Effects of longitudinal asymmetry in heavy-ion collisions

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In collisions of identical nuclei at a given impact parameter, the number of nucleons participating in the overlap region of each nucleus can be unequal due to nuclear density fluctuations. The asymmetry due to the unequal number of participating nucleons, referred to as longitudinal asymmetry, causes a shift in the center-of-mass rapidity of the participant zone. The information of the event asymmetry allows us to isolate and study the effect of longitudinal asymmetry on rapidity distribution of final state particles. In a Monte Carlo Glauber model the average rapidity shift is found to be almost linearly related to the asymmetry. Using toy models, as well as Monte Carlo data for Pb-Pb collisions at 2.76 TeV generated with HIJING, two different versions of AMPT and DPMJET models, we demonstrate that the effect of asymmetry on final state rapidity distribution can be quantitatively related to the average rapidity shift via a third-order polynomial with a dominantly linear term. The coefficients of the polynomial are proportional to the rapidity shift with the dependence being sensitive to the details of the rapidity distribution. Experimental estimates of the spectator asymmetry through the measurement of spectator nucleons in a zero-degree calorimeter may hence be used to further constrain the initial conditions in ultra-relativistic heavy-ion collisions.

I. INTRODUCTION

In collisions of heavy ions the geometrically overlapping region created by interacting nucleons from each nucleus is called the participant zone. Even at fixed impact parameter, the number of participating nucleons from each nucleus fluctuates around the mean due to fluctuations in the positions of the nucleons around the mean nuclear density profile. Event by event, the participant zone therefore has a net nonzero momentum in the nucleon-nucleon center-of-mass (c.m.) frame, and hence its rapidity is shifted with respect to the c.m. frame, and is denoted by y_0 [1].

Experimental data and simulated data from different event generators show that the total produced particle multiplicity, measured over a wide phase space region, scales approximately with the number of participants [2,3]. The observed N_{part} scaling indicates that the number of participants or wounded nucleons is a relevant parameter affecting the production and distribution of produced particles even at LHC energies. Fluctuations of the fireball shape in the longitudinal direction are expected to create nontrivial rapidity correlations, as explicitly demonstrated using the wounded nucleon model [4]. The different components of the fluctuating fireball shape suggested in Ref. [4] were recently extracted from the measured two-particle rapidity correlations [5].

The distribution of charged particles averaged over a large number of events in collisions of identical nuclei is observed to be symmetric about the rapidity of the nucleon-nucleon c.m. frame. The observed forward-backward asymmetry in collisions of nonidentical nuclei d-Au [6] and p-Pb [7] has been argued to be due to the shift of the rapidity of the participant zone. An unequal number of participants in a collision of two identical nuclei produces a shift of the participant zone. This shift can be observed by measuring asymmetry in the energy of the zero-degree calorimeters on either side of the interaction vertex, even though its estimate in central collisions is marred by large relative fluctuations; the measurement of shift may facilitate to separate the effect of fluctuations on various observables [8]. Preliminary results of the ALICE Collaboration show a difference between pseudorapidity distribution of charged particles in Pb-Pb collision events of different asymmetries, as estimated from the measurement of spectator neutrons in the neutron zero-degree calorimeters [9]. Simulations based on a fluid dynamical framework demonstrate the effect of longitudinal fluctuations on the azimuthal anisotropy coefficients and their rapidity dependence; a significant decrease in the values of $v_1(y)$, and a wide plateaulike behavior for $v_2(y)$, both near midrapidity, has been estimated due to the event-by-event fluctuations affecting the rapidity of the participant zone, the latter being a conserved quantity [10]. The similar transverse-momentum dependence of the rapidity-even directed flow and the corresponding estimate from two-particle correlations at midrapidity indicate a weak correlation between fluctuating participant and spectator symmetry planes and suggest the possibility of using the spectator nucleons to further determine and constrain the effect of initial conditions [11]. This possibility has recently been further explored by model studies using AMPT [12].

It has been argued that the vorticity arising due to the initial state angular momentum may survive the evolution process in

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a low viscosity state of quark-gluon plasma and may manifest in the rapidity dependence of directed flow, $v_1(y)$; however, its observability is affected by initial state fluctuations necessitating the requirement to determine the event-by-event center of mass [13]. The need for determination of the event-by-event center-of-mass rapidity is also highlighted by the possible observation of Λ polarization in the c.m. frame, which may confirm attainment of local thermodynamical equilibrium and persistence of vorticity until freeze-out of the expanding matter [14,15]. The observation of Λ polarization at the Relativistic Heavy Ion Collider requires that the models describing the evolution of heavy-ion collisions incorporate the effect of large vorticity, thereby providing a complete characterization of the system necessary to understand the dynamics of quarks and gluons in extreme conditions [16].

In the present work, we investigate the possible effect of the net (nonzero) momentum of the participant zone on experimentally measurable distributions of produced particles by exploring possible correlations between the participant asymmetry and the distribution of particles in the kinematic phase space. Events of the same net momentum can be selected by classifying events on the basis of measured asymmetry in spectators for any centrality. The rapidity distribution of events of any asymmetry class is studied relative to corresponding distribution of another asymmetry class. The method has the advantage that most experimental uncertainties and corrections affecting the single particle distributions are canceled. All variables used to develop this analysis can be estimated experimentally.

The paper is organized as follows. The rapidity shift of the participant zone due to asymmetry of the event is discussed in Sec. II. The effect of a rapidity shift is estimated using a toy model on a Gaussian rapidity distribution and is discussed in Sec. III. Section IV. discusses the effect on various charged particle rapidity distributions for variable rapidity shifts as calculated using Glauber model. The results of the present work are summarized in Sec. V.

II. RAPIDITY SHIFT OF PARTICIPANT ZONE

If the numbers of nucleons participating from the two colliding nuclei are A and B, respectively, then the participant zone has a net momentum in the nucleon-nucleon c.m. frame. The net momentum corresponds to a shift in the rapidity of the participant zone, which can be approximated as

$$y_0 \cong \frac{1}{2} \ln \frac{A}{B}. \qquad (1)$$

Assuming each of the A (B) nucleons has a fixed momentum p ($-p$), Eq. (1) is obtained using the sum of four-momentum vectors $(0,0,Ap,AE)$ and $(0,0,-Bp,BE)$, with $E^2 = m_0^2 + p^2$, and neglecting $m_0 \ll p$. Since at the LHC in the TeV scale $m_0/p < 10^{-6}$, we replace the "$\cong$" sign by the equality sign hereafter.

Defining the asymmetry of participants for each event as $\alpha_{\text{part}} = \frac{A-B}{A+B}$, the rapidity shift y_0 can be written as

$$y_0 = \frac{1}{2} \ln \frac{1 + \alpha_{\text{part}}}{1 - \alpha_{\text{part}}} \qquad (2)$$

TABLE I. Centrality classes defined by impact parameter as well as corresponding $\langle N_{\text{part}} \rangle$ and $\langle |y_0| \rangle$ values.

Centrality	$b_{\min}$ (fm)	$b_{\max}$ (fm)	$\langle N_{\text{part}} \rangle$	$|y_0|$
0–5%	0.0	3.61	383.9	0.0144
5–10%	3.61	5.12	330.0	0.0263
10–15%	5.12	6.27	280.2	0.0352
15–20%	6.27	7.24	236.5	0.0431
20–25%	7.24	8.09	198.5	0.0512
25–30%	8.09	8.86	165.5	0.0589
30–35%	8.86	9.57	136.5	0.0678
35–40%	9.57	10.23	110.2	0.0777
40–45%	10.23	10.85	88.6	0.0887
45–50%	10.85	11.43	70.2	0.1012
50–55%	11.43	11.99	54.6	0.1155
55–60%	11.99	12.52	41.6	0.1326
60–65%	12.52	13.03	31.0	0.1528
65–70%	13.03	13.52	22.5	0.1764

and has a unique correspondence with α_{part}. For small α_{part}, the shift follows $y_0 \cong \alpha_{\text{part}}$. The unequal number of nucleons in the participant zone implies an unequal number of spectators of the two colliding nuclei, $N - A$ and $N - B$, respectively, where N is the total number of nucleons in each nucleus. The spectator asymmetry $\alpha_{\text{spec}} = \frac{(N-A)-(N-B)}{(N-A)+(N-B)} = \frac{B-A}{2N-(A+B)}$ is related to the participant asymmetry via $\alpha_{\text{spec}} = -\alpha_{\text{part}} \frac{A+B}{2N-(A+B)}$. Finally, the rapidity shift y_0 is related to the spectator asymmetry as

$$y_0 = \frac{1}{2} \ln \frac{(A+B)(1+\alpha_{\text{spec}}) - 2N\alpha_{\text{spec}}}{(A+B)(1-\alpha_{\text{spec}}) + 2N\alpha_{\text{spec}}}, \qquad (3)$$

which is accessible to experiment. Unlike the unique correspondence between α_{part} and y_0, the presence of the $(A+B)$ term in Eq. (3) leads to a distribution of y_0 for a given value of α_{spec}, even at fixed impact parameter or centrality.

The rapidity shift y_0 [Eq. (1)] as well as its dependence on α_{part} [Eq. (2)] and α_{spec} [Eq. (3)] can be calculated within a Monte Carlo Glauber (MCG) framework [17], as implemented in Refs. [18,19] or in Ref. [20]. In the present work, we have generated 1.2 million minimum bias events of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using HIJING (version 1.383) [20] with default settings. The generated impact parameter (b) is used to define the event centrality. Limits on b used for 5%-wide centrality intervals with corresponding $\langle N_{\text{part}} \rangle$ are provided in Table I. The mean number of participants provides an estimate of the order of magnitude of the rapidity shift. Assuming that the number of nucleons from each of the two nuclei fluctuate by their root mean square while retaining the total number to be equal to N_{part}, the resulting value of rapidity shift for the most central class of events would be ≈ 0.05. In practice, events in any centrality class will have a distribution peaked at zero. The distributions of y_0, α_{part}, and α_{spec} calculated with the HIJING MCG framework are shown in Fig. 1 for three centrality classes along with a Gaussian fit for each. The width of the y_0 distribution increases with decreasing centrality; i.e., for larger impact parameters the relative fluctuations increase since the number of participants decreases. Events can be
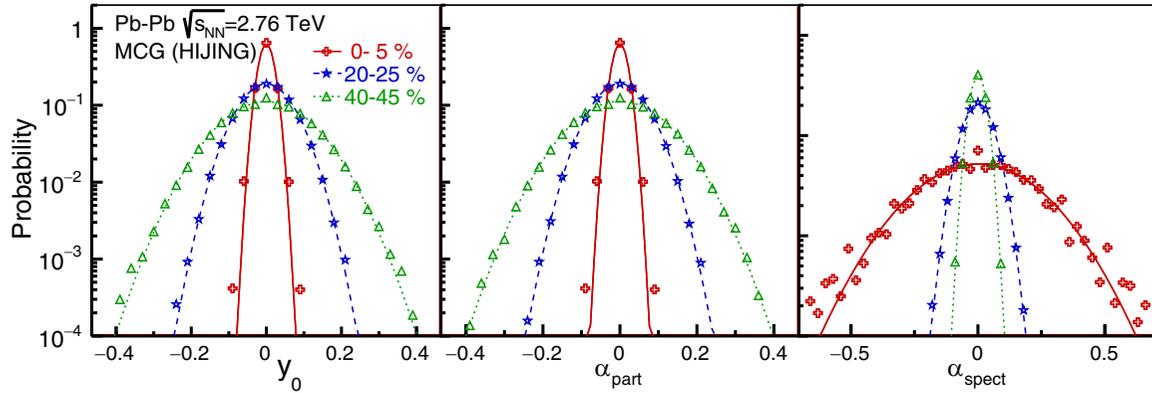
FIG. 1. The distributions of the participant-zone rapidity shift y_0 (left panel), of the participant asymmetry α_{part} (middle panel), and of the spectator asymmetry α_{spec} for 0–5%, 20–25%, and 40–45% Pb-Pb centrality classes calculated with the HIJING MCG model.

classified according to their rapidity shift: $y_0 < 0$ are events of negative asymmetry (−asym) and $y_0 > 0$ are events of positive asymmetry (+asym). For each centrality class, the mean value of $|y_0|$ is also reported in Table I. The increase of $|y_0|$ with decreasing collision centrality is in agreement with results obtained earlier [1]. The α_{part} distributions are nearly identical to the y_0 distributions, while the α_{spec} distributions are different. The widths of the α_{spec} distributions increase with increasing centrality; i.e., the relative fluctuations increase with decreasing number of spectator nucleons.

Figure 2 displays event-by-event distributions of y_0 versus α_{part} and α_{spec}, respectively, obtained for the 20–25% Pb-Pb centrality class with the HIJING MCG model. The unique correspondence between y_0 and α_{part} is illustrated in the left-hand panel of Fig. 2. The lack of a unique relation between y_0 and α_{spec} due to the presence of the $(A + B)$ term in Eq. (3) leads to a distribution of y_0 for a given value of α_{spec}, even at fixed impact parameter or centrality, as illustrated in the right-hand panel of Fig. 2. It can be regarded as the response matrix to obtain the values of $\langle y_0 \rangle$ for a given range of α_{spec}. The mean values $\langle y_0 \rangle$ as a function of the α_{spec} asymmetry are shown in Fig. 3 for three different centralities for 0–5%, 20–25%, and 40–45% Pb-Pb centrality classes calculated with the HIJING MCG model.

If the experiments could measure the number of nucleons in the participant zone, A and B, the participant-zone rapidity shift y_0 could be determined for each collision. However, neither A and B nor α_{part} is directly amenable to experimental measurement. The asymmetry α_{spec} can be estimated by measuring the number of spectator nucleons through their energy deposited in the zero-degree calorimeters on either side of the interaction vertex in collider experiments [8]. Using unfolding methods and the estimated values of α_{spec}, one can obtain an estimate of $\langle y_0 \rangle$, e.g., by using the response matrix in the right-hand panel of Fig. 2. Almost all estimates of y_0 based on Glauber-like models will show similar results even if there are differences in details. The ALICE experiment has determined a response matrix using information on the number of neutrons in the spectator and also using the energy deposited in the zero-degree calorimeter, where a Glauber Monte Carlo model has been tuned to reproduce the energy distributions in neutron zero-degree calorimeters [21].

FIG. 2. Event-by-event distributions of y_0 versus α_{part} (left panel) and y_0 versus α_{spec} (right panel) for the 20–25% Pb-Pb centrality class calculated with the HIJING MCG model.
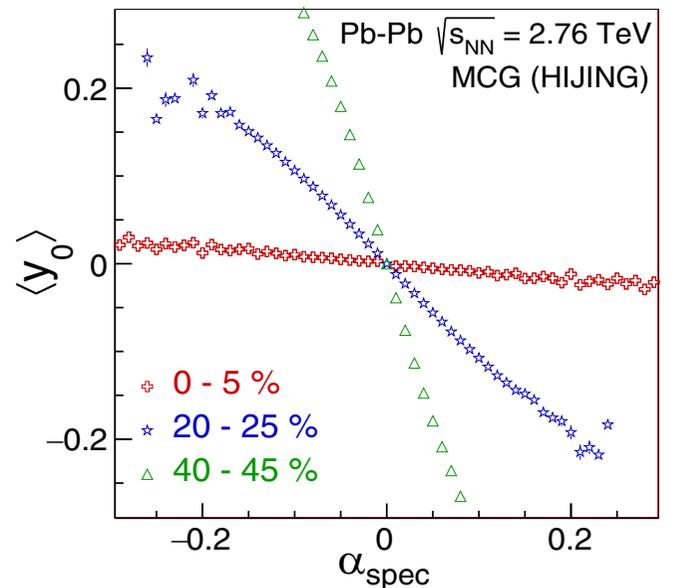
FIG. 3. The mean participant-zone rapidity shift $\langle y_0 \rangle$ versus α_{spec} for 0–5%, 20–25%, and 40–45% Pb-Pb centrality classes calculated with the HIJING MCG model.

III. CONSTANT RAPIDITY SHIFT AND GAUSSIAN CHARGED PARTICLE RAPIDITY DISTRIBUTION

The measured rapidity distribution of charged particles produced in collisions of identical nuclei can be described by distributions which are symmetric about the c.m. rapidity [2,3]. A Gaussian form is among the more common distributions used to describe data. We assume that the particles produced in asymmetric collisions of identical nuclei are also distributed symmetrically in the c.m. frame of the participant zone. Considering that the rapidity of the participant zone is shifted by y_0 from the rapidity of the nucleon-nucleon c.m. system, a symmetric distribution in the participant zone will appear as a shifted distribution in the nucleon-nucleon c.m. frame, which is also the laboratory frame for most collider experiments. For fixed y_0, the rapidity distributions of produced particles can be written as a Gaussian distribution of width σ:

$$\frac{dN}{dy} = N_0 \exp\left(-\frac{(y - y_0)^2}{2\sigma^2}\right). \quad (4)$$

For symmetric collisions $y_0 = 0$, while for longitudinally asymmetric collisions y_0 is finite. The positive and negative values of y_0 correspond to the net momentum of the participant zone in the positive and negative directions, respectively, causing positive and negative participant (α_{part}) asymmetries, respectively. Taking the ratio of single particle rapidity distributions of different asymmetry classes will eliminate the uncertainties arising due to experimental corrections and fluctuations affecting event-by-event distribution. The ratio of the rapidity distribution of particles in collisions with positive asymmetry to the distribution in collisions of negative asymmetry yields

$$\frac{\left(\frac{dN}{dy}\right)_{+\text{asym}}}{\left(\frac{dN}{dy}\right)_{-\text{asym}}} = \exp\left(\frac{4yy_0}{\sigma^2}\right) = \sum_{n=0}^{\infty} c_n^g(y_0, \sigma)y^n, \quad (5)$$

where $c_n^g = (4y_0/\sigma^2)^n/n!$ are the coefficients of the Taylor expansion of the exponential function, and the superscript g of the coefficients stands for the Gaussian shape of the parent rapidity distribution. The coefficients depend upon the parameters of the parent rapidity distribution and on the rapidity shift y_0. These parameters are effectively fixed by selecting events on the basis of centrality and asymmetry. For typical values of y_0 equal to 0.1 and σ equal to 3.6, the ratio $\frac{c_2^g}{c_1^g} \sim 0.015$ and the ratio $\frac{c_3^g}{c_1^g} \sim 0.00015$ with subsequent terms having negligible contribution to the values of the function describing the ratio of the two rapidity distributions. Hence, for a Gaussian rapidity distribution, where the relation between the shift of the participant-zone rapidity and the coefficients c_n are analytically known, the dominant contribution can be expected for the linear term. The linear term is related to the rapidity shift via $y_0 = \frac{c_1^g \sigma^2}{4}$.

These results have been validated using a toy model simulation by generating Gaussian rapidity distributions which are shifted by a constant magnitude. The top panel of Fig. 4 shows two rapidity distributions for $\sigma = 3.6$ shifted by $y_0 \pm 0.1$. The unshifted distribution would obviously lie in between the two distributions and is not drawn. The bottom panel of Fig. 4 shows the ratio of $\frac{dN}{dy}$ distributions for events with $y_0 = +0.1$
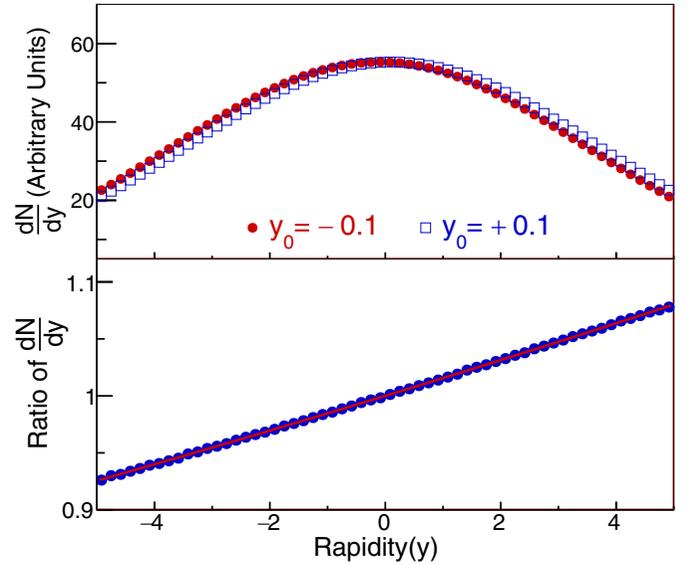
FIG. 4. Top: Gaussian $\frac{dN}{dy}$ distributions for $\sigma = 3.6$ shifted by $y_0 \pm 0.1$ obtained by the toy model. Bottom: Ratio of the $\frac{dN}{dy}$ distributions fitted to a third-order polynomial. The coefficients are 0.015, 1.1×10^{-4}, and 2.2×10^{-7}, respectively, with $\chi^2/\text{dof} = 125/117$.

to those with $y_0 = -0.1$, and the ratio is fitted to a third-order polynomial. The coefficient of the linear term is dominant, with the other coefficients smaller by two and four orders of magnitude, respectively, as expected from Eq. (5). The same calculation is repeated for different values of the shift y_0 to obtain the coefficients of the third-order polynomial fit as a function of y_0, as shown in Fig. 5. The dependence of the coefficients on the rapidity shift known from Eq. (5) is indicated with dashed lines, and agrees very well with the numerical calculation. The figure demonstrates that the
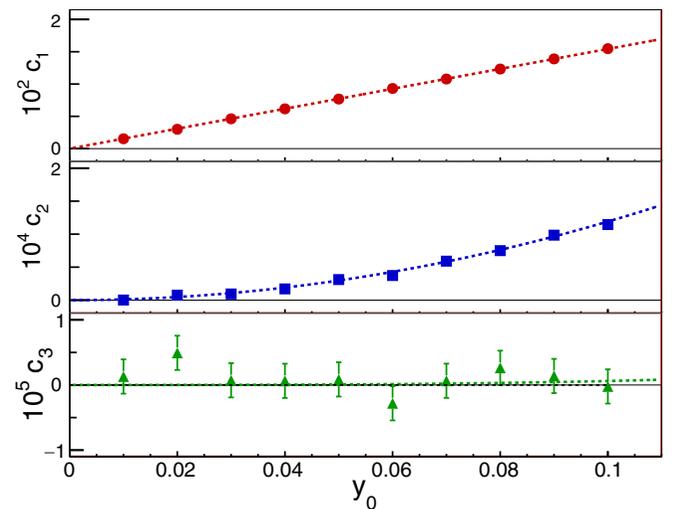
FIG. 5. The dependencies of c_1^g, c_2^g, and c_3^g on y_0 for fixed $\sigma = 3.6$ obtained by the toy model. Dashed lines correspond to analytical functions of the coefficients from Eq. (5).

dominant contribution to the $\frac{dN}{dy}$ ratio arises from the first coefficient, which is linearly related to the rapidity shift y_0.

IV. VARIABLE SHIFT AND VARIOUS CHARGED PARTICLE RAPIDITY DISTRIBUTIONS

In the previous section we discussed the relation of coefficients of the third-order polynomial fit to the ratio of $\frac{dN}{dy}$ distributions, assuming that the $\frac{dN}{dy}$ distributions are Gaussian in nature, and that all events have the same value of y_0. In the following, the values of y_0 for different events are chosen according to the distribution of y_0 from the HIJING MCG model, as shown for a few centrality classes in the left-hand panel of Fig. 1. As before, the rapidity distribution of particles $\frac{dN}{dy}$ is generated using a toy simulation taking into account event by event the rapidity shift y_0.

In addition to a Gaussian shape for the rapidity distribution, inspired by the possibility of a double Woods-Saxon distribution [22], or a Woods-Saxon-like distribution [2], we also consider that the rapidities of produced particles be described by a Woods-Saxon distribution:

$$\frac{dN}{dy} = N_0 \frac{1}{1 + \exp\left(\frac{|(y - y_0)| - a}{c}\right)}, \quad (6)$$

where $y_0 = 0$ for symmetric events, y_0 is positive for events with positive asymmetry, and y_0 is negative for events with negative asymmetry. Taking the ratio of the $\frac{dN}{dy}$ for events of opposite asymmetry and making a Taylor expansion about

$y = 0$ yields a polynomial in y, which can be written as

$$\frac{\left(\frac{dN}{dy}\right)_{+\text{asym}}}{\left(\frac{dN}{dy}\right)_{-\text{asym}}} = \sum_{n=0}^{\infty} c_n^{\text{ws}}(y_0, a, c) y^n. \quad (7)$$

The coefficients c_n^{ws} depend on the shift in rapidity and the parameters of the Woods-Saxon distribution in a nontrivial way. For a given set of parameters, however, the dependence on the rapidity shift y_0 can be computed numerically.

We investigate the systematic effect of the rapidity shift on the coefficients characterizing the ratio of Gaussian and Woods-Saxon rapidity distributions for different asymmetry classes. Using the parametrized form of experimental η and p_T distributions in conjunction with the relative yield of pions, kaons, and protons [3,23], toy model simulations provide the rapidity distribution. This resulting $\frac{dN}{dy}$ distribution is fitted once to a Gaussian form and then to a Woods-Saxon form to obtain the values of the parameters. Using these values of the parameters and the y_0 distribution obtained from HIJING events (Fig. 1), the rapidity distributions are obtained separately for positive and negative values of y_0 corresponding to different centrality classes. The ratio of the two distributions is fitted to a third-order polynomial as shown in Fig. 6 for four centrality classes. In each case, the χ^2/dof are the smallest in the most central class and are about 0.64 and 0.83 for Gaussian and Woods-Saxon rapidity distributions, respectively.

To investigate the possible contribution originating from the dynamics of the particle production mechanism, or, in general, of any final state effects, the charged-particle rapidity
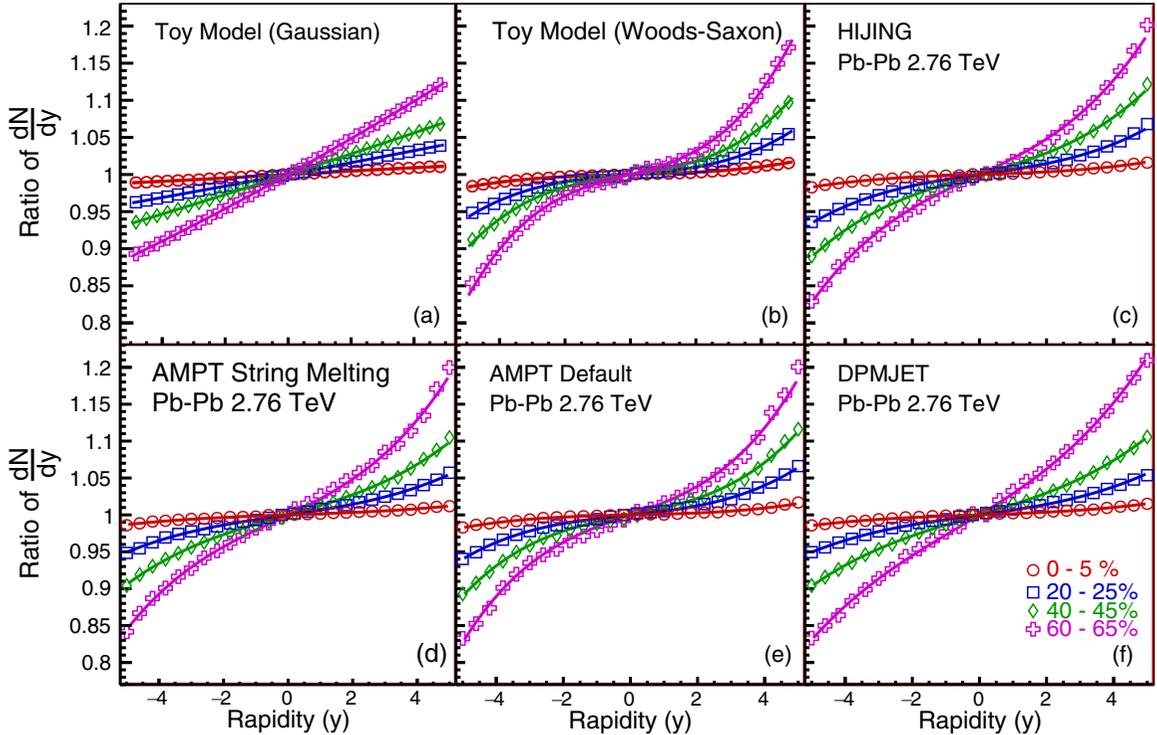
FIG. 6. The ratio of $\frac{dN}{dy}$ distributions for events with positive ($y_0 > 0$) and with negative ($y_0 < 0$) asymmetry. Rapidity distributions corresponding to (a) parametrized Gaussian form, (b) parametrized Woods-Saxon form, (c) HIJING, (d) AMPT (default), (e) AMPT (string melting), and (f) DPMJET (default). The ratios, along with fits to third-order polynomials, are shown for four centrality classes.
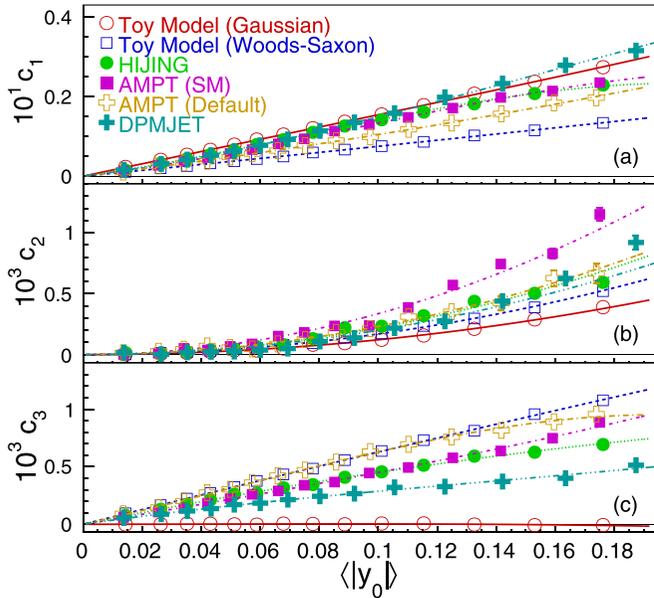
FIG. 7. The coefficients c_1, c_2, and c_3 of the third-order polynomial fit to the ratio of $\frac{dN}{dy}$ distributions versus $\langle|y_0|\rangle$ for the six forms of rapidity distributions. Polynomial fits are to guide the eye. The coefficients c_n demonstrate a dependence on $\langle|y_0|\rangle$. The rapidity distributions are obtained in 14 centrality intervals up to 70% centrality with corresponding $\langle|y_0|\rangle$ as given in Table I.

distribution obtained from some commonly used event generators was also used. We generated about 1.2 million events of HIJING and about 1 million events each of both versions of AMPT (default and string melting) [24], and of DPMJET [25] for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The rapidity shift y_0 is determined for each generated event from the number of participating nucleons from each of the two colliding nuclei. The average rapidity distributions corresponding to positive and negative values of y_0 are obtained. The ratio of these two rapidity distributions is fitted to a third-order polynomial to obtain the values of the coefficients. The ratios and the fits are shown in Fig. 6, along with the results for toy model simulations for parametrized rapidity distributions. The differences in the parent rapidity distributions manifest themselves in the ratios and the values of the coefficients in the polynomial.

For all rapidity distributions, the coefficients for the quadratic and cubic terms in the polynomial fitting of the ratio are much smaller than those of the linear term. The dependence of the first three coefficients c_n on the mean rapidity shift $\langle|y_0|\rangle$ is shown in Fig. 7. The six different rapidity distributions yield different dependence of the coefficients on $\langle|y_0|\rangle$, indicating the possibility of determining the details of the rapidity distribution from the knowledge of the behavior of the coefficients.

V. SUMMARY

In collisions of identical nuclei at a given impact parameter, the number of nucleons participating in the overlap region of each nucleus, estimated with a Monte Carlo Glauber model,

can be unequal due to nuclear density fluctuations (Fig. 1). The asymmetry due to the unequal number of participating nucleons causes a rapidity shift of the participant zone (Fig. 2), which may be experimentally accessible by measuring the energy of the spectator nucleons, as was also argued in Ref. [8]. The average rapidity shift has been found to be almost linearly related to the asymmetry (Fig. 3). The effect of the small rapidity shift in the rapidity distributions was estimated by taking the ratio of the distributions of events of positive and negative asymmetries. The success of the method was demonstrated by using a toy model to illustrate that such a ratio can effectively be described by a third-order polynomial (Fig. 4), where the coefficients are related to the rapidity shift and are shown for Gaussian rapidity distributions for constant rapidity shift (Fig. 5). The effect on the ratio of rapidity distributions for positive and negative asymmetry was systematically studied for Gaussian and Woods-Saxon particle rapidity distributions, using a toy model simulation and taking the distribution of y_0 from Fig. 1. The ratios and the polynomial fits are shown in Figs. 6(a) and 6(b). The possible effect of dynamics of particle production is investigated using the ratio of rapidity distributions for positive and negative asymmetries from different event generators. The ratios and the fitted polynomials for rapidity distributions obtained from HIJING, AMPT, and DPMJET models are shown in Figs. 6(c)–6(f) for four centrality classes. The ratios are sensitive to the detailed shape of the parent rapidity distribution (Fig. 6) and can be quantitatively described by a third-order polynomial with a dominantly linear term (Fig. 7). The relation between coefficients and the rapidity shift confirms that the effect of initial state longitudinal asymmetry survives through the particle production process and the subsequent evolution to the observed final state. Experimentally, estimates of the longitudinal asymmetry via measurements of the spectator asymmetry can be used to systematically investigate the influence of the longitudinal asymmetry on various observables, and hence may further constrain the initial conditions in ultra-relativistic heavy-ion collisions. Recent results from the ALICE Collaboration confirm that the longitudinal fluctuations affect the pseudorapidity distributions; the effect finds a simple explanation in terms of the rapidity shift of the participant zone and shows a sensitivity to the shape of the rapidity distribution [21]. As indicated in Sec. I, determination of an event-by-event c.m. frame may be necessary for a complete description of the evolution of heavy-ion collisions, to separate the effects of initial state fluctuations from the dynamical evolution. Further attempts to devise methods for the determination of the c.m. of the participant zone in each event, using experimentally measurable quantities, is under investigation.

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