GLISSANDO 2: GLauber Initial-State Simulation AND mOre..., ver. 2 ⋆

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Abstract

We present an extended version of GLISSANDO, a Monte-Carlo generator for Glauber-like models of the initial stage of relativistic heavy-ion collisions. The increased functionality of the code incorporates a parametrization of shape of nuclei, including light nuclei needed in the NA61 experiment, the nuclear deformation, a possibility of using correlated distributions of nucleons in nuclei read from external files, an option of overlaying distributions of produced particles dependent on the space-time rapidity, the inclusion of the core-corona effect, or the output of the source distributions that can be used in event-by-event hydrodynamics. Together with other features, such as incorporation of various variants of Glauber models, or the implementation of a realistic NN collision profile, the generator offers a realistic and practical approach to describe the early phase of the collision in 3+1 dimensions; the predictions may later be used in modeling the intermediate evolution phase, e.g., with hydrodynamics. The software is integrated with the ROOT platform. The supplied scripts compute and plot numerous features of the distributions, such as the multiplicity distributions and centrality classes, harmonic asymmetry coefficients and their correlations, forward-backward correlations, etc. The code can also be used for the proton-nucleus and deuteron-nucleus collisions.

Key words: Glauber model, wounded nucleons, Monte Carlo generator, relativistic heavy-ion collisions, LHC, RHIC, SPS
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Program summary

Title of the program: `GLISSANDO 2` ver. 2.702
Catalog identifier:
Program summary URL:
http://www.ujk.edu.pl/homepages/mryb/GLISSANDO/index.html
Program obtainable from:
http://www.ujk.edu.pl/homepages/mryb/GLISSANDO/index.html
Licensing provisions: none
Computer: any computer with a `C++` compiler and the `ROOT` environment (optionally with `doxygen`), tested with Intel Xeon X5650, 2.67 GHz, 2 GB RAM
Operating system under which the program has been tested: Linux Ubuntu 7.04-12.04 (`gcc` 4.1.3-4.6.3), Scientific Linux CERN 5.10 (`gcc` 4.1.2), `ROOT` ver. 5.28–5.34/09
Programming language used: `C++` with the `ROOT` libraries
Memory required to execute with typical data: below 120 MB
No. of lines in distributed program, including test data: 3000
No. of bytes in distributed program, including test data and manual: 450 kB
Distribution format: tar.gz
Nature of physical problem: Glauber models of the initial state in relativistic heavy-ion collisions
Method of solution: Glauber Monte-Carlo simulation of collision events, analyzed with `ROOT`
Restrictions concerning the complexity of the problem: none
Optional software: doxygen [1]
Typical running time: 80 s/10000 events for the wounded-nucleon model and 100 s/10000 events for the mixed model with the Γ distribution, minimum-bias Pb+Pb collisions and hard-sphere wounding profile. A typical high-statistics "physics" run with 500000 events takes about 1 hour. The use of the Gaussian wounding profile increases the time by about a factor of 2. (All times for Intel Xeon X5650, 2.67 GHz, 2 GB RAM)

1 Introduction

This paper presents an updated and largely enhanced version of the program `GLISSANDO` – GLauber Initial-State Simulation AND mOre..., originally published in [2].

The popular Glauber [3–6] approach to the early phase of relativistic heavy-ion

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collisions is both physical and practical to use in a variety of applications where modelling of the initial phase is needed. In this semi-classical approach the individual collisions between the nucleons (*wounded nucleons* [7, 8], possibly admixed with *binary collisions* [9,10]) deposit entropy or energy density with a certain distribution in the transverse plane and rapidity [11–15]. The obtained spatial distribution of *sources*, which fluctuates event-by-event according to the statistical nature of the distributions of nucleons in the colliding nuclei, is usually used as input for the intermediate phase of the evolution, typically modelled with relativistic hydrodynamics or cascade models (for a review of the heavy-ion phenomenology see, e.g., [16]). The strength of the sources may fluctuate as well, according to a superimposed distribution [2]. We call this variable *relative deposited strength* (RDS).

On the experimental side, the usefulness of the Glauber Monte Carlo simulations comes from the fact that in collider experiments one usually determines in this way the dependence of the number of participants on centrality [2, 6, 17–19]. On the physics side, the presence of the event-by-event fluctuations in the initial Glauber phase (for recent reviews see [20, 21]) is a crucial aspect of the approach. These geometric fluctuations [22–52] are carried over to the final distributions of the experimentally measured hadrons. They influence the harmonic flow coefficients, in particular generate the odd components such as the triangular flow [53–55], as well as induce the correlations between the reaction planes of various harmonic flow components [39, 41, 44, 51, 56]. The output of Glauber Monte Carlo simulations may be used as input for the event-by-event hydrodynamics [25, 46, 55, 57–62],

Other aspects are also studied theoretically in this approach, such as the forward-backward correlations [11, 13, 14, 63, 64], the two-dimensional correlations in relative rapidity and azimuth [65], or the jet quenching [66, 67].

The applications listed above show that in the active field of studying the initial stage of the relativistic heavy-ion collisions there is demand for tools implementing the Glauber modeling, which our updated version of `GLISSANDO` tries to satisfy. The new features implemented in `GLISSANDO 2` include:

- Parametrization of shape of all typical nuclei, including light nuclei. This is useful in applications for the NA61 experiment, where the mass-number scan will be carried out [68].
- Inclusion of the deformation of the colliding nuclei [69–71]. In particular, the deformation effects are relevant for the collisions involving the deformed Au and U nuclei [72] recently used at RHIC.
- Possibility of using correlated distributions of nucleons in nuclei [73, 74], which may be read-in from external files prepared earlier with other codes, e.g., [75]. Certainly, the two-body correlations are important, as they influence the fluctuations [76, 77].

- Generalization of the NN collision profile a shape which interpolates between the step function and a Gaussian profile [78]. Such an extension is relevant for the collisions at the LHC energies, allowing to reproduce the measured values of both the total and elastic NN cross sections [79].
- Inclusion of the negative binomial overlaid distribution (in addition to the Poissonian and Gamma distributions).
- Possibility of overlaying distributions of the produced particles which depend on the space-time rapidity. This feature extends the model into a fully 3+1 dimensional tool.
- Inclusion of the core-corona effect [80–83].
- The structure of the `C++` code has been simplified and the organization of the package is restructured.
- A `doxygen`-generated [1] reference manual is available, which is useful for those who wish to alter the code for their needs.

We recall the original relevant features of the code:

- Possibility of superimposing a distribution of weights over the distribution of individual sources, reflecting the fact that the elementary collisions may result in the deposition of a varying amount of the entropy/energy.
- The built-in analysis of the shape fluctuations [24, 26, 27, 29].
- Evaluation and storage of the two-dimensional density profiles to be used "off-line" in other analyses, such us the event-by-event initial condition for hydrodynamics, jet quenching, *etc.*
- Output of the event-by-event data that can be used to generate input for hydrodynamics.
- The code can also be directly used for the proton-nucleus and deuteron-nucleus collisions. The Hulthen distribution is used to describe the NN separation in the deuteron.
- The code uses the standard CERN `ROOT` libraries and data structures.

In this paper we only describe the new features of `GLISSANDO 2`, hence the user should also refer to the original paper for a more complete description of the physics behind the code and its basic features [2]. The functionality of `GLISSANDO 2` and the format of the input and output files is down-compatible with the original version.

2 New features in GLISSANDO 2

2.1 Parametrization of density distributions of light nuclei

For the light nuclei with mass number $3 \leq A \leq 16$, a harmonic oscillator shell model density is used [84–86]:

$$\rho\,(r) = \frac{4}{\pi^{3/2} C^3} \left[1 + \frac{A-4}{6} \left(\frac{r}{C} \right)^2 \right] \exp\,(-r^2/C^2),$$
$$C^2 = \left(\frac{5}{2} - \frac{4}{A} \right)^{-1} \left(\langle r_{ch}^2 \rangle_A - \langle r_{ch}^2 \rangle_p \right), \tag{1}$$

where $\langle r_{ch}^2 \rangle_A$ and $\langle r_{ch}^2 \rangle_p = 0.7714\ \mathrm{fm}^2$ are the mean squared charge radii of the nucleus and the proton, respectively [87]. The values of the harmonic oscillator shell model parameter $\langle r_{ch}^2 \rangle_A$ for frequently used light nuclei are collected in Table 1.

Since the nucleons are not point-like, the centers of the nucleons cannot be closer than particular expulsion distance d; this is the usual simple way to introduce the short-range repulsion in Glauber Monte Carlo models. The magnitude of d should be of the order of the hard-core repulsion range in the nuclear potential. The repulsion implemented via an expulsion radius increases somewhat the size R of the nucleus and this swelling must be compensated by an appropriate shrinkage the parameters of the distribution from which the positions of centers of nucleons are generated (see Ref. [2] for a more detailed discussion). Accordingly, when $d > 0$, appropriately smaller values of the parameter $\langle r_{ch}^2 \rangle_A$ must be used to ensure that the single-particle radial density of the simulated nucleus is properly reproduced. These reduced values are given in the third column of Table 1.

We note that the correlated distributions, such as those with $d > 0$ are needed only in studies of observables sensitive to correlations, such as, e.g., the multiplicity fluctuations or participant eccentricities of the fireball.

2.2 Parametrization of density distributions of heavy nuclei

For heavy nuclei with $A > 16$, the nuclear distributions are well described by the Woods-Saxon profiles with the radius and thickness parameters given by

$$R = \left(1.12 A^{1/3} - 0.86 A^{-1/3} \right)\ \mathrm{fm},\ \ a = 0.54\ \mathrm{fm}. \tag{2}$$

Table 1
Harmonic oscillator shell model parameter $\langle r^2_{ch}\rangle_A$ for several light nuclei [87]. The values include the case with no NN repulsion ($d = 0$) and with the repulsion implemented via expulsion radius of $d = 0.9$ fm.

Nucleus	$\langle r^2_{ch}\rangle_A$ [fm^2]	
	$d = 0$	$d = 0.9$ fm
^{4}He	2.81	2.45
^{6}Li	6.7	6.4
^{7}Be	7.00	6.69
^{8}Li	5.47	5.1
^{9}Be	6.35	6.0
^{10}B	5.89	5.5
^{11}B	5.79	5.36
^{12}C	6.10	5.66
^{13}C	6.06	5.6
^{14}N	6.54	6.08
^{15}N	6.79	6.32
^{16}O	7.29	6.81

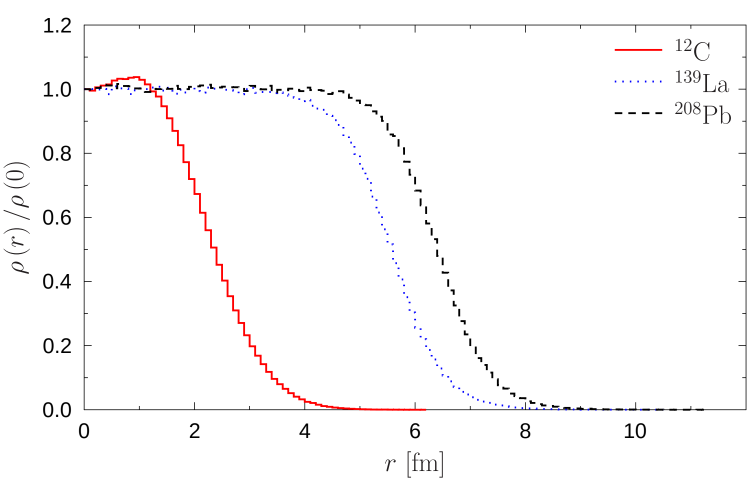

Fig. 1. Nuclear density distributions for ^{12}C (harmonic oscillator shell), ^{139}La and ^{208}Pb nuclei.

We recall that Ref. [73] provide distributions of nucleons in nuclei which incorporate the central repulsive Gaussian two-body correlations between nucleons. The one-body Woods-Saxon distributions as well as the nucleon-nucleon correlations turn out to be well approximated by the hard-core repulsion with $d = 0.9$ fm [74, 88] and the parametrization [2]

$$R = \left(1.1A^{1/3} - 0.656A^{-1/3}\right)\ \text{fm},\ a = 0.459\ \text{fm}, \tag{3}$$

used in `GLISSANDO 2` when $d = 0.9$ fm.

Figure 1 shows the nuclear one-body densities following from the applied parameterizations for a few sample nuclei.

2.3 Nuclear density distributions with deformation

As originally argued by Filip et al. [69–71], the nuclear deformation plays a relevant role in the "geometry" of the collision. In collisions of deformed nuclei, the orientation of nuclei relative to each other and to the beam axis influences the initial eccentricities and introduces an additional source of the initial fluctuations. Since recently the UU collisions were registered at BNL RHIC [89–91], the inclusion of the nuclear deformation in Glauber Monte Carlo simulations is desired [72]. In `GLISSANDO 2`, the spatial distribution of nucleons in colliding heavy nuclei (A$>$ 16) can be generated from the deformed Woods-Saxon density

$$\rho\left(r\right) = \frac{\rho_0}{1 + \exp\left(r - R\left(1 + \beta_2 Y_{20} + \beta_4 Y_{40}\right)\right)/a}. \tag{4}$$

where β_2 and β_4 are the deformation parameters, while Y_{20} and Y_{40} are the spherical harmonics. The parameters for the ^{63}Cu , ^{129}Xe , ^{197}Au , and ^{238}U nuclei, which are the nuclides used in the experiments [89–91] at RHIC, are listed in Table 2.

The deformation of these nuclei introduces a significant modification in the shape of the density profiles, as shown on Fig. 2. We compare the density distribution of an (artificially) spherical gold nucleus ($A = 197$) to the case of the physical ^{197}Au, exhibiting oblate deformation. We also show ^{63}Cu(prolate deformation), and a very strongly deformed ^{238}U(prolate deformation).

Table 2
The parameters of the Woods-Saxon nuclear density distribution taken from Eqs. (2) and (3), and the deformation coefficients taken from [92].

nucleus	R [fm]		a [fm]		β_2	β_4
	$d = 0$	$d = 0.9$ fm	$d = 0$	$d = 0.9$ fm		
^{63}Cu	4.24	4.21	0.54	0.459	0.162	-0.006
^{129}Xe	5.49	5.43	0.54	0.459	0.143	-0.001
^{197}Au	6.37	6.29	0.54	0.459	-0.13	-0.03
^{238}U	6.8	6.71	0.54	0.459	0.28	0.093

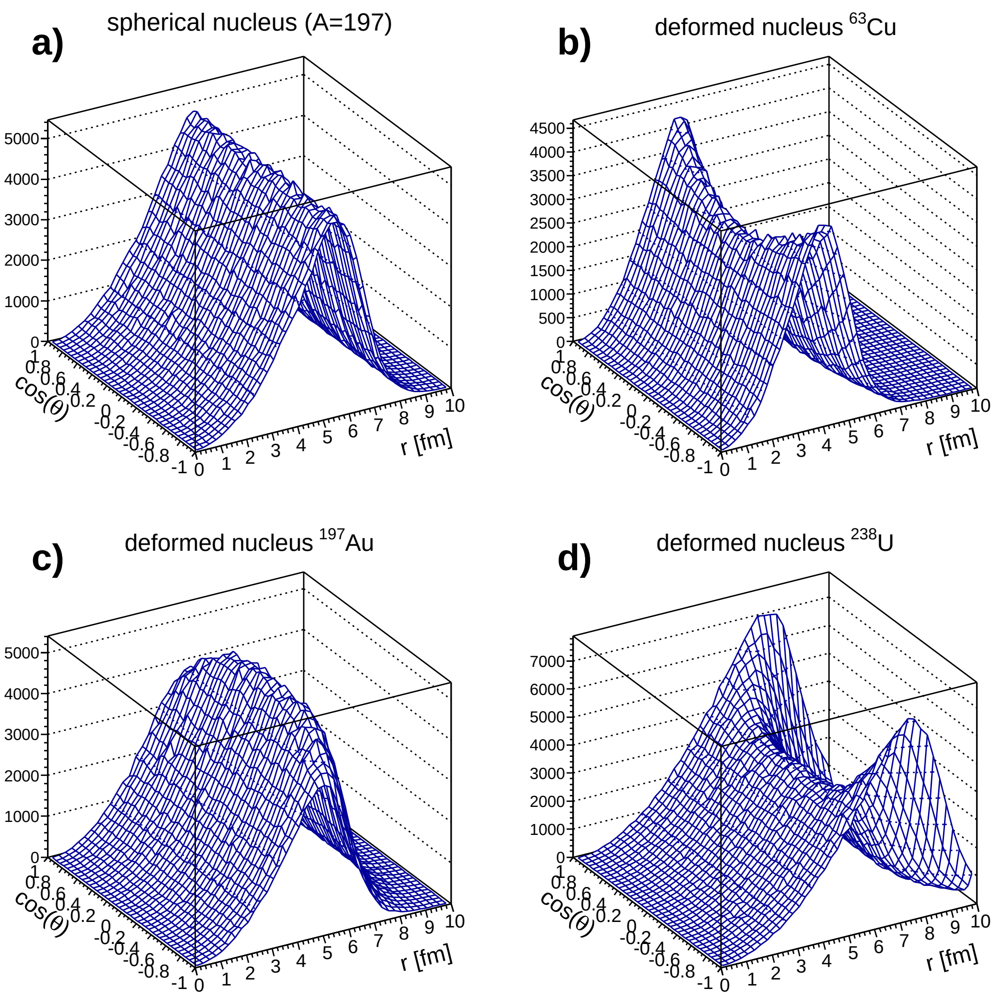

Fig. 2. The density profiles of the spherical nucleus with $A = 197$ (a) and the deformed nuclei ^{63}Cu (b), ^{197}Au (c), and ^{238}U (d).

The deformed nuclear distribution is randomly generated according to Eq. (4) with the symmetry axis aligned with the beam direction. Before the collision, the nucleus is randomly rotated in three dimensions, first by the polar angle and later by the azimuthal angle.

The deformation parameters for the colliding nuclei A and B are called `BETA2A`, `BETA4A` and `BETA2B`, `BETA4B`, respectively, and are read from the input file. The rotation of nuclei A and B is controlled by four parameters `ROTA_PHI`, `ROTA_THETA` and `ROTB_PHI`, `ROTB_THETA` respectively. For the default case of random rotation these parameters are set to -1. The code also accepts parameters `ROTA_THETA`, `ROTB_THETA` equal to the fixed polar angle θ in the range $[0, 180]$, and `ROTA_PHI`, `ROTB_PHI` equal to the fixed azimuthal angle from the range $[0, 360]$. Fixing the rotation angles allows for test simulations with frozen orientations of the colliding nuclei.

2.4 Collision profile

Let the total inelastic NN cross section be denoted by σ_{in} and the corresponding radius parameter $R = \sqrt{\sigma_{\text{in}}/\pi}$. The original version of the code incorporated the popular hard-sphere collision profile (with the meaning that the two nucleons collide if their impact parameter is less than R),

$$p_{\text{HS}}(b) = \Theta(R - b), \tag{5}$$

and the Gaussian profile,

$$p_{\text{G}}(b) = A \exp\left(-\frac{Ab^2}{R^2}\right), \tag{6}$$

which with $A = 0.92$ for the RHIC energies led to realistic values of the inelastic and elastic cross sections in the NN collisions [78]. At the LHC energies a modification of the collision profile is needed to accomplish this goal. We follow Ref. [79] and use

$$p_{\Gamma}(b) = G\Gamma\left(\frac{1}{\omega}, \frac{Gb^2}{R^2\omega}\right)/\Gamma\left(\frac{1}{\omega}\right), \tag{7}$$

where $\Gamma(z)$ and $\Gamma(\alpha, z)$ denote the Euler Gamma and incomplete Gamma functions, while $\omega \in (0, 1)$ is a parameter.

The profile (7) smoothly interpolates between (6)(the limit $\omega \to 1$) and (5) (the limit $\omega \to 0$). Importantly, the parametrization (7) allows to properly reproduce the experimental values $\sigma_{\text{in}} = 73$ mb and $\sigma_{\text{el}} = 25$ mb [93], which is achieved with $G = 1$ and $\omega = 0.4$. In Fig. 3 we show the shapes of the nucleon-nucleon wounding profile functions $p(b)$ for the hard-sphere, Gaussian, and Gamma choices.

The choice of the wounding profile in `GLISSANDO 2` is controlled by the preprocessor directive `_nnwp_`.

2.5 Superposition model

In the present version of the code we have added the negative binomial as an option for the overlaid distribution. Thus the possibilities are: no overlaid distribution (`MODEL=0`), Poisson distribution (`MODEL=1`), gamma distribution (`MODEL=2`), and negative binomial distribution (`MODEL=3`). The first three cases

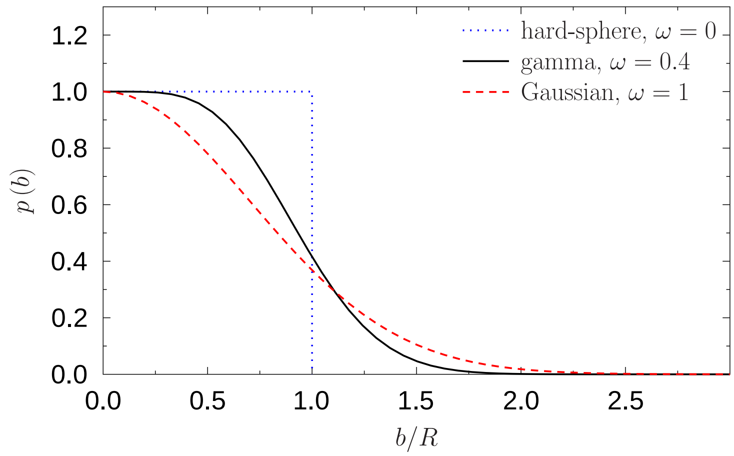

Fig. 3. Nucleon-nucleon wounding profile function $p\,(b)$ for the hard-sphere, Gaussian and Gamma choices. The Gamma profile with parameters $G = 1$ and $\omega = 0.4$ [79] approximately reproduces the TOTEM data [93] for the elastic differential cross section measured in the proton-proton interactions at $\sqrt{s_{NN}} = 7$ TeV.

are described in the original paper [2]. The negative binomial distribution generates the discrete weights according to the formula

$$g(w;\kappa,k) = \frac{\Gamma(w\kappa + k)}{\Gamma(w\kappa+1)\Gamma(k)} \frac{\left(\frac{\kappa}{k}\right)^{w\kappa}}{\left(1+\frac{\kappa}{k}\right)^{w\kappa+k}}, \quad w = 0, \frac{1}{\kappa}, \frac{2}{\kappa}, \dots . \tag{8}$$

This distribution has $\langle w \rangle = 1$ and $\sigma(w)^2 = 1/\kappa + 1/k$.

The negative binomial distribution can be supplied independently for the wounded nucleons and binary collisions. The parameter κ is denoted as `Uw` and `Ubin`, respectively, while $k = \texttt{Uw}^2/(\texttt{Vw} - \texttt{Uw})$ for wounded nucleons or $k = \texttt{Ubin}^2/(\texttt{Vbin} - \texttt{Ubin})$ for binary collisions. Then $\sigma(w)^2 = \texttt{Uw}/\texttt{Vw}^2$ or $\sigma(w)^2 = \texttt{Ubin}/\texttt{Vbin}^2$, respectively.

2.6 Eccentricities

In the present version, all transverse-plane Fourier eccentricity parameters of the created fireball are evaluated as *participant eccentricities* (or variable axes [2]) in what became the standard way,

$$\epsilon_n^* = \frac{\langle r^n \cos[n(\phi - \Phi_n)] \rangle}{\langle r^n \rangle}, \;\; \Phi_n = \mathrm{atan2}\left(\frac{\langle r^n \sin(n\phi) \rangle}{\langle r^n \cos(n\phi) \rangle} \right),$$

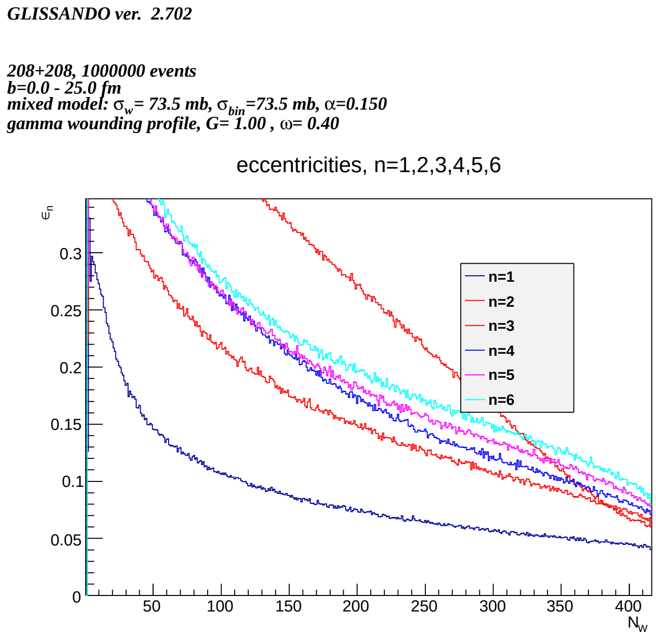

Fig. 4. The eccentricities ϵ_n^* as functions of the number of wounded nucleons for Pb+Pb collisions at the LHC.

with the exception that for $n = 1$ the weight is r^3 [37]. An example of a simulation providing the eccentricity parameters is given in Fig. 4.

2.7 Core-corona model

`GLISSANDO 2` stores the information on how many times a given nucleon interacted with nucleons from the other nucleus. This allows for a simple separation of the core (nucleons that interacted more than ones) and corona (nucleons that interacted exactly ones) [81–83]. A sample simulation is presented in Fig. 5.

2.8 Rapidity distributions

We implement in the code the following profiles for the space-time rapidity ($\eta_\parallel$) distributions [15]:

$$
\begin{aligned}
f(\eta_\parallel) &= \exp\left(-\frac{(|\eta_\parallel| - \eta_0)^2}{2\sigma_\eta^2}\theta(|\eta_\parallel| - \eta_0)\right), \\
f_+(\eta_\parallel) &= f_F(\eta_\parallel) f(\eta_\parallel), \\
f_-(\eta_\parallel) &= f_F(-\eta_\parallel) f(\eta_\parallel), \qquad (9)
\end{aligned}
$$

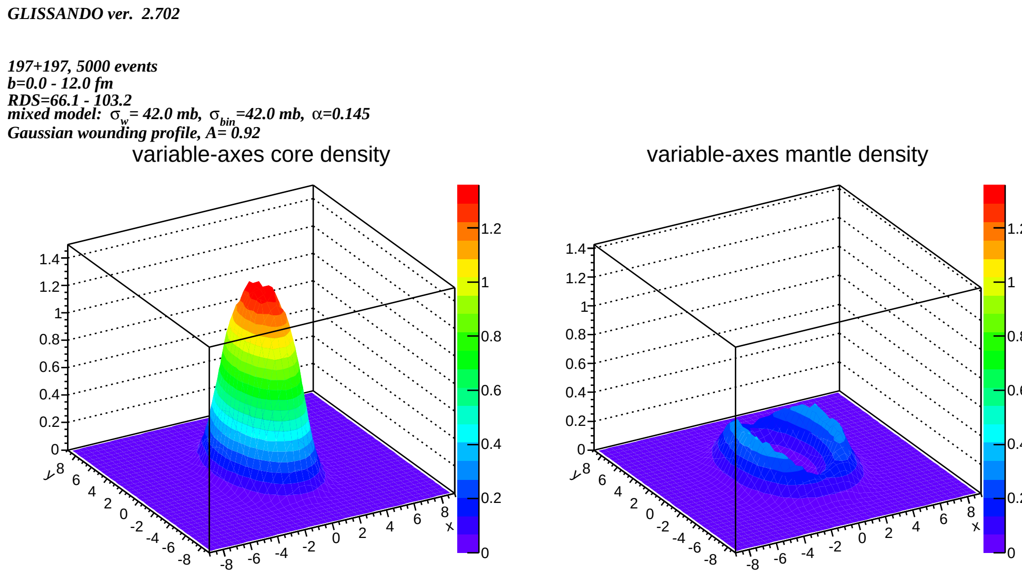

Fig. 5. The core and corona distributions.

where

$$f_F(\eta_{\parallel}) = \begin{cases} 0, & \eta_{\parallel} \leq -\eta_m \\ \frac{\eta_{\parallel}+\eta_m}{2\eta_m}, & -\eta_m < \eta_{\parallel} < \eta_m \\ 1, & \eta_m \leq \eta_{\parallel} \end{cases} \tag{10}$$

The functions $f_{\pm}$ are used for the forward (+) and backward (-) moving wounded nucleons, while f is used for the binary collisions.

We adopt a mechanism where a number of sources are generated from each wounded nucleon or binary collision according to the above probability distributions. The input parameter `NUMRAP` controls the number of sources, which is equal to `NUMRAP*w[i]`, where `w[i]` denotes the weight.

The following values of the parameters, implemented in the code as `ETA0`, `ETAM`, and
tt SIGETA describe the RHIC data after the hydrodynamic evolution [15]:

$$\eta_0 = 1, \ \eta_m = 3.36, \ \sigma_\eta = 1.3. \tag{11}$$

The emission profiles (10 were used by one of us (PB) in Ref. [15] to describe successfully the pseudorapidity spectra and the directed flow in Au+Au collisions at RHIC. A physical motivation for these "triangular" parametrizations has been given in [11,13–15,94]. The form (10) results in a tilted distribution in the transverse coordinate-spatial pseudorapidity space. This is demonstrated

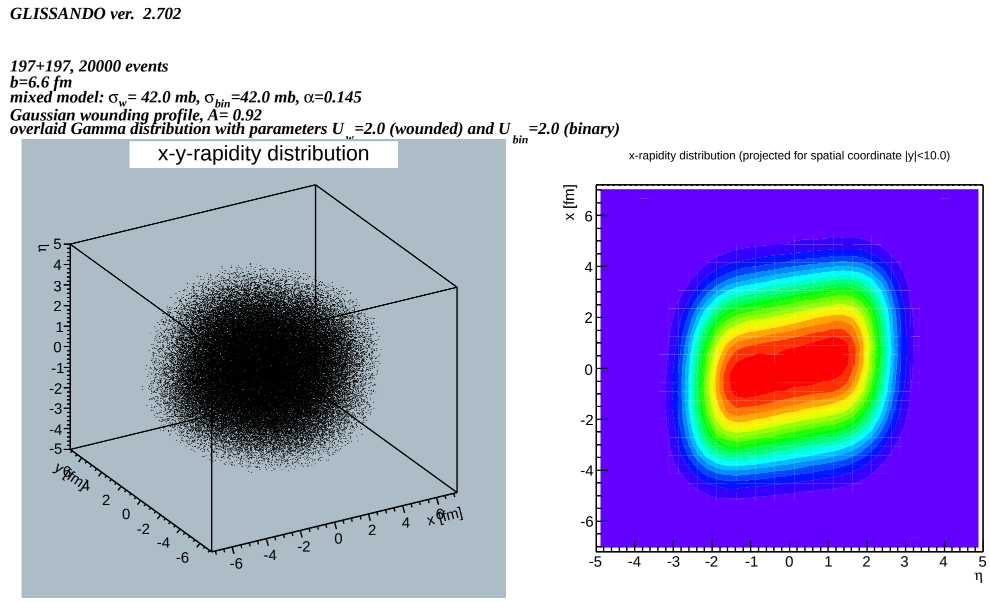

Fig. 6. Distributions involving pseudorapidity for Au+Au collisions at RHIC.

in Fig. 6.

For the LHC energies, the proper values of the parameters describing the longitudinal distribution of sources can be provided after the experimental results for the pseudorapidity spectra become available.

3 Installation and running

It is necessary to have the `ROOT` package [95] installed. After obtaining the `GLISSANDO` distribution, the user should simply run

```
make
```

which creates the binary file `glissando2`.

In order to optionally recreate the reference manual, `doxygen` [1] should be installed first. and then the command

```
make cleandoc
make doc
```

should be executed. This needs to be done only when the user wishes to regenerate the latex reference manual and/or create its html version. The configuration is controlled by the supplied `Doxyfile`. The original reference manual is provided in the distribution in the pdf format as `/doc/latex/refman.pdf`

After the installation, an instructive presentation of the capabilities of the present version of the code can be carried out with the shell script

```
./run.sh
```

The created `eps` files are by default displayed with `ghostview`, which should be installed prior to the run. Alternatively, the user may edit the file `run.sh` and replace `gv` with his favorite postscript viewer. The presentation in `run.sh` goes over typical applications of the code, including the new features, and gives the user a warm-up before making his own simulations. One can also run the script without prompts by executing

```
./run.sh < one.dat
```

For simulations of the A+B collisions the running command has the syntax

```
./glissando2 [input_file] [output_file]
```

A and B mean here any nucleus, including the deuteron and the proton. When the input and output file-name arguments are absent, their default values are

```
input.dat - default input
glissando.root - default output
```

Typical input files are also provided with the distribution. The input parameters and their defaults are described in Appendix B. Thus we may simply type `./glissando2` for the basic run.

4 Customization

4.1 Makefile

The `Makefile` contains instructions for compilation and linking. The user may modify the line with the preprocessor options, which control the running mode of the code. The default, needed for the most typical simulations, is

```
PREPROCESS := -D_nnwp_=1 -D_files_=0 -D_profile_=0
                  -D_weight_=0 -D_rapidity_=0 -D_evout_=0
```

The meaning of the parameters is as follows:

```
 _nnwp_    =2  - use the Gamma wounding profile
           =1  - use Gaussian wounding profile (more realistic),
           =0  - use the hard-sphere profile
```

```
 _files_   =1  - read the nuclear distributions from external files,
           =0  - generate nuclear distributions randomly
 _profile_ =1  - generate the nucleon profile and NN correlation data,
           =0  - do not
 _weight_  =1  - generate the NN collision profiles and the RDS ditributions,
           =0  - do not
 _rapidity_=1  - generate the data for the rapidity distributions,
           =0  - do not
 _evout_   =1  - generate event-by-event data
           =0  - do not
```

Instead of modifying the file, the user may run, for instance

```
make clean
make 'PREPROCESS = -D_nnwp_=1 -D_rapidity_=1'
```

to produce the binary code with the Gaussian wounding profile generating the rapidity distributions.

Another functionality is the storage of the current version of the package,

```
make package
```

as well as file cleaning options:

```
make clean
make cleandoc
make cleanoutput
```

4.2 Input

The input file is a standard ASCII file. Every line contains the name of the parameter separated with space from its value. When the parameter is missing from the input file, or a line containing it is connected out with the # symbol, a default value supplied in the code is used. See Appendix B for details.

4.3 Output

A typical output to the console is shown in Table 3. The subsequent self-explanatory lines give the info on the input: the version of the code, initial time, name of the input file used and the values of parameters reset from the default, the seed for the `ROOT` random-number generator, the requested number of events, the mass numbers of nuclei (with 1 corresponding to the proton and 2 to the deuteron), the Woods-Saxon parameters, the deformation parameters, the expulsion distance, the type and parameters of the model (wounded, binary, mixed, hot-spot), the window in the impact parameter, the number of wounded nucleons or the value of RDS, the dispersion parameters for the location of sources, and the live counter for events. The final output consists of the total nucleus-nucleus cross section in the given window, σ_{AB}, the equivalent hard-sphere radius defined as $\sqrt{\sigma_{AB}/\pi}/2$, and the efficiency parameter, denoting the ratio of events where the nuclei collided to all the Monte-Carlo generated events. Next come averages of basic quantities with their standard deviations: the number of the wounded nucleons, binary collisions, RDS, and eccentricity parameters. Finally, the execution time is printed.

The results of the simulation are stored in the `ROOT` output file. To see the physical results, the user should enter the `ROOT` environment

```
root
```

and execute one of the supplied scripts. An alternative method of executing the scripts is provided in the example shell `run.sh`, for instance one can execute

```
./glissando2 input/input_S_Pb.dat output/SPb.root
cd output
root -b -l -q -x "../macro/epsilon.C(\"SPb.root\")"
```

4.4 Reading external distributions

The external files with the distributions have the format

```
x   y   z   k
```

where x, y, and z denote the Cartesian coordinates of the centers on nucleons in fm, while $k = 0$ for neutrons and $k = 1$ for protons. The file must contain $A * n$ such lines, where A is the mass number of the nucleus, and n is the number of configurations. The files with the correlated distributions of Alvioli et al. [73] for ^{16}O, ^{14}Ca, and ^{208}Pb can be obtained from `http://www.phys.psu.edu/malvioli/eventgenerator/`. The user must then create from the stored files one big file, for instance running

```
cat o16-1.dat o16-2.dat o16-3.dat [more files] > o16.dat
```

The file `o16.dat` must be placed in the relative subdirectory `nucl`. To use the external files the code must be compiled through

```
make 'PREPROCESS = -D_files_=1'
```

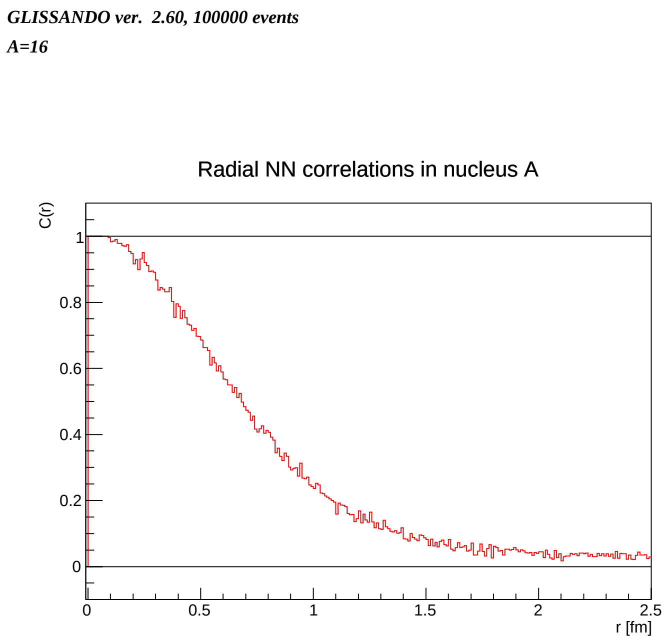

Fig. 7. Two-body NN correlations in oxygen 16, generated for the distributions in files downloaded from [75].

and executed as

```
./glissando2 [input_file] [output_file] [nucleus_A_file] [nucleus_B_file]
```

If the syntax

```
./glissando2 [input_file] [output_file] [nucleus_A_file]
```

is used, then the distribution of the nucleons in nucleus A is read from the file, while for the nucleus B it is generated randomly. This syntax should also be used for the collisions of nucleus A with the proton or deuteron.

4.5 Generating output for hydrodynamics

The pre-compiler flag `_evout_=1` switches the event-by-event output to an external file, storing the position of sources and other information in each event to the output file `output/ebye.out`. Its content consists of the blocks

```
n
```

followed with n lines of the format

```
x y z c w
```

where n is the number of sources in a given collision, x and y are the transverse coordinates in fm, $|c|$ indicates how many times a wounded nucleon collided, with positive (negative) c corresponding to nucleus A (B), while $c = 0$ indicates the binary collisions. The last entry is the weight w (RDS). The number of blocks equals to the number of events.

For the event-averaged densities the user may instead use the script hydro.C

4.6 Fixing centrality cuts

Most potential users of the code will run it with their preferred values of parameters and typically with division in centrality classes. To carry out the analysis for a given centrality class, a two-step procedure is needed. First, a minimum-bias calculation must be done, with no (or broad-range) values for the W0, W1, RDS0, and RDS1 parameters, as well as BMIN=0 and BMAX set to a value approximately equal to twice the sum of the radii of the two colliding nuclei. Next, the macro/centrality2.C script must be run in root. The values of
tt W0, W1, or RDS0, RDS1 determining the centrality classes can be read off from the generated file output/centrality2.dat. Then the input file must be modified with the proper values for W0, W1 supplied (if centrality is to be determined by the number of the wounded nucleons), or RDS0, RDS1 (if centrality is to be determined by the relative deposited strength RDS).

5 Structure of the code

For those readers who may wish to modify the code, we very briefly describe the structure of GLISSANDO 2.

As both the nuclei and the Glauber sources created in the collision constitute certain spatial distributions of points (with weights), we have defined a general class distr to create, store, and manipulate such distributions (file build/include/distib.h). Translations, rotations, evaluation of harmonic coefficients, etc., are function members of this class. A derivative class nucleus is used to create the nuclear distributions, which may either be generated randomly with a specified distributions, or read from prepared earlier external files.

The class collision and its derivative collision_rap (file collision.h) execute the collision of the two nuclei for the case without and with the rapidity distributions, respectively. A specific model of the collision and generation of sources is implemented through the parameters in the input file. The result is a spatial distribution of sources with specified weights (RDS).

The auxiliary classes `counter`, `counter2`, and `counter_2D` (file `counter.h`) create useful counters to store and evaluate statistical properties such as the mean, variance, etc., of various physical random variables.

Finally, file `build/include/functions2.h` contains definitions of the functions (the Woods-Saxon and deformed Woods-Saxon distributions, the Hulthen function, etc.), some statistical distributions, structures for the input, initialization of histograms, and other technical elements.

More details concerning the structure of the code are to be found in the supplied reference manual created with `doxygen`.

6 Summary

We have described an extended version of `GLISSANDO`, hoping it will continue to be a useful tool for the heavy-ion community. Moreover, the simplified object-oriented structure of the code, together with the technical reference manual, should make it simple to tailor to particular needs in future applications. The authors welcome all comments, suggestions, and questions from the users.

A Contents of the package

The files included in the `GLISSANDO 2` distribution are listed in Table A.1.

B Description of input and output

The basic model parameters, collected in Table B.1, can be supplied in the input file. The sign # at the beginning of the line comments out the line and then the default value of the parameter set in the code is used. See the sample file `input.dat`.

The meaning of variables stored in the output `GLISSANDO 2 Root` files is explained in Tables B.2 and B.3.

Table B.1: Parameters of the input file.

name	default	description
ISEED	0	seed for the random number generator, if 0 a random seed is generated
EVENTS	50000	number of generated events
NBIN	40	number of bins for histograms in ρ, x, or y
FBIN	72	number of bins for histograms in the azimuthal angle
NUMA	208	mass number of nucleus A
NUMB	208	mass number of nucleus B
RWSA	6.407	Woods-Saxon radius for the distribution of centers, nucleus A [fm] (208Pb with the fix-last method)
AWSA	0.459	Woods-Saxon width, nucleus A [fm]
BETA2A	0.	deformation parameter β_2, nucleus A
BETA4A	0.	deformation parameter β_4, nucleus A
ROTA_THETA	-1	rotation parameter (angle θ), -1 - random rotation, nucleus A
ROTA_PHI	-1	rotation parameter (angle ϕ), -1 - random rotation, nucleus A
RWSB	6.407	Woods-Saxon radius for the distribution of centers, nucleus B [fm]
AWSB	0.459	Woods-Saxon width, nucleus B [fm]
BETA2B	0.	deformation parameter β_2, nucleus B
BETA4B	0.0	deformation parameter β_4, nucleus B
ROTB_THETA	-1	rotation parameter (angle θ), -1 - random rotation, nucleus B
ROTB_PHI	-1	rotation parameter (angle ϕ), -1 - random rotation, nucleus B
RCHA	5.66	harmonic oscillator shell model density mean squared charge radii of nucleus A (12C-nucleus)
RCHB	5.66	harmonic oscillator shell model density mean squared charge radii of nucleus B (12C-nucleus)
RCHP	0.7714	harmonic oscillator shell model density mean squared charge radii of proton
WFA	0	the w parameter of the Fermi distribution, nucleus A
WFB	0	the w parameter of the Fermi distribution, nucleus B
CD	0.9	closest allowed distance between centers of nucleons [fm]
SNN	73.5	NN "wounding" cross section [mb]
SBIN	73.5	NN binary cross section [mb]
ALPHA	0.15	0 - wounded, 1 - binary, 0.145 - LHC@2.76 TeV/nucleon
MODEL	0	0 - constant superimposed weight=1, 1 - Poisson, 2 - Gamma, 3 - Negative Binomial
Uw	2.	Poisson, Gamma or NegBin parameter for wounded

Continued on Next Page...

Table B.1 – Continued

name	default	description
Ubin	2.	Poisson, Gamma or NegBin parameter for binary
Vw	4.	Negative binomial variance, wounded nucleons
Vbin	4.	Negative binomial variance, binary collisions
DW	0.	dispersion of the location of the source for wounded nucleons [fm]
DBIN	0.	dispersion of the location of the source for binary collisions [fm]
WMIN	2	minimum number of wounded nucleons to record the event
W0	2	minimum allowed number of wounded nucleons
W1	1000	maximum allowed number of wounded nucleons
RDS0	0	minimum allowed RDS
RDS1	100000	maximum allowed RDS
NNWP	0	0 - hard-sphere NN wounding profile, 1 - Gaussian NN wounding profile, 2 - Gamma NN wounding profile
GA	0.92	central value of the Gaussian wounding profile
GAMA	1.	central value of the Gamma wounding profile
OMEGA	0.4	relative variance of cross-section fluctuations for the Gamma wounding profile
SHIFT	1	1 - shift the coordinates of the fireball to the c.m. in the fixed-axes case, 0 - do not shift
RET	0	0 - fix-last algorithm, 1 - return-to-beginning algorithm for nuclear density
FULL	0	1 - provide the full information on events (obsolete), 0 - do not
DOBIN	0	1 - compute the binary collisions also for the case ALPHA=0, 0 - do not compute the binary collisions for the case ALPHA=0
FILES	0	1 - read distribution from files, 0 - do not
NUMRAP	10	number of particles per unit weight generated in the whole rapidity range
RAPRANGE	5.	range in rapidity
ETA0	1.	2*ETA0 is the width of the plateau in η
ETAM	3.36	parameter of the Bialas-Czyz-Bozek model
SIGETA	1.3	parameter controlling the width of the rapidity distribution
MAXYRAP	10.	maximum absolute value of the y coordinate in the x-y-rapidity histogram
FBRAP	2.5	forward rapidity for the forward-backward analysis (backward rapidity = - FBRAP)

Continued on Next Page…

Table B.1 – Continued

name	default	description
ARANK	2	rank of the Fourier moment for the forward-backward analysis
PP	-1	power of the transverse radius in the Fourier moments
RO	0	rank of the rotation axes (0 - rotation rank = rank of the Fourier moment)
PI	4. arctan(1.)	the number π
BMIN	0.	minimum impact parameter [fm]
BMAX	25.	maximum impact parameter [fm]
BTOT		range parameter for histograms [fm]

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Table 3
A typical output to the console from GLISSANDO2, generated with `./glissando2 input/input_p_Pb.dat` (case of central p+Pb collisions at the LHC).

```
*******************************************************
GLISSANDO 2 ver. 2.7xx
ver. 2: \protect\vrule width0pt\protect\href{http://arxiv.org.abs/xx13.xxxx}{http://arxiv.o
ver. 1: Computer Physics Communications 180(2009)69, \protect\vrule width0pt\protect\href{h
and Phys. Rev. C81(2010)064909 for implementation of the NN correlations
(tested with ROOT ver. 5.28--5.34)
*******************************************************
Simulation of nucleus-nucleus collisions in Glauber models
-------------------------------------------------------
parameters reset from default in input/input_p_Pb.dat :
EVENTS 30000
NUMA 1
NUMB 208
RWSB -1
ALPHA 0
SNN 73
W0 15
BMAX 7
Woods-Saxon parameters: RWSB=6.40677fm, AWSB=0.459fm (see the paper)

generates Root output file output/glissando.root
random seed: 3045191687, number of events: 30000
1+208, RB=6.40677fm, aB=0.459fm, dB=0.9fm

wounded nucleon model: sig_w=73mb
   (binary collisions not counted)
Gaussian NN collision profile, Ga=0.92
rank of rotation corresponds to the rank of the given Fourier moment
power of transverse radius in eccentricities = rank (see the paper)
window: b_min=0fm, b_max=7fm, Nw_min=15, Nw_max=1000

event: 30000     (100%)

Some quantities for the specified b, N_w, and RDS window
(+/- gives the e-by-e standard deviation):
A+B cross section = 306.405mb
efficiency (accepted/all) = 19.9045%
N_w = 17.2806+/-2.21813
relative deposited strength (RDS) = 8.64028+/-1.10906

participant eccentricities:
eps_1 = 0.192552+/-0.107269
eps_2 = 0.305913+/-0.149797
eps_3 = 0.366467+/-0.171138
eps_4 = 0.434756+/-0.195091

Finish: Sat Sep 14 13:40:08 2013
(0h:1m:35s)
```

Table A.1
The contents of `GLISSANDO 2` package: file names and their descriptions.

file name	description
README	basic instructions
Makefile	makefile for `glissando2`
version	stores the minor version number
Doxyfile	configuration for `doxygen`
run.sh	shell script displaying the possibilities
one.dat	auxiliary file
build/src/glissando2.cxx	the `GLISSANDO 2` source file
build/include/functions2.h	the function library
build/include/collisions.h	the collisions library
build/include/distrib.h	the distributions library
build/include/counter.h	the counter library
addons/interpolation.cxx	source for interpolation code
addons/interpolation.mk	make file for interpolation code
addons/retrieve.cxx	template code for retrieving info from the full event tree
addons/retrieve.mk	makefile for retrieve
input/input*.dat	input files for various collisions
macro/angles.C	script generating the plot of the correlation between principal axes in the forward and backward rapidities
macro/centrality2.C	script generating centrality classes
macro/core_mantle.C	script generating the core and corona distributions
macro/corr.C	script generating the NN correlation plot
macro/density.C	script generating the distributions
macro/dxdy.C	script for center-of-mass coordinates vs. N_w
macro/epsilon.C	script for eccentricity vs N_w
macro/epsilon_b.C	script for eccentricity vs b
macro/epsilon_c.C	script for eccentricity vs centrality
macro/fitr.C	script displaying and fitting the nuclear density profile
macro/fourier.C	script generating first few harnonic components of the distributions
macro/hydro.C	script generating input grid for hydrodynamic calculations
macro/info.C	script giving information on the stored output file
macro/label.C	script generating the label used in plots
macro/mult.C	script for multiplicity fluctuations
macro/overlay.C	script examining the overlaid distributions
macro/profile2.C	script for Fourier profiles
macro/profile2_deformation_*.C	scripts for r-cos(θ) profiles of deformed nuclei
macro/size.C	script generating the event-by-event scaled standard deviation of the size parameter
macro/tilted.C	script generating the tilted initial profile in the x-rapidity space at y=0
macro/wounding_profile.C	script generating the wounding and binary-collision profiles
doc/latex/refman.pdf	the `doxygen` reference manual

Table B.2
Some of histograms stored in the output `ROOT` file. $\langle . \rangle$ denotes the mean and var the variance of the specified quantity.

xyhistr	variable-axes density in the $x-y$ variables
c0rhist	variable-axes density in the $\rho-\phi$ variables (not normalized)
c0rhp	$f_0^*(\rho)$ [see Eq. (22-23) in [2] for the notation below]
c2rhp	$f_2^*(\rho)$
c4rhp	$f_4^*(\rho)$
c6rhp	$f_6^*(\rho)$
s1rhp	$g_1^*(\rho)$
s3rhp	$g_3^*(\rho)$
nx	$\langle x \rangle$ [fm] vs. N_w
nx2	var(x) [fm]^2 vs. N_w
ny	$\langle y \rangle$ [fm] vs. N_w
ny2	var(y) [fm]^2 vs. N_w
nepsp	$\langle \epsilon^* \rangle$ vs. N_w
nepsp2	var$(\epsilon^*)/\langle \epsilon^* \rangle^2$ vs. N_w
nuni	event multiplicity vs. N_w
nepspb	$\langle \epsilon^* \rangle$ vs. b
nepsp2b	var$(\epsilon^*)/\langle \epsilon^* \rangle^2$ vs. b
nunib	event multiplicity vs. b
ntarg	$\langle N_w^B \rangle$ vs. N_w^A
ntarg2	var$(N_w^B)/\langle N_w^B \rangle$ vs. N_w^A
nbinar	$\langle N_{\rm bin} \rangle$ vs. N_w^A
nbinar2	var$(N_{\rm bin})/\langle N_{\rm bin} \rangle$ vs. N_w^A
nwei	$\langle RDS \rangle$ vs. N_w^A
nwei2	var$(RDS)/\langle RDS \rangle$ vs. N_w^A
nuni	event multiplicity vs. N_w^A

Table B.3
Trees and their contents stored in the output ROOT file.

TTree param	all parameters of the calculation
TTree density	(generated only by `glissando_profile.exe`)
r	radius of the nucleon in nucleus A [fm]
wd	weight generated by the superposition distribution
TTree phys	
sitot	the nucleus-nucleus cross section [mb]
eps_variable	event-by-event average ϵ^*
sigma_eps_variable	event-by-event standard deviation of ϵ^*
TTree events	
nwA	number of wounded nucleons in A
nwB	number of wounded nucleons in B
nwAB	total number of wounded nucleons
nbin	number of binary collisions
npa	RDS
b	impact parameter
size	weighted average of the distance fom origin (c.m. frame)
ep1	$< r^3 \cos(\phi - \phi^*) > / < r^3 >$
ep	$< r^2 \cos(2(\phi - \phi^*)) > / < r^2 >$
ep3	$< r^3 \cos(3(\phi - \phi^*)) > / < r^3 >$
ep4	$< r^4 \cos(4(\phi - \phi^*)) > / < r^4 >$
ep5	$< r^5 \cos(5(\phi - \phi^*)) > / < r^5 >$
ep6	$< r^6 \cos(6(\phi - \phi^*)) > / < r^6 >$
phir	the rotation angle ϕ^*
phi2_plus	the rotation angle ϕ^*, increased rapidity
phi2_minus	the rotation angle ϕ^*, decreased rapidity
phir3	the rotation angle ϕ_3^*
phir4	the rotation angle ϕ_4^*
phir5	the rotation angle ϕ_5^*
phir6	the rotation angle ϕ_6^*
xx	x c.m. coordinate [fm] (before shifting)
yy	y c.m. coordinate [fm] (before shifting)