Isolating the chiral magnetic effect from backgrounds by pair invariant mass

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ABSTRACT: Topological gluon configurations in quantum chromodynamics induce quark chirality imbalance in local domains, which can result in the chiral magnetic effect (CME)—an electric charge separation along a strong magnetic field. Experimental searches for the CME in relativistic heavy ion collisions via the charge-dependent azimuthal correlator ($\Delta \gamma$) suffer from large backgrounds arising from particle correlations (e.g. due to resonance decays) coupled with the elliptic anisotropy. We propose differential measurements of the $\Delta \gamma$ as a function of the pair invariant mass ($m_{\text{inv}}$), by restricting to high $m_{\text{inv}}$ thus relatively background free, and by studying the $m_{\text{inv}}$ dependence to separate the possible CME signal from backgrounds. We demonstrate by model studies the feasibility and effectiveness of such measurements for the CME search.
1 Introduction

Topological gluon configurations may form in local metastable domains in quantum chromodynamics (QCD) [1–3]. Under the approximate chiral symmetry restoration, interactions with those gluon fields can change the overall chirality of quarks in those domains, resulting in a non-vanishing topological charge [4, 5]. The chirality imbalance yields an electric charge separation under a strong magnetic field, a phenomenon called the chiral magnetic effect (CME) [6–8]. Strong magnetic fields are generated at early times by the spectator protons in relativistic heavy ion collisions, raising the possibility to detect the CME in those collisions [9, 10]. An observation of the CME would confirm a fundamental property of QCD and is therefore of great importance [11]. CME-like phenomena are not specific only to QCD and may have been observed in condensed matter physics [12].

A commonly used variable to measure the CME-induced charge separation in heavy ion collisions is the three-point correlator [9],

$$\gamma \equiv \langle \cos(\alpha + \beta - 2\psi) \rangle,$$

where $\alpha$ and $\beta$ are the azimuthal angles of two particles and $\psi$ is that of the reaction plane (span by the beam and impact parameter directions of the colliding nuclei). Charge separation along the magnetic field ($\vec{B}$), which is perpendicular to $\psi$ on average, would yield different values of $\gamma$ for particle pairs of same-sign (SS) and opposite-sign (OS) charges: $\gamma_{SS} = -1$, $\gamma_{OS} = +1$. However, there exist background correlations unrelated to the CME [9, 13–20]. For example, transverse momentum conservation induces correlations among particles enhancing back-to-back pairs [14–18]. This background is independent of particle charges, affecting SS and OS pairs equally and cancels in the difference, $\Delta\gamma \equiv \gamma_{OS} - \gamma_{SS}$. Recent experimental searches have thus focused on the $\Delta\gamma$ observable [11]; the CME would yield $\Delta\gamma > 0$. There are, however, also mundane physics that differ between SS and OS pairs. One such physics is resonance/cluster decays [9, 13–18], more significantly affecting OS pairs than SS pairs. Backgrounds arise from the
coupling of elliptical anisotropy ($v_2$, a common phenomenon in heavy ion collisions [21]) of resonances/clusters and the angular correlations between their decay daughters (non-flow) [9, 13, 14, 17]. Take $\rho \rightarrow \pi^+\pi^-$ as an example. The background is $(\Delta \gamma)_\rho = r_\rho \gamma_\rho$, where $r_\rho = N_\rho/(N_\pi^+ N_\pi^-)$ is the relative abundance of $\rho$-decay pairs over all OS pairs, and 

$$\gamma_\rho \equiv \langle f_\rho v_{2,\rho} \rangle = \langle \cos(\alpha + \beta - 2\phi_\rho) \cos(2(\phi_\rho - \psi)) \rangle$$

quantifies the $\rho$ decay angular correlations coupled with its $v_2$ [9, 22].

Experimentally, significant positive $\Delta \gamma$ values have been observed at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) [23–27]. The relative background and CME contributions are under extensive debate [28]. The recent observations of comparable $\Delta \gamma$ in small system collisions [29–32], where any CME signals would average to zero [29, 33], challenge the CME interpretation of the measured $\Delta \gamma$ in heavy ion collisions. The major difficulty in distinguishing CME from backgrounds with the $\Delta \gamma$ observable is their similar behaviors with respect to the event multiplicity [31, 32]. This is because the magnetic field strength, to which the CME is sensitive, has a similar dependence as the $v_2$ (backgrounds) on the event multiplicity [10, 34–37]. There have been various proposals and attempts to reduce or eliminate the backgrounds [22, 30, 38–42]. The central idea is to “hold” the magnetic field fixed (in a narrow centrality) and vary the event-by-event $v_2$ from statistical and dynamical fluctuations [37, 40, 43]. The first attempt was carried out by STAR [40] where a charge asymmetry observable was analyzed as a function of the observed event-by-event $v_2$. A linear dependence was observed, expected from background, and the intercept was extracted representing a background-suppressed signal. ALICE [42] divided their data in each collision centrality according to $v_2$ in one phase space, and found the $\Delta \gamma$ to be approximately proportional to the $v_2$ in the phase space of the $\Delta \gamma$ measurement, consistent with background contributions. However, as recently pointed out by two of us [22], those methods suppressing background may not completely eliminate it. Another way to help search for the CME is to compare isobaric collisions [43], where the magnetic fields differ and the backgrounds are expected to be the same [44]. However, these simple expectations may not be correct because of the non-identifical isobaric nuclear structures [45].

A new method to search for the CME, as we demonstrate in this article, is to eliminate the resonance background contributions using particle pair invariant mass ($m_{inv}$) by (i) applying a lower cut on the $m_{inv}$, and (ii) fitting the low $m_{inv}$ region by a two-component model. We illustrate our method using the AMPT (A Multi-Phase Transport) model [46] and a toy Monte Carlo (MC) simulation. In both, the resonance masses are sampled from Breit-Wigner distributions [47, 48]. We use pions within pseudorapidity $|\eta| < 1$ and 0.2 $< p_T < 2$ GeV/c.

2 High-$m_{inv}$ region: a transport model study with null CME

AMPT is a parton transport model [46]. It consists of a fluctuating initial condition, parton elastic scatterings, quark coalescence for hadronization, and hadronic interactions. The initial condition is taken from HIJING [49]. The string melting version [50] is used in this study. Two-body elastic parton scatterings are treated with Zhang’s Parton Cascade [51],
where the parton scattering cross section is set to 3 mb. After partons stop interacting, a simple quark coalescence model is applied to describe the hadronization process that converts partons into hadrons [52]. Subsequent interactions of these formed hadrons are modeled by a hadron cascade [52]. However, it is known that this version of the hadron cascade does not conserve charge, which is critical to the charge correlation study here. The hadronic scatterings, while responsible for the majority of the $v_2$ mass splitting, are unimportant for the main development of $v_2$ [53, 54], and thus may not be critical for the CME backgrounds. We thus turn off hadronic cascade in AMPT for our study here, as was done in Ref. [55]. AMPT has been quite successful in describing variety of heavy ion data [48]. It reproduces approximately the measured particle yields and distributions, and therefore should approximately describe those of resonances as well, which is relevant to the CME background study here. We simulate Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV of various impact parameter ($b$) ranges. For simplicity we use the known reaction plane in our analysis, fixed at $\psi = 0$.

Figure 1(a) shows the $m_{\text{inv}}$ distribution of the excess OS over SS pion pairs ($N \equiv N_{\text{OS}} - N_{\text{SS}}$), with $b = 6.8$-8.2 fm (corresponding to the 20-30% centrality of Au+Au collisions [56], and average pion multiplicities $N_{\pi^+} \approx N_{\pi^-} \approx 210$ within $|\eta| < 1$). The $\rho$ peak is evident; the lower mass peaks are from Dalitz decays of $\eta$ and $\omega$ mesons (the $K_S$ is kept stable in AMPT). Figure 1(b) shows the $\Delta \gamma$ as a function of $m_{\text{inv}}$. The $\rho$ contribution is clearly seen in the $\rho$ mass region. Since no CME is present in AMPT, the finite $\Delta \gamma$ at $m_{\text{inv}} \lesssim 2$ GeV/$c^2$ must be due to correlations from resonance decays, or generally, correlated pion pairs. This has been observed before [31, 55]. For $m_{\text{inv}} > 2$ GeV/$c^2$ where resonance contribution to the OS over SS excess is small, the $\Delta \gamma$ value is essentially zero, as expected.

Figure 2 shows the $\Delta \gamma$ in AMPT from all pairs and $\Delta \gamma(m_{\text{inv}} > 2$ GeV/$c^2$) from pairs with $m_{\text{inv}} > 2$ GeV/$c^2$. The positive $\Delta \gamma$ is due to backgrounds; in $\Delta \gamma(m_{\text{inv}} > 2$ GeV/$c^2$) this background is essentially eliminated, and as expected the result is consistent with zero. With the $11 \times 10^6$ AMPT events simulated for 200 GeV Au+Au collisions with $b = 6.6$-8.2 fm, the inclusive $\Delta \gamma$ value is $(8.1 \pm 0.1) \times 10^{-5}$, and $\Delta \gamma(m_{\text{inv}} > 2$ GeV/$c^2$) = $(-0.6 \pm 0.8) \times 10^{-5}$. This represents a null signal with an upper limit of 20% of the inclusive $\Delta \gamma$ with 98% confidence level (CL).

3 High-$m_{\text{inv}}$ region: a toy model study with finite CME

In light of the AMPT results, we propose to apply a lower $m_{\text{inv}}$ cut in real data analysis to search for the CME. We illustrate this point further by using a toy MC with input CME signal. Our toy model generates primordial $\pi^\pm, K_S$, and resonances ($\rho, \eta, \omega$), and decays the $K_S$ and resonances (via both two- and three-body decays [47]). Particle kinematics are sampled according to

$$\frac{d^2N}{dp_T d\eta d\phi} = \frac{d^2N}{2\pi dp_T d\eta} \left(1 + 2v_2 \cos 2\phi + 2a_1 \sin \phi \right),$$

(3.1)

where $a_1$ is the CME signal parameter [9]. The particle $dN/dy, p_T$ spectra, and $v_2$ correspond to the 40-50% centrality of Au+Au collisions; they are as same as those used in
Figure 1. (a) Excess of opposite-sign (OS) over same-sign (SS) pion pairs, and (b) $\Delta \gamma \equiv \gamma_{\text{OS}} - \gamma_{\text{SS}}$ as a function of pair invariant mass ($m_{\text{inv}}$). Used are total $11 \times 10^6$ AMPT events of 200 GeV Au+Au collisions with $b = 6.8$-8.2 fm.

Figure 2. The $\Delta \gamma$ as a function of impact parameter $b$ in 200 GeV Au+Au collisions by AMPT for all pion pairs (black markers) and for pairs with $m_{\text{inv}} > 2$ GeV/$c^2$ (red markers).

Ref. [57] except that the primordial pion $p_T$ spectra are parameterized here with a better agreement with data at high $p_T$, and we have added $K_S$. The pion multiplicities within $|\eta| < 1$ are $N_{\pi^+} \approx N_{\pi^-} \approx 100$ and those of primordial pions are $N_{\pi^+}^{\text{prim}} \approx N_{\pi^-}^{\text{prim}} \approx 60$. The $K_S$ multiplicity is taken to be $1/5$ of the measured $\rho$'s [58], because some $K_S$'s would have both their decay pions reconstructed as primary particles in experiments (such as STAR). We generate $200 \times 10^6$ events with an input CME signal of overall strength $a_1 = \pm 0.008$ for
primordial $\pi^\pm$; for $K_S$ and resonances $a_1 = 0$. Our input CME is independent of the particle $p_T$. This is supported by a recent theoretical study [59], where the CME is insensitive to $p_T$ once $p_T$ is above 0.2 GeV/$c$.

Figure 3(a) shows the relative OS pair excess, $r(m_{inv}) \equiv (N_{OS} - N_{SS})/N_{OS}$ as a function of $m_{inv}$ from the toy MC. The $K_S$ and $\rho$ peaks are evident. Figure 3(b) shows the $\Delta \gamma(m_{inv})$: the $K_S$ and $\rho$ contributions are clear. The inclusive $\Delta \gamma$ from Fig. 3(b) is $(24.5 \pm 0.1) \times 10^{-5}$; our input CME signal of $2a_1^2$, diluted by $(N_{\pi}^{prim}/N_{\pi})^2$, is $4.6 \times 10^{-5}$, about 20% of the inclusive $\Delta \gamma$ value. The $\Delta \gamma(m_{inv})$ distribution in Fig. 3(b) has a pedestal corresponding to the input CME signal. The pedestal extends to high $m_{inv}$ (not shown) where resonance backgrounds vanish. A lower $m_{inv}$ cut removes backgrounds to $r(m_{inv})$ but not the CME signal. The value $\Delta \gamma(m_{inv}>2 \text{ GeV}/c^2) = (4.5 \pm 0.8) \times 10^{-5}$ is consistent with the input CME signal, and it would present a $5\sigma$ measurement.

The CME is generally believed to be a low-$p_T$ phenomenon [5], and would thus be more prominent in the low $m_{inv}$ region. With a $m_{inv} > 2 \text{ GeV}/c^2$ cut we used here, the particle average $p_T$ is typically 1.2 GeV/$c$. This is not very high and the CME may still be present above such a mass cut. Moreover, a recent study [59] indicates that the CME signal is rather independent of $p_T$ at $p_T > 0.2 \text{ GeV}/c$, suggesting that the signal can persist to high $m_{inv}$. Nevertheless, our proposal to apply a lower $m_{inv}$ cut will eliminate resonance contributions to $\Delta \gamma$: any measured remaining positive $\Delta \gamma$ would point to the interesting possibility of the existence of the CME. A null measurement at high $m_{inv}$, on the other hand, does not necessarily mean null CME also at low $m_{inv}$.

4 Low-$m_{inv}$ region: a two-component model fit

In what follows, we illustrate a fit method to potentially identify the possible CME at low $m_{inv}$. Still use $\rho \rightarrow \pi^+\pi^-$ as an example, and consider the event to be composed of primordial pions containing CME signals ($\gamma_{\text{CME}}$) and common (charge-independent) backgrounds, such as momentum conservation ($\gamma_{\text{m.c.}}$) [16, 18], and decay pions containing correlations from the decay [9, 17, 22]. We have

$$\Delta \gamma = \frac{N_{SS}(\gamma_{\text{CME}} + \gamma_{\text{m.c.}}) + N_{\rho}\gamma_{\rho}}{N_{SS} + N_{\rho}} - (-\gamma_{\text{CME}} + \gamma_{\text{m.c.}}) = r(\gamma_{\rho} - \gamma_{\text{m.c.}}) + (1-r/2)\Delta \gamma_{\text{CME}}. \quad (4.1)$$

(If one normalized $\gamma_{OS}$ by $N_{SS}$ instead, then Eq. (4.1) would become simpler, $\Delta \gamma' = r'\gamma_{\rho} + \Delta \gamma_{\text{CME}}$ with $r' = (N_{OS} - N_{SS})/N_{SS}$.) Considering Eq. (4.1), the $\Delta \gamma$ can be expressed by two terms:

$$\Delta \gamma(m_{inv}) = r(m_{inv})R(m_{inv}) + \Delta \gamma_{\text{CME}}(m_{inv}). \quad (4.2)$$

The first term is resonance contributions, where the response function

$$R(m_{inv}) \equiv \langle f(m_{inv})v_2(m_{inv}) \rangle - \gamma_{\text{m.c.}}. \quad (4.3)$$

is likely a smooth function of $m_{inv}$ while $r(m_{inv})$ contains resonance spectral profile (Fig. 3(a)). Consequently, the first term is not smooth but a peaked function of $m_{inv}$. The second term in Eq. (4.2) is the CME signal which should be a smooth function of $m_{inv}$ (note we
Figure 3. (a) $r = (N_{OS} - N_{SS})/N_{SS}$, (b) $\Delta \gamma$, and (c) $\Delta \gamma/r$ as a function of $m_{\text{inv}}$ from the toy MC simulation of total $200 \times 10^6$ events. Included are primordial $\pi^{\pm}$, and $K_S, \rho, \eta, \omega$ resonances, using parameters corresponding to measurements in Au+Au collisions of the 40-50% centrality. A CME signal $a_1 = \pm 0.008$ is included.

have dropped the negligible $r/2)$. However, the exact functional form of $\Delta \gamma_{\text{CME}}(m_{\text{inv}})$ is presently unknown and needs theoretical input. The different dependences of the two terms can be exploited to identify CME signals at low $m_{\text{inv}}$. This is illustrated in Fig. 3(c) where the ratio of $\Delta \gamma/r$ is depicted. If CME signal is present, as is the case in our toy MC, $\Delta \gamma/r$ should not be smooth, but with a deviation resembling the inverse shape of $r$ in Fig. 3(a). This is clearly seen in Fig. 3(c) in the $\rho$ mass region, although not as clear in the $K_S$ mass region.

In Eq. (4.2), $\Delta \gamma(m_{\text{inv}})$ and $r(m_{\text{inv}})$ are measured, and $R(m_{\text{inv}})$ results from known physics and can in principle be obtained from models. AMPT indicates that $R(m_{\text{inv}})$ is a first-order polynomial. We can thus take a step further to fit the $\Delta \gamma(m_{\text{inv}})$ in Fig. 3(b) by Eq. (4.2) taking $R(m_{\text{inv}})$ as a first-order polynomial fit function, treating CME as a $m_{\text{inv}}$-independent fit parameter (our input CME signal is $p_T$ independent). The fit result is superimposed as the red histogram in Fig. 3(b), and in Fig. 3(c) after divided by $r(m_{\text{inv}})$ from Fig. 3(a). The straight line in blue in Fig. 3(c) is the fit result for $R(m_{\text{inv}})$. The difference between the fit red histogram and the blue line is $\Delta \gamma_{\text{CME}}/r(m_{\text{inv}})$, which shows the inverse shape of $r(m_{\text{inv}})$. It is found, with the simulated statistics, that the inverse-
shape feature becomes hard to identify when the CME input signal is smaller than 10\% of the inclusive $\Delta \gamma$. The fit parameters are written in Fig. 3(b). The fit parameter for CME is $\Delta \gamma_{\text{CME}} = (4.2 \pm 0.2) \times 10^{-5}$, not far away from the input CME signal of $4.6 \times 10^{-5}$. The fit $\chi^2/\text{ndf} = 108/75$ is not ideal because of the approximation for the $m_{\text{inv}}$-dependence of $R(m_{\text{inv}})$, but it presents a potentially viable way to extract CME signals from data even at low $m_{\text{inv}}$.

Theoretically, the $m_{\text{inv}}$ dependence of the CME is unknown. The likely sphaleron or instanton mechanism for transitions between QCD vacuum states \cite{2, 5, 6, 10}, leading to the CME, might yield a broad $m_{\text{inv}}$ distribution around $m_{\text{inv}} \sim 1 \text{ GeV/c}$. With such a CME signal, assuming a $m_{\text{inv}}$-independent CME in our fit would probably still yield a reasonable average CME signal. To illustrate this point, we simulate sphalerons/instantons by a broad Gaussian mass distribution at $1 \text{ GeV/c}^2$ with width $0.5 \text{ GeV/c}^2$. Each sphaleron/instanton is at rest and decays into a $\pi^+\pi^-$ pair where the decay polar angle is uniform in $\sin \theta$ and the azimuthal angles of $\pi^\pm$ are sampled according to $dN/d\phi \propto 1 \pm \sin \phi$. The number of sphalerons/instantons is Poisson and on average $0.7\%$ $(0.9\%$ within $|\eta| < 1$) of the event single charge pion multiplicity. The pion azimuthal distributions in the form of Eq. (3.1) are $dN_{\pi^\pm}/d\phi \propto 1 + 2v^2 \cos 2\phi + 0.009 \times (1 \pm \sin \phi)$. This gives an effective CME signal of $2a_1^2 \approx 4.0 \times 10^{-5}$. We apply our fit method, still assuming a constant CME, and obtain $\Delta \gamma_{\text{CME}} = (3.7 \pm 0.2) \times 10^{-5}$, consistent with the input signal, with $\chi^2/\text{ndf} = 187/75$.

5 Discussion and summary

The STAR experiment at RHIC has accumulated Au+Au minimum bias data samples of $15 \times 10^6$ events from Run-4 \cite{23, 24}, $57 \times 10^6$ events from Run-7 \cite{27}, and $500 \times 10^6$ events from Run-11 \cite{60}. If the CME signal is $1/3$ of the measured inclusive $\Delta \gamma$ \cite{23, 24} and independent of $m_{\text{inv}}$, these data samples (with the 20-60\% centrality) could yield, based on our toy MC study, a better than $5\sigma$ measurement of $\Delta \gamma(m_{\text{inv}} \geq 2 \text{ GeV/c}^2)$. If the CME signal is unobservable, then our analysis method could set, based on our AMPT result, an upper limit with 98\% CL on the CME of 5\% at $m_{\text{inv}} \geq 2 \text{ GeV/c}^2$ relative to the measured inclusive $\Delta \gamma$. It is likely that the CME contribution decreases with $m_{\text{inv}}$ and, depending on the detailed physics mechanism, may become difficult to observe at $m_{\text{inv}} \geq 2 \text{ GeV/c}^2$.

Our fit method can be used to explore and extract CME signals at low $m_{\text{inv}}$. The method relies on the rather robust assumption of different $m_{\text{inv}}$ dependences of peaked resonance contributions and smooth CME signal, lifting the major difficulty of similar dependences of the background and CME on experimental variables thus far. Obviously a better theoretical guidance of the $m_{\text{inv}}$ dependence of the CME would help its experimental search.

In summary, topological charge fluctuations, resulting in the chiral magnetic effect (CME) and charge separation in relativistic heavy ion collisions, are fundamental properties of QCD. Experimental charge separation measurements by the azimuthal correlator ($\Delta \gamma$) suffer from major backgrounds from resonance decays (generally, charge conservation) coupled with elliptic anisotropy. In this article, we propose to measure the $\Delta \gamma$ differentially as a function of the particle pair invariant mass ($m_{\text{inv}}$). By using the AMPT (A Multi-Phase Transport) model, we demonstrate that one can essentially eliminate resonance decay
backgrounds to $\Delta\gamma$ by applying a lower cut on $m_{\text{inv}}$. With a $m_{\text{inv}} > 2$ GeV/c$^2$ cut, an upper limit on the CME of 20% of the inclusive $\Delta\gamma$ can be achieved with $11 \times 10^6$ AMPT events of 200 GeV Au+Au collisions with impact parameter $b = 6.6-8.2$ fm. By using a toy Monte Carlo simulation with realistic resonance distributions and a $p_T$-independent input CME signal, we show that the resonance decay backgrounds are eliminated by the $m_{\text{inv}} > 2$ GeV/c$^2$ cut and the CME signal remains. With input CME signal of $a_1 = 0.008$ (20% of the total $\Delta\gamma$) and $200 \times 10^6$ events corresponding to the 40-50% centrality of Au+Au collisions, a $5\sigma$ CME measurement could be achieved at $m_{\text{inv}} > 2$ GeV/c$^2$. We further show that one may be able to separate the presumably smooth CME signals from peaked resonance decay backgrounds in the low $m_{\text{inv}}$ region by exploiting their different $m_{\text{inv}}$ dependences. We show this by the toy MC with a $p_T$-independent CME signal as well as the signal from a broad sphaleron/instanton mass distribution. Our proposed invariant mass method should help the ongoing experimental search for the CME at RHIC and the LHC, and might be able to give a quantitative answer on the CME with the heavy ion data already on tape.

Acknowledgments

We thank Prof. Zi-Wei Lin for useful discussions. This work was supported in part by the National Natural Science Foundation of China Grant Nos. 11647306 and 11747312 and the U.S. Department of Energy Grant No. DE-SC0012910. HL acknowledges financial support from the China Scholarship Council.

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