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Cumulants vs correlation functions and the QCD phase diagram at low energies

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Abstract

We discuss the relation between particle number cumulants and genuine correlation functions. It is argued that measuring multi-particle correlation functions could provide cleaner information on possible non-trivial dynamics in heavy-ion collisions.

Keywords: QCD phase diagram, Beam energy scan, Net-baryon density

1. Introduction

The search for structures in the QCD phase diagram is one of the most exciting topics of strong interaction physics, see e.g., a recent overview by Luo and Xu [1].

In this paper we focus on the measurement of net-proton cumulants [2–4], K_n, performed by the STAR Collaboration at RHIC [1, 5]. By definition

$$K_1 \equiv \langle N \rangle; \quad K_2 \equiv \langle (\delta N)^2 \rangle; \quad K_3 \equiv \langle (\delta N)^3 \rangle; \quad K_4 \equiv \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2, \tag{1}$$

where $\delta N = N - \langle N \rangle$ and N is the net-proton number. At low energies the number of produced anti-protons is negligible and N can be very well approximated by the proton number.

STAR measured K_4/K_2 and K_3/K_2 in Au+Au collisions for energies ranging from 7.7 GeV to 200 GeV. The most intriguing preliminary results are (i) a large value of $K_4/K_2 \approx 3.5$, with rather large error bars, at $\sqrt{s} = 7.7$ GeV and (ii) a small value of $K_4/K_2 \approx 0.2$ at energies close to 19 GeV.

The interpretation of the STAR data is challenging since the cumulant ratios are sensitive to various sources of fluctuations, see, e.g., [1].

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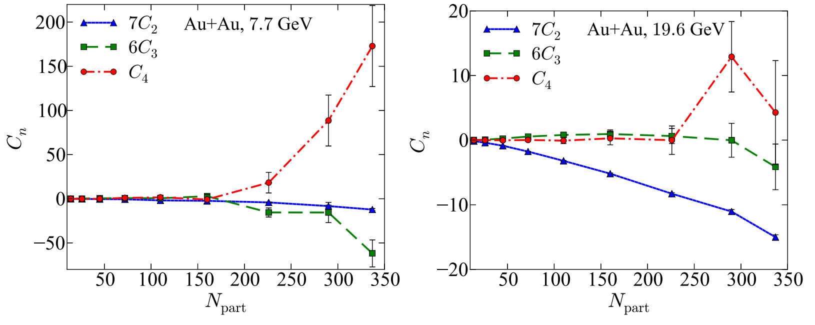

Fig. 1. Centrality dependence of multi-proton correlation functions for $\sqrt{s}$ = 7.7 GeV (left) and 19.6 GeV (right). Results are based on the preliminary STAR data [5].

2. Results

In a system of protons (we neglect antiprotons) without any correlations the cumulants are given by the average number of protons, $K_n = \langle N \rangle$, which at 7.7 GeV, for a given STAR acceptance $|y| < 0.5$ and $0.4 < p_t < 2$ GeV, is roughly 40. Consequently, any nontrivial physics related to correlations between protons might not be clearly visible. It seems natural to measure the genuine multi-proton correlation functions. Performing straightforward calculations [6, 7] we obtain

$$K_2 = \langle N \rangle + C_2, \tag{2}$$

$$K_3 = \langle N \rangle + 3C_2 + C_3, \tag{3}$$

$$K_4 = \langle N \rangle + 7C_2 + 6C_3 + C_4, \tag{4}$$

where C_n is the n–proton genuine correlation function. $C_n = 0$ for a proton system with no correlations. Using the preliminary STAR data we can straightforwardly extract C_n. This is presented in Fig. 1.

We observe that a large value of $K_4/K_2 \approx 3.5$ at 7.7 GeV is driven by a positive genuine four-proton correlation. This is in contrast to 19.6 GeV, where the signal is driven by a negative two-proton correlation.

To put the STAR numbers in perspective let us consider a simple model. Suppose we have clusters, with Poisson multiplicity distribution, which decay into a fixed number of proton, m. In this case $C_n = \langle N_{\rm cl} \rangle\, m!/(m-n)!$ where $\langle N_{\rm cl} \rangle$ is the average number of proton clusters. Taking $m = 4$ (four-proton clusters) we obtain $C_4 = 24 \langle N_{\rm cl} \rangle$. In order to get $C_4 \sim 170$ we need to assume $\langle N_{\rm cl} \rangle = 6 - 8$. It means that $24 - 32$

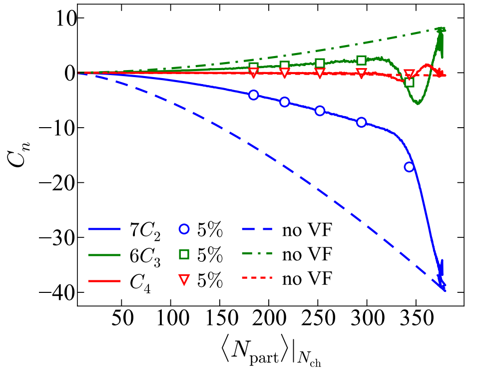

Fig. 2. Multi-proton correlation functions in Au+Au collisions at $\sqrt{s}$ = 7.7 GeV. “no VF” denotes the contribution without volume fluctuation. The circles, triangles and squares are the results for the five most central bins.

protons, out of 40 measured protons, should originate from such clusters. This is a rather large fraction, indeed.

One natural source of multi-proton correlations are the fluctuations of the number of wounded nucleons, $N_{\rm part}$, which we also call volume fluctuation. We verified that this contribution is way too small to explain the preliminary STAR data. In particular, the obtained value of C_4 is smaller by roughly three orders of magnitude. This is demonstrated in Fig. 2.[1] In this model we assume only two natural sources of correlations namely (i) baryon conservation and (ii) volume fluctuation. More details can be found in Ref. [8].

It seems clear that in order to understand the preliminary STAR data, in particular the large value of four-proton correlation function, we need a nontrivial source of strong correlations between protons. For example, in Ref. [8] the preliminary STAR data could be qualitatively reproduced if assuming the collective stopping of four-proton clusters or, equivalently, eight-nucleon clusters. It remains to be seen whether the observed strong correlations indeed originate from the collective stopping of protons (currently not understood), or perhaps we witness the first evidence of proton clustering related to a nontrivial structure of the QCD phase diagram. This problem requires further study.

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[1] We closely follow the STAR procedure and use the tightest centrality cuts, that is, we calculate C_n at a given number of produced charged particles $N_{\rm ch}$ (except protons) in $|\eta| < 1$ [5].