Two-body nucleon-nucleon correlations in Glauber models of relativistic heavy-ion collisions

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We investigate the influence of the central two-body nucleon-nucleon correlations on several quantities observed in relativistic heavy-ion collisions. It is demonstrated with explicit Monte Carlo simulations that the basic correlation measures observed in relativistic heavy-ion collisions, such as the fluctuations of participant eccentricity, initial size fluctuations, or the fluctuations of the number of sources producing particles, are all sensitive to the inclusion of the two-body correlations. The effect is at the level of about 10–20%. Moreover, the realistic (Gaussian) correlation function gives indistinguishable results from the hard-core repulsion, with the expulsion distance set to 0.9 fm. Thus, we verify that for investigations of the considered correlation measures, it is sufficient to use the Monte Carlo generators accounting for the hard-core repulsion.

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I. INTRODUCTION

The atomic nucleus is closer to a self-bound saturated liquid than to a Fermi gas of noninteracting particles, as is for simplicity frequently assumed in studies of relativistic heavy-ion collisions. Thus the inclusion of correlations in the initial configuration of nucleons in the colliding nuclei is *a priori* very important. Recently Alvioli, Drescher, and Strikman [1,2] generated distributions of nucleons in nuclei which account for the central two-body nucleon-nucleon (*NN*) correlations. The procedure, based on the Metropolis search for configurations satisfying constraints imposed by the *NN* correlations, reproduces the one-body Woods-Saxon distributions, as well as central *NN* correlations, taken in the Gaussian form. This calculation is a very important step in the investigations using the Glauber approach [3,4] to relativistic heavy-ion collisions, as it is well known [5,6] that correlations induce event-by-event fluctuations of the measured quantities.

The Glauber Monte Carlo codes [7–10] (for a discussion of physics issues see Ref. [9] and the review [11]) which model the early phase of the collision have not been incorporating, for practical reasons, realistic *NN* correlations. Instead, the hard-core expulsion, easy to implement, is used. In that method, centers of nucleons, whose positions are randomly generated according to the Woods-Saxon one-body distribution, are not allowed to be placed closer to one-another than the expulsion distance $d \sim 1$ fm, which simulates the hard-core *NN* repulsion. It is not *a priori* clear that the results obtained with the realistic (Gaussian) and the hard-core correlations should be the same for various correlation measures used in the heavy-ion studies. Moreover, it is not obvious what precise value of d should be taken to make the simulations most realistic.

The purpose of this article is to investigate, with the help of explicit Glauber Monte Carlo simulations by GLISSANDO [9], the role of the central two-body *NN* correlations for several popular observables in relativistic heavy-ion collisions. In particular, we look at the following *fluctuation measures*: the participant eccentricity fluctuations related to the fluctuations of the elliptic flow [12–24], the multiplicity fluctuations as analyzed in the setup of the CERN NA49 experiment [25], and the recently investigated initial size fluctuations [26], which influence the transverse-momentum fluctuations [27–42]. We find that all these measures are sensitive to the inclusion of the two-body correlations at a level of about 10–20%. However, the realistic (Gaussian) correlation function gives virtually indistinguishable results from the calculations with the hard-core repulsion, with the expulsion distance tuned to $d = 0.9$ fm. Thus, we will argue that for all practical terms of modeling the Glauber initial phase of the collision, it is sufficient to use the Monte Carlo generators with the hard-core repulsion.

Certainly, the method of Ref. [1] is more general, as it allows to include correlations from attractive forces, as well as introduce the isospin dependence. These were recently considered in Ref. [43], and when these distributions are published, they can be implemented in Glauber generators and tested in a similar way as in the present work.

II. NUCLEAR CORRELATIONS

The method of Ref. [1] imposes a given form of one- and two-body nucleon distributions. The one-body density is parametrized with the standard Woods-Saxon form

$$\rho^{(1)}(r) = \frac{A}{1 + e^{\frac{r-R}{a}}}. \tag{1}$$

Our fit to the distributions for ^{208}Pb from [2] yields the optimum parameters

$$R = 6.59(1)\,\text{fm}, \quad a = 0.549(2)\,\text{fm} \quad (^{208}\text{Pb}), \tag{2}$$

where the uncertainties follow from the regression analysis on the available sample [2] of 10^5 configurations. The result of our numerical simulation is displayed in Fig. 1 with the open symbols.

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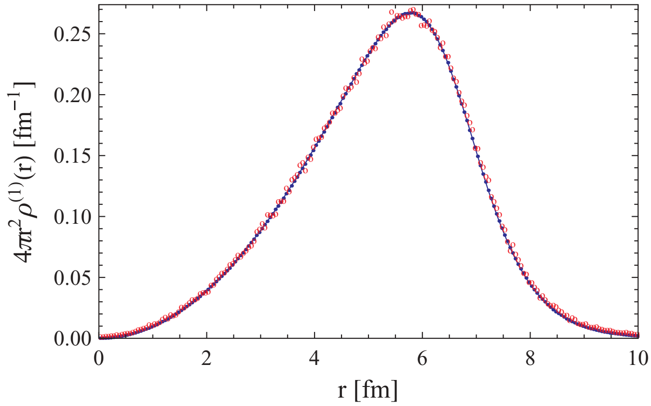

FIG. 1. (Color online) Radial one-body density of centers of nucleons in ^{208}Pb, $4\pi r^2 \rho^{(1)}(r)$, obtained numerically from the distributions of Ref. [1,2] (open dots), with the dashed line showing the Woods-Saxon fit with the optimum parameters (2). Filled dots show the results of the calculation with the hard-core correlations with parameters (10), with the solid line representing the Woods-Saxon fit. All points and lines overlap, showing the agreement between the two methods in obtaining the one-body distribution.

Similarly, for the lightest available nucleus, ^{16}O, we find from Ref. [2]

$$R = 2.593(1)\,\text{fm}, \quad a = 0.492(1)\,\text{fm} \quad (^{16}\text{O}). \tag{3}$$

The radial two-body correlation function $C(r)$ is defined as [1]

$$C(r) = 1 - \frac{\rho_C^{(2)}(r)}{\rho_U^{(2)}(r)}, \tag{4}$$

where $\rho_C^{(2)}(r)$ and $\rho_U^{(2)}(r)$ are the correlated and uncorrelated radial two-body densities,

$$\rho_i^{(2)}(r) = \int d^2\Omega \int d^3R \rho_i^{(2)}(\boldsymbol{R} + \boldsymbol{r}/2, \boldsymbol{R} - \boldsymbol{r}/2). \tag{5}$$

Here $\rho_i^{(2)}(\boldsymbol{r_1}, \boldsymbol{r_2})$, $i = C, U$, denotes the appropriate two-nucleon density, $\boldsymbol{r}$ is the relative coordinate, $r = |\boldsymbol{r}|$, and Ω corresponds to the two angles associated with $\boldsymbol{r}$, over which the density is integrated. The correlated density is read off from the distributions [2] with the help of GLISSANDO by histogramming the relative distances between the centers of nucleons in the same nucleus, while the uncorrelated density is found by taking the pairs of nucleons from *different* nuclei (this corresponds to the well-known *mixing technique*, which gets rid of correlations). The result of our procedure is shown in Fig. 2. We recover the Gaussian central *NN* correlation, implemented in the procedure of Ref. [1],

$$C(r) = e^{-\frac{r^2}{2b^2}}, \tag{6}$$

with

$$b = 0.561(1)\,\text{fm} \quad (^{208}\text{Pb}) \tag{7}$$

and

$$b = 0.552(1)\,\text{fm} \quad (^{16}\text{O}). \tag{8}$$

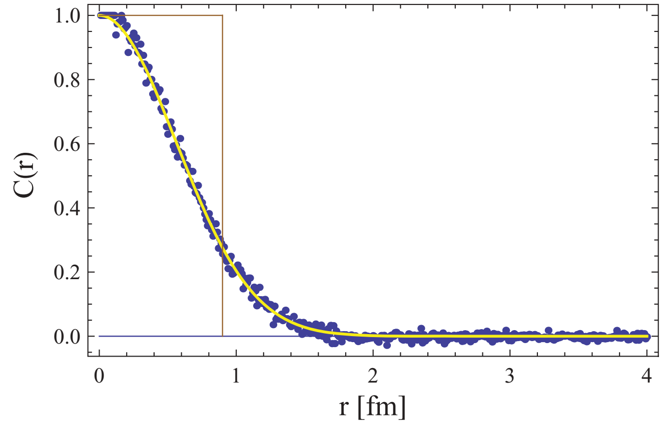

FIG. 2. (Color online) Central two-body *NN* radial correlation density for ^{208}Pb, obtained from Eq. (4) (points), and the Gaussian fit of Eqs. (6), and (7) (line). The vertical line indicates the hard-core expulsion with $d = 0.9$ fm.

The tiny uncertainties come from the finite sample of 10^5 configurations from Ref. [2].

Thus indeed the distributions of Refs. [1,2] properly implement the one-body Woods-Saxon density and the Gaussian central two-body correlations. The purpose of the above study was to read off the one-body parameters (2), which in the following sections will be input in the generation of the uncorrelated distributions by the Glauber simulations with GLISSANDO [9]. Results from the uncorrelated distributions will be compared to the correlated case, where the correlated distributions of Ref. [1] will be fed directly into our simulations.

III. GLAUBER MODELS

The prototype Glauber model used in the heavy-ion phenomenology is the *wounded-nucleon model* [44]. A wounded nucleon has collided inelastically at least once in the collision process. Variants of the approach [9,45–47] admix a certain fraction of binary collisions to the wounded nucleons, which leads to a better overall description of multiplicities of the produced particles. In the *mixed model*, investigated in this work, the number of the produced particles is proportional to the number of *sources*

$$N_s = (1 - \alpha)N_w/2 + \alpha N_{\text{bin}}, \tag{9}$$

where N_w is the number of the wounded nucleons and N_{bin} the number of binary *NN* collisions. The fits to particle multiplicities of Ref. [47] give $\alpha = 0.145$ for collisions at $\sqrt{s_{NN}} = 200$ GeV and $\alpha = 0.12$ for $\sqrt{s_{NN}} = 19.6$ GeV. Extrapolation to the Large Hadron Collider energies yields $\alpha \simeq 0.2$.

More sophisticated approaches [48–50] discriminate between the nucleons which have collided only once (corona) and more than once (core), which leads to an appealing physical picture. Also, the wounded-quark model [51–56] yields a successful phenomenology. All in all, the Glauber picture of the initial stage of the relativistic heavy-ion collision is a key element of many phenomenological analyses of the particle production mechanism.

In this article we apply the mixed model for the ^{208}Pb-^{208}Pb collisions, with $\alpha = 0.12$, corresponding to the highest Super Proton Synchrotron energy. We term the locations of centers of the wounded nucleons or the binary collisions as "sources," with the weight of the wounded nucleon $w_i = (1-\alpha)/2$, and the weight of the binary collision $w_i = \alpha$. A source emits particles, according to a superposed distribution [9].

While for the one-body measures, such as the particle multiplicities or spectra, only the one-body distributions matter and correlations are irrelevant, the fluctuations measures are expected to be sensitive to the *NN* correlations in the nucleon distributions. These are examined in detail in the next section.

IV. RESULTS OF SIMULATIONS

In this section we compare the results of the Glauber calculation initialized with the distributions of Refs. [1,2] (solid lines in the figures), with uncorrelated distributions (dashed lines), and with the distributions accounting for the hard-core repulsion with the expulsion radius $d = 0.9$ fm (dotted lines). The simulations are performed with GLISSANDO [9].

We note that in the case with no correlations at all we simply use the Woods-Saxon parameters (2), while in the case with the hard-core repulsion we need to start with a somewhat more compact distribution, as the expulsion leads to swelling, as explained in Ref. [9]. We find that starting the Monte Carlo generation for ^{208}Pb with

$$R = 6.44\,\text{fm}, \quad a = 0.549\,\text{fm}, \quad d = 0.9\,\text{fm} \quad (^{208}\text{Pb}) \tag{10}$$

leads to the one-body distribution with parameter values (2). The two cases are compared in Fig. 1, where the Monte Carlo points and the fitted curves overlap within the thickness of the lines.

For ^{16}O we find that the parameters

$$R = 2.487\,\text{fm}, \quad a = 0.493\,\text{fm}, \quad d = 0.9\,\text{fm} \quad (^{16}\text{O}) \tag{11}$$

yield a very exact reproduction for the Gaussian-correlation case of Eq. (3), with the quality of the agreement similar to the case of ^{208}Pb of Fig. 1.

We stress that it is not true that the Monte Carlo generation of the nuclear distributions with the hard-core repulsion leads to too large radii. Simply, the effect must be compensated with the shrinkage of the initial ("bare") radius [9]. The applied construction, with the shrunk "bare" one-body distributions, is important, as that way all calculations presented in the figures correspond to *identical* one-body distribution, and the differences in results are caused entirely by the two-body correlations, which differ in various methods.

A. Eccentricity

We start with a measure sensitive to the fluctuations, the so-called *participant* eccentricity. This measure appears in the studies of the event-by-event fluctuations of the initial shape, in particular of its elliptic component [12–24]. The effect is important, as the fluctuations lead to enhanced eccentricity of the initial system and, as a result of the subsequent hydrodynamic evolution, to enhanced elliptic flow. The participant eccentricity is defined in each event as

$$\varepsilon^* = \frac{\sqrt{\left(\sigma_x^2 - \sigma_y^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_x^2 + \sigma_y^2}, \tag{12}$$

where σ_x^2 and σ_y^2 are the variances of the two transverse coordinates and σ_{xy} is the covariance. Specifically, in each event

$$\langle x \rangle = \frac{\sum_i w_i x_i}{\sum_i w_i}, \qquad \sigma_x^2 = \frac{\sum_i w_i (x_i - \langle x \rangle)^2}{\sum_i w_i} \tag{13}$$

and similarly for the y variable and the covariance. The index i runs over all generated sources, and w_i are the weights. The quantity ε^* has the interpretation of the eccentricity evaluated event by event in a *variable reference frame* [21], rotated in such a way that the eccentricity in a given event is maximized.

In Fig. 3 we show the dependence of the event-by-event average, $\langle \varepsilon^* \rangle$, on the number of wounded nucleons (determining the *centrality* of the event). We note that the three calculations are virtually indistinguishable, except for a tiny difference for the most central collisions, where the uncorrelated case is a few percentages higher. The same conclusions were reached in the analogous study of eccentricity in Ref. [57].

Figure 4 shows the scaled standard deviation, $\Delta\varepsilon^*/\langle\varepsilon^*\rangle$, obtained from our event-by-event analysis. We note a significant difference between the uncorrelated case, which has up to 10% larger fluctuations at intermediate centralities, and the cases with correlations. However, the calculations with the realistic *NN* correlations and the hard-core correlations give an indistinguishable result, with the two curves overlapping within the statistical noise.

The short horizontal line at the most central events corresponds to the theoretical value $\sqrt{4/\pi - 1}$ of Ref. [21], following from the central limit theorem.

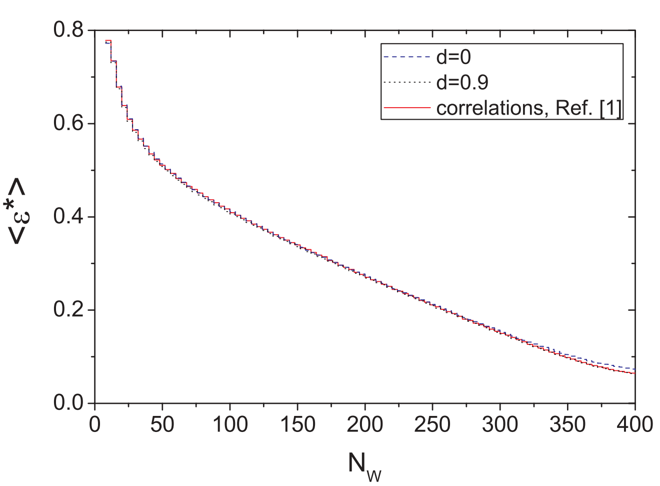

FIG. 3. (Color online) The average participant eccentricity, $\langle\varepsilon^*\rangle$, vs. the number of wounded nucleons, N_w, obtained with the three investigated nucleon distributions described in the text.

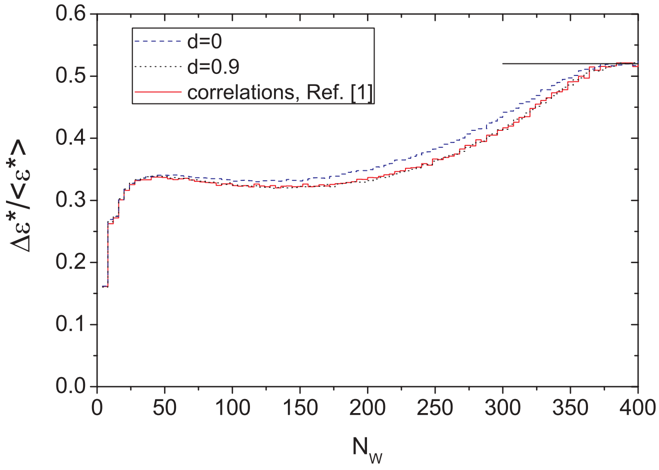

FIG. 4. (Color online) The scaled standard deviation $\Delta\varepsilon^*/\langle\varepsilon^*\rangle$, obtained from an event-by-event study. The short horizontal line at the most central events corresponds to the theoretical value $\sqrt{4/\pi - 1}$ of Ref. [21] following from the central limit theorem. ^{208}Pb-^{208}Pb collisions.

B. Multiplicity fluctuations

Next, we consider a quantity relevant for the multiplicity fluctuations as measured in the NA49 experimental setup [25], where the number of participants from the *projectile* nucleus is determined via the VETO calorimeter. Significant fluctuations of the number of sources may follow in this case from the fact that even at a fixed number of the wounded nucleons in the projectile, the number of wounded nucleons in the target fluctuates due to the statistical nature of the Glauber approach. In superposition models the scaled variance of the produced particle, N, satisfies the equality

$$\frac{\mathrm{var}(N)}{\langle N\rangle} = \frac{\mathrm{var}(m)}{\langle m\rangle} + \langle m\rangle \frac{\mathrm{var}(N_s)}{\langle N_s\rangle}, \tag{14}$$

where m is the multiplicity of particle produced from a single source and N_s is the number of sources [25]. Both terms in Eq. (14) contribute to the measured number of produced particles. We recall [58,59] that simple superposition models with the effect of fluctuations of the target wounded nucleons are not able to explain the data of Ref. [25], and their proper description remains a challange. Nevertheless, for the present purpose of analyzing the importance of the NN correlations, the quantity serves its purpose. The fluctuations of multiplicity in nucleus-nucleus collisions were also investigated experimentally in Refs. [60–63].

In Fig. 5 we show the scaled variance of the *total* number of sources defined in Eq. (9),

$$\omega = \frac{\mathrm{var}(N_s)}{\langle N_s\rangle}, \tag{15}$$

plotted as a function of the number of wounded nucleons in the projectile, N_w^{PROJ}. We note a significant, about 20%, reduction of ω when the two-body NN correlations are included. However, again there is no noticeable difference between the realistic (Gaussian) correlations and the hard-core expulsion, as the two lower curves in the figure overlap.

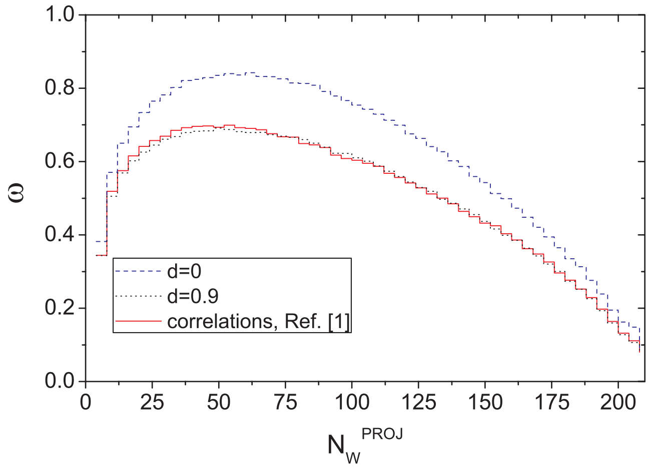

FIG. 5. (Color online) The scaled variance of the number of sources, ω, plotted as a function of the number of wounded nucleons in the projectile, N_w^{PROJ}, for ^{208}Pb-^{208}Pb collisions.

For the case of ^{16}O-^{16}O collisions, the corresponding results are displayed in Fig. 6. Again, we note a very close agreement between the cases of the Gaussian correlations of Ref. [1,2] and the hard-core correlations with $d = 0.9$ fm. For other measures of the fluctuations presented in this work for the ^{208}Pb-^{208}Pb only, these conclusions are the same.

C. Size fluctuations

Finally, we look at the event-by-event *size* fluctuations, namely the fluctuations of the variable

$$r = \sum_i w_i \sqrt{(x_i - \langle x\rangle)^2 + (y_i - \langle y\rangle)^2}. \tag{16}$$

It was recently shown in Ref. [26] that the initial size fluctuations are carried over via hydrodynamics and statistical hadronization into the event-by-event transverse-momentum fluctuations [27–42], where they lead to a natural description of the Relativistic Heavy Ion Collider data for the measure $\sigma_{\mathrm{dyn}}(p_T)$. In Fig. 7 we show the scaled standard deviation of r. Once again, the presence of the NN correlations

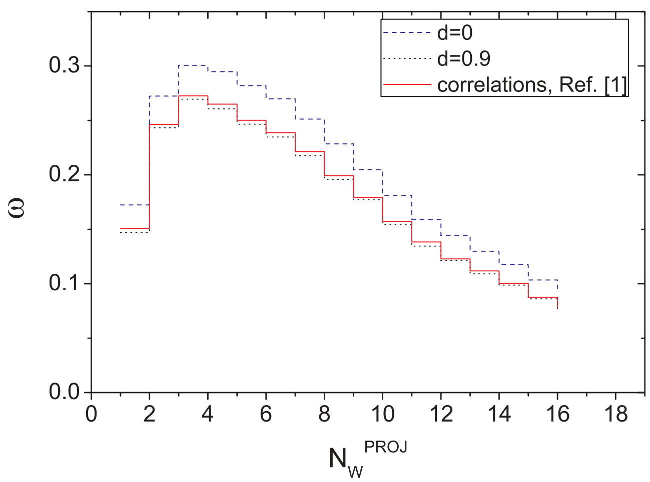

FIG. 6. (Color online) Same as Fig. 5 but for ^{16}O-^{16}O collisions.

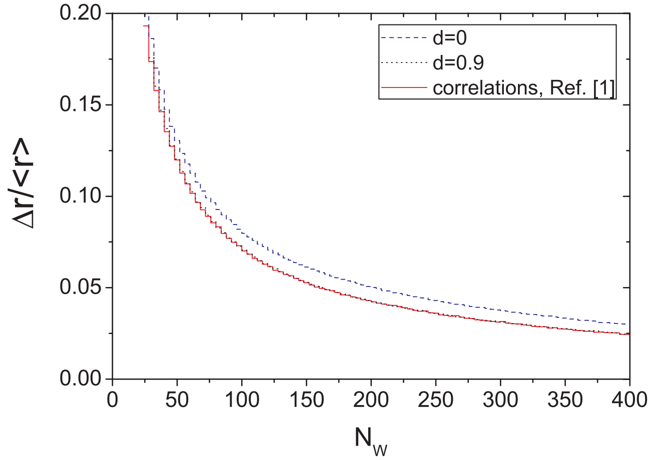

FIG. 7. (Color online) The scaled standard deviation of the size variable r of Eq. (16), plotted as a function of the total number of wounded nucleons, N_w, for ^{208}Pb-^{208}Pb collisions.

reduces somewhat the fluctuations, while the realistic and hard-core correlations with $d = 0.9$ fm give virtually the same result.

V. IMPACT-PARAMETER STUDY

In theoretical calculation one uses the impact parameter b to classify the centrality of the collision. Although this quantity is not observed experimentally, it is of interest due to its interpretational simplicity. In studies of fluctuations, however, care is needed, as N_w and other measures fluctuate as functions of b [64]. We first recall how N_w and its variance depend on b, which is displayed in Figs. 8 and 9.

All studies of the previous sections can be repeated in the function of b. As an example, in Fig. 10 we provide the scaled standard deviation of the participant eccentricity in the ^{208}Pb-^{208}Pb collision, plotted as a function of b. The qualitative conclusions are the same as in the discussion of Fig. 4.

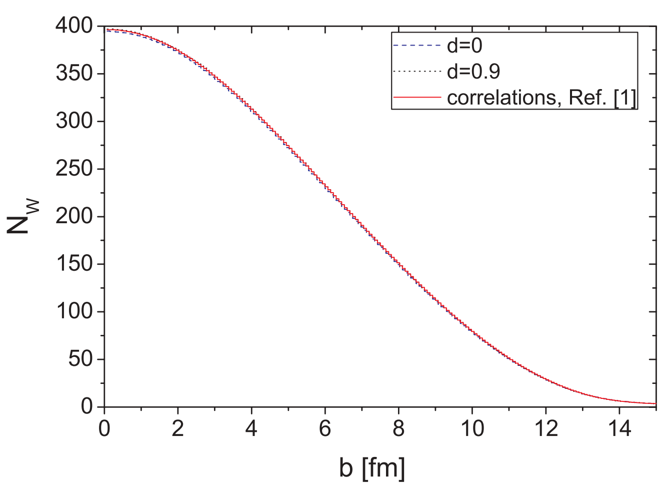

FIG. 8. (Color online) Average number of the wounded nucleons in the ^{208}Pb-^{208}Pb collision, plotted as a function of the impact parameter.

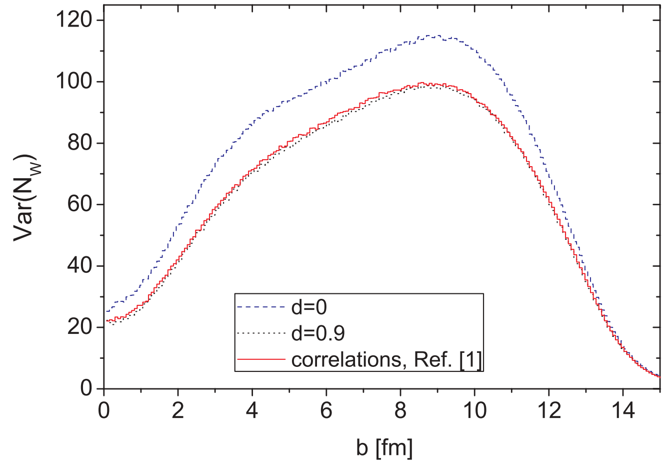

FIG. 9. (Color online) Same as in Fig. 8 for the variance of the number of the wounded nucleons.

VI. CONCLUSIONS

We have checked by carrying out explicit Glauber Monte Carlo simulations with GLISSANDO [9], that the inclusion of the central *NN* correlations influences the fluctuation measures in relativistic heavy-ion collisions at a level of, say, 10–20%. We have studied both heavy (^{208}Pb) and light (^{16}O) nuclei. Comparison of the realistic (Gaussian) correlations implemented in Ref. [1] and the hard-core correlations, typically used in the Glauber Monte Carlo codes, shows that they lead to the same results when the hard-core expulsion distance between the centers of nucleons is tuned to

$$d = 0.9\,\text{fm}. \tag{17}$$

Thus the main message for the practitioners of the Glauber Monte Carlo models is that, at least for the investigated observables, the implementation of the hard-core repulsion with d given by Eq. (17), straightforward to implement in Monte Carlo generators, leads to realistic predictions. We note that the dependence of the results on the value of d is a sensitive

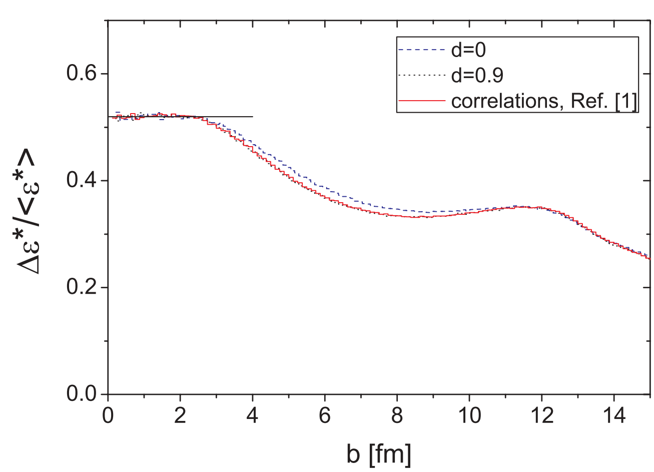

FIG. 10. (Color online) Scaled standard deviation of the participant eccentricity in the ^{208}Pb-^{208}Pb collision, plotted as a function of the impact parameter.

effect, as the excluded volume scales as d^3. Importantly, the one-body density is kept fixed with the help of appropriately adjusting the distribution used in the Monte Carlo generator.

Certainly, the general method of Ref. [1] allows one to implement channel-dependent *NN* correlations, as well as the nuclear attraction, relevant at intermediate distances. The role of these effects for the fluctuation measures in relativistic heavy-ion collisions can be investigated in a manner similar to that used in this work. In essence, every effect which increases the "regularity" of the initial nucleon distributions of the colliding nuclei, such as the considered central *NN* correlations, will have the tendency of decreasing the event-by-event fluctuations in nuclear collisions generated by the Glauber models.

ACKNOWLEDGMENTS

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