Strangeness at high temperatures

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Abstract. We use up to fourth order cumulants of net strangeness fluctuations and their correlations with net baryon number fluctuations to extract information on the strange meson and baryon contribution to the low temperature hadron resonance gas, the dissolution of strange hadronic states in the crossover region of the QCD transition and the quasi-particle nature of strange quark contributions to the high temperature quark-gluon plasma phase.

1. Introduction

At RHIC and the LHC, quark gluon plasma is created by means of heavy ion collisions. The initial conditions of such collisions are free of net strangeness. It is theoretically well understood [1] and experimentally verified [2] that many strange, anti-strange quarks are created during these collisions. This will ultimately lead to event-by-event fluctuations of strangeness, as long as only a fixed subsystem (specific kinetic window) is observed. To what extent the created fireball reaches chemical equilibrium before its hadronic freeze out — depending on collision energy and system size — is, however, still under debate. Furthermore, it is questionable whether strange hadrons also freeze-out in the critical crossover region ($T \approx T_c$) that is controlled by the light quark sector. Based on the very smooth behavior of strangeness fluctuations [3, 4] it has been suggested [5, 6] that deconfinement for strange quarks takes place at a temperature significantly larger than T_c, determined by chiral symmetry breaking. This would imply the existence of strange bound sates inside the QGP for some temperatures $T > T_c$. A detailed analysis of various cumulants of net strangeness fluctuations and baryon number strangeness correlations obtained by the BNL-Bielefeld Collaboration [7] supports, however, the statement that the strangeness liberation temperature is consistent with T_c. We will briefly repeat this study here. We obtain these cumulants as derivatives of the logarithm of the QCD partition function, or equivalently of the pressure (P) in units of T^4, with respect to the chemical potentials. In general we define

$$\chi_{mn}^{XY} = \left.\frac{\partial^{(m+n)}[P(T,\hat{\mu}_X,\hat{\mu}_Y)/T^4]}{\partial\hat{\mu}_X^m \partial\hat{\mu}_Y^n}\right|_{\vec{\mu}=0} , \qquad (1)$$

where $X, Y = B, S, Q$ are the quantum numbers of net baryon (B), net strangeness (S) and net electric charge (Q) and $\hat{\mu}_X = \mu_X/T$ are the corresponding chemical potentials with $\vec{\mu} = (\mu_B, \mu_S, \mu_Q)$. We will also use the notations $\chi_{0n}^{XY} \equiv \chi_n^Y$ and $\chi_{m0}^{XY} \equiv \chi_m^X$. The various χ_{mn}^{XY} cary information on the quantum numbers of the relevant degrees of freedom in the system [8, 9]. Note, however, that the quantities χ_{mn}^{XY} also define the Taylor expansion coefficients of the pressure with respect to $\hat{\mu}_X$ and $\hat{\mu}_Y$. Their study is thus important also for other reasons such as a critical point search [10, 11] or the analysis of the freeze out properties of heavy ion collisions [12]. In the following, we will compare our non-perturbative lattice QCD results to an uncorrelated gas of hadrons at low temperatures and to an uncorrelated gas of quarks at high temperatures, with special emphasis on the strangeness fluctuations. Here the lattice calculations have been performed with highly improved staggered quarks (HISQ) and almost physical quark masses (the ratio of light to strange quark mass is 1/20, with a strange quark mass that was fixed to its physical value). The lattice sizes have been chosen as $N_\sigma^3 \times N_\tau$, with aspect ratio $N_\sigma/N_\tau = 4$ and $N_\sigma = 24$ and 32. A continuum limit is still to be taken and will require at least one even finer lattice spacing. However, from the stability of our current results we estimate very small effects of the nonzero lattice spacing. For the comparison with the HRG we take all particles and resonances up to a mass cutoff of 2.5 GeV into account.

2. Strangeness in the hadronic phase

Strange hadrons are relatively heavy. Even the lightest strange meson ($K^\pm$) is with 493 MeV heavy enough to be treated in Boltzmann approximation, in the relevant temperature interval just around the chiral crossover ($T_c = 154 \pm 9$ MeV [13]). The pressure that is build up within an uncorrelated gas of all known strange hadrons and resonances (P_S^{HRG}) receives contributions from 4 different strangeness sectors, namely from strange mesons ($|S| = 1, M$) and strange baryons ($|S| = i, B$) with $i = 1, 2, 3$, respectively. Assuming Boltzmann statistics, the μ_B and μ_S dependence is simple and solely determined by the baryonic and strange charges of the hadrons, *i.e.* grouped into the 4 different sectors we find for the partial pressure of all strange hadrons:

$$
\begin{aligned}
P_S^{\mathrm{HRG}}(T,\hat\mu_B,\hat\mu_S) &= P^{\mathrm{HRG}}_{|S|=1,M}(T)\cosh(\hat\mu_S) + P^{HRG}_{|S|=1,B}(T)\cosh(\hat\mu_B-\hat\mu_S)\\
&+ P^{HRG}_{|S|=2,B}(T)\cosh(\hat\mu_B-2\hat\mu_S) + P^{HRG}_{|S|=3,B}(T)\cosh(\hat\mu_B-3\hat\mu_S)\,. \qquad (2)
\end{aligned}
$$

As long as strange hadrons, with baryonic and strange charges that fall into the before mentioned strangeness sectors, are a valid description of the strangeness carrying degrees of freedom in the system, Eq. (2) will imply various relations between correlations of net baryon number and net strangeness χ_{mn}^{BS}, that can be checked in (lattice) QCD. In particular we can use these relations to calculate the partial pressures of the different strangeness sectors from all fluctuations and correlations χ_{mn}^{BS} up to fourth order, *i.e.* with $0 \le m \le 4$, $1 \le n \le 4$, $(m+n) \le 4$ and $m+n$ even, we can use 6 different BS-correlations. It is easy to see that according to Eq. (2), all 6 χ_{mn}^{BS} that we use, can be written as linear combinations of the 4 partial pressures. To obtain the partial pressures we have to invert this linear mapping. We find that the linear mapping has a kernel of dimension 2, consequently our solution is not uniquely defined but will depend on two parameters c_1 and c_2. As a result, we find the operators that project onto the 4 different partial pressures, given by

$$
\begin{aligned}
M(c_1,c_2) &= \chi_2^S - \chi_{22}^{BS} + c_1 v_1 + c_2 v_2\,, &(3)\\
B_1(c_1,c_2) &= \frac{1}{2}\left(\chi_4^S - \chi_2^S + 5\chi_{13}^{BS} + 7\chi_{22}^{BS}\right) + c_1 v_1 + c_2 v_2\,, &(4)\\
B_2(c_1,c_2) &= -\frac{1}{4}\left(\chi_4^S - \chi_2^S + 4\chi_{13}^{BS} + 4\chi_{22}^{BS}\right) + c_1 v_1 + c_2 v_2\,, &(5)\\
B_3(c_1,c_2) &= \frac{1}{18}\left(\chi_4^S - \chi_2^S + 3\chi_{13}^{BS} + 3\chi_{22}^{BS}\right) + c_1 v_1 + c_2 v_2\,, &(6)
\end{aligned}
$$

where $v_1 = \chi_{31}^{BS} - \chi_{11}^{BS}$ and $v_2 = \frac{1}{3}(\chi_2^S - \chi_4^S) - 2\chi_{13}^{BS} - 4\chi_{22}^{BS} - 2\chi_{31}^{BS}$ are 2 linear independent basis vectors of the kernel. Therefore, as long as the uncorrelated gas of hadrons is a valid description of QCD, the combinations v_1 and v_2 have to vanish[1] and do not contribute to

[1] Of course, the uncorrelated gas model will be an approximation at all temperatures and v_1 and v_2 are thus not be expected to vanish exactly , *i.e.* they are no order parameters.

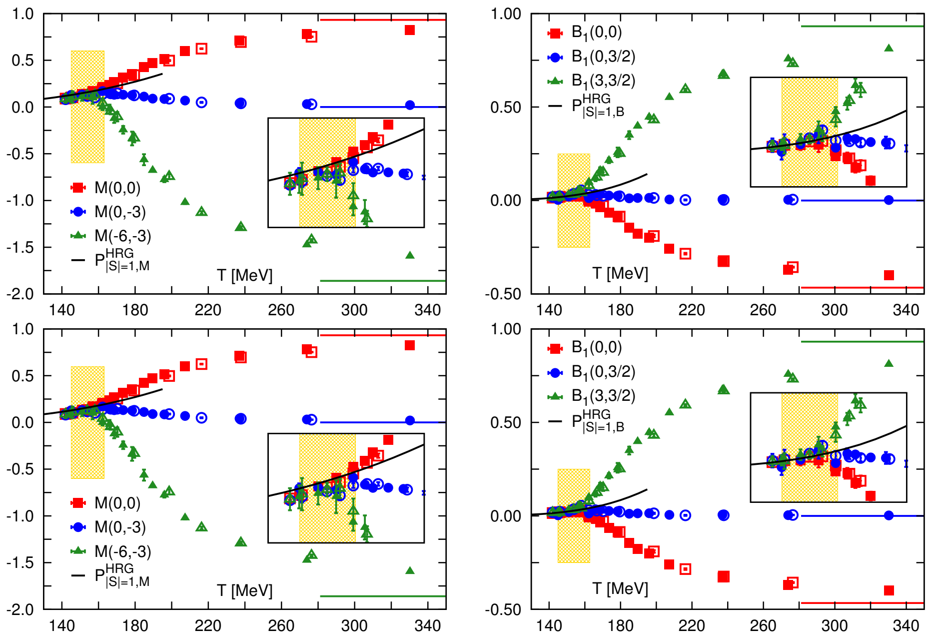

Figure 1. Operators that project for low temperatures onto the partial pressure of strange mesons (top-left), baryons with strangeness $|S| = 1$ (top-right), $|S| = 2$ (bottom-left) and $|S| = 3$ (bottom-right). Results from $N_\tau = 6$ and 8 lattices are shown by open and full symbols, respectively. Also shown are results from the HRG model (black solid lines). Vertical bands indicate the chiral corossover temperature [13].

Eqs. (3-6). In Fig. 1, we show our results for the partial pressure, obtained in the 4 different strangeness sectors, *i.e.* we plot our data for the strangeness fluctuations and correlations in the combinations given by Eqs. (3-6) for 3 different choices of the parameter c_1 and c_2, respectively (color coded). We find that for temperatures $T \lesssim 160$ MeV, all three different combinations agree, in each of the four sectors. In addition we find agreement with the HRG results shown as solid black lines, in the same temperature range. One can thus conclude that for $T \lesssim 160$ MeV, an uncorrelated gas of hadrons is compatible with the relevant strange degrees of freedom in QCD. The same conclusion can be drawn from Fig. 2 (left), where we show the combinations v_1 and v_2, that serve as an indicator for the validity of the HRG, *i.e.* they vanish as long as the strange degrees of freedom can be described by hadrons. Here we also show the difference of second and fourth order net baryon number fluctuations $(\chi_2^B - \chi_4^B)$. This quantity also vanishes in the HRG but, in contrast to v_1, v_2 receives contributions from all baryons, including the light sector. All quantities shown in Fig. 2 (left) behave rather similar and in particular break away from the HRG in the crossover region $T \sim (154 \pm 9)$ MeV. We thus have no indication that strange hadrons survive the chiral crossover.

3. The plasma phase

Finally we probe the strange degrees of freedom in the high temperature phase, were we expect to find strangeness to be carried by quasi free quarks. As strange quarks carry baryon number 1/3 and electric charge $-1/3$, an interchange of derivatives with respect to $\hat{\mu}_B$ and $\hat{\mu}_Q$ in a gas of free strange quarks will only lead to a sign change. The ratio $-\chi_{211}^{BQS}/\chi_{121}^{BQS}$ thus reaches unity for large temperatures were quarks behave as free particles. In Fig. 2 (right), where we plot this ratio, we find deviations from the free quark gas result, which are of the order of $(10-15)\%$ for

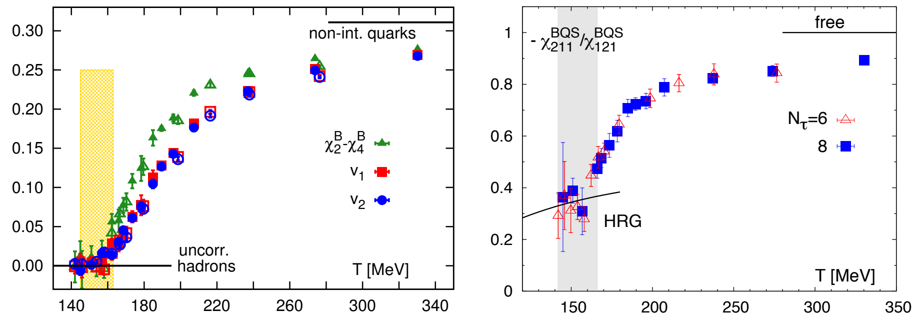

Figure 2. Left: quantities that vanish within and uncorrelated gas of hadrons (Boltzmann approximation). Right: quantity that reaches unity in an uncorrelated gas of quark and gluons. In both cases we show results from $N_\tau = 6$ and 8 lattices by open and full symbols, respectively

$T \gtrsim 300$ MeV. Similar deviations have also been found in other bulk thermodynamic quantities like pressure and energy density. In the hadronic sector, this ratio projects onto strange charged baryons. Here the charge one and two sectors are weighted differently by the cumulants χ_{211}^{BQS} and χ_{121}^{BQS} and the ratio will be less than unity. We have also plotted the HRG result in Fig. 2 (right), and find agreement with the HRG for $T \lesssim 160$ MeV.

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