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Analysis of Kaon fluctuations from the beam energy scan at RHIC

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Abstract

We analyze the recent STAR collaboration results on net-kaon fluctuations in the framework of the Hadron Resonance Gas (HRG) model. Our purpose is to extract the freeze-out temperature and chemical potential as functions of the collision energy. In our HRG model, we use the complete hadron spectrum from the latest PDG list. These results are compared to the freeze-out parameters obtained from a combined analysis of net-electric charge and net-proton fluctuations. At the highest collision energies, kaons need about 10-15 MeV higher freeze-out temperatures than the light hadrons. Predictions for moment ratios of the net-Lambda multiplicity distribution are obtained along the freeze-out lines. Lambda fluctuations are sensitive to the difference in the freeze-out temperatures observed in our analysis.

Keywords: Heavy-ion collisions, QCD thermodynamics, Quark-gluon plasma

1. Introduction

The Quark-Gluon Plasma (QGP), the phase of matter which permeated the universe just a few microseconds after the Big Bang, is routinely being created in heavy-ion collision experiments currently taking place at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC).The transition from color-neutral hadrons to quarks and gluons is an analytical crossover at low baryonic density, as shown in first-principle, lattice QCD simulations [1, 2, 3].

After hadronization, the evolution of a heavy-ion collision is characterized by two important points: the moment at which all inelastic collisions between hadrons cease (the chemical freeze-out), and the one at which also elastic collisions cease (the thermal freeze-out). The freeze-out temperature and chemical potential, $\{T_f, \mu_{Bf}\}$ can be obtained through thermal fits of particle yields and ratios [4, 5, 6, 7].At small baryon densities, light hadrons seem to prefer a lower T_f compared to strange hadrons [8, 9].

Fluctuations of conserved charges can be useful to clarify the issue, since they are more sensitive than yields to the freeze-out parameters [10], and they can be calculated from first-principle lattice QCD simulations [11, 12, 13, 14, 15, 16, 17] (for a recent review, see e.g. [18]). The fluctuations of net-protons [19], net-charge [20], and net-kaons [21] have been recently published by the STAR collaboration. The net-proton

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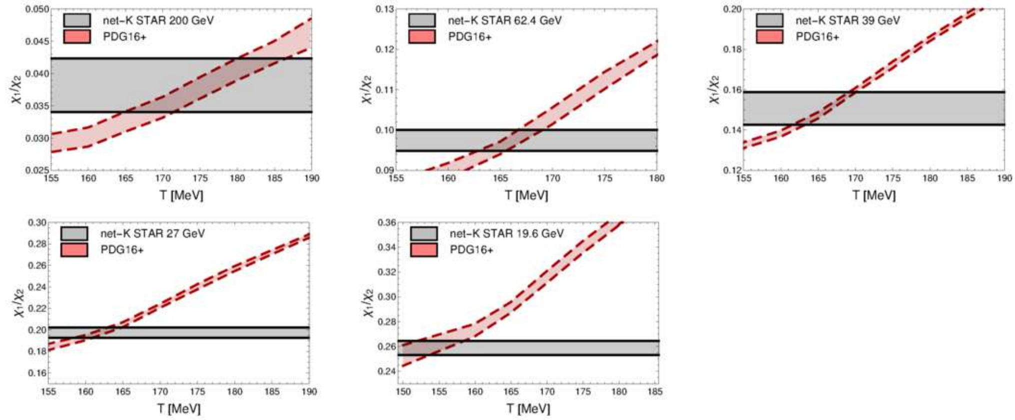

Fig. 1. χ_1^K/χ_2^K calculated along the isentropic trajectories (pink band), compared to the experimental value for $(M/\sigma^2)_K$ from [21] (gray band) at different collision energies.

and net-charge fluctuations lead to a lower T_f than the one quoted in the thermal fits [22], as pointed out in a previous study in the Hadron Resonance Gas (HRG) model [23],

In our analysis [24], we calculate the net-kaon fluctuations in the HRG model and compare them to the recent STAR data from the Beam Energy Scan [21]. We use the PDG2016+ list defined in [25], and take into account resonance decays and the experimental cuts in rapidity and momentum. We find that kaons need larger freeze-out temperatures, compared to the light hadrons. We also predict the values of the Λ fluctuations, calculated at the freeze-out parameters of the kaons and of the light hadrons. The results show a clear separation, which will hopefully be resolved by the forthcoming experimental results [26].

2. Results and conclusions

The net-kaon fluctuations are obtained in the HRG model through the following formula:

$$\tilde{\chi}_n^{K^\pm} = \sum_i^{N_{HRG}} (Pr_{i\to K^\pm} S_i)^n \frac{d_i}{4\pi^2} \frac{\partial^n}{\partial \mu_S^n} \left\{ \int_{-0.5}^{0.5} \mathrm{d}y \int_{0.2}^{1.6} \mathrm{d}p_T \frac{p_T \sqrt{p_T^2 + m_k^2}\,\mathrm{Cosh}[y]}{(-1)^{B_k+1} + \exp((\mathrm{Cosh}[y]\sqrt{p_T^2 + m_k^2} - (B_i\mu_b + S_i\mu_S + Q_i\mu_Q))/T)} \right\} \quad (1)$$

were $Pr_{i\to K^\pm} = Br_{i\to K^\pm} n_i(K^\pm)$ is the probability for a resonance i to decay into a charged kaon, $Br_{i\to K^\pm}$ is the branching for the resonance i to decay into $K^\pm$ and $n_i(K^\pm)$ is the number of times particle i appears in the channel $K^\pm$. For $n \geq 2$, cross-terms appear in the above equation.

We consider the ratio χ_1^K/χ_2^K in our analysis, since the experimental uncertainty, as well as effects of non-thermal origin, are smaller in this case. In order to independently fit T_f and μ_{Bf}, we would need two such ratios. For this reason, we calculate χ_1^K/χ_2^K along the isentropic trajectories from Ref. [27], obtained from lattice QCD simulations for the Taylor reconstructed Equation of State at finite μ_B. In this way we take into account the possibility that kaons can freeze-out at a different moment in the evolution of the system at a given collision energy, related to the light particle freeze-out point by the conservation of S/N_B. The chemical potentials μ_S and μ_Q are fixed by imposing the experimental conditions $\sum_{i\in S} n_i(T,\mu_B,\mu_Q,\mu_S) = 0$, $\sum_{i\in Q} n_i(T,\mu_B,\mu_Q,\mu_S) = 0.4 \sum_{i\in B} n_i(T,\mu_B,\mu_Q,\mu_S)$. The curves for χ_1^K/χ_2^K along the isentropes are shown in Fig. 1 as functions of the temperature, in comparison to the experimental value. The authors of Ref. [28] performed a fit of χ_1^K/χ_2^K and the strange anti-baryon over baryon yield ratios, in order to independently fit T_f and μ_{Bf}, finding similar results to ours.

Fig. 2 shows T_f and μ_{Bf} that we obtain from our analysis, compared to the ones obtained previously [23] through a combined fit of χ_1^p/χ_2^p and χ_1^Q/χ_2^Q at RHIC. The figure also shows the results of the thermal fits from the STAR collaboration at $\sqrt{s}$ = 39 GeV [9], obtained fitting all measured ground-state yields (which agrees with our freeze-out point from net-kaon fluctuations) and only protons, pions and kaons (which agrees with the freeze-out point for light particles).

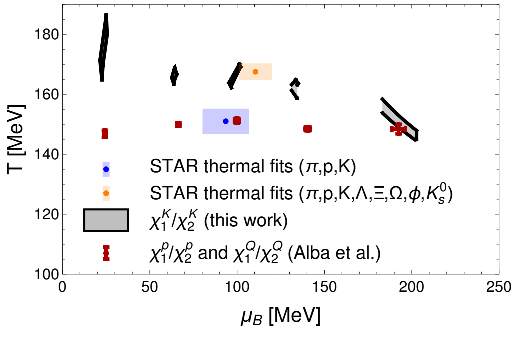

Fig. 2. Freeze-out parameters from the Beam Energy Scan at RHIC. The red points were obtained from the combined fit of χ_1^p/χ_2^p and χ_1^Q/χ_2^Q [23]. The gray bands are obtained from the fit of χ_1^K/χ_2^K in this work. Also shown are the freeze-out parameters obtained by the STAR collaboration at $\sqrt{s}$ = 39 GeV [9] from thermal fits to all measured ground-state yields (orange) and only to protons, pions and kaons (blue).

Fig. 3 shows our predictions for $\chi_2^\Lambda/\chi_1^\Lambda$ (left) and $\chi_3^\Lambda/\chi_2^\Lambda$ (right) as functions of the collision energy, calculated at T_f and μ_{Bf} for net-Kaons (red), and for light particles (blue). The separation between the two scenarios will hopefully be resolved by the future experimental data.

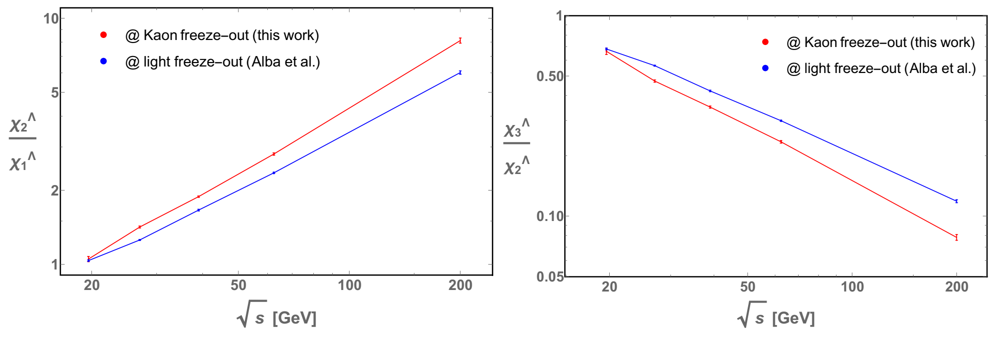

Fig. 3. Left: $\chi_2^\Lambda/\chi_1^\Lambda$ as a function of $\sqrt{s}$. Right: $\chi_3^\Lambda/\chi_2^\Lambda$ as a function of $\sqrt{s}$. In both panels, the red points are calculated at the T_f and μ_{Bf} for net-Kaons, while the blue points are calculated at the values of T_f and μ_{Bf} for light particles from [23].

Our analysis shows a tension between the freeze-out parameters obtained, within the HRG model, from a combined fit of χ_1^p/χ_2^p and χ_1^Q/χ_2^Q vs. χ_1^K/χ_2^K. This could be due to different effects. Lattice QCD indicates that strange quarks might hadronize at a higher temperature [14], naturally leading to a higher chemical freeze-out temperature as well. Interactions in the hadronic phase might be partially responsible for this observation [29, 30, 31, 32, 33]. Future data on net-Λ fluctuations will help to clarify this issue.

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