Search for the Chiral Magnetic Effect by the STAR Experiment

Gang Wang (UCLA)

for the STAR Collaboration

Supported in part by

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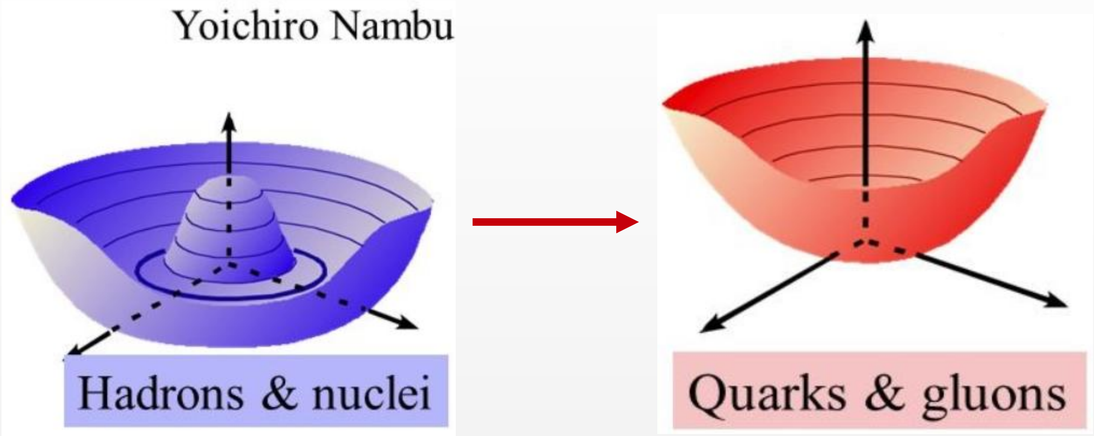
STAR

UCLA BRUINS

Chiral Magnetic Effect: $J \propto \mu_5 B$

1 Chiral symmetry restoration (massless quarks)



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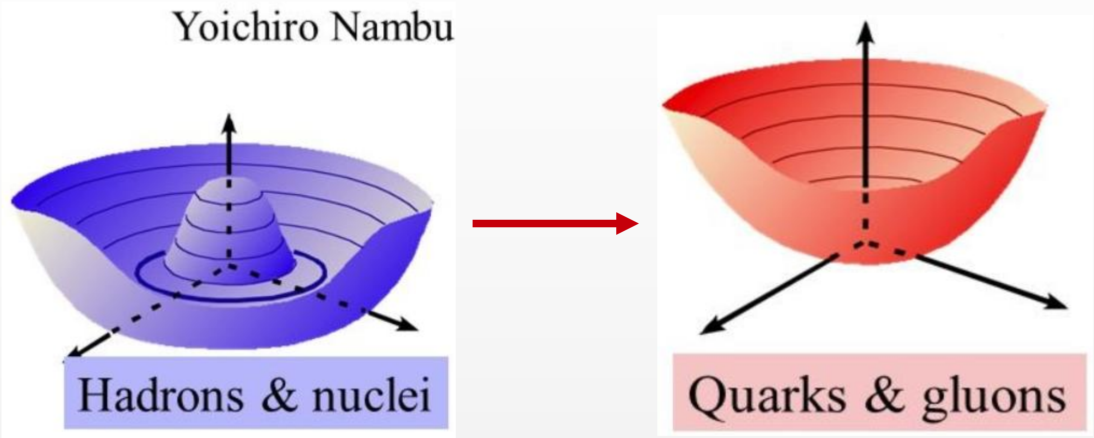
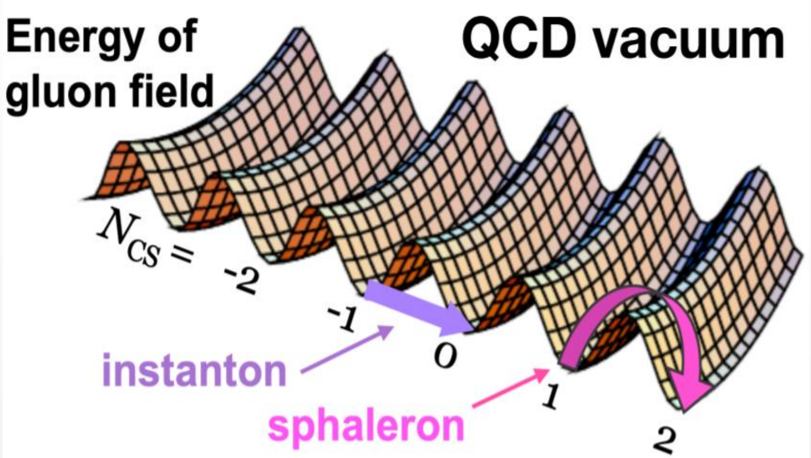


2 Chirality imbalance (finite μ_5, Local Parity Violation）



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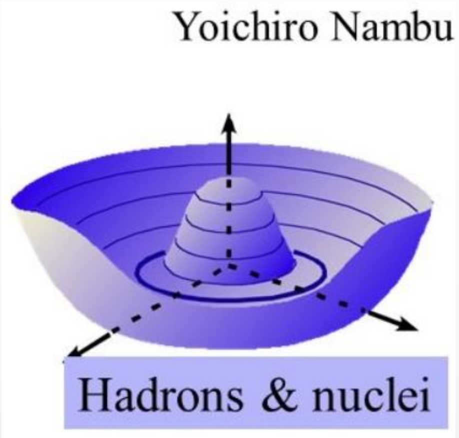

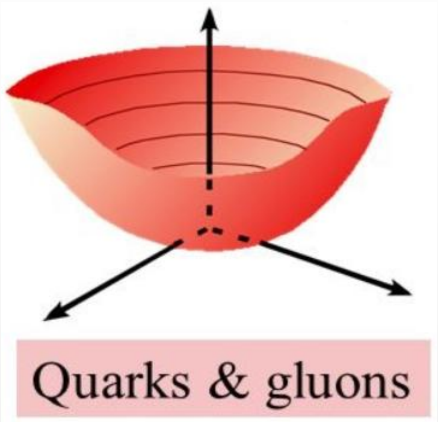

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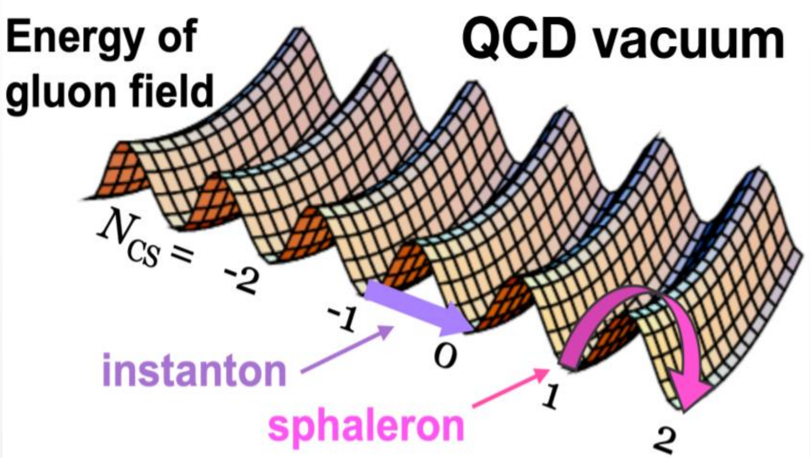
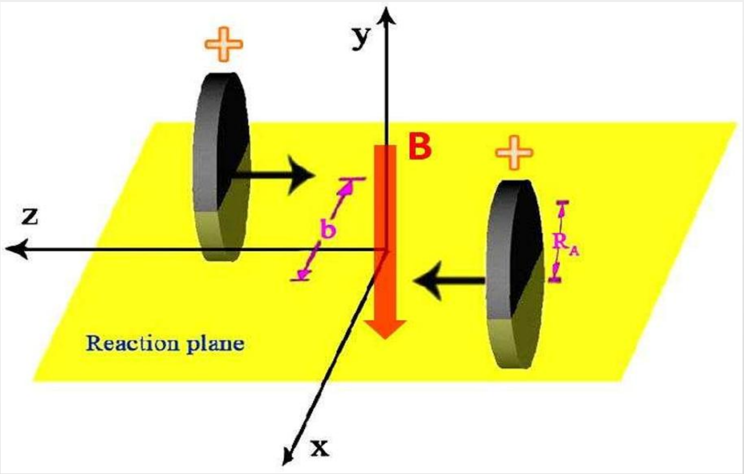


3 Strong magnetic field (B ~ 10^{18} Gauss)



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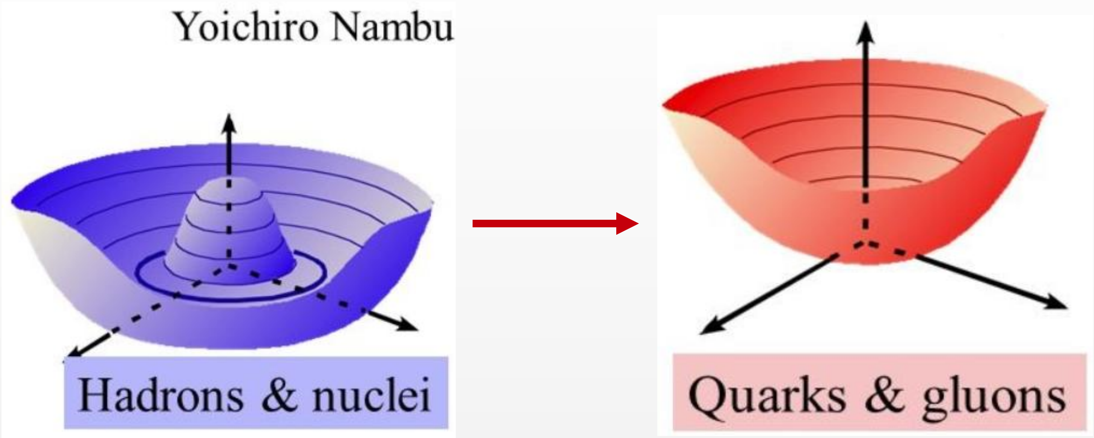

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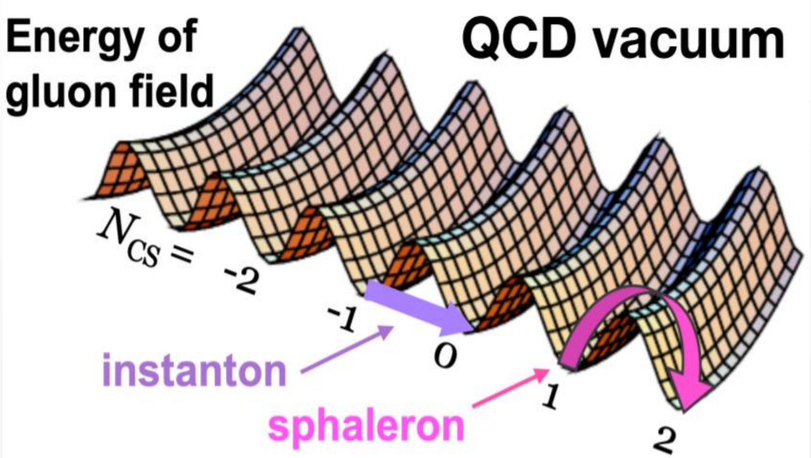

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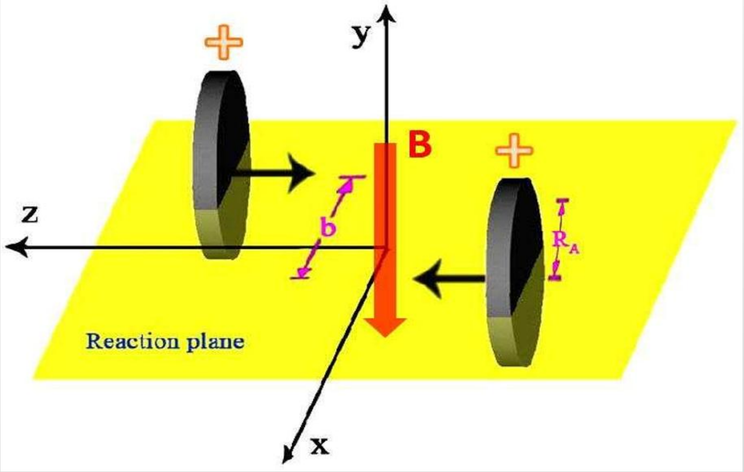
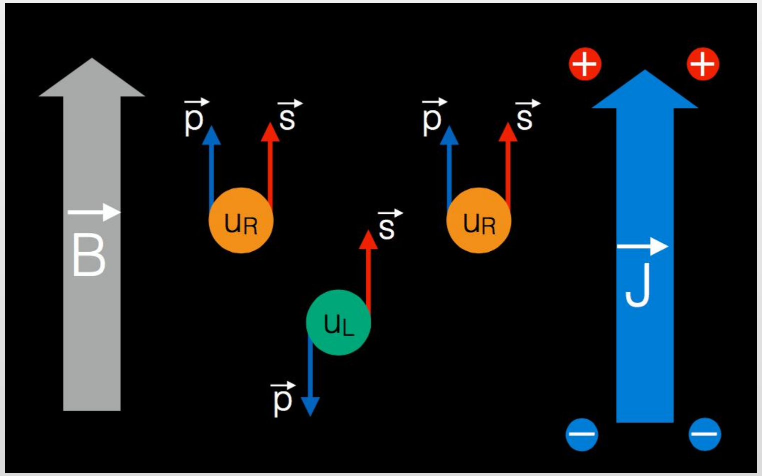


Experimental manifestation: charge separation across the reaction plane

4 Chiral Magnetic Effect (J || B)



Observables in search of CME

$$\frac{dN_\alpha}{d\phi^*} \approx \frac{N_\alpha}{2\pi}[1 + 2v_{1,\alpha}\cos(\phi^*) + 2v_{2,\alpha}\cos(2\phi^*) + 2v_{3,\alpha}\cos(3\phi^*) + ... + 2a_{1,\alpha}\sin(\phi^*) + ...] \qquad \phi^* = \phi - \Psi_{\mathrm{RP}}$$

CME-sensitive observables on the market:

- γ correlaor

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

- *R* correlaor

  N. N. Ajitanand *et al.*, Phys. Rev. C83, 011901(R) (2011)

- Signed balance functions

  A. H. Tang, Chin. Phys. C,44, No.5 054101 (2020)

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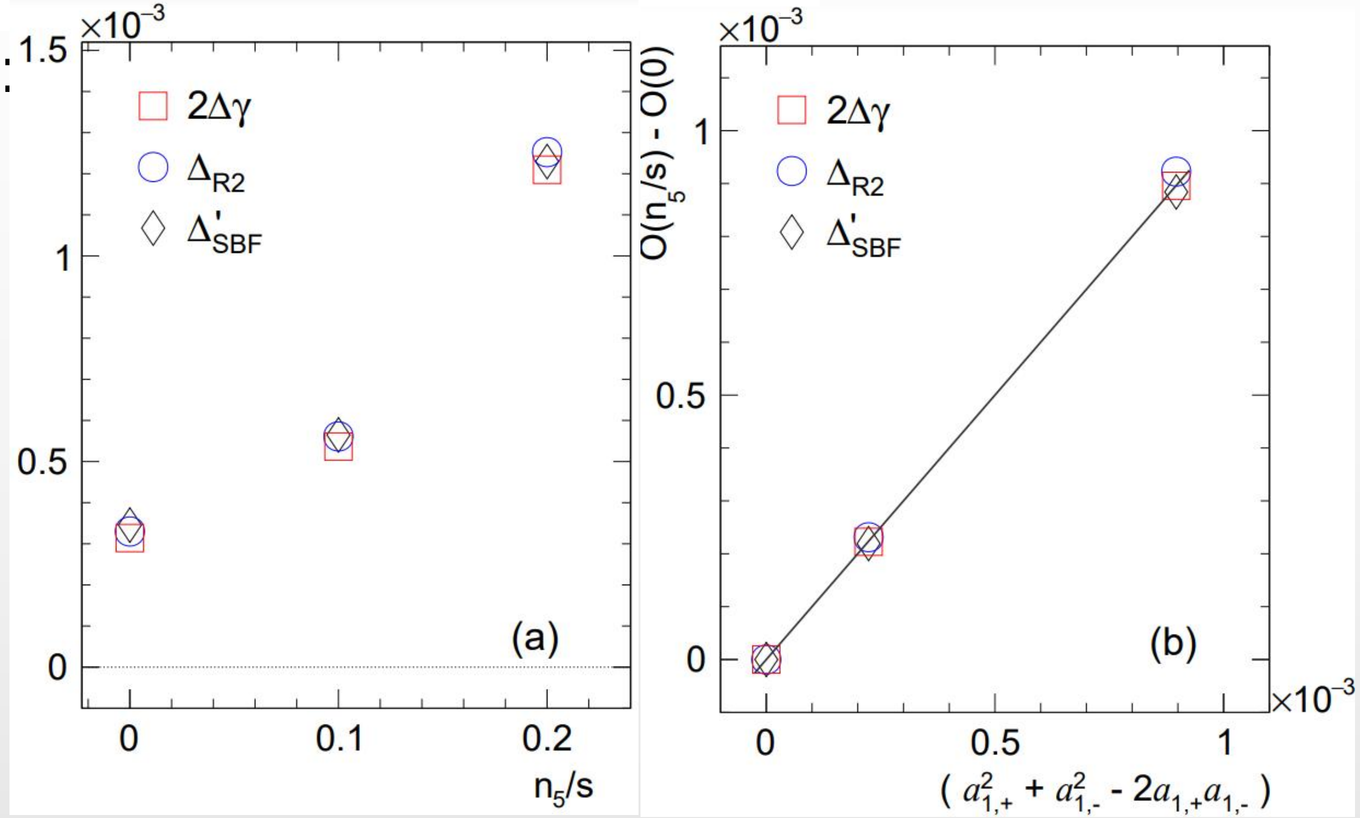
Here we focus on

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

And the CME signal should cause

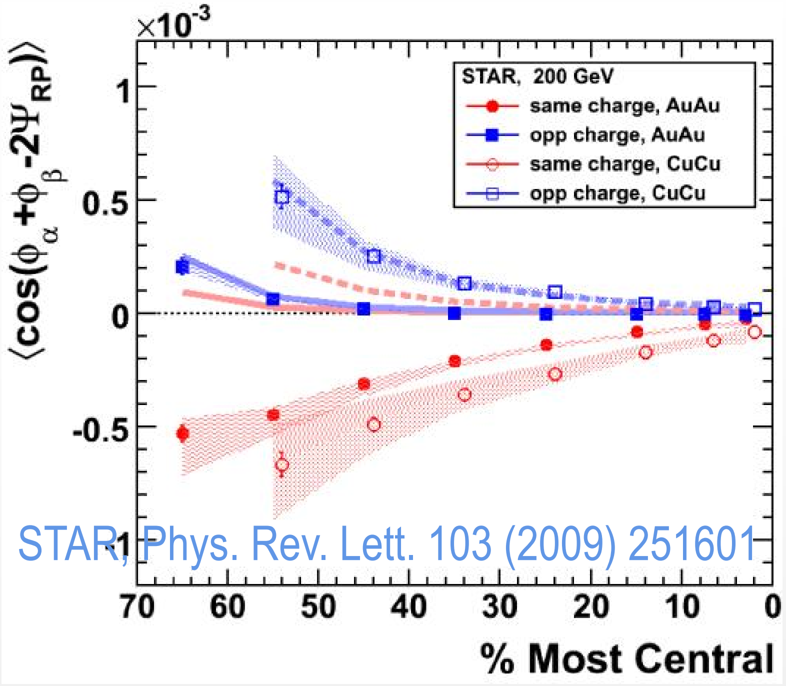
$$\Delta\gamma_{112} \equiv \gamma_{112}^{\mathrm{OS}} - \gamma_{112}^{\mathrm{SS}} > 0$$

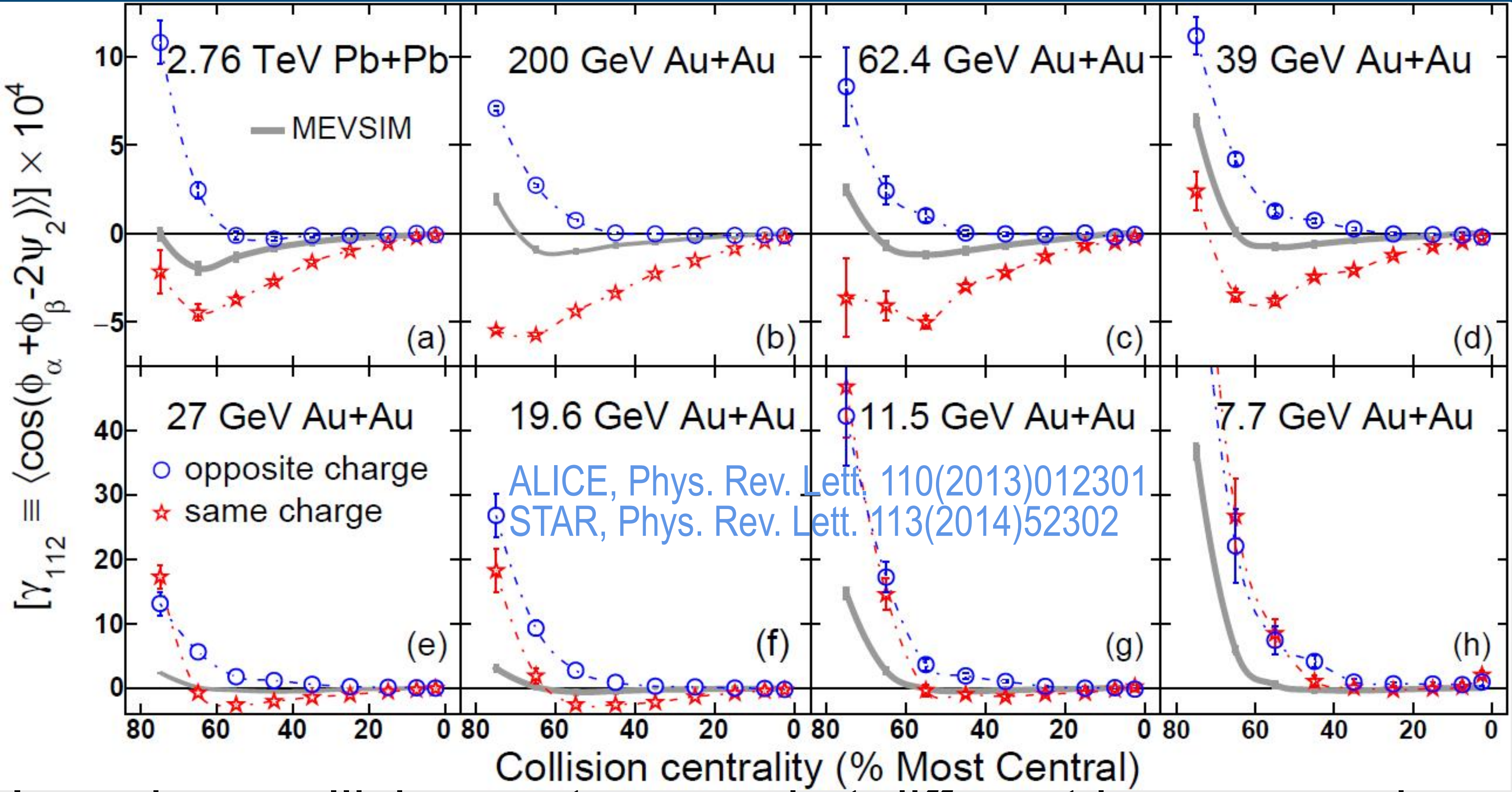


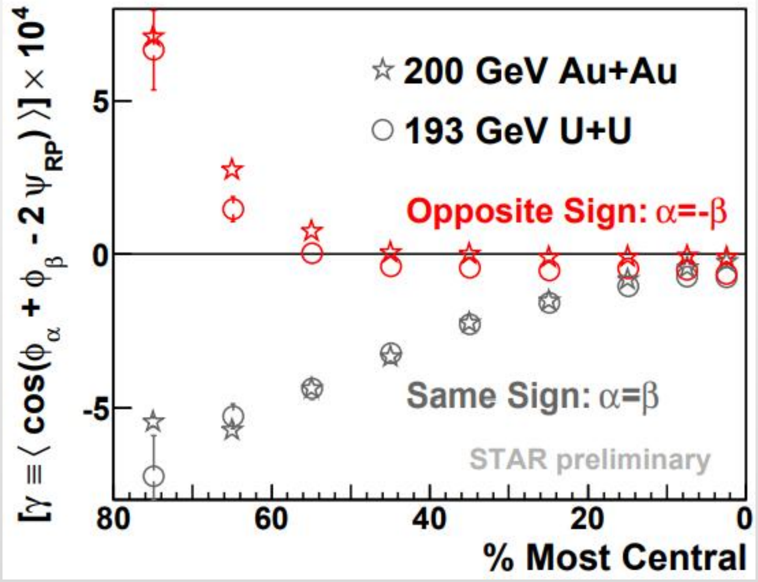
S. Choudhury et al.(STAR), Chinese Phys. C 46 (2022) 014101.

AVFD simulations show that these methods have similar sensitivities to the CME signal and to the background.

γ_{112} measurements at RHIC/LHC







In various collision systems and at different beam energies, positively finite $\Delta\gamma_{112}$ meets the CME expectation, **but** could contain contributions from:

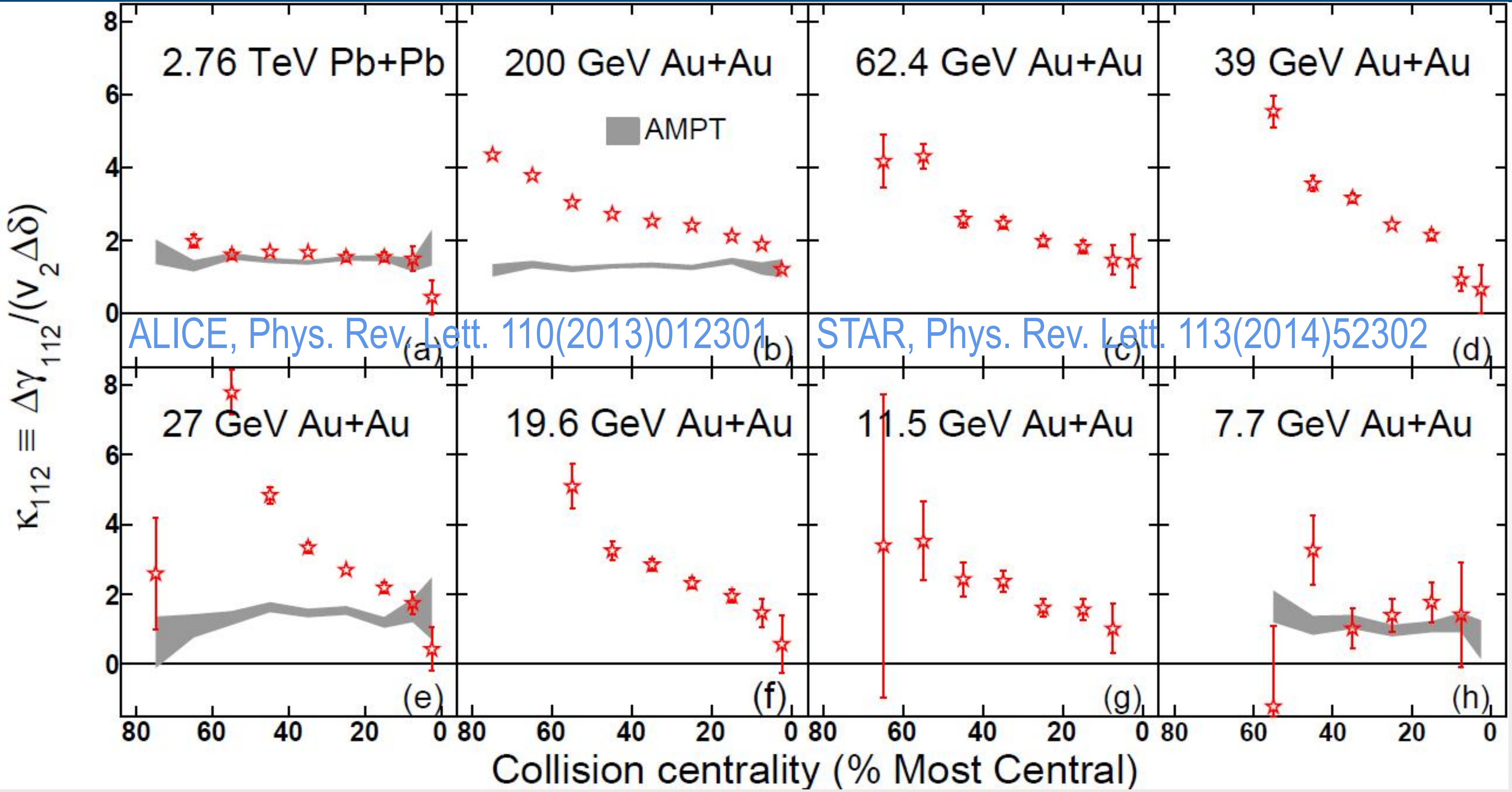
- Flow-related background $\propto v_2$ (elliptic flow)
- Nonflow-related background (di-jets)

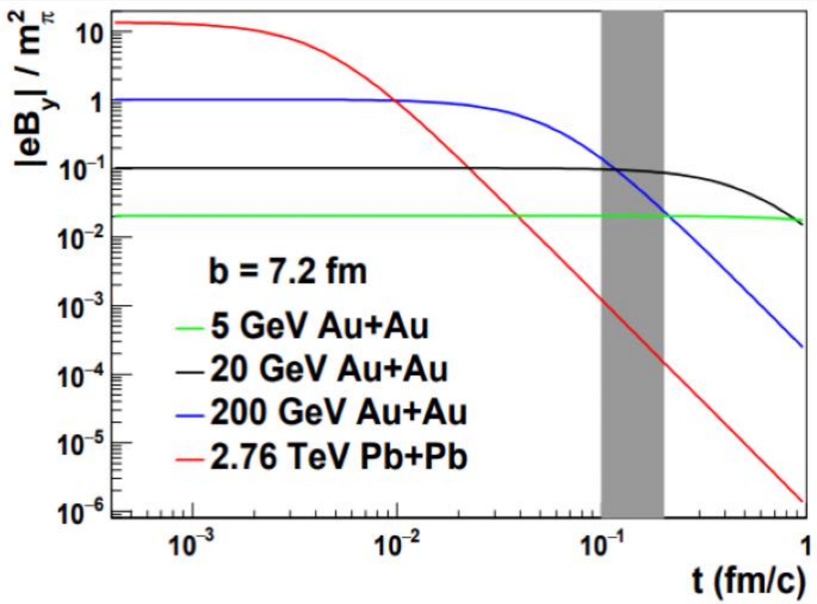
κ_{112} measurements at RHIC/LHC

$$\kappa_{112} \equiv \Delta\gamma_{112}/(v_2\Delta\delta)$$

$$\delta \equiv \langle\cos(\phi_\alpha - \phi_\beta)\rangle$$

Normalized quantity facilitates comparison between data and model calculations (AMPT).

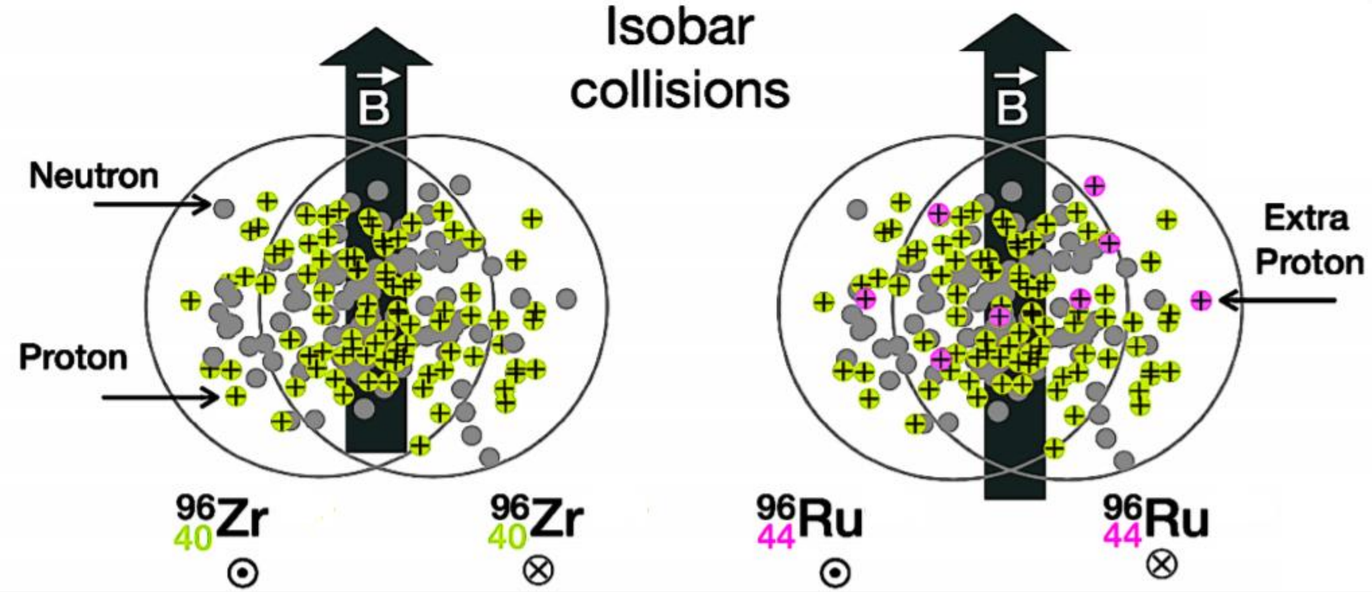




Compared with a pure-background model, the CME signal seems to disappear at 7.7 GeV and 2.76 TeV.

- very low beam energies: no chiral symmetry restoration?
- very high energies: no duration of the magnetic field?

Isobar collisions: prospect



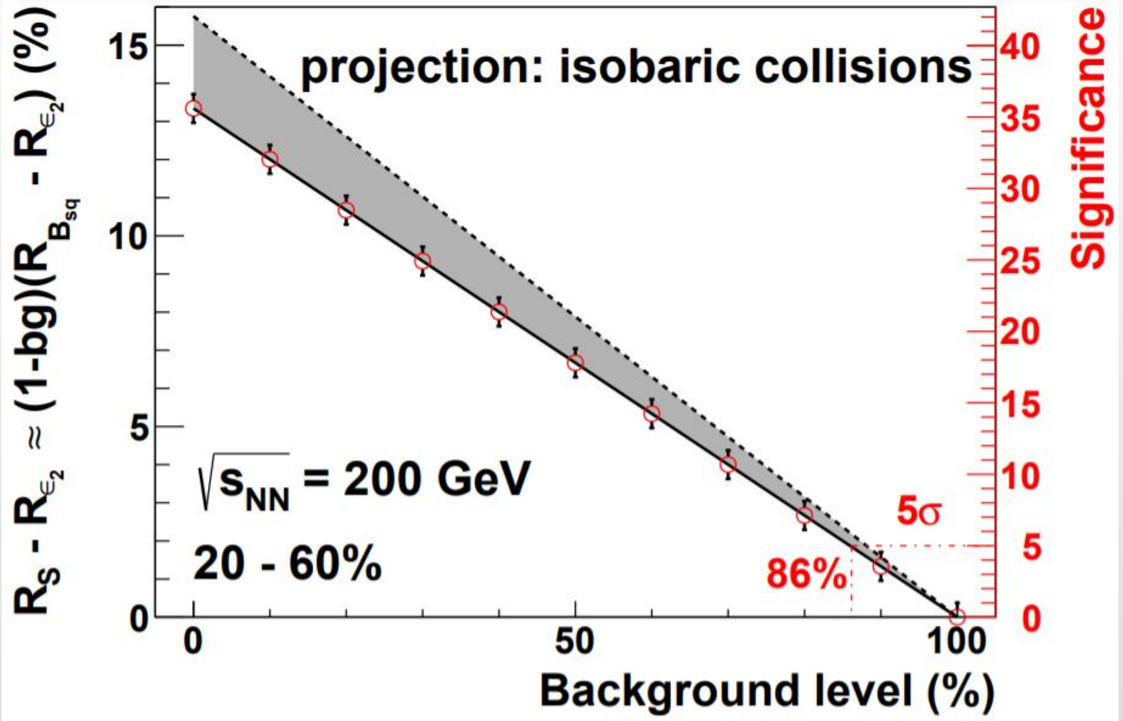
Compare the two isobaric systems:

- CME: B-field^2 is ~15% larger in Ru+Ru
- Flow-related BKG: utilize $\Delta\gamma_{112}/v_2$
- Nonflow-related BKG: almost same

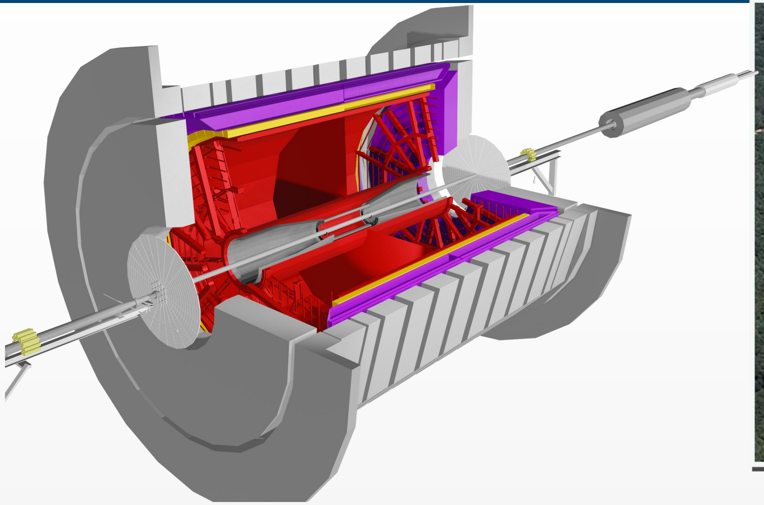
Isobar collisions provide best possible control of signal and background.

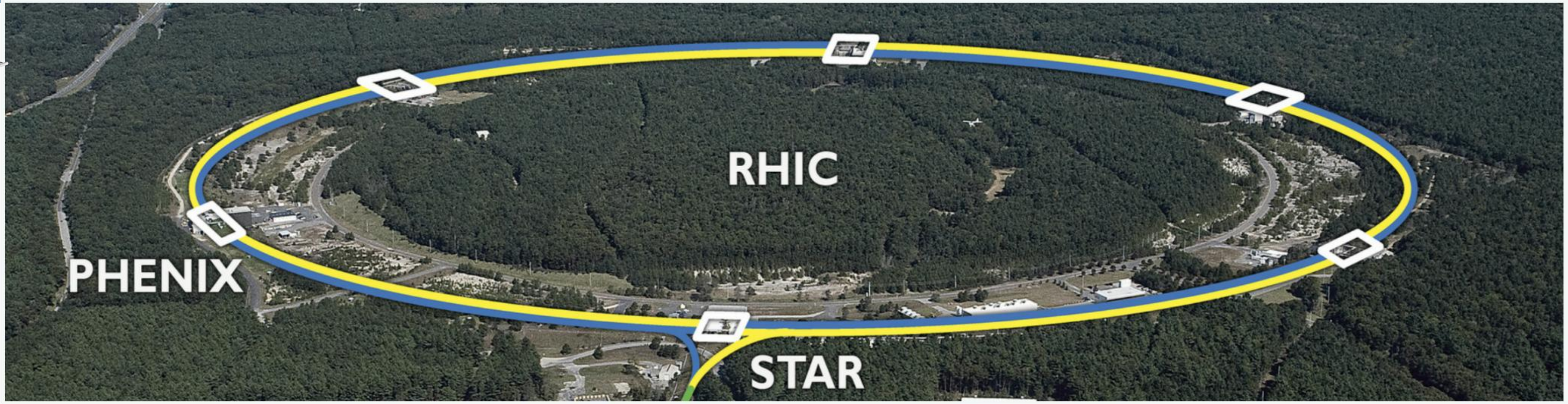
2.5 B events per species:

- uncertainty of 0.4% in the $\Delta\gamma/v_2$ ratio.
- if f_{CME} > 14%, $\Delta\gamma_{112}/v_2$ difference > 2%, yielding a 5σ significance.
- f_{CME} is the unknown CME fraction in $\Delta\gamma_{112}$.



Isobar program: data collection in 2018





Successful data taking of isobar collisions at RHIC/STAR

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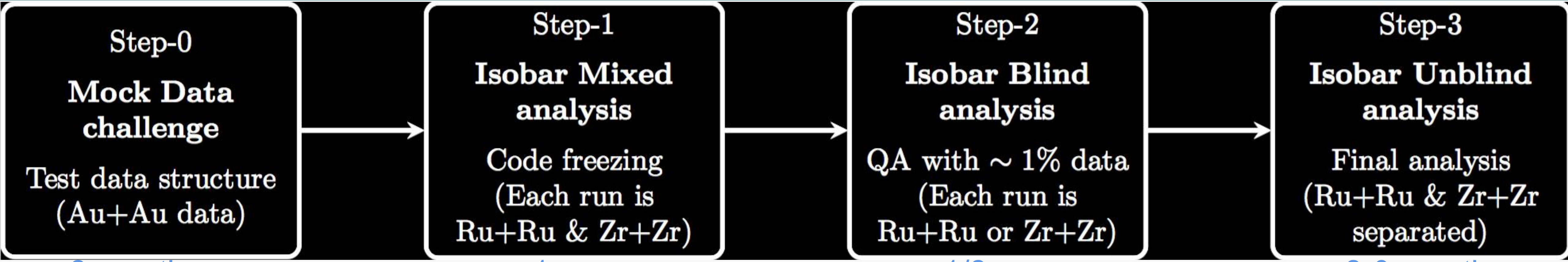
Search for the chiral magnetic effect with isobar collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider

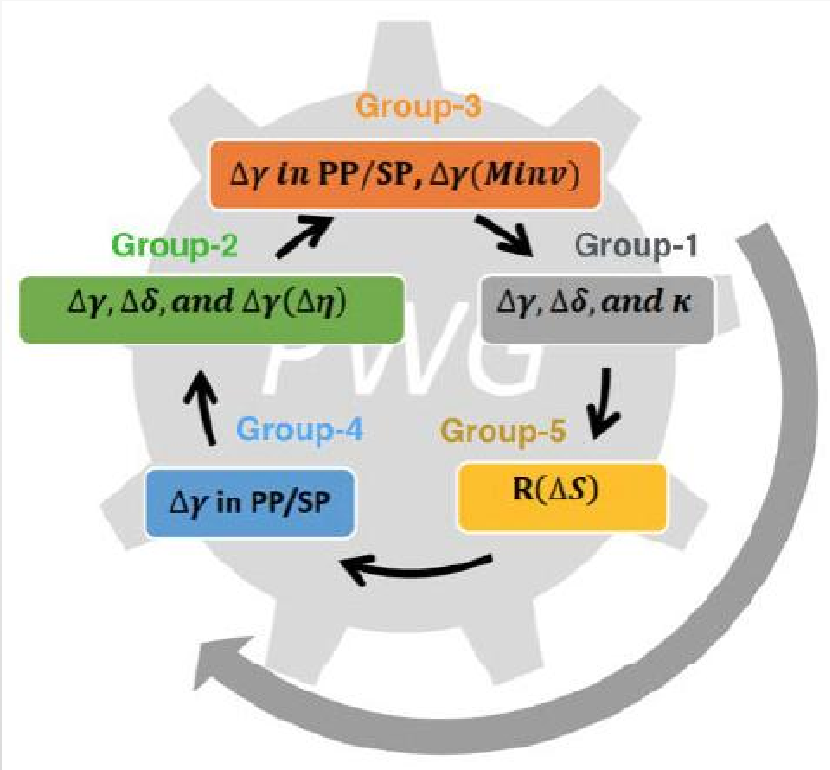
M. S. Abdallah *et al.* (STAR Collaboration)
Phys. Rev. C **105**, 014901 – Published 3 January 2022

First publication after 3 years and many people's efforts...

Isobar blind analysis

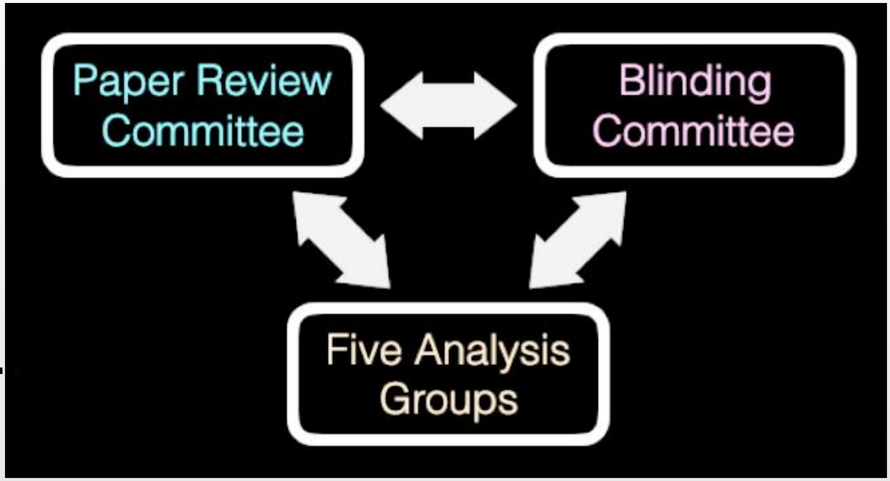


~ 2 months | ~1 year | ~1/2 year | ~2-3 months



Blinding committee decides the procedure.
STAR, Nucl. Sci. Tech. 32 (2021) 48

Five independent groups run each other's frozen code.



No access to species-specific information until last step.
Everything documented (not written → not allowed)

Case for CME & interpretation must be pre-defined.

Centrality definition

Blind analysis: compare observables at matching centrality between two isobar systems.

STAR, Phys. Rev. C 105 (2022) 14901

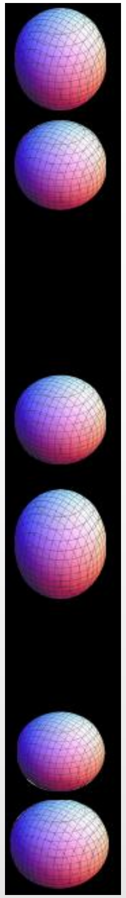
Nucleus	Case-1 [83] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158
$^{96}_{40}$Zr	5.02	0.46	0.08

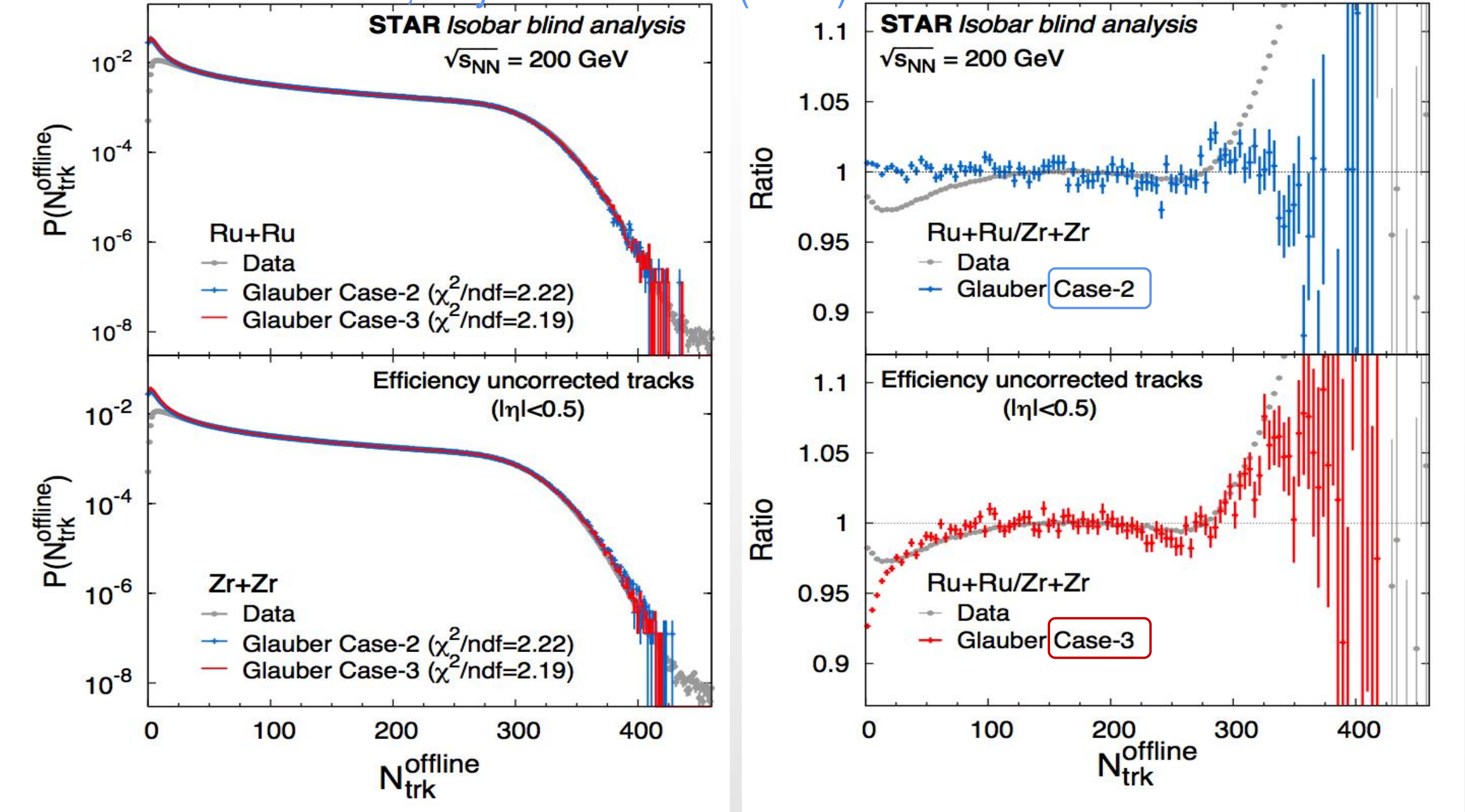
Deng *et al.*, PRC 94, 041901 (2016)

Nucleus	Case-2 [83] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.053
$^{96}_{40}$Zr	5.02	0.46	0.217

Xu *et al.*, PRL. 121, 022301 (2018)

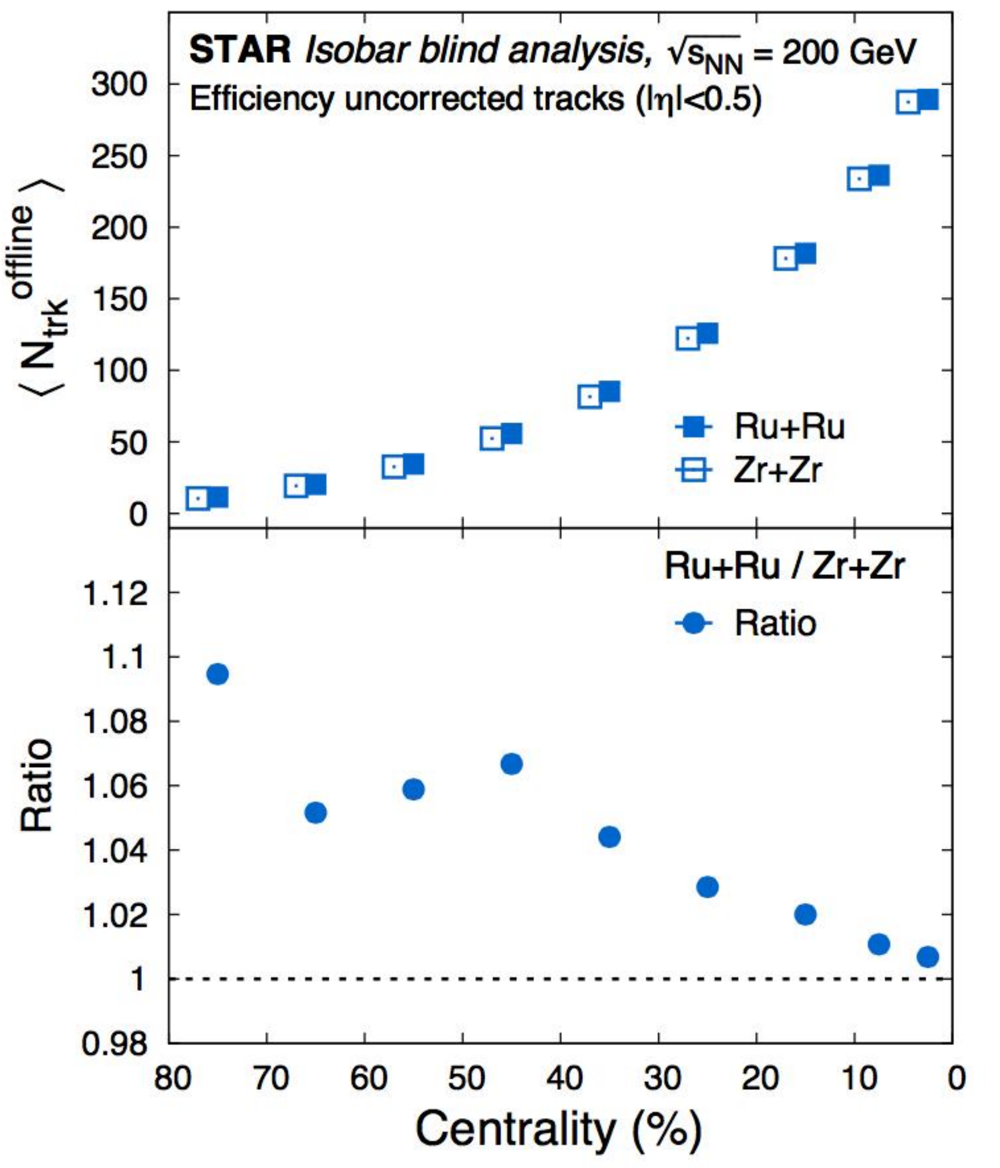
Nucleus	Case-3 [113] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.067	0.500	0
$^{96}_{40}$Zr	4.965	0.556	0





MC-Glauber model fits the uncorrected multiplicity distribution. Woods-Saxon parameters with thicker neutron skin in Zr (no deformation) gives the best fit of the multiplicity distributions.

Multiplicity mismatch



Case-3 (thicker neutron skin in Zr and zero β_2) gives the best fit of the multiplicity distributions.

However, multiplicity (efficiency uncorrected) is larger in Ru+Ru than in Zr+Zr in such a matching centrality.

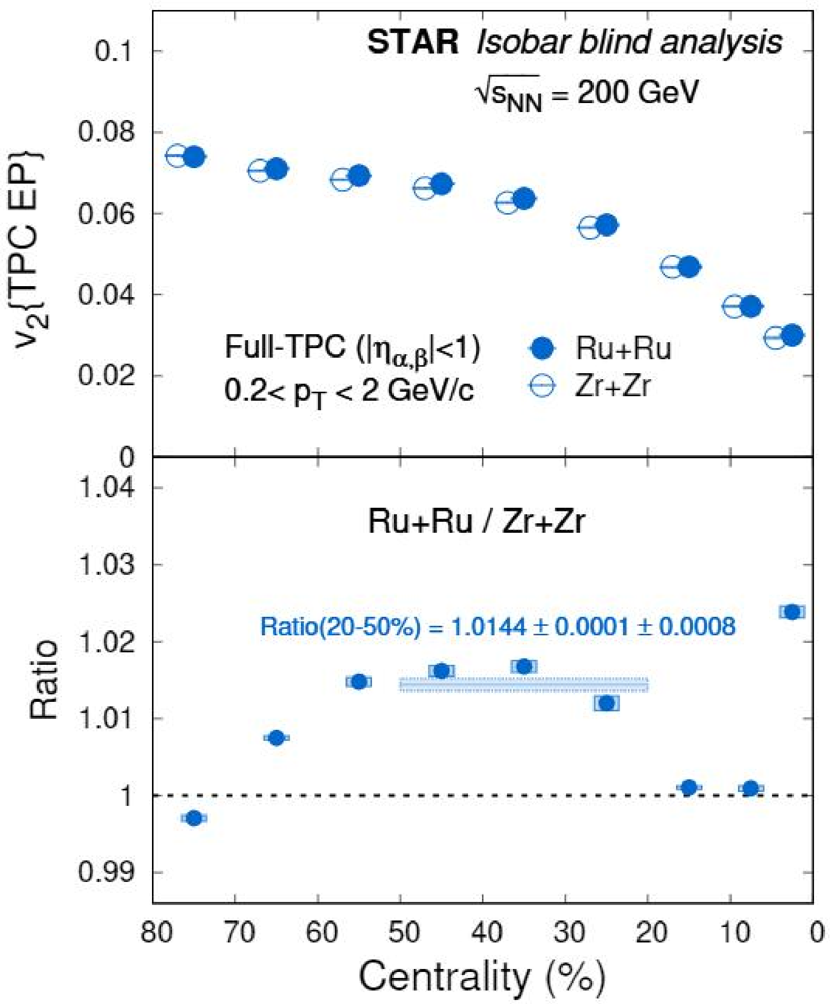
This can affect background (and signal) difference between the two isobaric systems.

Case-1 and **Case-2** give (almost) the same multiplicity in Ru+Ru and Zr+Zr, but they don't describe the multiplicity distribution so well.

In the end, the blind analysis sticks to **Case-3**.

STAR, Phys. Rev. C 105 (2022) 14901

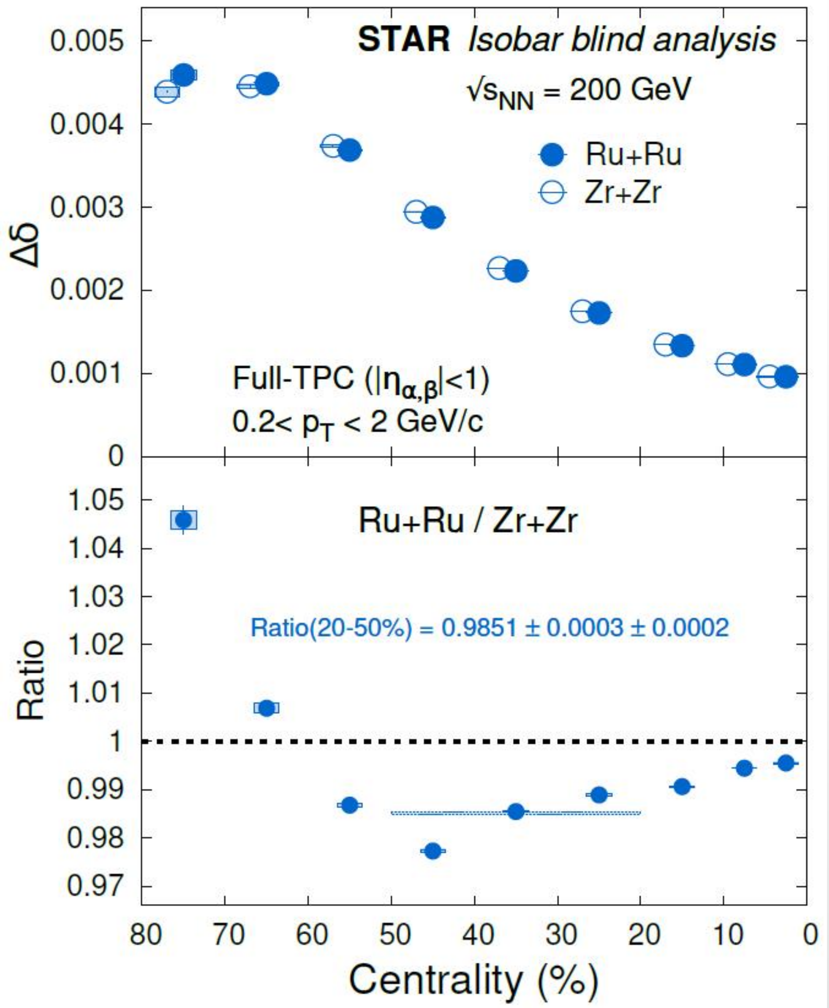
v_2 and $\Delta\delta$



STAR has multiple sets of results with different kinematic cuts. I will use the set with smallest statistical errors as a demonstration.

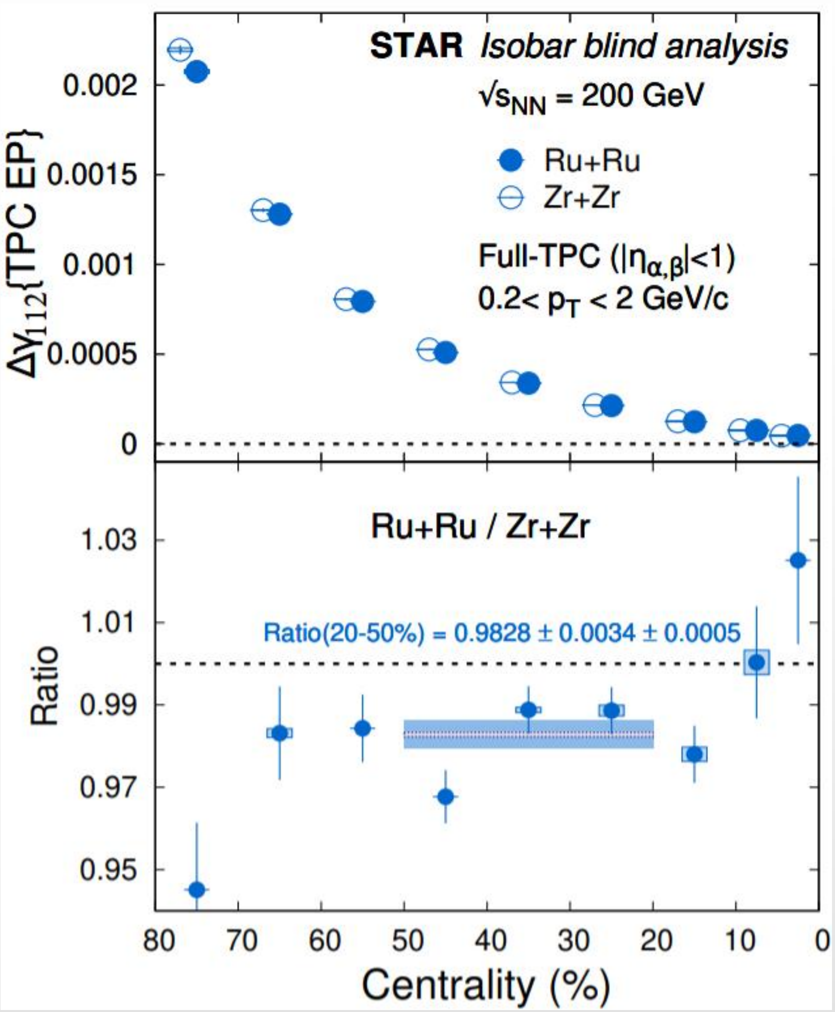
Both v_2 and $\Delta\delta$ contribute to the background, and their ratios of Ru+Ru to Zr+Zr are not exactly unity.

At matching centrality, the below-unity $\Delta\delta$ ratio could even fake a CME signal.



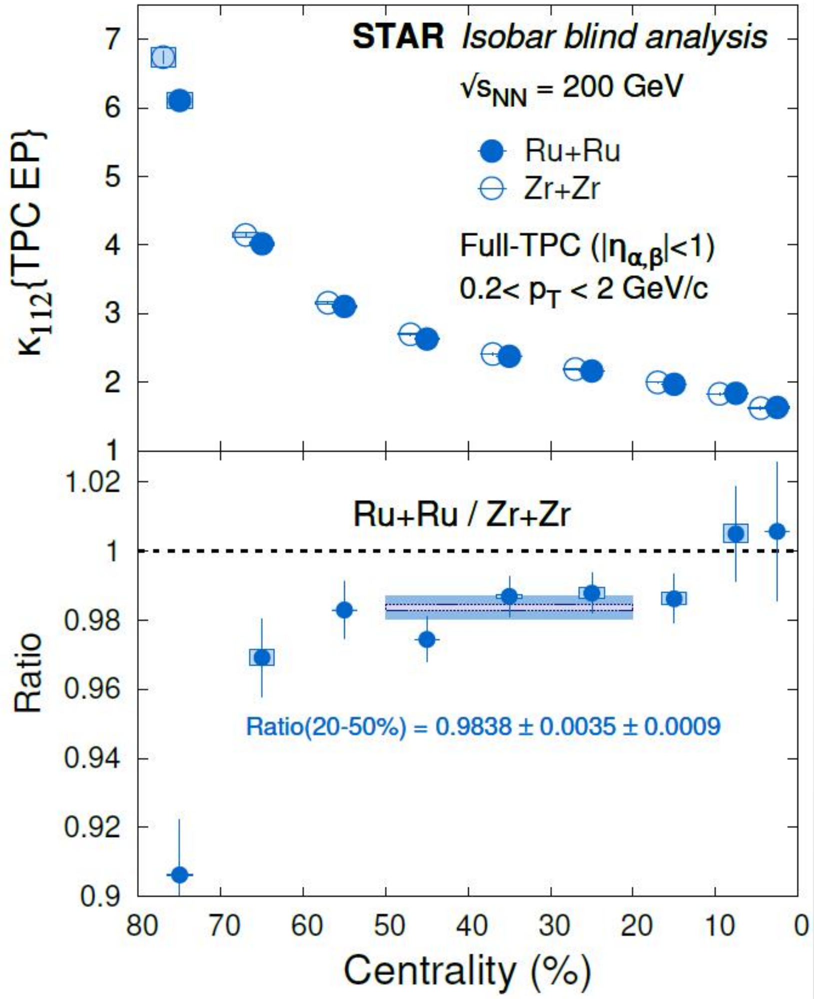
STAR, Phys. Rev. C 105 (2022) 14901

$\Delta\gamma_{112}$ and κ_{112}



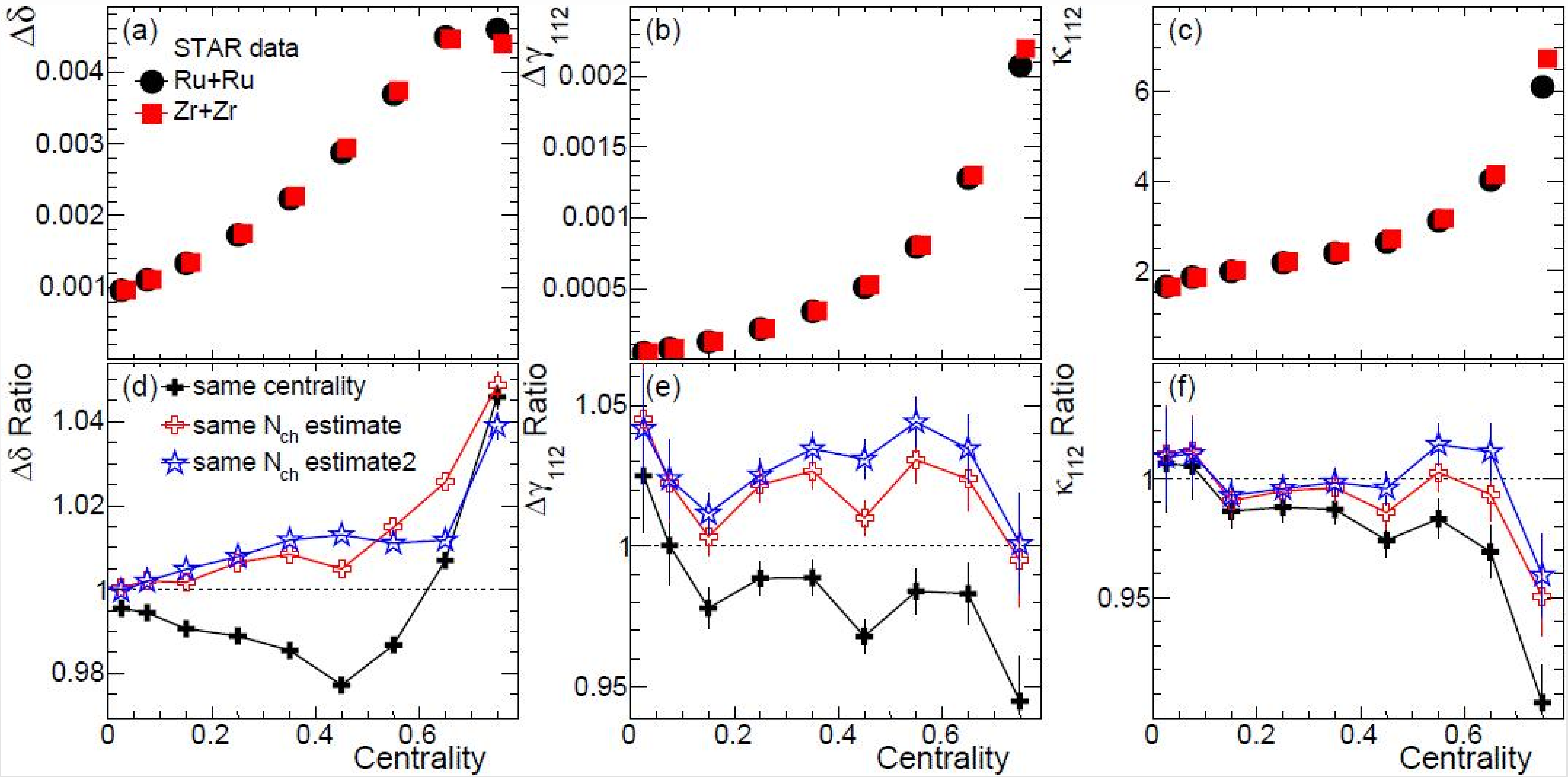
Both $\Delta\gamma_{112}$ and κ_{112} ratios of Ru+Ru to Zr+Zr go significantly below unity!

How can we understand this?



STAR, Phys. Rev. C 105 (2022) 14901

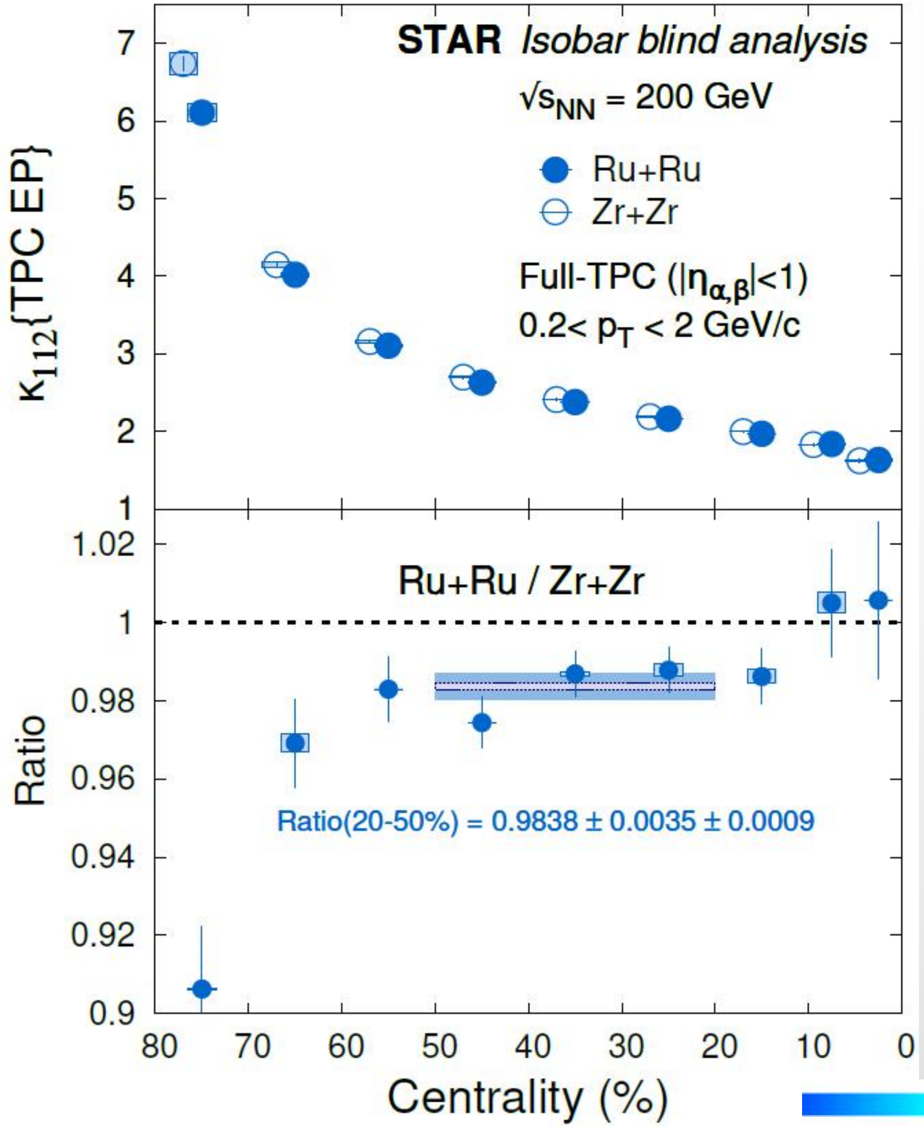
Matching centrality or matching multiplicity?



Qualitative change at matching multiplicity: κ_{112} ratios are more consistent with unity.

STAR, Phys. Rev. C 105 (2022) 14901   J. Jia, G. Wang, C. Zhang, arXiv:2203.12654

κ_{112} ratio ≈ 1+15% f_{CME}



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

Pre-defined CME signature,

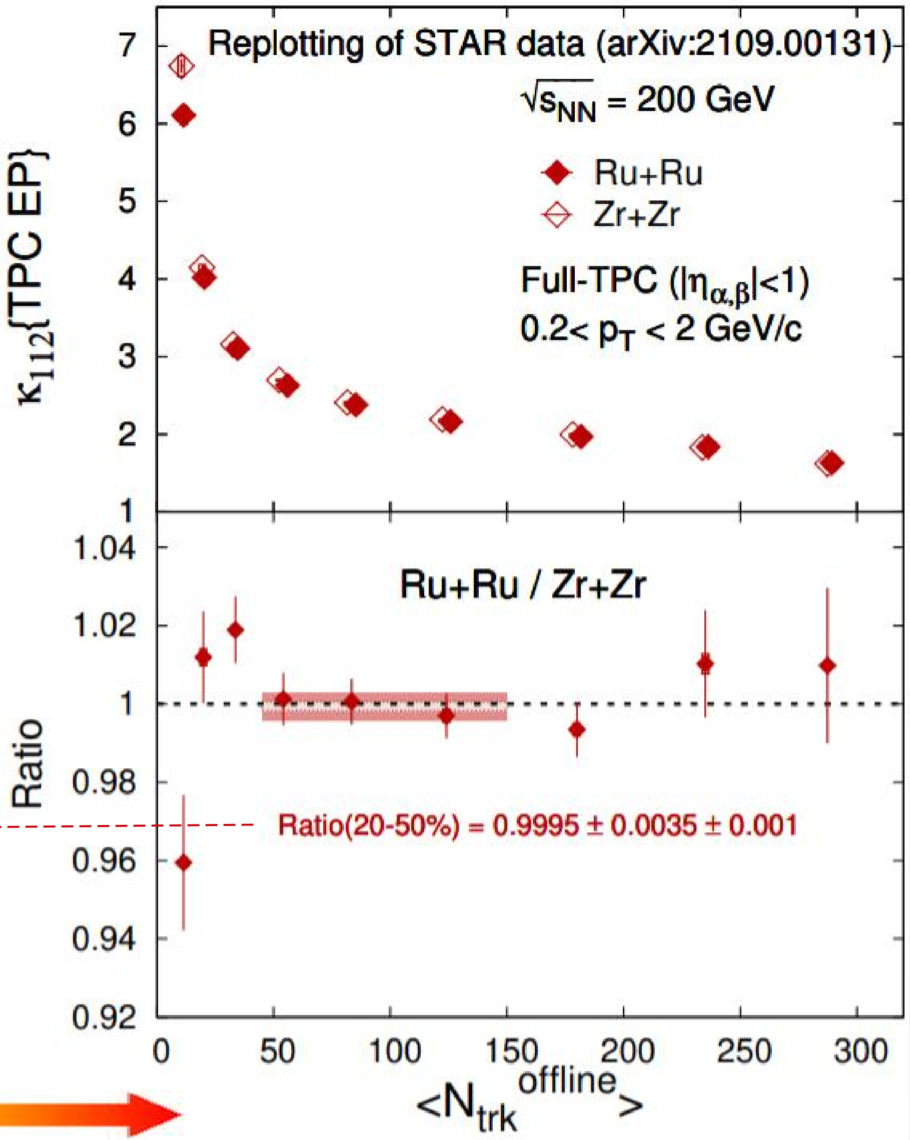
$$\frac{\kappa_{112}^{\mathrm{Ru+Ru}}}{\kappa_{112}^{\mathrm{Zr+Zr}}} > 1$$

is NOT seen.

Upper limit (95% CL):

1.0066 for κ_{112} ratio;

~4% for f_{CME}.



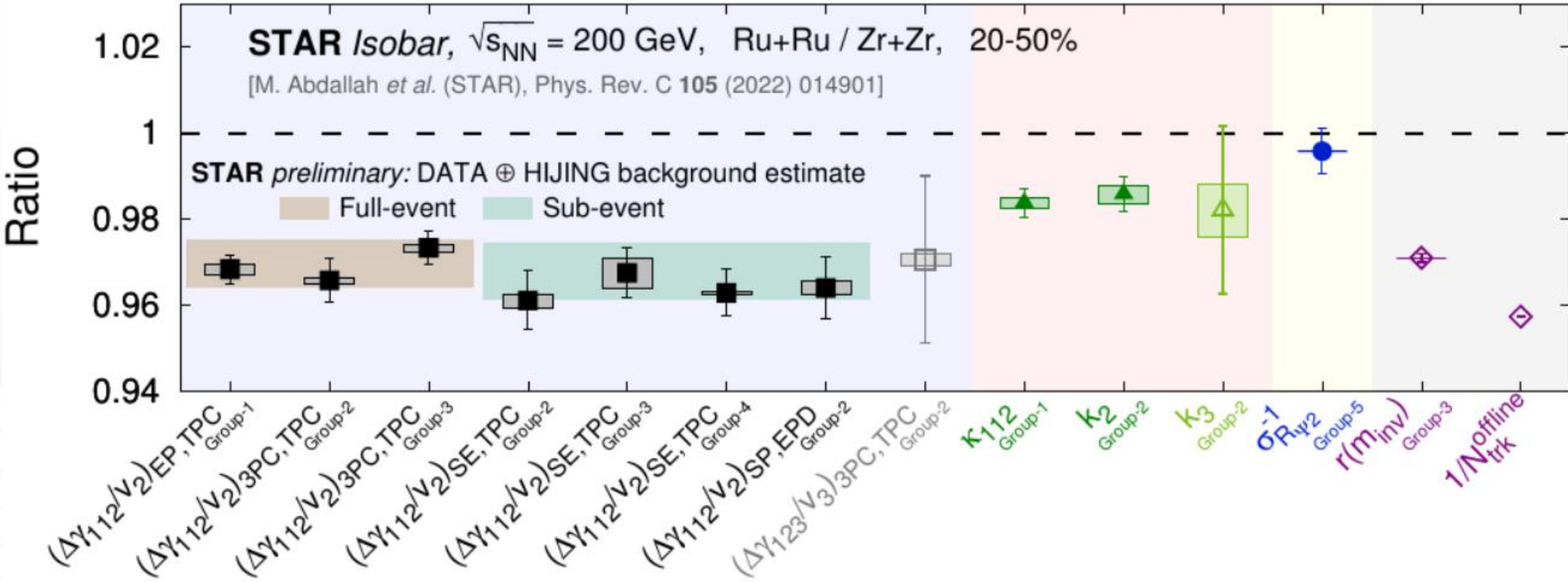
Small interpolation before taking ratios

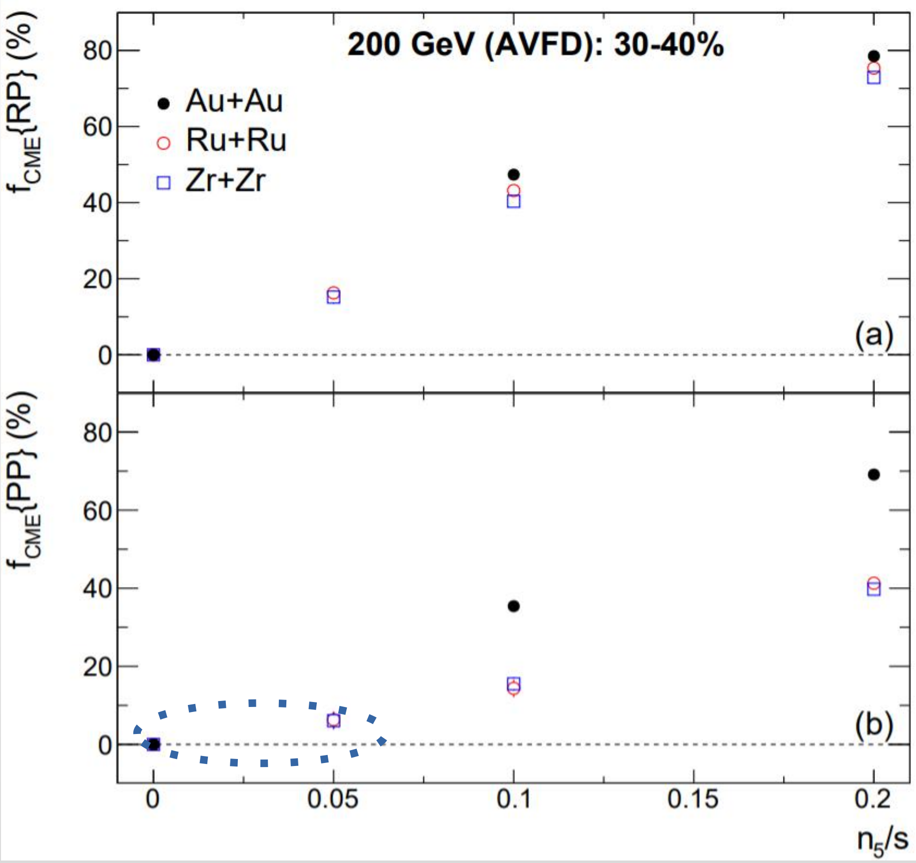
STAR, Phys. Rev. C 105 (2022) 14901

J. Jia, G. Wang, C. Zhang, arXiv:2203.12654

Post-blinding

$\Delta\gamma_{112}$ results are consistent with preliminary background estimate within current uncertainty.

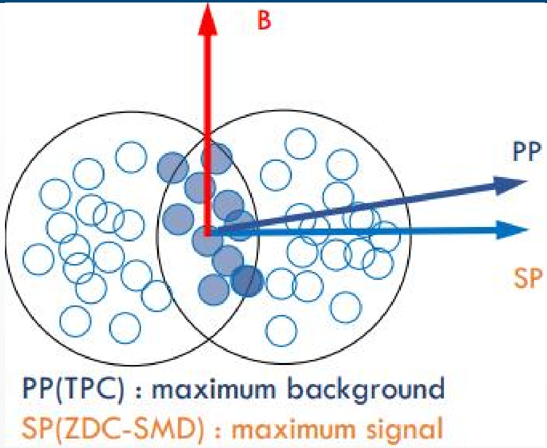




Why is f_{CME} so small?
AVFD simulation:
f_{CME} is smaller in isobar than Au+Au, especially when using the participant plane.
smaller system → larger fluctuation → larger BKG & smaller CME signal → lower f_{CME}

R. Milton *et al*, Phys. Rev. C 104 (2021) 064906

The bright side

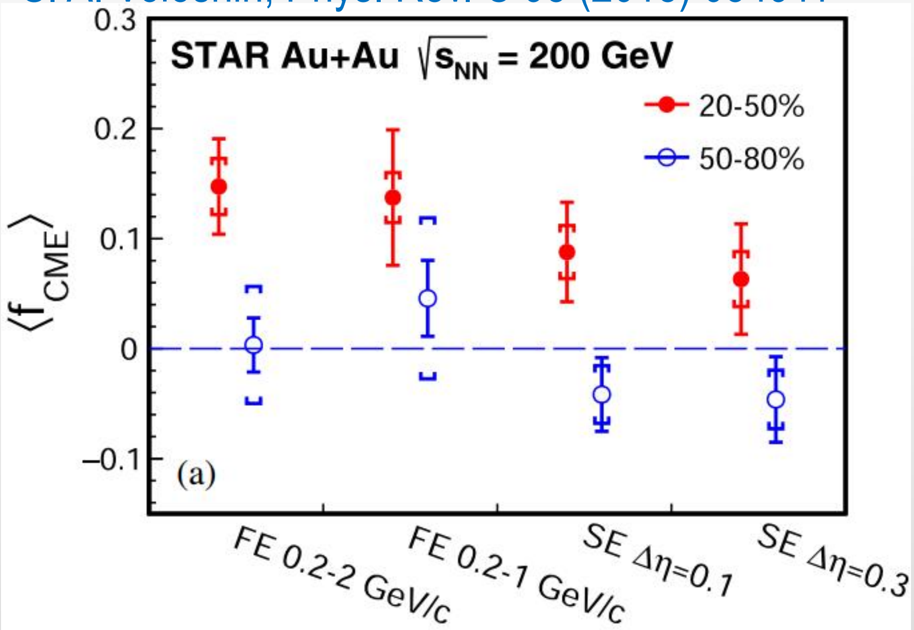


$$\Delta\gamma\{PP\} = \Delta\gamma_{CME}\{PP\} + \Delta\gamma_{BKG}\{PP\}$$
$$\Delta\gamma\{SP\} = \Delta\gamma_{CME}\{PP\}/a + \Delta\gamma_{BKG}\{PP\}a$$

$$a = \langle \cos 2(\Psi_{PP} - \Psi_{SP}) \rangle$$

$$f_{CME}^{PP} = \frac{\frac{\Delta\gamma\{SP\}}{\Delta\gamma\{PP\}}/a - 1}{1/a^2 - 1}$$

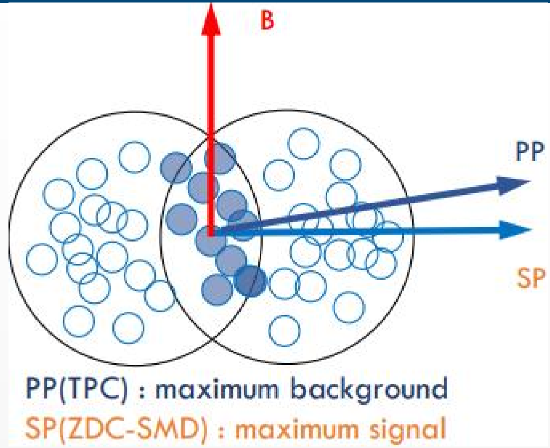
H-J. Xu, et al, CPC 42 (2018) 084103;
S. A. Voloshin, Phys. Rev. C 98 (2018) 054911



The difference between different event plane types indicates a finite f_{CME} in Au+Au at 200 GeV. More data to come!

M. S. Abdallah et al. (STAR) Phys. Rev. Lett, 128 (2022) 092301

The bright side



$$\Delta\gamma\{PP\} = \Delta\gamma_{CME}\{PP\} + \Delta\gamma_{BKG}\{PP\}$$
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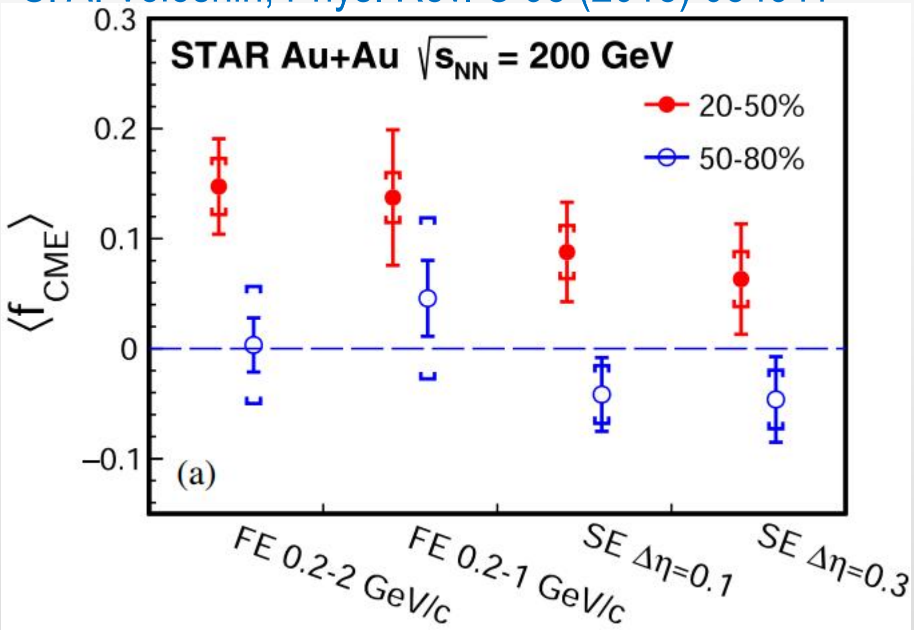

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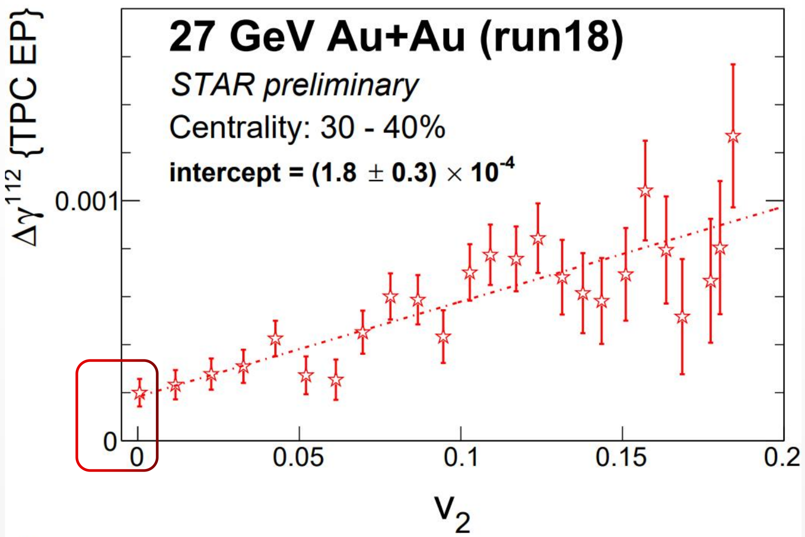
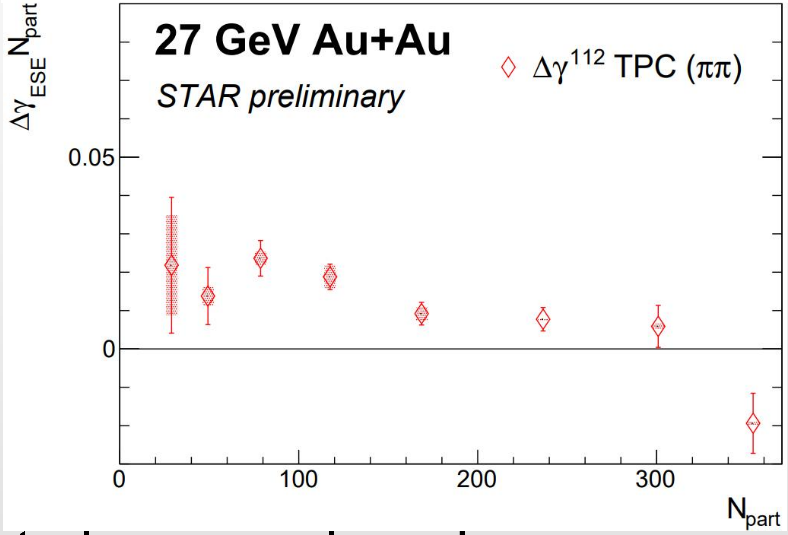
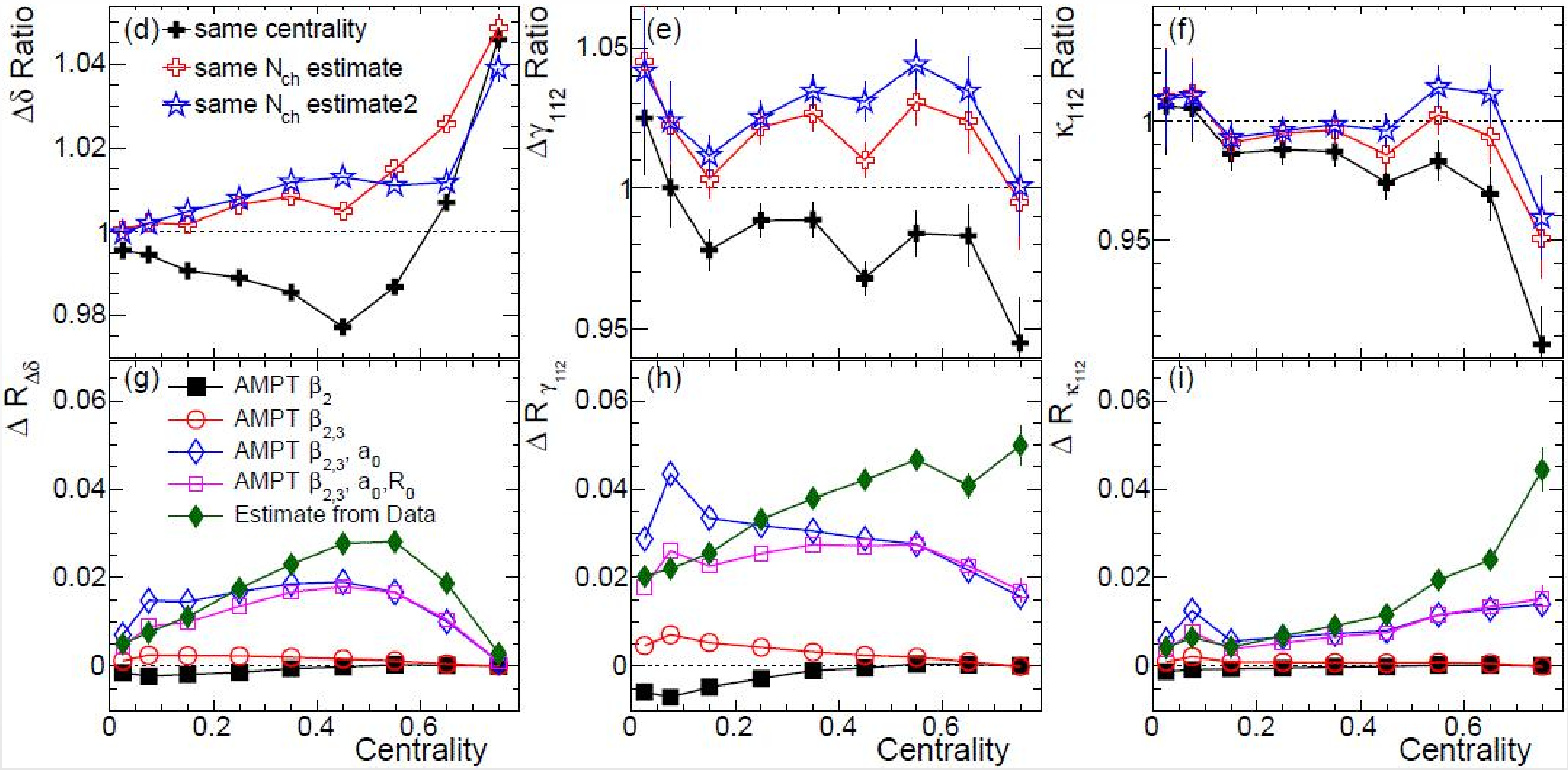




Event-shape engineering
- suppresses v_2-related background
- enhances f_{CME} (finite at 27 GeV?)

Backup slides

Matching centrality or matching multiplicity?



$$\rho(r,\theta,\phi) \propto \frac{1}{1+e^{[r-R_0(1+\beta_2 Y_2^0(\theta,\phi)+\beta_3 Y_3^0(\theta,\phi))]/a_0}}$$

J. Jia, G. Wang, C. Zhang, arXiv:2203.12654

The difference between matching centrality and matching multiplicity comes from a_0, surface diffuseness.

Isobar: charge ceparation measured with R_{Ψ_2}

$$R_{\psi_2}(\Delta S) = C_{\psi_2}(\Delta S)/C^{\perp}_{\psi_2}(\Delta S)$$

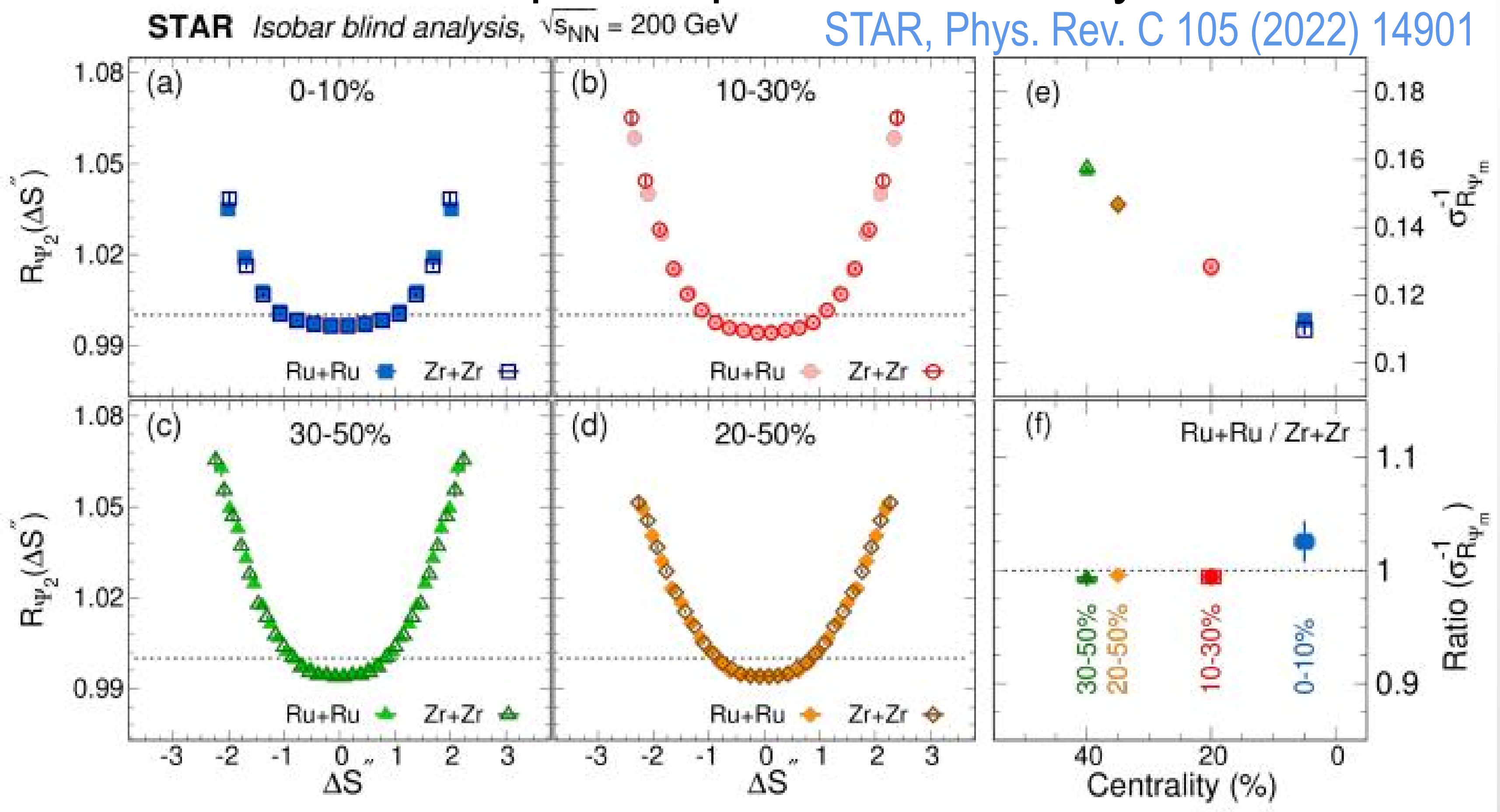
$$C_{\psi_2} = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)}$$

$$\Delta S = \left\{ \frac{\sum_{i=1}^{n+} w_i^+ \sin(\phi_i - \psi_2)}{\sum_{i=1}^{n+} w_i^+} - \frac{\sum_{i=1}^{n-} w_i^- \sin(\phi_i - \psi_2)}{\sum_{i=1}^{n-} w_i^-} \right\}$$

σ_{ψ_2} is the Gaussian width of the respective $R(\Delta S'')$

Measurement of the in-plane and out-of-plane distributions of the dipole separation event by event.

STAR, Phys. Rev. C 105 (2022) 14901



Predefined CME signature:

$$1/\sigma_{\psi_2}^{\text{Ru+Ru}} > 1/\sigma_{\psi_2}^{\text{Zr+Zr}}$$

No significant difference is observed between the two isobaric systems