A novel invariant mass method to isolate resonance backgrounds from the chiral magnetic effect

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1. Introduction

The chiral magnetic effect (CME) refers to charge separation along the strong magnetic field produced by the spectator protons. Charge separation arises from the chirality imbalance of quarks in local domains caused by topological charge fluctuations in quantum chromodynamics (QCD). Such local domains violate the parity (P) and charge conjugation parity (CP) symmetries, which could explain the magnitude of the matter-antimatter asymmetry in the present universe.

Extensive efforts have been devoted to search for the CME in heavy-ion collisions at RHIC and the LHC. The most commonly used observable is the three-point correlator, \( \gamma = \cos(\alpha + \beta - 2\psi_{RP}) \), where \( \alpha \) and \( \beta \) are the azimuthal angles of two charged particles and \( \psi_{RP} \) is that of the reaction plane. Because of charge-independent backgrounds, the difference \( \Delta \gamma = \gamma_{OS} - \gamma_{SS} \) is often used, where \( \gamma_{OS} \) and \( \gamma_{SS} \) refer to opposite-sign (OS) and same-sign (SS) observables, respectively. There also exist, however, charge-dependent backgrounds, mainly from particle correlations due to resonance decays coupled with the
resonance elliptic flow \( \gamma \): \( \gamma \approx \langle \cos(\alpha + \beta - 2\psi_{\text{reso}}) \rangle \cdot v_{2,\text{reso}} \). This resonance background was noted by Voloshin [6] but the quantitative estimate was off by 1-2 orders of magnitude (or a factor of \( v_2 \)) [6,7]. When the first experimental data became available [8], it was immediately realized that the data could be largely contaminated by resonance (or cluster) decay backgrounds [9].

Particle pair invariant mass \( (m_{\text{inv}}) \) is a common means to identify resonances. In this contribution, we illustrate the invariant mass method [10,5] and demonstrate that it can be used to measure the CME signal essentially free of resonance backgrounds.

2. Results

We use the AMPT (A Multi-Phase Transport) model to illustrate the invariant mass method. The upper left panel of Fig. 1 shows the excess of OS over SS pairs as a function of \( m_{\text{inv}} \). The lower left panel shows the response function \( \Delta \gamma(m_{\text{inv}}) \). The structures are similar in \( r \) and \( \Delta \gamma \); the \( \Delta \gamma \) correlator traces the distribution of resonances. This demonstrates clearly that resonances are the sources of the finite \( \Delta \gamma \) in AMPT.

Most of the \( \pi-\pi \) resonances are located in the low \( m_{\text{inv}} \) region [11]. It is possible to exclude them entirely by applying a lower \( m_{\text{inv}} \) cut. The right panel of Fig. 1 shows the average \( \Delta \gamma \) at \( m_{\text{inv}} > 2 \text{ GeV}^2 \), compared to the inclusive \( \Delta \gamma \) measurement [10]. The high mass \( \Delta \gamma \) is drastically reduced from the inclusive data. There is no CME in AMPT, and the \( \Delta \gamma \) signal at large mass is indeed consistent with zero. This demonstrates that a lower \( m_{\text{inv}} \) cut can eliminate essentially all resonance decay backgrounds.

It is generally expected that the CME is a low \( p_T \) phenomenon and its contribution to high mass may be small [2,8]. A recent dynamical model study [12] indicates, however, that the CME signal is rather independent of \( p_T \) at \( p_T > 0.2 \text{ GeV}/c \) (see Fig. 2 left panel), suggesting that the signal may persist to high \( m_{\text{inv}} \). The lower right panel of Fig. 2 shows the \( \langle p_T \rangle \) of single pions and pion pairs as a function of \( m_{\text{inv}} \). A cut of \( m_{\text{inv}} > 2 \text{ GeV}^2 \) corresponds to \( p_T \approx 1.2 \text{ GeV}/c \) which is not very high. The CME signal, if appreciable, should show up in the \( m_{\text{inv}} > 2 \text{ GeV}^2 \) region.

One may apply a two-component model [10], \( \Delta \gamma(m_{\text{inv}}) \approx r(m_{\text{inv}})R(m_{\text{inv}}) + \Delta \gamma_{\text{CME}}(m_{\text{inv}}) \), to extract the possible CME from the low \( m_{\text{inv}} \) data. The first term on the r.h.s. is resonance contributions where the response function \( R(m_{\text{inv}}) \) is smooth, while \( r(m_{\text{inv}}) \) contains resonance mass shapes. Consequently, the first term is not “smooth” but a peaked function of \( m_{\text{inv}} \). The second term on the r.h.s. is the CME signal which should be a smooth function of \( m_{\text{inv}} \). The \( m_{\text{inv}} \) dependences of the CME and background are distinct, and this can be exploited to identify CME signals at low \( m_{\text{inv}} \). Figure 3 shows a toy model simulation including resonances and an input CME signal [10]. Guided by AMPT input [10], the response function \( R(m_{\text{inv}}) \) was assumed to be linear. Various forms of \( \Delta \gamma_{\text{CME}}(m_{\text{inv}}) \) were studied [13]. The two-component model fit is
able to extract the input CME signal. The lower panel of Fig. 3 shows a visual illustration: the ratio of \( \Delta \gamma(m_{\text{inv}})/r(m_{\text{inv}}) \) shows a structured modulation on top of a smooth dependence. The structure is due to the ratio of \( \Delta \gamma_{\text{CME}}/r \). With the 20% input CME signal, the inverse structure of \( r \) can be visually identified [10].

One difficulty above is that the exact functional form of \( R(m_{\text{inv}}) \) is unknown. To overcome this difficulty, STAR used the event-shape engineering technique [14], dividing events from each narrow centrality bin into two classes according to the event-by-event \( q_2 \) [15]. Since the magnetic fields are approximately equal while the backgrounds differ, the \( \Delta \gamma(m_{\text{inv}}) \) difference between the two classes is a good measure of the background shape. Figure 4 shows \( \Delta \gamma_A \) and \( \Delta \gamma_B \) from such two \( q_2 \) classes and the difference \( \Delta \gamma_A - \Delta \gamma_B \) in 20-50% Au+Au collisions [14]. The inclusive \( \Delta \gamma(m_{\text{inv}}) \) of all events is also shown. With the background shape given by \( \Delta \gamma_A - \Delta \gamma_B \), the CME can be extracted from a fit \( \Delta \gamma = k(\Delta \gamma_A - \Delta \gamma_B) + \Delta \gamma_{\text{CME}} \). Since the same data are used in \( \gamma \) and \( \Delta \gamma_A - \Delta \gamma_B \), their statistical errors are somewhat correlated. To properly handle statistical errors, one can simply fit the independent measurements of \( \Delta \gamma_A \) versus \( \Delta \gamma_B \), namely \( \Delta \gamma_A = b \Delta \gamma_B + (1 - b) \Delta \gamma_{\text{CME}} \), where \( b \) and \( \Delta \gamma_{\text{CME}} \) are the fit parameters. The right panels of Fig. 4 show such fits for the STAR Run-16 Au+Au data [14]. Note that in this fit model the background is not required to be strictly proportional to \( v_2 \). The CME signal is assumed to be independent of \( m_{\text{inv}} \). The good fit quality seen in Fig. 4 indicates that this is a good assumption.
3. Summary

The Chiral Magnetic Effect (CME) arises from local parity violation caused by topological charge fluctuations in QCD. The CME-induced charge separation measurements by the three-point \( \Delta \gamma \) correlator is contaminated by a major background from resonance decays coupled with elliptic flow. We propose differential \( \Delta \gamma \) measurements as function of the particle pair invariant mass \( (m_{\text{inv}}) \). We show by AMPT and toy-model simulations that (1) \( \Delta \gamma \) in the high \( m_{\text{inv}} \) region is essentially free of resonance backgrounds, and (2) in the low \( m_{\text{inv}} \) region, the CME signal may be extracted from a two-component model. We further discuss a data analysis application using the invariant mass method together with event-shape engineering.

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References

[1] Quark Matter 2018, these proceedings.
[2] D. Kharzeev, Phys.Lett. B633 (2006) 260–264; D. E. Kharzeev, L. D. McLerran, H. J. Warringa, Nucl.Phys. A803 (2008) 227–253; K. Fukushima, D. E. Kharzeev, H. J. Warringa, Phys.Rev. D78 (2008) 074033.
[3] D. Kharzeev, R. Pisarski, M. H. Tytgat, Phys.Rev.Lett. 81 (1998) 512–515.
[4] D. E. Kharzeev, J. Liao, S. A. Voloshin, G. Wang, Prog. Part. Nucl. Phys. 88 (2018) 50–72.
[5] J. Zhao, Int. J. Mod. Phys. A33 (13) (2018) 1830010, arXiv:1805.02814[nucl-ex]; J. Zhao, Z. Tu, F. Wang, arXiv: 1807.05083[nucl-ex].
[6] S. A. Voloshin, Phys.Rev. C70 (2004) 057901.
[7] F. Wang, J. Zhao, Phys. Rev. C95 (5) (2017) 051901.
[8] B. Abelev, et al. (STAR Collaboration), Phys.Rev.Lett. 103 (2009) 251601; Id., Phys.Rev. C81 (2010) 054908.
[9] F. Wang, Phys.Rev. C81 (2010) 064902; S. Pratt, S. Schlichting, S. Gavin, Phys.Rev. C84 (2011) 024909; A. Bzdak, V. Koch, J. Liao, Phys.Rev. C83 (2011) 014905.
[10] J. Zhao, H. Li, F. Wang, arXiv:1705.05410[nucl-ex].
[11] K. A. Olive, et al., Review of Particle Physics, Chin. Phys. C38 (2014) 090001.
[12] S. Shi, Y. Jiang, E. Lilleskov, J. Liao, Annals Phys. 394 (2018) 50–72.
[13] J. Zhao (STAR Collaboration), EPJ Web Conf. 172 (2018) 01005, arXiv:1712.00394[nucl-ex]; Id., Int. J. Mod. Phys. Conf. Ser., 46, 1860010 (2018), arXiv:1802.03283[nucl-ex].
[14] J. Zhao (STAR Collaboration), these proceedings, arXiv:1807.09925[nucl-ex].
[15] J. Schukraft, A. Timmins, S. A. Voloshin, Phys. Lett. B719 (2013) 394–398.