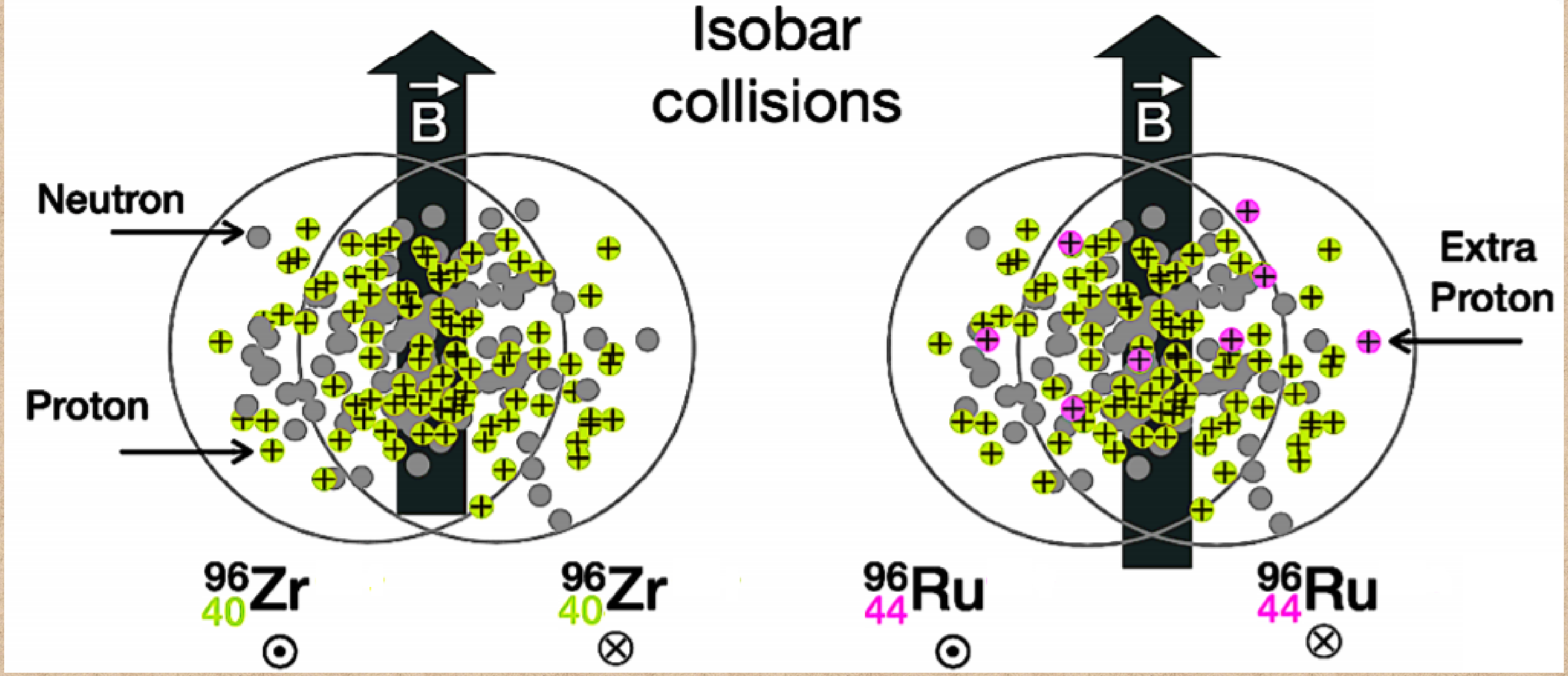


Understanding of STAR Group-1 Results on the CME in Isobar Collisions

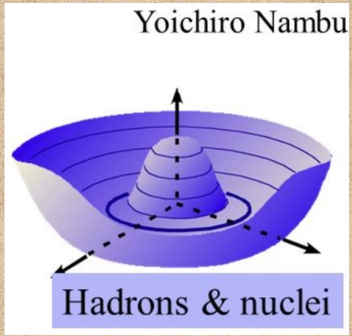
Gang Wang (UCLA)

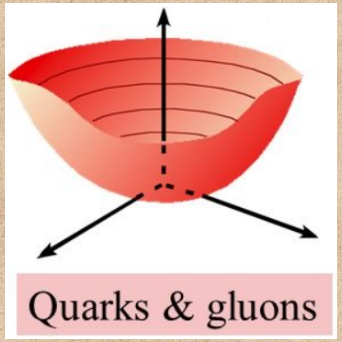
Based on STAR data (arXiv:2109.00131)

The 6th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

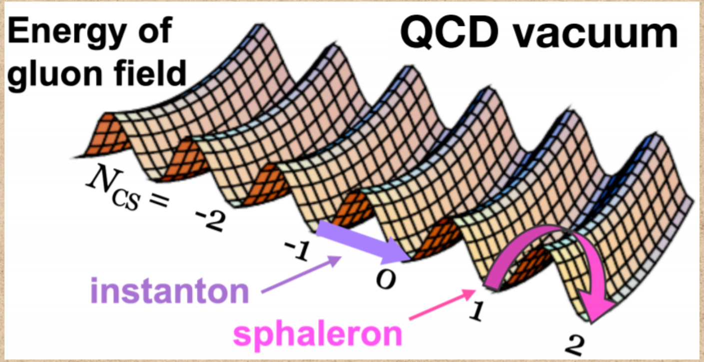
CME: $J \propto \mu_5 B$

1 Chiral symmetry restoration (massless quarks)

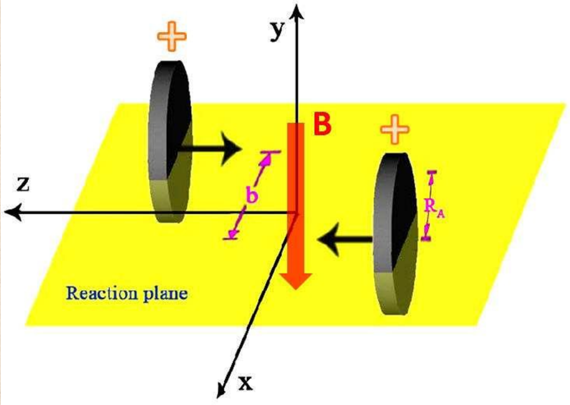




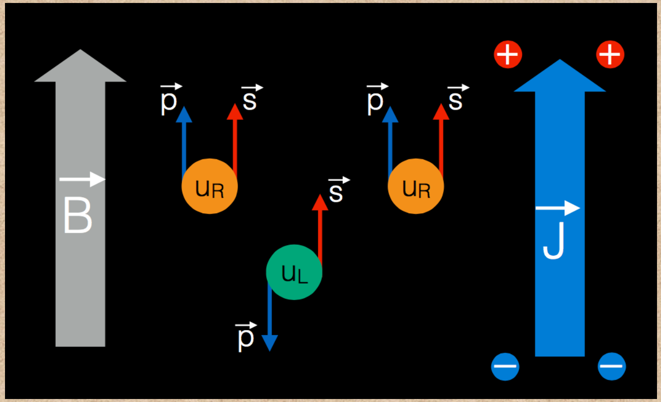
2 Chirality imbalance (finite μ_5)



3 Strong magnetic field (B)



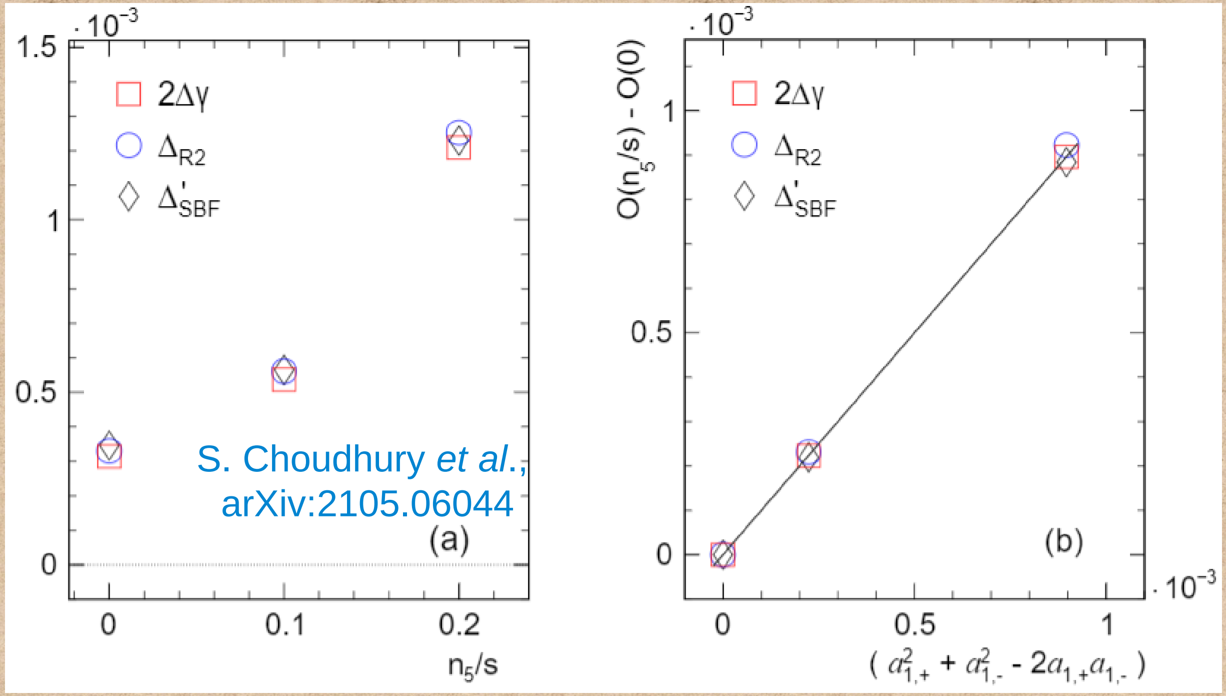
4 Chiral Magnetic Effect ($J \parallel B$)



Observables in Search of CME

Various 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)



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

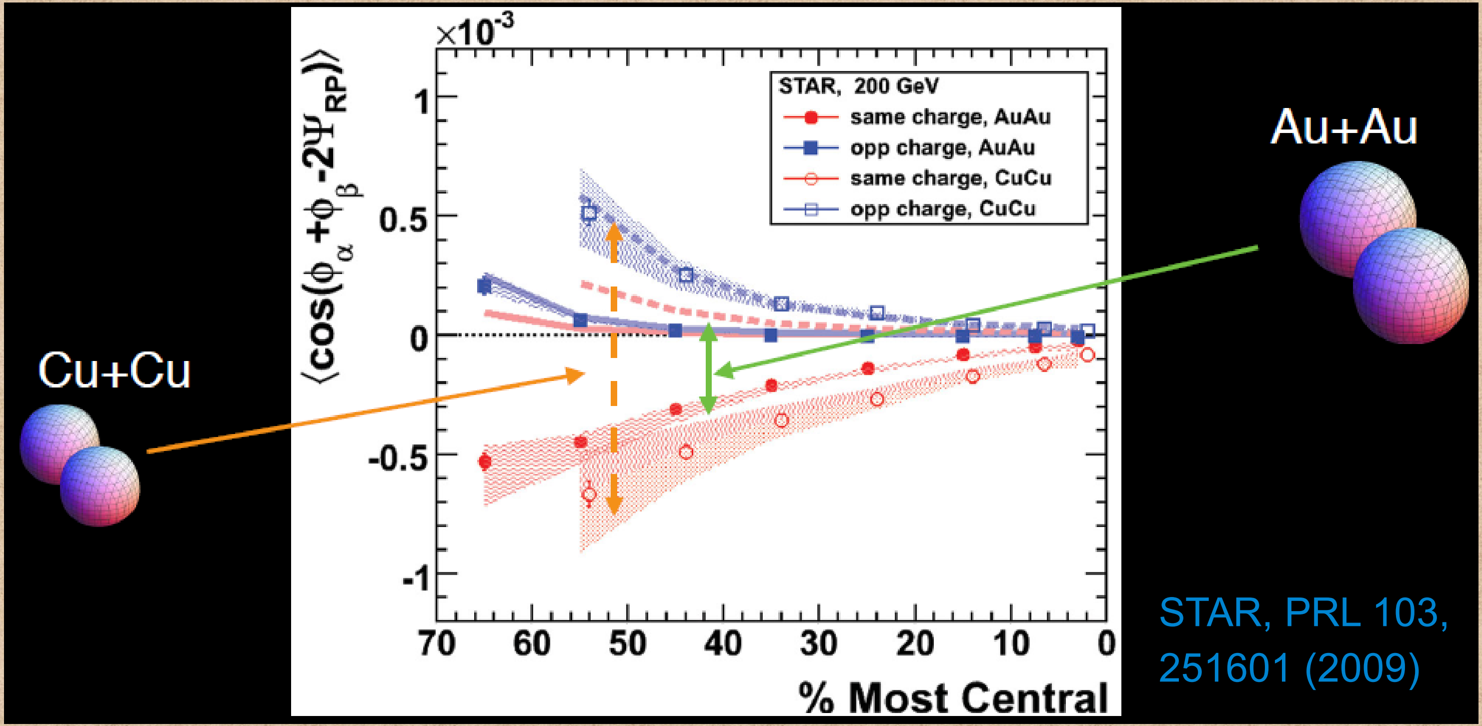
Here we focus on

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

And the CME should cause

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

$\Delta\gamma_{112}$ measurements at RHIC



STAR, PRL 103, 251601 (2009)

The positively finite $\Delta\gamma_{112}$ could contain contributions from:

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

Isobar program: long journey since 2010

Testing the Chiral Magnetic Effect with Central $U + U$ Collisions

Sergei A. Voloshin
Phys. Rev. Lett. **105**, 172301 – Published 19 October 2010

ABSTRACT

A quark interaction with topologically nontrivial gluonic fields, instantons and sphalerons, violates $\mathscr{P}$ and $\mathscr{CP}$ symmetry. In the strong magnetic field of a noncentral nuclear collision such interactions lead to the charge separation along the magnetic field, the so-called chiral magnetic effect (CME). Recent results from the STAR collaboration on charge dependent correlations are consistent with theoretical expectations for CME but may have contributions from other effects, which prevents definitive interpretation of the data. Here I propose to use central body-body $U + U$ collisions to disentangle correlations due to CME from possible background correlations due to elliptic flow. Further, more quantitative studies can be performed with collision of isobaric beams

Testing the chiral magnetic effect with isobaric collisions

Wei-Tian Deng, Xu-Guang Huang, Guo-Liang Ma, and Gang Wang
Phys. Rev. C **94**, 041901(R) – Published 28 October 2016

Chinese Physics C > 2017, Vol. 41 > Issue(7) : 072001 DOI: 10.1088/1674-1137/41/7/072001

Status of the chiral magnetic effect and collisions of isobars

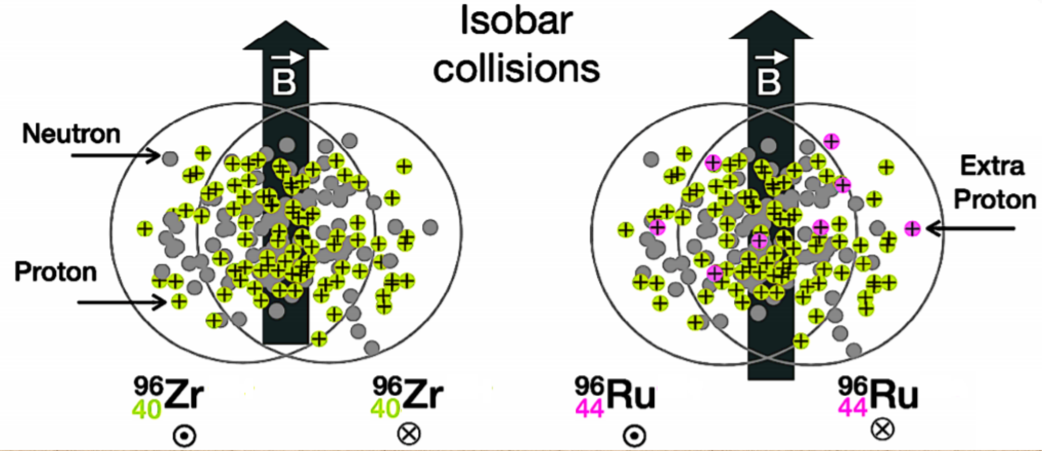
Volker Koch [1], Soeren Schlichting [2], Vladimir Skokov [3], Paul Sorensen [2], Jim Thomas [1], Sergei Voloshin [4], Gang Wang [5], Ho-Ung Yee [3,6]

The isobar idea was first mentioned in Voloshin's paper.

Then examined by many detailed studies, committees, workshops

And 3 years of Beam Use Request by STAR (2015-2017)

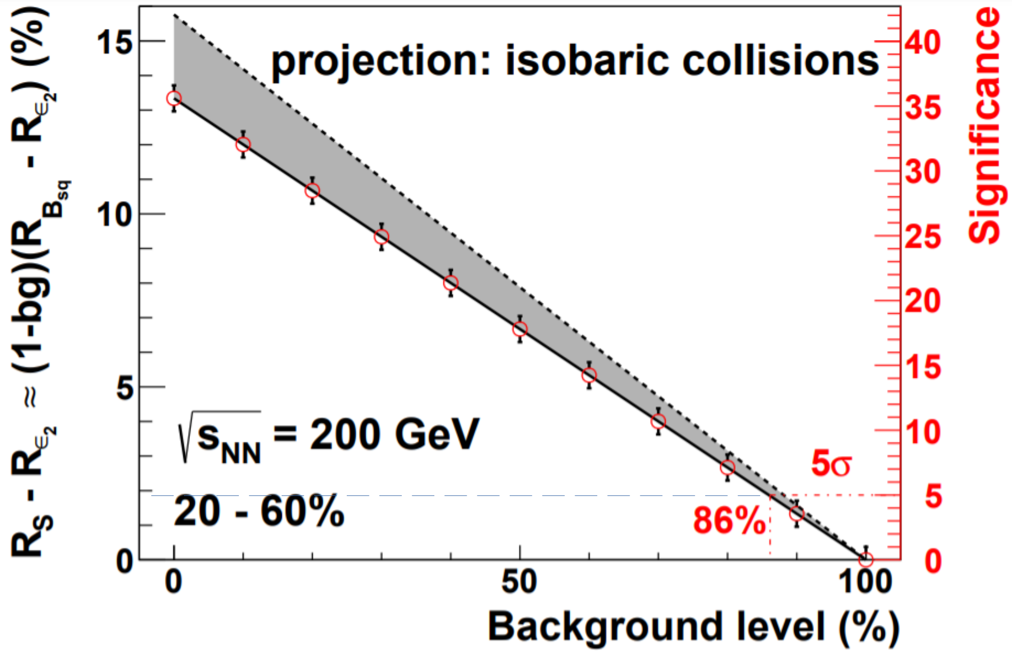
Isobar collisions: prospect



Compare the two isobaric systems:

- CME: B-field^2 is ~13% larger in Ru+Ru
- Flow-related BKG: utilize $\Delta\gamma_{112}/v_2$
- Nonflow-related BKG: almost same

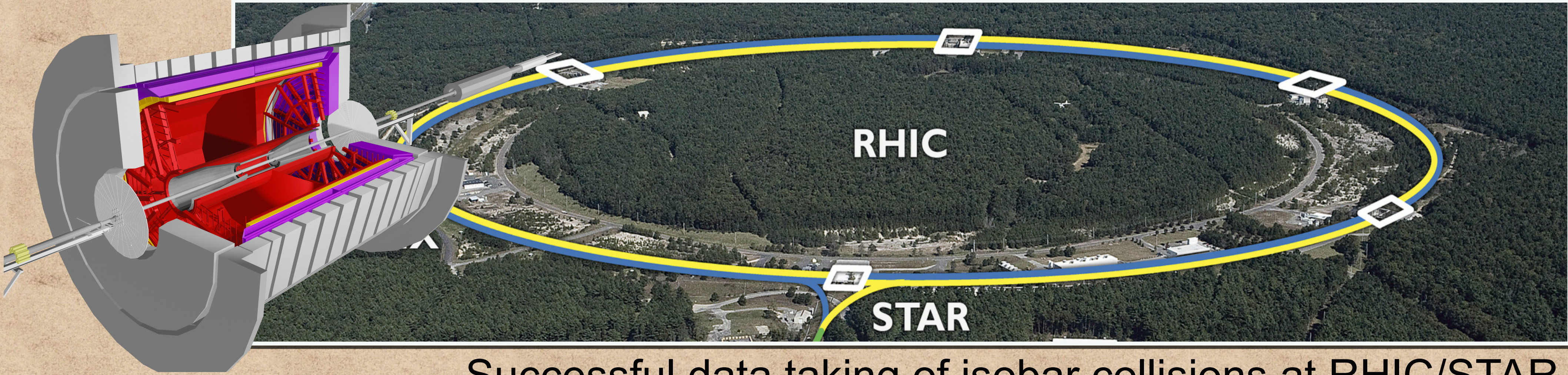
Isobar collisions provide best possible control of signal and background.



2.5 B events per species:

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

Isobar program: data collection in 2018



Successful data taking of isobar collisions at RHIC/STAR

arXiv.org > nucl-ex > arXiv:2109.00131

Search...

Help | Advanced Se

Nuclear Experiment

[Submitted on 1 Sep 2021]

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

STAR Collaboration: M. S. Abdallah, B. E. Aboona, J. Adam, L. Adamczyk, J. R. Adams, J. K. Adkins, G. Agakishiev, I. Aggarwal, M. M. Aggarwal, Z. Ahammed, I. Alekseev, D. M. Anderson, A. Aparin, E. C. Aschenauer, M. U. Ashraf, F. G. Atetalla, A. Attri, G. S. Averichev, V. Bairathi, W. Baker, J. G. Ball Cap, K. Barish, A. Behera, R. Bellwied, P. Bhagat, A. Bhasin, J. Bielcik, J. Bielcikova, I. G. Bordyuzhin, J. D. Brandenburg, A. V. Brandin, I. Bunzarov, X. Z. Cai, H. Caines, M. Calderón de la Barca Sánchez, D. Cebra, I. Chakaberia, P. Chaloupka, B. K. Chan, F-H. Chang, Z. Chang, N. Chankova-Bunzarova, A. Chatterjee, S. Chattopadhyay, D. Chen, J. Chen, J. H. Chen, X. Chen, Z. Chen, J. Cheng, M. Chevalier, S. Choudhury, W. Christie, X. Chu, H. J. Crawford, M. Csanád, M. Daugherity, T. G. Dedovich, I. M. Deppner, A. A. Derevschikov, A. Dhamija, L. Di Carlo, L. Didenko, P. Dixit, X. Dong, J. L. Drachenberg, E. Duckworth, J. C. Dunlop, N. Elsey, J. Engelage, G. Eppley, S. Esumi, O. Evdokimov, A. Ewigleben, O. Eyser, R. Fatemi, F. M. Fawzi, S. Fazio, P. Federic, J. Fedorisin, C. J. Feng, Y. Feng, P. Filip, E. Finch, Y. Fisyak, A. Francisco, C. Fu, L. Fulek, C. A. Gagliardi, T. Galatyuk, F. Geurts, N. Ghimire, A. Gibson, K. Gopal, X. Gou, D. Grosnick, A. Gupta, W. Guryn, A. I. Hamad et al. (298 additional authors not shown)

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.

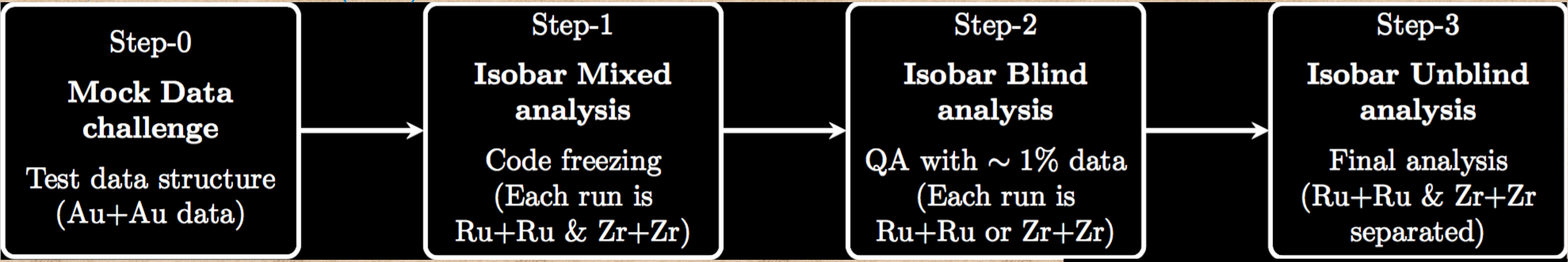
Comments: 43 pages, 27 figures

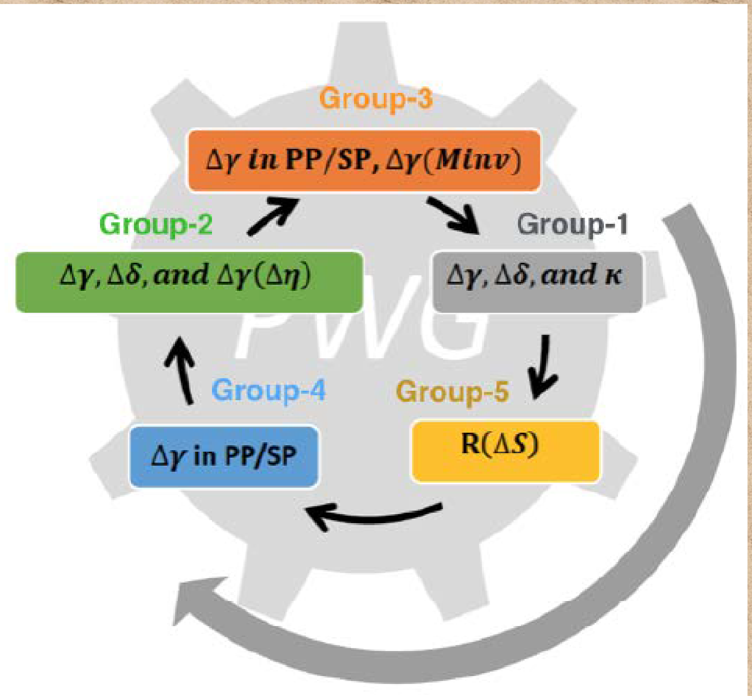
Subjects: **Nuclear Experiment (nucl-ex)**; High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)

Now after 3 years and many people's effort...

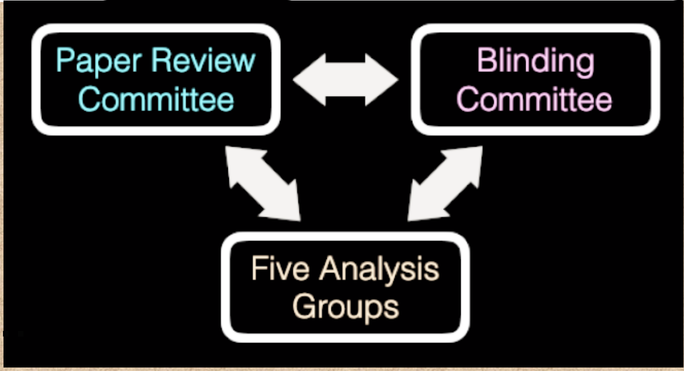
Steps of isobar blind analysis

STAR, Nucl. Sci. Tech. 32 (2021) 48





Blinding committee decides the procedure.



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.

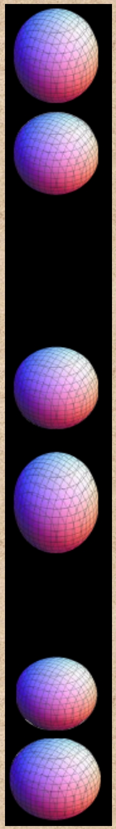
Nucleus	Case-1 [83] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158
$^{96}_{40}$Zr	5.02	0.46	0.08

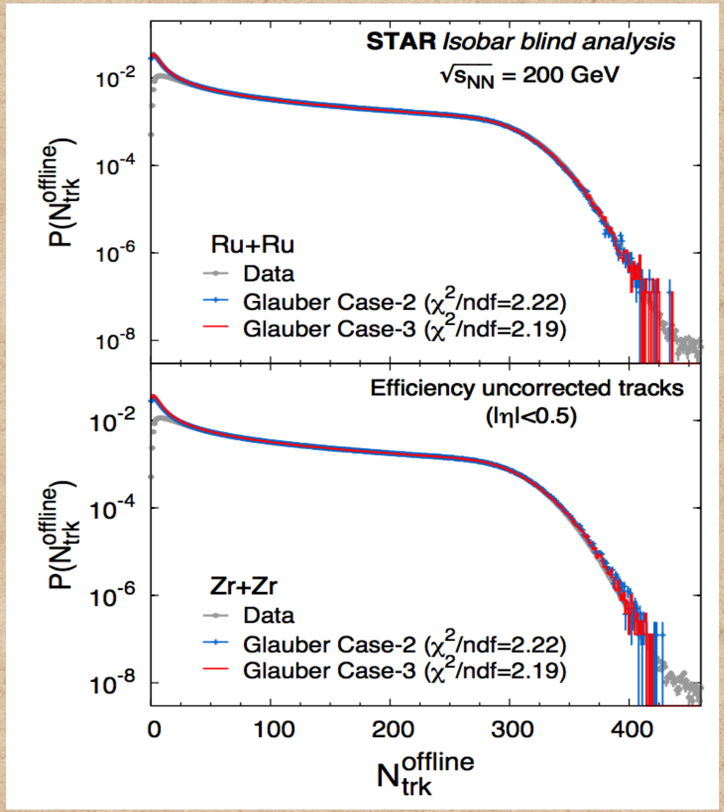
Deng *et al.*, PRC 94, 041901 (2016)

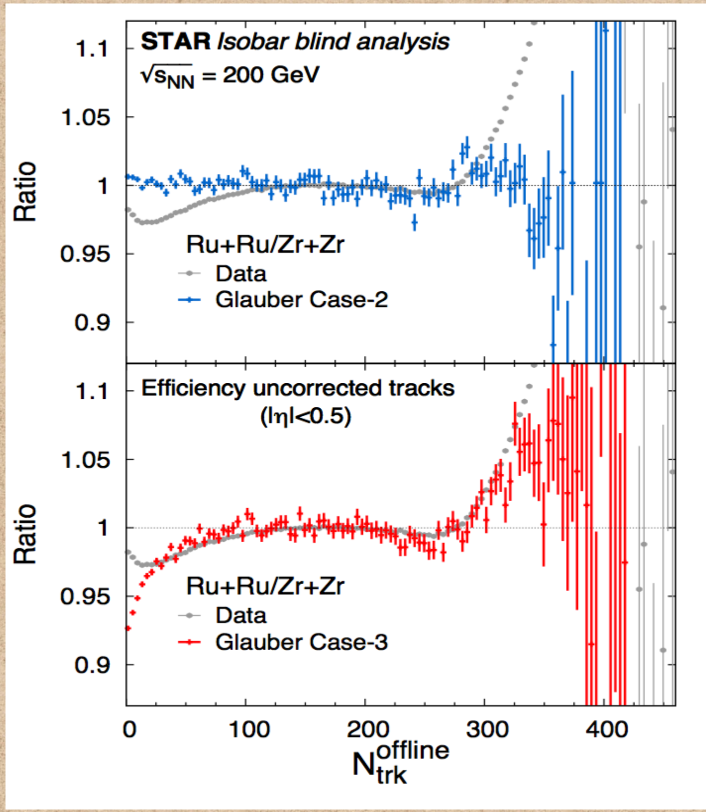
Nucleus	Case-2 [83] R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.053
$^{96}_{40}$Zr	5.02	0.46	0.217

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

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

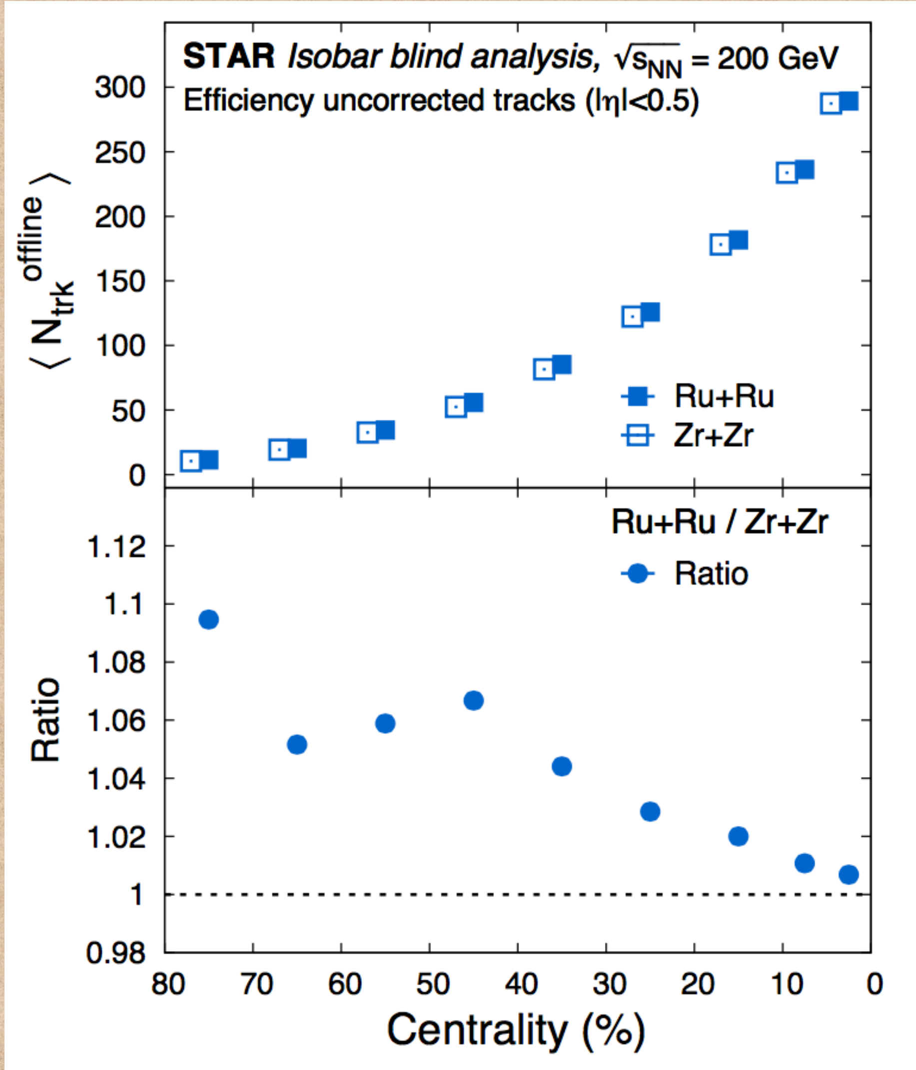






MC-Glauber model fits the uncorrected multiplicity distribution. Woods-Saxon parameters with thicker neutron skin in Zr (no deformation) gives the best fit of the multiplicity distributions.

Multiplicity mismatch



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

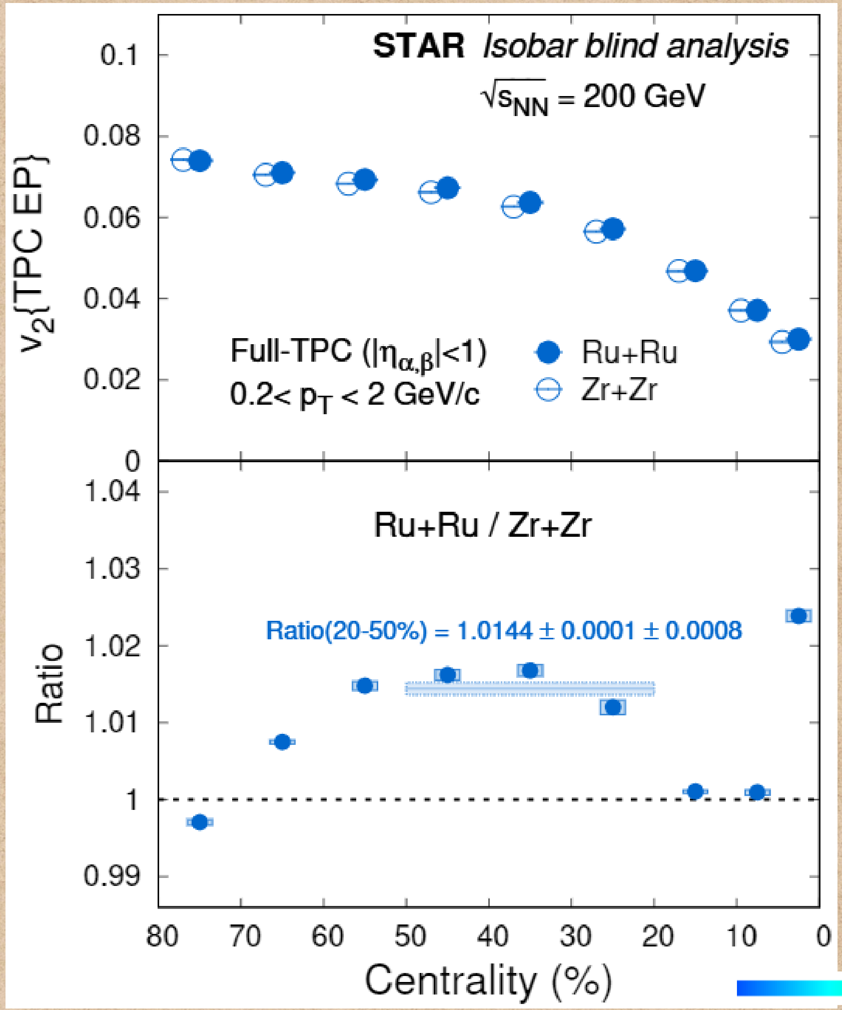
However, multiplicity (efficiency uncorrected) is larger in Ru+Ru than in Zr+Zr in such matching centrality.

This can affects 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.

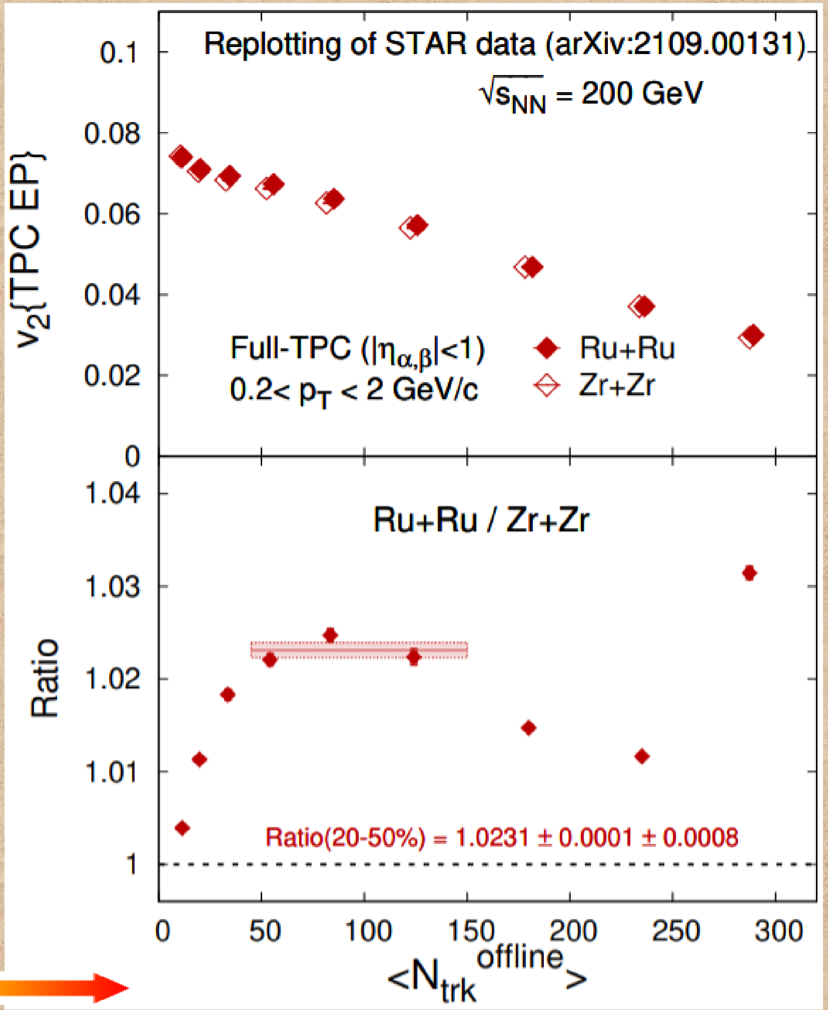
In the end, the blind analysis sticks to **Case-3**.

v_2 ratio



The v_2 ratio of Ru+Ru to Zr+Zr becomes larger when the x-axis changes to multiplicity.

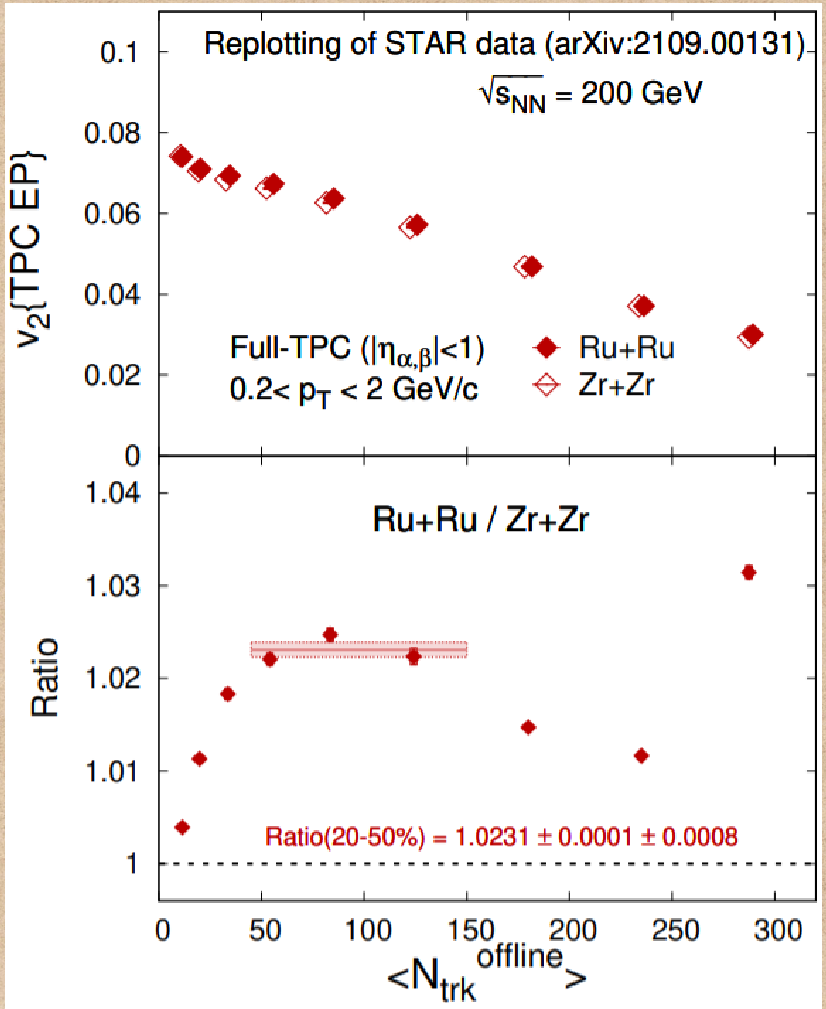
This ratio enhancement is true for all other observables.



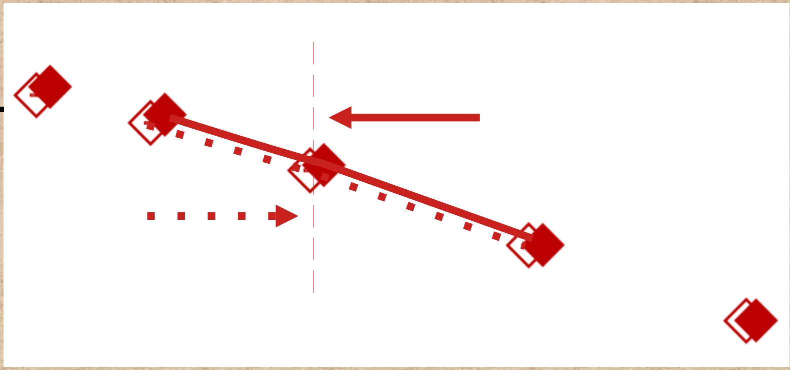
For further v_n study, see Chunjian Zhang's DNP talk: https://drive.google.com/file/d/1oLcxi7wE-DIcRAiBjN9Q4Y2Cy2i9AvIU/view?usp=sharing

Small interpolation before taking ratios.

Interpolation: my personal approach



3 adjacent points determine a unique 2nd-order polynomial.

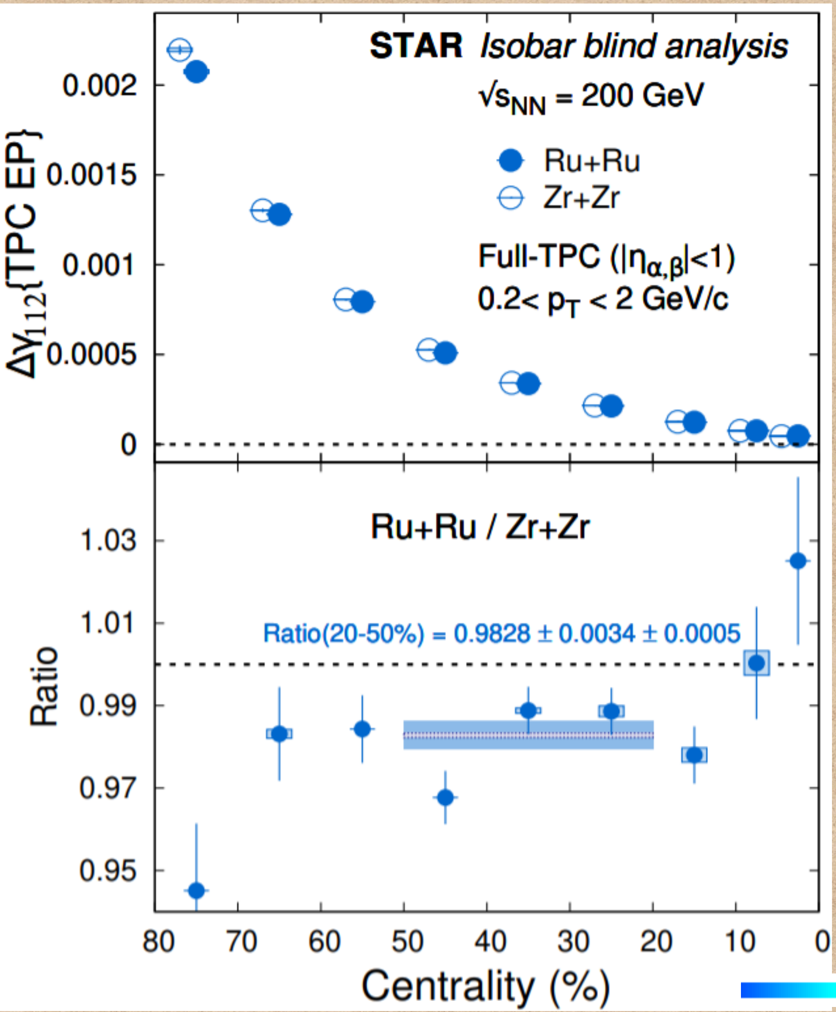


Shift Ru+Ru curve slightly to the left;
Shift Zr+Zr curve slightly to the right;
Both to the same point: $(M_{RuRu} + M_{ZrZr})/2$.

The right-most Ru+Ru point is projected to the location of the right-most Zr+Zr point.
The left-most Zr+Zr point is projected to the location of the left-most Ru+Ru point.

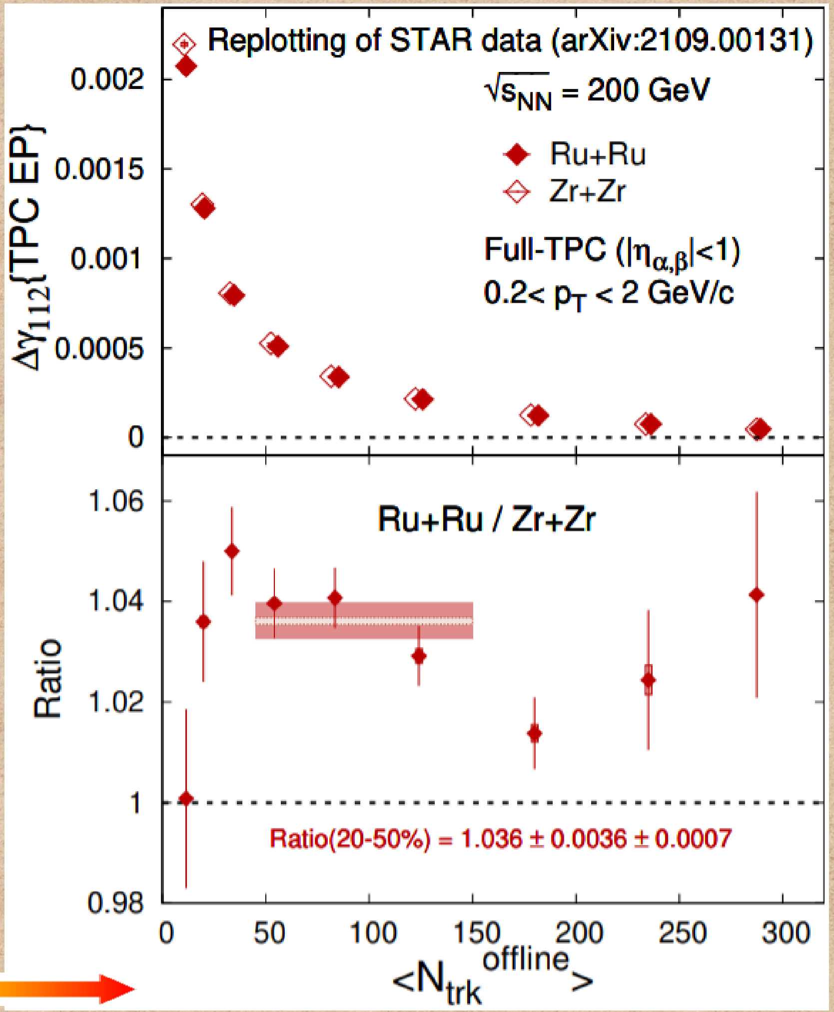
Small interpolation before taking ratios.

$\Delta\gamma_{112}$ ratio



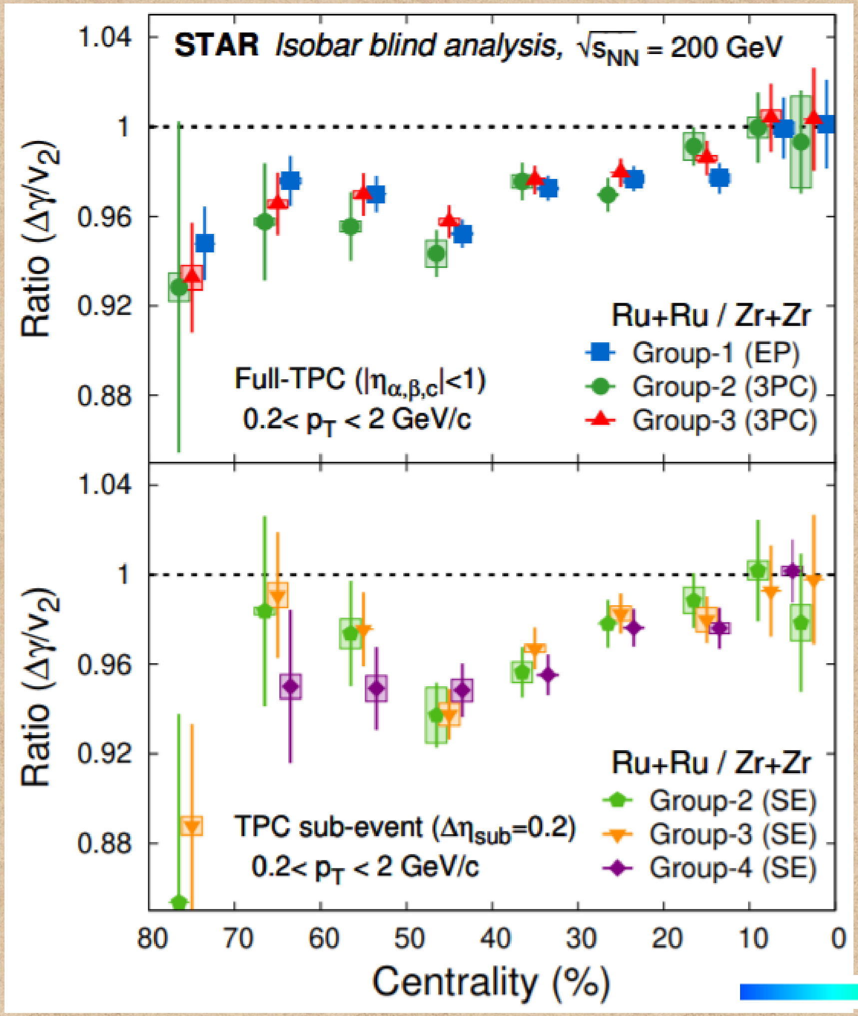
At matching multiplicity, the $\Delta\gamma_{112}$ ratio goes above unity.

This is more reasonable even in the pure BKG scenario (since v_2 ratio is above unity).



Small interpolation before taking ratios.

$\Delta\gamma_{112}/v_2$ ratio

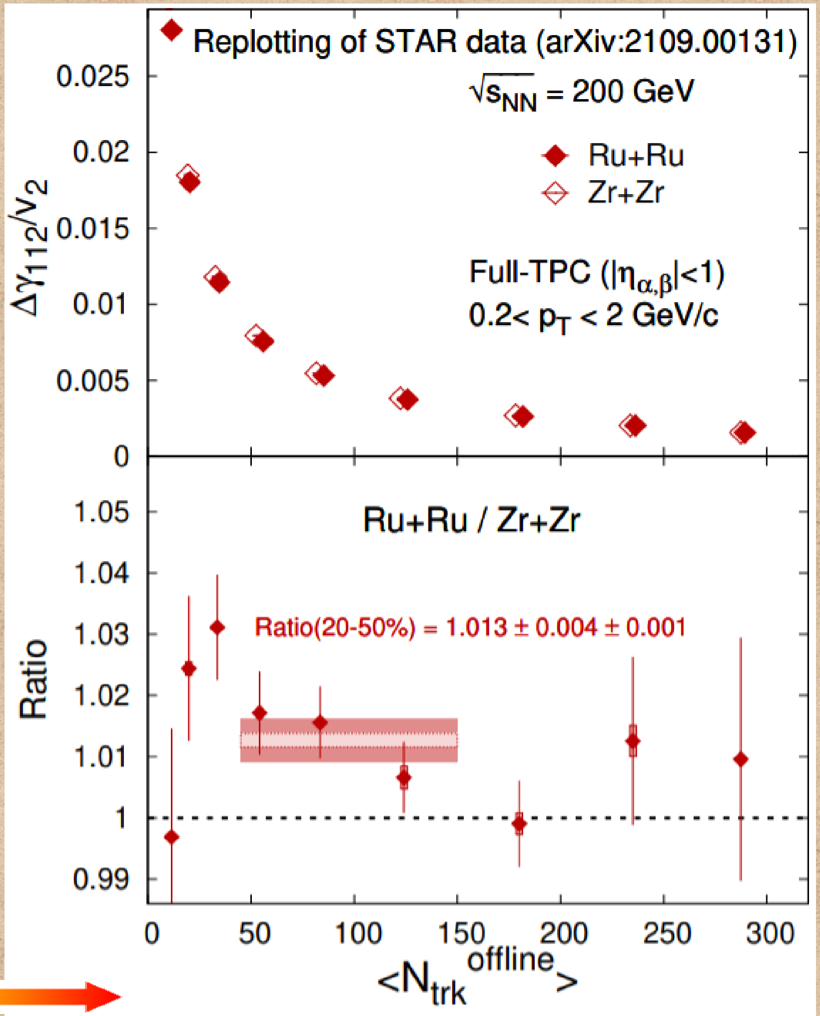


Different groups show good consistency.

At matching multiplicity, the $\Delta\gamma_{112}/v_2$ ratio goes above unity.

If we stop here, we are good with a 3σ effect.

But...



Small interpolation before taking ratios.

$\Delta\gamma_{112}/v_2$ may be not enough

$$\gamma_{112} \equiv \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle$$
$$= \langle\cos(\phi_\alpha - \phi_\beta + 2\phi_\beta - 2\Psi_2)\rangle$$
$$= \langle\cos(\phi_\beta - \phi_\alpha)\cos(2\phi_\beta - 2\Psi_2)\rangle + \langle\sin(\phi_\beta - \phi_\alpha)\sin(2\phi_\beta - 2\Psi_2)\rangle$$
$$= \delta \cdot v_2 + \langle\langle\cos(\phi_\beta - \phi_\alpha)\cos(2\phi_\beta - 2\Psi_2)\rangle\rangle + \langle\langle\sin(\phi_\beta - \phi_\alpha)\sin(2\phi_\beta - 2\Psi_2)\rangle\rangle$$

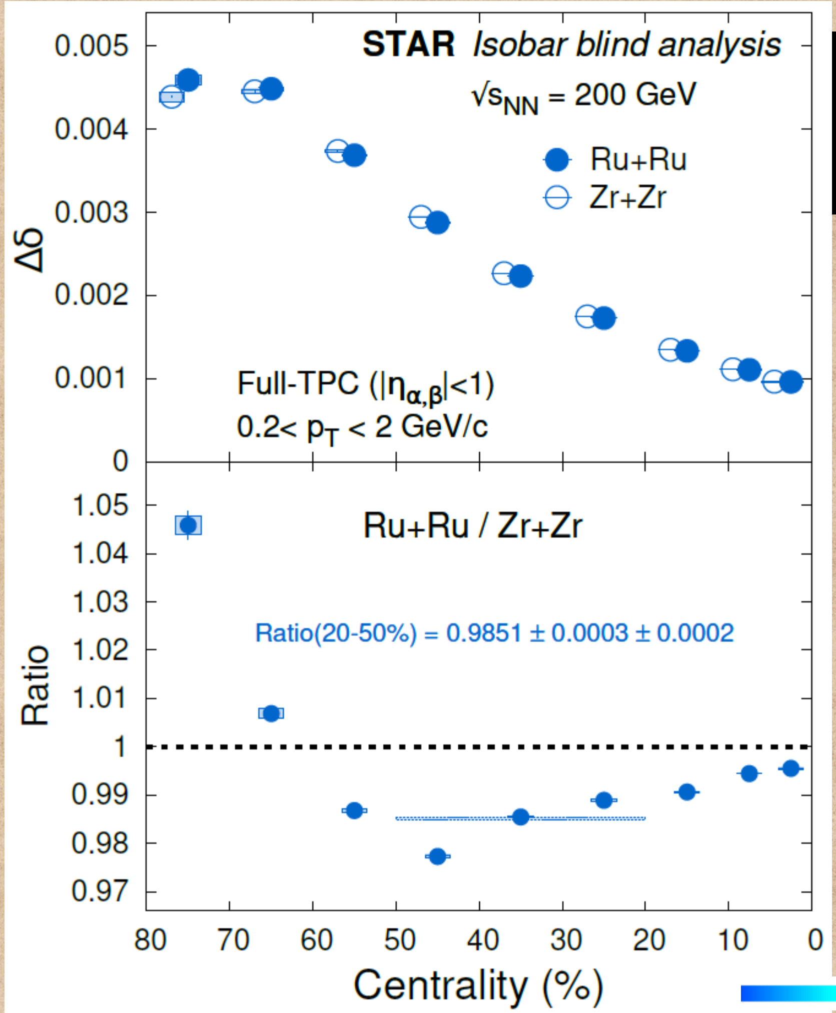
$$v_2 = \langle\cos(2\phi - \Psi_2)\rangle$$
$$\times$$
$$\delta = \langle\cos(\phi_\alpha - \phi_\beta)\rangle$$

The cumulant, <<...>>, denotes the "true" correlation between *a* and *b*, $\langle\langle a^*b\rangle\rangle \equiv \langle a^*b\rangle - \langle a\rangle\langle b\rangle$.

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

κ_{112} considers one more BKG factor than $\Delta\gamma_{112}/v_2$.

Δδ ratio

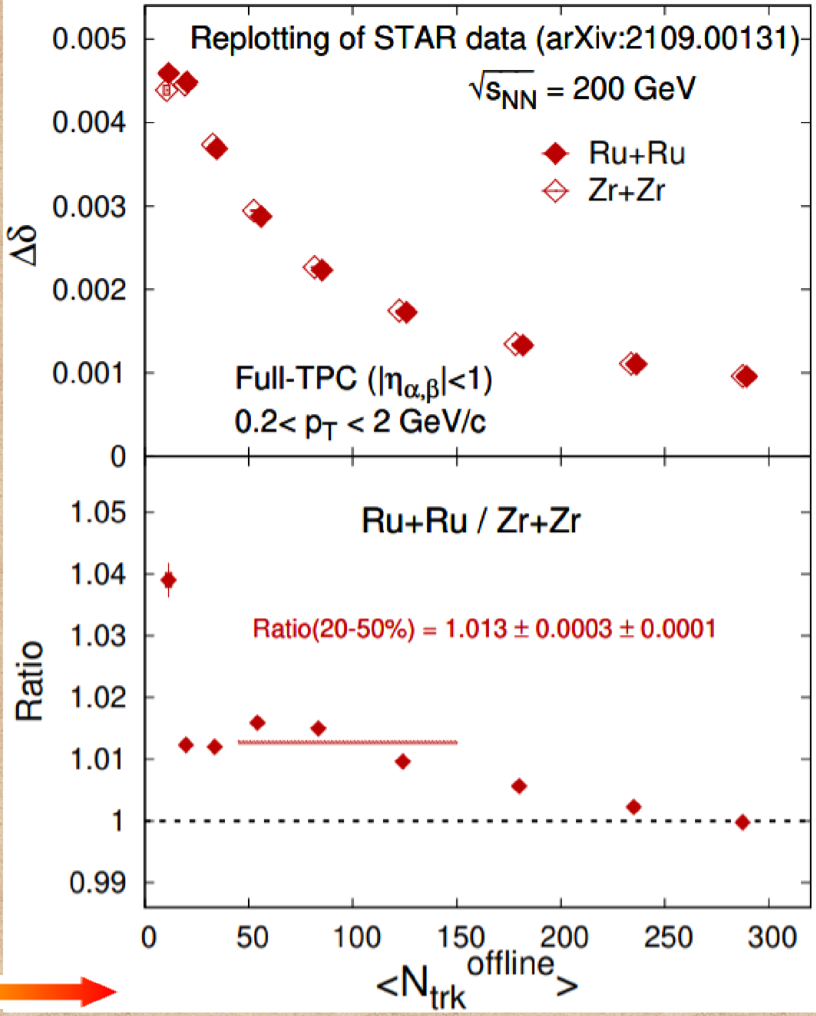


$$\delta \equiv \langle \cos(\phi_\alpha - \phi_\beta) \rangle$$

$$\Delta\delta = \delta(OS) - \delta(SS)$$

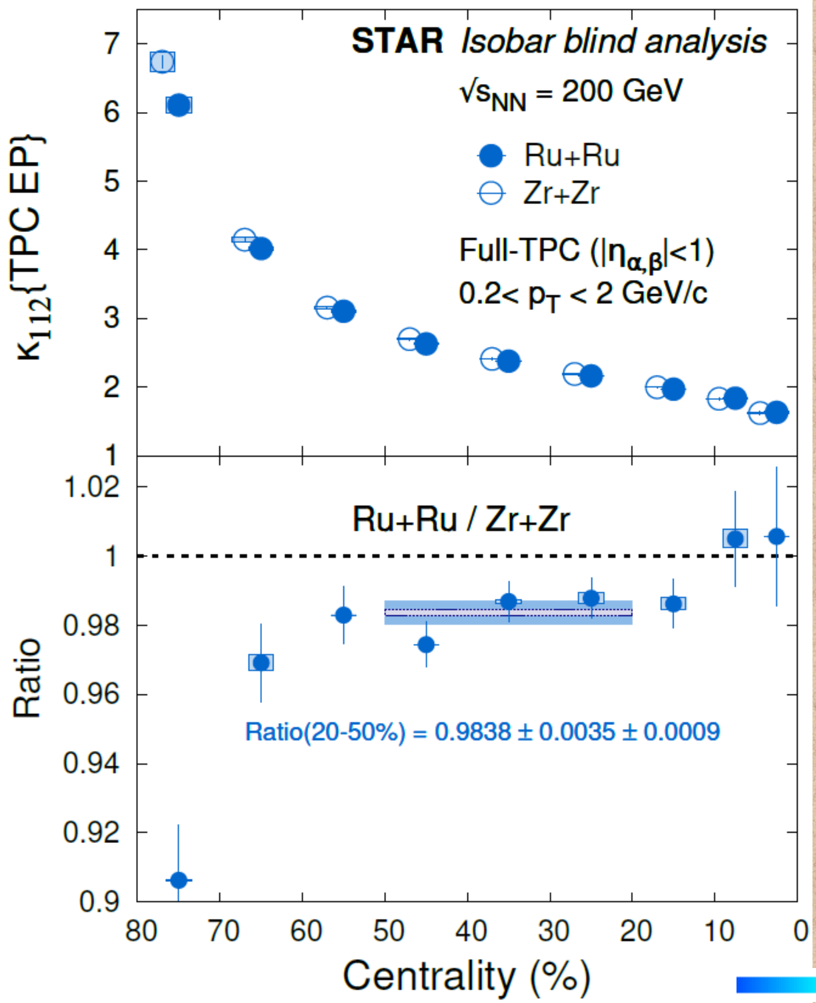
At matching centrality, the below-unity Δδ ratio could fake a CME signal.

At matching multiplicity, the Δδ ratio goes above unity.



Small interpolation before taking ratios.

κ_{112} ratio ≈ 1+13% f_{CME}



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

Pre-defined CME signature,

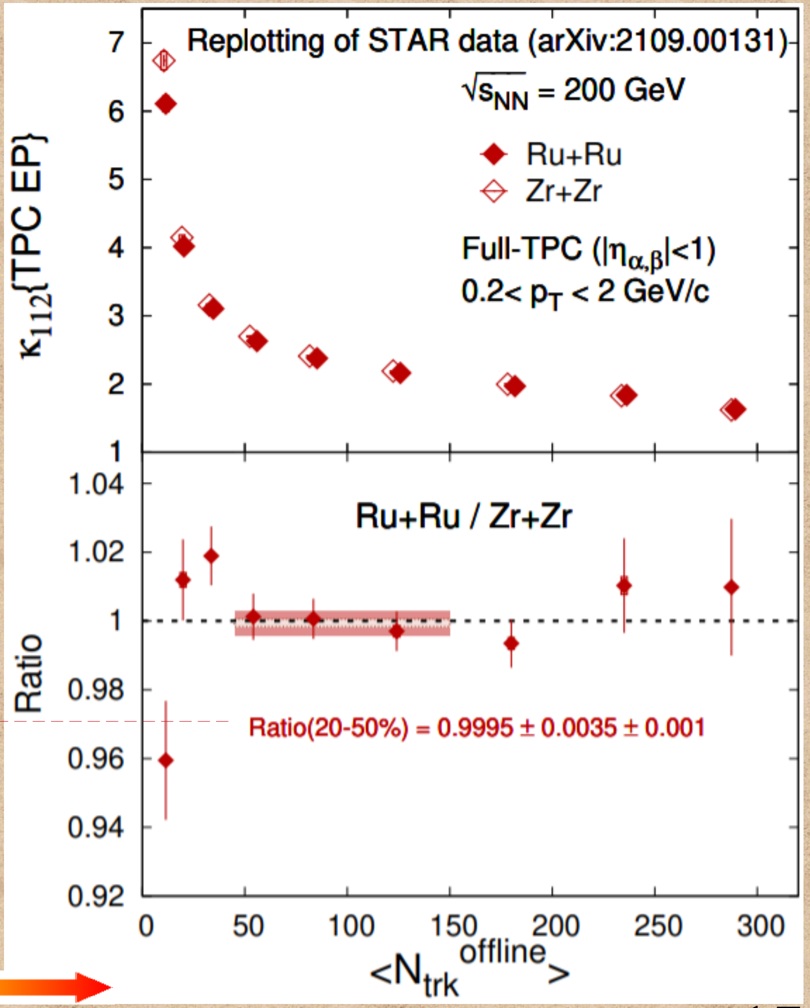
$$\frac{\kappa_{112}^{\mathrm{Ru+Ru}}}{\kappa_{112}^{\mathrm{Zr+Zr}}} > 1$$

is NOT seen.

Upper limit (95% CL):

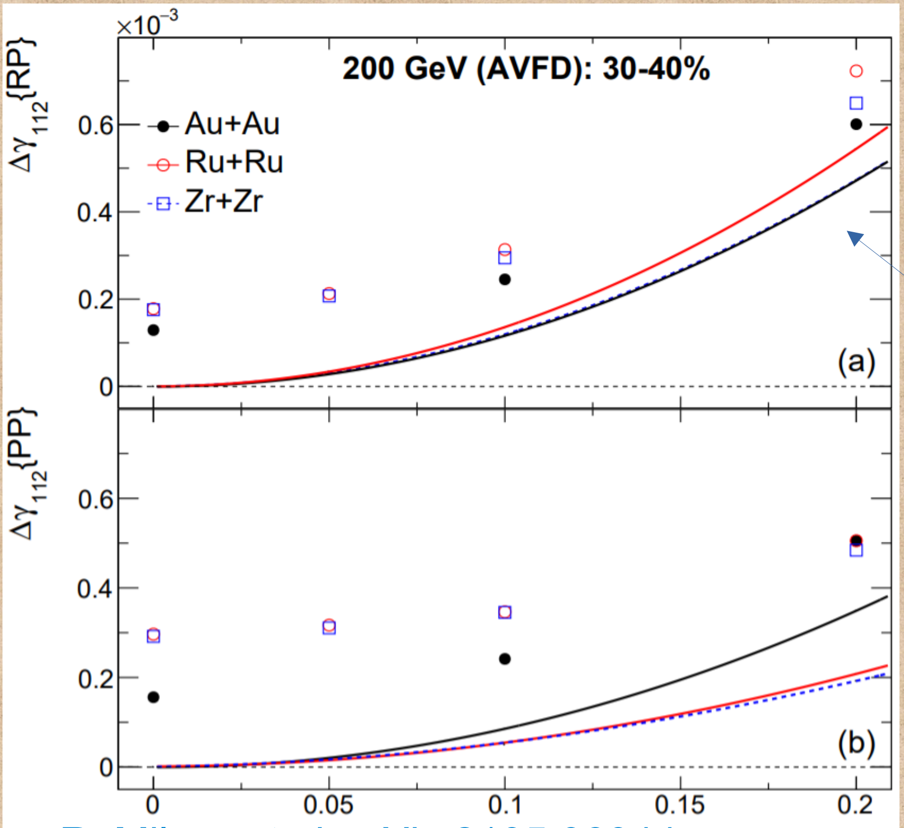
1.0066 for κ_{112} ratio;

~5% for f_{CME}.



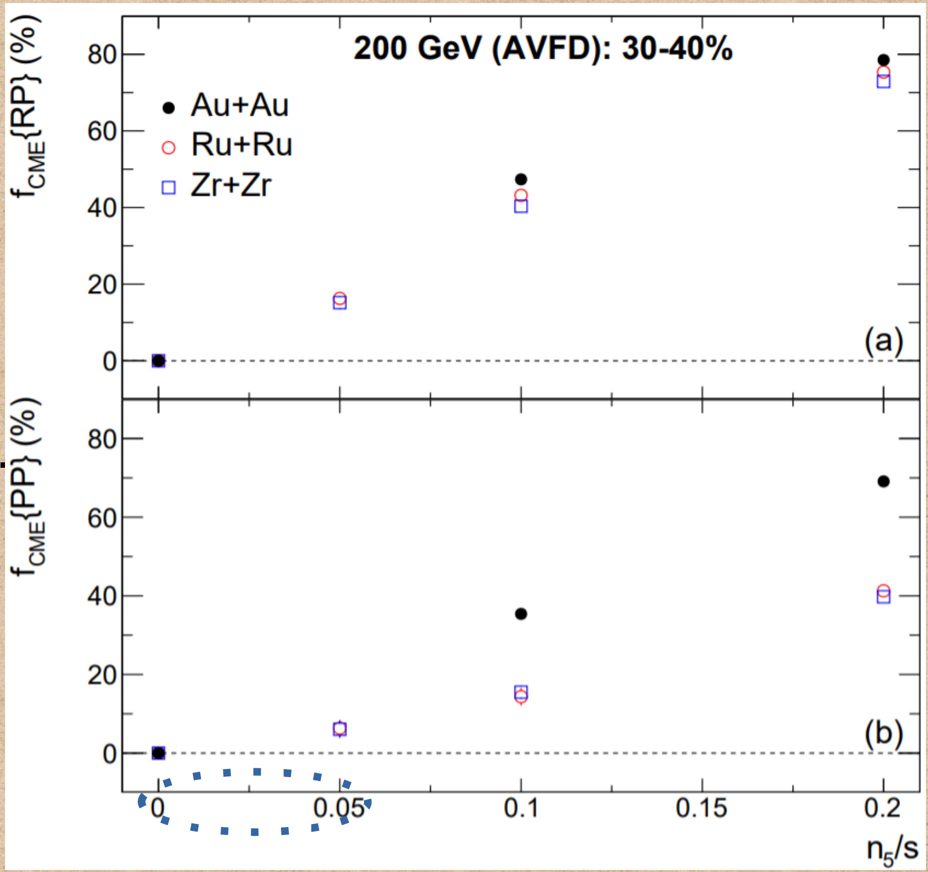
Small interpolation before taking ratios.

Why f_{CME} so low?



R. Milton *et al*, arXiv:2105.06044

Lines are true signals.



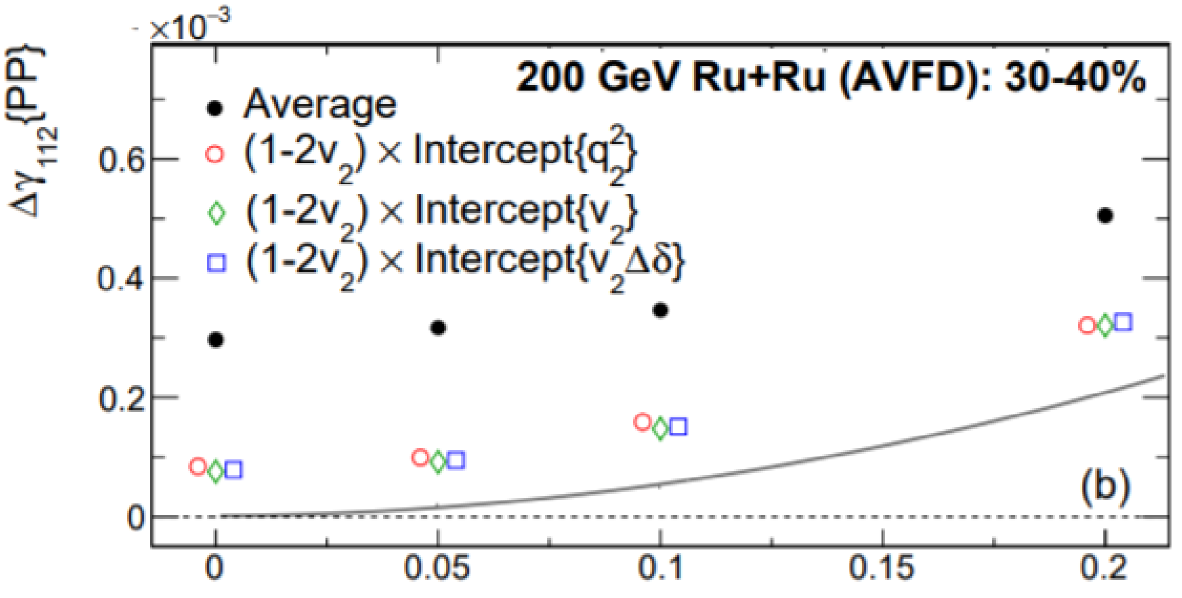
AVFD: f_{CME} is smaller in isobar than Au+Au, especially with participant plane.

smaller system → larger fluctuation → larger BKG & smaller CME signal → lower f_{CME}

Conclusion and outlook

The blind analysis of isobar data was successfully performed.

- Procedures were well documented and strictly followed.
- Good consistency among 5 groups.
- In 20-50% centrality, upper limit (95% CL): 1.0066 for κ_{112} ratio, or roughly 5% for f_{CME}.

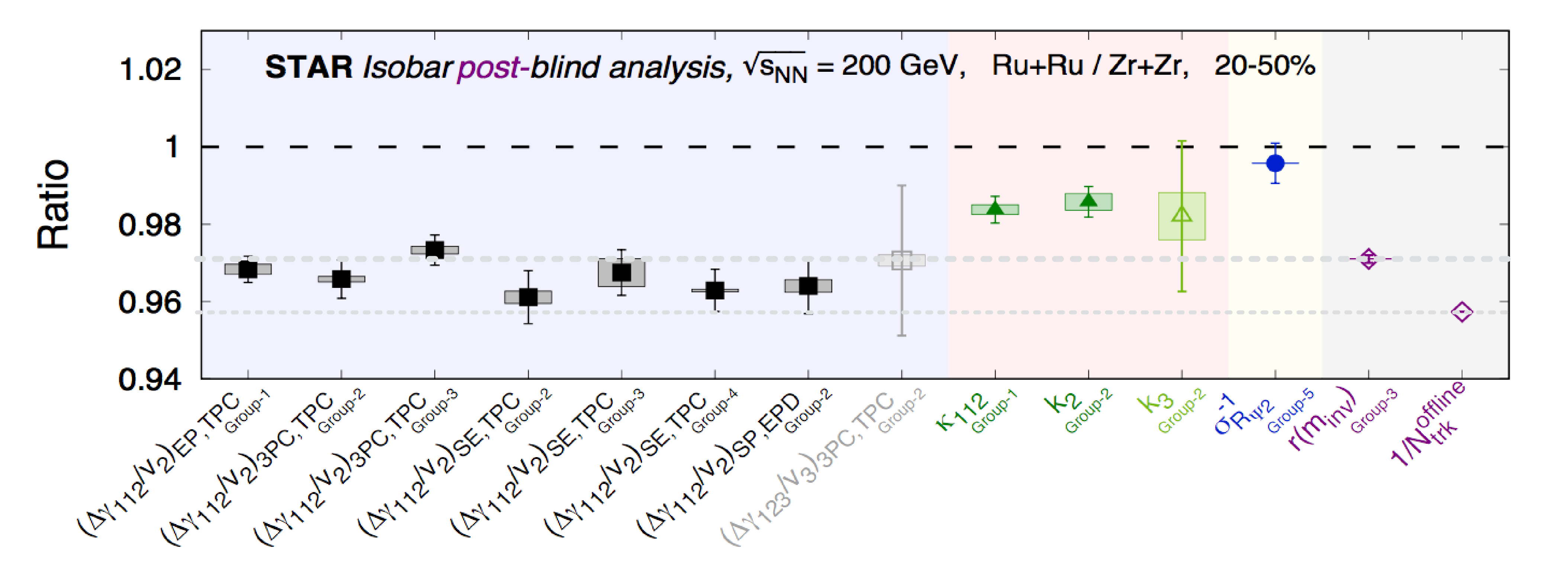


R. Milton *et al*, arXiv:2105.06044

- Multiplicity mismatch is temporarily handled with simple interpolations. Not the best way.
- Should match both v_2 and M.
- Event-shape-engineering could enhance f_{CME} by suppressing BKG.

Backup slides

Post-blinding



Why are ratios of $\Delta\gamma/v_2$ below unity? Better baselines are needed.

Alternative baselines also do not present a clear case for the CME.

Ratios should be taken at the matching multiplicity.