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Study of Forward-Backward Multiplicity Fluctuations and Correlations with Pseudorapidity

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Abstract—Multiplicity fluctuations in two separated pseudorapidity intervals are studied in terms of strongly intensive variables. This work presents results obtained in the MC model with quark-gluon strings as objects extended in pseudorapidity space and acting as particle emitting sources. The string interactions are implemented within the discrete model of local string fusion. Strings of fluctuating length in pseudorapidity are considered in order to estimate the non-critical background of fluctuations. The results on the dependence of strongly intensive observables on the width of acceptance windows, on the pseudorapidity separation between them and on the string density qualitatively describe the available data from the NA61/SHINE and ALICE experiments.

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THE MODERN BATTLE SCENE

In the ongoing comprehensive exploration of the QCD phase diagram $T-\mu_B$ [1], a number of attempts are done in order to find out whether the critical point of strongly interacting matter exists and, if so, to define its position in the phase diagram. Lattice QCD calculations predict the smooth crossover from hadron gas to the QGP phase in the LHC energy range at zero net-baryon density. Meanwhile, the experimental evidence points to some phase transition which occurs at lower collision energies [2]. In this scenario, the search for the critical point of strongly interacting matter seems to be the essential effort to our better understanding of nature.

In order to probe the diagram in a wide range of temperature and the baryon-chemical potential of the system at the freeze-out stage, experiments perform the beam-energy-scan. If the system freeze-out occurs in the vicinity of a critical point, the final particles are expected [3] to carry some critical fluctuation signals originating from the divergence of the correlation length in the primary system. However, one needs to ensure the elimination of the trivial volume fluctuations.

The special variables [4] manifested to be independent of the volume and fluctuations of the volume in the model of independent sources or for the ideal Boltzmann gas in GCE are used in the study of fluctuations. Namely, the strongly intensive quantity $\Sigma[A, B]$ was defined [4] as a function of any extensive event variables A and B. The normalisation [5] demands $\Sigma[A, B]$ to be equal to unity in the case of independent particles, whereas by the construction $\Sigma[A, B]$ equals zero in the absence of A and B fluctuations.

In [6, 7] the study of fluctuations was extended to explore their pseudorapidity dependence, which corresponds to the change of the baryo-chemical potential at the freeze-out stage [8] and provides an additional scan of the phase diagram. The analysis was done for the strongly intensive variable $\Sigma[N_F, N_B]$ [9]:

$$\Sigma[N_F, N_B] = \frac{1}{N_F + N_B}[\langle N_B\rangle \omega[N_F] + \langle N_F\rangle \omega[N_B] - 2(\langle N_F \cdot N_B\rangle - \langle N_F\rangle\langle N_B\rangle)]. \quad (1)$$

COLOUR STRINGS APPROACH AND THE MOTIVATION

The proper interpretation of the experimental results requires an adequate understanding of the full picture of heavy-ion collisions, which appears to be pretty tough for the step-by-step description.

Apparently, the models with the two stages scenario of multi-particle production are widely used in this problem. Namely, the phenomenological model of quark-gluon strings [10] successfully describes the production of the soft p_T range of spectra. The model harks back to the Dual Parton model [11] and the Regge approach [12]. The Lund model [13] represents the string as the longitudinally extended object stretched between the flying outwards wounded quarks and formed by the colour field lines gathered together due to the gluon self-interaction. The hadronization then is conventionally implemented as the quark-antiquark pair creation inside the flux tube due to the growing of colour field with the string length. Then, the string remnants depending on their energy correspond either to the colourless final hadrons or to string-like resonances decaying by the same mechanism until all the string fragments are identified with the measured hadrons.

The beauty of the model is that the first step being described by the particle sources formed after the collision may straightforwardly account for the initial conditions. Thus, the estimation of the non-critical background of fluctuations caused by the string end points position variations would serve as a baseline on the top of which the search for the critical fluctuations should be proceed. Moreover, the finite size of strings in transverse plane essentially implicates their interaction, which affects their properties and consequently the decay into observed particles. As shown in [14], $\Sigma[N_F, N_B]$ already loses its quality of strong intensity in the model with the sources of two types. Therefore, the comparison of the model calculation with the experimental data would provide the possibility to clarify the properties of the particles sources. Furthermore, since the particles produced by strings cover the wide rapidity range, the study of the long-range pseudorapidity fluctuations in terms of $\Sigma[N_F, N_B]$ in the MC model of interacting quark-gluon strings with a finite length in pseudorapidity is the focus of the present work.

MC MODEL OF INTERACTING QUARK-GLUON STRINGS OF THE FINITE LENGTH IN PSEUDORAPIDITY

The present research is dedicated to the development of the MC model of interacting colour strings of fluctuating length and position in pseudorapidity space. The similar concepts are widely used in modern event generators and are considered in some recent papers [15]. However, the simplicity of the presented model provides the direct possibility to address the question of the influence of the initial conditions on the final measures and clarify the picture of the particle sources origin based on the comparison with the available experimental data.

The model starts with the generation of the number of strings per event according to the Poisson distribution with different mean values in order to check the dependence of $\Sigma[N_F, N_B]$ on the string density. The strings' end positions in the pseudorapidity space are generated according to the uniform distribution in some range (we used interval [–4, 4]), which eventually breaks the translation invariance in pseudorapidity. This corresponds to the picture of strings stretched between wounded quarks with different x_F values. The global model parameter such as the number of particles produced by string per rapidity unit μ is chosen to be equal unity; the minimal pseudorapidity string length equals 0.3 units. The particle production is performed in the way that the number of particles emitted by the string in the certain pseudorapidity interval $\delta\eta$ is defined by the Poisson distribution with the mean $\langle N \rangle = \mu\delta\eta$.

The study of long-range correlations and fluctuations in two pseudorapidity intervals separated by the changing $\Delta\eta$ is the essential approach in order to eliminate the impact of the resonance decay products. Up to now the model does not account for any short-range correlations. Moreover, the particle production in Forward and Backward pseudorapidity intervals by the same string is independent.

The more realistic story is to consider the string interaction, which has an essential origin since strings have a finite size in the transverse dimension and one may expect their overlapping in the case of high string density [16]. The most efficient way to account for the string interaction from the point of view of computation is to consider the discrete model of local string fusion [17]. In this model, the distribution of strings centers is generated on the transverse lattice of equal cells. Therefore, if the number of strings in the same lattice cell is w, one may assume their effective fusion, which results in the mean particle multiplicity produced by the new "fused" string with higher colour field density according to $\langle N^{\text{fusion}} \rangle = \sqrt{w}\mu\delta\eta$ [18].

In this model, the estimate of the non-critical background of fluctuations comes from the string ends positions variations, which along with the string fusion forms the effective long strings with the mutable color field density, which affects the results on correlation and joint fluctuations of N_F and N_B.

RESULTS ON THE $\Sigma[N_F, N_B]$ IN THE DEVELOPED MC MODEL AND CONCLUSIONS

The present research is focused on the verifying the influence of the initial conditions of collisions on the final observables extracted from the experimental data. The Monte Carlo model of interacting quark-gluon strings of finite length in pseudorapidity was developed. Within the model it was shown that fluctuations caused by strings ends positions variations qualitatively describe the behaviour of strongly intensive variable $\Sigma[N_F, N_B]$ in the experimental data of the NA61/SHINE experiment at CERN SPS [6]. Namely, the grows of $\Sigma[N_F, N_B]$ with the pseudorapidity interval width $\delta\eta$ and the distance $\Delta\eta$ between Forward-Backward windows is reproduced (Figs. 1a, 1b).

The check (Figs. 1a, 1b) of the string fusion influence on the $\Sigma[N_F, N_B]$ measure revealed that

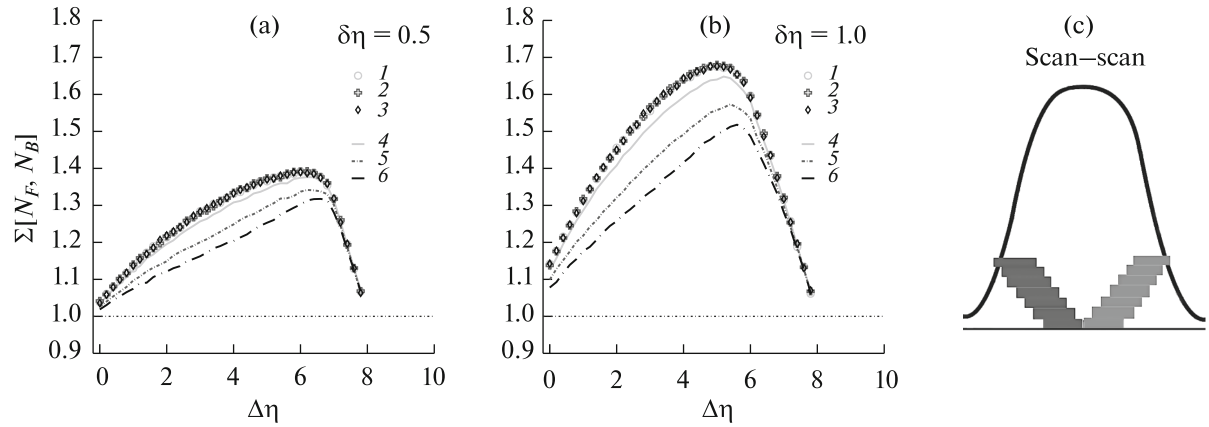

Fig. 1. MC model results for $\Sigma[N_F, N_B]$ as a function of a distance $\Delta\eta$ between Forward and Backward pseudorapidity intervals. The dots represent the independent sources with mean number of strings per event $\langle N_{str} \rangle$ equals to 8 (*1*), 30 (*2*) or 50 (*3*) and lines correspond to the string fusion with $\langle N_{str} \rangle$ equals to 8 (*4*), 30 (*5*) or 50 (*6*) all in a transverse lattice of 25 cells. The string ends were generated in pseudorapidity interval [–4, 4]. Results for the pseudorapidity window width (a) $\delta\eta = 0.5$ and (b) $\delta\eta = 1.0$ are presented. Panel (c) shows pseudorapidity intervals configurations.

$\Sigma[N_F, N_B]$ remains strongly intensive in the case of independent particle sources. However, the value of $\Sigma[N_F, N_B]$ considered in the discrete model of local string fusion decreases with the number of strings, which uncovers the limits of its quality of strong intensity. These prominent results are consistent with the experimental evidence of the ALICE experiment at LHC in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV displaying the decrease of $\Sigma[N_F, N_B]$ for the more central collisions [7]. The value of $\Sigma[N_F, N_B]$ demonstrates the maximum (Figs. 1a, 1b) when the pseudorapidity windows coverage exceeds (Fig. 1c) the width of the particles pseudorapidity distribution with $\Delta\eta$, which brings the reverse decrease of $\Sigma[N_F, N_B]$ to unity due to the vanishing number of particles in the acceptance according to $\Sigma[N_F, N_B]$ definition. In the region of the largest $\Delta\eta$ the coincidence of the $\Sigma[N_F, N_B]$ values for the independent particle sources (points) and fused strings (lines) reflects the low probability to have string fusion here.

The result of the present research (Fig. 1) together with the dependence of the $\Sigma[N_F, N_B]$ on the centrality in the model of infinitely long quark-gluon strings with the two types of particle sources [14] places in question the absolute applicability of $\Sigma[N_F, N_B]$ as the strongly intensive measure of fluctuations. Moreover, the obtained result provides us an access to the better understanding of the particle sources dynamics.

FUTURE PROSPECTS

The simplest analysis extension is to study the joint fluctuations of the event multiplicity N and the scalar sum of the particle transverse momenta P_T in terms of $\Sigma[N_F, P_{T,B}]$, which requires the generation of particle momentum p_T according to the Schwinger mechanism. The further development of the model assumes the introduction of the short-range correlations for the particles produced by the same string, which requires the parameterization of some effective correlation length, as for example was done in [14]. Also the Bose–Einstein correlations and Coulomb interactions will be considered. The major step of improvement is to calculate the quark-gluon string ends positions in pseudorapidity according to the PDFs of the valence and sea quarks.

The advanced model could be used in the view of searching for the sources of a new type, the nature of which in nucleus-nucleus collisions may origin from the quark-gluon strings fusion effect.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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