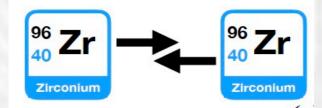


Search for the Chiral Magnetic Effect results from isobar collisions at



Sergei A. Voloshin



Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{_{\rm NN}}} = 200$ GeV by the STAR Collaboration at RHIC

STAR Collaboration arXiv:2109.00131v1 [nucl-ex] 1 Sep 2021

+ one slide on results from

Search for the chiral magnetic effect via charge-dependent azimuthal correlations relative to spectator and participant planes in Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$

STAR Collaboration arXiv:2106.09243v1 [nucl-ex] 17 Jun 2021

Outline:

CME: observables and background First measurements STAR isobar blind analysis results **Implications**

(a)

Supported by



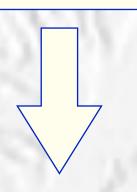
[13] D. Kharzeev, Parity violation in hot QCD: Why it can happen,

Chiral magnetic effect

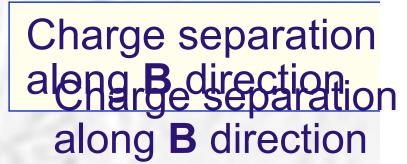
Chiralityimhalaaree

4

Magnetic field Magnetic field



Anomalous transport
Electrical our transport,
malentic field
magnetic field

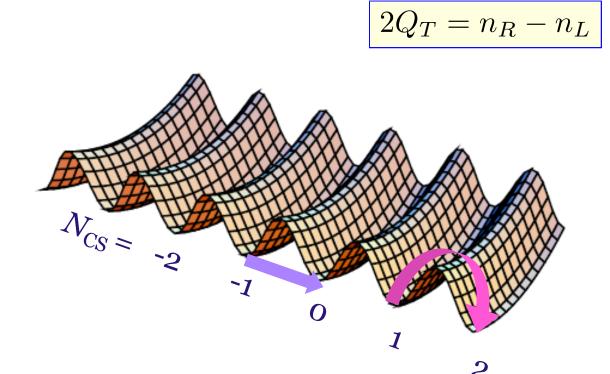


 $\mu_5 \propto \mathbf{E} \cdot \mathbf{B}$ h Chira (CME

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

Phen

STAR@



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

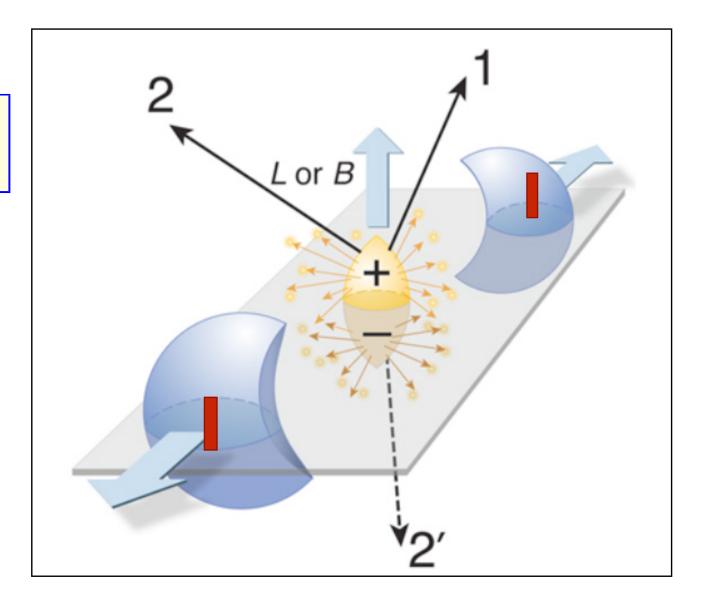
nce the dynamics of QGP field = chiral magnetic effect

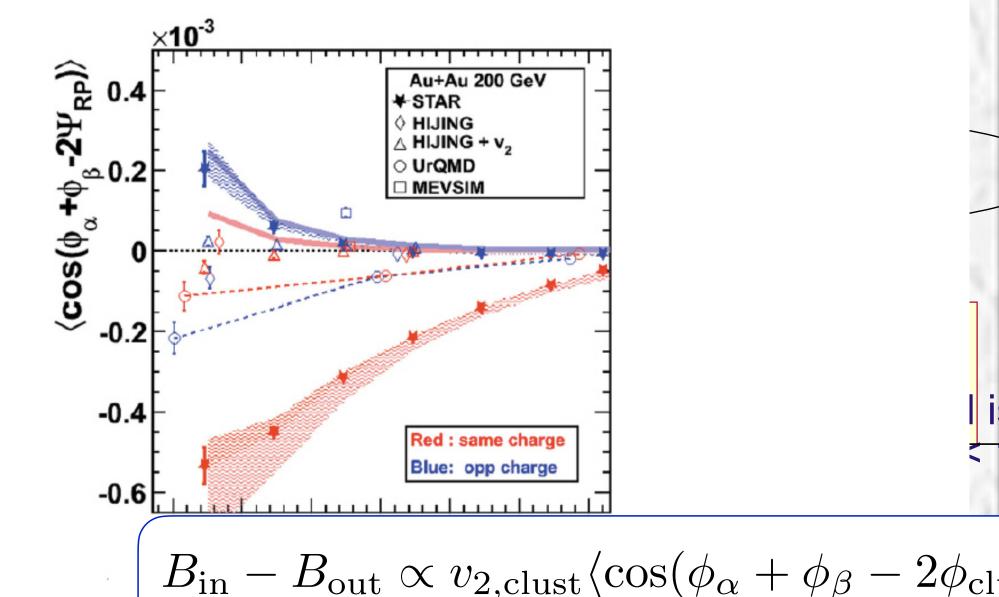
erran, Warringa, Fukushima 2007-2008):

$$\frac{N_c e}{2\pi^2} \mu_A \mathbf{B}$$

azimuthal correlation. Voloshin 2004,

12-2014







PRL **103**, 251601 (2009)

First measurments

Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS

week ending 18 DECEMBER 2009 PHYSICAL REVIEW C 81, 054908 (2010)

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



Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

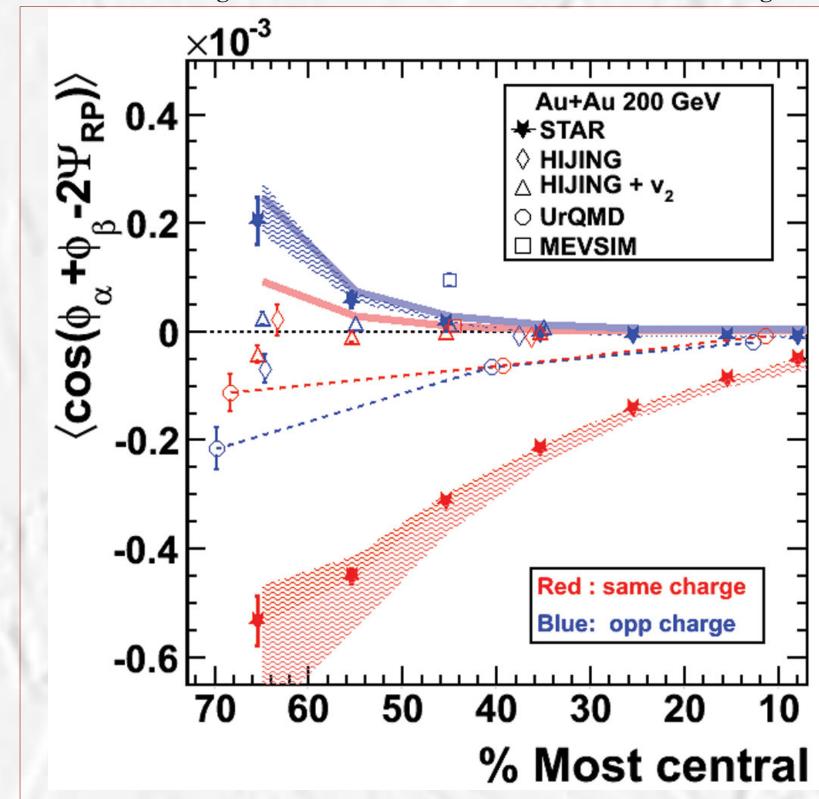


FIG. 4 (color). $\langle\cos(\phi_{\alpha}+\phi_{\beta}-2\Psi_{RP})\rangle$ results from 200 GeV Au + Au collisions are compared to calculations with event generators HIJING (with and without an "elliptic flow afterburner"), URQMD (connected by dashed lines), and MEVSIM. Thick lines represent HIJING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

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

No event generator could explain more than 1/3 of the signal

$$\Delta \gamma = \gamma_{\rm opp} - \gamma_{\rm same}$$

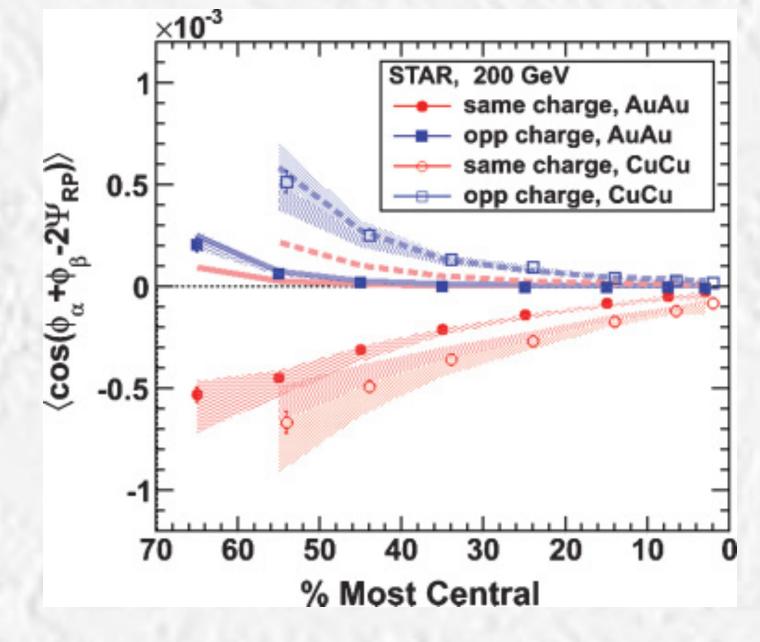


FIG. 7. (Color online) $\langle\cos(\phi_a+\phi_\beta-2\Psi_{RP})\rangle$ in Au + Au and Cu + Cu collisions at $\sqrt{s_{NN}}=200$ GeV calculated using Eq. (7). The error bars show the statistical errors. The shaded areas reflect the uncertainty in the elliptic flow values used in calculations, with 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).

STAR * Types of the background

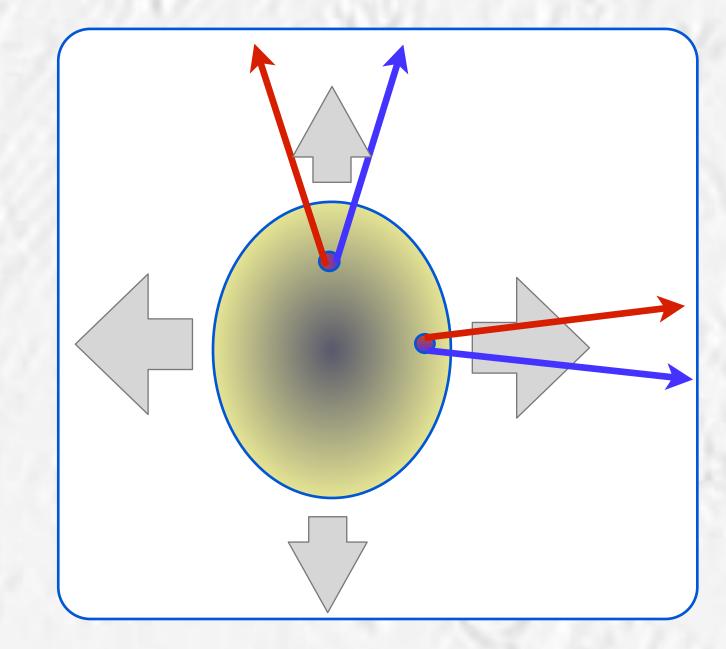
I. Physics (RP dependent).

(Can not be suppressed)

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

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

$$B_{\rm in} - B_{\rm out} \propto v_{\rm 2,clust} \langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\phi_{\rm clust}) \rangle$$



Local charge conservation (LCC)

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

Note, LCC:

- 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

II. Measurements (RP independent).

(depends on method, in principle can be reduced)

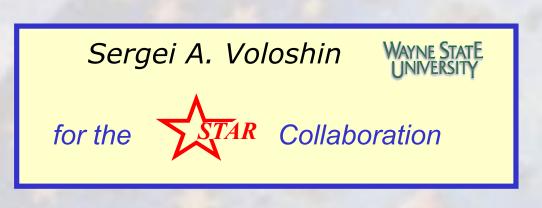
$$\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle \xrightarrow{?} \langle \cos(\phi_a + \phi_b - 2\Psi_2) \rangle v_{2,c}$$

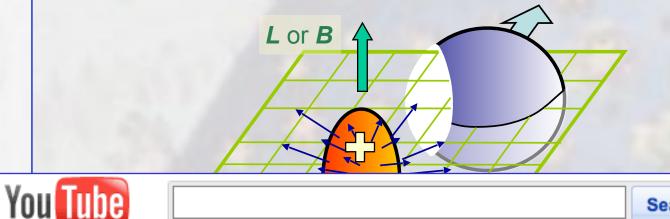
STAR ★ APS 2010 meeting

Developing a program



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



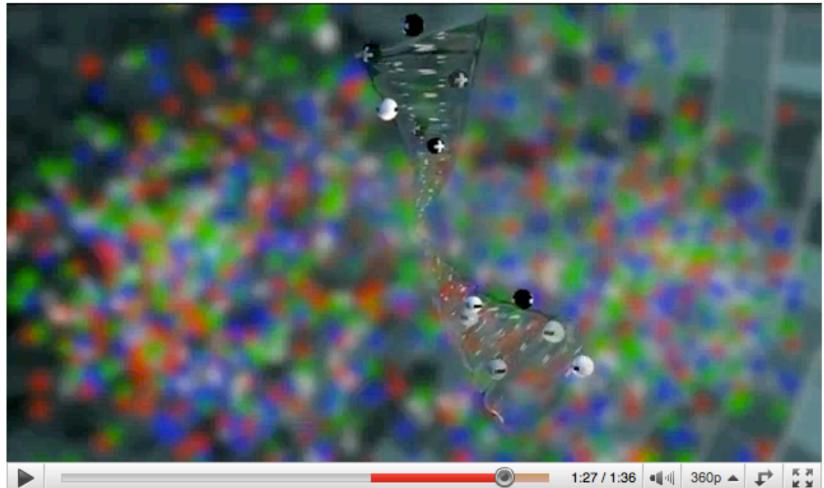


Outline:

- Chiral Magnetic Effect
- STAR results (PRL, arXiv: 0909.1717, sul

ections

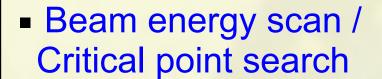
Hot Quark Soup Produced at RHIC



Selected for a Viewpoin SICAL REVIÊW Correlations and Po Dedicated experimental and theoretical program focused on the local parity violation, and more generally on non-perturbative QCD: structure of the vacuum, hadronization, etc.

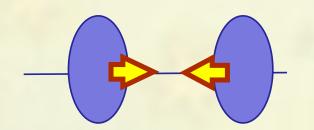
Experiment:





Isobaric beams

 High statistics PID studies / properties of the clusters



Such collisions ("easy" to trigger on) will have low magnetic field and large elliptic flow – clean test of the \mathcal{LPV} effect.

Look for a critical behavior, as \mathcal{LPV} predicted to depend strongly on deconfinement and chiral symmetry restoration

Colliding isobaric nuclei (the same mass number and different charge) and by that controlling the magnetic field

$$^{96}_{44}$$
Ru $+^{96}_{44}$ Ru $^{96}_{40}$ Zr $+^{96}_{40}$ Zr

Note that such studies will be also very valuable for understanding the initial conditions, baryon stopping, origin of the directed flow, etc.

in particular with neutral particles; see also next slide

APS April meeting, Washington DC, February 15, 2010

S.A. Voloshin



page 21

It is likely that the measurements are 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

 $f_{\rm CME} = \Delta \gamma^{\rm CME} / \Delta \gamma$

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

Collision energy dependence, Beam energy scan (signal should disappear at lower energies)



Isobar collisions (vary magnetic field while keeping the same background)

Event Shape Engineering (increase/decrease background)



Gamma wrt different Event Planes (Participants, Spectators)

Higher harmonic correlators (background, no signal)

Small system collisions (background, no signal)

Very central 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 ideas/observables (invariant mass, Signed BF, R-correlator)

Studies of the EM fields



Isobar collisions



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

PRL **105**, 172301 (2010)

PHYSICAL REVIEW LETTERS

week ending 22 OCTOBER 2010

Deng et al. PHYSICAL REVIEW C 94, 041901(R) (2016)

STAR 2018 Beam Use Request

Testing the Chiral Magnetic Effect with Central U + U Collisions

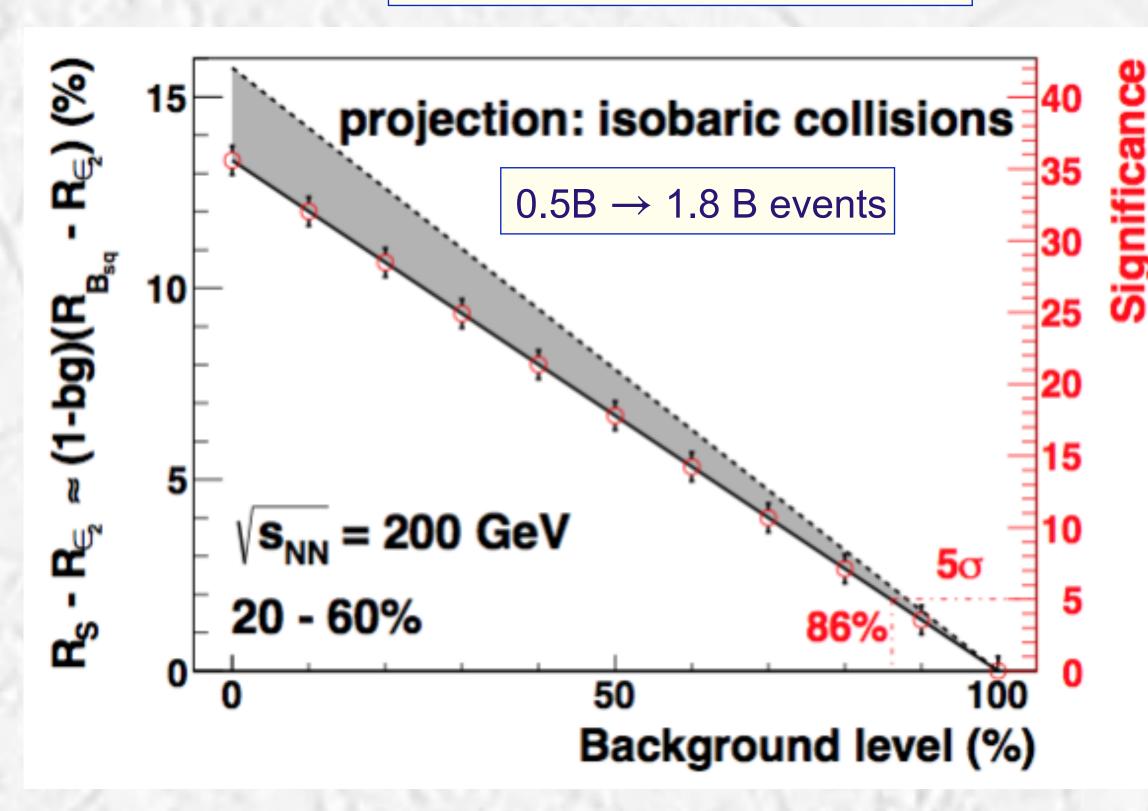
Sergei A. Voloshin

The charge separation dependence on the strength of the magnetic field can be further studied with the collision of isobaric nuclei, such as $^{96}_{44}$ Ru and 4096 Zr. These nuclei have

$$\frac{(\Delta \gamma/v_2)_{\rm Ru+Ru}}{(\Delta \gamma/v_2)_{\rm Zr+Zr}} \approx 1 + f_{\rm CME}^{\rm Zr+Zr}[(B_{\rm Ru+Ru}/B_{\rm Zr+Zr})^2 - 1]$$

$$\approx 0.18$$

To measure $f_{\rm CME}$ at the level of 3% one has to measure the double ratio with accuracy 0.6%



$$f_{\text{CME}} = 1 - f_{\text{BG}}$$

													61									P11112 -088	-1 S	22 S	48 -48	638	158	-58	458	107 8	24 M	108	4.15M	92 S	20,90 M	711142 0.58	PM143 2650	PM 144 363 D	17.
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41	Nb88	Nb	89 N	1690	Nb91	Nb92	Nb93	Nb94	Nb95	Nb96	Nb97	Nb98	Nb99	Nb100	Nb101	l Nb102	2 Nb10	03 Nb104	Nb10:	5 Nb10	6 Nb10	7 Nb108	0.30 s Nb109		Summer 2016 — extensive discussion of possible isobar pairs:														
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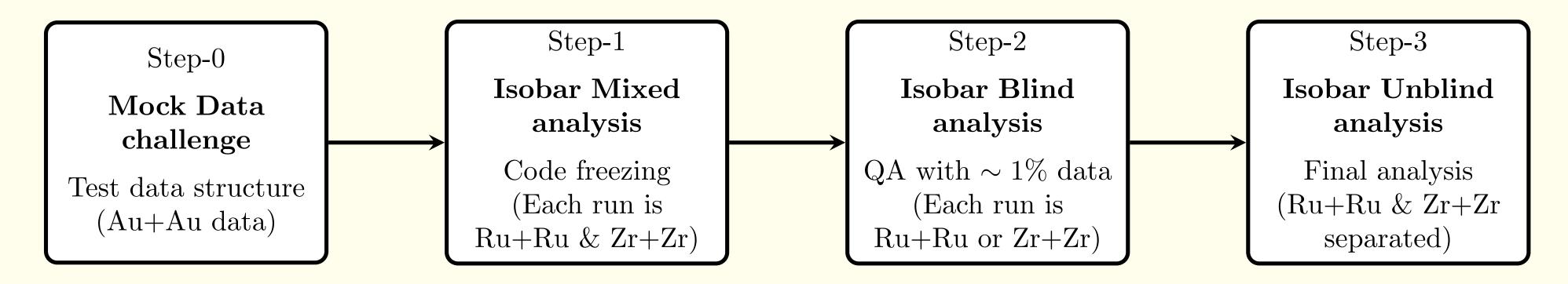


Blinding procedure

2017 BNL NPP Program Advisory Committee recommended blind analyses of CME studies of Run-18 isobar data

STAR develops Methods for a blind analysis of isobar data collected by the STAR collaboration

NUCL SCI TECH (2021) 32:48 https://doi.org/10.1007/s41365-021-00878-y



- Step-0 Mock Data challenge
- Step-1 Provide output files composed of collision data from a mix of the two isobar species Time-dependent QA tuned. Codes, and Analysis Notes are frozen
- Step-2 Provide files that blind the isobar species but do not "mix" data from different data acquisition runs Only allow "run-by-run" corrections
- Step-3 Full unblinding. Codes run by analyzers from a different group.

STAR Analysis organization

Prior to the blind analysis, the CME signatures are predefined as a significant excess of the CME-sensitive observables in Ru+Ru collisions over those in Zr+Zr collisions, owing to a larger magnetic field in the former.

- Five institutional groups within the collaboration perform blind analyses of the isobar data
- Each group focuses on a specific analysis method
- Substantial overlap of some analyses helps to cross-check results
- All analyses have a common set of variations for the purpose of systematic uncertainty determination
- Set of common and analysis-specific variables for data QA and selection of the data with stable detector performance

The paper includes results ONLY for predefined observables described in the Analyses Notes and a very limited (~1/2 page) post-blinding section



Data taking

- Large data set needed to hit small statistical uncertainty target
- Systematic uncertainties between species need to be controlled below that level

Special RHIC conditions (G. Marr et al., 10th International Particle Accelerator Conference (2019) pp. 28-32)

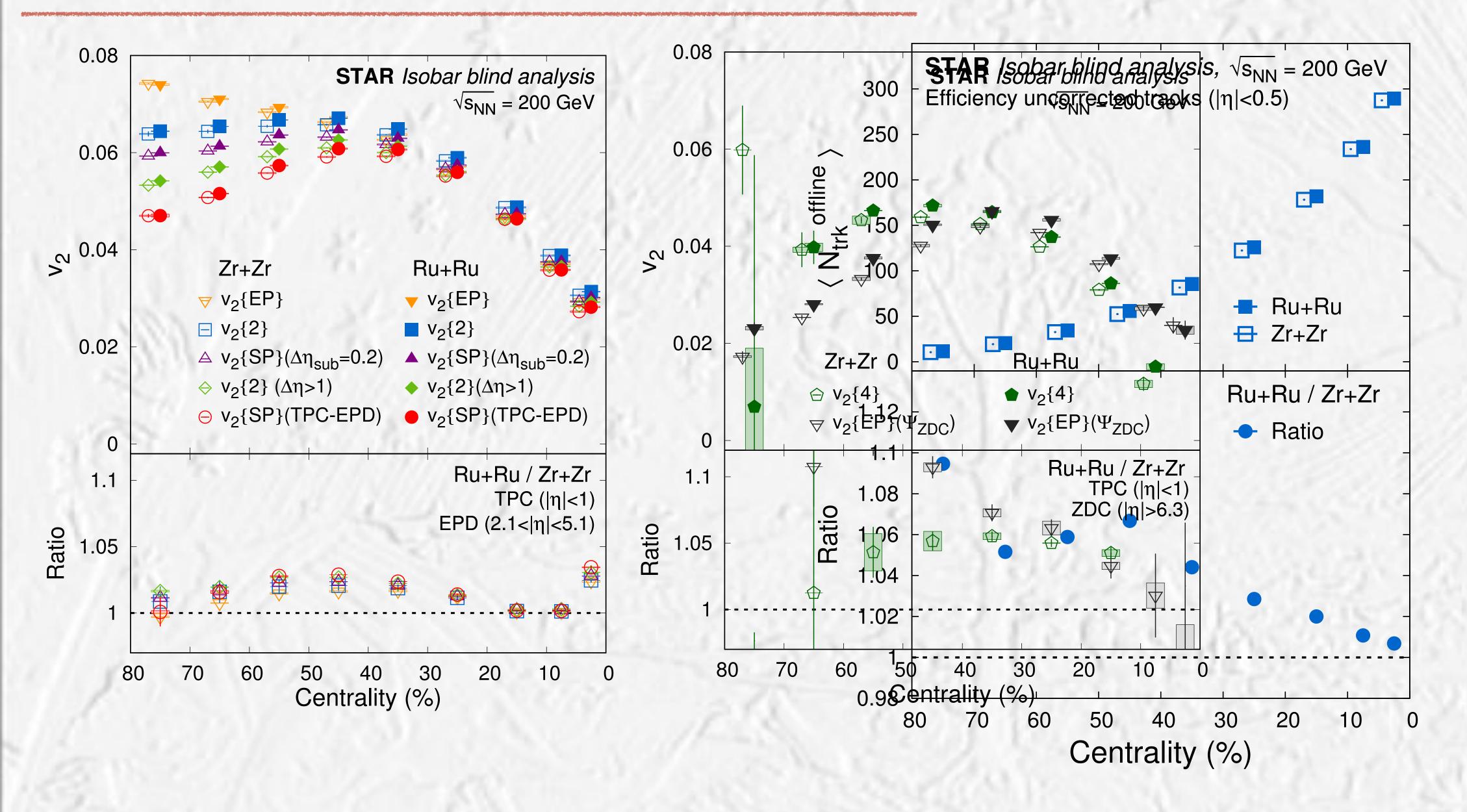
- Alternate the isobar species between each store of beam in RHIC
- Keep long stores with constant beam luminosity
- Match luminosities between the species
- Adjust the luminosity in such a way that the hadronic interaction rate at STAR is close to 10 kHz.

Precision target achieved:

A precision down to 0.4% is achieved, as anticipated, in the relative magnitudes of the pertinent observables between the two isobar systems



v₂ and multiplicity





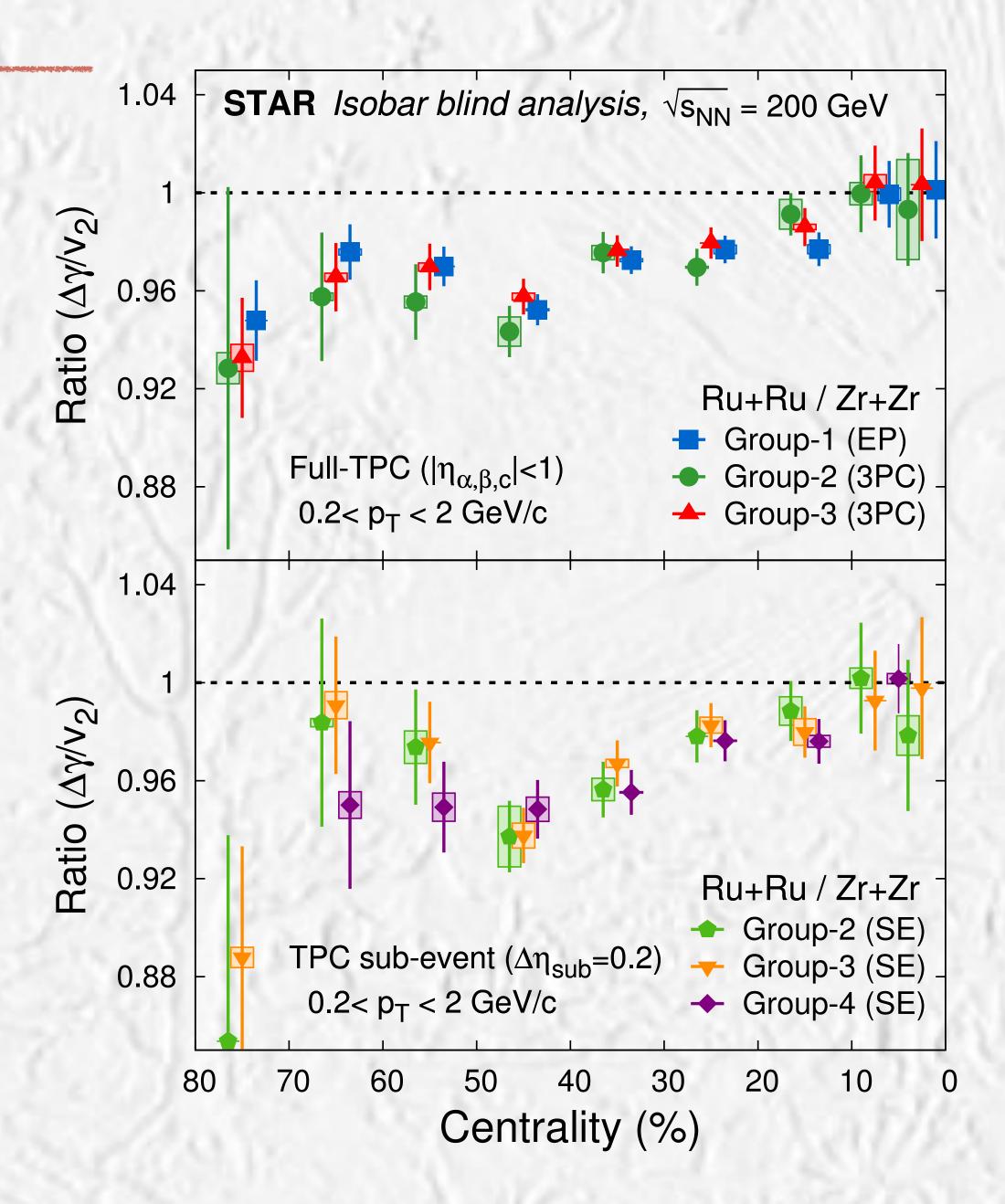
 $(\Delta \gamma / \nu_2)$

Groups 1 - 4

$$\frac{(\Delta \gamma/v_2)_{\text{Ru+Ru}}}{(\Delta \gamma/v_2)_{\text{Zr+Zr}}} = 1 + f_{\text{CME}}^{\text{Zr+Zr}}[(B_{\text{Ru+Ru}}/B_{\text{Zr+Zr}})^2 - 1].$$

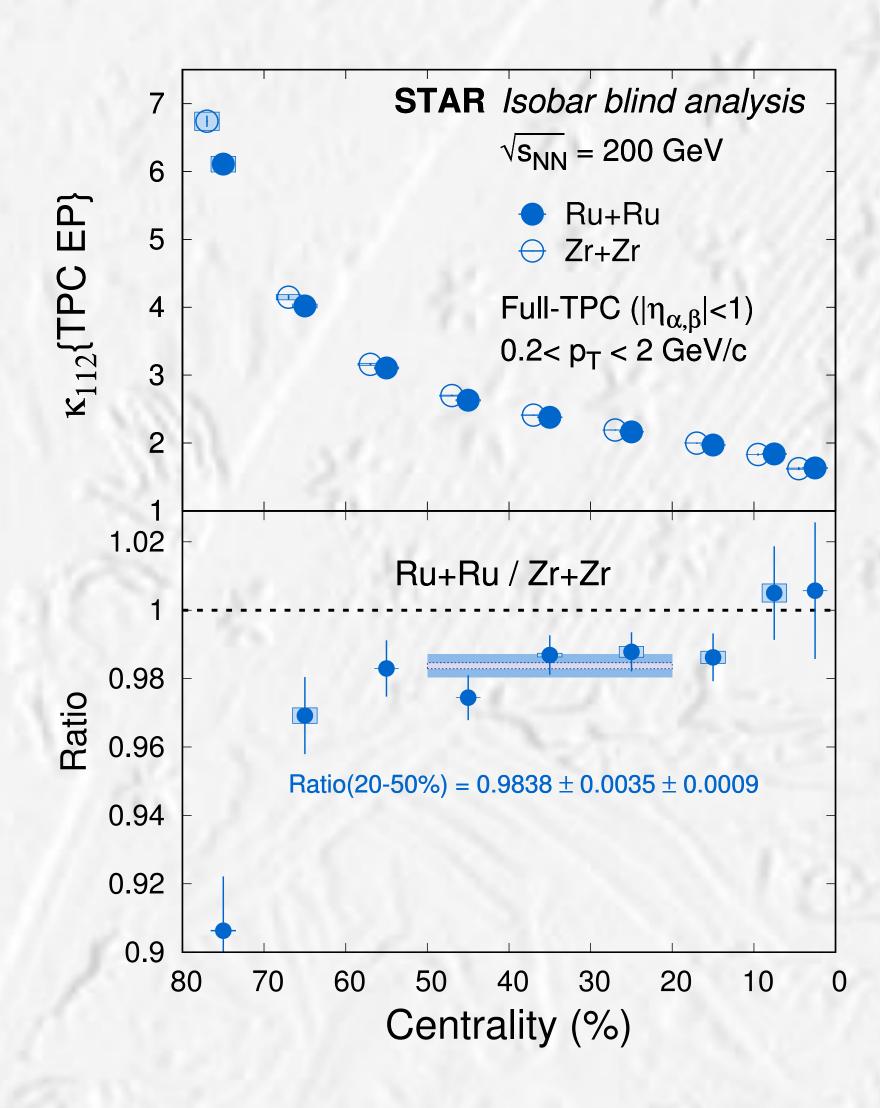
Note:

- In most cases the calculation of double ratio does not require knowledge of the Reaction Plane resolution.
- SE (subevent) η gap between subevents, $\Delta\gamma$ calculation in a narrower η window





"kappa" observable



Group 1

$$\delta = \langle \cos(\phi_{\alpha} - \phi_{\beta}) \rangle$$

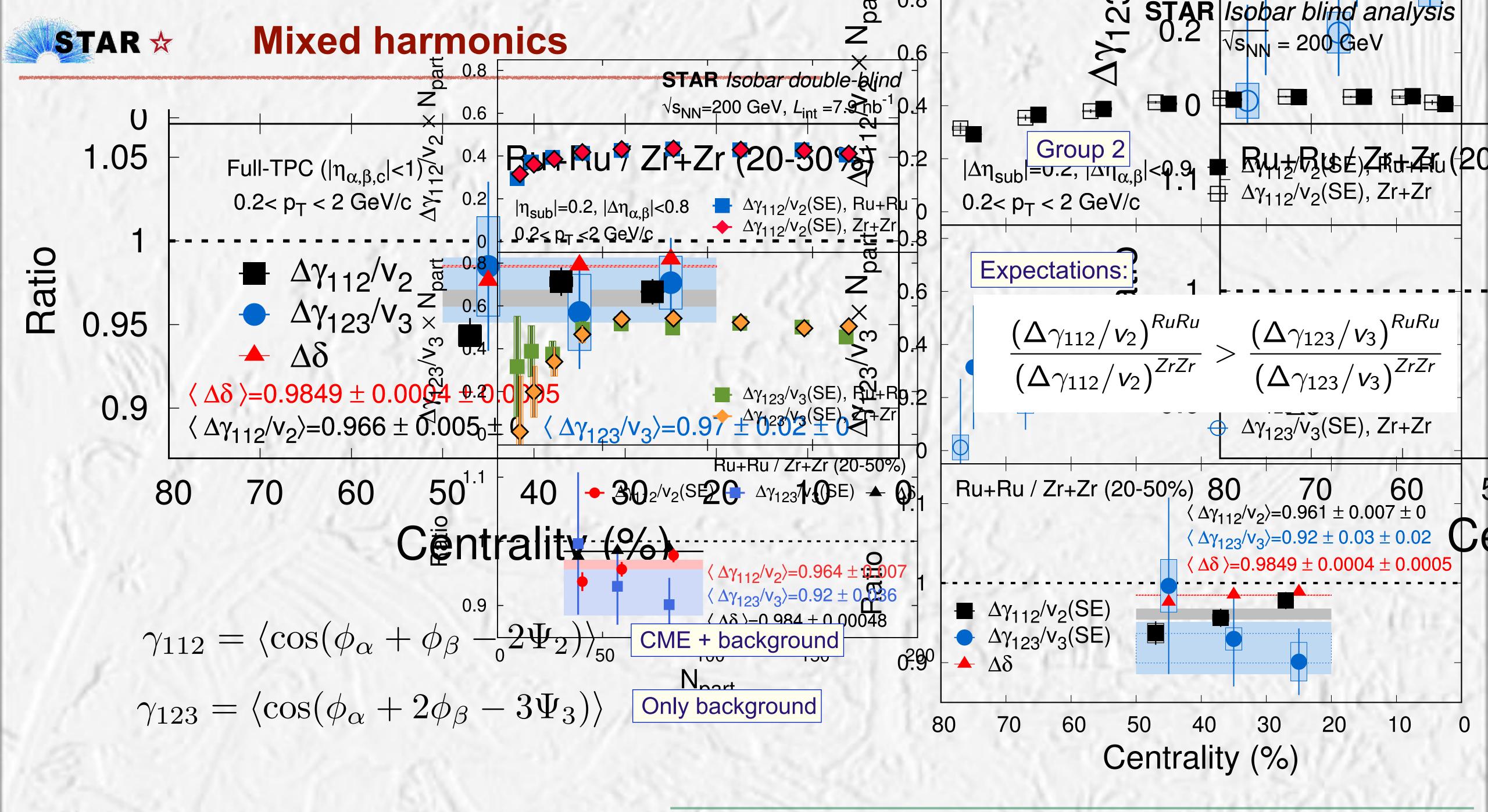
$$= (\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{\text{IN}}) + (\langle a_{1,\alpha} a_{1,\beta} \rangle + B_{\text{OUT}})$$

$$\kappa_{112} \equiv \frac{\Delta \gamma_{112}}{v_2 \, \Delta \delta} \, .$$

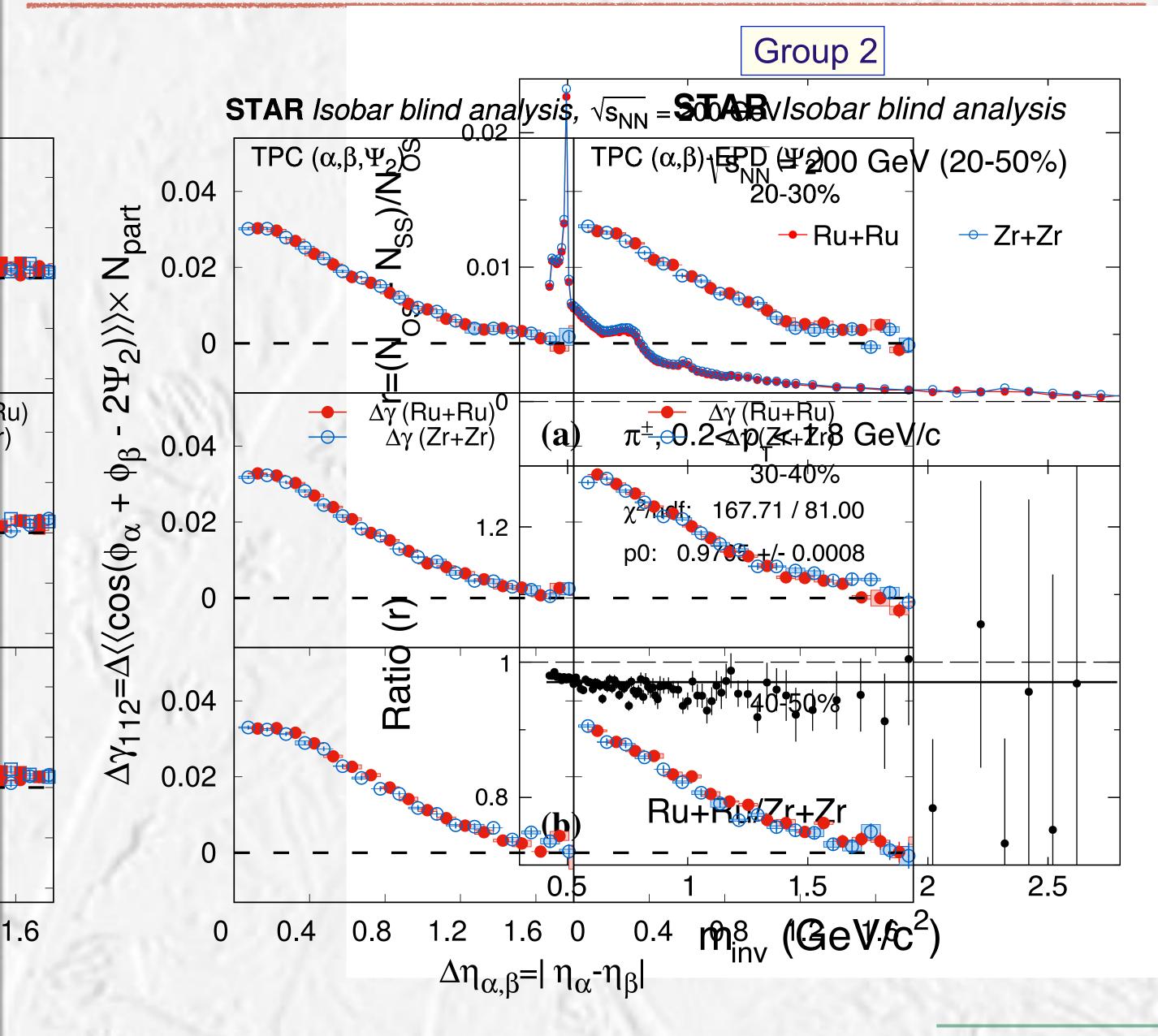
$$\frac{\kappa_{112}^{\rm Ru+Ru}}{\kappa_{112}^{\rm Zr+Zr}} > 1$$

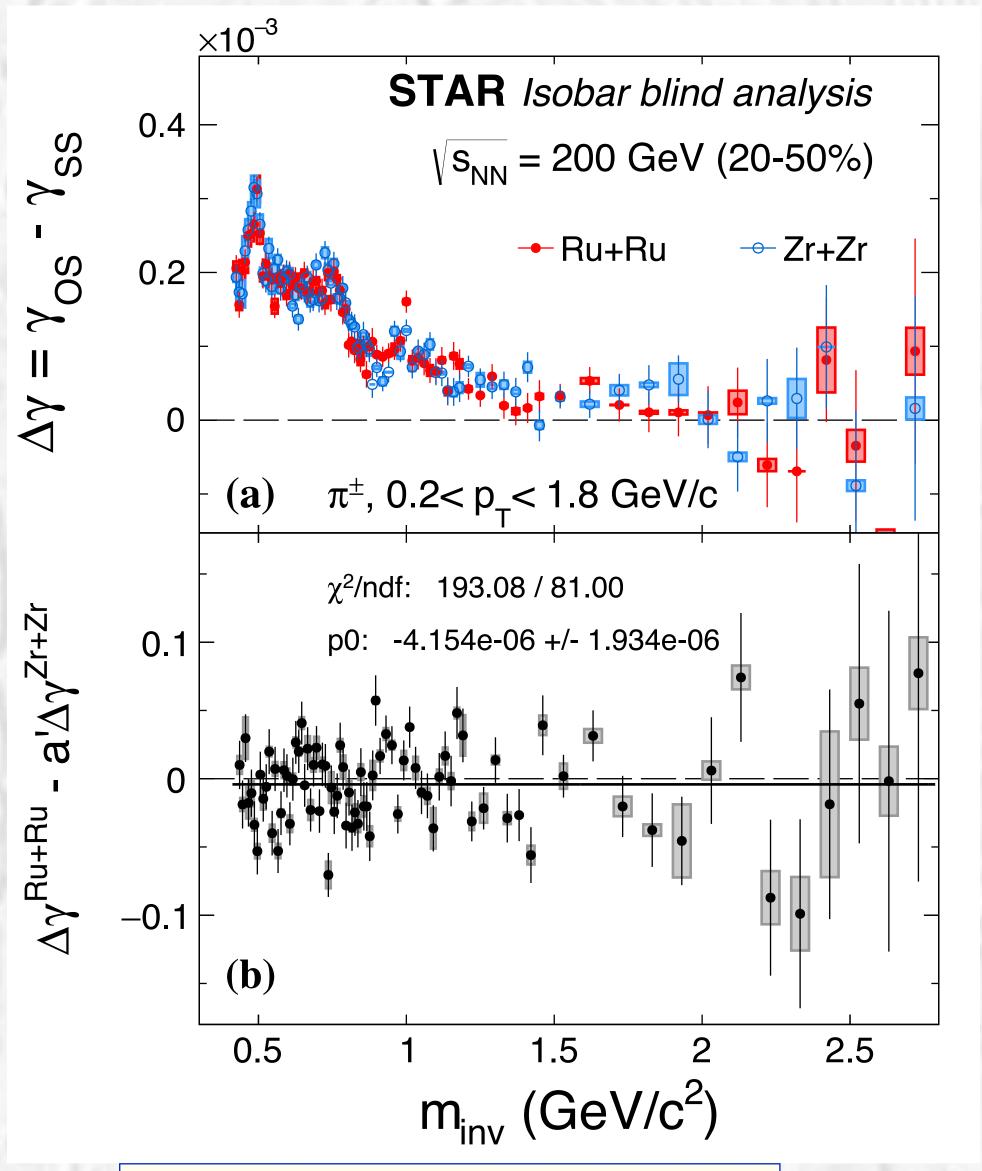
$$\frac{k_2^{\text{Ru}+\text{Ru}}}{k_2^{\text{Zr}+\text{Zr}}} > \frac{k_3^{\text{Ru}+\text{Ru}}}{k_3^{\text{Zr}+\text{Zr}}}$$

Expectations are not met









No obvious enhancement anywhere



STAR & Correlations wrt participant and spectator planes

PHYSICAL REVIEW C 98, 054911 (2018)

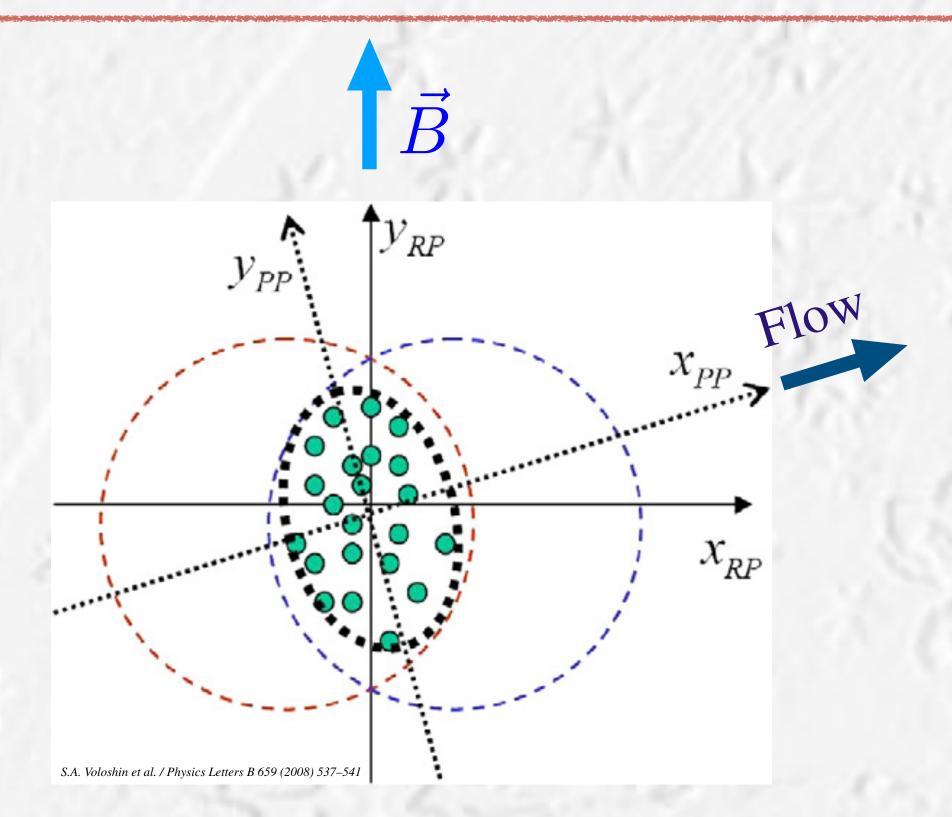


Fig. 1. The definitions of the RP and PP coordinate systems.

Assumption: spectator plane defines the magnetic field direction

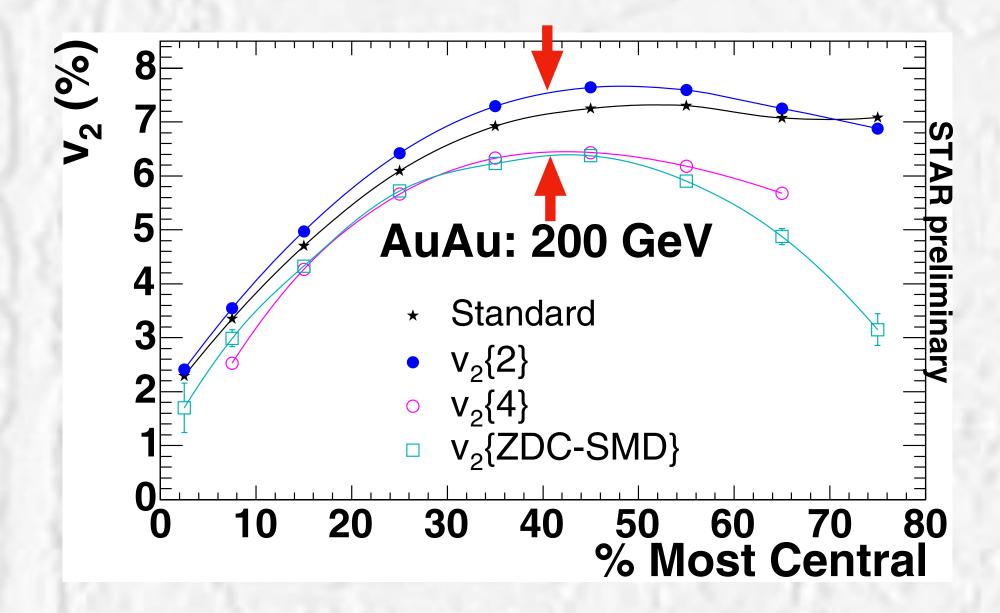
Estimate of the signal from the chiral magnetic effect in heavy-ion collisions from measurements relative to the participant and spectator flow planes

> 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*

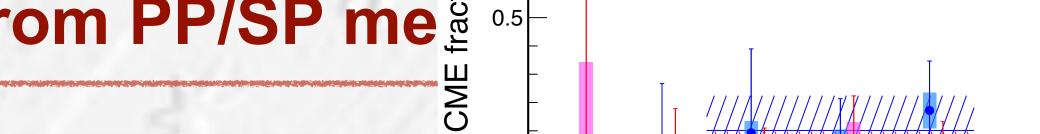
Hao-Jie Xu (徐浩洁)¹, Jie Zhao (赵杰)², Xiao-Bao Wang (王小保)¹, Han-Lin Li (李汉林)³, Zi-Wei Lin (林子威)^{4,5}, Cai-Wan Shen (沈彩万)¹ and Fu-Qiang Wang (王福强)^{1,2} Published 1 July 2018 • © 2018 Chinese Physical Society and the Institute of High Energy

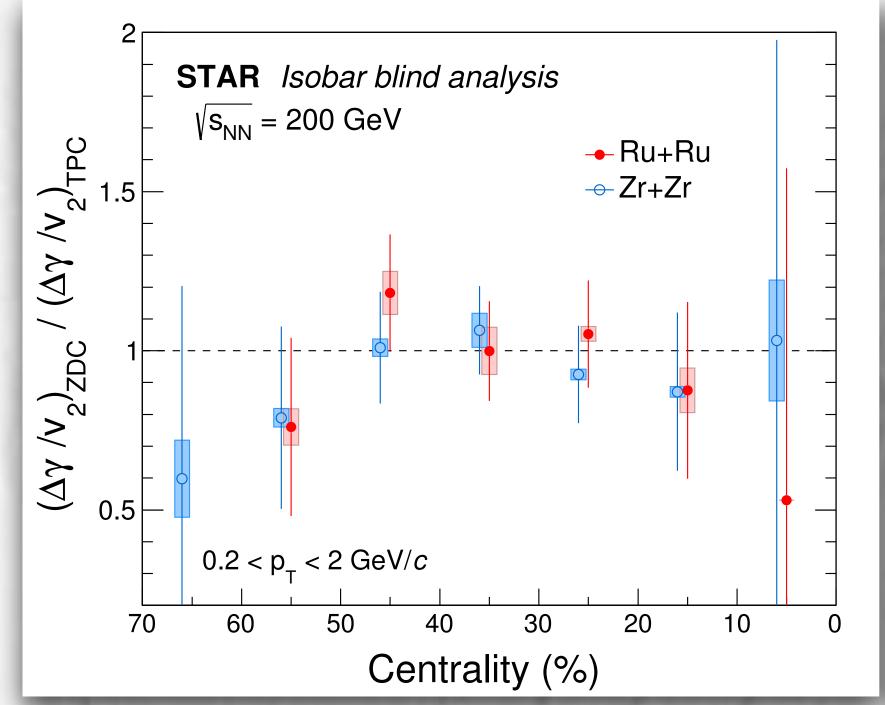
Chinese Physics C, Volume 42, Number 8

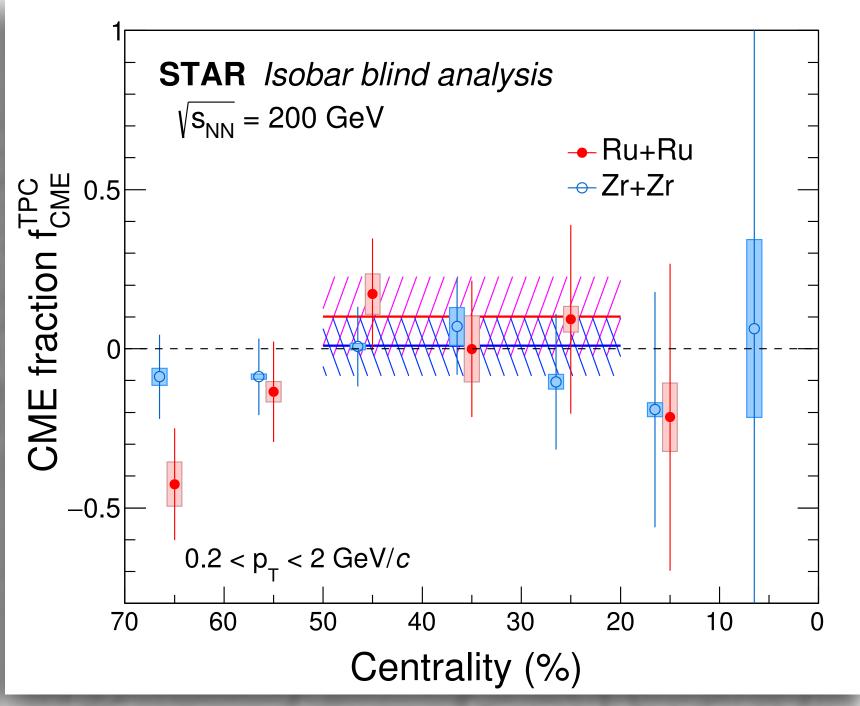


Decorrelation is strong enough to measure the difference in the CME signal

STAR * J_{CME} from PP/SP me is 0.5







0.2<p_{_}<2 GeV/*c*

Group 4 (also done by group 3)

Ru:
$$0.101 \pm 0.123 \text{ (stat.)} \pm 0.023 \text{ (syst.)}$$
 Zr: $0.009 \pm 0.088 \text{ (stat.)} \pm 0.033 \text{ (syst.)}$

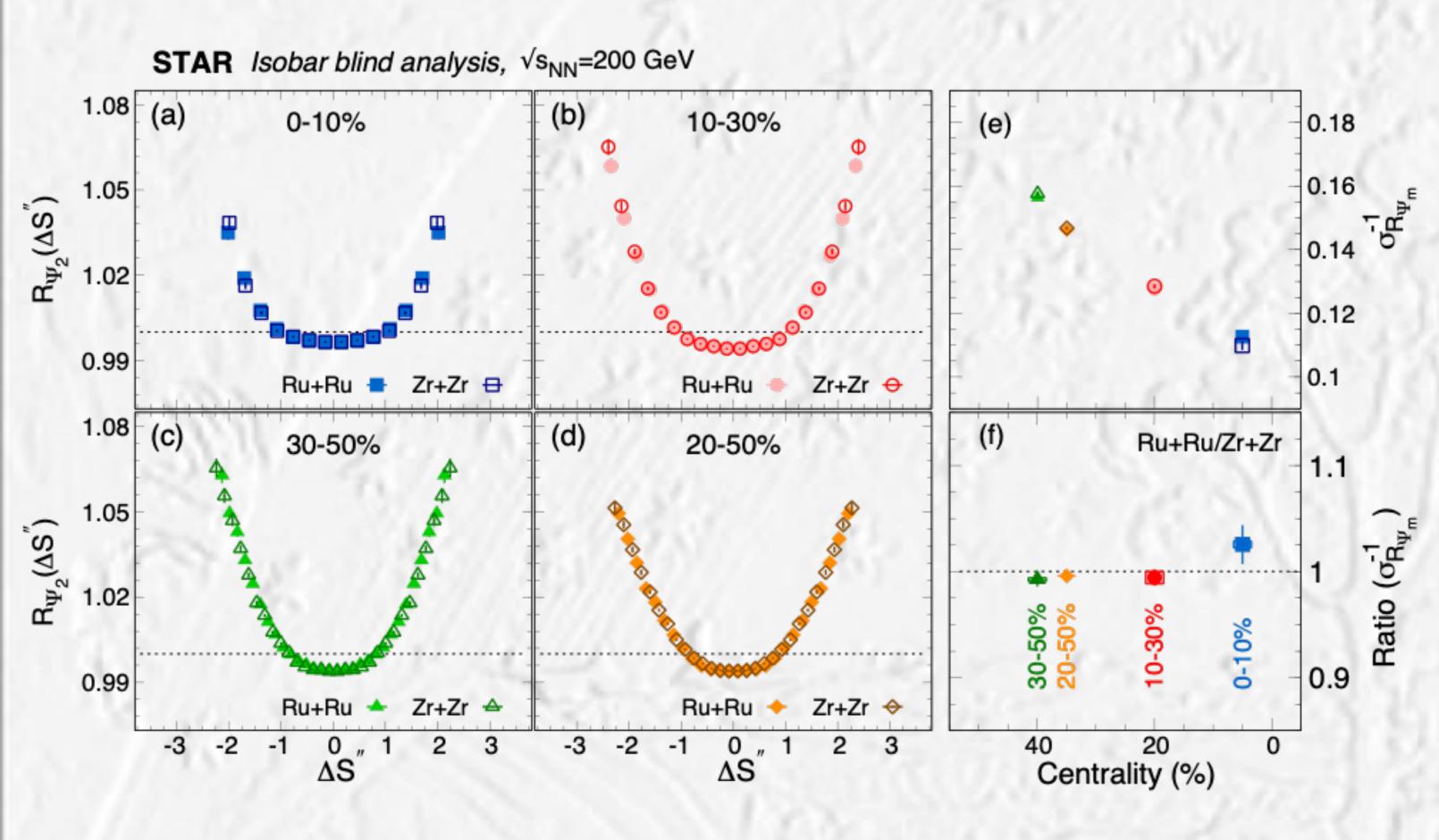
$$\frac{(\Delta \gamma/v_2)_{\text{spectator}}}{(\Delta \gamma/v_2)_{\text{participant}}} = \frac{(\Delta \gamma/v_2)_{\text{ZDC}}}{(\Delta \gamma/v_2)_{\text{TPC}}} = \frac{\Delta \langle \cos(\phi_\alpha + \phi_\beta - \Psi_1^{\text{W}} - \Psi_1^{\text{E}}) \rangle / \langle \cos(2\phi - \Psi_1^{\text{W}} - \Psi_1^{\text{E}}) \rangle}{\Delta \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / \langle \cos(2\phi_\alpha - 2\phi_c) \rangle}.$$

$$\frac{(\Delta\gamma/v_2)_{\rm ZDC}}{(\Delta\gamma/v_2)_{\rm TPC}} = 1 + f_{\rm CME}^{\rm TPC} \left(\frac{v_2^2\{{\rm TPC}\}}{v_2^2\{{\rm ZDC}\}} - 1\right)$$

$$\sqrt{s_{\rm NN}} = 200~{\rm GeV} \qquad 0.2 < p_{\rm T} < 2~{\rm GeV/c}$$

$$page~18 \qquad APS~DNP~meeting,~October~11,~2021$$

R-variable



Group 5

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

$$C_{\Psi_2}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)},$$

$$\Delta S = \frac{\sum_{i=1}^{n^+} w_i^+ \sin(\Delta \varphi_2)}{\sum_{i=1}^{n^+} w_i^+} - \frac{\sum_{i=1}^{n^-} w_i^- \sin(\Delta \varphi_2)}{\sum_{i=1}^{n^-} w_i^-},$$

Predefined CME signature:

$$1/\sigma_{R_{\Psi_2}}(\mathrm{Ru}+\mathrm{Ru}) > 1/\sigma_{\mathrm{R}_{\Psi_2}}(\mathrm{Zr}+\mathrm{Zr})$$

No CME signature that satisfies the predefined criteria observed

For the relation to $\Delta \gamma$ see S. Choudhury (Fudan U.), et al. e-Print: 2105.06044

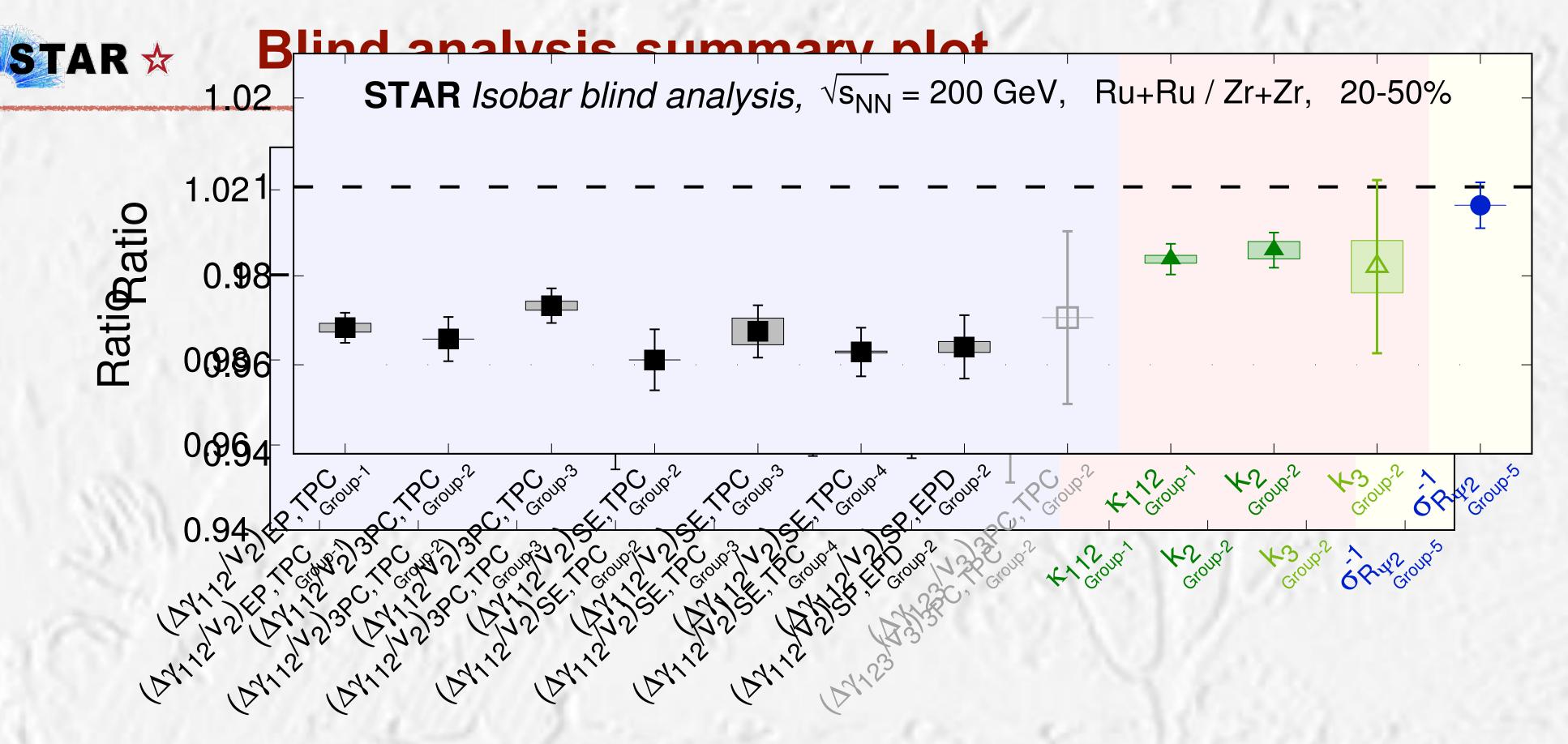
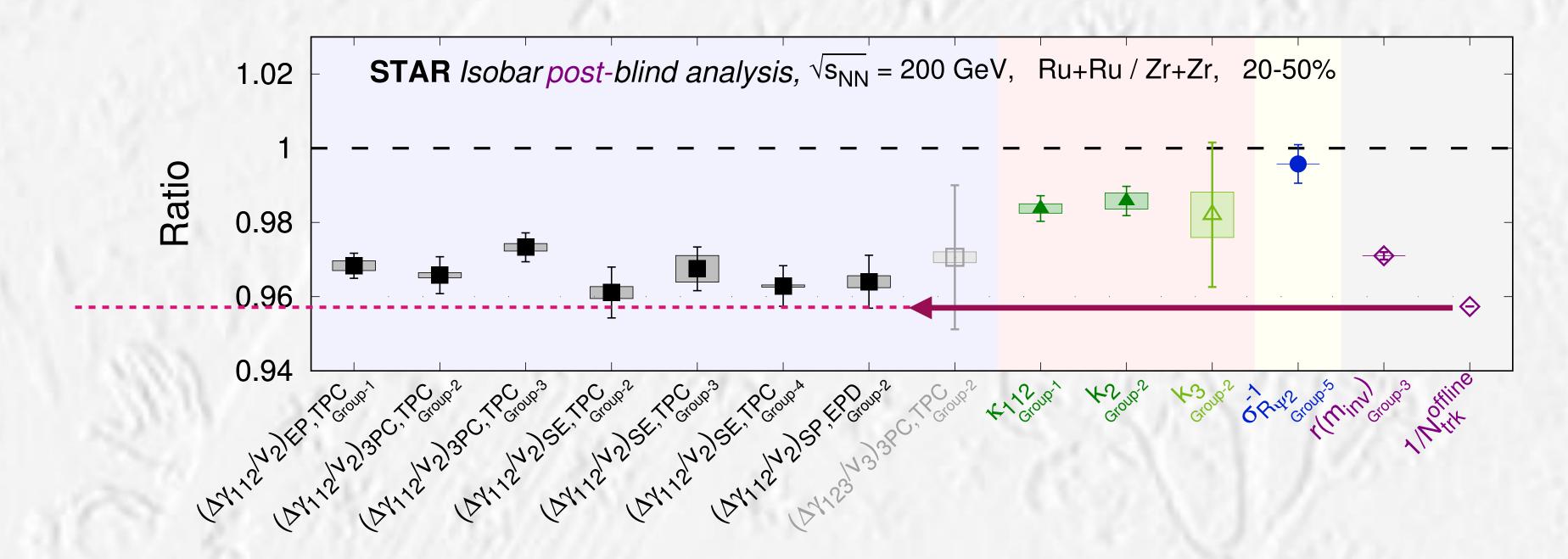


FIG. 26. Compilation of results from the blind analysis. Only results contrasting between the two isobar systems are shown. Results are shown in terms of the ratio of measures in Ru+Ru collisions over Zr+Zr collisions. Solid dark symbols show CME-sensitive measures whereas open light symbols show counterpart measures that are supposed to be insensitive to CME. The vertical lines indicate statistical uncertainties whereas boxes indicate systematic uncertainties. The colors in the background are intended to separate different types of measures. The fact that CME-sensitive observable ratios lie below unity leads to the conclusion that no predefined CME signatures are observed in this blind analysis.

No CME signature that satisfies the predefined criteria observed



Summary plot (post-blinding)



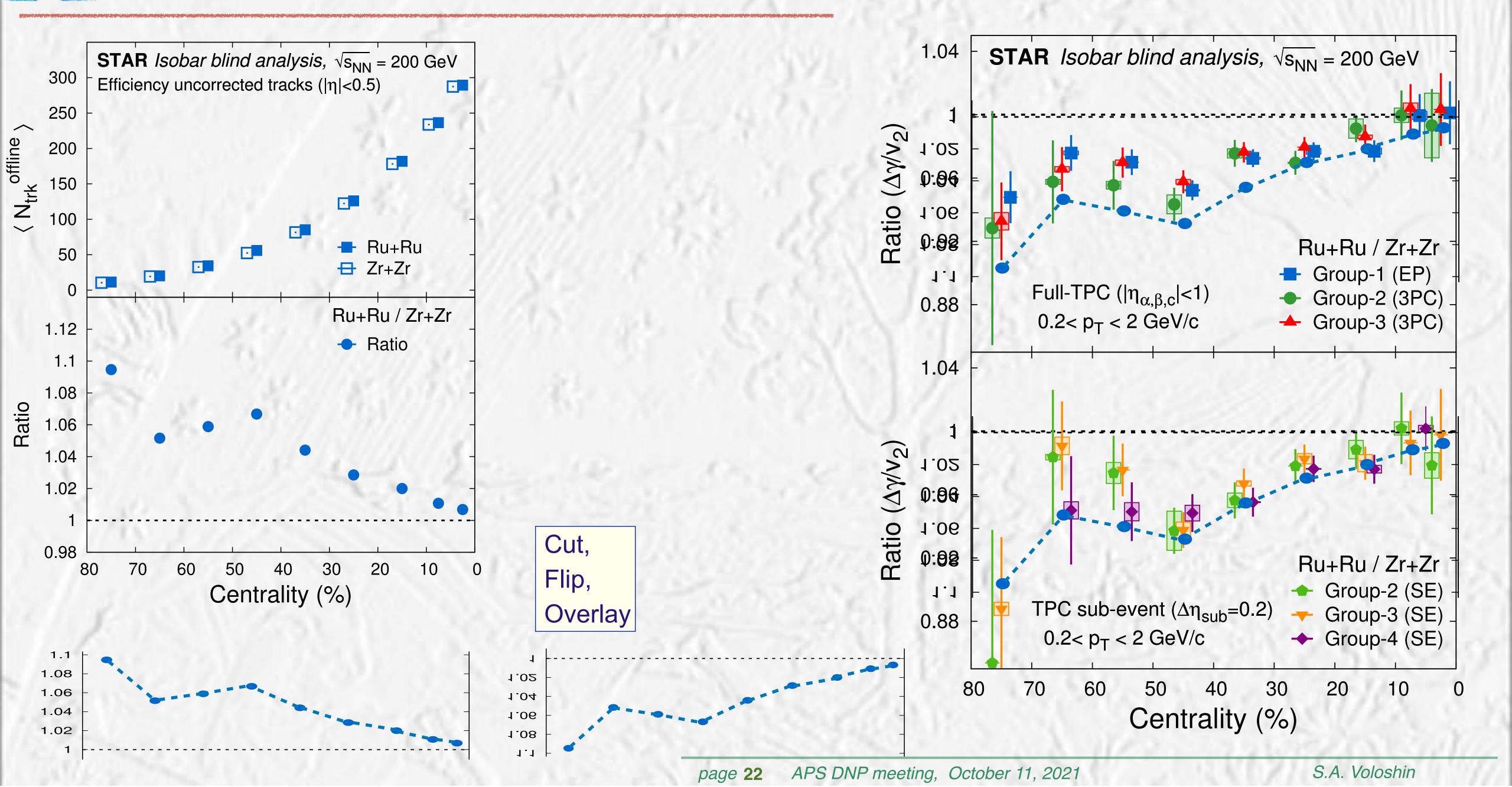
Two most right points added for post-blinding discussion

FIG. 27. Compilation of post-blinding results. This figure is largely the same as Fig. 26 with the following differences: numerical changes in the results from the new run-by-run QA algorithm are treated as an additional systematic uncertainty added in quadrature, and two data points (open markers) have been added on the right to indicate the ratio of inverse multiplicities $(N_{\text{trk}}^{\text{offline}})$ and the ratio of relative pair multiplicity difference (r) as explained in the text.

Any two particle correlation due to small clusters scale as 1/multiplicity! A better comparison might be for $[N_{ch}^{\rm Ru}(\Delta\gamma/v_2)_{\rm Ru}]/[N_{ch}^{\rm Zr}(\Delta\gamma/v_2)_{\rm Zr}]$

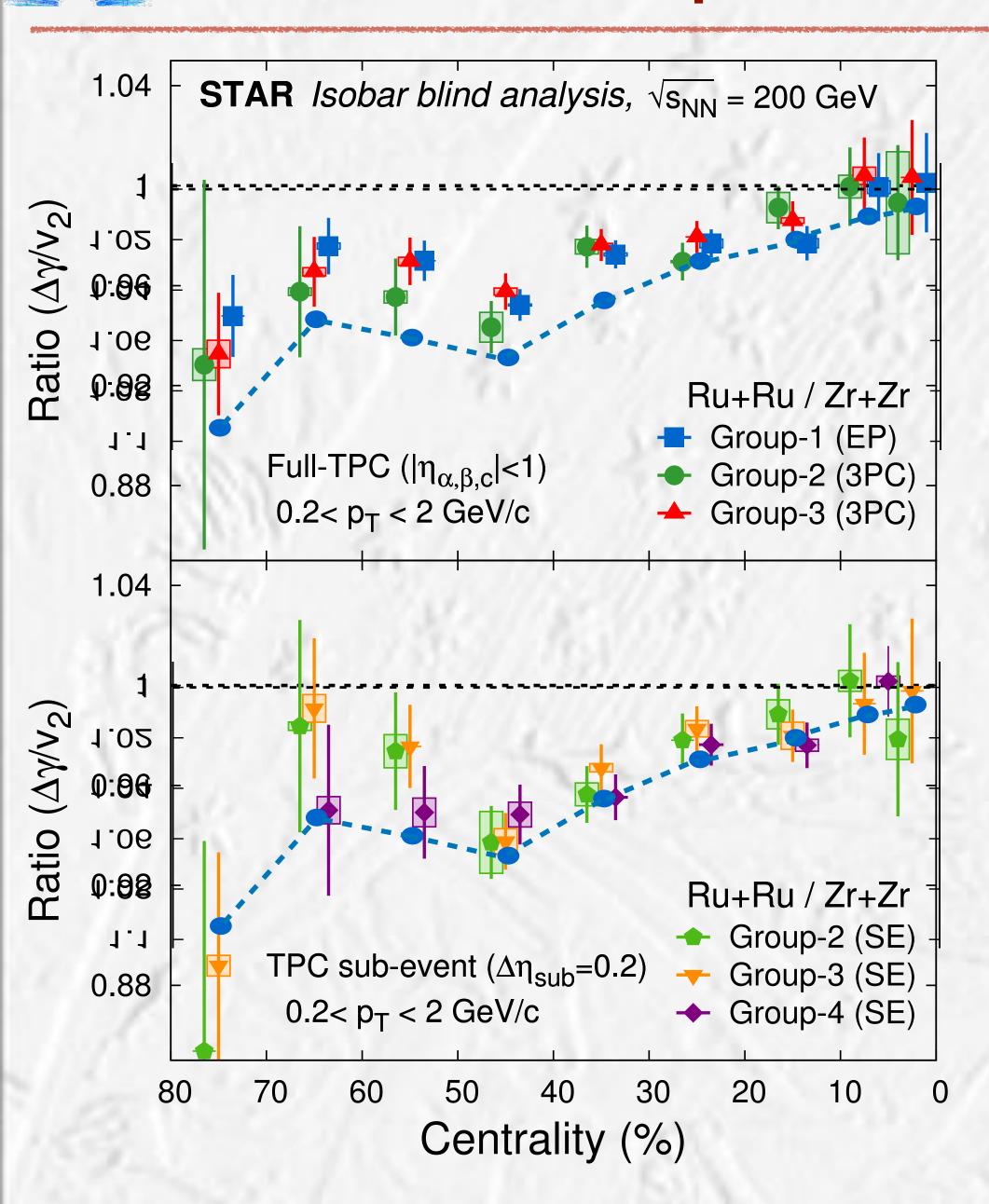


Multiplicity scaling





Toward 1% precision



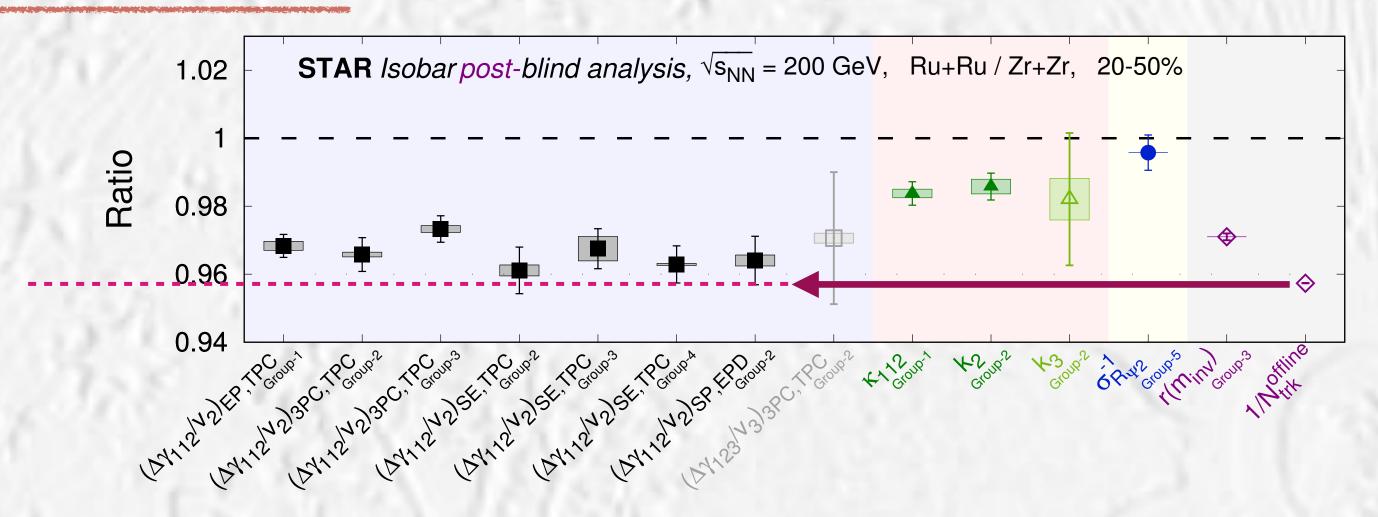


FIG. 27. Compilation of post-blinding results. This figure is largely the same as Fig. 26 with the following differences: numerical changes in the results from the new run-by-run QA algorithm are treated as an additional systematic uncertainty added in quadrature, and two data points (open markers) have been added on the right to indicate the ratio of inverse multiplicities $(N_{\rm trk}^{\rm offline})$ and the ratio of relative pair multiplicity difference (r) as explained in the text.

To establish exact limits, one need to resolve/understand systematics in the ratio

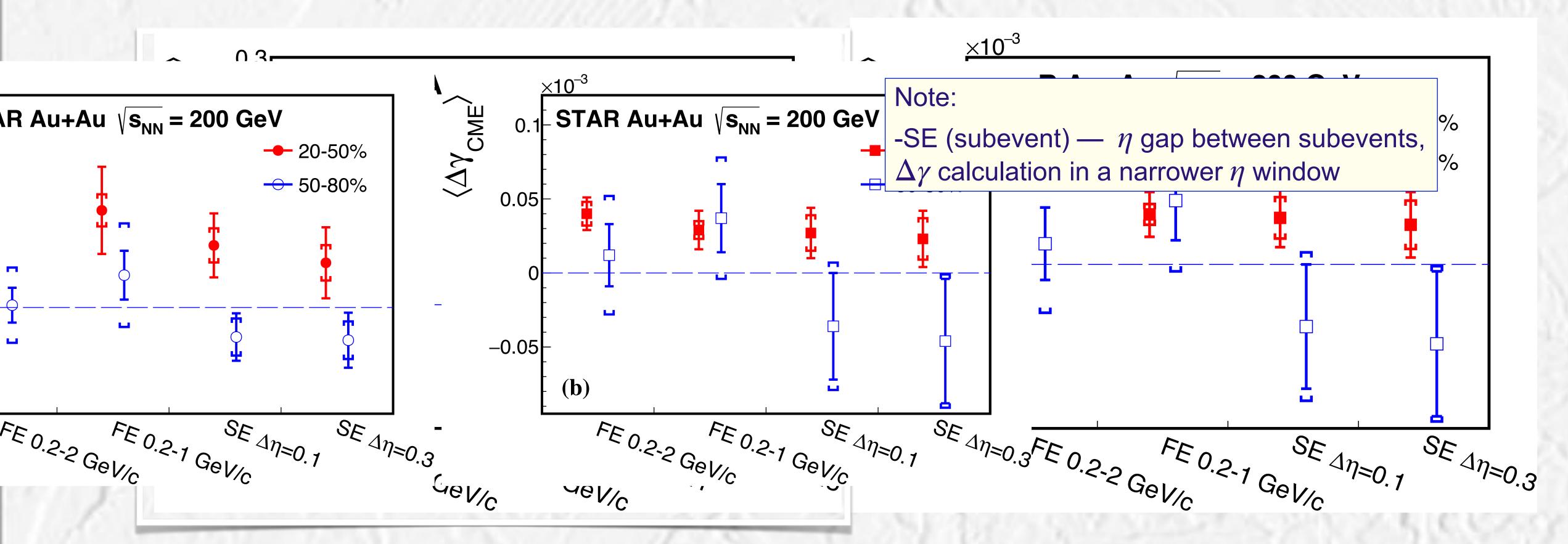
$$\frac{(\Delta \gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta \gamma/v_2)_{\mathrm{Zr+Zr}}}$$

up to a (sub)percent level (note difference between results from different groups, "Full" vs "SE").

STAR \Leftrightarrow STAR: f_{CME} from $\Delta \gamma$, PP/SP

Search for the chiral magnetic effect via charge-dependent azimuthal correlations relative to spectator and participant planes in Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$

STAR Collaboration arXiv:2106.09243v1 [nucl-ex] 17 Jun 2021



Error bars show statistical uncertainties; the caps indicate the systematic uncertainties.



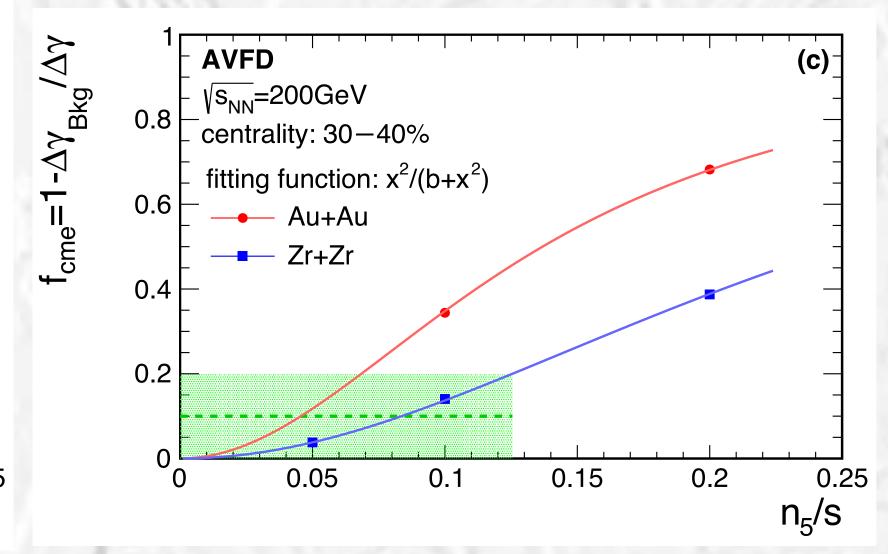
Implications. Conclusions

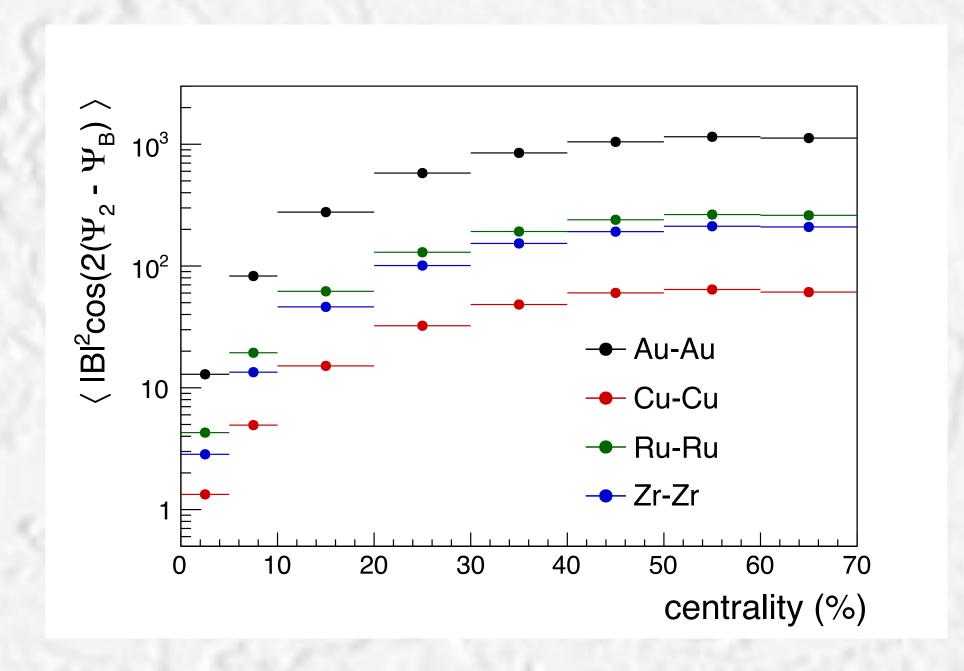
STAR isobars:

- No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.
- Accurate upper limits for $f_{\rm CME}$ are being evaluated.

Isobar results do not exclude a bigger signal in AuAu. The signal could be significantly smaller in such (relatively small nuclei) collisions

Y. Feng, Y. Lin, J. Zhao, and F. Wang, Phys. Lett. B 820, 136549 (2021),





The signal could depend strongly on the system size.

Calculations by A. Dobrin (private communication)

Isobar run was a real success (not only for the CME search) Should we request for more? $^{136}_{54}$ Ce, $^{136}_{50}$ Xe?



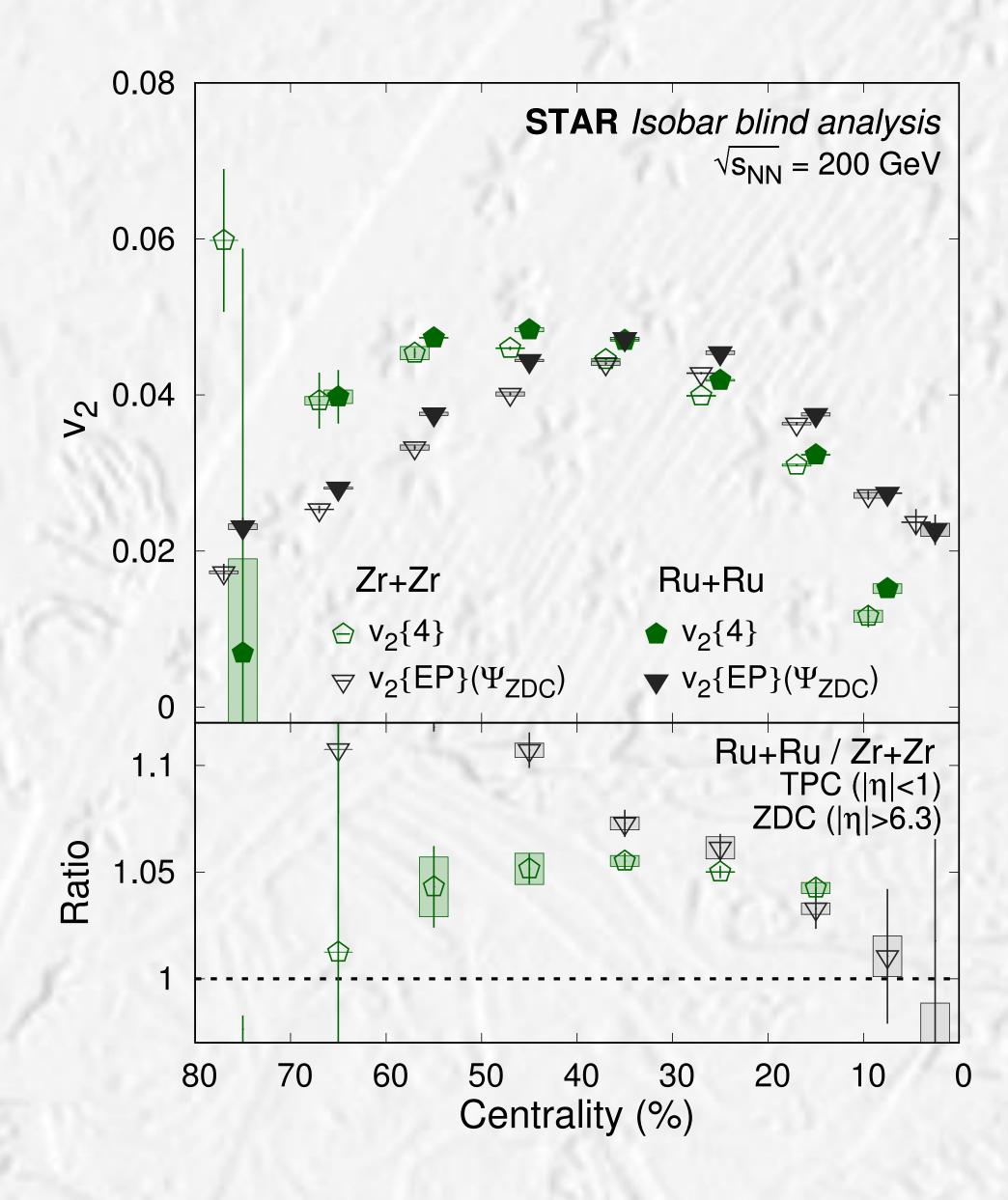
Acknowledgements

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EXTRA SLIDES

$v_2\{2\}, v_2\{ZDC\}$





Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 200$ GeV by the STAR Collaboration at RHIC

STAR Collaboration arXiv:2109.00131v1 [nucl-ex] 1 Sep 2021

The chiral magnetic effect (CME) is predicted to occur as a consequence of a local violation of \mathcal{P} and \mathcal{CP} symmetries of the strong interaction amidst a strong electro-magnetic field generated in relativistic heavy-ion collisions. Experimental manifestation of the CME involves a separation of positively and negatively charged hadrons along the direction of the magnetic field. Previous measurements of the CME-sensitive charge-separation observables remain inconclusive because of large background contributions. In order to better control the influence of signal and backgrounds, the STAR Collaboration performed a blind analysis of a large data sample of approximately 3.8 billion isobar collisions of $^{96}_{44}$ Ru+ $^{96}_{44}$ Ru and $^{96}_{40}$ Zr+ $^{96}_{40}$ Zr at $\sqrt{s_{NN}} = 200$ GeV. Prior to the blind analysis, the CME signatures are predefined as a significant excess of the CME-sensitive observables in Ru+Ru collisions over those in Zr+Zr collisions, owing to a larger magnetic field in the former. A precision down to 0.4% is achieved, as anticipated, in the relative magnitudes of the pertinent observables between the two isobar systems. Observed differences in the multiplicity and flow harmonics at the matching centrality indicate that the magnitude of the CME background is different between the two species. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.