An extended $R^{(2)}_{\Psi_m}(\Delta S_2)$ correlator for detecting and characterizing the Chiral Magnetic Wave

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The extended $R^{(2)}_{\Psi_m}(\Delta S_2)$ correlator is presented and examined for its efficacy to detect and characterize the quadrupole charge separation ($\Delta S_2$) associated with the purported Chiral Magnetic Wave (CMW) produced in heavy-ion collisions. Sensitivity tests involving varying degrees of proxy CMW signals injected into events simulated with the Multi-Phase Transport Model (AMPT), show that the $R^{(2)}_{\Psi_m}(\Delta S_2)$ correlator provides discernible responses for background- and CMW-driven charge separation. This distinction could aid identification of the CMW via measurements of the $R^{(2)}_{\Psi_m}(\Delta S_2)$ and $R^{(2)}_{\Psi_\alpha}(\Delta S_2)$ correlators, relative to the second- ($\Psi_2$) and third-order ($\Psi_3$) event planes. The tests also indicate a level of sensitivity that would allow for robust experimental characterization of the CMW signal.

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Heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) can lead to a magnetized chiral relativistic quark-gluon plasma (QGP) [1–3], in which the mass of fermions are negligible compared to the temperature and/or chemical potential. Such a plasma, which is akin to the primordial plasma in the early Universe [4,5] and several types of degenerate forms of matter in compact stars [6], have pseudo-relativistic analogs in Dirac and Weyl materials [7–11]. It is further characterized not only by an exactly conserved electric charge but also by an approximately conserved chiral charge, violated only by the quantum chiral anomaly [12,13].

The study of anomalous transport in magnetized chiral plasmas can give fundamental insight not only on the complex interplay of chiral symmetry restoration, axial anomaly and gluon topology in the QGP [4–14,17], but also on the evolution of magnetic fields in the early Universe [15–19]. Two of the principal anomalous processes in these plasmas [for electric and chiral charge chemical potential $\mu_{V,A} \neq 0$] are the chiral separation effect (CSE) [20,22] and the chiral magnetic effect (CME) [22]. The CSE is derived from the induction of a non-dissipative chiral axial current:

$$\vec{J}_A = \frac{e\vec{B}}{2\pi^2} \mu_A, \text{for } \mu_A \neq 0,$$

where $\mu_V$ is the vector (electric) chemical potential and $\vec{B}$ is the magnetic field. The CME is similarly characterized by the vector current:

$$\vec{J}_V = \frac{e\vec{B}}{2\pi^2} \mu_A, \text{for } \mu_A \neq 0,$$

where $\mu_A$ is the axial chemical potential that quantifies the axial charge asymmetry or imbalance between right- and left-handed quarks in the plasma [22,23].

The interplay between the CSE and CME in the QGP produced in heavy ion collisions, can lead to the production of a gapless collective mode – termed the chiral magnetic wave (CMW) [20], stemming from the coupling between the density waves of the electric and chiral charges. The propagation of the CMW is sustained by alternating oscillations of the local electric and chiral charge densities that feed into each other to ultimately transport positive (negative) charges out-of-plane and negative (positive) charges in-plane to form an electric quadrupole. Here, the reaction plane $\Psi_{RP}$, is defined by the impact vector $\vec{b}$ and the beam direction, so the poles of the quadrupole lie along the direction of the $\vec{B}$-field (out-of-plane) which is essentially perpendicular to $\Psi_{RP}$.

The electric charge quadrupole can induce charge-dependent quadrupole correlations between the positively- and negatively-charged particles produced in the collisions [2,4,6,20,23]. Such correlations can be measured with suitable correlators to aid full characterization of the CMW.

A pervasive approach employed in prior, as well as ongoing experimental studies of the CMW, is to measure the elliptic- or quadrupole flow difference between
negatively- and positively charged particles:  

\[ \Delta v_2 \equiv \frac{v^- - v^+}{r A_{ch}}, \]

\[ A_{ch} = \frac{(N^+ - N^-)}{(N^+ + N^-)} \]  

(3)
a function of charge asymmetry \( A_{ch} \). Here, \( N^\pm \) denotes the number of positively- (negatively-) charged hadrons measured in a given event; the slope parameter \( r \), which is experimentally determined from the measurements, is purported to give an estimate of the strength of the CMW signal. \( \Psi_{RP} \) is the azimuthal emission angle of the charged hadrons measured in a given event; the slope parameter \( m \), as the ratio:

\[ R_{\Psi_{m}}(\Delta S_d) = C_{\Psi_{m}}(\Delta S_d) / C_{\Psi_{m}}(\Delta S_d), \quad m = 2, 3, \]  

(4)

where \( d = 1 \) and \( 2 \) denote dipole and quadrupole charge separation respectively, and \( C_{\Psi_{m}}(\Delta S_d) \) and \( C_{\Psi_{m}}(\Delta S_d) \) are correlation functions designed to quantify the dipole and quadrupole charge separation \( \Delta S_d \), parallel and perpendicular (respectively) to the \( B \)-field, i.e., perpendicular and parallel (respectively) to \( \Psi_{RP} \).

The correlation functions used to quantify the dipole and quadrupole charge separation parallel to the \( B \)-field, are constructed from the ratio of two distributions:

\[ C_{\Psi_{m}}(\Delta S_d) = \frac{N_{\text{real}}(\Delta S_d)}{N_{\text{Shuffled}}(\Delta S_d)}, \quad m = 2, 3, \]  

(5)

where \( N_{\text{real}}(\Delta S_d) \) is the distribution over events, of charge separation relative to the \( \Psi_{m} \) planes in each event:

\[ \Delta S_d = \frac{1}{p} \sum_{p} \sin\left(\frac{\pi d}{3} \Delta \phi_m\right) - \frac{1}{n} \sum_{n} \sin\left(\frac{\pi d}{3} \Delta \phi_m\right), \]  

(6)

where \( n \) and \( p \) are the numbers of negatively- and positively charged hadrons, respectively, and \( \phi_m \) is the azimuthal emission angle of the charged hadrons. The \( N_{\text{Shuffled}}(\Delta S_d) \) distribution is similarly obtained from the same events, following random reassignment (shuffling) of the charge of each particle in an event.

This procedure ensures identical properties for the numerator and the denominator in Eq. except for the charge-dependent correlations which are of interest.

The correlation functions \( C_{\Psi_{m}}(\Delta S_d) \), used to quantify the dipole and quadrupole charge separation perpendicular to the \( B \)-field, are constructed with the same procedure outlined for \( C_{\Psi_{m}}(\Delta S_d) \), but with \( \Psi_{m} \) replaced by \( \Psi_{m} + \pi / m d \). Note that this rotation of \( \Psi_{m} \) maps the sine terms in Eq. into cosine terms.

The correlator \( R_{\Psi_{m}}(\Delta S_d) = C_{\Psi_{m}}(\Delta S_d) / C_{\Psi_{m}}(\Delta S_d) \), gives a measure of the magnitude of the charge separation (dipole and quadrupole) parallel to the \( B \)-field (perpendicular to \( \Psi_{2} \)), relative to that for charge separation perpendicular to the \( B \)-field (parallel to \( \Psi_{2} \)). Since the CME- and CMW-driven charge separations are strongly correlated with the \( B \)-field direction, the correlators \( R_{\Psi_{m}}(\Delta S_d) = C_{\Psi_{m}}(\Delta S_d) / C_{\Psi_{m}}(\Delta S_d) \) are insensitive to them, due to the absence of a strong correlation between the \( B \)-field and the orientation of the \( \Psi_{m} \) plane. For small systems such as \( p / d / He+Au \) and \( p / Pb \), a similar insensitivity is to be expected for \( R_{\Psi_{m}}(\Delta S_d) \), due to the weak correlation between the \( B \)-field and the orientation of the \( \Psi_{m} \) plane. For background-driven charge separation however, similar patterns are to be expected for both the \( R_{\Psi_{m}}(\Delta S_d) \) and \( R_{\Psi_{m}}(\Delta S_d) \) distributions.

The response and the sensitivity of the \( R_{\Psi_{m}}(\Delta S_1) \) correlator to CME-driven charge separation is detailed in Refs. \( 38, 41 \). For CMW-driven charge separation, \( R_{\Psi_{m}}(\Delta S_2) \) is expected to show an approximately linear dependence on \( \Delta S_2 \) for \( |\Delta S_2| \lesssim 3 \), due to a shift in the distributions for \( C_{\Psi_{m}}(\Delta S_d) \) relative to \( C_{\Psi_{m}}(\Delta S_d) \), induced by the CMW. Thus, the slope of the plot of \( R_{\Psi_{m}}(\Delta S_2) \) vs. \( \Delta S_2 \), encodes the magnitude of the CMW signal. This slope is also influenced by particle number fluctuations and the resolution of the \( \Psi_{m} \) plane which fluctuates about \( \Psi_{RP} \). The influence of the particle number fluctuations can be minimized by scaling \( \Delta S_2 \) by the width \( \sigma_{\Delta m} \) of the distribution for \( N_{\text{shuffled}}(\Delta S_2) \), i.e., \( \Delta S_2' = \Delta S_2 / \sigma_{\Delta m} \). Similarly, the effects of the event plane resolution can be accounted for by scaling \( \Delta S_2' \) by the resolution factor \( \delta_{\text{res}} \), i.e., \( \Delta S_2'' = \Delta S_2' / \delta_{\text{res}} \), where \( \delta_{\text{res}} \) is the event plane resolution. The efficacy of these scaling factors have been confirmed via detailed simulation studies, as well as with data-driven studies.

Our sensitivity studies for \( R_{\Psi_{m}}(\Delta S_2) \), relative to the \( \Psi_2 \) and \( \Psi_3 \) event planes, are performed with AMPT events in which varying degrees of proxy CMW-driven quadrupole charge separation were introduced. The AMPT model is known to give a good representation of the experimentally measured particle yields, spectra, flow, etc., \( 42, 43 \). Therefore, it provides a reasonable estimate of both the magnitude and the properties of the background-driven quadrupole charge separation expected in the data collected at RHIC and the LHC.
We simulated Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the same AMPT model version used in our prior studies \cite{41,42}; this version incorporates both string melting and local charge conservation. In brief, the model follows four primary stages: (i) an initial-state, (ii) a parton cascade phase, (iii) a hadronization phase in which partons are converted to hadrons, and (iv) a hadronic re-scattering phase. The initial-state essentially simulates the spatial and momentum distributions of mini-jet partons from QCD hard processes and soft string excitations as encoded in the HIJING model \cite{50,51}. The parton cascade considers the strong interactions among partons via elastic partonic collisions \cite{52}. Hadronization is simulated via a coalescence mechanism. After hadronization, the ART model is invoked to simulate baryon-baryon, baryon-meson and meson-meson interactions \cite{52}.

A formal mechanism for generation of the CMW is not implemented in the AMPT model. However, a proxy CMW-induced quadrupole charge separation can be implemented \cite{13,54} by interchanging the the position coordinates \((x, y, z)\) for a fraction \(f_q\) of the in-plane light quarks \((u, d\) and \(s)\) carrying positive (negative) charges with out-of-plane quarks carrying negative (positive) charges, at the start of the partonic stage. This procedure lends itself to two quadrupole charge configurations, relative to the in-plane and out-of-plane orientations. The first or Type (I), is for events with negative net charge \(A_{ch} < -0.01\) in which the \(u\) and \(d\) are set to be concentrated on the equator of the quadrupole (in-plane), while \(\bar{d}\) and \(\bar{u}\) quarks are set to be concentrated at the poles of the quadrupole (out-of-plane). The second or Type (II), is for events with positive net charge \(A_{ch} > -0.01\) in which the in-plane and out-of-plane quark configurations are swapped. The latter configuration was employed for the bulk of the AMPT events generated with proxy input signals. The magnitude of the proxy CMW signal is set by the fraction \(f_q\), which serves to characterize the strength of the quadrupole charge separation.

The AMPT events with varying degrees of proxy CMW signals were analyzed with the \(R_{q_{2\gamma}}^{(2)}(\Delta S'_{2})\) correlators to identify and quantify their response to the respective input signals, following the requisite corrections for particle number fluctuations \((\Delta S'_{2} = \Delta S_{2}/\sigma_{\Delta_{th}})\) and event-plane resolution \((\Delta S''_{2} = \Delta S_{2}/\delta_{\text{Res}})\), as described earlier.

The top panels of Fig. 1 confirm the expected Gaussian distributions for \(N(\Delta S''_{2})\), as well as the shift in its mean value as \(f_q\) increases; the mean value is zero for \(f_q = 0\) (a) and progressively shifts to \(\Delta S''_{2} < 0\) for \(f_q > 0\) (b and c). These CMW-induced shifts for \(f_q > 0\), are made more transparent in Figs. 2 (d)-(f) where the shift of \(C_{\Psi_{2}}(\Delta S'_{2})\) relative to the \(C_{\Psi_{2}}(\Delta S''_{2})\) correlation function is apparent c.f. Fig. 1 (f).

The \(R_{q_{2\gamma}}^{(2)}(\Delta S'_{2})\) and \(R_{q_{2\gamma}}^{(2)}(\Delta S''_{2})\) correlators, obtained for several input values of \(f_q\), are shown in Fig. 2. They indicate an essentially flat distribution for \(R_{q_{2\gamma}}^{(2)}(\Delta S'_{2})\) irrespective of the value of \(f_q\). These patterns are consistent with the expected insensitivity of \(R_{q_{2\gamma}}^{(2)}(\Delta S''_{2})\) to CMW-driven charge separation due to the absence of a strong correlation between the \(\vec{B}\)-field and the orientation of the \(\Psi_3\) plane. Figs. 2 (a)-(f) show that the \(R_{q_{2\gamma}}^{(2)}(\Delta S''_{2})\) correlator evolves from a flat distribution for \(f_q = 0\), to an approximately linear dependence on \(\Delta S''_{2}\) (for \(|\Delta S''_{2}| \lesssim 3\)) with slopes that reflect the increase in the magnitude of the input CMW-driven charge separa-
suggest that the collisions (

FIG. 2. $R_{\Psi_m}^{(2)}(\Delta S_2)$ vs. $\Delta S''_2$ for several input values of quadrupole charge separation characterized by $f_q$, for 10-50% Au+Au collisions ($\sqrt{s_{NN}} = 200$ GeV).

FIG. 3. Comparison of the simulated $R_{\Psi_m}^{(2)}(\Delta S_2)$ correlators for $q_2$ selected events in 10–50% central, Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (a); $v_2(q_2)$ vs. $q_2$ for the same $q_2$-selected events. Panel (c) shows a comparison of the slopes extracted from $R_{\Psi_m}^{(2)}$ vs. $\Delta S''_2$ distributions shown in panel (a).

FIG. 4. $f_q$ dependence of the slopes extracted from the $R_{\Psi_m}^{(2)}(\Delta S_2)$ vs. $\Delta S''_2$ distributions. Results are shown for 10-50% central Au+Au ($\sqrt{s_{NN}} = 200$ GeV) AMPT events.

dition with $f_q$. These patterns not only confirm the input quadrupole charge separation signal in each case; they suggest that the $R_{\Psi_m}^{(2)}(\Delta S_2)$ correlator is relatively insensitive to a possible $v_2,3$-driven background [and their associated fluctuations] as well as the local charge conservation effects implemented in the AMPT model. Note the essentially flat distributions for $R_{\Psi_m}^{(2)}(\Delta S_2')$ and for $R_{\Psi_m}^{(2)}(\Delta S''_2)$ when the input signal is set to zero.

This insensitivity can be further checked via the event-shape engineering, through fractional cuts on the distribution of the magnitude of the $q_2$ flow vector [55]. Here, the underlying notion is that elliptic flow $v_2$, which is a major driver of background correlations, is strongly correlated with $q_2$ [56, 57]. Thus, the magnitude of the background correlations can be increased(decreased) by selecting events with larger(smaller) $q_2$ values. Such selections were made by splitting each event into three sub-events; $A[\eta < -0.3], B[|\eta| < 0.4]$, and $C[|\eta| > 0.3]$, where sub-event $B$ was used to evaluate $q_2$, and the other sub-events used to evaluate $R_{\Psi_m}^{(2)}(\Delta S_2')$ via the methods described earlier.

Figure 3 shows a comparison of the $q_2$-selected $R_{\Psi_m}^{(2)}(\Delta S_2')$ distributions (a), $v_2$ (b) and the slopes (c) extracted from the distributions shown in panel (a), respectively. These results were obtained for 10-50% central Au+Au collisions with $f_q=5\%$. They indicate that while $v_2$ increases with $q_2$, the corresponding slope for the $R_{\Psi_m}^{(2)}$ correlators (Fig. 3(c)) show little, if any, change. This insensitivity to the value of $q_2$ is incompatible with a dominating influence of background-driven contributions to $R_{\Psi_m}^{(2)}(\Delta S_2')$. It is noteworthy that a further analysis performed for background-driven charge separation with strong local charge conservation, also indicated that $R_{\Psi_m}^{(2)}(\Delta S_2')$ is essentially insensitive to this background.

The $R_{\Psi_m}^{(2)}(\Delta S''_2)$ distributions shown in Fig. 2 indicate slopes that visibly increase with $f_q$. To quantify the measured signal strengths, we extracted the slope $S$, of the
FIG. 5. $A_{ch}$ dependence of the slopes extracted from the $R_{\Psi_2}^{(2)}(\Delta S_{2''}^\prime)$ vs. $\Delta S_{2''}^\prime$ distributions for different $A_{ch}$ selections. The inset shows a normalized distribution of $A_{ch}$. Results are shown for 10–50% central Au+Au ($\sqrt{s_{NN}} = 200$ GeV) AMPT events.

respective $R_{\Psi_2}^{(2)}(\Delta S_{2''}^\prime)$ distributions shown in the figure. Fig. 4 indicates a linear dependence of these slopes on $f_q$. It also shows that the magnitude and trends of $S$ are independent of the event plane used in the analysis. These results suggest that the $R_{\Psi_2}^{(2)}$ correlator not only suppresses background, but is sensitive to small CMW-driven charge separation in the presence of such backgrounds.

The slopes of the $R_{\Psi_2}^{(2)}(\Delta S_{2''}^\prime)$ vs. $\Delta S_{2''}^\prime$ distributions can also be explored as a function of the charge asymmetry $A_{ch}$ as shown in Fig. 5. Here, the $A_{ch}$ distribution shown in the inset, hints at the fact that the model parameters used in the AMPT simulations were chosen to give a positive net charge, when averaged over all events. Fig. 5 shows the expected decrease of $S$ with $A_{ch}$ for $A_{ch} < 0$. It also shows that the sign of $S$ can even be flipped for sufficiently large negative values of $A_{ch}$, in accord with expectations. Fig. 5 also shows that the slopes for $R_{\Psi_2}^{(2)}(\Delta S_{2''}^\prime)$ vs. $\Delta S_{2''}^\prime$ are insensitive to $A_{ch}$, as might be expected. These dependencies could serve as further aids to CMW signal detection and characterization in experimental measurements.

In summary, we have extended the $R_{\Psi_2}^{(1)}(\Delta S_1)$ correlator, previously used to measure CME-induced dipole charge separation, to include the $R_{\Psi_2}^{(2)}(\Delta S_2)$ correlator, which can be used to measure CMW-driven quadrupole charge separation. Validation tests involving varying degrees of proxy CMW signals injected into AMPT events, show that the $R_{\Psi_2}^{(2)}(\Delta S_2)$ correlator provides discernible responses for background- and CMW-driven charge separation which could aid robust identification of the CMW. They also indicate a level of sensitivity that would allow for a robust experimental characterization of the purported CMW signals via $R_{\Psi_2}^{(2)}(\Delta S_2)$ measurements in heavy-ion collisions.

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