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Fluctuations and the QCD Phase Diagram *

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In this contribution we will discuss various issues related with the interpretation of fluctuation observables. In particular we will focus on the effect of fluctuations induced by the initial stopping of baryons at low beam energies.

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1. Introduction

Understanding the structure of the QCD phase diagram is one of the fundamental problems of the theory of strong interactions. From the theory side, the thermodynamics of QCD is explored by the number of approaches including first principle numerical lattice QCD (LQCD) and functional methods (see e.g. the contributions by F. Karsch and J. Pawlowski

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to these proceedings). Experimentally, the phase diagram is explored via heavy ion collisions at various energies and at several facilities such as the CERN SPS and RHIC. In addition new facilities are being planned to explore the high density region in even more detail, such as FAIR and NICA (see e.g. the contributions by N. Xu and P. Senger to these proceedings).

At vanishing net-baryon density, LQCD calculations find the transition between hadrons and quark/gluon degrees of freedom to be a crossover [1]. At finite baryon densities, where the predictive power of LQCD calculations is limited to small densities due to the fermion sign problem, many model calculations predict a first order phase transition at large densities and moderate temperatures (see e.g. [2]). If correct, this would imply the existence of a critical point at the end of a first order phase coexistence region.

Fluctuations of conserved charges are believed to be a promising probe to experimentally observe a possible critical point [3]. In particular higher order cumulants of the baryon number have received considerable attention theoretically [5] as well as experimentally [6, 7, 8]. However, the increased sensitivity of the higher order cumulants to the critical dynamics does not come for free: they probe the tails of the probability distribution which are also susceptible to various non-critical effects including baryon number conservation [9], volume or number of wounded nucleon fluctuations [10], detector efficiency and acceptance [11, 12, 13], hadronic rescattering [14], non-equilibrium effects [15, 16], correlations between centrality trigger and the observable, etc. These effects need to be understood for a sensible interpretation of the data.

The only means of increasing the net baryon density is to stop the nucleons form the incoming nuclei in the mid-rapidity region. This stopping of the baryons is obviously another source of fluctuations, and it is a priori not related to the dynamical fluctuations associated with a phase transition. This effect may be studied in event generators. However, in this case one relies on the specific model assumptions implemented in the generator. A first attempt to address this aspect in a more general fashion was reported in [17] and we will report the essential findings of this work in this contribution.

2. Baryon distributions at low energies

At low energies, $\sqrt{s} \lesssim 20\,\mathrm{GeV}$, where the number of anti-protons, and thus, produced protons, is negligible, the observed baryons originate entirely from the incoming nuclei. Therefore, the event-by-event distribution at mid-rapidity is strongly affected by the baryon stopping mechanism. Since there are no produced baryons, the baryon distribution is directly related to that of the wounded (or participating) nucleons. Consequently, the most simple model for the distribution of stopped baryons is simply to count the number of wounded nucleons $N_{\rm part}$ in a Glauber model and assign a binomial probability, p, that they end up in the rapidity interval of interest. Following [17] the resulting factorial cumulants or integrated correlation functions C_n (see [12, 18]) are given by the generating function

$$H(z) = \sum\nolimits_{N_{\rm part}} P(N_{\rm part}) \left[1 - p + pz\right]^{N_{\rm part}} . \qquad (1)$$

so that $C_n = \frac{d}{dz} \log(H(z))|_{z=1}$. Here $P(N_{\rm part})$ is the distribution of wounded nucleons, which is obtained from a Glauber calculation. The resulting values for the integrated correlation functions are show in Fig. 1 for the center of mass energy of $\sqrt{s} = 7.7\,\text{GeV}$. To put this results in perspective we should note that for central collisions an analysis [18] of the preliminary STAR data [8] resulted in values for the integrated correlation functions of $7C_2 \simeq -15$, $6C_3 \simeq -60$, and $C_4 \simeq 170$. While the simple Glauber model is able to reproduce the observed value of the two particle correlation, C_2, it severely under-predicts the values for C_3 and C_4, the latter by several orders of magnitude.

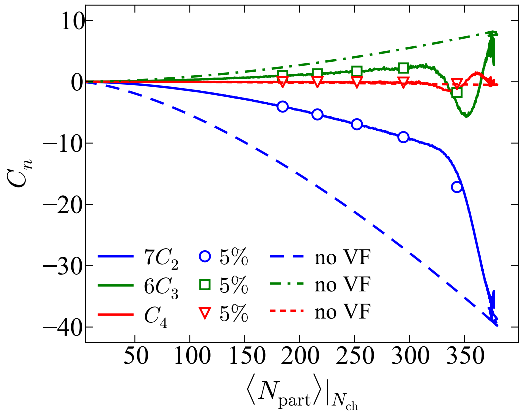

Fig. 1. Multi-particle correlations C_n in Au+Au collisions at $\sqrt{s} = 7.7$ GeV. The leading terms, where fluctuations of the number of wounded nucleons are not present, are denoted by "no VF". Also shown as circles, triangles and squares are the results for the five most central bins with a width of 5% of centrality.

Of course the present model assumes no correlation between the stopping of one nucleon with that of another. While this is probably a reasonable assumption at high energies, at very low energies, (quasi) elastic collisions give rise to pairwise stopping of nucleons. This effect has been estimated in [17] and is presented in the left panel of Fig. 2. There we show the resulting correlations C_n for a situation where we assume that eight pairs of protons are stopped together with a probability p_2, and that the remaining protons

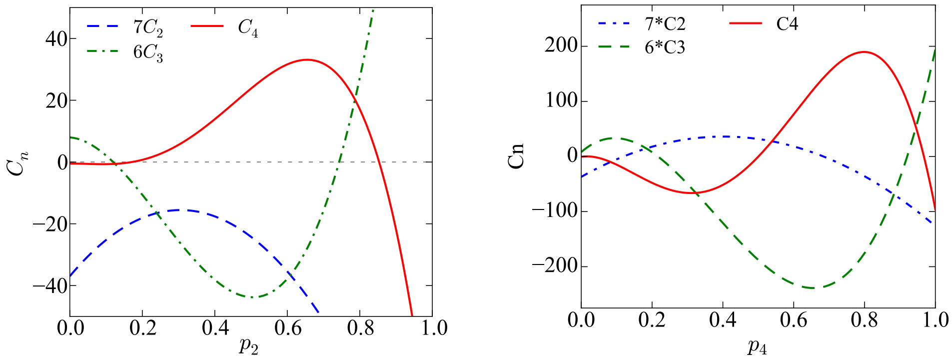

Fig. 2. Integrated multi-particle correlations C_n in the model where particles are correlated in pairs (left) and quartets (right) as a function of the probability for a pair (p_2) or a quartet (p_4) to end up in the rapidity bin. For larger values of p_2 and p_4 we obtain large values of C_3 and C_4. See the text for further explanation.

follow the independent stopping model discussed previously. Clearly, pairwise stopping neither reproduces the magnitude nor the sign of the observed correlations.

In order to obtain correlations which are in qualitative agreement with the preliminary STAR data, one has to make more drastic assumptions. As shown in the right panel of Fig. 2, assuming the correlated stopping of four proton quartets, the resulting correlation functions can be qualitatively reproduced if one assumes that the probability p_4 to stop the quartets is $p_4 \simeq 0.8$. Since we have isospin symmetry neutrons are as likely as protons, implying that in reality we have to stop eight-nucleon clusters, a rather interesting proposition.

Alternatively, one may argue that these clusters do not arise from collective stopping but are rather due to some dynamics of the system, such as bubble formation induced by a phase-transition. Clearly, more information is required to validate such a scenario. Also, if such clusters follow a (thermal) Poisson distribution, the signs of all correlations would be positive, contrary to what is seen in the data.

3. Conclusions

In this contribution we have reported on a study of the effect of baryon stopping on proton number correlations in low energy heavy ion collisions. We have shown that a simple Glauber model would explain the observed two-particle correlations but would severely under predict three- and four-particle correlations. Also, pairwise stopping, as expected to occur at low energies will not help the situations. Only extreme assumptions such as the stopping of proton quartets (nucleon octets) results in correlations comparable with observation. If these clusters arise from other dynamics, remains to be seen and requires further study.

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