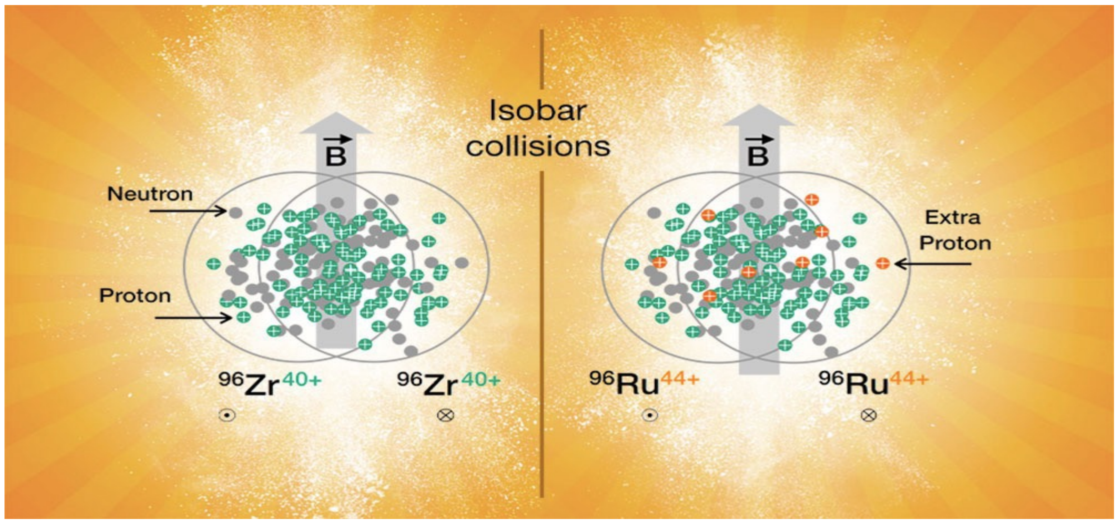
THE UNIVERSITY OF ILLINOIS AT CHICAGO

STAR

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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U.S. DEPARTMENT OF ENERGY | Office of Science

❖ Introduction

➢ Chiral Magnetic Effect (CME)

Electric Current

Chiral Magnetic Conductivity

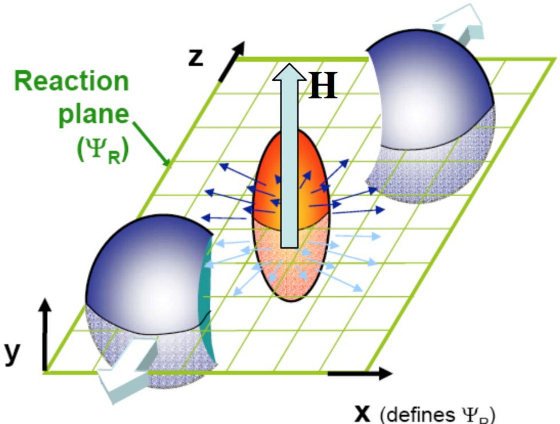
Chiral Chemical potential

$$\vec{J}_Q = \sigma_5 \vec{B}$$

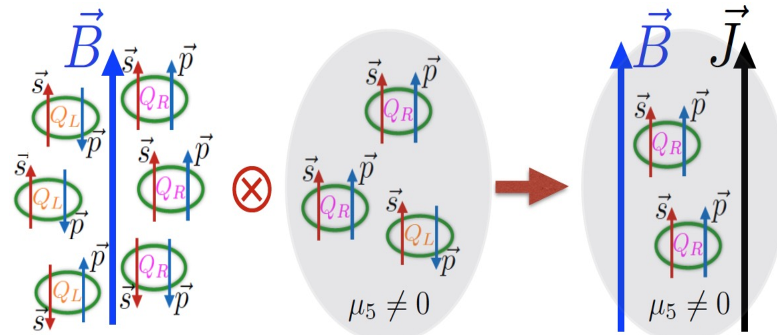
$$\sigma_5 = C_A \mu_5$$

Kharzeev
hep-ph/0406125

$$C_A = Q^2 / (4\pi^2)$$



D.E. Kharzeev
Prog.Part.Nucl.Phys. 75 (2014) 133-151



D.E. Kharzeev et al.
Prog.Part.Nucl.Phys. 88 (2016) 1-28

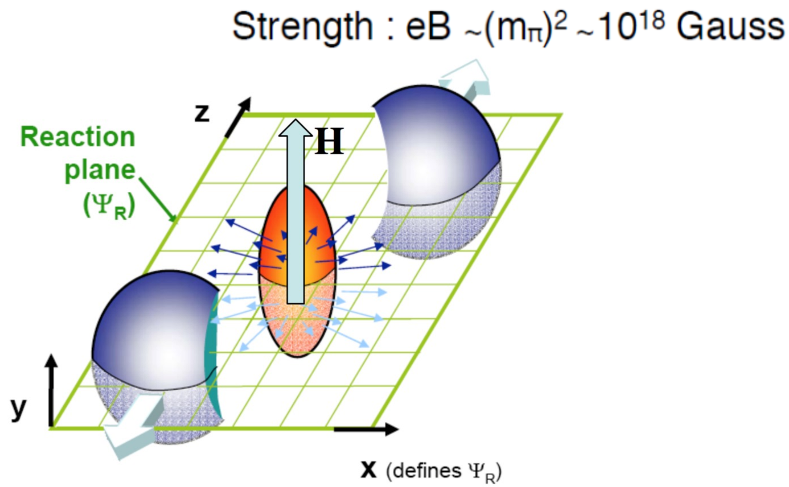
- ➢ In non-central collisions a strong magnetic field is created ⊥ to Ψ_{RP}

- ➢ Magnetic field acts on the chiral fermions with $\mu_5 \neq 0$ leading to an electric current along the magnetic field which results in a charge separation

❖ Introduction

➢ Chiral Magnetic Effect (CME)

D.E. Kharzeev
Prog.Part.Nucl.Phys. 75 (2014) 133-151



CME-driven charge separation leads to a dipole term in the azimuthal distribution of the produced charged hadrons:

$$\frac{dN^{ch}}{d\phi} \propto 1 \pm 2\, a_1^{ch} \sin(\phi) + \cdots \qquad\qquad a_1^{ch} \propto \mu_5 \vec{B}$$

Can we identify & characterize this dipole moment?

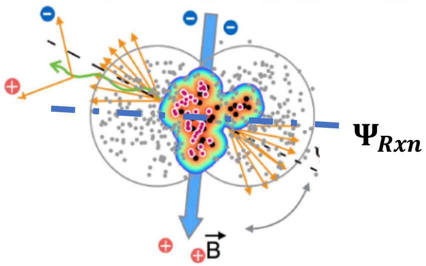
The CME correlators, have been used extensively for experimental measurements.

Introduction

Correlators to measure dipole charge separation

A well-known approach is to use the γ correlator to measure the dipole charge separation

$$\gamma^{a,b} = \langle \cos(\phi_1^{a} + \phi_2^{b} - 2\Psi_2) \rangle$$



Voloshin, PRC 70 (2004) 057901

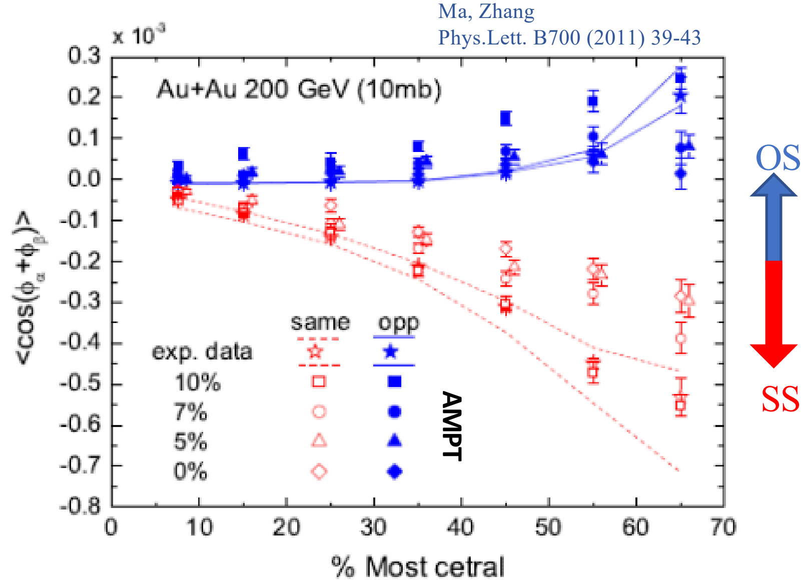
$$\gamma^{\alpha,\beta} = -\langle a_\alpha a_\beta \rangle + \boxed{c\,\frac{v_2}{N}}$$

background

The background complicates signal extraction

STAR Collaboration
Phys.Rev.C 81 (2010) 054908

Ma, Zhang
Phys.Lett. B700 (2011) 39-43



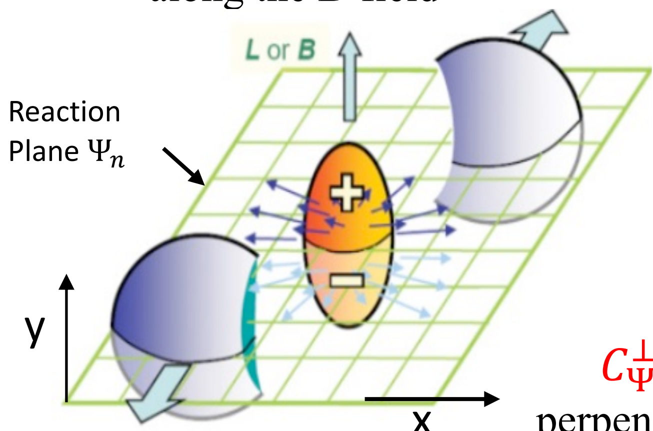
- Background can account for a sizeable part of the observed charge separation

❖ Introduction

➢ Correlators to measure dipole charge separation

The $R_{\Psi_m}(\Delta S)$ correlator is constructed for a given event plane Ψ_m via a ratio of two correlation functions

$C_{\Psi_2}(\Delta S)$ quantifies charge separation along the B-field



m = 2,3

$$R_{\Psi_m}(\Delta S) = \frac{C_{\Psi_m}(\Delta S)}{C^{\perp}_{\Psi_m}(\Delta S)}$$

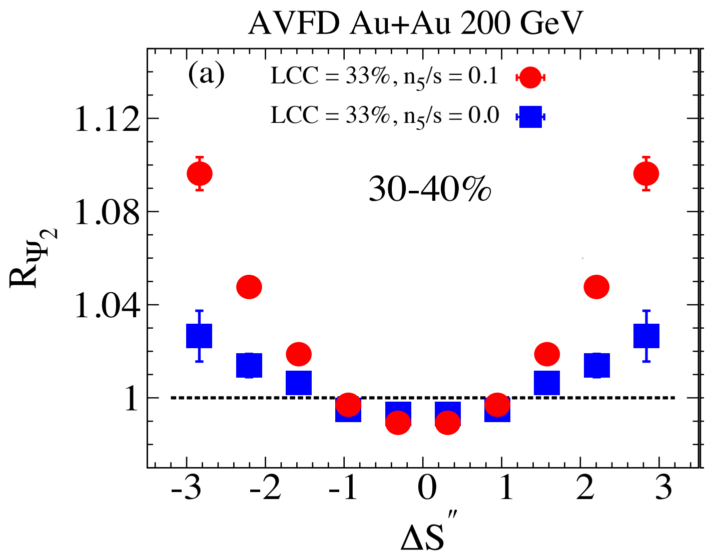
N. Magdy, et al.
PRC 97, 061901 (2018)
Piotr Bozek
PRC 97 (2018) 3, 034907
Niseem Magdy, et al.
PRC 98 (2018) 6, 061902
Yicheng Feng, et al.
PRC 98 (2018) 3, 034904
Yifeng Sun, et al.
PRC 98 (2018) 1, 014911

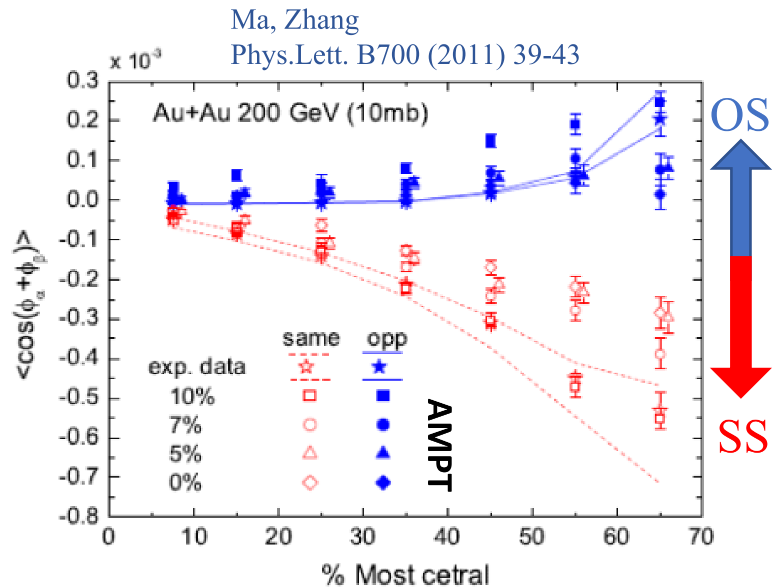
$C^{\perp}_{\Psi_2}(\Delta S)$ quantifies charge separation perpendicular to the B-field (only background)

The $R_{\Psi_2}(\Delta S)$ correlator measures the magnitude of charge separation parallel to the B-field, relative to that for charge separation perpendicular to the B-field

❖ Introduction

➢ Correlators to measure dipole charge separation

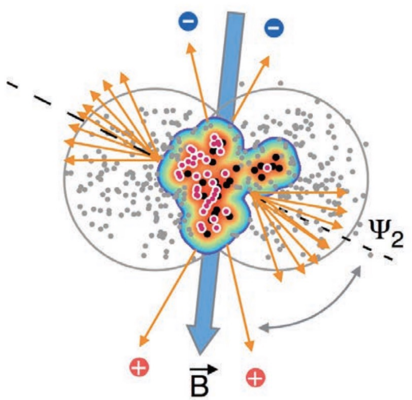


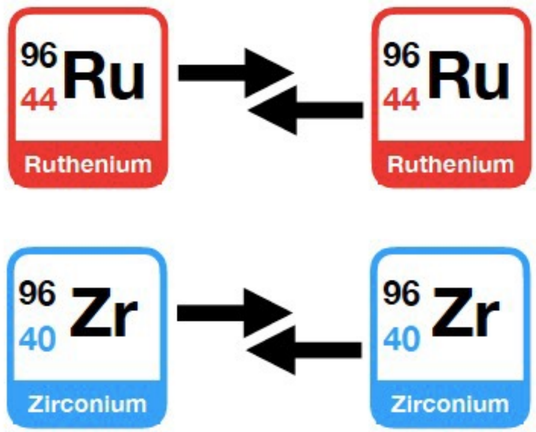


- ➢ The correlators' responses are similar for signal and background
- ➢ Background can account for a part, or all of the observed charge separation signal?

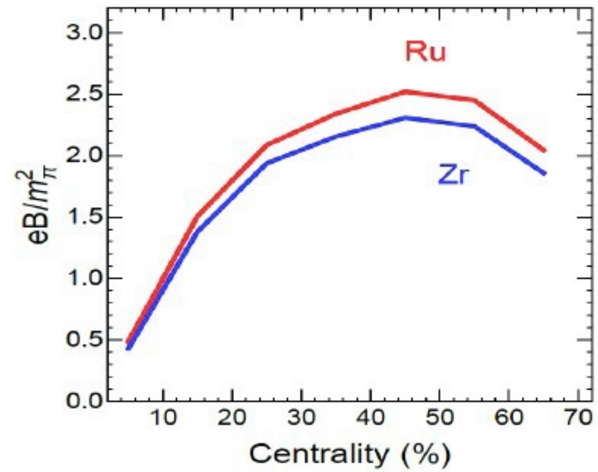
❖ Isobar Analysis:

- ➢ Separating the signal from background is the main subject of the ongoing work

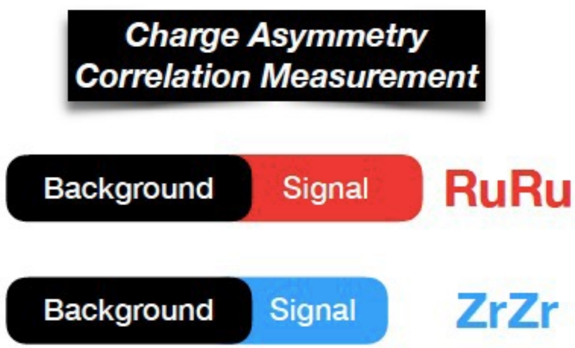




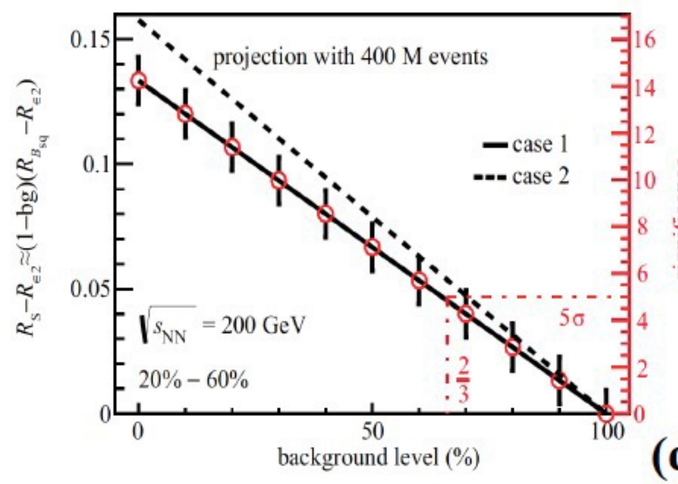
(a)



(b)



(c)



(d)

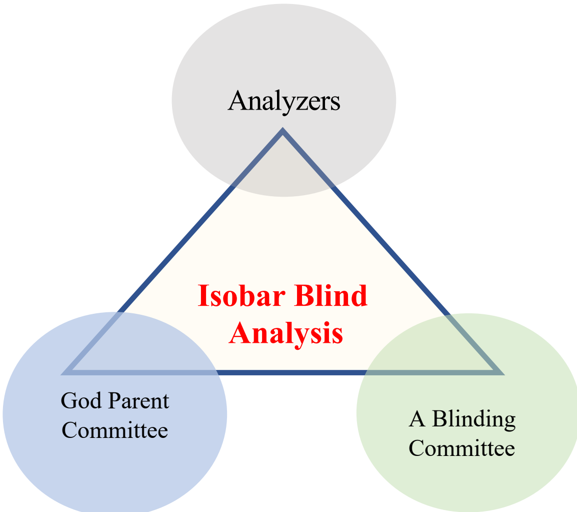
Isobars:

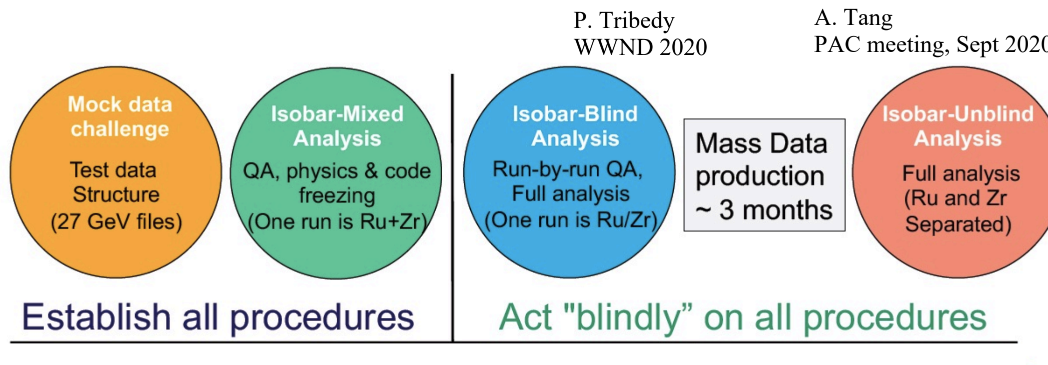
Similar shape → Similar background

Different Z → Different magnetic field

❖ Isobar Analysis:

➢ A large, collective effort





N. Magdy, et al. PRC 98 (2018) 6, 061902

A. Tang, CPC 44 054101 (2020)

H-J. Xu, et al, CPC 42, 084103 (2018)

S. Voloshin, PRC 98, 054911 (2018)

J. Zhao , et al, EPJC 79 (2019) 168

5-Isobar Blind Analyses

- ➢ $\Delta\gamma, \Delta\delta$ and κ
- ➢ $\Delta\gamma, \Delta\delta$ and $\Delta\gamma(\Delta\eta)$
- ➢ $\Delta\gamma$ in PP/SP and $\Delta\gamma(\mathrm{M_{inv}})$
- ➢ $\Delta\gamma$ in PP/SP
- ➢ $R(\Delta S)$ Correlator.

1-Isobar Unblinded Analysis

- ➢ The signed balance function

Case for CME:

- ➢ $\Delta\gamma$ and its derivatives
  $\Delta\gamma/v_2(\mathrm{Ru/Zr}) > 1$
  $\Delta\gamma_{112}/v_2(\mathrm{Ru/Zr}) > \Delta\gamma_{123}/v_3(\mathrm{Ru/Zr})$
  $\kappa(\mathrm{Ru/Zr}) > 1$
- ➢ $f_{CME}^{Ru} > f_{CME}^{Zr} > 0$
- ➢ $\sigma_{R\psi_2}^{-1}\left(\frac{Ru}{Zr}\right) > 1$

BNL, CCNU, Fudan, Huzhou, Purdue, SINAP, Stony Brook, Tsukuba, UCLA, UIC and Wayne State

❖ Isobar Analysis:

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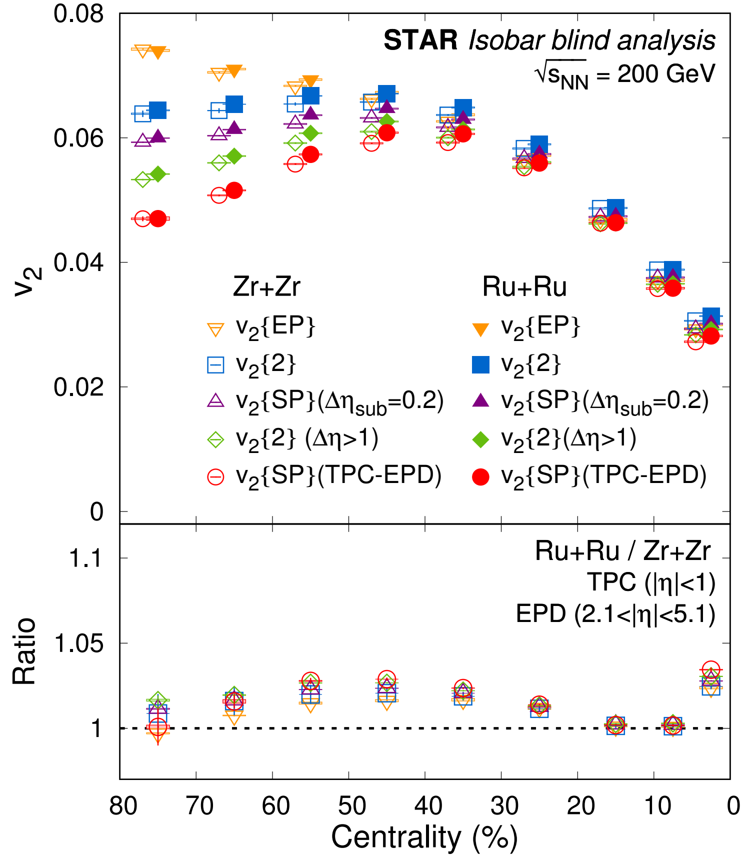
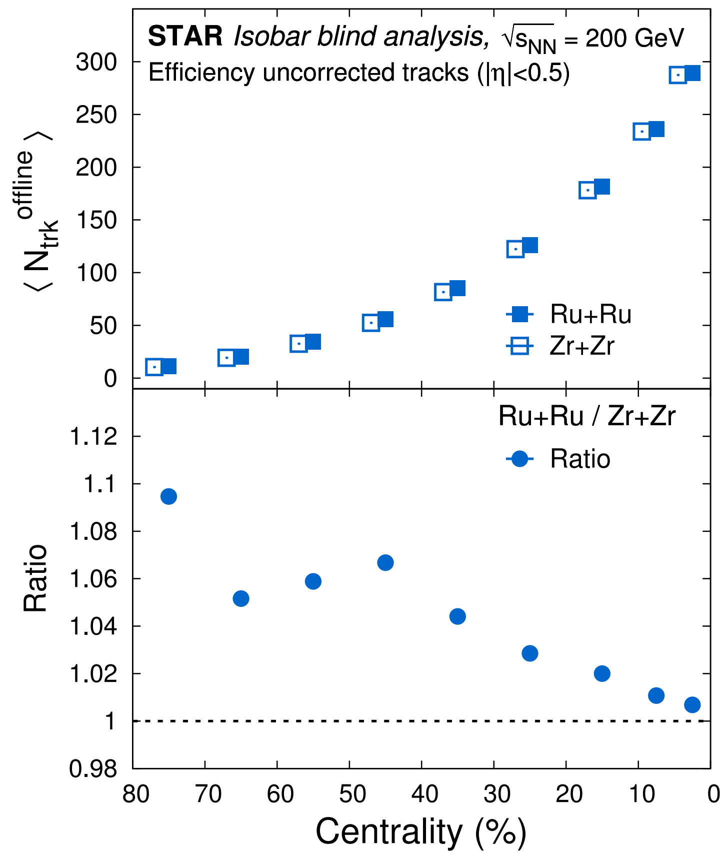
PRC 105, 014901 (2022)

➢ Expected CME background in isobar





➢ Observed differences in multiplicity and v_2 for same centrality
- ✓ Background differences for the two isobars are more complicated than previously thought
- ✓ The predefined CME signature could be invalid

Results from the isobar data

❖ Results

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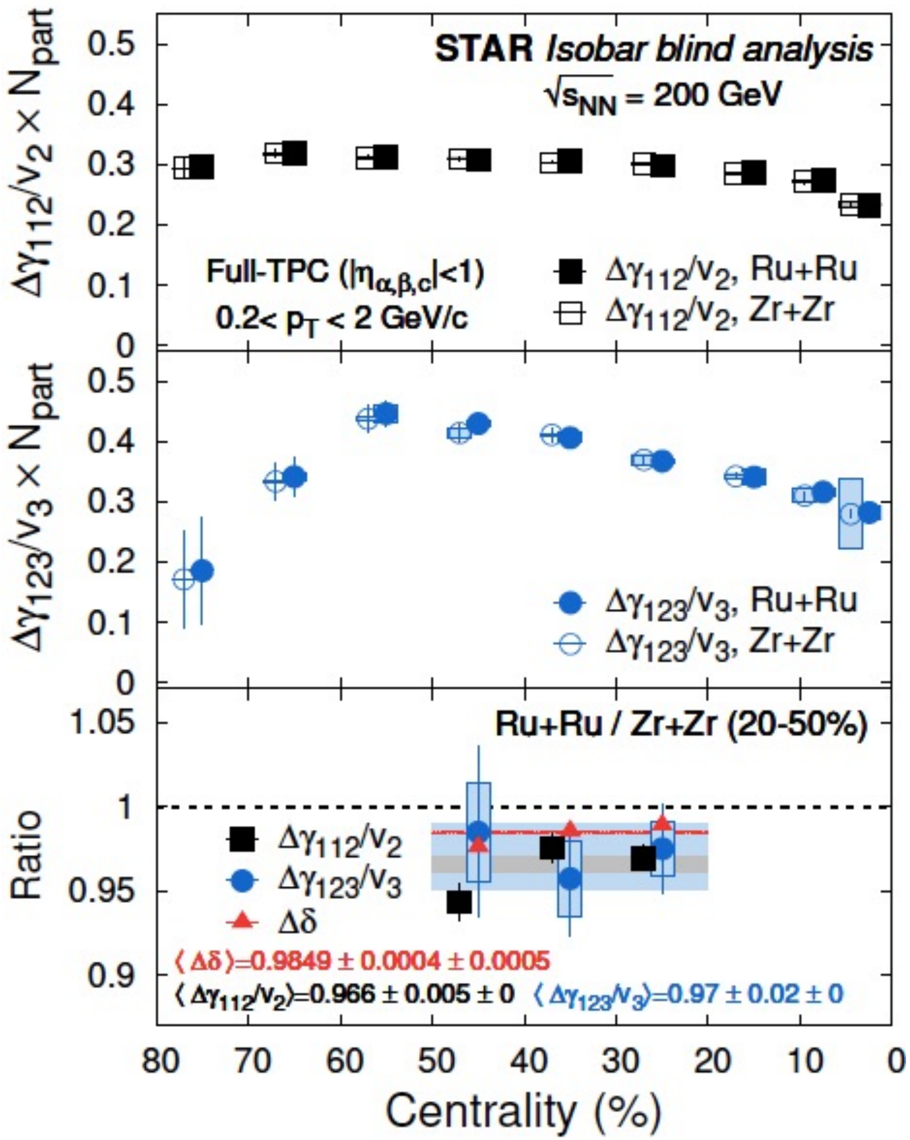
➢ $\Delta\gamma_{112}$ and $\Delta\gamma_{123}$



3rd order event plane not correlated with magnetic field

Predefined CME signature:

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

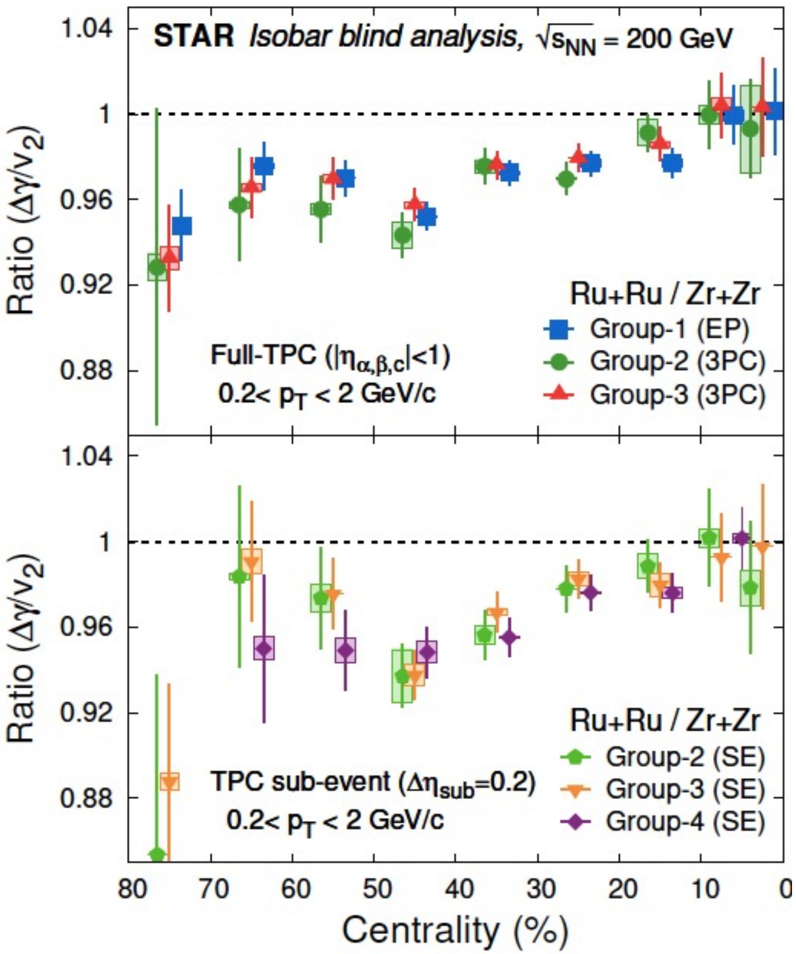
$$\frac{(\Delta\gamma_{112}/v_2)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{112}/v_2)^{\mathrm{Zr+Zr}}} > \frac{(\Delta\gamma_{123}/v_3)^{\mathrm{Ru+Ru}}}{(\Delta\gamma_{123}/v_3)^{\mathrm{Zr+Zr}}}\,,$$

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

No CME signature that satisfies the predefined criteria observed

Results

Consistency of the results



Measurements of similar quantities consistent:

- Results are not identical because of analysis specific event selection criteria and different methods
- Verified results consistent within the statistical fluctuations due to those differences

Predefined CME signature:

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

No CME signature that satisfies the predefined criteria observed

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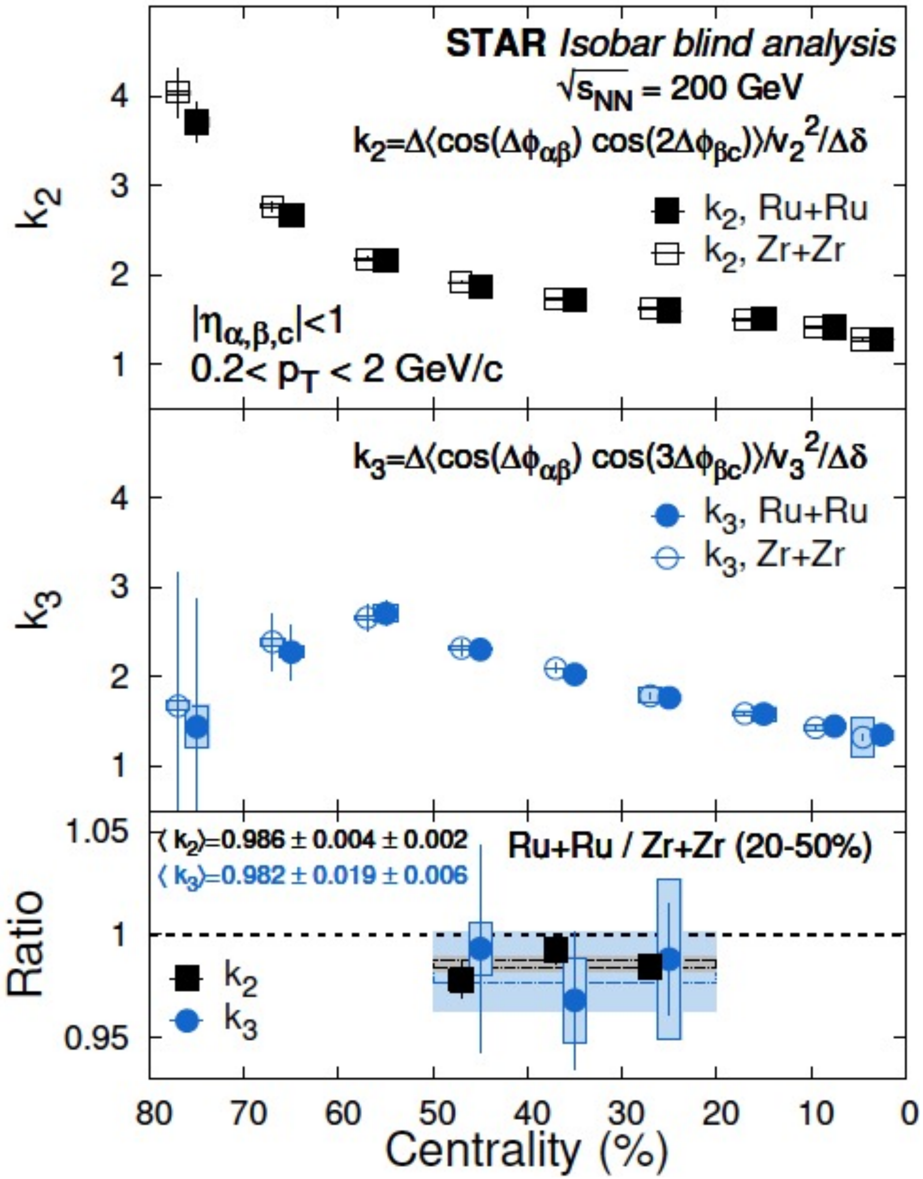
❖ Results

➢ 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:

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

No CME signature that satisfies the predefined criteria observed

❖ Results

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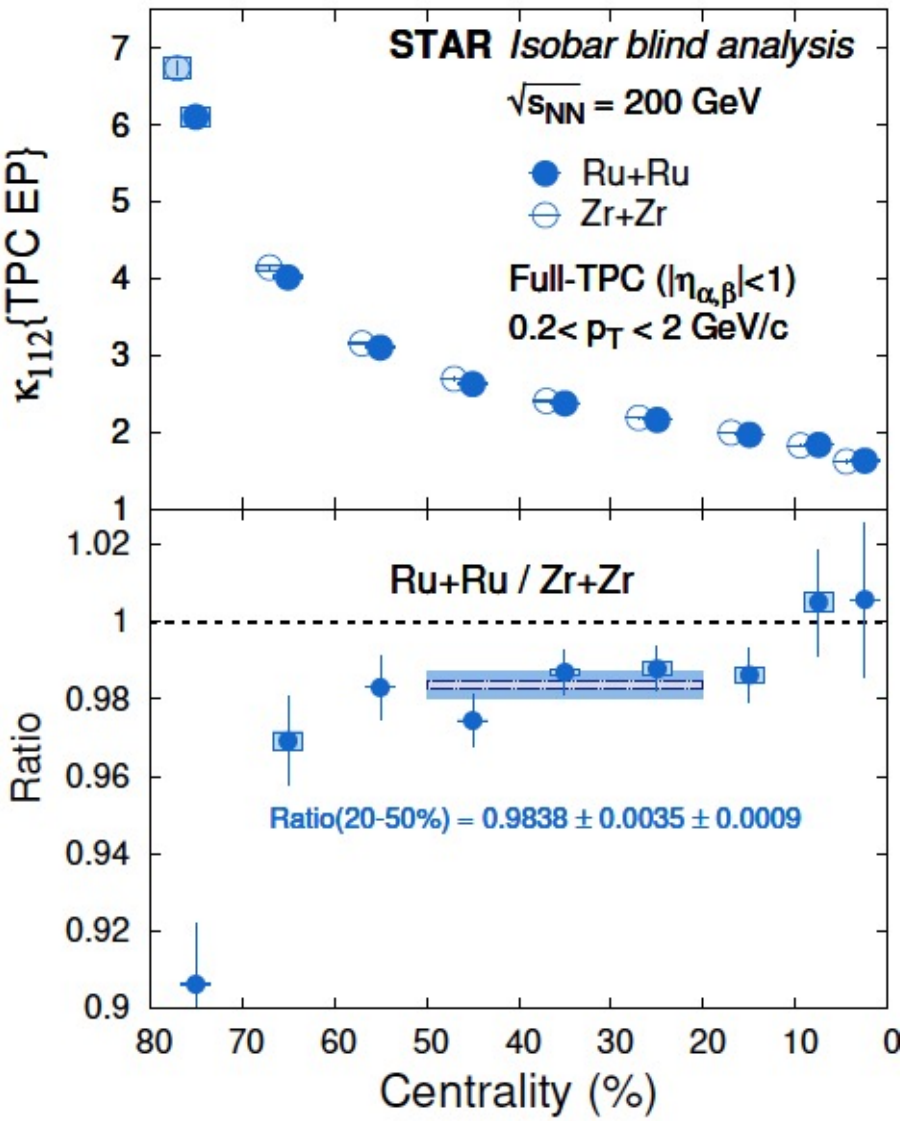
➢ $K_{112} \equiv \Delta\gamma_{112}/v_2\Delta\delta$

A precision down to 0.4% is reached, as anticipated



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

Predefined CME signature:

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

No CME signature that satisfies the predefined criteria observed

❖ Results

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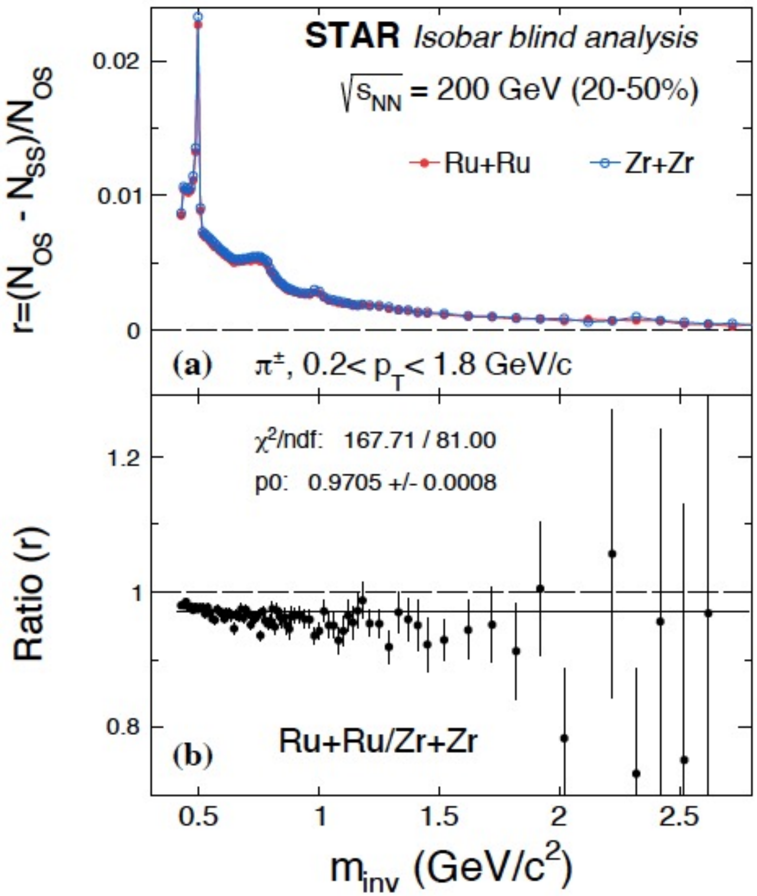
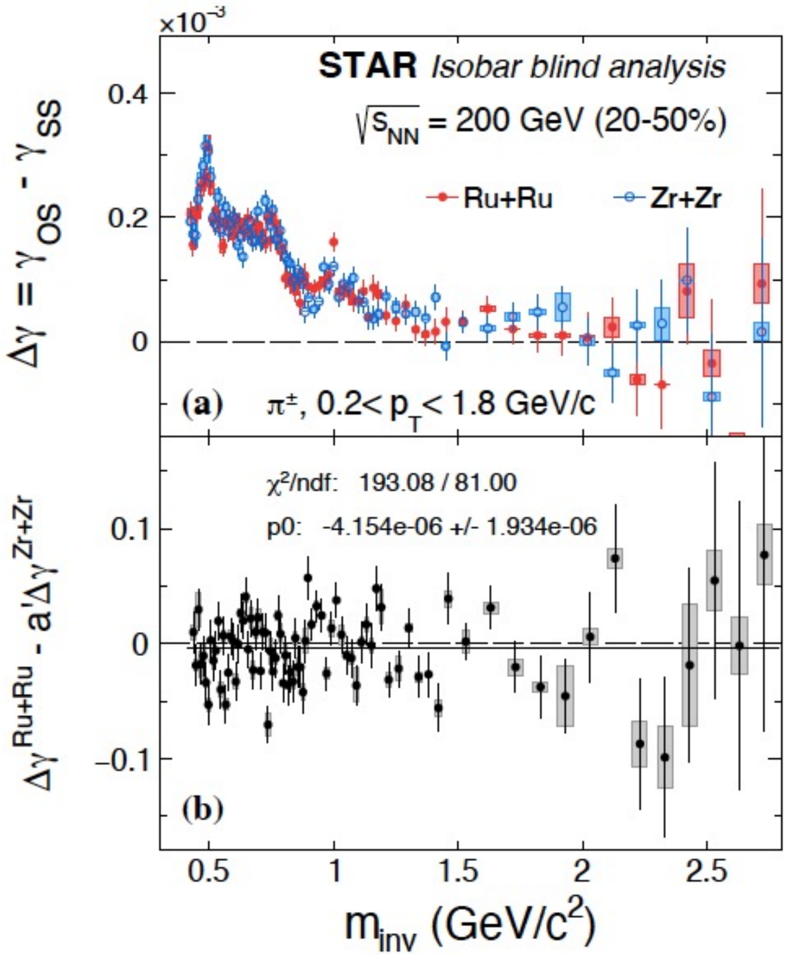
➢ $\Delta\gamma$ measurements in invariant mass

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





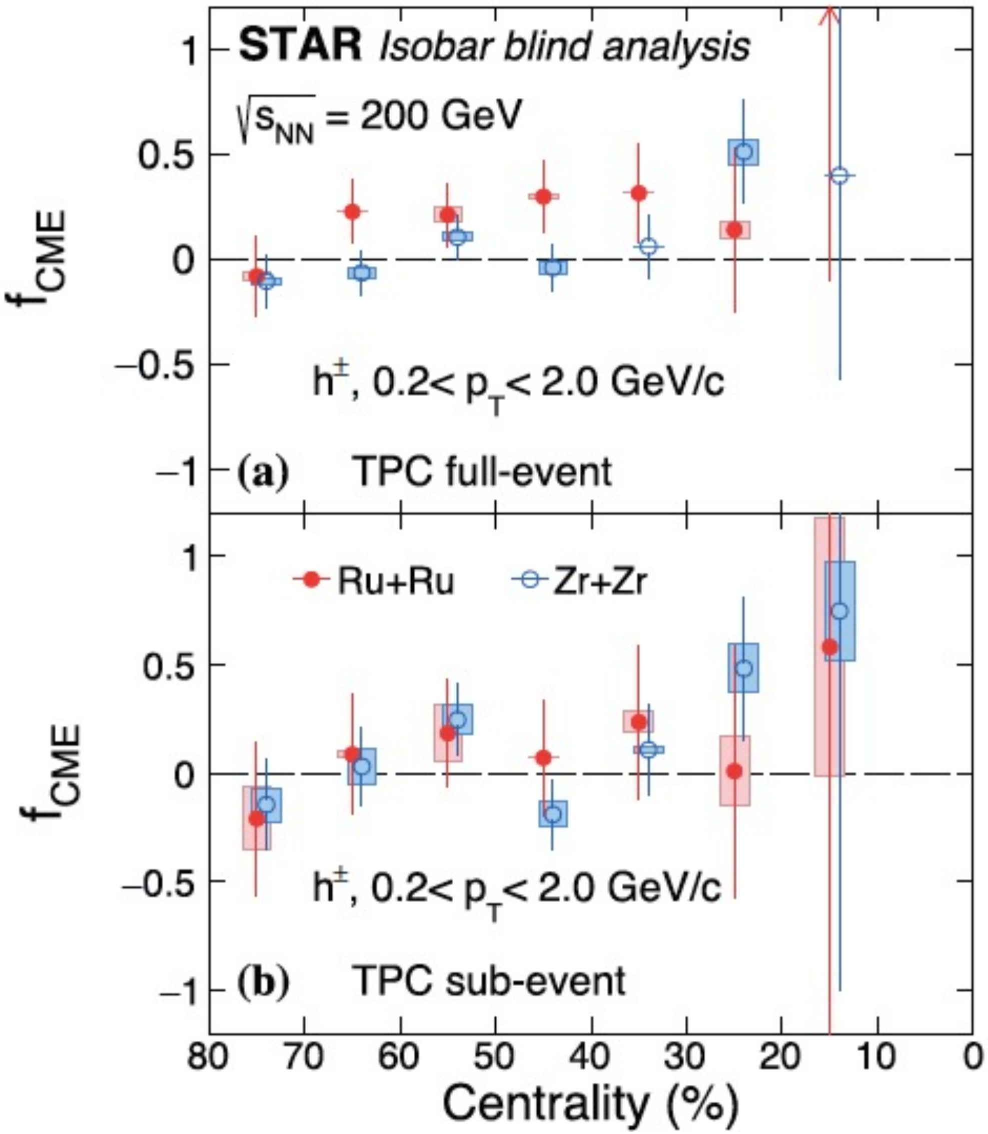
Predefined CME signature:

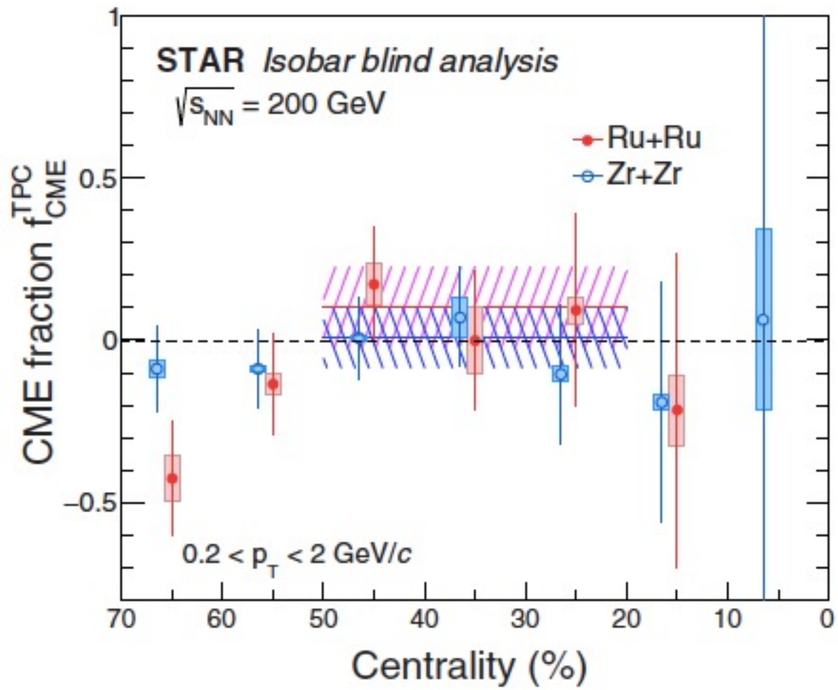
$$\Delta\gamma^{\mathrm{Ru+Ru}} - a'\Delta\gamma^{\mathrm{Zr+Zr}} > 0$$

No CME signature that satisfies the predefined criteria observed

❖ Results

➢ CME fraction f_{CME}





Predefined CME signature:

$$f_{CME}^{Ru} > f_{CME}^{Zr} > 0$$

No CME signature that satisfies the predefined criteria observed

❖ Results

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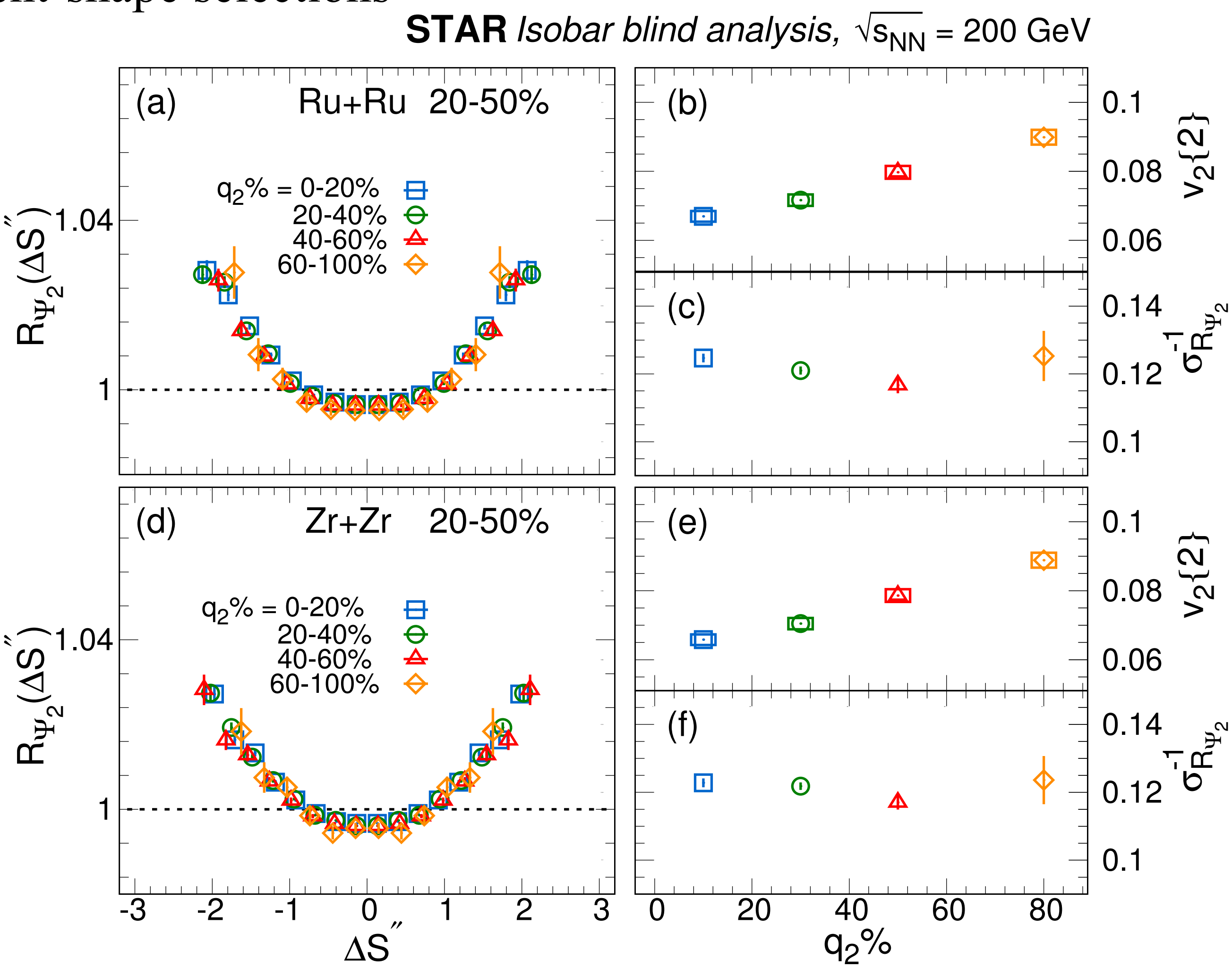
➢ $R_{\Psi_2}(\Delta S)$ measurements

✓ Event-shape selections



➢ The q_2-selected results indicate that $R_{\Psi_2}(\Delta S'')$ is not strongly influenced by the v_2 background-driven charge separation for up to ~30% change in v_2.

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PRC 105, 014901 (2022)

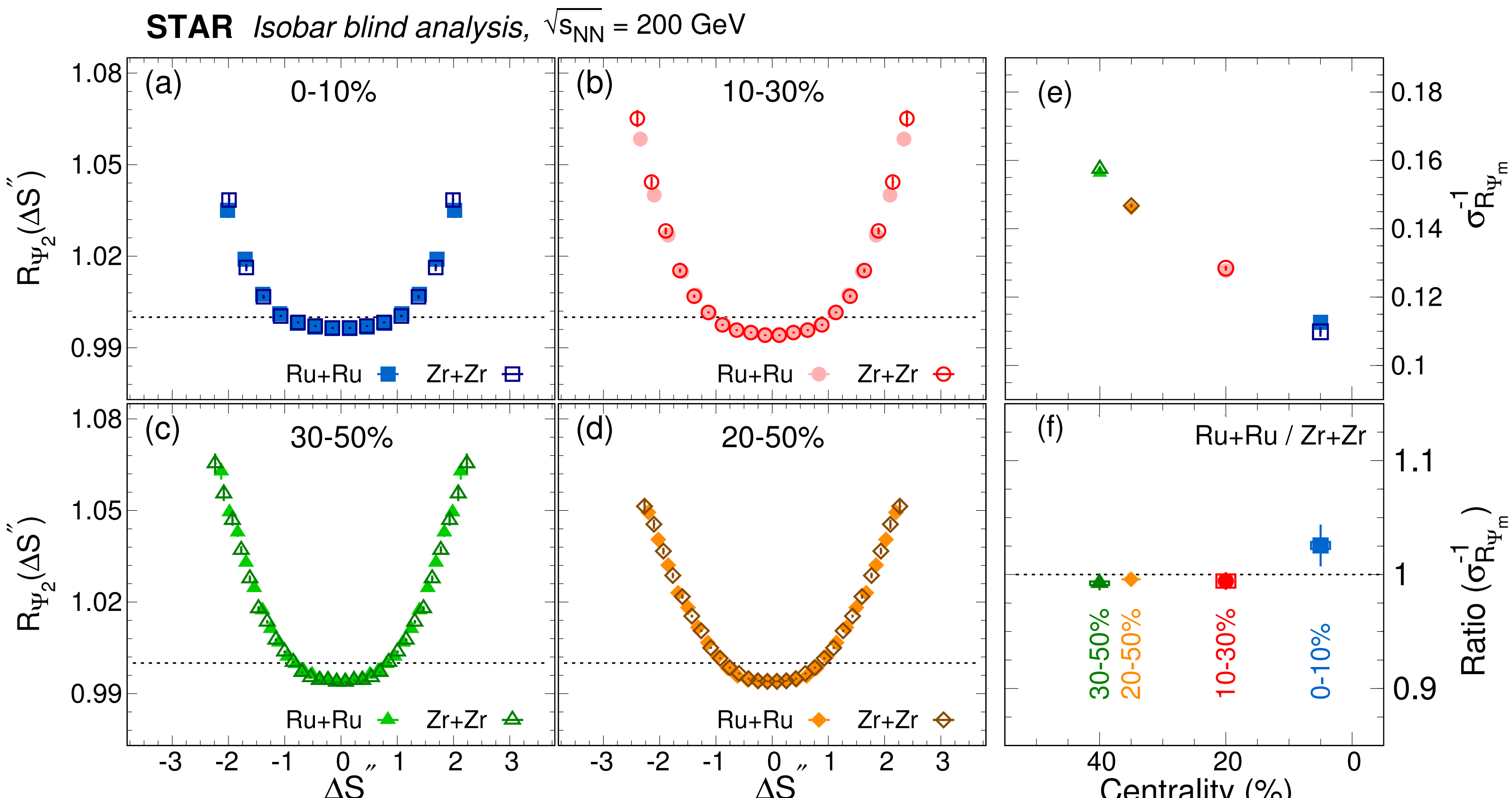
❖ Results

➢ $R_{\Psi_2}(\Delta S)$ measurements

✓ Centrality selections

Predefined CME signature:

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



➢ For the same centrality, the $R_{\Psi_2}(\Delta S'')$ correlators for the two isobars are similar.

No CME signature that satisfies the predefined criteria observed

❖ Results

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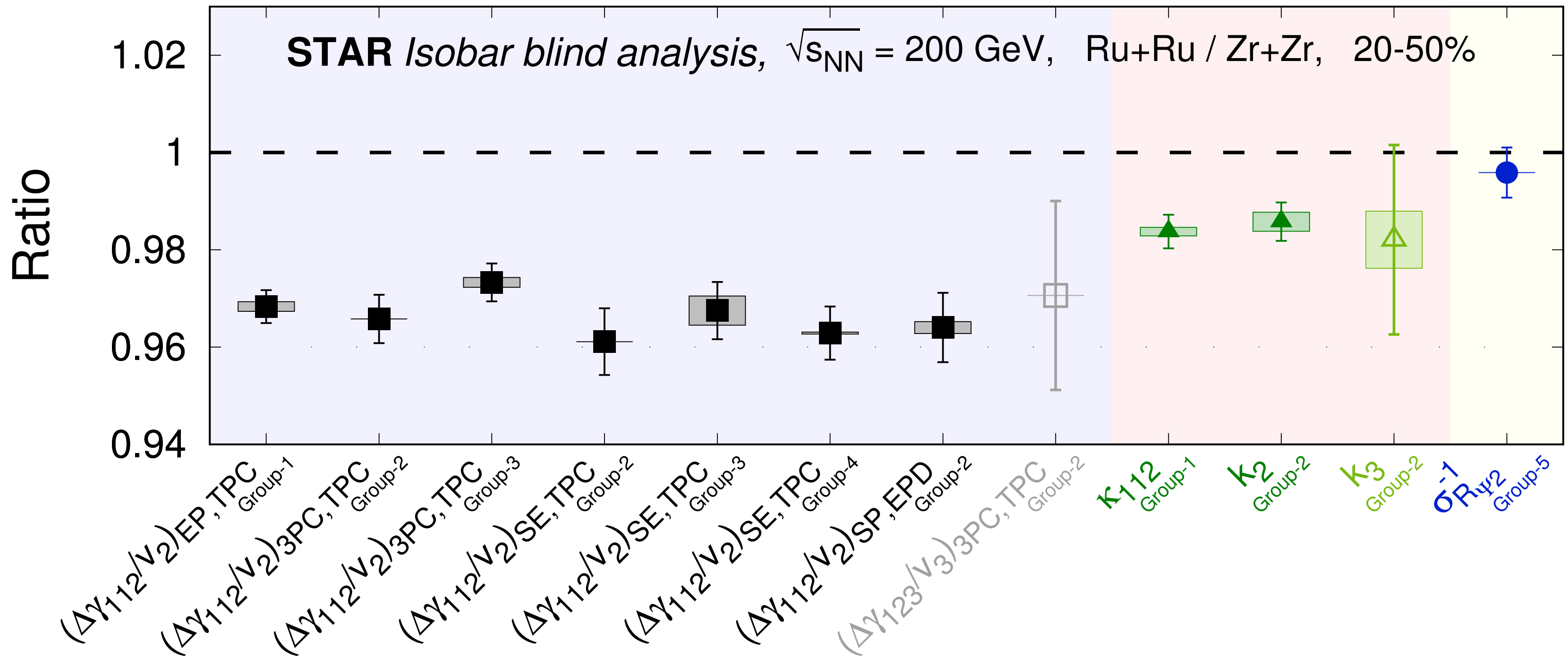
PRC 105, 014901 (2022)

Predefined CME signature:

- $\Delta\gamma$ and its derivatives
  - $\Delta\gamma/v_2(\mathrm{Ru/Zr}) > 1$
  - $\Delta\gamma_{112}/v_2(\mathrm{Ru/Zr}) > \Delta\gamma_{123}/v_3(\mathrm{Ru/Zr})$
  - $\kappa(\mathrm{Ru/Zr}) > 1$
- $\sigma^{-1}_{R\psi_2}\left(\frac{Ru}{Zr}\right) > 1$



The predefined CME signature is not observed

✓ Not an indication for the absence of the CME

❖ Conclusions

We report experimental measurements of the blind analysis designed to test the CME effect using a large data set of isobar ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr collisions at 200 GeV, taken by the STAR collaboration at RHIC.

- The backgrounds are reduced using the isobar collisions
- The criteria for a positive CME observation are predefined, before the blind analysis
- A precision down to 0.4% is reached, as anticipated, in the relative magnitudes of pertinent observables between the two isobar systems.
- Observed differences in multiplicity and v_2 for the same centrality
  - ✓ Background differences for the two isobars are more complicated than previously thought

The predefined CME signature is not observed

✓ Not an indication for the absence of the CME in the individual signal

- Ongoing work to characterize the effects of backgrounds

THANK YOU

- Event-shape selections can constrain the v_2 driven background
  - ✓ Events are further subdivided into groups with different q_2 magnitude:

$$Q_{2,x} = \sum_{i=1}^{M} \cos(2\,\varphi_i)$$

$$Q_{2,y} = \sum_{i=1}^{M} sin(2\,\varphi_i)$$

$$q_2 = \frac{\sqrt{Q_{2,x}^2 + Q_{2,y}^2}}{\sqrt{M}}$$