Influence of globally spin-aligned vector mesons to the measurements of the chiral magnetic effect in heavy-ion collisions

Diyu Shen[1,*], *Jinhui* Chen[1], *Aihong* Tang[2], and *Gang* Wang[3]

[1]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[2]Brookhaven National Laboratory, Upton, New York 11973
[3]Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA

Abstract. The chiral magnetic effect (CME) in high-energy heavy-ion collisions arises from the interplay between the chirality imbalance and the intense magnetic field and will cause a charge separation along the magnetic field direction. While the CME search is still ongoing in experiments, the non-CME contributions need to be excluded from the CME observables. In this work, we examine the influence of globally spin-aligned ρ mesons on the γ_{112} correlator, the $R_{\Psi_2}(\Delta S)$ correlator, and the signed balance functions, via a toy model and a multiphase transport model (AMPT). We find that the CME observables are sensitive to the 00-component of the spin density matrix, ρ_{00}: they receive positive (negative) contributions when ρ_{00} is larger (smaller) than 1/3.

1 Introduction

The generation of quark gluon plasma (QGP) in heavy-ion collisions involves many novel phenomena in strong interactions, such as the spin alignment of vector mesons and the chiral magnetic effect (CME). The CME observables in experiments include γ_{112} [1], $R(\Delta S)$ [2], and the signed balance functions [3]. In this work, we show that the polarized vector mesons have non-trivial contributions to these observables, with positive or negative contributions depending on whether ρ_{00} is larger or smaller than 1/3. Since pions are the most abundant particles, with approximately 80% of them originating from resonance decay at midrapidity at RHIC [4, 5], the spin alignment of ρ mesons, which constitute 60% of the total resonances, is important to the CME measurment.

2 Impact of ρ_{00} on the CME observables

2.1 The γ_{112} correlator

The γ_{112} correlator [1] is defined as $\gamma_{112} \equiv \left\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\mathrm{RP}}) \right\rangle$, where ϕ_α and ϕ_β are the azimuthal angles of particles α and β, respectively, and Ψ_{RP} represents the reaction plane. The bracket means averaging over all particle pairs and over all events. The difference in

*e-mail: dyshen@fudan.edu.cn

γ_{112} between opposite-sign (OS) and same-sign (SS) pairs is supposed to contain the CME signal, i.e., $\Delta\gamma_{112} \equiv \gamma_{112}^{\mathrm{OS}} - \gamma_{112}^{\mathrm{SS}} \approx 2a_1^2$. However, $\Delta\gamma_{112}$ is contaminated with backgrounds, e.g., decay daughters of flowing resonances [1]. In addition to elliptic flow, the global spin alignment could also contribute a background to $\Delta\gamma_{112}$. In the decay of $\rho \to \pi^+ + \pi^-$, the emission angle of $\pi^\pm$ can be expressed as $dN/d\phi^* \propto 1 - (3\rho_{00}/2 - 1/2)\cos 2\phi^*$, where ϕ^* is the azimuthal angle of the decay product in the ρ rest frame. In the absence of the CME, $\Delta\gamma_{112}$ can be expressed as [6]

$$\Delta\gamma_{112} = \frac{N_\rho}{N_+ N_-}\left[\frac{1}{8}(f_c + f_s)(3\rho_{00} - 1) - \frac{1}{2}(f_c - f_s)\right], \tag{1}$$

where f_c and f_s account for the Lorentz boost of the ρ meson. At a given v_2^ρ, the $\Delta\gamma_{112}$ measurement should have a linear dependence on the ρ_{00} value of ρ mesons.

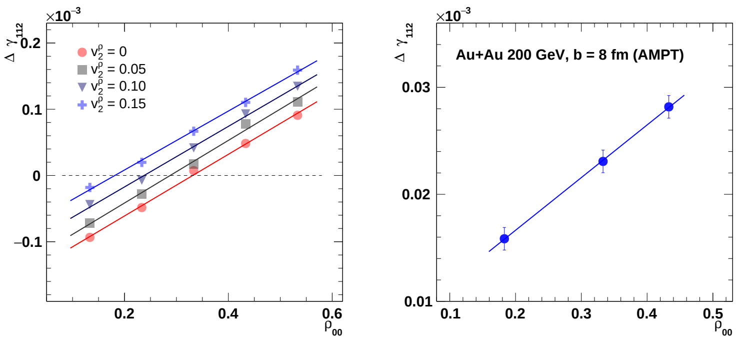

Figure 1. Toy model simulations (left) and AMPT (right) simulations of the π-π $\Delta\gamma_{112}$ correlation as a function of ρ-meson ρ_{00} with various inputs of v_2^ρ. Linear fits are applied to guide eyes.

We test the aforementioned idea with a toy model and the AMPT model, both without the CME but with the spin alignment effect. The details of the models can be found in Ref. [6]. The left panel of Fig. 1 shows the toy model simulations of π-π $\Delta\gamma_{112}$ with different v_2^ρ inputs. At a given v_2^ρ, $\Delta\gamma_{112}$ indeed increases linearly with ρ_{00}. $\Delta\gamma_{112}$ also increases with v_2^ρ at a fixed ρ_{00}, exhibiting the convolution of v_2^ρ and ρ_{00} in the background contribution from ρ mesons to $\Delta\gamma_{112}$. Note that the global spin alignment effect could give a negative contribution to the $\Delta\gamma_{112}$ measurement if ρ_{00} is smaller than 1/3. Results of AMPT calculations are similar to the toy model simulations. At $\rho_{00} = 1/3$, the positive $\Delta\gamma_{112}$, which is a non-CME background, may come from the positive v_2^ρ and transverse momentum conservation. The slope, $d\Delta\gamma_{112}/d\rho_{00}$, could be different between the toy model and the AMPT model, because of the different ρ-meson spectra.

2.2 The $R_{\Psi_2}(\Delta S)$ correlator

Another CME observable, $R_{\Psi_2}(\Delta S)$ [2], is defined as a double ratio of four distributions, $R_{\Psi_2}(\Delta S) \equiv [N(\Delta S_{\mathrm{real}})/N(\Delta S_{\mathrm{shuffled}})] \,/\, \left[N(\Delta S^\perp_{\mathrm{real}}))/(N(\Delta S^\perp_{\mathrm{shuffled}})\right]$, where $\Delta S = \langle \sin\Delta\phi_+\rangle - \langle \sin\Delta\phi_-\rangle$, $\Delta S^\perp = \langle\cos\Delta\phi_+\rangle - \langle\cos\Delta\phi_-\rangle$, and $\Delta\phi = \phi - \Psi_2$. Ψ_2 denotes the 2$^{\mathrm{nd}}$-order event plane. The subscripts "real" and "shuffled" represent real events and charge shuffled events, respectively. Ideally, the CME should cause a concave shape in $R_{\Psi_2}(\Delta S)$, which can be quantified by the width of a Gaussian fit, σ_R. Analytically, σ_R is related to the widths of the four initial distributions,

$$\frac{S_{\mathrm{concavity}}}{\sigma_R^2} = \frac{1}{\sigma^2(\Delta S_{\mathrm{real}})} - \frac{1}{\sigma^2(\Delta S_{\mathrm{shuffled}})} - \frac{1}{\sigma^2(\Delta S^\perp_{\mathrm{real}})} + \frac{1}{\sigma^2(\Delta S^\perp_{\mathrm{shuffled}})}. \tag{2}$$

$S_{\text{concavity}}$ is 1 (-1), when the $R_{\Psi_2}(\Delta S)$ distribution is convex (concave). Similar to the case of $\Delta\gamma_{112}$, we have [6]

$$\text{Sign}(S_{\text{concavity}}) = \text{Sign}\left[-\frac{N_\rho}{2N_+N_-}(3\rho_{00}-1)\right]. \tag{3}$$

In this case, if ρ_{00} is smaller (larger) than 1/3, $S_{\text{concavity}}$ becomes 1 (-1), and the $R_{\Psi_2}(\Delta S)$ distribution becomes convex (concave).

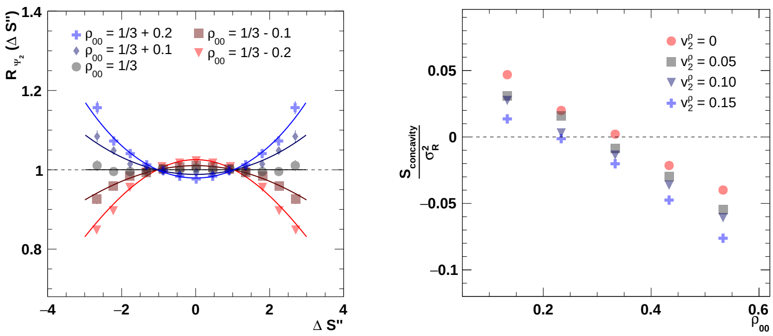

Figure 2. (Left) toy model simulations of the $R_{\Psi_2}(\Delta S'')$ with zero v_2^ρ and different ρ_{00} inputs. (Right) $S_{\text{concavity}}/\sigma_R^2$ extracted using Gaussian fits to $R_{\Psi_2}(\Delta S'')$ for different v_2^ρ and ρ_{00} inputs.

We take the same procedure as in Ref. [2] to correct the $R_{\Psi_2}(\Delta S)$ correlator for the particle number fluctuations, i.e., $\Delta S'' = \Delta S/\sigma_{\text{sh}}$, where σ_{sh} is the width of $N(\Delta S_{\text{shuffuled}})$. Figure 2(left) shows $R_{\Psi_2}(\Delta S'')$ as a function of ρ_{00} from the toy model with zero v_2^ρ. The $R_{\Psi_2}(\Delta S'')$ shapes are concave (convex) for $\rho_{00} > 1/3$ ($\rho_{00} < 1/3$), indicating a finite background from spin-aligned vector mesons. Figure 2(right) also shows $S_{\text{concavity}}/\sigma_R^2$ extracted using Gaussian fits for different v_2^ρ and ρ_{00} inputs. The red circles represent the case with zero v_2^ρ, and corroborate Eq. (3). At a given v_2^ρ, $S_{\text{concavity}}/\sigma_R^2$ decreases with increased ρ_{00}. On the other hand, at a given ρ_{00}, $S_{\text{concavity}}/\sigma_R^2$ also decreases with increased v_2^ρ.

2.3 The signed balance functions

The signed balance functions probe the CME by examining the momentum ordering between positively and negatively charged particles [3, 7], based on $\Delta B_y = (N_+ + N_-)[N_{y(+-)} - N_{y(-+)}]/(N_+N_-)$, where $N_{y(\alpha\beta)}$ is the number of pairs in which particle α is ahead of particle β along the y axis ($p_y^\alpha > p_y^\beta$) in an event. Similarly, ΔB_x can be constructed along the x axis. The CME will enhance the width of the ΔB_y distribution via the charge separation along the y axis, and therefore the final observable is the ratio $r \equiv \sigma(\Delta B_y)/\sigma(\Delta B_x)$. r can be calculated in both the laboratory frame (r_{lab}) and the ρ rest frame (r_{rest}). The CME will lead to $r_{\text{rest}} > r_{\text{lab}} > 1$. In this work, we focus on r_{lab}. It is more straightforward to define an observable based on the difference instead of the ratio [6],

$$\Delta\sigma^2(\Delta B) \equiv \sigma^2(\Delta B_y) - \sigma^2(\Delta B_x) \approx c_1 + c_2(3\rho_{00} - 1), \tag{4}$$

where c_1 and c_2 are constants depending on the spectra of ρ mesons, v_2^ρ, and v_2^π.

Figure 3 shows the toy model and AMPT simulations of $\Delta\sigma^2(\Delta B)$ as a function of ρ_{00} with various v_2^ρ inputs. At a given v_2^ρ, $\Delta\sigma^2(\Delta B)$ exhibits a linear dependence on ρ_{00}. Note that the slope, $d\Delta\sigma^2(\Delta B)/d\rho_{00}$, could be different between the toy model and the AMPT model, because of the different ρ-meson spectra.

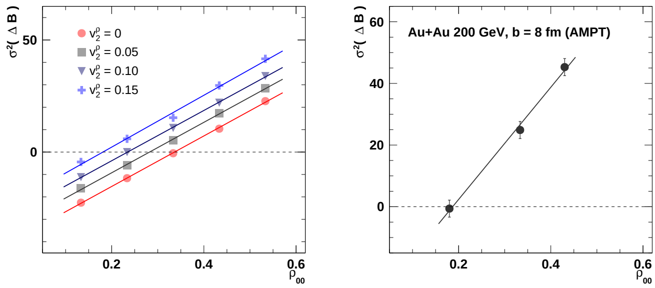

Figure 3. Toy model (left) and AMPT (right) simulations of $\Delta\sigma^2(\Delta B)$ as a function of ρ_{00} for various v_2^ρ inputs. Linear fits are applied to guide eyes.

3 Conclusion

In this work, we have demonstrated how the globally spin-aligned ρ mesons affect the CME observables involving pions, the $\Delta\gamma_{112}$ correlator, the $R_{\Psi_2}(\Delta S)$ correlator, and the signed balance functions. Qualitative derivations indicate that the ρ_{00} dependence originates from the anisotropic emission of the decay products, which imitates elliptic flow in the ρ rest frame. We find that all these observables are influenced not only by elliptic flow v_2^ρ, but also by the spin alignment ρ_{00} of ρ mesons.

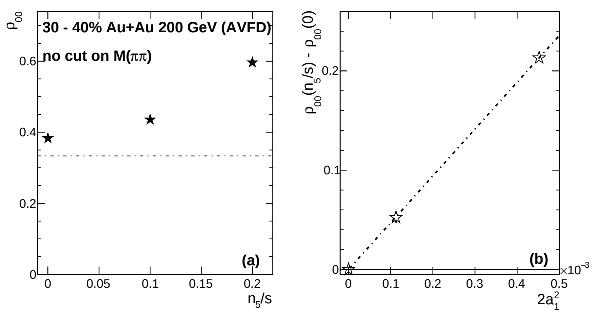

Figure 4. AVFD simulations of the ρ_{00} for the excess of $\pi^+\pi^-$ pairs over the same-sign pairs in 30–40% Au+Au at 200 GeV. The n_5/s denotes the CME strength. Panel (a) shows ρ_{00} as a function of n_5/s, and panel (b) shows the CME induced ρ_{00} as a function of the true signal, $2a_1^2$.

Nevertheless, the global spin alignment may partially stem from the CME-induced charge separation of π^+ and π^-, some of whom later form ρ mesons via coalescence. In that case, the CME tends to give a positive contribution to the ρ_{00} of ρ mesons. Figure 4 shows the ρ_{00} for the excess of $\pi^+\pi^-$ pairs over the same-sign pairs in the anomalous-viscous fluid dynamics (AVFD) model [8], which qualitatively illustrates the influence of the CME to the ρ_{00}. A more rigorous study to this effect is needed in the future.

References

[1] S.A. Voloshin, Phys. Rev. C **70**, 057901 (2004), `hep-ph/0406311`

[2] N. Magdy, S. Shi, J. Liao, N. Ajitanand, R.A. Lacey, Phys. Rev. C **97**, 061901 (2018), `1710.01717`

[3] A.H. Tang, Chin. Phys. C **44**, 054101 (2020), `1903.04622`

[4] X. Dong, S. Esumi, P. Sorensen, N. Xu, Z. Xu, Phys. Lett. B **597**, 328 (2004), `nucl-th/0403030`

[5] Z.b. Xu, J. Phys. G **30**, S325 (2004), `nucl-ex/0307014`

[6] D. Shen, J. Chen, A. Tang, G. Wang, Phys. Lett. B **839**, 137777 (2023), `2212.03056`

[7] S. Choudhury et al., Chin. Phys. C **46**, 014101 (2022), `2105.06044`

[8] S. Shi, H. Zhang, D. Hou, J. Liao, Phys. Rev. Lett. **125**, 242301 (2020), `1910.14010`