Investigation of Elliptic Flow and Chiral Magnetic Effect with the STAR Detector

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Introduction

The main goal of the heavy-ion physics program at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) is to investigate the properties of nuclear matter under extreme conditions specifically the quark–gluon plasma (QGP) [1]. The QGP is primordial state of matter believed to have existed shortly after the Big Bang, consisting of quarks and gluons moving freely. 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) [2, 3]. To probe the existence and properties of the CME, extensive theoretical and experimental efforts have been made, particularly by experiments at RHIC and LHC. These experiments involve analyzing azimuthal correlations of 2- and 3-particle correlations (δ- and γ-correlator) to search for charge separation patterns indicative of the CME. This thesis research focused on investigating the charge separation effect and identifying the potential events that exhibit characteristics similar to the CME.

Methodology

It is important to recognize that not every heavy-ion collision environment is suitable for producing the CME. Therefore, it becomes crucial to search for the CME signal in each event individually to isolate potential events that exhibit back-to-back charge separation. A novel method, the Sliding Dumbbell Method (SDM) [4–7] has been developed to identify potential CME-like events with higher back-to-back charge separation on an event-by-event basis within each collision centrality. The azimuthal plane in each event is scanned by sliding the dumbbell of 90° in steps of $\delta\phi = 1°$, while calculating Db_{+-} for each region, to obtain maximum values of Db_{+-} (Db^{max}_{+-}) in each event with a condition that $Db_{asy} < 0.25$. Db_{+-} is the sum of positive and negative charge fraction on "a" and "b" side of dumbbell. The fractional charge separation across the dumbbell in each event is defined as, $f_{DbCS} = Db^{max}_{+-} - 1$. The charge separation (f_{DbCS}) distributions are obtained for each collision centrality and subdivided into ten percentile bins, ranging from 0–10% to 90–100%. Two-particle ($\delta = \langle cos(\phi_a - \phi_b)\rangle$) and three-particle ($\gamma = \langle cos(\phi_a + \phi_b - 2\Psi_{RP})\rangle$) correlators, calculated via Q-cumulant method, are computed for different charge combinations and for each f_{DbCS} bin in each centrality. To extract the fractional CME signal in the top f_{DbCS} bins, two types of backgrounds were considered. The charge shuffled background (γ_{ChS}) involved random shuffling of charges to destroy charge-dependent correlations, while keeping their momenta (i.e., θ and ϕ) unchanged in an event, ensuring that flow is not affected. The shuffling of charges of particles in an event, kills not only the CME-like correlations but also correlations amongst produced particles. To restore correlations amongst particles, the γ correlator is calculated from the corresponding events in the original events' sample for the sliced bin of ChS events, termed as correlated background (γ_{Corr}).

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Simulation Results

To validate the SDM, a CME-like signal is externally injected by flipping charges of particles in the events generated by the AMPT at $\sqrt{s_{NN}} = 200$ GeV. The percentage of the externally injected signal varies across different collision centralities. Table I lists the fraction of CME contributions for the top f_{DbCS} bins for CME samples with different CME-like signal injected [4].

$$f_{CME} = 1 - \frac{\Delta\gamma_{Bkg}}{\Delta\gamma_{Data/AMPT}} \qquad (1)$$
$$\Delta\gamma_{Bkg} = \Delta\gamma_{ChS} + \Delta\gamma_{Corr}$$

The f_{CME} is calculated for each bin of the f_{DbCS} using equation 1. The AVFD model is also analyzed for different collision systems, such as Au+Au, Ru+Ru, and Zr+Zr, for 30-40% collision centrality at $\sqrt{s_{NN}} = 200$ GeV with different levels of CME signal injection (i.e., n_5/s =0.0, 0.1, 0.2) with 33% LCC (local Charge Conservation). In Au+Au collisions, f_{CME} doubles for n_5/s=0.1 and triples for n_5/s=0.2 compared to n_5/s=0. For isobaric collisions, the increase is less pronounced, and results are consistent within errors for Ru+Ru and Zr+Zr collisions. The SDM effectively distinguishes CME signals from background even in situations where LCC is present.

TABLE I: The f_{CME} values for different f_{DbCS} bins for 20-60% collision centralities for different CME-like signal injected AMPT samples [4].

f_{DbCS}	**CME**			
	50-60% ∼4% CME	40-50% ∼2% CME	30-40% ∼1.4% CME	20-30% ∼0.9% CME
0-10%	0.508±0.079	0.53±0.046	0.555±0.094	0.530±0.055
10-20%	0.533±0.146	0.56±0.085	0.615±0.175	0.540±0.115
20-30%	0.354±0.155	0.319±0.154	0.061±0.304	-
30-40%	0.010±0.246	-	-	-

STAR Results

The STAR data for Au+Au collisions and isobar collisions (Ru+Ru and Zr+Zr) at $\sqrt{s_{NN}} = 200$ GeV were analyzed for experimental studies. The values of δ and γ correlators in the top f_{DbCS} bins showed a significant increase compared to the average values in the corresponding centrality. CME-like events were observed in the top 20% f_{DbCS} bins in Au+Au and isobar collisions, suggesting glimpses of CME signal. Similar trends were observed for the ChS background, but with reduced magnitudes (i.e., $\Delta\gamma_{Data} > \Delta\gamma_{ChS}$). For Au+Au collisions, the CME fraction (f_{CME}) ranged from ∼8-13% in top f_{DbCS} bins for 10-50% collision centrality. For isobar collisions, no significant differences were observed when comparing the background-scaled $\Delta\gamma$ in the top 20% f_{DbCS} bins. The double ratio $\left(\frac{(\Delta\gamma_{Data}/\Delta\gamma_{Bkg})_{Ru}}{(\Delta\gamma_{Data}/\Delta\gamma_{Bkg})_{Zr}}\right)$ was fitted with a straight line (1.007 ± 0.003), indicating no significant enhancement of the CME signal in Ru+Ru collisions compared to Zr+Zr collisions, contrary to initial expectations. However, CME-like events are observed in the top 20% f_{DbCS} bins, representing approximately 2-5% CME signal in both isobar collisions. Overall, this research aims to understand and identify the CME phenomenon in heavy-ion collisions, develop methods for detecting CME-like events, and utilize theoretical models to study the effects of the magnetic field and axial charge density on the QGP's evolution.

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