FLUCTUATIONS OF CONSERVED CHARGES IN STRONG MAGNETIC FIELDS FROM LATTICE QCD*

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We present the first lattice QCD results of the second-order fluctuations of, and correlations among net-baryon number, electric charge, and strangeness in (2+1)-flavor lattice QCD in the presence of a background magnetic field with physical pion mass $m_\pi = 135$ MeV. To mimic the magnetic field strength produced in the early stage of heavy-ion collision experiments, we use 6 different values of the magnetic field strength up to $\sim 10\,m_\pi^2$. We find that the correlations between baryon number and electric charge along the transition line are substantially affected by magnetic fields in the current eB window, which could be useful for probing the existence of a magnetic field in heavy-ion collision experiments.

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1. Introduction

The QCD phase structure in the nonzero magnetic fields has recently gained a lot of attention as the strong magnetic field is expected to be present in the early stage of peripheral heavy-ion collisions [1–3], early universe [4], and magnetars [5]. The chiral magnetic effect might be observed in heavy-ion collision experimental observations if the magnetic field lasts long enough [6, 7]. The lifetime of the magnetic field highly depends on the medium electrical conductivity, which is difficult to determine due to the inverse problem in first-principles calculations [8–10]. Many efforts have been made to search for the signal of a magnetic field in the heavy-ion collision experiments [11–15]. Fluctuations of and correlations among net-baryon number (B), strangeness (S), and electric charge (Q) have been very useful to probe the changes in degrees of freedom in QCD as well as the QCD phase structure at zero magnetic fields [16, 17], as they are both theoretically computable and experimentally measurable. On the other hand, the fluctuations

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and correlations of B, Q, and S in nonzero magnetic fields have rarely been studied. Most of the published studies are based on the hadron resonance gas model [18–21] and the Polyakov–Nambu–Jona-Lasinio model [22]. In our previous study, we present the lattice result of the fluctuations and correlations of B, Q, and S in nonzero magnetic fields for the first time where the computation was done using the highly improved staggered fermions with a pion mass about 220 MeV [23]. We found that the fluctuations and correlations of B, Q, and S are strongly affected by the magnetic fields. In this paper, we extend the lattice QCD studies to the case with physical pion mass $m_\pi = 135$ MeV, and focus on a smaller temperature interval around the pseudo-critical temperature ranging from $0.9\,T_{\rm pc}$ to $1.1\,T_{\rm pc}$. To mimic the magnetic field strength produced in the early stage of heavy-ion collision experiments, we now have 6 different values of the magnetic field strength eB up to $10\,m_\pi^2$.

2. Second order fluctuations of conserved charges and computational setup

To calculate the fluctuations of conserved charges and their correlations in a thermal medium, the starting point is the pressure p expressed in terms of the logarithm of partition function Z as follows:

$$\frac{p}{T^4} \equiv \frac{1}{VT^3} \ln Z\left(V, T, \mu_B, \mu_S, \mu_Q\right) , \tag{1}$$

where the baryon (B), strangeness (S), and electric charge (Q) chemical potentials have the following relations with the quark chemical potentials μ_u, μ_d, and μ_s:

$$\begin{aligned} \mu_u &= \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q \,, \\ \mu_d &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q \,, \\ \mu_s &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S \,. \end{aligned} \tag{2}$$

The fluctuations of the conserved charges and their correlations can be obtained by taking the derivatives of pressure with respect to the chemical potentials from lattice calculations evaluated at zero chemical potentials

$$\begin{aligned} \hat{\chi}_{ijk}^{uds} &= \left.\frac{\partial^{i+j+k} p/T^4}{\partial\left(\mu_u/T\right)^i \partial\left(\mu_d/T\right)^j \partial\left(\mu_s/T\right)^k}\right|_{\mu_{u,d,s}=0} , \\ \hat{\chi}_{ijk}^{BQS} &= \left.\frac{\partial^{i+j+k} p/T^4}{\partial\left(\mu_B/T\right)^i \partial\left(\mu_Q/T\right)^j \partial\left(\mu_S/T\right)^k}\right|_{\mu_{B,Q,S}=0} . \end{aligned} \tag{3}$$

Here in our study, we focus on the computation of quadratic fluctuations and correlations, *i.e.* $i+j+k=2$. The expressions of quadratic fluctuations $\hat{\chi}_{ijk}^{BQS}$ in terms of $\hat{\chi}_{ijk}^{uds}$ can be easily obtained via Eq. (2).

The magnetic field is introduced along the z direction and is described by a fixed factor $u_\mu(n)$ of the U(1) field which is introduced in the Landau gauge [24, 25]. In our current simulations of (2+1)-flavor QCD in nonzero magnetic fields, the highly improved staggered quarks are adopted [26]. The strange-quark mass and the light-quark mass are fixed to their physical values $m_s^{\rm phy}$ and $m_l^{\rm phy}$. To perform simulations at nonzero temperature, we change the lattice spacing a at fixed N_τ to have different temperatures. Values of N_τ are fixed to 8 and 12. The temperature ranges from $\sim 0.9\,T_{\rm pc}$ to $\sim 1.1\,T_{\rm pc}$. The values of magnetic flux N_b are $1, 2, 3, 4$, and 6 which correspond to the magnetic field strength $eB < 10\,m_\pi^2$. Since the lattice spacing a is not a constant, the interpolations of lattice data at different T and N_b are needed to have constant magnetic field strength in physical units among different temperatures as a varies with temperature.

3. Results and discussions

In heavy-ion collision experiments, the initial magnetic field strength varies from central collisions to peripheral collisions. Therefore, we would like to propose an $R_{\rm cp}$-like quantity to detect the existence of magnetic fields in heavy-ion collisions. $R_{\rm cp}(X)$ means the ratio of a certain quantity X obtained in central collisions (weak/vanishing magnetic field) to that in peripheral collisions (strong magnetic fields). To achieve this, we normalize the observable along the transition line by the value of observable at vanishing magnetic fields: $X\left(eB, T_{\rm pc}(eB)\right)/X\left(0, T_{\rm pc}(0)\right)$.

In Fig. 1, we show the eB dependence of the normalized $2^{\rm nd}$-order fluctuation and correlations of baryon number, electric charge, and strangeness along the transition line. These values equal unity at $eB=0$ by definition, and the deviation from unity thus shows the magnitude of the influence induced by the magnetic field. From Fig. 1, we can see that net-baryon number related quantities: χ_2^B, χ_{11}^{BS} and χ_{11}^{BQ} are considerably influenced by the magnetic field. In particular, $R_{\rm cp}$-like quantity for $\frac{\chi_{11}^{BQ}(eB,T_{\rm pc}(eB))}{\chi_{11}^{BQ}(0,T_{\rm pc}(0))}$ reaches ~ 2 at $eB \sim 9\,m_\pi^2$. This is a significant effect which might be useful for probing the existence of a magnetic field in heavy-ion collision experiments. We remark here that our current results serve as a QCD baseline for the behavior of quadratic fluctuations and the correlation of conserved charges in external magnetic fields, and further studies are needed to connect to experimental observations.

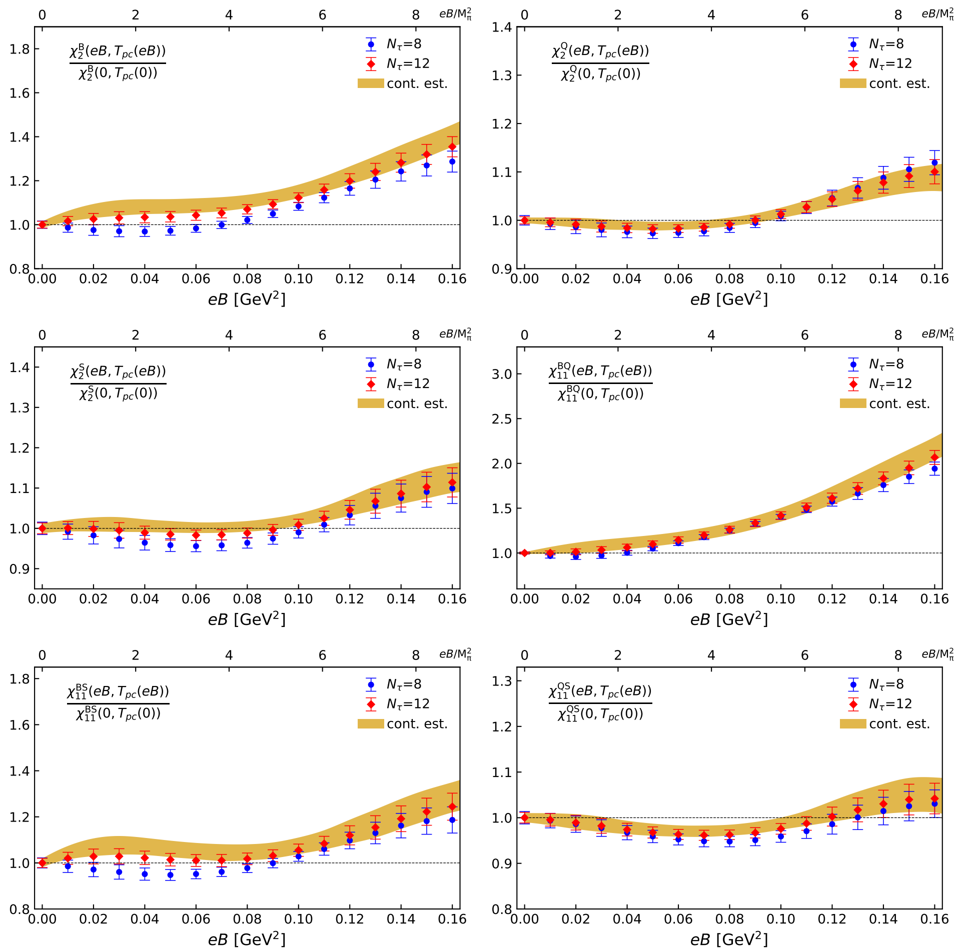

Fig. 1. (Color online) Normalized 2$^{\rm nd}$-order fluctuations of, and correlations among baryon number (B), electric charge (Q), and strangeness (S) along the transition line $T \equiv T_{\rm pc}(eB)$. The continuum estimates are denoted by the yellow/gray band based on the lattice QCD data obtained on $N_\tau = 8$ (blue dots) and $N_\tau = 12$ (red diamonds) lattices.

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