Indications for Cluster Melting from Forward-Backward Charge Fluctuations at RHIC Energies

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We study forward-backward charge fluctuations to probe the correlations among produced particles in ultra relativistic heavy ion collisions. We develop a model that describes the forward-backward dynamical fluctuations and apply it to interpret the recent PHOBOS data. Within the present model, the dynamical fluctuations are related to the particle production mechanism via cluster decay and to long range correlations between the forward and backward rapidity hemispheres. We argue that with a tight centrality cut, PHOBOS may see a strong decrease of the dynamical fluctuations. Within the present model, this deterioration of the correlation among the produced hadrons can be interpreted as a sign for the production of a hot, dense and interacting medium.

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I. INTRODUCTION

One of the main goals of the heavy ion program is to understand the nature of the hadron production mechanism (e.g. parton coalescence, string fragmentation or cluster decay). Recent RHIC data on jet quenching and elliptic flow (v_2) can be interpreted as an evidence of forming a quark gluon plasma (QGP) during the collision of two heavy gold nuclei at center of mass energy $\sqrt{s_{NN}}$ = 200 GeV [1]. However, the detailed mechanism how the deconfined partonic matter transforms to hadrons is still unknown.

Using correlations and fluctuations to probe the nature of the created QCD matter has been proposed by many authors [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. Unfortunately, the experimental exploration of most of the suggested fluctuation signals did not yield positive evidence for the formation of a QGP. Nevertheless, this must not be seen as a contradiction to the formation of a partonic state at RHIC or SPS energies, because the proposed signatures may be weakened due to many effects (e.g. the phase transition is not a strict first order transition - which is the case for RHIC energies). Other possibilities are that rescattering and/or re-thermalization in the late QGP or in the subsequent hadronic stage may blur the fluctuation signals. Furthermore, the fluctuation signals might be modified and cloaked by the hadronization process itself. However, we want to point out that recent studies of rescattering and/or diffusion in the hadronic environment, seem to indicate that the diffusion in the hadronic stage might be small enough to allow a survival of the initial correlations [24].

In this letter we explore the forward-backward charge fluctuations [25, 26, 27, 28] to probe the particle production mechanism via cluster decay. Long ago, the number k of charged particles produced per cluster decay was estimated in pp and p$\overline{\text{p}}$ interactions by the UA5 experiment [29]. It was found that the effective multiplicity per cluster is $k \approx 2$. Recently, the PHOBOS experiment performed a similar analysis for Au+Au reactions at $\sqrt{s_{NN}}$ = 200 GeV and reports that $k = 2.7$ for peripheral collisions and $k = 2.2$ for central collisions. Note that all measured cluster multiplicities are larger than expected for a hadron resonance gas ($k_{\text{HG}} = 1.5$) [7], indicating that the measured charge correlations can not be described by simple statistical models based on hadronic degrees of freedom.

Our goal is to explore how the cluster structure changes if deconfined matter is formed. The meaning of the term cluster is rather general, for example it could be a hadronic resonance, a partonic string or a QGP droplet. Either the survival or the destruction of the clusters provides indirect information about the properties of the surrounding medium. For example what is the percentage of particles produced by cluster decays, are the hadronic expectations compatible with the data or not and if a hot and dense (partonic?) medium is formed or not.

This letter is organized as follows: In Section II we develop a model that describes the multiplicity fluctuations σ_C^2 as measured by the PHOBOS experiment [25, 26, 27, 28]. This measure is sensitive to charged particle production via cluster decay. In Section III we apply our model to interpret the PHOBOS data and to estimate the fraction f of particles produced via cluster decay. In Section IV we discuss the results of our analysis of the measured data [25, 26, 27, 28] for central Au+Au collisions. Next, we address how the formation of a dense medium affects the dynamical fluctuations because it might influence both the cluster multiplicity and the short range rapidity correlation length. Finally, we comment on the behavior of the dynamical fluctuations

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in central collisions. In Section V we summarize the main results of this letter.

II. THE MODEL

In this section we develop a model to describe forward-backward charge correlations. We define two symmetric rapidity regions at $\pm\eta$ with equal width $\Delta\eta$. The number of charged particles in the forward rapidity interval $\eta \pm \Delta\eta/2$ is N_F while the corresponding number in the backward hemisphere $-\eta \pm \Delta\eta/2$ is given by N_B. We define the correlation variable C such that

$$C = \frac{N_F - N_B}{\sqrt{N_F + N_B}} \quad . \tag{1}$$

The event-by-event fluctuations (variance) σ_C^2 of C are decomposed into two parts, weighted by the respective fractions f and $(1-f)$ of particles from the different sources:

$$\sigma_C^2 = f\sigma_{\rm SR}^2 + (1-f)\sigma_{\rm LR}^2 \quad . \tag{2}$$

The first term in Eq. (2) $\sigma_{\rm SR}^2$ denotes the short range correlation due to cluster decays. This term is a direct measure of the particle production via cluster decay. As discussed above, the specific nature of the clusters is rather general.

$\sigma_{\rm SR}^2$ depends on the observability of the decay daughters in the rapidity width $\Delta\eta$, so that when $\Delta\eta$ is larger than the size of the cluster one is able to observe all the decay products of this cluster. However, if $\Delta\eta$ is small one may “loose” the decay products of such a cluster. To model this rapidity window effect we propose the following form

$$\sigma_{\rm SR}^2 = k\left[1 - \exp(-\Delta\eta/\lambda_{\rm short})\right] \quad , \tag{3}$$

where $\lambda_{\rm short}$ is the rapidity correlation length between particles produced as a result of the cluster decay and k is the aforementioned multiplicity per cluster.

The second term $\sigma_{\rm LR}^2$ in equation (2) includes the fluctuations due to long range correlations between particles in both hemispheres and the background particles that are statistically independent. To describe the long range correlation, it is convenient to introduce a two body distribution function $\rho_2(\eta_1,\eta_2)$. Such that

$$\rho_2(\eta_1,\eta_2) = A\exp\left[-\frac{(\eta_1-\eta_2)^2}{2\lambda_{\rm long}^2}\right] \quad , \tag{4}$$

where A is the amplitude of the correlation function, giving the strength of the two body distribution when $\eta_1 = \eta_2$. Generally, A is a product of the true amplitude and a function that might depend on the motion of the center of mass rapidity of the pair $\eta_c = (\eta_1+\eta_2)/2$. For the present study, we assume that A is independent of η and $\Delta\eta$. Under these assumptions, the long range contribution to the total fluctuations can be calculated from

$$\sigma_{\rm LR}^2 = 1 - A\int_{-\eta-\Delta\eta/2}^{-\eta+\Delta\eta/2} {\rm d}\eta_1 \int_{\eta-\Delta\eta/2}^{\eta+\Delta\eta/2} {\rm d}\eta_2\ \exp\left[-\frac{(\eta_1-\eta_2)^2}{2\lambda_{\rm long}^2}\right] . \tag{5}$$

Next, we decompose the total multiplicity N in each rapidity window $\Delta\eta$ in two parts such that $N = N_{\rm SR} + N_{\rm LR}$ where $N_{\rm SR}$ is the charged particle abundance produced from the decay of all clusters inside $\Delta\eta$ and $N_{\rm LR}$ is the number of particles migrated from outside into the rapidity window under investigation.

In each rapidity bin $\Delta\eta$, the fraction of particles produced by cluster decay f is given by $f = N_{\rm SR}/N$. With the weighting of $\sigma_{\rm SR}^2$ and $\sigma_{\rm LR}^2$ by f and $(1-f)$, and the abbreviation $\xi = (1-f)A$ one rewrites Equation (2) using Eqs. (3) and (5) as

$$\sigma_C^2 = 1 + f\left[k\left(1 - {\rm e}^{-\frac{\Delta\eta}{\lambda_{\rm short}}}\right) - 1\right] - \xi F(\lambda_{\rm long},\Delta\eta,\eta), \tag{6}$$

where $F(\lambda_{\rm long},\Delta\eta,\eta)$ is the result of the double integral in Equation (5). Equation (6) includes different physical situations, e.g. in case of vanishing short range correlation $f = 0$, and σ_C^2 is determined solely by long range correlations. In case of $f = 1$, only short range correlations (i.e. cluster decays) contribute to the dynamical fluctuations. Therefore, if measurements are done such that the two bins centered around $\pm\eta$ are far from each other, the contribution from long range correlations becomes negligible. Only in this case, an increase of the bin size $\Delta\eta$ to $\Delta\eta \gg \lambda_{\rm short}$ leads to the commonly used approximation $\sigma_C^2 \approx k$ from which the true cluster multiplicity can be deduced. Another limiting value obeyed by Eq. (6) is that for a very large η the dynamical fluctuations σ_C^2 do approach the poisson value $\sigma_C^2 = 1$. This is due to the vanishing of the long range correlations and the low multiplicity which drives the fraction of correlated particles to be zero.

Before we analyze the PHOBOS data let us shortly summarize the assumptions used in the above derivations: (I) There is only one type of clusters. (II) All clusters decay to the same number of particles k, i.e. fluctuations of k itself are not included in the present model.

III. RESULTS

In this section we study the dynamical fluctuations σ_C^2 for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. We extract the values of f and ξ from PHOBOS data reported in [25, 26, 27, 28]. Table I summarizes our findings on the parameters of the present model. With these parameters, we predict σ_C^2 as a function of η and $\Delta\eta$. Figure 1 depicts both PHOBOS data for 0% − 20% central Au+Au collisions (symbols) and our model results (line) for the

data	f	ξ	$\lambda_{\rm short}$	$\lambda_{\rm long}$
Au+Au 0% − 20%	0.88	1.8	0.4	0.7
Au+Au 40% − 60%	0.99	2.5	0.6	0.9

TABLE I: Parameters of our model as estimated by analyzing 0%−20% central and 40%−60% peripheral Au+Au PHOBOS data at $\sqrt{s_{\rm NN}} = 200$ GeV using equation (6).

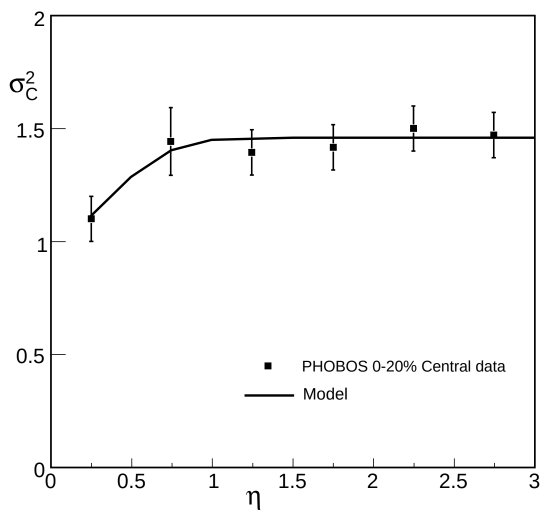

FIG. 1: σ_C^2 versus rapidity η for $0\% - 20\%$ central Au+Au at $\Delta\eta = 2$. Black squares are PHOBOS data [25, 26, 27, 28]. The line is the model calculation using equation (6).

dynamical fluctuations σ_C^2 as a function of η while the width of the observation window $\Delta\eta$ is kept as $\Delta\eta = 0.5$.

In Fig. 2 we show σ_C^2 versus $\Delta\eta$, while the center of the observation window is fixed at $\eta = 2$. We emphasize that the same parameter set (see Table I) is used for both data sets in Figs. 1 and 2.

Before we discuss the interpretation of our model results, let us turn to semi-peripheral collisions. Figs. 3 and 4 depict the PHOBOS results on $40\% - 60\%$ peripheral collisions. As for central collisions, the model allows to describe both data samples with the same parameter set simultaneously (cf. Table I). The dynamical fluctuations σ_C^2 measured at $\eta = 2$ for $40\% - 60\%$ peripheral Au+Au collisions and a very wide rapidity windows $\Delta\eta = 2$ yield an effective cluster multiplicity of $k \approx 2.7$ (see Fig. 4).

One observes that the short range correlation length $\lambda_{\rm short}$ is 0.6 for peripheral collisions and decreases towards $\lambda_{\rm short} = 0.4$ in central collisions. This decrease of the short range correlation length is consistent with Ref. [30, 31, 32] and was speculated to be a signal for the formation of a quark gluon plasma. The fraction of correlated particles decreases from almost 100% in peripheral collisions to 88% for central reactions.

IV. CENTRALITY DEPENDANCE OF σ_C^2

In Fig. 5 we show the experimental results from the UA5 and the PHOBOS experiment on the fluctuations

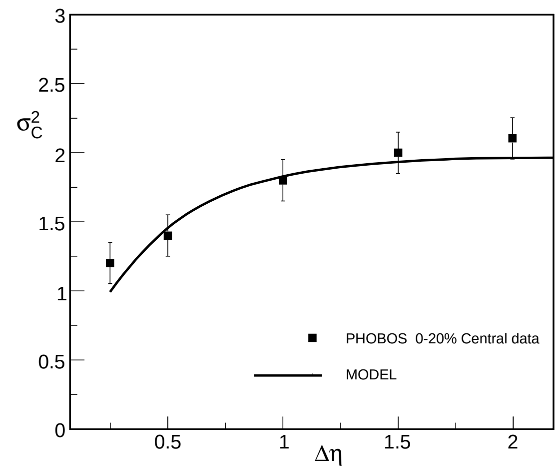

FIG. 2: σ_C^2 as a function of $\Delta\eta$ for $0\% - 20\%$ central Au+Au at $\eta = 2$. Black squares are PHOBOS data [25, 26, 27, 28]. The line is the model calculation using equation (6).

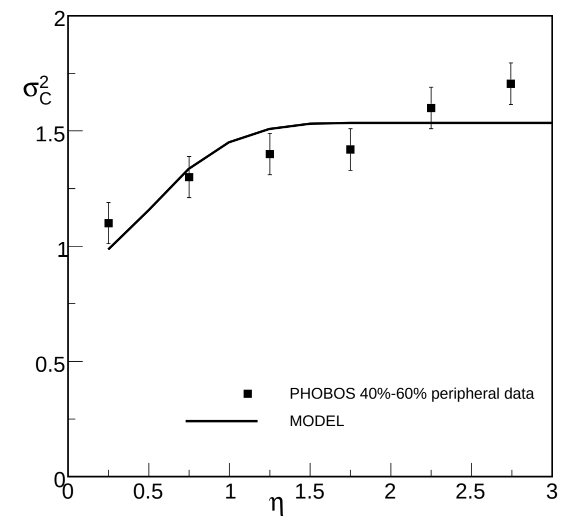

FIG. 3: σ_C^2 versus rapidity η for 40%−60% peripheral Au+Au at $\Delta\eta = 0.5$. Black squares are PHOBOS data [25, 26, 27, 28]. The line is the model calculation using equation (6).

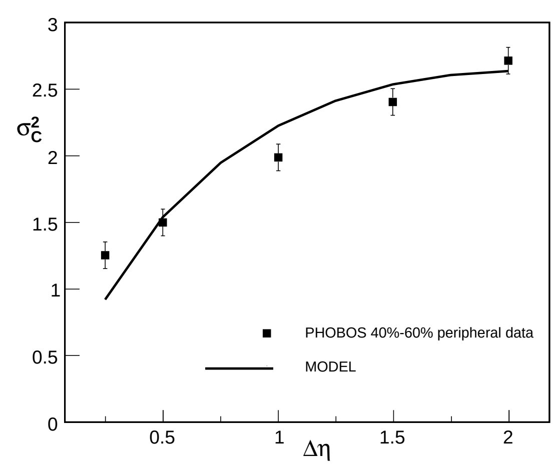

FIG. 4: σ_C^2 versus $\Delta\eta$ for $40\% - 60\%$ peripheral Au+Au at $\eta = 2$. Black squares are PHOBOS data [25, 26, 27, 28]. The line is the model calculation using equation (6).

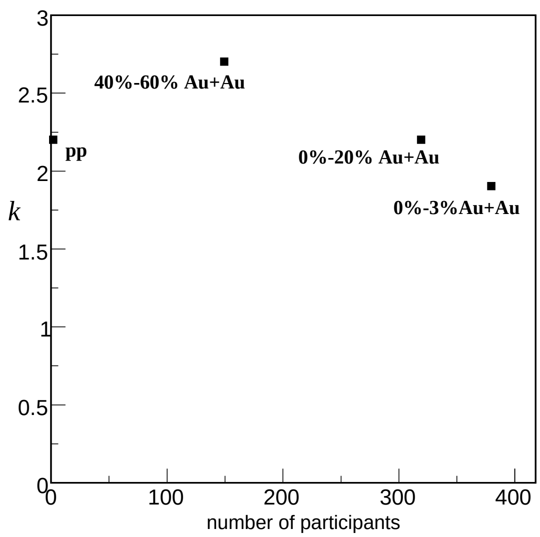

FIG. 5: Cluster multiplicity k versus the number of participants. The last point represents 0%-3% Au+Au is computed by extrapolating our model parameters in Table I.

of the forward-backward correlation σ_C^2 for p$\overline{\rm p}$ (Au+Au) at different centralities.

From Fig. 5, we see that σ_C^2 starts at 2.2 for p$\overline{\rm p}$ and then increases to 2.7 for $40\% - 60\%$ peripheral and then goes down to 2.2 again for $0\% - 20\%$ central Au+Au. This behavior has important consequences that will help to understand the particles productions mechanism in nucleus-nucleus collisions compared to nucleon-nucleon collisions as we will discuss next.

The increase in the dynamic fluctuations for $40\% - 60\%$ peripheral collisions compared to p$\overline{\rm p}$ at the same energy might be attributed to the difference in the dynamics of the collisions between p$\overline{\rm p}$ and nucleus-nucleus collisions. First let us consider the string picture for particles production in p$\overline{\rm p}$ collisions. During such collisions a few strings between the quarks in both protons form and are subsequently fragmented into hadrons. If the same picture holds for nucleus-nucleus collisions, then σ_C^2 in both p$\overline{\rm p}$ and Au+Au will be similar and σ_C^2 has a flat centrality dependence. However, experimental data indicates that the cluster multiplicity k is increased in $40\% - 60\%$ peripheral Au+Au collisions compared to p$\overline{\rm p}$ interactions. An explanation of this enhancement might be found in the context of string fusion models [33]. Here, the fusion process might increase the probability of high mass clusters compared to p$\overline{\rm p}$ collisions, resulting in a higher multiplicity per cluster.

If the formation of heavier clusters is the explanation for the increase of k in Au+Au compared to p$\overline{\rm p}$, then one expects an even further increase of k towards central Au+Au collisions. This enhancement will be observable if interactions with the surrounding medium are negligible compared to the increase in k due to string fusion. Fig. 5 shows that this is not the case, because the cluster multiplicity in $0\% - 20\%$ central Au+Au collisions decreases to $k = 2.2$. In addition, the number of correlated particles f also decreases towards more central Au+Au reactions (cf. Table I). This indicates that in central collisions the interactions with the hot and dense QCD matter results in smaller clusters (reducing the value of k) as compared to peripheral collisions. With even tighter centrality cuts one might be able to see a complete melting of the clusters leading to independent uncorrelated particle emission patterns (i.e. $\sigma_C^2 = 1$ and $k = 1$).

To test this idea, we linearly extrapolate those parameters in Table I to $0\% - 3\%$ Au+Au collisions. The last point in Fig. 5 corresponds to this centrality cuts. We find that $k \approx 1.9, \lambda_{\rm short} \approx 0.3$. This means that clusters formed at the most central collisions are partially melted compared to mid-peripheral collisions. Also the short range correlation length $\lambda_{\rm short}$ becomes smaller. It is worth to mention that the decrease of the rapidity correlation length seems to be a general feature of nucleus-nucleus collisions at high energies since the width of the balance function expected to decrease with centrality as a result of late hadronization as mentioned in Ref. [34]. This decrease is observed in the data reported in [35, 36].

To distinguish between hadronic and QGP effects, σ_C^2 should be measured at different energies and ion sizes and also with different transverse momentum cuts to include/exclude the effects of mini-jets, since jets hadronize into a shower of hadrons which might mimic a clustering effect (within the jet cone). Thus, limiting the measurement of σ_C^2 to the soft region (i.e. $p_t < 2$ GeV) allows to minimize jet artifacts.

In this case conclusive statement can be given by comparing peripheral data to the central one to extract f and k for different initial conditions and to study how both f and k change as a function of the initial partonic volume, life time and energy density.

V. SUMMARY AND CONCLUSION

In this letter we present a model to analyze forward-backward dynamical fluctuations as recently measured by the PHOBOS collaboration in Au+Au reactions at $\sqrt{s_{\rm NN}} = 200$ GeV. We find that the effective cluster multiplicity in central collisions is lower than for peripheral collisions. Also the short range rapidity correlation length decreases towards more central interactions.

This might indicate that the clusters are “melted” in central collisions, resulting in a smaller fraction of correlated particles (decrease of f). One can test the degree of melting by measuring k as a function of centrality, and especially for very central Au+Au collisions. If one observes that $k \to 1$, all clusters are melted and the final particles are independently emitted.

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