Proton number fluctuations in partial chemical equilibrium

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Abstract

The search for the critical point of QCD is one of the discussed topics in todays physics. A promising observable are the net proton number fluctuations. The STAR collaboration has recently published data of these in central Au+Au collisions for different energies. The Hadron Resonance Gas model in partial chemical equilibrium is used to study the effect of the cooling temperature to the net proton number fluctuations for Au+Au reactions at 7.7 GeV. The scaled skewness and kurtosis turn out to only weakly change with the temperature.

Introduction

The search for the critical point of QCD is one of the most interesting questions in todays physics from the theoretical point as also from the experimental point of view. A promising observable to find the critical point seems to be net-baryon number fluctuations. Since not all baryons can be measured experimentally, the net proton number fluctuations are measured. They are reasonably well approximating the net-baryon number fluctuations. The STAR experiment recently has shown very interesting results on the proton number fluctuations [1]. But many effects have to be taken into account, such that not all particles can be detected and baryon number is only conserved in the whole collision. A baseline model to study these fluctuations is the Hadron Resonance Gas (HRG) model. Calculations of the fluctuations have been done at chemical freeze-out [2, 3]. However, a question is how the cumulants evolve as functions of temperature in partial chemical equilibrium while the fireball cools down and freezes out kinetically. We therefore use the HRG model with partial chemical equilibrium to study the fluctuations as function of temperature in Au+Au reactions at 7.7 GeV.

The Hadron Resonance Gas Model in partial chemical equilibrium

- The density of species i can be calculated from the logarithm of the grand canonical partition function with the help of the modified Bessel functions of second order $K_2(n\beta m_i)$:

$$n_i = \frac{1}{V}\frac{d\ln \mathcal{Z}_i}{d(\beta\mu_i)} = \frac{g_i}{2\pi^2}\frac{m_i^2}{\beta}\sum_{n=1}^{\infty}\frac{(\pm1)^{n-1}}{n}e^{n\beta\mu_i}K_2(n\beta m_i) + \sum_R \langle N_i^{(R)}\rangle_R n_R^{(d)} \tag{1}$$

where m_i is the mass, μ_i the chemical potential, and g_i the degeneracy factor of species i.
- All stable species acquire temperature dependent $\mu_i(T)$. They are chosen so that total numbers of stable hadrons (after resonance decays) as well as total entropy are invariant of the temperature. For each particle species the ratio of density to entropy density stays constant at given temperature and chemical potential μ_i [4].
- The chemical potential of a resonance R is the sum of the chemical potentials of the stable hadrons which are produced in the decay:

$$\mu_R = \sum_i \langle N_i^{(R)}\rangle_R \mu_i \tag{2}$$

where $\langle N_i^{(R)}\rangle_R$ is the average production number of hadron produced of the resonance decay according to the branching ratios.
- From that, one can calculate each chemical potential as function of temperature and can derive the total pressure which is needed to study the cumulants:

$$\beta^4 p = \frac{\sum_i \ln \mathcal{Z}_i}{VT^3}\,. \tag{3}$$

Contributions to the fluctuations

- The cumulants of the net-proton number κ_l are given by:

$$\kappa_l = \langle(\Delta N_{p-\bar{p}})^l\rangle_c = \langle(\Delta N_p)^l\rangle_c + (-1)^l\langle(\Delta N_{\bar{p}})^l\rangle_c\,. \tag{4}$$

- Many different terms contribute to the net-proton number fluctuations. The first terms in each of the following equations are the direct proton number fluctuations. Furthermore, there are also fluctuations of the numbers of resonances that produce protons when they decay (black terms).
- Finally, resonance decay is a probabilistic process and if a resonance has more than one decay channel, the number of protons that come from its decay may also fluctuate. All these processes are included below (blue terms) [2, 3]:

$$\langle N_p\rangle_c = VT^3\frac{\partial(\beta^4 p)}{\partial(\beta\mu_p)}, \tag{5}$$

$$\langle(\Delta N_p)^2\rangle_c = VT^3\frac{\partial^2(\beta^4 p)}{\partial(\beta\mu_p)^2} + \sum_R \langle N_R^{(d)}\rangle\langle(\Delta N_p^{(R)})^2\rangle_R\,, \tag{6}$$

$$\langle(\Delta N_p)^3\rangle_c = VT^3\frac{\partial^3(\beta^4 p)}{\partial(\beta\mu_p)^3} + 3\sum_R \langle(\Delta N_R^{(d)})^2\rangle\langle N_p^{(R)}\rangle_R\langle(\Delta N_p^{(R)})^2\rangle_R + \sum_R \langle N_R^{(d)}\rangle\langle(\Delta N_p^{(R)})^3\rangle_R\,, \tag{7}$$

$$\langle(\Delta N_p)^4\rangle_c = VT^3\frac{\partial^4(\beta^4 p)}{\partial(\beta\mu_p)^4} + 6\sum_R \langle(\Delta N_R^{(d)})^3\rangle\langle N_p^{(R)}\rangle_R^2\langle(\Delta N_p^{(R)})^2\rangle_R + \sum_R \langle(\Delta N_R^{(d)})^2\rangle\left[3\langle(\Delta N_p^{(R)})^2\rangle_R^2 + 4\langle N_p^{(R)}\rangle_R\langle(\Delta N_p^{(R)})^3\rangle_R\right] + \sum_R \langle N_R^{(d)}\rangle\langle(\Delta N_p^{(R)})^4\rangle_{R,c}, \tag{8}$$

(9)

where $\sum_R \langle N_R^{(d)}\rangle\langle(\Delta N_p^{(R)})^l\rangle_R$ are the fluctuations of the proton number produced from one resonance in different decay channels.

Results

In the following, we present the temperature dependence of the cumulants of the net-proton number for central Au+Au collisions at 7.7 GeV.

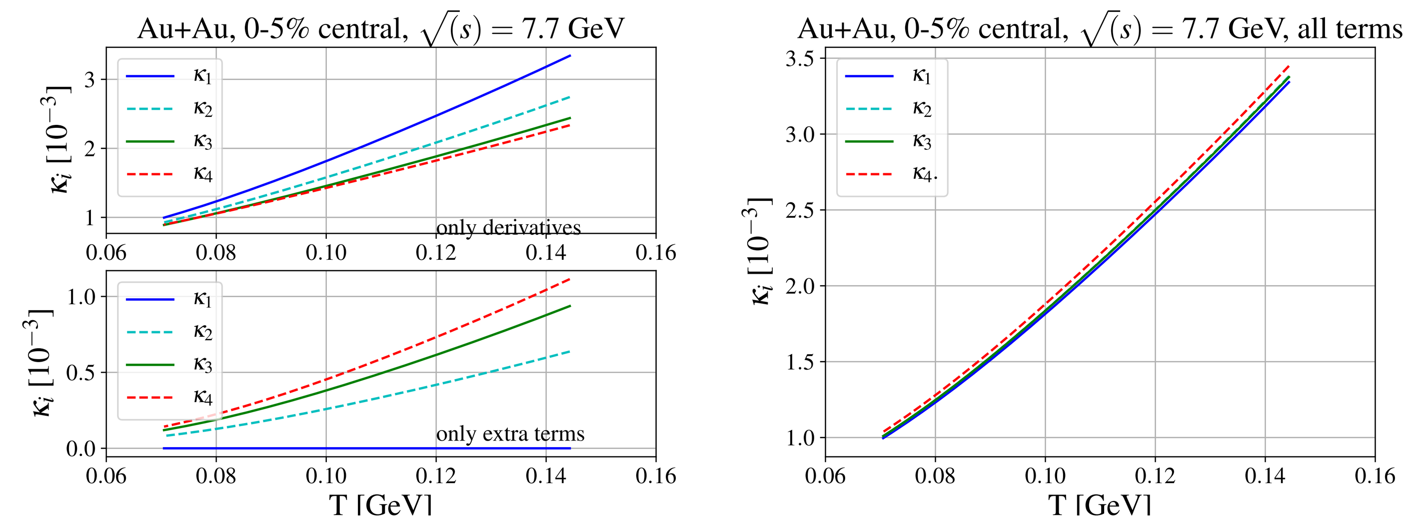

Figure 1: Cumulants as functions of temperature T for central Au+Au collisions at 7.7 GeV. On the left the cumulants of the partition function derivatives (black terms, upper picture) and the resonance decay fluctuations (blue terms, lower picture) are shown. On the right, the cumulants according to the full fluctuations are shown.

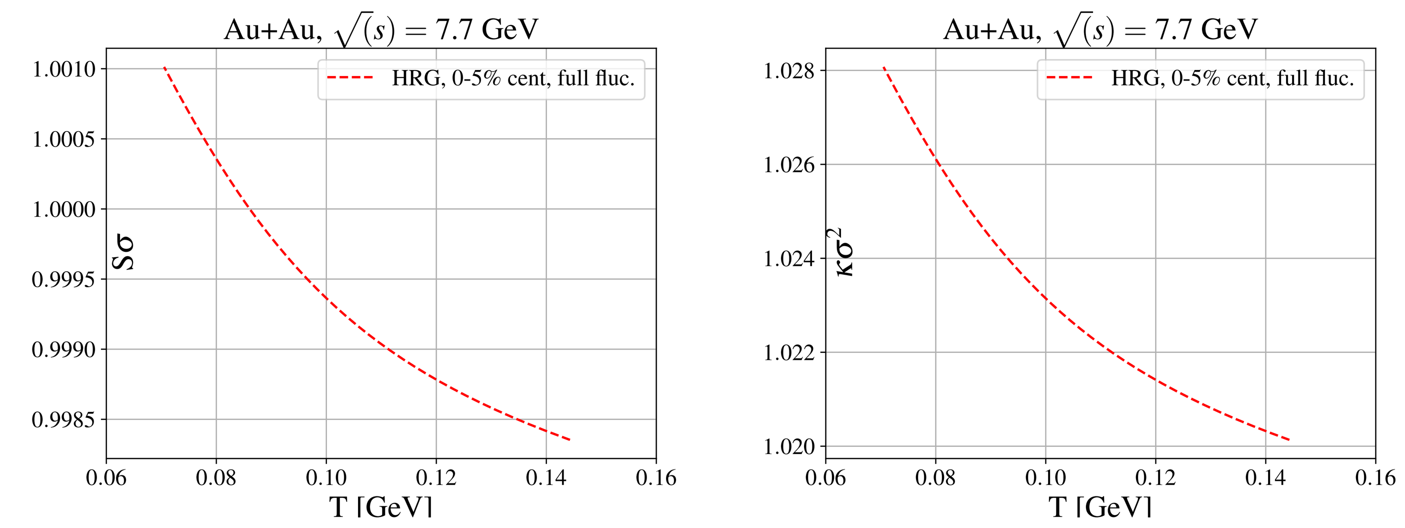

Figure 2: Scaled skewness $S\sigma = \frac{\kappa_3}{\kappa_2}$ and skaled curtosis $\kappa\sigma^2 = \frac{\kappa_4}{\kappa_2}$ as functions of temperature T for central Au+Au collisions at 7.7 GeV for for all contributions of the fluctuations.

- The derivatives of the pressure as well as the fluctuations due to the different resonance decay channels result in decreasing cumulants as the temperature is lowered.
- All cumulants behave similarly as functions of temperature if all fluctuations are taken into account. As consequence of that the cumulant ratios stay nearly constant as can be seen in Figure 2.

Conclusions

- The HRG model in partial chemical equlibrium was used to study the net proton number cumulants as function of decreasing temperature after chemical freeze-out.
- It was found that both the direct fluctuations as well as the net-proton number fluctuations as consequence of the resonance decays decrease when the temperature is lowered.
- Taking all contributions into account, this results in similar behaving cumulants and almost constant ratios.

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