CME search in isobar ($^{96}_{44}Ru$+$^{96}_{44}Ru$ and $^{96}_{40}Zr$+$^{96}_{40}Zr$) collisions at $\sqrt{s_{\mathrm{N}N}} = 200$ GeV using SDM 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. Isobar program at RHIC was conducted to address this problem. Also, in order to study the CME, a new approach known as the Sliding Dumbbell Method (SDM) has been developed. This method searches for the back-to-back charge separation on an event-by-event basis. The SDM facilitates the selection of events corresponding to various charge separations (f_{DbCS}) across the dumbbell. A partitioning of the charge separation distributions for each collision centrality into 10 percentile bins is done in order to find potential CME-like events that correspond to the highest charge separation across the dumbbell. Results for two- and three-particle correlators for isobar (Ru+Ru and Zr+Zr) collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV will be presented for each bin of f_{DbCS} in each collision centrality. The background contribution due to statistical fluctuations is obtained by randomly shuffling the charges of the particles in a particular collision centrality. Correlated backgrounds are calculated for each f_{DbCS} bin of charged shuffled events using their corresponding original events.

1 Introduction

In non-central heavy-ion collisions, P-odd meta-stable states and the strong magnetic field generated by highly energetic spectator protons lead to the separation of oppositely charged particles along the system's angular momentum direction and perpendicular to the reaction plane, known as the Chiral Magnetic Effect (CME) [1, 2]. Isobaric collisions of $^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr nuclei, had been proposed as a promising approach to address the challenges associated with the detection of the CME in heavy-ion collisions [3]. 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. This enhanced magnetic field is expected to lead to a proportional increase in the CME contribution in Ru+Ru collisions, while the similarity in mass numbers of the colliding nuclei ensures comparable flow-driven backgrounds [4].

2 Analysis Technique and Details

A novel technique, the Sliding Dumbbell Method (SDM) [5] is developed to isolate and extract an enriched sample of CME-like events within each collision centrality. In the SDM, the azimuthal plane in each event is scanned by sliding the dumbbell of $\Delta\phi = 90^\circ$ in steps of $\delta\phi = 1^\circ$ while calculating Db_{+-} for each region. The maximum values of Db_{+-} (Db^{max}_{+-}) is selected in each event with a condition that $\mid Db_{asy} \mid < 0.25$. Db_{+-} is the sum of positive and negative charge fractions on "a" and "b" side of dumbbell, defined as:

$$Db_{+-} = \frac{n^a_+}{(n^a_+ + n^a_-)} + \frac{n^b_-}{(n^b_+ + n^b_-)}, \tag{1}$$

where n^a_+ and n^a_- (n^b_+ and n^b_-) are numbers of positive and negative charged particles on "a" ("b") side of the dumbbell. The SDM calculates Db^{max}_{+-} using the charge excess asymmetry across the dumbbell, denoted as Db_{asy}.

$$Db_{asy} = \frac{Pos^a_{ex} - Neg^b_{ex}}{Pos^a_{ex} + Neg^b_{ex}} \tag{2}$$

Where $Pos^{a}_{ex} = n^{a}_{+} - n^{a}_{-}$ ($Neg^{b}_{ex} = n^{b}_{-} - n^{b}_{+}$) is the positive (negative) charged particle excess on side "a" ("b") of the dumbbell. The charge separation across the dumbbell ($f_{DbCS} = Db^{max}_{+-} - 1$) distributions are obtained for each centrality class and subdivided into ten percentile bins, ranging from 0-10% to 90-100% for each collision centrality. Two- and three-particle correlators are computed for different charge combinations and for each f_{DbCS} bin in each centrality. For the background estimation Charge Shuffle (ChS) and Correlated (Corr) backgrounds are used.

Charge Shuffle background (ChS): This background is generated from the data (Ru+Ru and Zr+Zr) itself in which the the charges of particles are shuffled randomly while keeping their momenta (i.e., θ and ϕ) unchanged.

Correlated background (Corr): To recover correlations amongst particles which were destroyed in charge shuffling, we obtain the correlations from the original events corresponding to the particular f_{DbCS} bin of charge shuffled events.

Analysis Details: We used the minimum bias events (∼50% of the available MB data) from the isobar collisions (${}^{96}_{44}$Ru+${}^{96}_{44}$Ru and ${}^{96}_{40}$Zr+${}^{96}_{40}$Zr) at $\sqrt{s_{\rm NN}} = 200$ GeV. Events with -35 $< V_z <$ 25 and tracks with $\mid \eta \mid < 1$, $0.2 < p_T < 2.0$ GeV/c and DCA < 3 cm are used for the analysis.

3 Results and Discussions

The f_{DbCS} distributions for different collision centralities are compared in figure 1 for Ru+Ru and Zr+Zr collisions. It can be seen that f^{Ru+Ru}_{DbCS} distributions are almost

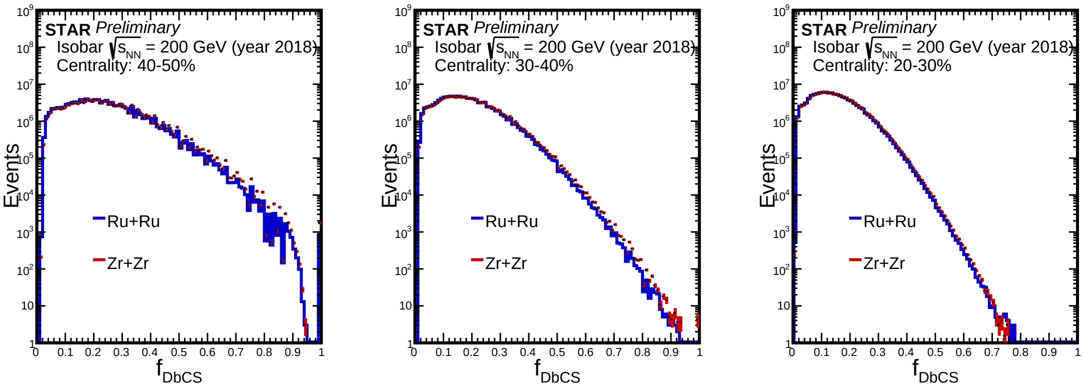

Figure 1: Comparison of f_{DbCS} distributions for Ru+Ru and Zr+Zr collisions at $\sqrt{s_{\rm NN}} = 200$ GeV in different collision centralities.

similar to f_{DbCS}^{Zr+Zr} distributions. Also, the distributions are moving towards higher values of f_{DbCS} with decreasing collision centralities for both Ru+Ru and Zr+Zr collisions. Figure 2 (Left) presents the dependence of γ-correlator for opposite-sign (OS) and same-sign (SS) charge pairs, respectively, on f_{DbCS} for 0-60% collision centralities for Ru+Ru (blue color) and Zr+Zr (red color) collisions. It can be seen that $\gamma_{OS} > 0$ and $\gamma_{SS} < 0$ for top f_{DbCS} bins (i.e., for 0-20% (0-30%) f_{DbCS} for 0-40% (40-60%) collision centralities), as expected for CME type events. Figure 2 (Right) displays the dependence of $\Delta\gamma$ on f_{DbCS} for 0-60% collision centralities, indicating that $\Delta\gamma$ is smaller for Ru+Ru than those of Zr+Zr collisions. The values of $\Delta\gamma$ in the top f_{DbCS} bins have increased many times than the average values [4]. The dependence of $\Delta\gamma$

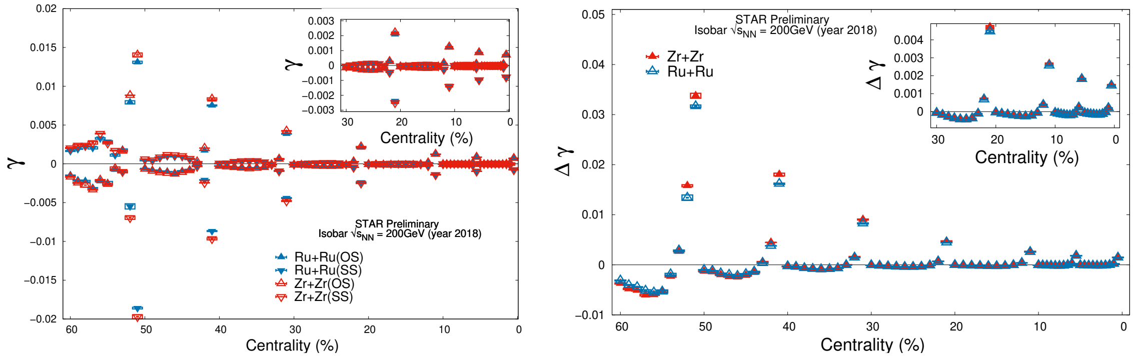

Figure 2: γ (Left) and $\Delta\gamma$ (Right) in different f_{DbCS} bins for different centrality bins for Ru+Ru and Zr+Zr collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. Boxes represent the systematic errors while the statistical errors (represented by bars) are within the marker sizes.

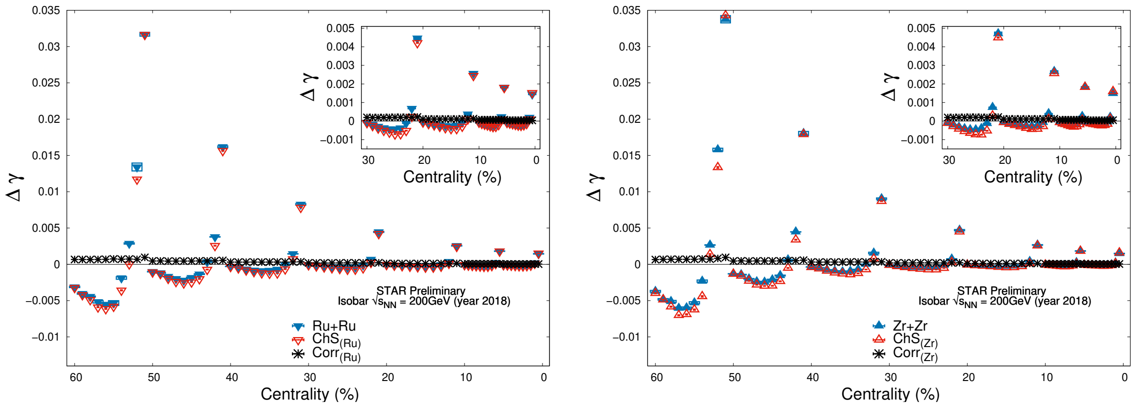

Figure 3: f_{DbCS} dependence on $\Delta\gamma$ for Ru+Ru (Left) and Zr+Zr (Right) collisions, $ChS_{Ru(Zr)}$ and $Corr_{Ru(Zr)}$ background for 0-60% collision centralities.

on f_{DbCS} for Ru+Ru (Left) and Zr+Zr (Right) collisions and their respective backgrounds i.e., $ChS_{Ru/Zr}$ and $Corr_{Ru/Zr}$ background, for 0-60% collision centralities is displayed in figure 3. The data points ($\Delta\gamma_{data}$) for the top 20% f_{DbCS} bins are higher than the total background ($\Delta\gamma_{ChS} + \Delta\gamma_{Corr}$) for 30-50% collision centralities.

4 Summary

In summary, we obtained the three-particle (γ) correlator for isobar (Ru+Ru and Zr+Zr) collisions using the SDM to investigate the Chiral Magnetic Effect. The charge separation (f_{DbCS}) distribution extends towards higher f_{DbCS} values with decreasing collision centrality. It is observed that $\gamma_{OS} > 0$ and $\gamma_{SS} < 0$ for top 20% (30%) f_{DbCS} bins for 0-40% (40-60%) collision centralities. We obtained two different backgrounds, i.e., Charge Shuffle (ChS) due to statistical fluctuation and Correlated (Corr) background from the data itself. Additionaly, $\Delta\gamma_{data}$ for the top 20% f_{DbCS} bins are higher than the total background ($\Delta\gamma_{ChS} + \Delta\gamma_{Corr}$) for 30-50% collision centralities for both isobaric collisions. We are conducting a detailed analysis with the full data set to explore a possible CME signal in the top 20% f_{DbCS} bins.

References

1. S. A. Voloshin. Parity violation in hot QCD: How to detect it. Phys. Rev. C 2004;70:057901.
2. D. Kharzeev. Parity violation in hot QCD: Why it can happen, and how to look for it. Phys. Lett. B 2006;633:260.
3. S. A. Voloshin. Testing the Chiral Magnetic Effect with Central U+U Collisions. Phys. Rev. Lett. 2010;105:172301.
4. M. S. Abdallah *et al.* (STAR Collaboration). 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. Phys. Rev. C 2022;105:014901.
5. Jagbir Singh. Search for the Chiral Magnetic Effect using Sliding Dumbbell Method in Isobar Collisions (${}^{96}_{44}Ru + {}^{96}_{44}Ru$ and ${}^{96}_{40}Zr + {}^{96}_{40}Zr$) at RHIC. Proceedings of the DAE Symp. Nucl. Phys. 2022;66:1048.