

Fluctuations and Correlations of Quark Spin in Hot and Dense QCD Matter

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In this Letter, we examine the impact of QCD phase transitions on the quark spin fluctuations and correlations. We propose the quark-antiquark correlation, which relates to the vector meson spin alignment and the $\Lambda - \bar{\Lambda}$ correlation, and can be used as a novel probe of the critical end point (CEP) in the QCD phase diagram. Using the Nambu-Jona-Lanisio model, we qualitatively study the properties of quark-antiquark spin correlations. Our findings reveal a peak structure near the CEP of the chiral phase transition, which may serve as an experimental signature of the CEP and account for the non-monotonic behavior of ϕ meson alignment at low collision energies observed recently in experiments.

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Introduction—The large orbital angular momentum in the initial state of heavy ion collision experiments can result in rapid local rotation and the creation of fluid vortices [1–4]. Such rotating matter has recently attracted significant attention. One particularly intriguing phenomenon is spin polarization and alignment of hadrons in heavy ion collisions, which has been observed experimentally [5,6]. Theoretical predictions of global hyperon spin polarization [7] have been successfully described by numerous subsequent theoretical frameworks [8–23]. For detailed reviews, see [24–31].

However, the experimental measurements of ϕ meson spin alignment [6] significantly exceed theoretical expectations [32]. Various mechanisms have been proposed to explain these measurements, including quark coalescence and fragmentation effects, the vorticity tensor, strong mesonic fields, local spin alignment, medium-modified meson spectra, turbulent color fields and viscous corrections [33–47]. However, most of these mechanisms predict the ϕ meson ρ_{00} (the 00 component of spin density matrix) to be less than 1/3, which contradicts the experimental measurement. A proposed mechanism for strange quark

polarization, based on the effective ϕ meson field and its local spatial and temporal correlation effects, suggests a higher ϕ meson ρ_{00} [48–50]. Additionally, experimental data also show nonmonotonic behavior of ϕ -meson ρ_{00} at certain collision energies, suggesting the presence of unknown mechanisms.

Searching for the critical end point (CEP) is a key task in studying the quantum chromodynamics (QCD) phase structure [51,52], and estimates of the CEP in the QCD phase diagram have arrived at convergent results from different approaches in recent years [53–56]. In thermal equilibrium, a QCD system can be characterized by its dimensionless pressure, which is the logarithm of the QCD partition function. The Taylor expansion coefficients of this logarithm represent susceptibilities of conserved charges, defined as the n th order derivative of pressure with respect to the chemical potential of the conserved charge. These susceptibility ratios can be experimentally measured by the cumulant ratios of the event-by-event conserved charge multiplicity distributions [57]. Near the CEP, large correlation lengths make fluctuations of conserved charges sensitive probes for CEP detection [58]. Recent results from the STAR collaboration on the ratio of fourth-order to second-order net-proton cumulants show a nonmonotonic energy dependence with a significance of 3.1σ , suggesting the created system may have passed near the CEP [59].

In this Letter, we propose that quark spin correlation and fluctuation will be enhanced near the CEP, leading to observable imprints on vector meson spin alignment and $\Lambda - \bar{\Lambda}$ spin correlation [60,61] in experiments. Our results reveal a deep connection between spin polarization and QCD phase transitions, which are often considered

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separately in the literature. Recent studies indicate that phase transitions can slightly affect average spin polarization [62–64], but they do not consider quark spin fluctuation. Inspired by baryon number fluctuation near the CEP, we anticipate that critical quark spin fluctuation can provide measurable effects. Using the NJL model, we qualitatively study quark-antiquark correlation and spin fluctuation near the CEP, finding a peak structure close to the CEP. We propose that along the freeze-out line, the nonmonotonic behavior of hyperon correlation can serve as a signature for the CEP, alongside net baryon number fluctuation.

Quark-antiquark spin correlation—We define the quark-antiquark spin correlation as

$$\langle P_q P_{\bar{q}} \rangle_c = \frac{4(\langle S_q S_{\bar{q}} \rangle - \langle S_q \rangle \langle S_{\bar{q}} \rangle)}{\langle N_q N_{\bar{q}} \rangle - \langle N_q \rangle \langle N_{\bar{q}} \rangle}, \quad (1)$$

where S_q and $S_{\bar{q}}$ are the spins of the quark and antiquark, and N_q and $N_{\bar{q}}$ are their respective particle numbers. Since the quark has spin 1/2, a factor 4 in the numerator is introduced so that Eq. (1) corresponds to the correlation of spin polarization rate. To study how this observable is affected by the CEP, we adopt the Nambu-Jona-Lasinio (NJL) model under rotation with the Lagrangian

$$\mathcal{L} = \bar{\psi} [i e_a^\mu \gamma^a \nabla_\mu - m_0 + \mu \gamma^0] \psi + G[(\bar{\psi} \psi)^2 + (\bar{\psi} i \gamma^5 \vec{\tau} \psi)^2], \quad (2)$$

where $\psi = (u, d)^T$ is the two flavor quark field, $\nabla_\mu = \partial_\mu + \Gamma_\mu$ the covariant derivative, μ the quark chemical potential, related to the baryon chemical potential μ_B via $\mu = \mu_B/3$. The spin connection Γ_μ and vierbein e_a^μ are the same as [65,66]. In this Letter, we consider a rotating frame with a constant angular velocity $\vec{\Omega} = \Omega \hat{z}$, which can be described by the metric tensor

$$g_{\mu\nu} = \begin{pmatrix} 1 - r^2 \Omega^2 & \Omega y & -\Omega x & 0 \\ \Omega y & -1 & 0 & 0 \\ -\Omega x & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \quad (3)$$

with $r^2 = x^2 + y^2$. In the Lagrangian (2), we only take into account scalar interaction for simplicity since we are interested in the physics near the CEP qualitatively, which is not sensitive to the microscopic interaction. In general, the conserved quantity of the Lagrangian is total angular momentum along the rotation axis $J_z = L_z + S_z$. However, at $r = 0$, only the spin contribution survives, allowing us to approximate the mean net quark spin by taking the derivative of the partition function

$$\langle J_z \rangle \Big|_{r \approx 0} = \frac{\partial \ln Z}{\partial (\frac{\Omega}{T})} \Big|_{r \approx 0} \approx \frac{\partial \ln Z_0}{\partial (\frac{\Omega}{T})} = \langle S_z \rangle, \quad (4)$$

where

$$\ln Z_0 = -\frac{V}{T} V_{\text{eff}}^0, \quad (5)$$

and V_{eff}^0 is the local thermodynamic potential at $r = 0$. We can further define the n th order cumulant of spin fluctuation as

$$C_n = \frac{\partial^n \ln Z_0}{\partial (\frac{\Omega}{T})^n} = -\frac{V}{T} \frac{\partial^n V_{\text{eff}}^0}{\partial (\frac{\Omega}{T})^n}. \quad (6)$$

The second order cumulants corresponds to the variance $\langle \delta S^2 \rangle$, which is relevant in this work.

The thermodynamic potential can be directly calculated [65,66]. In order to obtain the correlation of quark and antiquark, we modified the thermodynamic potential to be

$$V_{\text{eff}}^0(\Omega_q, \Omega_{\bar{q}}, \mu_q, \mu_{\bar{q}}, \mu) = \frac{(m - m_0)^2}{4G} - N_c N_f \int_0^\Lambda \frac{d^3 p}{(2\pi)^3} [2\varepsilon_p - F(\Omega_q) - F(-\Omega_q) - \bar{F}(\Omega_{\bar{q}}) - \bar{F}(-\Omega_{\bar{q}})], \quad (7)$$

with

$$\begin{aligned} F(\Omega_q) &= T \ln(1 + e^{-(\varepsilon_p - \mu - \mu_q - \Omega_q/2)/T}), \\ \bar{F}(\Omega_{\bar{q}}) &= T \ln(1 + e^{-(\varepsilon_p + \mu - \mu_{\bar{q}} - \Omega_{\bar{q}}/2)/T}), \end{aligned} \quad (8)$$

and the dispersion relation $\varepsilon_p = \sqrt{p^2 + m^2}$. Here, Ω_q and $\Omega_{\bar{q}}$ are rotation acting only on quark and antiquark, respectively, and we also introduce a particle number chemical potential μ_q for quark and $\mu_{\bar{q}}$ for antiquark.

A detailed derivation of Eq. (7) is presented in Supplemental Material [67]. Then by taking derivative we can obtain the variance of quark and antiquark spin fluctuation

$$\begin{aligned} \langle \delta S_q^2 \rangle &= -\frac{V}{T} \frac{\partial^2 V_{\text{eff}}(\Omega_q, \Omega_{\bar{q}})}{\partial (\frac{\Omega_q}{T})^2} \Big|_{\Omega_q = \Omega_{\bar{q}} = \Omega}, \\ \langle \delta S_{\bar{q}}^2 \rangle &= -\frac{V}{T} \frac{\partial^2 V_{\text{eff}}(\Omega_q, \Omega_{\bar{q}})}{\partial (\frac{\Omega_{\bar{q}}}{T})^2} \Big|_{\Omega_q = \Omega_{\bar{q}} = \Omega}, \end{aligned} \quad (9)$$

TABLE I. Parameter set used for the NJL model.

Λ [MeV]	m_0 [MeV]	$G\Lambda^2$	N_c	N_f
587.9	5.6	2.44	3	2

and the variance of quark and antiquark particle number

$$\begin{aligned}\langle \delta N_q^2 \rangle &= -\frac{V}{T} \frac{\partial^2 V_{eff}}{\partial (\frac{\mu_q}{T})^2} \bigg|_{\mu_q = \mu_{\bar{q}} = 0}, \\ \langle \delta N_{\bar{q}}^2 \rangle &= -\frac{V}{T} \frac{\partial^2 V_{eff}}{\partial (\frac{\mu_{\bar{q}}}{T})^2} \bigg|_{\mu_q = \mu_{\bar{q}} = 0}.\end{aligned}\quad (10)$$

By separating total spin into quark and antiquark parts as $S = S_q + S_{\bar{q}}$, it is easy to prove the relation

$$\langle S_q S_{\bar{q}} \rangle - \langle S_q \rangle \langle S_{\bar{q}} \rangle = \frac{1}{2} (\langle \delta S^2 \rangle - \langle \delta S_q^2 \rangle - \langle \delta S_{\bar{q}}^2 \rangle), \quad (11)$$

and similarly

$$\langle N_q N_{\bar{q}} \rangle - \langle N_q \rangle \langle N_{\bar{q}} \rangle = \frac{1}{2} (\langle \delta N^2 \rangle - \langle \delta N_q^2 \rangle - \langle \delta N_{\bar{q}}^2 \rangle). \quad (12)$$

Finally, we obtain

$$\langle P_q P_{\bar{q}} \rangle_c = \frac{4(\langle \delta S^2 \rangle - \langle \delta S_q^2 \rangle - \langle \delta S_{\bar{q}}^2 \rangle)}{\langle \delta N^2 \rangle - \langle \delta N_q^2 \rangle - \langle \delta N_{\bar{q}}^2 \rangle}. \quad (13)$$

Note that although the factor V/T appears in Eq. (5), it will be canceled in the ratio, thus $\langle P_q P_{\bar{q}} \rangle_c$ is not affected by the system volume.

Numerical results—For numerical calculation, we choose the parameters listed in Table I for two flavor NJL model [68]. In this case the CEP is located at $T_{CEP} = 82.1$ MeV and $\mu_{CEP} = 322$ MeV. Here we fix the angular velocity to be $\Omega = 10$ MeV, which is a typical value for the fluid vorticity in the experiment. For comparison, we also calculate the correlation of quark-antiquark spin without including critical fluctuation, which can be easily written down with distribution function f_q and $f_{\bar{q}}$ as

$$\langle P_q P_{\bar{q}} \rangle_0 = \frac{\int d^3 p (f_q^\uparrow - f_q^\downarrow)(f_{\bar{q}}^\uparrow - f_{\bar{q}}^\downarrow)}{\int d^3 p (f_q^\uparrow + f_q^\downarrow)(f_{\bar{q}}^\uparrow + f_{\bar{q}}^\downarrow)}, \quad (14)$$

where

$$f_q^{\uparrow/\downarrow} = \frac{1}{e^{\beta(\epsilon_p - \mu \mp \frac{\Omega}{2})} + 1}, \quad f_{\bar{q}}^{\uparrow/\downarrow} = \frac{1}{e^{\beta(\epsilon_p + \mu \mp \frac{\Omega}{2})} + 1} \quad (15)$$

are the distributions of spin-up and spin-down quarks and antiquarks. We assume the distribution functions are

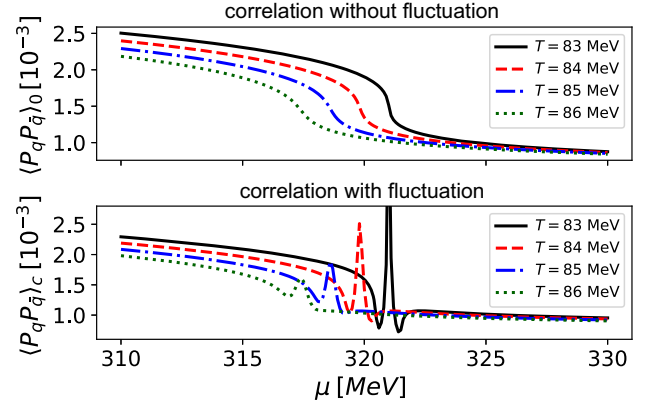


FIG. 1. Upper panel: quark-antiquark spin correlation $\langle P_q P_{\bar{q}} \rangle_0$ without critical fluctuation as a function of chemical potential. Lower panel: quark-antiquark spin correlation $\langle P_q P_{\bar{q}} \rangle_c$ with critical fluctuation as a function of chemical potential at $r = 0$. The angular velocity is chosen to be $\Omega = 10$ MeV.

homogeneous in space, which simplifies our analysis while still capturing the essential physics of the system.

The numerical results of $\langle P_q P_{\bar{q}} \rangle_0$ and $\langle P_q P_{\bar{q}} \rangle_c$ near the CEP are shown in Fig. 1. Both the upper and lower panels show similar trends. However, $\langle P_q P_{\bar{q}} \rangle_c$ has a peak structure which becomes higher as we decrease the temperature and approach the CEP. Besides, we also observe dip structures on the two sides of the peak when approaching CEP (which is most obvious at $T = 83$ MeV in Fig. 1). These peak and dip structures indicate the appearance of critical fluctuations near the CEP. Figure 2 presents the density plot of the connected correlation $\langle P_q P_{\bar{q}} \rangle_c$ and three freezeout lines. Note that the phase boundary obtained in the current NJL model is not in quantitative agreement with QCD

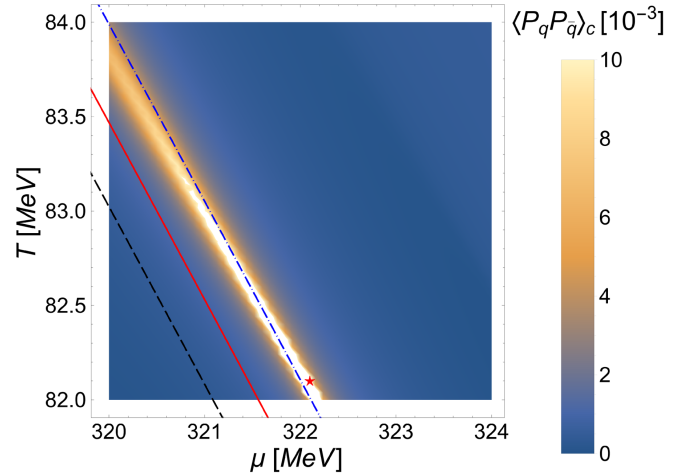


FIG. 2. The density plot of the connected correlation $\langle P_q P_{\bar{q}} \rangle_c$ at $r = 0$ with $\Omega = 10$ MeV. The solid, dash and dot-dashed line represent the hypothetical freezeout lines 1, 2, and 3 in Table II, respectively. The solid line is from Ref. [48]. The red star stands for the CEP.

TABLE II. Parameters for freeze-out lines.

	a_0 [GeV]	a_2 [GeV ⁻¹]	a_4 [GeV ⁻³]
Freeze-out 1	0.1831	0.4856	4.7589
Freeze-out 2	0.1831	0.49	4.7589
Freeze-out 3	0.1831	0.4756	4.8069

results [53,69–71]. Instead of using more realistic freeze-out lines, e.g., those extracted from experimental measurements [72–74], we employ hypothetical freeze-out lines, not far away from the CEP in this NJL model, which are parameterized as the form

$$T = a_0 - a_2\mu^2 - a_4\mu^4. \quad (16)$$

We utilize three distinct sets of parameters, as shown in Table II. From Fig. 2 one can see that the distances from the CEP to the three freeze-out lines are different. When the freeze-out line intersects the narrow crossover region near the CEP, the spin correlation will exhibit a noticeable peak structure.

Next, to study qualitatively how these peak and dip structures manifest in the collision energy dependence of vector meson spin alignment, we write the spin density matrix element ρ_{00} as [32]

$$\rho_{00} = \bar{\rho}_{00} - \delta\rho_{00}^\Omega, \quad (17)$$

where ρ_{00} is decomposed into a sum of contribution from thermodynamic fluctuations $-\delta\rho_{00}^\Omega$ investigated in this Letter and that from other sources $\bar{\rho}_{00}$, e.g., the strong force field as suggested in [49]. The minus sign on the right side in Eq. (17) is introduced for convenience, since the thermodynamic spin correlation is negative. If we neglect any other contributions except the thermodynamic fluctuations, one arrives at

$$\rho_{00} = \frac{1 - \langle P_q P_{\bar{q}} \rangle_c}{3 + \langle P_q P_{\bar{q}} \rangle_c} \approx \frac{1}{3} - \frac{4}{9} \langle P_q P_{\bar{q}} \rangle_c, \quad (18)$$

from which one obtains $\delta\rho_{00}^\Omega = \frac{4}{9} \langle P_q P_{\bar{q}} \rangle_c$. Moreover, one has $\bar{\rho}_{00} = 1/3$ if there is no other effects. Note that the decomposition in Eq. (17) as well as $\delta\rho_{00}^\Omega = \frac{4}{9} \langle P_q P_{\bar{q}} \rangle_c$ is valid if the value of $\bar{\rho}_{00}$ is not far away from $1/3$. In this work, we assume that the dominant contribution in $\bar{\rho}_{00}$ comes from the strong force field [49], which leads to $\bar{\rho}_{00} > 1/3$. In Fig. 3, we present the contribution of critical fluctuation $\delta\rho_{00}^\Omega$ at $r = 0$. Here we assume the quark chemical potential depends on the collision energy through $\mu = 2.477/(1 + 0.343\sqrt{s})$ [75]. It is evident that $\delta\rho_{00}^\Omega > 0$, which aligns with the expectation that rotation does not distinguish between quark and antiquark. Notice that the dot-dashed line (freeze-out 3) is very close to the CEP,

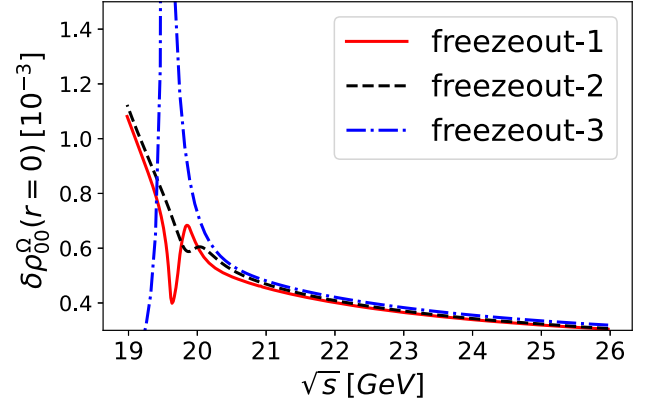


FIG. 3. $\delta\rho_{00}^\Omega$ at $r = 0$ as a function of the collision energy $\sqrt{s}$ along the three different freeze-out lines in Table II.

which exhibits a sharper peak and dip structure compared to the other lines. This suggests that the contribution of critical fluctuations to the quark-antiquark spin correlation is significant and is potentially detectable in experiment. However, the peaks in our qualitative results are relatively narrow. In realistic situations, we expect these peaks to be wider and higher, as we will discuss further.

We use the NJL model near the rotating center (i.e., $r = 0$) to conduct our calculations, which allows us to obtain the cumulants of spin by directly taking derivatives. As we move further from the center, orbital angular momentum becomes significant. In Supplemental Material [67] the calculations are also extended to the case of $r \neq 0$, where the contribution of orbital angular momentum is taken into account. It is found that the spin correlations increase with r and thus the behavior discussed here is even more prominent at $r \neq 0$. As r increases, the rotational effect becomes stronger due to the contribution from the large orbital angular momentum. Consequently, the location of the CEP will shift from that at $r = 0$. Previous model studies [76,77] indicate that both T_{CEP} and μ_{CEP} change with increasing r or Ω . Considering this, the position of the peak will vary for different values of r , bringing the CEP closer to the freeze-out line as shown in Supplemental Material [67]. Summing all the peaks at different r leads to a higher and wider overall peak structure. As a result, we can estimate the order of overall contribution from critical fluctuations $\delta\rho_{00}^\Omega$ to be about 10^{-2} . To illustrate this concept, we present a schematic figure of ϕ meson spin alignment ρ_{00} (Fig. 4). In this figure, we incorporate the contribution of critical fluctuations into the results of [49], which results in a significant dip in the transition region. Notably, recent results from BES-II also show a similar dip structure [78], which might support our proposal. In conclusion, we suggest that the effects of critical fluctuations on quark-antiquark correlations are measurable in experiments and may help understand the nonmonotonic behavior observed in current experimental data.

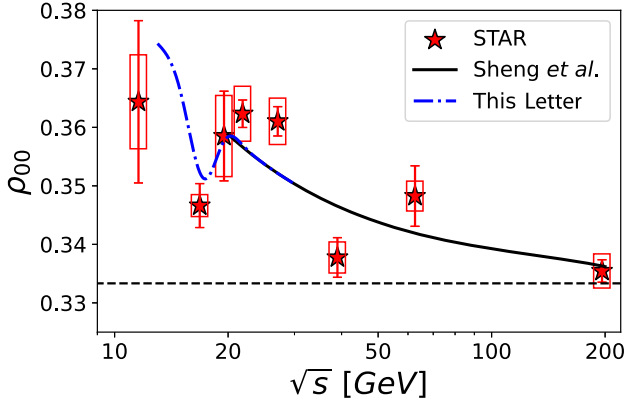


FIG. 4. A schematic figure including the critical fluctuation. The dashed line stands for $\rho_{00} = 1/3$. The dashed dot line is based on freeze-out 3 and our argument. The STAR data is from Ref. [78].

Conclusions and discussions—In this Letter, we investigate critical quark spin fluctuations near the CEP, a phenomenon hitherto unexplored in the literature. Our analysis reveals a pronounced peak in quark spin correlations near the CEP, primarily driven by the rapid variation of the order parameter within the crossover region. This observation serves as a distinctive signature of approaching the CEP.

We propose that the quark-antiquark correlation is potentially measurable through phenomena such as the ϕ meson spin alignment or hyperon-antihyperon correlation [45]

$$\frac{N_{H\bar{H}}^{\uparrow\uparrow} + N_{H\bar{H}}^{\downarrow\downarrow} - N_{H\bar{H}}^{\uparrow\downarrow} - N_{H\bar{H}}^{\downarrow\uparrow}}{N_{H\bar{H}}^{\uparrow\uparrow} + N_{H\bar{H}}^{\downarrow\downarrow} + N_{H\bar{H}}^{\uparrow\downarrow} + N_{H\bar{H}}^{\downarrow\uparrow}}, \quad (19)$$

which could be significantly influenced in the proximity of the CEP, where $N_{H\bar{H}}^{s_1 s_2}$ denotes the number of hyperon-antihyperon pairs with spin s_1 and s_2 , respectively. While further experimental data with improved statistical significance is necessary to confirm this second-order correlation, we suggest it as a promising candidate for future observations.

We should mention that since model calculations [79] and lattice studies [80,81] on the phase transition line in the T - Ω plane are in contradiction, the qualitative behavior of phase structure given by the NJL model may be not consistent with the one in the real world. However, the observed quark spin fluctuation near the CEP remains a robust conclusion, independent of whether the critical temperature increases or decreases with rotation.

We also emphasize that although in this work we use a 2-flavor NJL model which does not include the s quark, we have also checked the case of 2 + 1 flavor NJL model, computed the spin fluctuation of s quark, and have found that the qualitative conclusion does not change. In principle, our conclusions should apply to other vector mesons, such as the K^* and ρ mesons. However, the K^* and ρ mesons are more likely to be affected by hadronic

interactions, which could wash out the spin correlation, in comparison to the ϕ mesons [82]. Thus we expect the ϕ spin alignment serves as an appropriate candidate for the measurement. Moreover, we have also checked the case of PNJL model in Supplemental Material [67], and found that inclusion of the gluon background field has a minor effect on our results.

Note that the quark coalescence scenario is assumed in our theoretical calculations, which is widely used in the studies of spin alignment of vector mesons and hyperon polarization [7,49]. The spin density matrix of vector mesons or hyperons carries on the spin of constituent quarks. In the regime of low p_T and central rapidity, where the experimental measurements receive the most contributions, the mechanism of quark coalescence plays the dominant role, which is also consistent with thermodynamic description of the bulk property. This underlies the survival of the quark spin fluctuations from the hadronization, which is similar to the case of experimental measurements of the net-proton fluctuations.

It is also worth noting that the spin obtained by taking derivatives with respect to Ω_q or $\Omega_{\bar{q}}$ corresponds to the canonical spin tensor, which is a natural and convenient choice in our framework. However, the spin correlations studied here may, in general, depend on the choice of the so-called pseudogauge [83]. In principle, one can define a spin potential related to a chosen spin tensor under a given pseudogauge and compute the corresponding expectation values of spin correlations, following a procedure similar to that used in our analysis. While such an extension lies beyond the scope of the present study, it remains an interesting direction for future study. Nevertheless, we expect the qualitative behavior of spin correlations near the CEP to remain robust, provided that a consistent pseudogauge is employed throughout the analysis, especially near $r = 0$, as considered in this Letter.

The spin related effects such as the spin polarization and alignment are still active topics in the field of high energy nuclear physics. In this work, we mainly focus on the qualitative behavior of spin fluctuations within the NJL model calculations at thermal equilibrium. More detailed and realistic studies, such as the effects of the magnetic field and viscosity during the dynamic evolution from the initial stage [26,84,85], are required, which we leave for future studies.

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