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Bridging the gap between event-by-event fluctuation measurements and theory predictions in relativistic nuclear collisions

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Abstract

We develop methods to deal with non-dynamical contributions to event-by-event fluctuation measurements of net-particle numbers in relativistic nuclear collisions. These contributions arise from impact parameter fluctuations and from the requirement of overall net-baryon number or net-charge conservation and may mask the dynamical fluctuations of interest, such as those due to critical endpoints in the QCD phase diagram. Within a model of independent particle sources we derive formulae for net-particle fluctuations and develop a rigorous approach to take into account contributions from participant fluctuations in realistic experimental environments and at any cumulant order. Interestingly, contributions from participant fluctuations to the second and third cumulants of net-baryon distributions are found to vanish at mid-rapidity for LHC energies while higher cumulants of even order are non-zero even when the net-baryon number at mid-rapidity is zero. At lower beam energies the effect of participant fluctuations increases and induces spurious higher moments. The necessary corrections become large and need to be carefully taken into account before comparison to theory. We also provide a procedure for selecting the optimal phase–space coverage of particles for fluctuation analyses and discuss quantitatively the necessary correction due to global charge conservation.

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1. Introduction

Experimental investigations of fluctuations of conserved charges, expressed as cumulants of net-particle multiplicity distributions, probe the response of the system to external perturbations. For example, the liquid gas phase transition can be probed by the response of the volume to a change in pressure, which is encoded in the isothermal compressibility. Such measurements are hence particularly interesting for studies of possible critical phenomena and the existence of a critical endpoint in the QCD phase diagram [1–3]. To make any quantitative headway the objective is to isolate, in the experimental data, the dynamical part of the fluctuations and compare the corresponding cumulants to those from predictions for a thermal system as obtained by calculations within the framework of lattice gauge theory or other dynamical theories.

Indeed, for a thermal system of volume V and temperature T, within the Grand Canonical Ensemble, fluctuations of a given net-charge $\Delta N_B = N_B - N_{\bar{B}}$ are related to the corresponding reduced susceptibility $\hat{\chi}_2^B$ [4,5]:

$$\frac{1}{VT^3}\left(\left\langle \Delta N_B^2 \right\rangle - \langle \Delta N_B \rangle^2\right) = \hat{\chi}_2^B, \tag{1}$$

with $\hat{\chi}_2^B$ defined as the second derivative of the reduced thermodynamic pressure $\hat{p} \equiv \frac{p}{T^4}$ with respect to the corresponding reduced chemical potential $\hat{\mu}_B \equiv \frac{\mu_B}{T}$

$$\hat{\chi}_2^B = \frac{\partial^2 \hat{p}}{\partial \hat{\mu}_B^2}. \tag{2}$$

In a similar way, higher order cumulants are related to the corresponding higher order susceptibilities [6]. This means that the response function of the system to external parameters can be obtained from thermal averages of macroscopic variables by employing the probability distribution of micro-states of the system. Furthermore, in order to get rid of not directly measurable quantities such as volume and temperature, which enter into eq. (1), it is advocated in [7] to look for ratios of cumulants. However, a comment is in order here: eq. (1) is derived under the assumption that the volume of the system is fixed. Within the Wounded Nucleon Model this means that the number of participants is fixed in each event. In experiments, however, events are classified into centrality bins. In most theoretical approaches, centrality is specified using the collision impact parameter; zero for central collisions, and close to the sum of the radii of the colliding nuclei for peripheral collisions. More specifically, one can define a centrality window incorporating the $n\%$ most central collisions. Experimentally, however, one does not have direct access to the impact parameter, hence the centrality classes are typically defined as windows of energy deposited in a zero-degree calorimeter, the number of participants, the multiplicity of charged particles produced in a given acceptance, etc.

For the analysis of average quantities it is often not critical which of the centrality determination approaches are used, because all of them give similar results for such physical quantities. However, the situation changes dramatically if one considers event-by-event fluctuations of these quantities. In this case, the centrality determination details become crucial and differently influence the magnitude of measurements of moments such as described in eq. (1). It is, therefore, important to subtract from experimentally measured cumulants the contributions originating from the fluctuations in the number of wounded nucleons.