Event–by–event fluctuations in heavy–ion collisions and the quark–gluon string model

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Abstract

We apply dynamical string models of heavy–ions collisions at high energies to the analysis of event–by–event fluctuations. Main attention is devoted to a new variable proposed to study "equilibration" in heavy–ions collisions. Recent results of the NA49 collaboration at CERN SPS are compared with predictions of the Quark–Gluon String Model (QGSM), which gives a good description of different aspects of multiparticle production for collisions of nucleons and nuclei. It is shown that the new observable and other results of the NA49 analysis of event–by–event fluctuations are correctly reproduced in the model. We discuss dynamical effects responsible for these fluctuations and give the predictions for p–p, p–Pb and Pb–Pb collisions at RHIC and higher energies.
I. INTRODUCTION

An event–by–event analysis of heavy–ions collisions can give important information on the dynamics of these processes. In the paper [1] it was proposed to use an event–by–event analysis of transverse momentum fluctuations as a method for the study of ”equilibration” in high−energy nucleus–nucleus collisions. For this purpose a special variable $\Phi$ has been introduced in ref. [1] (the definition of this variable will be given below). The problem of ”equilibration” in high−energy heavy–ions collisions is very important in order to understand the conditions for quark–gluon plasma formation. Recent experimental results on event–by–event analysis of Pb–Pb collisions at CERN SPS by the NA49 collaboration [2] show that the value of $\Phi$ is substantially smaller than expected in the case of independent nucleon–nucleon collisions and its smallness was considered as an indication of ”equilibration” in the system.

This result has been discussed in the framework of different theoretical models. It was shown [3] that the increase of transverse momenta of hadrons due to multiple rescatterings leads to a substantial increase of $\Phi$. Incorporating this effect in the model of ref. [4] one finds an even stronger disagreement with the NA49 result. It was also demonstrated that strings fusion also leads to an increase of $\Phi$ in disagreement with experiment [3,5]. The results on the influence of final states interactions on the observable $\Phi$ are contradictory: in ref. [5] it was shown that final states interactions in the framework of the string model of ref. [5] have a small effect and do not allow to reach agreement with experiment, while in ref. [6] it was argued that final states interactions in the framework of the UrQMD model are essential and can decrease $\Phi$ to a value consistent with experiment. On the other hand, it was shown in ref. [8] that, in the case of fully equilibrated hadronic gas made mostly of pions, one expects large positive values for the variable $\Phi$ not consistent with the experimental observation.

In this note we study event–by–event fluctuations using the Monte–Carlo formulation [9] of the Quark–Gluon String Model (QGSM) [10]. The QGSM and the Dual Parton Model (DPM) [11] are closely related dynamical models based on $1/N$–expansion in QCD, string fragmentation and reggeon calculus. They give a good description of many characteristics of
multiparticle production in hadron–hadron, hadron–nucleus and nucleus–nucleus collisions (for a review see refs. [12]). Nuclear interactions in this model are treated in the Glauber–Gribov approach. It will be shown that the model reproduces the results of the event–by–event analysis of the NA49 experiment for the quantity Φ as well as for other fluctuations observed in this experiment [2]. We analyze the reason for the decrease of the quantity Φ from p–p to Pb–Pb collisions seen by the NA49 experiment and come to the conclusion that the quantity Φ is sensitive to many details of the interaction and can hardly be considered as a good measure of ”equilibration” in the system. We predict a strong increase of the value of Φ at energies of RHIC and higher. The model also gives definite predictions for event–by–event fluctuations in p–Pb collisions.

II. ANALYSIS OF EVENT–BY–EVENT FLUCTUATIONS OF TRANSVERSE MOMENTA

Let us remind briefly the method to study event–by–event fluctuations of transverse momenta of produced particles introduced in ref. [1]. It was proposed to define for each particle in a given event a variable 

\[ z_i = p_{T_i} - \langle p_T \rangle, \]

where \( p_{T_i} \) is the transverse momentum of the particle \( i \) and \( \langle p_T \rangle \) is the mean transverse momentum of particles averaged over all events. Using \( z_i \) the quantity \( Z = \Sigma_{i=1}^{N} z_i \) is defined, where \( N \) is the total number of particles in the event. If nucleus–nucleus collisions can be considered as a superposition of independent nucleon–nucleon collisions then it can be shown [1] that

\[ \frac{\langle Z^2 \rangle_{AA}}{\langle N \rangle_{AA}} = \frac{\langle Z^2 \rangle_{NN}}{\langle N \rangle_{NN}}. \]  

A derivation of this result is given in Appendix 1.

The averaging in eq.(1) is over all events in a given kinematical region. It was proposed in ref. [1] to characterize the degree of fluctuations by the variable

\[ \Phi = \sqrt{\frac{\langle Z^2 \rangle}{\langle N \rangle}} - \sqrt{\langle z^2 \rangle}, \]  

(2)
where $< z^2 >$ is the second moment of the single particle inclusive $z$–distribution. The quantity $< z^2 >$ corresponds to purely statistical fluctuations and is determined by mixing particles from different events. It was emphasized in ref. [1] that, if nucleus–nucleus collisions would be a simple superposition of independent nucleon–nucleon collisions, then the variable $\Phi$ would be the same as in the nucleon–nucleon case (see Appendix 1). In nucleon–nucleon collisions the quantity $\Phi$ is different from zero due to dynamical correlations and, in particular, due to the dependence of $< p_T >$ on the number of produced particles. It was proposed to attribute a possible decrease of the quantity $\Phi$ in A–A collisions to the effects of ”equilibration”.

Let us note that the model of independent N–N collisions for nucleus–nucleus interactions is an extremely oversimplified one. The Glauber model at high energies is not equivalent to independent N–N collisions even for N–A interactions. The space–time picture of hadron–nucleus interactions at high energies is absolutely different from a simple picture of successive reinteractions of an initial hadron with nucleons of the nucleus (see e.g. [13–15]). For nucleus–nucleus interactions there are extra correlations [14,16]. The model of independent N–N collisions does not even satisfy energy–momentum conservation, as a nucleon of one nucleus can not interact inelastically several times with nucleons of another nucleus having the same energy at each interaction.

In the QGSM as well as in DPM, the effects of multiple interactions in hadron–nucleus and nucleus–nucleus collisions are taken into account in the approach based on the topological expansion in QCD [12]. Probabilities of rescatterings are calculated in the framework of the Glauber–Gribov theory and multiparticle configurations in the final state are determined using AGK [17] cutting rules. In these models the Pomeron is related to the cylinder type diagrams, which correspond to the production of two chains of particles due to decays of two $qq$–$q$ strings. Multi–Pomeron exchanges are related to multi–cylinder diagrams which produce extra chains of type $q$ – $\bar{q}$. They are especially important in interactions with nuclei. Fragmentation of strings into hadrons is described according to ”regge counting rules” [18], which give correct triple–regge and double–regge limits of inclusive cross sections. Note, however, that in the Monte Carlo version used in this paper, the Artru–Menessier string fragmentation scheme is
implemented instead. All conservation laws (including energy–momentum conservations) are satisfied in this approach.

Let us emphasize that at energies $\sqrt{s} \sim 10$ GeV the cylinder–type diagrams give the dominant contributions for N–N collisions. Extra $q \rightarrow \bar{q}$ chains due to multi–cylinder diagrams have rather small length in rapidity (short chains) and do not lead to substantial contributions to particle production. In nucleon–nucleus and nucleus–nucleus collisions, the number of short chains is strongly increased compared to the nucleon–nucleon case (it is proportional to a number of collisions) and they should be taken into account in any realistic calculations of multiparticle production on nuclei. This means that for p–A and A–B collisions there are extra ”clusters” of particles (short chains, of type $q \rightarrow \bar{q}$) compared to the nucleon–nucleon interactions ”clusters” (long chains connecting valence quarks and diquarks of the colliding nucleons).

So we come to the conclusion that in the relativistic Glauber–Gribov dynamics the characteristics of final particles in N–A and A–B collisions can not be expressed in terms of N–N collisions only, as it was assumed in ref. [1], and eq.(1) is not valid in general. In Appendix 1 we give as an illustrative example the results in a model with two types of clusters. This model is a generalization of the single cluster model of ref. [1], and is much closer to QGSM and DPM.

The results of the Monte Carlo calculation for the quantity $\Phi$ are shown in Table 1 for p–p, p–Pb and central Pb–Pb collisions at SPS energies ($\sqrt{s} = 19.4$ GeV) and at RHIC ($\sqrt{s} = 200$ GeV). Predictions of the model for $\Phi$ are quite different for these two energies. At SPS there is a strong reduction of the quantity $\Phi$ for nuclear collisions compared to N–N collisions, while at RHIC the quantity $\Phi$ is predicted to be much larger than at SPS and about the same for Pb–Pb and p–p collisions. At LHC energies the value of $\Phi$, obtained in our model, is 160 MeV for p–p and even larger for Pb–Pb collisions (the Monte Carlo code we use does not allow to calculate precise values of the correlations at LHC energies due to a too large number of particle produced in each event; so in Table 1 we give predictions of the model at $\sqrt{s} = 540$ GeV and $\sqrt{s} = 1$ TeV to show the energy dependence of fluctuations). The results for SPS energies are in a reasonable agreement with experimental data of the NA49 Collaboration [2].
for p–p interactions at this energy is even higher than the estimate, based on the dependence of \( <p_T> \) on the number of charged particles, given in ref. [1]. The model reproduces this correlation reasonably well and shows that this is not the only source of fluctuations leading to a non-zero value of \( \Phi \). We find that the quantity \( \Phi \) is sensitive also to other types of correlations and, in particular, to the correlations related to conservation of \( p_T \) in the process.

Let us note that the quantity \( \Phi \) at SPS energies is very small and is defined in eq.(2) as a difference of two large numbers (see Table 1), so it is very sensitive to all details of dynamical models. Because of its smallness it is difficult to obtain a good accuracy in a Monte Carlo calculation of this quantity (especially for nucleus–nucleus collisions, where the maximum statistics possible in the Monte–Carlo is \( \approx 5000 \) events). In order to increase the statistics and to reduce this uncertainty we give in Table 1 results obtained for the total rapidity interval, while the experimental data of the NA49 Collaboration were obtained in a fixed rapidity interval \( 4 < y_{\text{lab}}^{\pi} < 5.5 \). The error in the values of \( \Phi \) in Table 1 is about 1 MeV for the lowest energies, and increases at high energy. Other properties of event by event fluctuations observed by NA49 Collaboration [2] were calculated under the condition of the experiment and are reproduced by the model reasonably well as it is shown in Fig.1.

It follows from Table 1 that at SPS energies there is an increase of the quantity \( \sqrt{\frac{\langle Z^2 \rangle}{\langle N \rangle}} \) from p–p to Pb–Pb collisions, but there is an even larger increase for \( \sqrt{\langle z^2 \rangle} \) due to the increase of \( <p_T> \) and to a change in the form of the \( p_T \) distribution. The effect of the correlations between \( <p_T> \) and the number of charged particles due to rescatterings is, to a large extent, compensated at these energies by energy–momentum conservation effects. As a result, we find no dependence of \( <p_T> \) on \( n_{ch} \) for Pb–Pb collisions at SPS. For RHIC energies a strong increase in the values of both \( \sqrt{\frac{\langle Z^2 \rangle}{\langle N \rangle}} \) and especially of \( \Phi \) is predicted (see Table 1). At these energies the increase of average transverse momentum with the number of rescatterings becomes very important in p–p interactions and is reproduced by the QGSM (Fig. 2a). It is shown in Fig. 2b that an increase of \( <p_T> \) with multiplicity is predicted at these energies even for Pb–Pb collisions, although the effect is less pronounced for heavy-ions collisions than for p–p. At LHC energies all these effects will be stronger than at RHIC and will produce an
increase of the quantity $\Phi$ in p–p, p–A and A–A collisions as energy increases.

The predictions of the model can be easily tested in future experiments at RHIC and LHC.

III. CONCLUSIONS

We have shown, in a Monte Carlo version of the QGSM, that at SPS energies the quantity $\Phi$, characterizing event–by–event transverse momentum fluctuations, decreases from $\Phi \sim 9$ MeV in p–p collisions to $\Phi \sim 2$ MeV in central Pb–Pb collisions. This result for Pb–Pb collisions agrees with the measurement of the NA49 Collaboration. In ref. [1], such a decrease between p–p and Pb–Pb was considered to be a test of equilibration of the dense system produced in central heavy ion collisions. We have obtained the same result in the framework of an independent string model.

At RHIC energies, we predict an increase in the value of $\Phi$ ($\Phi = 75 \div 80$ MeV). In this case $\Phi$ will be approximately the same in p–p and central Pb–Pb collisions. At higher energies the value of $\Phi$ is predicted to be larger and to increase from p–p to central Pb–Pb collisions.

Our analysis indicates that the quantity $\Phi$ can hardly be considered as a good measure of "equilibration" in the system. However, it can be used as a sensitive test of dynamical models.

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APPENDIX 1

Here we will consider a simplified model of multiparticle production with two types of "clusters", which is a generalization of the model of ref. [1], where clusters of only a single type were produced. As discussed above, these "clusters" correspond to $qq - q$ chains (clusters of the first type) and $q - \bar{q}$ chains (clusters of the second type). Nucleon–nucleon collision at SPS–energies can be described with a good accuracy by the production of two clusters of the first type, while for proton–nucleus and nucleus–nucleus interactions, production of the second type of clusters is important even in this energy range. For independent production of $k_1$ clusters of the first type and $k_2$ - of the second type, with average transverse momenta $< p_T >_i$ and multiplicity $< n >_i$ for the cluster $i$, the following results for $< Z >$ and $< Z^2 >$ can be obtained:

$$< Z >_{k_1,k_2} = k_1 < Z >_1 + k_2 < Z >_2$$  \hspace{1cm} (A.1)

where $< Z >_i = < n >_i (< p_T >_i - < P_T >)$ and $< P_T > = \frac{(< k_1 > < n_1 > < p_T >_1 + < k_2 > < n_2 > < p_T >_2)}{(< k_1 > < n_1 > + < k_2 > < n_2 >)}$.

$$< Z^2 >_{k_1,k_2} = k_1 < Z^2 >_1 + k_2 < Z^2 >_2 + k_1(k_1 - 1) < Z >^2_1 +$$

$$+ k_2(k_2 - 1) < Z >^2_2 + 2k_1k_2 < Z >_1 < Z >_2$$  \hspace{1cm} (A.2)

The expression for $< Z^2 >_{k_1,k_2}$ can be rewritten as

$$< Z^2 >_{k_1,k_2} = k_1(< Z^2 >_1 - < Z >^2_1) + k_2(< Z^2 >_2 - < Z >^2_2) + < Z >^2_{k_1,k_2}.$$  \hspace{1cm} (A.3)

For the quantity $\Phi$ in eq.(2) it is important that contrary to the case of a single cluster, the expression for $< Z^2 >$ contains negative terms proportional to $< Z >^2_i$.

Next we take the average over the number of produced clusters with some distribution $P_{k_1,k_2}$.
\[
\langle \langle Z^2 \rangle_{k_1k_2} \rangle = \sum_{k_1,k_2} P_{k_1k_2} \langle Z^2 \rangle_{k_1k_2} = \\
= \langle k_1 \rangle \left( \langle Z^2 \rangle_1 - \langle Z \rangle^2_1 \right) + \langle k_2 \rangle \left( \langle Z^2 \rangle_2 - \langle Z \rangle^2_2 \right) + \langle \langle Z \rangle^2_{k_1k_2} \rangle.
\] (A.4)

In the following we will denote this averaging simply by \( \langle Z^2 \rangle \). We shall concentrate on p–A collisions. In this case, it is easy to show that the last term in eq.(A.4) is small and can be neglected. To prove this we note that for p–A collisions, \( k_2 = k_1 - 2 \) with \( k_1 = \bar{n} + 1 \), where \( \bar{n} \) is the average number of collisions and, thus,

\[
\langle \langle Z \rangle^2_{k_1k_2} \rangle - \langle \langle Z \rangle_{k_1k_2} \rangle^2 = (\langle k^2_1 \rangle - \langle k_1 \rangle^2)(\langle Z \rangle_1 + \langle Z \rangle_2)^2.
\] (A.5)

Taking into account that (for fixed impact parameter) the distribution in \( k_1 \) is of a Poisson type with \( (\langle k^2_1 \rangle - \langle k_1 \rangle^2) = c_1 \langle k_1 \rangle \) and that

\[
\langle \langle Z \rangle_{k_1k_2} \rangle = \langle k_1 \rangle \langle Z \rangle_1 + \langle k_2 \rangle \langle Z \rangle_2 = \langle k_1 \rangle \langle Z \rangle_1 + (\langle k_1 \rangle - 2) \langle Z \rangle_2 = 0
\]

we obtain:

\[
\langle \langle Z \rangle^2_{k_1k_2} \rangle = \frac{4c_1 \langle Z \rangle^2_2}{\langle k_1 \rangle}.
\] (A.6)

For large values of \( \langle k_1 \rangle \) this quantity is much smaller than the other terms in the right–hand side of eq.(A.4).

The expressions for the quantities \( \langle N \rangle \) and \( \langle z^2 \rangle \), that enter into the definition of \( \Phi \) are selfevident

\[
\langle N \rangle = \langle k_1 \rangle \langle n_1 \rangle + \langle k_2 \rangle \langle n_2 \rangle
\] (A.7)

and

\[
\langle z^2 \rangle = \frac{\langle k_1 \rangle \langle z^2 \rangle_1 + \langle k_2 \rangle \langle z^2 \rangle_2}{\langle k_1 \rangle \langle n_1 \rangle + \langle k_2 \rangle \langle n_2 \rangle}.
\] (A.8)
Let us denote $\langle Z^2 \rangle_i \equiv \gamma_i$, $\langle k^2 \rangle_i \equiv \alpha$. Taking into account that $\delta_i \approx 2 \frac{\phi_i}{\sqrt{z_i}}$, $\gamma_i$ are much smaller than unity we obtain the following approximate expression for $\Phi$:

$$\Phi = \frac{\left[ (\delta_1 - \gamma_1) \langle z^2 \rangle_1 + (\delta_2 - \gamma_2) \alpha \langle z^2 \rangle_2 \right]}{2\sqrt{A}}$$

where $A = (1 + \alpha)(\langle z^2 \rangle_1 + \alpha \langle z^2 \rangle_2)$.

It is important that the terms proportional to $\gamma_i$ give negative contributions to $\Phi$ and can substantially decrease the value of $\Phi$.

For the case of clusters of the same type ($\gamma_i = 0, \langle Z^2 \rangle_1 = \langle Z^2 \rangle_2, \delta_1 = \delta_2$) we obtain:

$$\Phi = \frac{\delta_1}{2} \sqrt{\langle z^2 \rangle}$$

both for p–p and p–A. We recover in this way the result of ref. [1]. The discussion in this Appendix has been restricted to p–A interactions. The situation is more complicated in A–B collisions. Actually, even for p–A, we do not claim that the effect discussed in this Appendix is the main reason for the decrease of $\Phi$, obtained in the Monte Carlo calculations (see Table 1), between p–p and p–A collisions at SPS energies. Nevertheless, our example illustrates the important effect that a modification of the model (i. e., going from one to two types of clusters) can have on the quantity $\Phi$. 
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Table 1. The results of the Monte-Carlo calculation for the quantities $\sqrt{\langle Z^2 \rangle} \langle N \rangle$ (MeV), $\sqrt{\langle z^2 \rangle}$ (MeV) and $\Phi$ (MeV) for p-p, p-Pb and central Pb-Pb-collisions at SPS ($\sqrt{s} = 19.4$ GeV), RHIC ($\sqrt{s} = 200$ GeV) and higher ($\sqrt{s} = 540$ GeV and 1 TeV) energies. The results at 1 TeV have only an indicative value (see main text).
FIGURE CAPTIONS

Figure 1. Event spectra characterising the multiplicity, transverse momentum and rapidity distribution of charged particles per event for Pb-Pb collisions at $P_{lab} = 158$ AGeV/c and $b \leq 3.5$ fm in the rapidity interval $4 \leq y \leq 5.5$. The full lines are the Monte Carlo results. Experimental data are from ref. 2.

Figure 2. The dependence of the average transverse momentum on the multiplicity of charged particles in the window $|\eta| \leq 2.5$ at $\sqrt{s} = 200$ GeV for p–p collisions compared to experimental data [19] (Fig. 2a) and for Pb-Pb central collisions (Fig. 2b).
|       | \( \sqrt{s} \) (GeV) | \( \sqrt{<Z^2>/<N>} \) (MeV) | \( \sqrt{<z^2>} \) (MeV) | \( \Phi \) (MeV) |
|-------|------------------------|-------------------------------|---------------------|-----------------|
| p-p   | 19.4                   | 244.5                         | 235.5               | 9.0             |
| p-Pb  | 19.4                   | 243.5                         | 243.0               | 0.5             |
| Pb-Pb | 19.4                   | 265.6                         | 263.2               | 2.4             |
| p-p   | 200                    | 387.0                         | 310.6               | 76.4            |
| p-Pb  | 200                    | 433.7                         | 367.8               | 65.9            |
| Pb-Pb | 200                    | 508.9                         | 429.4               | 79.5            |
| p-p   | 540                    | 450.1                         | 323.6               | 126.5           |
| p-Pb  | 540                    | 524.3                         | 397.7               | 126.6           |
| Pb-Pb | 540                    | 622.6                         | 475.2               | 147.4           |
| p-p   | 1000                   | 455.5                         | 324.4               | 131             |
| p-Pb  | 1000                   | 524.5                         | 397.5               | 127             |
| Pb-Pb | 1000                   | 704.2                         | 484.3               | 220             |
