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DYNAMICAL FLUCTUATIONS NEAR THE QCD CRITICAL POINT AND THEIR IMPACT ON THE NET-PROTON KURTOSIS*

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We investigate the kurtosis of the net proton number and the chiral order parameter within the model of nonequilibrium chiral fluid dynamics for a crossover scenario near the critical point. Our model describes the interplay between a dynamical order parameter and a quark–gluon fluid during the expansion of the hot fireball created in a heavy-ion collision. A subsequent particlization process allows us to study experimental observables via an event-by-event analysis. We aim at understanding the interplay of two types of fluctuations: First, fluctuations in the chiral order parameter, and second, fluctuations in the net proton number. Our results show that both follow the same trend in a dynamical setup of a crossover transition. Although effects of finite size and inhomogeneity are present, the signal in the net-proton kurtosis develops clearly.

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1. Introduction

At high temperatures or densities exists the so-called quark–gluon plasma (QGP), characterized by the deconfinement of color charges and restoration of chiral symmetry. The transition from hadron gas to QGP is not a phase

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transition but rather an analytic crossover at vanishing baryochemical potential. For non-zero net-baryon densities, however, a critical point and first-order phase transition are conjectured. This idea is mainly supported by effective model studies [1] or Dyson–Schwinger equations [2]. The possibility of a critical region would necessarily mean that fluctuations of the order parameter or the net quark number show characteristic peak structures or sign changes [3,4]. Of particular interest for experiments here is the kurtosis, defined as the ratio c_4/c_2 of the respective generalized susceptibilities and related to the fourth cumulant of the corresponding observable. The STAR Collaboration at RHIC has measured the net-proton kurtosis as proxy for the net baryons in its beam-energy scan program. Although results showed a nonmonotonic behavior of the net-proton kurtosis as a function of the beam energy [5], we still require a thorough understanding of the dynamical processes during the evolution in a heavy-ion collision, mainly by adopting adequate dynamical models. Here, we present latest results from the NχFD model [6–10] after implementing a Cooper–Frye particlization procedure [11].

2. Nonequilibrium chiral fluid dynamics (NχFD)

The idea behind this model is to provide a dynamical description of a low-energy effective QCD model, which, in our case, is given by a linear sigma model with dilaton field with chiral order parameter σ and dilaton χ [12]

$$\mathcal{L} = \overline{q}\left(i\gamma^{\mu}\partial_{\mu} - g\sigma\right)q + \frac{1}{2}\left(\partial_{\mu}\sigma\right)^2 + \frac{1}{2}\left(\partial_{\mu}\chi\right)^2 + \mathcal{L}_A - U_{\sigma} - U_{\chi}\,. \tag{1}$$

The sigma field is propagated using the following Langevin equation of motion:

$$\partial_{\mu}\partial^{\mu}\sigma + \eta_{\sigma}\partial_{t}\sigma + \frac{\delta V_{\text{eff}}}{\delta\sigma} = \xi\,, \tag{2}$$

derived from the two-particle irreducible effective action, leading to a temperature-dependent damping coefficient η, as a result of the production of a quark–antiquark pair out of a sigma. The quark degrees of freedom are integrated out, constituting an ideal fluid coupled to the fields through an energy and momentum conserving source term. We have previously used this model to demonstrate effects of critical slowing down or formation of inhomogeneities at a first-order phase transition [8, 9].

Drawing comparisons to experimental observables becomes possible after implementing a Cooper–Frye freeze-out [13,14]. Hereby, we allow production of all nonstrange particles from the UrQMD model [15,16] on energy density hypersurfaces. Particles are produced such that the total baryon number and the total energy including energies of the fields σ, χ are exactly conserved in each event

$$e = e_{\text{fluid}} + \frac{1}{2}\left(\frac{\partial\sigma}{\partial t}\right)^2 + \frac{1}{2}\left(\nabla\sigma\right)^2 + U_\sigma + \frac{1}{2}\left(\frac{\partial\chi}{\partial t}\right)^2 + \frac{1}{2}\left(\nabla\chi\right)^2 + U_\chi\,. \quad (3)$$

To estimate the ability of this dynamical model to reproduce the desired critical fluctuations, we scrutinize its behavior by performing a simulation in a box with constant temperature, neglecting energy and momentum exchange between fields and fluid. We extract the variance of the sigma field on an event-by-event basis and find that it follows the curve of the sigma susceptibility, obtained as the second derivative of the thermodynamic potential, *cf.* Fig. 1. Results are obtained for a constant $\mu_q = 100$ MeV in the crossover regime left of the critical point of the model. Each point in this plot corresponds to one set of 10^7 simulations performed at the respective temperature.

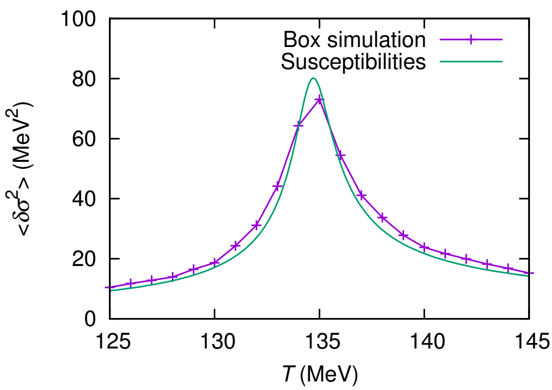

Fig. 1. Comparison of the sigma field variance from box simulations of the NχFD model to the susceptibility obtained from the thermodynamic potential.

2.1. Kurtosis of the net proton number in an expanding medium

We study a crossover evolution near the critical region of the model. An initial condition obtained from the UrQMD model is allowed to evolve according to the coupled dynamics of Langevin evolution and ideal fluid dynamics. We obtain subsequent particlizations along hypersurfaces of constant energy density to calculate the net proton number and the volume-averaged values of the sigma field.

In Fig. 2, we compare the kurtosis of the net proton number to the kurtosis of the sigma field. Here, we see a similar trend in the two curves as a function of energy density. The minima occur at nearly the same energy density of about $2.5e_0$. For the sigma field, we furthermore observe a maximum of the kurtosis at lower energy densities, well below the point where it is expected in an equilibrium phase transition. This behavior may be attributed to memory effects in this nonequilibrium evolution.

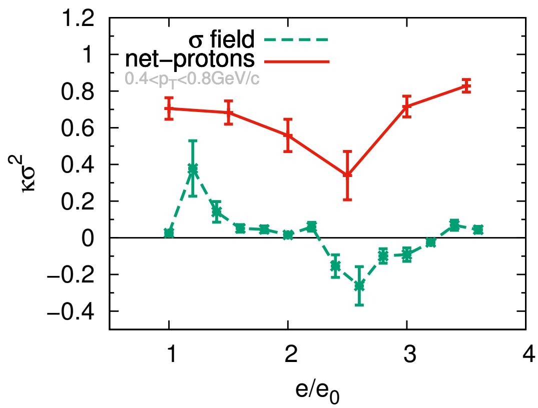

Fig. 2. Net-proton kurtosis as a function of freeze-out energy for a nonequilibrium evolution compared with the kurtosis of the sigma field. Figure from [11].

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