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Freeze-out properties from net-Kaon fluctuations at RHIC

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Abstract. We calculate the net-kaon mean-over-variance in the hadron resonance gas model and compare it to the experimental data by the STAR collaboration. We show that it is not possible to match the experimental values using the freeze-out parameters obtained from a combined fit of net-proton and net-electric charge mean-over-variance. At the highest collision energies, kaons need about 10-15 MeV higher freeze-out temperatures than the light hadrons. We also predict the variance-over-mean and skewness-times-variance for net-Λ particles at the light and strange chemical freeze-out parameters. It turns out that these Λ fluctuations are sensitive to the difference in the freeze-out temperatures observed in our analysis.

1. Introduction

Relativistic heavy ion collisions, currently taking place at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), are routinely creating a new phase of matter, the Quark-Gluon Plasma (QGP), which permeated the universe just a few microseconds after the Big Bang. First principle simulations of the theory of strong interactions (QCD) on a discretized lattice show that the transition from hadronic degrees of freedom to the QGP is an analytical crossover at low baryonic density [1, 2, 3].

After hadronization, it is possible to define two important points in the evolution of a heavy-ion collision: the chemical freeze-out, at which all inelastic collisions between the hadrons cease (the chemical composition of the system is fixed at this point), and the thermal freeze-out, at which also elastic collisions cease (the particle spectra are fixed at this point). The measured particle yields and fluctuations carry information about the chemical freeze-out. Thermal fits of particle yields and ratios allow us to extract the freeze-out temperature and chemical potential, $\{T_f, \mu_{Bf}\}$ [4, 5, 6, 7, 8]. It was pointed out that, at small baryon densities, there is a tension between the yields of light particles versus strange particles [9]: it appears that light hadrons prefer a lower T_f compared to strange hadrons. A similar effect was observed at RHIC [10].

Additional information can be gained by studying fluctuations of conserved charges: fluctuations are more sensitive than yields to the freeze-out parameters [11], and they can be calculated from first-principle lattice QCD simulations [12, 13, 14, 15, 16, 17, 18], thus providing a valuable tool to investigate this issue further (for a recent review, see e.g. [19]). The STAR collaboration recently published experimental measurements for the energy dependence of the fluctuations of net-protons [20], net-charge [21], and net-kaons [22]. Experimentally, one can only measure charged particles, so that K^0's, π^0's, and neutrons are not included in these measurements. A previous study in the Hadron Resonance Gas (HRG) model with all experimental effects, such as acceptance cuts in p_T and rapidity and isospin randomization [23], found that the net-proton and net-charge fluctuations indicate a lower chemical freeze-out temperature than the one quoted in the thermal fits [24].

In our analysis [25], we calculate the net-kaon fluctuations in the HRG model, taking into account resonance decays and with the same experimental cuts in rapidity and momentum, and compare them to the recent STAR data from the Beam Energy Scan [22]. We find that, even when using the most up-to-date particle data list as an input for the model, the kaons need larger freeze-out temperatures, compared to the light hadrons. We also predict the values of the Λ fluctuations, calculated in the HRG model at the freeze-out parameters of the kaons and of the light hadrons. The results show a clear separation, which can hopefully be resolved by the forthcoming experimental results.

2. Results and conclusions

We calculate the net-kaon fluctuations using the following formula:

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

Here $Pr_{i\to K^\pm} = Br_{i\to K^\pm} n_i(K^\pm)$ is the probability for a resonance i to decay into a charged kaon where $Br_{i\to K^\pm}$ 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 $K^\pm$. We use the same acceptance cuts as described in [22]. Notice that, for $n \geq 2$, there are cross-terms appearing in the above equation.

Since the experimental error-bar is smaller for lower order fluctuations, and the possible sources of non-thermal fluctuations should have a negligible effect in this case, we consider only the ratio of net-kaon mean over variance χ_1^K/χ_2^K in our analysis. Since we need two quantities to independently fit T_f and μ_{Bf}, we calculate χ_1^K/χ_2^K along the isentropic trajectories from Ref. [26], obtained using Lattice QCD results for the Taylor reconstructed QCD phase diagram at finite μ_B. These isentropes were determined by starting from the chemical freeze-out points for light hadrons from Ref. [23], calculating S/N_B at those points, and imposing that the ratio is conserved on the corresponding trajectory. 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 strangeness and electric charge chemical potentials are fixed by imposing the following conditions to match the experimental situation

$$\begin{aligned} \sum_{i\in S} n_i(T,\mu_B,\mu_Q,\mu_S) &= 0 \\ \sum_{i\in Q} n_i(T,\mu_B,\mu_Q,\mu_S) &= 0.4 \sum_{i\in B} n_i(T,\mu_B,\mu_Q,\mu_S) . \end{aligned} \quad (2)$$

This procedure allows us to determine both $\{T_f, \mu_{Bf}\}$ for kaons. The curves for χ_1^K/χ_2^K as functions of the temperature, calculated along the isentropes, are shown in Fig. 1. They are compared to the experimental values for the same quantity, from which the chemical freeze-out temperature can be determined. In a recent paper [27], Bluhm and Nahrgang performed a fit of

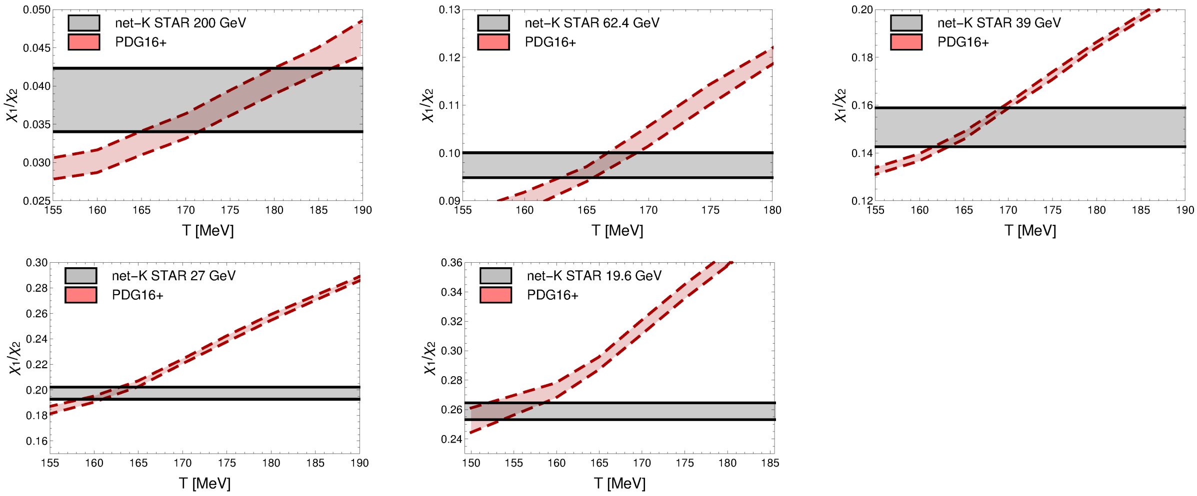

Figure 1. χ_1^K/χ_2^K calculated along the Lattice QCD isentropic trajectories (pink band) in the HRG model, compared to $(M/\sigma^2)_K$ data from [22] (gray band) at different collision energies.

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}.

In Fig. 2 we show the freeze-out temperature and chemical potentials that we obtain from our analysis, compared to T_f and μ_{Bf} obtained previously [23] through a combined fit of net-proton and net-electric charge fluctuations at RHIC. Also shown are two points corresponding to thermal fits from the STAR collaboration at $\sqrt{s} = 39$ GeV [10], obtained fitting all measured ground-state yields (orange point) and only protons, pions and kaons (blue point). As it is clear from the figure, the light freeze-out points from fluctuations agree with the thermal fits of light particles, while the freeze-out points obtained from net-kaon fluctuations agree with the thermal fits including multi-strange hadrons.

In Fig. 3 we show our predictions for net-Λ $\chi_2^\Lambda/\chi_1^\Lambda$ (left panel) and $\chi_3^\Lambda/\chi_2^\Lambda$ (right panel) as functions of the collision energy, calculated at the values of T_f and μ_{Bf} extracted from the fit of χ_1^K/χ_2^K (red points), and from the combined fit of χ_1^p/χ_2^p and χ_1^Q/χ_2^Q (blue points). Both observables show a clear separation between the two scenarios, that the future experimental results will hopefully be able to resolve.

In conclusion, our analysis points out a tension between the freeze-out parameters obtained, within the same 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 tension, already pointed out in thermal fits at the LHC and RHIC, could be due to different effects. From lattice QCD there is an indication that strange particles might hadronize at a higher temperature [15], naturally leading to a higher chemical freeze-out temperature as well. Interactions in the hadronic phase might be partially responsible for this observation [28, 29, 30, 31, 32, 33]. Hopefully, future experimental data on net-Λ fluctuations will help to clarify this issue.

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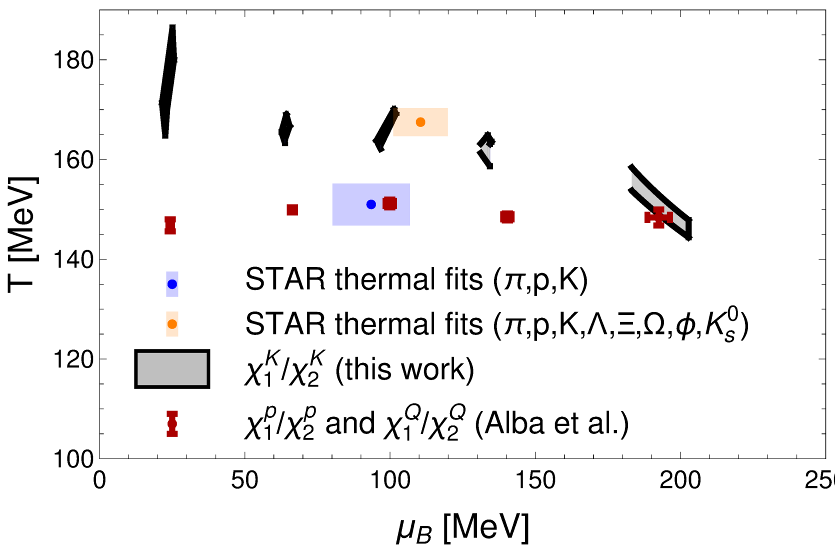

Figure 2. Freeze-out parameters at the highest five energies from the Beam Energy Scan at RHIC. The red points were obtained from the combined fit of χ_1^p/χ_2^p and χ_1^Q/χ_2^Q [23], the gray bands are obtained from the fit of χ_1^K/χ_2^K in this work. Also shown are the freeze-out parameters obtained by the STAR collaboration at $\sqrt{s}$ = 39 GeV [10] from thermal fits to all measured ground-state yields (orange point) and only to protons, pions and kaons (blue point).

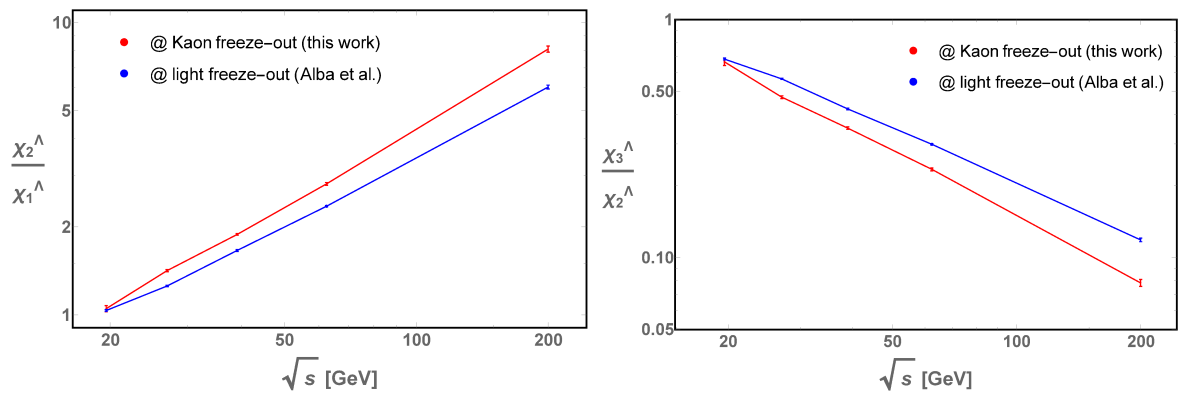

Figure 3. Left panel: $\chi_2^\Lambda/\chi_1^\Lambda$ as a function of $\sqrt{s}$. Right panel: $\chi_3^\Lambda/\chi_2^\Lambda$ as a function of $\sqrt{s}$. In both panels, the red points are calculated at the values of T_f and μ_{Bf} extracted from the fit of χ_1^K/χ_2^K, while the blue points are calculated at the values of T_f and μ_{Bf} extracted from the combined fit of χ_1^p/χ_2^p and χ_1^Q/χ_2^Q in Ref. [23].

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