Probing the Chiral Magnetic Wave in isobar collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV at RHIC-STAR

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Abstract. Chiral anomalies in Quantum Chromodynamics (QCD) can lead to phenomena such as the Chiral Magnetic Wave (CMW), which is a collective excitation of chiral charges in the presence of a magnetic field. Investigating this effect could provide valuable insights into the interaction between magnetic fields and chiral anomalies in heavy-ion collisions. The CMW is expected to induce charge-dependent elliptic flow in heavy-ion collisions. In this study, we explore the CMW by examining the difference in elliptic flow (v_2) between positively and negatively charged particles in Ru+Ru and Zr+Zr collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV at STAR. We analyse the covariance of v_2 and charge asymmetry (A_{ch}) for positive and negative charge particles, as well as their dependence on collision centrality, to detect the CMW signal. The results from both systems are compared to determine whether there is an enhanced signal in Ru+Ru collisions compared to Zr+Zr collisions, due to the presence of four additional protons in Ru.

Keywords: Chiral Magnetic Wave, charge asymmetry, heavy-ion collisions

1 Introduction

The Chiral Magnetic Wave (CMW) is a collective excitation in the quark-gluon plasma (QGP) arising from the interplay between the Chiral Magnetic Effect (CME) and the Chiral Separation Effect (CSE) [1, 2]. In the presence of a strong magnetic field, created by spectator protons, the CME induces a vector current along the magnetic field direction, while the CSE generates an axial current, resulting in the formation of an electric charge quadrupole moment leading to charge-dependent elliptic flow [3, 4]. The study of the CMW provides a unique opportunity to probe chiral symmetry restoration and explore the topological properties of the QGP [5].

The isobar collision system, involving $^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr, offers an ideal platform for investigating the CMW. These two colliding systems share similar initial conditions and bulk properties but differ in their nuclear charge, leading to a difference in the strength of the magnetic field [6]. Ruthenium, with four additional protons compared to Zirconium, is expected to give rise to an enhanced CMW signal while both systems having similar backgrounds.

2 Analysis details and Methodology

This analysis utilises Run 2018 data recorded by STAR Detector at RHIC for collisions of Ru+Ru and Zr+Zr at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. Approximately 1.6 billion events (for each Ru+Ru and Zr+Zr) are selected with primary vertex range $-35 < V_z < 25$ cm, and tracks satisfying pseudorapidity $|\eta| < 1$, transverse momentum range $0.15 < p_T < 2.0$ GeV/c and distance of closest approach (DCA) < 3 cm to the collision vertex, following the selection criteria of the CME isobar analysis [7].

Electric quadrupole moment induced by CMW may lead to charge-dependent elliptic flow (v_2) in relativistic heavy-ion collisions [8]. The difference in elliptic flow between negatively and positively charged particles (Δv_2) is theoretically hypothesised to scale linearly with the charge asymmetry (A_{ch}) defined as:

$$A_{ch} = \frac{N^+ - N^-}{N^+ + N^-} \tag{1}$$

where N^+ and N^- are the number of positively and negatively charged particles, respectively, in a event. The relationship between Δv_2 and A_{ch} is given by:

$$\Delta v_2 = v_2^- - v_2^+ \approx r A_{ch} \tag{2}$$

where v_2^- and v_2^+ denote the elliptic flow of negatively and positively charged particles, respectively. The parameter r, known as the slope, quantifies the strength of the electric quadrupole moment induced by the CMW. The slope parameter r can be determined by fitting Δv_2 vs A_{ch} in different centrality classes, where each class is divided into ten A_{ch} bins. Alternatively, it can be estimated using the covariance between $v_2^\pm$ and A_{ch} [9], given by:

$$\langle v_2^\pm A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^\pm \rangle \tag{3}$$

This method does not require dividing the centrality classes into A_{ch} bins and can be related to the slope as:

$$\langle v_2^\pm A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^\pm \rangle \approx \mp r \Big(\langle A_{ch}^2 \rangle - \langle A_{ch} \rangle^2 \Big)/2 = \mp r \sigma_{A_{ch}}^2/2 \tag{4}$$

The advantage of the covariance, also known as three particle correlator, is that it does not depend on the efficiency and detector acceptance. Furthermore, an integral covariance observable, defined as:

$$\Delta IC = \Big(\langle v_2^- A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^- \rangle \Big) - \Big(\langle v_2^+ A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^+ \rangle \Big) = r \sigma_{A_{ch}}^2 \tag{5}$$

also provides a way for estimating the slope parameter r. Unlike v_2, the CMW does not induce charge-dependent effects in higher-order anisotropy coefficients such as triangular flow (v_3) [10].

The Q-cumulant method [11] is employed to calculate anisotropic flow coefficients (v_n) by utilising multi-particle correlations derived from flow vectors

($Q_n \equiv \Sigma_{k=1}^{M} e^{in\psi_k}$). For two-particle correlations, the expressions for a single event and all events are given as:

$$\langle 2^{'} \rangle = \frac{p_n Q_n^* - m_q}{m_p M - m_q}, \qquad \langle\langle 2^{'} \rangle\rangle = \frac{\Sigma_{i=1}^{N} (w_{\langle 2^{'} \rangle})_i \langle 2^{'} \rangle_i}{\Sigma_{i=1}^{N} (w_{\langle 2^{'} \rangle})_i} \tag{6}$$

where p_n and Q_n^* denotes the flow vector components for particle of interest (POI) and reference particles (RFP), respectively. Here m_p and M are the number of POI and RFP, respectively, and m_q is the number of particles overlapping (labeled as both POI and RFP). The term $w_{\langle 2^{'} \rangle}$ is the event weight, typically taken as event multiplicity. The flow coefficient v_n can be estimated using:

$$v_n = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}} \tag{7}$$

where $d_n\{2\} = \langle\langle 2^{'} \rangle\rangle$ is differential second-order cumulant, and $c_n\{2\}$ represents reference flow calculated in the same way. To minimise short-range non-flow effects, an η gap of 0.3 is applied between POI and RFP [12].

3 Results and discussion

Fig. 1 (left) shows covariance of v_2 and A_{ch} for Ru+Ru and Zr+Zr collisions. Both collision systems exhibit similar covariance values for both positively and negatively charged particles, with splitting increasing from central to peripheral collisions. Fig. 1 (right) shows $\Delta IC/\sigma_{A_{ch}}^2$ (for v_2) calculated for Ru+Ru and Zr+Zr collisions. Similar values were observed for both collision systems. Despite Ru having four additional protons compared to Zr, which would theoretically generate a stronger magnetic field, no enhanced signal was detected in Ru+Ru collisions compared to Zr+Zr.
A similar analysis was conducted for the third-order harmonic coefficient (v_3). The covariance between v_3 and A_{ch} was evaluated as a function of centrality for both collision systems and is shown in Fig. 2 (left). Unlike the case of v_2, no significant splitting in the covariance of v_3 and A_{ch} was observed between positively

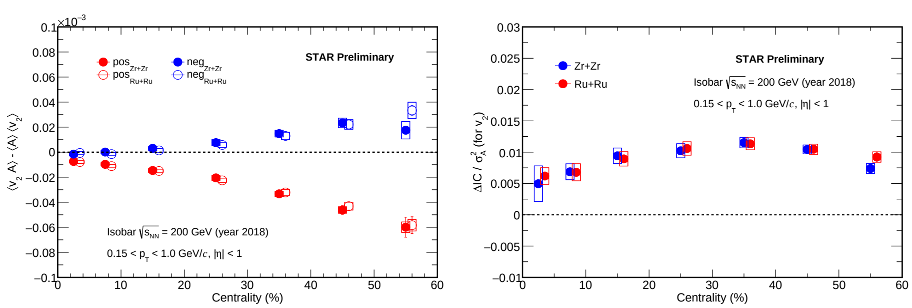

Fig. 1: (Left) Covariance between v_2 and A_{ch}, and (Right) $\Delta IC/\sigma_{A_{ch}}^2$ for v_2, in Ru+Ru and Zr+Zr collisions. Points are horizontally shifted for clarity.

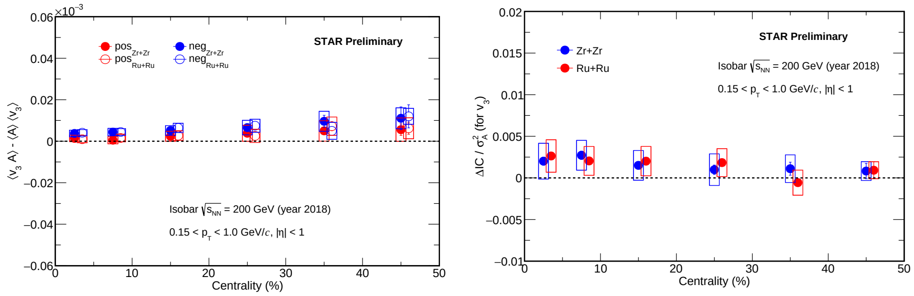

Fig. 2: (Left) Covariance between v_3 and A_{ch}, and (Right) $\Delta IC/\sigma^2_{A_{ch}}$ for v_3, in Ru+Ru and Zr+Zr collisions. Points are horizontally shifted for clarity.

and negatively charged particles for either Ru+Ru or Zr+Zr. $\Delta IC/\sigma^2_{A_{ch}}$ (for v_3) is also calculated and is shown in Fig. 2 (right). The values of $\Delta IC/\sigma^2_{A_{ch}}$ (for v_3) are close to zero and consistent across all centrality intervals in both Ru+Ru and Zr+Zr collisions.

4 Summary

This work presents an investigation of charge-dependent particle flow in relativistic heavy-ion collisions to probe the Chiral Magnetic Wave. Using data from approximately 1.6 billion each of Ru+Ru and Zr+Zr collisions at $\sqrt{s_{\rm NN}} = 200$ GeV collected by the STAR experiment, the study examines the correlation between elliptic flow (v_2) and charge asymmetry (A_{ch}) for positively and negatively charged particles. The results reveal a splitting in the covariance of v_2 and A_{ch} for positive and negative charges, which grows from central to peripheral collisions in both Ru+Ru and Zr+Zr systems. Despite having four more protons than Zr, no significant enhancement of the CMW signal is observed in Ru+Ru collisions. Additionally, no charge-dependent effects are observed in the third harmonic flow (v_3). Further techniques, such as Event Shape Engineering (ESE), may help isolate initial geometry effects and flow fluctuations, enabling a more precise measurement of CMW-driven signals.

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