Abstract

The chiral magnetic effect (CME) refers to charge separation along a strong magnetic field between left- and right-handed quarks, caused by interactions with topological gluon fields from QCD vacuum fluctuations. We present two approaches to handle the dominant elliptic flow ($v_2$) background in the three-particle correlator ($\Delta \gamma_{112}$), sensitive to CME.

In the first approach, we present the $\Delta \gamma_{112}$ and $\Delta \gamma_{123}$ measurements in U+U and Au+Au collisions. While hydrodynamic simulations including resonance decays and local charge conservation predict that $\Delta \gamma_{112}$ scaled by $N_{\text{part}}/v_2$ will be similar in U+U and Au+Au collisions, the projected B-field exhibits a distinct difference between the two systems and with varying $N_{\text{part}}$. Therefore, U+U and Au+Au collisions provide configurations with different expectations for both CME signal and background. Moreover, the three-particle observable $\Delta \gamma_{123}$ scaled by $N_{\text{part}}/v_3$ provide baseline measurement for only the background.

In the second approach, we handle the $v_2$ background by measuring $\Delta \gamma_{112}$ with respect to the planes of spectators measured by Zero Degree Calorimeters and participants measured by Time Projection Chamber. These measurements contain different amounts of contributions from CME signal (along B-field, due to spectators) and $v_2$ background (determined by the participant geometry). With the two $\Delta \gamma_{112}$ measurements, the possible CME signal and the background contribution can be determined. We report such a measurement in Au+Au collisions at $\sqrt{s_{NN}} = 27$ GeV with the newly installed event plane detector, and report the new findings in U+U system where the spectator-participant plane correlations are expected to differ from those in Au+Au collisions.

Keywords: QCD, heavy-ion collisions, chiral magnetic effect, spectators plane, participant plane.

1. Introduction

Quark interactions with fluctuating topological gluon field can induce chirality imbalance and local parity violation in quantum chromodynamics (QCD) [1–3]. This can lead to electric charge separation in the presence of a strong magnetic field ($B$), a phenomenon known as the chiral magnetic effect (CME) [4,5]. Such a $B$-field may present in non-central heavy-ion collisions, generated by the spectator protons at early times [6,7]. Extensive theoretical and experimental efforts have been devoted to the search for the CME-induced charge separation along $B$ in heavy-ion collisions [8–11].
2. Results

We present two approaches to handle the dominant elliptic flow ($v_2$) background in the observable $\Delta \gamma_{112}$ (charge separation across second-order event plane), which is sensitive to CME.

In the first approach, we present the $\Delta \gamma_{112}$, $\Delta \gamma_{123}$, and $\Delta \gamma_{132}$ measurements in $U+U$ and $Au+Au$ collisions. The systematic studies of the $\Delta \gamma_{112}$, $\Delta \gamma_{123}$, and $\Delta \gamma_{132}$ in those two systems can provide insights on the CME signal and background behaviors. Left top panel of Fig. 1 show the expected B-field from MC-Glauber calculations [12], which indicate that $U+U$ and $Au+Au$ have large B-field difference at large $N_{\text{part}}$. Charge separation driven by CME should be sensitive to such difference. On the other hand, background model studies using hydrodynamic simulations [13] indicate background to be similar between $U+U$ and $Au+Au$ as seen in Fig. 1 (left bottom panel). Furthermore, the third-harmonic event plane ($\psi_3$) is not expected to be correlated with the magnetic field. Thus, one does not expect CME contribute to $\Delta \gamma_{123}$.

Right panels in Fig. 1 show the $\Delta \gamma_{112}$, $\Delta \gamma_{123}$, and $\Delta \gamma_{132}$ measurements in $U+U$ and $Au+Au$ collisions. Background contributions based on hydrodynamic simulations with local charge conservation and global momentum conservation are included for comparison. The mixed-harmonic correlations do not follow signal-only or background-only expectations. Interesting features in ultra-central collisions are observed, which need further investigations.

In the second approach, we study the $\Delta \gamma$ measurements with respect to the participant plane ($\psi_{PP}$) and spectator plane ($\psi_{SP}$). The CME refers to charge separation along the strong magnetic field. The magnetic field is mainly produced by spectator protons in heavy-ion collisions, strongest perpendicular to the $\psi_{SP}$. On the other hand, the major elliptic flow background is determined by the participant geometry, largest in the $\psi_{PP}$. The $\psi_{SP}$ and the $\psi_{PP}$ can be assessed, experimentally in STAR, by the spectator neutrons in Zero Degree Calorimeters ($\psi_{ZDC}$) and by midrapidity particles in the Time Projection Chamber ($\psi_{TPC}$), respectively. The $\Delta \gamma$ measurements with respect to $\psi_{ZDC}$ and $\psi_{TPC}$ can therefore resolve the possible CME signal (and the background). Consider the measured $\Delta \gamma$ to be composed of the $v_2$ background and the CME signal:

$$\Delta \gamma_{\psi_{TPC}} = \Delta \gamma_{\text{CME}}{\psi_{TPC}} + \Delta \gamma_{\text{Bkg}}{\psi_{TPC}}, \quad \Delta \gamma_{\psi_{ZDC}} = \Delta \gamma_{\text{CME}}{\psi_{ZDC}} + \Delta \gamma_{\text{Bkg}}{\psi_{ZDC}}.$$  \hspace{1cm} (1)

Assuming the CME is proportional to the magnetic field squared and background is proportional to $v_2$ [14], both projected onto the $\psi$ direction, we have:

$$\Delta \gamma_{\text{CME}}{\psi_{TPC}} = a \Delta \gamma_{\text{CME}}{\psi_{ZDC}}, \quad \Delta \gamma_{\text{Bkg}}{\psi_{TPC}} = a \Delta \gamma_{\text{Bkg}}{\psi_{ZDC}}.$$  \hspace{1cm} (2)
where \( a = \langle \cos(2(\psi_{ZDC} - \psi_{TPC}) \rangle \). The parameter \( a \) can be readily obtained from the \( v_2 \) measurements:

\[
a = v_2[\psi_{ZDC}]/v_2[\psi_{TPC}].
\] (3)

The CME signal relative to the inclusive \( \Delta \gamma[\psi_{TPC}] \) measurement is then given by:

\[
I_{CME}^{EP} = \Delta \gamma_{CME}[\psi_{TPC}]/\Delta \gamma[\psi_{TPC}] = (A/a - 1)/(1/a^2 - 1),
\] (4)

where:

\[
A = \Delta \gamma[\psi_{ZDC}]/\Delta \gamma[\psi_{TPC}].
\] (5)

Note the only two free parameters \( a \) and \( A \) can be measured experimentally.

Applying this method, we have previously reported the measurements of possible CME signal fraction in 200 GeV Au+Au collisions, revealing dominant background contribution \cite{15}. Here, we report our findings in U+U collisions where the spectator-participant plane correlations are expected to differ from those in Au+Au collisions. Top panels in Fig. 2 show the measured \( v_2 \) (left) and \( \Delta \gamma \) (right) with respect to the \( \psi_{ZDC} \) and \( \psi_{TPC} \), as a functions of collision centrality. Bottom panels in Fig. 2 show the ratio of \( v_2 \) (left) measured with respect to the \( \psi_{ZDC} \) and that with respect to the \( \psi_{TPC} \), the \( a \) in Eq. 3 and the ratio of \( \Delta \gamma \) (right), the \( A \) in Eq. 5 as functions of the collision centrality in Au+Au 200 GeV and U+U 193 GeV. Data indicate difference in \( v_2 \) between central U+U and Au+Au. And the “a” and “A” are similar both in trend and magnitude, which indicate background contribution dominates in the \( \Delta \gamma_{12} \) measurements.

![Figure 2](image-url)

Fig. 2. The centrality dependence of the \( v_2 \) (top left) and \( \Delta \gamma \) (top right) measured with respect to the ZDC and TPC event planes. The corresponding ratios of the \( v_2 \) (bottom left) and \( \Delta \gamma \) (bottom right) measured with respect to these two planes.

Figure 3 shows the extracted CME fractions \( f_{CME}^{EP} \) at Au+Au 200 GeV and U+U 193 GeV. The combined result is \( f_{CME} = 8 \pm 4 \pm 8\% \).

In Au+Au collisions at \( \sqrt{s}\text{NN}=27 \text{ GeV} \), the differential \( \Delta \gamma \) measurements can be achieved by the newly installed Event Plane Detector (EPD) \((2.1 < |y| < 5.1)\) \cite{16}. At this energy, the rapidity of the colliding beam \( (y_{\text{beam}}=3.4) \) falls in the middle of EPD acceptance. Therefore, the EPD can provide an unique way to search for CME using both \( \psi_{pp} \), by outer EPD, and \( \psi_{SP} \), by inner EPD. Top panel in Fig. 4 shows the multiplicity and \( v_2 \) scaled \( \Delta \gamma \) measurements with respect to the \( \psi_{pp} \) and \( \psi_{SP} \) from EPD \cite{17}. The bottom panel shows that the corresponding ratio of \( v_2 \) or \( \Delta \gamma \) measurements with \( \psi_{SP} \) over the one with \( \psi_{pp} \) is consistent with unity with large uncertainty, indicating CME fraction is consistent with zero. More quantitative studies are in progress.
3. Summary

In summary, we report mixed-harmonic three-particle correlation studies in Au+Au and U+U collisions at $\sqrt{s_{NN}}=200$ and 193 GeV, respectively. The results indicate that background models capture most of the observed trends. Meanwhile interesting features are observed in ultra-central Au+Au and U+U collisions, which need further investigations. We also report $v_2$ and $\Delta y$ measurements with respect to $\psi_{ZDC}$ and $\psi_{TPC}$, and extract the possible CME signal fraction assuming the proportionality of the CME and background to the projection onto the corresponding plane. The extracted possible CME fraction is $(8 \pm 4 \pm 8\%)$ averaged over 20-50% centrality in Au+Au 200 GeV and U+U 193 GeV collisions. We further explore the Au+Au 27 GeV data, where the newly installed EPD can be sensitive to both spectator and participant planes.

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