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Multiplicity fluctuations of net protons on the hydrodynamic freeze-out surface

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Abstract

This proceeding briefly summarizes our recent work on calculating the correlated fluctuations of net protons on the hydrodynamic freeze-out surface near the QCD critical point. For both Poisson and Binomial baselines, our calculations could roughly reproduce the energy dependent cumulant C_4 and $\kappa\sigma^2$ of net protons, but always over-predict C_2 and C_3 due to the positive contributions from the static critical fluctuations.

Keywords: Relativistic heavy-ion collisions, QCD critical point, correlations and fluctuations

1. Introduction

One of the fundamental goals of Relativistic Heavy Ion Collisions (RHIC) is to locate the critical point of the QCD phase diagram [1]. To search the critical point in experiment, the STAR collaboration has systematically measured the higher cumulants of net-protons in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV [2, 3, 4]. With the maximum transverse momentum increased from 0.8 to 2 GeV, the measured cumulant ratios $\kappa\sigma^2$ of net protons show large deviations from the Poisson baselines and present an obvious non-monotonic behavior in the most central Au+Au collisions [4], which hints the signal of the QCD critical point. To quantitatively study these experimental data, we need to develop dynamical models near the QCD critical point. Currently, most of the dynamical models near the QCD critical point, e.g. chiral fluid dynamics, focus on the dynamical evolution of the bulk matter [5]. In a recent paper [6], we introduced a freeze-out scheme for the dynamical models near the QCD critical point through coupling the decoupled classical particles with the order parameter field. With a modified distribution function, we calculated the correlated fluctuations of net protons on the hydrodynamic freeze-out surface in Au+Au collisions at various collision energies. In this proceeding, we will briefly summarize the main results of that paper.

2. The formalism and set-ups

In traditional hydrodynamics, the particles emitted from the freeze-out surface can be calculated through the Cooper-Frye formula with a classical distribution function $f(x, p)$ [7]. In the vicinity of the critical

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point, we assume the effective mass of the classical particles strongly fluctuates through interacting with the order parameter field: $\delta m = g\sigma(x)$, which introduces a modified distribution function that also correlated fluctuates in position space [6]. To the linear order of $\sigma(x)$, the modified distribution function can be expanded as:

$$f = f_0 + \delta f = f_0 \left(1 - g\sigma/\left(\gamma T\right)\right), \tag{1}$$

where f_0 is the traditional equilibrium distribution function, δf is the fluctuation deviated from the equilibrium part, $\gamma = \frac{p^\mu u_\mu}{m}$ is the covariant Lorentz factor and the coupling constant $g = \frac{dm}{d\sigma}$. With such expansion, the connected 2-point 3-point and 4-point correlators $\langle \delta f_1 \delta f_2 \rangle_c$, $\langle \delta f_1 \delta f_2 \delta f_3 \rangle_c$ and $\langle \delta f_1 \delta f_2 \delta f_3 \delta f_4 \rangle_c$ are proportional to $\langle \sigma_1 \sigma_2 \rangle_c$, $\langle \sigma_1 \sigma_2 \sigma_3 \rangle_c$ and $\langle \sigma_1 \sigma_2 \sigma_3 \sigma_4 \rangle_c$, respectively. Integrating over the whole freezeout surface for theses correlators gives the explicit forms of the critical fluctuations for produced hadrons [6]:

$$\left\langle (\delta N)^2 \right\rangle_c = \left(\frac{1}{(2\pi)^3}\right)^2 \prod_{i=1,2} \left(\int \frac{1}{E_i} d^3 p_i \int_{\Sigma_i} p_{i\mu} d\sigma_i^\mu \right) \frac{f_{01} f_{02}}{\gamma_1 \gamma_2} \frac{g^2}{T^2} \langle \sigma_1 \sigma_2 \rangle_c \,, \tag{2}$$

$$\left\langle (\delta N)^3 \right\rangle_c = \left(\frac{1}{(2\pi)^3}\right)^3 \prod_{i=1,2,3} \left(\int \frac{1}{E_i} d^3 p_i \int_{\Sigma_i} p_{i\mu} d\sigma_i^\mu \right) \frac{f_{01} f_{02} f_{03}}{\gamma_1 \gamma_2 \gamma_3} (-1) \frac{g^3}{T^3} \langle \sigma_1 \sigma_2 \sigma_3 \rangle_c \,, \tag{3}$$

$$\left\langle (\delta N)^4 \right\rangle_c = \left(\frac{1}{(2\pi)^3}\right)^4 \prod_{i=1,2,3,4} \left(\int \frac{1}{E_i} d^3 p_i \int_{\Sigma_i} p_{i\mu} d\sigma_i^\mu \right) \frac{f_{01} f_{02} f_{03} f_{04}}{\gamma_1 \gamma_2 \gamma_3 \gamma_4} \frac{g^4}{T^4} \langle \sigma_1 \sigma_2 \sigma_3 \sigma_4 \rangle_c \,. \tag{4}$$

where the correlators of the sigma field can be derived from the probability distribution function with cubic and quartic terms $P[\sigma] = \exp\left\{-\Omega\left[\sigma\right]/T\right\} = \exp\left\{-\int d^3x \left[\frac{1}{2}\left(\nabla\sigma\right)^2 + \frac{1}{2}m_\sigma^2\sigma^2 + \frac{\lambda_3}{3}\sigma^3 + \frac{\lambda_4}{4}\sigma^4\right]/T\right\}$ [8, 9]. With such equilibrium distribution $P[\sigma]$, the deduced $\left\langle (\delta N)^2 \right\rangle_c$, $\left\langle (\delta N)^3 \right\rangle_c$ and $\left\langle (\delta N)^4 \right\rangle_c$ belong to the category of static critical fluctuations. If replacing the related integrations on the freeze-out surface by integrations over the whole position space, the standard formula for a static and infinite medium given by Stephanov in 2009 [8] can be reproduced [6].

To obtain the needed freezeout surface Σ, we implement the viscous hydrodynamic code VISH2+1[7] and extend its 2+1-d freezeout surface to the longitudinal direction with the momentum and space rapidity correlations. For simplicity, we neglect succeeding hadronic scatterings and resonance decays below T_c. We assume the critical and noncritical fluctuations are independent, and use the Poission and Binomial distributions as the non-critical fluctuations baselines. Correspondingly, the total cumulants are expressed as: $C_n = (C_n)^{non-critical} + (C_n)^{critical}$, $n = 2, 3, 4$ (with $(C_n)^{critical} = \langle (\delta N)^n \rangle_c$). To roughly fit the trends of C_2, C_3 and C_4 of net protons, we tune the couplings g, $\tilde{\lambda}_3$ $\left(\lambda_3 = \tilde{\lambda}_3 T \left(T\xi\right)^{-3/2}\right)$ and $\tilde{\lambda}_4$ $\left(\lambda_4 = \tilde{\lambda}_4 \left(T\xi\right)^{-1}\right)$, and the correlation length ξ within the allowed parameter ranges for each collision energy (please refer to [6] for details).

3. Numerical results

Fig. 1 and Fig. 2 show the energy dependence of cumulants $C_1 - C_4$ for net protons in the most central Au+Au collisions with either Poisson or Binomial baselines. After tuning g, ξ, $\tilde{\lambda}_3$ and $\tilde{\lambda}_4$ within the allowed parameter ranges, we roughly describe the decreasing trend of C_2 and C_3 and the non-monotonic behavior of C_4 with the increase of collision energy. However, C_2 and C_3 from our model calculations are always above the Poisson/Binomial baselines due to the positive contributions from the critical fluctuations. For the Binomial baselines, our model calculations can nicely fit the energy dependent C_4 within two different p_T ranges. However, if using the Poisson baselines, our calculations can not simultaneously describe the C_4 data at lower collision energies. For Au+Au collisions below 11.5 GeV, the measured C_4 are higher than the Poisson expectation values for $0.4 < p_T < 2$ GeV, but lower than the Poisson expectation values for $0.4 < p_T < 0.8$ GeV. For Eqs.(2-4), the change of the p_T ranges only affects the magnitude of the $C_n^{critial}$ from the critical fluctuations, rather than their signs, which thus can not explain the C_4 data at lower collision energies with the Poisson baseline.