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CORRELATIONS AND FLUCTUATIONS FROM LATTICE QCD: WUPPERTAL–BUDAPEST RESULTS*

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We present the new results of the Wuppertal–Budapest Lattice QCD Collaboration on flavor diagonal and non-diagonal quark number susceptibilities with $2+1$ staggered quark flavors, in a temperature regime between 125 and 400 MeV. A Symanzik improved gauge and a stout-link improved staggered fermion action is utilized; the light and strange quark masses are set to their physical values. Lattices with $N_t = 6, 8, 10, 12, 16$ are used. We perform a continuum extrapolation of all observables under study. Preliminary results for charm quark susceptibilities are also presented, with the charm quark treated at the partially quenched level.

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1. Introduction

Correlations and fluctuations of conserved charges have been proposed long ago [1, 2] as possible candidates to signal the QCD phase transition [3]. They can be obtained as linear combinations of quark number susceptibilities which can be calculated on the lattice at zero chemical potential [4, 5]. These observables can give us an insight on the nature of the matter under study [4, 6]. Indeed, diagonal susceptibilities measure the response of the quark number density to a change in the quark chemical potential, showing a rapid rise in the vicinity of the phase transition. Non-diagonal susceptibilities give us information about the correlation between different flavors. They are supposed to vanish in a non-interacting quark-gluon plasma (QGP), yet

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being non-zero in perturbative QCD at large temperatures due to the presence of flavor-mixing diagrams [7]. A quantitative analysis of this observable allows one to get an insight on the presence of bound states in the QGP [8]. Analogously, one can obtain information about the presence of bound states in the QGP from the baryon-strangeness correlator, proposed to this purpose in Ref. [9]. Quark number susceptibilities also allow to expand thermodynamic quantities in Taylor series (which is a truncation of the full multiparameter reweighting method [10, 11]) around $\mu = 0$ [12].

In the present contribution, we show the results of our collaboration on some of these observables, with $2+1$ dynamical staggered quark flavors, in a temperature regime between 125 and 400 MeV [13]. The light and strange quark masses are set to their physical values, with a ratio $m_s/m_{u,d} = 28.15$. Lattices with $N_t = 6,\ 8,\ 10,\ 12,\ 16$ are used. Continuum extrapolations are performed for all observables under study. We compare our results to the predictions of the HRG model with resonances up to 2.5 GeV mass at small temperatures, and of the Hard Thermal Loop (HTL) resummation scheme at large temperatures, when available. Preliminary results on charm quark number susceptibilities are also shown, for $N_t = 10$ and with the charm quark treated at the partial-quenching level.

2. Details of the lattice simulations

The lattice action is the same as we used in [14, 15], namely a tree-level Symanzik improved gauge, and a stout-improved staggered fermionic action (see Ref. [16] for details). The stout-smearing [17] yields an improved discretization of the fermion-gauge vertex and reduces a staggered artefact, the so-called taste violation (analogously to ours, an alternative link-smearing scheme, the HISQ action [18] suppresses the taste breaking in a similar way. The latter is used by the HotQCD Collaboration in its latest studies [19–21]). Taste symmetry breaking is a discretization error which is important mainly at low energies. In the staggered fermion formulation, hadron masses are not unique at any finite lattice spacing [22]. Each continuum hadron state has a corresponding multiplet of states on the lattice: due to the taste symmetry violation the masses of these states are split. The impact of this effect on the thermodynamic observables has been recently discussed in the HRG framework [23, 24].

For details about the simulation algorithm we refer the reader to [15].

In analogy with what we did in [14, 15], we set the scale at the physical point by simulating at $T = 0$ with physical quark masses [15] and reproducing the kaon and pion masses and the kaon decay constant. This gives an uncertainty of about 2% in the scale setting.

3. Observables under study

The baryon number B, strangeness S and electric charge Q fluctuations can be obtained, at vanishing chemical potentials, from the QCD partition function. The relationships between the quark chemical potentials and those of the conserved charges are

$$\mu_u = \tfrac{1}{3}\mu_B + \tfrac{2}{3}\mu_Q\,, \qquad \mu_d = \tfrac{1}{3}\mu_B - \tfrac{1}{3}\mu_Q\,, \qquad \mu_s = \tfrac{1}{3}\mu_B - \tfrac{1}{3}\mu_Q - \mu_S\,. \quad (1)$$

Starting from the QCD pressure,

$$\frac{p}{T^4} = \frac{1}{VT^3} \ln Z\left(V, T, \mu_B, \mu_S, \mu_Q\right)\,, \quad (2)$$

we can define the moments of charge fluctuations as follows

$$\chi^{BSQ}_{lmn} = \frac{\partial^{\,l+m+n} p/T^4}{\partial\left(\mu_B/T\right)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}\,. \quad (3)$$

In the present paper, we will concentrate on the quadratic fluctuations and on the correlators among different charges or quark flavors. Given the relationships between chemical potentials (1) the diagonal susceptibilities of the conserved charges can be obtained from quark number susceptibilities in the following way

$$\begin{aligned}
\chi_2^B &= \tfrac{1}{9}\left[\chi_2^u + \chi_2^d + \chi_2^s + 2\chi_{11}^{us} + 2\chi_{11}^{ds} + 2\chi_{11}^{ud}\right]\,, \\
\chi_2^Q &= \tfrac{1}{9}\left[4\chi_2^u + \chi_2^d + \chi_2^s - 4\chi_{11}^{us} + 2\chi_{11}^{ds} - 4\chi_{11}^{ud}\right]\,, \\
\chi_2^S &= \chi_2^s\,. \quad (4)
\end{aligned}$$

The baryon-strangeness correlator, which was proposed in Ref. [9] as a diagnostic to understand the nature of the degrees of freedom in the QGP, is defined in the following way

$$C_{BS} = -3\frac{\langle N_B N_S\rangle}{\langle N_S^2\rangle} = 1 + \frac{\chi_{11}^{us} + \chi_{11}^{ds}}{\chi_2^s}\,. \quad (5)$$

4. Results and conclusions

The behavior of light and strange quark number susceptibilities as functions of the temperature is shown in the two panels of Fig. 1. The different symbols correspond to different values of N_t, from 6 to 16. The continuum extrapolation is performed through a parabolic fit in the variable $(1/N_t)^2$, over five N_t values from 6 to 16. The band shows the spread of the results

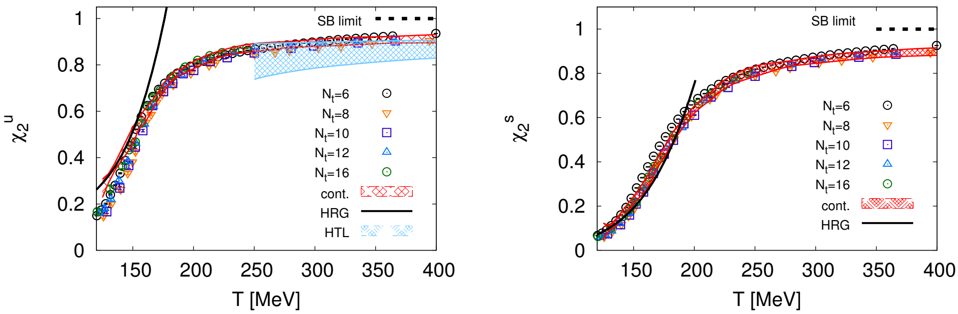

Fig. 1. Left panel: Diagonal light quark susceptibility as a function of the temperature. Right panel: Diagonal strange quark susceptibility as a function of the temperature. In both panels, the different symbols correspond to different N_t values. The grey (red) band is the continuum extrapolation. The black curve is the HRG model prediction for these observables. The dashed line shows the ideal gas limit. The light grey (light blue) band in the left panel is the HTL prediction taken from Ref. [7].

of other possible fits. Both observables show a rapid rise in a certain temperature range, and reach approximately 90% of the ideal gas value at large temperatures. However, the temperature around which the susceptibilities rise is approximately 15–20 MeV larger for strange quarks than for light quarks. The quark-mass dependence effect is even more evident in the case of charm quark susceptibilities. We show all three on the same plot in the right panel of Fig. 2.

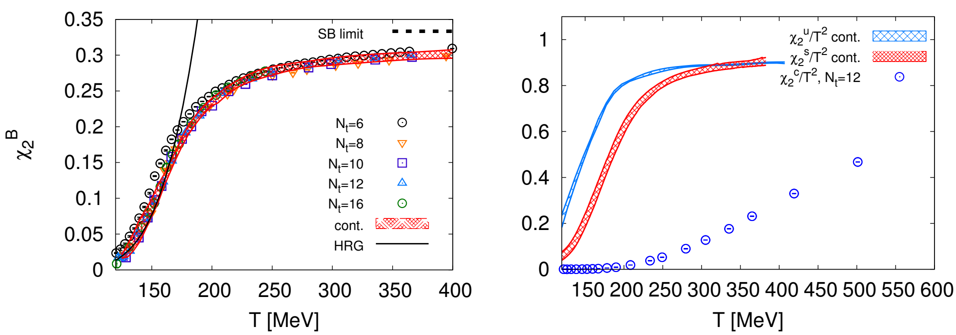

Fig. 2. Left panel: Quadratic fluctuation of baryon number as a function of the temperature. The different dots correspond to different N_t values. The grey (red) band is the continuum extrapolation. The black curve is the HRG model prediction. The dashed line shows the ideal gas limit. Right panel: Comparison between light, strange and charm quark number susceptibilities. For the first two the fully dynamical, continuum extrapolated result is given. For the third one, the charm quark is treated at the partially quenched level and results are presented for the smallest lattice spacing under study, corresponding to $N_t = 12$.

The non-diagonal us susceptibility measures the degree of correlation between different flavors. This observable vanishes in the limit of an ideal, non-interacting QGP. We show our result in the left panel of Fig. 3. χ_{11}^{us} is non-zero in the entire temperature range under study. It has a dip in the vicinity of the transition, where the correlation between u and s quarks turns out to be maximal. It agrees with the HRG model prediction in the hadronic phase. A quantitative comparison between lattice results and predictions for a purely partonic QGP state can give us information about the probability of bound states survival above T_c [8]. The baryon-strangeness correlator C_{BS} defined in Eq. (5) is supposed to be equal to one for a non-interacting QGP, while it is generally smaller than one in a hadronic system. We show our result for this observable in the right panel of Fig. 3. For small temperatures it agrees with the HRG model result, and it shows a rapid rise across the phase transition.

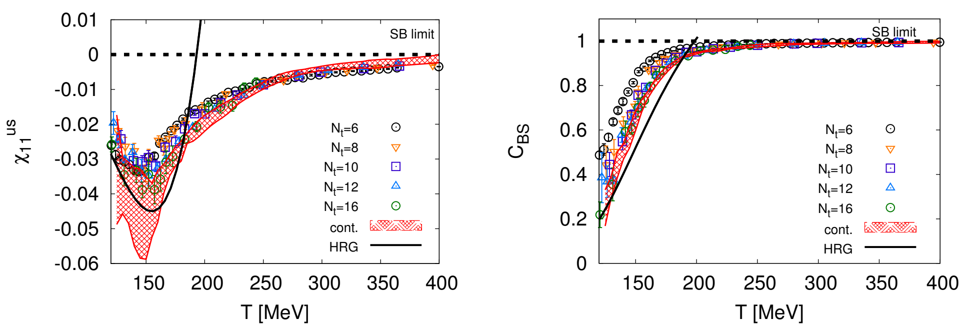

Fig. 3. Left panel: Non-diagonal u–s correlator as a function of temperature. Right panel: Baryon-strangeness correlator as a function of temperature. In both panels, the different symbols correspond to different N_t values, the grey (red) band is the continuum extrapolation and the black, solid curve is the HRG model result. The ideal gas limit is shown by the black, dashed line.

Quadratic baryon number fluctuations can be obtained from the above partonic susceptibilities through Eqs. (4). We show our results for this observable in Fig. 2. In the low-temperature, hadronic phase we have a very good agreement with the HRG model predictions. In the vicinity of the phase transition, this quantity shows a rapid rise with temperature. At large temperature it reaches approximately 90% of the ideal gas value.

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