Workshop on Electromagnetic Effects in Strongly Interacting Matter

Search for the Chiral Magnetic Effect in Heavy-ion Collisions

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Supported in part by

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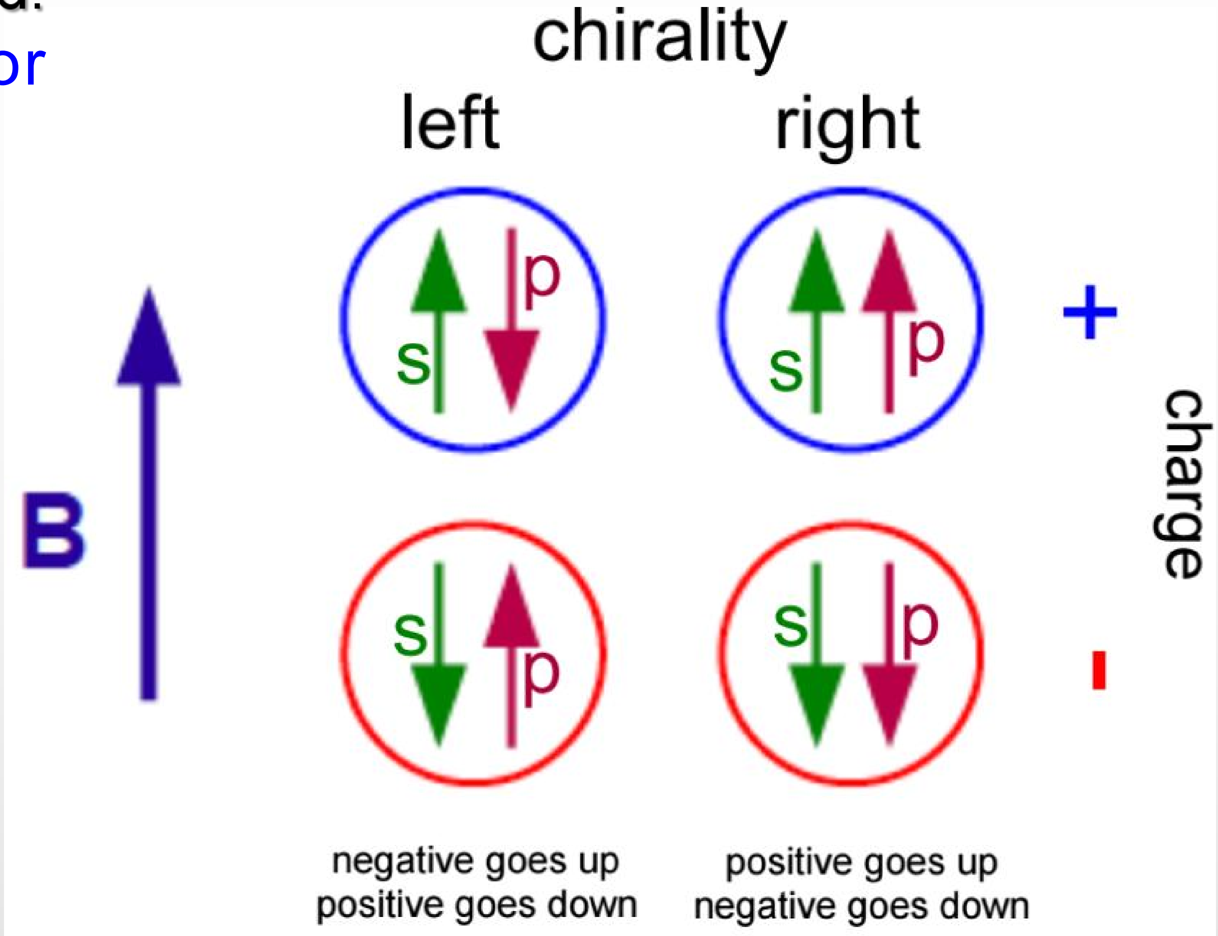
Chiral Magnetic Effect

spin alignment in B-field:
opposite directions for opposite charges



handedness:
momentum and spin, aligned or anti-aligned

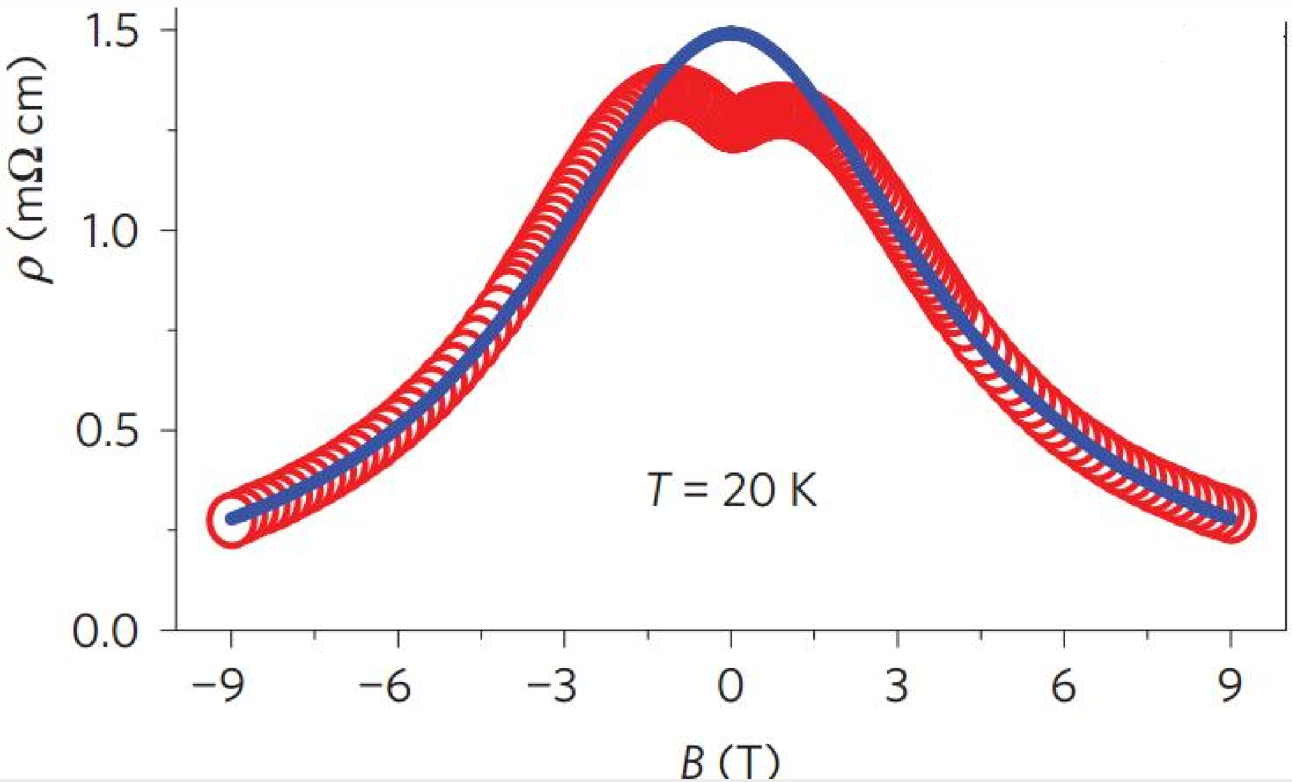
courtesy of P.Sorensen

An excess of right or left handed quarks lead to a current flow along the magnetic field.

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

Chiral Magnetic Effect in $ZrTe_5$

Q. Li et al, Nature Physics 12, 550 (2016)



$$\boxed{\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}}$$

Man-made chirality:

$$\mu_5 = \frac{3}{4}\frac{v^3}{\pi^2}\frac{e^2}{\hbar^2 c}\frac{\mathbf{E}\cdot\mathbf{B}}{T^2+\frac{\mu^2}{\pi^2}}\tau_V$$

When E||B, CME conductivity is

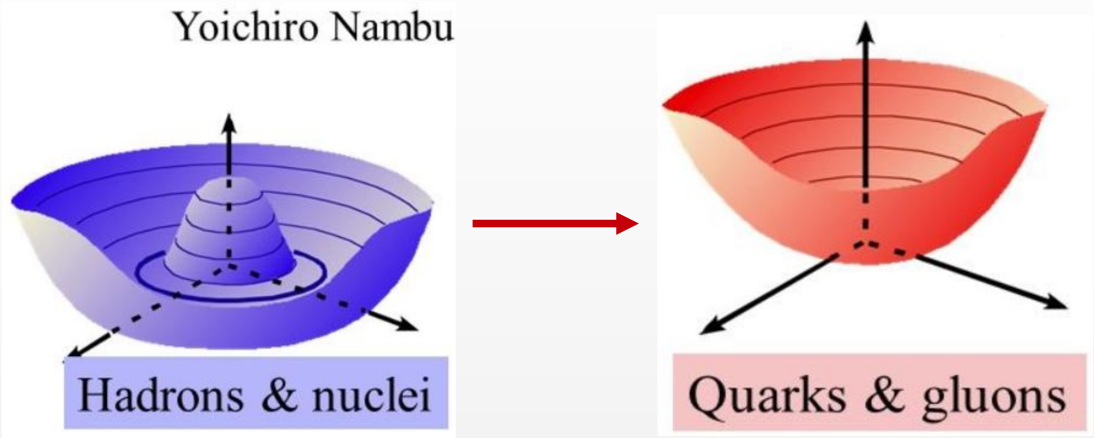
$$\sigma^{zz}_{\mathrm{CME}} = \frac{e^2}{\pi\hbar}\frac{3}{8}\frac{e^2}{\hbar c}\frac{v^3}{\pi^3}\frac{\tau_V}{T^2+\frac{\mu^2}{\pi^2}}B^2$$

B dependence of the negative magneto-resistance is nicely fitted with the CME contribution to the electrical conductivity.

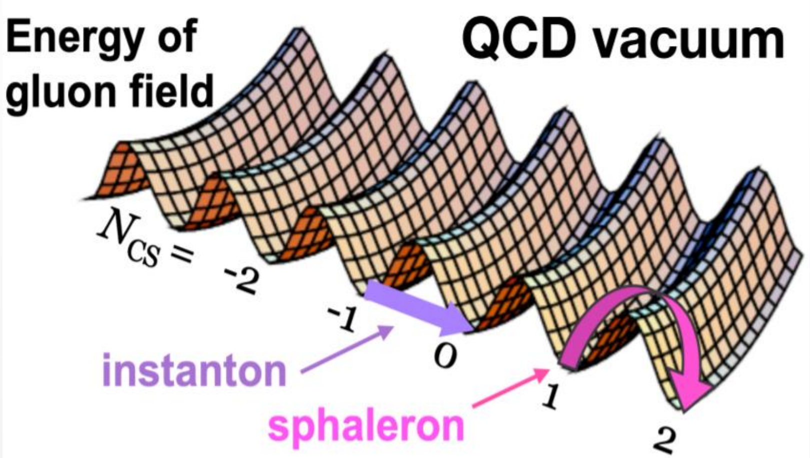
This is followed by a whole industry of CME in semimetals...

CME in Heavy-ion Collisions

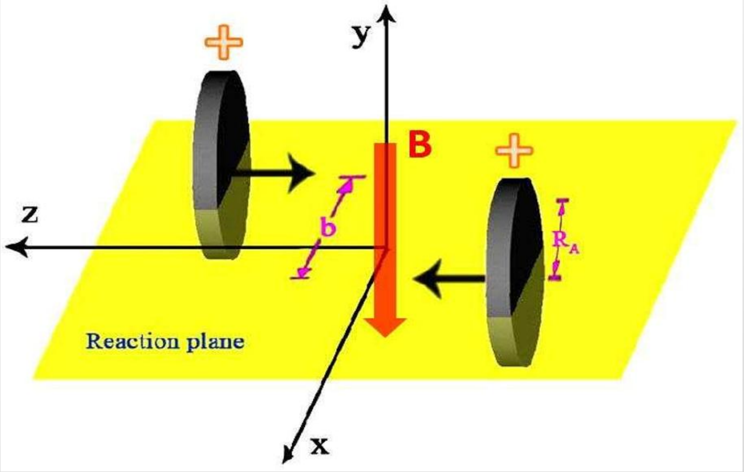
1 Chiral symmetry restoration (massless quarks)



2 Chirality imbalance (finite μ_5, Local Parity Violation）

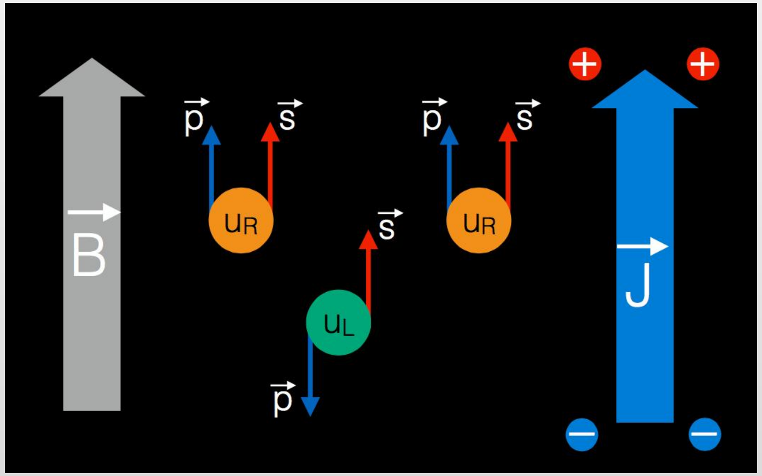


3 Strong magnetic field (B ~ 10^{18} Gauss)



Experimental manifestation: charge separation across the reaction plane

4 Chiral Magnetic Effect (J || B)

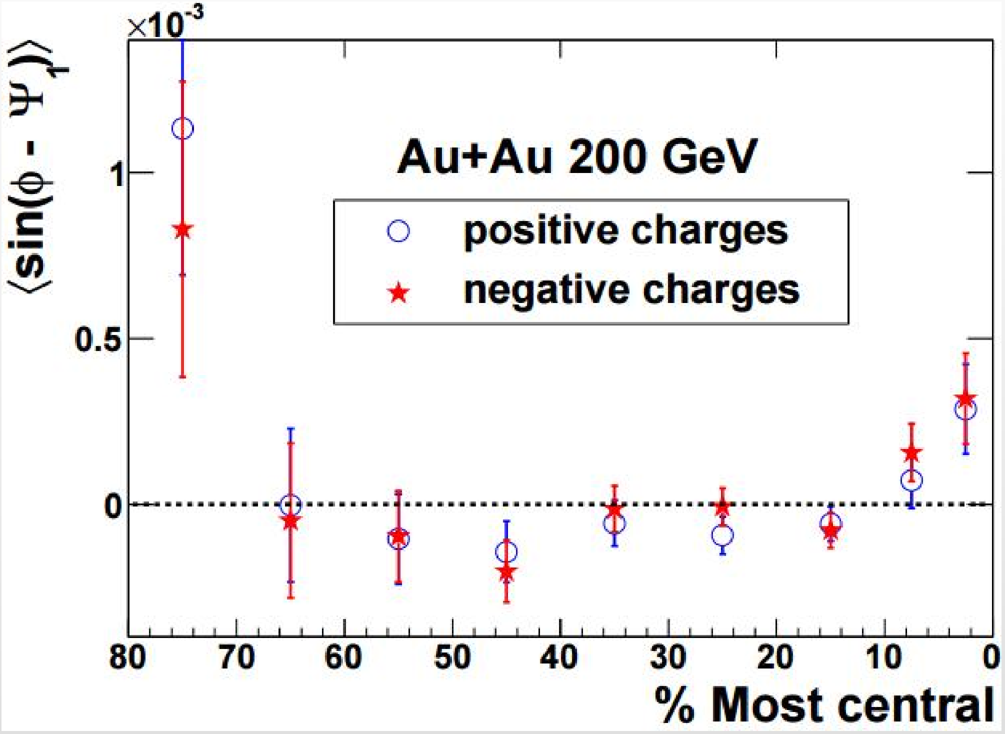


Observables in search of CME

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

$$\phi^* = \phi - \Psi_{RP}$$

An event-average of P-odd quantity "$a_{1,\pm}$" yields zero, because μ_5 flips sign from event to event.

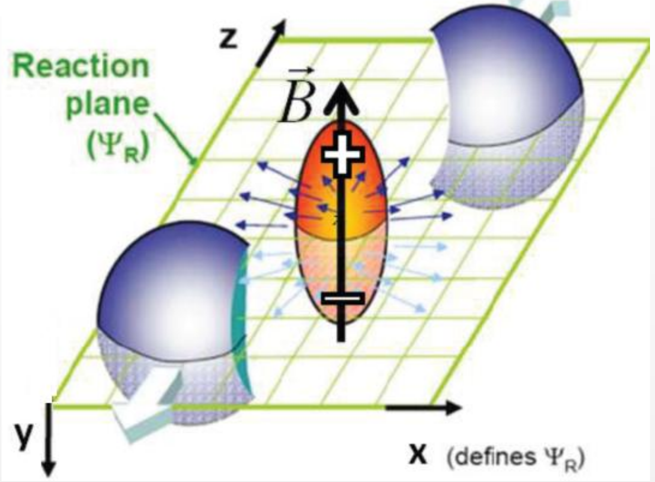


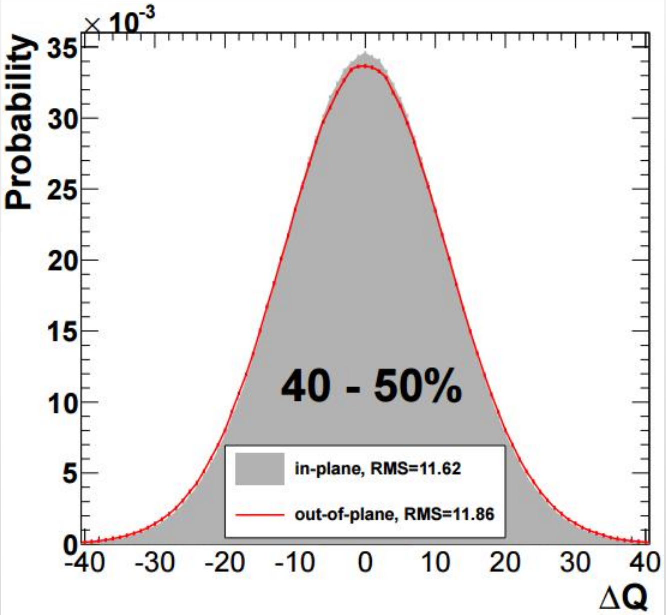
STAR, PRC 88 (2013) 64911

There should be more out-of-plane charge fluctuation than in-plane.

Indeed, we see this effect, which is on percent level!

Au+Au 200 GeV
RMS:
in-plane = 11.62
out-of-plane = 11.86





Observables in search of CME

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)

Here we focus on

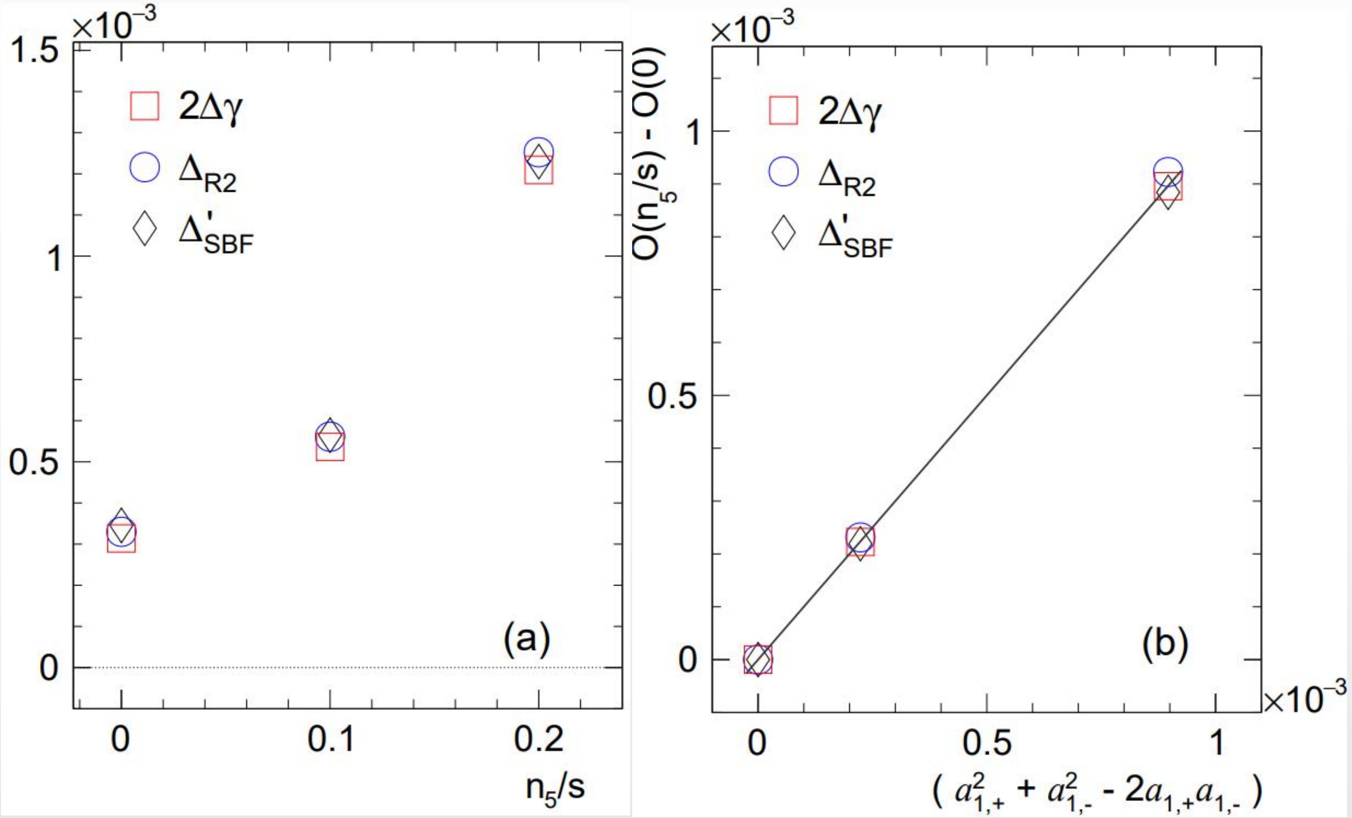
$$\gamma_{112} \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$$

$$= \left[\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in} \right] - \left[\langle a_\alpha a_\beta \rangle + B_{out} \right]$$

And the CME signal should cause

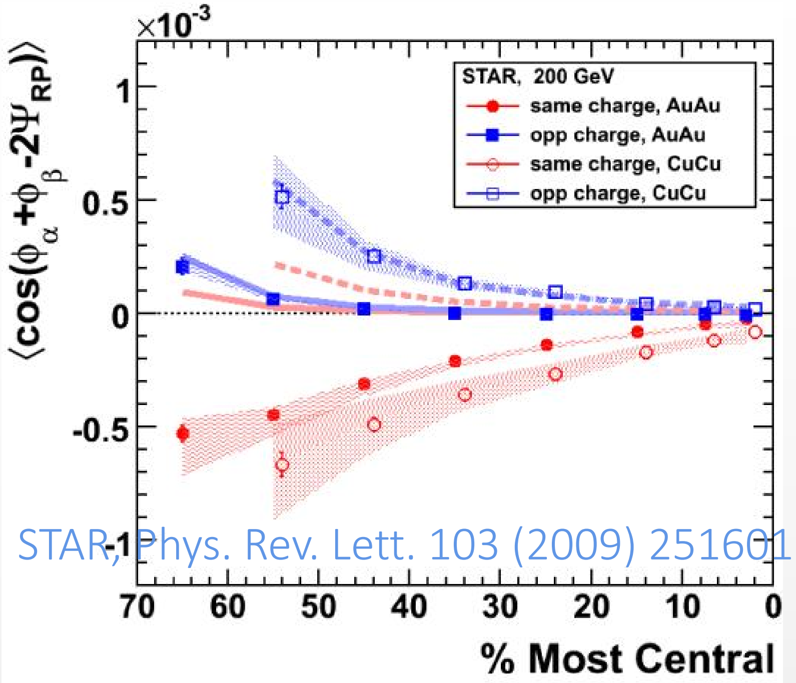
$$\Delta\gamma_{112} \equiv \gamma_{112}^{\mathrm{OS}} - \gamma_{112}^{\mathrm{SS}} > 0$$

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

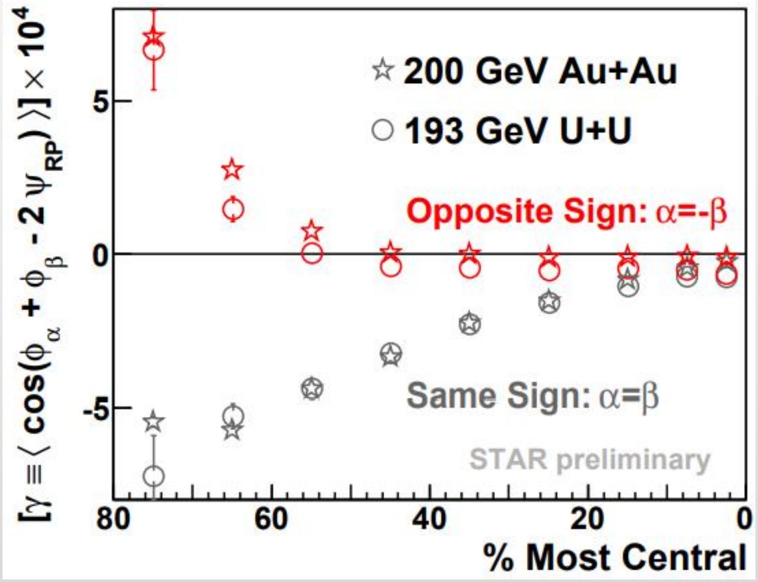


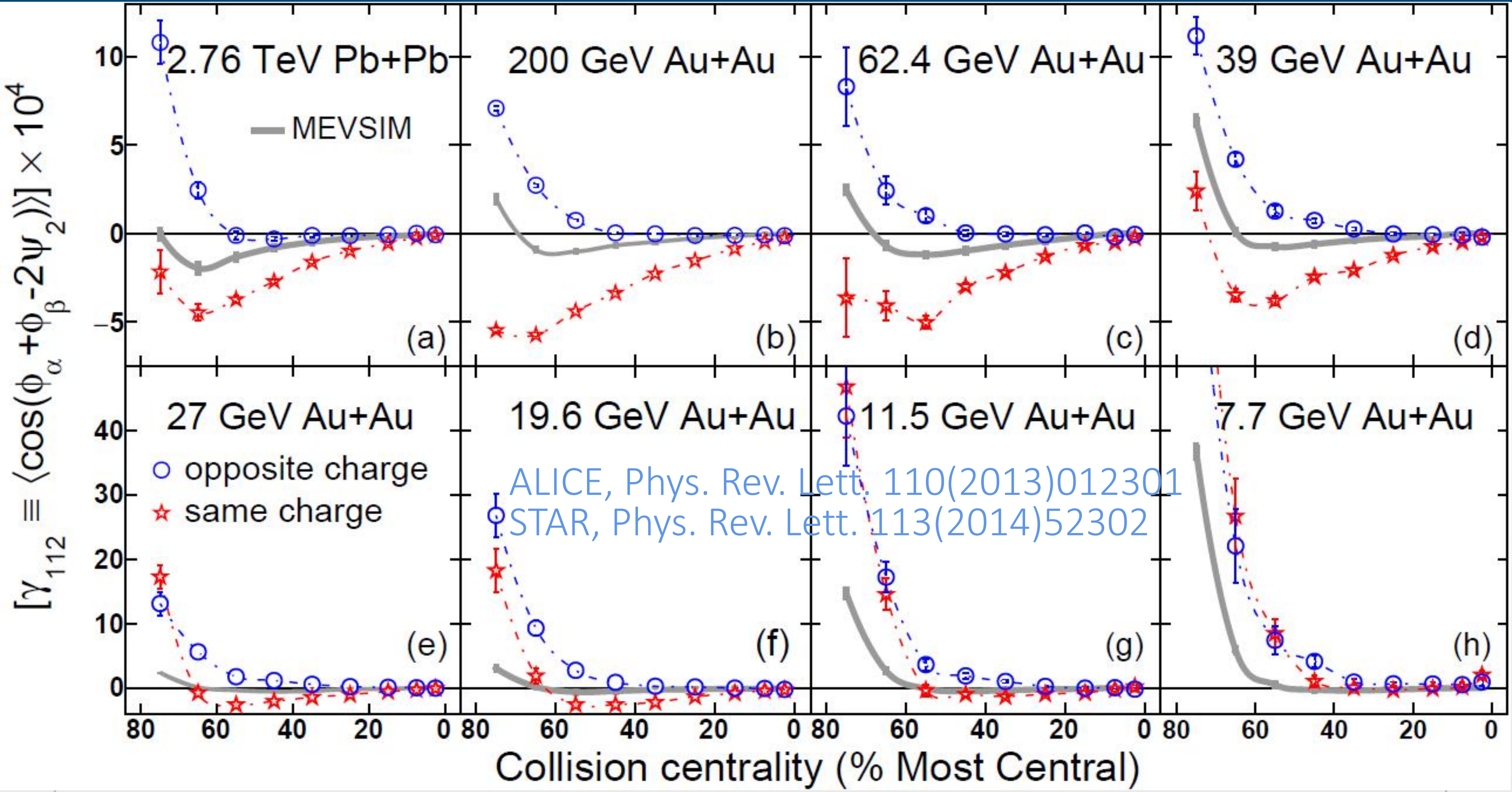
AVFD simulations show that these methods have similar sensitivities to the CME signal and to the background.

γ_{112} measurements at RHIC/LHC



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





ALICE, Phys. Rev. Lett. 110(2013)012301

STAR, Phys. Rev. Lett. 113(2014)52302

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

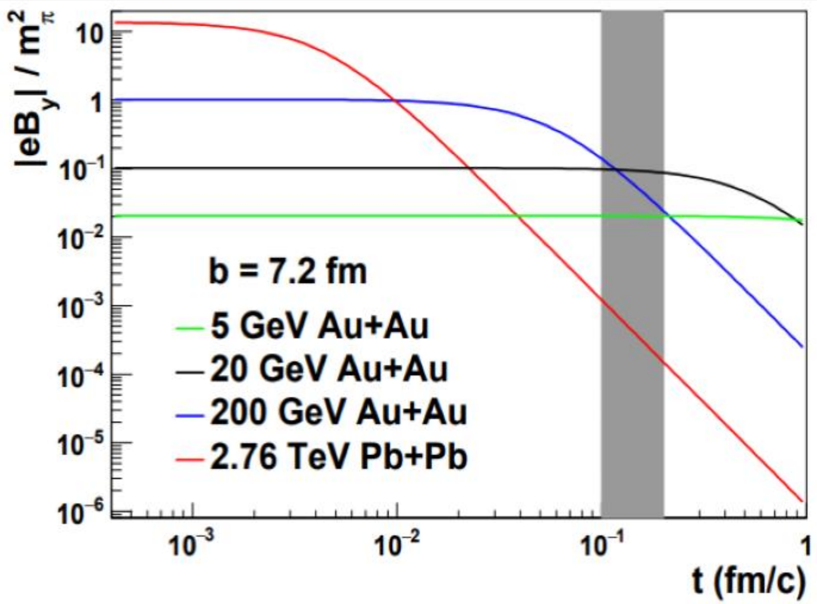
- **Flow-related** background $\propto$ v_2 (elliptic flow)
- **Nonflow-related** background (di-jets)

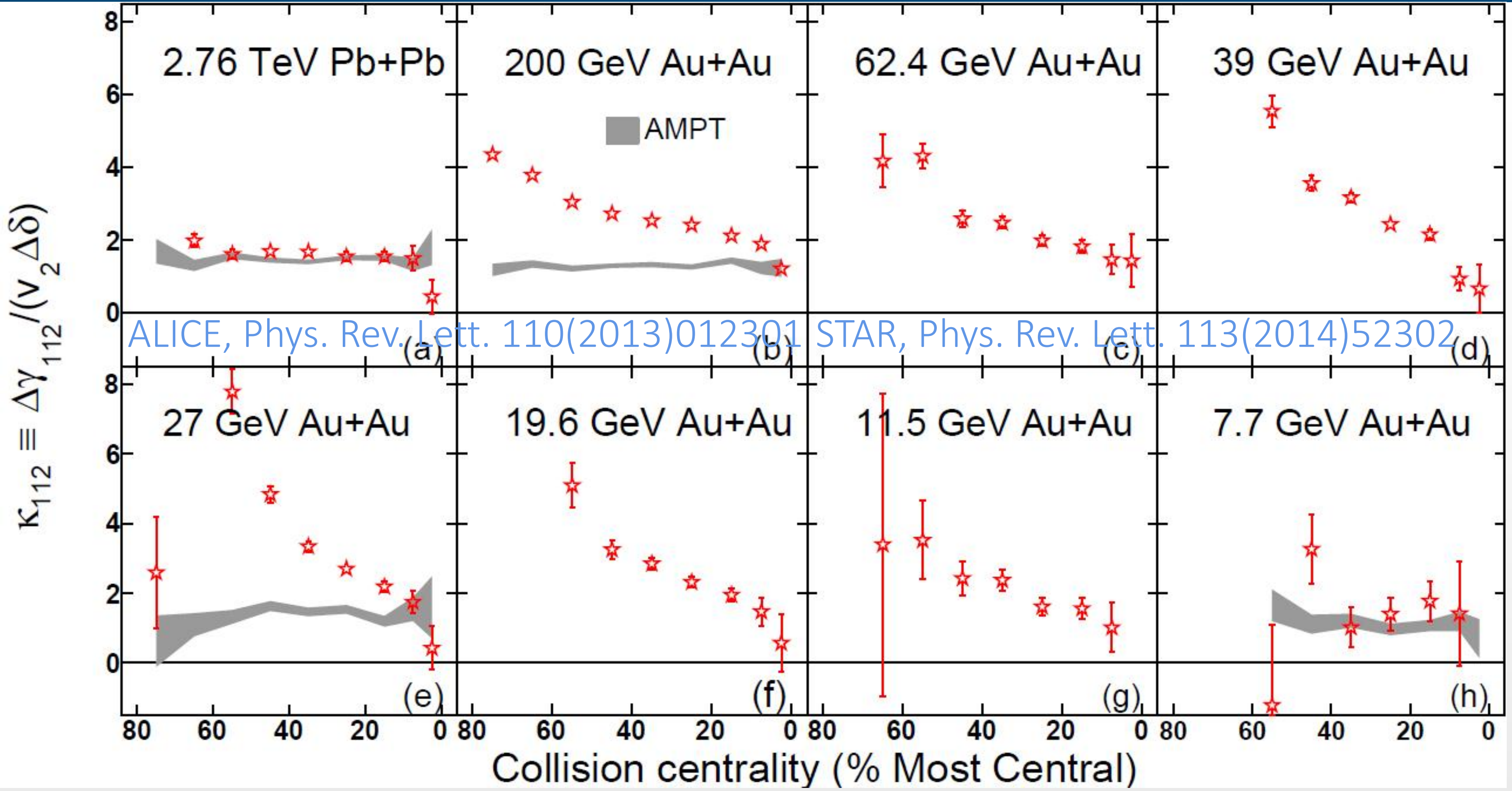
κ_{112} measurements at RHIC/LHC

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

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

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



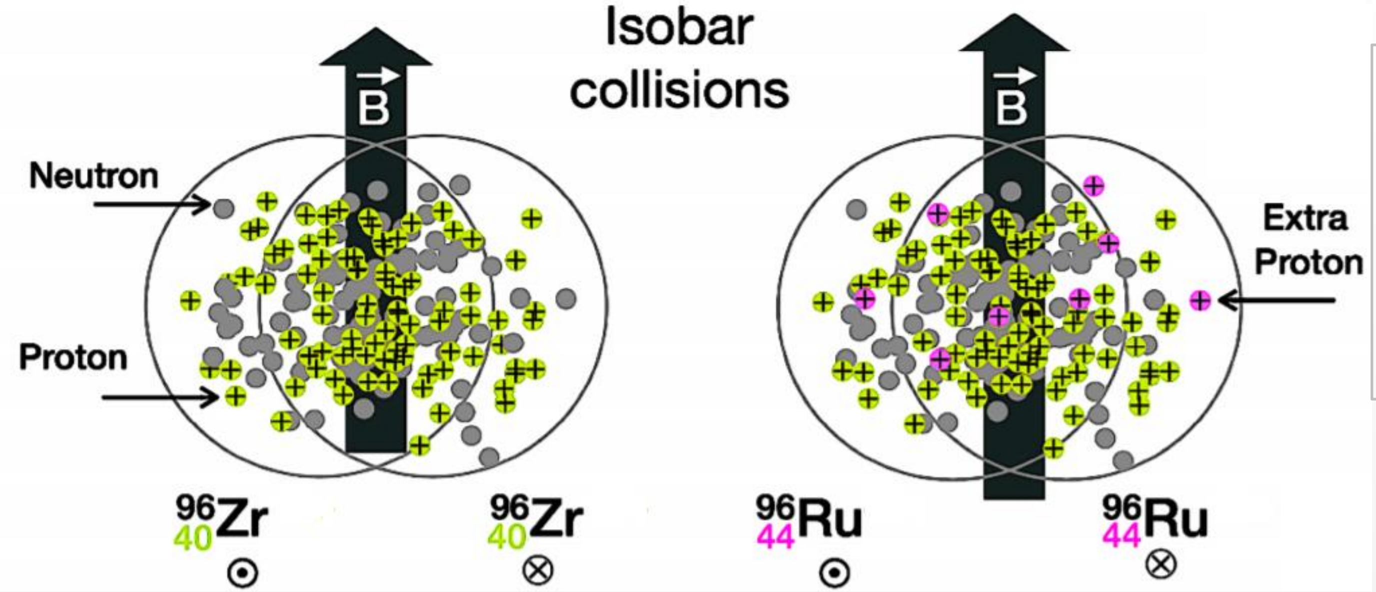


ALICE, Phys. Rev. Lett. 110(2013)012301 STAR, Phys. Rev. Lett. 113(2014)52302

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

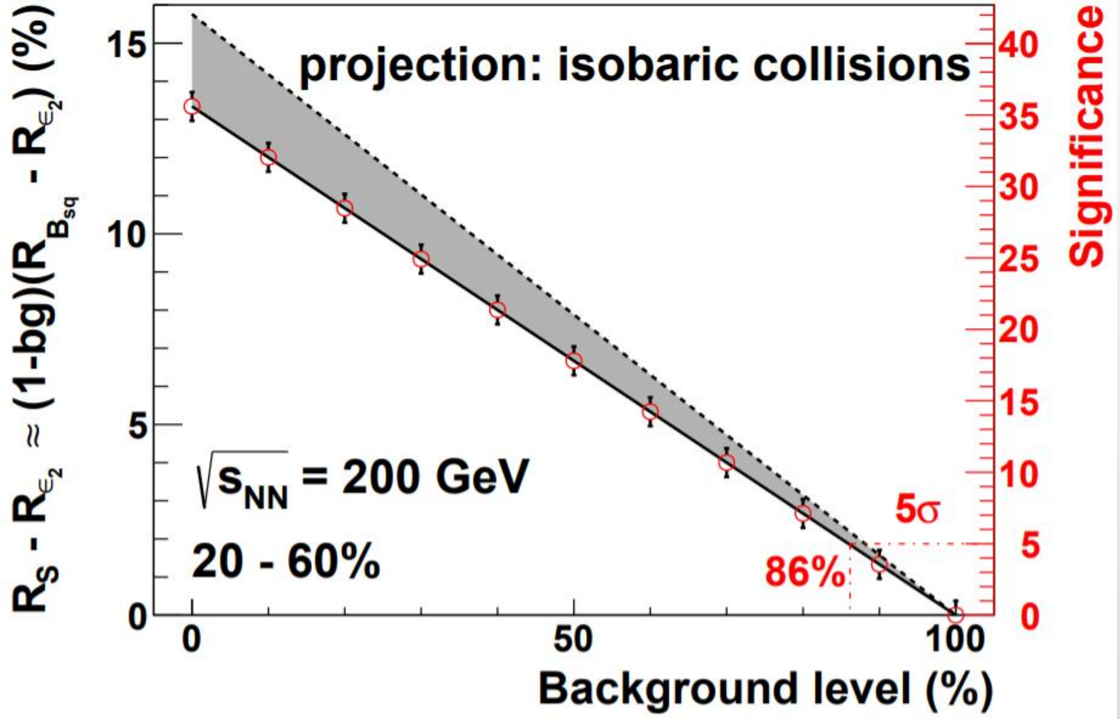
- very low beam energies: no chiral symmetry restoration?
- very high energies: no duration of the magnetic field?

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

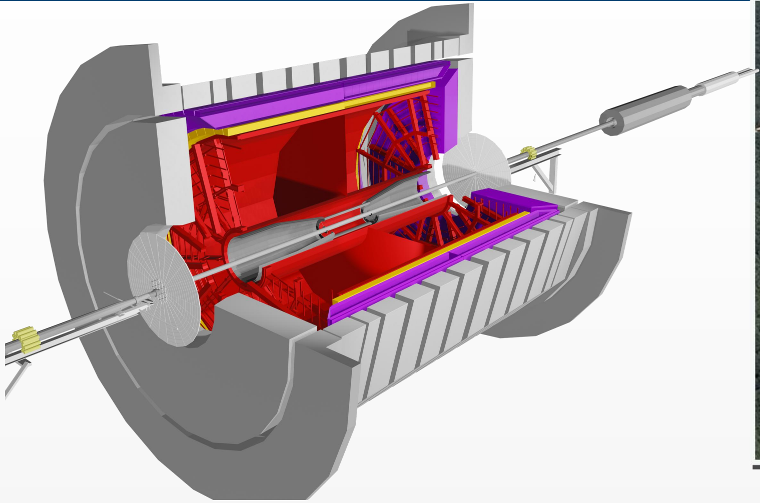


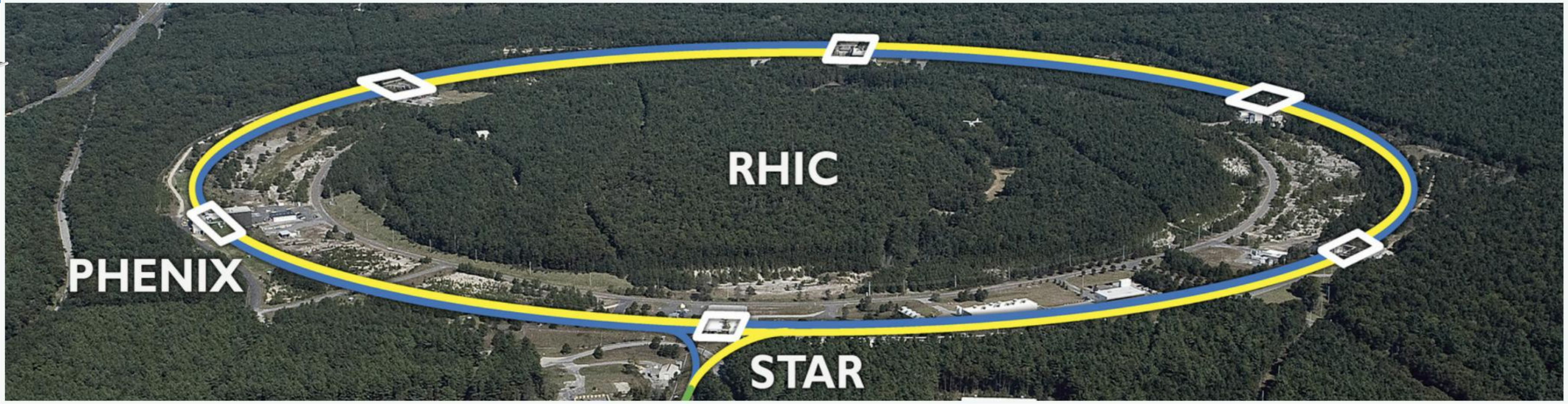
Isobar collisions provide best possible control of signal and background.

2.5 B events per species:

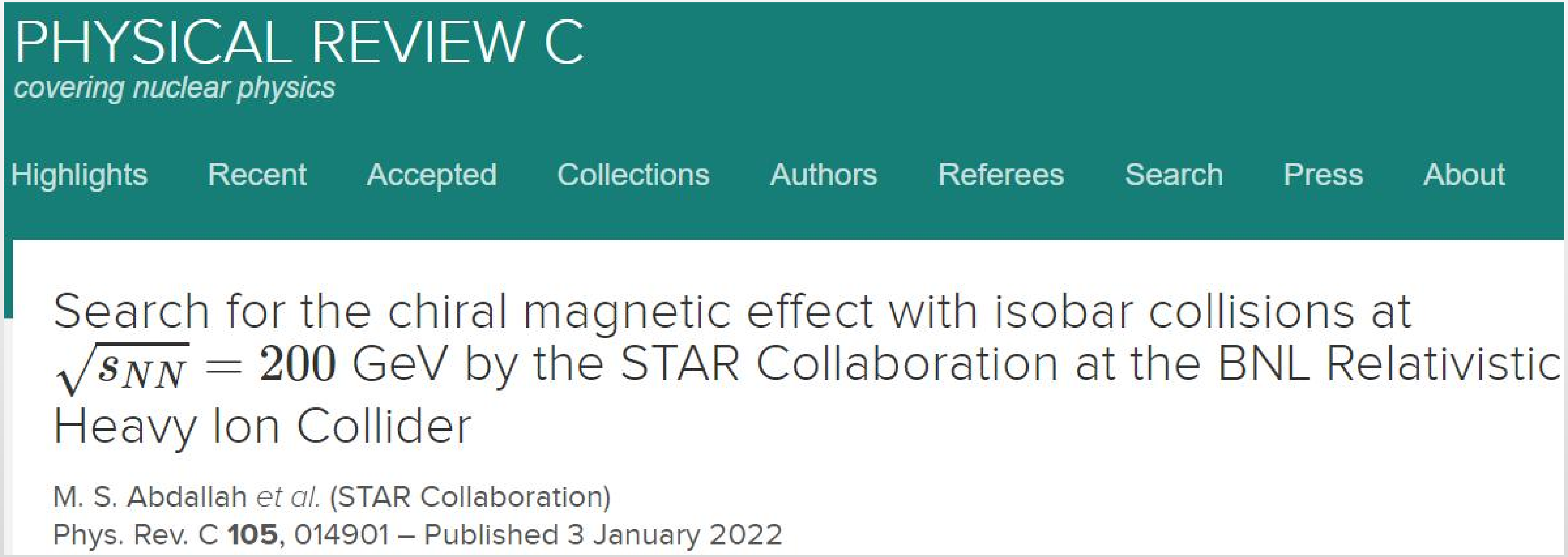
- uncertainty of 0.4% in the $\Delta\gamma/v_2$ ratio.
- if f_{CME} > 14%, $\Delta\gamma_{112}/v_2$ difference > 2%, yielding a 5σ significance.
- f_{CME} is the unknown CME fraction in $\Delta\gamma_{112}$.

Isobar program: data collection in 2018





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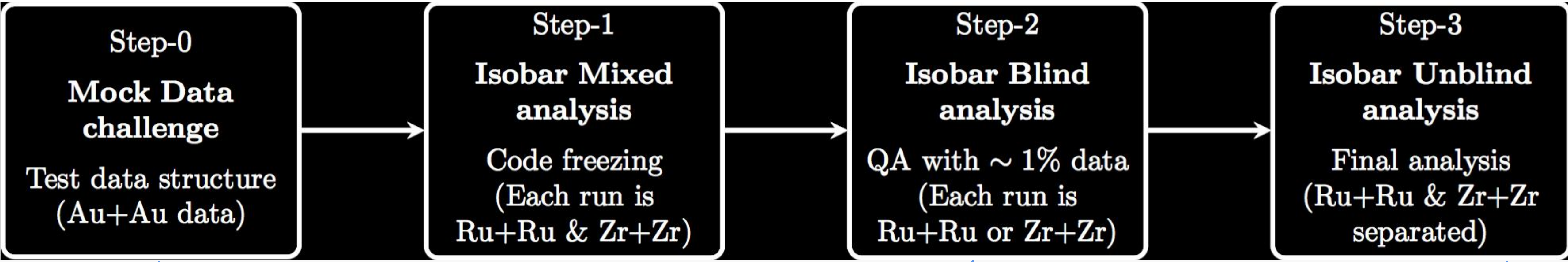
Search for the chiral magnetic effect with isobar collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider

M. S. Abdallah *et al.* (STAR Collaboration)

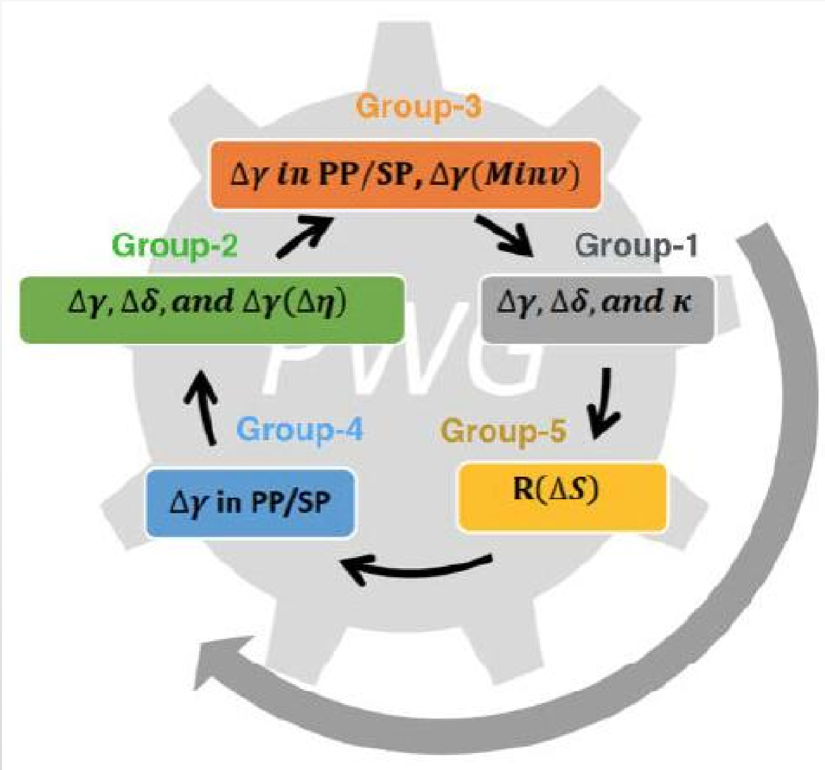
Phys. Rev. C **105**, 014901 – Published 3 January 2022

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

Isobar blind analysis



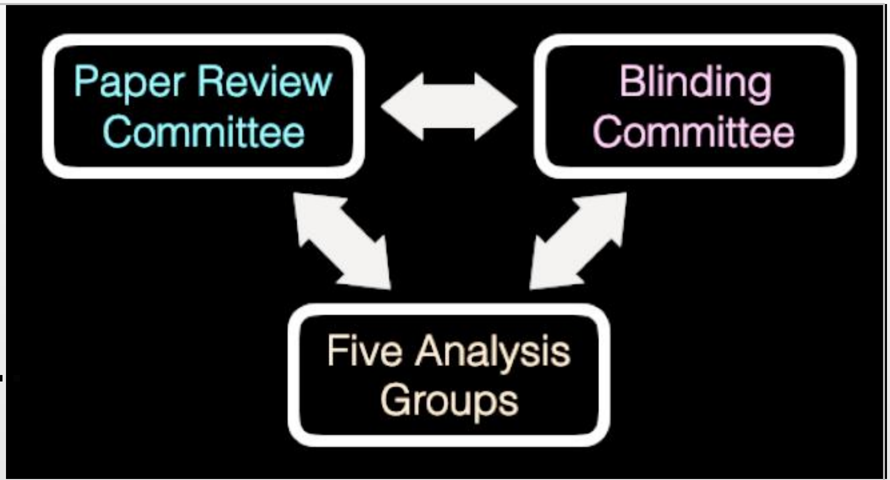
~ 2 months ~1 year ~1/2 year ~2-3 months



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.

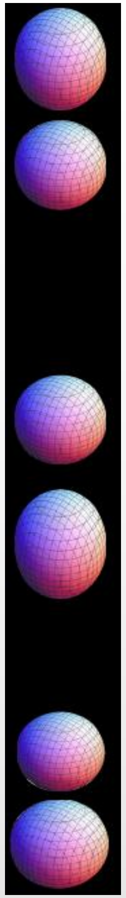
Nucleus	Case-1 [83] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158
$^{96}_{40}$Zr	5.02	0.46	0.08

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

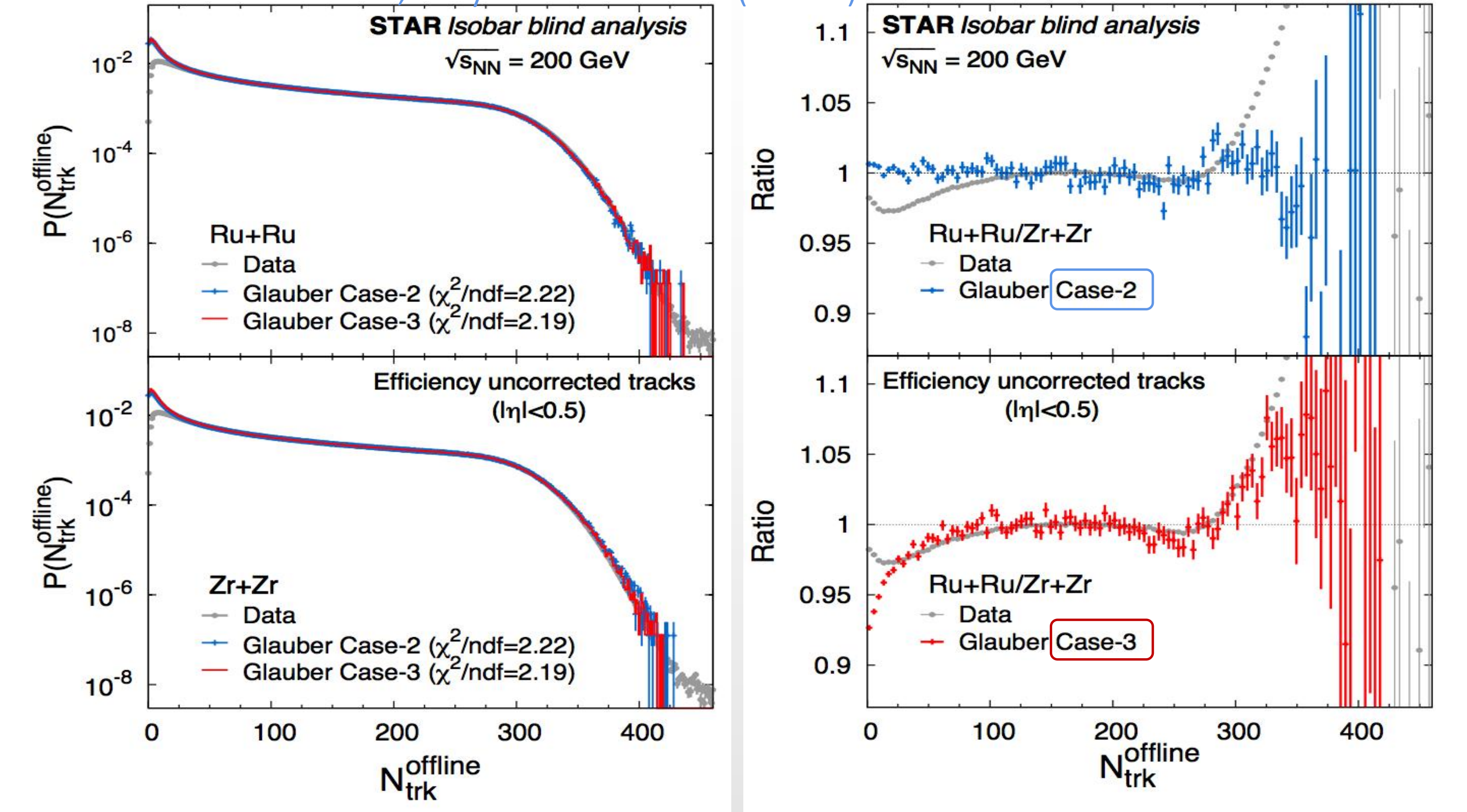
Nucleus	Case-2 [83] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.053
$^{96}_{40}$Zr	5.02	0.46	0.217

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

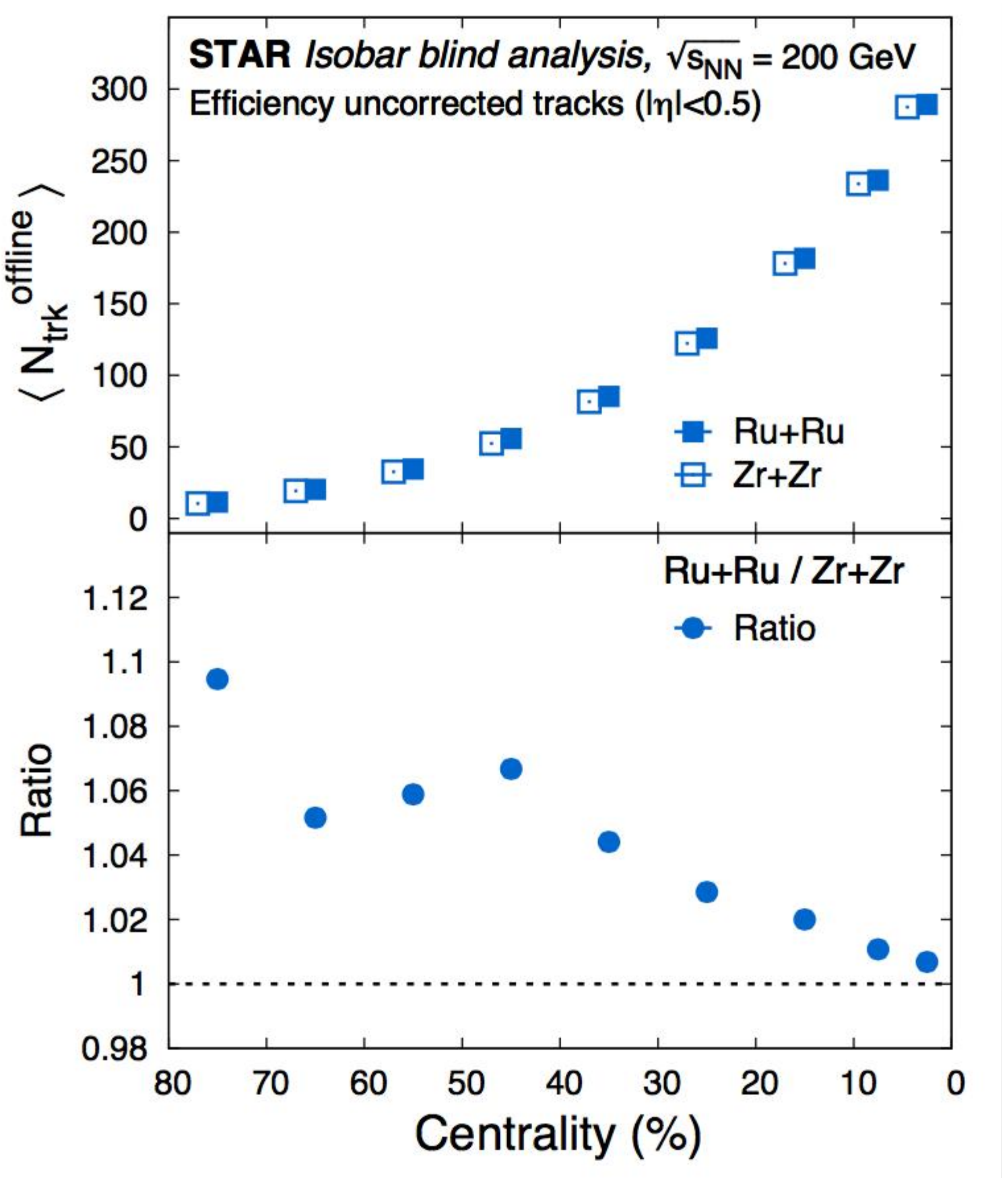


STAR, Phys. Rev. C 105 (2022) 14901



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



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

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

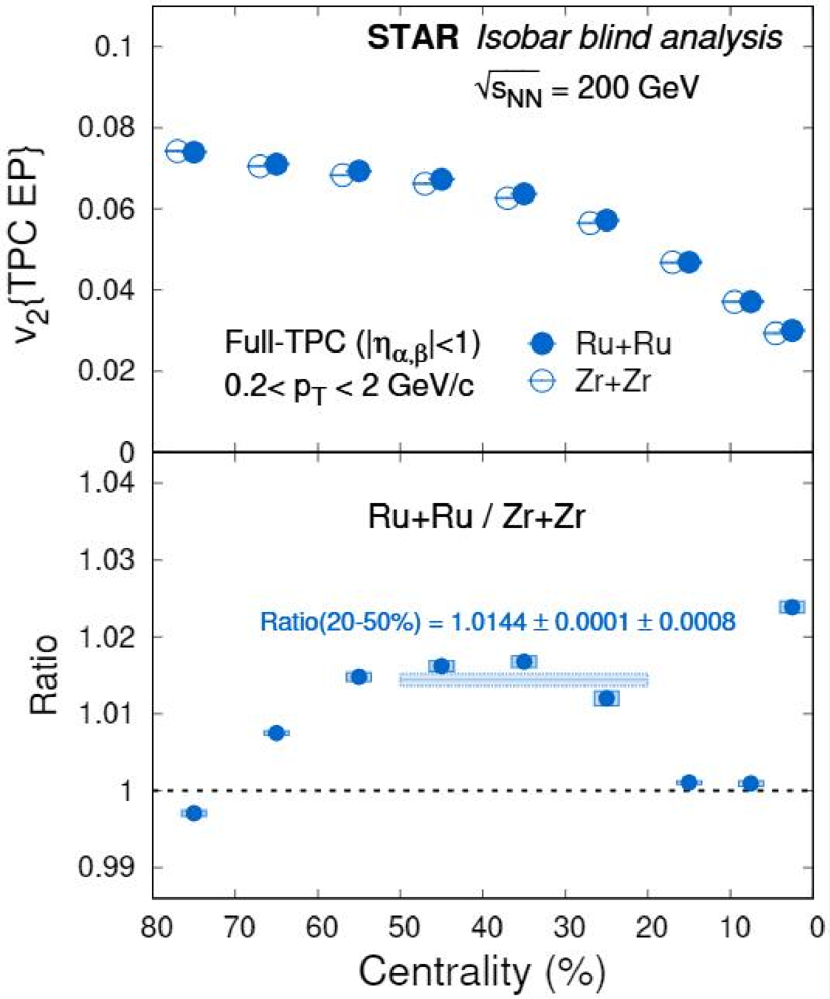
However, multiplicity (efficiency uncorrected) is larger in Ru+Ru than in Zr+Zr in such a matching centrality.

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.

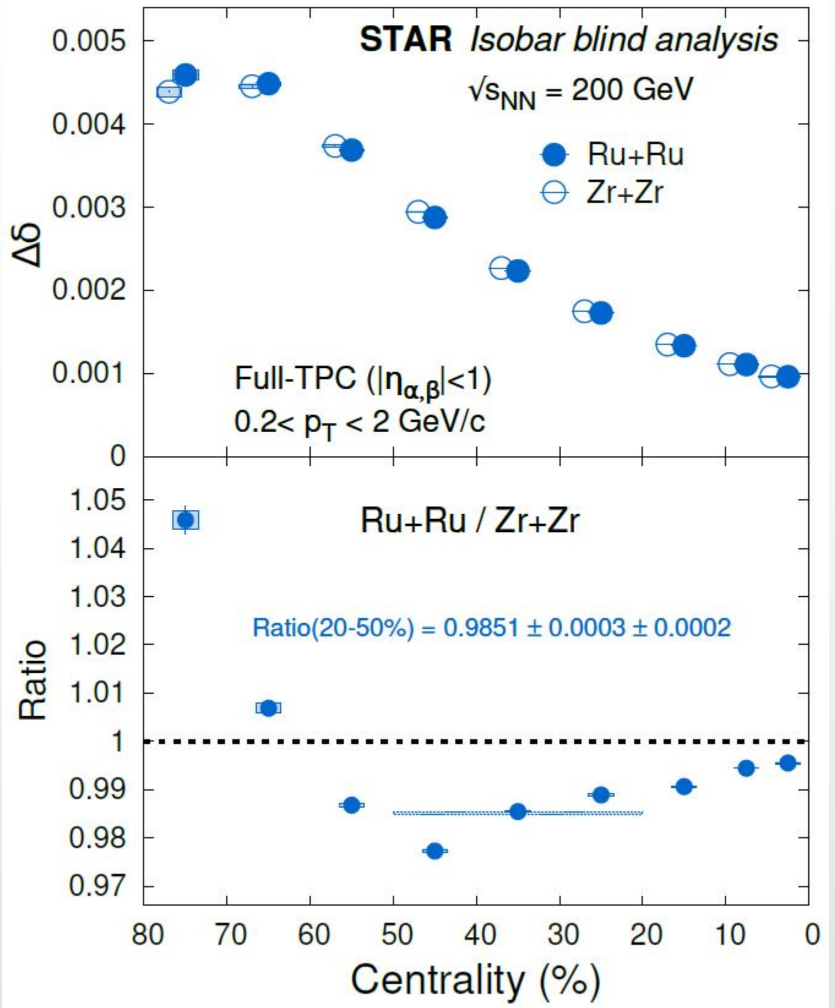
v_2 and $\Delta\delta$



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

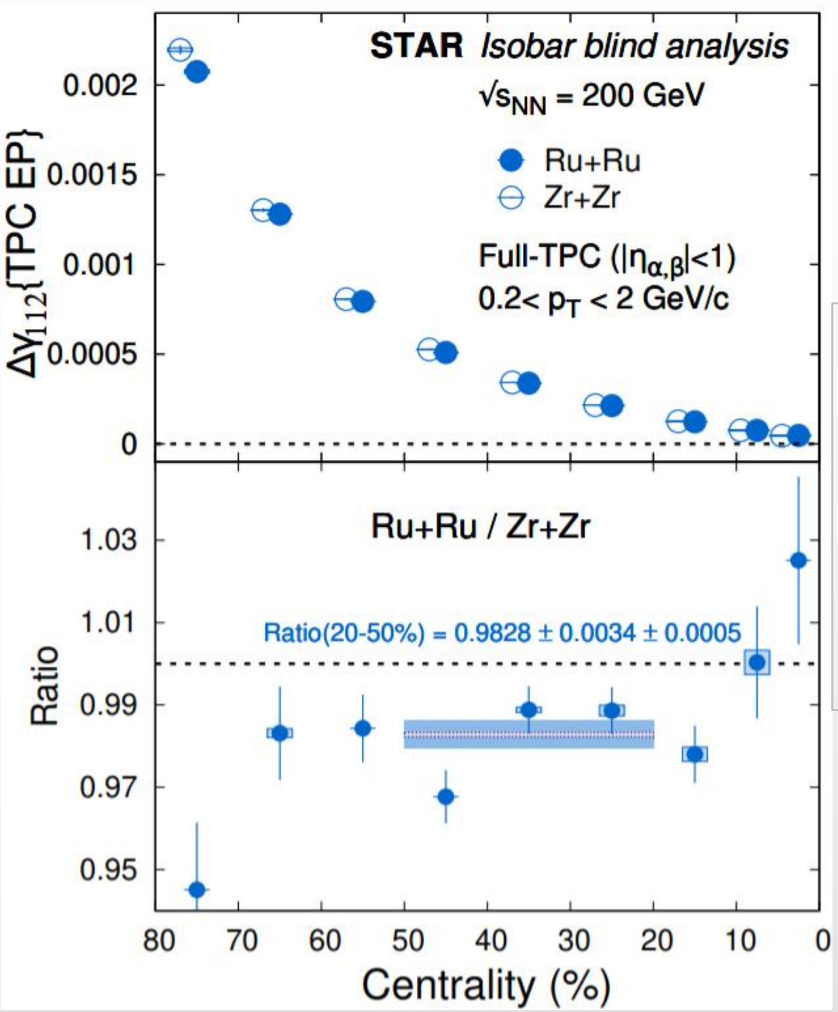
Both v_2 and $\Delta\delta$ contribute to the background, and their ratios of Ru+Ru to Zr+Zr are not exactly unity.

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



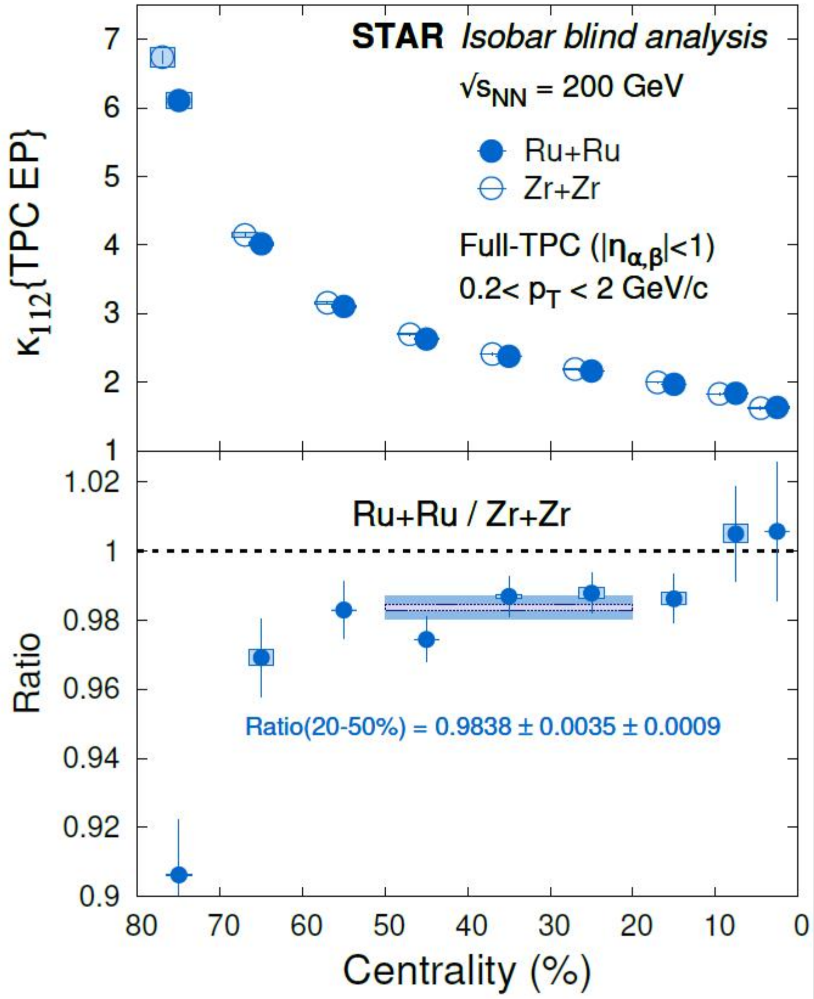
STAR, Phys. Rev. C 105 (2022) 14901

$\Delta\gamma_{112}$ and κ_{112}



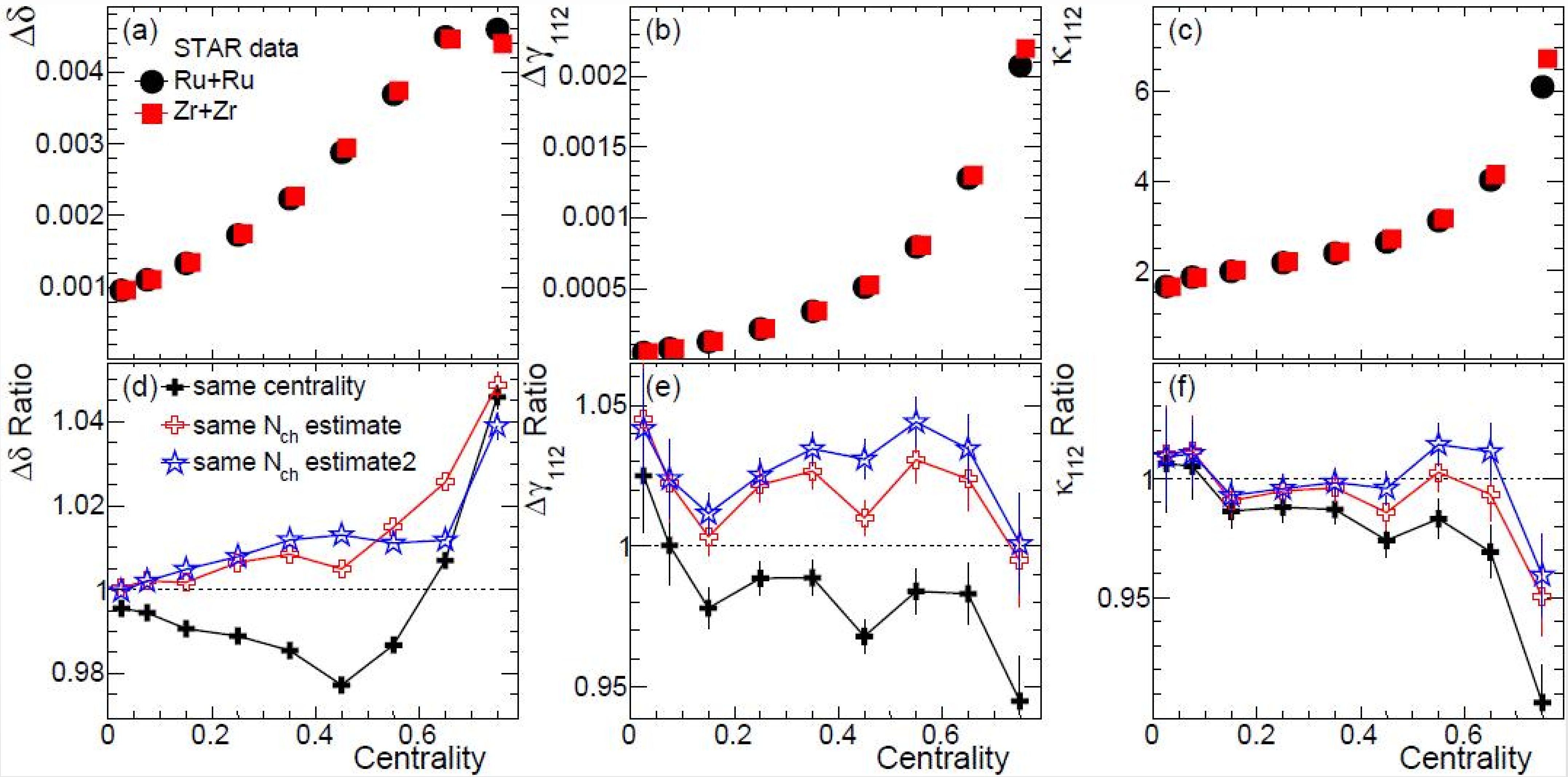
Both $\Delta\gamma_{112}$ and κ_{112} ratios of Ru+Ru to Zr+Zr go significantly below unity!

How can we understand this?



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

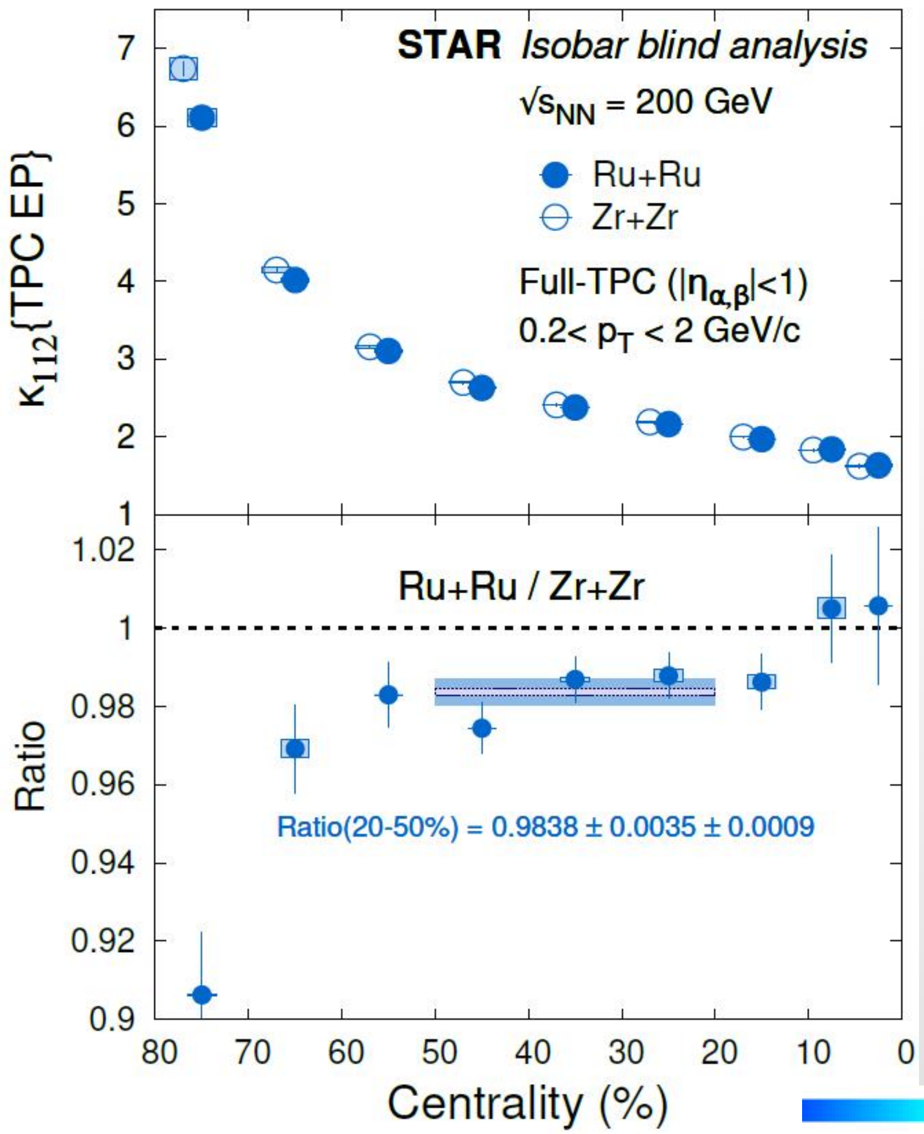
Matching centrality or matching multiplicity?



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,

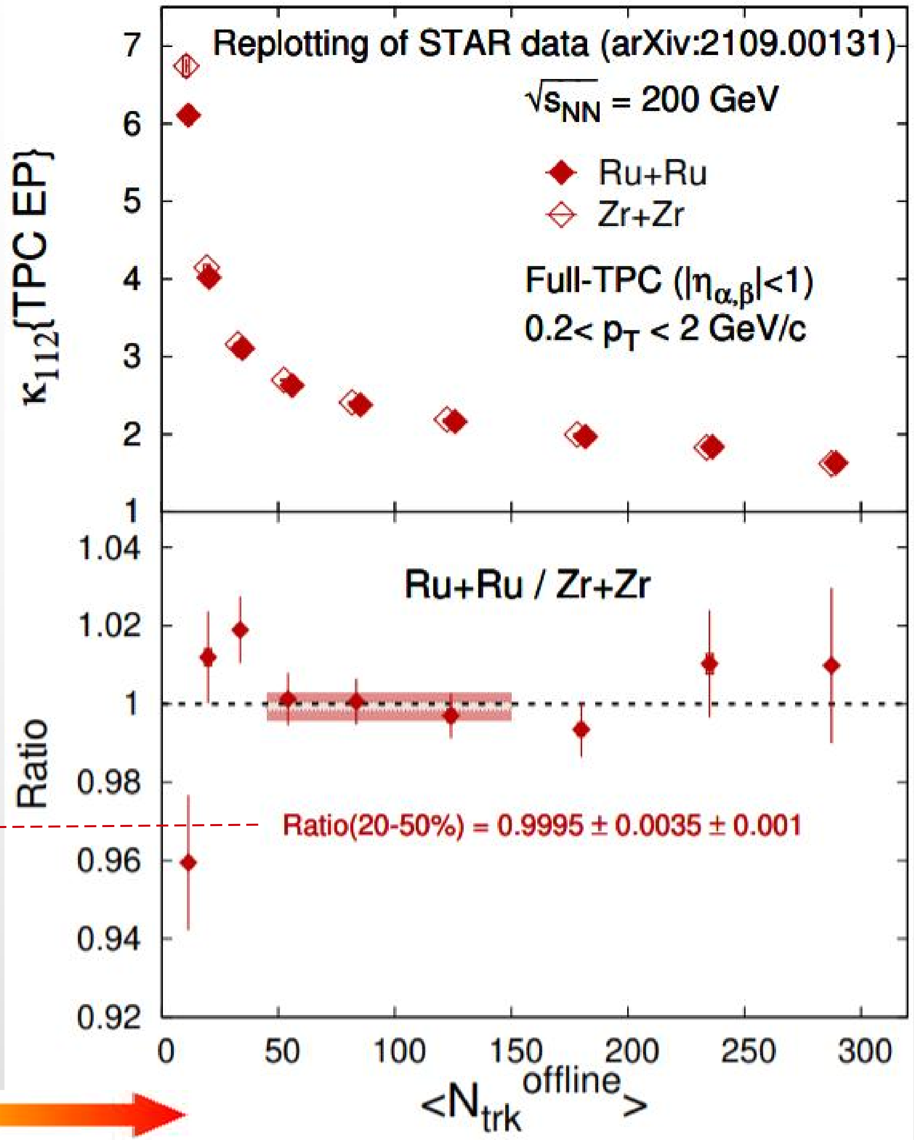
$$\frac{\kappa_{112}^{\mathrm{Ru+Ru}}}{\kappa_{112}^{\mathrm{Zr+Zr}}} > 1$$

is NOT seen.

Upper limit (95% CL):

1.0066 for κ_{112} ratio;

~4% for f_{CME}.

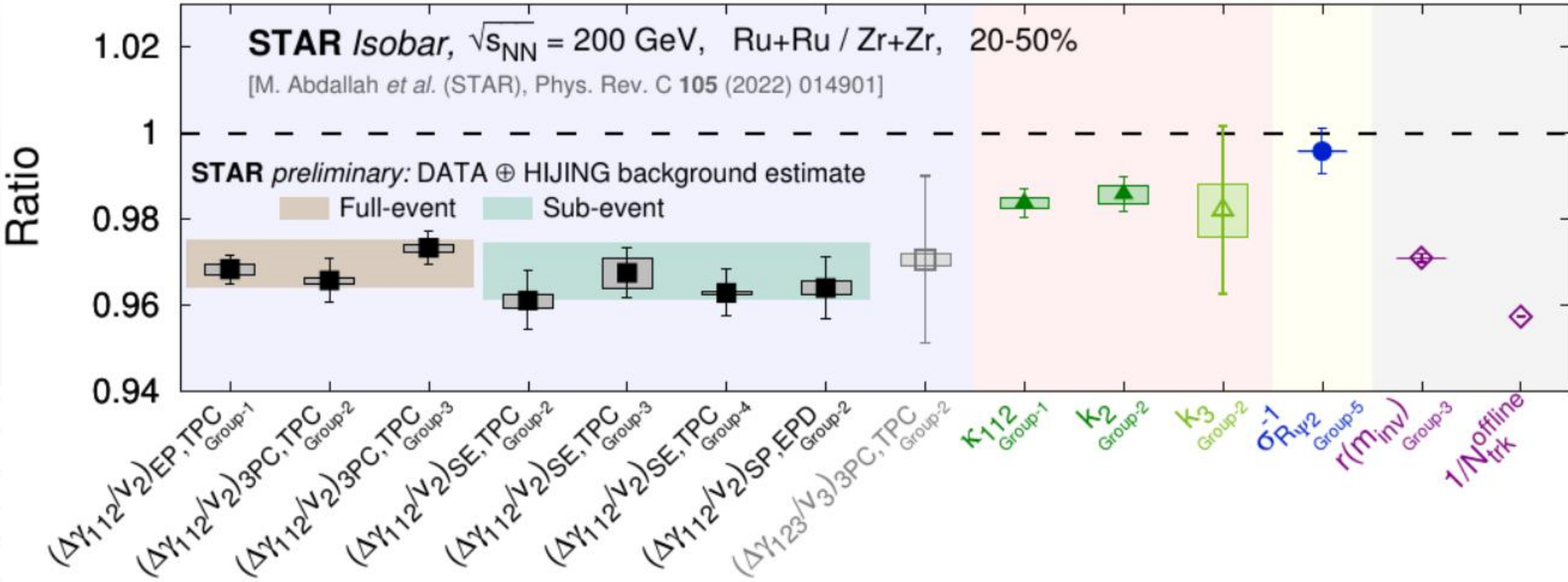


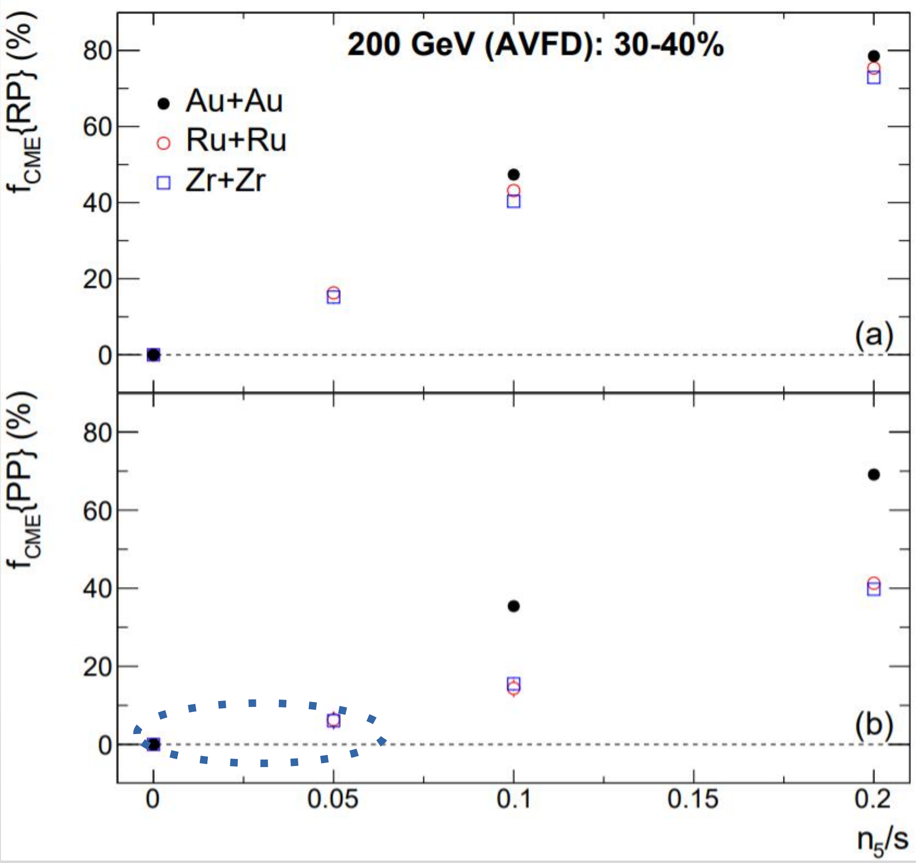
Small interpolation before taking ratios

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.

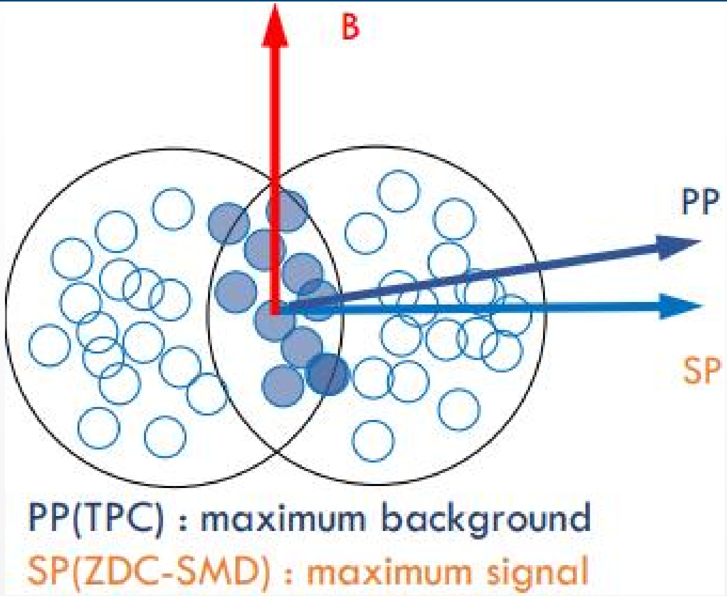




Why is f_{CME} so small?
AVFD simulation:
f_{CME} is smaller in isobar than Au+Au, especially when using the participant plane.
smaller system → larger fluctuation → larger BKG & smaller CME signal → lower f_{CME}

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

The bright side: PP vs SP



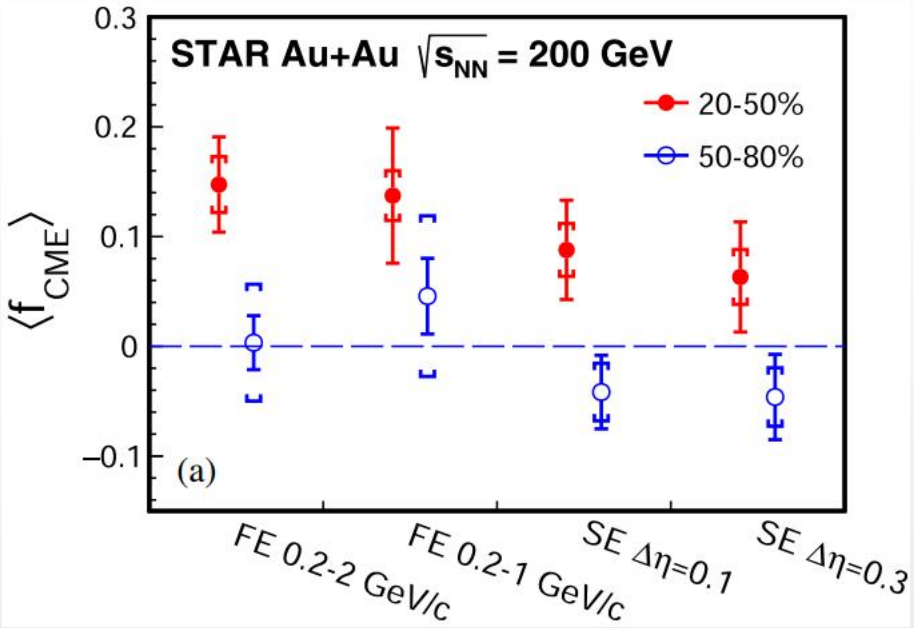
$$\Delta\gamma\{PP\} = \Delta\gamma_{CME}\{PP\} + \Delta\gamma_{BKG}\{PP\}$$
$$\Delta\gamma\{SP\} = \Delta\gamma_{CME}\{PP\}/a + \Delta\gamma_{BKG}\{PP\}a$$

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

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

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

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



When switching from participant plane (PP) to spectator plane (SP), the CME signal increases, and the background decreases, by the same factor:

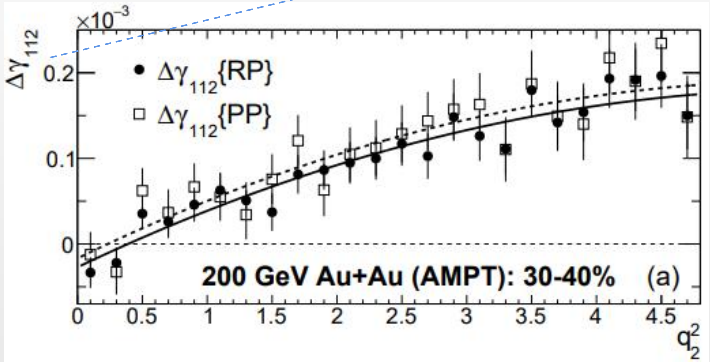
- SP is a proxy of the reaction plane, more closely related to the B field.
- v_2\{SP\} is smaller than v_2\{PP\} due to fluctuation, and the background is driven by v_2.

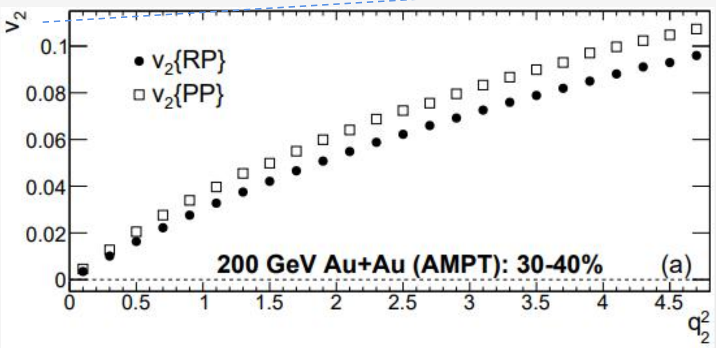
The difference between different event plane types indicates a finite f_{CME} in Au+Au at 200 GeV. More data to come!

The bright side: Event Shape Selection

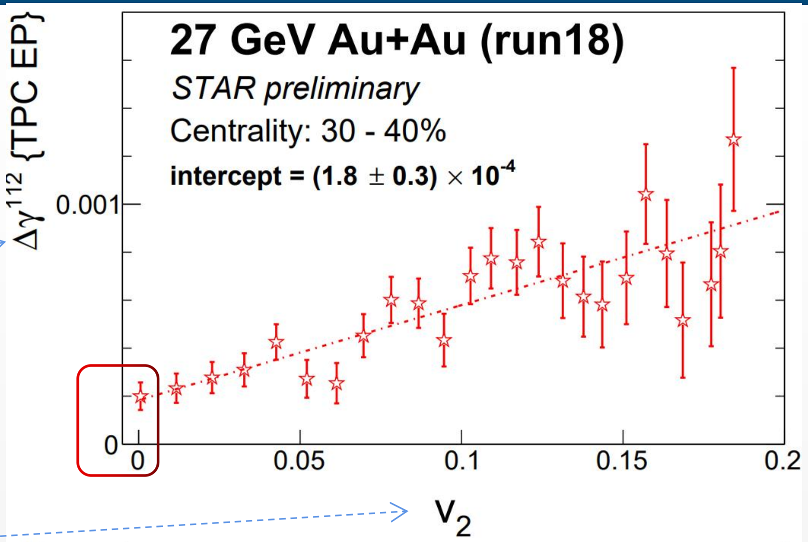
q is the magnitude of the flow vector of the sub-event (A) under study.

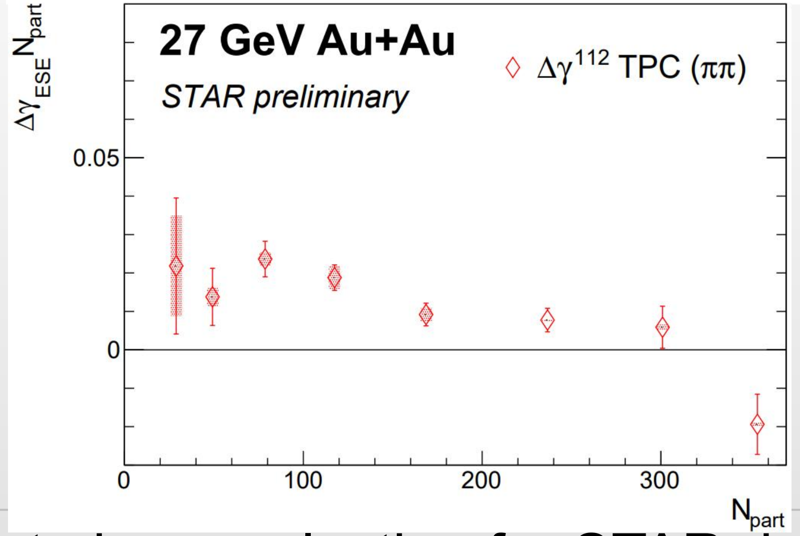
$$\overrightarrow{q_n}^{A} = (q_{n,x}^{A}, q_{n,y}^{A}) \qquad q_{n,x}^{A} = \frac{1}{\sqrt{N}}\sum_{i}^{N}\cos(n\phi_i^{A}), \qquad q_{n,y}^{A} = \frac{1}{\sqrt{N}}\sum_{i}^{N}\sin(n\phi_i^{A}),$$





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





For events in each q^{A} class, v_2 and $\Delta\gamma$ are measured for POIs in sub-event (A), and EP is estimated from another sub-event (B).

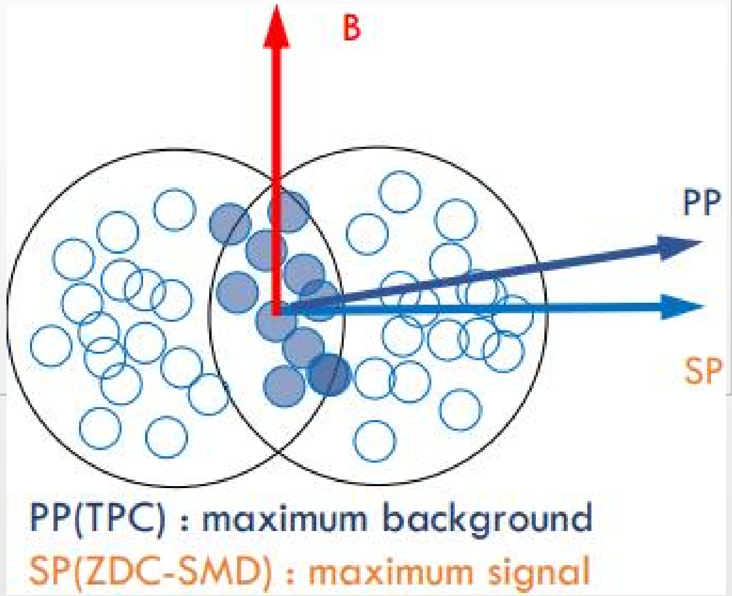
Event-shape selection for STAR data:

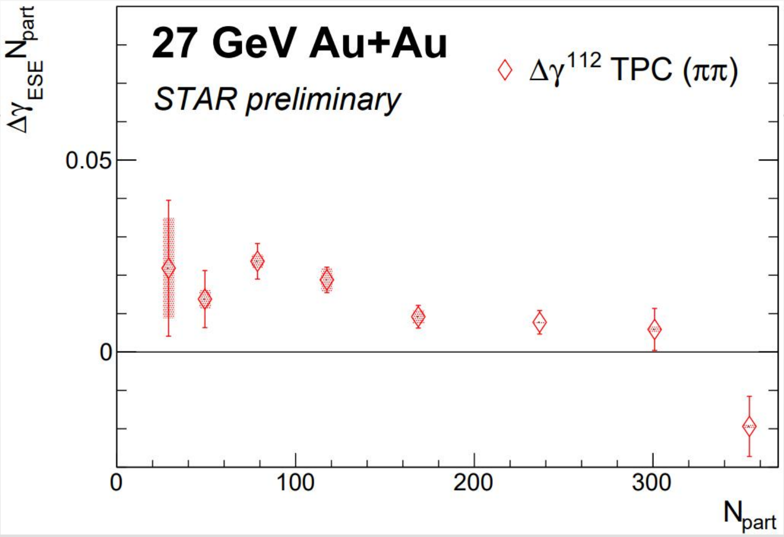
- suppresses v_2-related background
- enhances f_{CME} (finite at 27 GeV?)

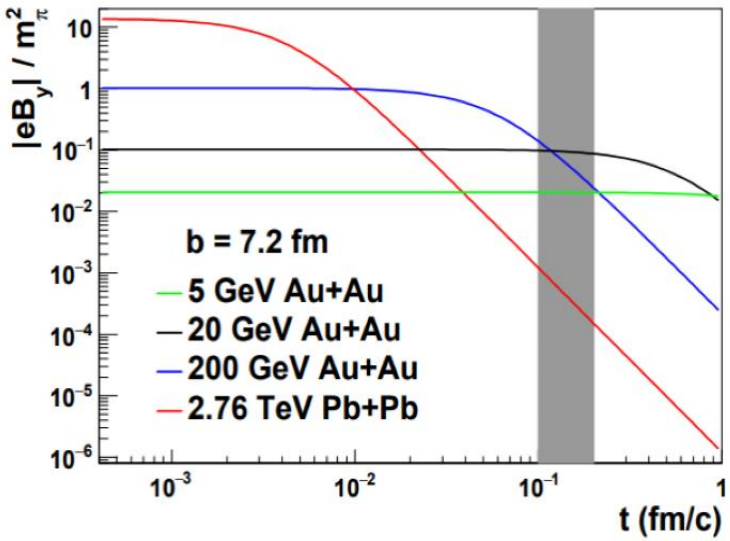
Summary

- The CME search bears great importance in heavy-ion collisions:
  - Superstrong initial B field, chiral symmetry restoration, vacuum transition...
- Past measurements show indication of CME, but are contaminated with backgrounds.
- From isobar data, no predefined CME signatures have been observed.

- We should focus back on larger systems:
  - Different event plane types
  - Event shape selection
  - BES-II: long B-field duration

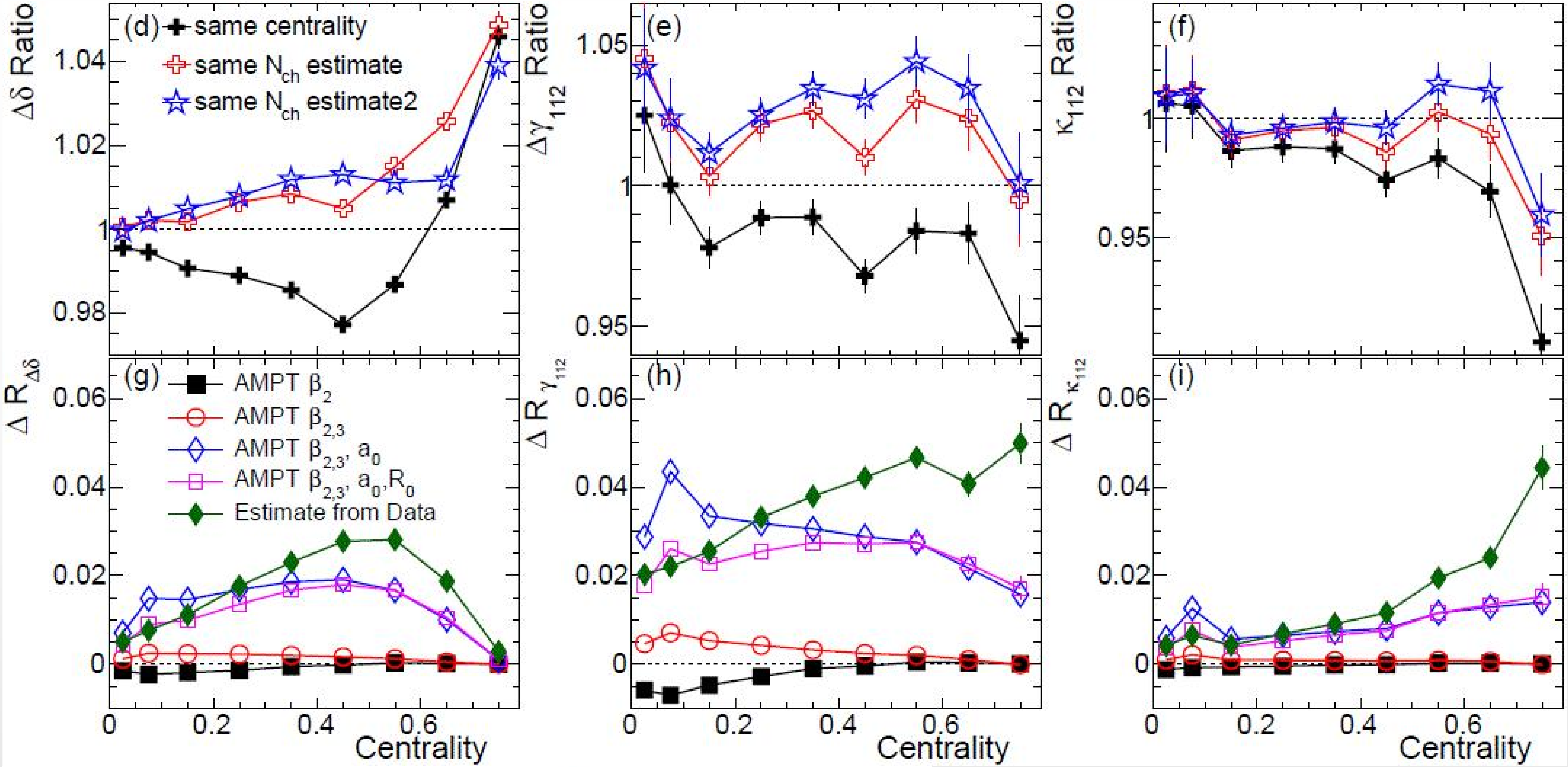






Backup slides

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}

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

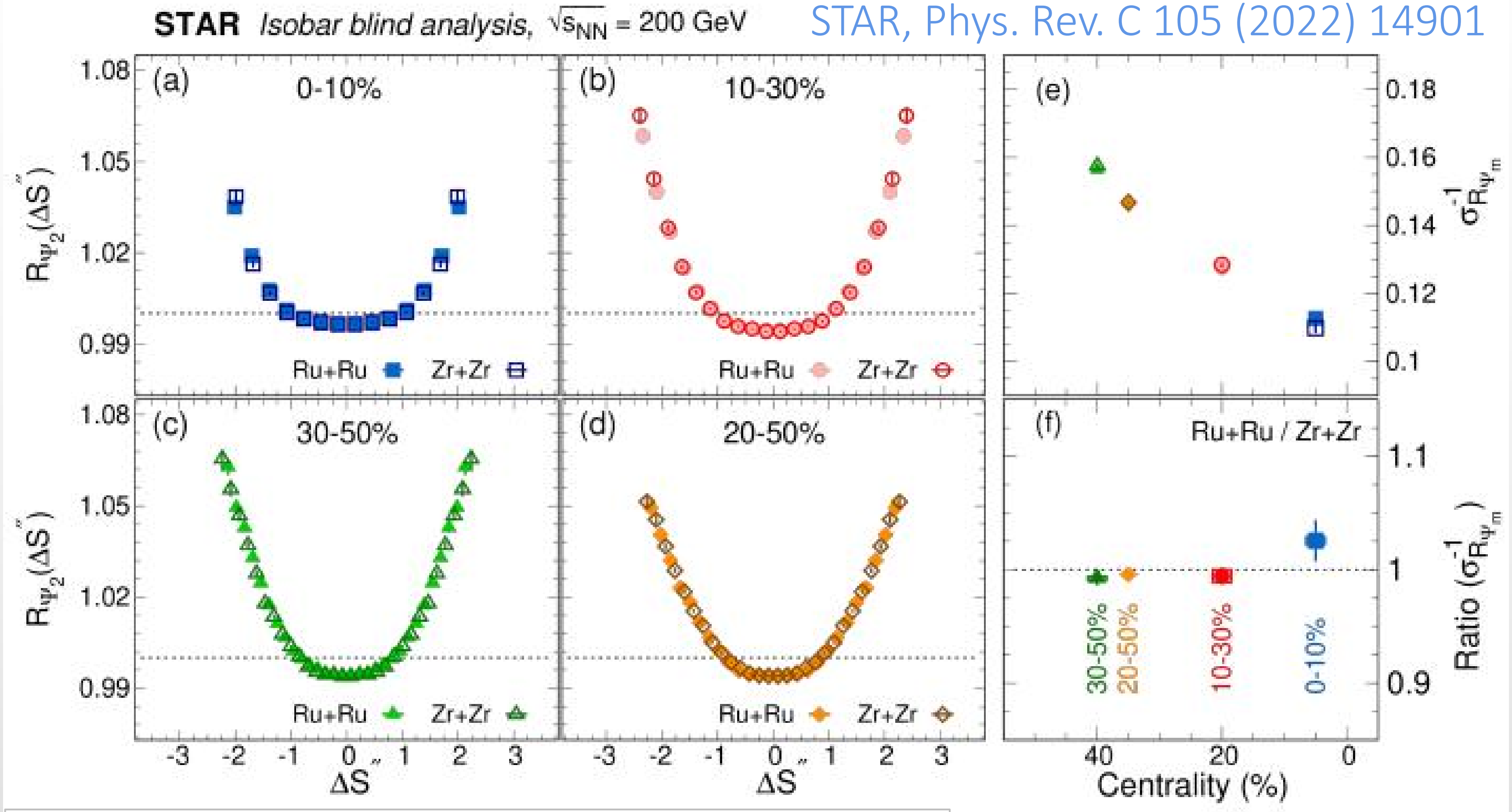
$$C_{\psi_2} = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)}$$

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

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:

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

No significant difference is observed between the two isobaric systems