A model for computing the probability density of event-by-event participant center-of-mass rapidity $y_{c.m.}$ is presented. The evaluations of the $y_{c.m.}$ distribution are performed for different collision energies and different centralities. We show that for certain conditions the rapidity distribution is described by a Gaussian with a variance determined mostly by the collision centrality. It is found that the width of the $y_{c.m.}$ distribution increases strongly for more peripheral collisions, while it depends weakly on the collision energy. Other theoretical estimates of rapidity distribution are presented and questions of interaction and separation between spectators and participants are discussed.

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I. INTRODUCTION

To describe the many-particle interacting system created in heavy-ion collisions (participant system) different models such as hydrodynamics or kinetic transport models are used. Along with the participants there are also spectators, which are nucleons emerged from the colliding nuclei that do not take part in any reaction with other nucleons during the collision process and move with their initial momenta. The number of spectators from each of the nuclei changes event-by-event (EbE) and, due to this fluctuation, the center-of-mass of participant system does not coincide with the collider center-of-mass system (c.m.s), i.e. the participant c.m. rapidity, $y_{c.m.}$, may be non-zero in a particular event. The EbE fluctuations of $y_{c.m.}$ can be especially significant in peripheral collisions when impact parameter of colliding nuclei is large and the mass of the spectators is essential.

When comparing different observables which depend on rapidity, for instance collective flow (calculated e.g. in a hydrodynamical model) with experimental measurements, it could be important to account for participant c.m. fluctuations, which may influence the results [1–3]. Possible influence of EbE longitudinal fireball density fluctuations on measurable two-particle rapidity correlation function was recently studied in [4].

In the present work a simplified model for the calculation of the EbE $y_{c.m.}$ distribution is presented, and center-of-mass rapidity fluctuations are discussed.

II. THE MODEL

A. Participant rapidity from spectators

We consider the collision of two identical heavy nuclei with mass number $A$, and we analyze the probability for a nucleon to become a spectator or a participant. The many-particle system created in heavy-ion collisions can be divided into three subsystems (Fig. 1): spectators from the projectile, (A), spectators from the target (B) and the participant particles (P). The conservation of four-momentum provides us with the following expressions for the total energy and longitudinal momentum in the collider c.m.s.:

$$E_{tot} = E_A + E_B + E_P,$$

$$P_{tot}^z = P_A^z + P_B^z + P_P^z = 0.$$

The c.m. rapidity of the participant system can then be expressed as

$$y_P = \frac{1}{2} \ln \frac{P_P^z + E_P}{P_P^z - E_P}.$$

Using Eqs. (1)–(2) we can express $y_P$ in terms of spectator energy and momentum [3]

$$y_{c.m.} \approx y_P = \text{arctanh} \left[ \frac{-(P_A^z + P_B^z)}{E_{tot} - E_A - E_B} \right].$$

Next we will neglect the initial Fermi motion of nucleons in the colliding nuclei compared to their collective colli-
sion energy. In this case we can express $E_{\text{tot}}$, $E_{A(B)}$ and $p^{z}_{A(B)}$ in terms of spectator numbers $N_A$ and $N_B$ as

$$E_{\text{tot}} = 2A p^{0}_l,$$  \hspace{1cm} (5)

$$E_A = N_A p^0_l,$$  \hspace{1cm} (6)

$$E_B = N_B p^0_l,$$  \hspace{1cm} (7)

$$p^{z}_A = N_A p^z_l,$$  \hspace{1cm} (8)

$$p^{z}_B = -N_B p^z_l,$$  \hspace{1cm} (9)

where $p^{0}_l = \sqrt{s}/2$ and $p^z_l = \sqrt{s}/4 - m_N$ are the initial nucleon energy and momentum respectively, and hence the spectator nucleon energy and momentum. Here $m_N = 938$ MeV/c$^2$ is the nucleon mass. The c.m. rapidity can be expressed now in terms of the spectator numbers $N_A$ and $N_B$ as

$$y_P(N_A, N_B) = \text{arctanh} \left( \frac{N_B - N_A}{2A - N_A - N_B} v^z \right),$$  \hspace{1cm} (10)

where $v^z = p^z_l / p^{0}_l$ is the initial velocity of nucleons. It is seen from this relation that within our model only discrete set of values of $y^{c.m.}$ are possible. This is a consequence of neglecting the Fermi motion of nucleons, which would smear the momenta of spectators if accounted for, and also a consequence of neglecting the interaction between spectators and participants. Thus, we can determine the probabilities of different participant rapidities, $y^{c.m.}$, if we can determine the probabilities of spectator numbers $N_A$ and $N_B$.

### B. Spectator number probability

The transverse distribution of spectators in the collision of heavy ions can be evaluated from the Glauber-Sitenko approach $^{2, 3}$.

$$\frac{d^2 N_{\text{spec}}}{dx dy} = T_A(x - b/2, y) \left[ 1 - \frac{\sigma_{NN} T_B(x + b/2, y)}{A} \right]^A + T_B(x + b/2, y) \left[ 1 - \frac{\sigma_{NN} T_A(x - b/2, y)}{A} \right]^A,$$  \hspace{1cm} (11)

where $b$ is the impact parameter, $\sigma_{NN}$ is the nucleon-nucleon reaction cross section and

$$T_{A(B)}(x, y) = \int dz \rho_{A(B)}(x, y, z)$$

is the thickness function of the projectile (target) nucleus. Here

$$\rho_{A(B)}(x, y, z) \propto \left[ 1 + \exp \left( \frac{r - R}{\alpha} \right) \right]^{-1}$$  \hspace{1cm} (12)

is the Woods-Saxon nuclear density distribution in nucleus. For large mass number, $A$, we have $(1 - \sigma_{NN} T_B/A)^A \approx \exp(-\sigma_{NN} T_B)$ and in this case

Eq. (11) is often written in terms of exponents. The first term on the right-hand side of Eq. (11) is the transverse distribution of the spectators from the projectile nucleus and the second term is the transverse distribution of the spectators from the target nucleus. The probability that a nucleon from the projectile will become a spectator (which is the same as the probability for a nucleon from the target due to symmetry) can be expressed as

$$p_A = p_B = p = \frac{1}{A} \int dx dy T_A(x - b/2, y) \times \left( 1 - \frac{\sigma_{NN} T_B(x + b/2, y)}{A} \right)^A.$$  \hspace{1cm} (13)

The dependence of this probability on the impact parameter for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is depicted in Fig. 2. The values of parameters used for calculations are $\sigma_{NN} = 70$ mb, $A = 208$, $R = 6.53$ fm and $\alpha = 0.545$. Using parameter $p$ from (13) we can determine the probability that there will be $N_{A(B)}$ spectators in the projectile (target) as a binomial distribution

$$p(N_A) = \left( \frac{A}{N_A} \right) p^{N_A} (1 - p)^{A - N_A},$$  \hspace{1cm} (14)

$$p(N_B) = \left( \frac{A}{N_B} \right) p^{N_B} (1 - p)^{A - N_B}.$$  \hspace{1cm} (15)

Here we have assumed that the initial many-nucleon distribution function can be approximately expressed as a product of one-nucleon distribution functions, i.e. the momenta and spatial positions of nucleons are uncorrelated. Next, one can take the number of spectators in the projectile as independent of the number of spectators in the target. This is not exactly true: e.g. if there are participants from one nucleus then there were reactions between the colliding nucleons, and there should also be participants from the other nucleus. This implies that, for a fixed number, $N_A$, of spectators in projectile nucleus we can expect the number of spectators, $N_B$, in target nucleus to fluctuate around the value $(N_B) \approx N_A$. Analogous statement can be found in Ref. 11, where this subject was analyzed within the microscopic transport models. So, the numbers of spectators from different nuclei are not fully uncorrelated. Meanwhile, for the sake of simplicity, we assume that the number of spectators in the projectile is independent of the number of spectators in the target. But we can expect this approximation to work well if we have colliding heavy ions with large mass numbers. Using this approximation we can write

$$p(N_A, N_B) \approx p(N_A) p(N_B).$$  \hspace{1cm} (16)
approximation of Poisson distribution is applicable. In our case these conditions are the following: the average numbers, which determines the conditions when the Gaussian solid red line indicates the lower threshold value for these (dotted green line) and participants (dashed blue line). The (b) The same dependence of the average number of spectators impact parameter for Pb+Pb collisions at large enough, e.g. momentum of spectators, the rapidity is defined solelycrete set of values. Because we neglect the smearing of \( N_p \) for some conditions the binomial distributions discontinuous rapidity distribution if we allow the quantities\( \text{discrete sets of values. It is possible to obtain a contin-} \)

As mentioned above, in our approach \( y^P \) takes discrete set of values. Because we neglect the smearing of momentum of spectators, the rapidity is defined solely by the spectator numbers, \( N_A \) and \( N_B \), which so far take discrete sets of values. It is possible to obtain a continuous rapidity distribution if we allow the quantities \( N_A \) and \( N_B \) to take continuous values. It is well known that for some conditions the binomial distributions \( p(N_A) \) and \( p(N_B) \) can be accurately approximated by the Gaussian distribution with mean \( Ap \) and variance \( Ap(1-p) \) as

\[
p(N_{A(B)}) \Rightarrow N_{A(B)} = \frac{\exp \left( -\frac{(N_{A(B)}-Ap)^2}{2Ap(1-p)} \right)}{\sqrt{2\pi Ap(1-p)}}. \tag{17}
\]

In our case these conditions are the following: the average spectator and participant numbers \( Ap \) and \( A(1-p) \) are large enough, e.g. \( Ap > 5 \) and \( A(1-p) > 5 \). It is seen from Fig. 2 that these conditions are quite well satisfied in our model for heavy ions, especially for non-central collisions. Using the Gaussian approximation we can write the rapidity distribution function as

\[
f_P(y) = \int_0^A dN_A \int_0^A dN_B \rho(N_A) \rho(N_B)
\times \delta \left[ y - y_P(N_A, N_B) \right]
= \int_{-\infty}^{\infty} dN_A \int_{-\infty}^{\infty} dN_B \tilde{\rho}(N_A) \tilde{\rho}(N_B)
\times \delta \left[ y - y_P(N_A, N_B) \right], \tag{18}
\]

where to switch to infinite integration limits we introduce

\[
\tilde{\rho}(N_{A(B)}) = \rho(N_{A(B)}) \theta(A - N_{A(B)}) \theta(N_{A(B)}). \tag{19}
\]

Let us now define the new variables:

\[
N = \frac{1}{2} (N_A + N_B), \quad n = N_B - N_A,
\]

\[
f_P(y) = \int_{-\infty}^{\infty} dN \int_{-\infty}^{\infty} dn \tilde{\rho}(N + n/2) \tilde{\rho}(N - n/2)
\times \delta \left[ y - \arctanh \left( \frac{n}{2(A - N)} v_1 \right) \right]. \tag{20}
\]

Then we make a transformation to a new variable in the \( \delta \)-function in accordance with the rule: \( \delta[y - f(u; N)] = \delta[n - F(y; N)]/|f'(\bar{\tau})| \), where

\[
\bar{\tau} = F(y; N) = \frac{1}{v_1} 2(A - N) \tanh y. \tag{21}
\]

After introducing \( f'(\bar{\tau}) \) explicitly, the rapidity distribution becomes

\[
f_P(y) = \int_{-\infty}^{\infty} dN \tilde{\rho}(N + \bar{\tau}/2) \tilde{\rho}(N - \bar{\tau}/2) \frac{2(A - N)}{v_1 \cosh^2 y}. \tag{22}
\]

In order to compute the integral in \( (22) \) we will use the following approximation

\[
\tilde{\rho}(N \pm \bar{\tau}/2) \approx \rho(N \pm \bar{\tau}/2). \tag{23}
\]

This approximation works well in the case when the original binomial distribution \( (15) \) is well approximated by the Gaussian \( (17) \). The presence of the Gaussian allows one to neglect the Heaviside theta functions in the integration in \( (22) \), which we perform using expression \( (17) \) for \( \rho(N \pm \bar{\tau}/2) \) and obtain

\[
f_P(y) = \frac{A(1-p)}{\pi p} v_1^2 \exp \left[ -\frac{A(1-p)}{p} \frac{\tanh^2 y}{v_1^2 + \tanh^2 y} \right] \cosh^2 y \left[ v_1^2 + \tanh^2 y \right]^{\frac{1}{2}}. \tag{24}
\]
comes
With these approximations the rapidity distribution becomes close to 1, which allows us to write (tanh since we deal with relativistic collision energies

\[
\frac{\delta y^2}{\langle y^2 \rangle} \approx \frac{1}{1 + \tanh^2 y}.
\]

This is actually a Gaussian distribution around \( y = 0 \) with variance

\[
\delta y^2 = \frac{p v^2}{2A(1 - p)}.
\]

The expression for the variance gives the following result: rapidity fluctuations are stronger for higher nucleon spectator probability \( p \), i.e. they are increasing with the increase of impact parameter. For \( p = 0 \) there are no spectators in the system and therefore collider c.m.s. and participant c.m.s. coincide. This result is reproduced by Eq. \( 26 \) in our model.

The dependence of standard deviation, \( \sqrt{\delta y^2} \), given by this Gaussian distribution on collision impact parameter for Pb+Pb collisions at \( \sqrt{s} = 2.76 \) TeV is depicted in Fig. 4. It is seen that the standard deviation of rapidity (which is basically a distribution width) stays significantly smaller than 1, hence justifying our approximation of rapidity distribution for small values of \( y \). We can expect the total rapidity distribution given by the Gaussian in Eq. \( 26 \) to work well for most conditions in heavy-ion collisions.

Expression \( 27 \) for \( \sqrt{\delta y^2} \) can be rewritten in terms of mass number \( A \) and average number of participants, \( N_p = A(1 - p) \). It reads as

\[
\delta y^2 = \frac{\frac{1}{2}}{N_p} \frac{1}{A}.
\]

It is interesting to explore the dependence of rapidity fluctuations on the average number of participants \( N_p \) for different pairs of colliding nuclei \( A + A \). This dependence is depicted in Fig. 4 for Pb+Pb, In+In, S+S and C+C collisions. There we take the initial nucleon velocity, \( v_1 = 1 \), since just ultra-relativistic collision energies are considered. Notice that, for fixed average number of participants, \( N_p \), the rapidity fluctuations are stronger in
collisions of heavier nuclei. For instance, if we consider central collisions of light nuclei, then the rapidity fluctuations in "equivalent" non-central collisions of heavier nuclei will be bigger. Here "equivalent" means that in both colliding systems the average number of participants, $N_p$, is the same. Similar amplification of fluctuations with respect to the mass number was obtained in Ref. [10].

III. CALCULATION RESULTS

Let us calculate the participant c.m. rapidity distribution for various collision conditions. The dependence of nucleon spectator probability $p$ from (18) on the impact parameter was considered in section II. This dependence for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is depicted in Fig. 2a. It is seen that the nucleon spectator probability strongly depends on the centrality of the collision: it is small, but non-zero for central collisions, about 0.5 for mid-central collisions, and closer to unity for peripheral collisions.

Next, we will explore the participant c.m. rapidity distribution for different centralities but for the same collision energy on the participant c.m. rapidity fluctuations. To do that we consider Pb+Pb collisions at three different energies: $\sqrt{s_{NN}} = 6.41$ GeV ($E_{\text{kin}} = 20$ GeV), $\sqrt{s_{NN}} = 17.32$ GeV ($E_{\text{kin}} = 158$ GeV) and $\sqrt{s_{NN}} = 2.76$ TeV. The first two energies correspond to CERN-SPS experiments and the third one to the CERN-LHC experiment. We take $\sigma_{NN} = 33$ mb for both SPS energies and $\sigma_{NN} = 70$ mb for LHC energy. The calculation results for different energies for peripheral collisions ($b = 9.5$ fm) are presented in Fig. 3.

We can see that the collision energy influence on participant c.m. rapidity fluctuations is rather weak, especially compared to the centrality dependence. This can be explained by the fact that for high energies the rapidity distribution is well described in the ultra-relativistic limit [25], and the difference between LHC energy and SPS energies is due to doubling of the nucleon-nucleon cross section which still does not lead to a significant change in rapidity fluctuations.

A. Other Theoretical Estimates

Longitudinal fluctuations arising from initial state fluctuations in the PACIAE parton and hadron molecular dynamics model were analyzed recently [11], and the fluctuation of the center-of-mass rapidity of the system was conservatively estimated to be $\Delta y^{c.m.} = 0.1$, by neglecting all pre-equilibrium emission effects that increase the

![FIG. 5. Participant center-of-mass rapidity distribution for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for three different centralities.](image)

![FIG. 6. Participant center-of-mass rapidity distribution for peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 6.41$ GeV ($E_{\text{kin}} = 20$ GeV), $\sqrt{s_{NN}} = 17.32$ GeV ($E_{\text{kin}} = 158$ GeV) and $\sqrt{s_{NN}} = 2.76$ TeV.](image)
y^{c.m.}-fluctuations.

The unique separation of participants and spectators in realistic situations is not trivial. Between the participants and spectators some level of interaction may remain at the separation, and a small number of nucleons cannot be classified definitely as either participants or spectators. This indefiniteness may result in increase or decrease of $y^{c.m.}$-fluctuations. Longitudinal fluctuations may influence other observables also [12, 13].

Next we will compare our model calculations with corresponding calculations within the UrQMD microscopic transport model [14, 15]. The EbE c.m. rapidity can be computed in UrQMD using Eq. (3). There we can account for the Fermi motion as well as for initial nucleon correlations, however, a large number of simulated UrQMD events are necessary to obtain smooth distribution. The comparison of the participant c.m. rapidity distribution calculated within our model and with the UrQMD model for Pb+Pb collisions at $\sqrt{s_{NN}} = 17.32$ GeV ($E_{\text{kin}} = 158$ GeV) with $\sigma_{NN} = 33$ mb for peripheral collisions ($b = 9.5$ fm) is presented in Fig. 7.

One can see that there is a difference in the distributions calculated within these two models, the distribution from UrQMD is wider. The difference is relatively small compared to the difference arising from changing the collision centrality (see Fig. 5). The difference, which is seen in Fig. 7 can be attributed to neglecting the initial many-nucleon correlations as well as the spectator number correlations for nucleons from the colliding nuclei, which were assumed in our model. It could also be questioned whether nucleons, which did not take part in any reaction in UrQMD may be correctly identified as spectators in the Glauber-Sitenko approach.

The separation of spectators from participants is studied in Ref. [16]. Here the pre-equilibrium emission of one or two nucleons plays a non-negligible role. The (thermal) equilibration is demonstratively not present for particles, which interacted fewer than 4-6 times. These cannot be considered as parts of a participant system, and usually have large longitudinal and small transverse momenta, although these do not reach the Zero Degree Calorimeters, so experimentally these are not identified as spectators. Similar considerations were used to describe the strangeness enhancement within the core-corona picture [17], where nucleons which have scattered only once were regarded as corona nucleons and were not part of a fireball. In central and semi-peripheral reactions these pre-equilibrium particles may influence the $y^{c.m.}$-fluctuations considerably. For example, if we exclude nucleons from the participant system which collided less than six times, $M < 6$, then in central collisions the center-of-mass rapidity fluctuation doubles, see Fig. 8. However, there is little change in rapidity distribution in case of peripheral collisions (Fig. 8b).
B. Participant angular momentum

The model also provides an estimate of the total angular momentum of the initial participant system. The angular momentum, $L_{\text{tot}}^P$, of the participant system can be calculated as the difference of total angular momentum, $L_{\text{tot}}$, and the angular momentum of spectators, $L_{\text{tot}}^S$. The quantities $L_{\text{tot}}$ and $L_{\text{tot}}^S$ can be calculated with the use of nuclei thickness functions $T_{A(B)}(x,y)$ and using the transverse distribution of spectators $T_{A(B)}^S(x,y)$ as

$$L_{\text{tot}} = p_i^A \int dx dy x [T_A(x - b/2, y) - T_B(x + b/2, y)],$$
$$L_{\text{tot}}^S = p_i^B \int dx dy x [T_A^S(x, y) - T_B^S(x, y)],$$
$$L_{\text{tot}}^P = L_{\text{tot}} - L_{\text{tot}}^S.$$

The transverse distribution of spectators can be determined from the Glauber-Sitenko model as \[11\]. Another approach is to consider as participants all nucleons in the overlap region of colliding nuclei \[1, 2, 18, 19\].

First of all the angular momentum for LHC Pb+Pb reactions at $\sqrt{s_{NN}} = 2.76$ TeV is about two orders of magnitude larger than that at SPS energy of at $\sqrt{s_{NN}} = 17.32$ GeV (see Fig. 9) and one order of magnitude larger than for Au+Au reactions RHIC energy of $\sqrt{s_{NN}} = 200$ GeV \[19\].

The angular momentum is the largest for nuclei with a Woods-Saxon radial density profile, see Eq. \[12\], due to the presence of the diffusion zone with a tail, which effectively increases angular momentum. For nuclei with homogeneous nuclear density where the density profile has a sharp boundary we consider all nucleons from the overlap region as participants and all other nucleons as spectators (Hard Sphere Nuclei). In this case the angular momentum is about a factor of two less than for a Woods-Saxon profile (see Fig. 9).

If, in addition, a transparency in the overlap region is assumed due to the finite NN cross section (Soft Sphere Nuclei) then the angular momentum is further reduced by 2% and 15% at LHC and SPS energies, respectively (see Fig. 9).

Thus, in fluid dynamical and in molecular dynamics models, the assumed initial state leaves some freedom for the angular momentum of the participant system.

IV. CONCLUSIONS

A simple model to calculate the participant c.m. rapidity distribution is developed and used to analyze the rapidity fluctuations for different conditions in heavy-ion collisions. In the model a weak initial nucleon-nucleon correlation in colliding nuclei and weak correlations between spectator numbers from different nuclei are assumed and the interaction between spectators and participants is neglected. The main input parameter in the model is the probability for a nucleon to be a spectator, which is determined from the Glauber-Sitenko approach in the current work. Different models for calculating this probability are applicable.

It is shown that for small rapidity values the rapidity distribution can be well approximated by the Gaussian distribution with variance determined by the nucleon spectator probability and by initial nucleon velocities. The calculation results confirm that this approximation works well in a wide range of collision energies and centralities.

It is shown that rapidity fluctuations strongly depend on impact parameter – they are stronger for more peripheral collisions and these fluctuations should be taken into account in calculation and interpretation of various rapidity-dependent observables \[6\]. It is necessary to note that, if we consider collisions of two different pairs of nuclei, for instance $A_1 + A_1$ and $A_2 + A_2$ with $A_1 > A_2$, where the number of participants is the same in both collisions, then the rapidity fluctuations are smaller in collisions $A_2 + A_2$ of lighter nuclei. Recent studies \[6\] indicate a possibility of experimental measurement of the $y^{\text{c.m.}}$ fluctuations.

The collision energy dependence of rapidity fluctua-
tions appears to be weak. Comparison with similar c.m. rapidity distribution calculations within the UrQMD model shows qualitative agreement, however, some indefiniteness in identification of spectators and participants, for instance pre-equilibrium emission of nucleons, may lead to extra sources of participant c.m. fluctuations, especially at more central collisions.

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