



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

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ABSTRACT

A Multi-Phase Transport (AMPT) model is used to study the detection sensitivity of two of the primary correlators – $\Delta\gamma$ and R_{ψ_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 $f_{\text{CME}} = \Delta\gamma_{\text{CME}}/\Delta\gamma$, 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_{ψ_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_{ψ_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 [1–3]. Topologically nontrivial sphaleron transitions [via the axial anomaly] [4–6] can induce different densities of right- and left-handed quarks in the plasma fireballs, resulting in a quark electric current along the \vec{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) [7,8]:

$$\vec{J}_Q = N_c \mu_5 \frac{Q^2}{2\pi^2} \vec{B}, \quad (1)$$

where, N_c is the color factor, μ_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 [8–11].

Full characterization of the CME, which manifests experimentally as the separation of electrical charges along the \vec{B} -field [7,8], can give fundamental insight on anomalous transport and the interplay of chiral symmetry restoration, axial anomaly and gluon topology in the QGP [12–16].

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 [17]:

$$\frac{dN^{\text{ch}}}{d\phi} \propto 1 + 2 \sum_n (v_n \cos(n\Delta\phi) + a_n \sin(n\Delta\phi) + \dots) \quad (2)$$

where $\Delta\phi = \phi - \Psi_{\text{RP}}$ 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 \mathcal{P} and \mathcal{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.

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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 (cf. 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 [14,18–22]. 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 backgrounds. The latter requirement is especially important for ongoing measurements [at RHIC] designed to detect the small signal difference between the Ru+Ru and Zr+Zr isobars [23].

In this work we use the AMPT model [24] with varying amounts of input charge separation ΔS , characterized by the partonic dipole term a_1 , to study the detection sensitivity of the $\Delta\gamma$ and the $R_{\Psi_2}(\Delta S)$ correlators. The model is known to give a good representation of the experimentally measured particle yields, spectra, flow, etc., [24–29]. Therefore, it provides a realistic estimate of both the magnitude and the properties of the background-driven charge separation one might encounter in the data sets collected at RHIC and the LHC.

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 mini-jet 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 [34,35]:

$$f_0 = \frac{N_{\uparrow(\downarrow)}^{+(-)} - N_{\downarrow(\uparrow)}^{+(-)}}{N_{\uparrow(\downarrow)}^{+(-)} + N_{\downarrow(\uparrow)}^{+(-)}}, \quad f_0 = \frac{4}{\pi} a_1 \quad (3)$$

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, $\Delta\gamma$ [17], has been widely used at RHIC [38–44] and the LHC [22,45] in ongoing attempts to identify and quantify CME-driven charge separation:

$$\gamma_{\alpha\beta} = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{EP}) \rangle, \quad \Delta\gamma = \gamma_{OS} - \gamma_{SS},$$

where Ψ_{EP} is the azimuthal angle of the event plane, ϕ denote the particle azimuthal emission angles, α, β denote the electric charge (+) or (−) and SS and OS represent same-sign (++, −−) and opposite-sign (+−) charges. 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 (Ψ_{RP}) and the participant plane (Ψ_{PP})

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

to simultaneously constrain the CME and background (Bkg) contributions to $\Delta\gamma$ [46,47]:

$$\begin{aligned} \Delta\gamma(\Psi_{PP}) &= \Delta\gamma_{CME}(\Psi_{PP}) + \Delta\gamma_{Bkg}(\Psi_{PP}), \\ \Delta\gamma(\Psi_{RP}) &= \Delta\gamma_{CME}(\Psi_{RP}) + \Delta\gamma_{Bkg}(\Psi_{RP}), \end{aligned} \quad (5)$$

and

$$\begin{aligned} \Delta\gamma_{CME}(\Psi_{PP}) &= r_2 \times \Delta\gamma_{CME}(\Psi_{RP}), \\ \Delta\gamma_{Bkg}(\Psi_{RP}) &= r_2 \times \Delta\gamma_{Bkg}(\Psi_{PP}), \end{aligned} \quad (6)$$

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 [46];

$$\begin{aligned} f_{CME} &= \Delta\gamma_{CME}(\Psi_{PP}) / \Delta\gamma(\Psi_{PP}) = f_1 / f_2, \\ \text{where } f_1 &= \frac{r_1}{r_2} - 1 \quad \text{and} \quad f_2 = \frac{1}{r_2^2} - 1. \end{aligned} \quad (7)$$

The underlying idea behind the constraints expressed in Eqs. (4) – (7) is that the v_2 -driven background is more strongly correlated with Ψ_{PP} [determined by the maximal particle density in the elliptic azimuthal anisotropy and the beam axis], than with Ψ_{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 Ψ_{PP} and stronger correlation with Ψ_{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. [48] and [49]. It is constructed for each event plane Ψ_m , as the ratio:

$$R_{\Psi_m}(\Delta S) = C_{\Psi_m}(\Delta S) / C_{\Psi_m}^\perp(\Delta S), \quad m = 2, 3, \quad (8)$$

where $C_{\Psi_m}(\Delta S)$ and $C_{\Psi_m}^\perp(\Delta S)$ are correlation functions that quantify charge separation ΔS , parallel and perpendicular (respectively) to the \vec{B} -field. $C_{\Psi_2}(\Delta S)$ measures both CME- and background-driven

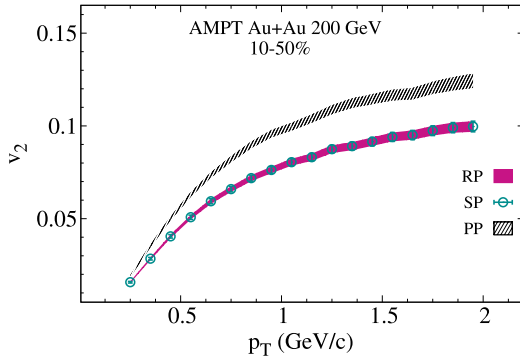


Fig. 1. Comparison of the simulated $v_2(p_T)$ obtained in 10–50% Au+Au collisions ($\sqrt{s_{NN}} = 200$ GeV) with Ψ_{RP} , Ψ_{SP} and Ψ_{PP} , see text.

charge separation while $C_{\Psi_2}^{\perp}(\Delta S)$ measures only background-driven charge separation. The absence of a strong correlation between the orientation of the Ψ_3 plane and the \vec{B} -field, also renders $C_{\Psi_3}(\Delta S)$ and $C_{\Psi_2}^{\perp}(\Delta S)$ 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 [50]:

$$C_{\Psi_m}(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)}, \quad m = 2, 3, \quad (9)$$

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

$$\Delta S = \langle S_p^{h+} \rangle - \langle S_n^{h-} \rangle, \quad (10)$$

$$\Delta S = \frac{\sum_1^p \sin(\frac{m}{2} \Delta \varphi_m)}{p} - \frac{\sum_1^n \sin(\frac{m}{2} \Delta \varphi_m)}{n}, \quad (11)$$

where n and p are the numbers of negatively- and positively charged hadrons in an event, $\Delta \varphi_m = \phi - \Psi_m$ and ϕ 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 $C_{\Psi_m}^{\perp}(\Delta S)$, 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 Ψ_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 σ_{Ψ_2} of the concave-shaped distribution for $R_{\Psi_2}(\Delta S)$, which is also influenced by particle number fluctuations and the resolution of Ψ_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 ΔS by the width $\sigma_{\Delta S}$ of the distribution for $N_{\text{shuffled}}(\Delta S)$ i.e., $\Delta S' = \Delta S / \sigma_{\Delta S}$. Similarly, the effects of the event plane resolution can be accounted for by scaling $\Delta S'$ by the resolution factor δ_{Res} , i.e., $\Delta S'' = \Delta S' \times \delta_{\text{Res}}$, where $\delta_{\text{Res}} = \sigma_{\text{Res}} \times e^{(1-\sigma_{\text{Res}})^2}$ and σ_{Res} is the event plane resolution [48].

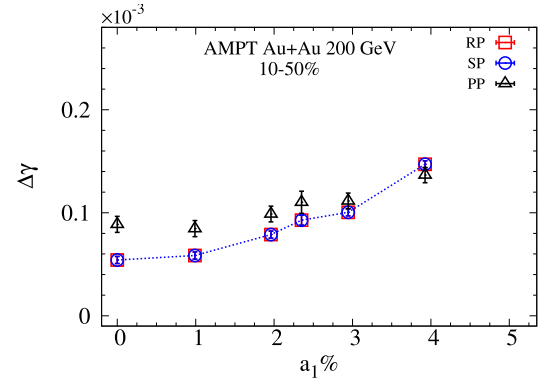


Fig. 2. Comparison of the simulated $\Delta\gamma$ obtained in 10–50% Au+Au collisions ($\sqrt{s_{NN}} = 200$ GeV) with respect to Ψ_{RP} , Ψ_{SP} and Ψ_{PP} , for several input charge separation fractions characterized by the P -odd dipole coefficient a_1 .

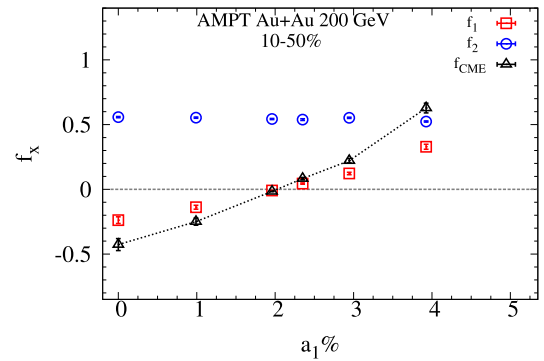


Fig. 3. The dependence of f_1 , f_2 and f_{CME} on different input charge separation characterized by the dipole coefficient a_1 , see Eqs. (3) and (7). Results are shown for 10–50% central Au+Au ($\sqrt{s_{NN}} = 200$ GeV) AMPT events.

The empirical exponential factor is obtained from extensive data-driven studies involving both experimental and simulated data.

The 10–50% central AMPT events, generated for several input values of charge separation f_0 (cf. Eq. (3)), relative to the reaction- Ψ_{RP} , spectator- Ψ_{SP} and the participant plane Ψ_{PP} , were analyzed to extract f_{CME} via the $\Delta\gamma$ correlator and σ_{Ψ_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 $|\eta| < 1.0$ and transverse momentum $0.2 < p_T < 2$ GeV/c. To enhance the statistical significance of the measurements, the participant plane Ψ_{PP} was determined with charged hadrons in the range $2.5 < \eta < 4.0$. The charge separation of charged hadrons in $|\eta| < 1.0$ were then measured relative to Ψ_{PP} . Representative results are summarized in Figs. 1 – 4.

Fig. 1 compares the $v_2(p_T)$ obtained with Ψ_{RP} , Ψ_{SP} and Ψ_{PP} for 10–50% Au+Au collisions. It shows the expected similarity between the results for Ψ_{RP} and Ψ_{SP} , as well as larger values for Ψ_{PP} that confirm the enhanced fluctuations associated with the participant geometry and consequently, the initial-state eccentricity ε_2 . This difference is essential for the procedure outlined in Eqs. (4) – (7).

A similar comparison of the $\Delta\gamma$ results for the three planes is given in Fig. 2. It shows that for $a_1 \lesssim 3\%$, the $\Delta\gamma$ values obtained with Ψ_{PP} are larger than those obtained with Ψ_{RP} and Ψ_{SP} ; there is also little, if any, difference between the values obtained with Ψ_{RP} and Ψ_{SP} over the full range of the input a_1 values. This latter trend is to be expected since the fluctuation of Ψ_{SP} about Ψ_{RP} is small. For $a_1 \gtrsim 4\%$, the $\Delta\gamma$ values for Ψ_{RP} and Ψ_{SP} become larger than the ones for Ψ_{PP} (not shown in Fig. 2), consistent with a stronger influence from the proxy CME-driven charge separation.

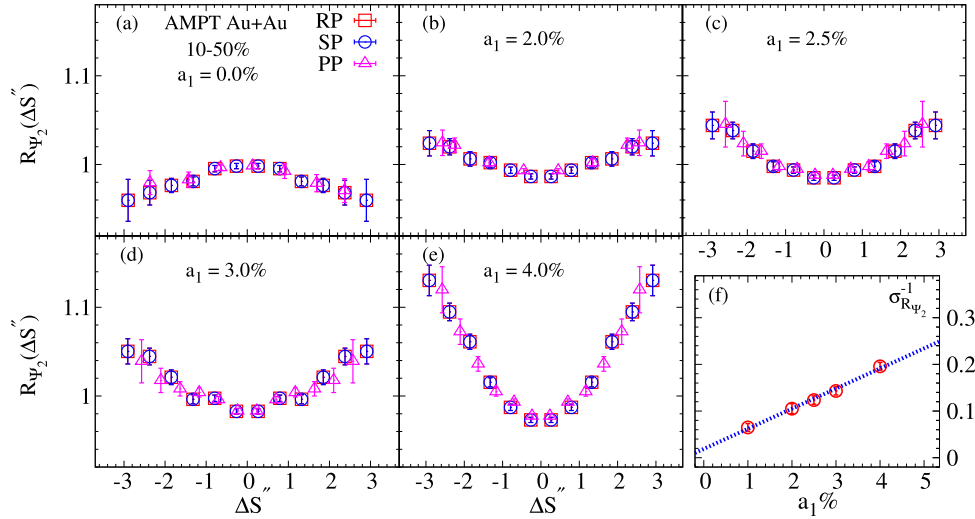


Fig. 4. Comparison of the $R_{\Psi_2}(\Delta S)$ correlators obtained with respect to Ψ_{RP} , Ψ_{SP} and Ψ_{PP} for several a_1 values, as indicated, for 10–50% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (a) – (e). Panel (f) shows the a_1 dependence of the inverse widths $\sigma_{R_{\Psi_2}}^{-1}$, extracted from the $R_{\Psi_2}(\Delta S)$ distributions; the dotted line represents a linear fit.

The extracted values of v_2 and $\Delta\gamma$, with respect to Ψ_{PP} and Ψ_{SP} were used to evaluate f_1 , f_2 and f_{CME} following the procedure outlined in Eqs. (4) – (7) [46]. Fig. 3 summarizes the a_1 dependence of f_1 , f_2 and f_{CME} . It indicates a flat f_2 , consistent with the expectation that the v_2 fluctuations should be relatively insensitive to the introduction of small a_1 signals. By contrast, f_1 and f_{CME} , which are both negative for $a_1 \lesssim 2.5\%$, show an increase with a_1 and become positive for $a_1 \gtrsim 2.5\%$. The negative values observed for f_{CME} suggests that for $a_1 \lesssim 2.5\%$, the correlator is either (i) unable to make the robust distinction between signal and background required to measure the input proxy CME-signal or (ii) the assumptions used to estimate f_{CME} are invalid. Note that f_{CME} is only 0.6 even for a relatively large input signal of $a_1 = 4.0\%$.

The change from negative to positive values for f_{CME} (cf. Fig. 3) suggests a “turn-on” a_1 value, below which, the modified $\Delta\gamma$ correlator (cf. Eqs. (4) – (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 $f_{CME} \leq 0.0$ 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_{CME} measurements.

The sensitivity of the $R_{\Psi_{XX}}(\Delta S)$ ($XX = RP, SP, PP$) 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 Ψ_{RP} , Ψ_{SP} and Ψ_{PP} for several values of a_1 as indicated. In each of these plots, ΔS 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 confirms the expected trend.

To quantify the implied signal strengths, we extracted the width $\sigma_{R_{\Psi_2}}$ of the $R_{\Psi_2}(\Delta S)$ distributions obtained for the respective values of a_1 . Fig. 4(f) shows the inverse widths $\sigma_{R_{\Psi_2}}^{-1}$ 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 $\sigma_{R_{\Psi_2}}$ with good accuracy. These results suggest that the $R_{\Psi_m}(\Delta S)$ 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 $R_{\Psi_2}(\Delta S)$ 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 $f_{CME} = \Delta\gamma_{CME}/\Delta\gamma$, 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 restrictions 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 (Ψ_{RP} , Ψ_{SP} or Ψ_{PP}) used for their extraction. These results not only have implications for the interpretation of current and future $f_{CME} = \Delta\gamma_{CME}/\Delta\gamma$ 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] V. Skokov, A.Yu. Illarionov, V. Toneev, Estimate of the magnetic field strength in heavy-ion collisions, *Int. J. Mod. Phys. A* 24 (2009) 5925–5932, arXiv:0907.1396 [nucl-th].
- [2] L. McLerran, V. Skokov, Comments about the electromagnetic field in heavy-ion collisions, *Nucl. Phys. A* 929 (2014) 184–190, arXiv:1305.0774 [hep-ph].
- [3] Kirill Tuchin, Electromagnetic field and the chiral magnetic effect in the quark-gluon plasma, *Phys. Rev. C* 91 (2015) 064902, arXiv:1411.1363 [hep-ph].
- [4] N.S. Manton, Topology in the Weinberg-Salam theory, *Phys. Rev. D* 28 (1983) 2019.
- [5] Frans R. Klinkhamer, N.S. Manton, A saddle point solution in the Weinberg-Salam theory, *Phys. Rev. D* 30 (1984) 2212.
- [6] Guy D. Moore, Do we understand the sphaleron rate?, in: *Strong and Electroweak Matter. Proceedings, Meeting, SEWM 2000, Marseille, France, June 13–17, 2000, June 2000*, pp. 82–94, arXiv:hep-ph/0009161 [hep-ph].
- [7] Dmitri Kharzeev, Parity violation in hot QCD: why it can happen, and how to look for it, *Phys. Lett. B* 633 (2006) 260–264, arXiv:hep-ph/0406125.
- [8] Kenji Fukushima, Dmitri E. Kharzeev, Harmen J. Warringa, The chiral magnetic effect, *Phys. Rev. D* 78 (2008) 074033, arXiv:0808.3382 [hep-ph].
- [9] T. Son Dam, Piotr Surowka, Hydrodynamics with triangle anomalies, *Phys. Rev. Lett.* 103 (2009) 191601, arXiv:0906.5044 [hep-th].
- [10] Valentin I. Zakharov, Chiral magnetic effect in hydrodynamic approximation, *Lect. Notes Phys.* 871 (2012) 295, <https://doi.org/10.1007/978-3-642-37305-3-11>, arXiv:1210.2186 [hep-ph], 2013.
- [11] Kenji Fukushima, Views of the chiral magnetic effect, *Lect. Notes Phys.* 871 (2013) 241–259, arXiv:1209.5064 [hep-ph].
- [12] Guy D. Moore, Marcus Tassler, The sphaleron rate in SU(N) gauge theory, *J. High Energy Phys.* 02 (2011) 105, arXiv:1011.1167 [hep-ph].
- [13] M. Mace, S. Schlichting, R. Venugopalan, Off-equilibrium sphaleron transitions in the Glasma, *Phys. Rev. D* 93 (2016) 074036, arXiv:1601.07342 [hep-ph].
- [14] Jinfeng Liao, Volker Koch, Adam Bzdak, On the charge separation effect in relativistic heavy ion collisions, *Phys. Rev. C* 82 (2010) 054902, arXiv:1005.5380 [nucl-th].
- [15] D.E. Kharzeev, J. Liao, S.A. Voloshin, G. Wang, Chiral magnetic and vortical effects in high-energy nuclear collisions—a status report, *Prog. Part. Nucl. Phys.* 88 (2016) 1–28, arXiv:1511.04050 [hep-ph].
- [16] Volker Koch, Soeren Schlichting, Vladimir Skokov, Paul Sorensen, Jim Thomas, Sergei Voloshin, Gang Wang, Ho-Ung Yee, Status of the chiral magnetic effect and collisions of isobars, *Chin. Phys. C* 41 (2017) 072001, arXiv:1608.00982 [nucl-th].
- [17] Sergei A. Voloshin, Parity violation in hot QCD: how to detect it, *Phys. Rev. C* 70 (2004) 057901, arXiv:hep-ph/0406311 [hep-ph].
- [18] Fuqiang Wang, Effects of cluster particle correlations on local parity violation observables, *Phys. Rev. C* 81 (2010) 064902, arXiv:0911.1482 [nucl-ex].
- [19] Adam Bzdak, Volker Koch, Jinfeng Liao, Azimuthal correlations from transverse momentum conservation and possible local parity violation, arXiv:1008.4919 [nucl-th], 2010.
- [20] Soren Schlichting, Scott Pratt, Charge conservation at energies available at the BNL relativistic heavy ion collider and contributions to local parity violation observables, *Phys. Rev. C* 83 (2011) 014913, arXiv:1009.4283 [nucl-th].
- [21] Berndt Muller, Andreas Schafer, Charge fluctuations from the chiral magnetic effect in nuclear collisions, *Phys. Rev. C* 82 (2010) 057902, arXiv:1009.1053 [hep-ph].
- [22] Vardan Khachatryan, et al., CMS, Observation of charge-dependent azimuthal correlations in p-Pb collisions and its implication for the search for the chiral magnetic effect, *Phys. Rev. Lett.* 118 (12) (2017) 122301, <https://doi.org/10.1103/PhysRevLett.118.122301>, arXiv:1610.00263 [nucl-ex].
- [23] J. Adam, et al., STAR, Methods for a blind analysis of isobar data collected by the STAR collaboration, arXiv:1911.00596 [nucl-ex], 2019.
- [24] Zi-Wei Lin, Che Ming Ko, Bao-An Li, Bin Zhang, Subrata Pal, A multi-phase transport model for relativistic heavy ion collisions, *Phys. Rev. C* 72 (2005) 064901, arXiv:nucl-th/0411110 [nucl-th].
- [25] Guo-Liang Ma, Zi-Wei Lin, Predictions for $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb collisions from a multi-phase transport model, *Phys. Rev. C* 93 (2016) 054911, arXiv:1601.08160 [nucl-th].
- [26] Guo-Liang Ma, Decomposition of the jet fragmentation function in high-energy heavy-ion collisions, *Phys. Rev. C* 88 (2013) 021902, arXiv:1306.1306 [nucl-th].
- [27] Guo-Liang Ma, Medium modifications of jet shapes in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV within a multiphase transport model, *Phys. Rev. C* 89 (2014) 024902, arXiv:1309.5555 [nucl-th].
- [28] Adam Bzdak, Guo-Liang Ma, Elliptic and triangular flow in p+Pb and peripheral Pb+Pb collisions from parton scatterings, *Phys. Rev. Lett.* 113 (2014) 252301, arXiv:1406.2804 [hep-ph].
- [29] Mao-Wu Nie, Peng Huo, Jiangyong Jia, Guo-Liang Ma, Multiparticle azimuthal cumulants in p+Pb collisions from a multiphase transport model, *Phys. Rev. C* 98 (2018) 034903, arXiv:1802.00374 [hep-ph].
- [30] Xin-Nian Wang, Miklos Gyulassy, HIJING: a Monte Carlo model for multiple jet production in p p, p A and A A collisions, *Phys. Rev. D* 44 (1991) 3501–3516.
- [31] Miklos Gyulassy, Xin-Nian Wang, HIJING 1.0: a Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions, *Comput. Phys. Commun.* 83 (1994) 307, arXiv:nucl-th/9502021 [nucl-th].
- [32] Bin Zhang, ZPC 1.0.1: a parton cascade for ultrarelativistic heavy ion collisions, *Comput. Phys. Commun.* 109 (1998) 193–206, arXiv:nucl-th/9709009 [nucl-th].
- [33] Bao-An Li, Che Ming Ko, Formation of superdense hadronic matter in high-energy heavy ion collisions, *Phys. Rev. C* 52 (1995) 2037–2063, arXiv:nucl-th/9505016 [nucl-th].
- [34] Guo-Liang Ma, Bin Zhang, Effects of final state interactions on charge separation in relativistic heavy ion collisions, *Phys. Lett. B* 700 (2011) 39–43, arXiv:1101.1701 [nucl-th].
- [35] Ling Huang, Mao-Wu Nie, Guo-Liang Ma, Sensitivity analysis for observables of the chiral magnetic effect using a multiphase transport model, *Phys. Rev. C* 101 (2020) 024916, arXiv:1906.11631 [nucl-th].
- [36] Shuzhe Shi, Yin Jiang, Elias Lileskov, Jinfeng Liao, Anomalous chiral transport in heavy ion collisions from anomalous-viscous fluid dynamics, *Ann. Phys.* 394 (2018) 50–72, arXiv:1711.02496 [nucl-th].
- [37] Yin Jiang, Shuzhe Shi, Yi Yin, Jinfeng Liao, Quantifying the chiral magnetic effect from anomalous-viscous fluid dynamics, *Chin. Phys. C* 42 (2018) 011001, arXiv:1611.04586 [nucl-th].
- [38] B.I. Abelev, et al., STAR, Azimuthal charged-particle correlations and possible local strong parity violation, *Phys. Rev. Lett.* 103 (2009) 251601, arXiv:0909.1739 [nucl-ex].
- [39] B.I. Abelev, et al., STAR, Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy ion collisions, *Phys. Rev. C* 81 (2010) 054908, arXiv:0909.1717 [nucl-ex].
- [40] L. Adamczyk, et al., STAR, Fluctuations of charge separation perpendicular to the event plane and local parity violation in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at the BNL relativistic heavy ion collider, *Phys. Rev. C* 88 (2013) 064911, arXiv:1302.3802 [nucl-ex].
- [41] L. Adamczyk, et al., STAR, Measurement of charge multiplicity asymmetry correlations in high-energy nucleus-nucleus collisions at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. C* 89 (2014) 044908, arXiv:1303.0901 [nucl-ex].
- [42] L. Adamczyk, et al., STAR, Beam-energy dependence of charge separation along the magnetic field in Au+Au collisions at RHIC, *Phys. Rev. Lett.* 113 (2014) 052302, arXiv:1404.1433 [nucl-ex].
- [43] S.T.A.R. Prithwish Tribedy, Disentangling flow and signals of chiral magnetic effect in U+U, Au+Au and p+Au collisions, in: *Quark Matter 2017, Chicago, Illinois, USA, 2017, 2017*, arXiv:1704.03845 [nucl-ex].
- [44] Jie Zhao, Hanlin Li, Fuqiang Wang, Isolating the chiral magnetic effect from backgrounds by pair invariant mass, *Eur. Phys. J. C* 79 (2019) 168, arXiv:1705.05410 [nucl-ex].
- [45] Betty Abelev, et al., ALICE, Charge separation relative to the reaction plane in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, *Phys. Rev. Lett.* 110 (2013) 012301, arXiv:1207.0900 [nucl-ex].
- [46] Hao-jie Xu, Jie Zhao, Xiaobao Wang, Hanlin Li, Zi-Wei Lin, Caiwan Shen, Fuqiang Wang, Varying the chiral magnetic effect relative to flow in a single nucleus-nucleus collision, *Chin. Phys. C* 42 (2018) 084103, arXiv:1710.07265 [nucl-th].
- [47] Sergei A. Voloshin, Estimate of the signal from the chiral magnetic effect in heavy-ion collisions from measurements relative to the participant and spectator flow planes, *Phys. Rev. C* 98 (2018) 054911, arXiv:1805.05300 [nucl-ex].
- [48] Niseem Magdy, Shuzhe Shi, Jinfeng Liao, N. Ajitanand, Roy A. Lacey, New correlator to detect and characterize the chiral magnetic effect, *Phys. Rev. C* 97 (2018) 061901, arXiv:1710.01717 [physics.data-an].
- [49] Niseem Magdy, Shuzhe Shi, Jinfeng Liao, Peifeng Liu, Roy A. Lacey, Examination of the observability of a chiral magnetically driven charge-separation difference in collisions of the $^{96}_{44}\text{Ru} + ^{96}_{44}\text{Ru}$ and $^{96}_{40}\text{Zr} + ^{96}_{40}\text{Zr}$ isobars at energies available at the BNL relativistic heavy ion collider, *Phys. Rev. C* 98 (2018) 061902, arXiv:1803.02416 [nucl-ex].
- [50] N.N. Ajitanand, Roy A. Lacey, A. Taranenko, J.M. Alexander, A new method for the experimental study of topological effects in the quark-gluon plasma, *Phys. Rev. C* 83 (2011) 011901, arXiv:1009.5624 [nucl-ex].