Strangeness at finite temperature from Lattice QCD

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Abstract. The precision reached by recent lattice QCD results allows for the first time to investigate whether the measured hadronic spectrum is missing some additional strange states, which are predicted by the Quark Model but have not yet been detected. This can be done by comparing some sensitive thermodynamic observables from lattice QCD to the predictions of the Hadron Resonance Gas model (with the inclusion of decays [3]). We propose a set of observables, defined as linear combinations of conserved charge fluctuations, where one can separate baryons by their strange quark content. These observables can isolate the multiplicity fluctuations of kaons from lattice QCD, which can then be compared with experimental results.

1. Introduction

In the 1960's Ralf Hagedorn proposed [1] that if there was a limiting temperature of the universe, now known as the Hagedorn Temperature, then the addition of increasingly more energy to a system would no longer increase the temperature but rather create more massive, highly degenerate resonances. The consequence of this idea was an exponentially increasing mass spectrum

$$N(M) = \sum_i d_i \Theta_i(M - M_i) \tag{1}$$

summed over the degeneracy, d_i, of the known hadrons. In 2004 [2] and 2015 [3] the experimentally measured hadrons from the Particle Data Group [4] confirmed the continually exponentially increasing mass spectrum, as Hagedorn originally suggested.

Meanwhile, high energy heavy-ion collisions at RHIC and the LHC probed temperatures surpassing Hagedorn's original limiting temperature, producing a deconfined state of matter known as the Quark Gluon Plasma. We now understand, thanks to first principle Lattice QCD calculations, that there is a cross-over phase transition [5], not a limiting temperature. In this framework we can understand the Hagedorn temperature as roughly equivalent to the critical temperature and then expect the effect of an exponentially increasing mass spectrum to appear close to the phase transition. Indeed, including missing resonances close to the phase transition can affect dynamical chemical equilibrium [6, 7, 8, 9], decrease the shear viscosity over entropy ratio [10, 11, 12, 13], affect the elliptical flow [14, 15], and improve thermal fits [16].

2. Missing States

Recent comparisons to Lattice Quantum Chromodynamic calculations [17] suggested that there may be missing strange hadrons as calculated from Quark Model states [18, 19] due to a mismatch in the strange chemical potential to baryon chemical potential in Lattice QCD vs. the Hadron Resonance gas model from the known PDG spectrum [4]. Further more, there were suggestions [17, 20, 21] that missing resonances could account for the p/π vs. strange hadron tension at LHC when it comes to the thermal fits [22]. However, in [17] the decays of the Quark Model states were not considered, which are necessary for thermal fits.

Fig. 1 shows the exponentially increasing mass spectra including Quark Model states, implying that these missing resonances are consistent with Hagedorn's original postulate. Using the known branching ratios from [4], we extrapolated up the branching ratios of the Quark Model states taking all quantum numbers into account. We analyzed the net-proton and net-charge fluctuations (χ_1/χ_2) as in [23], to extract the corresponding T and μ_B across energies in the Beam Energy Scan. The results in Fig. 2 show that the addition of the Quark Model states slightly decreases the freeze-out temperature but overall only has a small affect (similar to [16]).

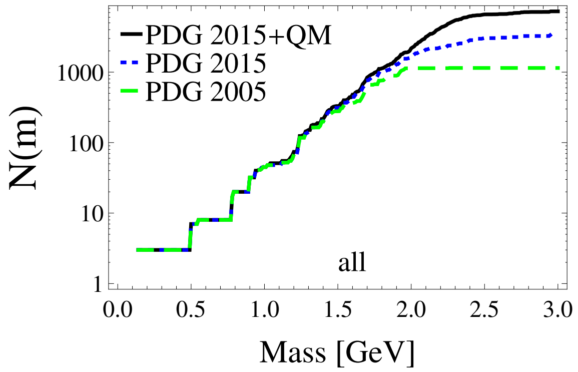

Figure 1. Mass spectrum, Eq. (1), of the strange mesons for the PDG05, PDG15, and PDG15+Quark Model states.

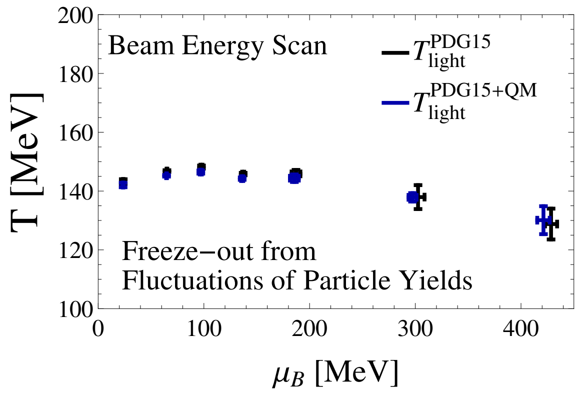

Figure 2. Freeze-out lines extracted from χ_1/χ_2 of the PDG vs. PDG+Quark Model states using net-p and net-Q fluctuations.

3. Strangeness chemical freeze-out from Lattice QCD

An alternative picture was also suggested to resolve the tension between the light and strange hadrons at LHC. In Lattice QCD, the inflection point of susceptibilities can provide clues of about the temperature of hadronization. Using the light susceptibility one finds an inflection point around $T\sim 150$ MeV whereas the inflection point for the strangeness susceptibility is around $T\sim 165$ MeV [24]. Considering there is ~ 15 MeV difference between light and strange hadrons, a logical consequence of this may be that strange hadrons reach chemical equilibrium at higher temperatures than light hadrons. If this is true, it would be consistent with the tension between the light and strange hadrons because it would increase the population of strange baryons, which are typically under-predicted using lower temperatures.

This idea is consistent with many dynamical models. In UrQMD there is no specified chemical freeze-out temperature such that each particle species reaches chemical equilibrium on a different time scale [25]. Similarly, using multi-body hadronic interactions via rate equations, one can also reach chemical equilibrium on different time scales depending on the species. However, if one can provide directly from first-principle Lattice calculations that different chemical equilibration temperatures are needed then it gives significantly more weight to these dynamical models.

Furthermore, it will then require the hadronization schemes to be updated uniformly to include different temperatures for light and strange hadrons.

In order to extract the chemical freeze-out temperature from the lattice we use ratios of susceptibilities as discussed in [23, 26, 27]. In the experiment, the only strange multiplicity fluctuations (and their corresponding moments of these distributions) that can be currently measured at the Beam Energy Scan are charged kaons [28]. However, on the lattice all particles exist as well as their corresponding interactions. In order to extract only the charged kaon contribution, we implement partial pressures for charged strange mesons as in [29] $\frac{\chi_2^K}{\chi_1^K} = \frac{\cosh(\hat{\mu}_S+\hat{\mu}_Q)}{\sinh(\hat{\mu}_S+\hat{\mu}_Q)}$ where $\hat{\mu}_S$ and $\hat{\mu}_Q$ are supplied from the Wuppertal Budapest collaboration.

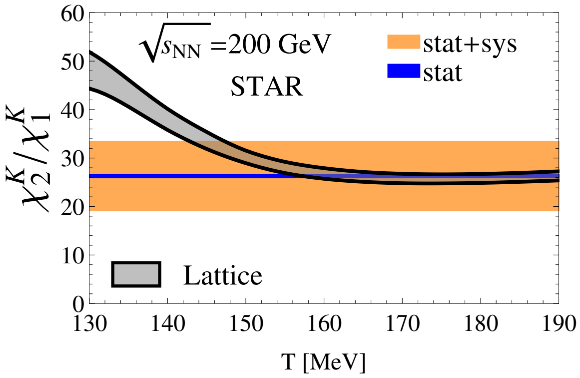

Figure 3. Net-K from Lattice QCD (Wuppertal-Budapest) vs. preliminary STAR data

In Fig 3 a comparison between the Lattice QCD kaon partial pressure is shown compared to the preliminary STAR data. Due to the large error bars, it is not yet possible to extract the strange chemical freeze-out temperature. Eventual smaller experimental error bars would give a decisive answer to the tension between light and strange hadrons.

4. Conclusions

We introduce two approaches to study possible differences in light vs. strange chemical equilibration temperatures. The first is to include states predicted from the Quark Model while modeling their decay channels to study the tension between light and strange hadrons. While the addition of extra resonances has only a small affect on the light freeze-out temperature, the affect on the strange freeze-out remains to be seen since the kaon fluctuation error bars are too large to extract a meaningful strangeness freeze-out temperature. The second approach is a new method to extract the charged, strange susceptibilities from Lattice QCD to determine the strange freeze-out temperature from first principles. Once the kaon error bars are decreased, we may be able to settle the tension between light and strange hadrons.

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