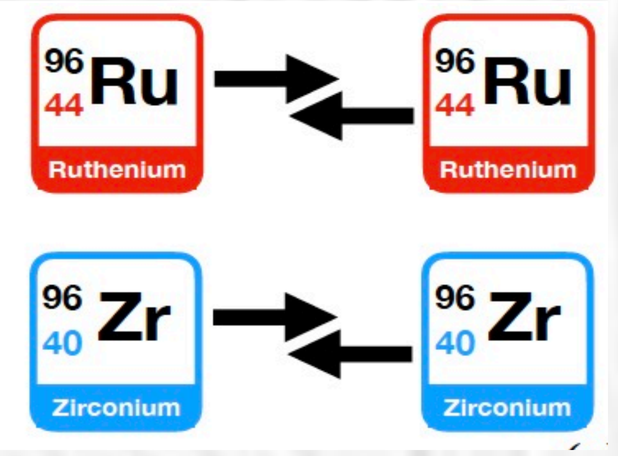
# Search for the Chiral Magnetic Effect: comments on the STAR group-4 results




*Sergei A. Voloshin* WAYNE STATE UNIVERSITY

*Group-4:*
Takafumi Niida (U. of Tsukuba)
Sergei Voloshin (Wayne State U.)

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

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

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

Outline:

*Group-4 specifics*:
- $\Delta\gamma/v_2$ [Ru] / [Zr]
- [SP] / [PP]

Comparison to other groups

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# Isobar collisions

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

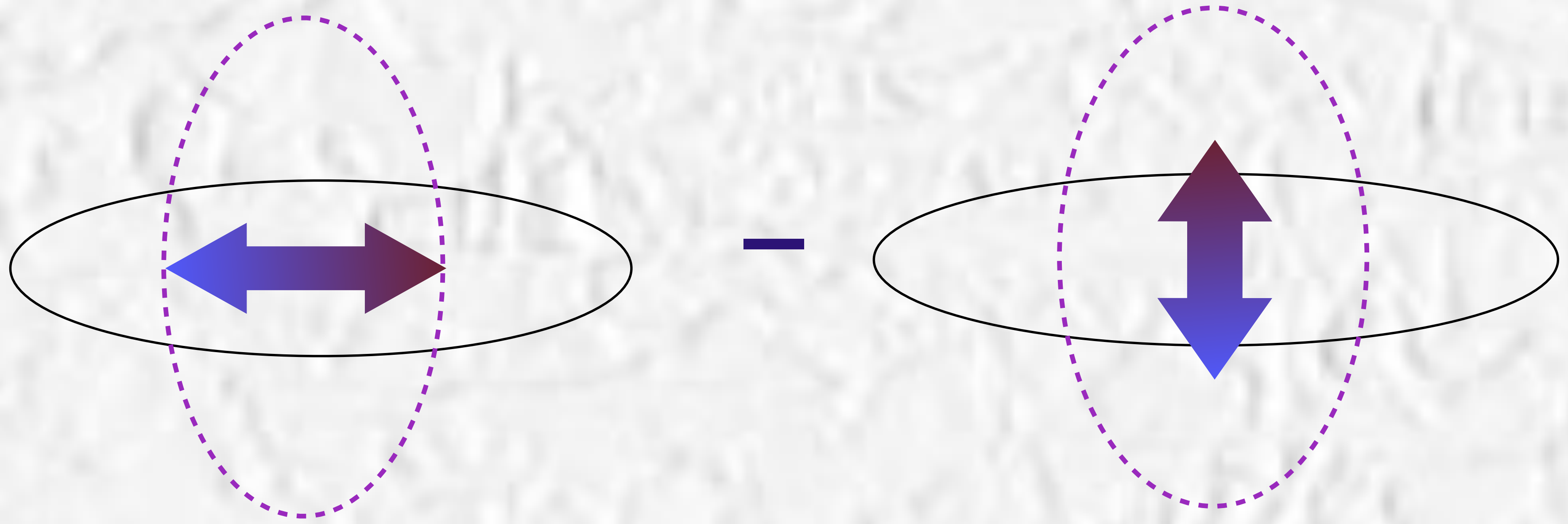
Suggestion of using isobar beams
$^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$ and $^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$
to disentangle CME signal from BG

Goal: $f_{\mathrm{CME}} = \Delta\gamma^{\mathrm{CME}}/\Delta\gamma$

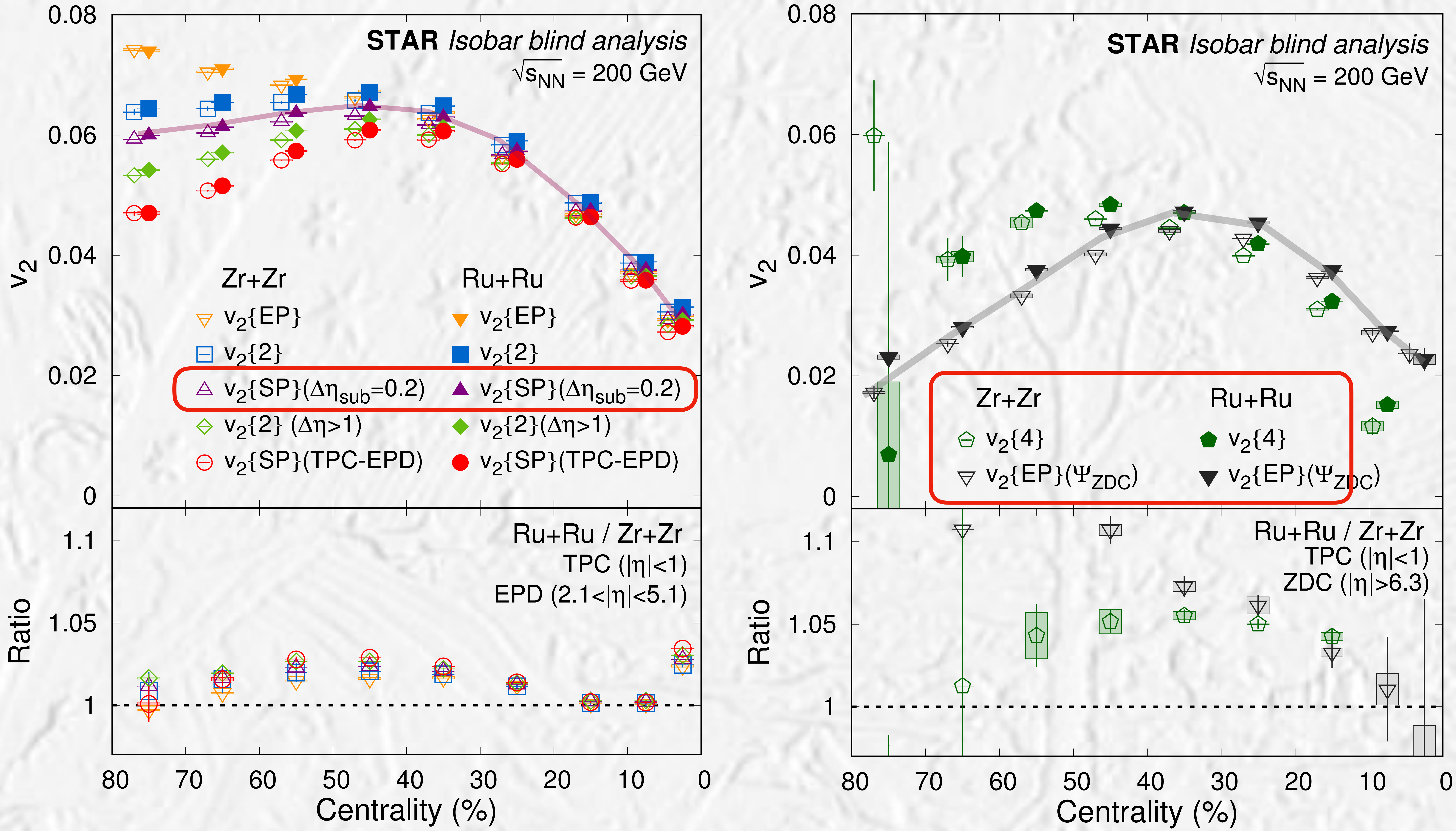
$$\frac{(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}}}{(\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}} \approx 1 + f_{\mathrm{CME}}^{\mathrm{Zr+Zr}}\underbrace{[(B_{\mathrm{Ru+Ru}}/B_{\mathrm{Zr+Zr}})^2 - 1]}_{\approx 0.18}$$

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

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

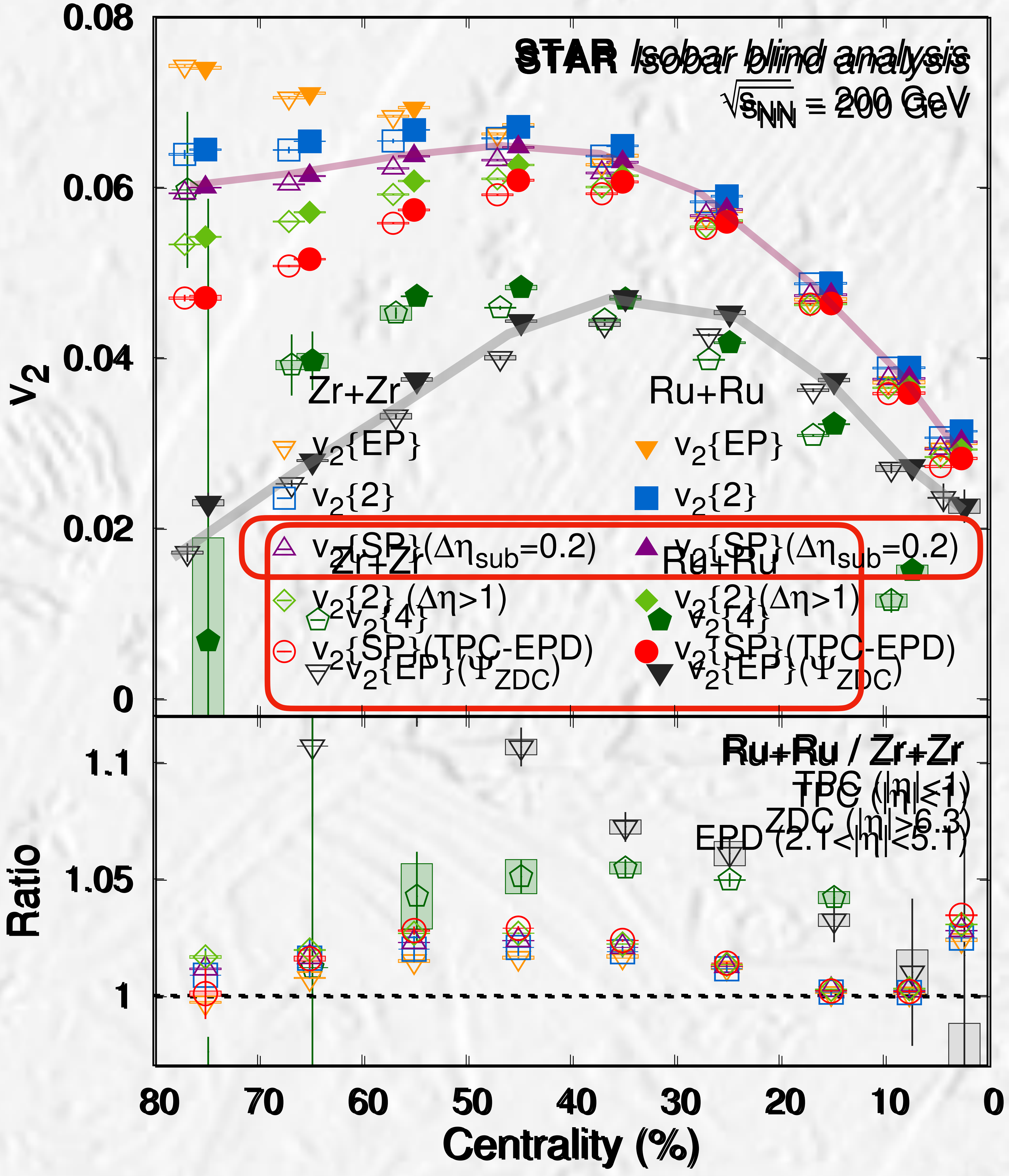


# $v_2\{2\}$, $v_2\{ZDC\}$




Lines added to guide the eye

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




$$v_2\{\mathrm{TPC}\} = \sqrt{\langle \cos(2\phi_\alpha^{\mathrm{E}} - 2\phi_\alpha^{\mathrm{W}}) \rangle}$$

*Group-4 specifics*:

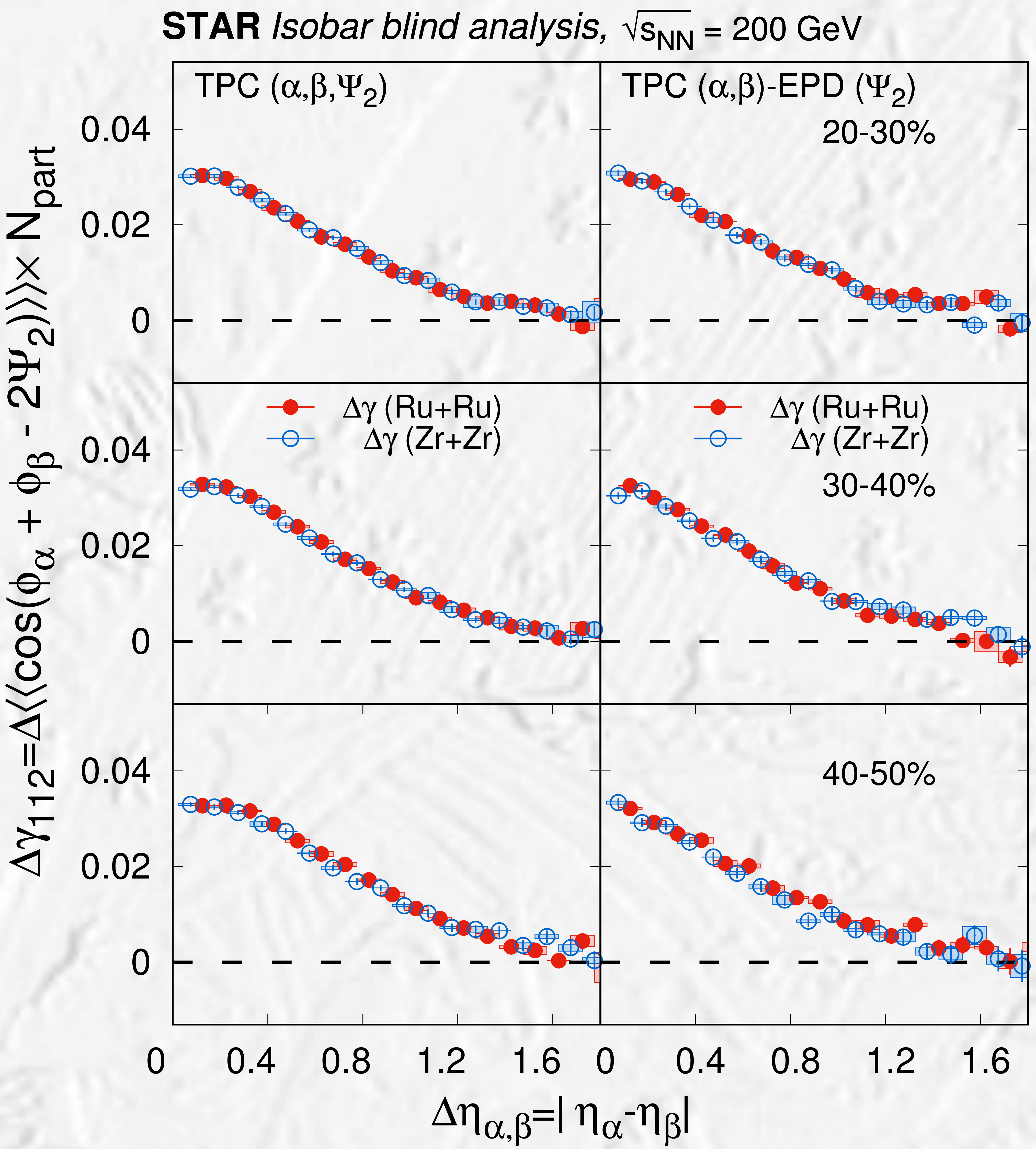
- default: $v_2$ from same charge correlations (usually suppresses > 50% of nonflow)
- systematics includes "all charges", larger $\Delta\eta$ gaps

$$v_2\{\mathrm{ZDC}\} = \frac{\langle \cos(2\phi_\alpha - \Psi_1^{\mathrm{E}} - \Psi_1^{\mathrm{E}}) \rangle}{\langle \cos(\Psi_1^{\mathrm{W}} - \Psi_1^{\mathrm{E}}) \rangle}$$

*Group-4 specifics*:

Using this approach allows to avoid "extrapolation" of the RP resolution from sub- to full event (usually done assuming Gaussian distribution of the flow vectors) as well as a similar "extrapolation" from the first harmonic to the second harmonic

# $\Delta\gamma$ vs $\Delta\eta_{\alpha\beta}$




*Group-4 specifics*:
- Calculates $\Delta\gamma$ only in subevents (default values $0.1 < |\eta| < 1.0$)

Restricting $\Delta\gamma$ calculation to about half of the entire $\Delta\eta$ region increases the "signal" for 30-50%

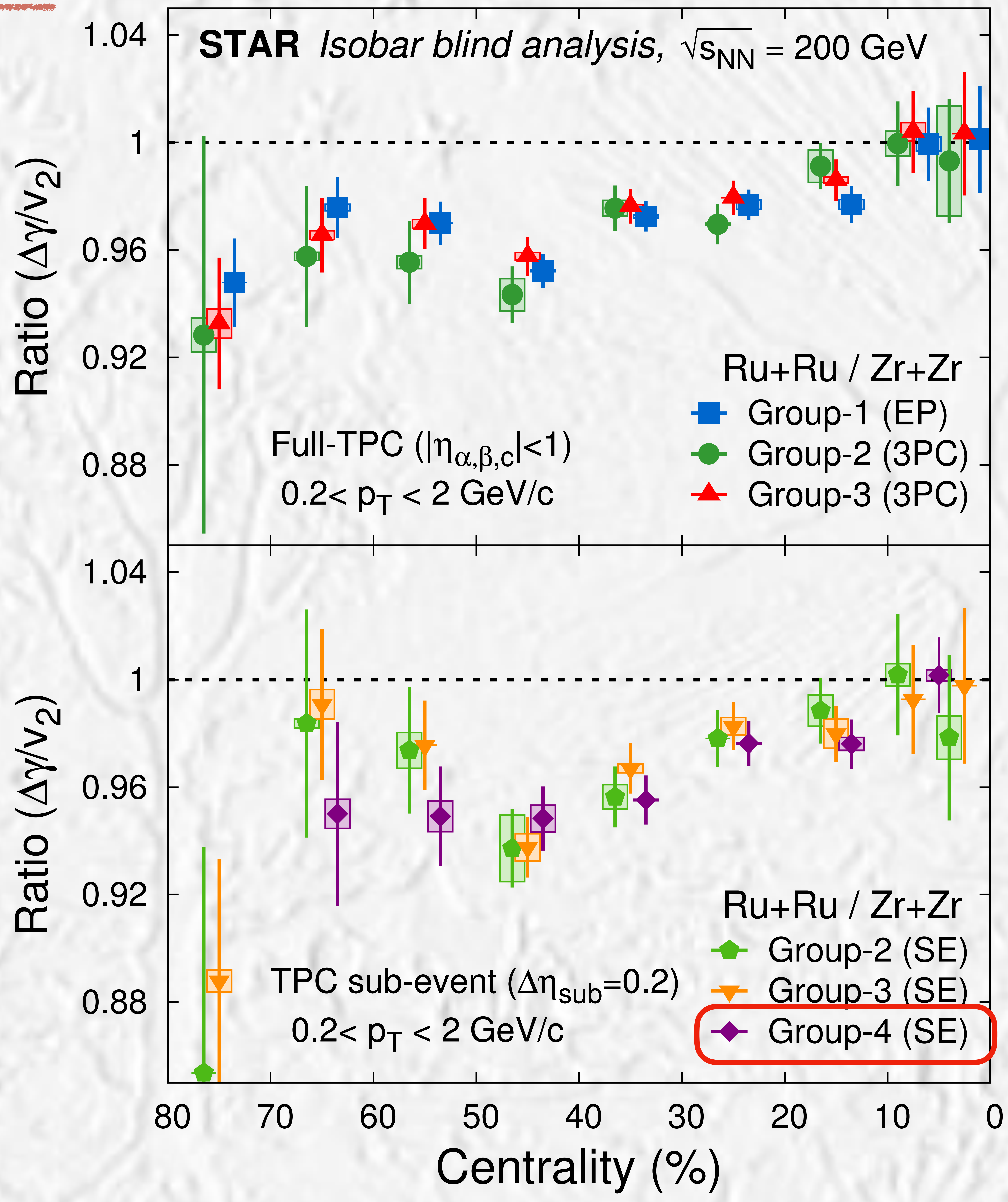
Note that the CME and BG might have different dependence on $\Delta\eta_{\alpha\beta}$

# $(\Delta\gamma/v_2)$

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

Note:
- The calculation of the double ratio does not require knowledge of the Reaction Plane resolution.
- SE (subevent) — $\eta$ gap between subevents, $\Delta\gamma$ calculation in a narrower $\eta$ window

*Group-4 specifics*:
- default: $v_2$ from same charge correlations (usually suppresses > 50% of nonflow)
- systematics includes:
  - "all charges",
  - larger $\Delta\eta$ gaps



# Summary plot (post-blinding)

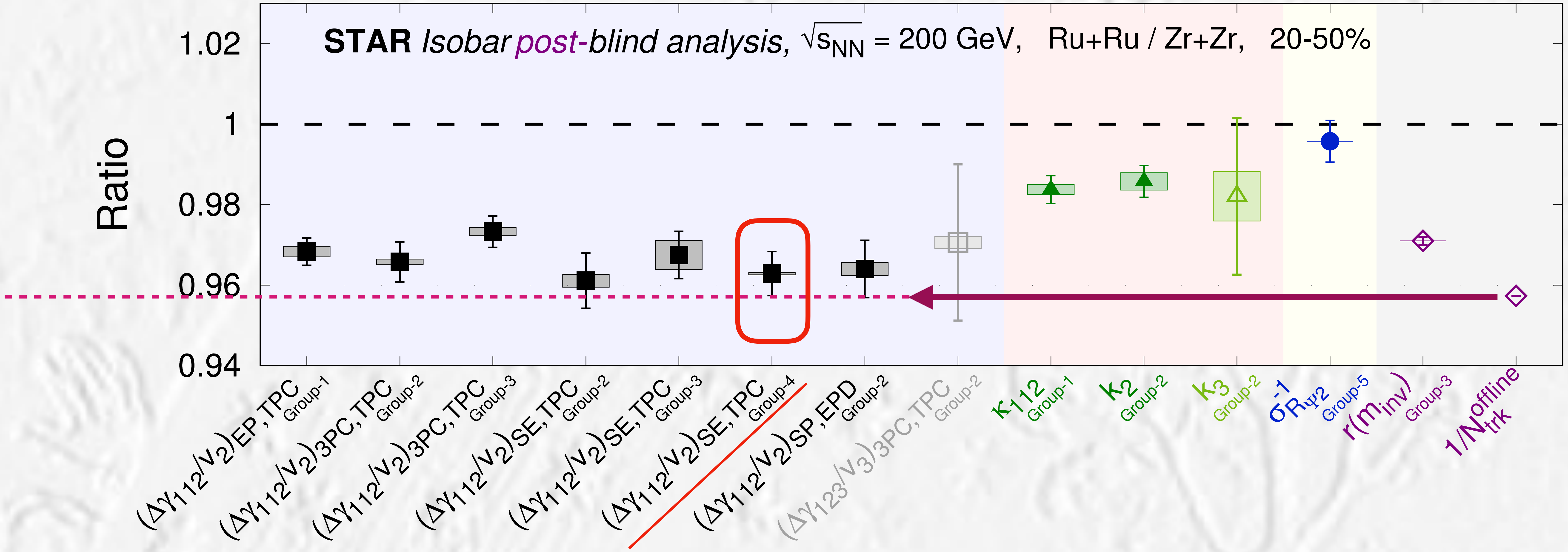


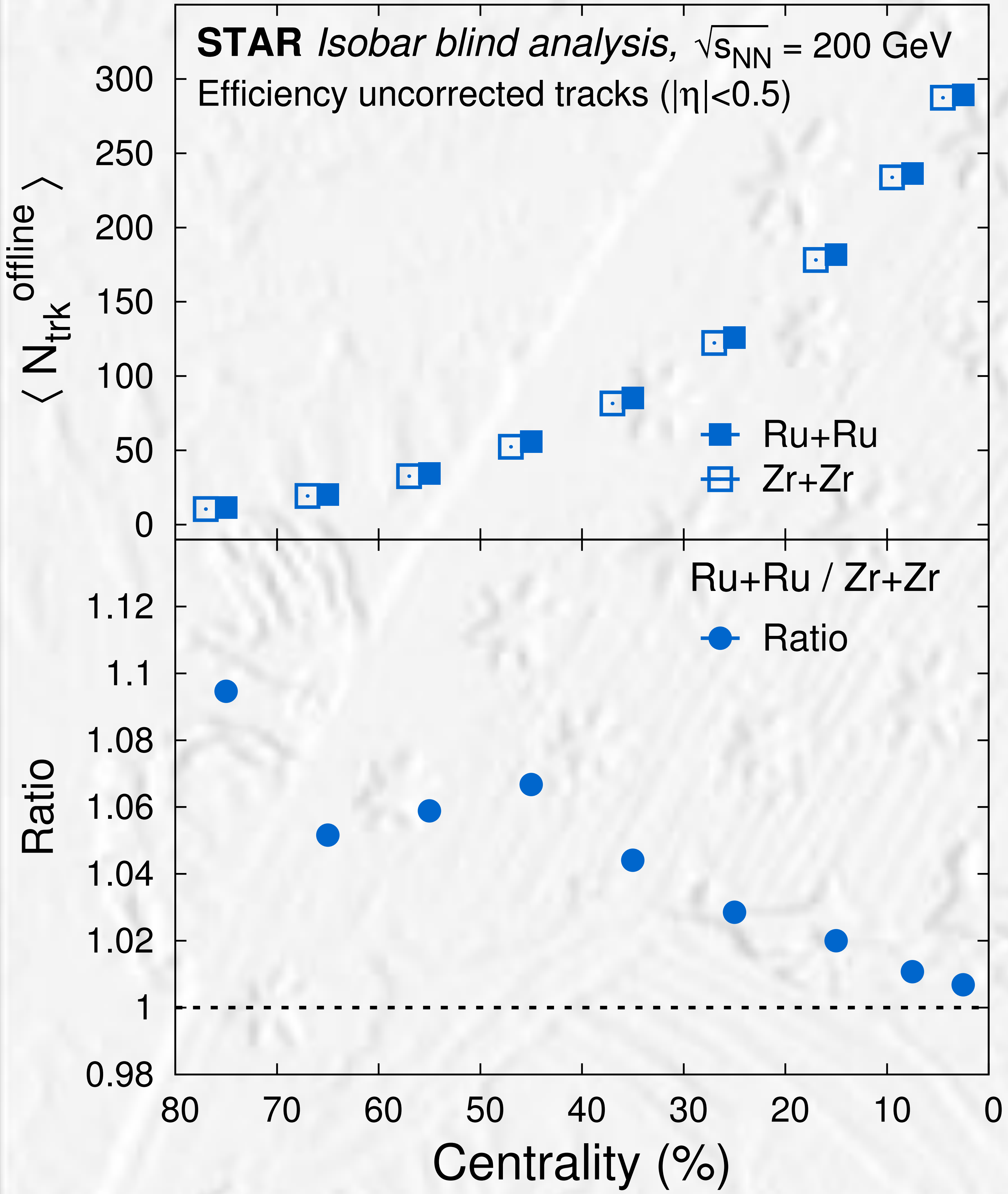

FIG. 27. Compilation of post-blinding results. This figure is largely the same as Fig. 26 with the following differences: numerical changes in the results from the new run-by-run QA algorithm are treated as an additional systematic uncertainty added in quadrature, and two data points (open markers) have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

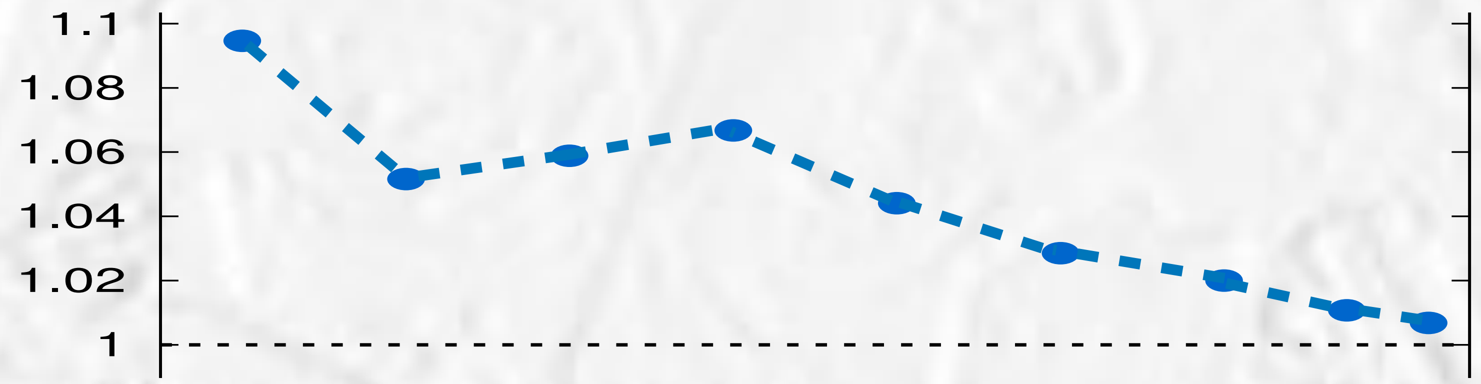
Two most right points added for post-blinding discussion

Any two particle correlation due to small clusters scale as 1/multiplicity!

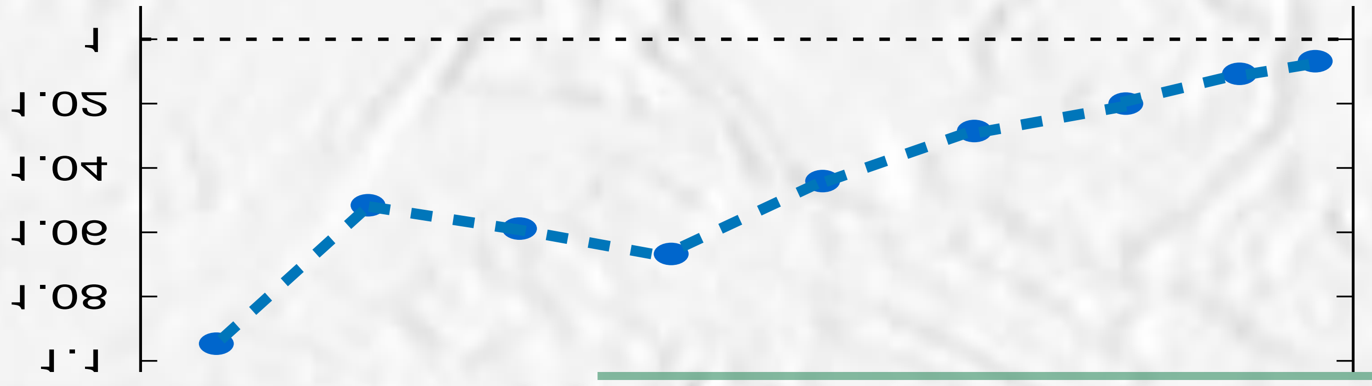
A better comparison might be for $[N^{\rm Ru}_{ch}(\Delta\gamma/v_2)_{\rm Ru}]/[N^{\rm Zr}_{ch}(\Delta\gamma/v_2)_{\rm Zr}]$

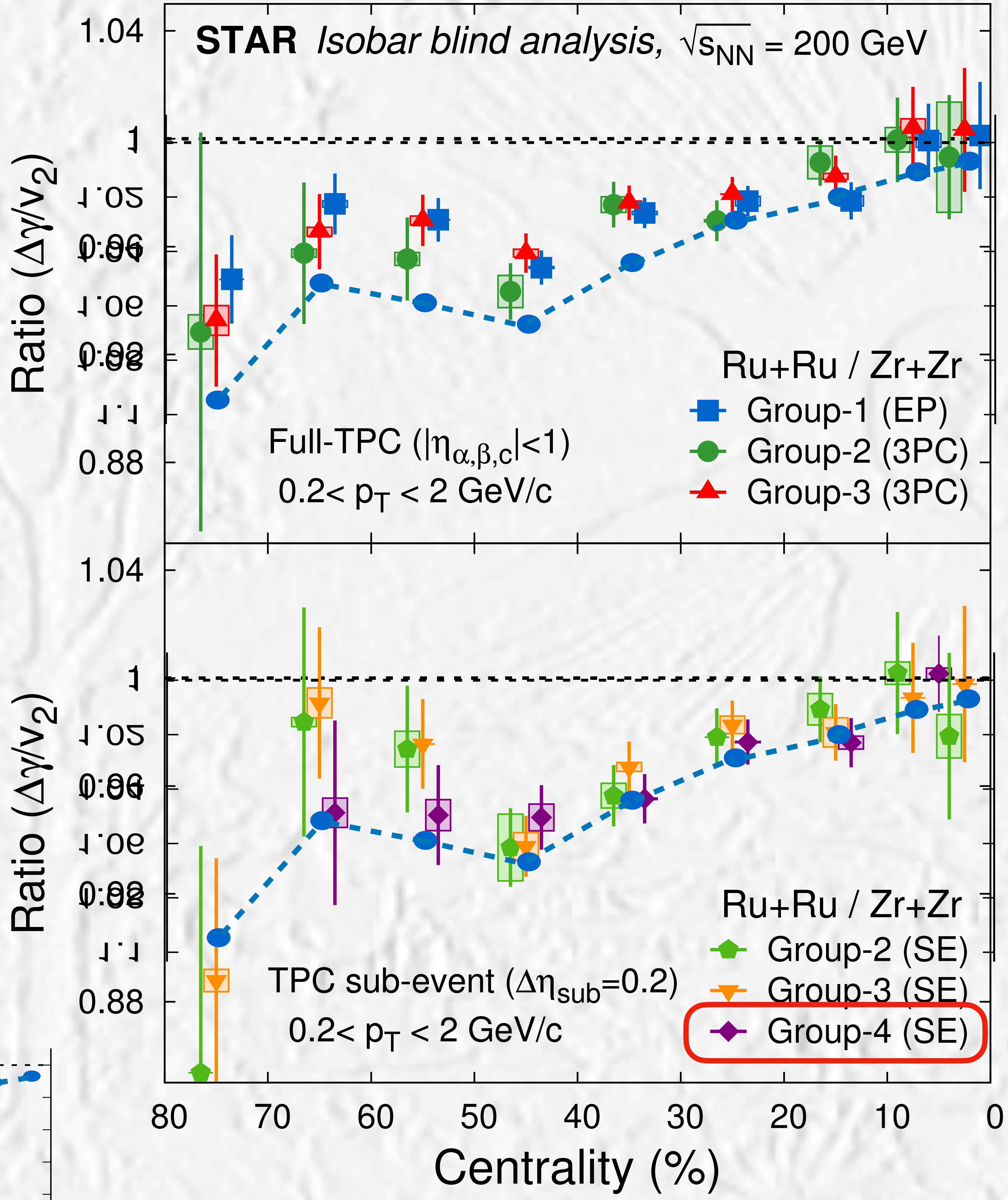
# Multiplicity scaling



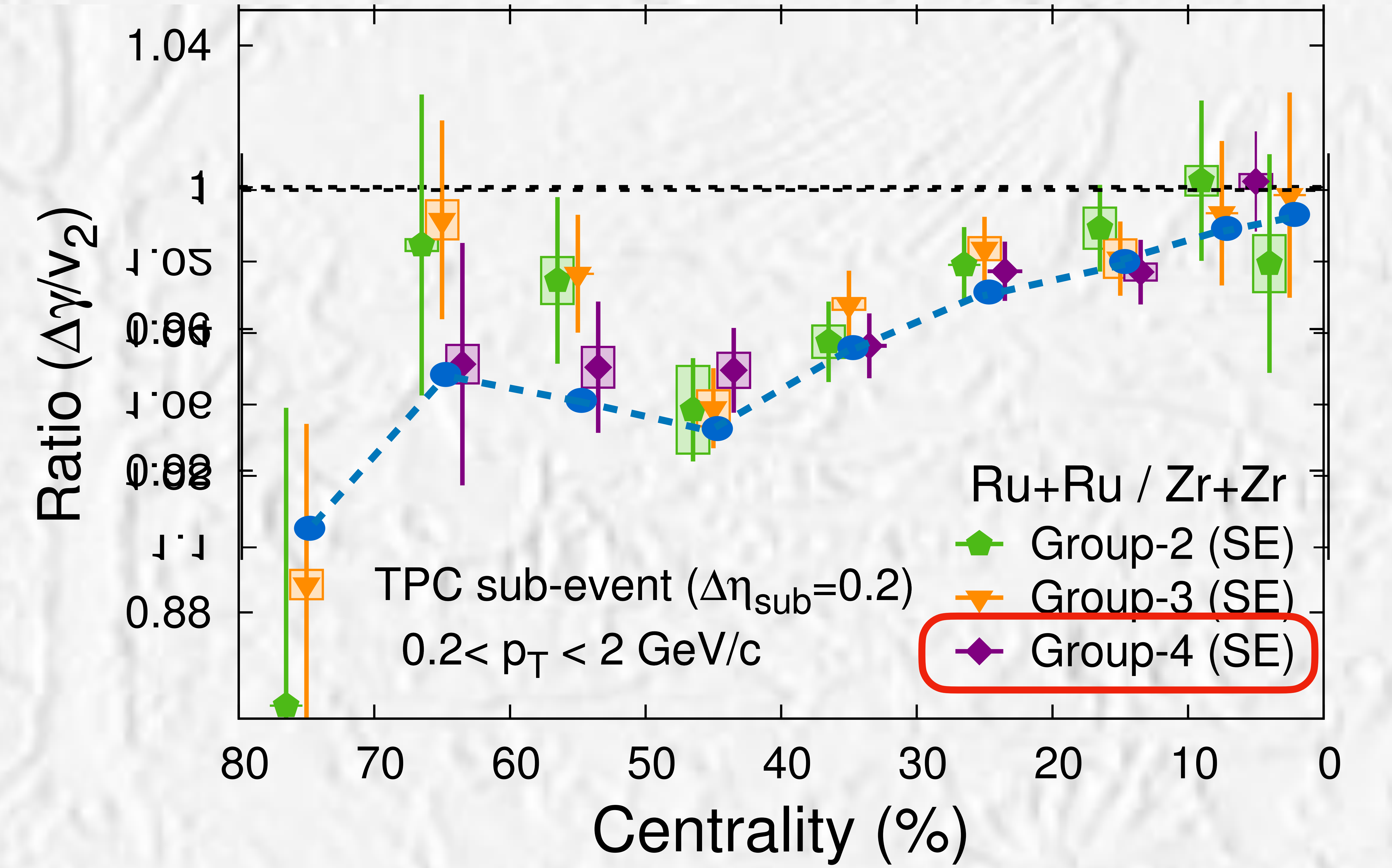




Cut,
Flip,
Overlay





# Zooming in …




The deviation from dashed line $\lesssim 1\,\%$

Taking at "face value" it translates to $f_{\rm CME} \lesssim 5\,\%$

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

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

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

# Correlations wrt participant and spectator planes

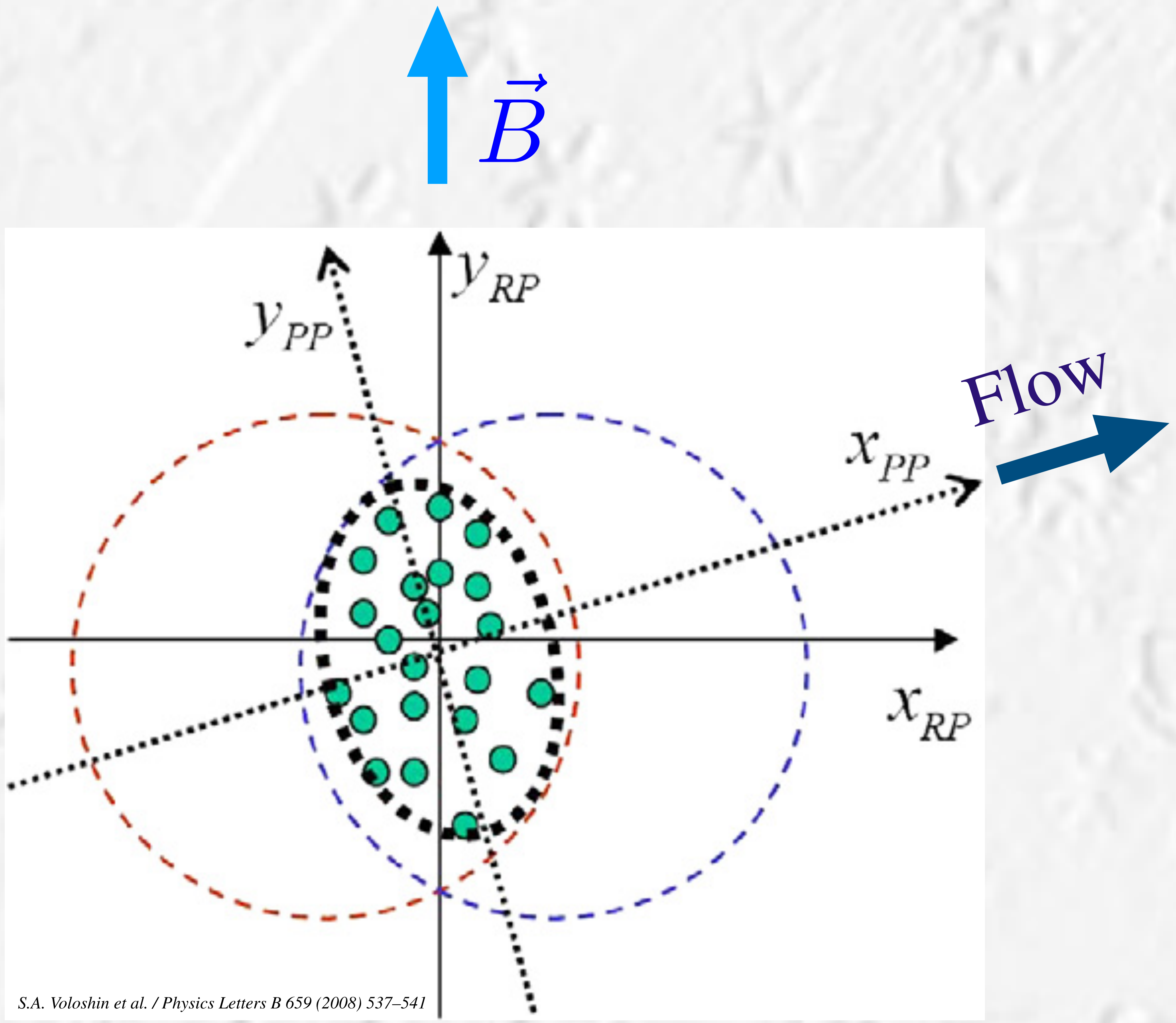



Fig. 1. The definitions of the *RP* and *PP* coordinate systems.

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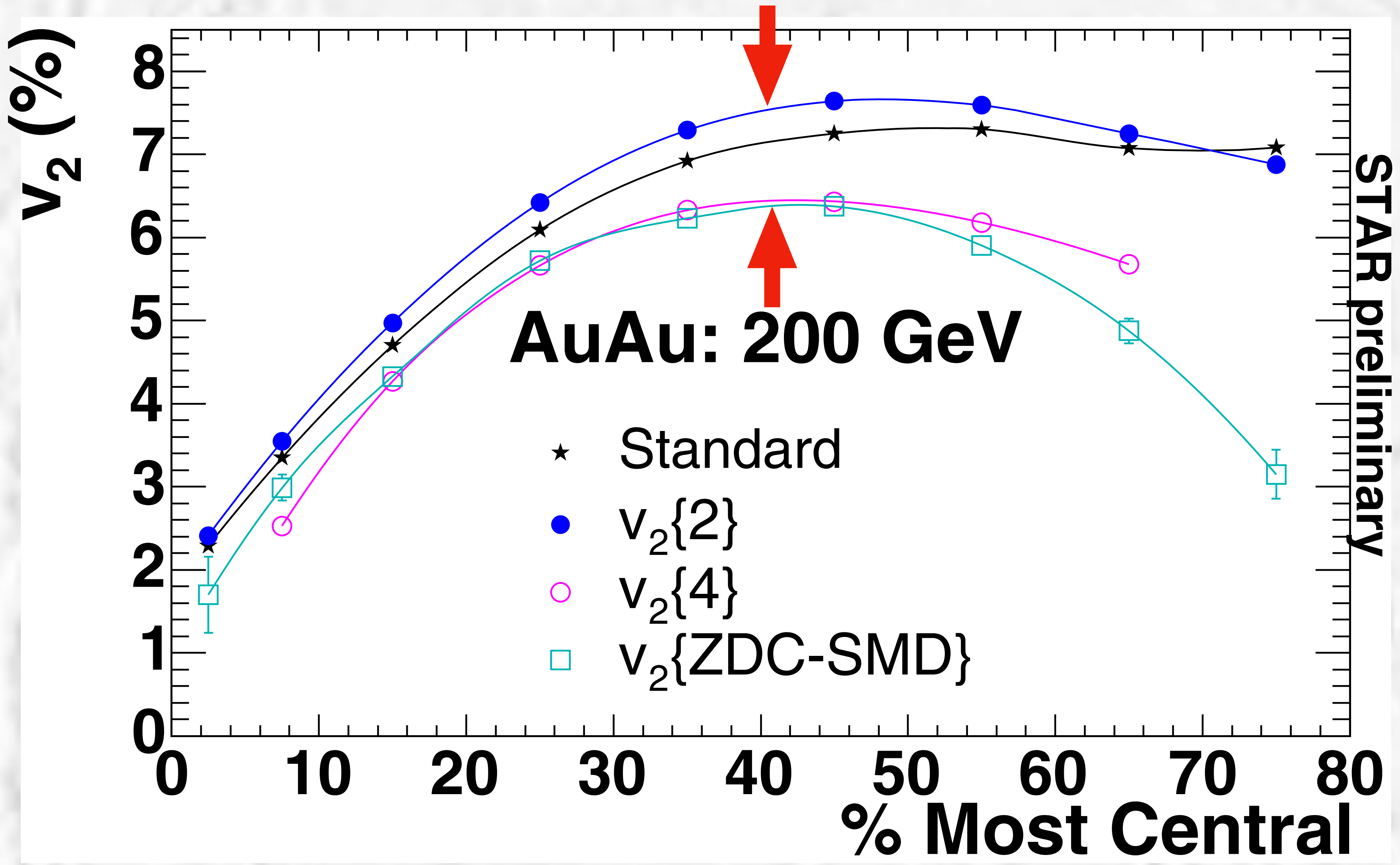
Varying the chiral magnetic effect relative to flow in a single nucleus-nucleus collision*


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]

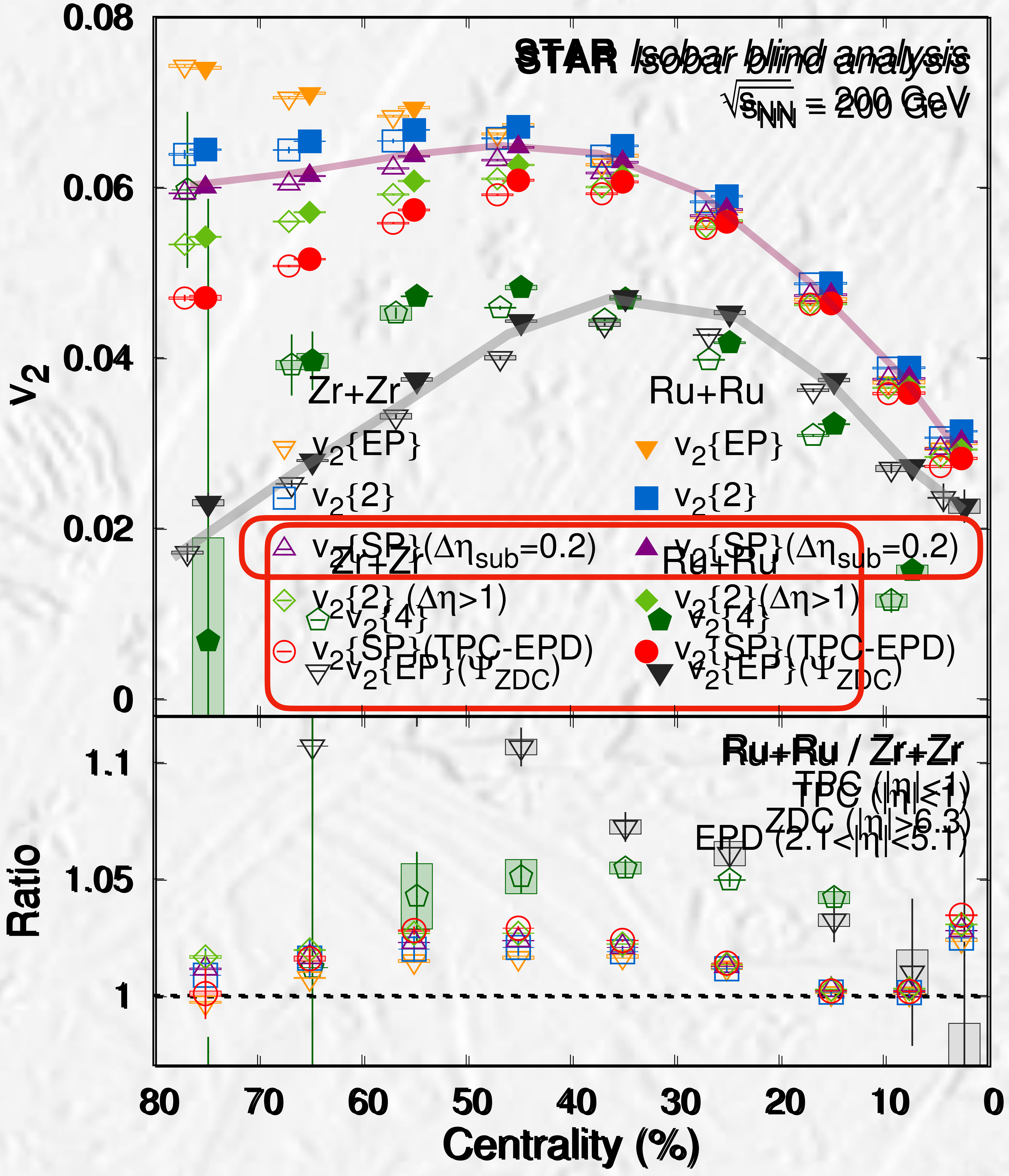


Published 1 July 2018 • © 2018 Chinese Physical Society and the Institute of High Energy
Chinese Physics C, Volume 42, Number 8


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

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



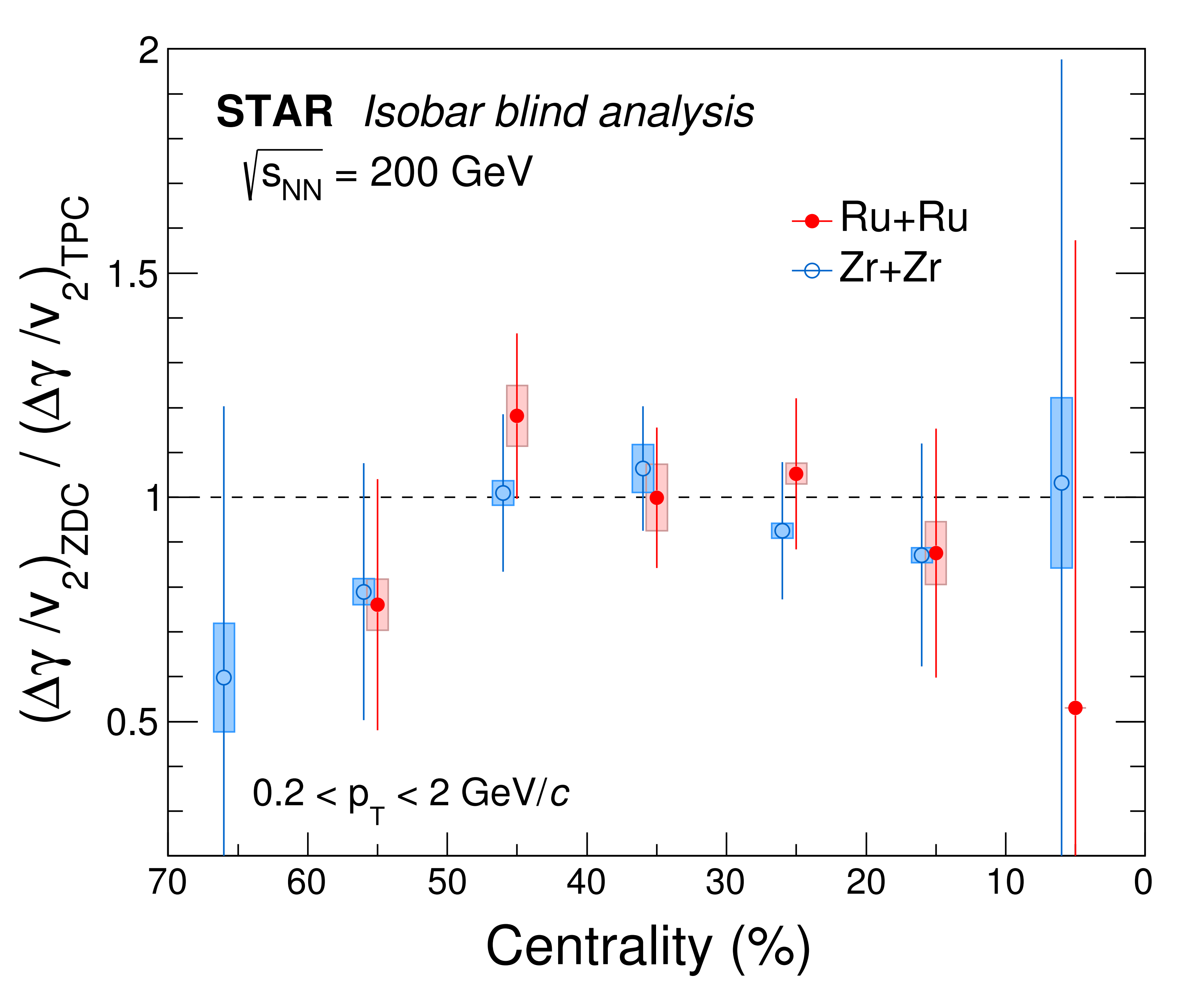

$$v_2\{\mathrm{TPC}\} = \sqrt{\langle \cos(2\phi_\alpha^{\mathrm{E}} - 2\phi_\alpha^{\mathrm{W}}) \rangle}$$

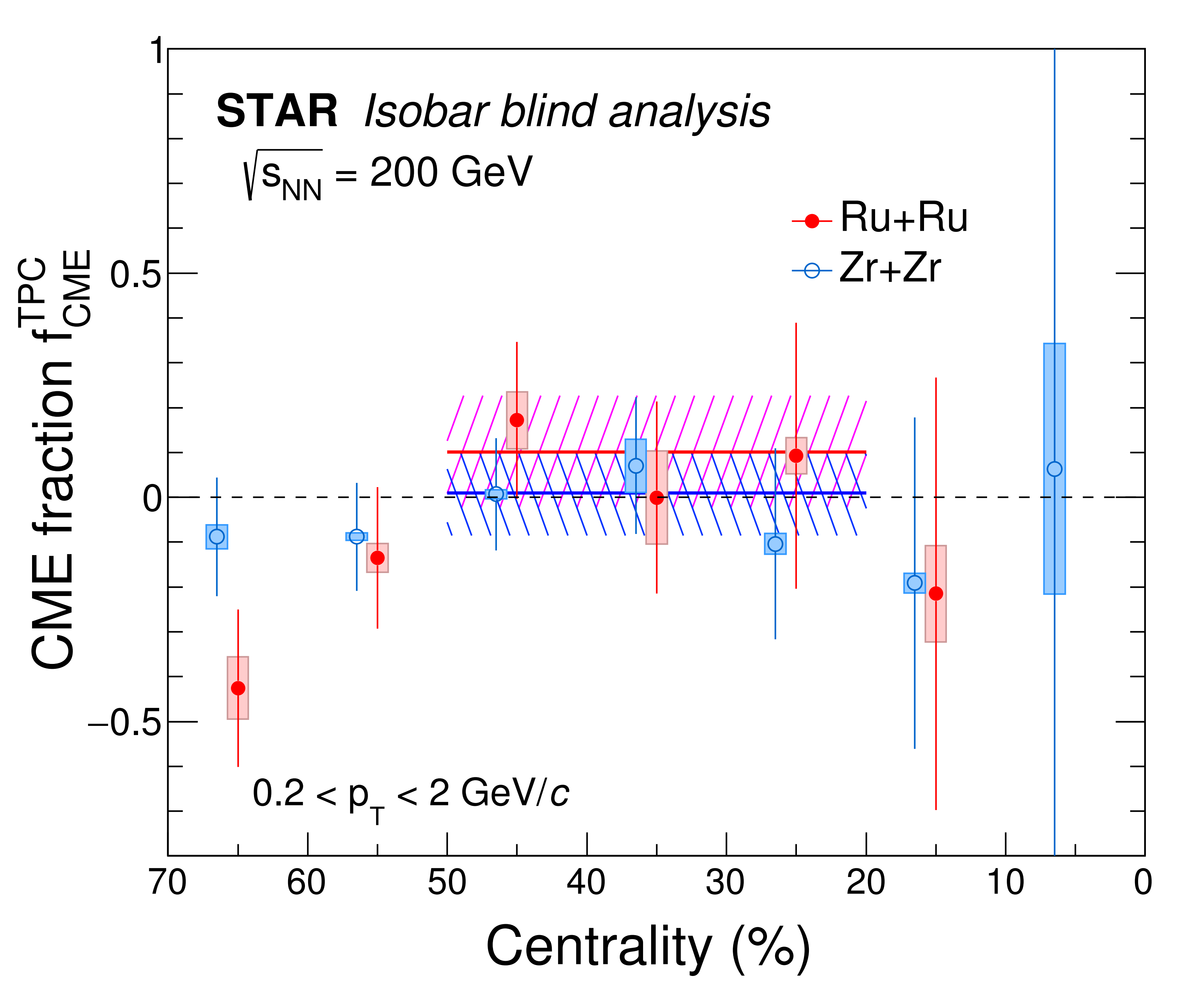
*Group-4 specifics*:
- default: $v_2$ from same charge correlations (usually suppresses > 50% of nonflow)
- systematics includes “all charges”, larger $\Delta\eta$ gaps

$$v_2\{\mathrm{ZDC}\} = \frac{\langle \cos(2\phi_\alpha - \Psi_1^{\mathrm{E}} - \Psi_1^{\mathrm{E}}) \rangle}{\langle \cos(\Psi_1^{\mathrm{W}} - \Psi_1^{\mathrm{E}}) \rangle}$$

*Group-4 specifics*:
Using this approach allows avoid extrapolation of the RP resolution from sub- to full event (usually done assuming Gaussian distribution of the flow vectors) as well as “extrapolation” from first harmonic to the second harmonic

# $f_{\mathrm{CME}}$ from PP/SP measurements




Group 4 (also done by group 3)

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

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

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

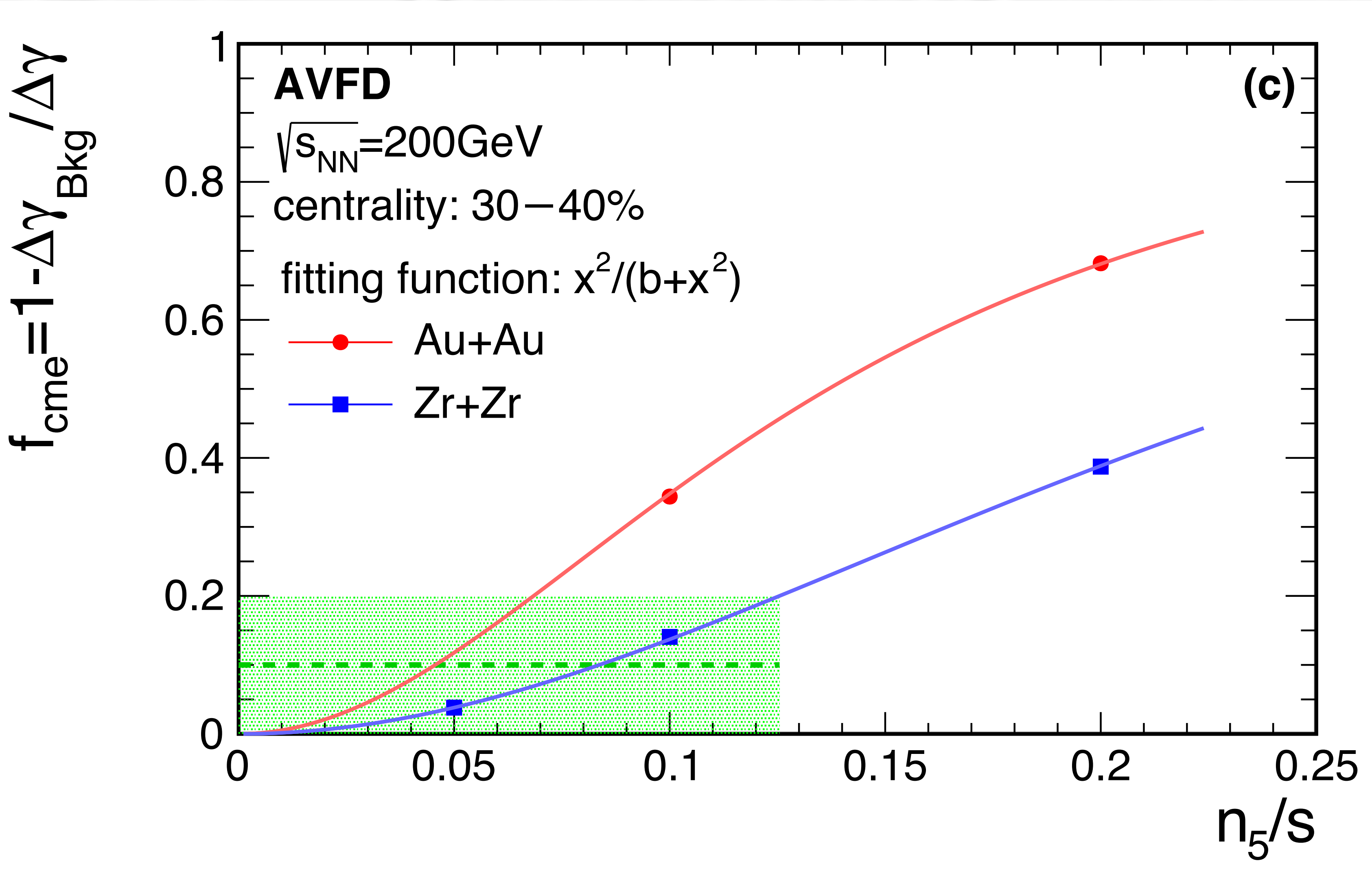
*Group-4 specifics*:
Using this approach allows to avoid “extrapolation” of the RP resolution from sub- to full event (usually done assuming Gaussian distribution of the flow vectors) as well as a similar “extrapolation” from the first harmonic to the second harmonic

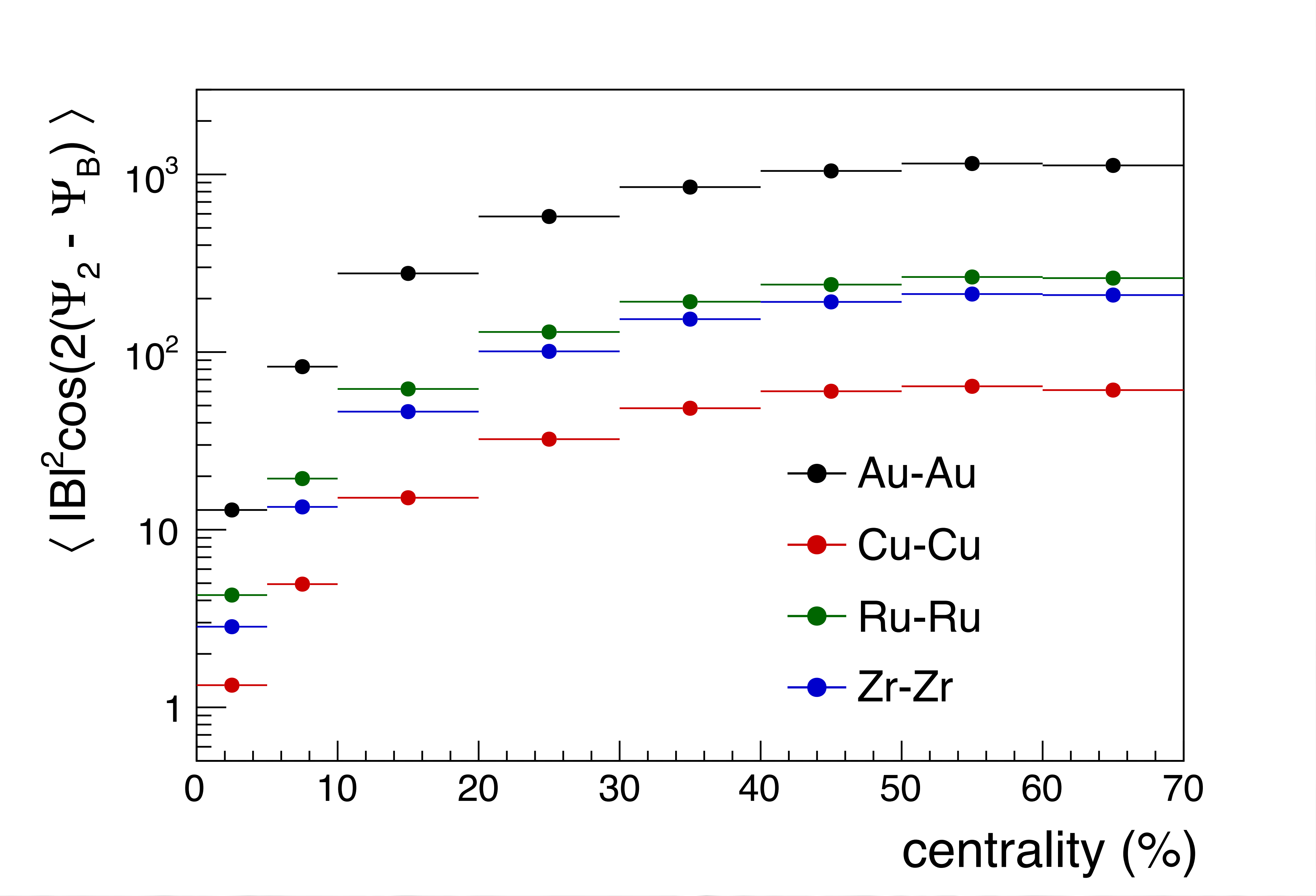
# Conclusions

- 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.
  [goal — "baseline" - "approach" uncertainty:
  a few percent difference in Ru/Zr correlations × a few percent "non-flow/non-CME" contribution to $(\Delta\gamma/v_2)$ ]

- 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 ?

# EXTRA SLIDES

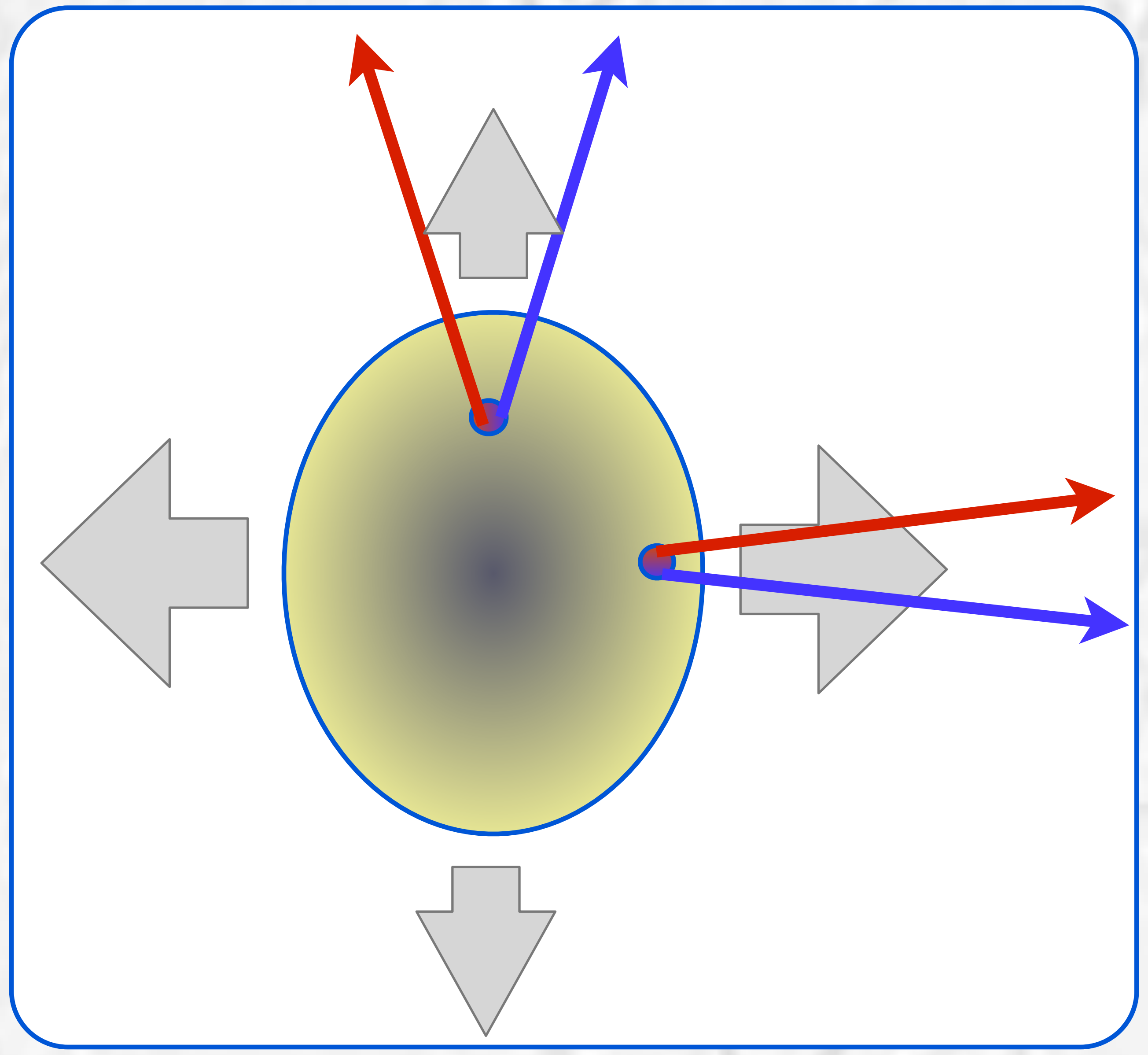
# Types of the background

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

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

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

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



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)

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

# CME and the "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

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

+

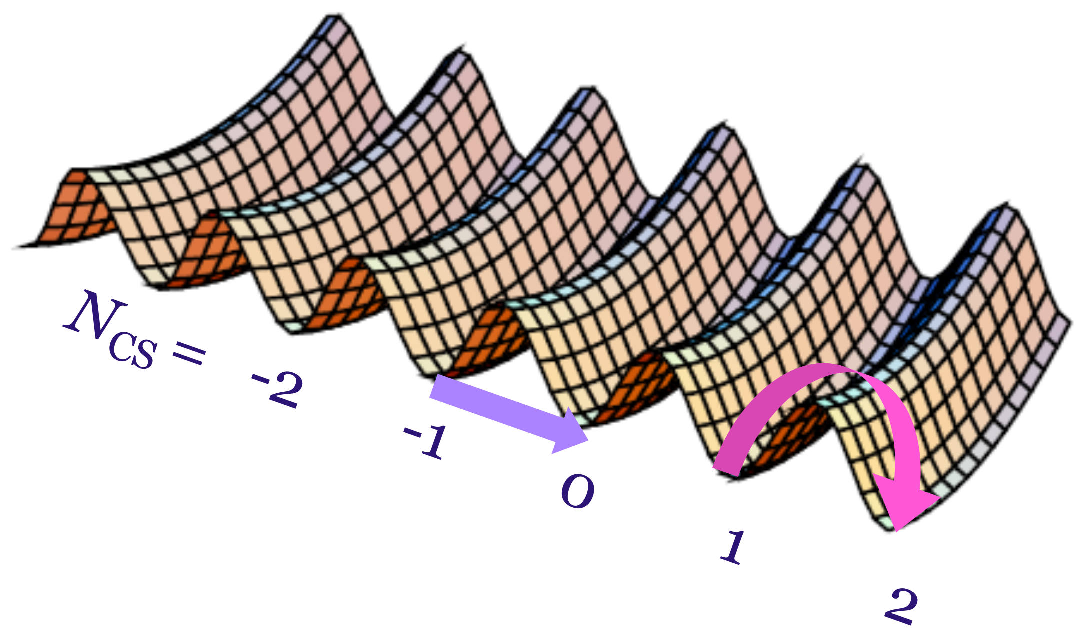
Magnetic field

*Anomalous transport*, Electric current along magnetic field

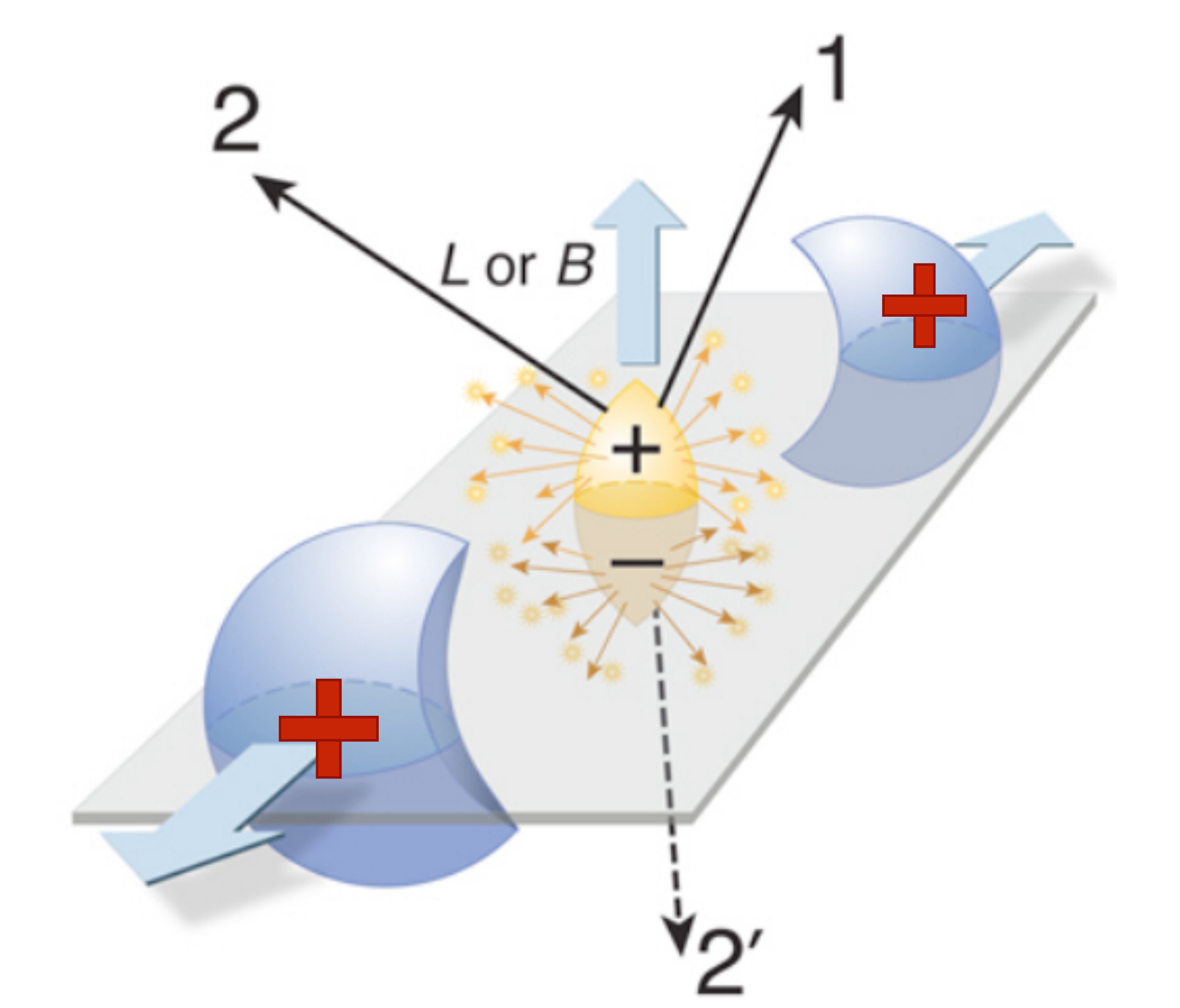
$\mathbf{J} = \frac{e^2}{2\pi^2}\mu_5 \mathbf{B}$

Charge separation along **B** direction

$2Q_T = n_R - n_L$



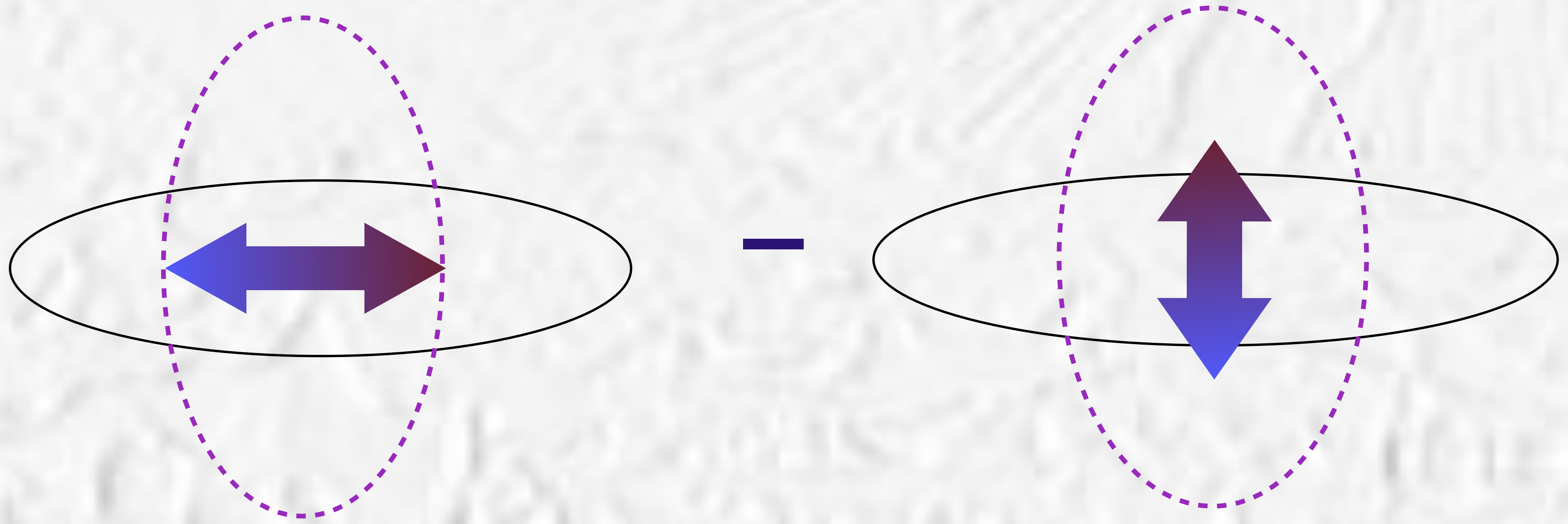

Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua via tunneling or go-over-barrier




Effective particle distribution

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

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



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

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