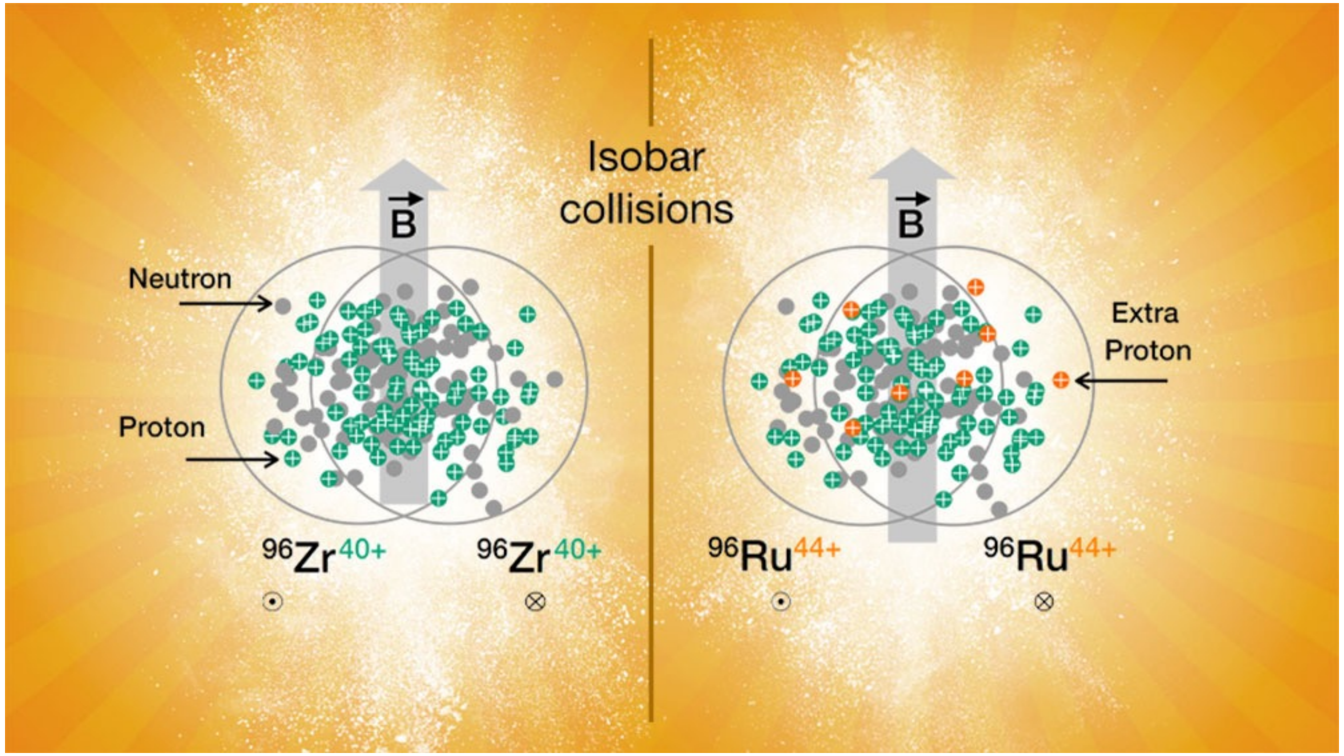
Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC



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Contents of this talk from paper submitted to Phys. Rev. C, arXiv:2109.00131

https://arxiv.org/abs/2109.00131

https://drupal.star.bnl.gov/STAR/publications/search-chiral-magnetic-effect-isobar-collisions-sqrtsnn-200-gev-star-collaboration-rhic

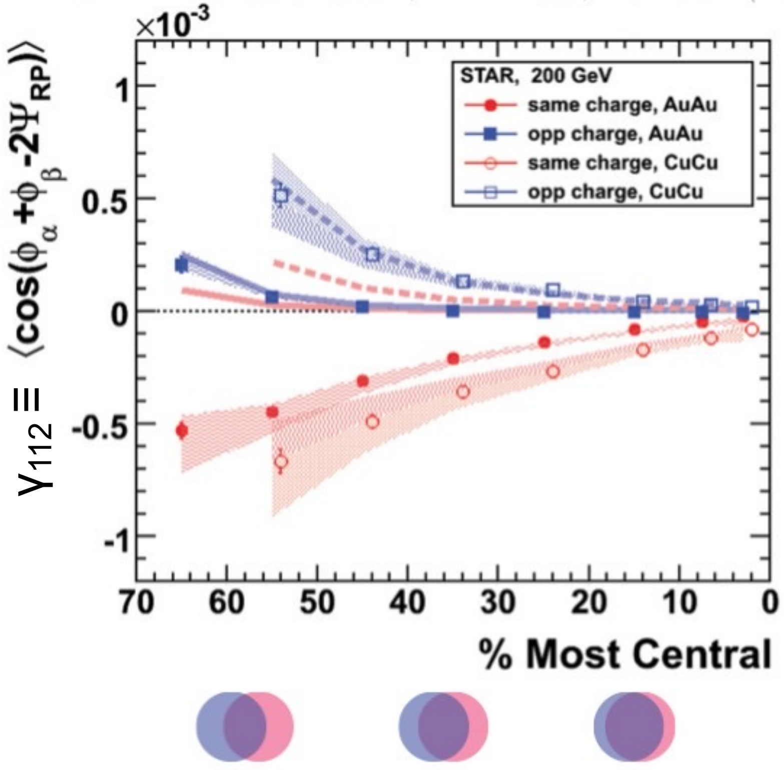
Abstract (beginning only)

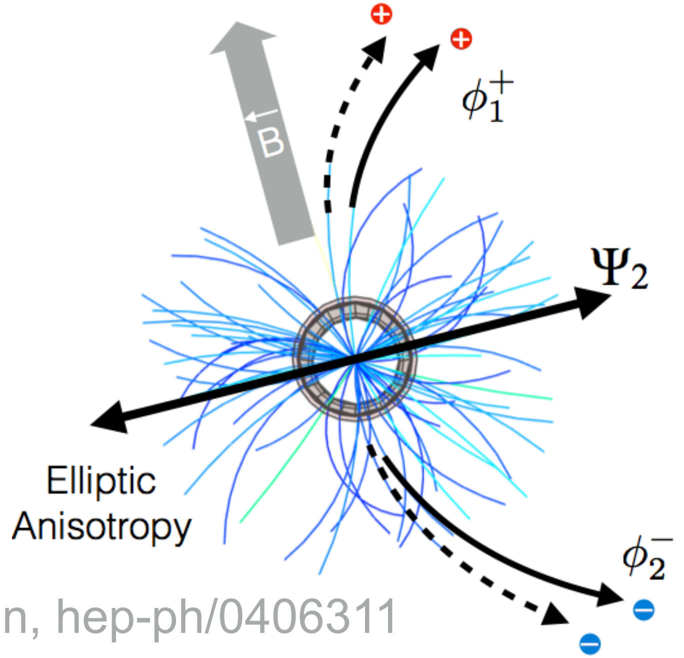
- *The chiral magnetic effect (CME) is predicted to occur as a consequence of a local violation of P and CP symmetries of the strong interaction amidst a strong electro-magnetic field generated in relativistic heavy-ion collisions.*
- *Experimental manifestation of the CME involves a separation of positively 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* $^{96}Ru+^{96}Ru$ *and* $^{96}Zr+^{96}Zr$ *at* $\sqrt{s_{NN}} = 200$ *GeV.*

History 1: the γ correlator

STAR collaboration, PRL 103, 251601 (2009)

$\Delta\gamma_{112} = \gamma_{112}^{\text{Opposite Charge}} - \gamma_{112}^{\text{Same Charge}}$





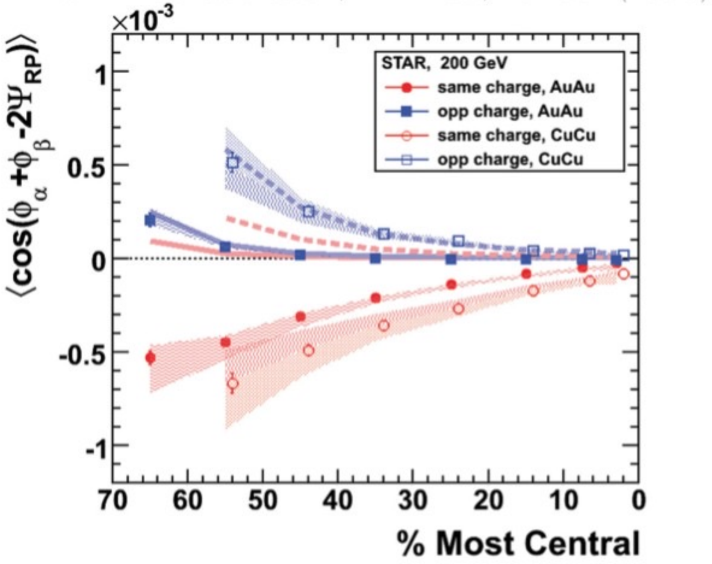
Voloshin, hep-ph/0406311

- Chiral Magnetic Effect will lead to charge imbalance along B field
  - B field aligned perpendicular to second-order reaction plane Ψ_2
- γ correlator: designed to measure charge imbalance across Ψ_2
  - sensitive to the preferential emission of positively and negatively charged particles to the opposite sides of the RP

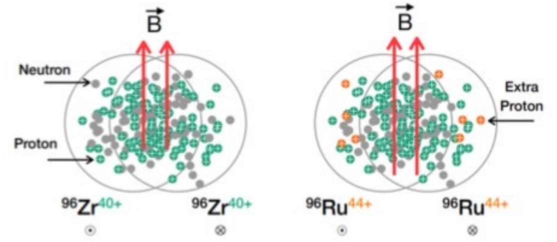
History 2: Backgrounds

First measurements

STAR collaboration, PRL 103, 251601 (2009)



Isobar idea: Change signal while keeping background fixed



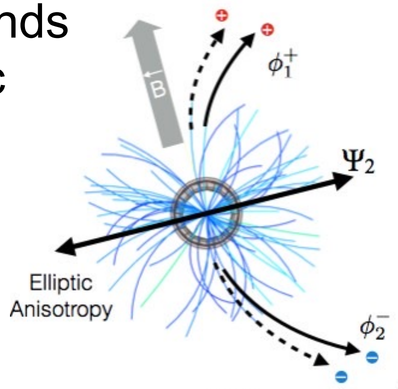
$$\Delta\gamma^{Ru+Ru} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

? $\neq$ $\approx$ $=$

$$\Delta\gamma^{Zr+Zr} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

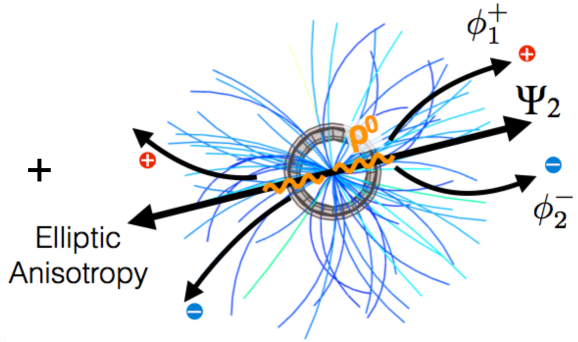
From B-field
10-18% different

Backgrounds can mimic signal

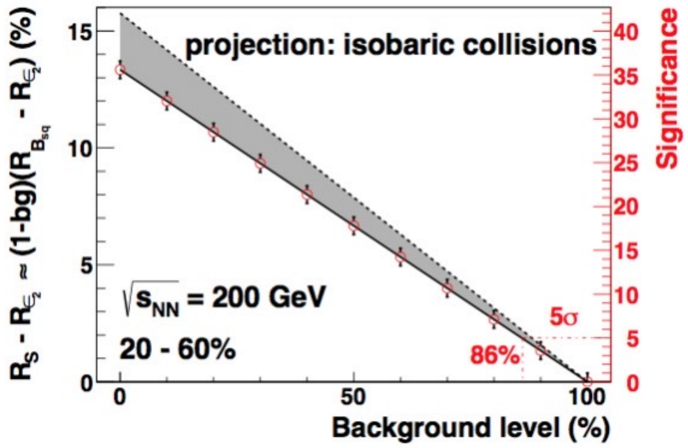


CME

\+



Flow + conservation (non-flow)



2018 Beam Use Request: Would see signal if background contributed up to ~80-85% to measure

Previous measurements of the CME-sensitive charge-separation observables remain inconclusive because of large background contributions.

Precision

Large data set needed to hit small statistical uncertainty target

Systematic uncertainties between species need to be controlled below that level

Special RHIC conditions See G. Marr et al., in 10th International Particle Accelerator Conference (2019) pp. 28–32

1. Alternate the isobar species between each store of beam in RHIC
2. Keep long stores with constant beam luminosity
3. Match luminosities between the species
4. Adjust the luminosity in such a way that the hadronic interaction rate at STAR is close to 10 kHz.

Precision target achieved:

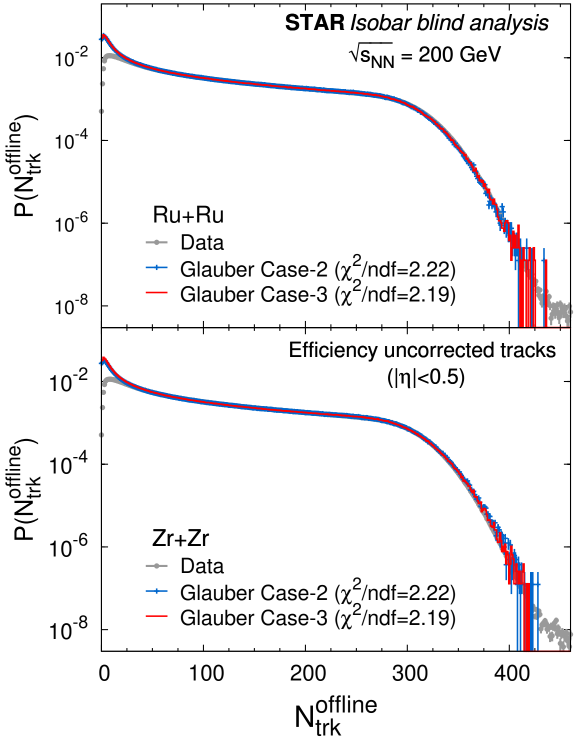
A precision down to 0.4% is achieved, as anticipated, in the relative magnitudes of the pertinent observables between the two isobar systems

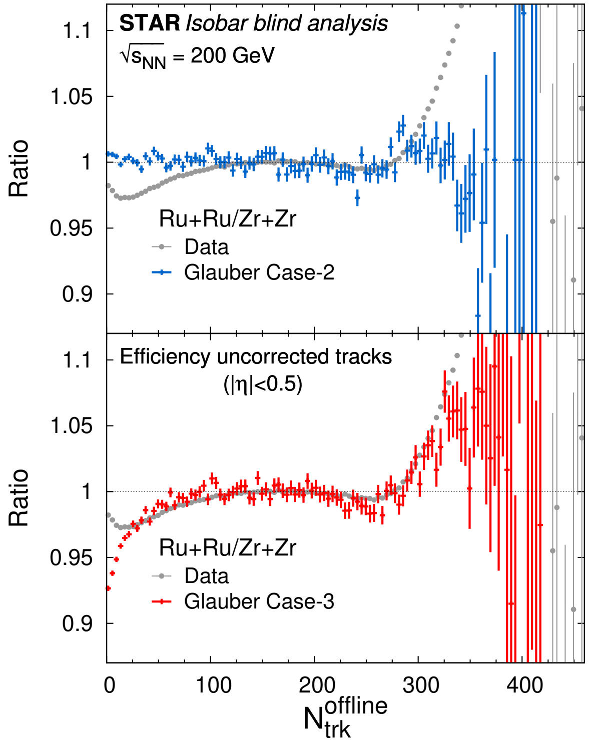
Measurements

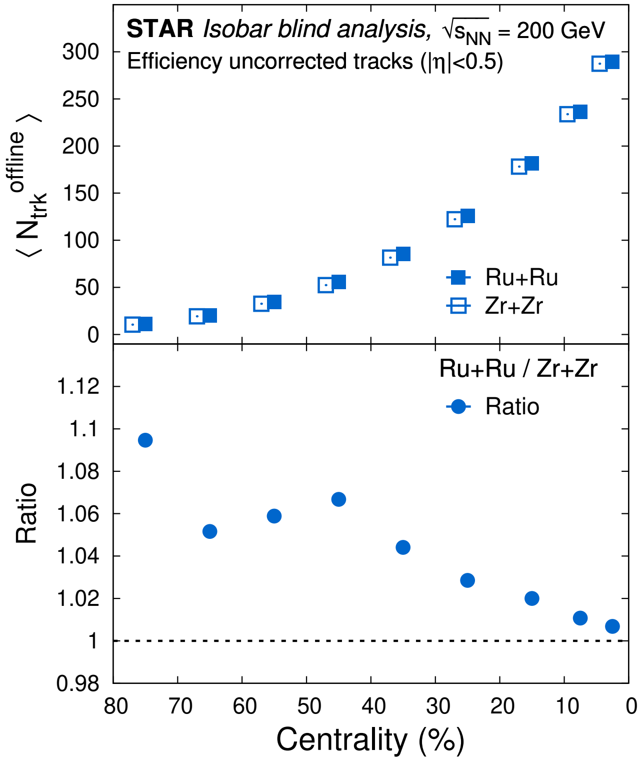
Prior to the blind analysis, the CME signatures are predefined as a significant excess of the CME-sensitive observables in Ru+Ru collisions over those in Zr+Zr collisions, owing to a larger magnetic field in the former.

- Five institutional groups within the collaboration perform blind analyses of the isobar data
  - Each group focuses on a specific analysis method
  - Substantial overlap of some analyses helps to cross-check results
  - All analyses have a common set of variations for the purpose of systematic uncertainty determination
  - Because of different detector requirements, set of common and analysis-specific QA variables for data QA and selection of regions of the data sample with stable detector performance
- For each observable/approach, we pre-define a set of the CME signatures prior to the blind analysis, for which high significance (5σ) must be observed for an affirmative observation of the CME.

Centrality





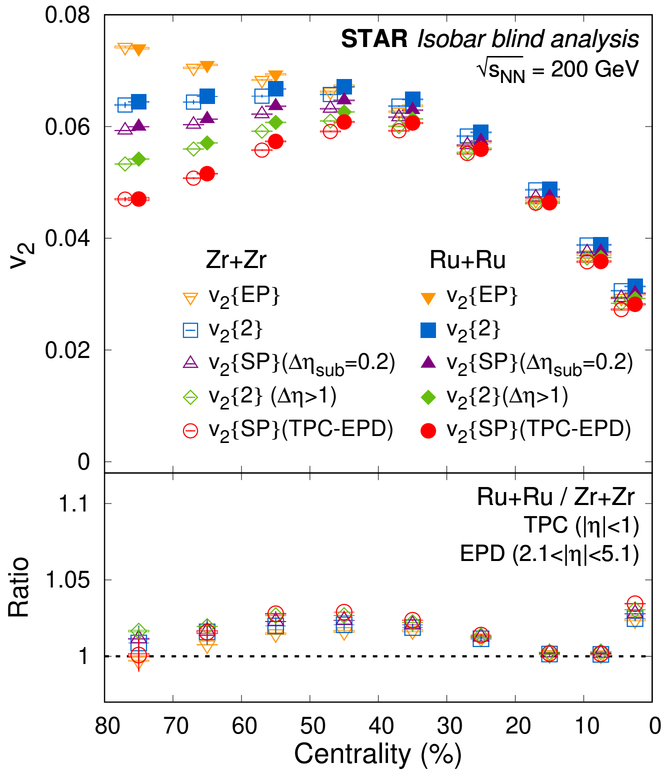


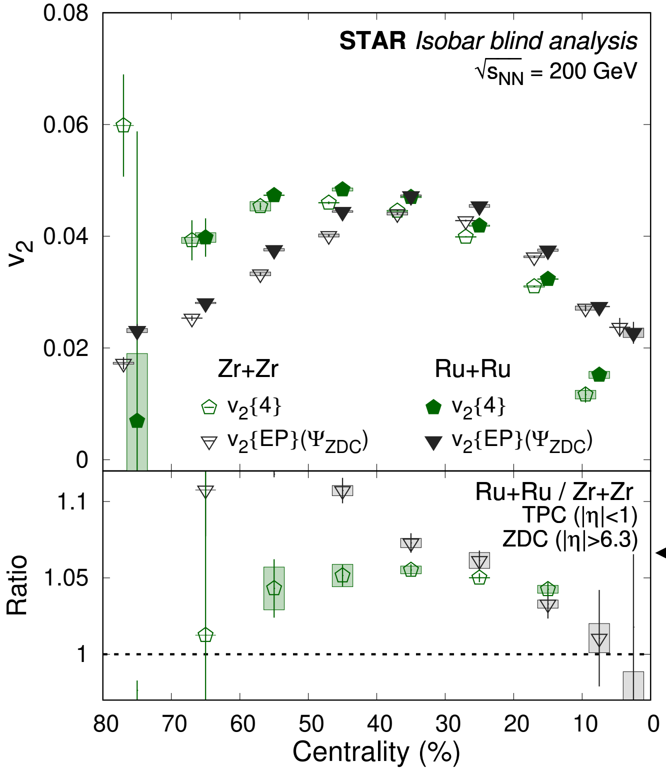
- 3 sets of Woods-Saxon parameters from the literature investigated
  - Fit to multiplicity distributions using two-component nucleon-based Monte Carlo Glauber
  - Best fit from Case 3: different neutron skin, but no quadrupole moments
  - Potential for further improvement
    - Adjust WS parameters, better treatment of integers N, different treatment of sub-nucleon fluctuations

	Case-1 [83]			Case-2 [83]			Case-3 [113]		
Nucleus	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2	R (fm)	a (fm)	β_2
$^{96}_{44}$Ru	5.085	0.46	0.158	5.085	0.46	0.053	5.067	0.500	0
$^{96}_{40}$Zr	5.02	0.46	0.08	5.02	0.46	0.217	4.965	0.556	0

- Result: Difference in multiplicity between isobars at matching centrality

Flow harmonic v_2





- As expected, different methods result in different v_2 for both Ru and Zr
  - Potentially pseudorapidity dependence of non-flow, de-correlation and flow fluctuations
- Ratios fall on a common curve
  - Except, notably, $v_2\{4\}$ and $v_2(\Psi_{ZDC})$
- Differences between Ru and Zr at the multiple % level

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.

RESULTS

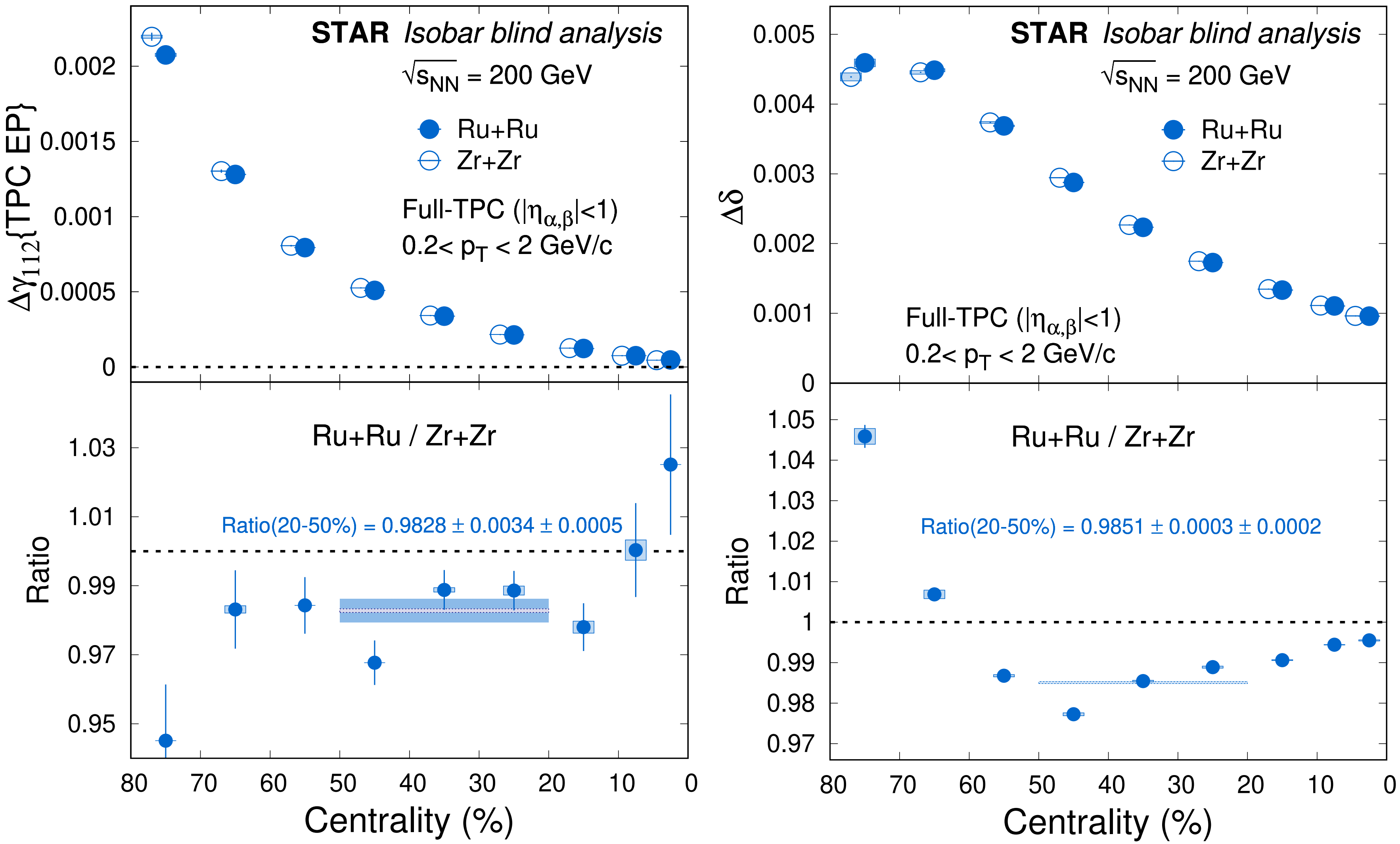
Precision

$\gamma_{112}\{\mathrm{EP}\} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2^{\mathrm{TPC}}) \rangle$

$\Delta\gamma = \gamma_{112}(OS) - \gamma_{112}(SS)$

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

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

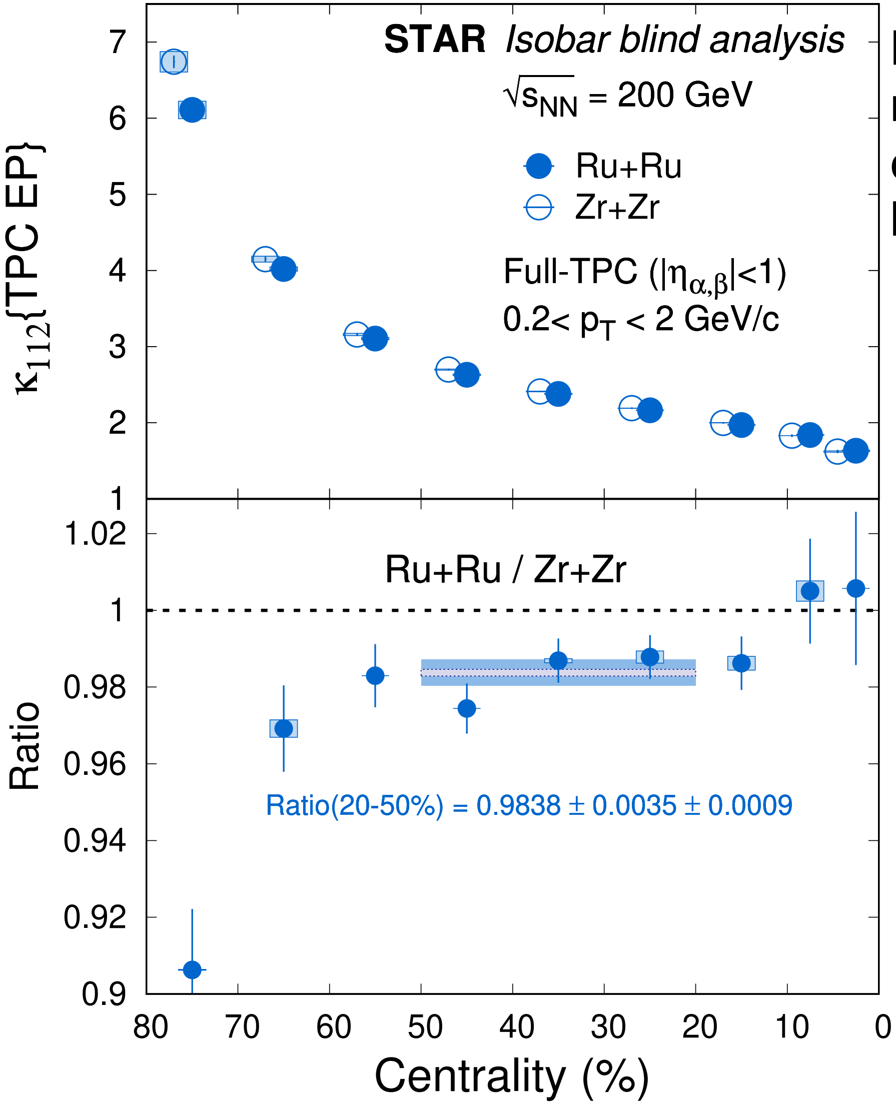


Group 1: Focus on full TPC event plane to maximize statistical precision

- Tested: Ratios insensitive to short-range correlations

Anticipated precision down to 0.4% achieved

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



Normalization by v_2 and $\Delta\delta$ motivated by structure of coupling of v_2 and $\Delta\delta$ in background contributions

Predefined CME signature:

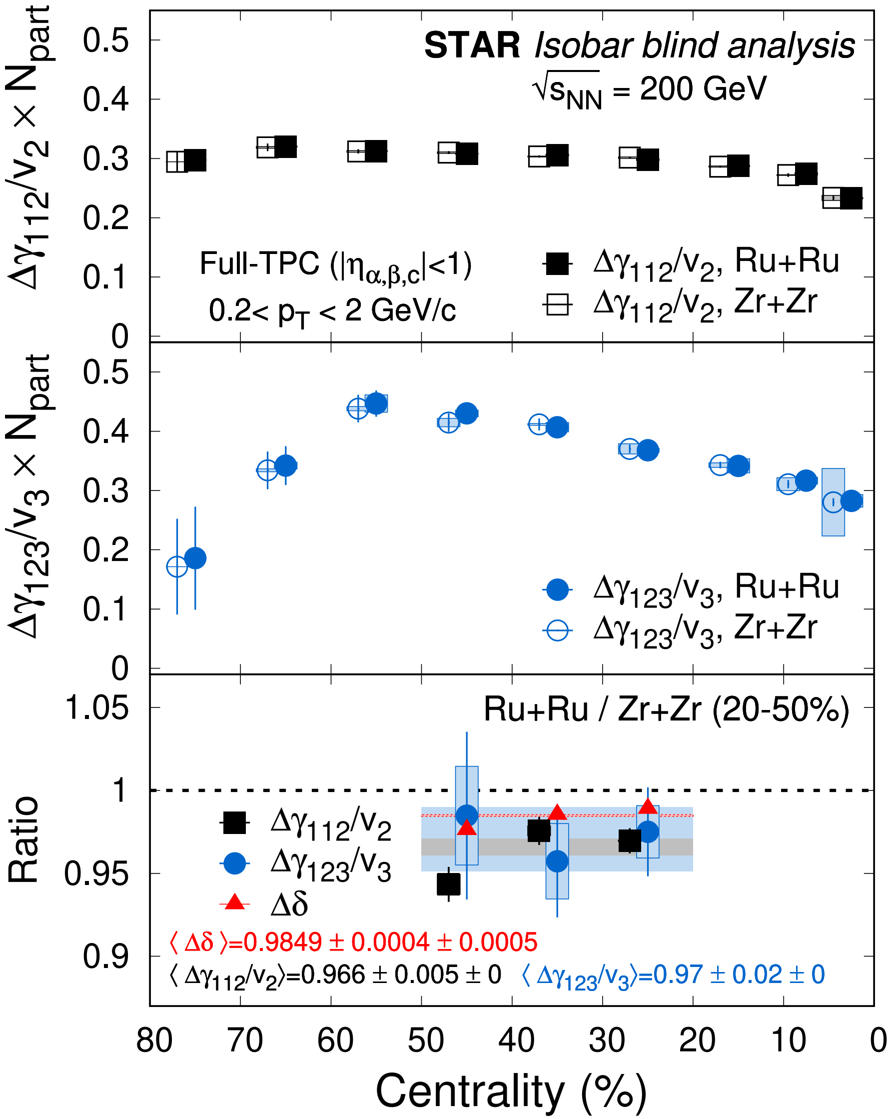
$$\frac{\kappa_{112}^{\mathrm{Ru+Ru}}}{\kappa_{112}^{\mathrm{Zr+Zr}}} > 1.$$

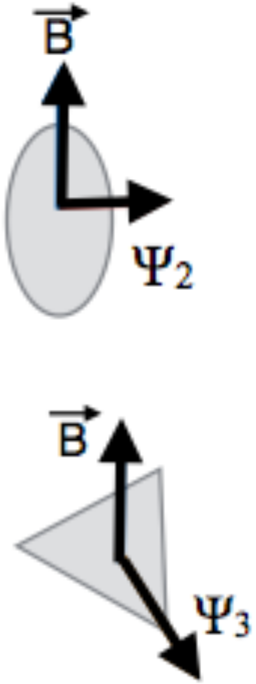
Not seen

No CME signature that satisfies the predefined criteria observed

Group 2: Mixed Harmonics (Full TPC)

$$\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$$





3[rd] order Event Plane not correlated with Magnetic Field

Predefined CME signature:

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > 1\,,$$

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\gamma_{123}/v_3)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{123}/v_3)^{\mathrm{Zr+Zr}}}\,,$$

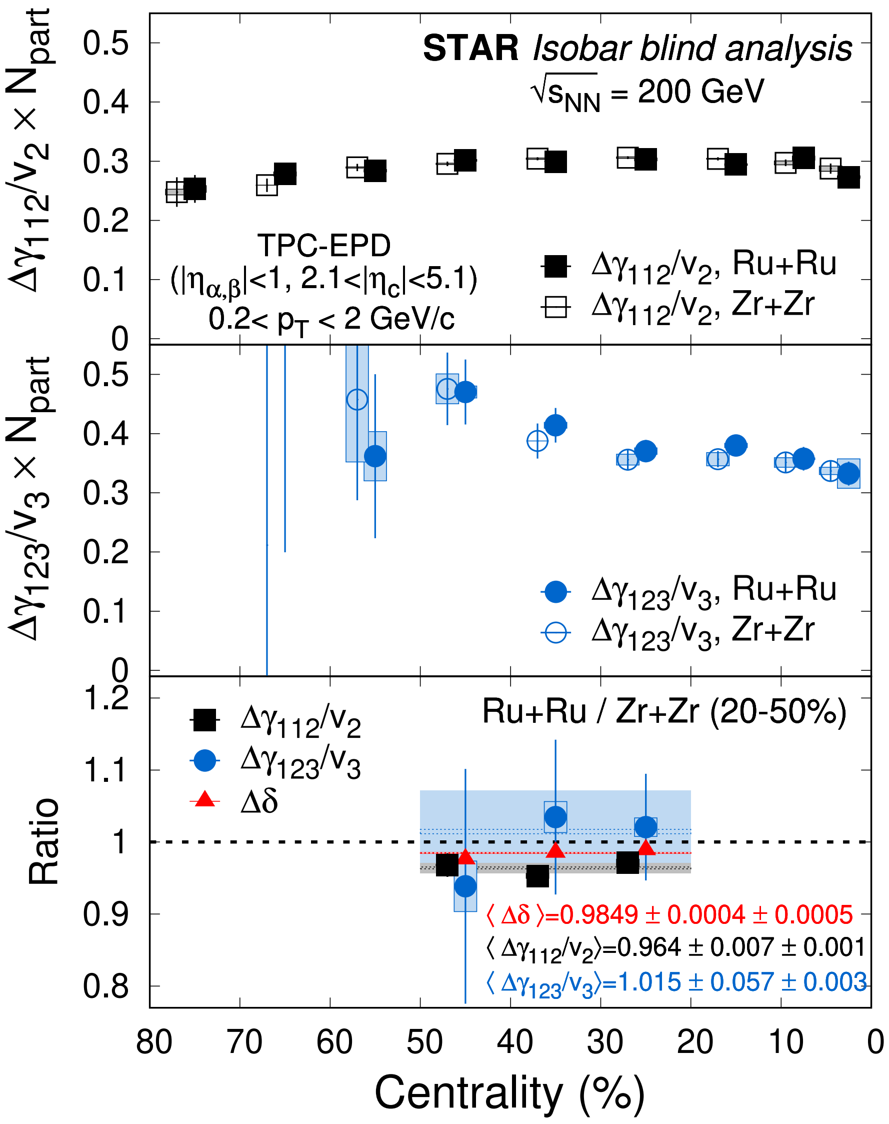
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\delta)^{\mathrm{Ru+Ru}}}{(\Delta\delta)^{\mathrm{Zr+Zr}}}\,.$$

Not seen

No CME signature that satisfies the predefined criteria observed

Group 2: Mixed Harmonics (TPC-EPD)

$\gamma_{123} \equiv \langle\cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3)\rangle$



EPD provides large pseudorapidity difference between charged particles and Event Planes

Predefined CME signature:

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > 1\,,$$

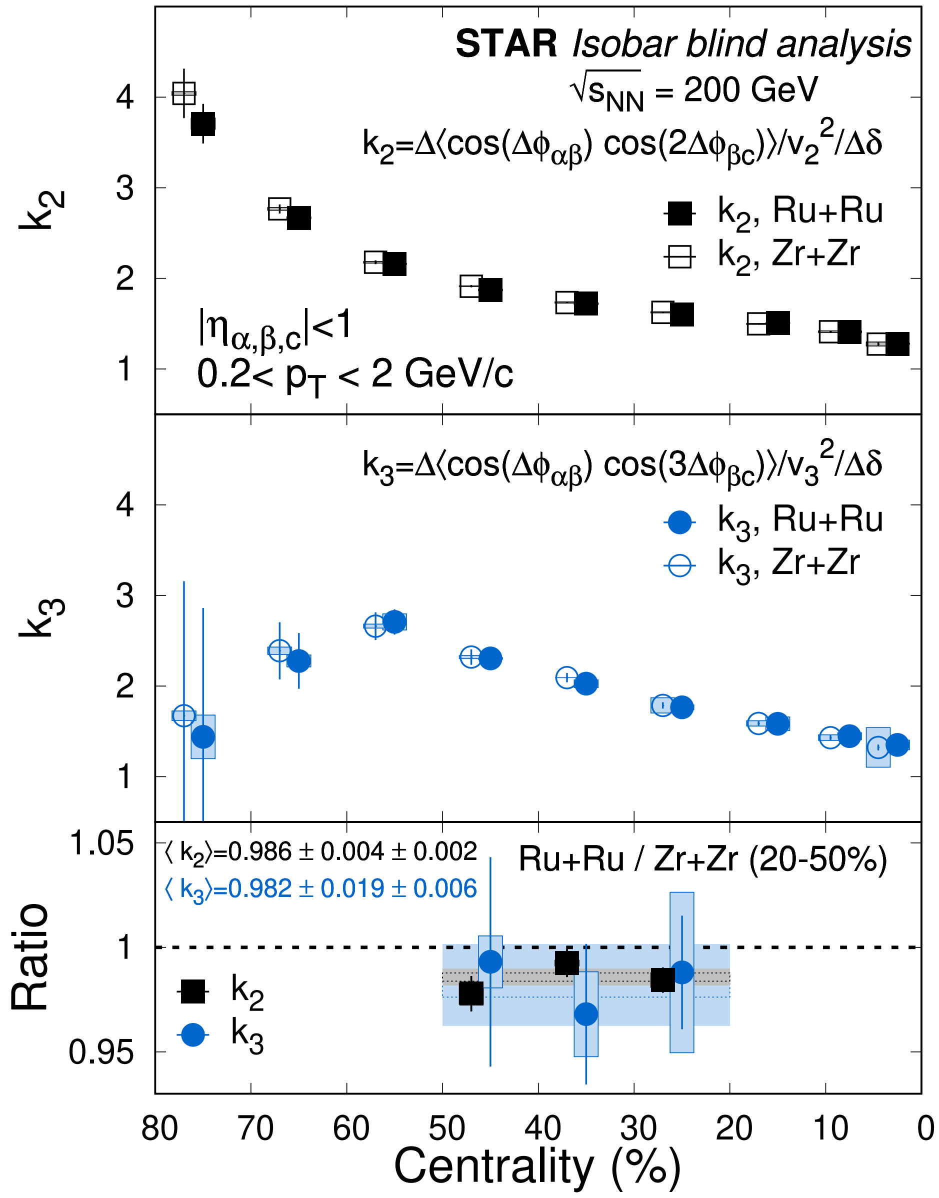
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\gamma_{123}/v_3)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{123}/v_3)^{\mathrm{Zr+Zr}}}\,,$$

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\delta)^{\mathrm{Ru+Ru}}}{(\Delta\delta)^{\mathrm{Zr+Zr}}}\,.$$

Not seen

No CME signature that satisfies the predefined criteria observed

Group 2: Factorization Breaking Measure



$$k_n = \frac{\Delta\langle\cos(\Delta\phi_{\alpha\beta})\cos(n\Delta\phi_{\beta c})\rangle}{v_n^2\{2\}\Delta\delta_{\alpha\beta}}$$

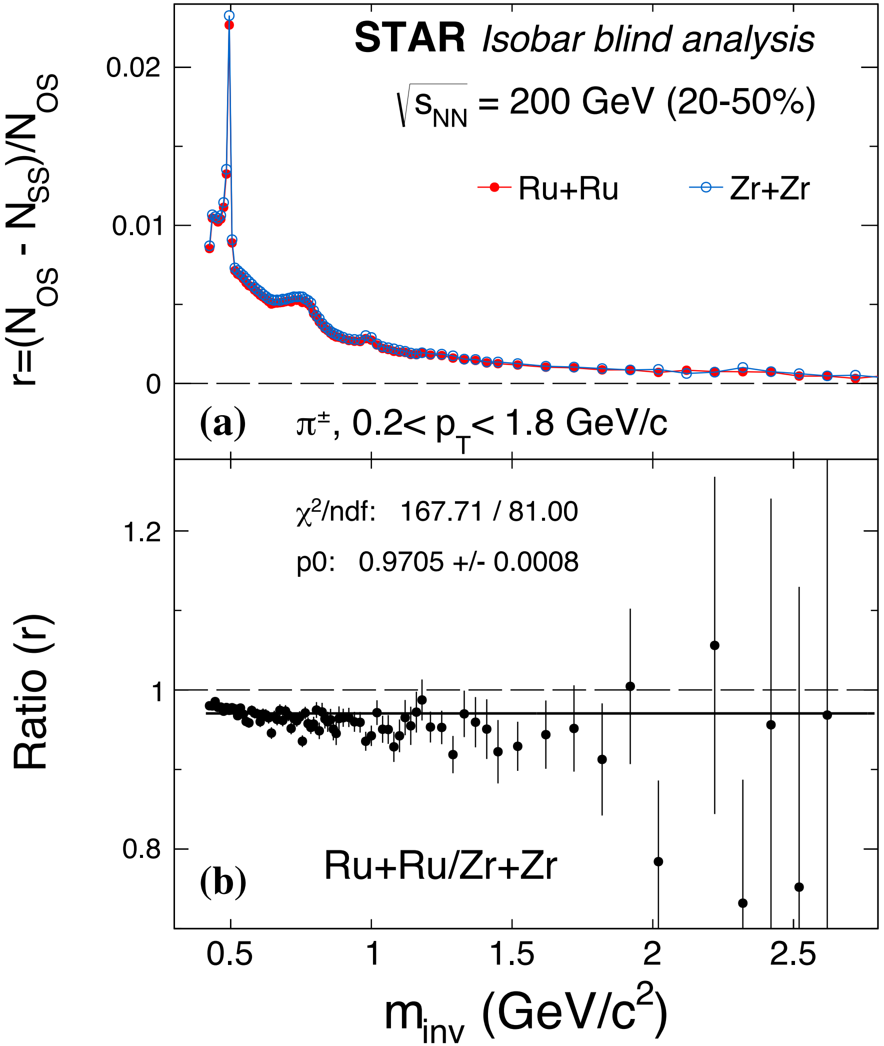
Predefined CME signature:

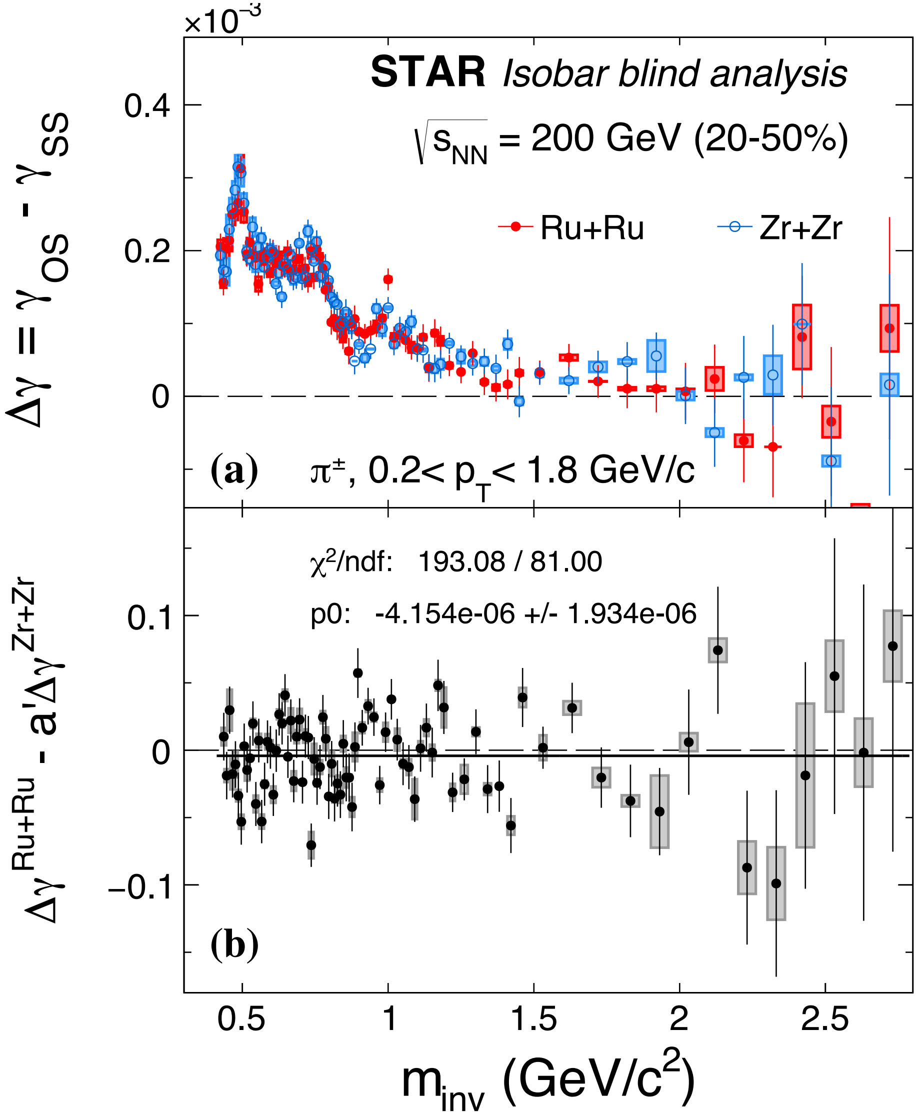
$$\frac{k_2^{\mathrm{Ru+Ru}}}{k_2^{\mathrm{Zr+Zr}}} > \frac{k_3^{\mathrm{Ru+Ru}}}{k_3^{\mathrm{Zr+Zr}}}.$$

Not seen

No CME signature that satisfies the predefined criteria observed

Group 3: Differential in m_{inv}





$$a' = v_2^{\mathrm{Ru+Ru}} / v_2^{\mathrm{Zr+Zr}}$$

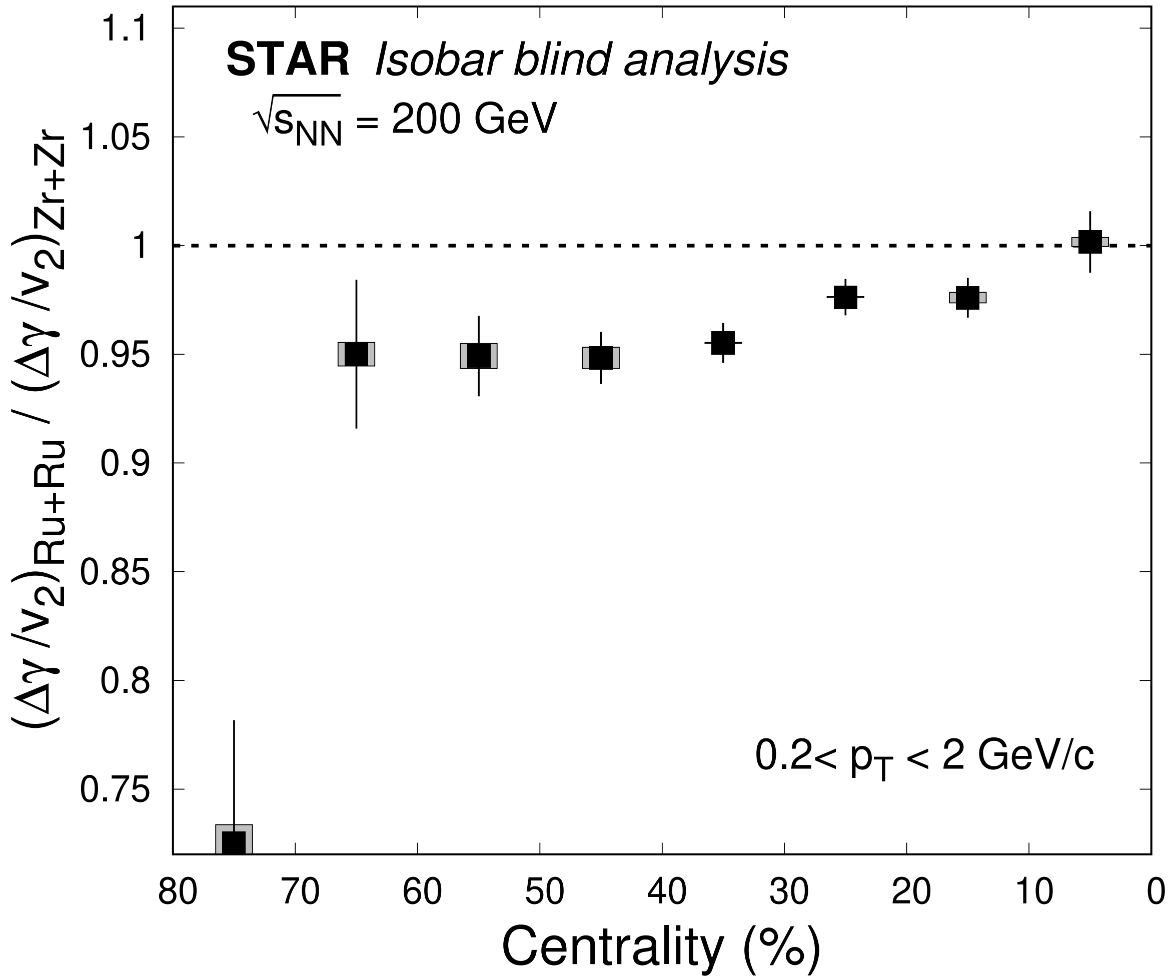
Predefined CME signature:

$$\Delta\gamma^{\mathrm{Ru+Ru}} - a'\Delta\gamma^{\mathrm{Zr+Zr}} > 0 \,.$$

Not seen

No CME signature that satisfies the predefined criteria observed

Group 4: Double ratio



Direct calculation cancels resolution and reduces systematics

$$(\Delta\gamma/v_2)_{\mathrm{TPC}} = \frac{\Delta\langle\cos(\phi_\alpha + \phi_\beta - 2\phi_c)\rangle}{\langle\cos(2\phi_\alpha - 2\phi_c)\rangle}$$

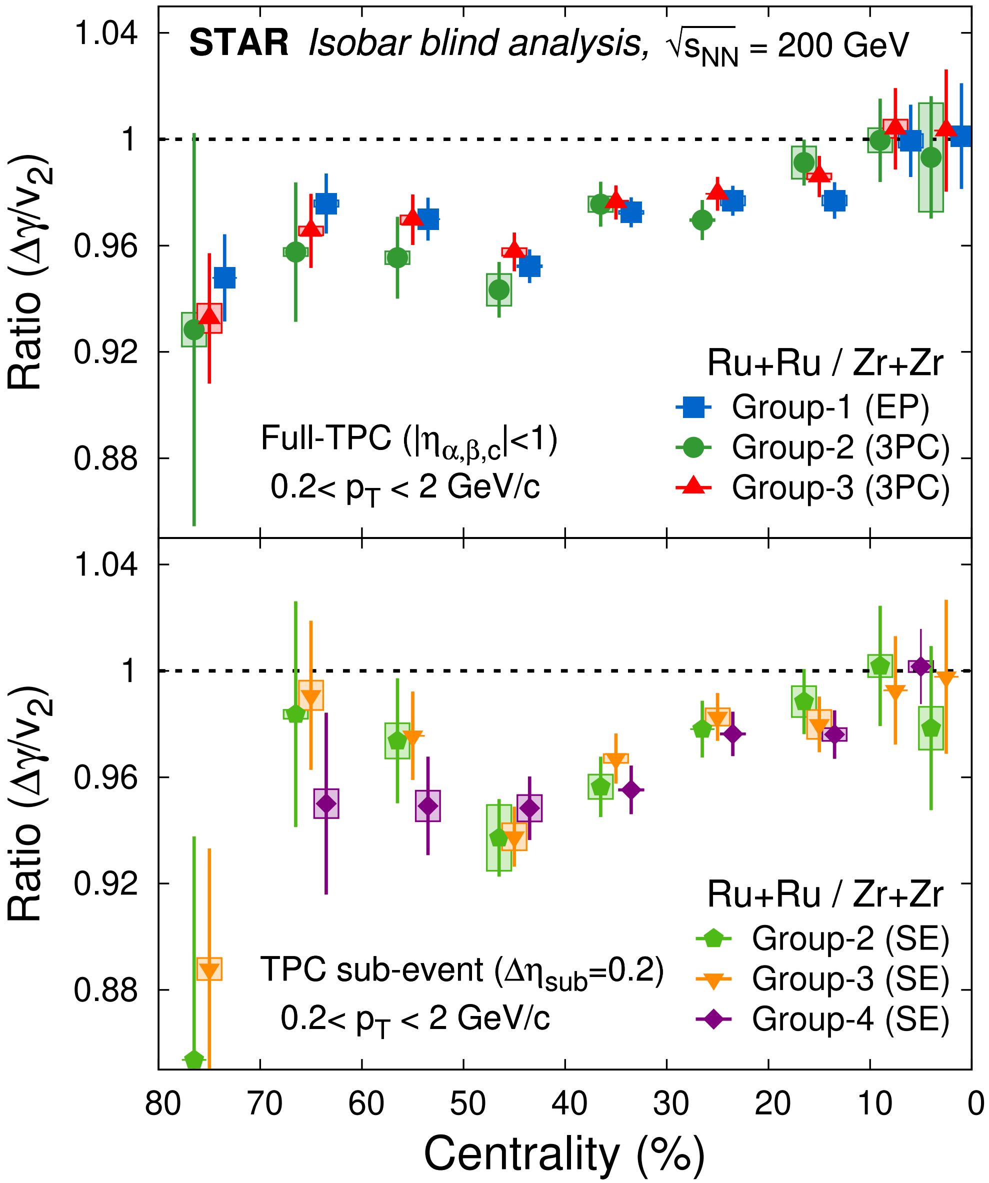
Predefined CME signature:

$$\frac{(\Delta\gamma_{112}/v_2)^{RuRu}}{(\Delta\gamma_{112}/v_2)^{ZrZr}} > 1$$

Not seen

No CME signature that satisfies the predefined criteria observed

Groups 1-4: Consistency of results



- Measurements of similar quantities consistent
  - Statistical uncertainties largely, but not completely, correlated among different groups
  - Results are not identical because of analysis-specific event selection criteria and slightly different methods
  - Verified results consistent within the statistical fluctuations due to those differences

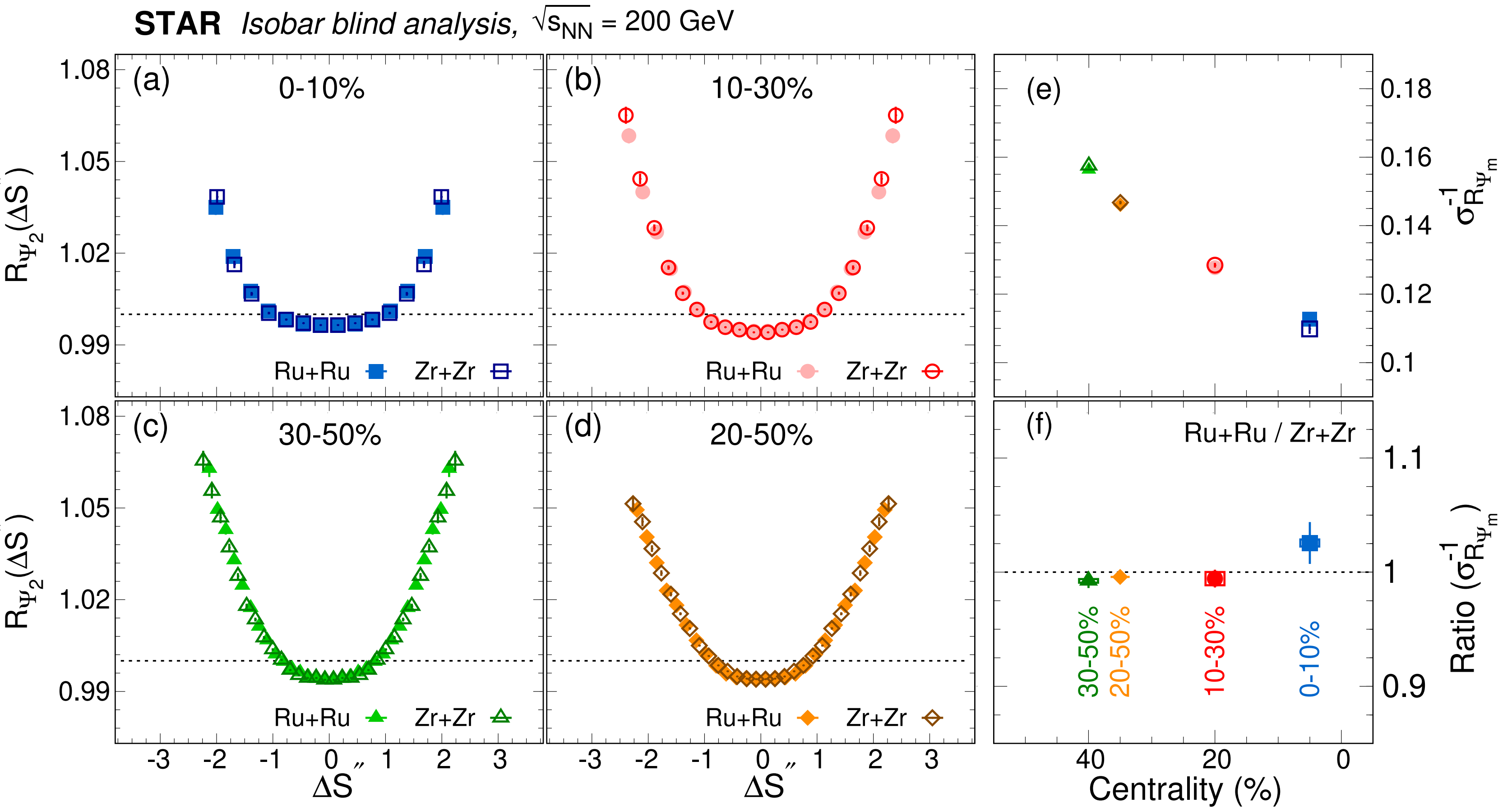
Predefined CME signature:

$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > 1$$

Not seen

No CME signature that satisfies the predefined criteria observed

Group 5: R Variable



$$R_{\Psi_2}(\Delta S) = C_{\Psi_2}(\Delta S)/C^{\perp}_{\Psi_2}(\Delta S),$$

$$C_{\Psi_2}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)},$$

$$\Delta S = \frac{\sum_1^{n^+} w_i^+ \sin(\Delta\varphi_2)}{\sum_1^{n^+} w_i^+} - \frac{\sum_1^{n^-} w_i^- \sin(\Delta\varphi_2)}{\sum_1^{n^-} w_i^-},$$

Predefined CME signature:

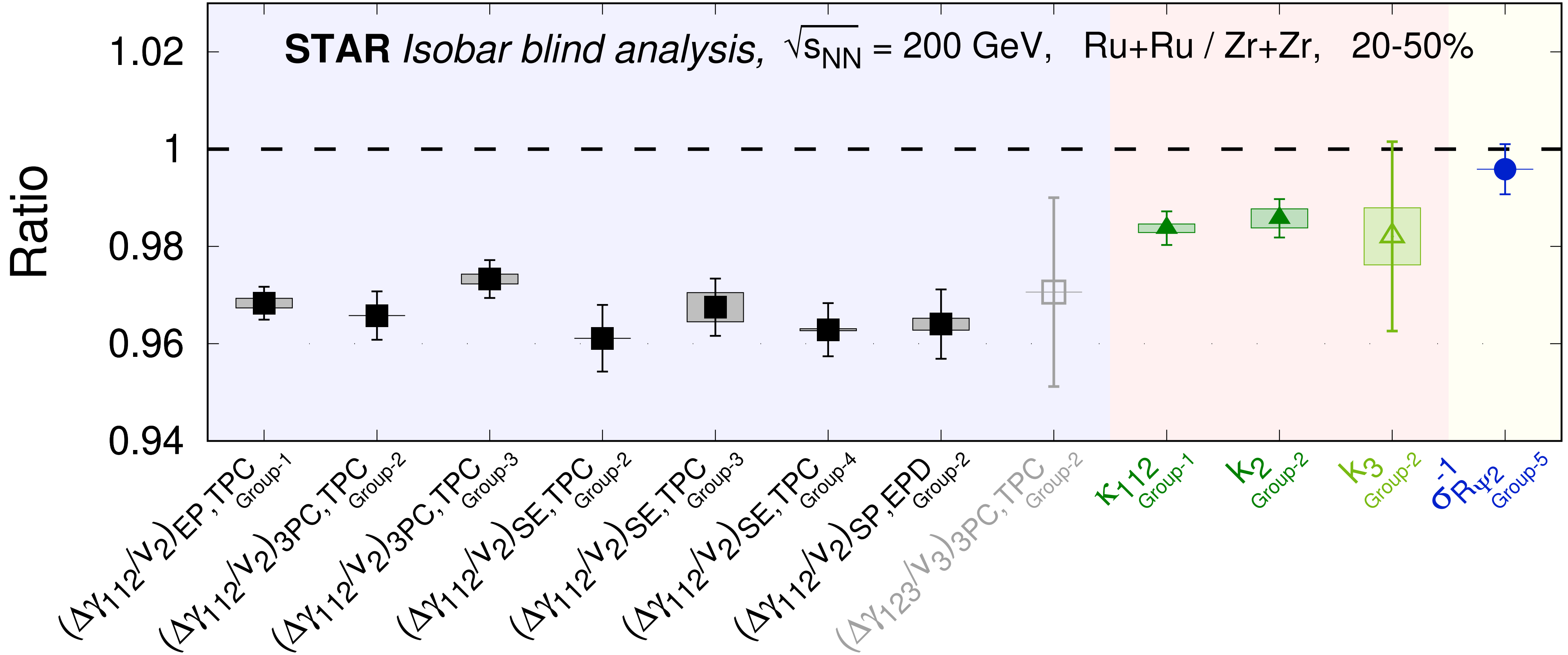
$$1/\sigma_{R_{\Psi_2}}(\mathrm{Ru+Ru}) > 1/\sigma_{R_{\Psi_2}}(\mathrm{Zr+Zr})$$

Not seen

No CME signature that satisfies the predefined criteria observed

Compilation of results

Predefined CME signatures: ratios involving Ψ_2 > those involving Ψ_3 , and > 1



Not Seen

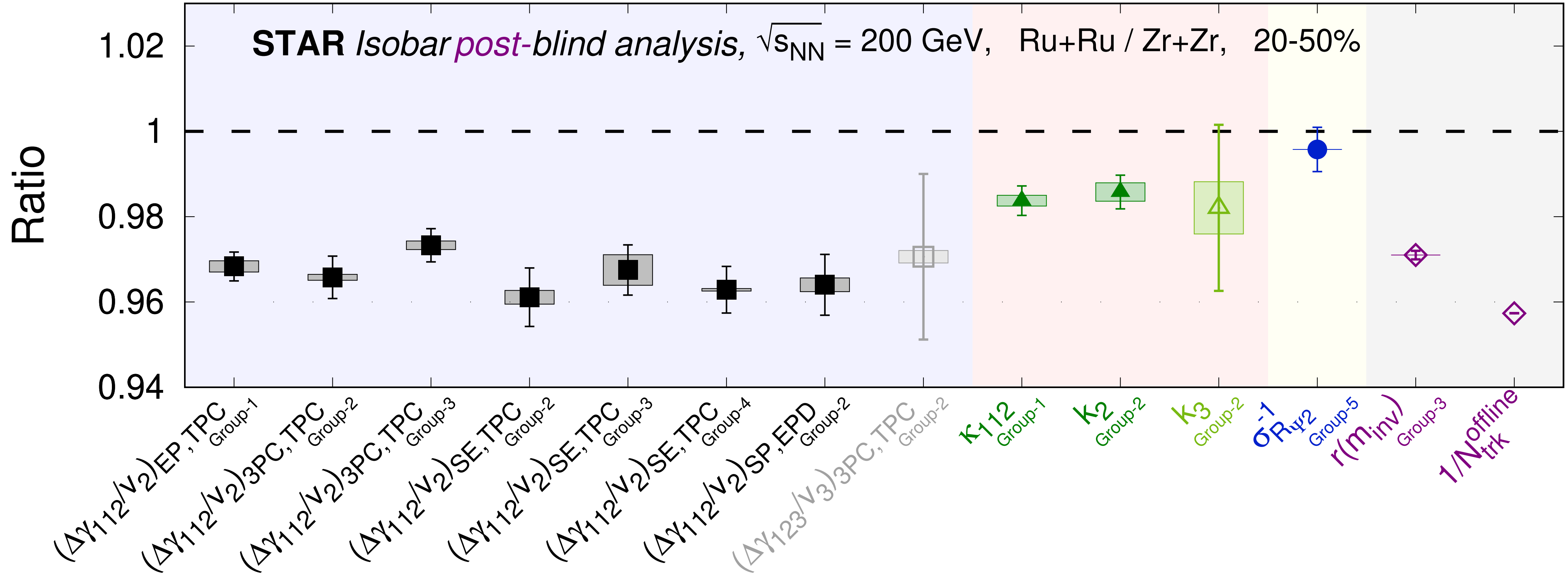
No CME signature that satisfies the predefined criteria observed

Note: other measurements in paper that I don't have time to show in this talk (spectator-participant analysis for CME signal fraction, Δη dependence of correlations, …): All come to this conclusion

Conclusion

- We report an experimental test of the CME by a blind analysis of a large statistics data set of isobar $^{96}Ru+^{96}Ru$ and $^{96}Zr+^{96}Zr$ collisions at nucleon-nucleon center-of-mass energy of 200 GeV, taken in 2018 by the STAR collaboration at RHIC.
- The backgrounds are reduced using the difference in observables between the two isobar collision systems.
- The criteria for a positive CME observation are predefined, prior to the blind analysis, as a significant excess of the CME-sensitive observables in Ru+Ru collisions over those in Zr+Zr collisions.
- Consistent results are obtained by the five independent groups in this blind analysis.
- A precision down to 0.4% is achieved, as anticipated, in the relative magnitudes of 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 pre-defined criteria has been observed in isobar collisions in this blind analysis

Post Blinding Considerations



- Baseline against which to compare as documented in the blind analysis was unity
- Proper baseline for $(\Delta\gamma/v_2)$ may be the ratio of inverse multiplicities, or as an alternative r

The observed multiplicity difference between the isobars requires future CME analyses to better understand the baselines in order to best utilize the precision demonstrated in this analysis.

Acknowledgements

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