Experimental overview on chirality and polarization

Sergei A. Voloshin
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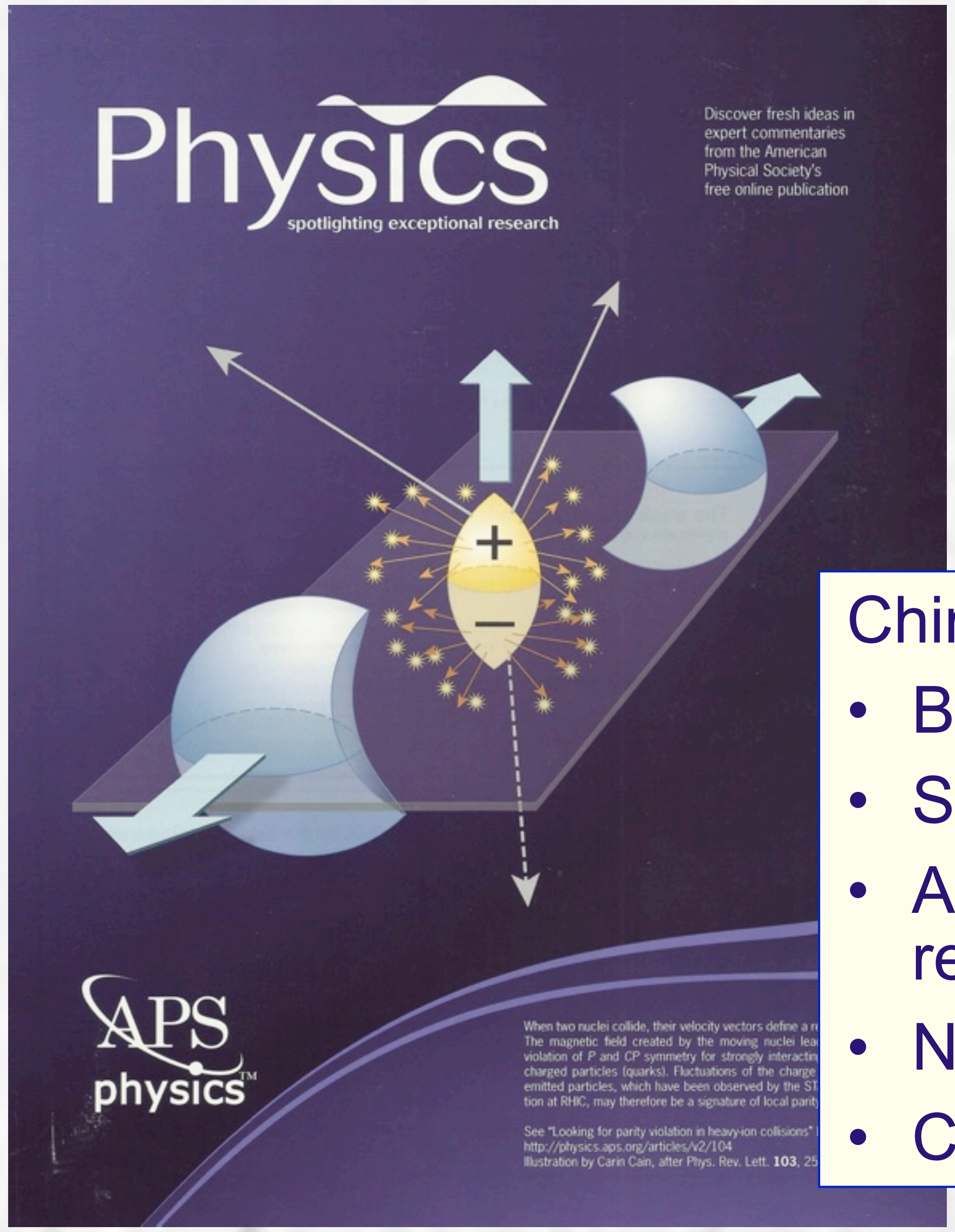
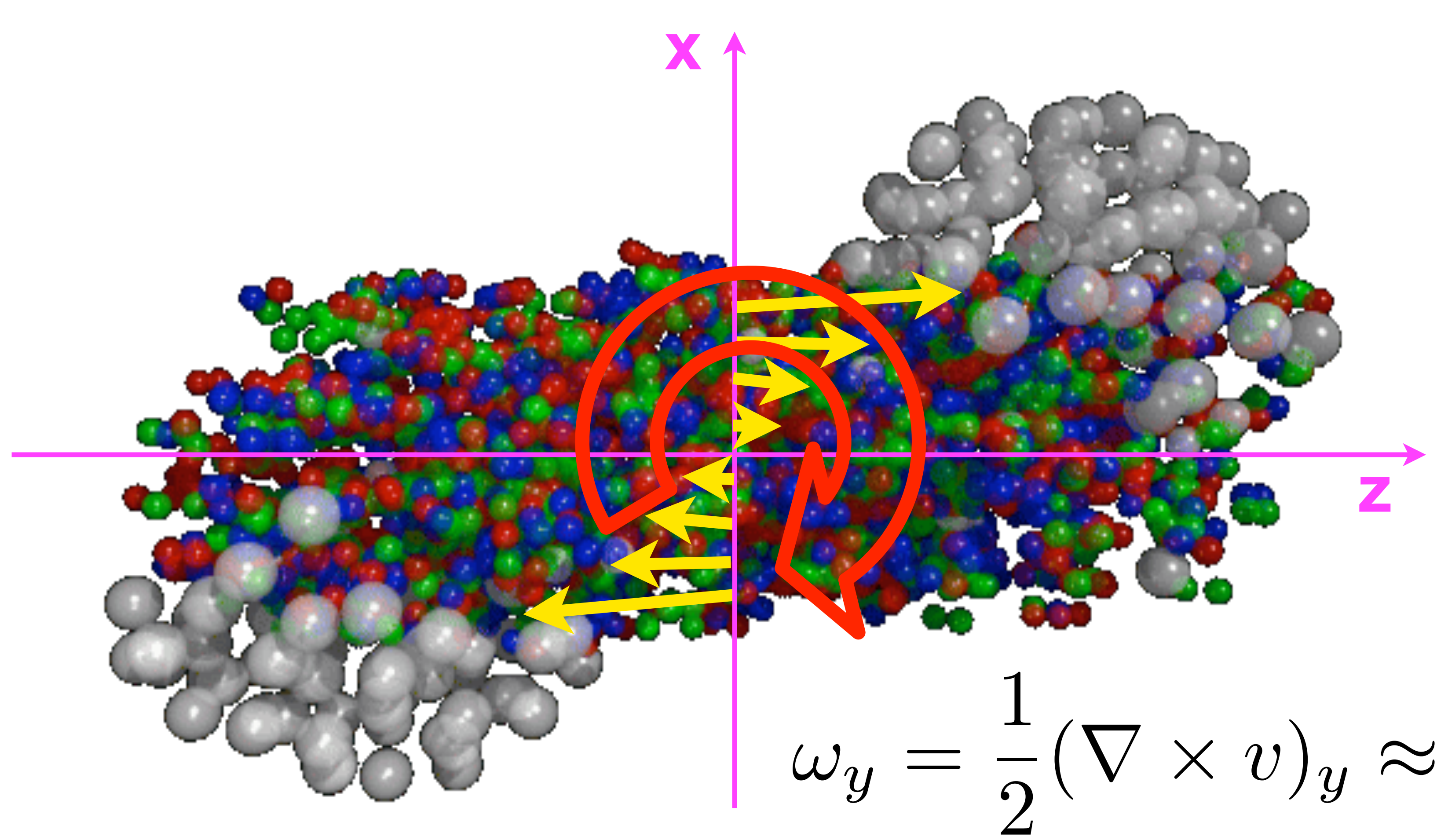
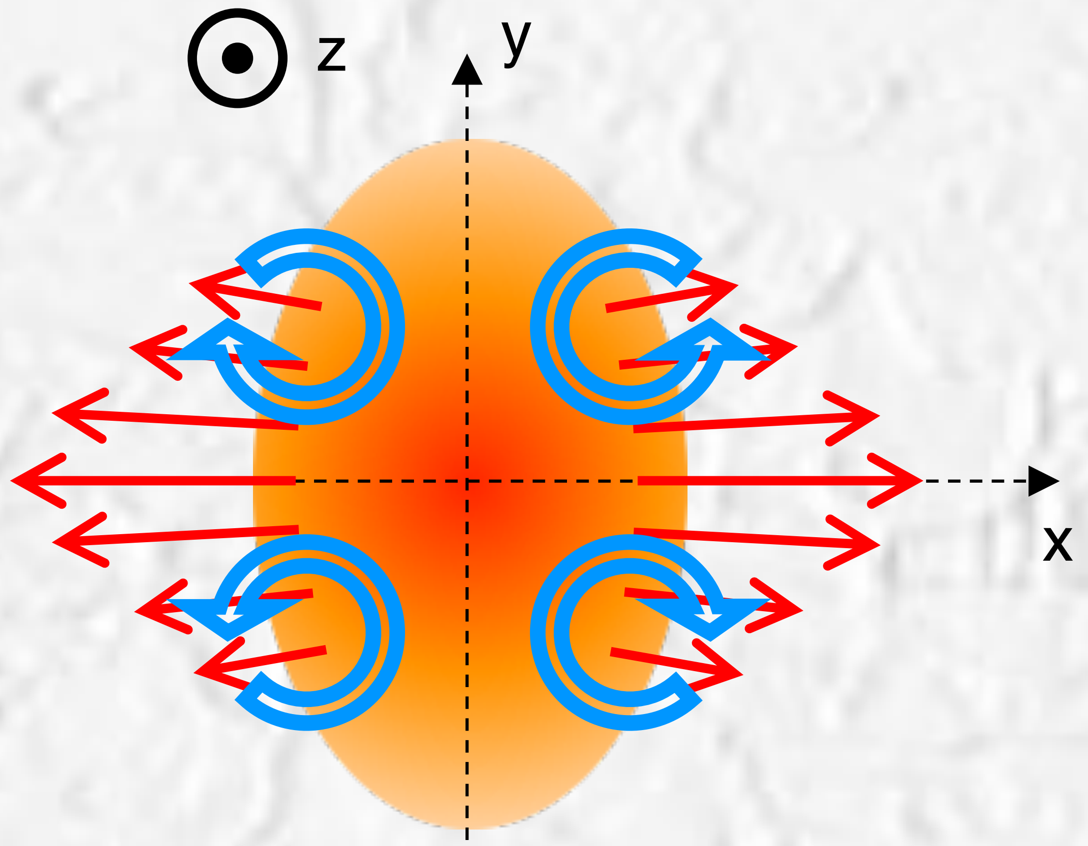


Chirality:
- Brief history / introduction
- Some old and new results
- Assumptions, and assumptions, realistic and not realistic
- New approaches
- Current limits and near future

Mostly on CME; CMW, CVE, only in passing



$$\omega_y = \frac{1}{2}(\nabla \times v)_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$



Vorticity:
- Intro, one page of history
- Global polarization: Λ, Ξ, Ω polarization
- Local, "z" polarization
- Spin alignment
- What is next

- EM fields estimates

Parity violation study with 3 particle correlations

Looking for the effect of D. Kharzeev, hep-ph/0406125

Sergei Voloshin
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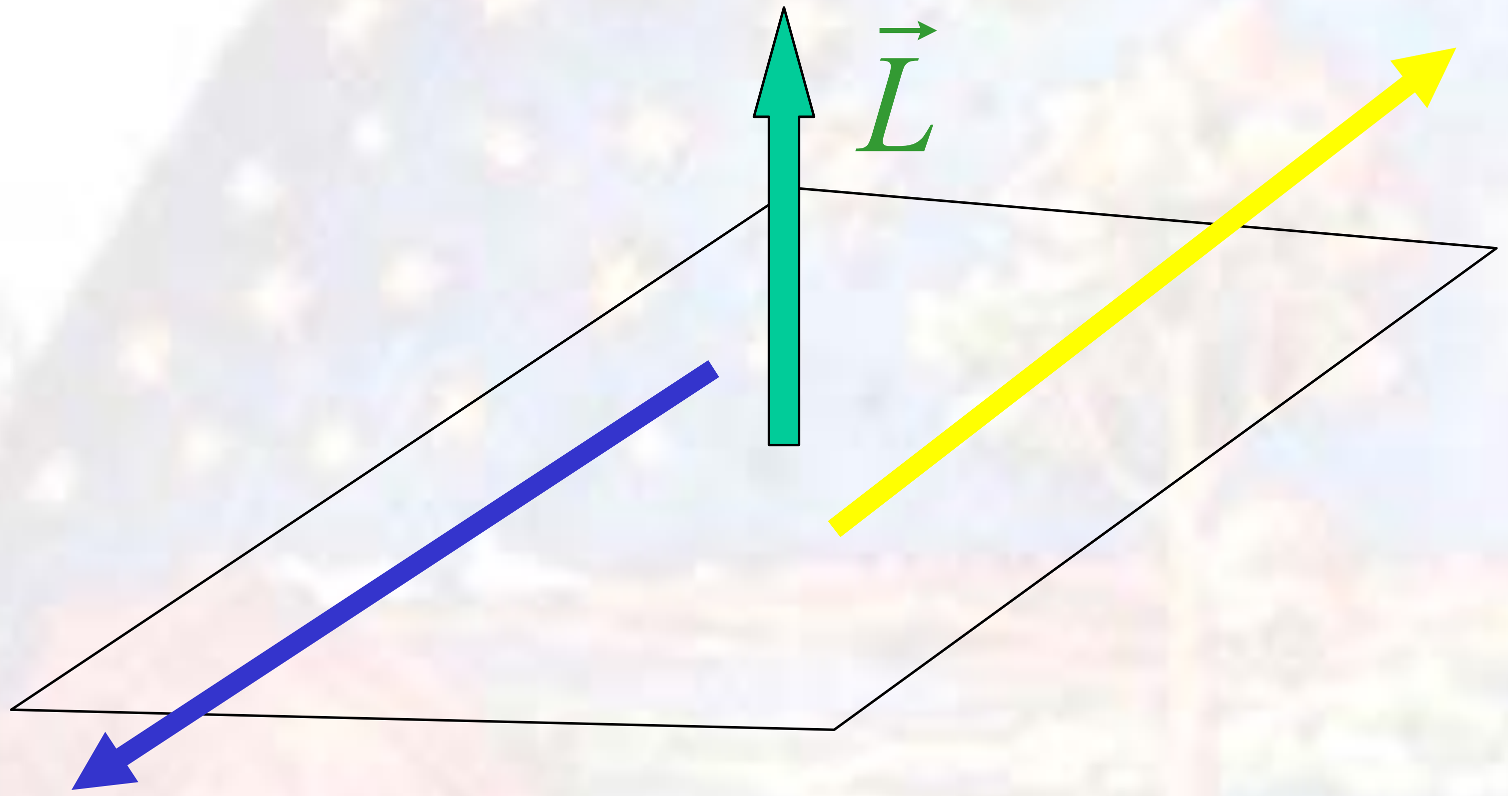


Mixed harmonic technique or 3-particle correlations

hep-ph/0406311

$$\frac{dN}{d\varphi} \propto 1 + 2a\sin\varphi$$

a > 0 ➔ preferential emission along the angular momentum
The sign can vary event by event, a~Q/N_π, where Q is the topological charge, |Q|=1,2,...
➔at dN/dy~100, |a|~1%.

projections onto reaction plane

Projections on the direction of angular momentum

All effects non sensitive to the RP cancel out!

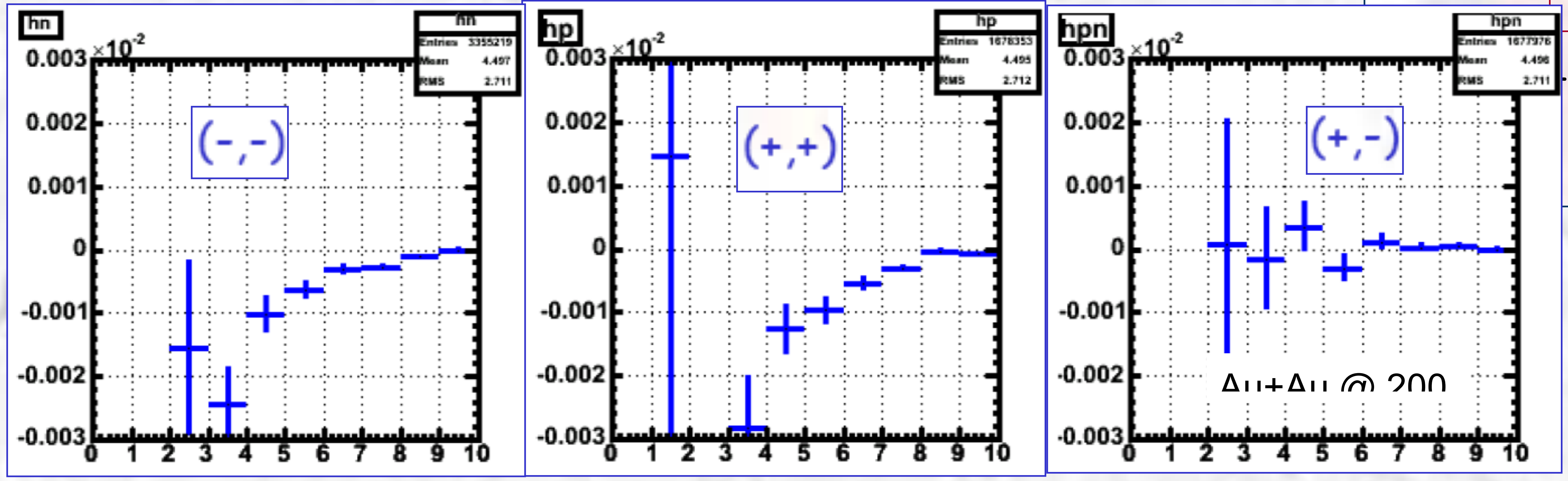
Possible systematics: clusters that flow

$$\langle \cos(\varphi_a - \Psi_2)\cos(\varphi_b - \Psi_2) - \sin(\varphi_a - \Psi_2)\sin(\varphi_b - \Psi_2) \rangle =$$
$$= \langle \cos(\varphi_a + \varphi_b - 2\Psi_2) \rangle = (v_{1,a}v_{1,b} - a_a a_b)\langle \cos(2\Psi_2 - 2\Psi_{RP}) \rangle$$

And using only one particle instead of the event flow vector

$$\langle \cos(\varphi_a - \varphi_c)\cos(\varphi_b - \varphi_c) - \sin(\varphi_a - \varphi_c)\sin(\varphi_b - \varphi_c) \rangle =$$
$$= \langle \cos(\varphi_a + \varphi_b - 2\varphi_c) \rangle = (v_{1,a}v_{1,b} - a_a a_b)v_{2,c}$$

hat for a rapidity region symmetric with respect to the midrapidity v_1=0



Note a cartoon from a discussion of the global polarization

Only (semi-)qualitative predictions from theory: charge separation along the magnetic field

- The data seems to agree with that; background possible.
- Still true today (?)

CME and "Gamma" correlator

D. Kharzeev, Parity violation in hot QCD: Why it can happen and how to look for it, Phys. Lett. B **633**, 260 (2006).

S. A. Voloshin, Parity violation in hot QCD: How to detect it, Phys. Rev. C **70**, 057901 (2004).

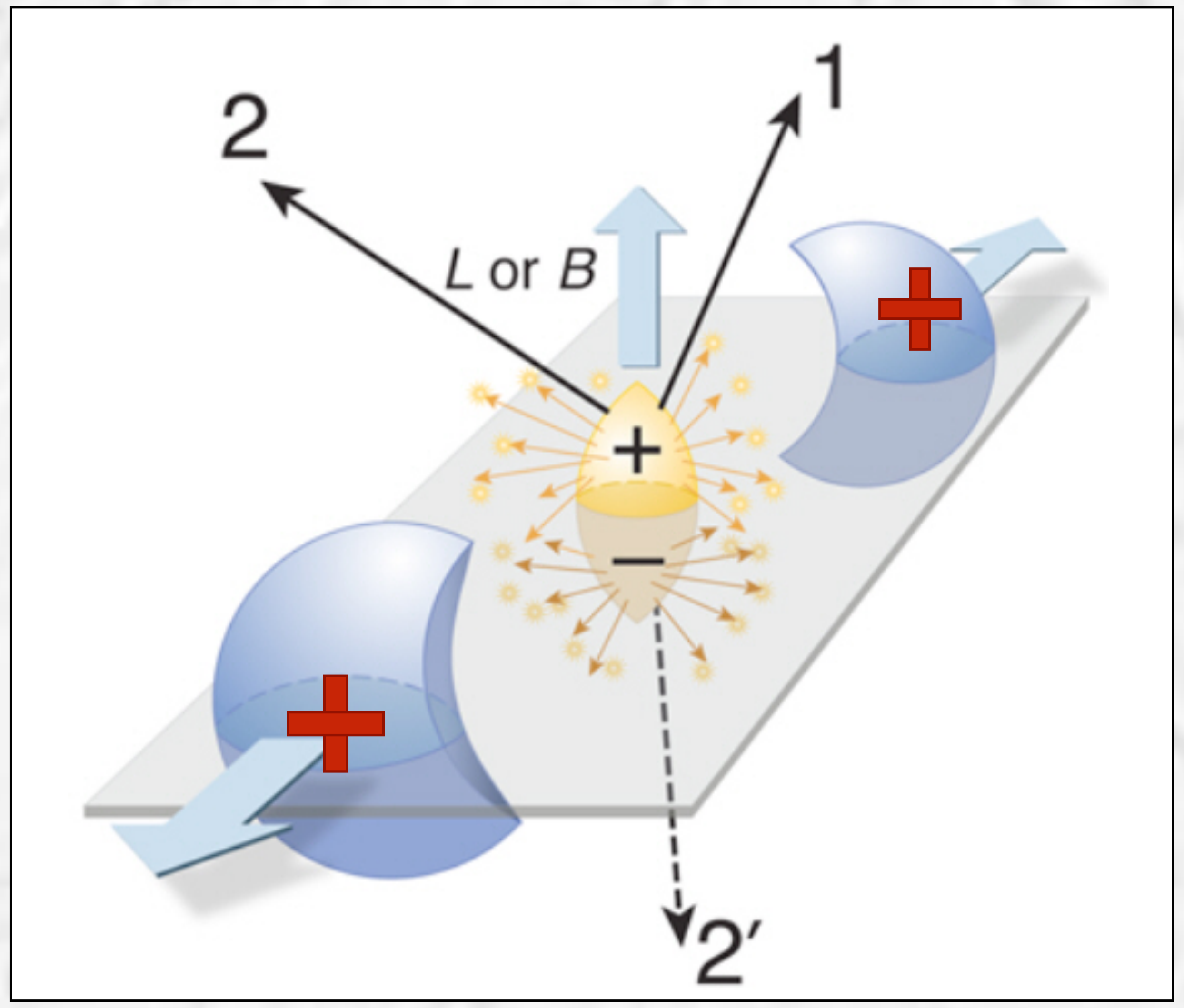
Chirality imbalance
+
Magnetic field

$\mu_5 \propto \mathbf{E} \cdot \mathbf{B}$

Anomalous transport,
Electric current along magnetic field

$\mathbf{J} = \frac{e^2}{2\pi^2} \mu_5 \mathbf{B}$

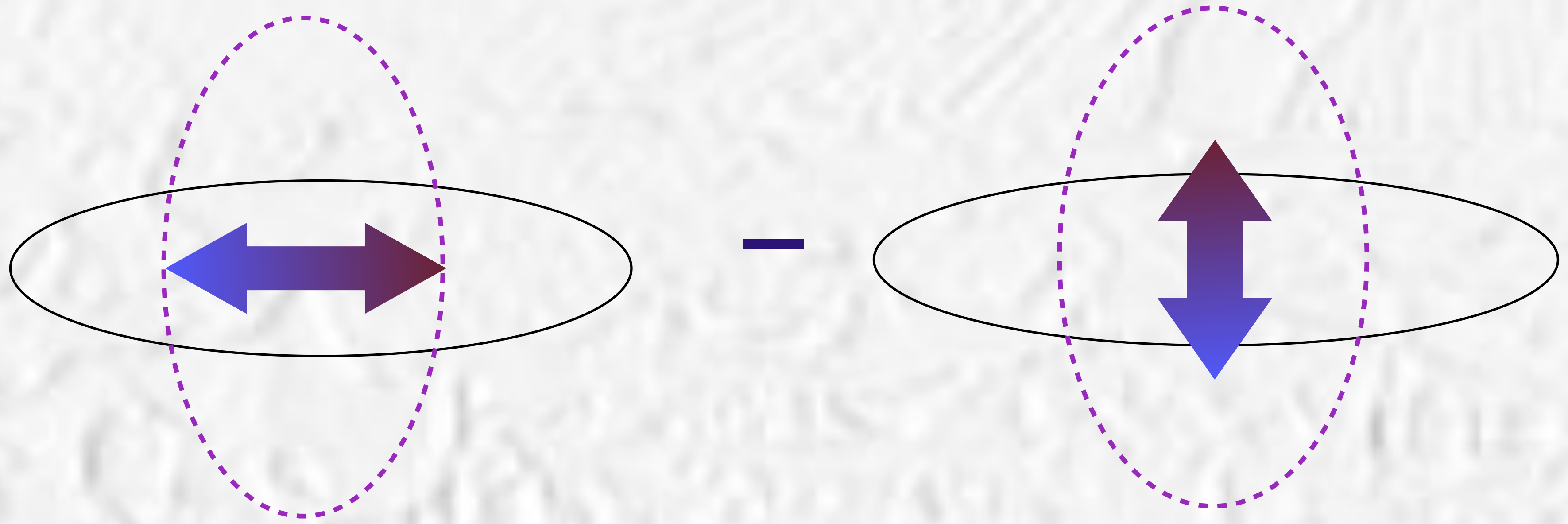
Charge separation along **B** direction



Effective particle distribution

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

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



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 $v_2 < 10^{-1}$.

2008-2010

Probe for the (strong interaction) parity violation effects in heavy ion collisions with three particle correlations

Sergei A. Voloshin*) for the STAR Collaboration
*) Wayne State University, U.S.A.

Abstract

In non-central relativistic heavy ion collisions, $\mathcal{P}$-odd domains, which might be created in the process of the collision, are predicted to lead to charge separation along the system orbital momentum [1]. An observable, P-even, but directly sensitive to the charge separation effect, has been proposed in [2] and is based on 3-particle mixed harmonics azimuthal correlations. We report the STAR measurements using this observable for Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}$=200 and 62 GeV. The results are reported as function of collision centrality, particle separation in rapidity, and particle transverse momentum. Effects that are not related to parity violation but might contribute to the signal are discussed.

QM2008 - first public showing of STAR results

PANIC 2008 Eilat, ISRAEL

Sergei A. Voloshin
Nuclear Physics A 827 (2009) 377c–382c

Suggestion of using isobar beams
$^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$ and $^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$
to disentangle CME signal from BG

QM2009

Experimental study of spontaneous strong parity violation in heavy ion collisions at RHIC

Sergei A. Voloshin, Wayne State University
The STAR Collaboration

Strong parity violation at STAR: Quantifying background effects with Monte-Carlo event generators and detector effects study
Ilya Selyuzhenkov (Indiana University) for the STAR Collaboration
Ilya.Selyuzhenkov@gmail.com

Quark Matter 2009

Strong parity violation at STAR:
Evaluating experimental measurement technique and estimating background contributions from multi-particle production
Evan Finch (Yale University), *for the STAR Collaboration*

Quark Matter 2009

Selected for a Viewpoint in *Physics*
PRL **103,** 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

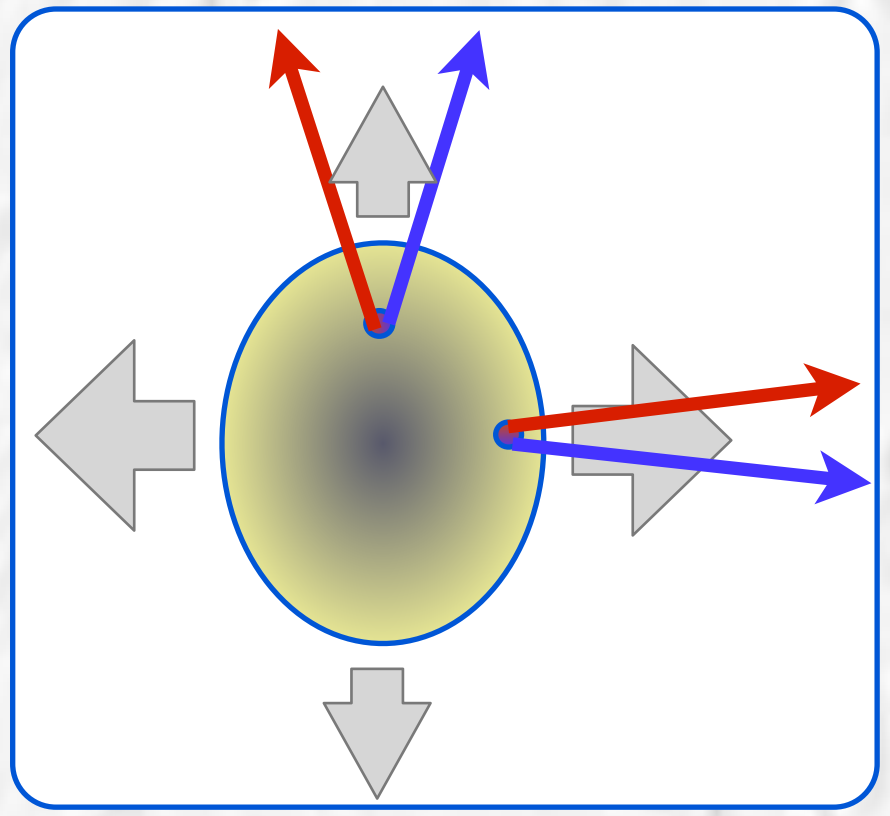
PHYSICAL REVIEW C **81**, 054908 (2010)

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions

Types of the background

I. Physics (RP dependent).
(Can not be suppressed)

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

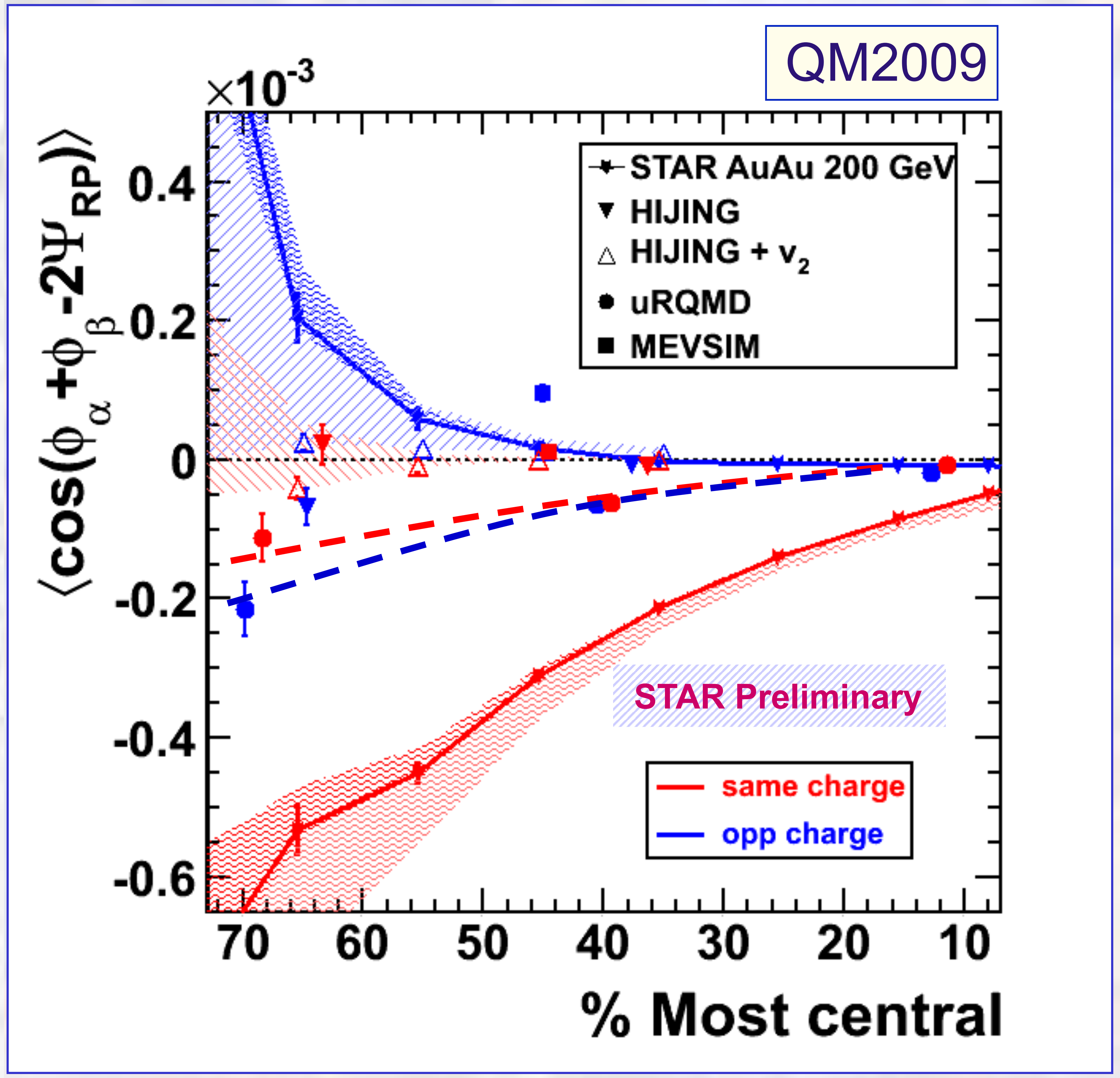


"Flowing clusters" (including LCC) charge dependent directed flow.

LCC: Pratt, arXiv:1002.1758v1[nucl-th]
Schlichting and Pratt, PRC83 014913 (2011)

- 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 the Blast Wave model

Global polarization (including vector mesons); Note: in 2007 limits on the global polarization and spin alignment were obtained.



HIJING+v2 = added "afterburner" to generate flow
MEVSIM: flow as in experiment, number of resonances maximum what is consistent with experiment

II. Measurements (RP independent).
(depends on method, in principle can be reduced)

$$\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle \overset{?}{\to} \langle \cos(\phi_a + \phi_b - 2\Psi_2) \rangle \, v_{2,c}$$

RP independent background is dominant in peripheral collisions !

The main reason why this analysis was not done in pp and pAu

First PRL, PRC (2009)

PHYSICAL REVIEW C **81**, 054908 (2010)

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions

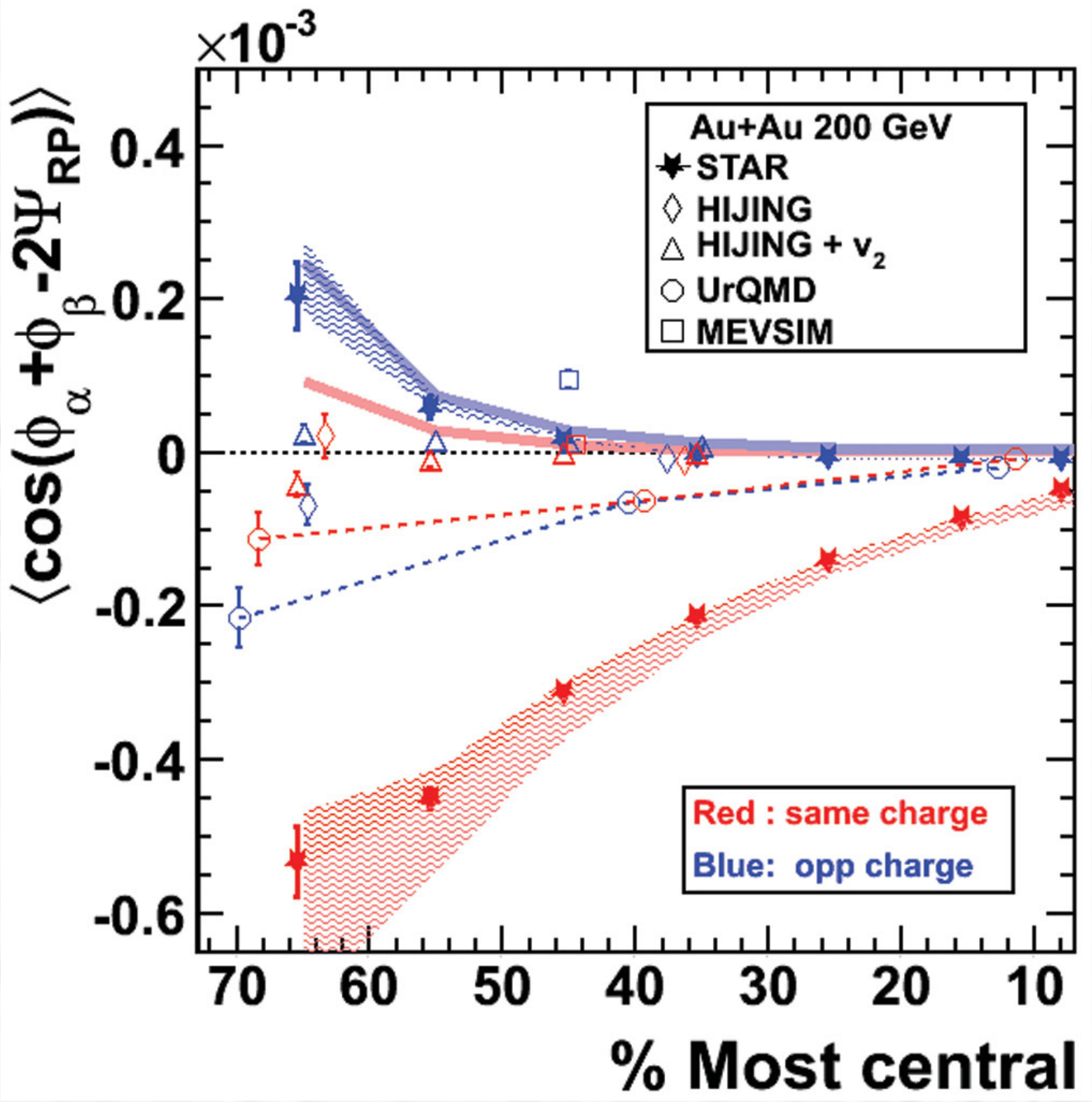


FIG. 4 (color). $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$ results from 200 GeV Au + Au collisions are compared to calculations with event generators HIJING (with and without an "elliptic flow after-burner"), URQMD (connected by dashed lines), and MEVSIM. Thick lines represent HIJING reaction-plane-independent background.

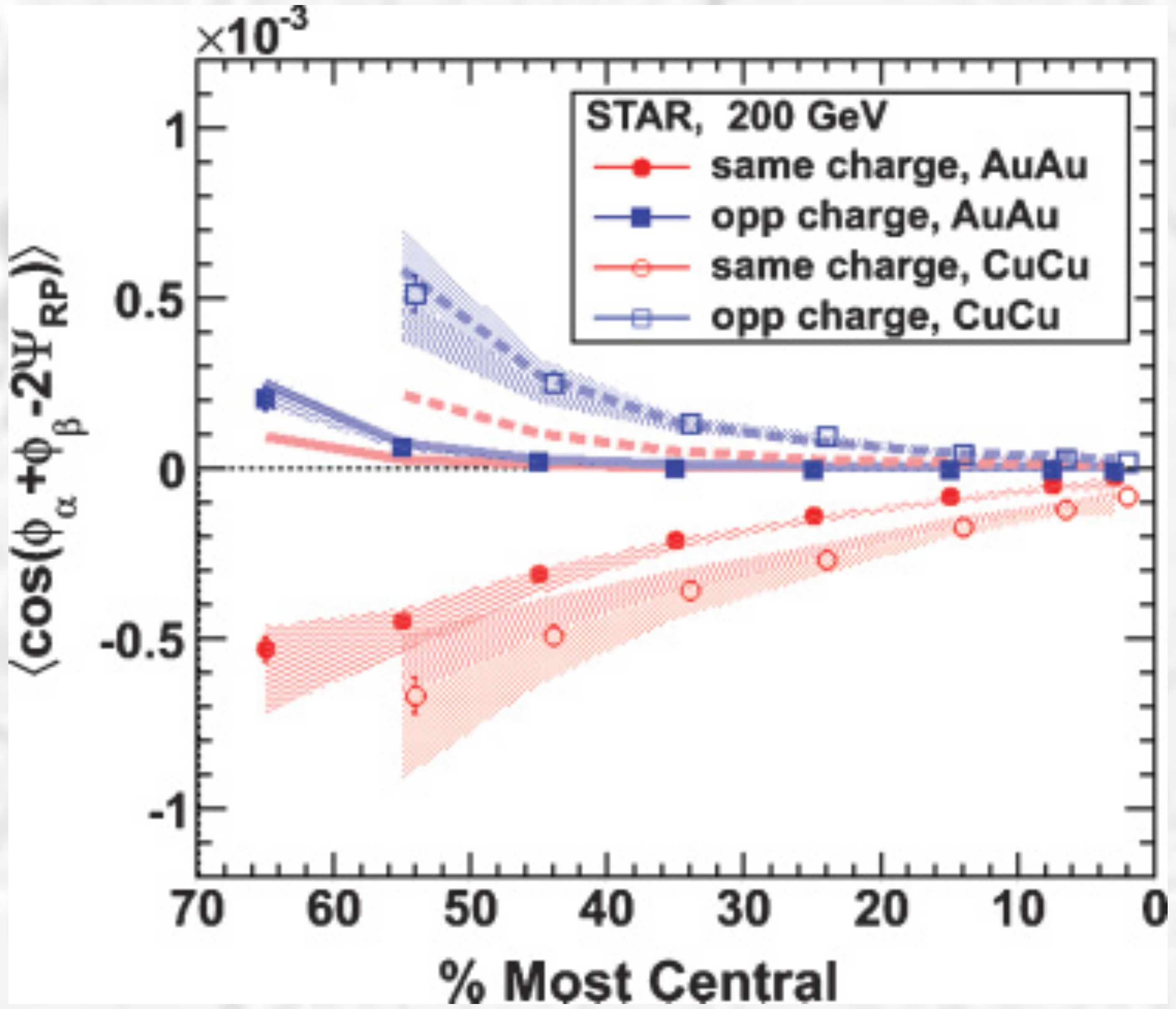
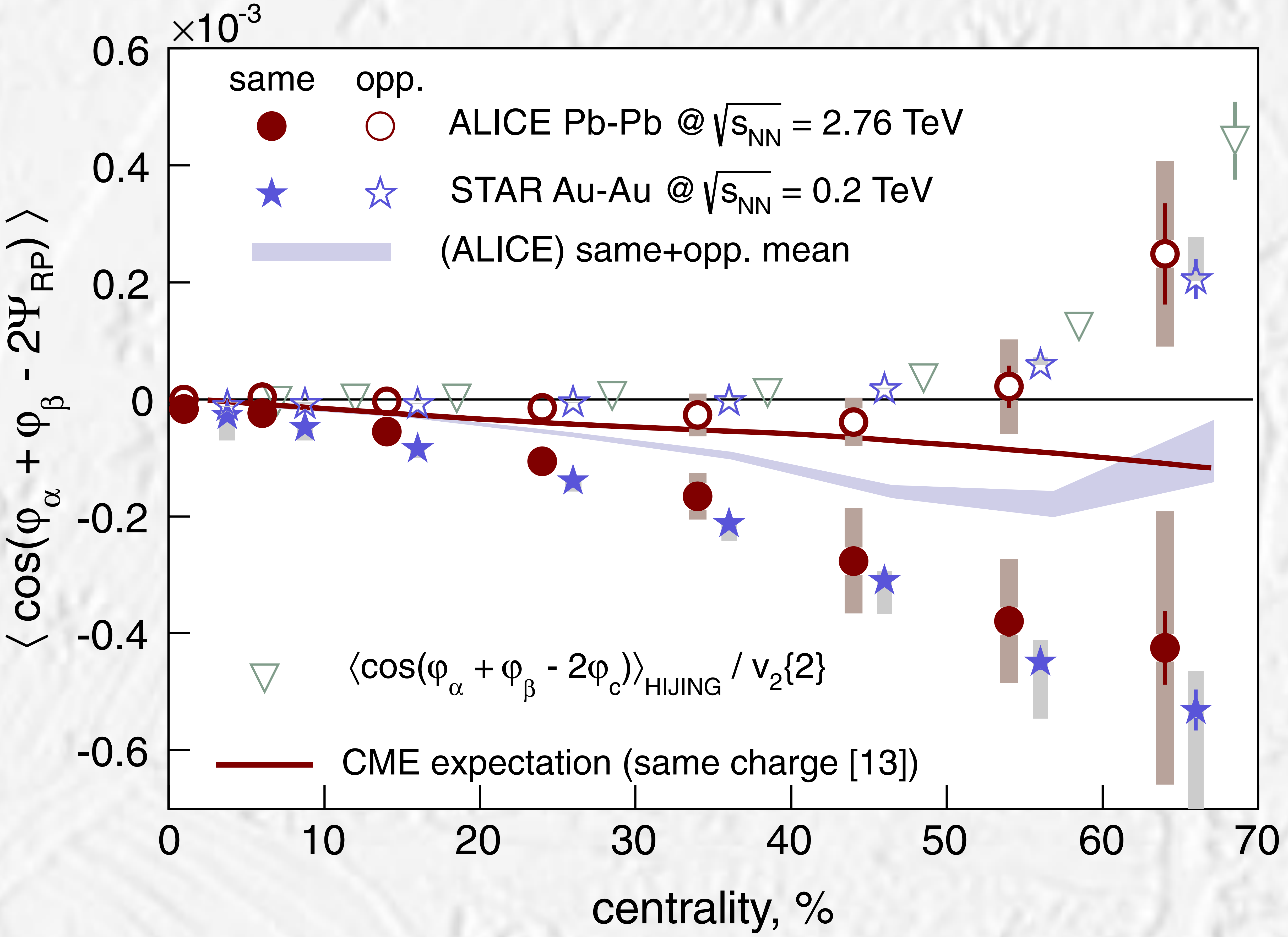


FIG. 7. (Color online) $\langle \cos(\phi_a + \phi_\beta - 2\Psi_{RP}) \rangle$ in Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV calculated using Eq. (7). The error bars show the statistical errors. The shaded areas reflect the uncertainty in the elliptic flow values used in calculations, with lower (in magnitude) limit obtained with elliptic flow from two-particle correlations and upper limit from four-particle cumulants. For details, see Sec. IV. Thick solid (Au + Au) and dashed (Cu + Cu) lines represent possible non-reaction-plane-dependent contribution from many-particle clusters as estimated by HIJING (see Sec. VII A).

LHC vs RHIC

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



RHIC and LHC results -- surprisingly close!

- 20% difference in $\Delta\eta$ window !
- (CME) no effect of the change in the magnetic field lifetime (?)
- (Bkg & CME) no effect of almost 3 times higher multiplicity density (?)

CME: Signal vs background

The measurements are likely dominated by the “background” (LCC?).

Goal: identification of the presence or the lack of the CME signal at the level of ~5% of the measured gamma correlator value

At hand: Signal depends on the magnetic field/vorticity the background depends on anisotropic flow

- Collision energy dependence, Beam energy scan (signal should disappear at lower energies)
- Event Shape Engineering (increase/decrease background)
- Isobar collisions (vary magnetic field keeping the same background)
- $(\Delta\gamma/v_2)$ with different Event Planes (Participant, Spectators)
- Higher/mixed harmonic correlators (background, no signal)
- Small system collisions (background, no signal)
- U+U (body-body vs tip-tip)
- Correlations with identified particles (e.g. for the next bullet)
- Cross-correlation of different observables, CME X CMW X CVE
- New(er) ideas/observables (invariant mass, R-correlator, signed BF, Helicity correlations)

?

- Studies of the EM fields

Event Shape Engineering

ESE - a technique to select events with large(r)/small(er) flow within the same centrality range

Application to the CME search: BG ~ v_2,
Signal - much weaker dependence (mostly due to decorrelations between **B** and Ψ_2)

1. Select events based on q_n-*vector* in one momentum region ("subevent")
2. Perform an analysis of these events in another region ("subevent").

$$X_n = \sum_{i=1}^{M} \cos(n\phi_i); \quad Y_n = \sum_{i=1}^{M} \sin(n\phi_i)$$

$$Q_n = \{X_n, iY_n\}; \quad q_n = |Q_n|/\sqrt{M}$$

ESE with cutting on q_2:
variation of flow values up to factor of ~2

Jürgen Schukraft [a], Anthony Timmins [b], Sergei A. Voloshin [c,*]
Physics Letters B 719 (2013) 394–398

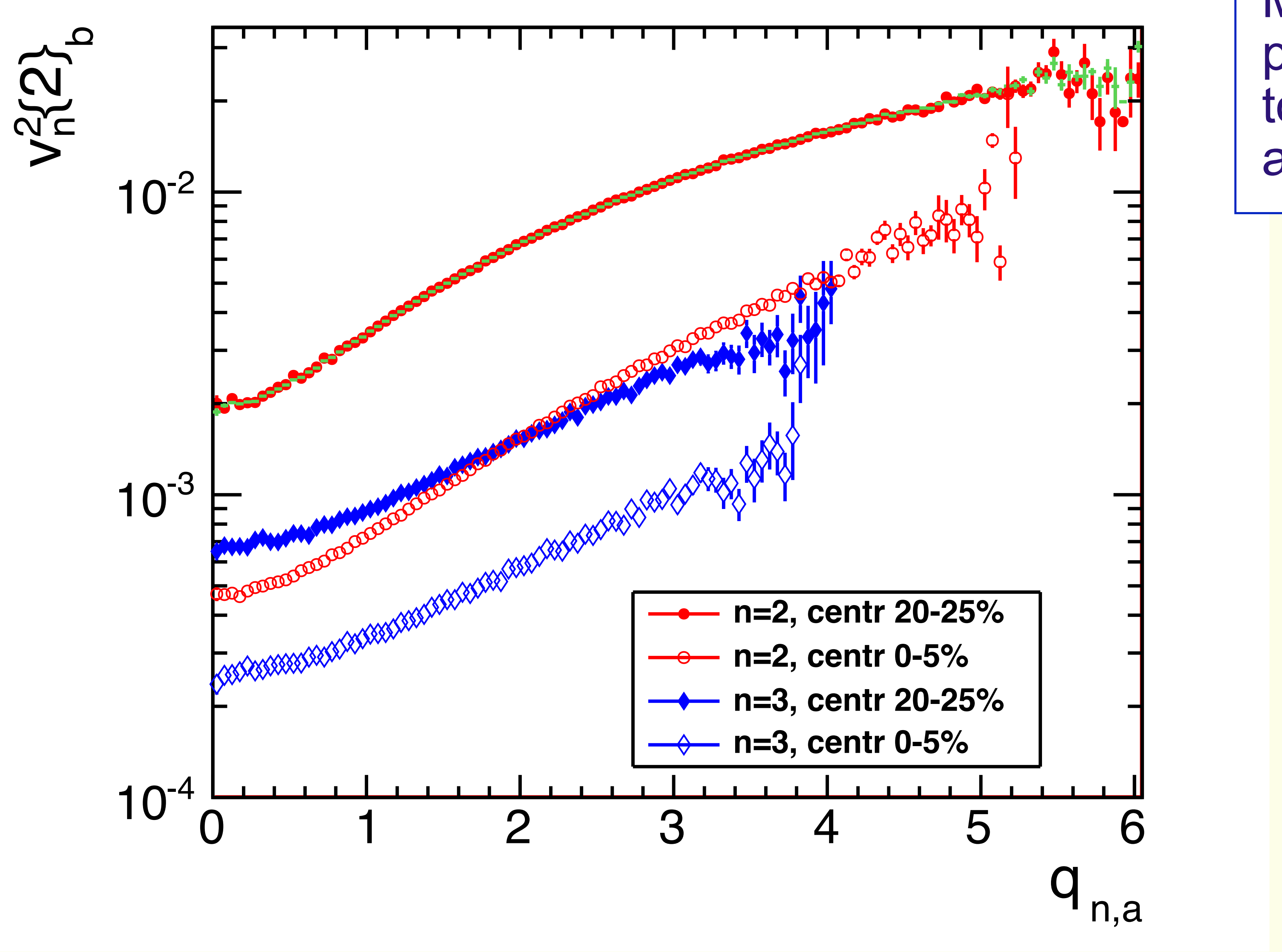


FIG. 1. (color online) Mean elliptic and triangular flow values in a-subevent as function of the corresponding q_n magnitude in b-subevent.

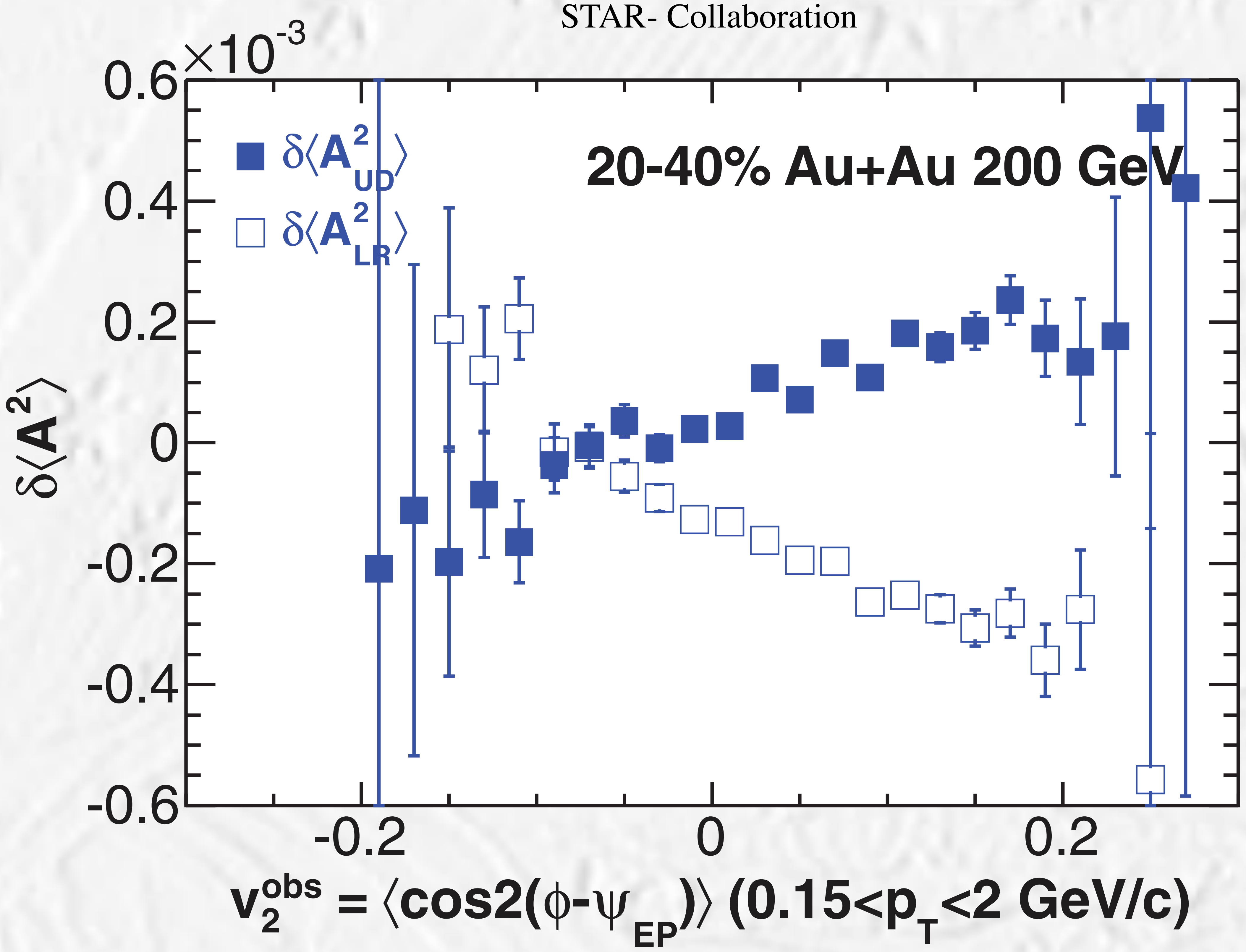
MC Glauber,with parameters tuned to LHC multiplicity and flow, $0<\eta_a<0.8$

Pseudo-ESE

PHYSICAL REVIEW C **89**, 044908 (2014)

Measurement of charge multiplicity asymmetry correlations in high-energy nucleus-nucleus collisions at $\sqrt{s_{NN}}$ = 200 GeV

STAR- Collaboration



v2obs (used for "ESE") and the signal are measured with the same particles (in the same pseudorapidity region)

Results are dominated by statistical fluctuations. No possibility to correct for the reaction plane resolution. Uninterpretable.

ESE, almost there

PHYSICAL REVIEW C **97**, 044912 (2018)

Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in *p*Pb and PbPb collisions at the CERN Large Hadron Collider

A. M. Sirunyan *et al.**
(CMS Collaboration)

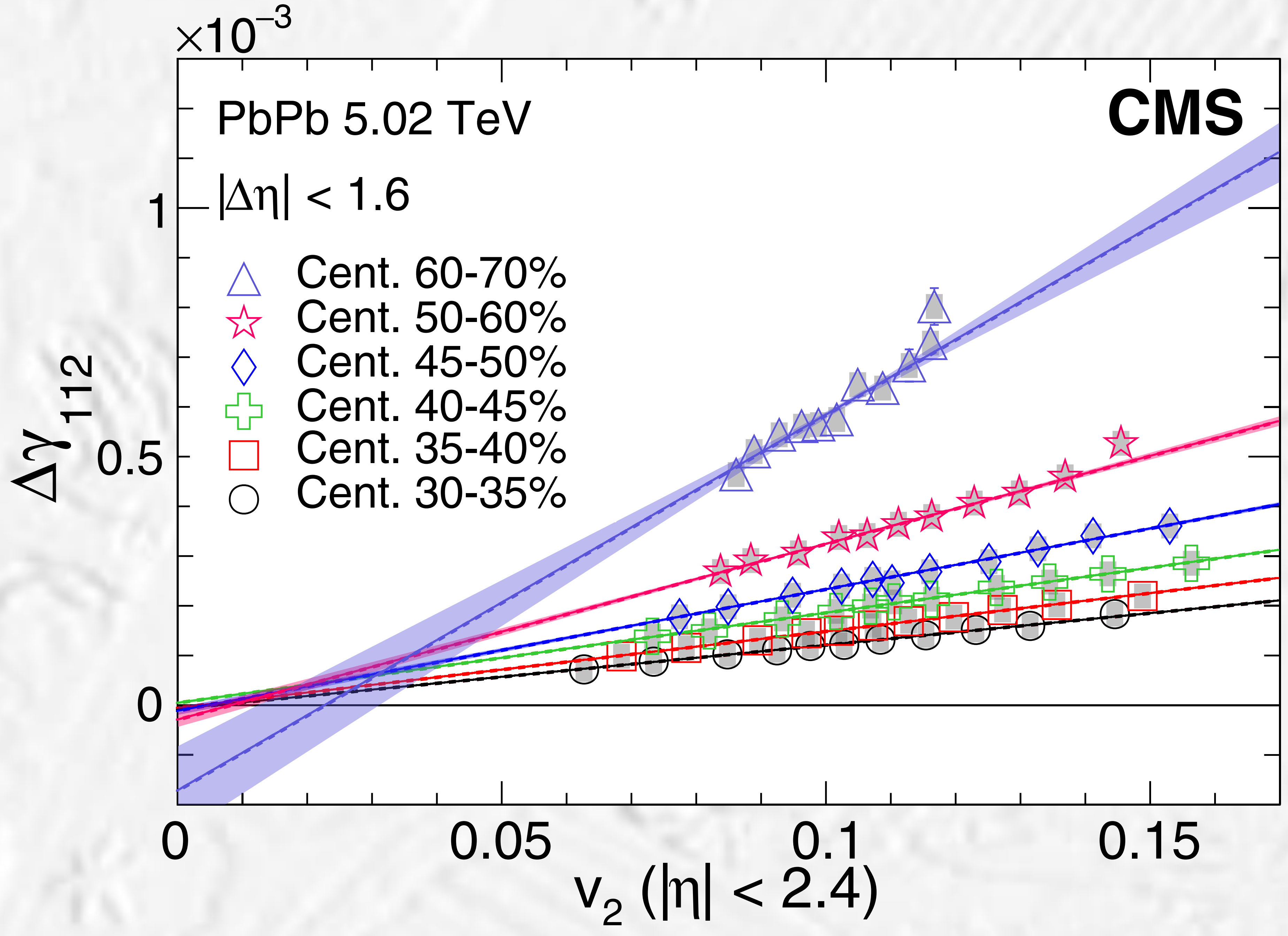


FIG. 12. The difference of the OS and SS three-particle correlators γ_{112} averaged over $|\Delta\eta| < 1.6$ as a function of v_2 evaluated in each q_2 class, for the multiplicity range $185 \leqslant N_{\rm trk}^{\rm offline} < 250$ in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV and PbPb collisions at 5.02 TeV (upper), and for different centrality classes in PbPb collisions at 5.02 TeV (lower). Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively. A one standard deviation uncertainty from the fit is also shown.

$$\Delta\gamma_{112} = a\, v_2 + b,$$

upper limit on the v_2-independent fraction of the three-particle correlator, or the possible CME signal contribution (assumed independent of v_2 within the same narrow multiplicity or centrality range), is estimated to be 13% for pPb data and 7% for PbPb data at a 95% confidence level. The data presented in

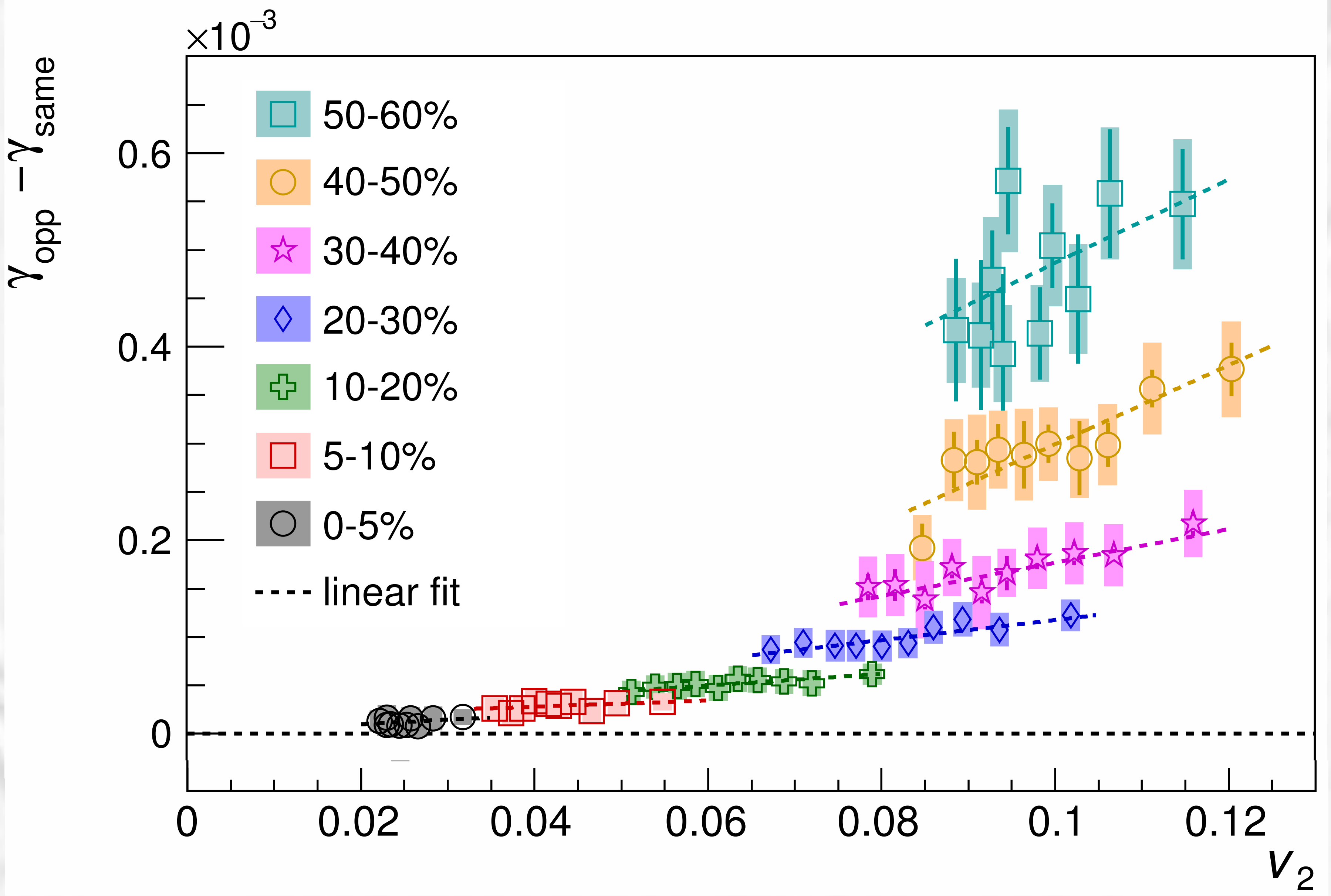
Does it make sense to talk about 95% CL, not including uncertainty on the assumptions?

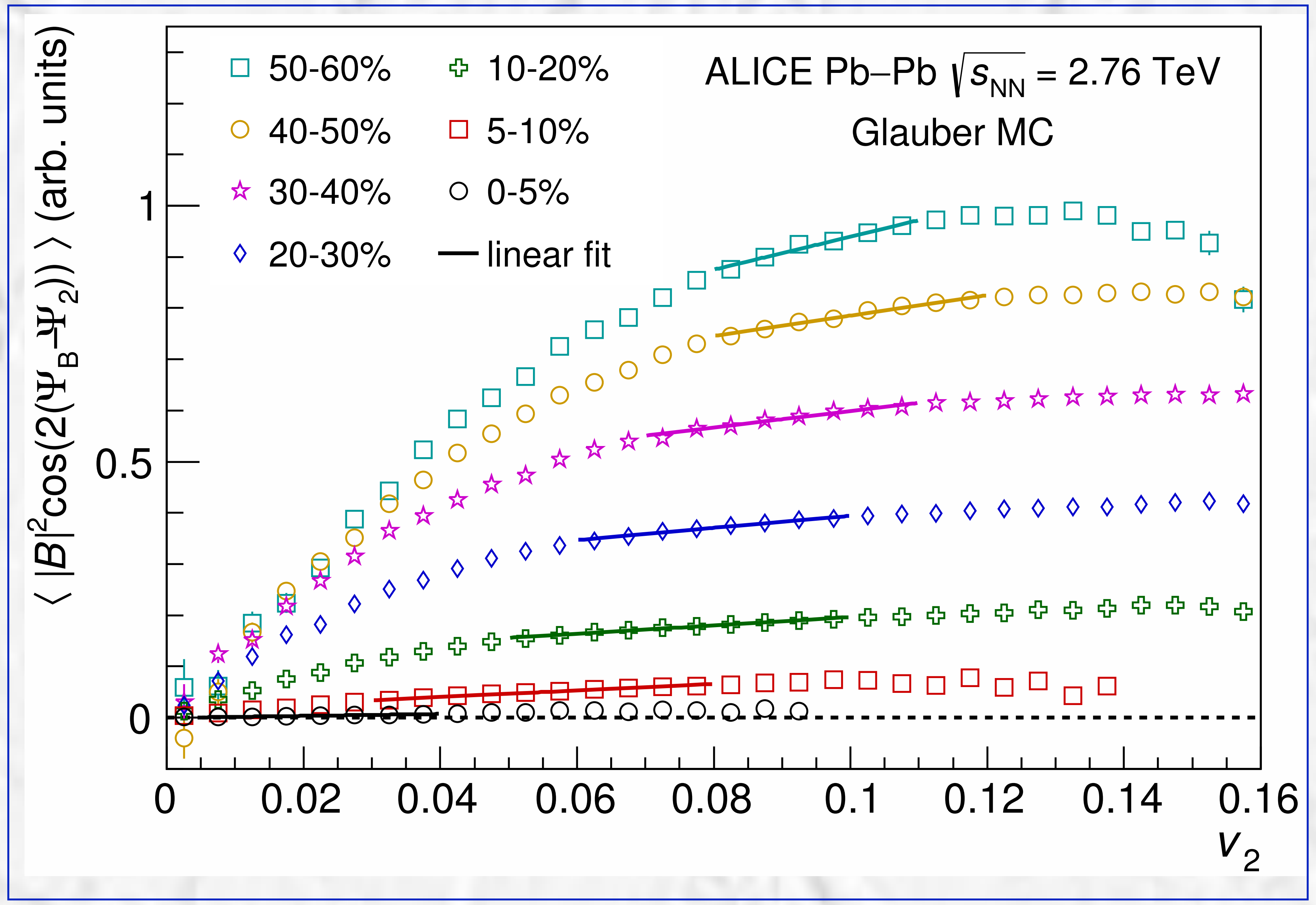
CME signal is not totally v_2 independent, the real limit is larger than 7%

ALICE: Event shape engineering

Constraining the magnitude of the Chiral Magnetic Effect with Event Shape Engineering in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Collaboration / Physics Letters B 777 (2018) 151–162





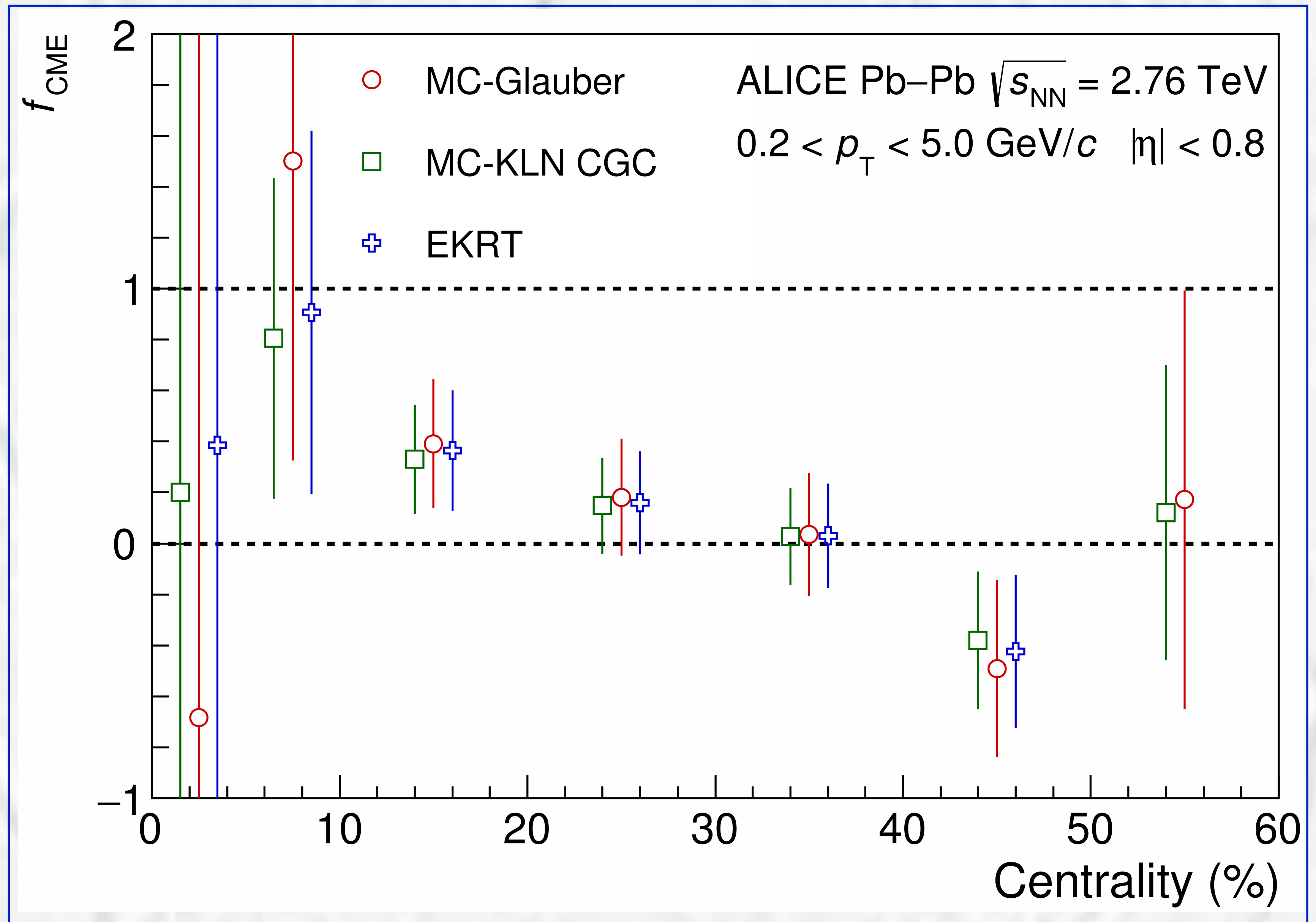


Fig. 6. (Colour online.) Centrality dependence of the CME fraction extracted from the slope parameter of fits to data and MC-Glauber [51], MC-KLN CGC [53,54] and EKRT [55] models, respectively (see text for details). The dashed lines indicate the physical parameter space of the CME fraction. Points are slightly shifted along the horizontal axis for better visibility. Only statistical uncertainties are shown.

Signal dependence on v_2 (due to decorrelation between the EP and magnetic field direction): almost no model dependence

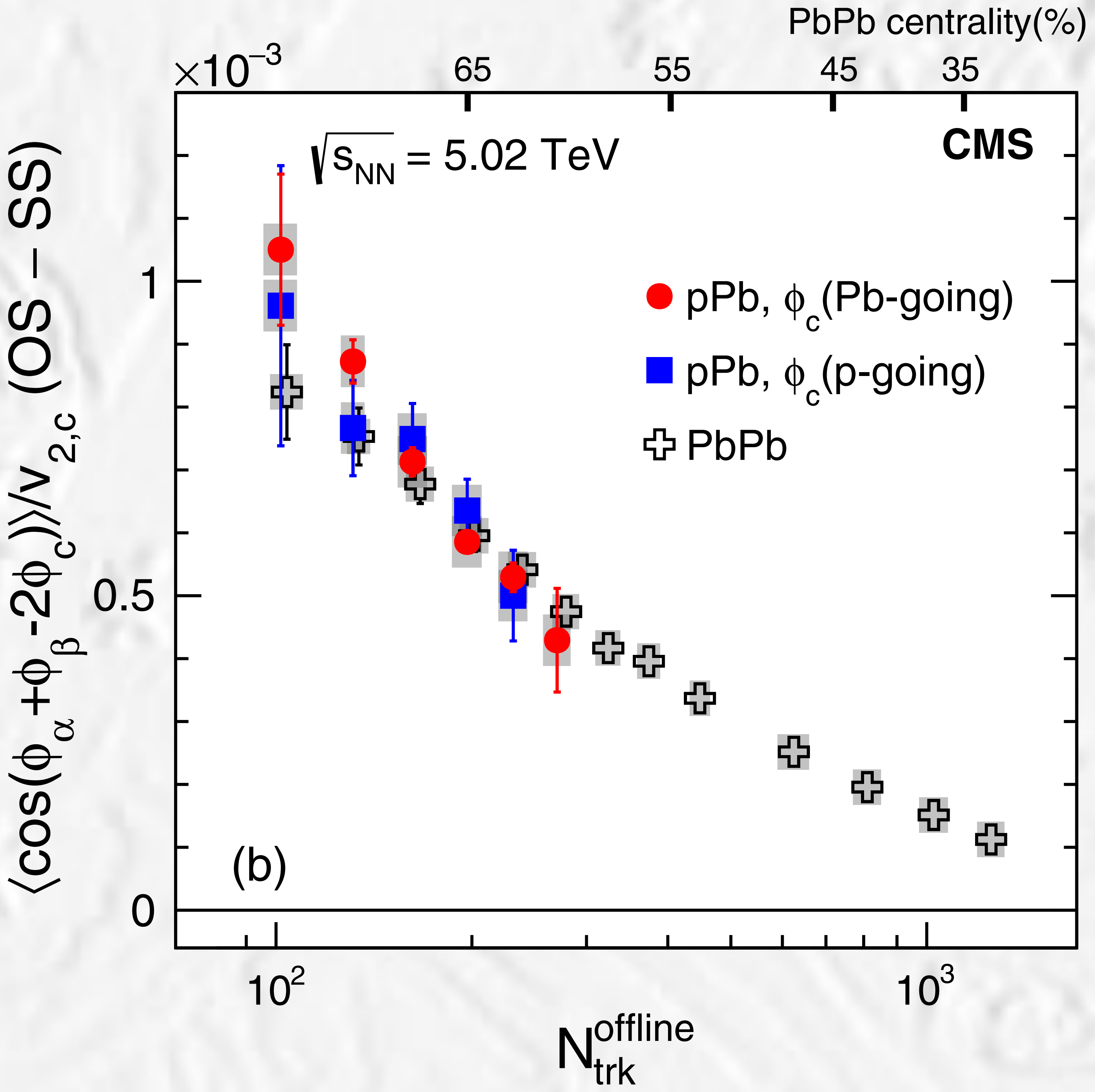
For mid-central collision the CME fraction $\lesssim$ 20%

Small systems I

PRL **118,** 122301 (2017) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2017

Observation of Charge-Dependent Azimuthal Correlations in *p*-Pb Collisions and Its Implication for the Search for the Chiral Magnetic Effect

V. Khachatryan *et al.*[*]
(CMS Collaboration)



These results challenge the CME interpretation for the observed charge-dependent azimuthal correlations in nucleus-nucleus collisions at RHIC and the LHC.

similarly

Charge-dependent pair correlations relative to a third particle in $p+$Au and $d+$Au collisions at RHIC

STAR Collaboration / Physics Letters B 798 (2019) 134975

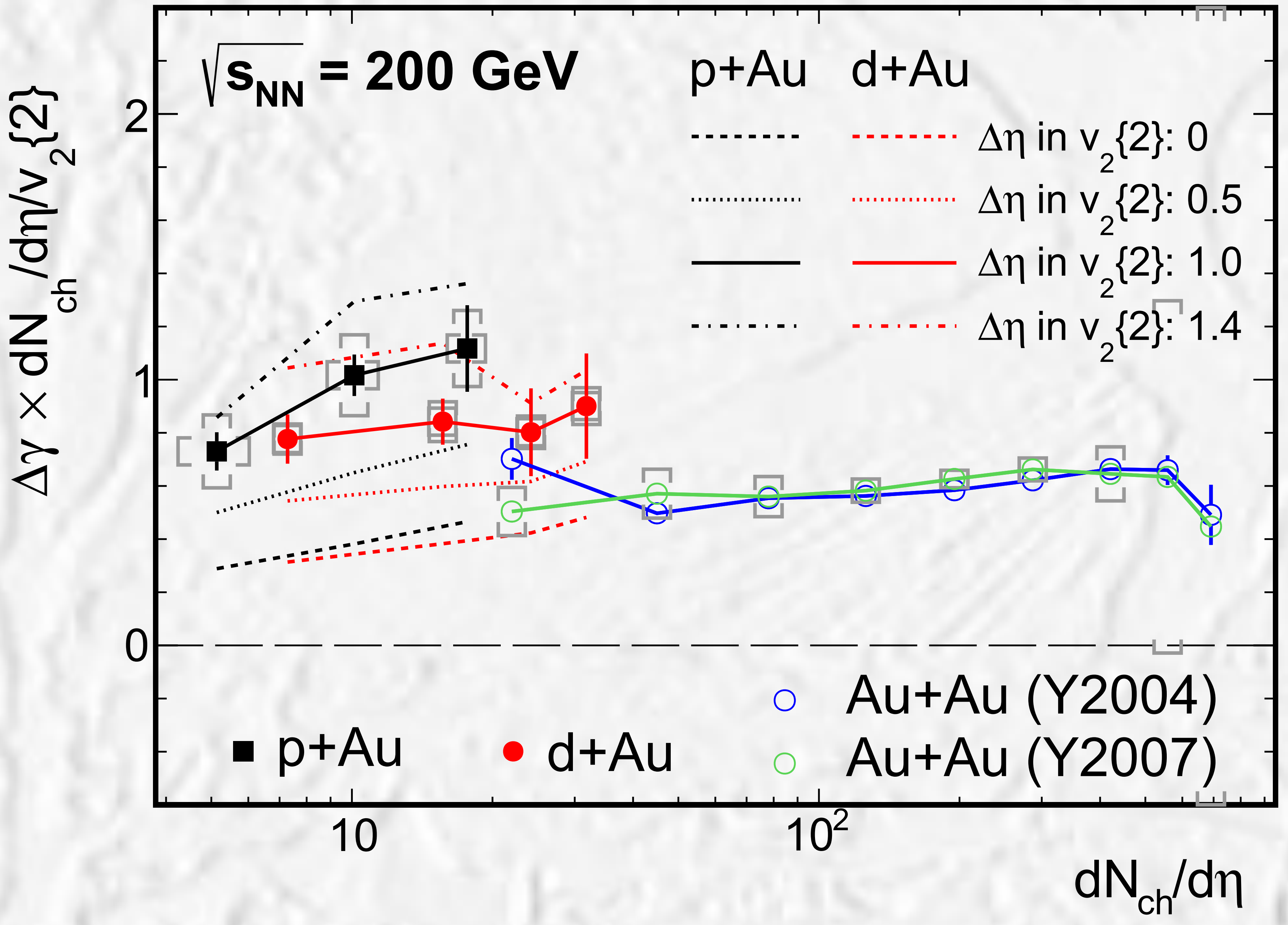


Fig. 4. The $\Delta\gamma \times dN_{ch}/d\eta/v_2$ in $p+$Au and $d+$Au collisions as a function of multiplicity, compared to that in Au + Au collisions [18,19,21]. The data points connected by solid lines are measured using $\Delta\eta$ gap of 1.0 in $v_2\{2\}$. Dashed lines represent the results using $v_{2,c}$ with η gaps of 0, 0.5 and 1.4.

Small systems II

Charge-dependent pair correlations relative to a third particle in $p+\mathrm{Au}$ and $d+\mathrm{Au}$ collisions at RHIC

STAR Collaboration / Physics Letters B 798 (2019) 134975

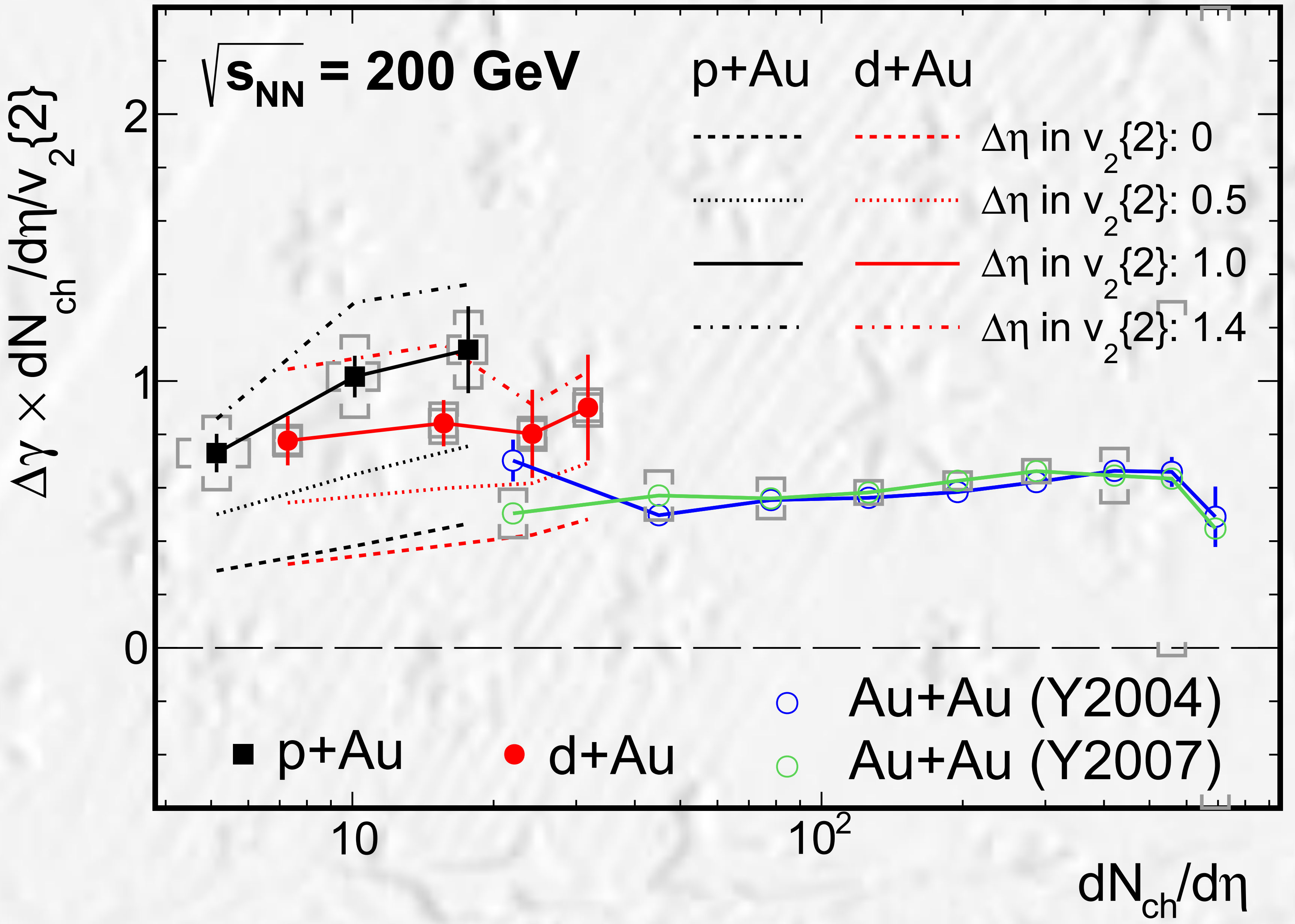
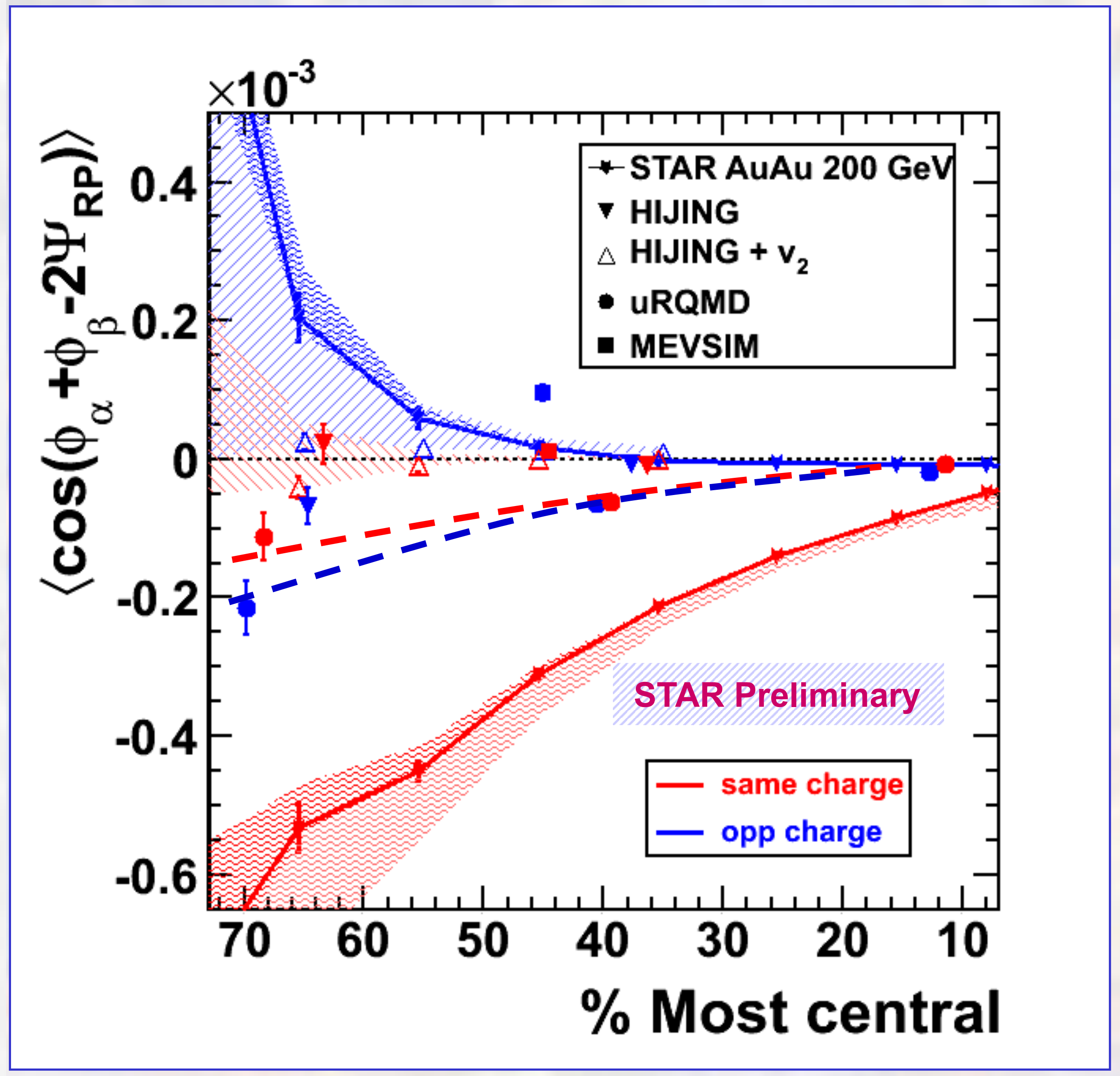


Fig. 4. The $\Delta\gamma \times dN_{\mathrm{ch}}/d\eta/v_2$ in $p+\mathrm{Au}$ and $d+\mathrm{Au}$ collisions as a function of multiplicity, compared to that in Au + Au collisions [18,19,21]. The data points connected by solid lines are measured using $\Delta\eta$ gap of 1.0 in $v_2\{2\}$. Dashed lines represent the results using $v_{2,c}$ with η gaps of 0, 0.5 and 1.4.



What is the “contribution” of the RP independent background to the measurement?

Answer - 100%. HIJING describes very well quantitatively both, “$\Delta\gamma$” and “v_2” (simulations done by the authors - not included in the paper).

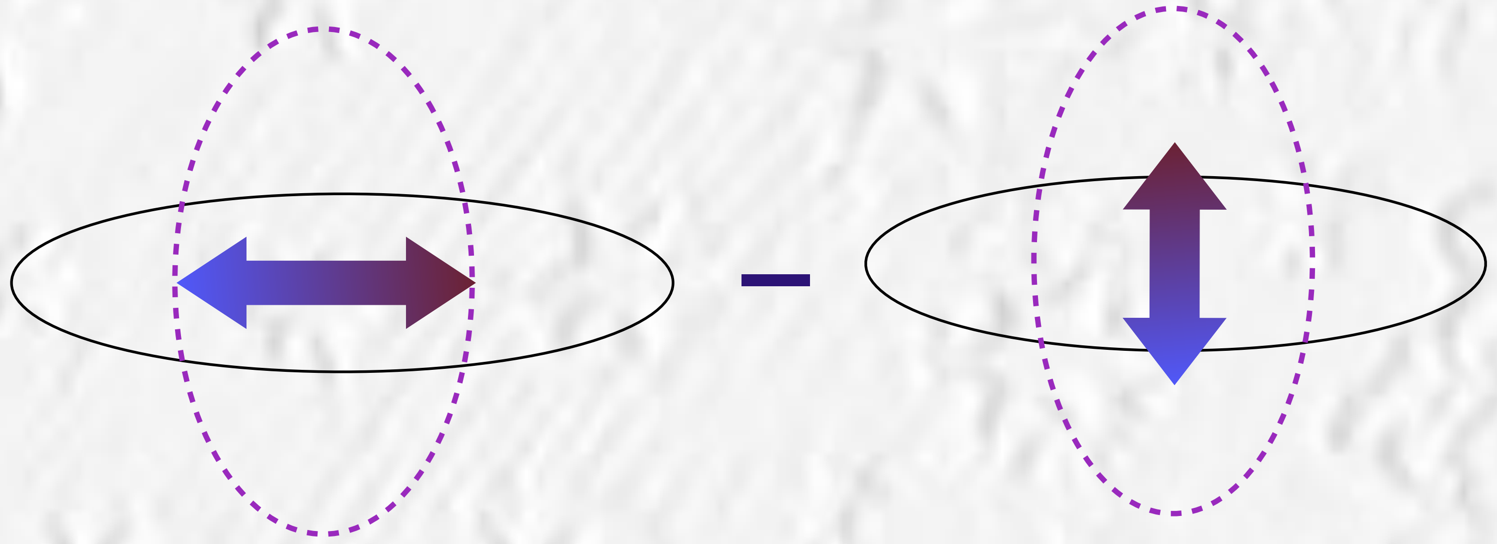
My view - until such a background is kept well under control, no meaningful conclusion can be made.
It is misleading not to include HIJING results in the paper.

Double/mixed harmonics I

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

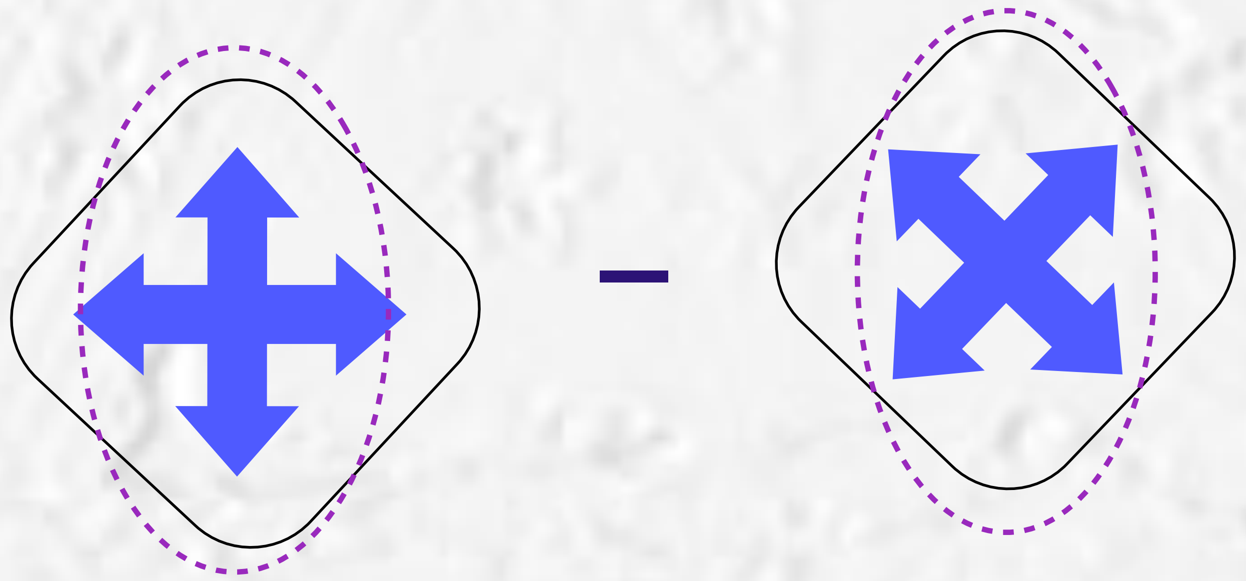
$$\langle\cos(\phi_a+\phi_b-2\Psi_2)\rangle = \langle\cos(\phi_a-\Psi_2)\cos(\phi_b-\Psi_2)\rangle - \langle\sin(\phi_a-\Psi_2)\sin(\phi_b-\Psi_2)\rangle$$

Charge dependent part:
- contribution from CME
- "flowing cluster" background

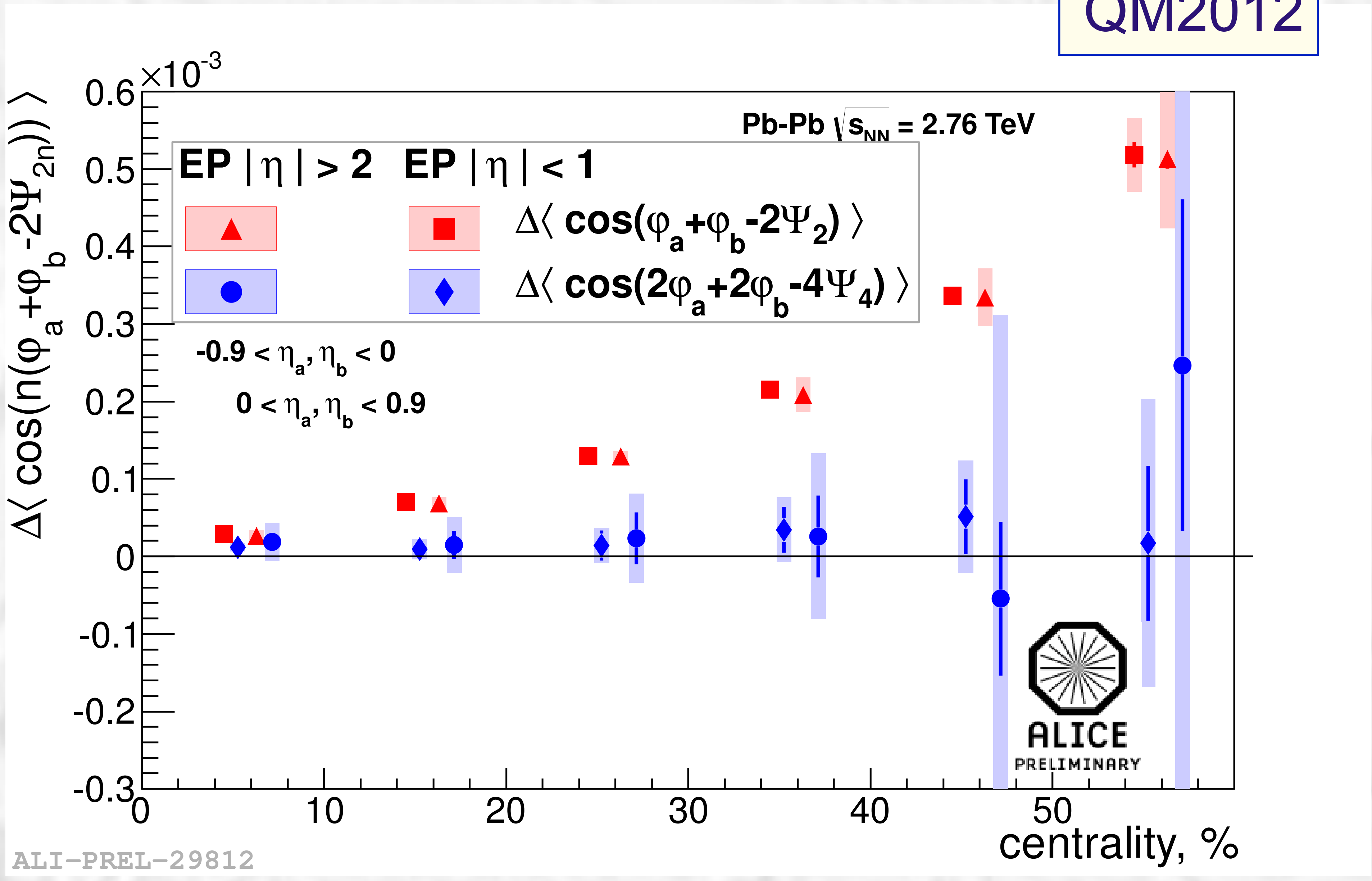


$$\langle\cos(2\phi_a+2\phi_b-4\Psi_4)\rangle = \langle\cos(2\phi_a-2\Psi_4)\cos(2\phi_b-2\Psi_4)\rangle - \langle\sin(2\phi_a-2\Psi_4)\sin(2\phi_b-2\Psi_4)\rangle$$

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



QM2012



$$\langle\cos(\phi_\alpha+\phi_\beta-2\Psi_2)\rangle = \langle\cos[(\phi_\alpha+\phi_\beta-2\phi_c)+(2\phi_c-2\Psi_2)]\rangle \approx \langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle\, v_{2,c}$$

$$\langle\cos(2\phi_\alpha+2\phi_\beta-4\Psi_2)\rangle = \langle\cos[(2\phi_\alpha+2\phi_\beta-4\phi_c)+(4\phi_c-4\Psi_2)]\rangle \approx \langle\cos(2\phi_\alpha+2\phi_\beta-4\phi_c)\rangle\, v_{4,c}$$

Quite different kinematic factors!

$\langle\cos(2\phi_\alpha+2\phi_\beta-4\phi_c)\rangle$ vs $\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle$

Requires detail knowledge of the nature of the background

Not suitable for precise estimates

Mixed harmonics II (also $\Delta\gamma,\ \Delta\delta;\ H, F, \kappa$)

PHYSICAL REVIEW C **97**, 044912 (2018)

Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in *p*Pb and PbPb collisions at the CERN Large Hadron Collider

A. M. Sirunyan *et al.**
(CMS Collaboration)

$$\gamma_{112} \equiv \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle$$

$$\gamma_{112}^{\rm bkg} = \kappa_2 \langle\cos(\phi_\alpha - \phi_\beta)\rangle\langle\cos 2(\phi_\beta - \Psi_{\rm RP})\rangle = \kappa_2\, \delta\, v_2.$$

$$\gamma_{123} \equiv \langle\cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3)\rangle,$$

$$\gamma_{123}^{\rm bkg} = \kappa_3 \langle\cos(\phi_\alpha - \phi_\beta)\rangle\langle\cos 3(\phi_\beta - \Psi_3)\rangle = \kappa_3\, \delta\, v_3,$$

APPENDIX A: GENERAL RELATION OF v_n HARMONICS AND TWO- AND THREE-PARTICLE AZIMUTHAL CORRELATIONS

In Sec. I, Eq. (5) can be derived in a way similar to Eq. (3), with details which can be found in Ref. [24]. Here, a general

$$\gamma_{1,n-1;n} = \frac{1}{2N^2}\int \rho_0(x_\alpha)\rho_0(x_\beta)\delta(x_\alpha,x_\beta) \times [v_n(x_\alpha) + v_n(x_\beta)]dx_\alpha\, dx_\beta,$$

where $N = \int \rho_0(x)dx$.

Therefore, this general form of $\gamma_{1,n-1;n}$ can be applied to any order n and decomposed into the two-particle correlator δ and the nth order harmonic v_n, where $n = 2$ and 3 are studied in detail in Sec. V A.

[24] A. Bzdak, V. Koch, and J. Liao, Charge-dependent correlations in relativistic heavy ion collisions and the chiral magnetic effect, Lect. Notes Phys. **871**, 503 (2013).

$$\langle\cos(\phi_a + \phi_b - 2\Psi_2)\rangle = \langle\cos[(\phi_a - \phi_b) + (2\phi_b - 2\Psi_2)]\rangle \neq \langle\cos(\phi_a - \phi_b)\rangle\langle\cos(2\phi_b - 2\Psi_2)\rangle$$

$$\langle\cos(\phi_a - 3\phi_b + 2\Psi_2)\rangle = \langle\cos[(\phi_a - \phi_b) - (2\phi_b - 2\Psi_2)]\rangle \neq \langle\cos(\phi_a - \phi_b)\rangle\langle\cos(2\phi_a - 2\Psi_2)\rangle$$

$\Delta\gamma,\ \Delta\delta;\ H, F, \kappa$

A better way to address it:

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle = \langle\cos[(\phi_\alpha + \phi_\beta - 2\phi_c) + (2\phi_c - 2\Psi_2)]\rangle \approx \langle\cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle\, v_{2,c}$$

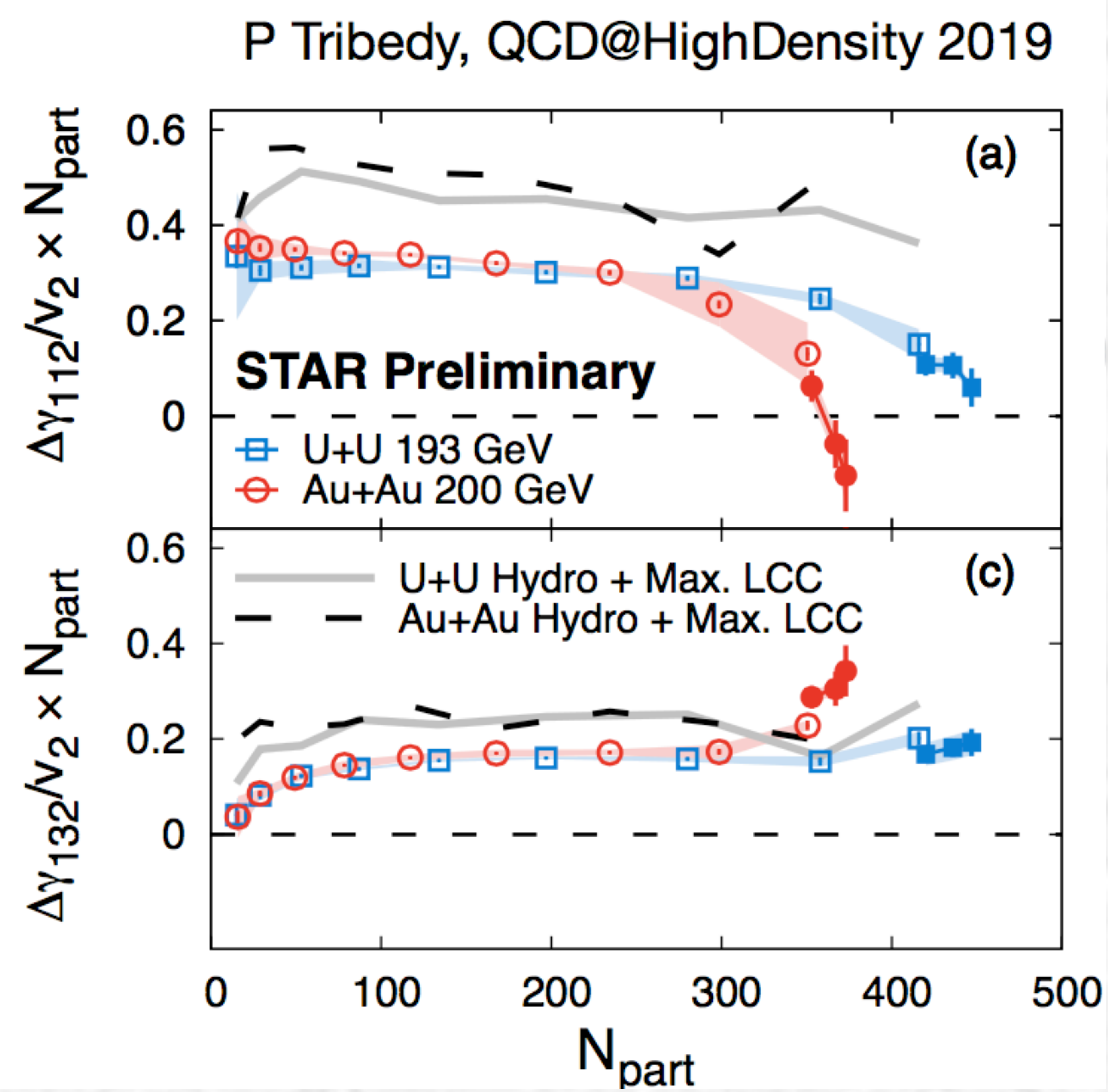
$$\langle\cos(\phi_\alpha - 3\phi_\beta + 2\Psi_2)\rangle = \langle\cos[(\phi_\alpha - 3\phi_\beta + 2\phi_c) - (2\phi_c - 2\Psi_2)]\rangle \approx \langle\cos(\phi_\alpha - 3\phi_\beta + 2\phi_c)\rangle\, v_{2,c}$$

To be be precise requires detailed knowledge of the background. Not that useful.

Mixed harmonics, III

$$\langle\cos(\phi_a+\phi_b-2\Psi_2)\rangle = \langle\cos[(\phi_a-\phi_b)+(2\phi_b-2\Psi_2)]\rangle \neq \langle\cos(\phi_a-\phi_b)\rangle\langle\cos(2\phi_b-2\Psi_2)\rangle$$

$$\langle\cos(\phi_a-3\phi_b+2\Psi_2)\rangle = \langle\cos[(\phi_a-\phi_b)-(2\phi_b-2\Psi_2)]\rangle \neq \langle\cos(\phi_a-\phi_b)\rangle\langle\cos(2\phi_a-2\Psi_2)\rangle$$



Measurements clearly show the difference (unlikely due to CME)

$\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle$ vs

$\langle\cos(3\phi_\alpha-\phi_\beta-2\phi_c)\rangle$??

Higher/mixed harmonics:

Requires detail knowledge of the background nature

Not suitable for precise estimates

Delta-gamma vs invariant mass

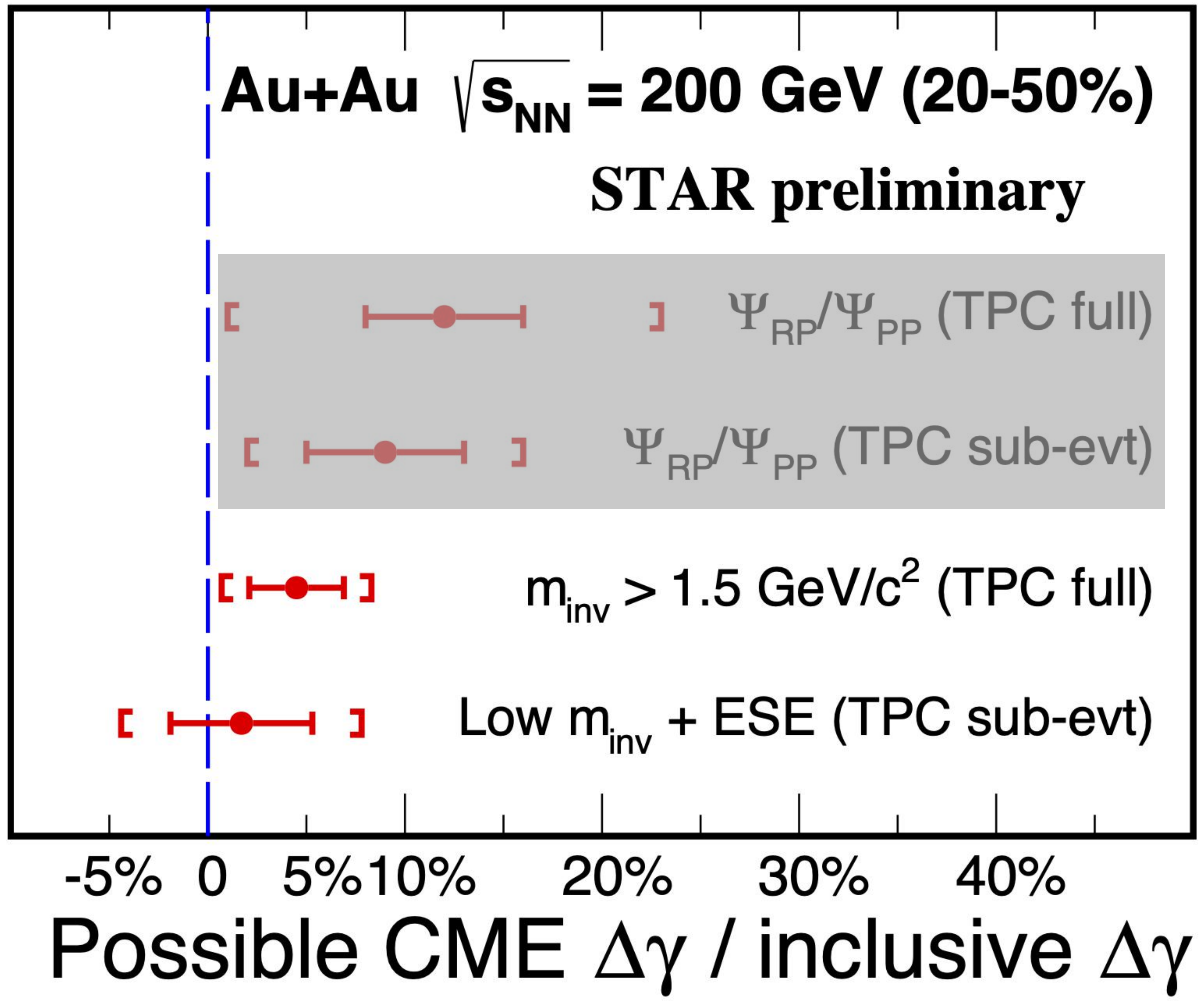
based on:

Isolating the chiral magnetic effect from backgrounds by pair invariant mass

Jie Zhao[1,a], Hanlin Li[1,2], Fuqiang Wang[1,3,b]

Eur. Phys. J. C (2019) 79:168
https://doi.org/10.1140/epjc/s10052-019-6671-1

J. Zhao (STAR collaboration), NPA 982 (2019) 535



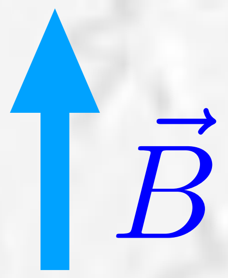
looking in the region where no resonance contribution is measured

assuming no dependence of the "CME part" of Delta-gamma on inv.mass

Both assumptions/approaches are far from being realistic. The obtained limits has little value.

In general it is a valid method, similar to other differential (vs pT, Delta-eta) measurements. Requires theoretical input on dependence of the signal on the invariant mass.

Correlations wrt participant and spectator planes



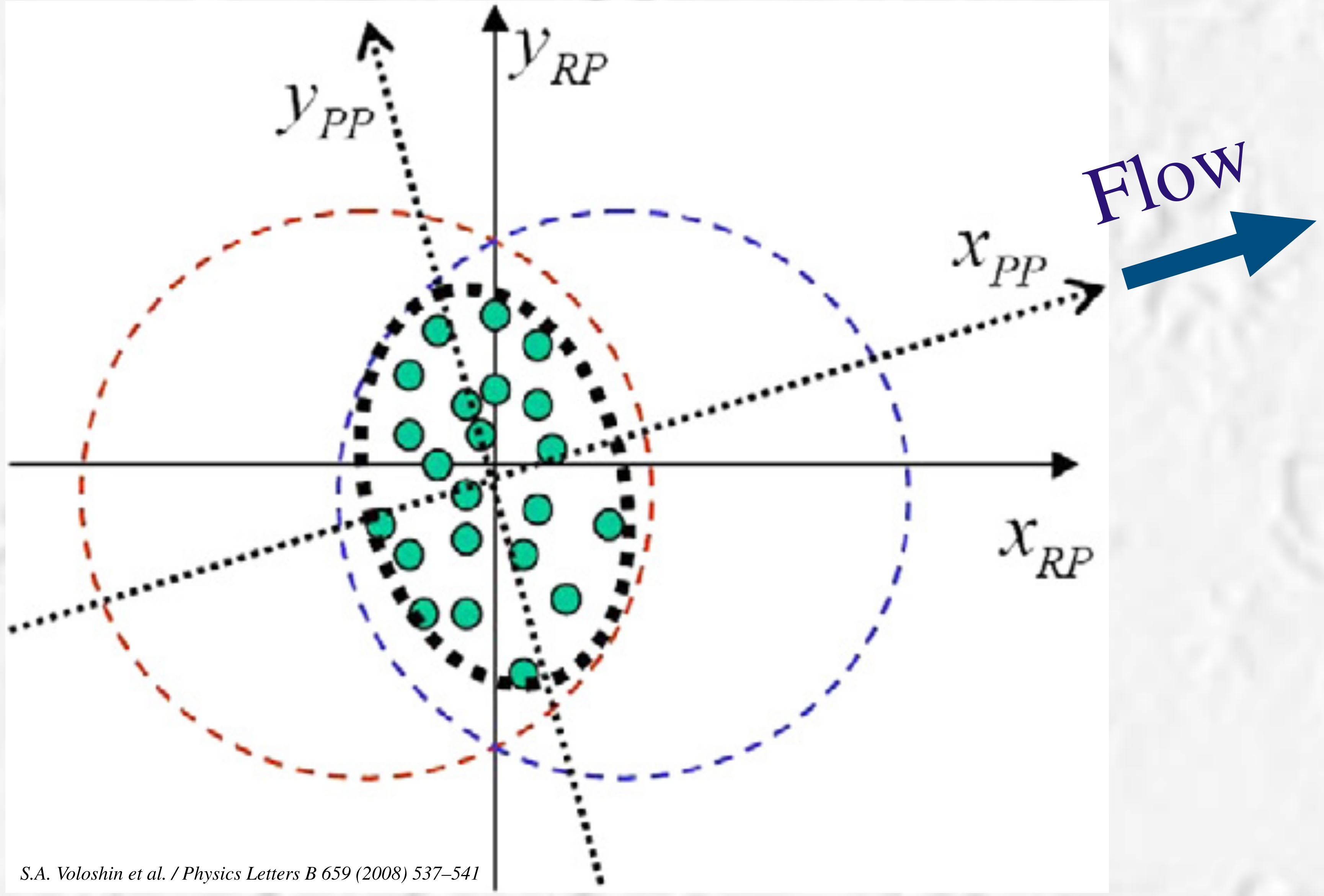


Fig. 1. The definitions of the *RP* and *PP* coordinate systems.

Assumption: spectator flow plane defines the magnetic field direction

PHYSICAL REVIEW C **98**, 054911 (2018)

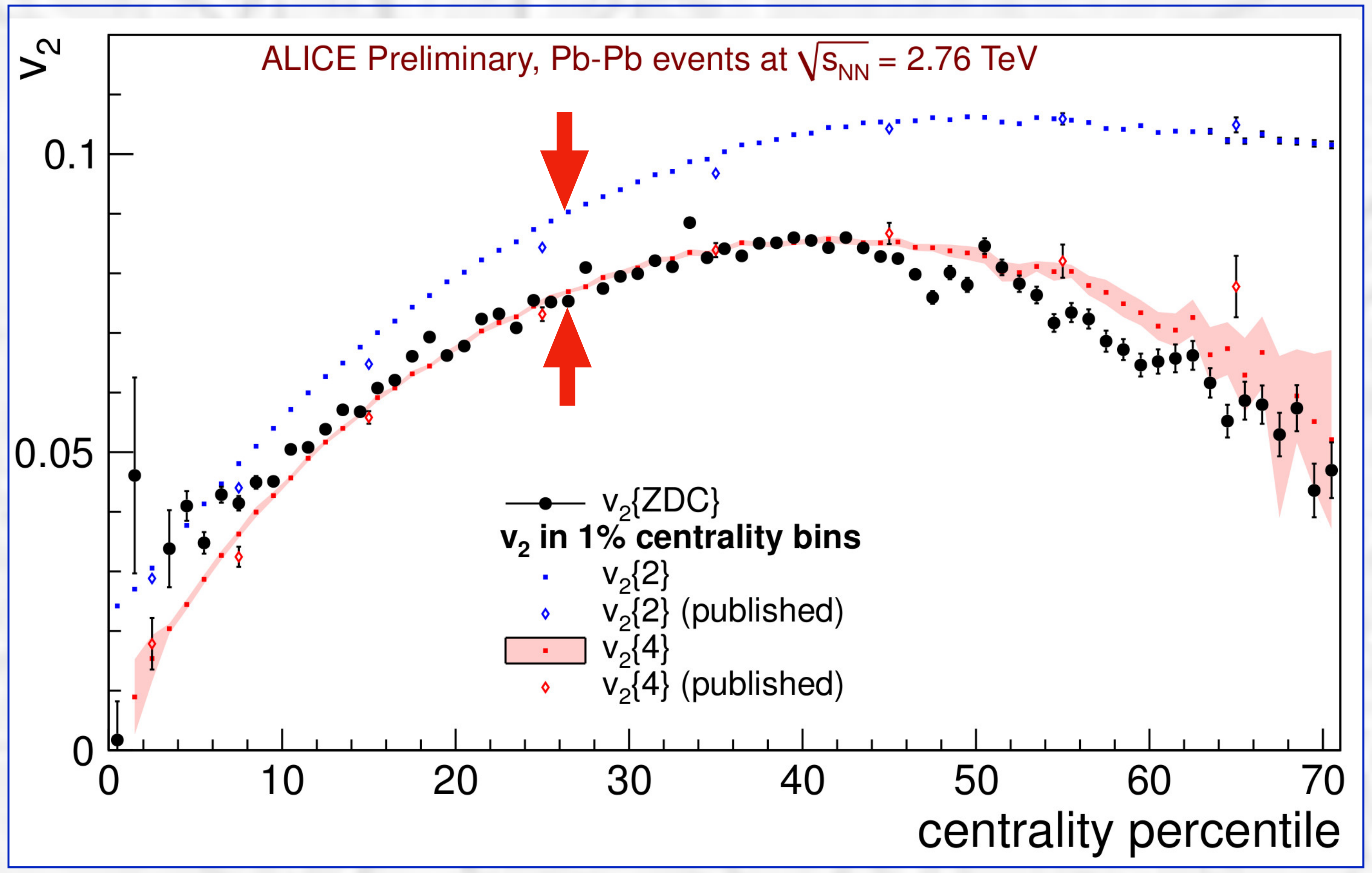
Estimate of the signal from the chiral magnetic effect in heavy-ion collisions from measurements relative to the participant and spectator flow planes

Sergei A. Voloshin
Wayne State University, 666 West Hancock, Detroit, Michigan 48201, USA

Varying the chiral magnetic effect relative to flow in a single nucleus-nucleus collision*

Hao-Jie Xu (徐浩洁)[1], Jie Zhao (赵杰)[2], Xiao-Bao Wang (王小保)[1], Han-Lin Li (李汉林)[3], Zi-Wei Lin (林子威)[4,5], Cai-Wan Shen (沈彩万)[1] and Fu-Qiang Wang (王福强)[1,2]

Published 1 July 2018 • © 2018 Chinese Physical Society and the Institute of High Energy
Chinese Physics C, Volume 42, Number 8



Decorrelation is strong enough to measure the difference in the CME signal

Testing "background scenario"

Sergei A. Voloshin
PHYSICAL REVIEW C **98**, 054911 (2018)

"Background scenario":

Note that for these calculations **no need** for separate "resolution" calculations (simplify statistical error calculations)

$$\frac{\Delta\langle\cos(\alpha+\beta-2c)\rangle}{\langle\cos(2a-2c)\rangle} \Big/ \frac{\Delta\langle\cos(\alpha+\beta-\Psi_{1,\mathrm{SPA}}-\Psi_{1,\mathrm{SPB}})\rangle}{\langle\cos(2a-\Psi_{1,\mathrm{SPA}}-\Psi_{1,\mathrm{SPB}})\rangle} = 1$$

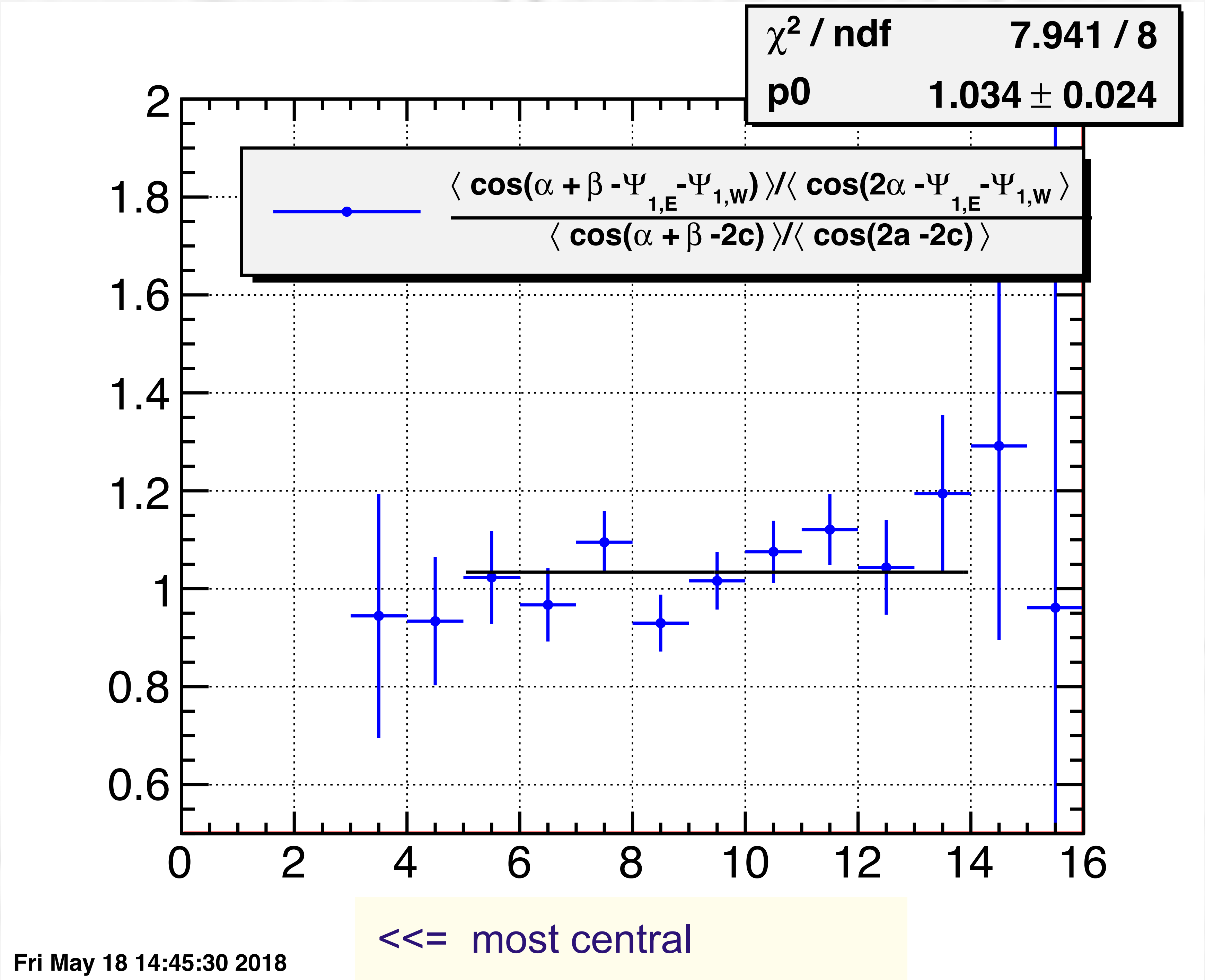
$a = \alpha, \beta$

The ratio can be calculated with any/all possible EPs

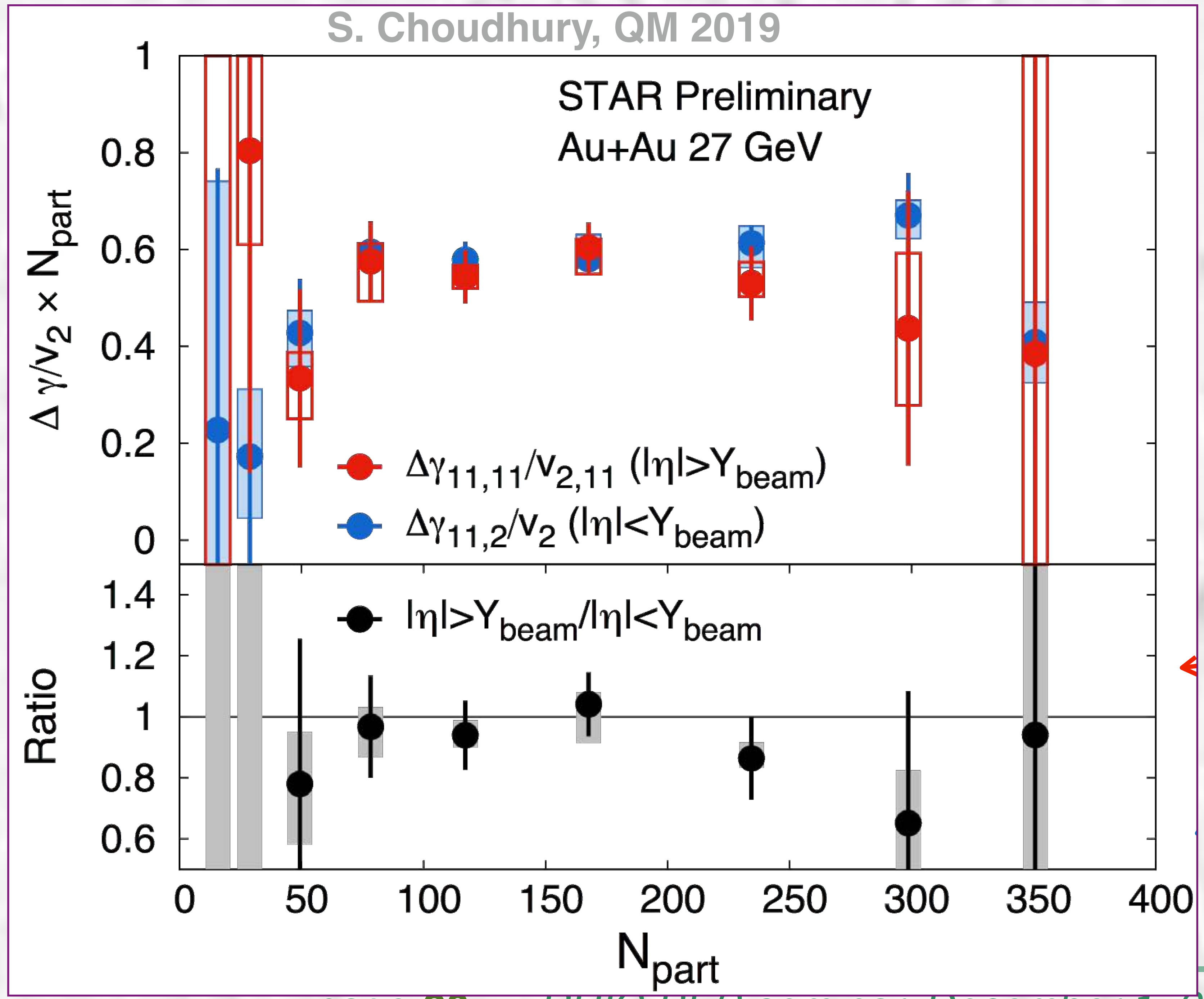
- if it deviates from unity - it indicates non-zero CME contribution, but to get the real fraction of the signal requires additional assumptions

$$\mathrm{Ratio} = 1 + \frac{1}{\Delta\gamma_{PP}}\left[\mathrm{CME_{SP}}\frac{v_2\{2\}}{v_2\{\mathrm{ZDC}\}} - \mathrm{CME_{PP}}\right]$$

Exact under only one, "main", assumption: BG $\propto$ v_2



<<= most central



Getting the CME fraction

$$\text{Ratio} = 1 + \frac{1}{\Delta\gamma_{PP}}\left[\text{CME}_{\text{SP}}\frac{v_2\{2\}}{v_2\{\text{ZDC}\}} - \text{CME}_{\text{PP}}\right]$$

Exact under only one, "main", assumption"

Requires no "non-flow" contribution, correctly treats flow fluctuations

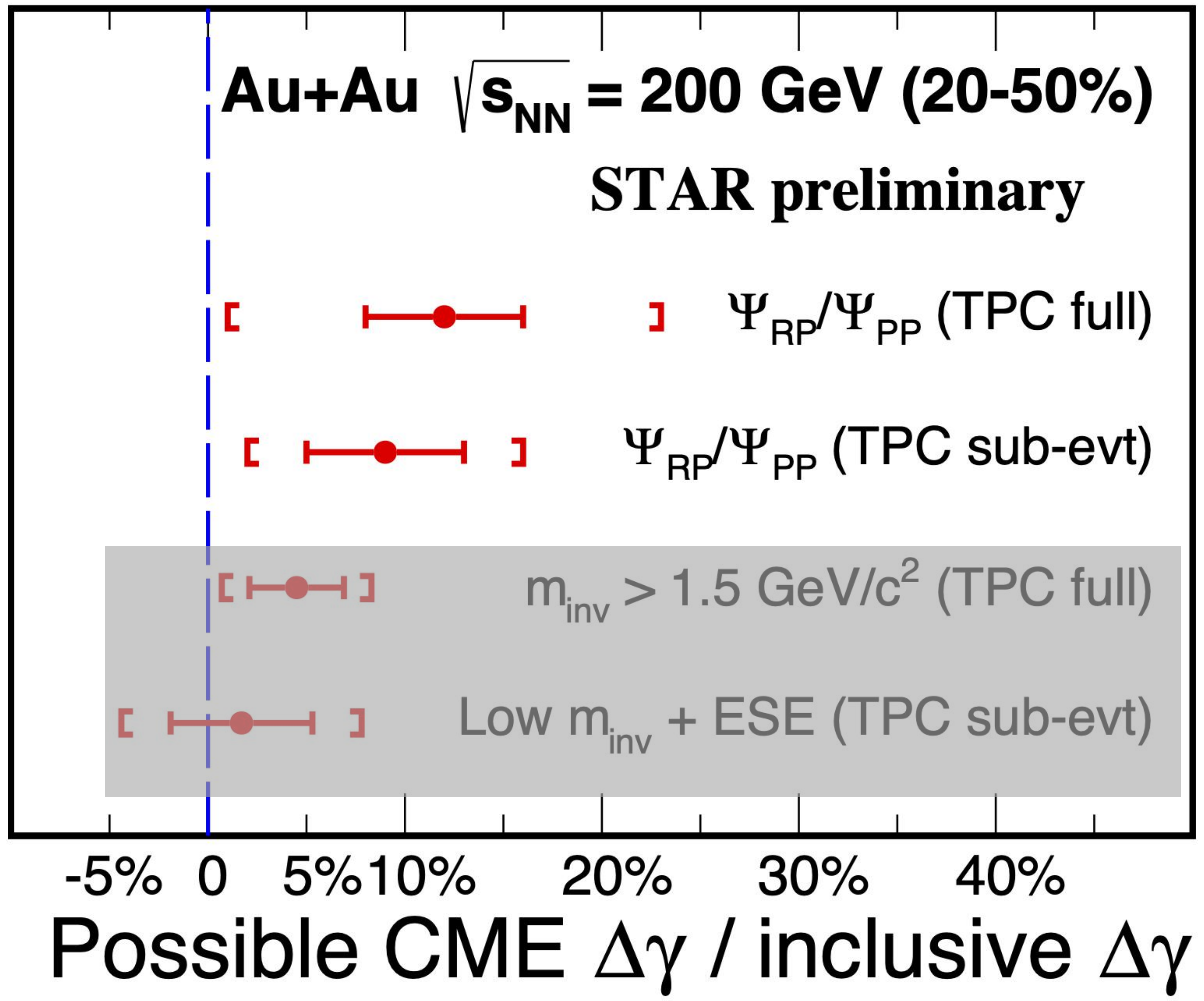
Possible further assumptions:

$$\text{CME}_{\text{SP}} = \text{CME}_{\text{PP}}\frac{v_2\{2\}}{v_2\{\text{ZDC}\}}$$

$$\frac{(\Delta\gamma/v_2)_{\text{SP}}}{(\Delta\gamma/v_2)_{\text{c}}} = 1 + f_{\text{PP}}^{\text{CME}}\left(\frac{\langle v_{2,\text{PP}}^2\rangle}{(v_2\{\Psi_{1,\text{SP}}\})^2} - 1\right)$$

If magnetic field is 100% correlated with the SP. "Working" hypothesis.

J. Zhao (STAR collaboration). NPA 982 (2019) 535



Possible non-flow in v_2. Real fraction can be lower

"Precision" of this method likely could be as low as 5%.

Requires careful removal of non-flow and account for flow fluctuations

Isobar collisions

"Double ratio" in analysis of isobar collisions
[instead of two different event planes — different isobar datasets

$$(\Delta\gamma/v_2)_{TPC} \quad = \quad \frac{\Delta\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle}{\langle\cos(2\phi_\alpha-2\phi_c)\rangle}$$

$$\frac{(\Delta\gamma/v_2)_{AA}}{(\Delta\gamma/v_2)_{BB}} = 1 + f_{CME}^{BB}[(H_{AA}/H_{BB})^2 - 1]$$

Subscripts "AA", "BB" == Ru, Zn

Note that the calculation of $(\Delta\gamma/v_2)$ quantities does not require knowledge of the reaction plane resolution [1]. It also "normalizes" the gamma correlator to the elliptic flow value and thus can be used for a direct comparison of the signals in different isobar collisions, even if the values of elliptic flow is slightly different in the two samples.

For isobar "double ratio", non-flow is much less of a problem!

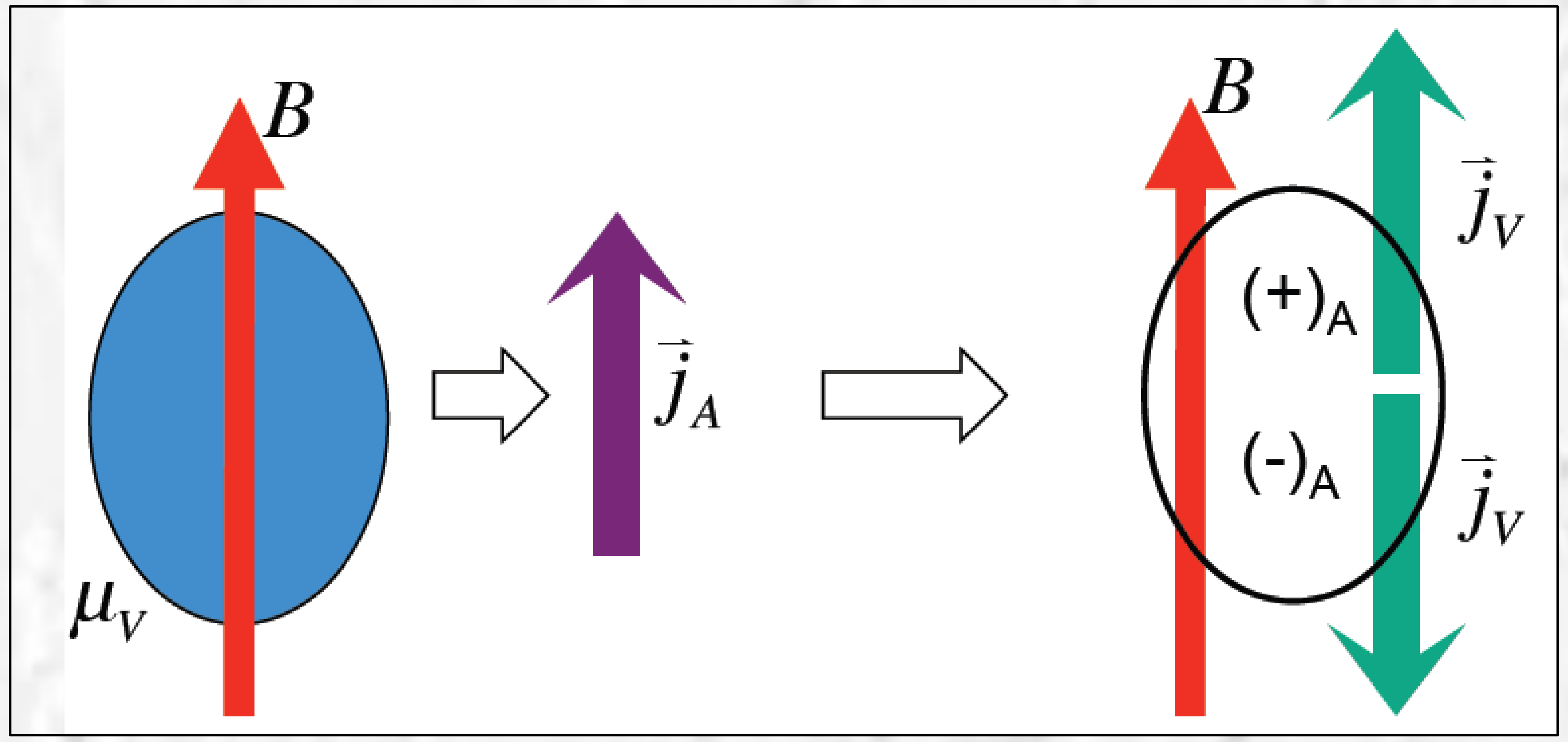
Double ratio is "assumption free",
insensitive to small differences in flow,
centrality determination, nonflow,

PP/SP planes still can be used for individual isobar
datasets to evaluate the CME fraction in each of them

Chiral Magnetic Wave

Yannis Burnier,[1] Dmitri E. Kharzeev,[1,2] Jinfeng Liao,[2] and Ho-Ung Yee[1]
PRL **107,** 052303 (2011)

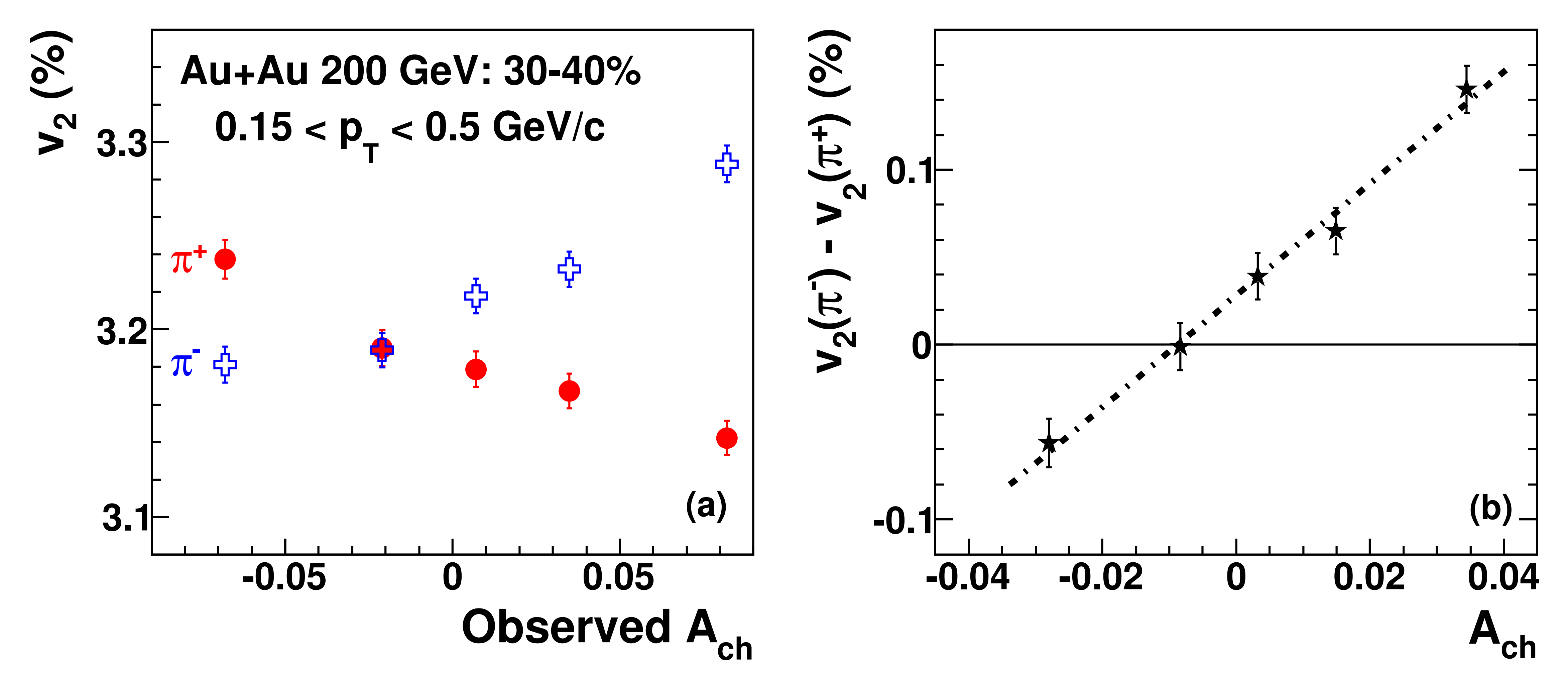
$$\mathbf{J_5} = \frac{1}{2\pi^2}\mu(Qe)\mathbf{B} \qquad \mathbf{J} = (Qe)\frac{1}{2\pi^2}\mu_5(Qe)\mathbf{B}$$



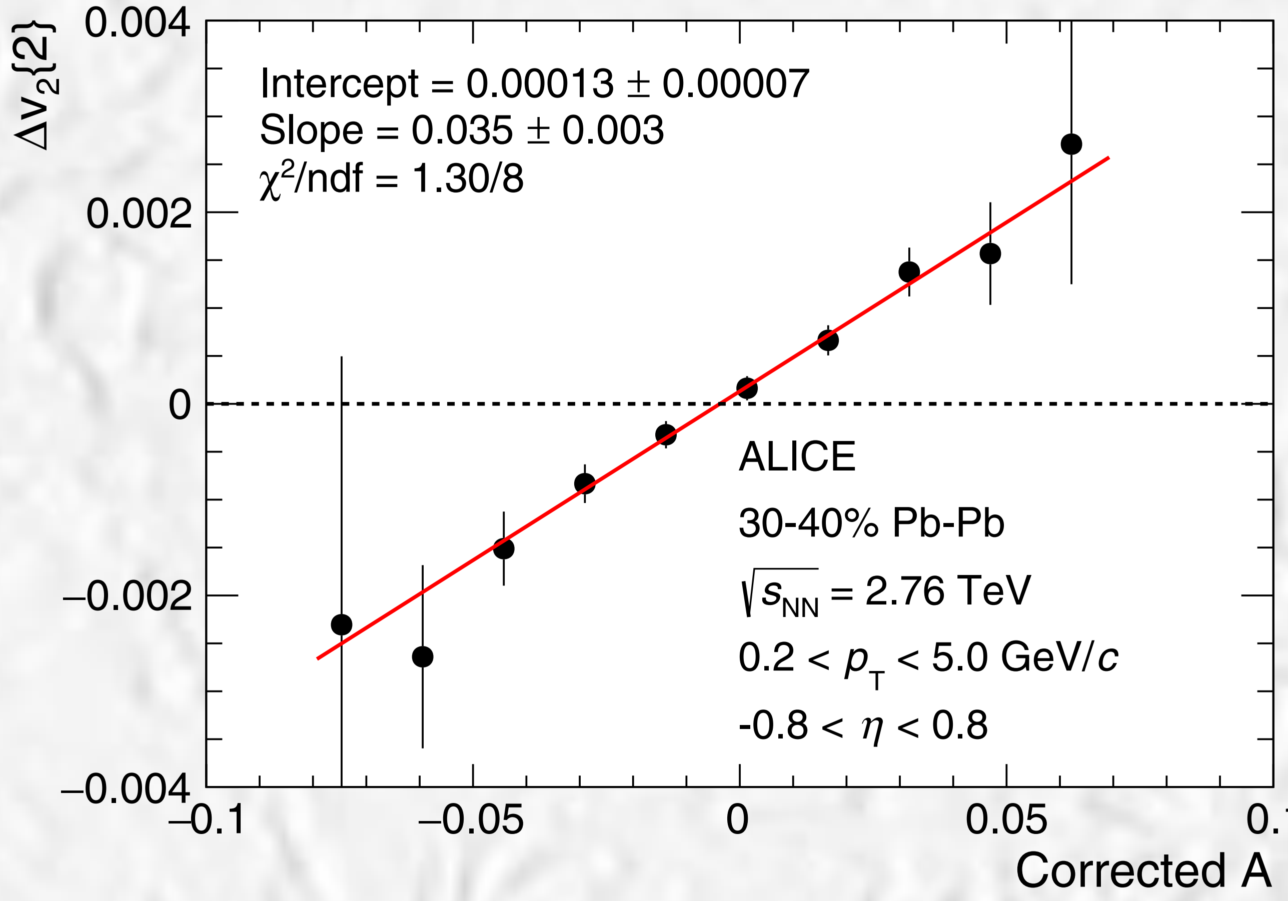
For a given sign of $\mu_V \propto A_\pm$, the difference in v_2 for positive and negative particles is uniquely predicted

$$v_2^\pm = v_2 \mp \frac{rA_\pm}{2}$$
$$A_\pm \equiv (\bar{N}_+ - \bar{N}_-)/(\bar{N}_+ + \bar{N}_-)$$

L. Adamczyk *et al.* (STAR Collaboration), Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions, Phys. Rev. Lett. **114**, 252302 (2015).



J. Adam *et al.* (ALICE Collaboration), Charge-dependent flow and the search for the chiral magnetic wave in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. C **93**, 044903 (2016).



3 particle correlator

J. Adam *et al.* (ALICE Collaboration), Charge-dependent flow and the search for the chiral magnetic wave in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. C **93**, 044903 (2016).

Three particle correlator

S. A. Voloshin and R. Belmont, Measuring and interpreting charge dependent anisotropic flow, Nucl. Phys. A **931**, 992 (2014).

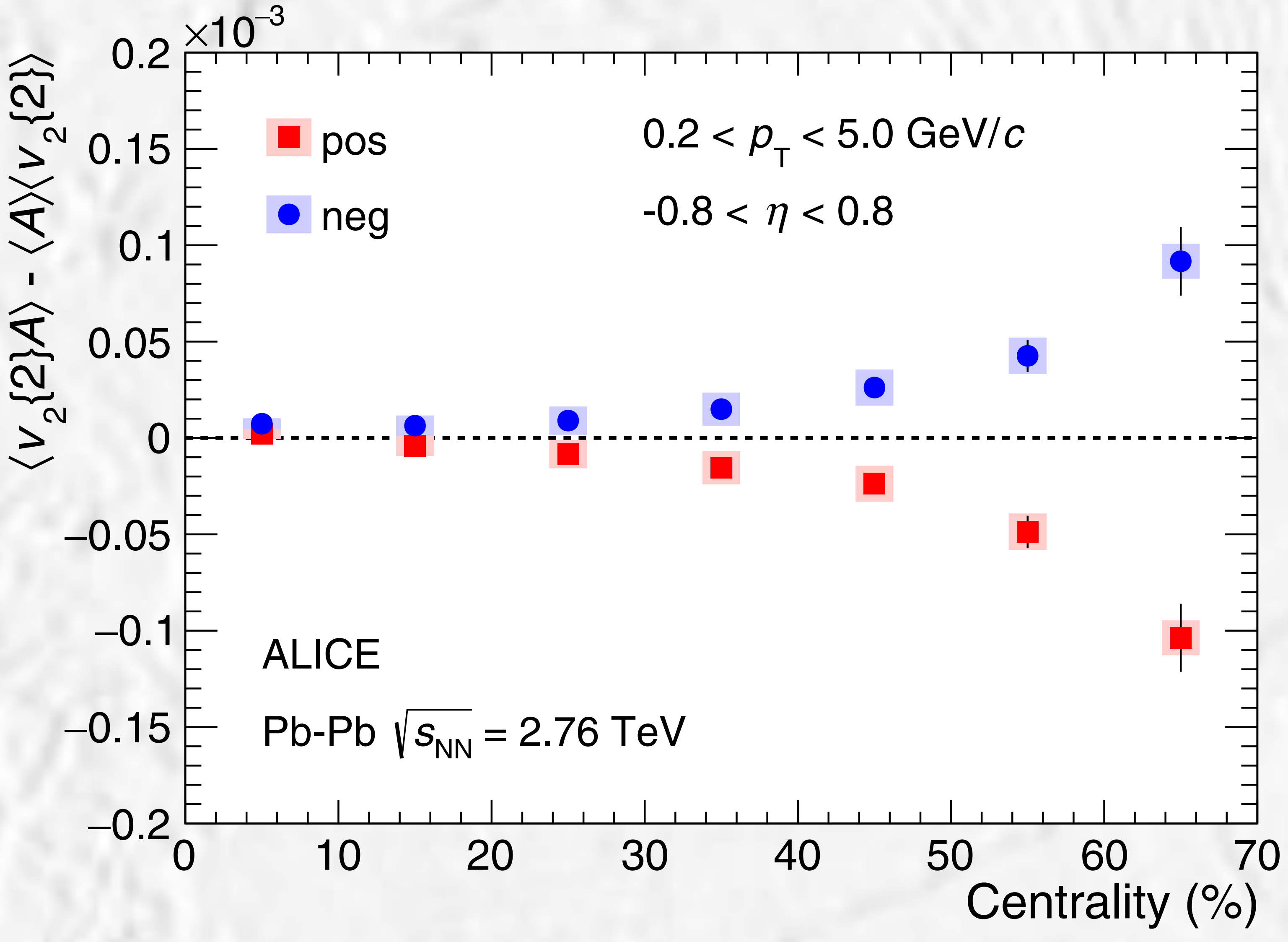
$$\langle c_3 \rangle = \frac{N_+ - N_-}{N_+ + N_-} \qquad A_{\rm ch} = (N_+ - N_-)/(N_+ + N_-)$$

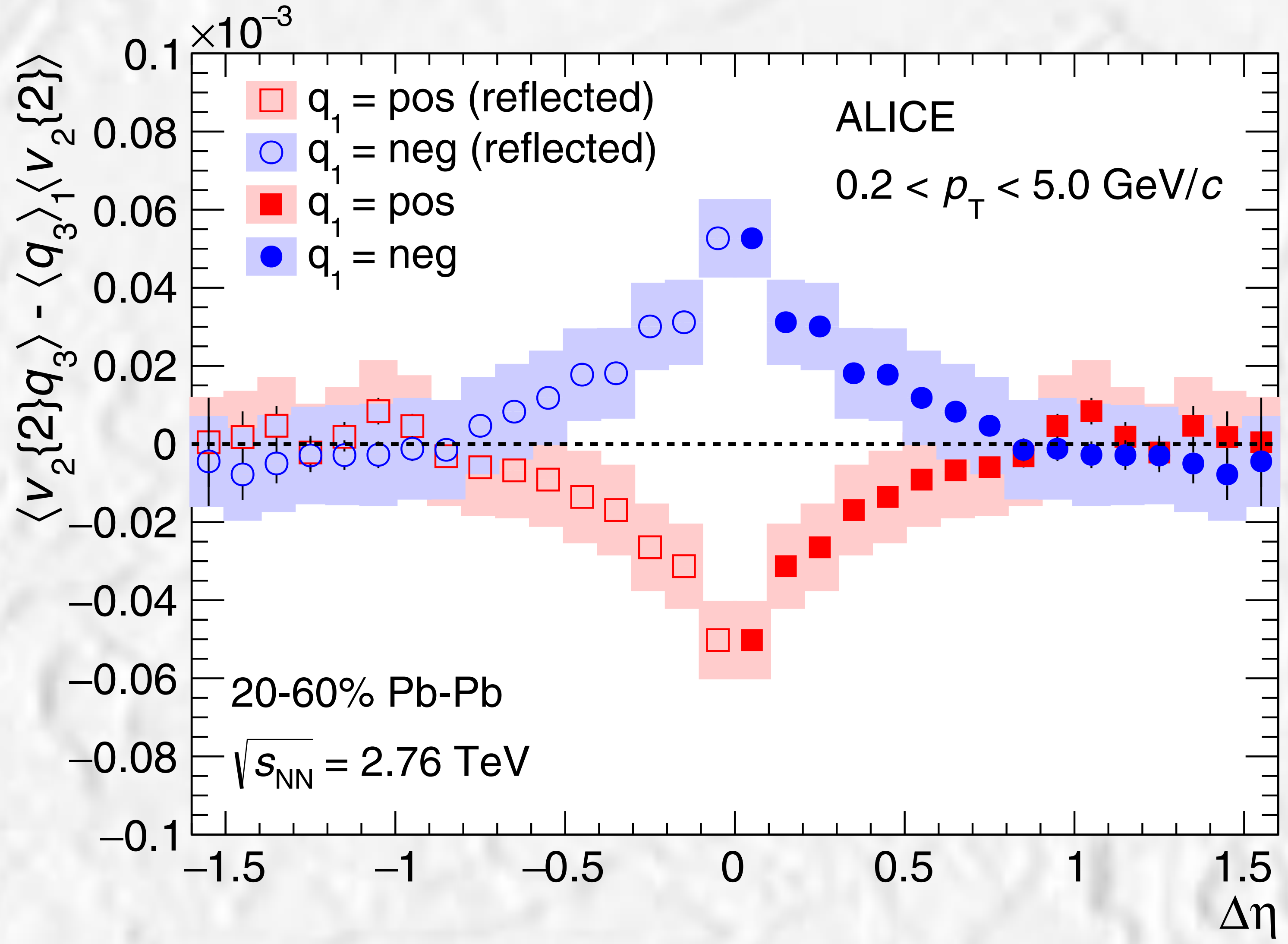
$$\langle\langle \cos[n(\phi_1 - \Psi_n)]\, c_3 \rangle\rangle \equiv \langle \cos[n(\phi_1 - \Psi_n)]\, c_3 \rangle - \langle \cos[n(\phi_1 - \Psi_n)] \rangle \langle c_3 \rangle_1$$

$\langle c_3 \rangle_1$ -- mean charge of particle "3" under condition of particle "1" being observed

- is tracking efficiency independent
- allows differential studies
- can be used for direct comparison between different experiments

In the integral form the correlator is "equivalent" to the slope of Δv_2 vs A (=slope*sigma^2_A)

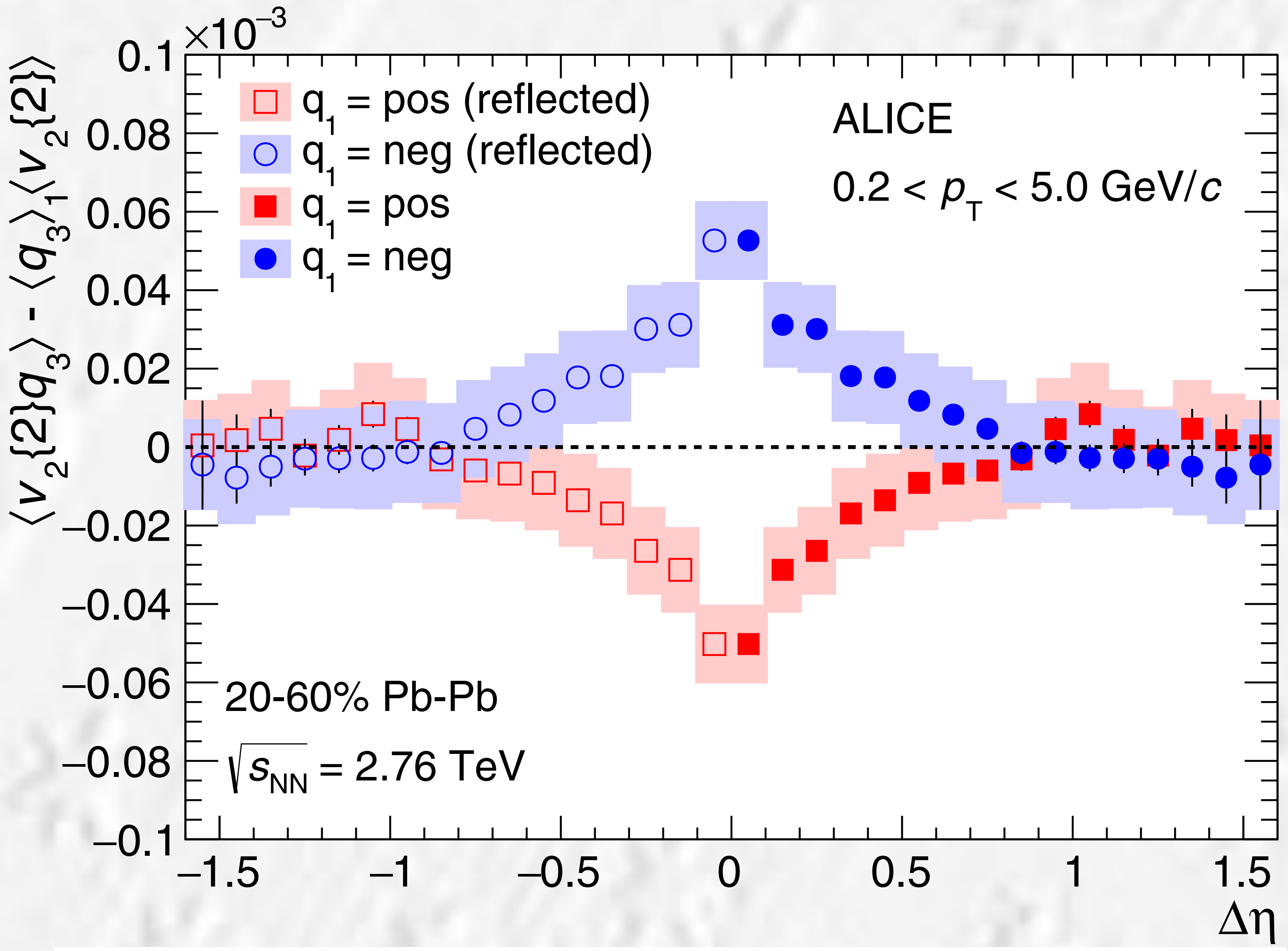


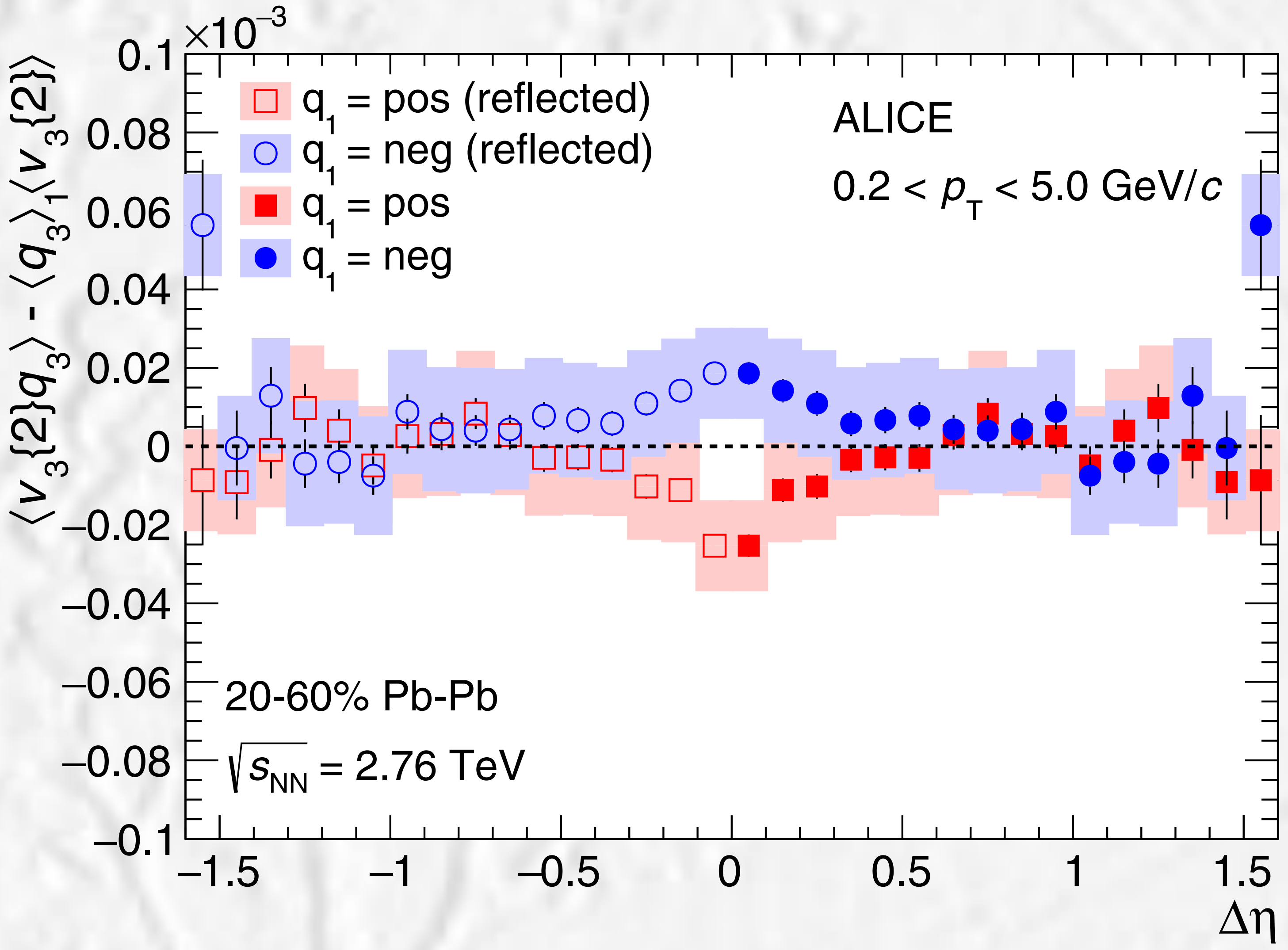


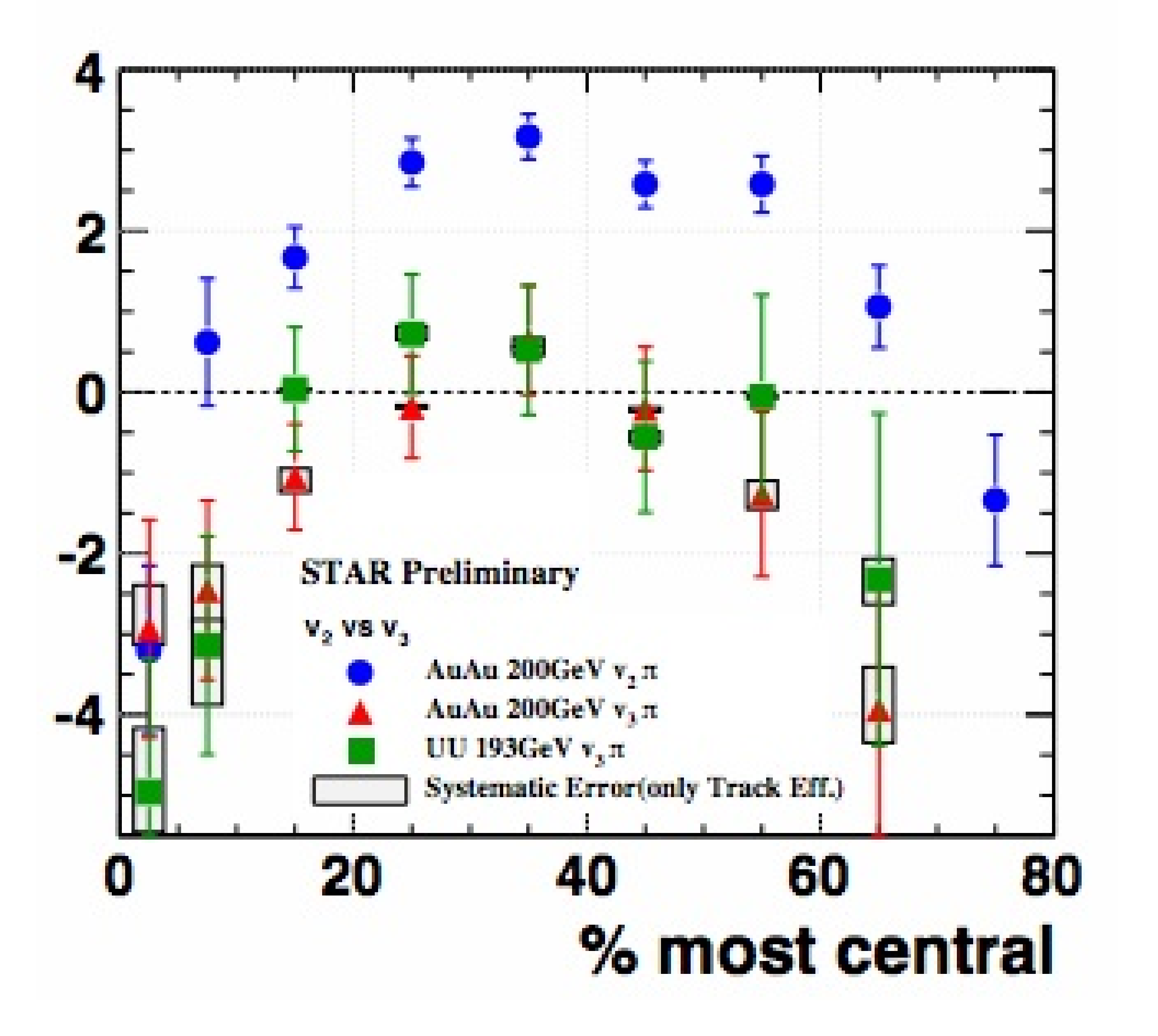
Clear signal, qualitatively consistent with expectations for CMW, pseudorapidity dependence similar to that of gamma correlator

Higher harmonics

CMW: v2 vs Ach, 3 pt correlator



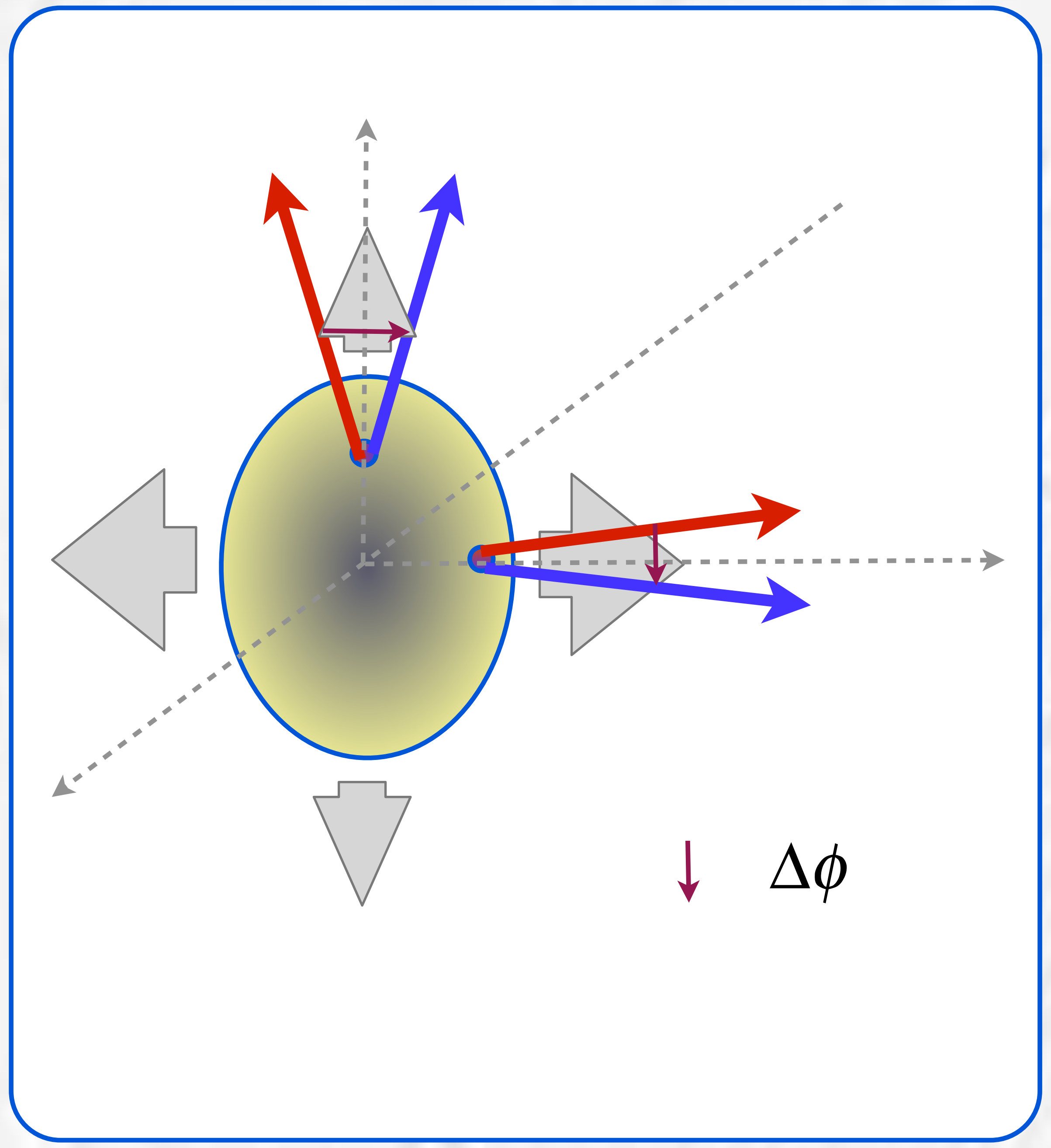


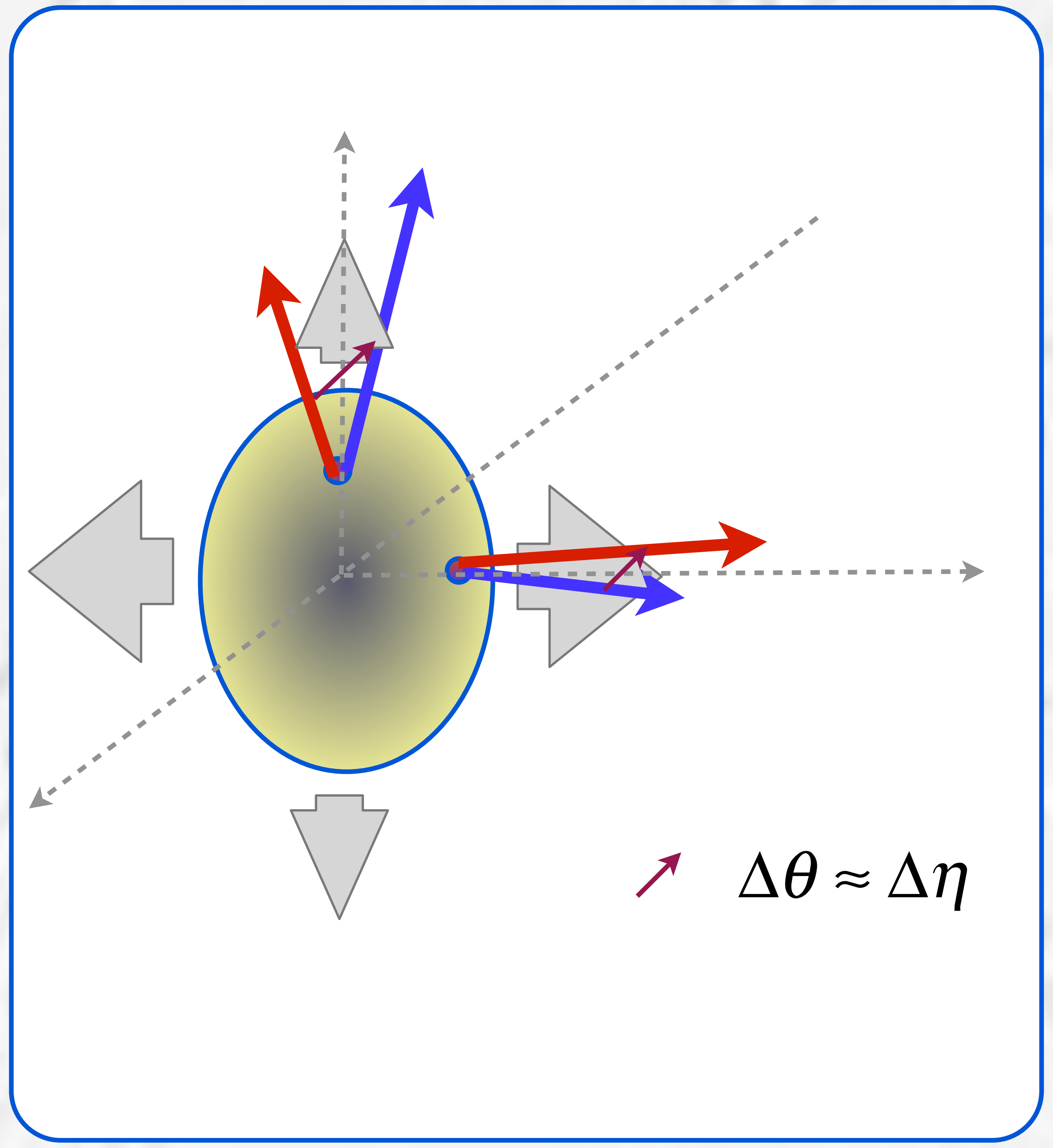


Can be difficult for quantitative interpretation similarly to the CME search

Cross-correlations:

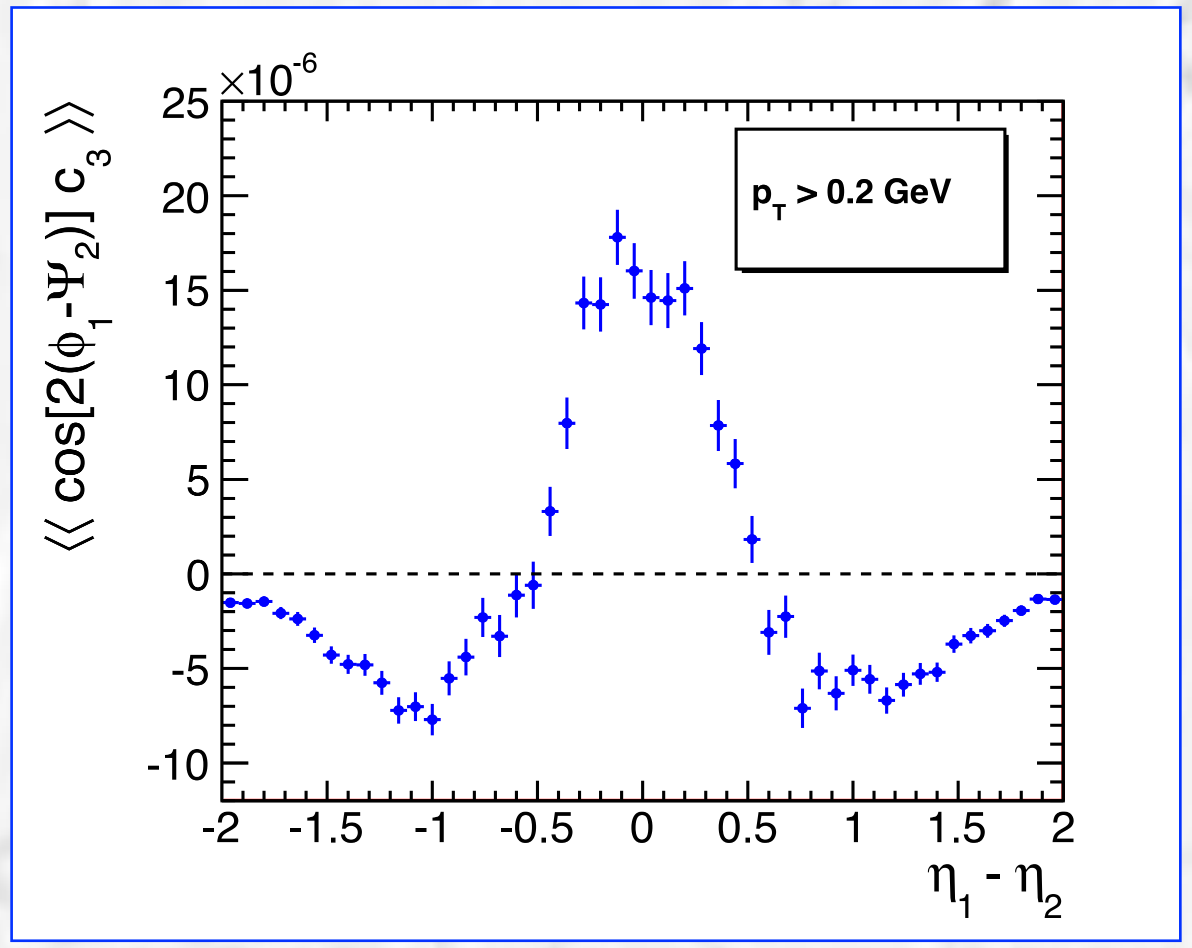
S.A. Voloshin, R. Belmont, Nuclear Phys. A 931 (2014) 992. arXiv:1408.0714



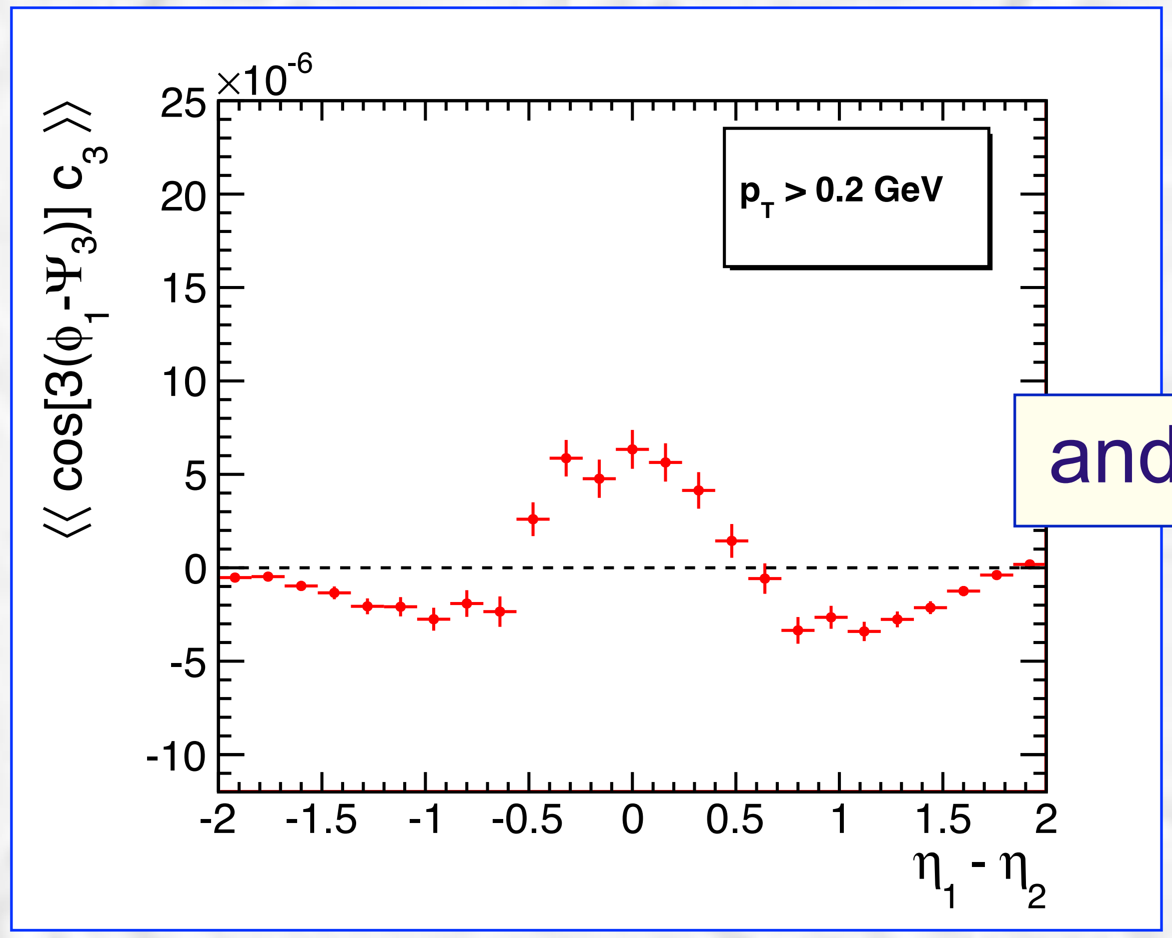


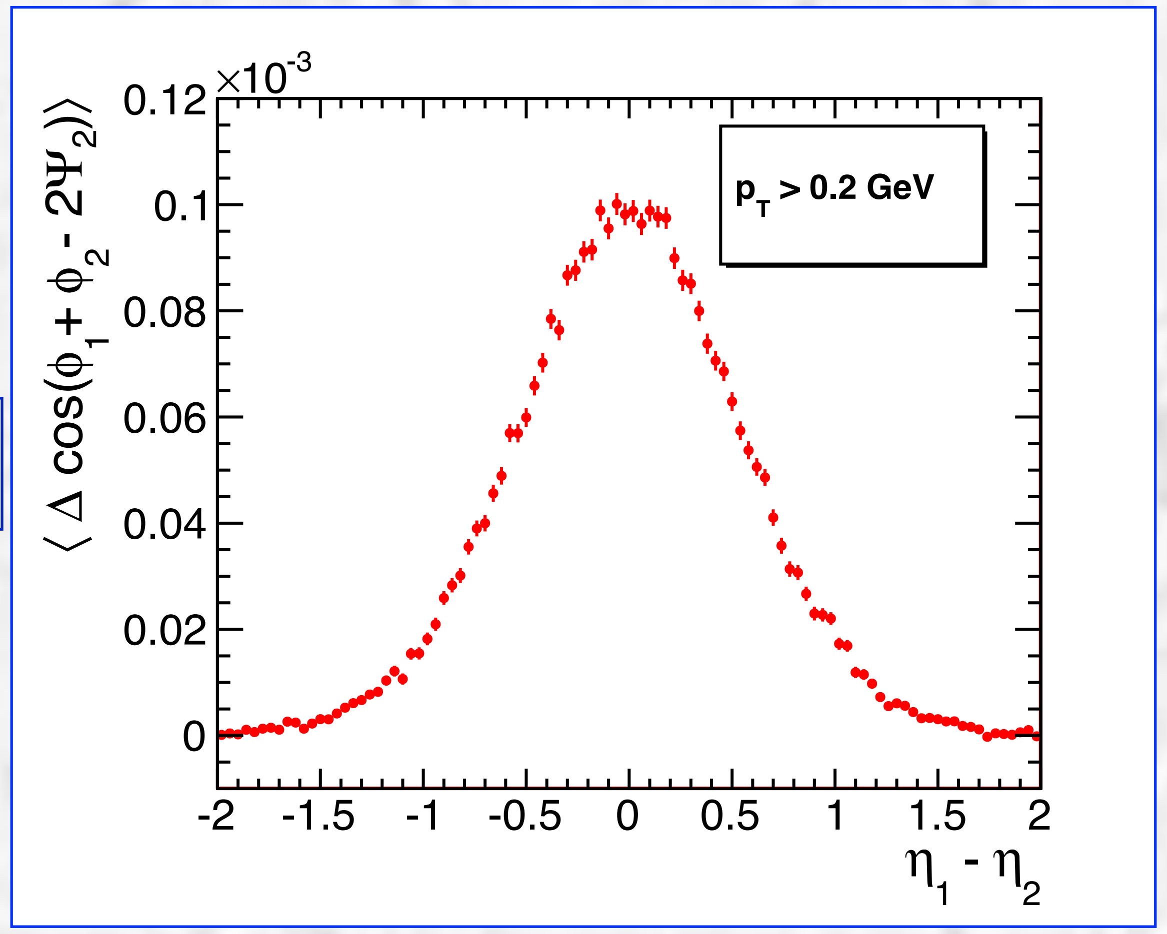
Larger radial flow narrows pair distribution in azimuth as well as in pseudorapidity

Could serve as a good test for the background nature



and





Similar predictions for p_T dependence

Final remarks CME/CMW search

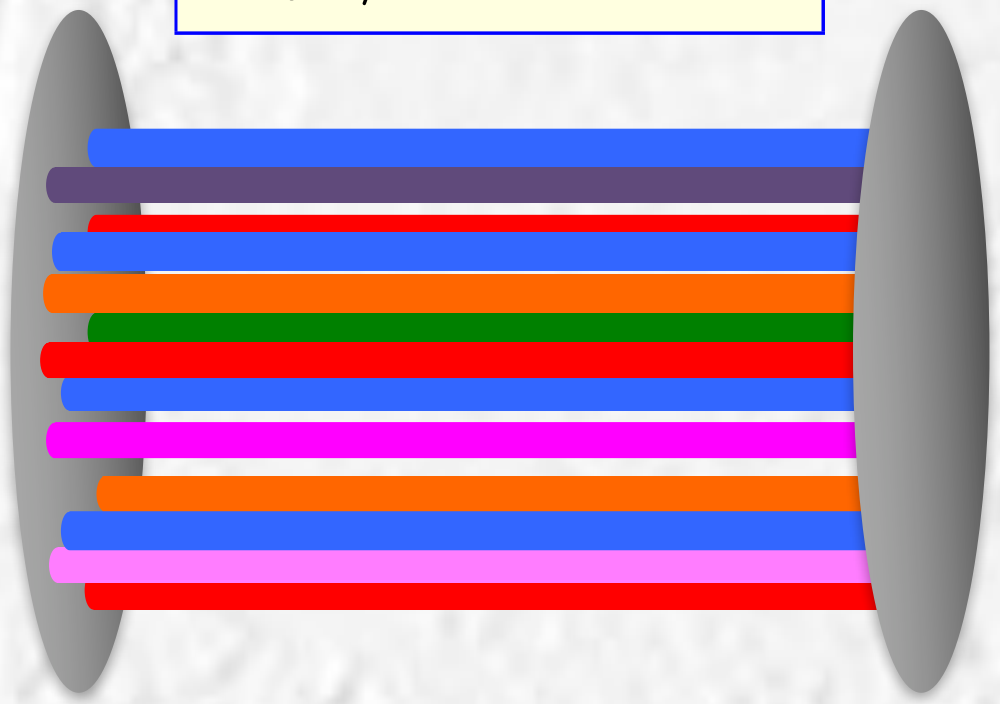
Current limit on the “CME fraction” is about < 15%
With isobars, ESE, SP/PP we will know it at the level ~ 5%

Getting anything better than that seems to be difficult

“New” directions:

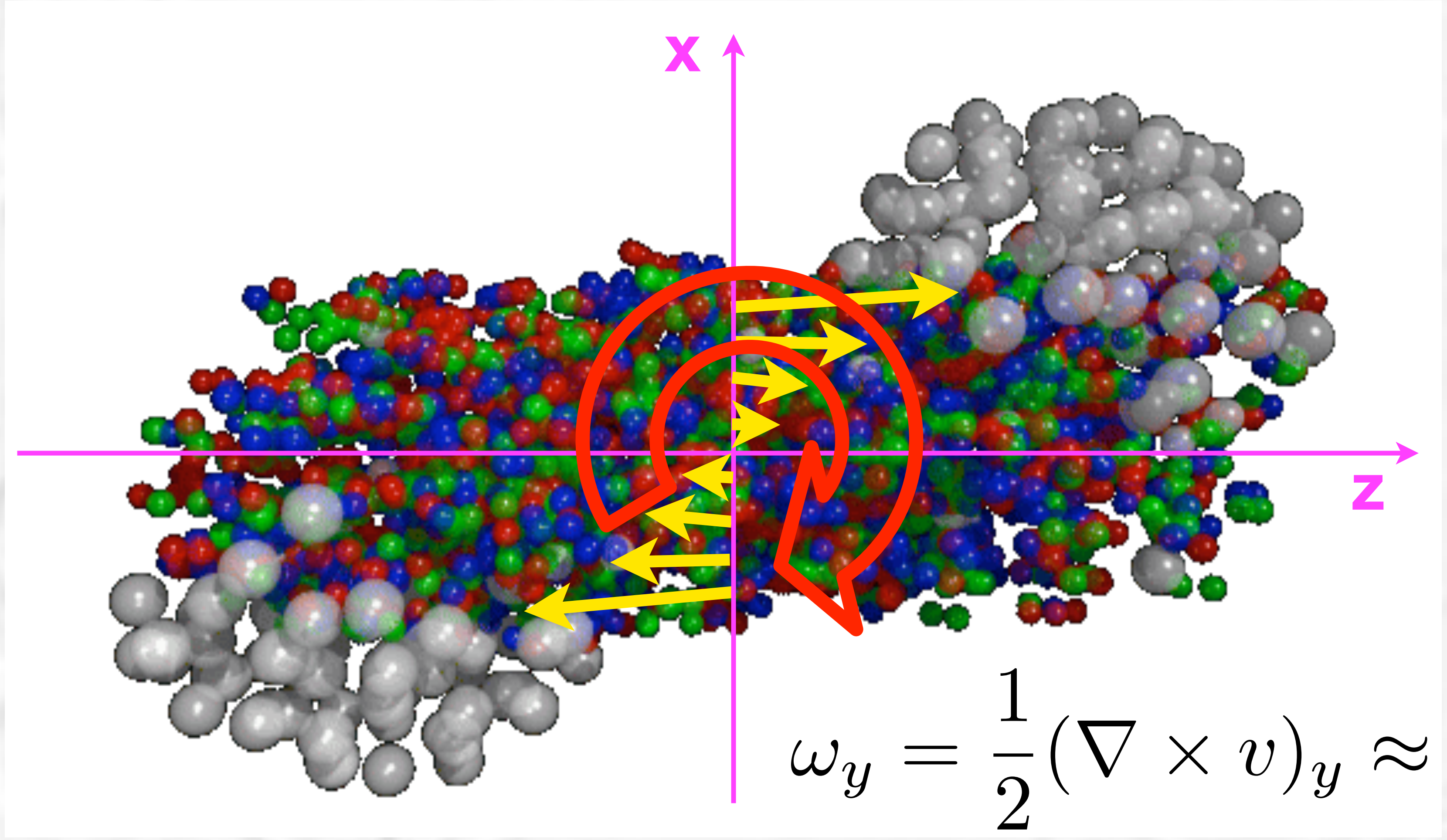
PID? $2N_f|Q|$ quark interaction?
many-particle correlation?

$dQ_5/dt \propto \mathbf{E} \cdot \mathbf{B}$

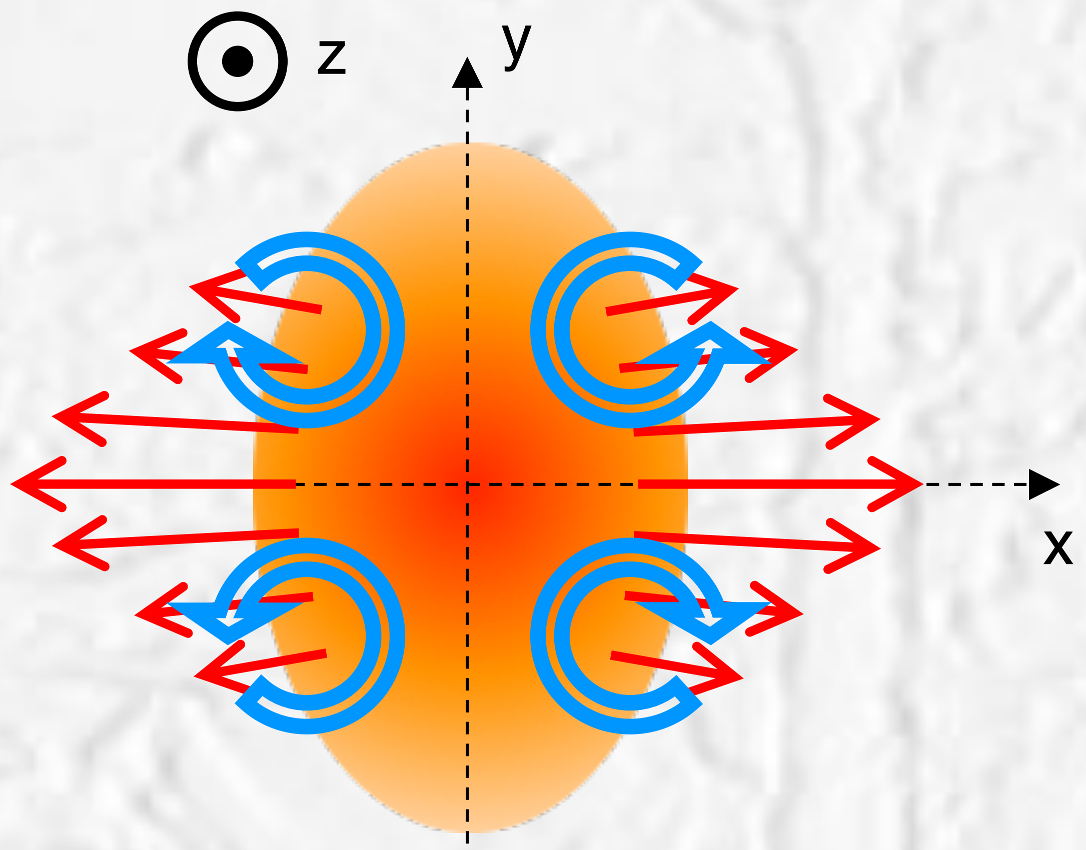


Glasma: do we have long range correlations in rapidity? Multiparticle?

Vorticity and polarization



$$\omega_y = \frac{1}{2}(\nabla \times v)_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$



Vorticity:

- Intro, one page of history
- Global polarization: Λ, Ξ, Ω polarization
- Local, “z” polarization
- Spin alignment

Brief history (~20 years in 60 seconds)

1987… +E 896, NA57

2003 STAR mtng in Prague -first ideas

2004 Idea goes "on-shell"

2007 Fist measurements

Relation to directed flow

First ideas on local vorticity

2013 ALICE Physics Week in Padova

2017 STAR measurements in BES

SQM - anisotropic flow -> zPol

2019/20 Ξ and Ω measurements

M. Jacob, J. Rafelski: Phys. Lett. 190 B (1987) 173

LONGITUDINAL $\bar{\Lambda}$ POLARIZATION, $\bar{\Xi}$ ABUNDANCE AND QUARK–GLUON PLASMA FORMATION

[nucl-th/0410079] Globally Polarized Quark-gluon Plasma in Non-central A+A Collisions
Authors: Zuo-Tang Liang (Shandong U), Xin-Nian Wang (LBNL)
(Submitted on 18 Oct 2004 (v1), last revised 7 Dec 2005 (this version, v5))

prediction P ~ 0.3

[nucl-th/0410089] Polarized secondary particles in unpolarized high energy hadron-hadro...
Authors: Sergei A. Voloshin
(Submitted on 21 Oct 2004)

$\rho^0 \longrightarrow \pi^+\pi^-$ | $s_y = 1 \longrightarrow l_y = 1$

⇕

$\pi^+\pi^- \longrightarrow \rho^0$ | $l_y = 1 \longrightarrow s_y = 1$

- Spin alignment -> v_2
- Relation to single spin asymmetries?

B. I. Abelev *et al.* (STAR Collaboration), Global polarization measurement in Au+Au collisions, Phys. Rev. C **76**, 024915 (2007); **95**, 039906(E) (2017).

$$P_H = \frac{8}{\pi\alpha_H}\langle\sin(\Psi_{\rm RP} - \phi_p)\rangle$$

Λ global polarization < 2%

B. Betz, M. Gyulassy, and G. Torrieri, Polarization probes of vorticity in heavy ion collisions, Phys. Rev. C **76**, 044901 (2007).

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Relativistic distribution function for particles with spin at local thermodynamical equilibrium, Annals Phys. **338**, 32 (2013).

STAR Collaboration, L. Adamczyk *et al.*, "Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid", *Nature* **548** (2017) 62–65,

S. A. Voloshin, "Vorticity and particle polarization in heavy ion collisions (experimental perspective)", arXiv:1710.08934 [nucl-ex]. [EPJ Web Conf.17,10700(2018)].

STAR Collaboration, J. Adam *et al.*, "Global polarization of Λ hyperons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV", *Phys. Rev.* **C98** (2018) 014910,

$$P_z = \frac{3}{\alpha_H}\langle\cos\theta_p^*\rangle$$

Non-relativistic statistical mechanics

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. **338**, 32 (2013), 1303.3431

Ren-hong Fang,[1] Long-gang Pang,[2] Qun Wang,[1] and Xin-nian Wang[3,4] arXiv:1604.04036v1

Spin s=1/2 !

$$\Pi_\mu(p) = \epsilon_{\mu\rho\sigma\tau}\frac{p^\tau}{8m}\frac{\int d\Sigma_\lambda p^\lambda n_F(1-n_F)\partial^\rho\beta^\sigma}{\int d\Sigma_\lambda p^\lambda n_F}$$

$$n_F = \frac{1}{e^{\beta(x)\cdot p-\mu/T}+1}.$$

$$\beta^\mu = u^\mu/T$$

$$\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$$

$$\tilde{\omega}_{\mu\nu} = \frac{1}{2}[\partial_\nu(u_\mu/T) - \partial_\mu(u_\nu/T)]$$

$$\omega^\alpha = \frac{1}{2}\varepsilon^{\alpha\mu\nu\sigma}u_\mu\omega_{\sigma\nu}$$

$$\Pi_\mu = W_\mu/m = -\frac{1}{2}\varepsilon_{\mu\rho\sigma\tau}S^{\rho\sigma}\frac{p^\tau}{m}$$

W_μ – Pauli-Lubanski pseudovector

$S^{\mu\nu} = \varepsilon^{\mu\nu\tau}S_\tau$ Rest frame: $\Pi_\mu = (0, \mathbf{s})$

F. Becattini, I. Karpenko, M. Lisa, I. Upsal, and S. Voloshin, "Global hyperon polarization at local thermodynamic equilibrium with vorticity, magnetic field and feed-down", *Phys. Rev.* **C95** no. 5, (2017) 054902, arXiv:1610.02506 [nucl-th].

Nonrelativistic statistical mechanics

$$p(T,\mu_i,\mathbf{B},\boldsymbol{\omega}) \propto \exp[(-E+\mu_i Q_i+\boldsymbol{\mu}\cdot\mathbf{B}+\boldsymbol{\omega}\cdot\mathbf{J})/T]$$

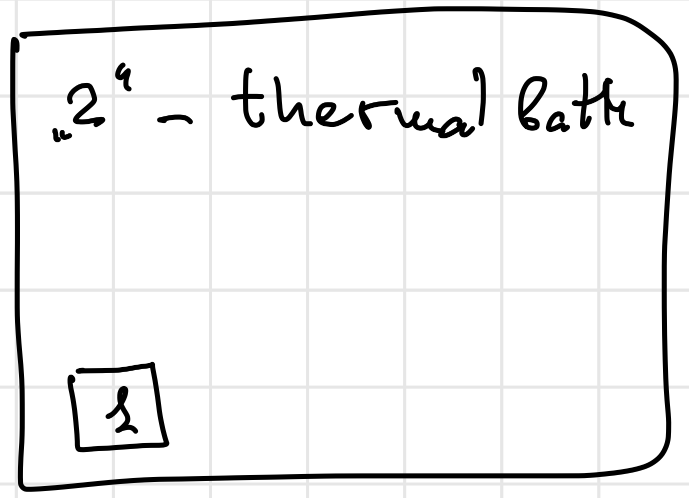
$$\mathbf{S} \approx \frac{S(S+1)}{3}\frac{\boldsymbol{\omega}}{T}$$

[28] L. D. Landau and E. M. Lifshits, *Statistical Physics*, 2nd Ed., Pergamon Press, 1969.

[29] A. Vilenkin, "Quantum Field Theory At Finite Temperature In A Rotating System," Phys. Rev. D **21**, 2260 (1980). doi:10.1103/PhysRevD.21.2260

+ many more

applicable for any spin



$E_1 + E_2 = E = \text{const}$

$J_{1z} + J_{2z} = J_z = \text{const}$

$J_{2z} = L_z$; $J_{1z} = S_z$

$\sigma_2\left(E_2 - \frac{L_{2z}}{2I}\right) \leftarrow$ entropy

probability $p \propto e^{\sigma_2}$

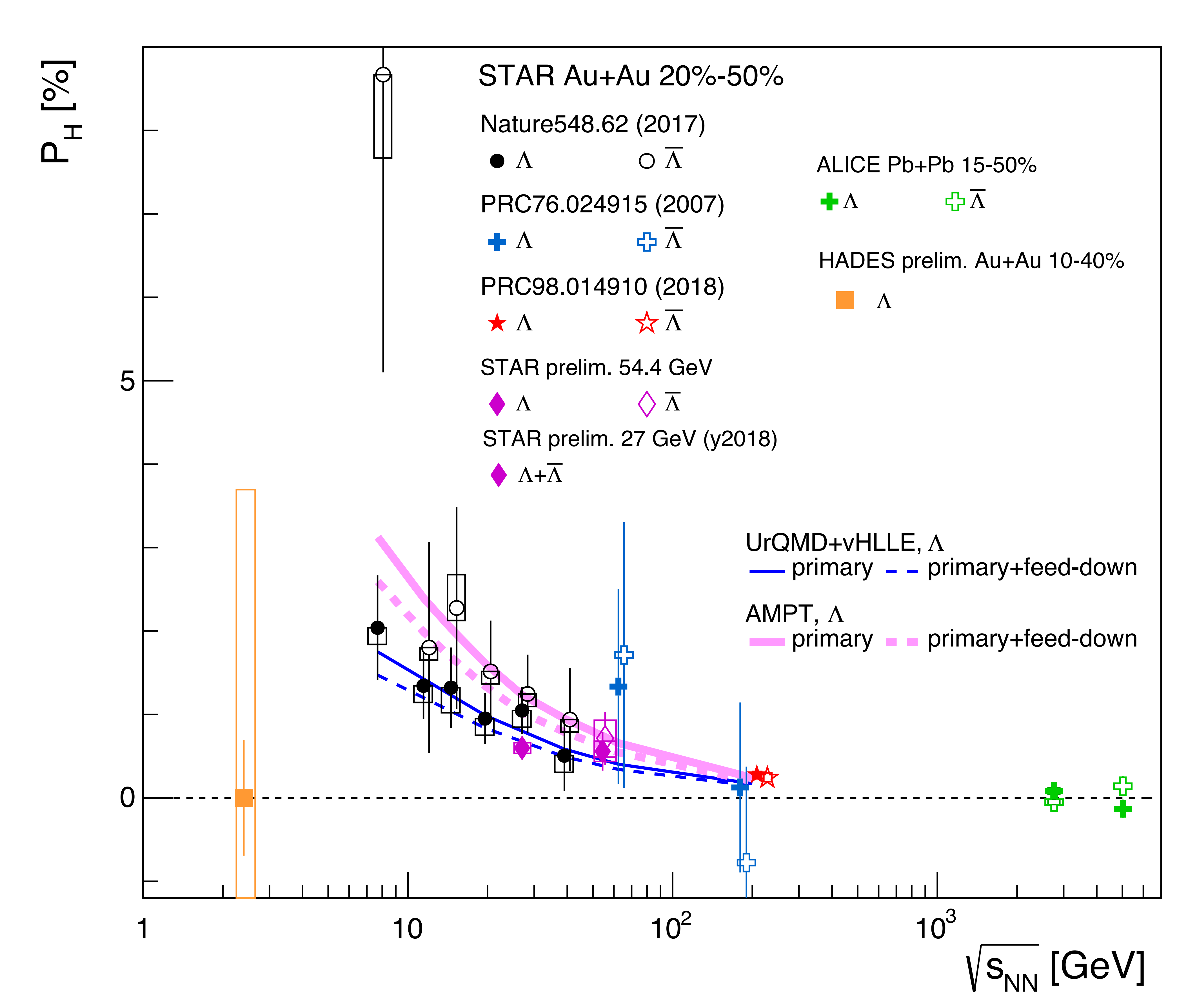
$\sigma_2 = \sigma_2^{(0)} + \frac{\partial\sigma}{\partial E}\Delta E_2 + \frac{\partial\sigma}{\partial L_z}\Delta L_z$

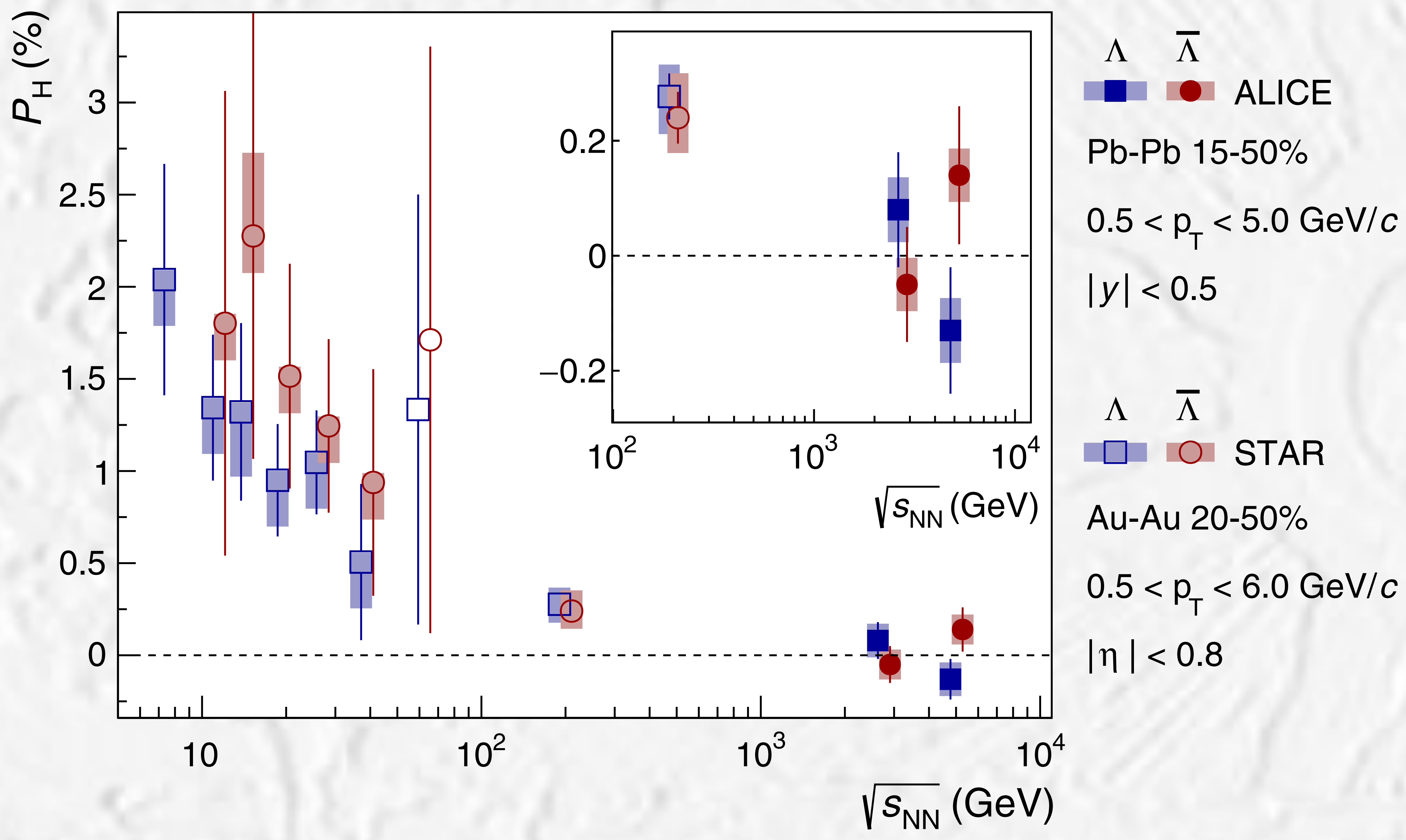
$\frac{\partial\sigma}{\partial E} = \frac{1}{T}$; $\frac{\partial\sigma}{\partial L_z} = \frac{\partial\sigma}{\partial E}\left(-\frac{L_z}{I}\right) = -\frac{\omega_z}{T}$

$p \propto e^{-E_1/T + \omega_z S_z/T}$

Question for theorists: what is the nonrelativisic limit for polarization due to temperature gradient and acceleration?

Global polarization vs $\sqrt{s_{NN}}$





Several model have rather satisfactory description of the energy dependence

Empirically the energy dependence follows closely $dv_1/d\eta$ dependence. predicting polarization values at LHC about 3 to 6 times smaller than at top RHIC energy

LHC18 data, in progress
Stat. errors ~30% smaller

Directed flow: tilted source ⊕ dipole flow

ALICE Collaboration, B. Abelev *et al.*, "Directed Flow of Charged Particles at Midrapidity Relative to the Spectator Plane in Pb-Pb Collisions at $\sqrt{s_{NN}}$=2.76 TeV", *Phys. Rev. Lett.* **111** no. 23, (2013) 232302, `arXiv:1306.4145 [nucl-ex]`.

← introduction and first measurements of v_1^{even} and $\langle p_x \rangle$!

STAR Collaboration, L. Adamczyk *et al.*, "Azimuthal anisotropy in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV", *Phys. Rev.* **C98** no. 1, (2018) 014915, `arXiv:1712.01332 [nucl-ex]`.

← idea of directed flow as a combination of "tilted source" and dipole flow

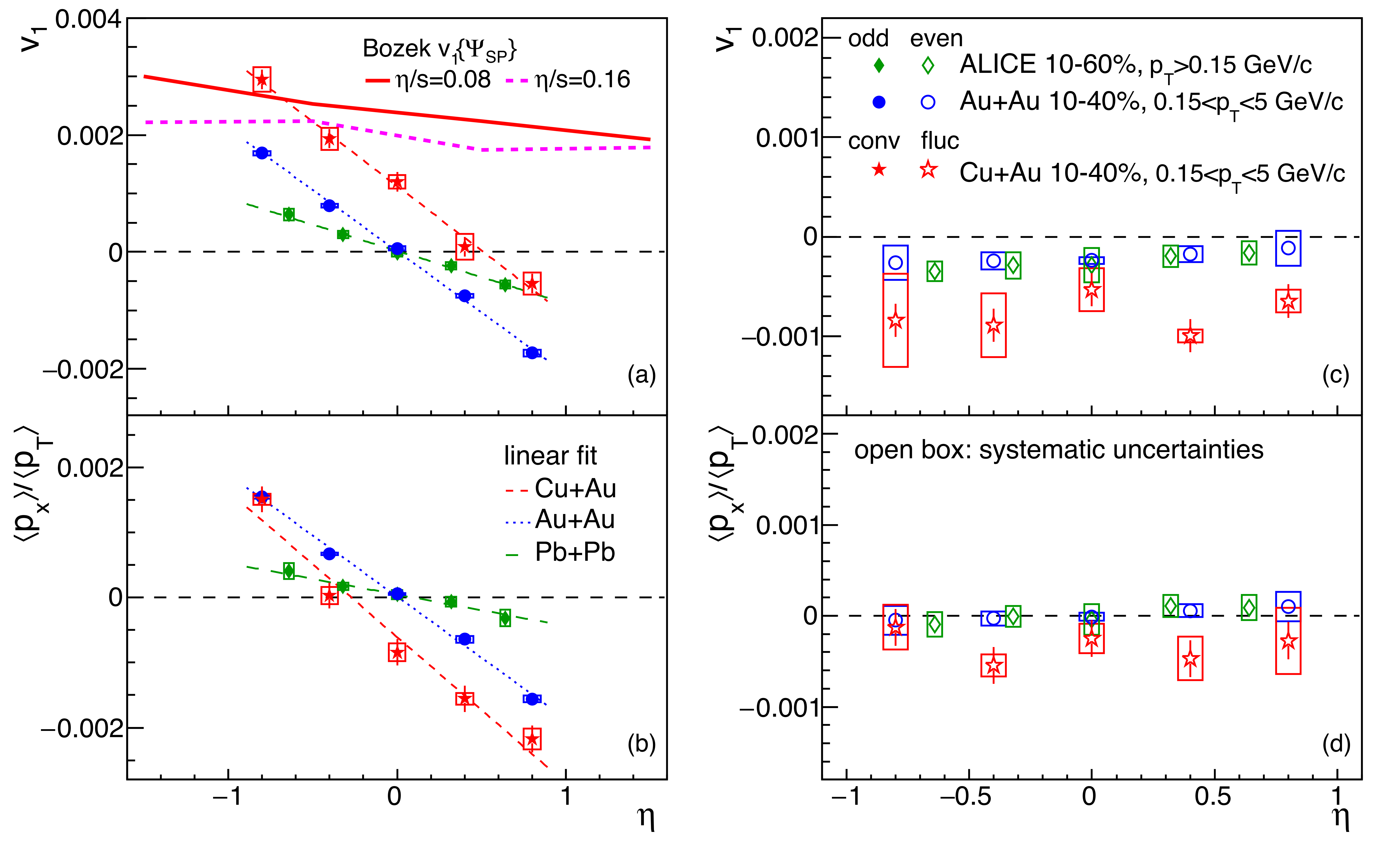


FIG. 5. (Color online) Charged particle "conventional" (left) and "fluctuation" (right) components of directed flow v_1 and momentum shift $\langle p_x \rangle / \langle p_T \rangle$ as a function of η in 10%-40% centrality for Cu+Au, Au+Au, and Pb+Pb collisions. Thick solid and dashed lines show the hydrodynamic model calculations with η/s=0.08 and 0.16, respectively, for Cu+Au collisions [31]. Thin lines in the left panel show a linear fit to the data.

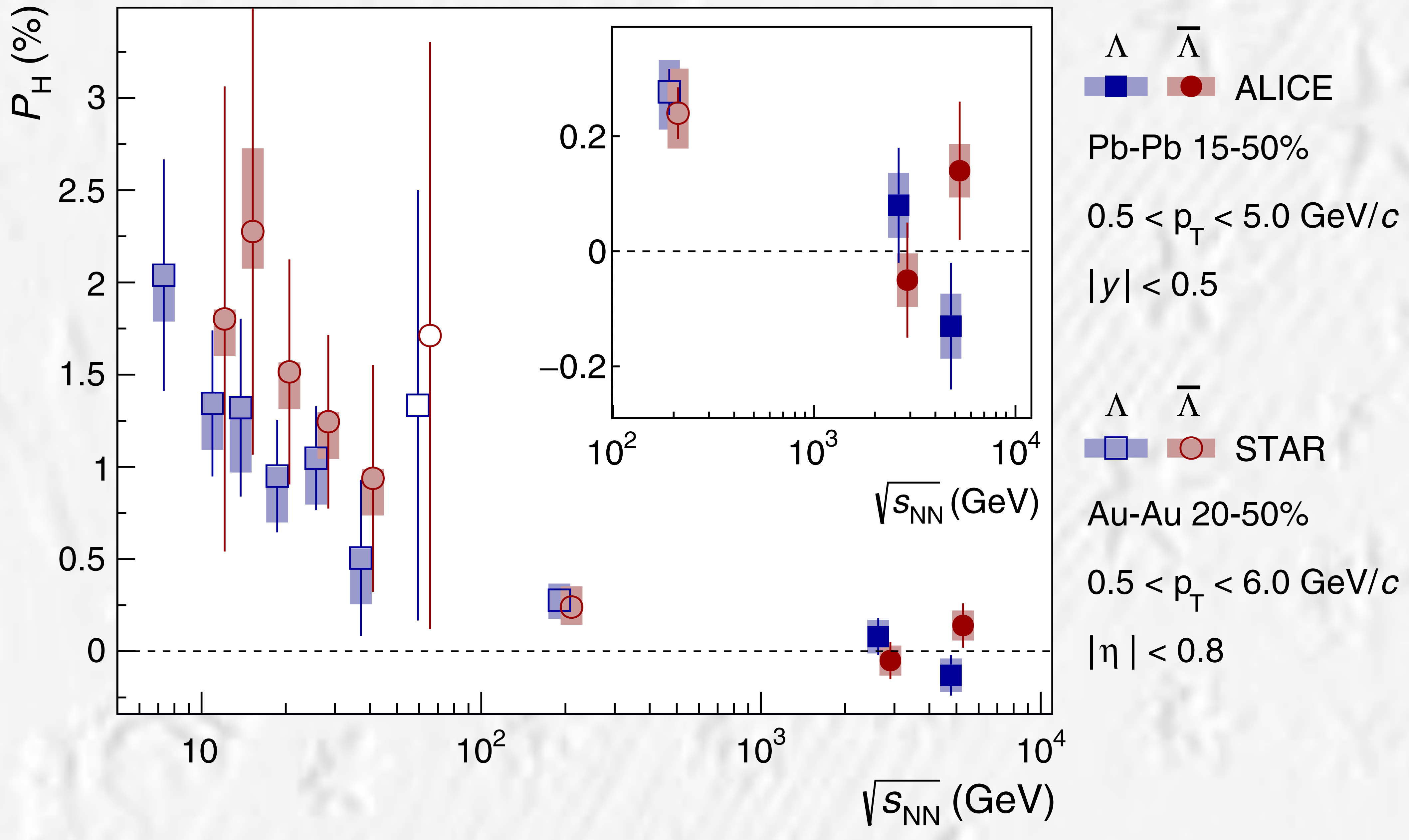
$$\frac{1}{\langle p_T \rangle} \frac{d \langle p_x \rangle}{d\eta} \approx 1.5\, \alpha_{ts} \frac{dv_1}{d\eta}$$

α_{ts} - fraction of "tilted source" contribution to v_1

- For mid-central collisions (20% - 40%) tilted source contribution is about 2/3, its fraction increases in more peripheral collisions.
- At LHC energies "tilted sources" contribution is smaller, about 1/3

→ polarization at LHC ~ 1/6 of that at RHIC 200 GeV

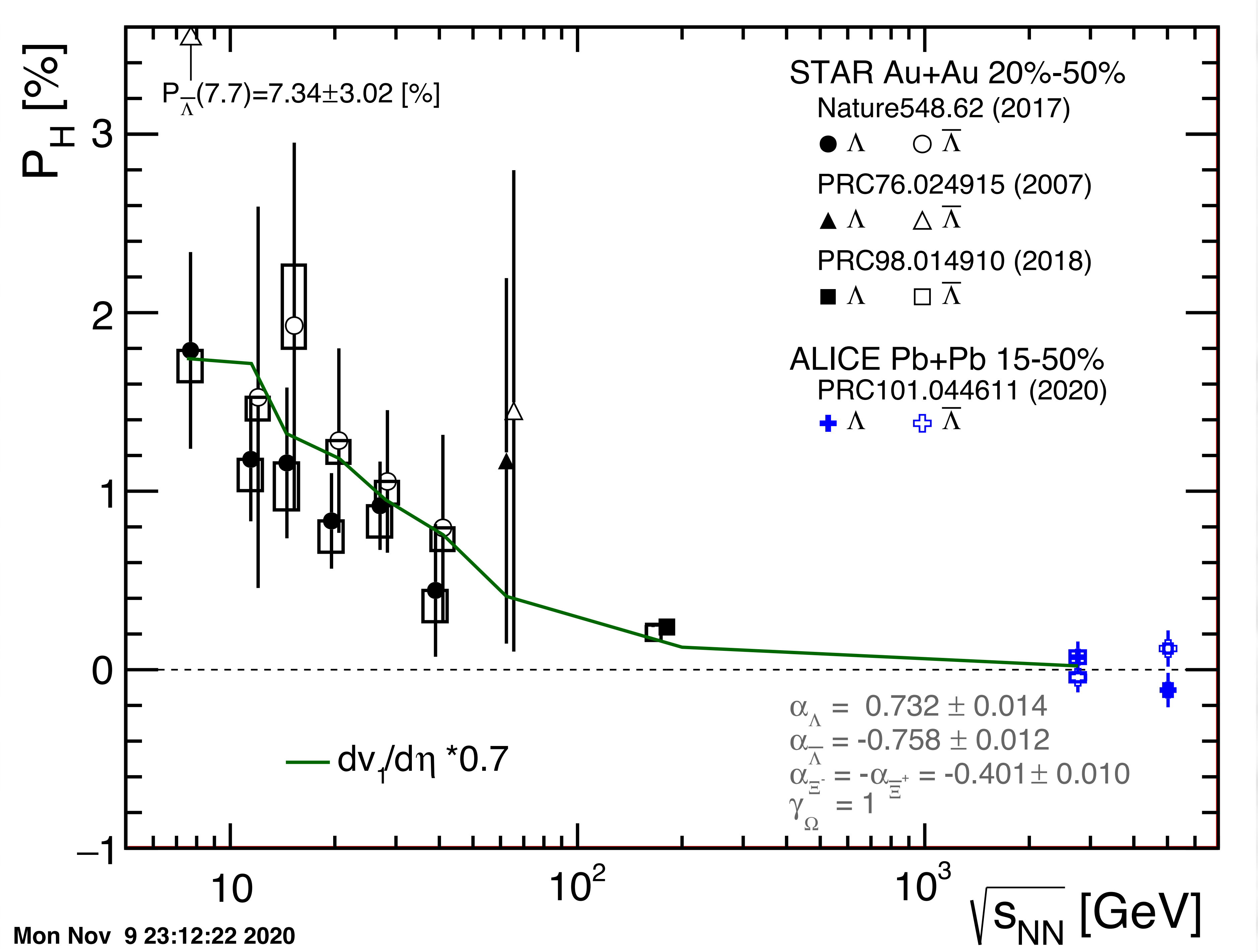
Directed flow and vorticity



F. Becattini, G. Inghirami, V. Rolando, A. Beraudo, L. Del Zanna, A. De Pace, M. Nardi, G. Pagliara, and V. Chandra, Eur. Phys. J. **C75**, 406 (2015), arXiv:1501.04468 [nucl-th]

Good description of directed flow requires accounting for vorticity!

Slope, $dv_1/d\eta$ proportional to ω?



According to this naive “extrapolation” yield polarization at LHC about 1/3 of that at highest RHIC energy

But, the directed flow has different components… “tilted source”, ‘dipole flow”…

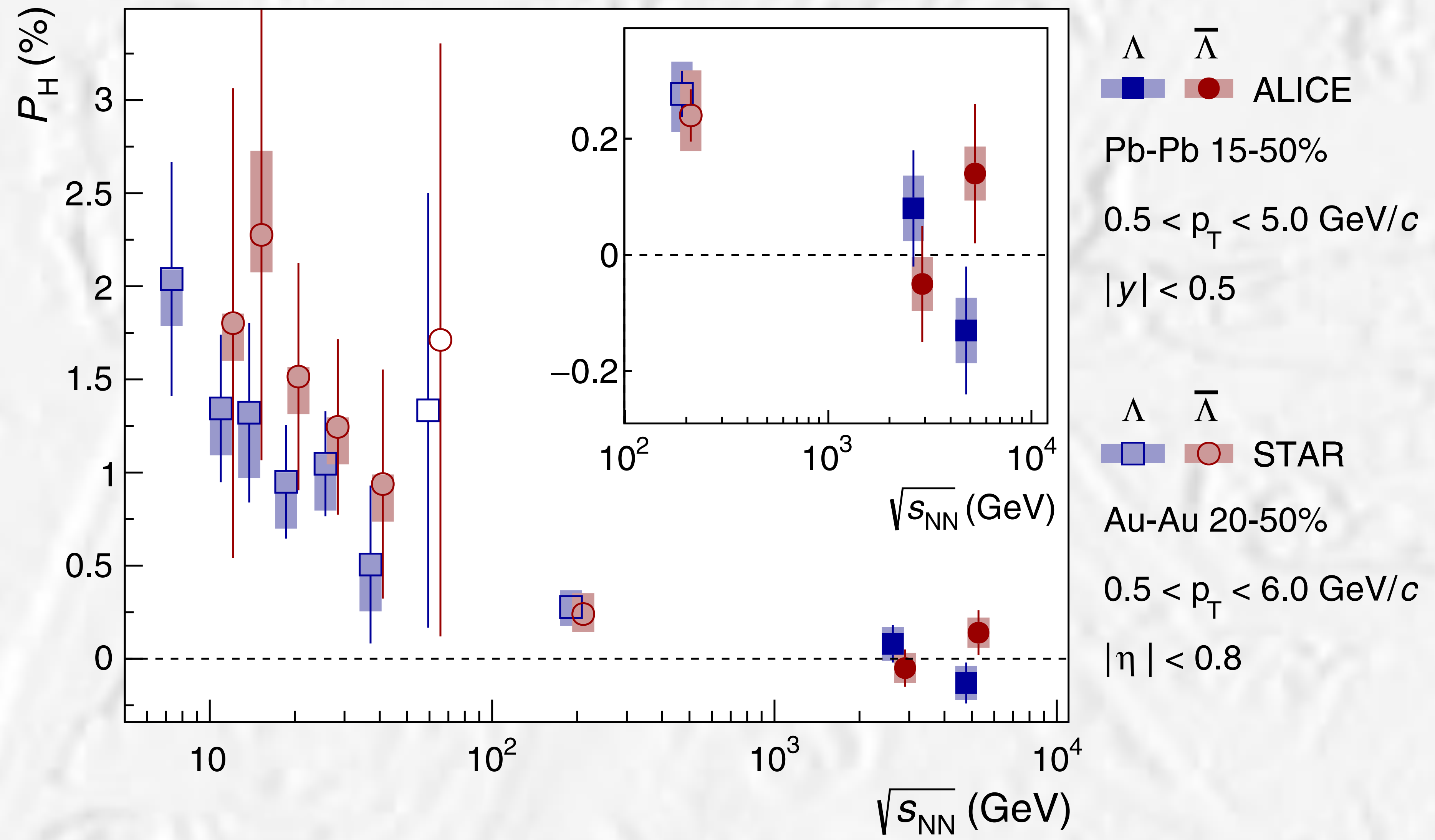
gPolarization and magnetic field

Becattini, Karpenko, Lisa, Upsal, and Voloshin,
PRC95.054902 (2017)

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar\Lambda} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

μ_Λ: Λ magnetic moment



L. McLerran, V. Skokov / Nuclear Physics A 929 (2014) 184–190

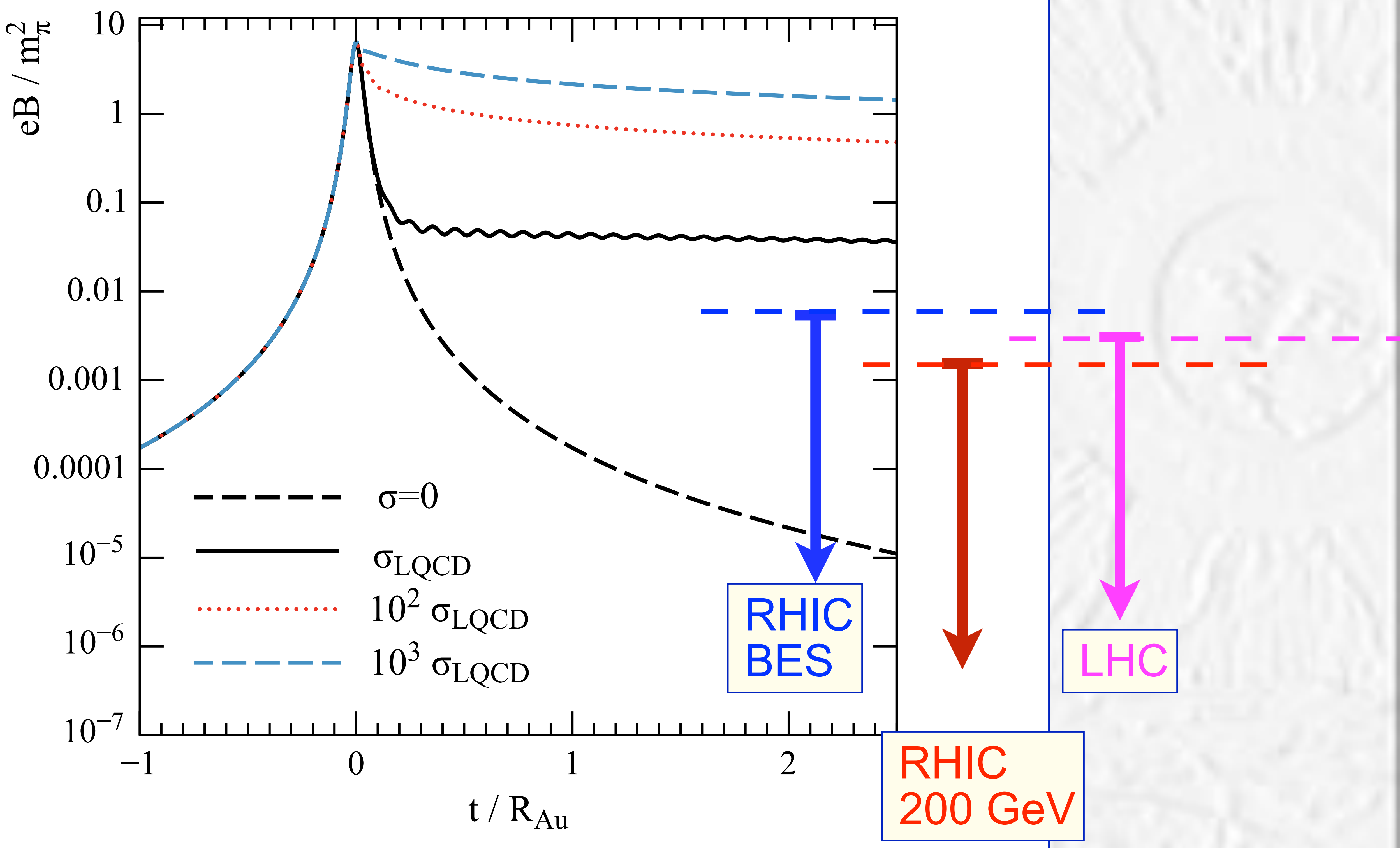


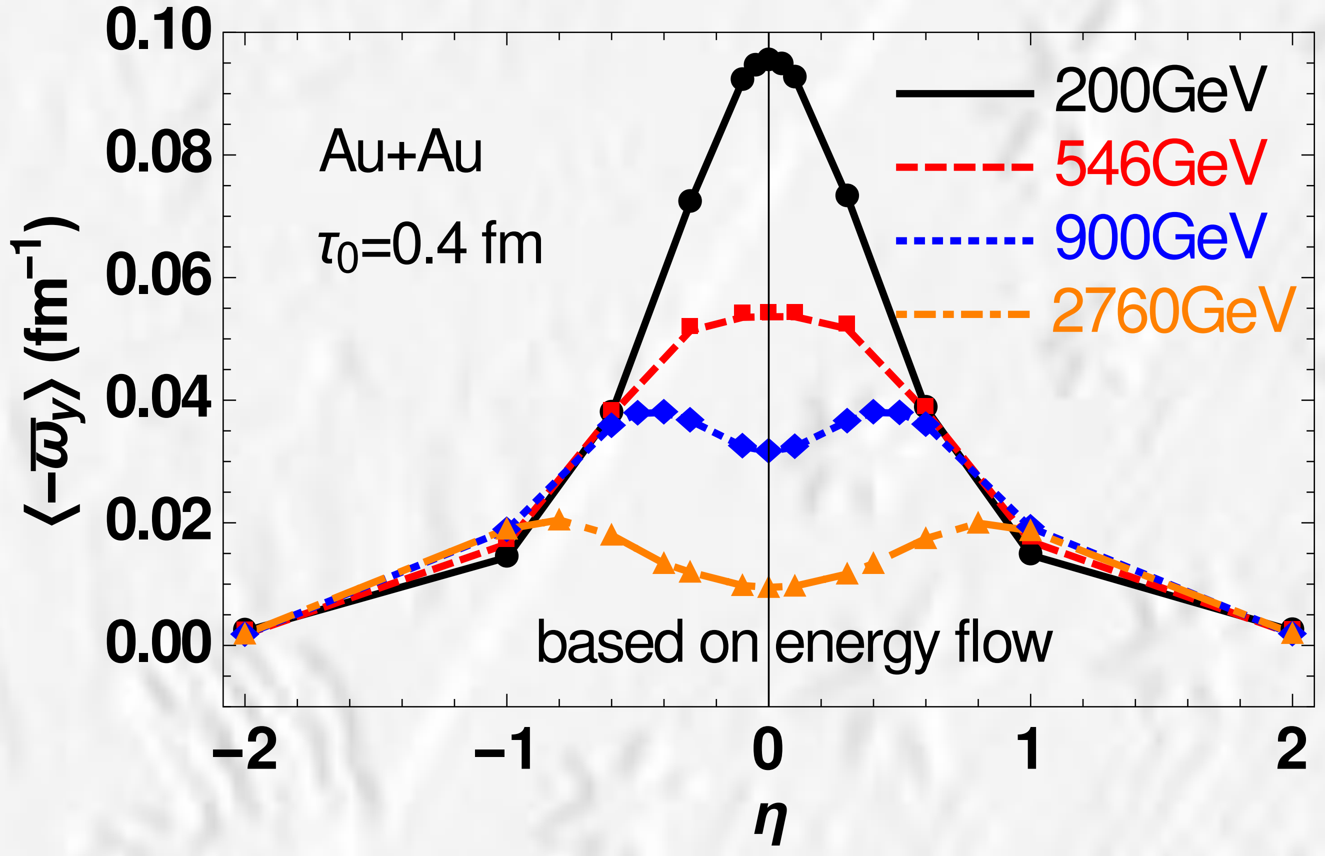
Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

Assumption: thermal equilibrium

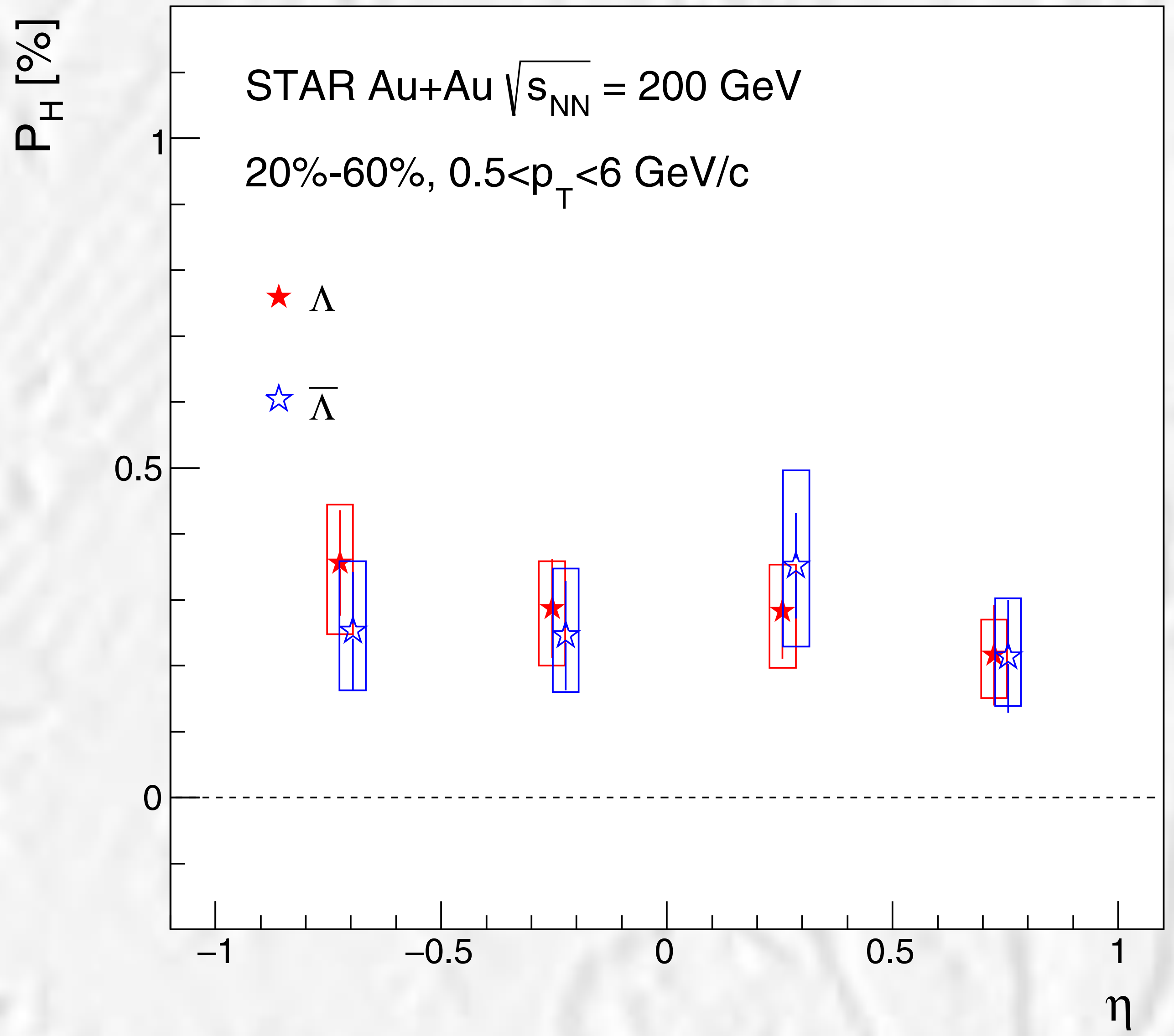
Significant limits on the magnetic field at freeze-out (time ~ 10 - 15 fm?)

gPolarization differentially

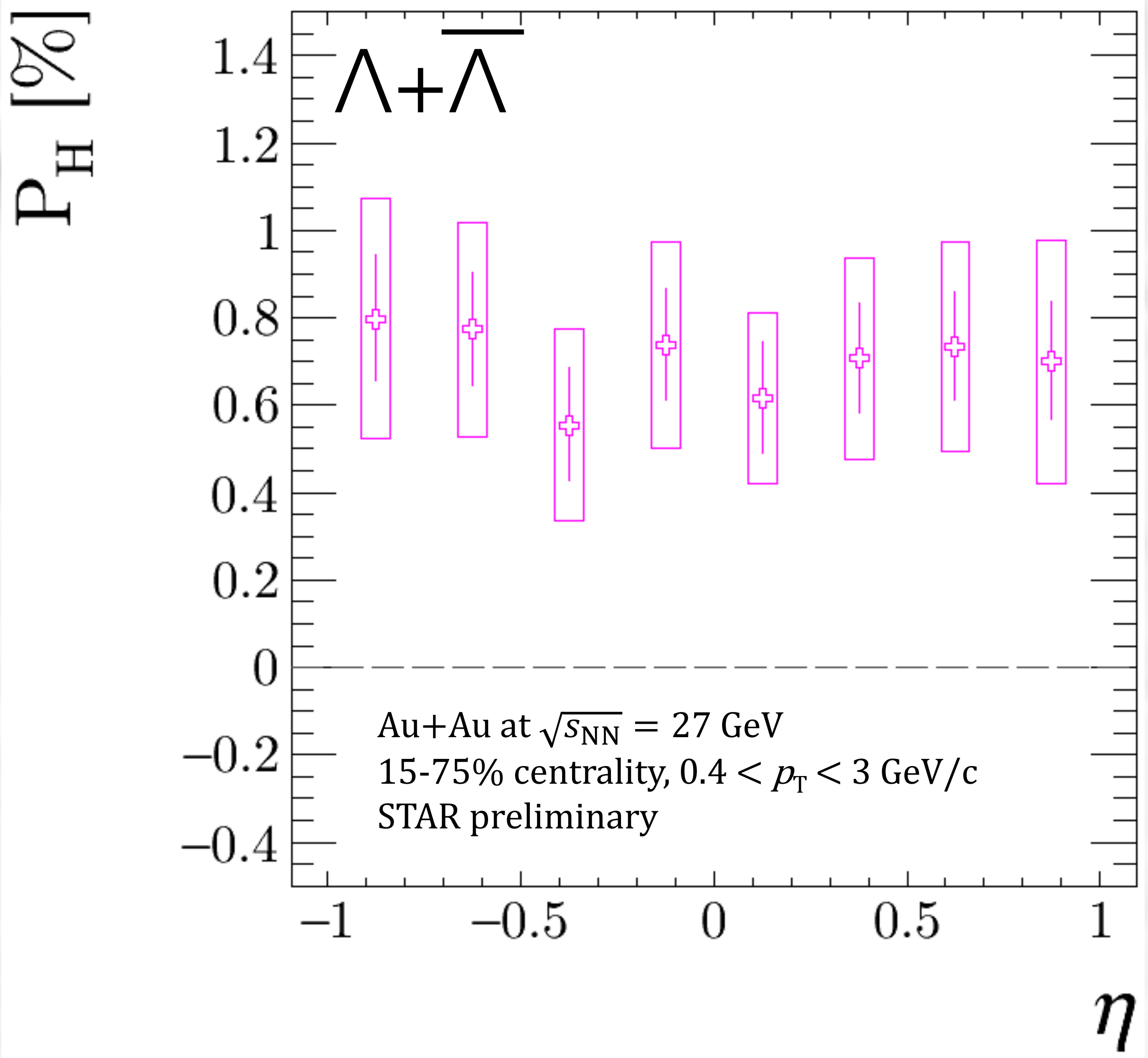
W.T.Feng and X.G.Huang, PRC93.064907 (2016)

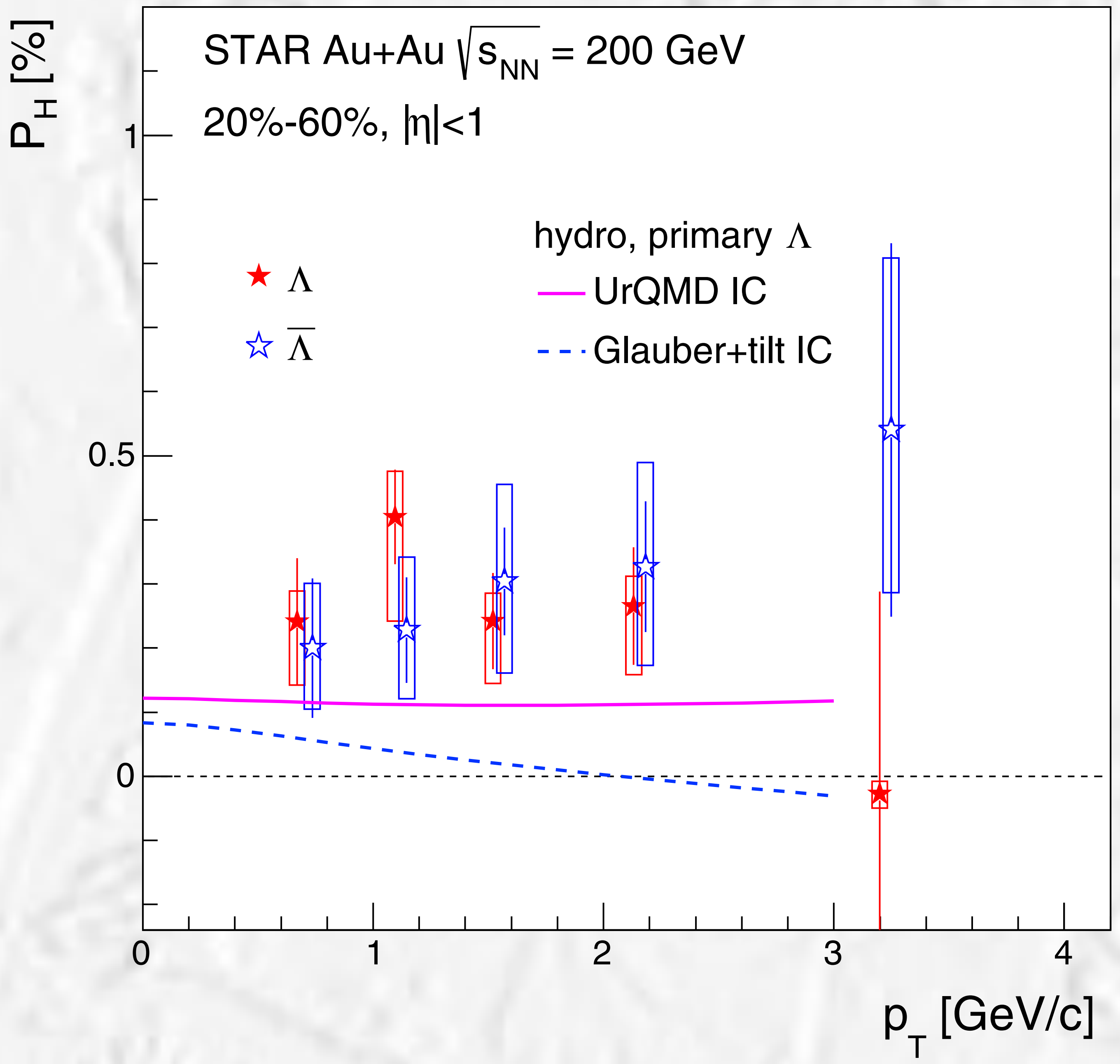


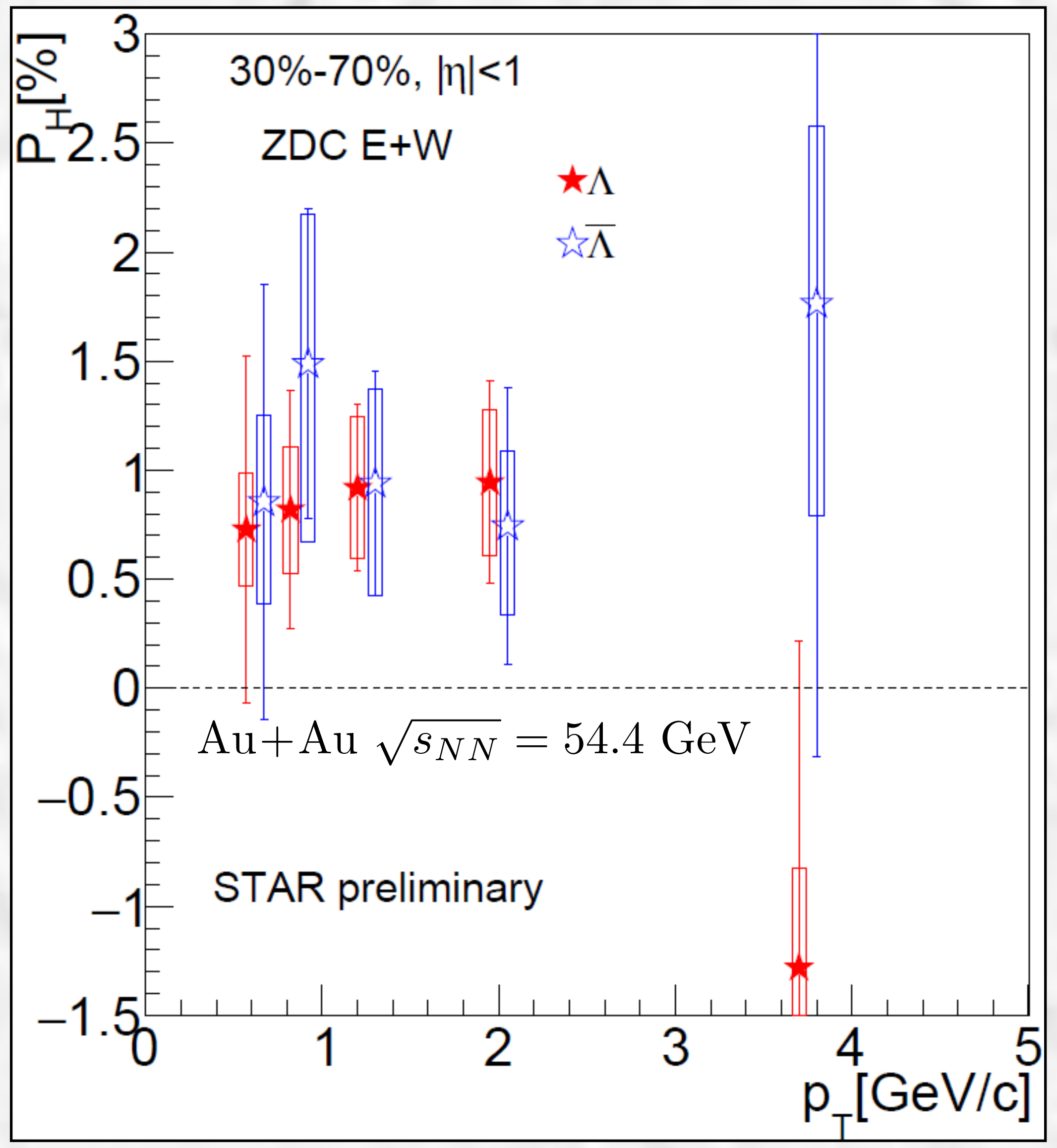
STAR, PRC98, 014910 (2018)

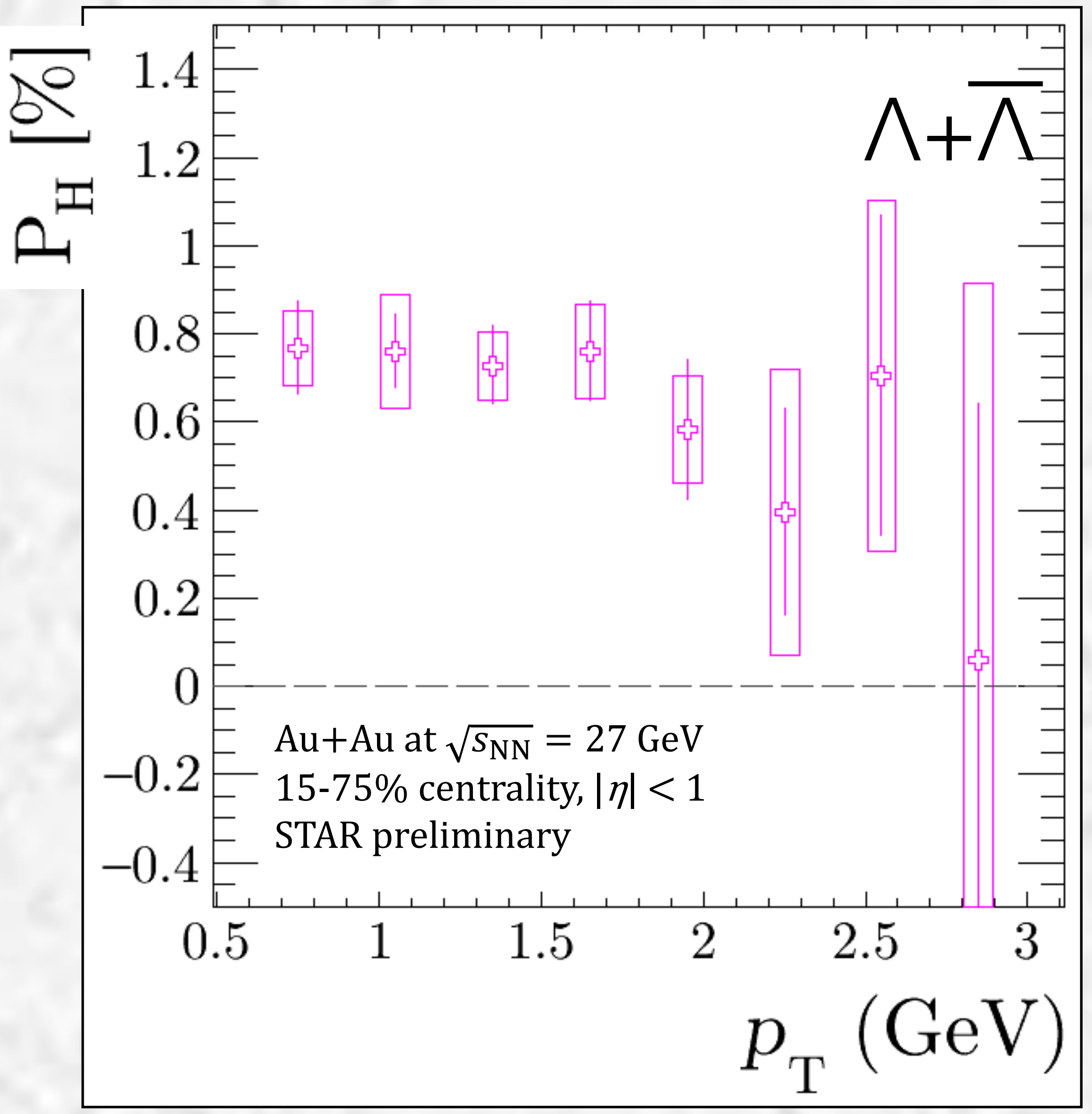


STAR, QM19









Hopefully available at LHC in Run 3

Feed-down and polarization transfer

F. Becattini, I. Karpenko, M. Lisa, I. Upsal, and S. Voloshin, "Global hyperon polarization at local thermodynamic equilibrium with vorticity, magnetic field and feed-down", *Phys. Rev.* **C95** no. 5, (2017) 054902, arXiv:1610.02506 [nucl-th].

- ~60% of measured Λ are feed-down from Σ*→Λπ, Σ^0→Λγ, Ξ→Λπ
- Polarization of parent particle R is transferred to its daughter Λ (Polarization transfer could be negative!)

$$\mathbf{S}^*_\Lambda = C\mathbf{S}^*_R$$

$C_{\Lambda R}$: coefficient of spin transfer from parent R to Λ

S_R : parent particle's spin

μ_R : magnetic moment of particle R

Decay	C
parity-conserving: $1/2^+ \to 1/2^+ \; 0^-$	$-1/3$
parity-conserving: $1/2^- \to 1/2^+ \; 0^-$	1
parity-conserving: $3/2^+ \to 1/2^+ \; 0^-$	$1/3$
parity-conserving: $3/2^- \to 1/2^+ \; 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	$+0.900$
$\Xi^- \to \Lambda + \pi^-$	$+0.927$
$\Sigma^0 \to \Lambda + \gamma$	-1/3

TABLE I. Polarization transfer factors C (see eq. (36)) for important decays $X \to \Lambda(\Sigma)\pi$

Primary Λ polarization is diluted by 15%-20% (model-dependent)

This also suggests that **the polarization of daughter particles can be used to measure the polarization of its parent!** e.g. Ξ, Ω

Measuring Ξ and Ω polarization

P. A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

	Mass (GeV/c²)	cτ (cm)	decay mode	decay parameter α_H	magnetic moment (μ_N)	spin
Λ (uds)	1.115683	7.89	Λ->πp (63.9%)	0.732±0.014	−0.613	1/2
Ξ^- (dss)	1.32171	4.91	Ξ^-->$\Lambda\pi^-$ (99.887%)	−0.401±0.010	−0.6507	1/2
Ω^- (sss)	1.67245	2.46	Ω^-->ΛK^- (67.8%)	0.0157±0.002	-2.02	3/2

- Different spin, magnetic moments, quark structure
- Less feed-down in Ξ and Ω compared to Λ
- Freeze-out at different time?

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*\right)$$

Smaller α, more difficult to measure P

T.D. Lee and C.N. Yang, Phys. Rev.108.1645 (1957)

$$\mathbf{P}_\Lambda^* = \frac{(\alpha_\Xi + \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*)\hat{\boldsymbol{p}}_\Lambda^* + \beta_\Xi \mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^* + \gamma_\Xi \hat{\boldsymbol{p}}_\Lambda^* \times (\mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^*)}{1 + \alpha_\Xi \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*}$$

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

α : P-violation

β : CP violation

Ξ, spin 1/2

$$\mathbf{P}_\Lambda^* = C_{\Xi^-\Lambda}\mathbf{P}_\Xi^* = \tfrac{1}{3}(1 + 2\gamma_\Xi)\,\mathbf{P}_\Xi^*$$

$$C_{\Xi^-\Lambda} = \tfrac{1}{3}(2 \times 0.89 + 1) = +0.927$$

Ω, spin 3/2, γ not known

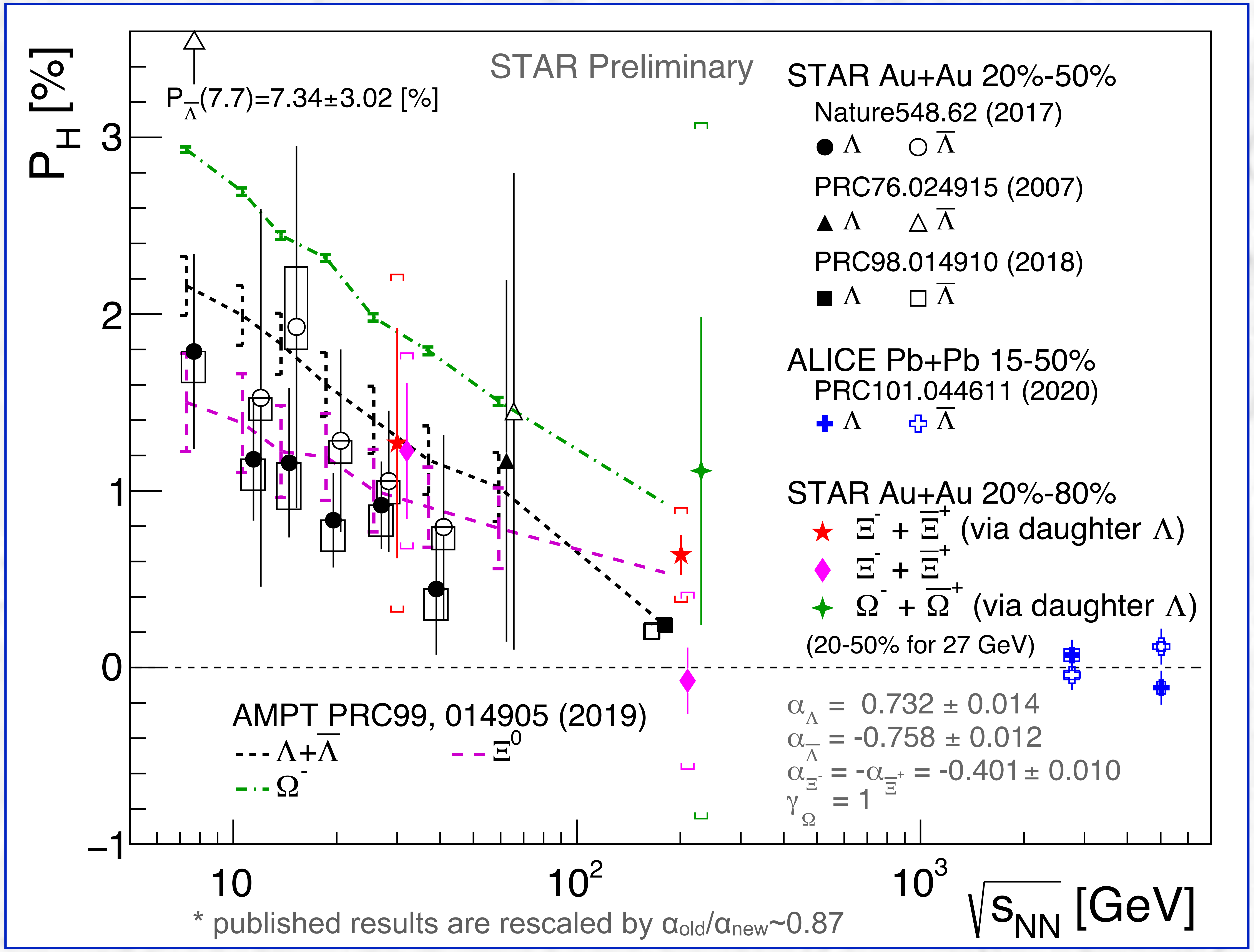
$\gamma_\Omega \approx \pm 1$

$$\mathbf{P}_\Lambda^* = C_{\Omega^-\Lambda}\mathbf{P}_\Omega^* = \tfrac{1}{5}(1 + 4\gamma_\Omega)\,\mathbf{P}_\Omega^*$$

$$C_{\Omega^-\Lambda} \approx 1 \text{ or } C_{\Omega^-\Lambda} \approx -0.6$$

Possibility to determine γ_Ω under assumption of the global polarization

Measuring Ξ and Ω polarization



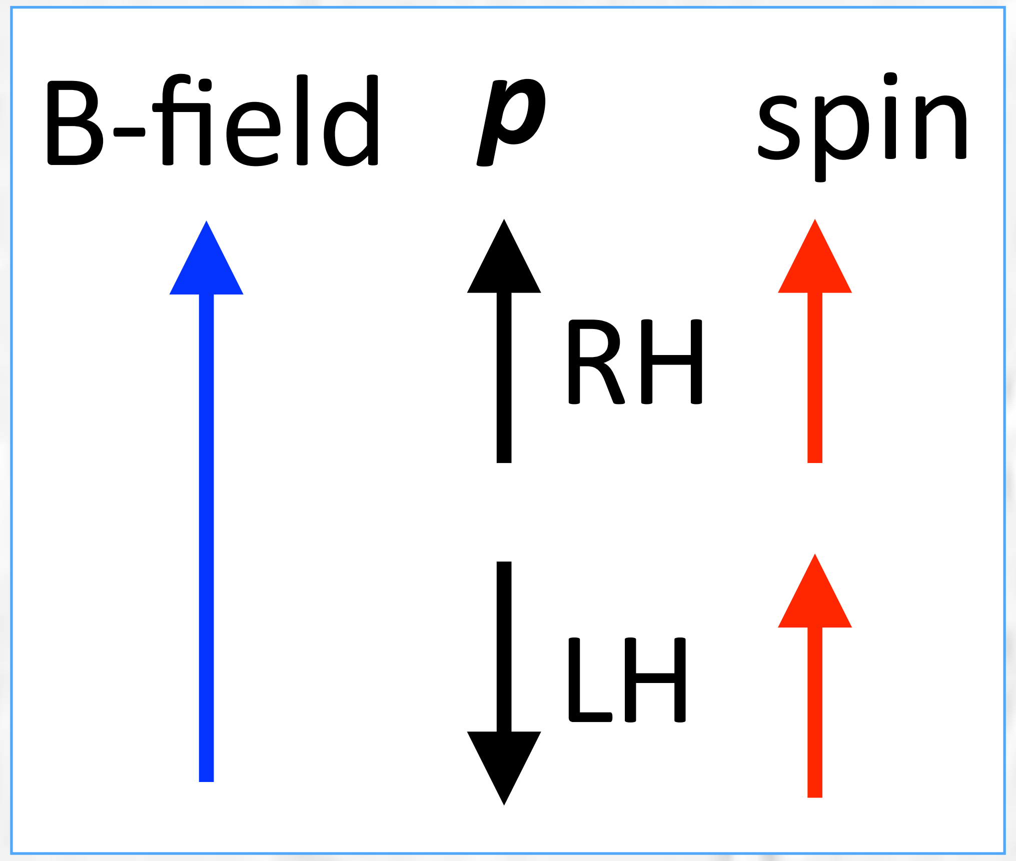
Ξ polarization might be slightly larger than that of Λ

Ω polarization results slightly favor $\gamma_\Omega = +1$

T. Niida (STAR) talk at RHIC/AGS Users meeting, 2020

CSE and global polarization

Chiral Separation Effect (CSE) - separation of the axial charge along the magnetic field



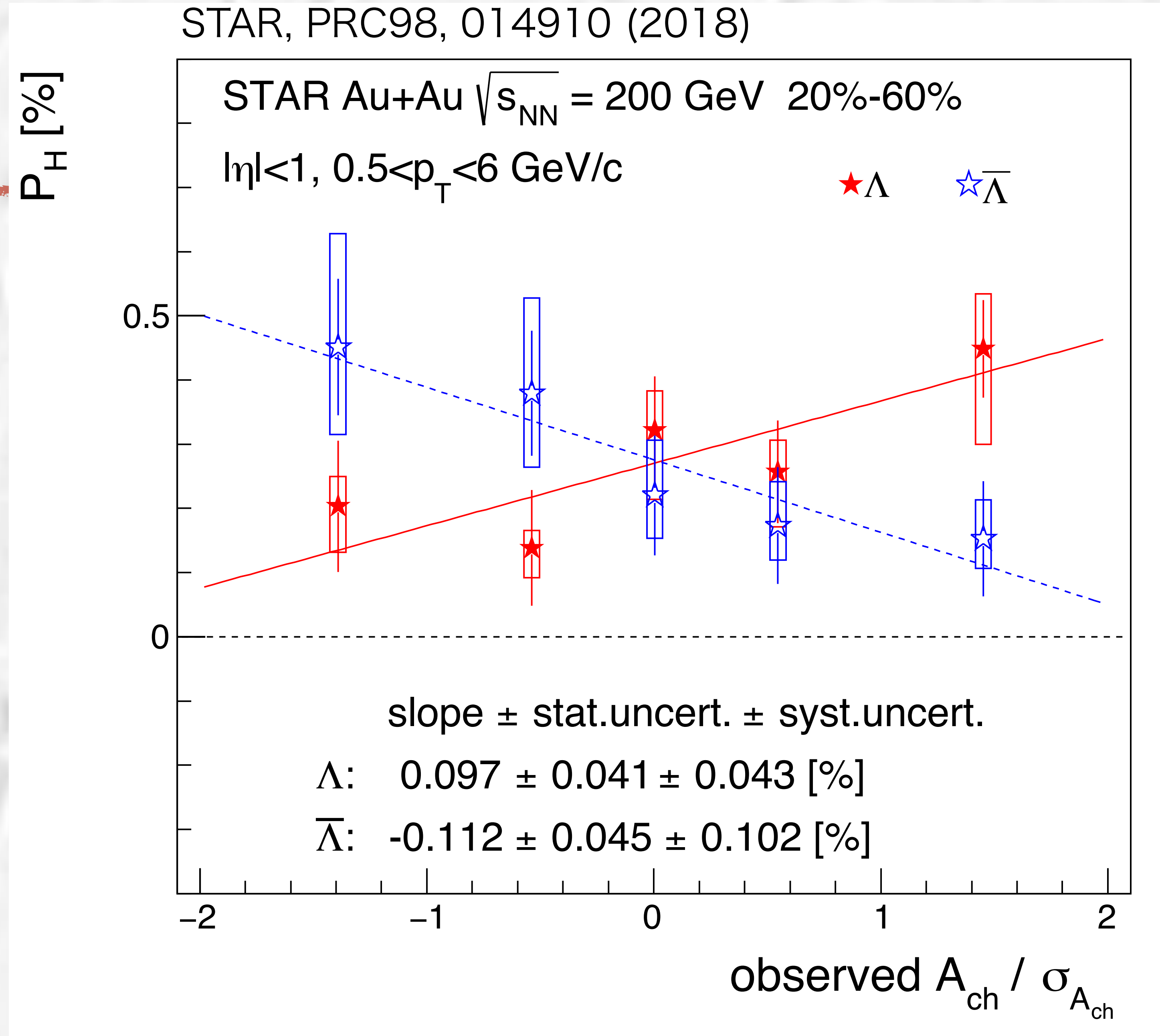
$$\mathbf{J}_5 = \frac{1}{2\pi^2}\mu(Qe)\mathbf{B}$$

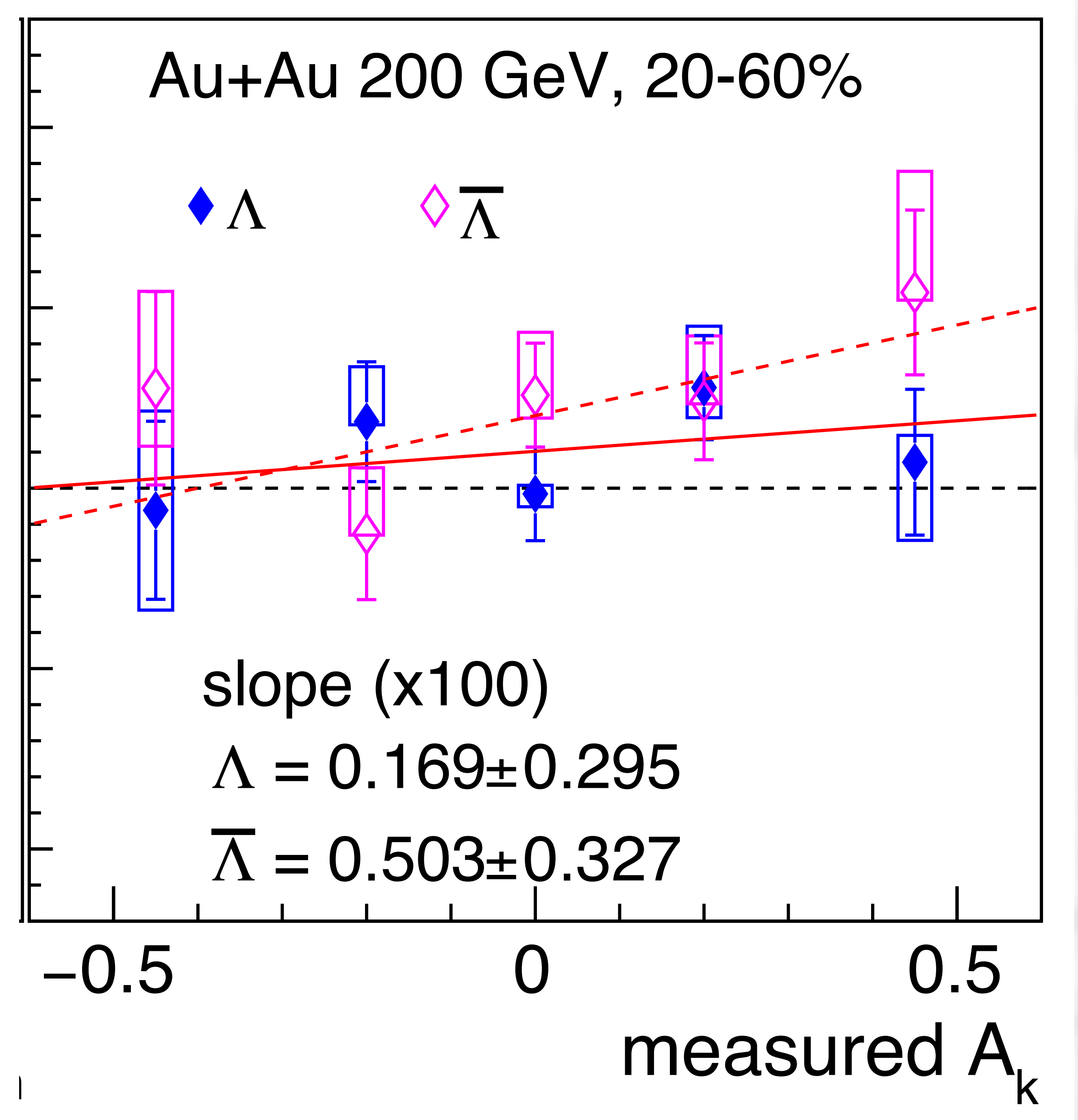
μ_V can be:
net baryon number,
electric charge,
net strangeness

$$\mu_v/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} \quad \text{or} \quad \mu_v/T \propto \frac{\langle N_{K^+} - N_{K^-} \rangle}{\langle N_{K^+} + N_{K^-} \rangle}$$

!!: 1/2 of the CMW phenomenon

Difficulties: vs charge - Λ is neutral (but Ξ is not!)
vs net kaons - low sensitivity to μ_V





T. Niida, QCD Chirality Workshop 2017

- A_{ch} dependence observed
  - Slopes of Λ and anti-Λ seem to be opposite (~2σ level)
- Possible contribution from axial charge or
- Quark vector chemical potential may explain the data

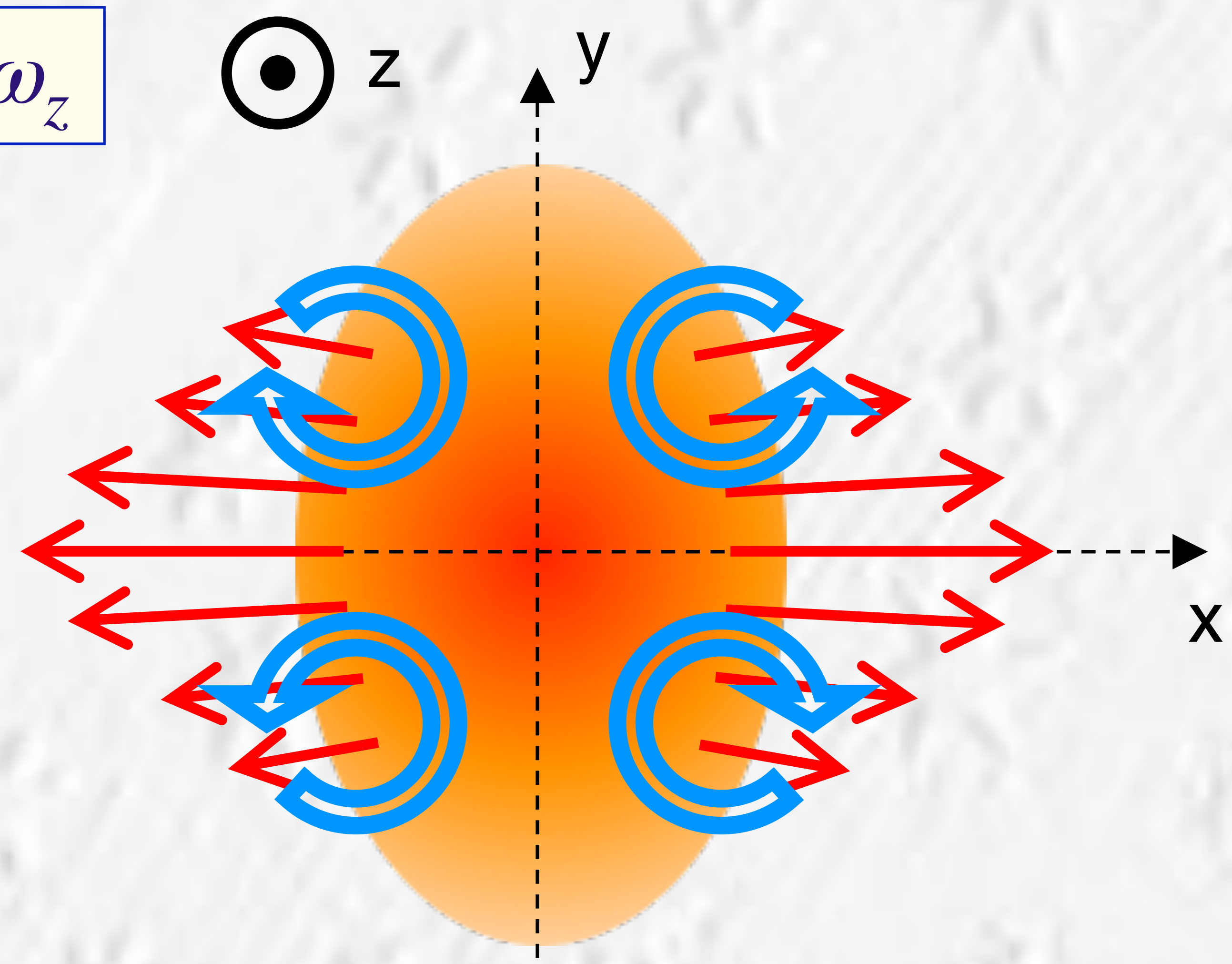
Sun and Ko, INT20-1-c

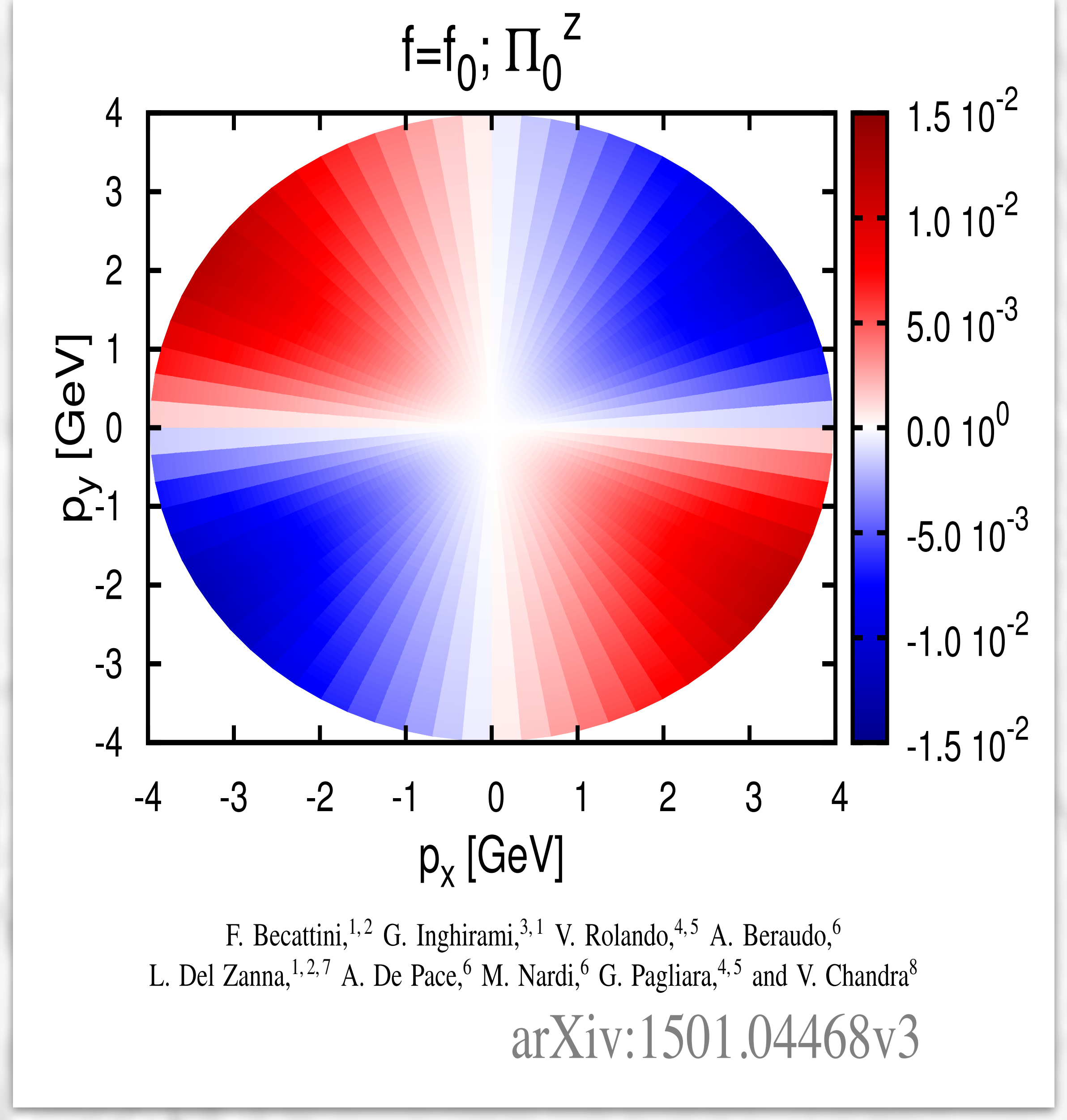
zPolarization

SQM2017

S. A. Voloshin, “Vorticity and particle polarization in heavy ion collisions (experimental perspective)”, arXiv:1710.08934 [nucl-ex]. [EPJ Web Conf.17,10700(2018)].

Anisotropic flow $\Rightarrow \omega_z$

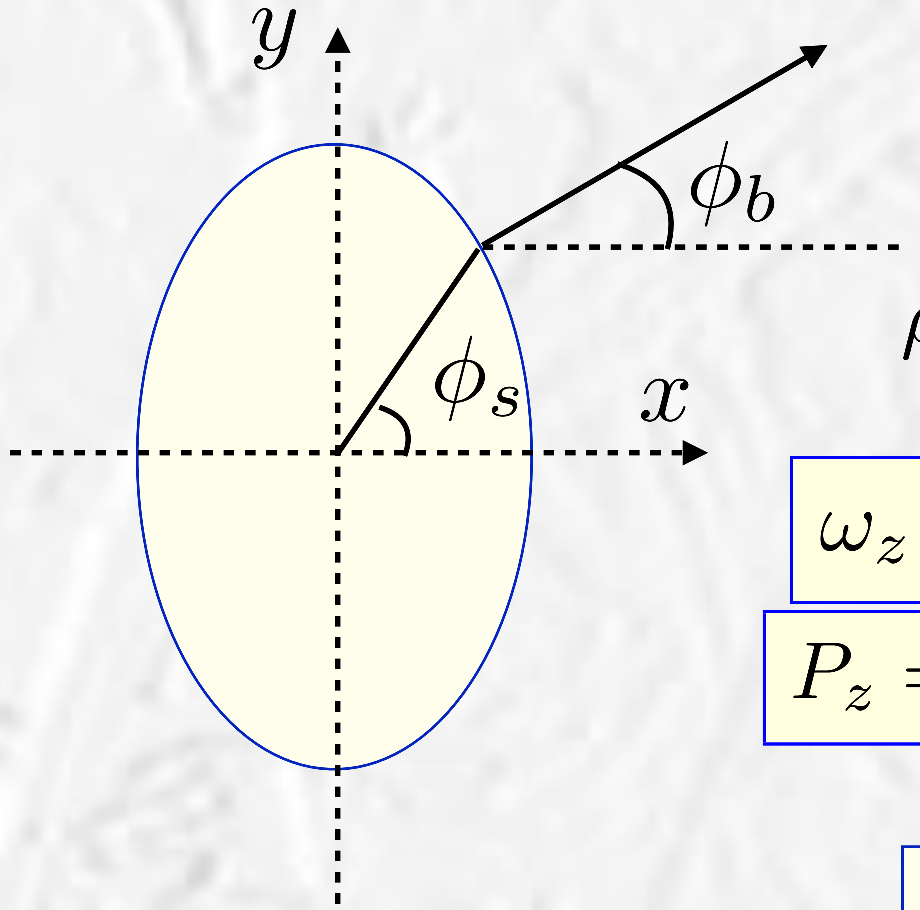




Plot not included in the paper

F. Becattini and I. Karpenko, “Collective Longitudinal Polarization in Relativistic Heavy-Ion Collisions at Very High Energy”, *Phys. Rev. Lett.* **120** no. 1, (2018) 012302, arXiv:1707.07984

Blast Wave:



$$r_{max} = R(1 - a\cos(2\phi_s))$$

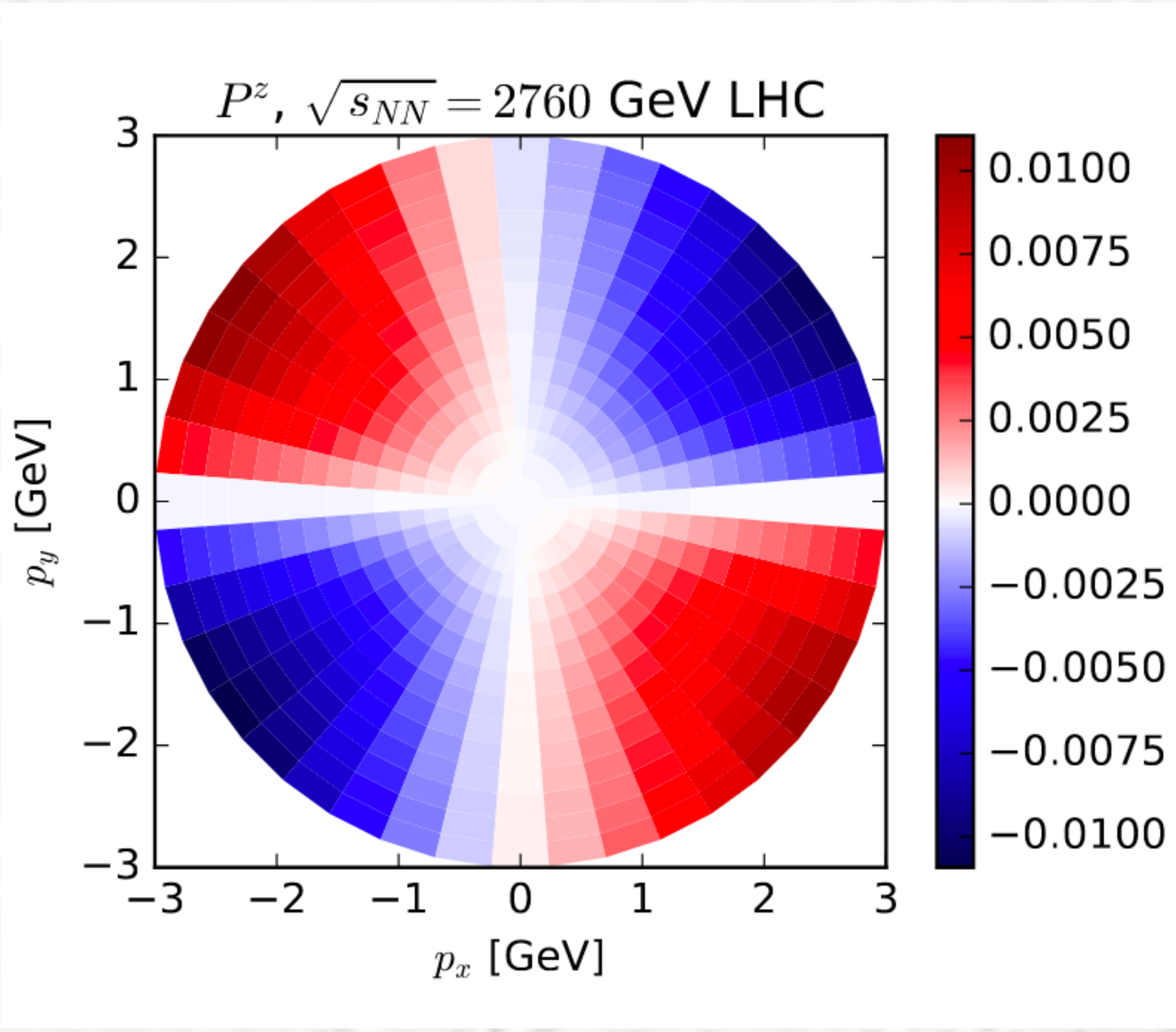
$$\rho \approx \rho_{t,max}[r/r_{max}(\phi_s)][1 + b\cos(2\phi_s]$$

$$\omega_z \approx (\rho_{t,max}/R)\sin(n\phi_s)[b_n - a_n]$$

$$P_z = \omega_z/(2T) \approx 0.1\sin(n\phi_s)[b_n - a_n]$$

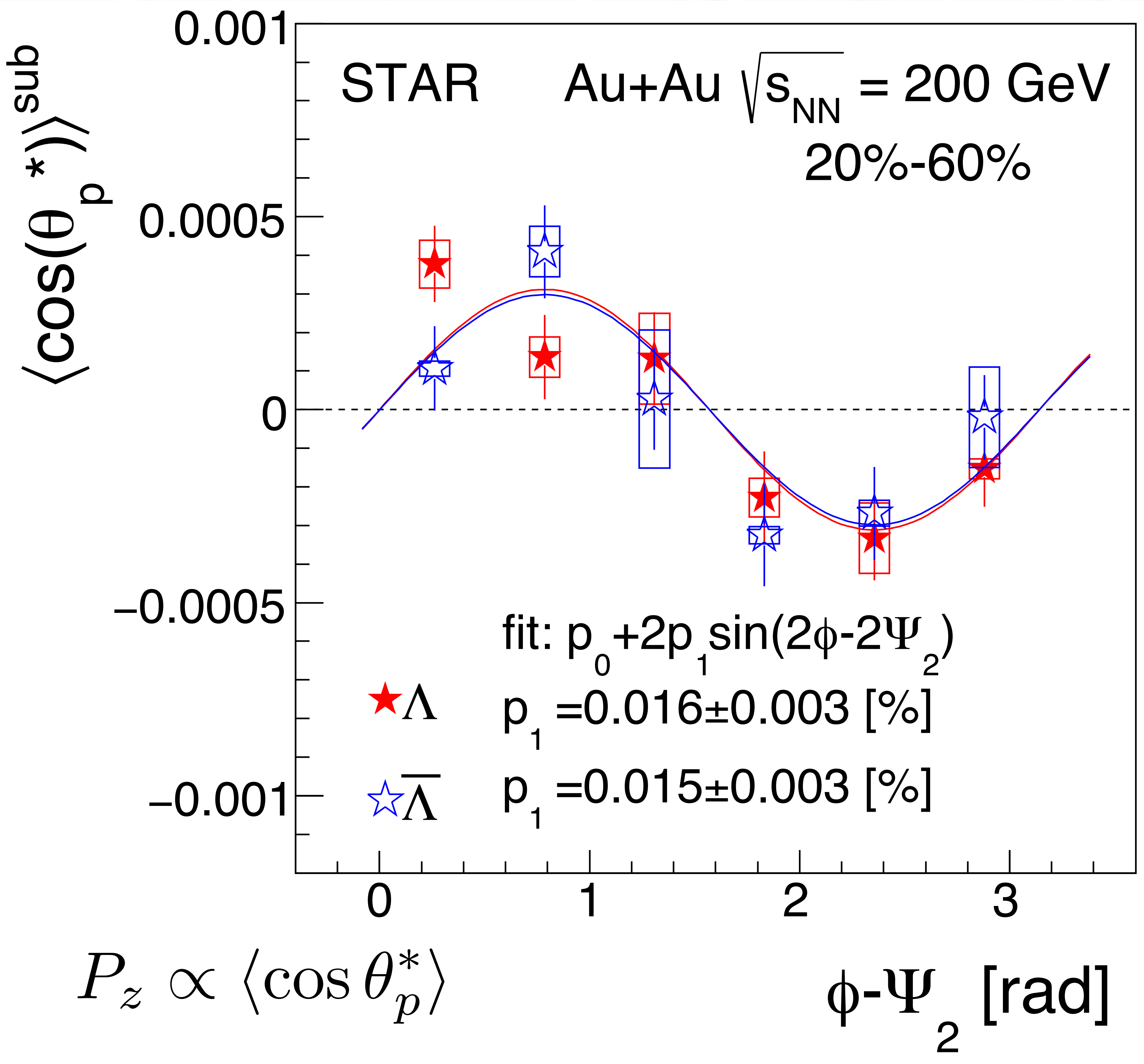
R≈10 fm, T≈100 MeV

$a_n,\ b_n$ of the order of a few percent



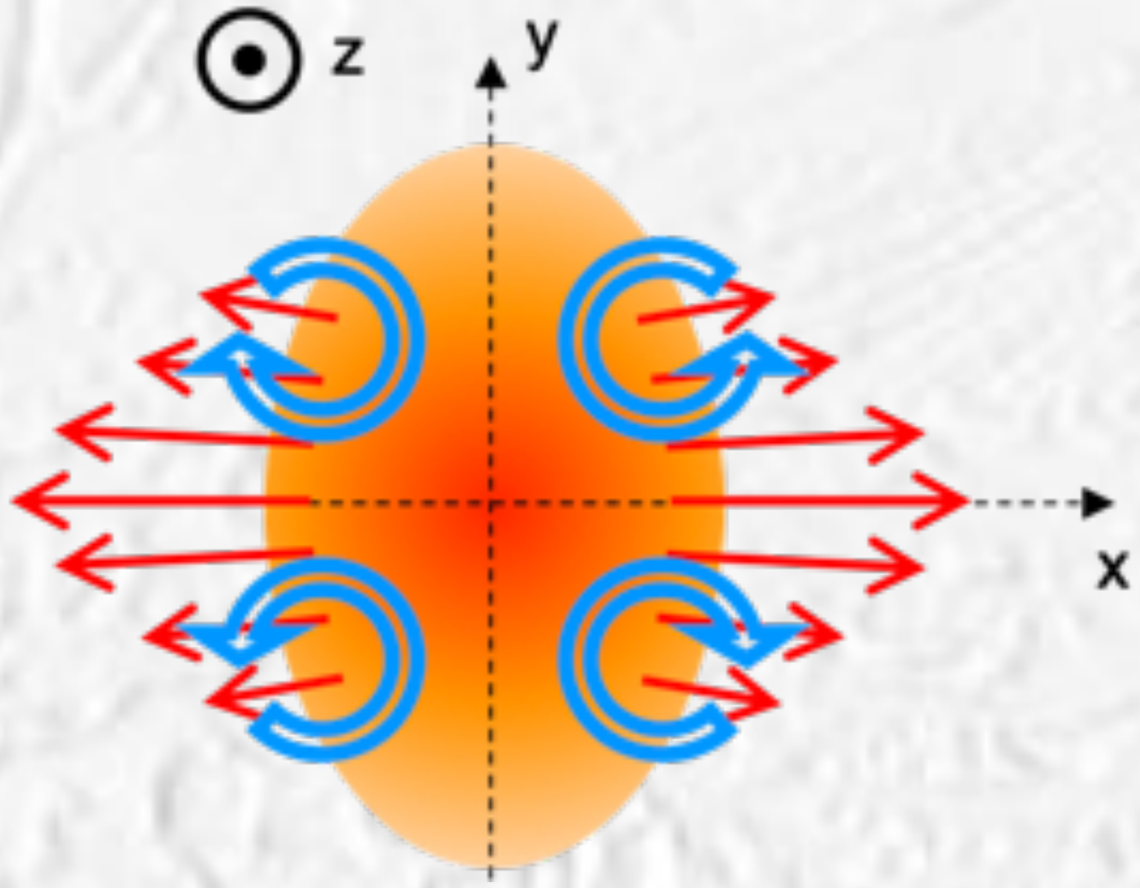
zPolarization

STAR, PRL123.13201 (2019)



Most models can not describe the sign/absolute value of P_z, but describe reasonably well the global polarization

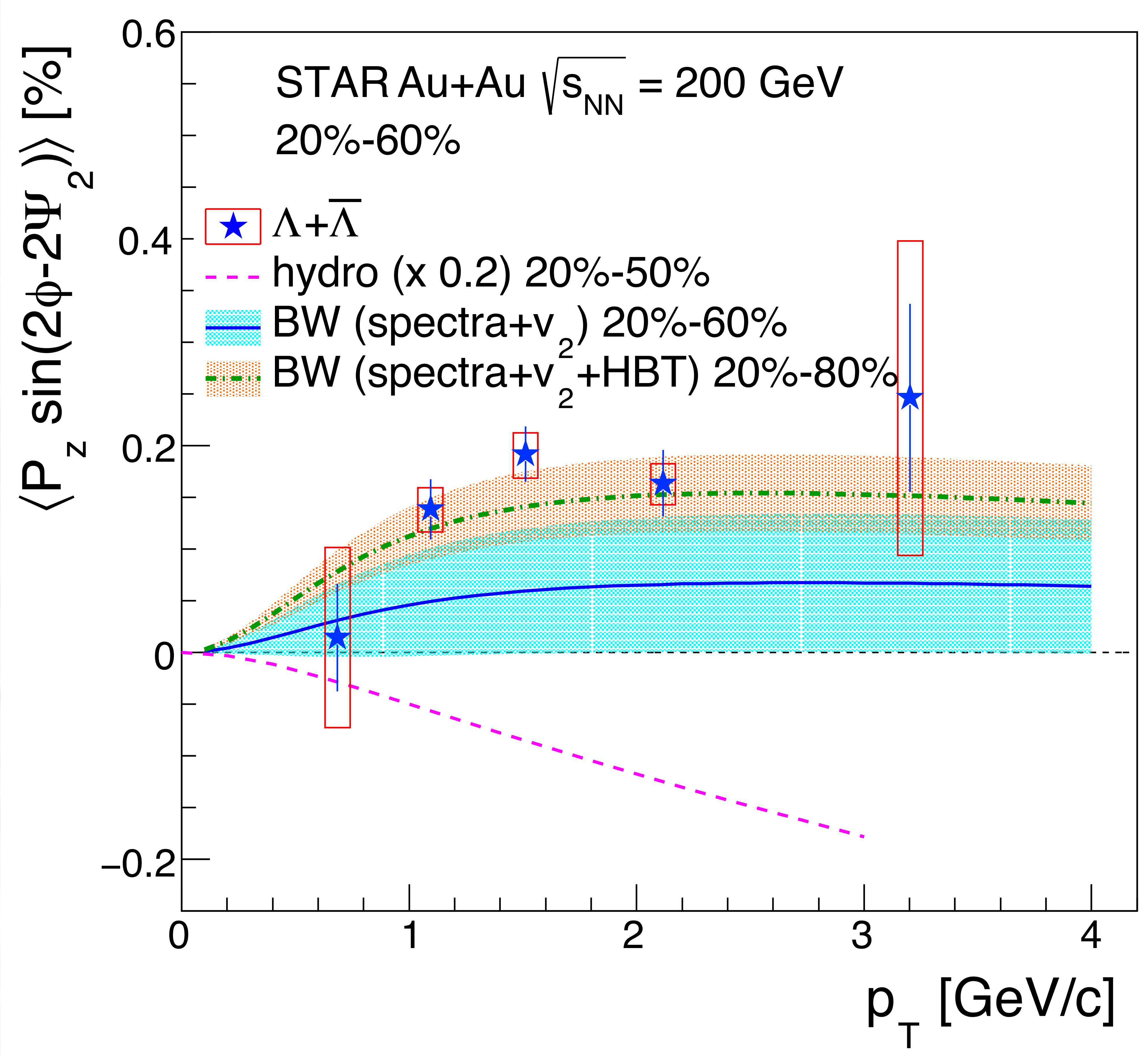
- F. Becattini and I. Karpenko, PRL.120.012302 (2018)
- X. Xia et al., PRC98.024905 (2018)
- Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- Y. Xie, D. Wang, and L. P. Csernai, Eur. Phys. J. C (2020) 80:39
- W. Florkowski et al., Phys. Rev. C 100, 054907 (2019)
- H.-Z. Wu et al., Phys. Rev. Research 1, 033058 (2019)

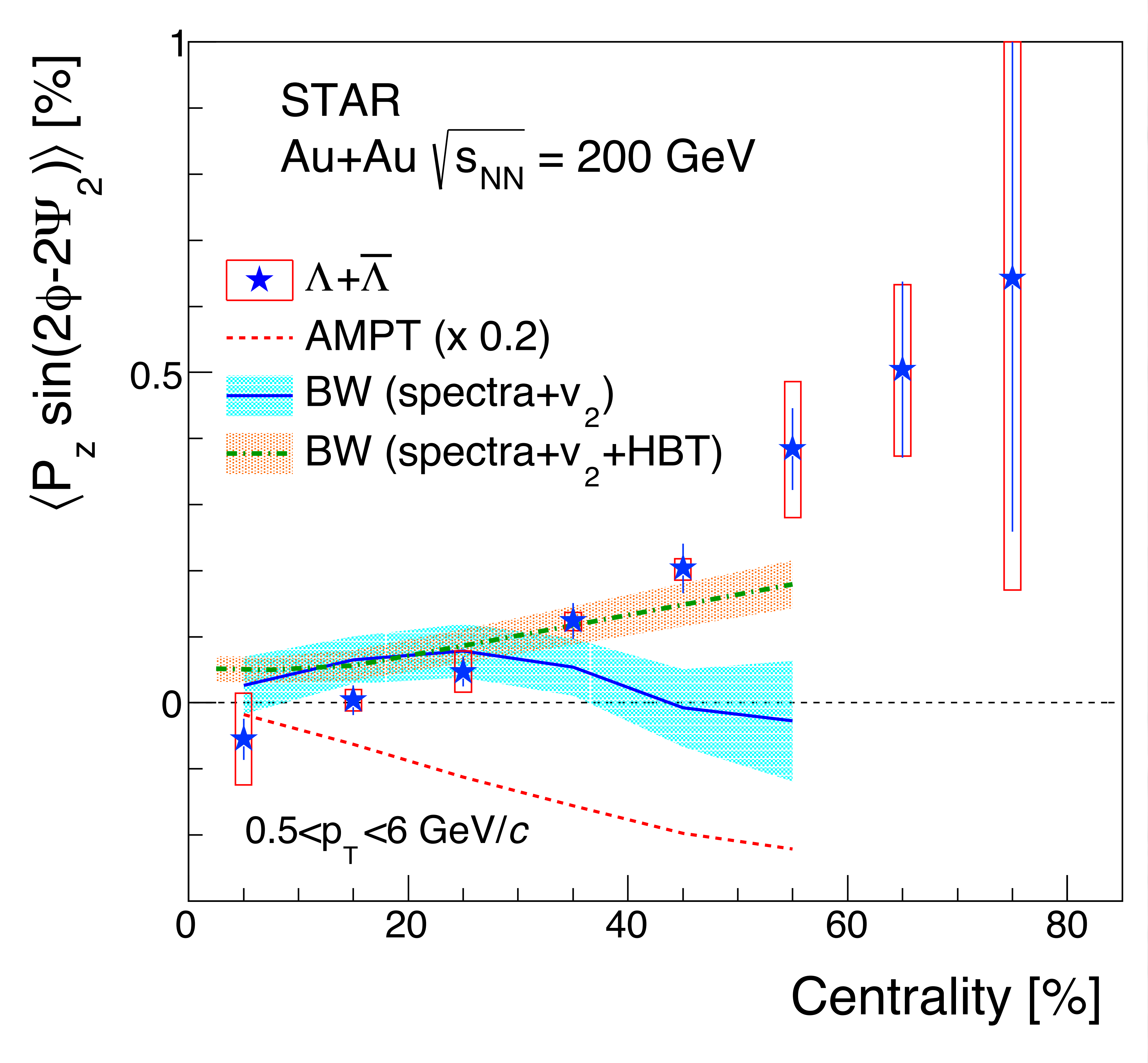


HYDRO, AMPT: It was noticed that the “kinematic non-relativistic vorticity” fits data well, but is (much) smaller than that including contributions from acceleration and temperature gradients

Centrality and p_T dependence

STAR, PRL123.13201 (2019)





$$\langle \omega_z \sin(2\phi)\rangle = \frac{\int d\phi_s \int rdr\, I_2(\alpha_t)K_1(\beta_t)\omega_z \sin(2\phi_b)}{\int d\phi_s \int rdr\, I_0(\alpha_t)K_1(\beta_t)}$$

$$\omega_z = \frac{1}{2}\left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right),$$

BW parameters obtained with HBT: STAR, PRC71.044906 (2005)

zPolarization, ALICE

Plans to release preliminary:
D. Sarkar (ALICE), IS2021

Make predictions!

Spin alignment in vector meson decays

Strong decays of vector mesons in to two (pseudo)scalar particles

$K^{*0} \to \pi + K$

$\phi \to K^- + K^+$

$$\frac{dN}{d\cos\theta^*} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

$\rho_{00} = w_0$ - probability for $s_z = 0$

$$\rho_{00} = \frac{1}{3} - \frac{4}{3}\langle\cos[2(\phi_p^* - \Psi_{\rm RP})]\rangle$$

$$\frac{dN}{d\cos\theta^*} \propto w_0|Y_{1,0}|^2 + w_{+1}|Y_{1,1}|^2 + w_{-1}|Y_{1,-1}|^2 \propto w_0\cos^2\theta^* + (w_{+1}+w_{-1})\sin^2\theta^*/2$$

$V \to l^+l^-$

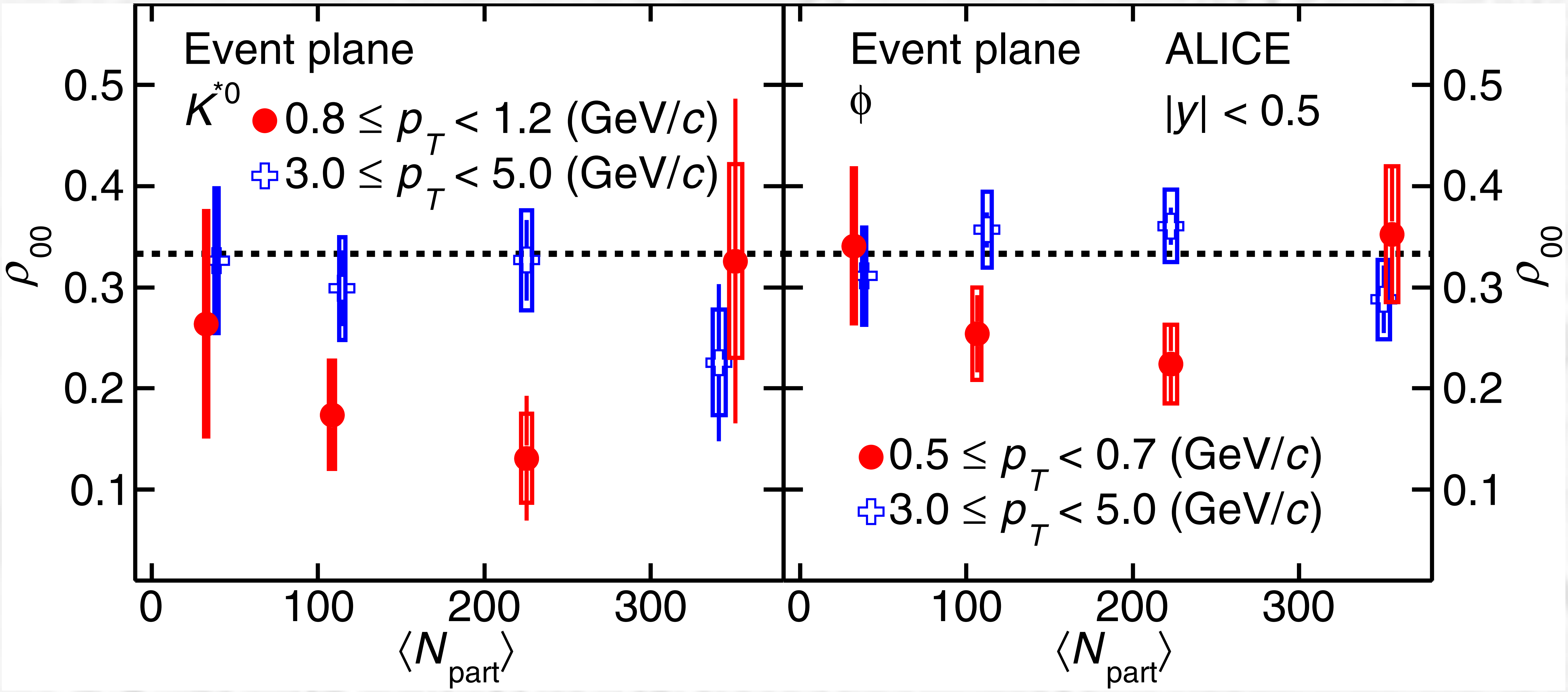
$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi\right)$$

Unlike $K^{0*} \to K\pi$ and $\phi \to K^+K^-$, the daughters in $J/\psi \to l^+l^-$ have spin 1/2

J/ψ, in progress

K^{*0} and ϕ spin alignment

ALICE, PRL125.012301 (2020)



Large deviation from 1/3, which cannot be explained in the vorticity picture: $\rho_{00} = \dfrac{1}{3 + (\omega/T)^2}$

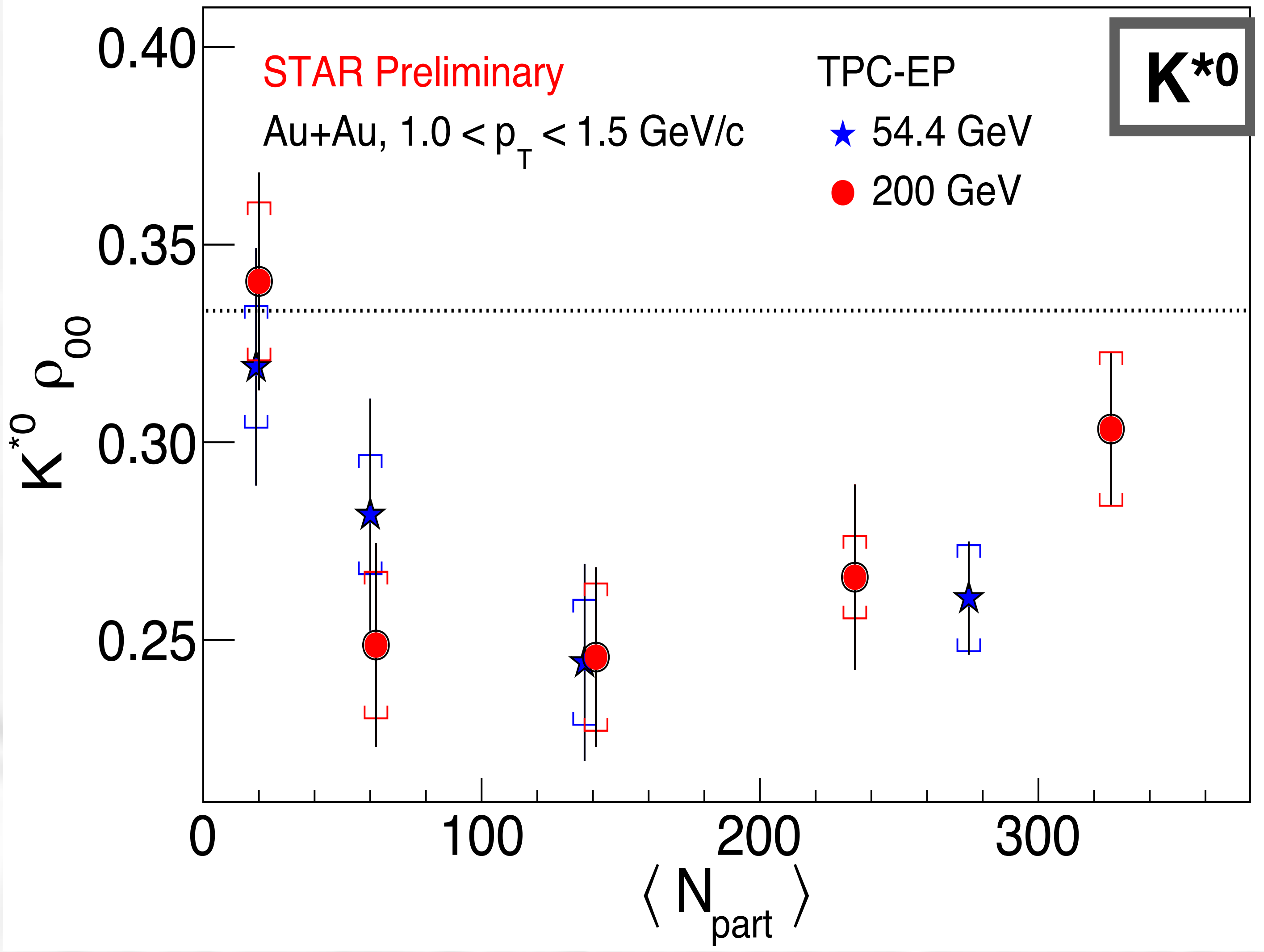
The deviations from 1/3 are different
- K* and φ at RHIC
- LHC and RHIC for φ

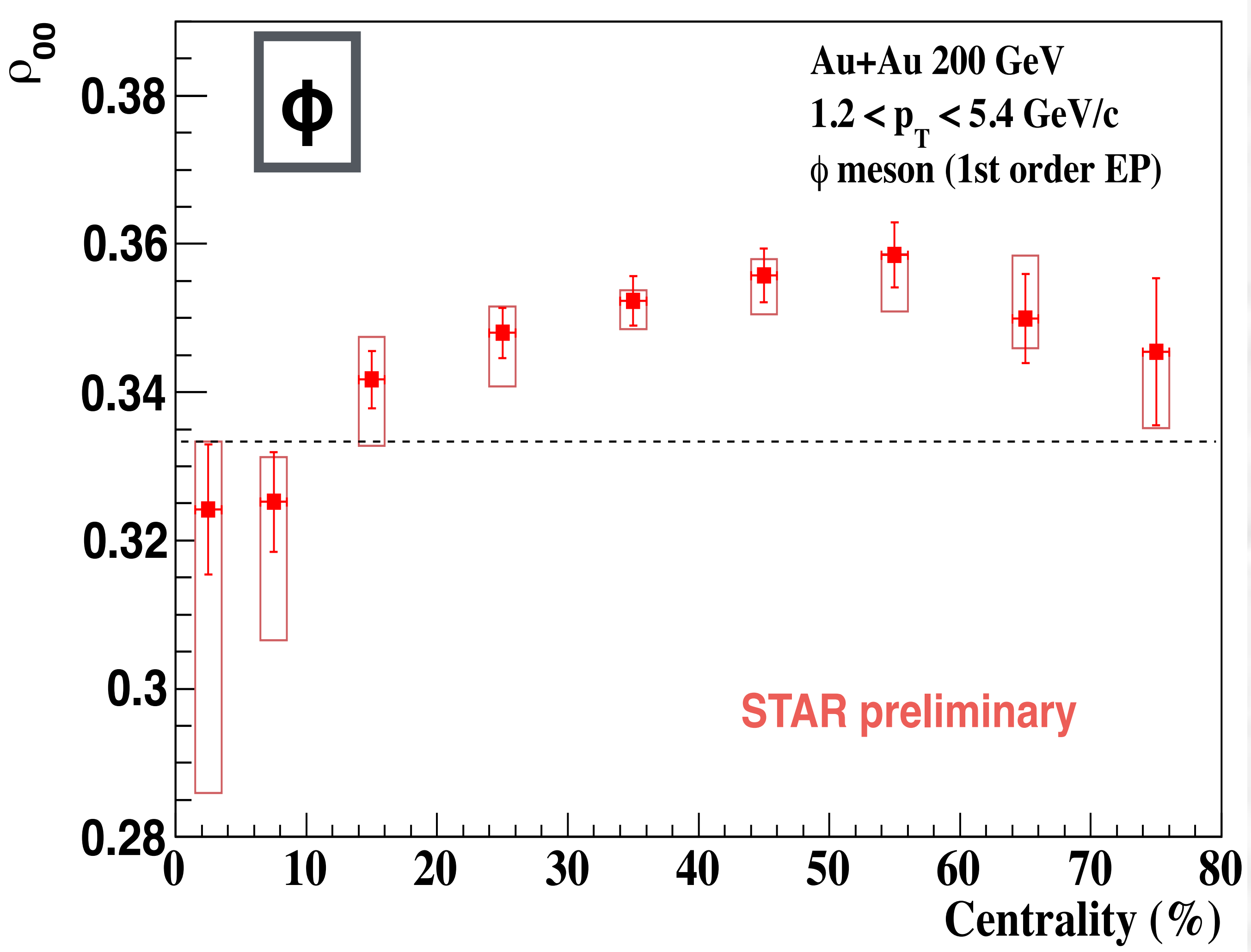
Thermal model:
$\rho_{00} = 0.15 \Rightarrow w(s_z = +1) = 0.82,$
$w(0) = 0.15, w(-1) = 0.03$

RHIC: Mean field of φ meson plays a role?
Does it change from RHIC to LHC?

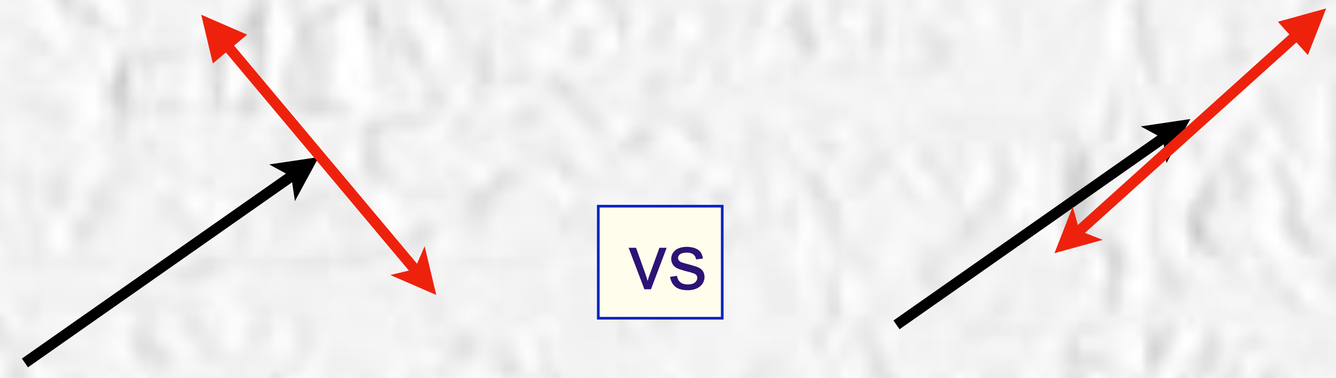
X. Sheng, L. Oliva, and Q. Wang, PRD101.096005(2020)
X. Sheng, Q.Wang, and X. Wang, PRD102.056013 (2020)

STAR, QM18, QM19





Reconstruction efficiency changes 100% with the emission angle relative to the reaction plane:



Summary

- Polarization measurements are very valuable for understanding of the QGP dynamics, hadronization, hadron spin structure

- RHIC: STAR 27 GeV Λ, $\bar{\Lambda}$
- BES II

LHC: High statistics Run3 data will bring many more possibilities

- Precision measurements of the global polarization
- more differential measurements of zPolarization
- measurements of other local polarization effects
- Measurement of Ξ and Ω polarization

Thank you for your attention!

EXTRA SLIDES, χ

Prehistory (1998 - …)

Preprehistory also exists..

$\mathcal{P}$-odd domains in heavy ion collisions

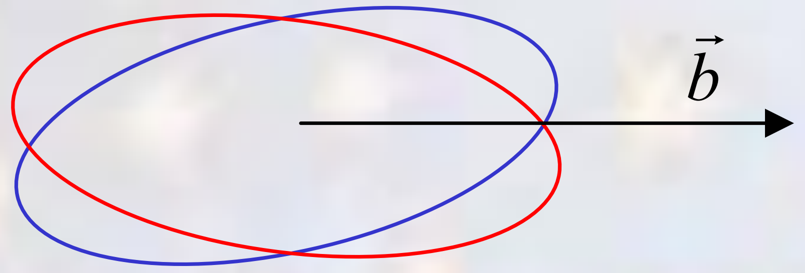
Efremov, Kharzeev, PLB366:311(1996) ← (DIS)
Kharzeev, Pisarsky, Tytgat, PRL81:512(1998)
Kharzeev, Pisarsky, PRD61:111901(2000)
Voloshin, PRC62:044901(2000)
Kharzeev, Krasnitz, Venugopalan, PLB545:298(2002)
Finch, Chikanian, Longacre, Sandweiss, Thomas, PRC65:014908(2002)

D. Kharzeev, R. D. Pisarski, and M. H. G. Tytgat, Phys. Rev. Lett. **81**, 512 (1998).

$$J=\sum_{\pi^+,\pi^-}\frac{(\vec{p}_{\pi^+}\times\vec{p}_{\pi^-})_z}{p_{\pi^+}p_{\pi^-}}.$$

Sergei A. Voloshin

PHYSICAL REVIEW C, VOLUME 62, 044901

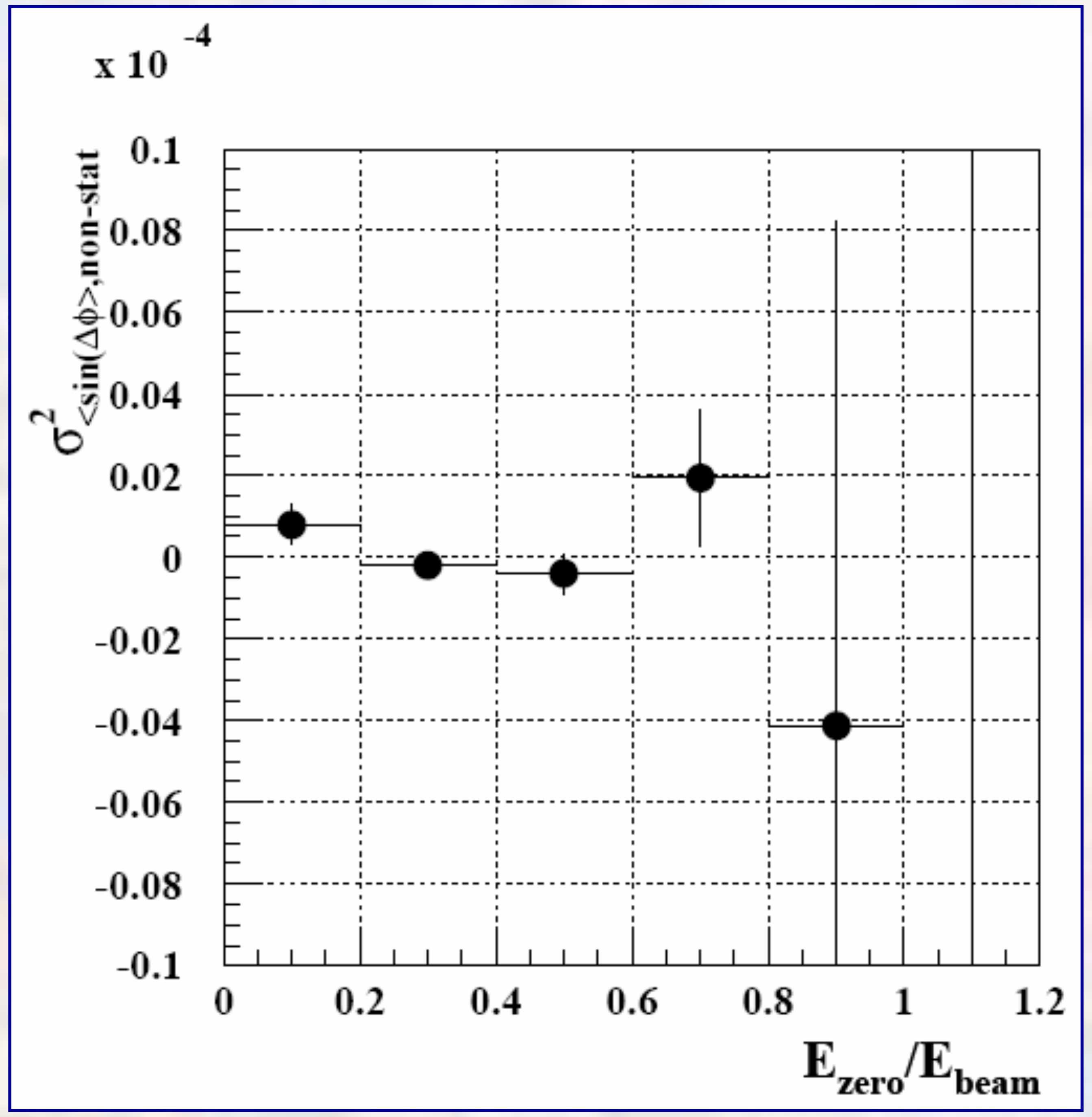
→ 

Difference in the orientation of the event plane determined with positive or negative particles!

$$\sigma_{\sin(\Delta\phi),nonstat}\approx\alpha(1-3)\times10^{-3}.$$

where α is the fraction of particles originating from the $\mathcal{P}$-odd domain

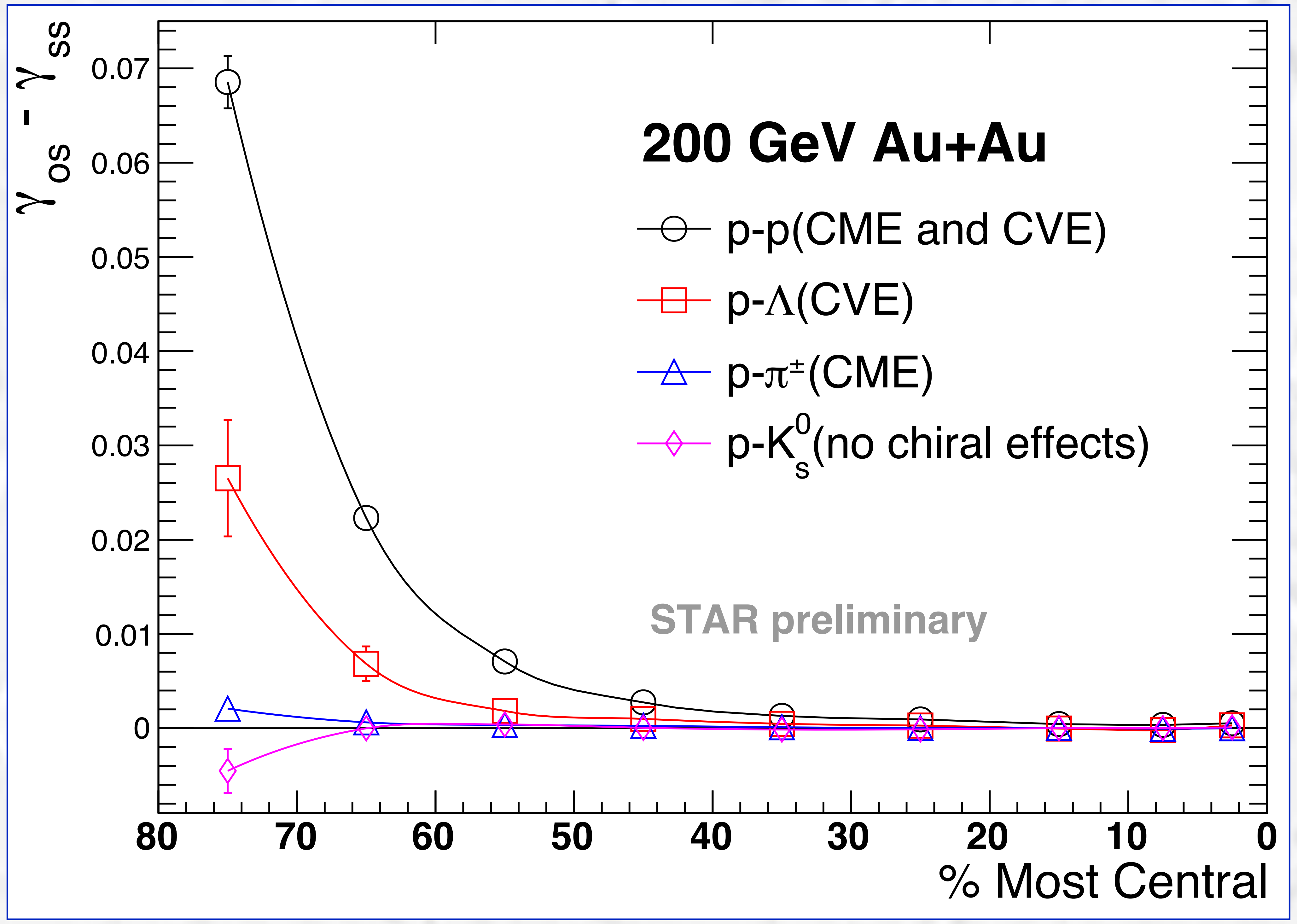
S. Voloshin and the NA49 Collaboration, "Search for parity violation in minimum bias Pb-Pb collisions at SPS," LBNL 1998 annual report, http://ie.lbl.gov/nsd1999/rnc/RNC.htm, report R10.

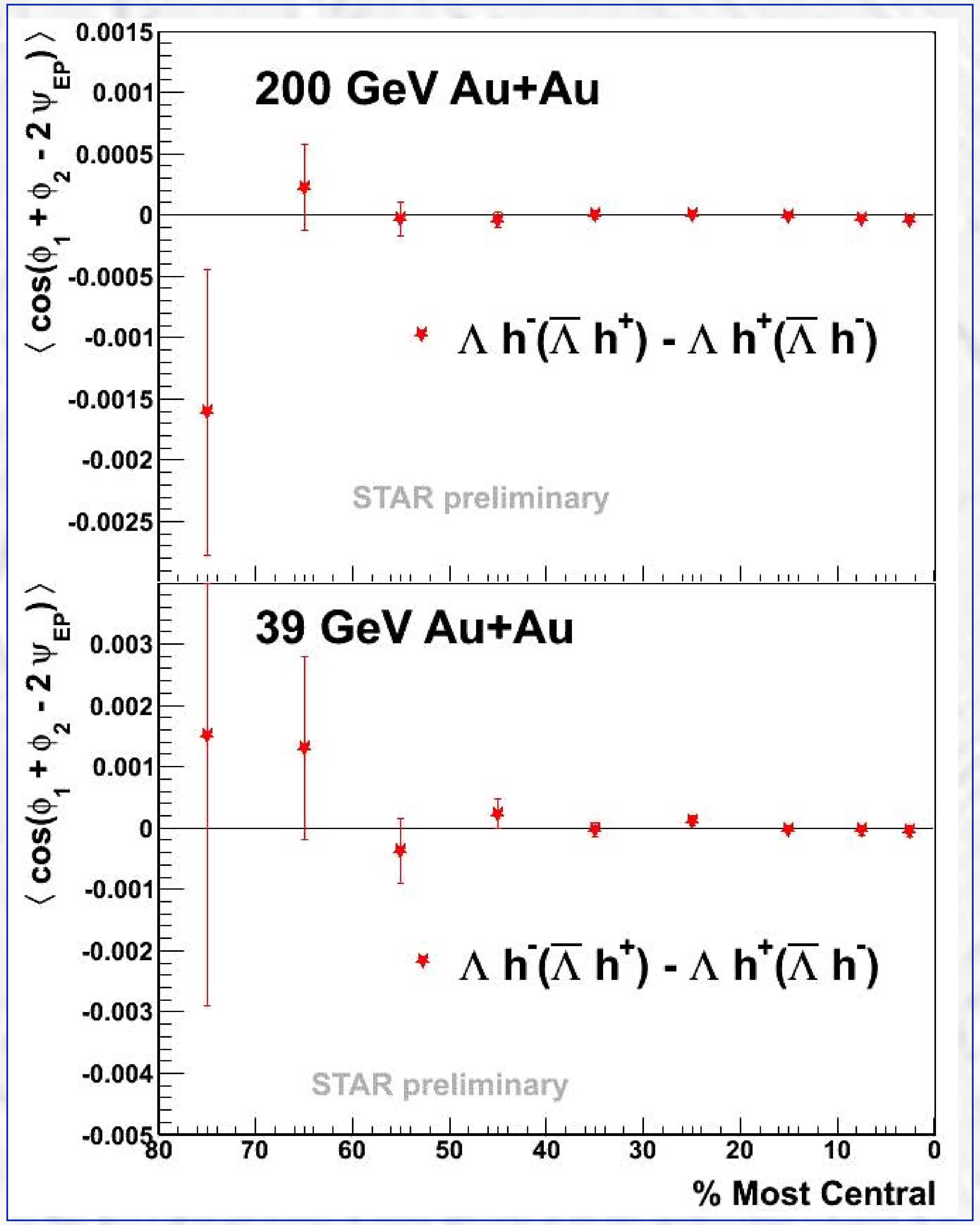


NA49 – QM'99

Cross correlations: CVE x CME comparison

(identified particle correlations)

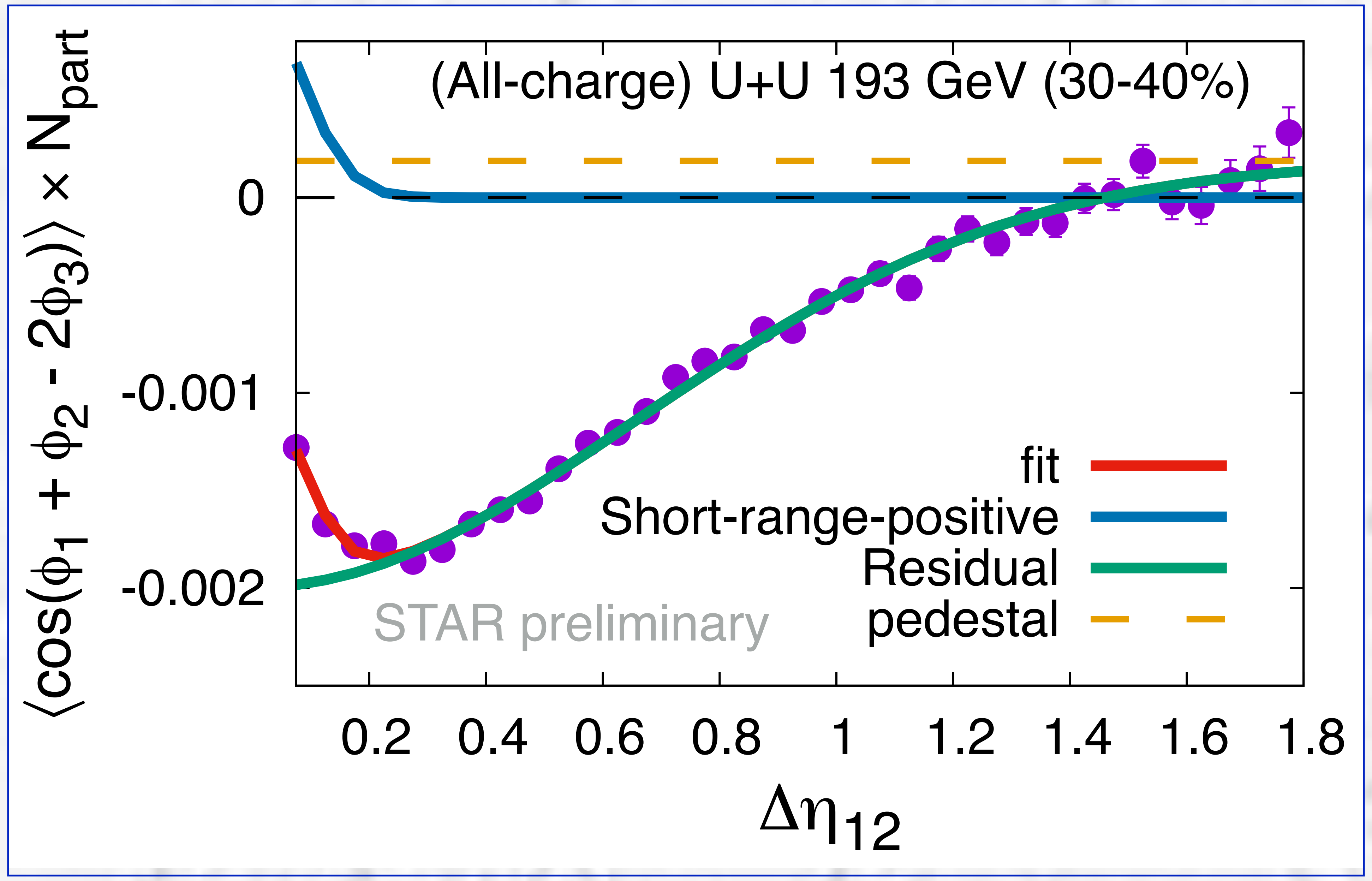


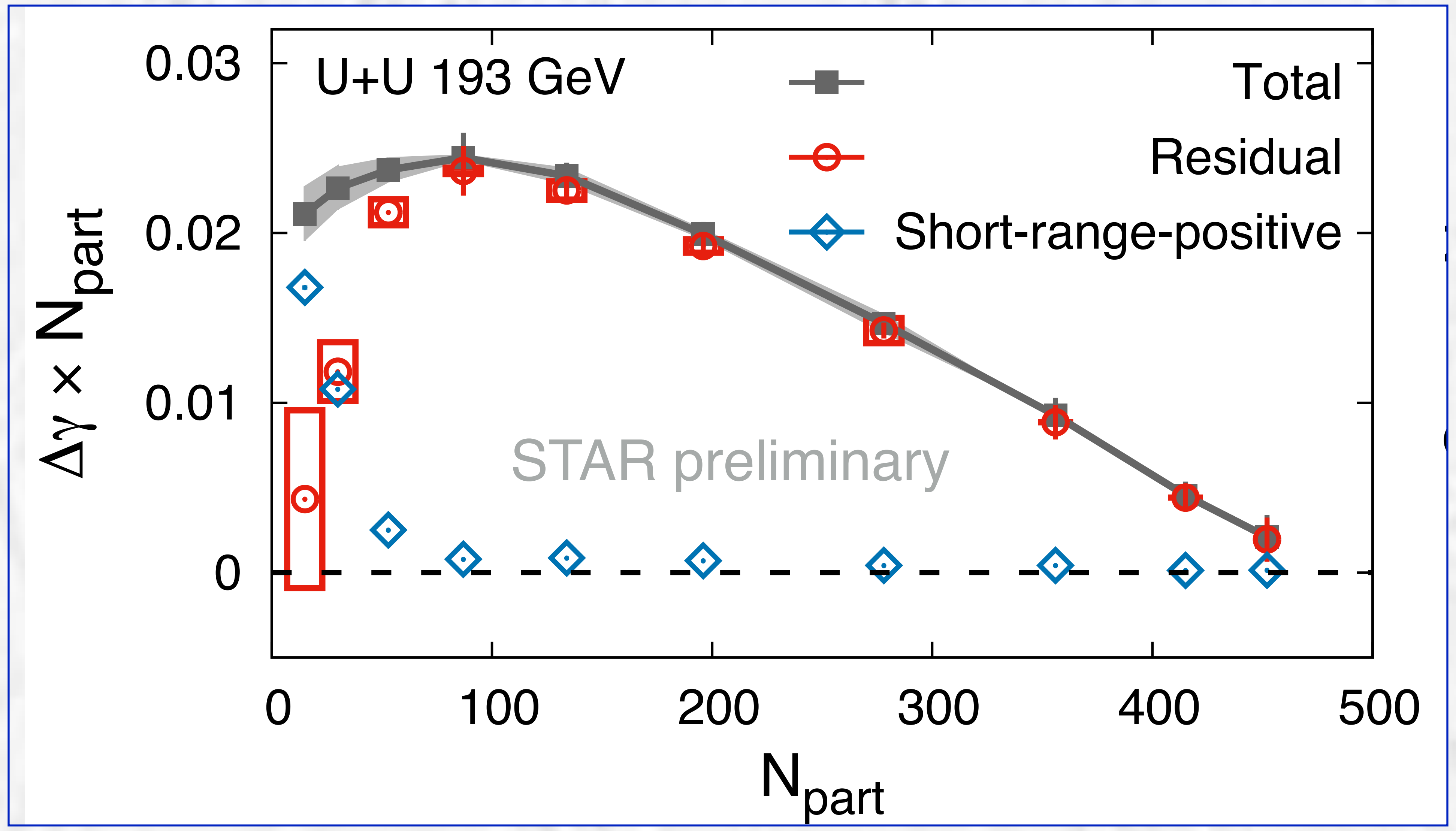


Lambda - CVE
proton - CVE+CME
pion - CME
K^0 - nothing?

Zero Lambda-pion correlations might be in contradiction to "CVE" and "CME" effect explanation

RP independent background II





XXVIth International Conference on Ultrelativistic Nucleus-Nucleus Collisions (Quark Matter 2017)

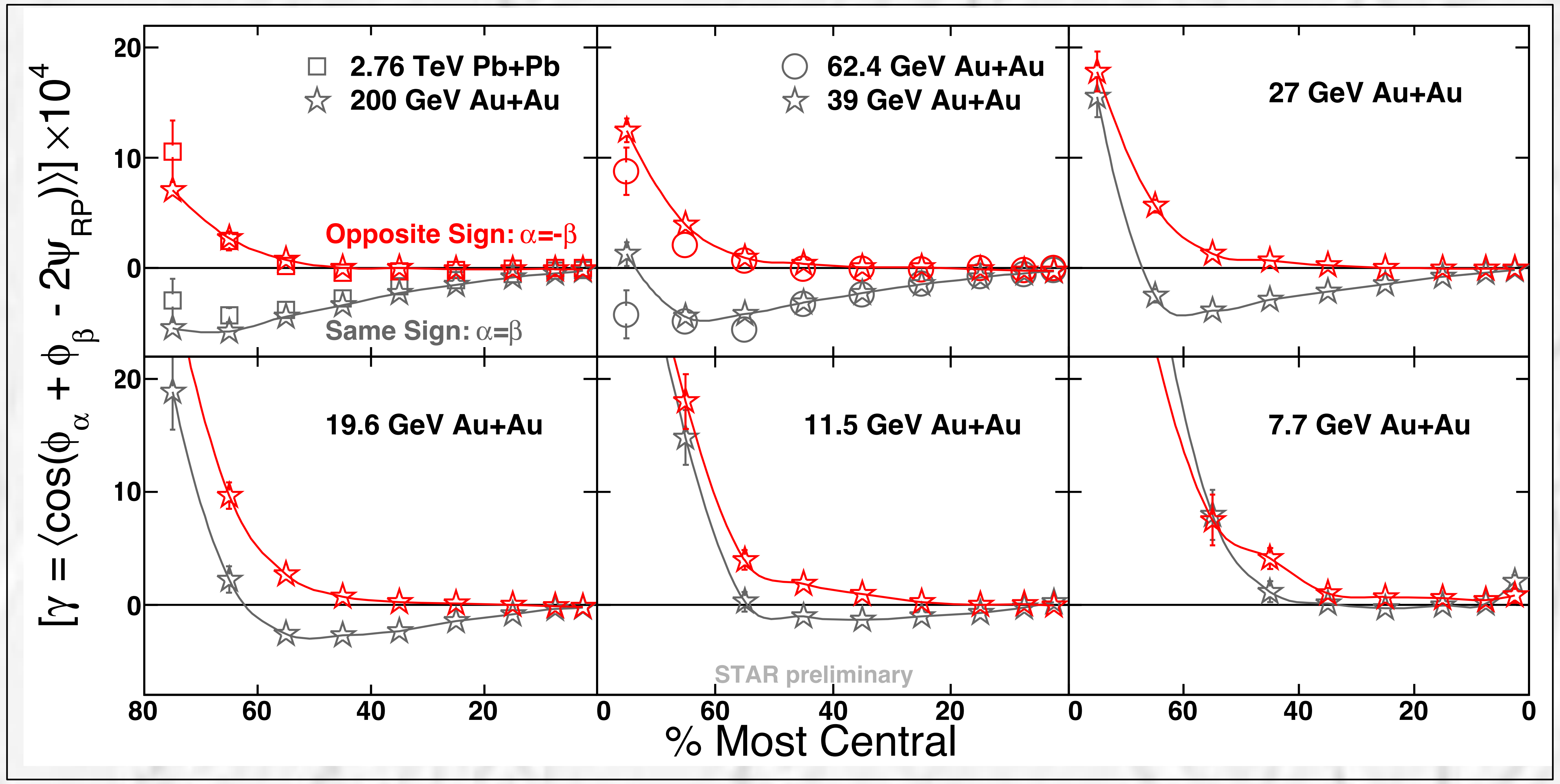
Disentangling flow and signals of Chiral Magnetic Effect in U+U, Au+Au and p+Au collisions

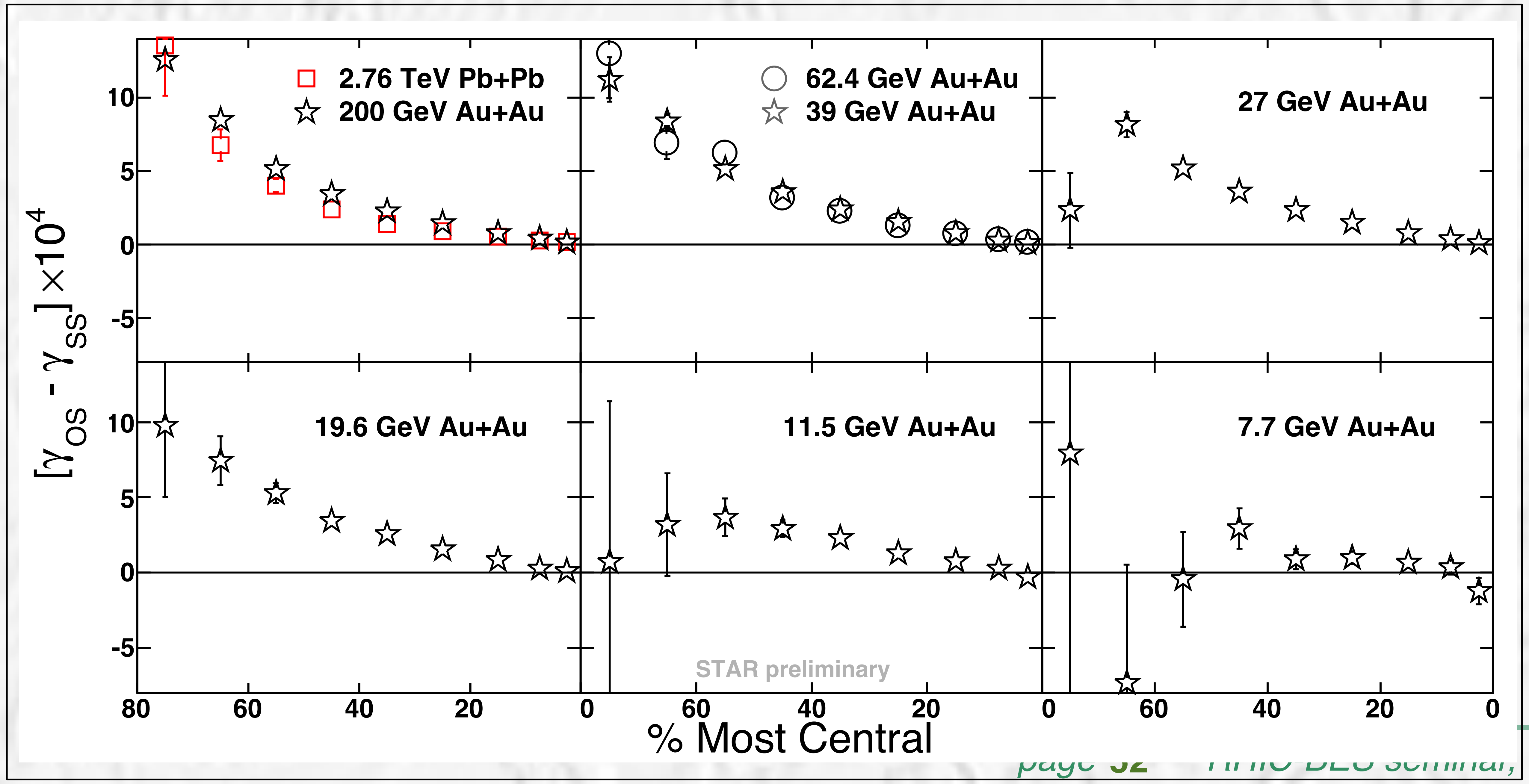
Prithwish Tribedy (for the STAR Collaboration)

"short range background"
=
RP independent ?

Can be checked,
Might be important for interpretation

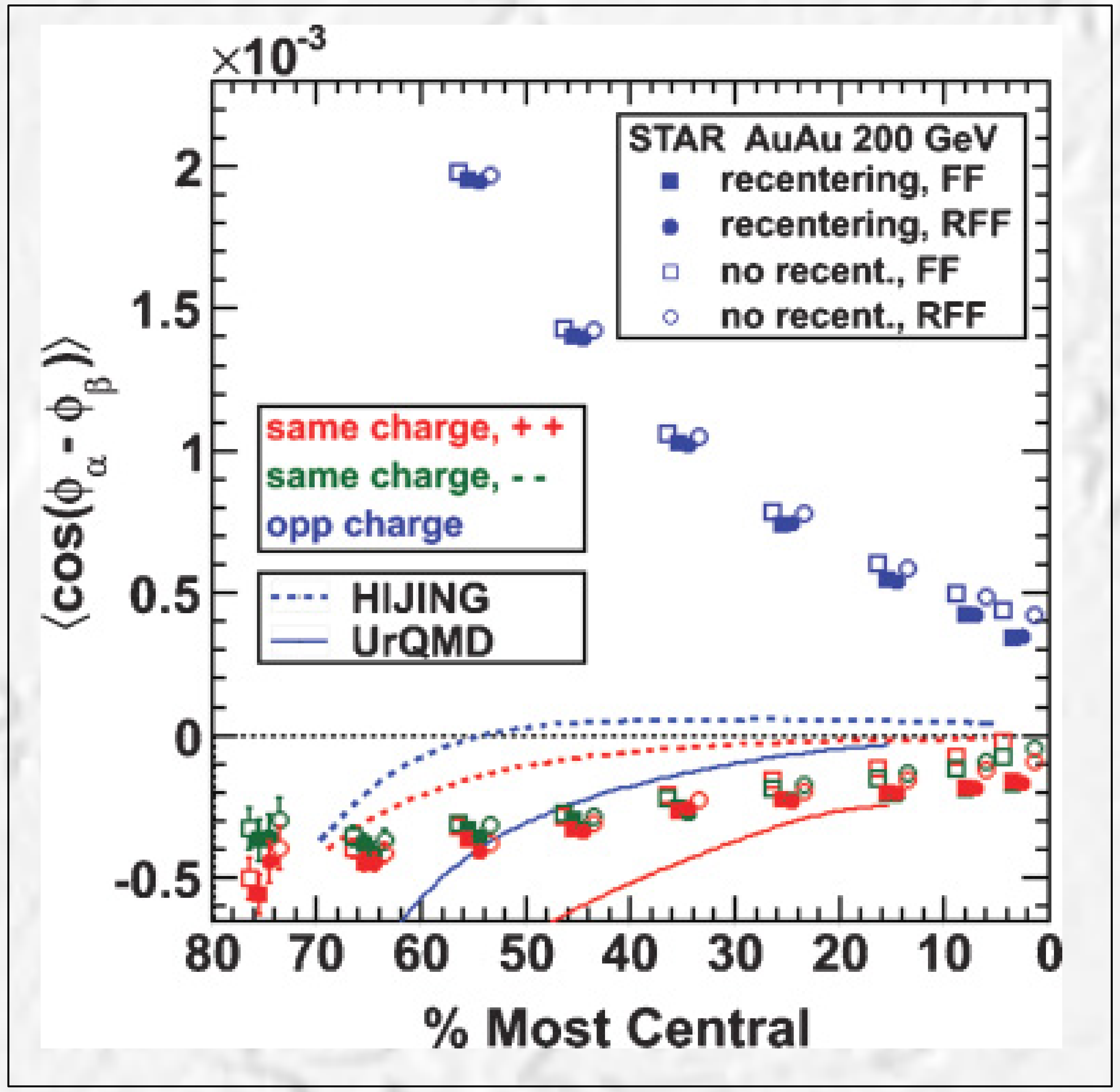
RHIC BES results

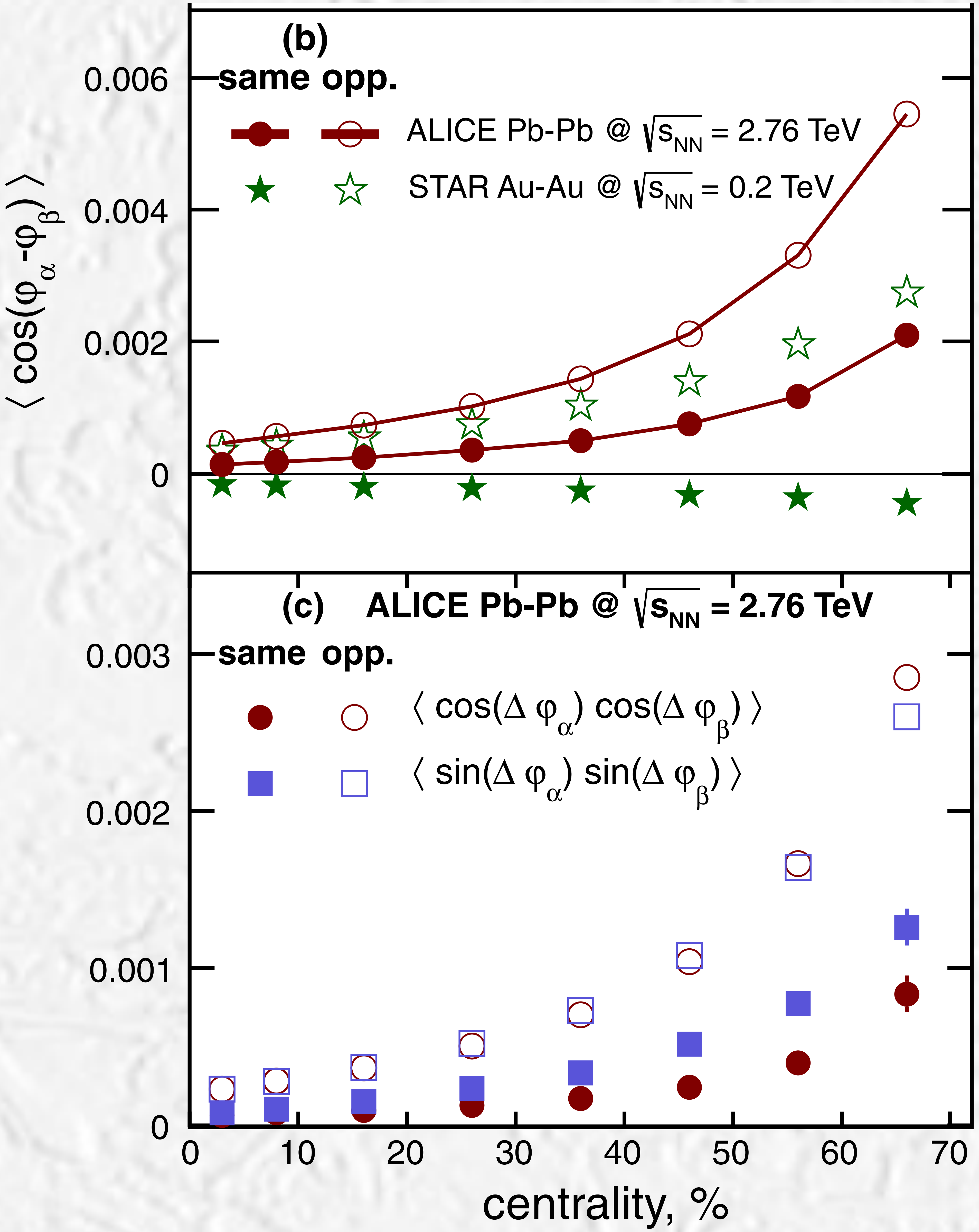




- Again, the signal is surprisingly “stable” over the wide range of energies
- Disappears at 7 GeV?

LHC vs RHIC, II





- HIJING and RQMD are way different from data
- 2-particle correlations are quite different at RHIC and LHC

Signed BF

XXVIIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2019)

Measurement of the charge separation along the magnetic field with Signed Balance Function in 200 GeV Au + Au collisions at STAR

Yufu Lin for the STAR Collaboration [1]

based on:

Probe Chiral Magnetic Effect with Signed Balance Function

A. H. Tang

- *Chin.Phys.C* 44 (2020) 5, 054101

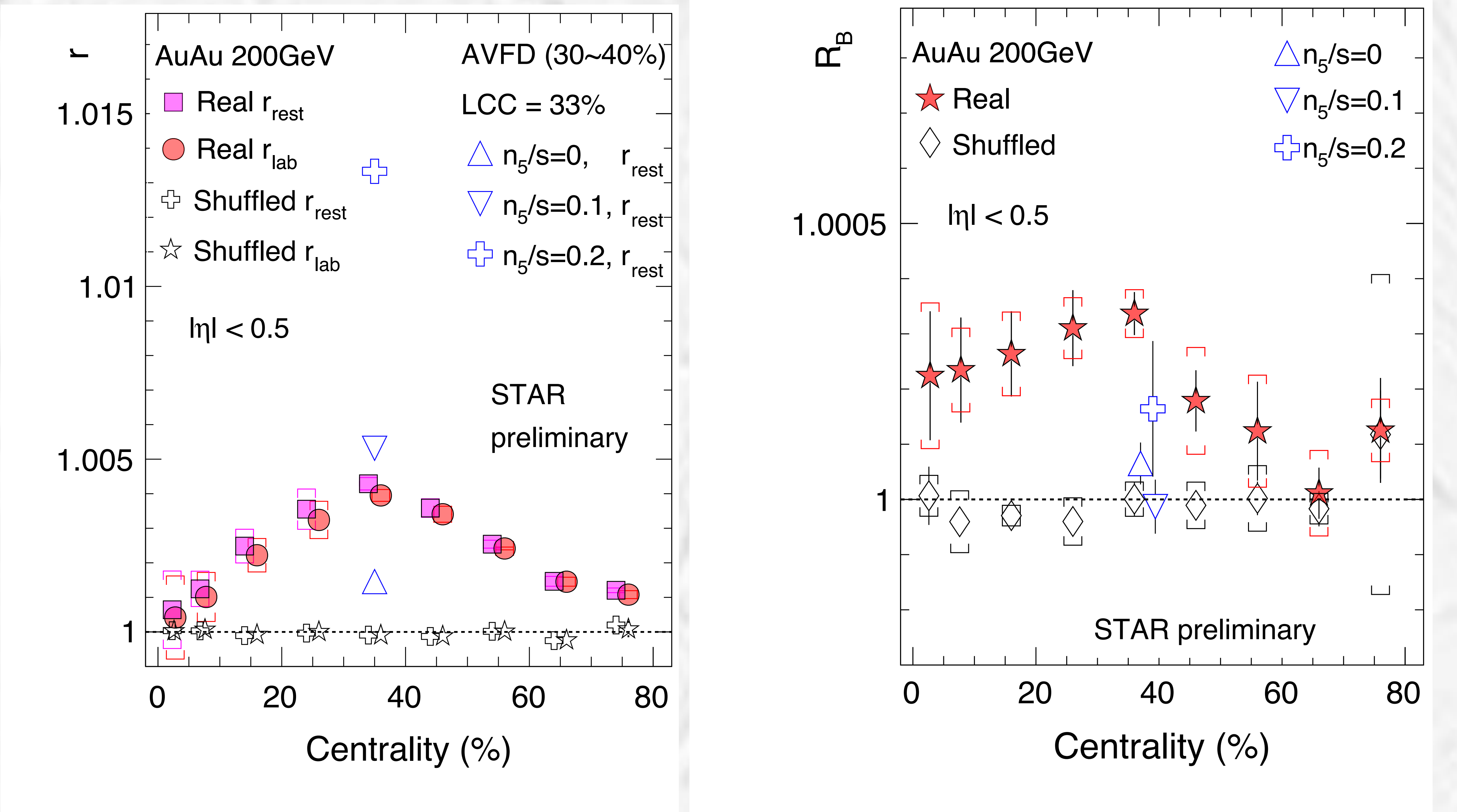


Fig. 5. (Color online) r_{rest}, r_{lab} and R_B as a function of centrality from Au + Au 200 GeV at STAR.

If both r_{rest} and R_B are larger than unity, then it can be regarded as a case in favor of the existence of CME. In Au+Au collisions at 200 GeV, r_{rest} , r_{lab} and R_B are found to be larger than unity, and larger than AVFD model calculation with no CME implemented. Our results are difficult to be explained by a background-only scenario.

Idea:

Particles get small impulses due to CME. Let us analyze the change in momentum, instead of azimuth. Count the signs of the relative momentum (y component) for each pair, in the lab frame and in the pair rest frame.

Might be slightly more “sensitive” that gamma, but effect is likely small. Needs further investigations. More difficult to calculate

"R" correlator

PHYSICAL REVIEW C **83**, 011901(R) (2011)

New method for the experimental study of topological effects in the quark-gluon plasma

N. N. Ajitanand, Roy A. Lacey, A. Taranenko, and J. M. Alexander

PHYSICAL REVIEW C **97**, 061901(R) (2018)

New correlator to detect and characterize the chiral magnetic effect

Niseem Magdy,[1,*] Shuzhe Shi,[2] Jinfeng Liao,[2] N. Ajitanand,[1,†] and Roy A. Lacey[1,‡]

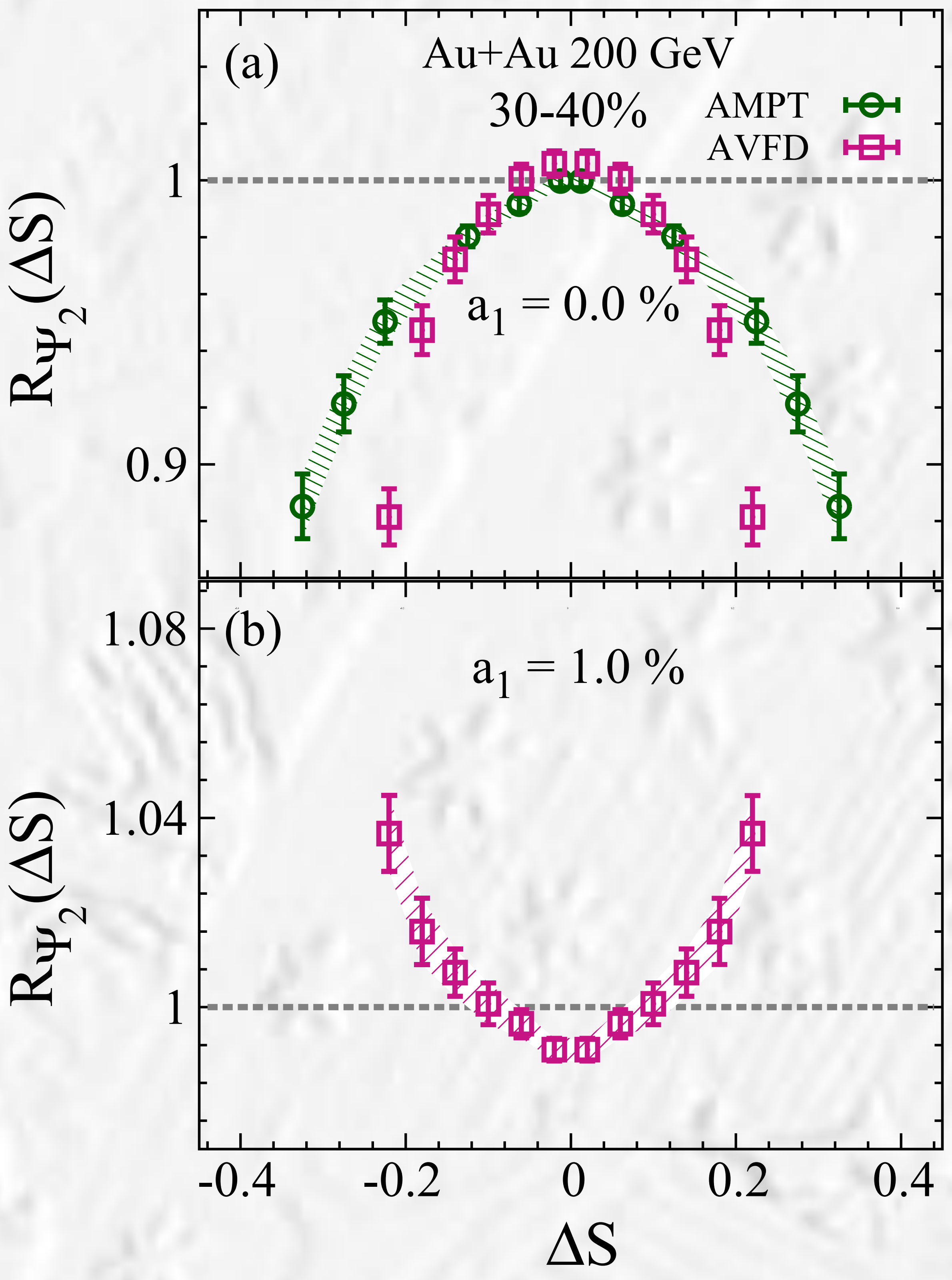


FIG. 1. Comparison of the $R(\Delta S)$ correlators for (a) background-driven charge separation ($a_1 = 0$) in 30–40% Au+Au collisions ($\sqrt{s_{NN}} = 200$ GeV) obtained with the AMPT and AVFD models, and (b) the combined effects of background- and CME-driven ($a_1 = 1.0\%$) charge separation in Au+Au collisions obtained with the AVFD model at the same centrality and beam energy.

$$R_{\Psi_2}(\Delta S) = C_{\Psi_2}(\Delta S)/C^{\perp}_{\Psi_2}(\Delta S),$$

$$C_{\Psi_m}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{Shuffled}}(\Delta S)}$$

$$\Delta S = \frac{\sum_1^p \sin\left(\frac{m}{2}\Delta\varphi_m\right)}{p} - \frac{\sum_1^n \sin\left(\frac{m}{2}\Delta\varphi_m\right)}{n}$$

The correlation functions $C^{\perp}_{\Psi_m}(\Delta S)$, used to quantify charge separation perpendicular to the $\vec{B}$ field, are constructed with the same procedure outlined for $C_{\Psi_m}(\Delta S)$, but with Ψ_m replaced by $\Psi_m + \pi/m$.

sin() —> cos() in the Eq. above

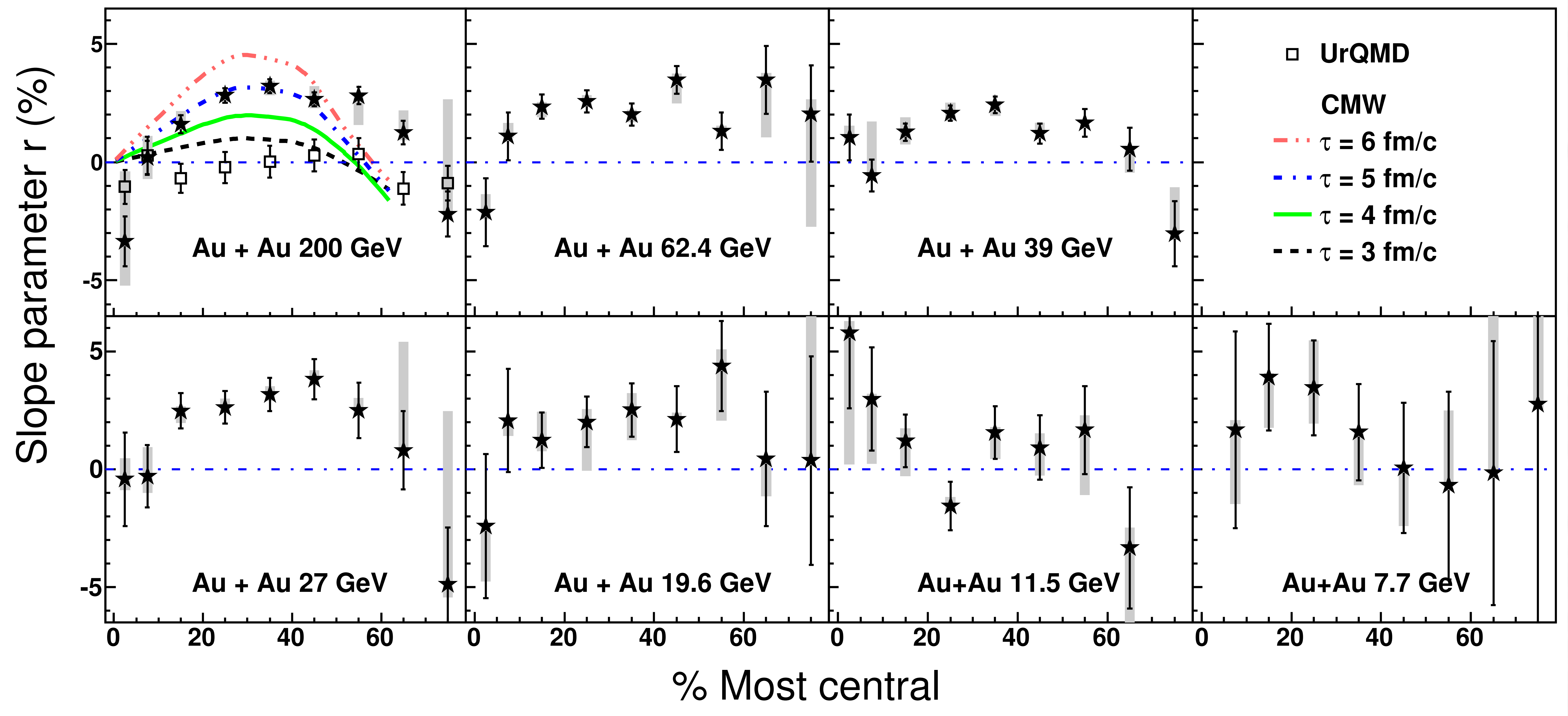
The shape of the ratio (concave, convex) depends on the widths of the distributions in the denominator and numerator. Those widths are determined by the value of 2-particle correlations (sin-sin or cos-cos). The it is simpler and much more transparent to compare those directly (as done in gamma correlator).

Does not seem to bring anything new

Difficult for quantitative analysis, e,g. what should be the relative contribution of the signal and background for the ratio to be flat?

Centrality/energy dependence

L. Adamczyk *et al.* (STAR Collaboration), Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions, Phys. Rev. Lett. **114**, 252302 (2015).



Energy dependence is not that obvious

CMW and LCC : Hydro

A. Bzdak, P. Bożek / Physics Letters B 726 (2013) 239–243

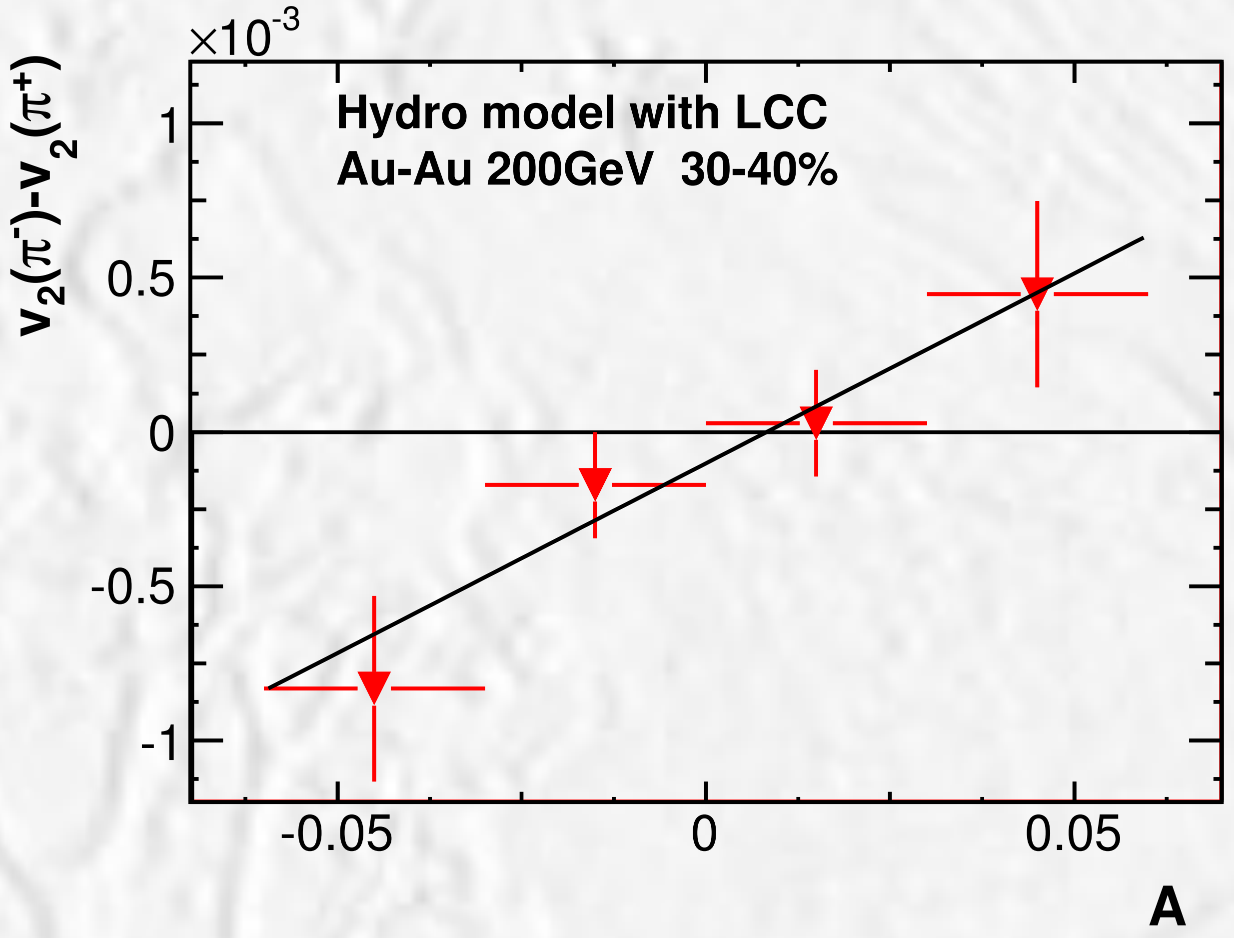


Fig. 4. The charge asymmetry dependence of π^+ and π^- elliptic flow coefficients in the hydrodynamic model followed by statistical emission with local charge conservation. We obtained $r = 0.012 \pm 0.004$ compared with the preliminary STAR data, $r_{exp} \approx 0.03$.

LCC = local charge conservation.

The results indicates that LCC plays a significant role (even though in this particular calculations it might underestimate the 'signal' by a factor of 3)

CME vs background. U+U

S. Voloshin, PRL 105 (2010) 172301

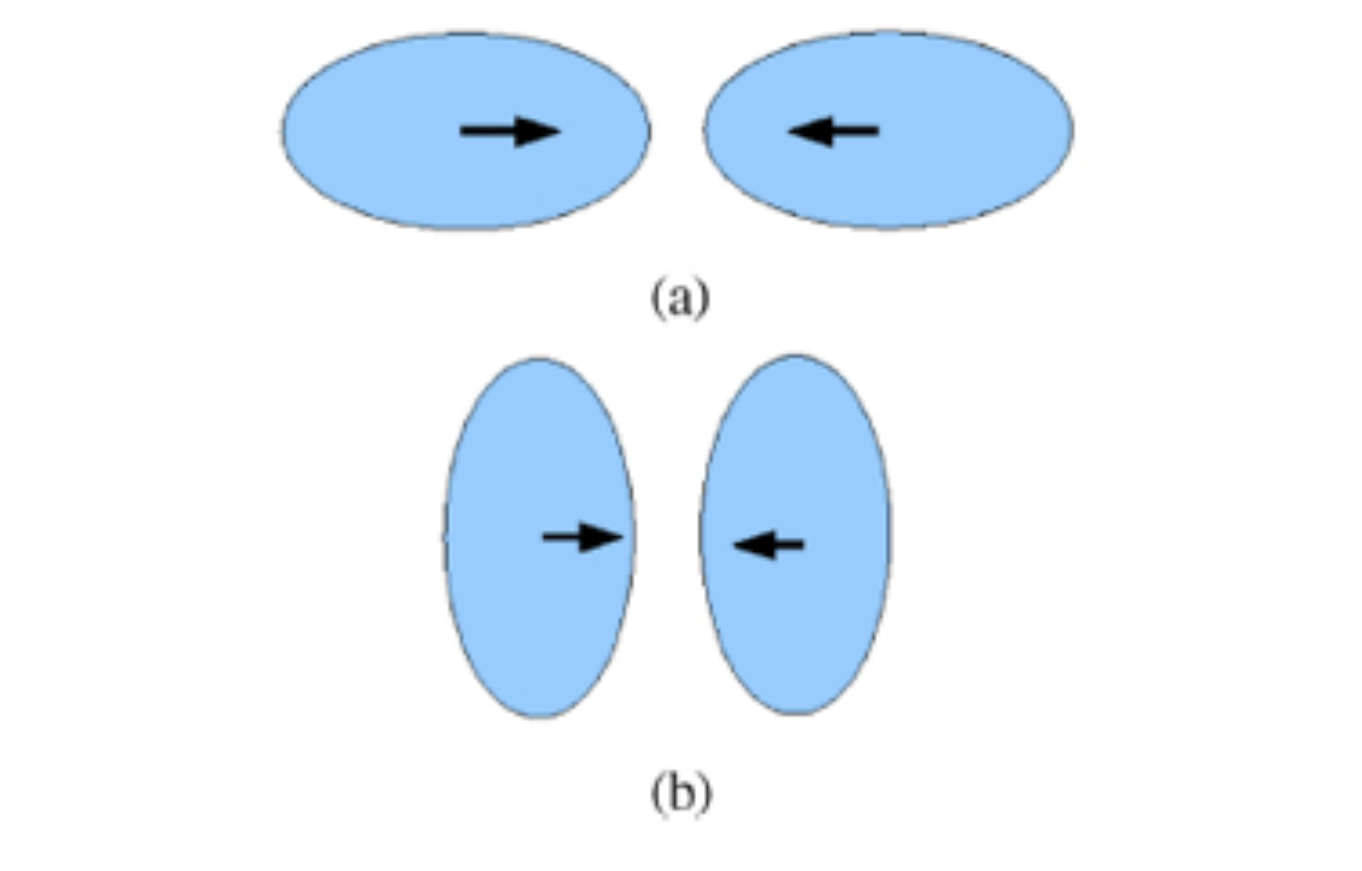


FIG. 1 (color online). Schematic view of central $U + U$ collisions: (a) tip-tip and (b) body-body.

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

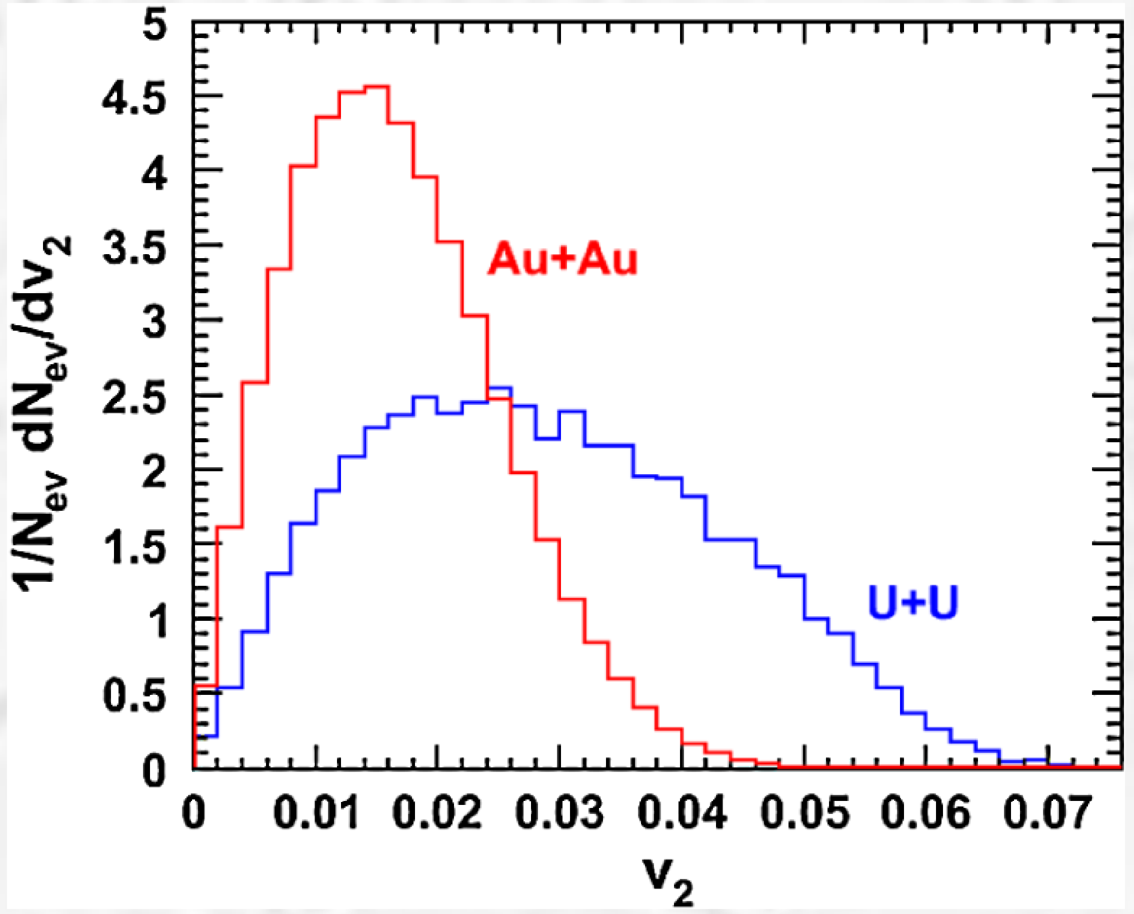


FIG. 2 (color online). Event distributions in v_2 for Au + Au and $U + U$ collisions in event samples with the number of spectators $N_{sp} < 20$.

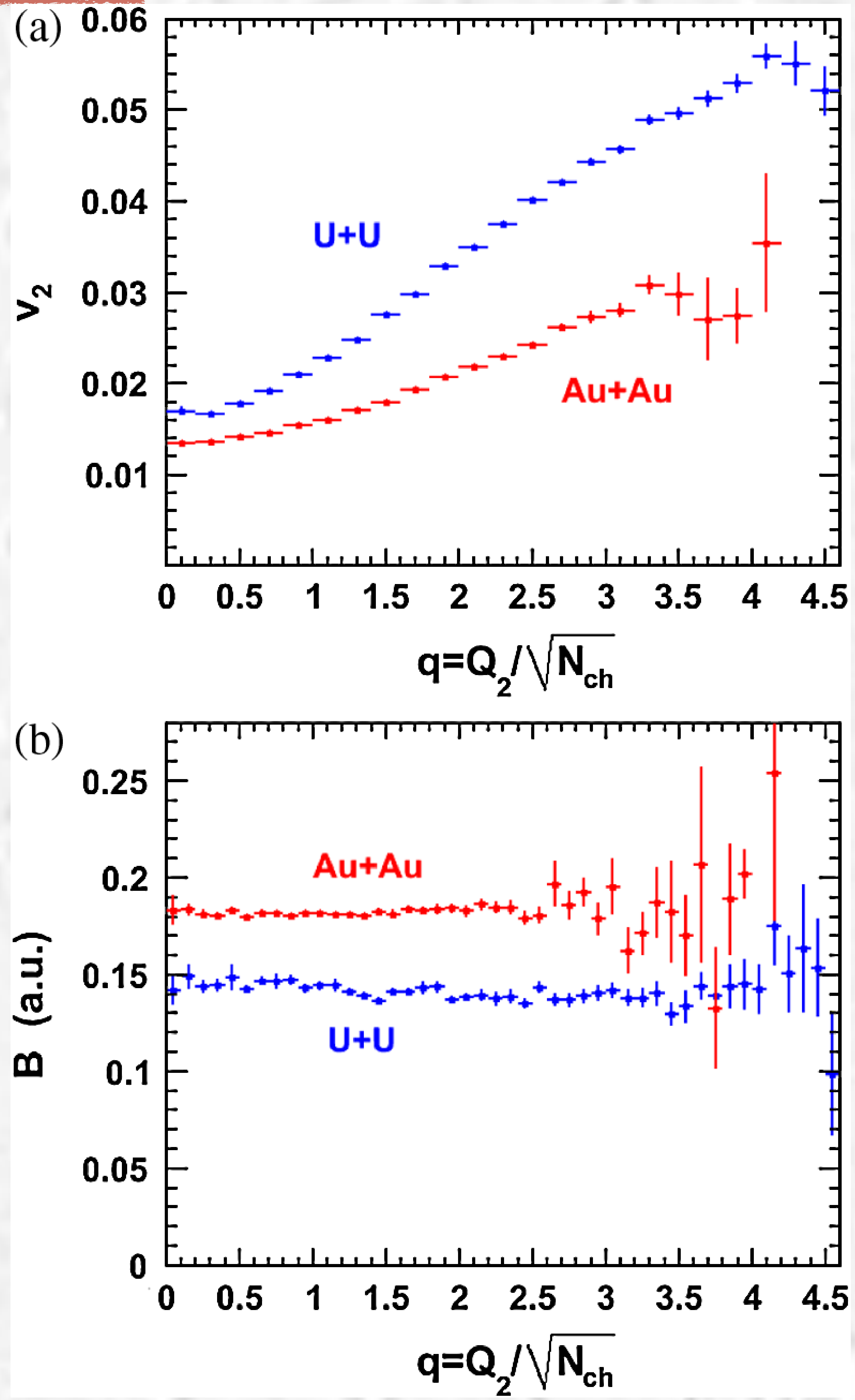


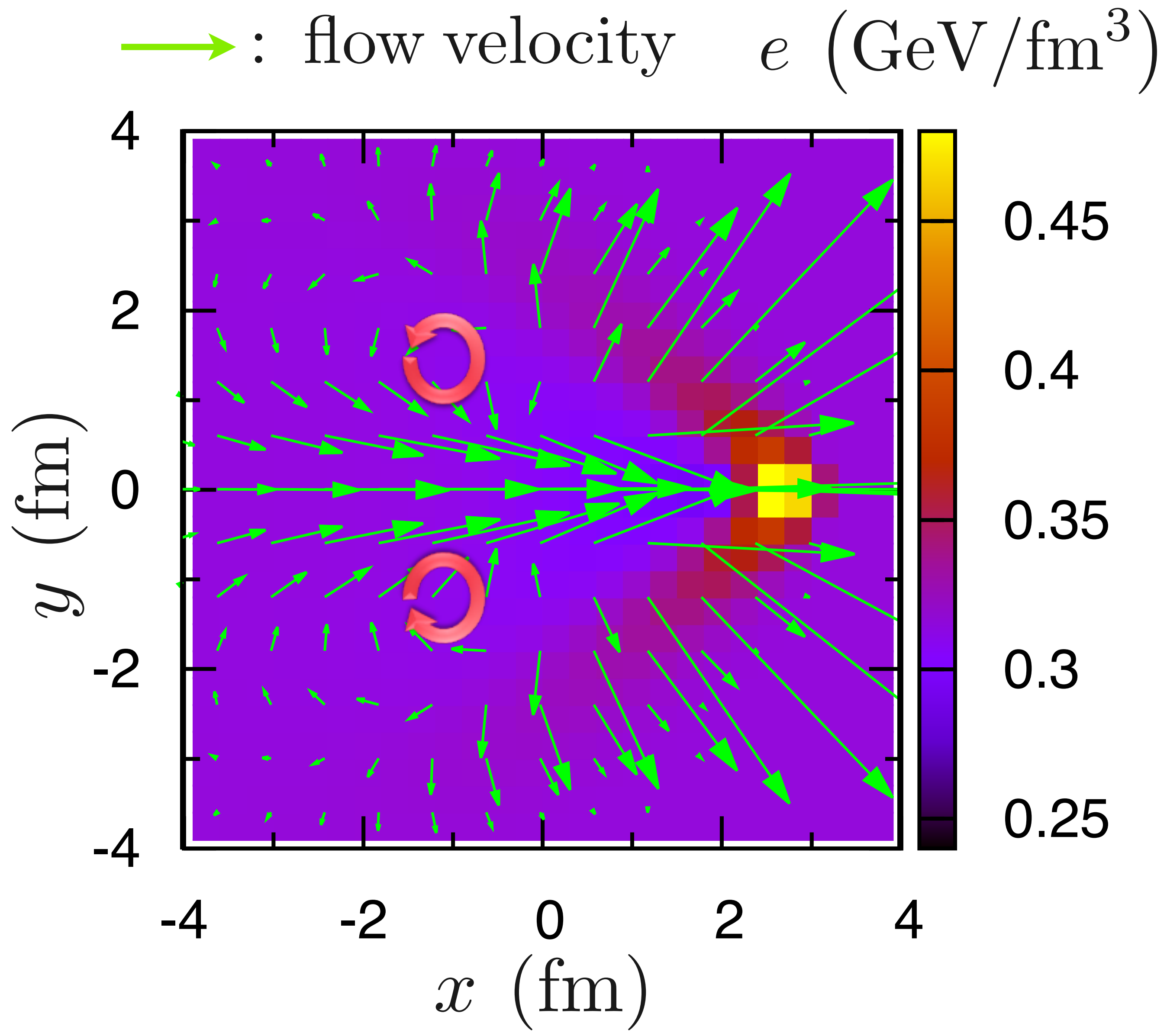
FIG. 3 (color online). Elliptic flow and the magnetic field (in arbitrary units) as a function of q, the magnitude of the flow vector, in events with the number of spectators $N_{sp} < 20$.

Note that one can use a similar trick with Au+Au, but there, one would "play" on fluctuations, not nuclear shape

EXTRA SLIDES, ω

Local vorticity

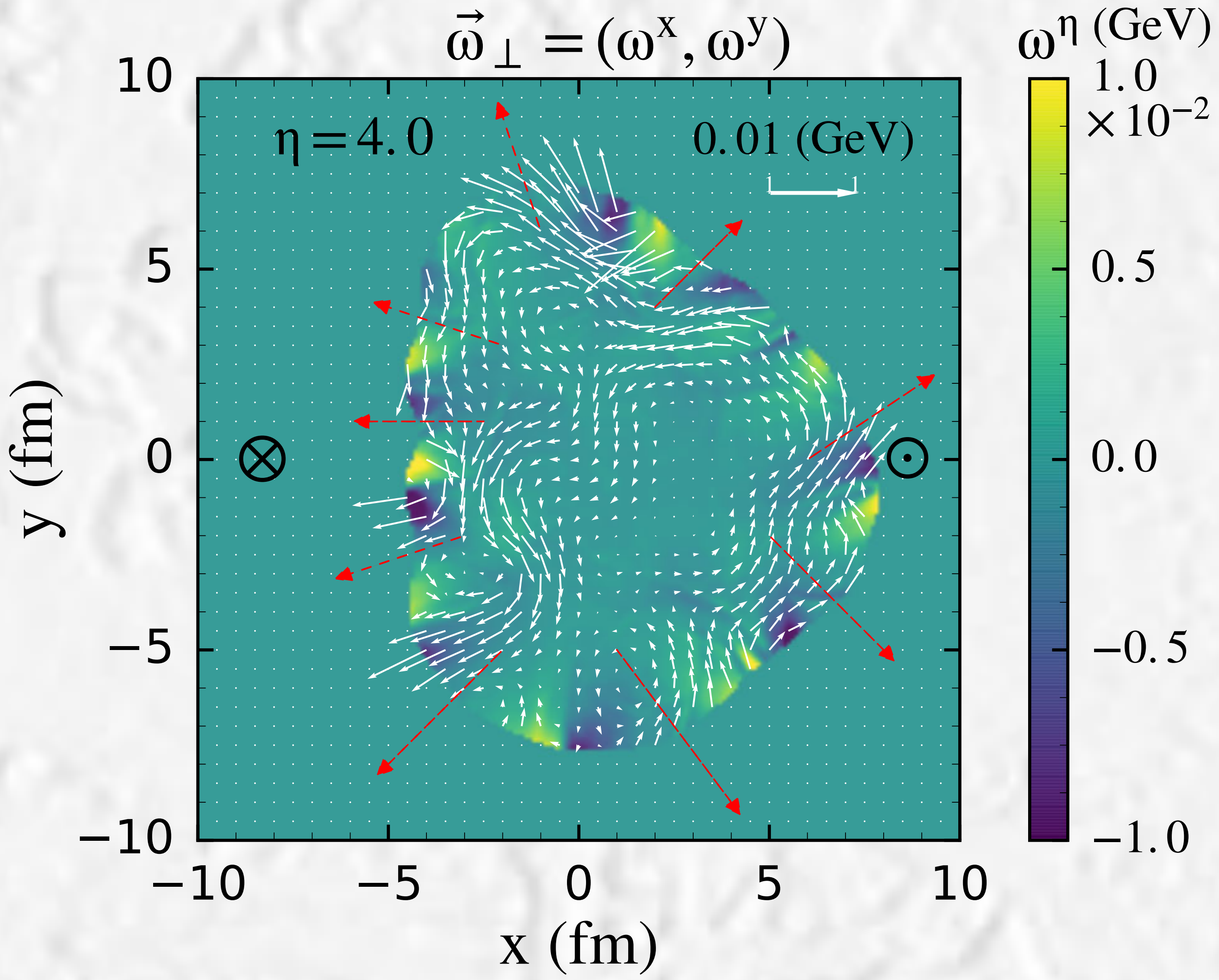
Vortex induced by jet

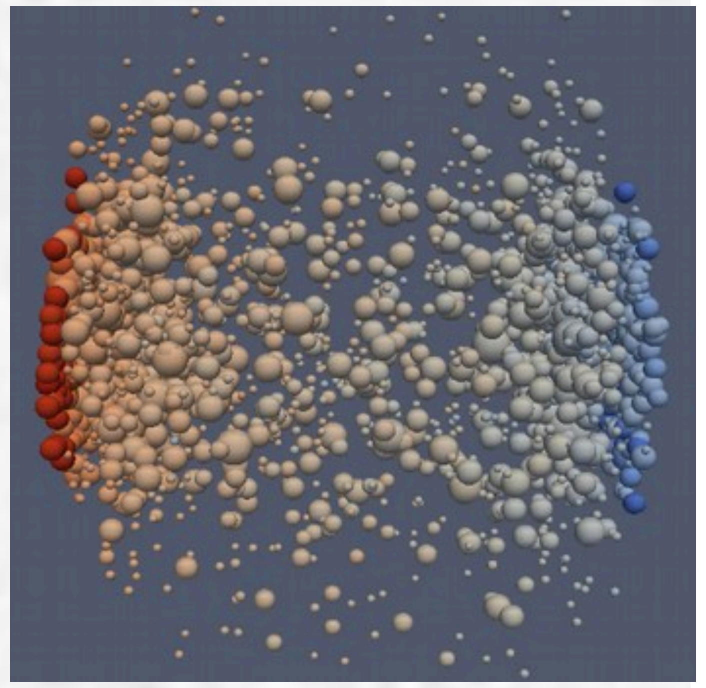


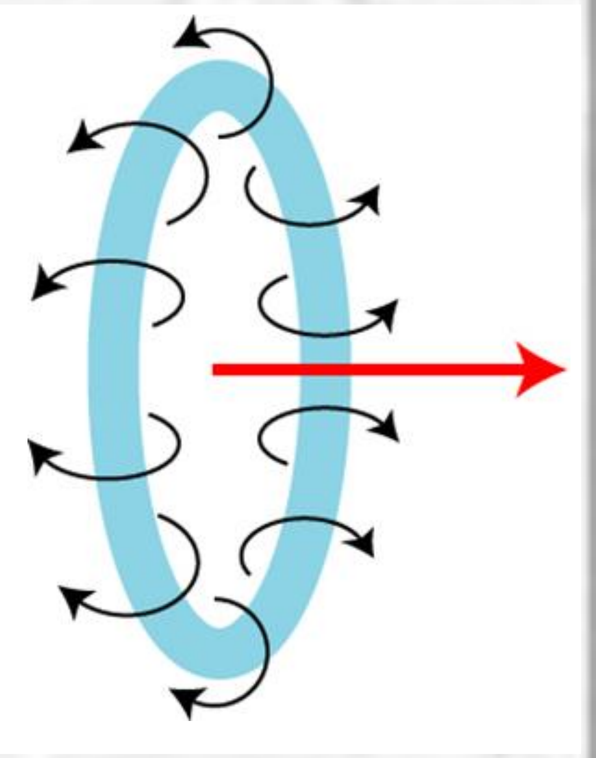
Y. Tachibana and T. Hirano, NPA904-905 (2013) 1023

B. Betz, M. Gyulassy, and G. Torrieri, PRC76.044901 (2007)

Local vorticity induced by collective flow







L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang, PRL117, 192301 (2016)

F. Becattini and I. Karpenko, PRL120.012302 (2018)

S. Voloshin, EPJ Web Conf.171, 07002 (2018)

X.-L. Xia et al., PRC98.024905 (2018)

Disagreement in P_z sign

Opposite sign

- UrQMD IC + hydrodynamic model
  F. Becattini and I. Karpenko, PRL.120.012302 (2018)
- AMPT
  X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)

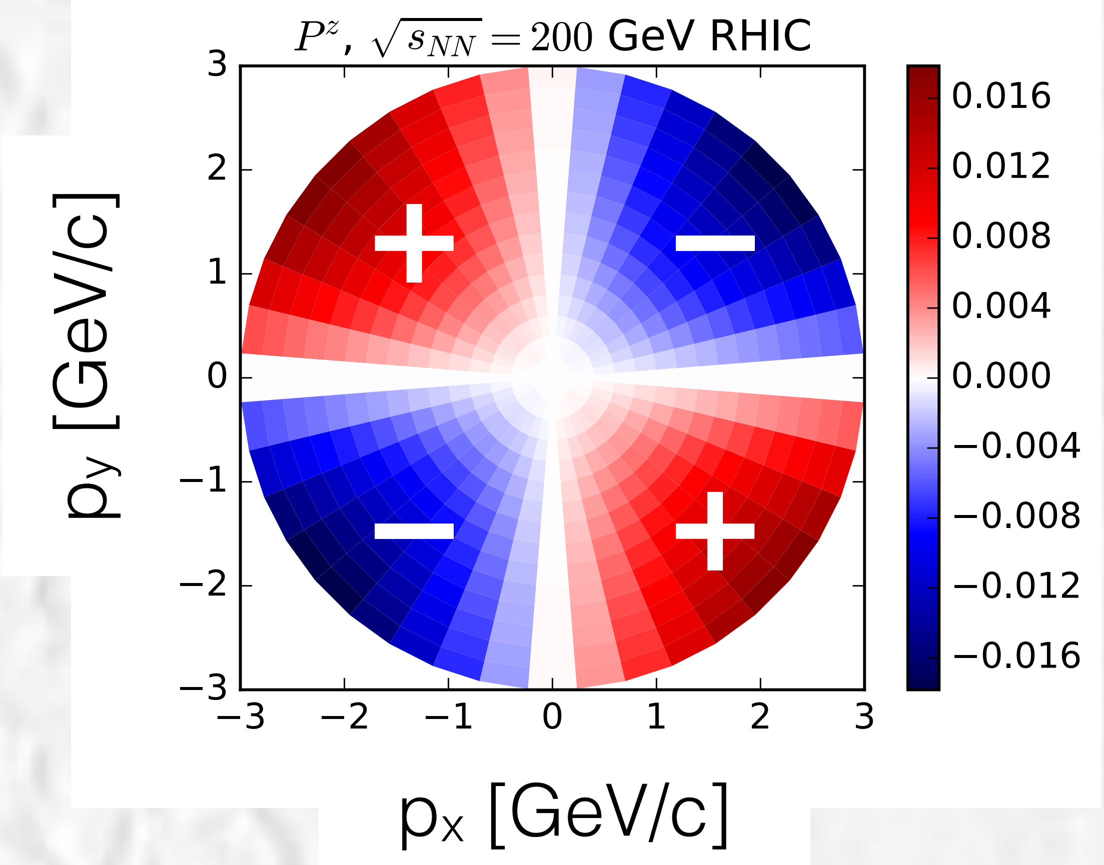
Same sign

- Chiral kinetic approach
  Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- High resolution (3+1)D PICR hydrodynamic model
  Y. Xie, D. Wang, and L. P. Csernai, EPJC80.39 (2020)
- Blast-wave model
  S. Voloshin, EPJ Web Conf.171, 07002 (2018), STAR, PRL123.13201

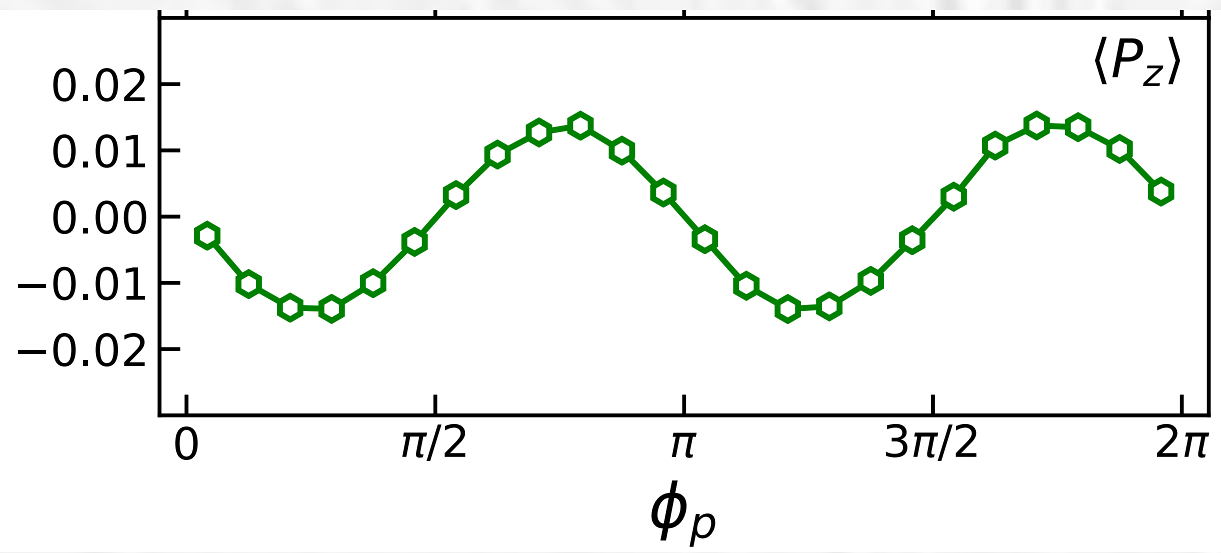
Partially (one of component showing the same sign)

- Glauber/AMPT IC + (3+1)D viscous hydrodynamics
  H.-Z. Wu et al., Phys. Rev. Research 1, 033058 (2019)
- Thermal model
  W. Florkowski et al., Phys. Rev. C 100, 054907 (2019)

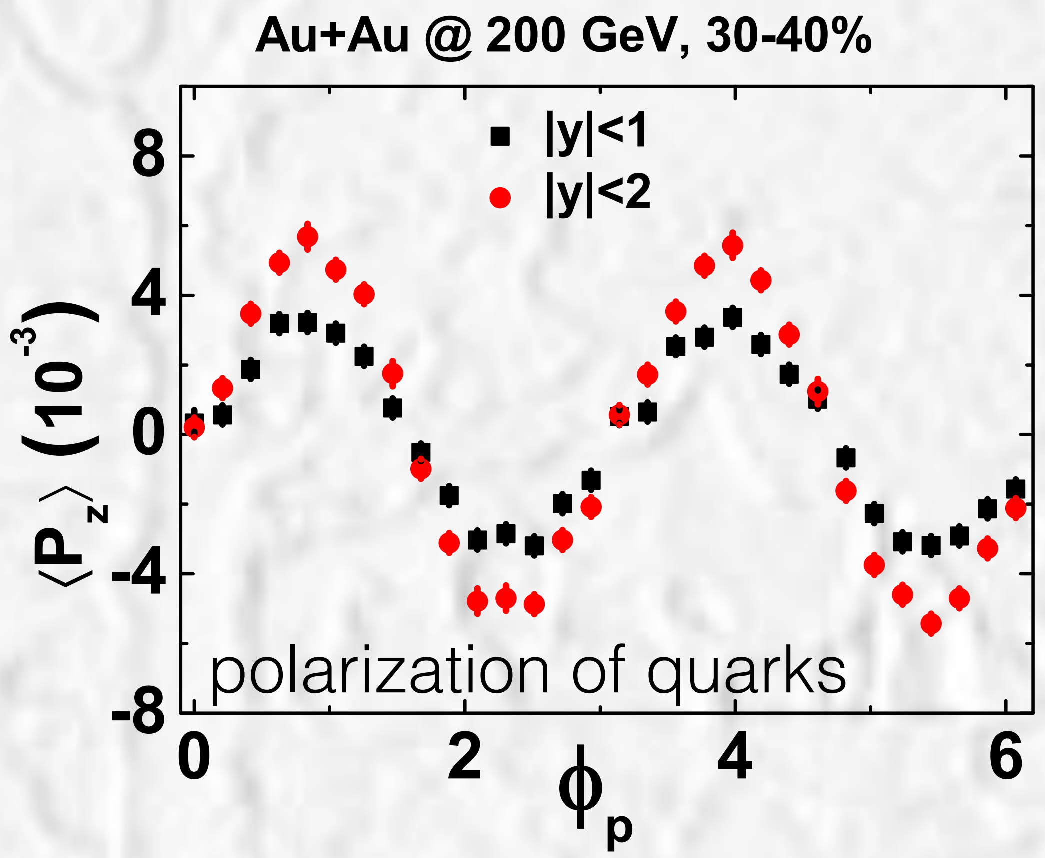
Hydrodynamic model



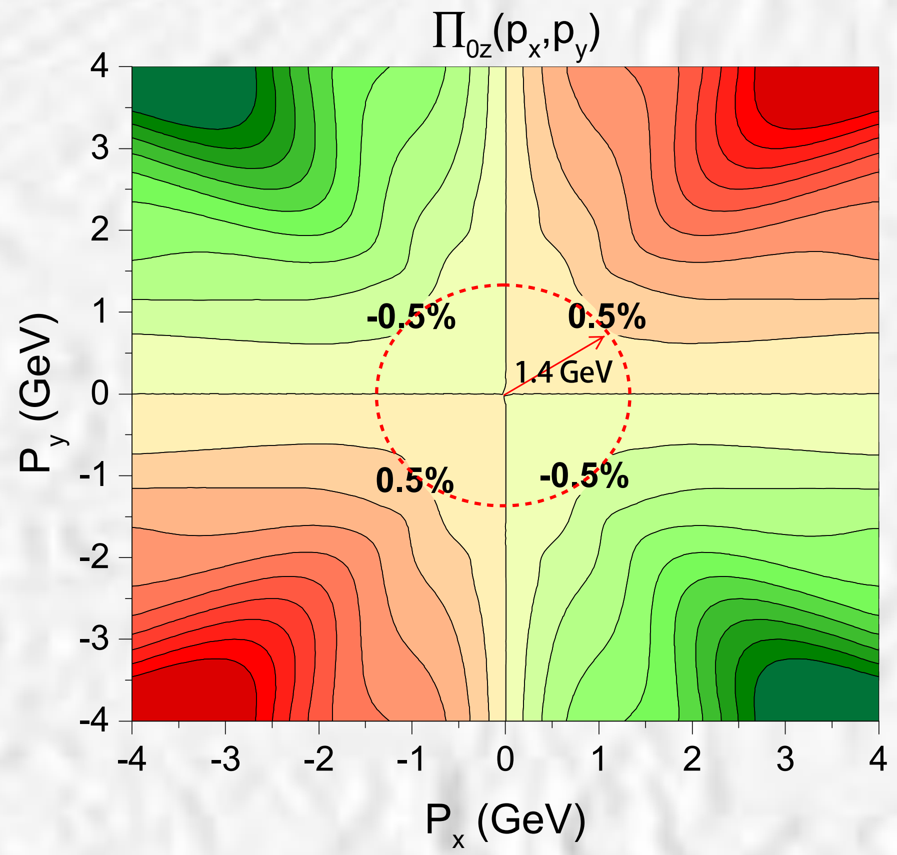
AMPT, Au+Au 200 GeV 20-50%



Chiral kinetic approach



PICR model



Incomplete thermal equilibrium of spin degree of freedom?

Slopes and intercepts

STAR, PRC, **98**, 014915 (2018)

$$\frac{1}{\langle p_T \rangle}\frac{d\langle p_x \rangle}{d\eta} \approx 1.5\,\alpha_{ts}\,\frac{dv_1}{d\eta}$$

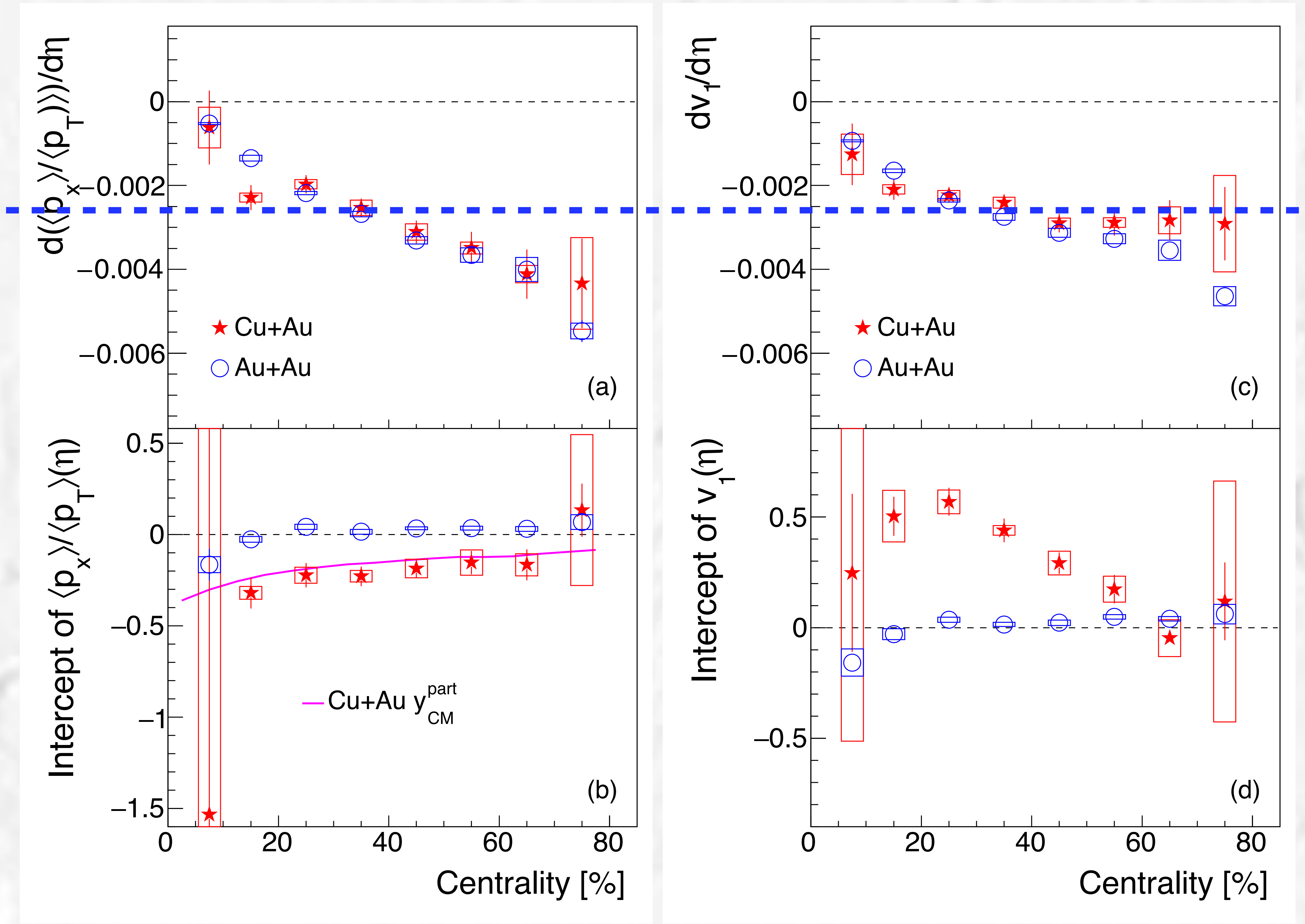


FIG. 6. (Color online) Slopes and intercepts of $\langle p_x\rangle/\langle p_T\rangle(\eta)$ and $v_1(\eta)$ as a function of centrality in Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The solid line shows the center-of-mass rapidity in Cu+Au collisions calculated by Cu and ... Glauber model. Open boxes show systematic uncertainties.

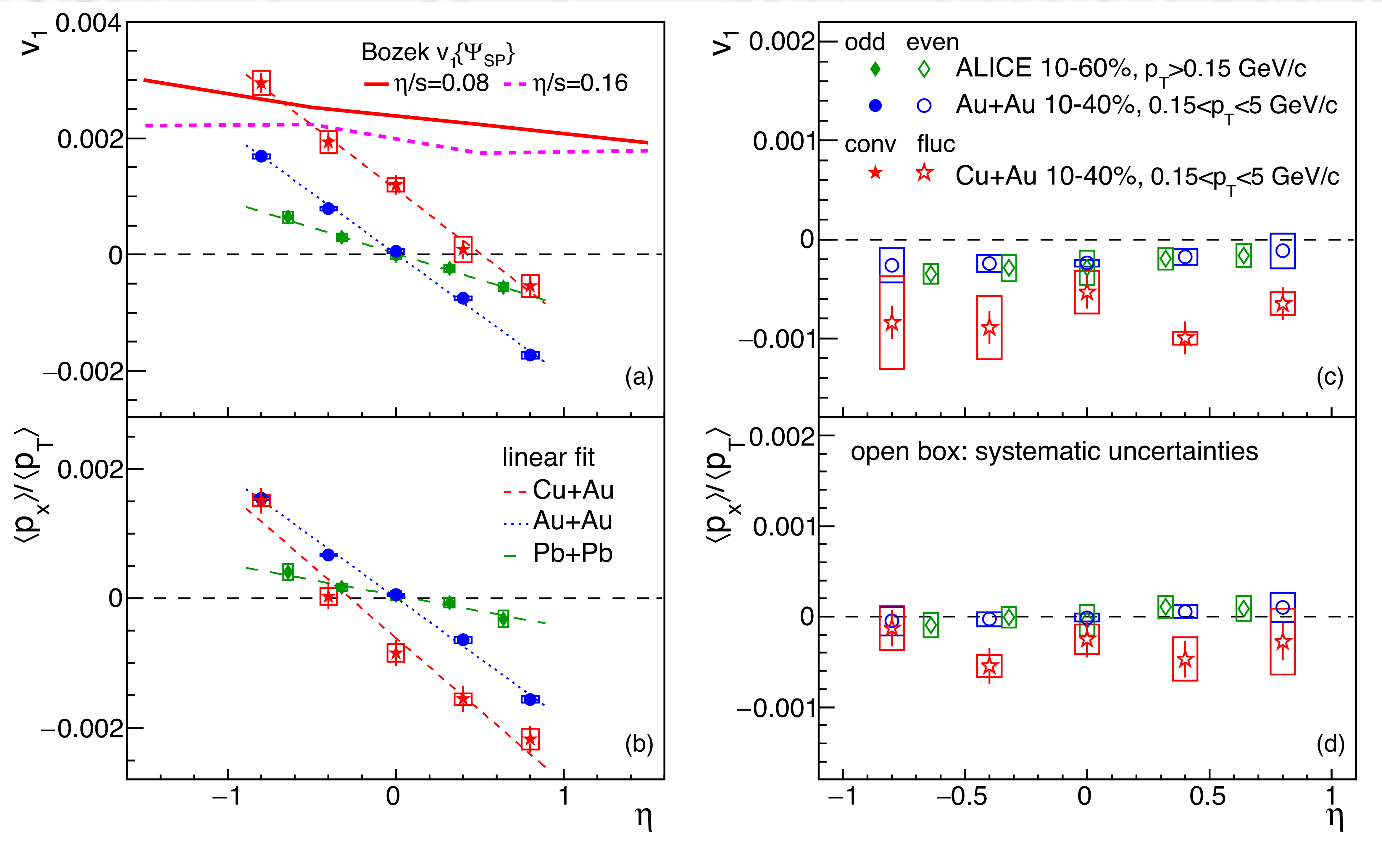


FIG. 5. (Color online) Charged particle "conventional" (left) and "fluctuation" (right) components of directed flow v_1 and momentum shift $\langle p_x\rangle/\langle p_T\rangle$ as a function of η in 10%-40% centrality for Cu+Au, Au+Au, and Pb+Pb collisions. Thick solid ... 6, respectively, for Cu+Au collisions [31].

$$y_{\rm CM} \sim \frac{1}{2}\ln(N_{\rm part}^{\rm Au}/N_{\rm part}^{\rm Cu})$$

- For mid-central collisions (20% - 40%) tilted source contribution is about 2/3, its fraction increases in more peripheral collisions.
- At LHC energies "tilted sources" contribution is smaller, about 1/3

→ polarization at LHC ~ 1/6 of that at RHIC 200 GeV