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Conserved charge fluctuations at vanishing and non-vanishing chemical potential

Frithjof Karsch

Fakultät für Physik, Universität Bielefeld, D-33615 Bielefeld, Germany
and
Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

Up to 6^{th} order cumulants of fluctuations of net baryon-number, net electric charge and net strangeness as well as correlations among these conserved charge fluctuations are now being calculated in lattice QCD. These cumulants provide a wealth of information on the properties of strong-interaction matter in the transition region from the low temperature hadronic phase to the quark-gluon plasma phase. They can be used to quantify deviations from hadron resonance gas (HRG) model calculations which frequently are used to determine thermal conditions realized in heavy ion collision experiments. Already some second order cumulants like the correlations between net baryon-number and net strangeness or net electric charge differ significantly at temperatures above 155 MeV in QCD and HRG model calculations. We show that these differences increase at non-zero baryon chemical potential constraining the applicability range of HRG model calculations to even smaller values of the temperature.

Keywords:
QCD thermodynamics, conserved charge fluctuations, chiral phase transition, freeze-out, hadron resonance gas

1. Introduction

The central goal of the beam energy scan (BES) program at RHIC is to seek evidence for the existence of a critical point in the phase diagram of strong-interaction matter. The hope is to detect this postulated second order phase transition point through the analysis of higher order cumulants of net charge fluctuations. Maxima of cumulants of net charge fluctuations, e.g. the 2^{nd} and 4^{th} order cumulants, trace the chiral crossover transition line at small values of the baryon chemical potential and diverge at a critical point.

In heavy ion experiments the observed net charge fluctuations are expected to reflect thermal conditions at the time of chemical-freeze out of various hadron species. If this freeze-out happens close to the pseudo-critical line for the chiral transition of QCD, where thermal fluctuations are large, the measured fluctuations have a chance to be indicative for the divergent fluctuations that will appear at a critical point in the QCD phase diagram.

A crucial anchor point for this scenario is to establish the relation between freeze-out and the QCD chiral transition at small or even vanishing net baryon chemical potential. In this case reliable theoretical calculations, based on Taylor series expansions in lattice QCD, exist and can be confronted with experimental findings at the LHC as well as the highest beam energies at RHIC. In experiments at the LHC one can

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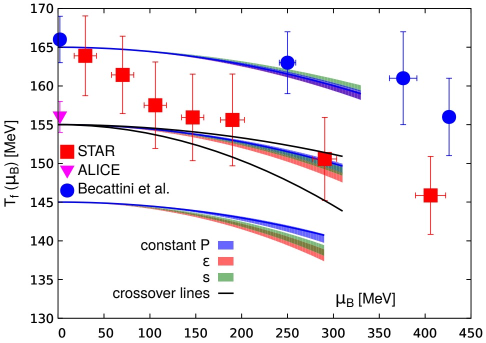

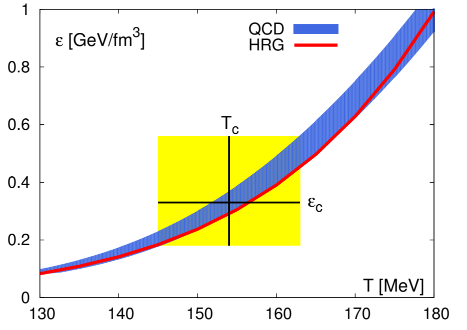

Fig. 1. *Left:* Lines of constant pressure, energy and entropy density, as given in Table II of Ref. [3], as function of baryon chemical potential. Solid black lines indicate the current uncertainty on the variation of the pseudo-critical temperature of the chiral transition, $T_c(\mu_B)$ with μ_B. For a discussion of the data points see text. *Right:* The energy density at $\mu_B = 0$ as function of temperature. The box reflects current errors on the crossover transition temperature, $T_c = 154(9)$ MeV.

analyze moments of charge fluctuations at almost vanishing baryon chemical potential (μ_B) which allows a direct comparison with lattice QCD calculations performed at $\mu_B = 0$.

2. Thermal conditions at vanishing net baryon number

The basic bulk thermodynamic observables, pressure (P), energy (ϵ) and entropy (s) density of strong-interaction matter at vanishing baryon chemical potential, have been calculated in lattice QCD (for a recent review see: [1]). These calculations have recently been extended to non-vanishing baryon number densities using analytic continuation of calculations performed at imaginary values of μ_B [2] and Taylor expansions in μ_B [3]. In Fig. 1 (left) we show results for lines of constant P, ϵ and s, in the T-μ_B plane (phase diagram) obtained from a Taylor series up to $O(\mu_B^4)$ [3]. Lines are drawn for three values of these observables in the crossover region for the QCD chiral transition, which is well characterized by the current uncertainty on the chiral transition temperature, $T_c = 154(9)$ MeV, at $\mu_B = 0$ [4]. As can be seen in Fig. 1 (right) in this temperature interval the energy density changes by about a factor three, $\epsilon_c = (0.34 \pm 0.16)$ GeV/fm^3 [5].

Also shown in Fig. 1 (left) are experimental results for freeze-out parameters determined by the ALICE Collaboration at the LHC [6] and the STAR Collaboration from the BES at RHIC [7] by comparing measured particle yields with predictions from a statistical hadronization model, which utilizes the thermodynamics of a hadron resonance gas. Obviously, there is a significant difference in the determination of the freeze-out temperature at $\mu_B \simeq 0$. While the ALICE result for the freeze-out temperature (T_f) agrees well with the central value of the pseudo-critical temperature (T_c), the STAR results favor a larger value, $T_f \sim 165$ MeV, which is close to the hadronization temperature obtained by Becattini et al. [8].

A 10 MeV accuracy for the determination of the freeze-out temperature, which anyhow is not considered to be a temperature uniquely defined for all particle species, but rather a statistical average, may be considered to be appropriate for many purposes. However, in the search for evidence for a critical point such a difference has substantial consequences for expected properties of net charge fluctuations as the size of the critical region, in which charge fluctuations may become large, may well be only of that order [9]. A 10 MeV difference between T_c and T_f thus may decide whether or not freeze-out happens in the critical region.

Cumulants of net charge fluctuations and correlations among fluctuations of different conserved charges, i.e. baryon number (B), electric charge (Q) and strangeness (S) can be obtained as derivatives of the logarithm of the QCD partition function [3],

$$\chi_n^X = \frac{1}{VT^3} \frac{\partial^n \ln Z(V,T,\vec{\mu})}{\partial X^n}\bigg|_{\vec{\mu}=0} \quad , \quad \chi_{nm}^{XY} = \frac{1}{VT^3} \frac{\partial^{(n+m)} \ln Z(V,T,\vec{\mu})}{\partial X^n \, \partial Y^m}\bigg|_{\vec{\mu}=0} \quad , \quad X,\ Y = B,\ Q,\ S \quad , \qquad (1)$$