Chiral Magnetic Effect in isobaric ($^{96}_{44}Ru +^{96}_{44} Ru$ and $^{96}_{40}Zr +^{96}_{40} Zr$) collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV using Sliding Dumbbell Method at RHIC

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Abstract

Experiments conducted in the last decade to search for the Chiral Magnetic Effect (CME) in heavy-ion collisions have been inconclusive. The RHIC's isobar program was implemented in an effort to resolve this issue. A new technique, the Sliding Dumbbell Method (SDM) has been developed to investigate the CME. The SDM enables the classification of potential CME-like events based on the charge separation across the dumbbell (f_{DbCS}). In this contribution, the results based on CME sensitive γ-correlator ($\gamma = \langle \cos(\phi_a + \phi_b - 2\Psi_{RP})\rangle$) is discussed for for each bin of f_{DbCS} in each collision centrality for isobaric collisions (Ru+Ru and $Zr + Zr$) at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV measured with the STAR detector.

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1. Introduction

Quantum Chromodynamics (QCD), the theory of strong interactions, predicts the existence of metastable domains characterized by fluctuating topological charges, which can induce chirality imbalance in quarks under extreme conditions of temperature and/or density, such as those present during the formation of the quark-gluon plasma (QGP) [1, 2]. In non-central heavy-ion collisions, the combination of parity-odd domains with the strong magnetic field generated by highly energetic spectator protons leads to the separation of oppositely charged particles along the magnetic field direction and perpendicular to the reaction plane, known as the Chiral Magnetic Effect (CME) [3–6]. The CME has been a subject of significant theoretical interest [7–9] and experimental exploration [10–13], particularly at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC).

To disentangle the CME signal from background effects, the RHIC isobar program proposed the use of nearly identical nuclear systems, ${}^{96}_{44}Ru$+${}^{96}_{44}Ru$ and ${}^{96}_{40}Zr$+${}^{96}_{40}Zr$, where the difference in proton number creates a controlled variation in the magnetic field strength [14, 15]. The STAR experiment at RHIC collected data from $Ru + Ru$ and $Zr + Zr$ collisions at a center-of-mass energy of $\sqrt{s_{\rm NN}}$ = 200 GeV in 2018 [15]. The larger atomic number of Ruthenium (${}^{96}_{44}$Ru) compared to Zirconium (${}^{96}_{40}$Zr) leads to an increase of approximately 15% in the squared magnetic field in $Ru + Ru$ collisions [16]. This enhanced magnetic field was expected to increase the CME signal, while the similar mass numbers ensured comparable flow-related background contributions in both systems. A blind analysis procedure was adopted by the STAR Collaboration for the isobar dataset to avoid potential bias in the search for the CME signal [16].

The most commonly used observable in the search for the Chiral Magnetic Effect (CME) is the three particle γ-correlator, initially proposed by Voloshin [3]. It is defined as:

$$\gamma = \langle \cos(\phi_a + \phi_b - 2\Psi_{RP}) \rangle \approx \frac{\langle \cos(\phi_a + \phi_b - 2\phi_c) \rangle}{v_{2,c}} \tag{1}$$

where, ϕ_a and ϕ_b denote the azimuthal angles of particles "a" and "b", respectively, while Ψ_{RP} represents the reaction plane angle. $v_{2,c}$ is the elliptic flow of third particle "c" having azimuthal angle ϕ_c. To estimate v_2 and compute multi-particle correlators, the Q-cumulant technique [17] is used.

In this study, the Sliding Dumbbell Method (SDM) [18, 19] is utilized to identify potential CME-like events. These events are subsequently analyzed using the γ correlator to verify whether or not they exhibit the expected characteristics of CME events.

2. Sliding Dumbbell Method

The "Sliding Dumbbell Method" [18, 19] has been designed to identify potential CME-like events in heavy-ion collisions that display higher back-to-back charge separation on an event-by-event basis. In the SDM, the azimuthal plane of each event is scanned by sliding a dumbbell-shaped region of $\Delta\phi = 90^\circ$ in steps of $\delta\phi = 1^\circ$, as detailed in Ref. [18]. This approach helps in identifying the region exhibiting the highest back-to-back charge separation. To quantify this separation, the parameter Db_{+-} is calculated. It represents the sum of the positive charge fraction on one side ("a") of the dumbbell and the negative charge fraction on the opposite side ("b") for each orientation of the dumbbell across the azimuthal plane, and is obtained as:

$$Db_{+-} = \frac{n_{+}^{a}}{(n_{+}^{a} + n_{-}^{a})} + \frac{n_{-}^{b}}{(n_{+}^{b} + n_{-}^{b})}, \tag{2}$$

where, $n_a^+(n_b^+)$ and $n_a^-(n_b^-)$ represent the number of positive and negative charged particles on sides "a" and "b" of the dumbbell, respectively. The $Db_{+-} = 2$ corresponds to 100% back-to-back charge separation while $Db_{+-} = 1$ means no back-to-back charge separation. Furthermore, the charge excess asymmetry across the dumbbell, Db_{asy}, is defined as:

$$Db_{+-}^{asy} = \frac{(n_a^+ - n_a^-) - (n_b^- - n_b^+)}{(n_a^+ - n_a^-) + (n_b^- - n_b^+)} \tag{3}$$

Here, $n_a^+ - n_a^-$ represents the excess positive charge on the "a" side of the dumbbell, while $n_b^- - n_b^+$ denotes the excess negative charge on the "b" side. By sliding the dumbbell in steps of $\delta\phi = 1^\circ$ across the azimuthal plane, 360 values of both Db_{+-} and Db_{asy} are obtained. The maximum value of Db_{+-}, denoted as Db_{+-}^{max}, is then selected under the constraint $\mid Db_{asy} \mid < 0.25$, ensuring the identification of CME-like events with balanced charge excess asymmetry [18]. The charge separation across the dumbbell, f_{DbCS}, referred to as charge separation, defined as:

$$f_{DbCS} = Db_{+-}^{max} - 1 \tag{4}$$

The charge separation (f_{DbCS}) distributions are obtained for each centrality class for data as well as charge shuffle background (as discussed in section 2.1). These distributions are subdivided into ten percentile bins, ranging from 0-10% (highest charge separation) to 90-100% (lowest charge separation) for each collision centrality. The three particle (γ) correlator is computed for different charge combinations and for each f_{DbCS} bin in each centrality for both data and background.

2.1. Background Estimation

We estimate the background contributions to the γ-correlator across different f_{DbCS} percentile bins using the SDM. We account for contributions that may result in higher charge separation purely by statistical fluctuations while preserving the intrinsic particle correlations. This is achieved by randomly shuffling the charges of particles within each event while keeping their momenta (i.e., θ and ϕ) unchanged. The charge-shuffled sample for a given centrality is then analyzed in the same manner as the original dataset [18]. The γ-correlator obtained from this charge-shuffled sample in a particular f_{DbCS} bin is denoted as γ_{ChS}.

Conversely, the charge correlations disrupted by the shuffling process are recovered from the original events corresponding to the same f_{DbCS} bins and the resulting γ-correlator is referred to as γ_{Corr}. Consequently, the total background contribution to the γ-correlator is calculated as:

$$\gamma_{Bkg} = \gamma_{ChS} + \gamma_{Corr} \tag{5}$$

3. Analysis Details

We used the minimum bias events from the isobar collisions ($^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr) at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV. Events with -35 < V_z < 25 cm and tracks with $|\ \eta\ | < 1$, 0.2 < p_T < 2.0 GeV/c and DCA < 3 cm are used for the analysis. After all event selection cuts, we analyze approximately 1.7 billion minimum-bias (MB) events each for $Ru + Ru$ and $Zr + Zr$ collisions.

4. Results and Discussion

Figure 1 illustrates the dependence of $\Delta\gamma$ on f_{DbCS} for $Ru + Ru$ (Left) and $Zr+Zr$ (Right) collisions, along with their respective backgrounds i.e., $\Delta\gamma^{Ru/Zr}_{ChS}$ and $\Delta\gamma^{Ru/Zr}_{Corr}$, for 0-60% collision centralities. The values of $\Delta\gamma$'s in the top f_{DbCS} bins are enhanced many times than the average values [16]. The data points ($\Delta\gamma_{data}$) for the top 20% f_{DbCS} bins have larger values than the total background contribution ($\Delta\gamma_{ChS} + \Delta\gamma_{Corr}$) in the 30-50% centrality range.

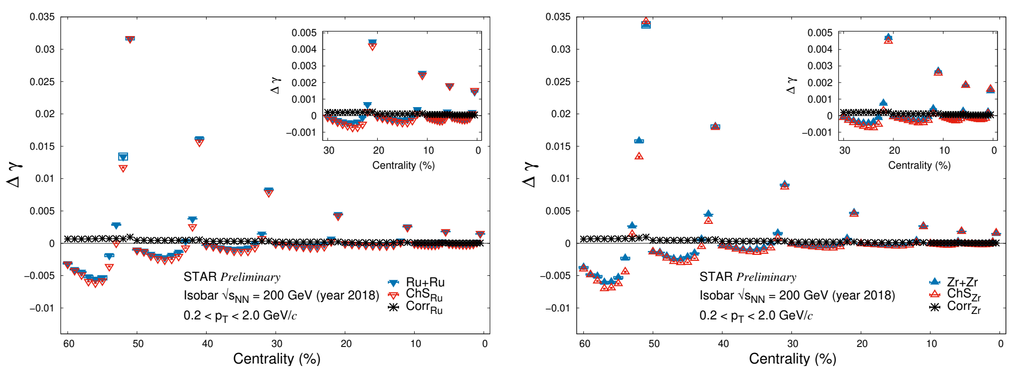

Figure 1: $\Delta\gamma$ dependence on f_{DbCS} for $Ru + Ru$ (Left) and $Zr + Zr$ (Right) collisions, including $ChS_{Ru(Zr)}$ and $Corr_{Ru(Zr)}$ backgrounds for 0-60% collision centralities. The boxes indicate the systematic errors, while the statistical errors, represented by bars, are within the marker sizes.

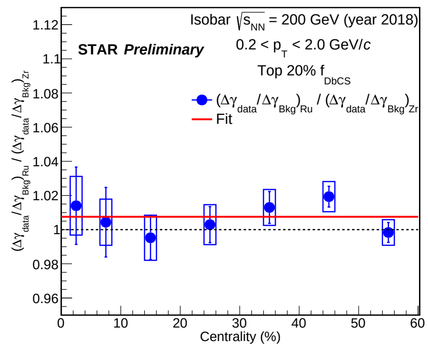

Figure 2: The double ratio ($\frac{(\Delta\gamma_{Data}/\Delta\gamma_{Bkg})_{Ru}}{(\Delta\gamma_{Data}/\Delta\gamma_{Bkg})_{Zr}}$) for 0-60% collision centralities. A straight-line (Pol0) fit is applied to the data, represented by the red line. The statistical errors are represented by bars, while the systematic errors are depicted by boxes.

Figure 2 presents the "double ratio", which compares the $\Delta\gamma_{\mathrm{Data}}/\Delta\gamma_{\mathrm{Bkg}}$ ratios between *Ru* + *Ru* and *Zr* + *Zr* collisions for top 20% f_{DbCS} bins. A "Pol0 fit" (straight line fit) is applied to the double ratio, resulting in a fitted value of 1.007 ± 0.003 for 0-60% centralities. This result suggests no significant enhancement of the CME signal in *Ru* + *Ru* collisions relative to *Zr* + *Zr* collisions, contrary to the initial expectations for isobar collisions [16].

5. Summary

In this study, isobaric collision data was analyzed using the Sliding Dumbbell Method (SDM), which identifies back-to-back charge separation on an event-by-event basis within each collision centrality. The values of $\Delta\gamma$'s in the top f_{DbCS} bins are significantly enhanced than the average values. Moreover in the top f_{DbCS} bins, $\Delta\gamma_{\mathrm{data}}$ exceeds the total background contribution. The double ratio ($\frac{(\Delta\gamma_{Data}/\Delta\gamma_{Bkg})_{Ru}}{(\Delta\gamma_{Data}/\Delta\gamma_{Bkg})_{Zr}}$) for top 20% f_{DbCS} bins suggests no significant enhancement of the CME signal in *Ru* + *Ru* collisions compared to *Zr* + *Zr* collisions, contradicting initial expectations for isobaric collisions. In the various techniques studied by the STAR experiment, the anticipated enhancement in *Ru* + *Ru*, due to a stronger magnetic field, has not been observed.

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