Search for the Chiral Magnetic Effect with Forced Match of Multiplicity and Elliptic Flow in Isobar Collisions at STAR

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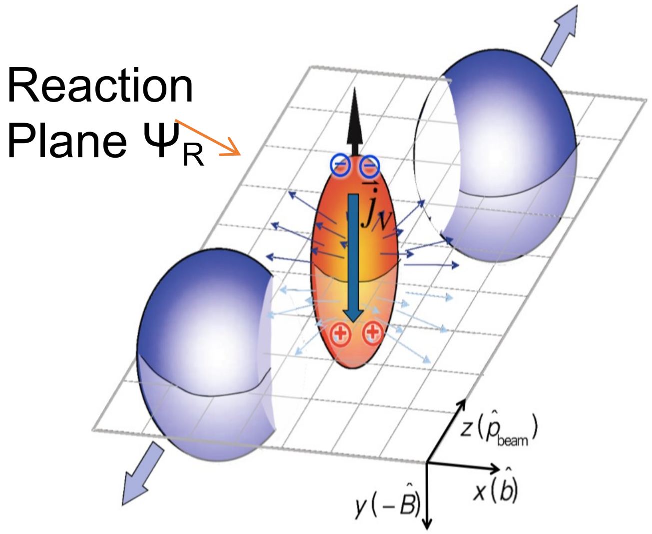
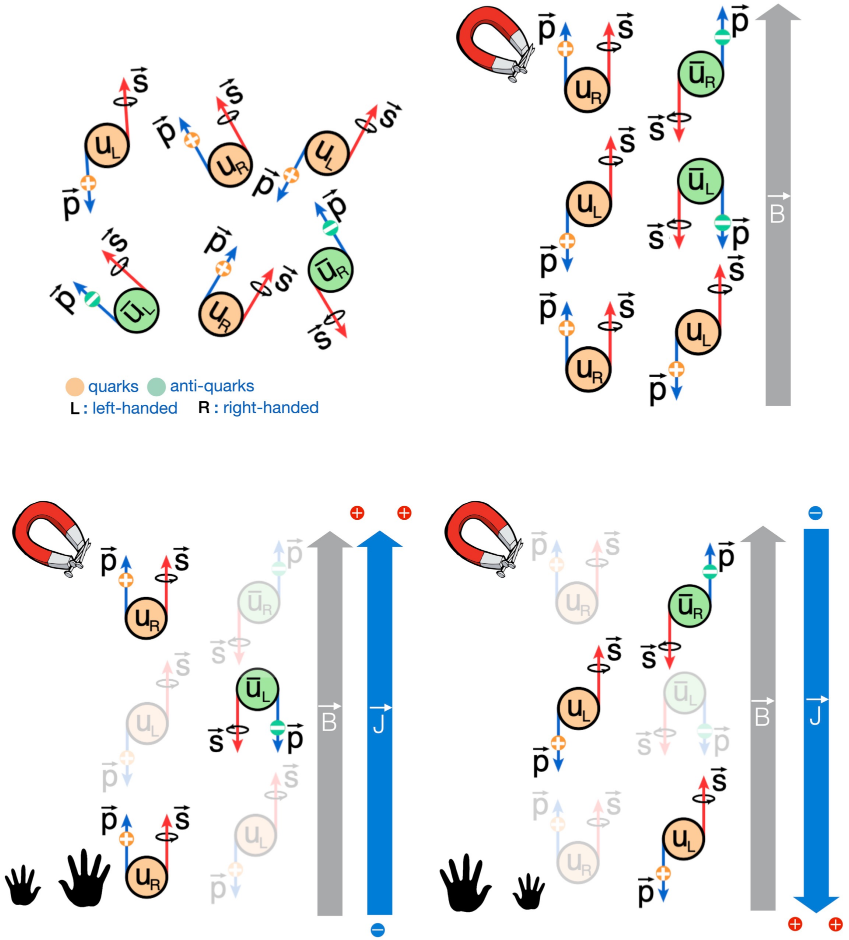
Chiral Magnetic Effect

In non-central collisions a strong magnetic field is produced ⊥ to Ψ_R

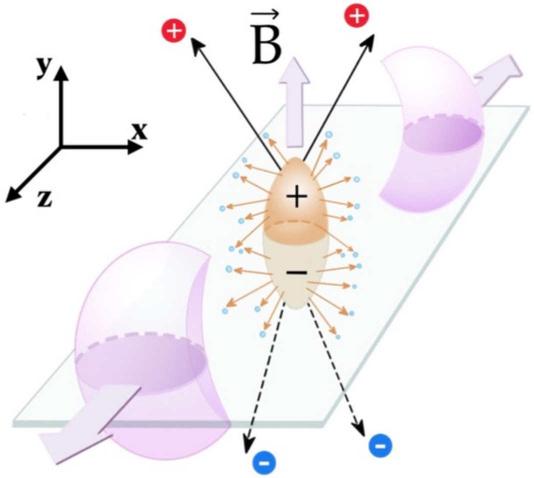


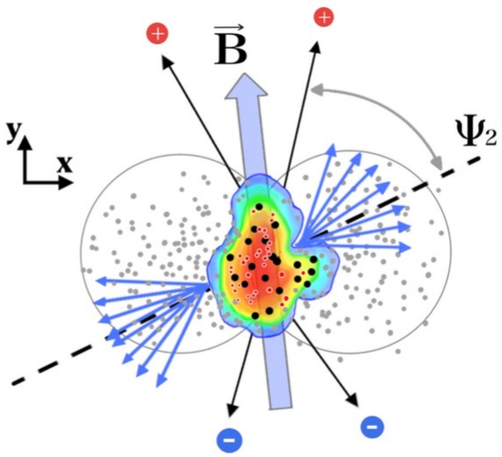
D. Kharzeev, Phys. Lett. B 633, 260 (2006)
D. Kharzeev and A. Zhitnitsky, Nucl. Phys. A 797, 67 (2007).
D. Kharzeev, J. Liao, P. Tribedy, arXiv:2405.05427



- CME: Charge seperation along the B due to strong magnetic field and local CP violation.

How to detect the CME?





The CME-induced charge transport and other modes of collective motion of the QGP, the azimuthal distribution of final-state particles can be Fourier-decomposed as:

$$\frac{dN_\alpha}{d\phi^*} = \frac{N_\alpha}{2\pi}\left[1 + 2v_{1,\alpha}\cos(\phi^*) + 2a_{1,\alpha}\sin(\phi^*) + 2v_{2,\alpha}\cos(2\phi^*) + \cdots\right]$$

The subscript α (+ or −) denotes the charge sign of a particle. The coefficients v1 and v2 are called “directed flow” and “elliptic flow,” respectively. The coefficient a_1 (with $a_{n,-} = -a_{n,+}$) characterizes the electric charge separation with respect to the RP.

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

How to detect the CME?

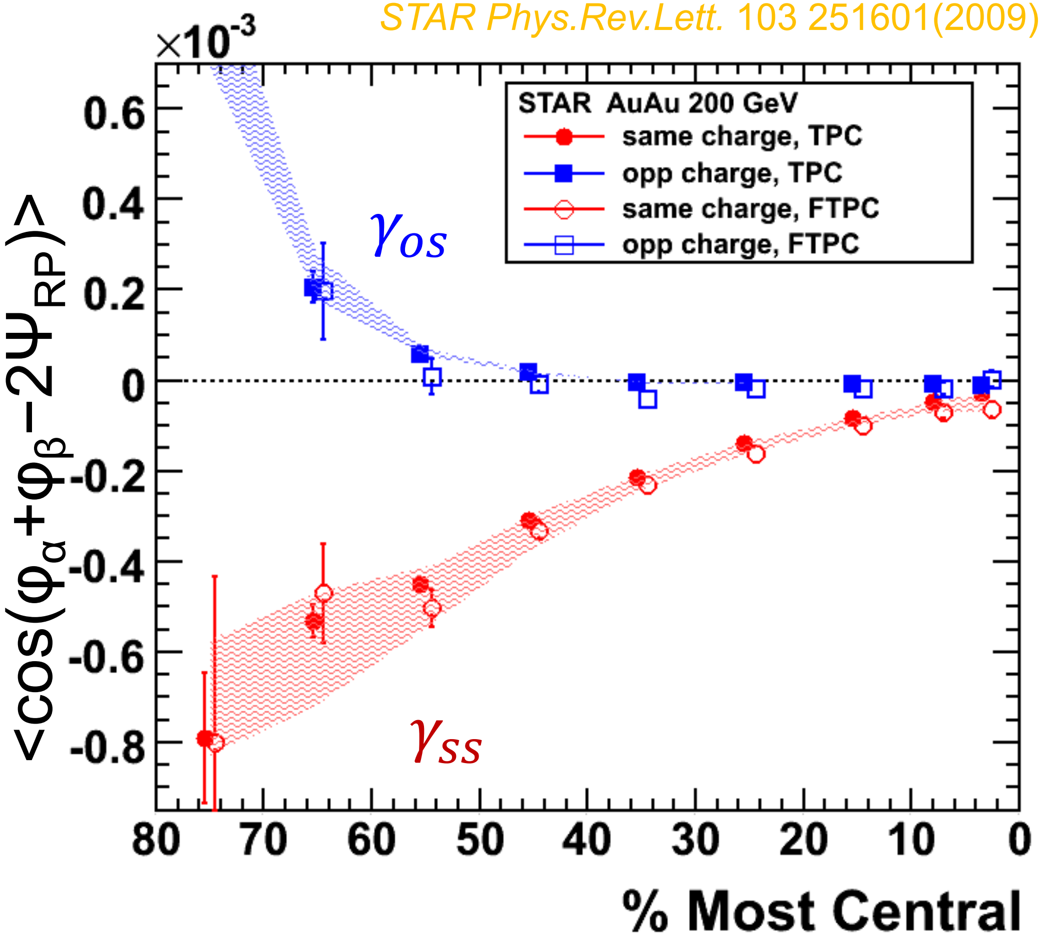
By utilizing the azimuthal correlation:

$$\gamma_{112} = \langle \cos(\phi_\alpha - \phi_\beta - 2\Psi_{RP}) \rangle$$
$$= \langle \cos(\phi_\alpha^*)\cos(\phi_\alpha^*) - \sin(\phi_\alpha^*)\sin(\phi_\alpha^*) \rangle$$
$$= (\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{IN}) + (\langle a_{1,\alpha} a_{1,\beta} \rangle + B_{OUT})$$

- To cancel the Bkg effects:

$$\Delta\gamma_{112} = \gamma_{112}^{OS} - \gamma_{112}^{SS}$$

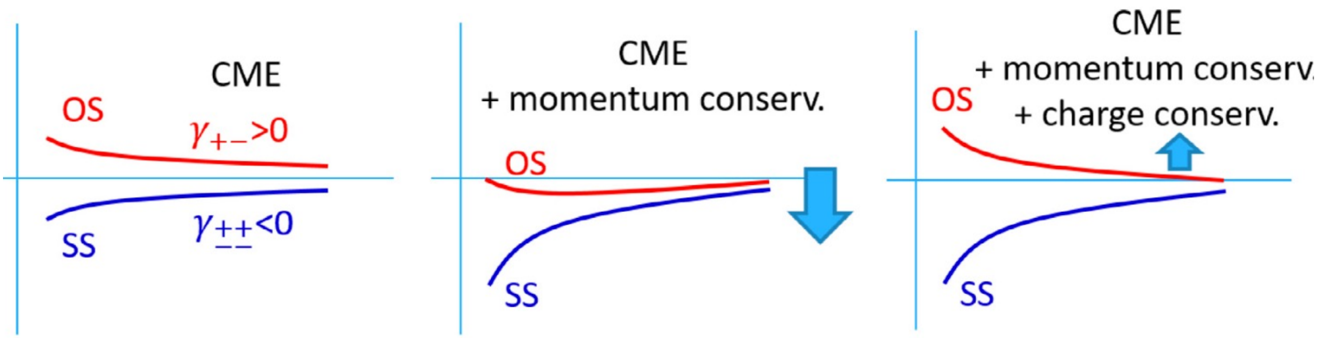
STAR Phys.Rev.Lett. 103 251601(2009)

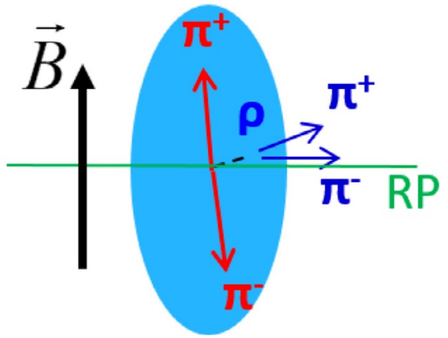


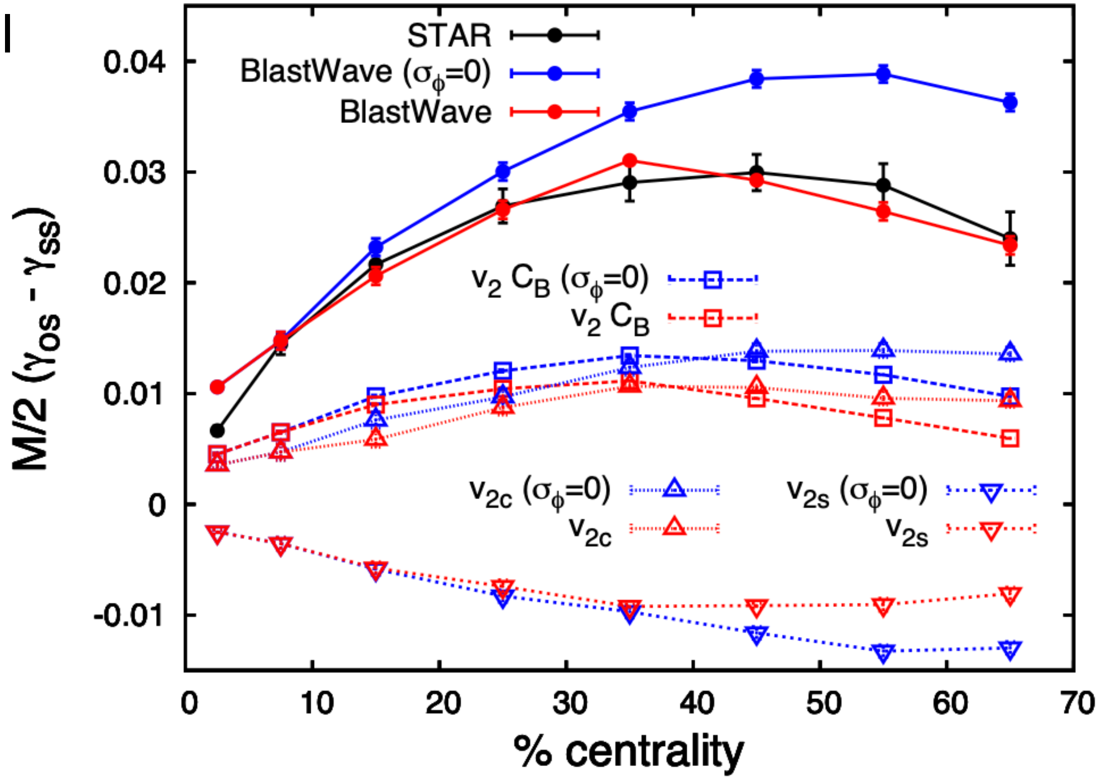
➢ Signal consistent with CME

Background Issues

Transverse momentum conservation(TMC) and local charge conservation (LCC):



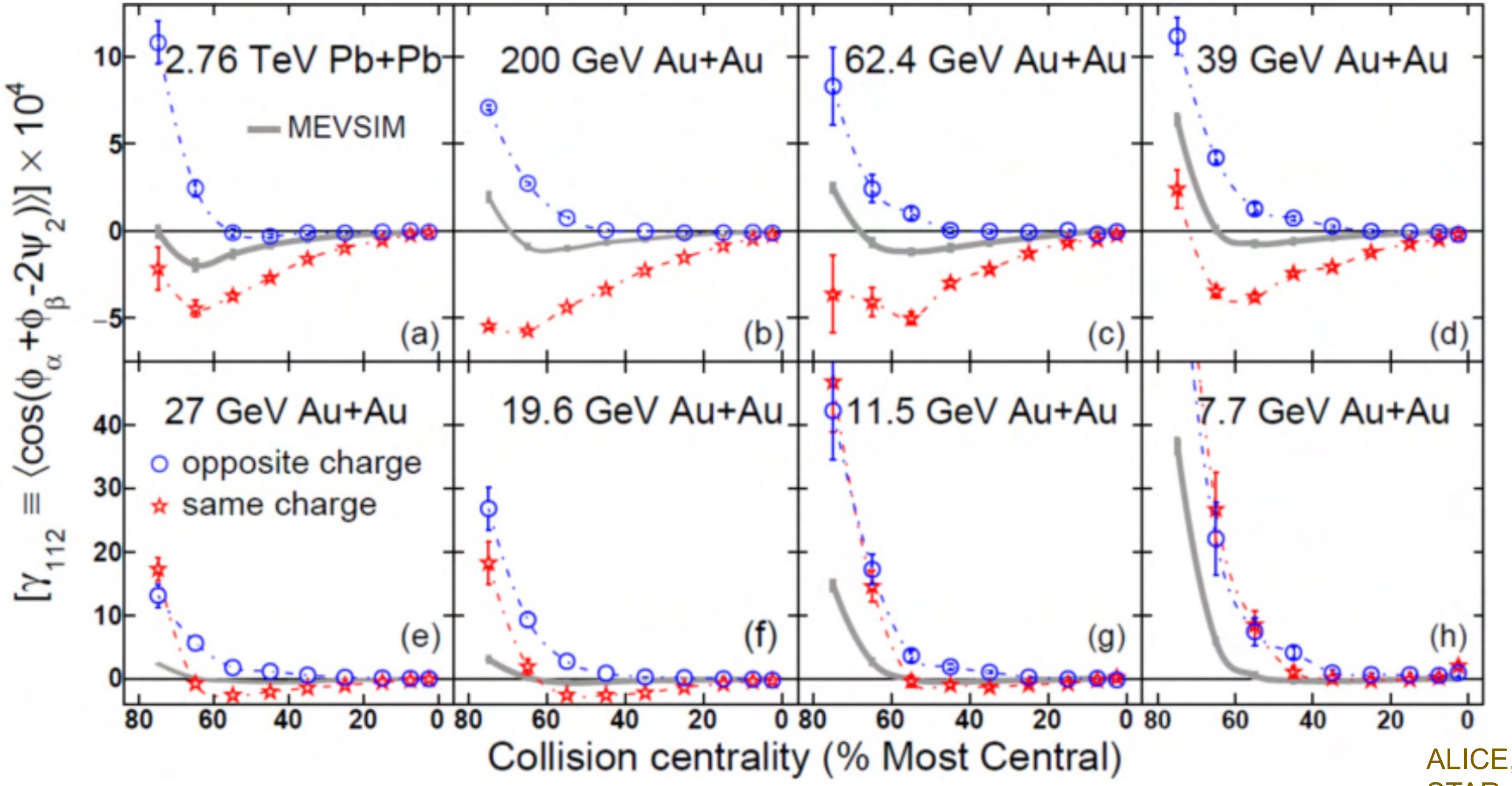




Schlichting, Pratt *Phys.Rev.C* 83 (2011) 014913
Bzdak, Koch, Liao, Lect.Notes Phys. 871 (2013) 503-536
Schlichting, Pratt, Gavin, *Phys.Rev.C* 84 (2011) 024909
Jie Zhao and Fuqiang Wang, PPNP 107, 200 (2019).

- v_2 + various effects (LCC, TMC, etc.) may explain much/all of the signal.

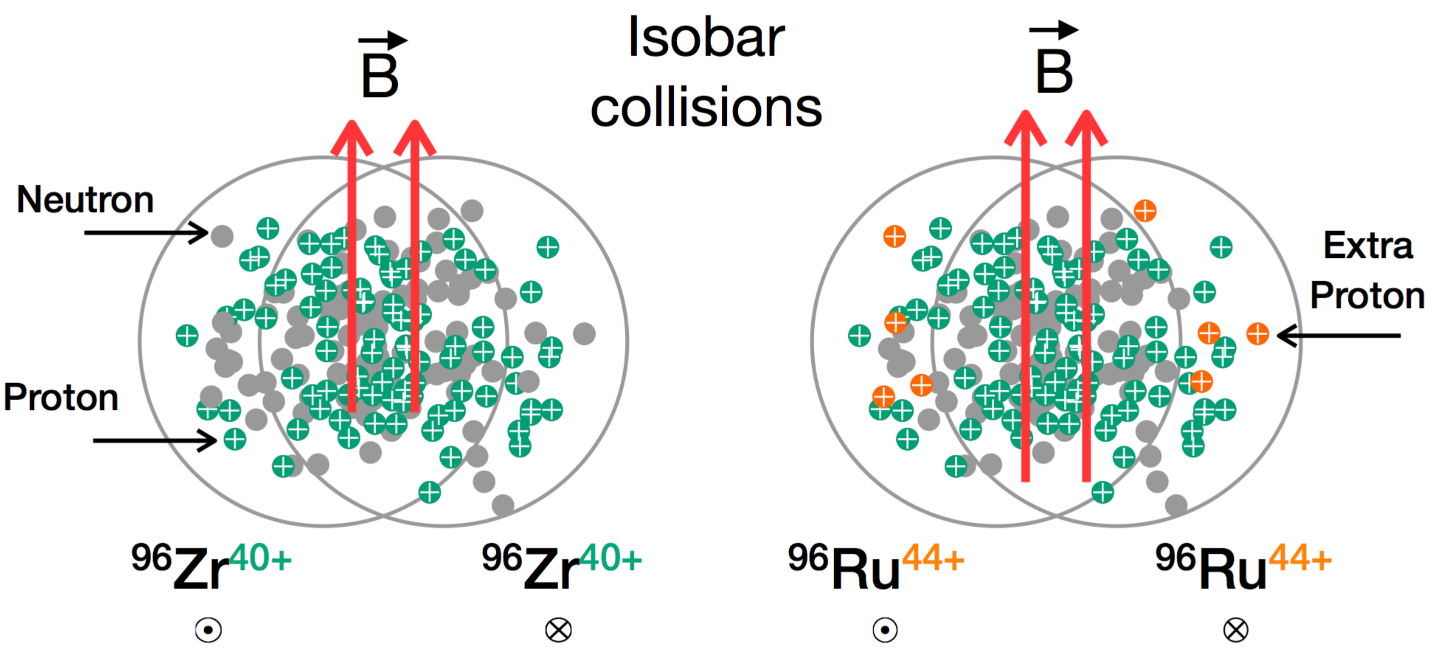
ALICE & STAR BES-I data



ALICE, Phys. Rev. Lett. 110 012301(2013)
STAR, Phys. Rev. Lett. 113 52302(2014)

- The positively finite $\Delta\gamma_{112}$ meets the CME expectation, but could contain contributions from backgrounds(v_2, nonflow-related)

Isobar Collisions: prospect



Sergei A. Voloshin， PRL105, 172301 (2010)
S. Shi, H. Zhang, D. Hou, and J. Liao, PRL125, 242301 (2020)
STAR， NUCL SCI TECH 32, 48 (2021)

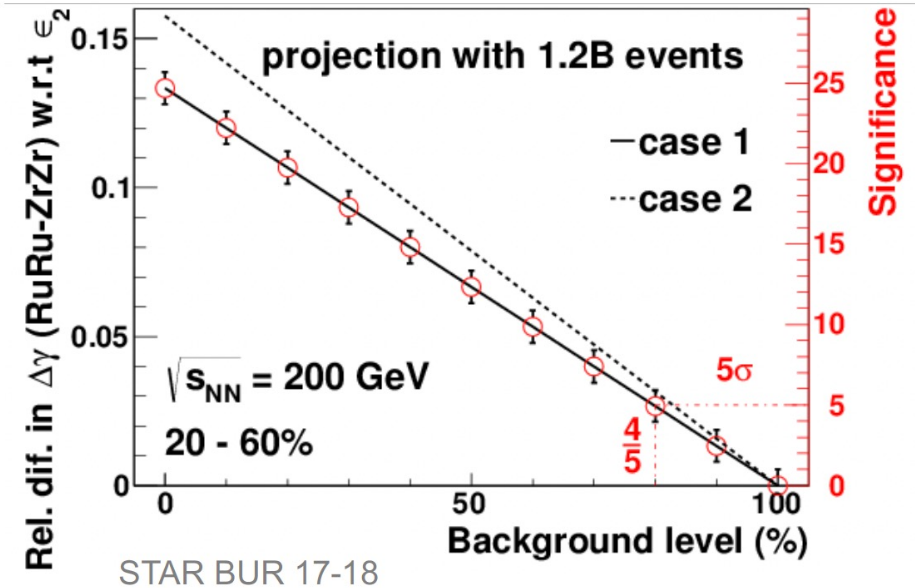
Compare the two isobaric systems:

- ✓ CME: B-field^2 is ~13% larger in Ru+Ru
- ✓ Backgrounds almost same (including flow and Nonflow)

$$\frac{\boldsymbol{Observable(Ru+Ru)}}{\boldsymbol{Observable(Zr+Zr)}} > \mathbf{1}$$

✓ The Isobar collisions offers the unique opportunity to detect CME.

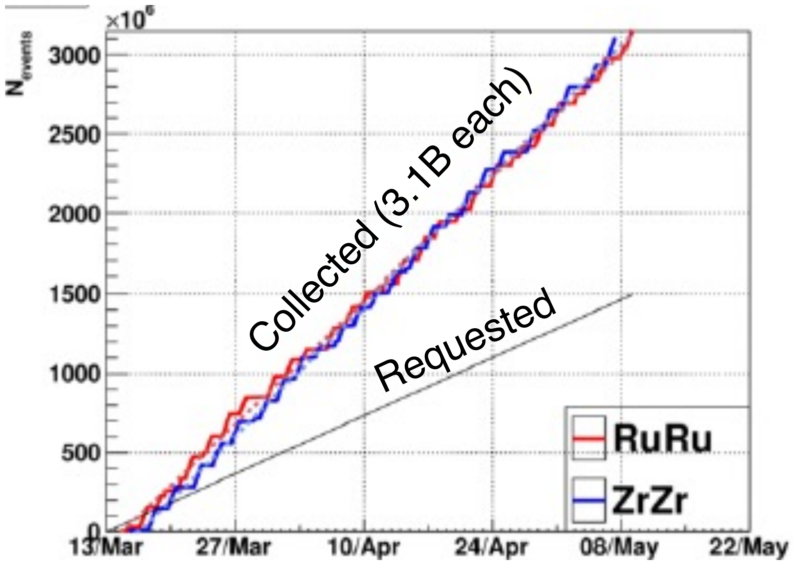
Isobar Collision at STAR

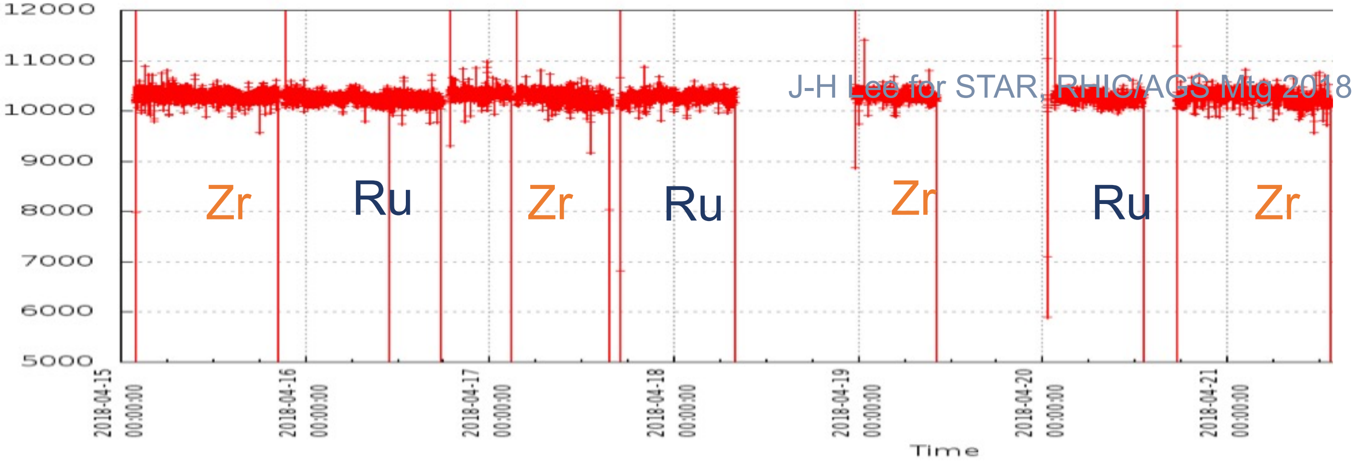


STAR BUR 17-18

$$\gamma \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

Data collected in 2018 RHIC run





Interleaved fills for isobar species to minimize systematic differences between two species.

Analysis method: Signed Balance Function(SBF)

By accounting momentum ordering:

1) Count pair's momentum ordering along y direction in p_y :

$$B_{P,y}(S_y) = \frac{N_{+-}(S_y) - N_{++}(S_y)}{N_+},$$

$$B_{N,y}(S_y) = \frac{N_{-+}(S_y) - N_{--}(S_y)}{N_-}$$

2) Count net-ordering (e.g. excess of pos. leading neg.) for each event :

$$\delta B_y(\pm 1) = B_{P,y}(\pm 1) - B_{N,y}(\pm 1),$$
$$\Delta B_y(\pm 1) = \delta B_y(+1) - \delta B_y(-1)$$
$$= \frac{N_+ + N_-}{N_+ N_-}\left[N_{y(+-)} - N_{y(-+)}\right]$$

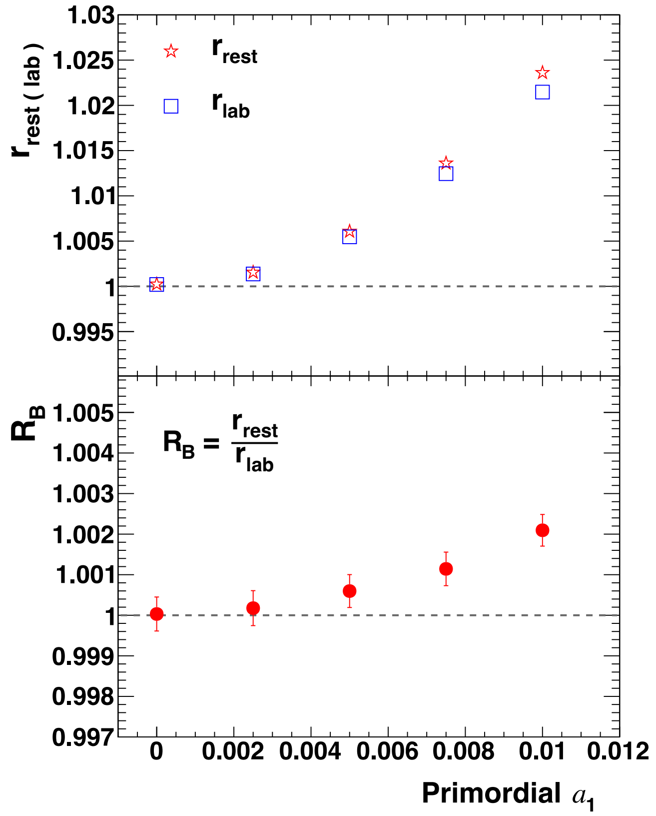
3) Look for enhanced event-by-event fluctuation of net ordering in y direction.

$$r = \frac{\sigma_{\Delta B_y}}{\sigma_{\Delta B_x}} \qquad R_B = \frac{r_{rest}}{r_{lab}}$$

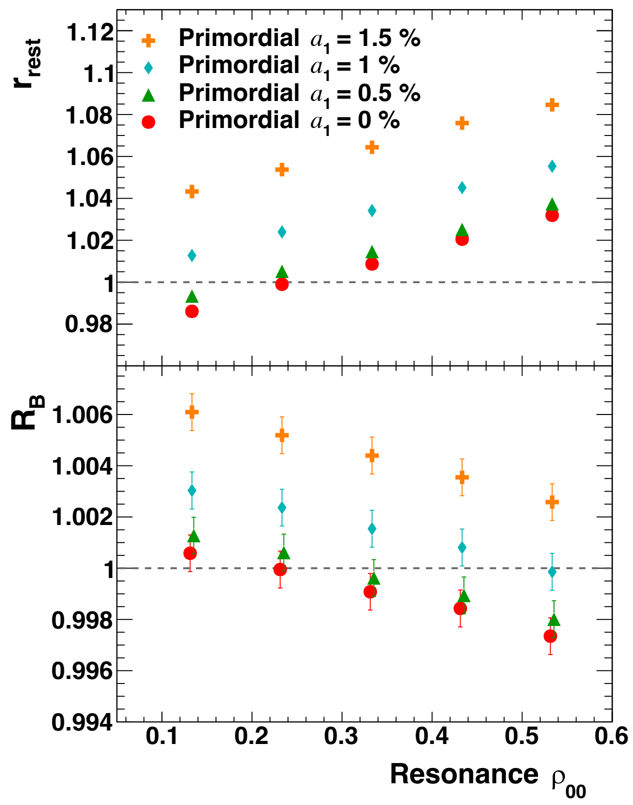
Where Nαβ denotes the number of positive -negative pairs with a sign of Sy in an event. Sy is labeled as +1 if $p^{\alpha}y > p^{\beta}y$, and -1 if vice versa, r_{lab} and r_{rest} are r calculate in the laboratory frame and pair rest frame separatly.

A.H. Tang, Chin. Phys. C 44, 054101 (2020)

Toy model: Signal only



Toy model: ρ_{00} + v_2 + CME



✓ Both r_{lab}, r_{rest} and R_B are sensitive to the CME signal, and r_{rest} and R_B respond in opposite directions to signal and

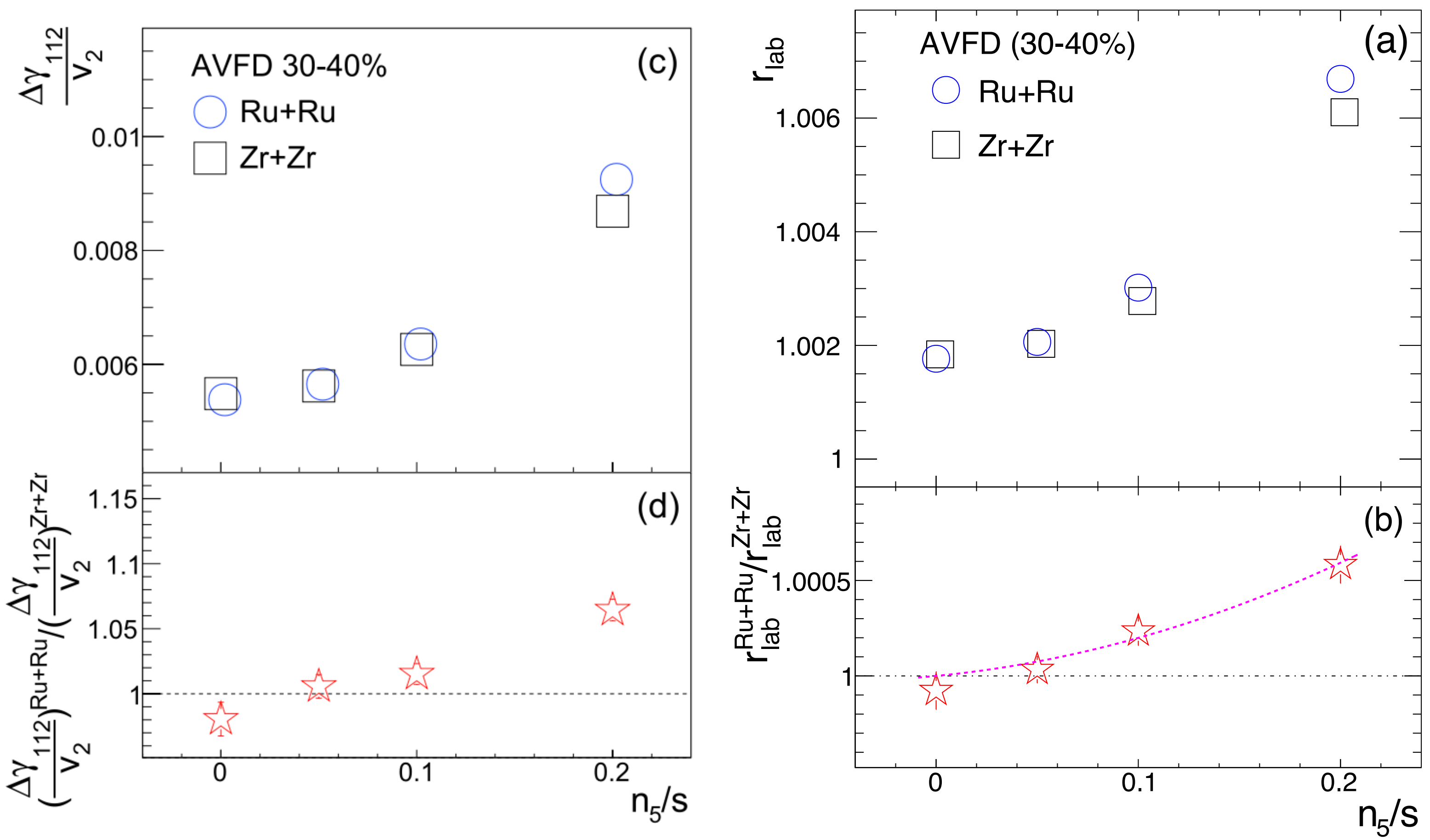
Sensitivity test with AVFD simulation

Key points in Anomalous Viscous Fluid Dynamics (AVFD) model.

The listed a_1 below is obtained with RP:

n_5/s	$a_{1,+}$ (%)		$a_{1,-}$ (%)	
	Ru+Ru	Zr+Zr	Ru+Ru	Zr+Zr
0	0	0	0	0
0.05	0.37	0.35	0.35	0.33
0.10	0.74	0.69	0.71	0.66
0.20	1.48	1.38	1.42	1.32

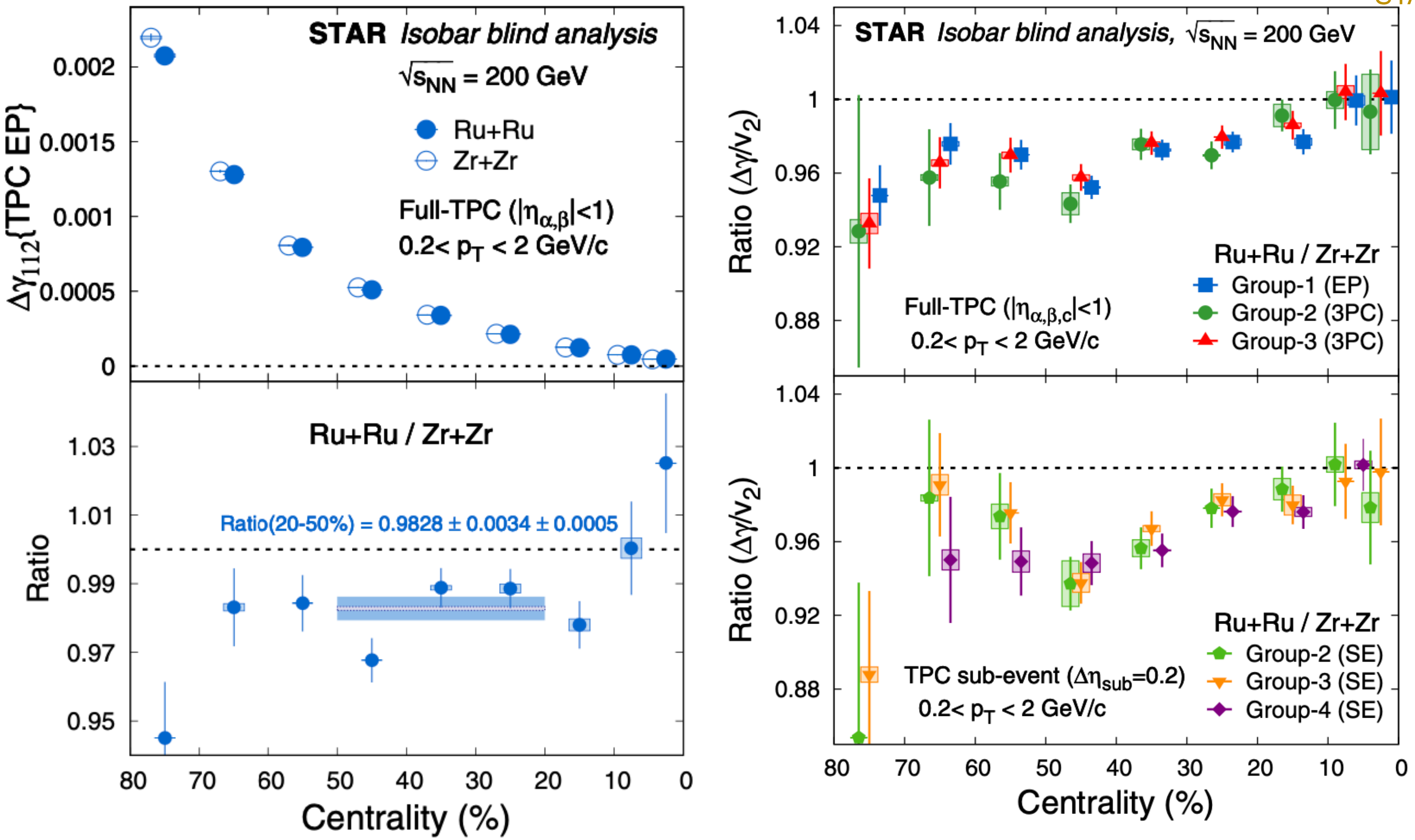
S. Choudhury, et al., Chin. Phys. C 46, 014101 (2022)



✓ The tiny difference in CME signals can be identified in both methods when the backgrounds are identical.

Isobar blind analysis

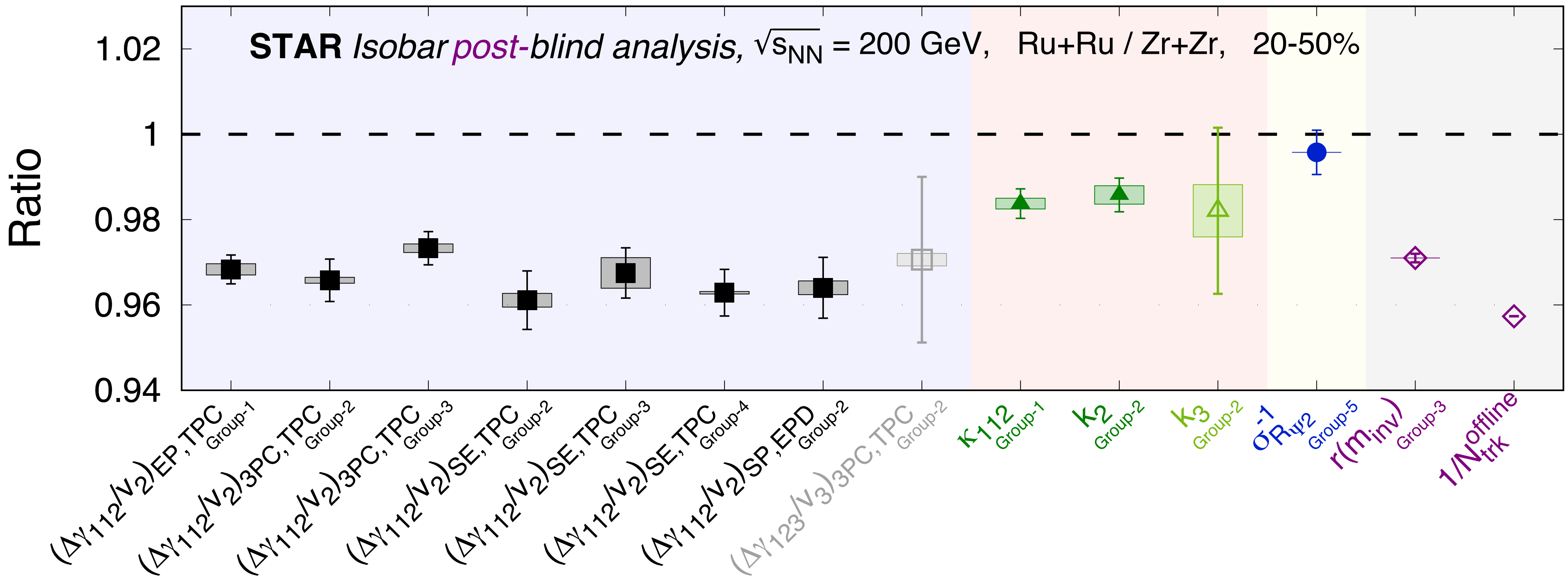
STAR, Phys. Rev. C 105, 014901 (2022)



- Both the ratio of $\Delta\gamma_{112}$ and $\frac{\Delta\gamma_{112}}{v_2}$ are smaller than 1.

Isobar blind analysis

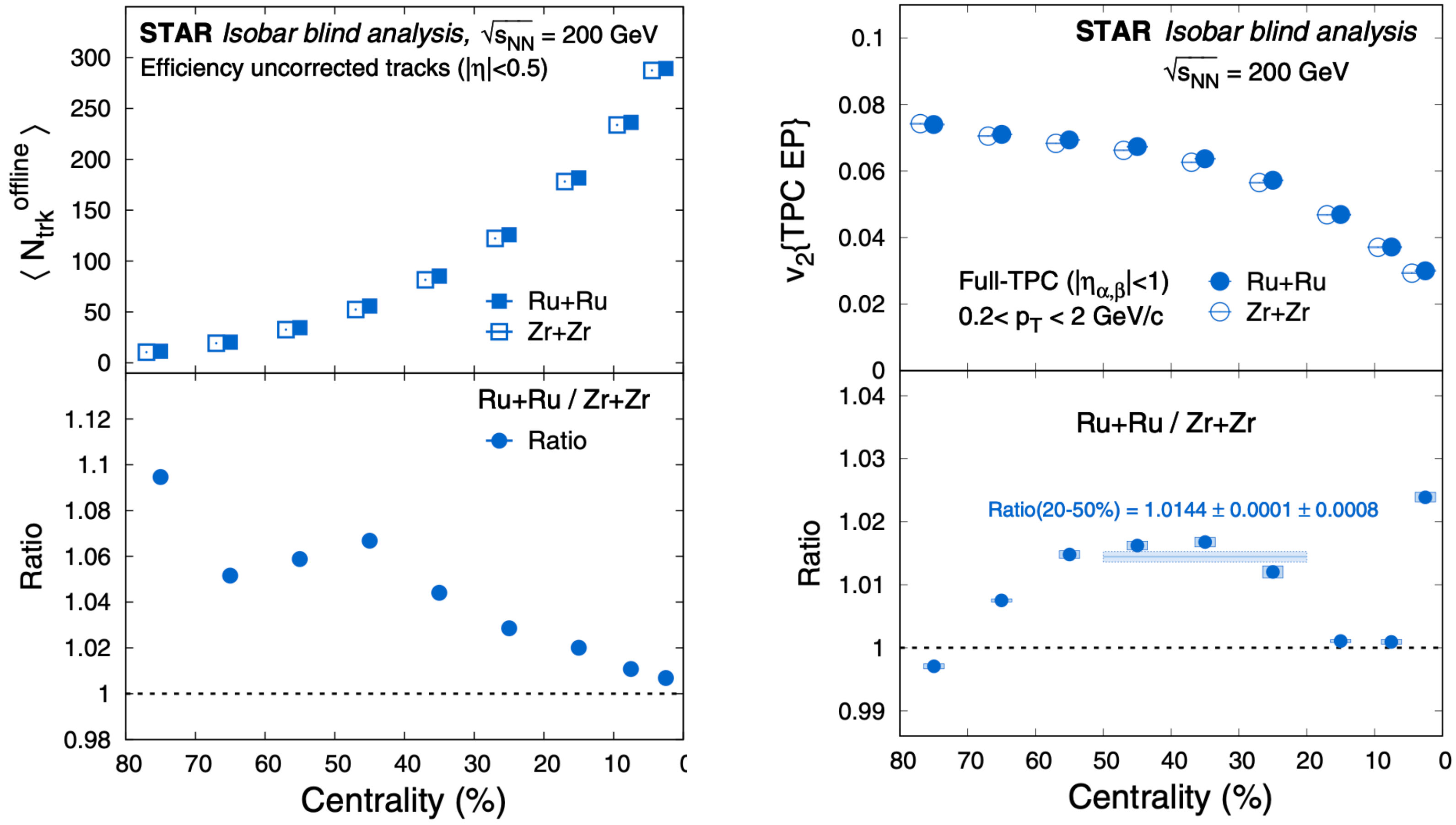
STAR, Phys. Rev. C 105, 014901 (2022)



- Pre-defined signature of CME is NOT observed.

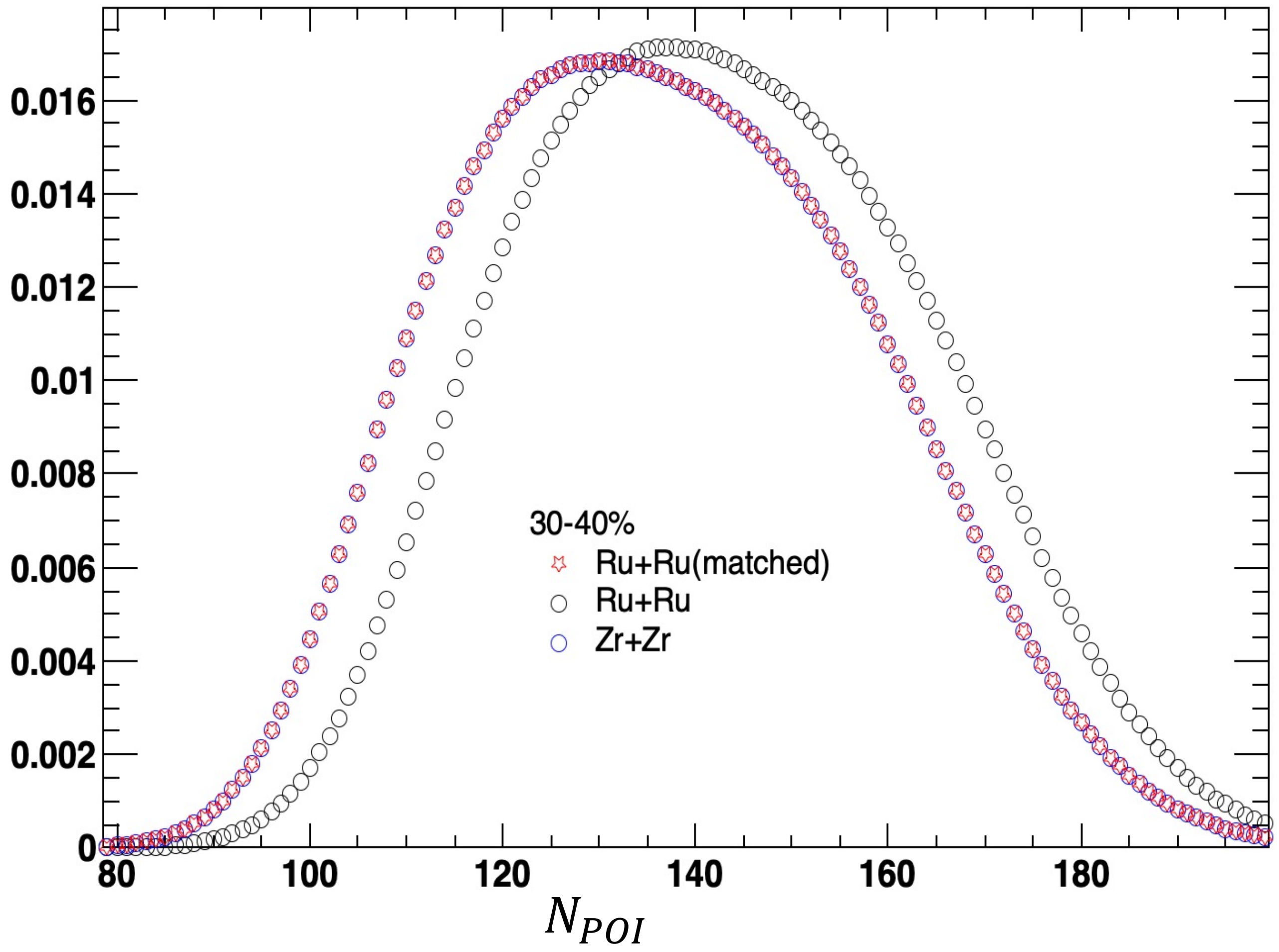
Unexpected differences of Backgrounds

STAR Isobar blind analysis, PRC 105, 014901 (2022)



➢ The difference of BKG between two Isobar system should be study.

Forced match to remove the backgrounds



Keep the Zr+Zr original and then match the Ru+Ru Distribution to Zr+Zr.

$$f_{w,bin} = N_{bin(Zr)} \,/\, N_{bin(Ru)}$$

$$S_O \mathrel{+}= O_{bin(Ru)} \cdot N_{bin(Ru)} \cdot f_{w,bin}$$

$$S_w \mathrel{+}= N_{bin(Ru)} \cdot f_{w,bin}$$

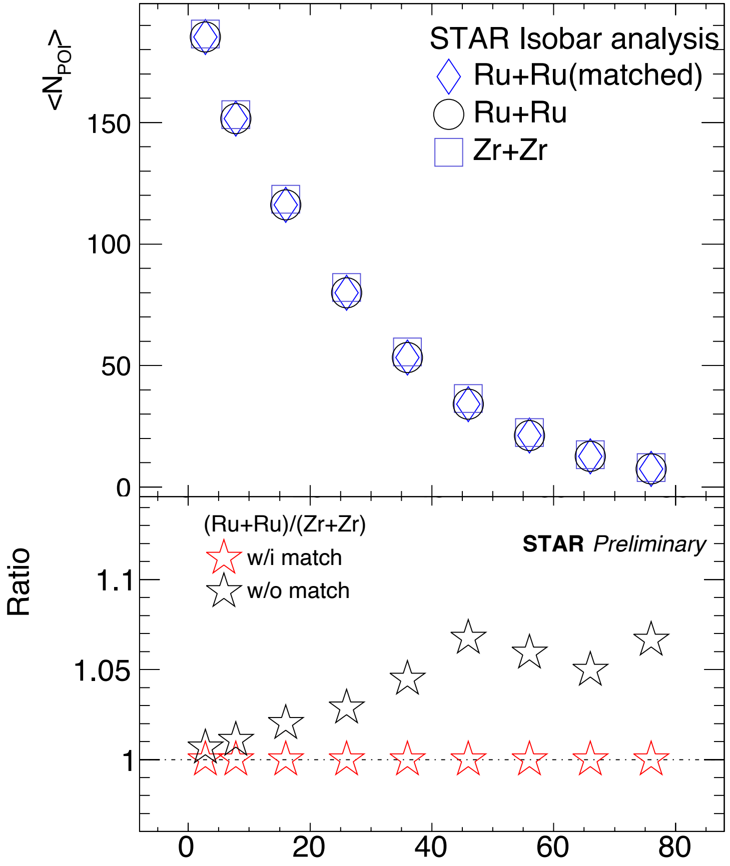
$$\mathbf{O_{Ru(matched)} = S_O \,/\, S_w}$$

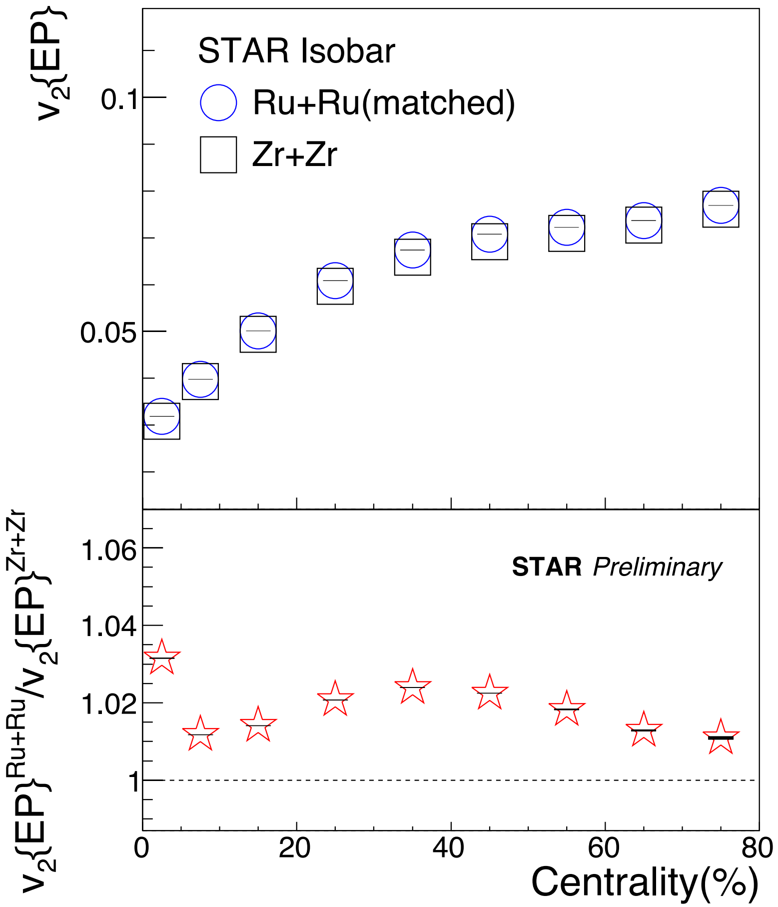
N_{bin}: normalized number of entries,
$f_{w,bin}$: weight factor, O_{bin} : observables
S_O and S_w are the sum of the observable and weight entries in total, respectively.

✓ The CME related backgrounds are tuned to be exactly the same with matched.

Analysis results: γ

- **γ**-correlator： Only the N_{POI} as the matching dimension.

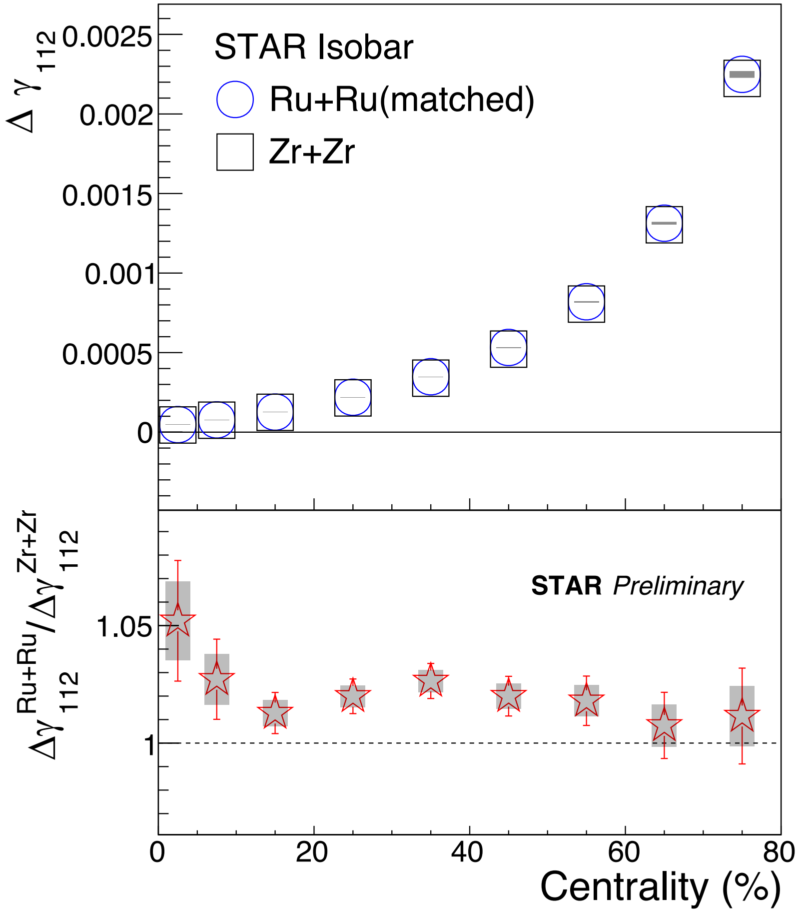


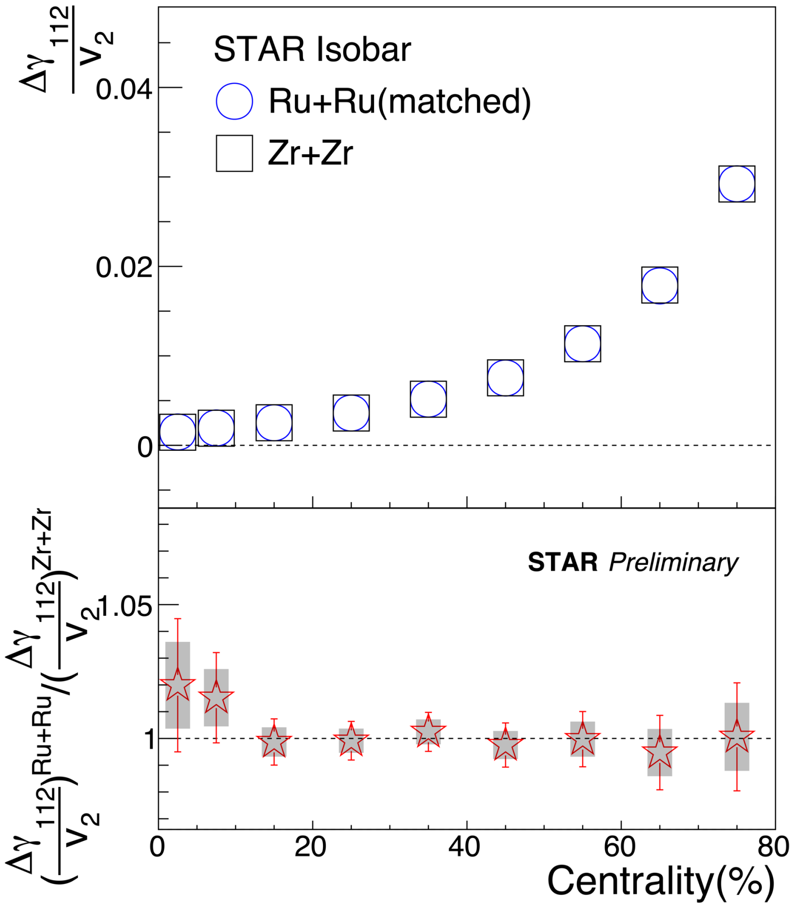


➢ The difference in N_{POI} is removed and v_2 is still different with N_{POI} match.

Analysis results: γ

- $\boldsymbol{\gamma}$-correlator： Only the N_{POI} as the matching dimension.

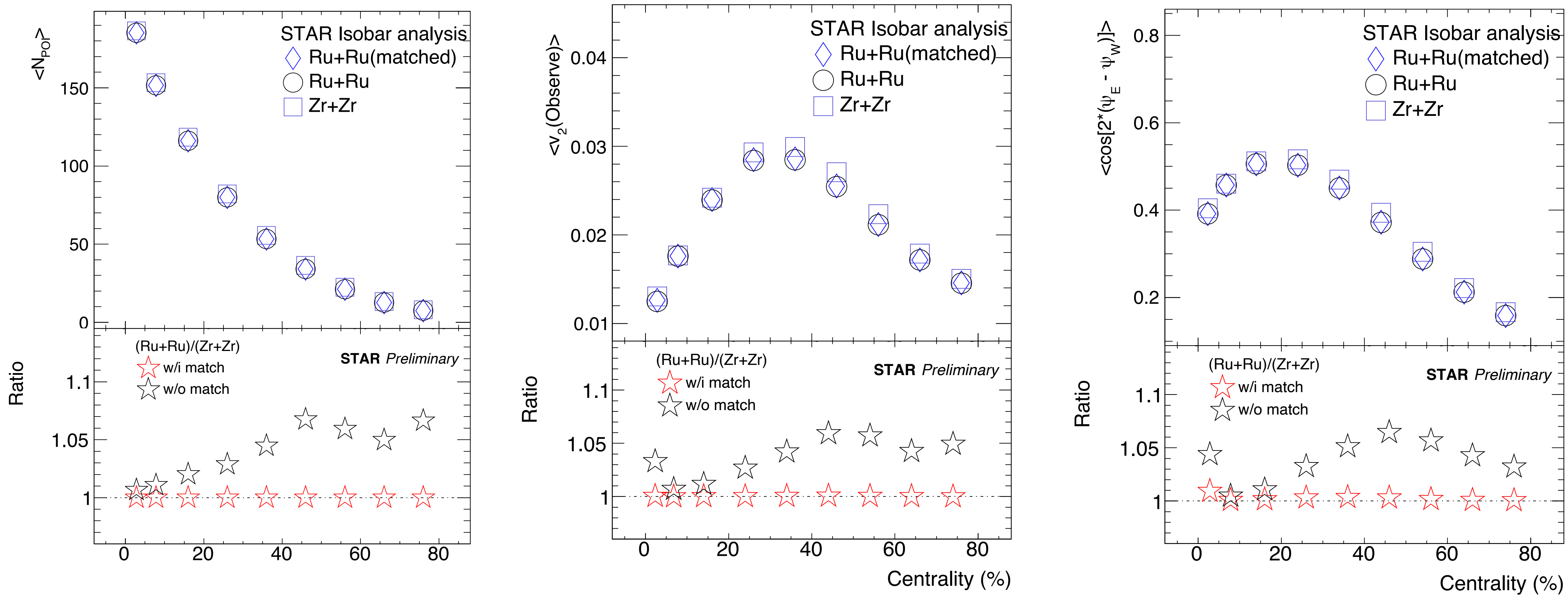




➢ The ratio $\frac{\Delta\gamma_{112}}{v_2} \approx 1$ with N_{POI} matched.

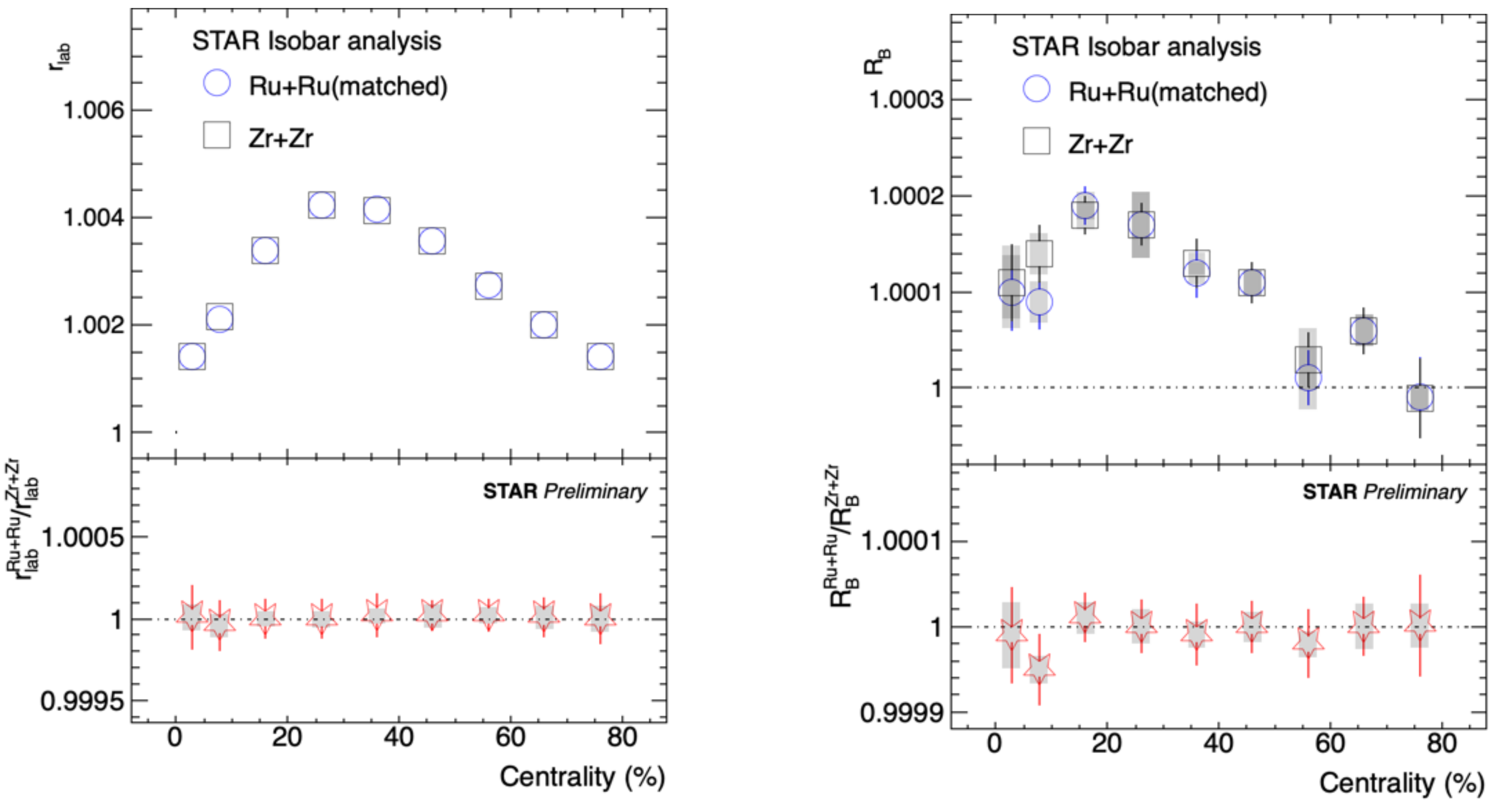
Analysis results: SBF

- SBF: N_{POI}, $v_2(observe)$ and $cos[2(\Psi_E - \Psi_W)]$ all as the matching dimensions.



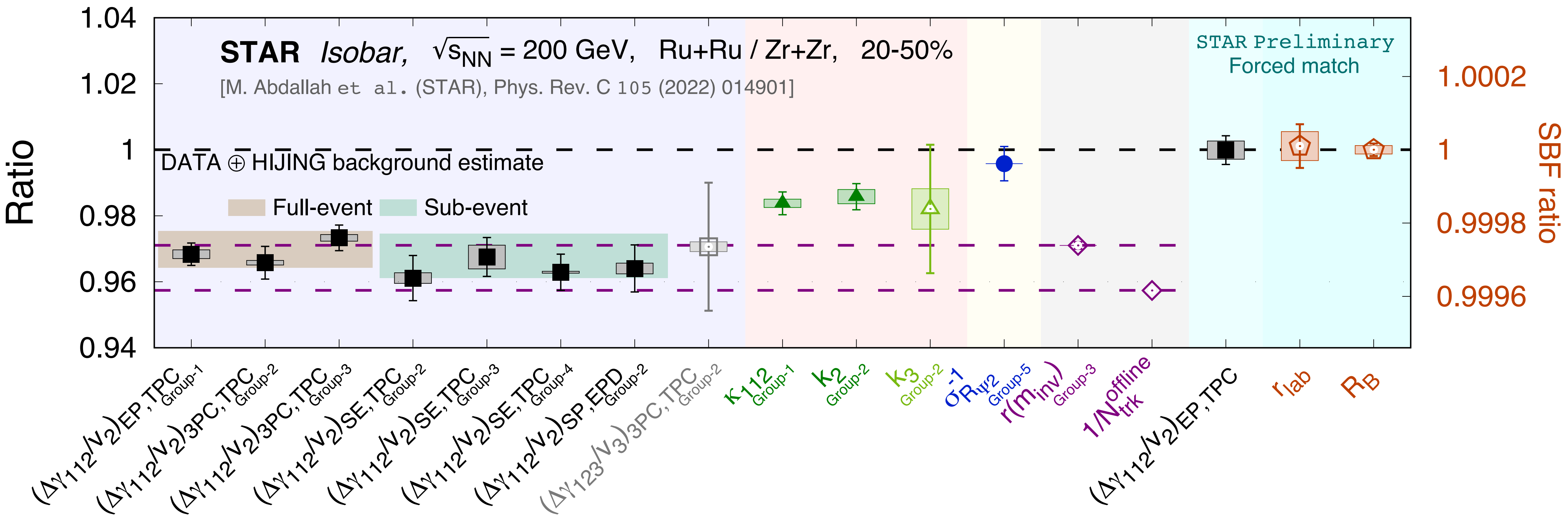
➢ The difference in N_{POI}, $v_2(observe)$ and $cos[2(\Psi_E - \Psi_W)]$ are removed.

Analysis results: SBF



➢ Both the ratio of r_{lab} and R_B are consistent with 1 with forced match.

Summary



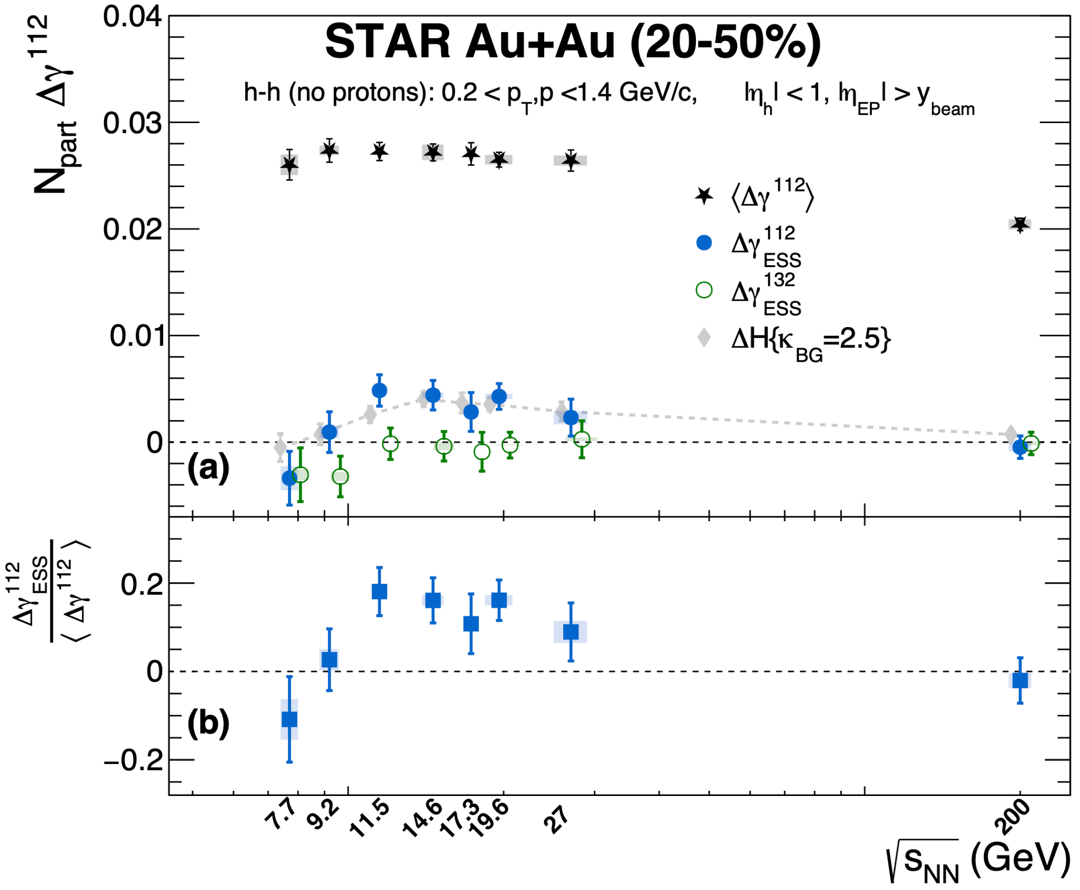
✓ No obvious CME signal has been observed in Isobar collisions.

Outlook

- RHIC Au+Au: Upcoming large data set 2023~2025, pushing measurements toward high sigma level for a decisive conclusion.

- Beam Energy Scan: Mapping the full range beam energy dependence of CME phenomenon from BES energies.

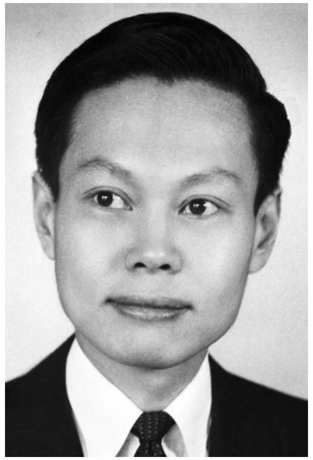
- …

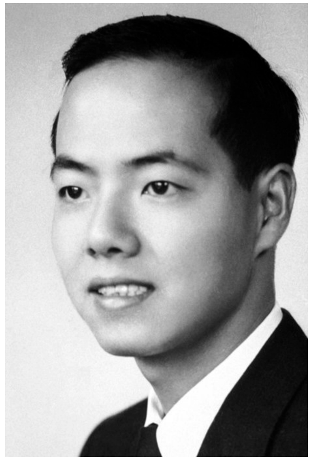


From Zhiwan Xu

Parity violation in Weak Interaction

- **The Nobel Prize in Physics 1957**





PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

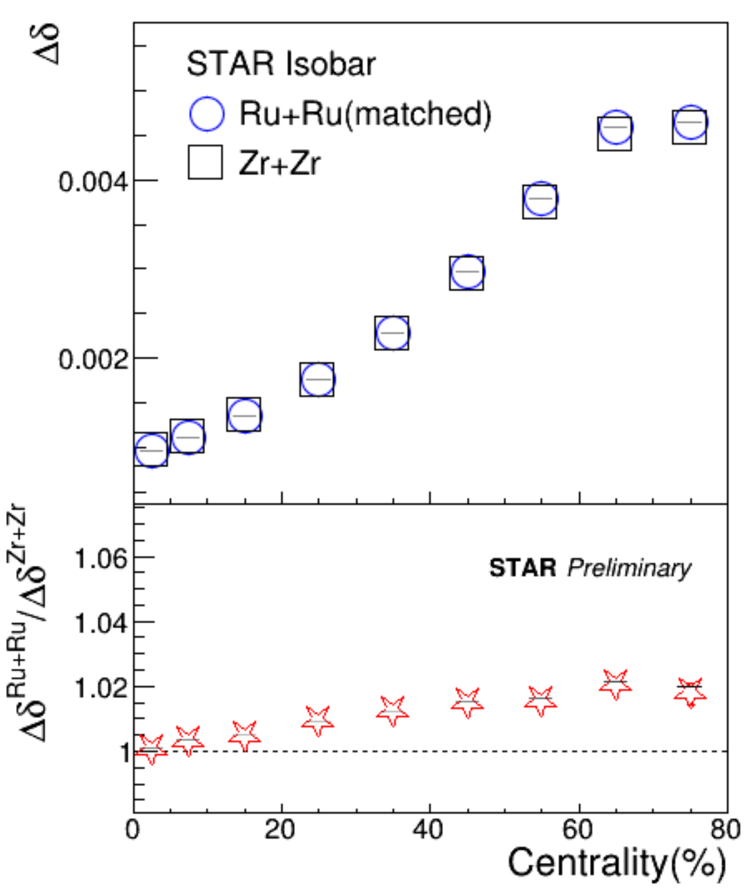
C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

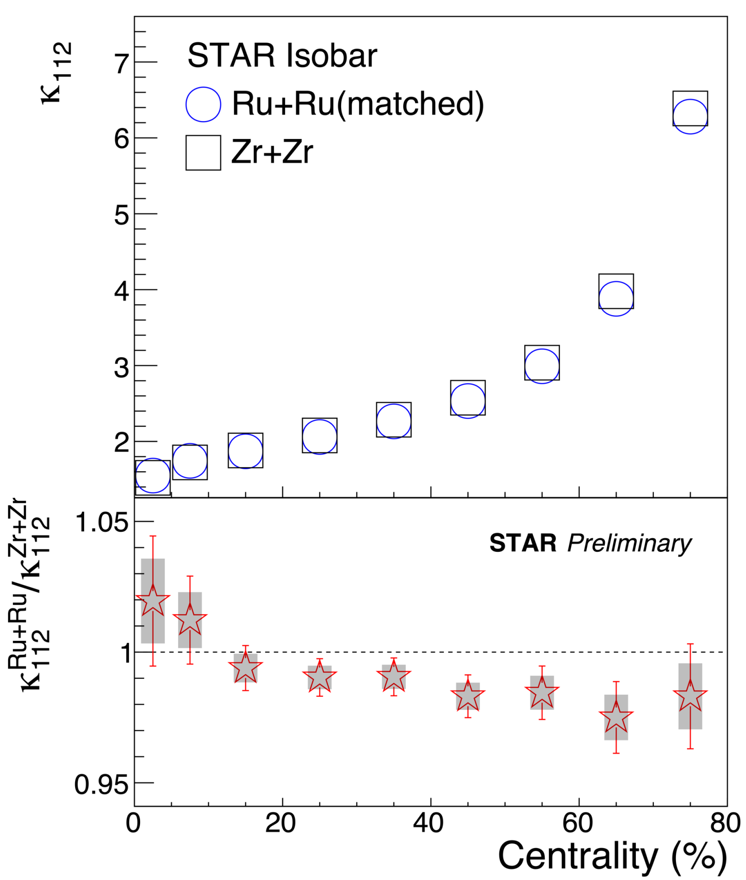
(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

❑ When could the parity violation in strong interaction be confirm?

Backup: Analysis results





$$\kappa_{112} = \frac{\Delta\gamma_{112}}{v_2 \cdot \Delta\delta}$$

The ratio of $\Delta\delta < 1$ and $\kappa_{112} > 1$ with CME signal.

- The ratio $\Delta\delta$ is larger than even after N_{POI} match.
- κ_{112} is below 1 with N_{POI} match.

Backup: SBF(1)

1) Count pair's momentum ordering in p_y :

$$B_{P,y}(S_y) = \frac{N_{+-}(S_y) - N_{++}(S_y)}{N_+}$$

$$B_{N,y}(S_y) = \frac{N_{-+}(S_y) - N_{--}(S_y)}{N_-}$$

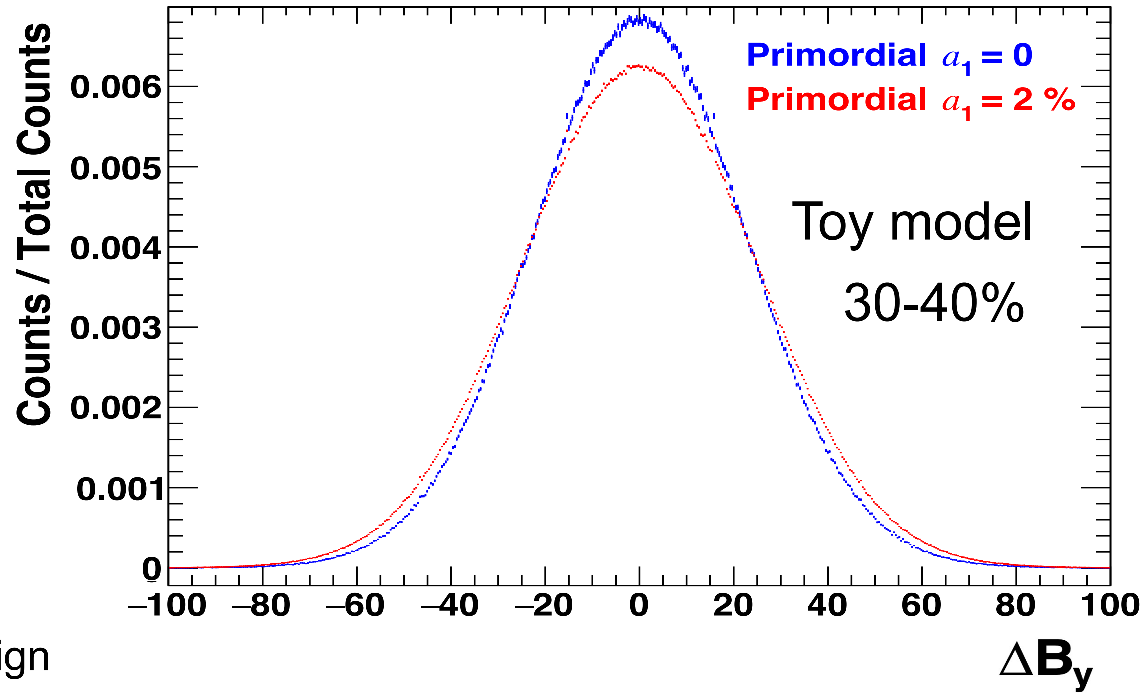
2) Count net-ordering (e.g. excess of pos. leading neg.) for each event :

$$\delta B_y(\pm 1) = B_{P,y}(\pm 1) - B_{N,y}(\pm 1)$$

$$\Delta B_y = \delta B_y(+1) - \delta B_y(-1)$$

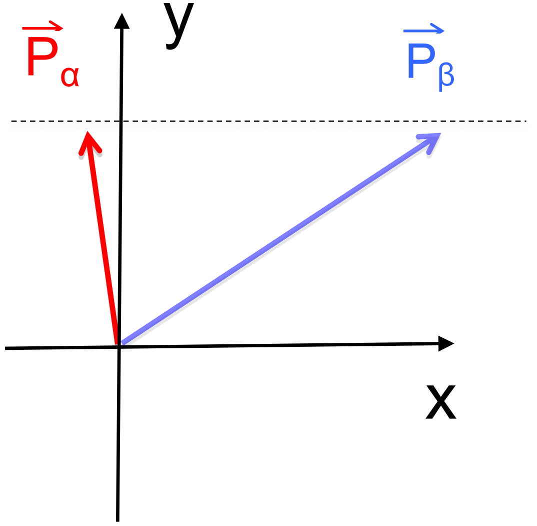
where $N_{\alpha\beta}$ denotes the number of positive -negative pairs with a sign of Sy in an event. S_y is labeled as +1 if $p^{\alpha}_y > p^{\beta}_y$, and -1 if vice versa.

3) Look for enhanced event-by-event fluctuation of net ordering in y direction.

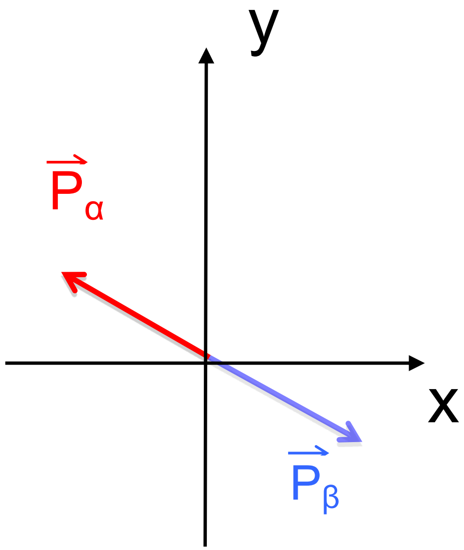


$$r = \frac{\sigma_{\Delta B_y}}{\sigma_{\Delta B_x}}$$ (>1 with CME)

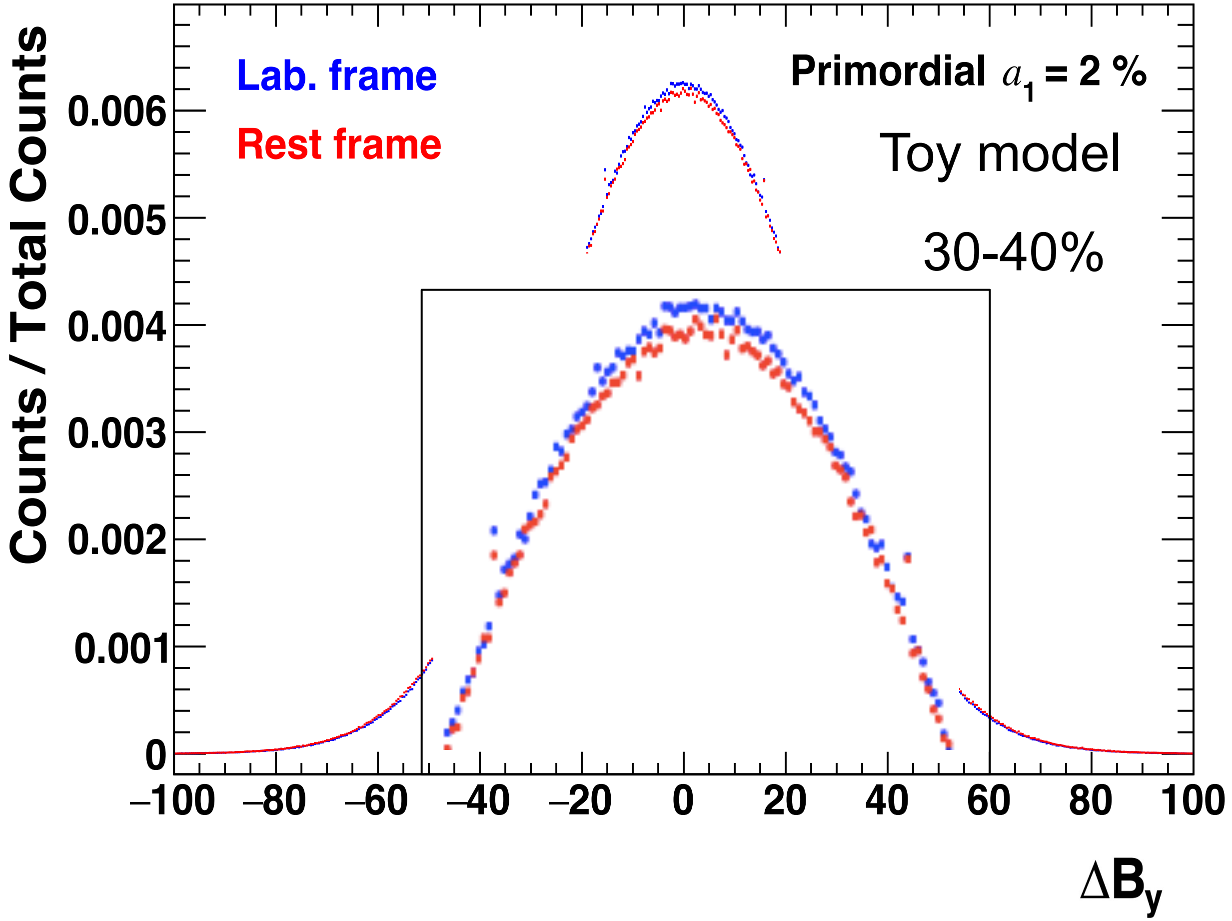
Backup: SBF(2)



Lab frame view
($p_y^\alpha = p_y^\beta$)



Rest frame view
($p_y^\alpha > p_y^\beta$)



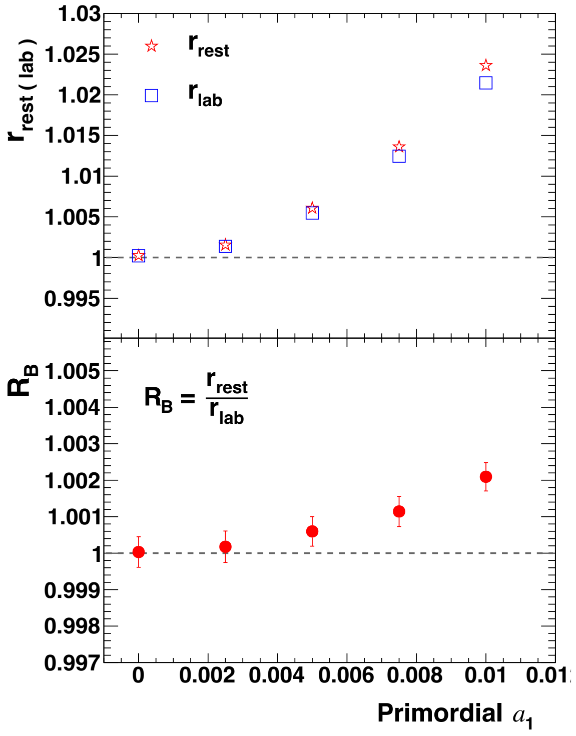
Rest frame has the best sensitivity to momentum ordering.

$$R_B = \frac{r_{rest}}{r_{lab}}$$ (>1 with CME)

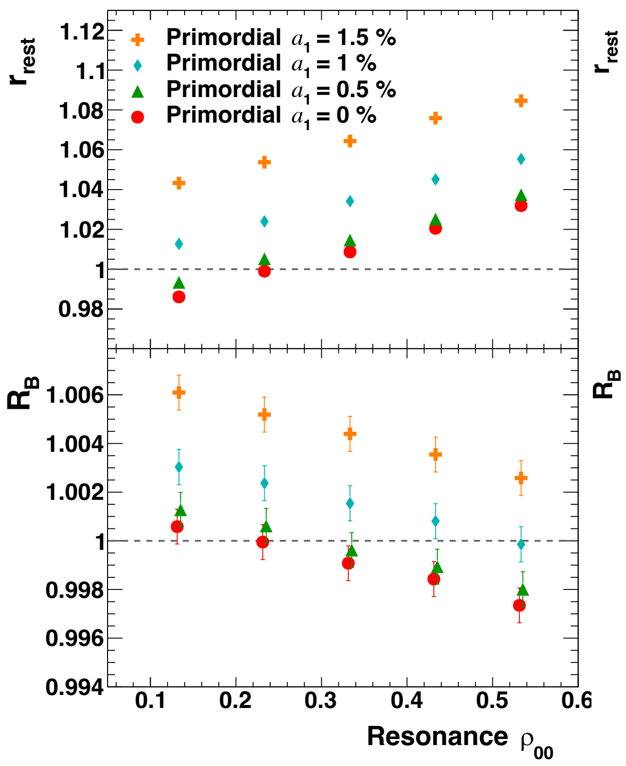
Backup: SBF(3)

Examining the momentum ordering of charged pairs along the in- and out-of-plane directions with balance function

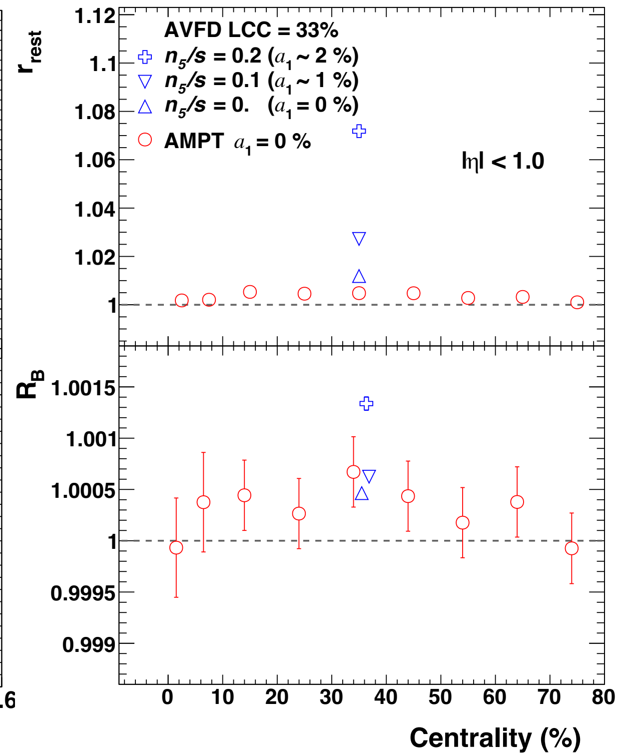
Toy model: Signal only



Toy model: ρ_{00} + v_2 + CME



AVFD and AVFD model



- Both r_{lab}, r_{rest} and R_B are sensitive to the CME signal.
- r_{rest} and R_B respond in opposite directions to signal and backgrounds arising from resonance v_2 and ρ_{00}, respectively.

A. Tang, Chinese Physics C Vol. 44, No. 5 (2020) 054101
Y. Lin, Nuclear Physics A 1005 (2021) 121828