A sensitivity study of the primary correlators used to characterize chiral-magnetically-driven charge separation

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A Multi-Phase Transport (AMPT) model is used to study the detection sensitivity of two of the primary correlators - $\Delta \gamma$ and $R\Psi_2$ - employed to characterize charge separation induced by the Chiral Magnetic Effect (CME). The study, performed relative to several event planes for different input “CME signals”, indicates a detection threshold for the fraction $f_{CME} = \Delta \gamma_{CME}/\Delta \gamma$, which renders the $\Delta \gamma$-correlator insensitive to values of the Fourier dipole coefficient $a_1 \lesssim 2.5\%$, that is larger than the purported signal(signal difference) for ion-ion(isobaric) collisions. By contrast, the $R\Psi_2$ correlator indicates concave-shaped distributions with inverse widths ($\sigma_{R\Psi_2}^{-1}$) that are linearly proportional to $a_1$, and independent of the character of the event plane used for their extraction. The sensitivity of the $R\Psi_2$ correlator to minimal CME-driven charge separation in the presence of realistic backgrounds, could aid better characterization of the CME in heavy-ion collisions.

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Ion-Ion collisions at both the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) create hot expanding fireballs of quark-gluon plasma (QGP) in the background of a strong magnetic field. Topologically nontrivial sphaleron transitions can induce different densities of right- and left-handed quarks in the plasma fireballs, resulting in a quark electric current along the $B$-field. This phenomenon of the generation of a quark electric current $(\vec{J}_Q)$ in the presence of a magnetic field is termed the chiral magnetic effect (CME):

$$\vec{J}_Q = \sigma_5 \vec{B}, \quad \sigma_5 = \mu_5 \frac{Q^2}{4\pi^2},$$

where, $\sigma_5$ is the chiral magnetic conductivity, $\mu_5$ is the chiral chemical potential that quantifies the axial charge asymmetry or imbalance between right- and left-handed quarks in the plasma, and $Q$ is the electric charge.

Full characterization of the CME, which manifests experimentally as the separation of electrical charges along the $B$-field, can give fundamental insight on anomalous transport and the interplay of chiral symmetry restoration, axial anomaly and gluon topology in the QGP.

Charge separation stems from the fact that the CME preferentially drives charged particles, originating from the same “P-odd domain”, along or opposite to the $\vec{B}$-field depending on their charge. This separation can be quantified via measurements of the first P-odd sine term $a_1$, in the Fourier decomposition of the charged-particle azimuthal distribution:

$$\frac{dN^{ch}}{d\phi} \propto [1 + 2 \sum_n v_n \cos(n\Delta \phi) + a_n \sin(n\Delta \phi) + ...]$$

where $\Delta \phi = \phi - \Psi_{RP}$ gives the particle azimuthal angle with respect to the reaction plane (RP) angle, and $v_n$ and $a_n$ denote the coefficients of $P$-even and $P$-odd Fourier terms, respectively. A direct measurement of the $P$-odd coefficients $a_n$, is not possible due to the strict global $P$ and $CP$ symmetry of QCD. However, their fluctuation and/or variance $\tilde{a}_n = \langle a_n^2 \rangle^{1/2}$ can be measured with suitable correlators.

The CME-driven charge separation is small because only a few particles from the same $P$-odd domain are correlated. Moreover, both the initial axial charge and the time evolution of the magnetic field (c.f. Eq. 1) are unconstrained theoretically, and it is uncertain whether an initial CME-driven charge separation could survive the signal-reducing effects of the reaction dynamics, and still produce a signal above the detection threshold. Besides, it is uncertain whether a charge separation that survives the expansion dynamics would still be discernible in the presence of the well-known background correlations which contribute and complicate the measurement of CME-driven charge separation. Thus, the correlators used to characterize the CME, not only need to suppress background-driven charge-dependent correlations, such as the ones from resonance decays, charge ordering in jets, etc., but should also be sensitive to small charge separation signals in the presence of these
The strength of the proxy CME signal is regulated by the collisions at RHIC and the LHC. Therefore, it provides a realistic estimate of both the tally measured particle yields, spectra, flow, etc., [24–29].

For these sensitivity tests, we simulated Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV with the new version of the AMPT model that incorporates string melting and local charge conservation. There are four primary ingredients for each of these collisions: (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 prior to kinetic freeze-out. The initial-state mainly simulates the spatial and momentum distributions of minijet partons from QCD hard processes and soft string excitations as encoded in the HIJING model [30, 31]. The parton cascade takes account of the strong interactions among partons through elastic partonic collisions controlled by a parton interaction cross section [32]. Hadronization, or the conversion from partonic to hadronic matter, is simulated via a coalescence mechanism. Subsequent to hadronization, the ART model is used to simulate baryon-baryon, baryon-meson and meson-meson interactions [33].

A formal mechanism for the CME is not implemented in AMPT. However, modifications can be made to the model to mimic CME-induced charge separation [34] by switching the \( p_y \) values of a fraction of the downward moving \( u (\bar{d}) \) quarks with those of the upward moving \( \bar{u} (d) \) quarks to produce a net charge-dipole separation in the initial-state. Here, the \( x \) axis is along the direction of the impact parameter \( b \), the \( z \) axis points along the beam direction, and the \( y \) axis is perpendicular to the \( x \) and \( z \) directions, i.e., the direction of the proxy \( \vec{B} \)-field. The strength of the proxy CME signal is regulated by the fraction \( f_0 \) of the initial input charge separation [31, 33]:

\[
f_0 = \frac{N_{\uparrow}^{(+)} - N_{\uparrow}^{(-)}}{N_{\uparrow}^{(+)} + N_{\uparrow}^{(-)}}, \quad f_0 = \frac{4}{\pi} a_1 \tag{3}
\]

where \( N \) is the number of a given species of quarks, “\( + \)” and “\( - \)” denote positive and negative charges, respectively, and \( \uparrow \) and \( \downarrow \) represent the directions along and opposite to that of the \( y \) axis. Eq. [3] also shows that the fraction \( f_0 \) is related to the \( P \)-odd dipole term \( a_1 \), defined in Eq. [2]. Note that this initial partonic charge separation \( a_1 \) is different from the final hadrons’ charge separation \( a_1 \), often referred to in the literature and implemented in other models. Cross-checks made with the Anomalous-Viscous Fluid Dynamics model [36, 37] suggests that the two are linearly proportional to a very good approximation. Simulated events, generated for a broad set of \( f_0 \) values, were analyzed with both the \( \Delta \gamma \) and the \( R_{\Psi_2}(\Delta S) \) correlators, to evaluate their respective sensitivity as discussed below quantitatively.

The charge-dependent correlator, \( \gamma_{\alpha\beta} \), has been widely used at RHIC [38–44] and the LHC [22, 45] in ongoing attempts to identify and quantify CME-driven charge separation:

\[
\gamma_{\alpha\beta} = \left\langle \cos \left( \phi_\alpha^{(\pm)} + \phi_\beta^{(\pm)} - 2\Psi_2 \right) \right\rangle, \quad \Delta \gamma = \gamma_{\beta} - \gamma_{\alpha},
\]

where \( \phi_\alpha, \phi_\beta \) denote the azimuthal emission angles for like-sign (+ +, − −) and unlike-sign (− +, + −) particle pairs. The question as to whether the experimental measurements for \( \Delta \gamma \) indicate the CME, remain inconclusive because of several known sources of background correlations that can account for most, if not all, of the measurements [14, 18–21].

A recent embellishment to the \( \Delta \gamma \) correlator is the proposal to leverage the ratios of \( \Delta \gamma \) and elliptic flow \( (v_2) \) measurements, obtained relative to the reaction plane \( (\Psi_{RP}) \) and the participant plane \( (\Psi_{PP}) \):

\[
r_1 = \frac{\Delta \gamma(\Psi_{RP})}{\Delta \gamma(\Psi_{PP})}, \quad r_2 = \frac{v_2(\Psi_{RP})}{v_2(\Psi_{PP})} \tag{4}
\]

to simultaneously constrain the CME and background (Bkg) contributions to \( \Delta \gamma \) [16, 17]:

\[
\Delta \gamma_{\Psi_{PP}} = \Delta \gamma_{\text{CME}(\Psi_{PP})} + \Delta \gamma_{\text{Bkg}(\Psi_{PP})}, \quad \Delta \gamma_{\Psi_{RP}} = \Delta \gamma_{\text{CME}(\Psi_{RP})} + \Delta \gamma_{\text{Bkg}(\Psi_{RP})}, \tag{5}
\]

and

\[
\Delta \gamma_{\text{CME}(\Psi_{PP})} = r_2 \times \Delta \gamma_{\text{CME}(\Psi_{RP})}, \quad \Delta \gamma_{\text{Bkg}(\Psi_{RP})} = r_2 \times \Delta \gamma_{\text{Bkg}(\Psi_{PP})}, \tag{6}
\]

where it is assumed that the CME is proportional to the magnetic field squared and the background (Bkg) is proportional to \( v_2 \). The fraction of the measured \( \Delta \gamma_{\Psi_{PP}} \), attributable to the CME, can then be estimated as [16]:

\[
f_{\text{CME}} = \frac{\Delta \gamma_{\text{CME}(\Psi_{PP})}}{\Delta \gamma_{\Psi_{PP}}} = f_1/f_2, \quad \text{where} \quad f_1 = \frac{r_2 - 1}{r_2} \quad \text{and} \quad f_2 = \frac{1}{r_2} - 1. \tag{7}
\]

The underlying idea behind the constraints expressed in Eqs. [4] - [7] is that the \( v_2 \)-driven background is more strongly correlated with \( \Psi_{PP} \) [determined by the maximal particle density in the elliptic azimuthal anisotropy and the beam axis], than with \( \Psi_{RP} \) [determined by the impact vector \( \vec{b} \) and the beam direction]. By contrast, the \( \vec{B} \)-field, which drives the CME, behaves oppositely – weaker correlation with \( \Psi_{PP} \) and stronger correlation...
with $\Psi_{RP}$. We will employ this new method of leveraging the measurements of $r_1$ and $r_2$ to extract $f_{CME}$ from AMPT events as discussed below.

The operational details of the construction and the response of the $R_{\Psi_m}(\Delta S)$ correlator is described in Refs. [18] and [49]. It is constructed for each event plane $\Psi_m$, as the ratio:

$$R_{\Psi_m}(\Delta S) = C_{\Psi_m}(\Delta S)/C_{\Psi_m}^\perp(\Delta S), \quad m = 2, 3,$$

where $C_{\Psi_m}(\Delta S)$ and $C_{\Psi_m}^\perp(\Delta S)$ are correlation functions that quantify charge separation $\Delta S$, parallel and perpendicular (respectively) to the $\vec{B}$-field. $C_{\Psi_2}(\Delta S)$ measures both CME- and background-driven charge separation while $C_{\Psi_3}^\perp(\Delta S)$ measures only background-driven charge separation. The absence of a strong correlation between the orientation of the $\Psi_3$ plane and the $\vec{B}$-field, also renders $C_{\Psi_3}(\Delta S)$ and $C_{\Psi_3}^\perp(\Delta S)$ insensitive to a CME-driven charge separation, but not to the background, so it can give crucial additional insight on the relative importance of background-driven and CME-driven charge separation. However, they are not required for the sensitivity studies presented in this work.

The correlation functions used to quantify charge separation parallel to the $\vec{B}$-field, are constructed from the ratio of two distributions [54]:

$$C_{\Psi_m}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)}, \quad m = 2, 3,$$

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

$$\Delta S = \langle s_{p^+}^m \rangle - \langle s_{n^+}^m \rangle,$$

$$\Delta S = \frac{\sum \sin(\Psi_m \Delta \varphi_m)}{p} - \frac{\sum \sin(\Psi_m \Delta \varphi_m)}{n},$$

where $n$ and $p$ are the numbers of negatively- and positively charged hadrons in an event, $\Delta \varphi_m = \phi - \Psi_m$ and $\phi$ is the azimuthal emission angle of the charged hadrons. The $N_{\text{shuffled}}(\Delta S)$ 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. (9) except for the charge-dependent correlations which are of interest. The correlation functions $C_{\Psi_m}(\Delta S)$, that quantify charge separation perpendicular to the $\vec{B}$-field, are constructed with the same procedure outlined for $C_{\Psi_m}(\Delta S)$, but with $\Psi_m$ replaced by $\Psi_m + \pi/m$, to ensure that a possible CME-driven charge separation does not contribute to $C_{\Psi_m}^\perp(\Delta S)$.

The magnitude of the CME-driven charge separation is reflected in the width $\sigma_{\Psi_2}$ of the concave-shaped distribution for $R_{\Psi_2}(\Delta S)$, which is also influenced by particle number fluctuations and the resolution of $\Psi_2$. That is, stronger CME-driven signals lead to narrower concave-shaped distributions (smaller widths), which are made broader by particle number fluctuations and poorer event-plane resolutions. The influence of the particle number fluctuations can be minimized by scaling $\Delta S$ by the width $\sigma_{\Delta S_{\text{sh}}}$ of the distribution for $N_{\text{shuffled}}(\Delta S)$ i.e., $\Delta S' = \Delta S/\sigma_{\Delta S_{\text{sh}}}$. Similarly, the effects of the event plane resolution can be accounted for by scaling $\Delta S'$ by the resolution factor $\delta_{\text{Res}}$, i.e., $\Delta S'' = \Delta S' \times \delta_{\text{Res}}$, where $\delta_{\text{Res}} = \sigma_{\text{Res}} \times e(1 - \sigma_{\text{Res}}^2)^{1/2}$ and $\sigma_{\text{Res}}$ is the event plane resolution [48].

The 10–50% central AMPT events, generated for several input values of charge separation $f_0$ (cf. Eq. (3)), relative to the reaction- $\Psi_{RP}$, spectator- $\Psi_{SP}$ and the participant plane $\Psi_{PP}$, were analyzed to extract $f_{CME}$ via the $\Delta \gamma$ correlator and $\sigma_{\Psi_2}$ via the $R_{\Psi_2}(\Delta S)$ correlator. Approximately $10^6$ events were generated for each value of $f_0$. The analyses included charged particles with
The change from negative to positive values for $f_{\text{CME}}$ (cf. Fig. 3) suggests a “turn-on” $a_1$ value, below which, the modified $\Delta \gamma$ correlator (cf. Eqs. 3 - 7) is unable to detect a CME-driven signal. This detection threshold could pose a significant limitation for CME detection and characterization with this correlator, because it is comparable to, or larger than the magnitude of the CME-driven charge separation expected in actual experiments. Equally important is the fact that $f_{\text{CME}} \leq 0.0$ does not give a robust indication of the absence of a CME signal. The latter could have important implications for the interpretation of current and future $f_{\text{CME}}$ measurements.

The sensitivity of the $R_{\Psi_{XX}}(\Delta S)$ ($XX = \text{RP, SP, PP}$) correlator to varying degrees of input CME-driven charge separation (characterized by $a_1$) was studied using the same AMPT events employed in the leveraged $\Delta \gamma$ study. Figs. 4(a) - (e) show the $R_{\Psi_{XX}}(\Delta S)$ correlator distributions obtained for 10 - 50% central Au+Au collisions, relative to $\Psi_{\text{RP}}$, $\Psi_{\text{SP}}$ and $\Psi_{\text{PP}}$ for several values of $a_1$ as indicated. In each of these plots, $\Delta S$ is scaled to account for the effects of number fluctuations and event plane resolution as outlined earlier and in Ref. [48].

The concave-shaped distribution, apparent in each panel of Fig. 4(b) - (e), confirms the input charge separation signal in each case; note the weakly convex-shaped distribution for $a_1 = 0$ in Fig. 4(a). Note as well that in contrast to the $\Delta \gamma$ correlator, the $R_{\Psi_{XX}}(\Delta S)$ distributions are independent of the plane used to measure them, suggesting that they are less sensitive to the $v_2$ driven background and their associated fluctuations. The apparent decrease in the widths of these distributions with $a_1$, also confirm the expected trend.

To quantify the implied signal strengths, we extracted the width $\sigma_{R_{\Psi_{XX}}}$ of the $R_{\Psi_{XX}}(\Delta S)$ distributions obtained for the respective values of $a_1$. Fig. 4(f) shows the inverse widths $\sigma_{R_{\Psi_{XX}}}^{-1}$ vs. $a_1$. They indicate an essentially linear dependence on $a_1$ (note the dotted line fit). Here, it is noteworthy that for $a_1 \lesssim 0.5\%$, significant additional statistics are required to determine $\sigma_{R_{\Psi_{XX}}}$ with good accuracy. These results suggests that the $R_{\Psi_{XX}}(\Delta S)$ correlator not only suppresses background, but is sensitive to very small CME-driven charge separation in the presence of such backgrounds.

In summary, we have used both the $R_{\Psi_{XX}}(\Delta S)$ correlator and an event-plane-leveraged version of the $\Delta \gamma$ correlator to analyze AMPT events with varying degrees of input proxy CME signals. Our sensitivity study indicates a turn-on threshold for $f_{\text{CME}} = \Delta \gamma_{\text{CME}}/\Delta \gamma$, which renders the leveraged $\Delta \gamma$-correlator insensitive to input signals with $a_1 \lesssim 2.5\%$. The magnitude of this detection threshold, which is comparable to that for the purported signal in heavy ion collisions and less than the signal difference for isobaric collisions, could pose significant re-
striictions on its use to detect the CME. By contrast, the $a_1$-dependent $R_{\Psi_2}(\Delta S)$ correlators indicate inverse widths $\sigma_{R_{\Psi_2}}^{-1}$ that are linearly dependent on $a_1$, and independent of the character of the event plane ($\Psi_{RP}$, $\Psi_{SP}$ or $\Psi_{PP}$) used for their extraction. These results not only have implications for the interpretation of current and future $f_{\text{CME}} = \Delta \gamma_{\text{CME}} / \Delta \gamma$ measurements; they further indicate that the $R_{\Psi_2}(\Delta S)$ correlator can provide robust quantification of minimal CME-driven charge separation in the presence of realistic backgrounds, that could aid characterization of the CME in RHIC and LHC collisions.

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