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Can Flavor Hierarchy in the QCD Phase Transition Change Our Understanding of Hadronization ?

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Our recent study of high precision, continuum extrapolated lattice QCD results performed with realistic quark and pion masses has yielded intriguing patterns in higher order susceptibilities which can be interpreted as evidence for bound state formation and a flavor hierarchy in the crossover region of the QCD phase transition. In these proceedings we are showing the latest lattice results and relate them to experimental data of particle yields. We also propose specific particle fluctuation measurements that can be directly compared to calculations in order to extract flavor specific chemical freeze-out temperatures.

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1. Introduction

The discovery of a deconfined partonic state of matter in heavy ion collisions at RHIC and the LHC [1, 2] enables us to investigate the mechanism of hadron formation from a state of free quarks and gluons to a state of colour-neutral particles of finite mass. The common interpretation has been that a finite volume deconfined state, which is thermally and chemically equilibrated, will cool down to a specific temperature at which hadronization occurs. Recently, this temperature has been calculated on the lattice to a very high precision based on continuum extrapolated finite temperature QCD thermodynamics. Such studies show that the finite-temperature QCD transition is merely an analytic crossover [3]. This means that during the cooling of the Universe the system transitioned from the phase dominated by colored particles to the hadronic phase over an extended period of time without the emission of latent heat. Since no unambiguous temperature can be assigned to this transition, the question arises whether hadrons of different quark composition freeze-out simultaneously or exhibit a flavor hierarchy [4, 5]. The results presented here hint at a more complex hadronization pattern due to specific features of the conserved quantum numbers involved. Although the differences between hadronic species are small (within 30 MeV) they might hint at fundamental differences in the hadronization temperatures for various quark states.

This question is relevant since the reported strangeness enhancement at SPS, RHIC and LHC energies (in particular in the multi-strange particle sector [6, 7, 8]), and the discovery of hypernuclei formation at RHIC [9] suggest the possibility of increased strange bound state production at the highest available collision energies. Furthermore, recent measurements in relativistic heavy-ion collisions at the LHC indicate a separation of chemical freeze-out temperatures between light and strange quark hadrons [10, 11].

In these proceedings we show a set of observables, obtained by means of continuum-extrapolated lattice QCD simulations, which indicate a flavor separation in the transition region of QCD. Such quantities are based on flavor-specific fluctuations, as well as on correlations between different flavors or conserved charges. The lattice framework is the one used by the Wuppertal-Budapest Collaboration based on tree level improved Symanzik gauge action and a staggered fermionic action with 2-level stout improvement (for a precise definition of the action see [12]). We show lattice results based on the continuum extrapolation from finite temporal spacing data sets using N_t=6,8,10,12. At T_c these temporal extensions correspond to a =0.22, 0.16, 0.13 and 0.11 fm lattice spacings, respectively. The lattice simulations were all carried out in a finite volume and with strange to light quark mass ratio at its physical value ($m_s/m_{ud} \approx 28$) as determined in Ref. [13].

2. Lattice results

Fluctuations of conserved charges can be expressed in a grand canonical ensemble as the derivatives of the partition function with respect to the conserved charge chemical potential. In QCD the net u, d and s quark numbers are conserved: we introduce μ_u, μ_d and μ_s as the corresponding chemical potentials. Fluctuations are then expressed in terms of derivatives of the pressure p of the equilibrated system:

$$\chi_{lmn}^{uds} = \frac{\partial^{l+m+n}(p/T^4)}{\partial(\mu_u/T)^l \partial(\mu_d/T)^m \partial(\mu_s/T)^n}. \tag{2.1}$$

Odd l+m+n combinations are sensitive to non-vanishing chemical potentials, but since our main interest in this paper is the physics at highest RHIC energies and the LHC, we work with vanishing μ-s. More precisely we concentrate on some quadratic and quartic fluctuations (thus $l+m+n$=2 or 4) and their ratios. Since these fluctuations are directly related to conserved currents, no renormalization ambiguity should appear. Our focus is on μ_L and μ_S which couple to the net light flavor density and the strangeness density, respectively. To study correlations with the flavor-mixed baryon number we also introduce the respective chemical potential μ_B:

$$
\begin{aligned}
\frac{\partial}{\partial \mu_L} &= \frac{1}{2}\frac{\partial}{\partial \mu_u} + \frac{1}{2}\frac{\partial}{\partial \mu_d}\,; \quad \frac{\partial}{\partial \mu_S} = -\frac{\partial}{\partial \mu_s} \\
\frac{\partial}{\partial \mu_B} &= \frac{1}{3}\frac{\partial}{\partial \mu_u} + \frac{1}{3}\frac{\partial}{\partial \mu_d} + \frac{1}{3}\frac{\partial}{\partial \mu_s}
\end{aligned}
\tag{2.2}
$$

The method for extracting the diagonal and off-diagonal quark number susceptibilities as well as the second and fourth order derivatives has been worked out in detail in Refs. [15, 16, 14, 17].

Already in 2006 the Wuppertal-Budapest Collaboration showed that the characteristic temperature of the transition in the strange sector (based on χ_2^s) is about 20 MeV higher than that for the light quark sector (based on the chiral susceptibility [18] or χ_2^u in Ref. [19]). Fig. 1 shows the latest, continuum extrapolated T-dependence of the light quark $\chi_2^L(T)$ and strange quark $\chi_2^s(T)$ susceptibilities. One striking observation is an approximate scaling relation between the T-dependencies of the lowest order light and strange quark susceptibilities, respectively. A rescaling in T for one of these observables closely reproduces the other one: $\chi_2^L(T\cdot x)$=$\chi_2^s(T)$ yielding a rescaling factor x=1.11 (see Fig. 1). This means that independent of a chosen point in the crossover region and its relation to the QCD phase transition, the similarity transformation between the two curves leads to a rather precise prediction for the difference between the transition temperatures of light and strange quarks. We find that the characteristic temperature difference is about $\simeq$ 15 MeV higher for the strange quark than for the light quarks.

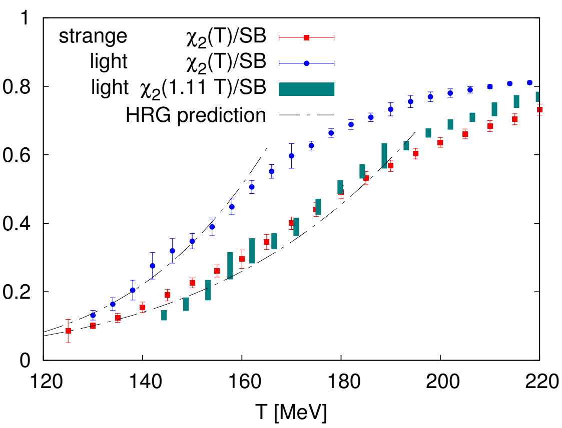

Figure 1: Light and strange quark susceptibilities in the continuum limit (plotted as blue circles and red squares, respectively). The transition temperatures defined by the inflection points for χ_2^L (150 MeV) and for χ_2^s (165 MeV) differ by $\approx$ 15 MeV. A rescaling transformation is shown with bars.

An additional way to identify bound states in a lattice calculation might be embedded in the lowest order non-diagonal (mixed) quark correlator for flavors that can potentially form a hadronic final state. As an example we calculated the non-diagonal $u-s$ susceptibilities, which should contain contributions from final state kaons. Fig.2 shows that the $u-s$ correlator on the lattice exhibits a pronounced structure in the vicinity of the phase transition. Although it was shown in Ref. [20] that correlations between different flavors are nonzero in perturbative QCD at large temperatures, due to the presence of flavor-mixing diagrams, the lattice data exhibit a strong enhancement of these correlations in the vicinity of T_c, which survives up to relatively large temperatures above the transition [14, 21] and which cannot be accounted for by the perturbative QCD contribution alone.

In order to draw conclusions on the presence of color neutral bound states in the region 1-2 T_c, we compare the lattice results to calculations performed with a PNJL model [4]. Here, the PNJL model is tuned in a way that all quark contributions and field fluctuations are taken into account but no hadronic contribution is calculated. Thus we expect that any difference between lattice and PNJL results will quantify the existence of hadronic bound states above the QCD transition temperature, as determined by the inflection point in the non-diagonal correlator curve as a function of temperature.

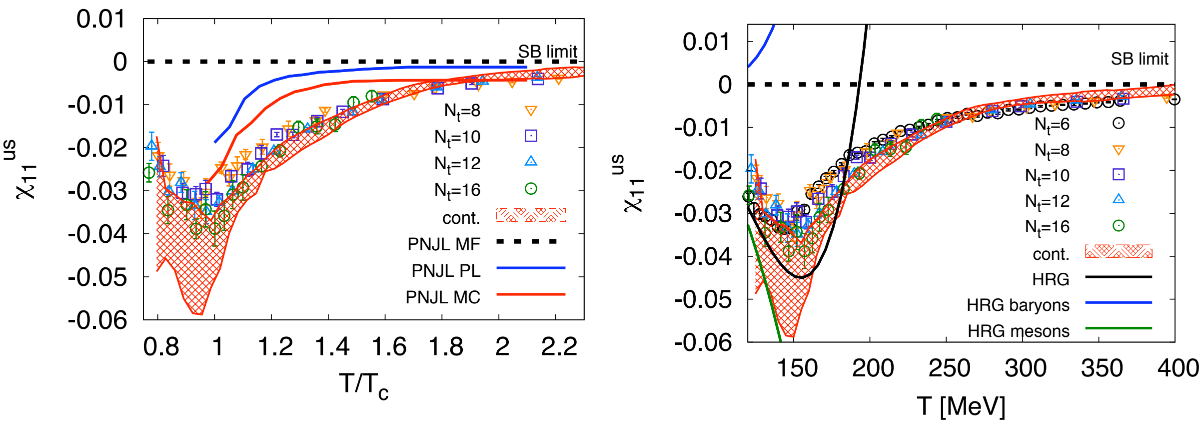

Figure 2: Left: Comparison between the lattice results for the $u-s$ correlator as a function of T/T_c [**?**], and the PNJL model results. The mean field PNJL result is zero for all temperatures, as expected (dashed curve). The blue curve corresponds to the PNJL model result when only the Polyakov loop fluctuations are taken into account. The red curve is the full PNJL model prediction, with fluctuations of all fields taken into account. Notice that the red curve will fall on the blue curve in the infinite volume limit. Right: Comparison between the lattice results for the $u-s$ correlator and Hadron Resonance Gas model results. The different curves show the contributions of baryons (blue), mesons (green) and the total (black) from the HRG model [23].

At the mean field level, the PNJL model has no correlations between the different quark flavors, therefore the corresponding $u-s$ correlator stays flat and equal to zero over the full temperature range. In order to properly estimate all possible contributions to this observable from colored degrees of freedom and mesonic zero modes, we need to go beyond mean field and take fluctuations of all fields (Polyakov loop, chiral condensates, pion and kaon condensates) into account. The importance of including fluctuations in the model is shown in Fig.2(left), where we compare the chiral condensate from lattice QCD (from Ref. [14]), the PNJL result at the mean-field level, and the PNJL result in which fluctuations of all fields are included. As it is evident, the inclusion of fluctuations makes the curve much smoother and brings it closer to the lattice data (a similar effect was observed in Ref. [22]). Still, the correlator values, in comparison to PNJL model calculations beyond mean-field in the temperature regime between 1-2 T_c, indicate that at least part of the mixed phase resides in color-neutral bound states.

Furthermore, the peculiar shape of the non-diagonal correlator near T_c (sharp dip and subsequent slow rise towards zero) can be interpreted when comparing it to the separate contributions of mesonic and baryonic states in a hadron resonance gas (HRG) calculation [23]. Mesonic states in the HRG model exhibit a negative correlation, whereas baryonic states yield a positive value (see Fig.2(right)). The dip and slow rise thus is likely caused by enhanced baryonic state formation (or survival) at higher temperatures. Still, the lattice data never exceed zero before full deconfinement is reached, which means that baryonic states never dominate the hadron formation.

Although there seems to be ample evidence from the diagonal and non-diagonal lowest order correlators for a flavor hierarchy in the QCD crossover, these basic susceptibilities are obviously influenced by the free quark masses. Recently it was argued in the literature that higher order susceptibilities, and in particular their ratios, might be a.) more sensitive to the underlying physics and b.) experimentally verifiable through particle yield fluctuation measurements [26, 27]. The most attractive proposed quantity is χ_4^f/χ_2^f, since the ratio does not depend on the volume and it can be used to determine the chemical freeze-out temperature independent of any statistical model assumptions [25]. Fig. 3 shows the T-dependence of χ_4/χ_2 for light and strange quarks.

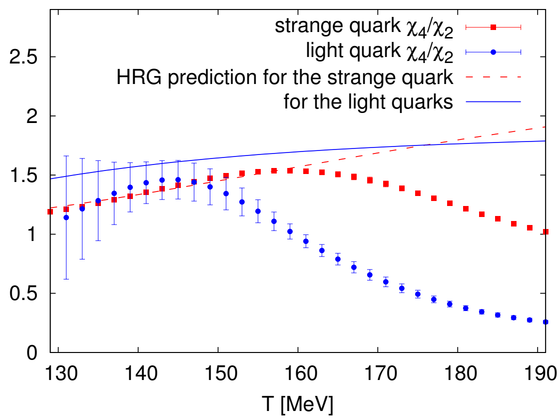

Figure 3: The T-dependence of the χ_4/χ_2 ratio for light and strange quarks in the continuum limit. The lattice data are compared to HRG calculations.

For the light quark susceptibilities (thus for observables related to net up+down quark numbers) the pion contribution, which is notoriously difficult to calculate on the lattice, is absent by definition. The figure shows two characteristic features: a) each lattice calculation exhibits a kink (or peak) at a particular temperature and b) this kink coincides with the temperature at which the lattice curve starts to deviate from predictions based on the hadron resonance gas (HRG), which is widely considered the temperature at which the hadronic states start to melt into their constituents. Interestingly enough, the separation between the kinks of the two flavors corresponds to the previously mentioned ≈15 MeV. In a scenario, in which the highest temperature where the HRG and lattice QCD agree is indicating a deconfinement temperature for a particular flavor Fig. 3 further supports the flavor separation of the characteristic temperatures.

3. Experimental results and proposed future measurements

The challenge is to unambiguously demonstrate such a flavor hierarchy experimentally. The effect could manifest itself to first order in the multiplicity distribution of identified particles. In case strange hadrons form at a higher temperature than their light quark counterparts, their abundance will be enhanced relative to a common low temperature freeze-out scenario. Therefore, the comparison of measured yields to a statistical hadronization model enables one to determine chemical freeze-out temperatures (T_{ch}) in a flavor-separated way. First results from ALICE indicate that the T_{ch} of strange hadrons is about 16 MeV higher than that of light hadrons (164 vs 148 MeV) [10, 11]. As in the case of the lattice parameters, this sensitivity to the freeze-out temperature, extracted from a statistical hadronization fit, is most pronounced for the multi-strange baryons. These temperature fits are model-dependent, though, and a direct comparison to the temperatures extracted from quark susceptibilities in lattice QCD likely requires corrections. For example, it was suggested that final state interactions between hadrons might modify the baryon yields [29, 30].

A more precise verification, less prone to alternate explanations, can be obtained by using the aforementioned higher order moment analysis of particle identified yields, since those moments can be directly related to the higher order susceptibilities on the lattice. In particular, the product of kurtosis and the square of the variance of the net multiplicity distributions corresponds to the susceptibility ratio [25] shown in Fig. 3. Even for this analysis, though, the caveat is the exact relation between the quark-based observable and the hadron-based measurement. Specifically, one needs to determine how many hadron species have to be measured in order to fully capture the transition behavior of the respective quark flavor. Preliminary studies show that taking into account only the dominant mesonic states is not sufficient. Baryonic states require significant acceptance and efficiency corrections, though, even under the assumption of statistical behavior of the higher moments of reconstructed particles in the detector acceptance [31]. Furthermore, corrections for hadronic resonance decays have to be considered. Still, based on first correction studies and initial results from the RHIC experiments for a subset of identified particle species [32], we expect that a flavor separation can be experimentally verified or falsified through specific freeze-out temperature measurements. Once the experimental results are approaching a certain value with small errors, one can extend the studies shown in Fig. 3 in this particular temperature region with additional higher precision lattice data.

4. Conclusions

In conclusion, we have presented high precision continuum extrapolated lattice calculations of flavor-specific susceptibility combinations at zero baryo-chemical potential and high temperatures. We have shown that flavor-dependent patterns emerge in the crossover region of the QCD transition. The T-dependence of the examined observables hints at a flavor separation, especially for quantities which are most sensitive to multi-strange states. We have proposed an experimental program that might allow an observation of a possible similar separation in the freeze-out temperatures. One can

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look for these effects at LHC, and potentially RHIC energies if the net multiplicity distributions of identified particles in the relevant quark sectors can be measured and efficiency corrected to the same high accuracy as the lattice QCD calculations.

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