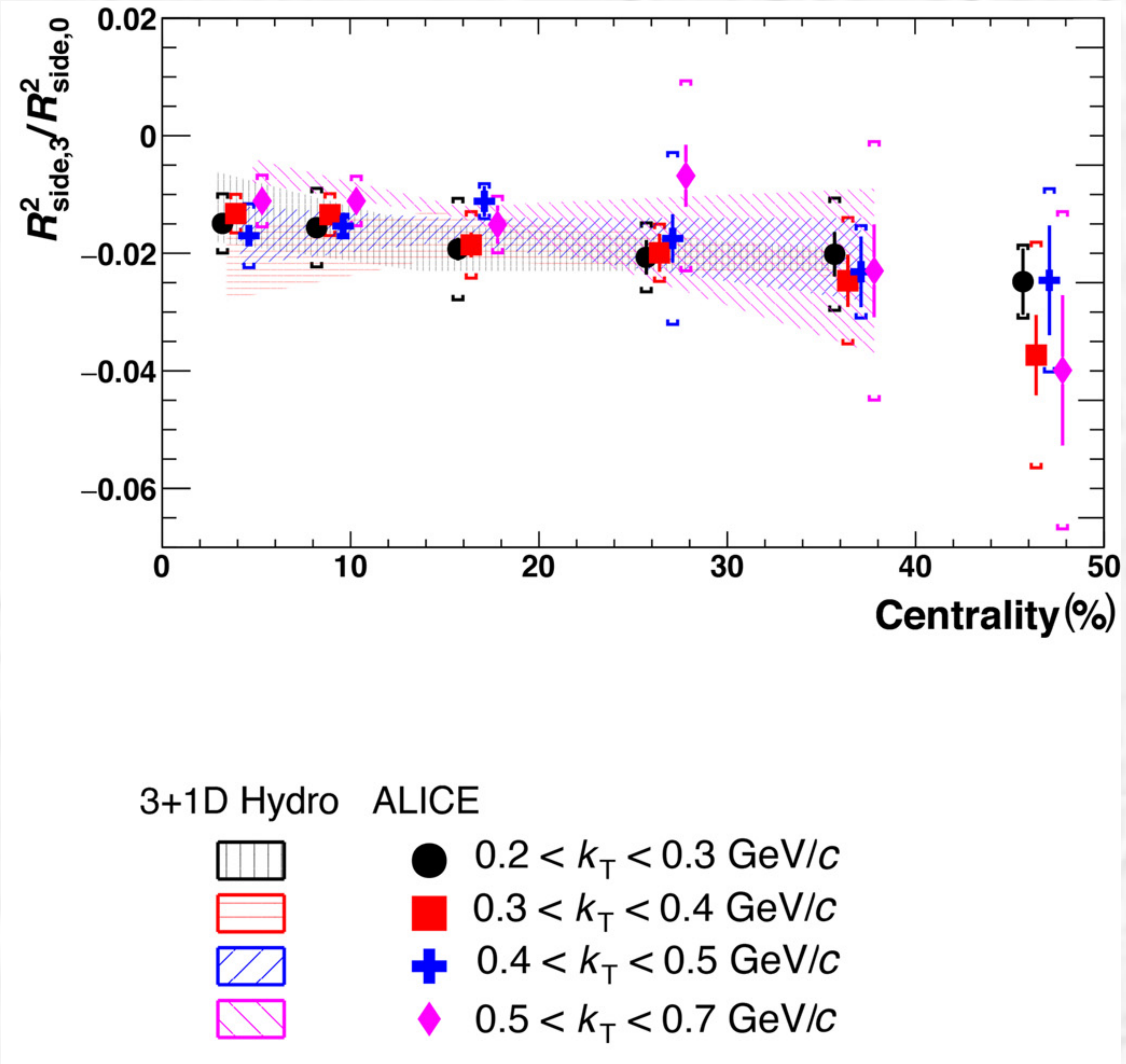
Can the collective expansion lead to nontrivial $R(\phi)$ dependence?
Yes, due to several effects:
- variation in the "blast wave" velocity
- variation in velocity gradients in "side" direction

Observation of the higher harmonics in azimuthat dependence of femtoscopic radii could originate only in the collective expansion of the source

ALICE, third harmonic HBT

ALICE Collaboration / Physics Letters B 785 (2018) 320–331

to the results from 3+1D hydrodynamical calculations. The observed radii oscillations unambiguously signal a collective expansion and anisotropy in the velocity fields. A comparison of the measured radii oscillations with the Blast-Wave model calculations indicate that the initial state triangularity is washed-out at freeze out.



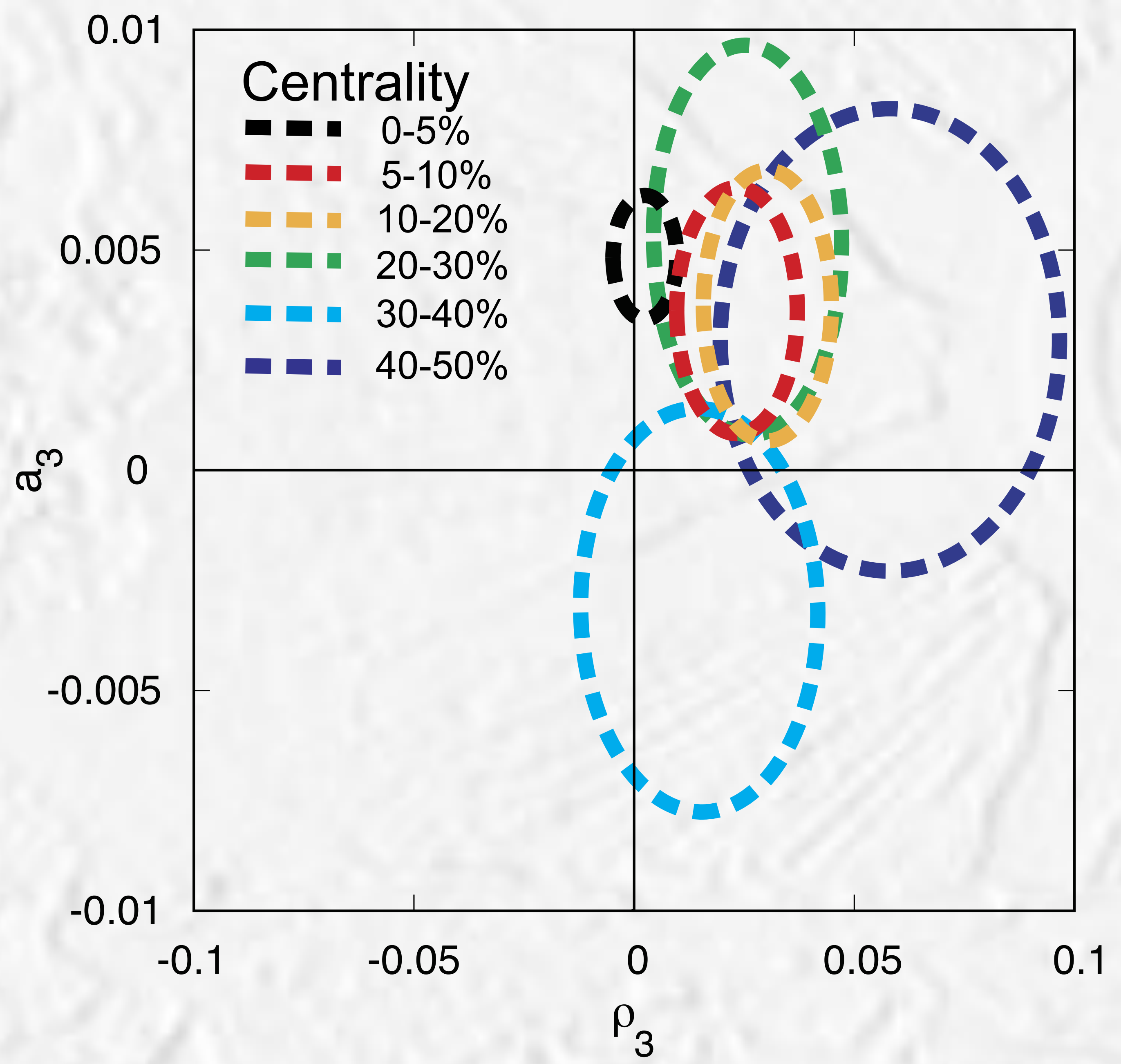
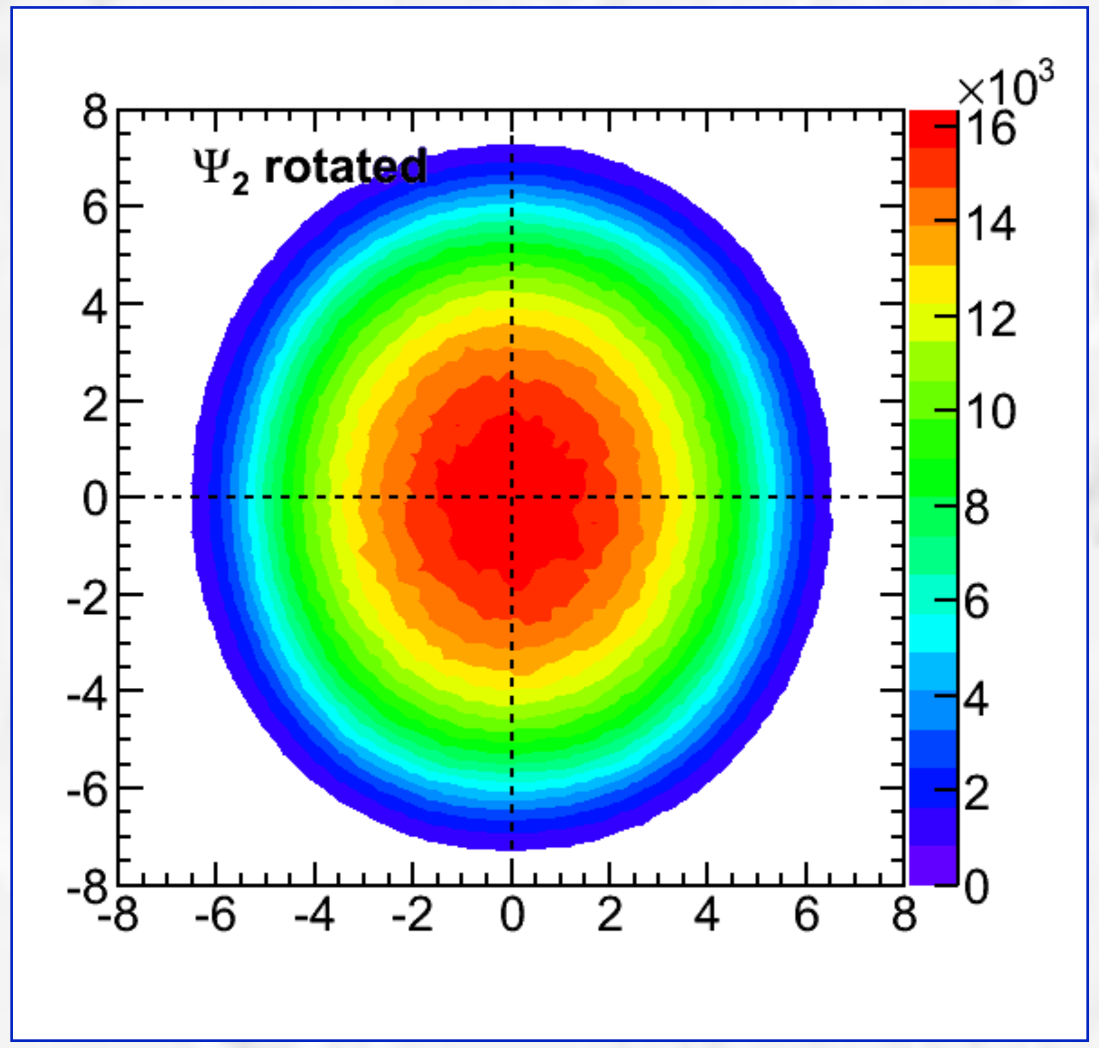
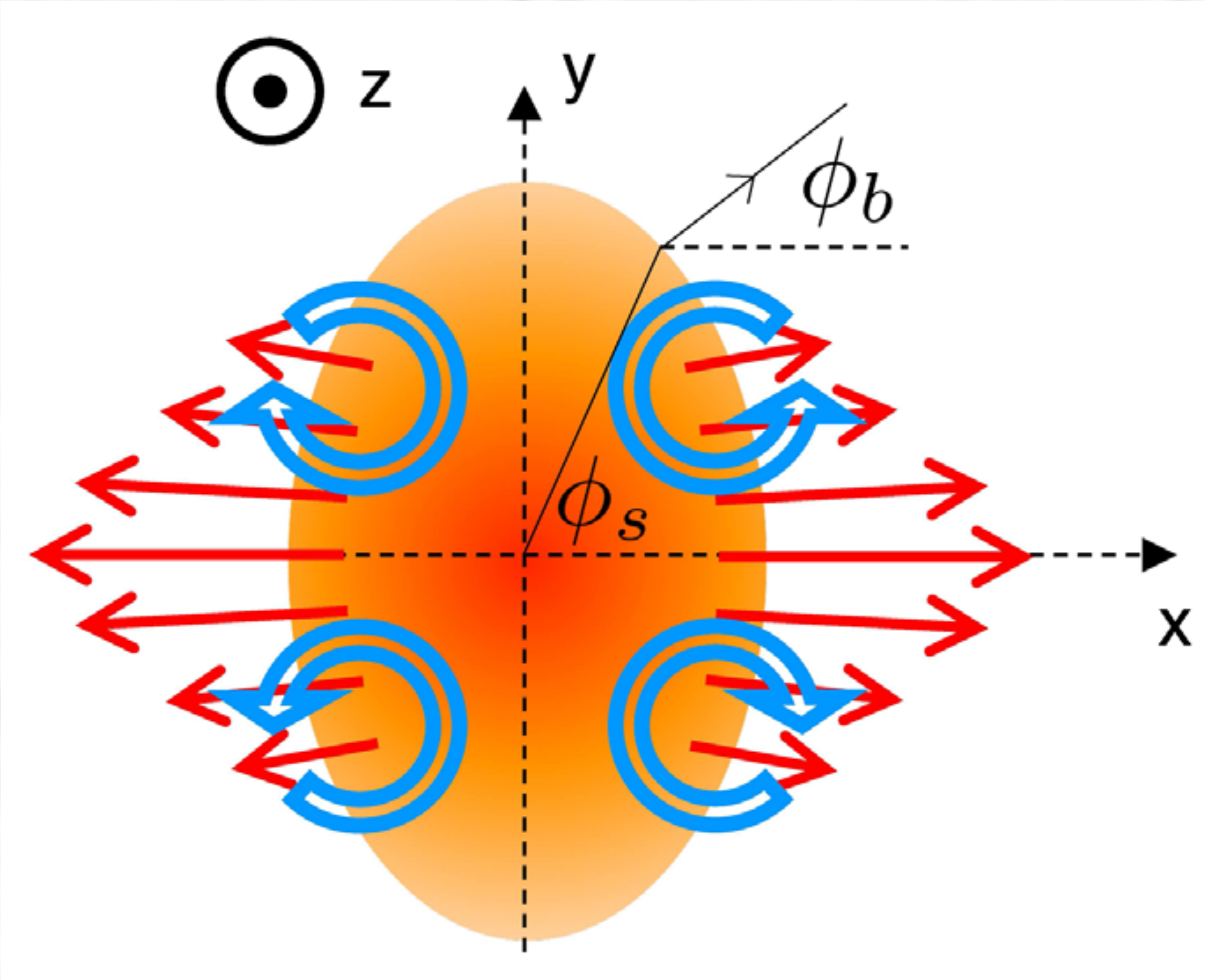


Fig. 5. Blast-Wave model [16] source parameters, final spatial (a_3) and transverse flow (ρ_3) anisotropies, for different centrality ranges, as obtained from the fit to ALICE radii oscillation parameters. The contours represent the one sigma uncertainty.

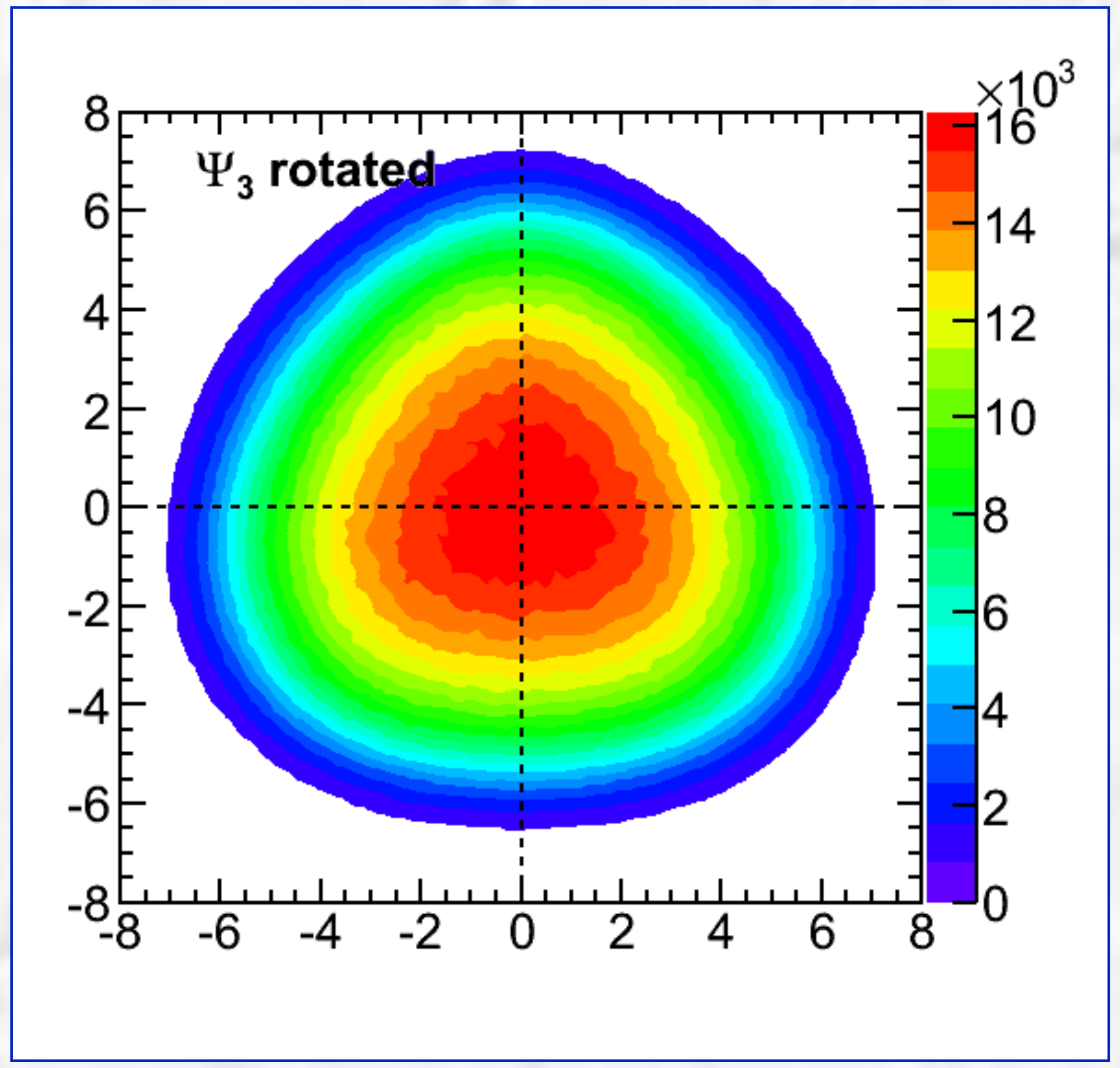
This results unambiguously indicate collective expansion of the source as no any other "evidence",

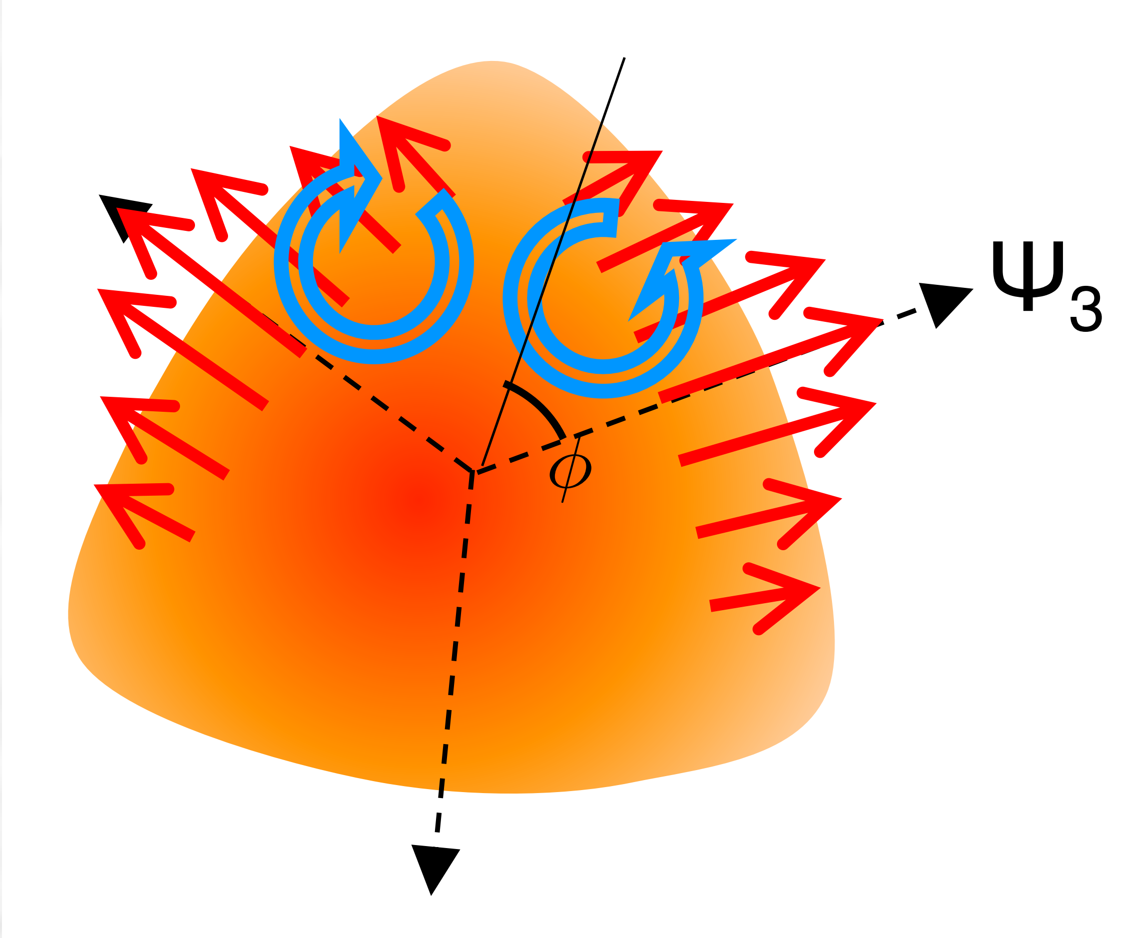
Anisotropic flow and vorticity



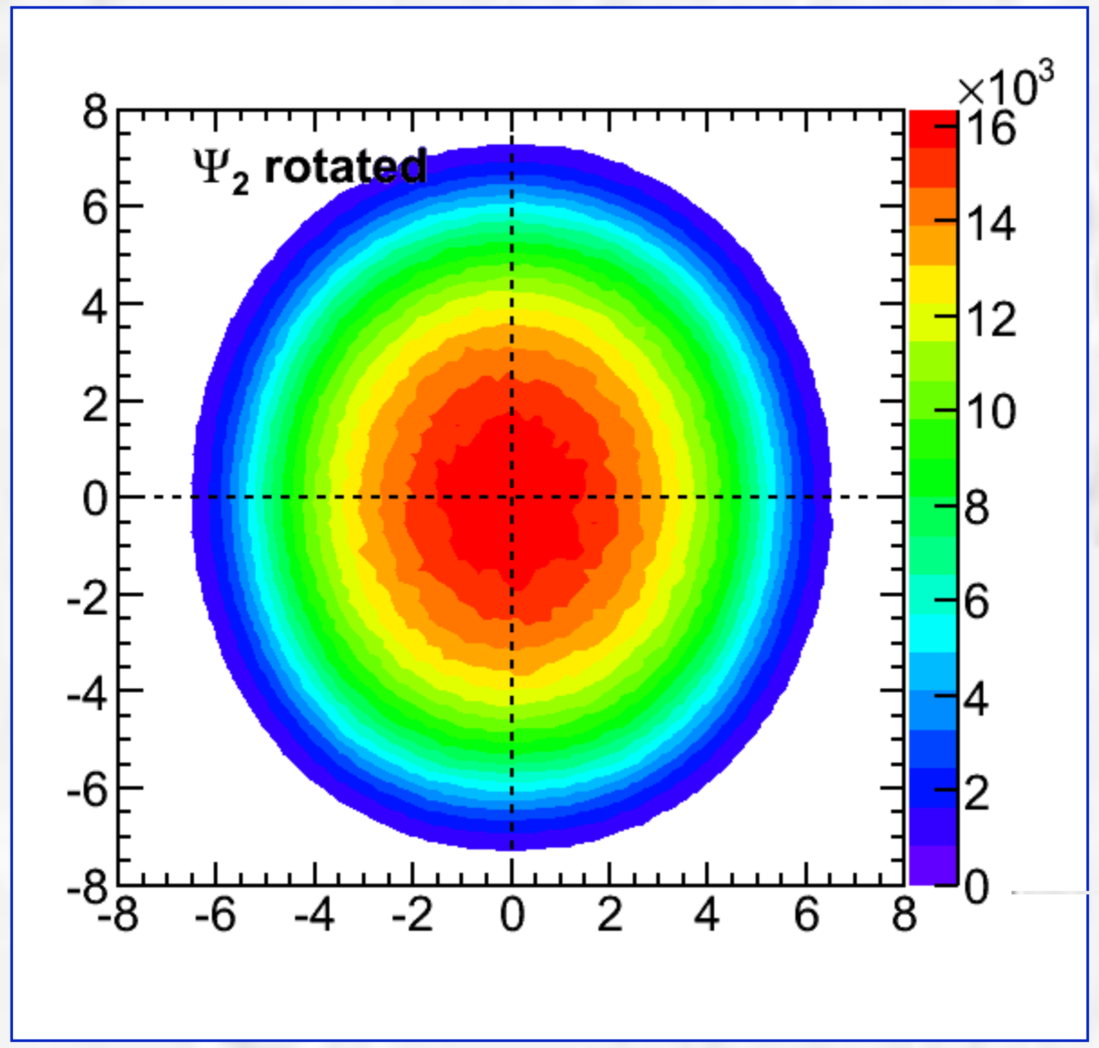


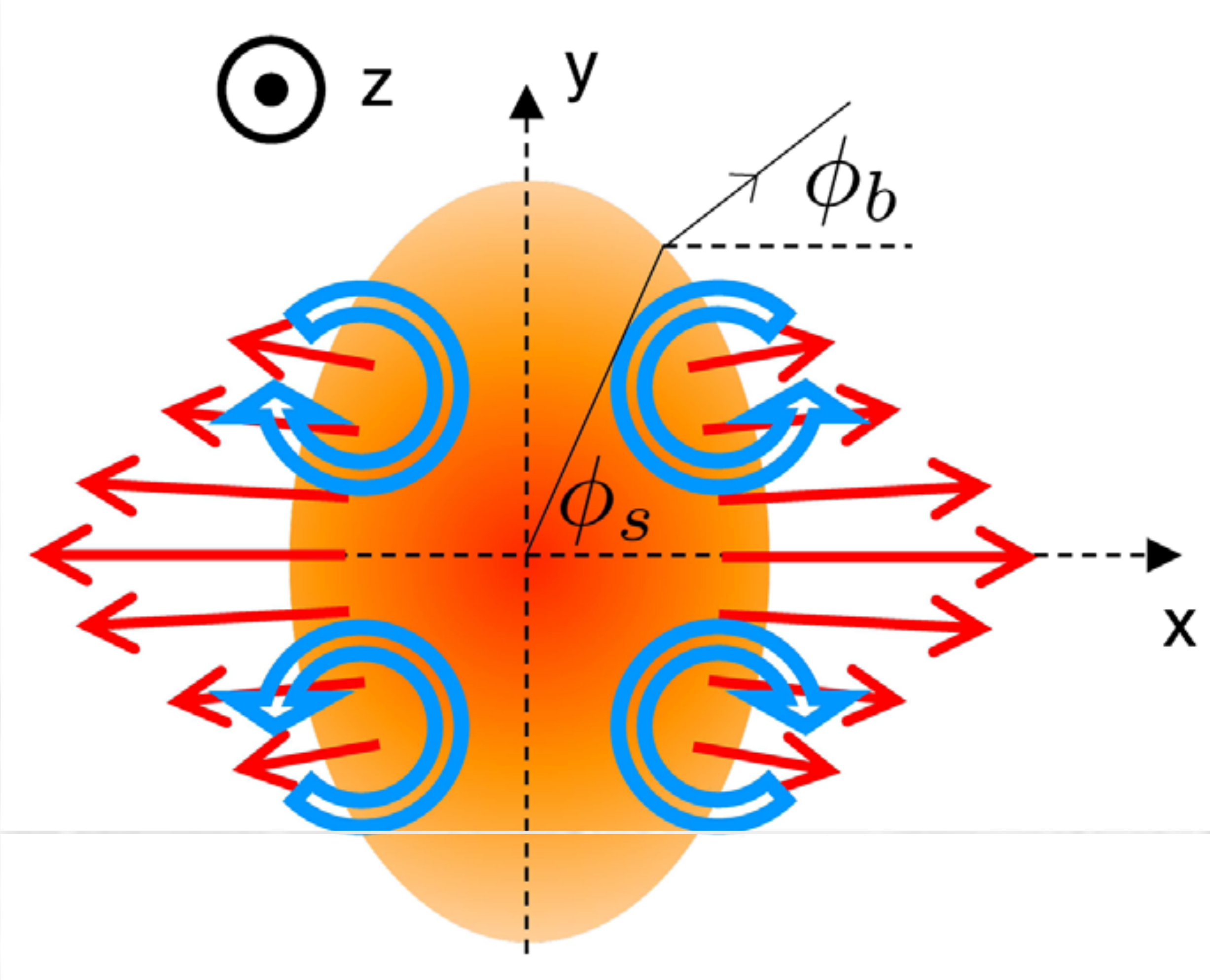
$$\omega = \frac{1}{2}\nabla\times\mathbf{v}$$



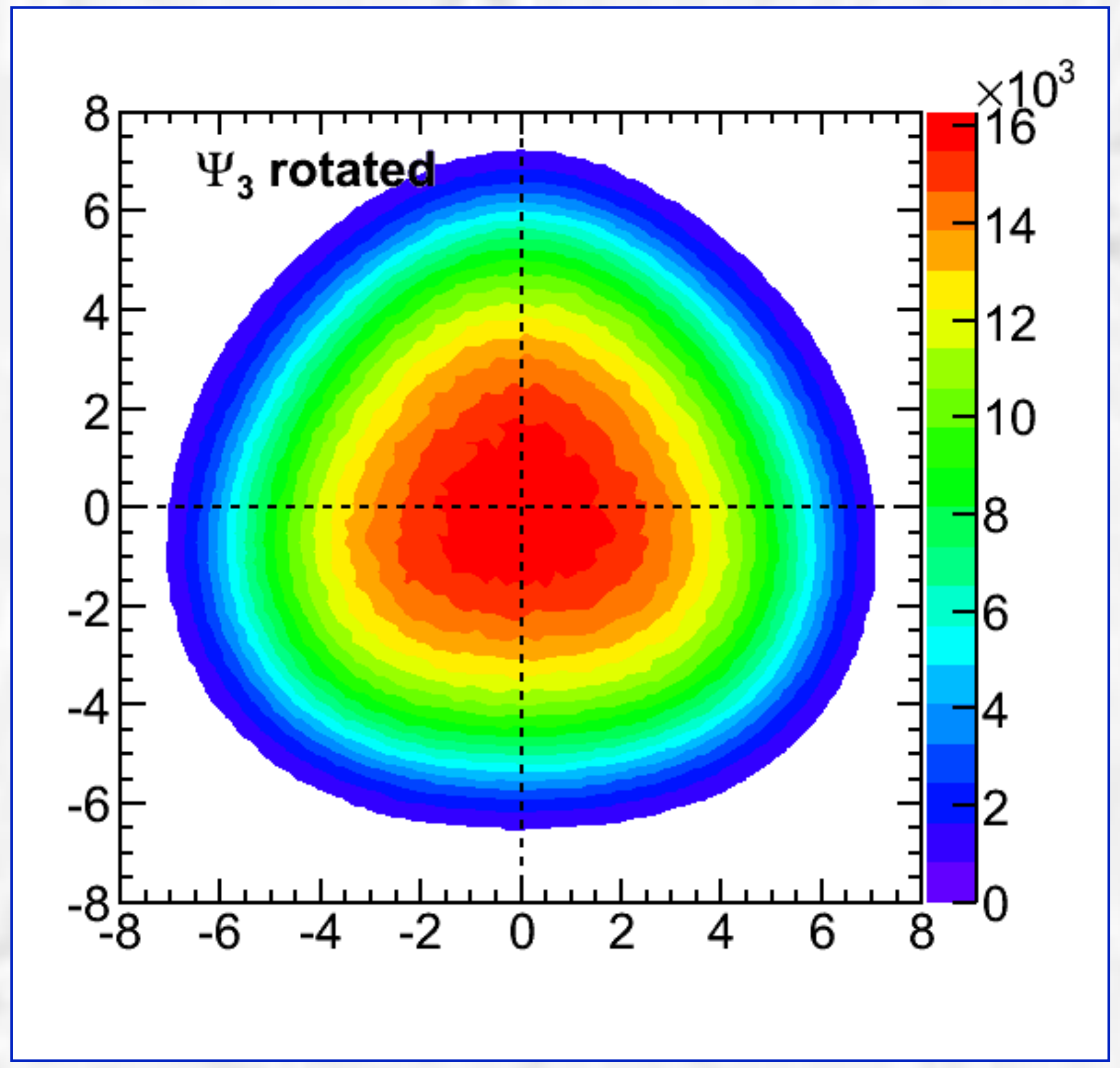


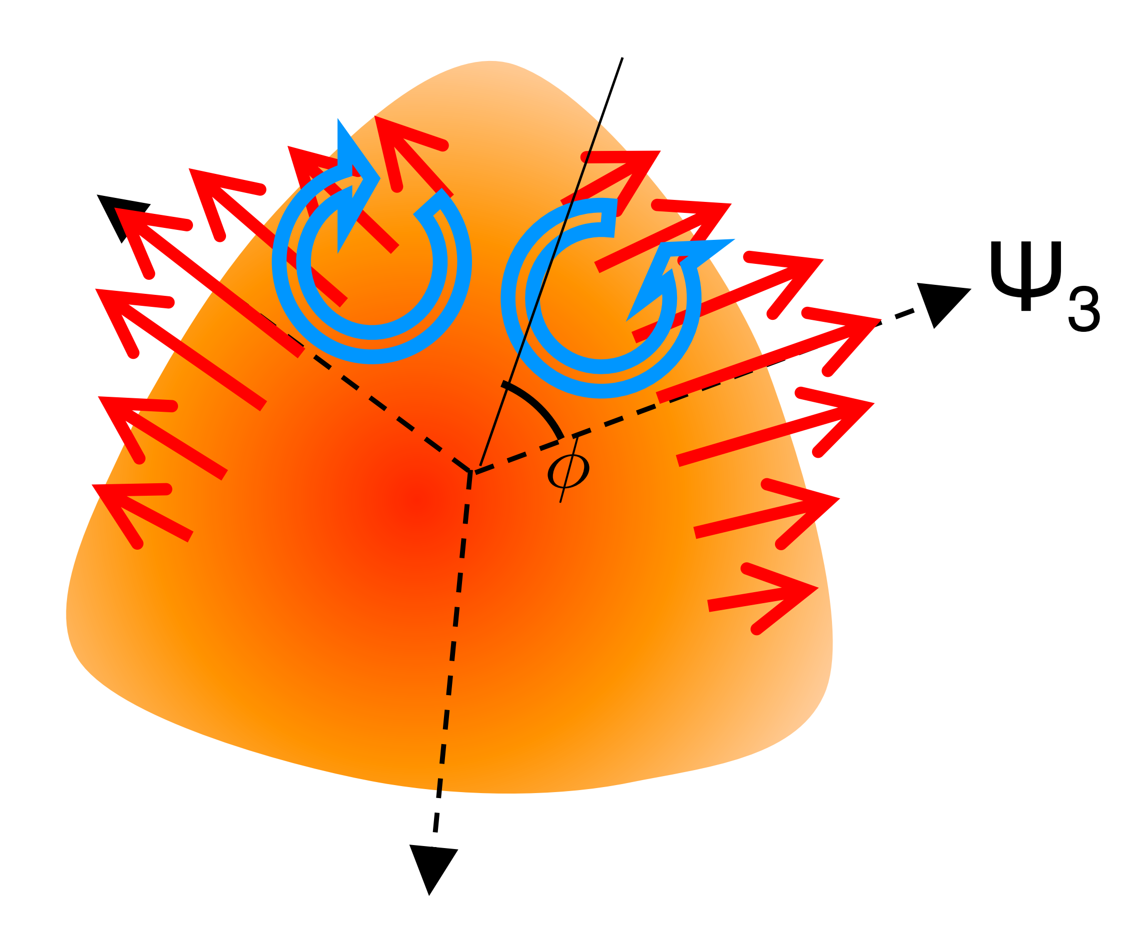
Anisotropic flow and vorticity



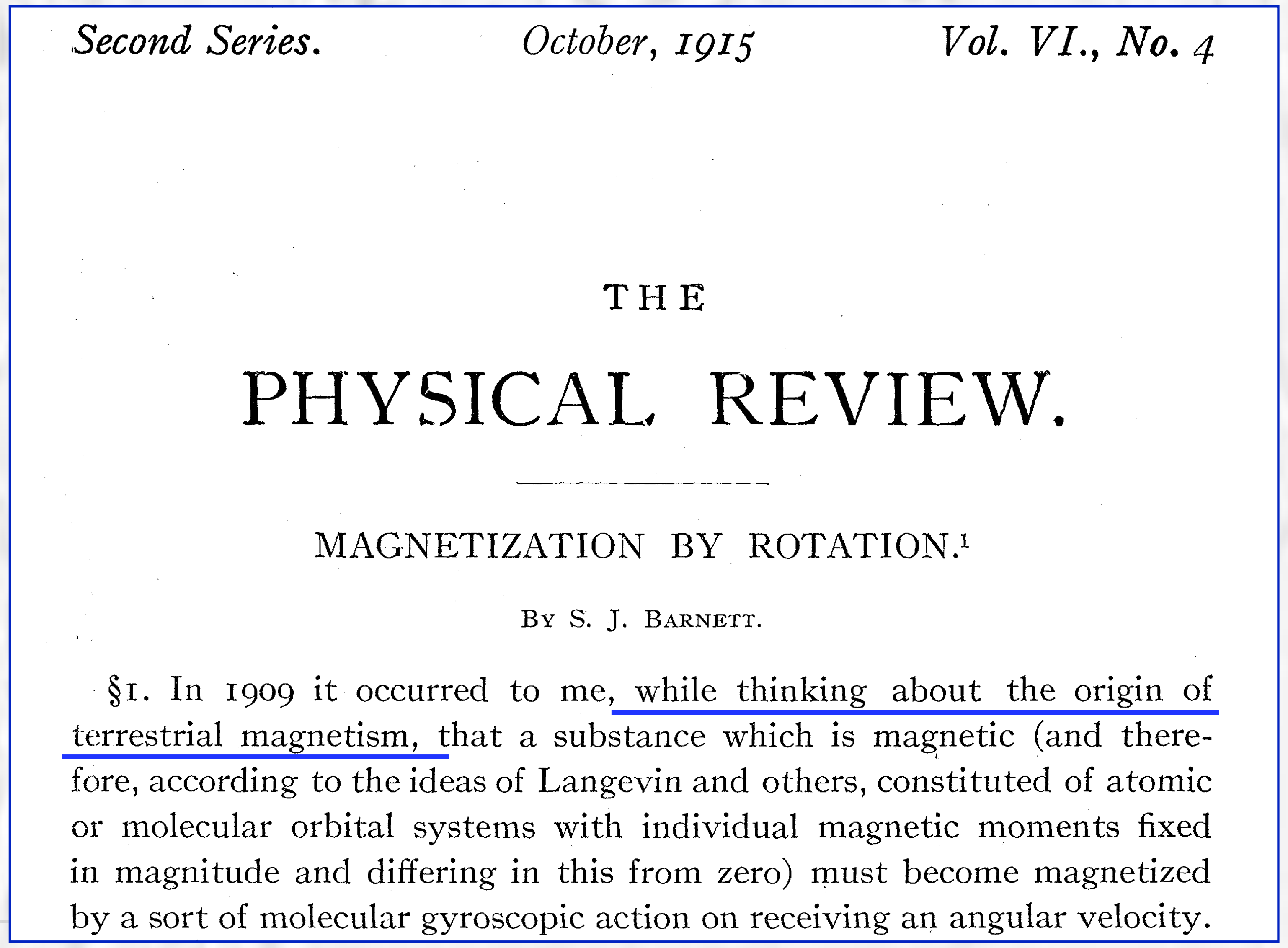


$$\omega = \frac{1}{2}\nabla\times\mathbf{v}$$





Barnett effect



Second Series. *October, 1915* *Vol. VI., No. 4*

THE

PHYSICAL REVIEW.

MAGNETIZATION BY ROTATION.[1]

By S. J. Barnett.

§1. In 1909 it occurred to me, while thinking about the origin of terrestrial magnetism, that a substance which is magnetic (and therefore, according to the ideas of Langevin and others, constituted of atomic or molecular orbital systems with individual magnetic moments fixed in magnitude and differing in this from zero) must become magnetized by a sort of molecular gyroscopic action on receiving an angular velocity.

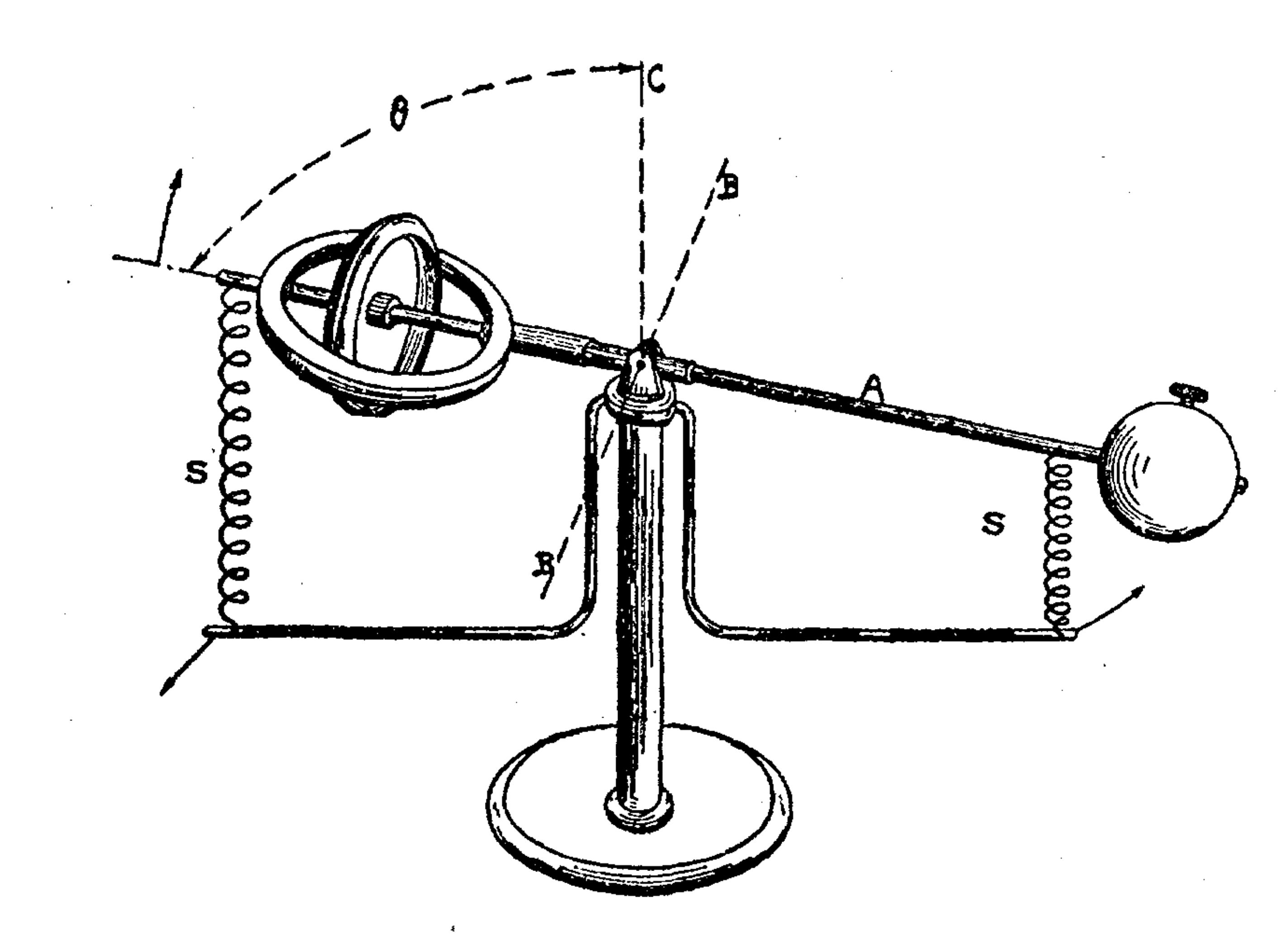
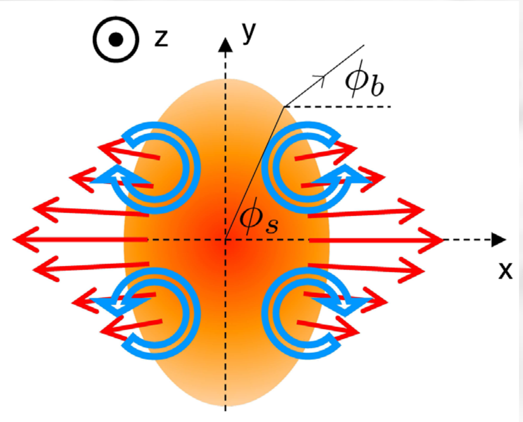
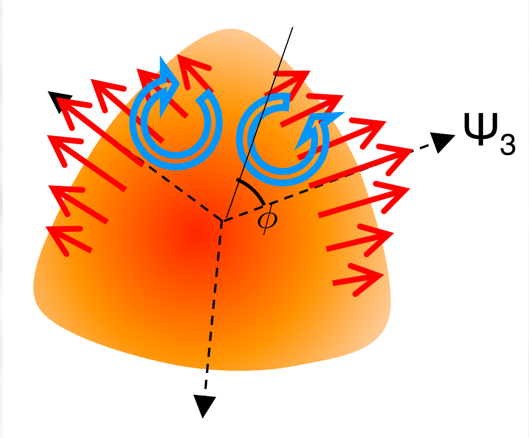


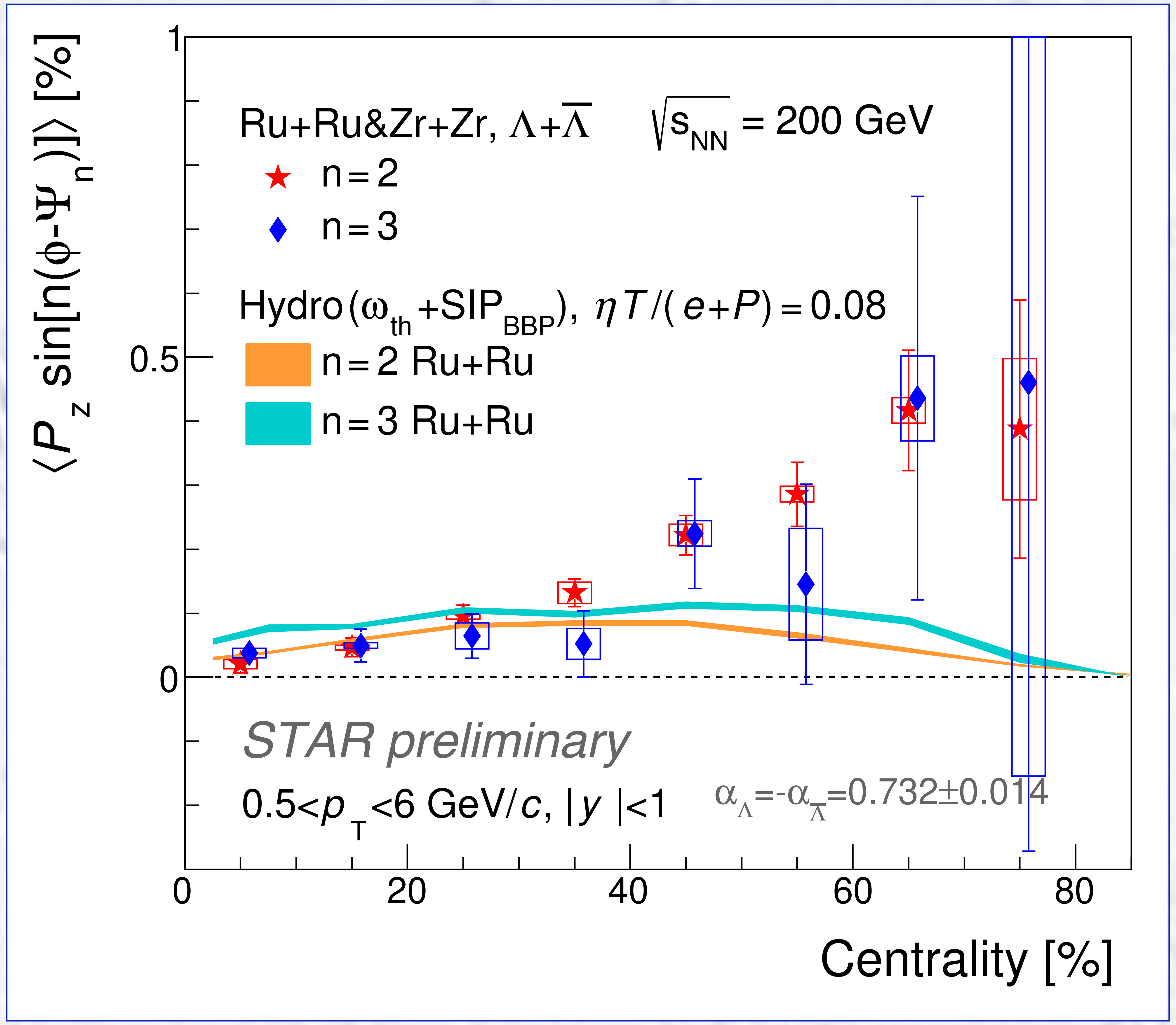
Fig. 2–1.

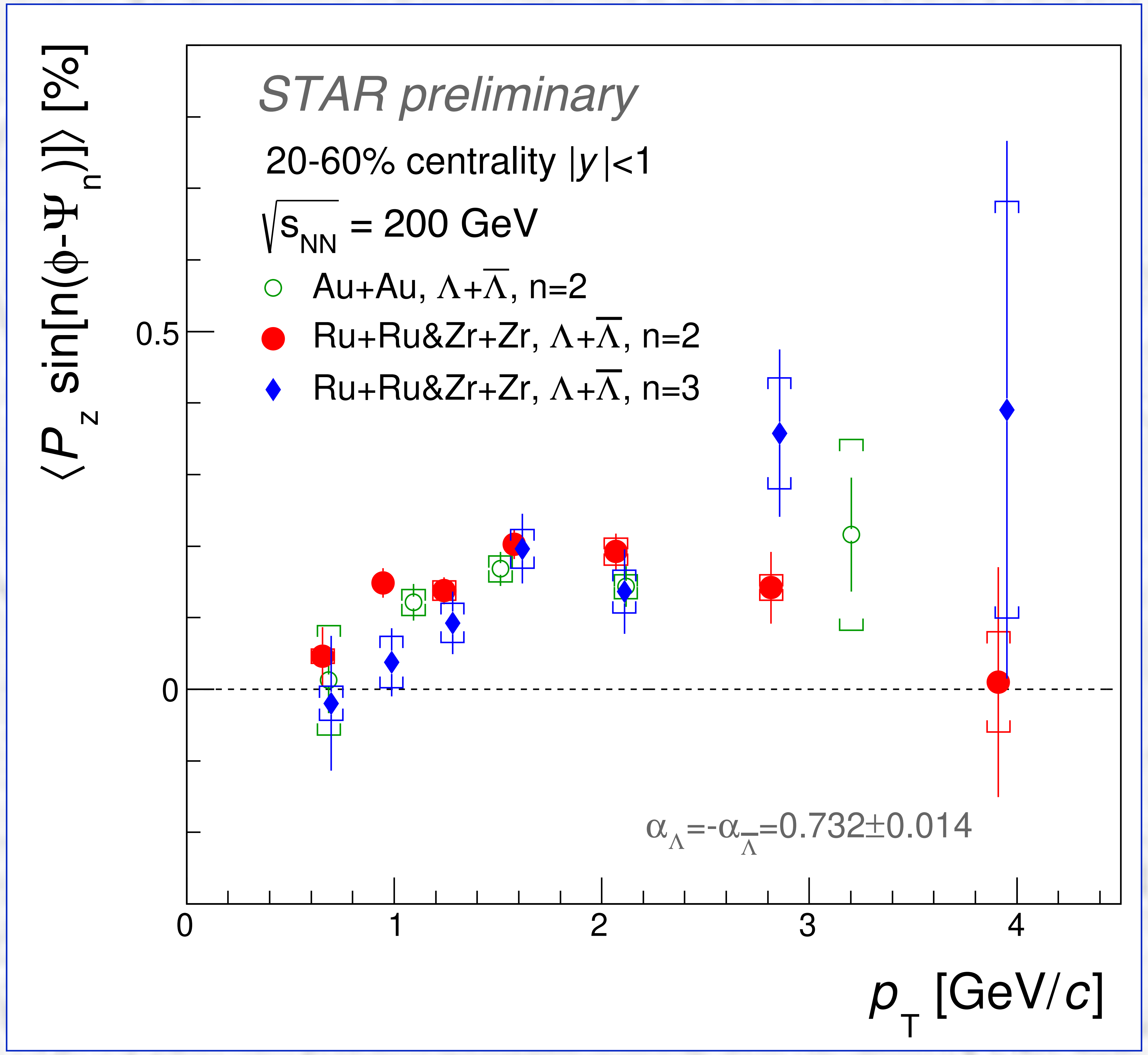
$$P \approx \omega/(2T)$$

$\langle P_z \sin[n(\phi_H - \Psi_n)] \rangle$









Using average over Ru+Ru and Zr+Zr

Assuming the same polarization for Λ and $\bar{\Lambda}$

Summary

Art: physics, inspiration, and much more

Flow, as a truly ideal fluid, has interpenetrated
all parts of heavy ion physics, it brings
new discoveries and contributes greatly
to our understanding of strongly interacting matter.

We are grateful to Art, who made it works.

EXTRA SLIDES

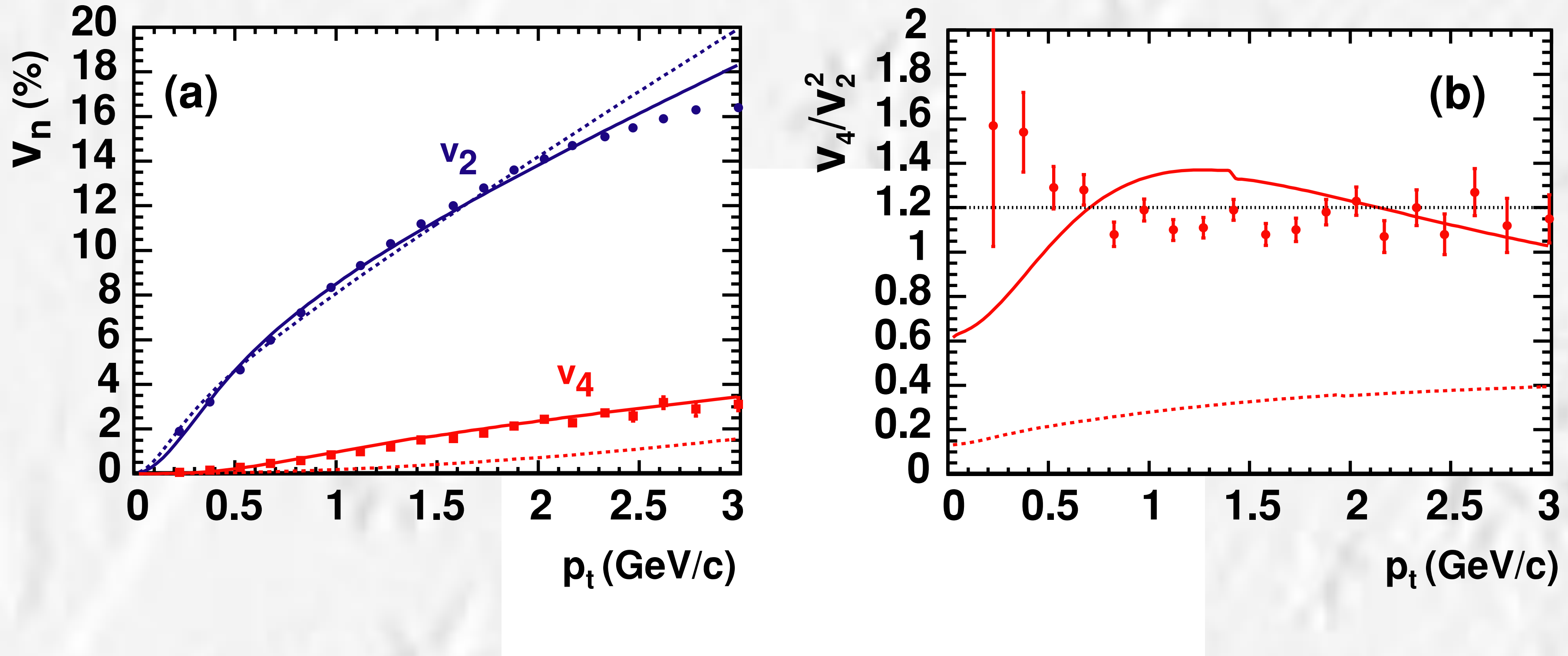


FIG. 22. (Color online) Graphs of v_n and v_4/v_2^2. The dashed lines are surface shell blast-wave fits with no ρ_4 or s_4 terms (see Sec. VI D) to the charged hadron v_2 minimum bias data. The resultant ratio v_4/v_2^2 is shown as the lower dashed line in the ratio graph (b). The solid lines are the fits with the addition of ρ_4 and s_4. The resultant ratio v_4/v_2^2 is shown as the solid curve in the ratio graph (b). The dotted line in the ratio graph (b) at 1.2 represents the average value of the data.

$$N\cdot(v_n\{2\}^2 - v_n\{k\}^2) = g_n$$

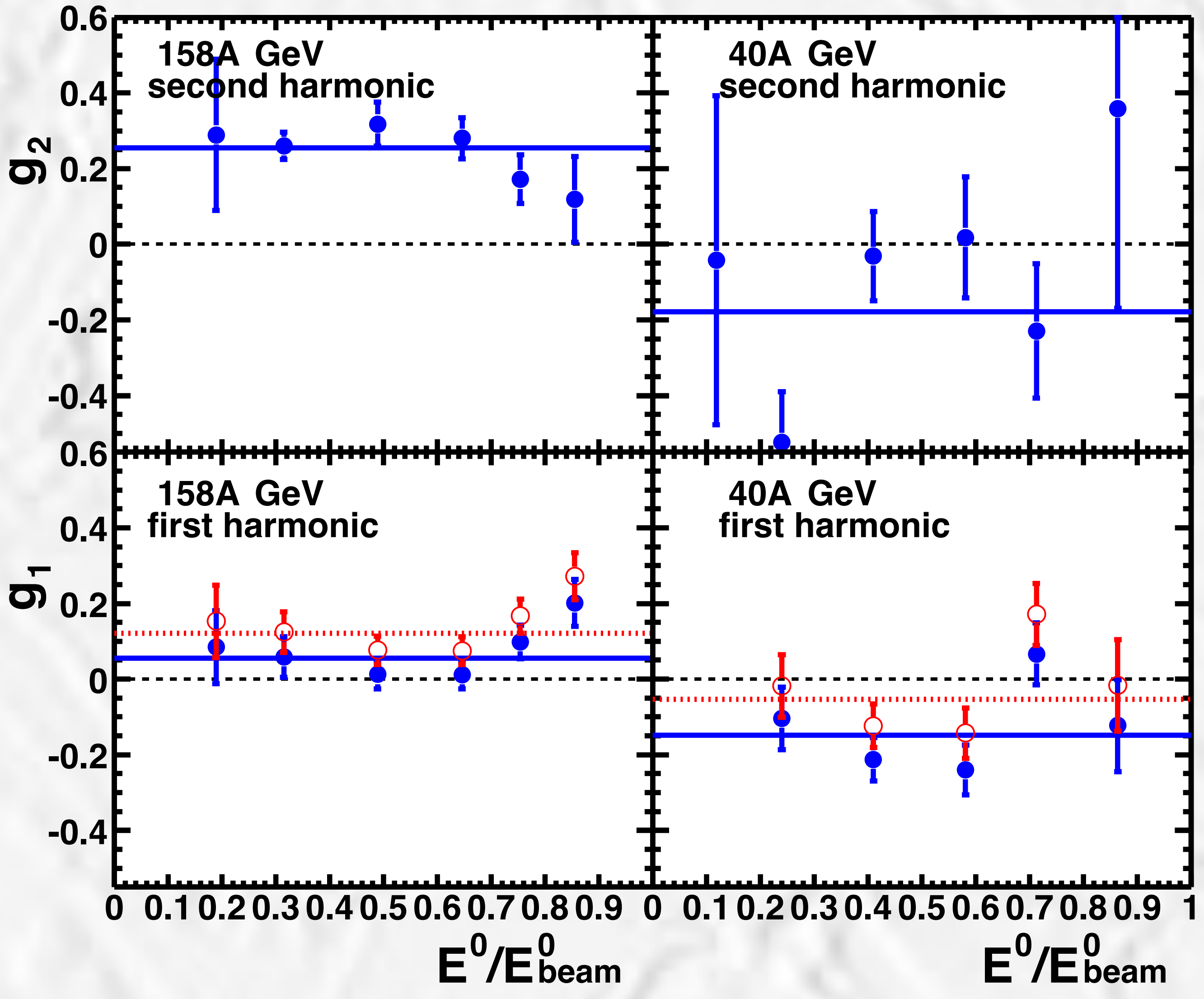


FIG. 22. (Color online) Nonflow azimuthal correlations from Eq. (16), for the first, g_1, (bottom) and second, g_2, (top) Fourier harmonics, from 158*A* GeV (left) and 40*A* GeV (right) Pb+Pb collisions. For g_1, the solid points represent all nonflow effects, while the open points are corrected for momentum conservation. The horizontal lines are at the mean values.

Q-vector products and multiparticle correlations

$$u = e^{i\phi}; \quad Q = \sum u; \quad Q_2 = \sum u^2$$

$$\langle u_i u_j^* \rangle = \left\langle \frac{1}{N(N-1)} \left(QQ^* - N \right) \right\rangle$$

$$\langle u_i u_j u_k^{*2} \rangle = \left\langle \frac{1}{N(N-1)(N-2)} \left[\left(Q^2 Q_2^* - N \right) - \left(Q_2 Q_2^* - N \right) - 2\left(QQ^* - N \right) \right] \right\rangle$$

$$\langle u_i u_j u_k^* u_l^* \rangle = \left\langle \frac{1}{N(N-1)(N-2)(N-3)} \left[\left(Q^2 Q^{*2} - N \right) - 2N(N-1) - 4(N-2)(QQ^* - N) - 2(Q^2 Q_2^* - N) + (Q_2 Q_2^* - N) \right] \right\rangle$$

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the beginning

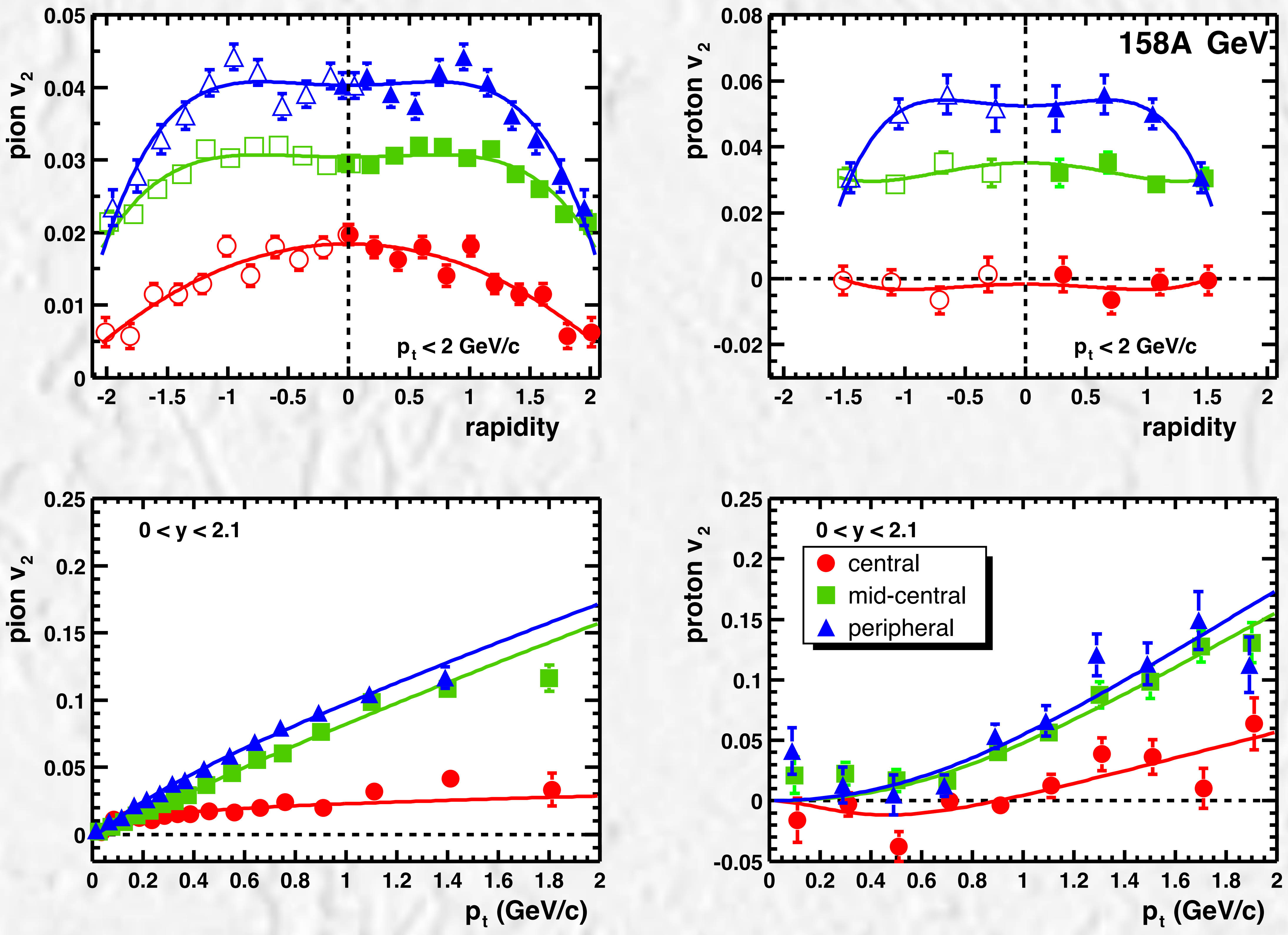

FIG. 6. (Color online) Elliptic flow obtained from the standard method as a function of rapidity (top) and transverse momentum (bottom) for charged pions (left) and protons (right) from 158*A* GeV Pb+Pb. Three centrality bins are shown. The open points in the top graphs have been reflected about midrapidity. Solid lines are polynomial fits (top) and blast wave model fits (bottom).