GLISSANDO 3: GLauber Initial-State Simulation AND mOre..., ver. 3 *

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Abstract

We present ver. 3 of GLISSANDO, a versatile Monte-Carlo generator for Glauber-like
models of the initial stages of ultra-relativistic heavy-ion collisions. The present
version incorporates the wounded quark model, which is phenomenologically suc-
sessful in reproducing multiplicities of particle production at RHIC and the LHC.
Within this model, one can study the nucleon substructure fluctuation effects, re-
cently explored in p-A collisions. In addition, the code includes the possibility of
investigating collisions of light nuclei, such as \(^3\text{He}\) and \(^3\text{H}\), or the \(\alpha\)-clustered \(^7,9\text{Be}\),
\(^{12}\text{C}\), and \(^{16}\text{O}\), where the deformation of the intrinsic wave function influences the
transverse shape of the initial state. The current version, being down-compatible,
retains the functionality of the previous releases, such as incorporation of various
variants of Glauber-like models, a smooth \(NN\) inelasticity profile in the impact pa-
rameter obtained from a parametrization of experimental data, fluctuating strength
of the entropy deposition, or realistic nuclear distributions of heavy nuclei with de-
formation. The code can provide output in the format containing the event-by-event
source location, which may be further used in modeling the intermediate evolution
phase, e.g., with hydrodynamics or transport models. The interface is simplified,
such that in the control input file the user may supply only the very basic informa-
tion, such as the collision energy, the mass numbers of the colliding nuclei, and the
model type. GLISSANDO 3 is integrated with the CERN ROOT platform. The package
includes numerous illustrative and useful ROOT scripts to compute and plot various
results.

Key words: ultra-relativistic nuclear collisions, Monte Carlo generators, wounded
quarks and nucleons, \(\alpha\)-clusterization, LHC, RHIC, SPS

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Program summary

Title of the program: GLISSANDO 3

Catalog identifier:

Program summary URL:

Program obtainable from:

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, 64 GB RAM

Operating system under which the program has been tested: Linux Debian 9.3 (gcc 6.3.0), Scientific Linux CERN 5.10 (gcc 4.1.2), ROOT ver. 5.34

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: 3700

No. of bytes in distributed program, including test data and manual: 3400 kB

Distribution format: tar.gz

Nature of physical problem: Glauber modeling of the initial stages of ultra-relativistic heavy-ion collisions

Method of solution: Monte-Carlo simulation of collisions, analyzed with ROOT

Restrictions concerning the complexity of the problem: none

Optional software: doxygen, to generate the reference manual

Typical running time: 50 s/10^6 events for the proton-proton at \( \sqrt{s} = 7 \) TeV in wounded quark model, 320 s/10^4 events for Au+Au minimum bias at \( \sqrt{s_{NN}} = 7 \) TeV in wounded nucleon model, and 335 s/10^4 events for Pb+Pb minimum bias at \( \sqrt{s_{NN}} = 2.76 \) TeV in wounded nucleon model. All times for Intel Xeon X5650, 2.67 GHz, 64 GB RAM.

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1 Introduction

We present an extended version of the package GLISSANDO – GLauber Initial-State Simulation AND mOre..., previously described in [3] (ver. 1) and [4] (ver. 2), where the user is directed for a more detailed description of the underlying physics and the features which remain unchanged in the present version.

With the on-going efforts to understand the nature of the ultra-relativistic nuclear collisions, more ideas and models are being explored. Consequently, the dedicated open-access software should follow these efforts and supply useful analysis tools. Concerning the earliest stage of such collisions, modeling based on the so-called Glauber approach [5–7], working well phenomenologically, were recently shown to be very successful in the variant with the wounded quarks [8–21] acting as the particle production sources, rather than the commonly used wounded nucleons [22,23] amended with binary collisions [24,25]. Implementation of the wounded quark model is the first major extension of GLISSANDO 3.

Second, collisions of small nuclei with non-uniform distribution of nucleons may offer further stringent tests of the geometry-flow transmutation mechanism, including the event-by-event fluctuations [26–60]. Moreover, the heavy-light reactions may provide insight into the ground-state clusterization structure in light nuclei [61–63]. We thus offer a possibility of simulating reactions with $^3$He (studied experimentally in [64]) or $^3$H nuclei, which may be thought of as small triangles, as well as collisions involving light α-clustered nuclei, such as $^7$Be (dumbbell), $^{12}$C (triangle), and $^{16}$O (tetrahedron).

The user interface to the code has been greatly simplified. In GLISSANDO 3, it suffices to provide the type of the model used (wounded nucleons or wounded quarks), the energy of the collision, and the mass numbers of the colliding nuclei. The appropriate $NN$ inelastic cross section and its profile in the impact parameter are then automatically generated from interpolation formulas based on the experimental $pp$ scattering data. Specifically, we use here the COMPETE model parametrization implemented in the Particle Data Group review [65], which offers statistically the best description on the $pp$ and $p\bar{p}$ scattering data over a very broad range of the collision energies.

As in the previous releases, the output of GLISSANDO 3 is generated in two ways. The key features of the formed initial states are stored in a ROOT tree containing ready to use results in a compact form. In addition, a full event-by-event output can be generated for use in event-by-event studies of further evolution stages, such as hydrodynamics [30,54,66,72] or transport.

The new features implemented in GLISSANDO 3 include:
• State-of-the art nucleon-nucleon inelastic cross sections and their impact-parameter profiles.
• Implementation of the wounded quark (in general, wounded parton) model.
• Possibility of colliding $^3$He and $^3$H, with the distributions from external files.
• Inclusion of $\alpha$-clustered structure of $^7$Be, $^{12}$C, and $^{16}$O nuclei.
• Possibility of studying the effect of the proton fluctuations in the framework of the wounded quark model.
• Simplified user interface.

The main retained features of the previous releases incorporate:

• Parametrization of distributions of all popular nuclei, in particular those used in the energy - system-size scan of the NA61/SHINE [73].
• Inclusion of the nuclear deformation [74,76].
• Possibility of using externally-generated (correlated) nuclear distributions, e.g., [77] for $^{208}$Pb, $^{197}$Au or $^{16}$O.
• Possibility of studying proton-nucleus and deuteron-nucleus collisions.
• Possibility of overlaying weights over the distribution of sources (Poisson, Gamma, negative binomial).
• Study of the core-corona effect [79, 82].
• Output of the event-by-event data with location of the sources to a text file, to be used for initialization of hydrodynamics of transport codes.
• A reference manual generated with doxygen [2] may be useful for those who wish to tailor the code.

2 New features in GLISSANDO 3

2.1 Inelastic cross sections and inelasticity profiles

With new measurements of the total, elastic, and differential elastic cross section, in particular at the LHC [83,85] and in cosmic rays [86], new parameterizations of the $pp$ and $p\bar{p}$ scattering amplitudes became available. A standard description is provided by the COMPAS group within the COMPETE model, presented in Sec. 52 of the 2016 edition of the Review of Particle Physics [65]. In GLISSANDO 3 we use this parameterization of the data as the most complete one.

The inelastic profile function, determining the probability of an inelastic $NN$ collision at impact parameter $b$ and collision energy $\sqrt{s}$ is defined as

$$p_{\text{in}}(b, s) = \sigma_{\text{tot}}(b, s) - \sigma_{\text{el}}(b, s) = 4p \Im h(b, s) - 4p^2|h(b, s)|^2,$$  

(1)
Fig. 1. The inelastic profile plotted as a function of the impact parameter for three sample $pp$ collision energies $\sqrt{s}$. The points indicate the COMPETE model parametrization, whereas the lines show the interpolation according to Eq. (4),

where $h(b, s)$ is the Fourier-Bessel transform of the $pp$ elastic scattering amplitude $f(s, -q^2)$,

$$2p h(b, s) = 2 \int_0^{\infty} q dq J_0(bq) f(s, -q^2),$$  \hspace{1cm} (2)

with $p = \sqrt{s/4 - m_N^2}$ denoting the CM momentum of the nucleon. Using the COMPETE model for $f(s, -q^2)$ with parametrization from [65], we thus obtain $\sigma_{in}(b, s)$. In the code, rather than using these long formulas involving a numerical integration in Eq. (2), we apply a simple parametrization of the inelastic profile of the form [87],

$$p_{in}(s, b) = G \Gamma \left( \frac{1}{\omega(s)}, \frac{\pi G(s)b^2}{\omega(s)\sigma_{in}(s)} \right) / \Gamma \left( \frac{1}{\omega(s)} \right),$$  \hspace{1cm} (3)

where $\Gamma(a, z)$ denotes the incomplete Euler $\Gamma$ function, $\sigma_{in}(s)$ is the inelastic cross section, and $G(s)$ and $\omega(s)$ are suitably adjusted parameters such that the COMPETE results are accurately reproduced. The values obtained from our fit can be efficiently represented with interpolating functions (which we use for $\sqrt{s} \geq 5$ GeV):

$$\sigma_{in}(s) = \left[ 40.32(\sqrt{s}/\text{GeV} + 53.08)^{0.104} - 30.15 - 8.75/(s/\text{GeV}) \right] \text{mb},$$  \hspace{1cm} (4)

$$G(s) = \frac{33.82 + 1.27(\sqrt{s}/\text{GeV})^{0.85}}{32.10(\sqrt{s}/\text{GeV})^{0.063} + 1.28(\sqrt{s}/\text{GeV})^{0.85} - 10^{-8}},$$

$$\omega(s) = \frac{-3.97 + 4.41(\sqrt{s}/\text{GeV})^{0.24}}{1 + 4.41(\sqrt{s}/\text{GeV})^{0.40} - 0.27(\sqrt{s}/\text{GeV})^{0.24}}.$$  \hspace{1cm} (3)

Note that the applied expressions are for shear numerical convenience and do not reflect physical mechanisms of high-energy $pp$ scattering.
Fig. 2. The inelastic $pp$ cross section (left) and parameters $G$ and $\omega$ (right), plotted as functions of the collision energy.

The quality of the interpolating formulas is illustrated in Fig. 1, where we compare the inelastic profile functions from the COMPETE model to Eq. (3) with parameters (4) for three selected collision energies. The interpolated dependence of parameters on the collision energy, as given by formulas (4), is displayed in Fig. 2.

2.2 Wounded quarks

In the wounded quark model [8–11] the valence quarks play the role of elementary scatterers. The approach is implemented in GLISSANDO 3, as it has proved to be phenomenologically successful in describing the multiplicity of produced hadrons in a variety of reactions, with the linear scaling

$$\frac{dN_{\text{ch}}}{d\eta} \sim Q_{\text{W}}$$

well satisfied. Here $N_{\text{ch}}$ denotes the observed charged hadrons, and $Q_{\text{W}}$ the number of wounded quarks in a giver reaction and centrality class. It was first noticed that the RHIC data follow the scaling [12], further explored at RHIC by the PHENIX Collaboration [15, 16], as well as at the SPS [13]. See also [14–21] for further developments.

Our implementation of the model is described in detail in [18]. The nucleon consists of three quarks distributed according to a radial density

$$\rho(r) = \text{const} \ r^2 e^{-\sqrt{\frac{2}{3} \left(1 - \frac{1}{p}\right) \frac{r}{r_0(x)}}},$$

where $p = \frac{Q_{\text{W}}}{\sqrt{s}}$, with $Q_{\text{W}}$ the number of wounded quarks in a reaction and centrality class.
where \( p \) is the number of partons (\( p = 3 \) for the wounded quark model). The factor \( 1 - 1/p \) accounts for the center-of-mass corrections; a shift to the center of mass of the nucleon is carried out after randomly generating the positions of the centers of quarks. As \( r_0 \) is adjusted phenomenologically (see the following), the presence of this factor in formula (6) is conventional.

In the wounded quark approach one needs to choose the quark-quark inelasticity profile. We take it in the Gaussian form

\[
p_{\text{in}}^{qq}(s, b) = e^{-\frac{ab^2}{\sigma_{\text{in}}^{qq}(s)}}, \tag{7}
\]

where \( \sigma_{\text{in}}^{qq}(s) \) is the quark-quark inelastic cross section.

Thus our wounded quark implementation brings in two parameters: \( r_0(s) \) and \( \sigma_{\text{in}}^{qq}(s) \). Their values are chosen in such a way that the resulting \( NN \) collision profile reproduces the COMPETE parametrization discussed in Sec. 2.1. In other words, we impose the desired feature that the \( NN \) inelasticity profile is the same if one uses nucleons or quarks as elementary scatterers. With our restricted parameterizations of Eq. (6) and (7), this cannot be accomplished in an exact manner, but optimization leads to a very close agreement. This can be seen in Fig. 3, where we compare the \( NN \) elasticity profiles obtained in the nucleon and quark models for \( \sqrt{s} = 7 \) TeV. The quality of agreement is similar at other collision energies.

The optimum values of the quark model parameters can be interpolated as follows:
Fig. 4. Dependence of the quark distribution parameter $r_0$ (left) and the inelastic quark-quark cross section (right) on the collision energy.

$$\sigma_{\text{in}}^{qq}(s) = [-2.09 + 3.42(\sqrt{s}/\text{GeV} + 63.09)^{0.17} + 1.23/(\sqrt{s}/\text{GeV})] \text{mb},$$  \hspace{1cm} (8)  

$$r_0(s) = [0.305 - 0.178(\sqrt{s}/\text{GeV})^{-0.409}] \text{fm}.$$  

The dependence on $s$ is visualized in Fig. 4. The effective number of partons $p$ can be set to be different from $p = 3$. In that case the user must readjust the parameters $\sigma_{\text{in}}^{qq}$ and $r_0$ in order to reproduce the NN inelasticity profile.

As in previous releases of our code, centers of nucleons in a nucleus are distributed according to a Woods-Saxon density with additional NN repulsion \cite{2}, or are taken from external calculations, e.g., \cite{77}. Nuclear shape deformation \cite{74, 75, 88, 89} is implemented for deformed nuclei, such as $^{63}$Cu, $^{197}$Au, or $^{238}$U, in the same manner as in GLISSANDO 2.

2.3 Reactions with light clustered nuclei

GLISSANDO 3 offers a possibility to collide nuclei whose structure exhibits clustering. Specifically, we implement $^7$Be as $\alpha + ^3$He, $^9$Be as $2\alpha + \text{neutron}$, $^{12}$C as $3\alpha$, and $^{16}$O as $4\alpha$ (see Fig. 5). The details of our fixing of geometric parameters of the distributions are presented in \cite{63}. The parameters are adjusted in such way that the one-body nuclear distributions \cite{90, 91} are matched. We first arrange the positions of clusters as in Fig. 5 separating the centers by
Table 1
Parameters of the distribution of light clustered nuclei used in GLISSANDO 3.

| Nucleus | \( l \) [fm] | \( r_\alpha \) [fm] | \( r_{3\text{He}} \) [fm] | \( r_n \) [fm] |
|---------|---------------|--------------------|----------------|--------------|
| \(^7\text{Be}\) | 3.2 | 1.2 | 1.4 | - |
| \(^9\text{Be}\) | 3.6 | 1.1 | - | 1.9 |
| \(^{12}\text{C}\) | 2.8 | 1.1 | - | - |
| \(^{16}\text{O}\) | 3.2 | 1.1 | - | - |

The distance \( l \). The distribution of the centers of nucleons in each cluster is randomly generated according to a Gaussian

\[
f_i(\vec{r}) = \text{const} \exp \left( -\frac{3}{2} \frac{(\vec{r} - \vec{c}_i)^2}{r_c^2} \right),
\]

where \( \vec{r} \) denotes the coordinate of the nucleon and \( \vec{c}_i \) is the position of the center of the cluster \( i \). The width of the cluster is controlled with \( r_c \), the rms radius of the cluster. Then the positions of the nucleons are generated sequentially, switching between clusters 1, 2, \ldots, 1, 2, \ldots, until all the needed nucleons are placed.

For the case of \(^9\text{Be}\) we place the extra neutron on top of the two \( \alpha \) clusters. The distribution is

\[
f_n(\vec{r}) = \text{const} \ r^2 \exp \left( -\frac{3}{2} \frac{r^2}{r_n^2} \right),
\]

and it exhibits a hole in the middle.

The values of parameters used in the code are collected in Table 1

One may do many physical studies with light clustered nuclei, in particular looking for clusterization signatures in harmonic flow patterns [61–63, 92]. In Fig. 6 we present an example of a quantity, the symmetric cumulant of elliptic and triangular flows, which displays different behavior on the model with clusters compared to the case without clusters (uniform).

2.4 Rapidity modeling

The modeling in rapidity, present to some extent in ver. 2 of the code, has been removed. This is because, unlike the modeling in the transverse plane where the Glauber approach became one of the standards, the longitudinal...
Fig. 6. The scaled symmetric cumulant of eccentricities in collisions of clustered and uniform $^{12}\text{C}$ nucleus with $^{197}\text{Au}$. The symmetric cumulant is defined as $\text{SC}(a,b) = \langle ab \rangle - \langle a \rangle \langle b \rangle$ (generated with script sc_comp.C).

modeling has much freedom and is under development. If the user wishes to model the rapidity dependence of the fireball, she/he may use the transverse distributions (generated event-by-event and written to an output file) in an external application.

3 Installation and running

The user must first install the CERN ROOT package [1]. After downloading and unpacking GLISSANDO 3, the command

```
make
```

should be run, which creates the executable binary glissando3.

To optionally recreate the doxygen manual (provided as /doc/latex/refman.pdf with the distribution), the doxygen [2] package should be installed and the following commands executed:

```
make cleandoc
make doc
```

With the code installed, the user may look at an instructive presentation of the main features of the present version by executing the shell script

```
./demo_ver_3.sh
```

To see the created pdf files evince should be installed prior to the run. To use another pdf viewer, the line VIEW=evince should be edited in demo_ver_3.sh.
The features of ver. 2, retained in the present release, may be explored by executing

```
./demo_ver_2.sh
```

For collisions of two nuclei, the standard running command has the syntax

```
./glissando3 [input_file] [output_file]
```

where the nuclei can be any, including the proton and the deuteron. When the input or output arguments are absent, the defaults are

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

The input parameters with their defaults are collected in Appendix A.

3.1 Makefile

The `Makefile` contains commands for compilation and linking. It can be used for profiling the code by modifying the preprocessor options. Most importantly, the user should decide if she/he uses the nucleon or the quark version of the model. In the nucleon case the standard preprocessor options should read

```bash
PREPROCESS := -D_partons_=0 -D_nnwp_=2
  -D_bindep_=1 -D_files_=0 -D_profile_=0 -D_weight_=0 -D_evout_=0
  -D_clusters_=0 -D_uncluster_=0 -D_pardis_=0 -D_rdsconv_=1
```

whereas for the wounded quark model

```bash
PREPROCESS := -D_partons_=1 -D_nnwp_=1
  -D_bindep_=1 -D_files_=0 -D_profile_=0 -D_weight_=0 -D_evout_=0
  -D_clusters_=0 -D_uncluster_=0 -D_pardis_=0 -D_rdsconv_=1
```

The meaning of all preprocessor parameters is as follows:

- `_nnwp_=0` - hard-sphere NN wounding profile, =1 - Gaussian, =2 - gamma
- `_bindep_=1` - binary and wounding depend on each other, =0 - do not
- `_files_=1` - read the nuclear distributions from external files, =0 - generate randomly
- `_profile_=1` - generate the nucleon profile and NN correlation data, =0 - do not
- `_weight_=1` - generate data for the NN collision profiles
  and for the weight (RDS) distributions, 0 - do not
- `_evout_=0` - do not generate the text event data, =1 - short, =2 - long
- `_clusters_=1` - generate clusters in light nuclei, =0 do not
- `_uncluster_=1` - smoothe out the alpha clusters in nucleus A,
The user may modify the Makefile file to suit his needs, or, alternatively, run `make` for example as follows:

```
make 'PREPROCESS = -D_partons_=1 -D_nnwp_=1 -D_evout_=1 '
```

to produce the binary code for the wounded quark model with the Gaussian wounding profile and with generation of some results to an external ASCII file.

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

```
make package
```

as well as the cleaning options:

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

### 3.2 Input

The input file is a standard ASCII file. Every line contains the name of the parameter separated with space from the assigned value. The sequence of the lines with parameters is flexible. When a parameter is missing in the input file, or a line containing it is commented out with `#`, the default value is used. See Appendix A for details concerning the input parameters.

### 3.3 Output

A typical output from a run of GLISSANDO 3 to the console is shown in Table 2.

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 or examine the output Root file. An alternative method of executing the Root scripts is provided in the example shell demo_ver_3.sh.

The preprocessor option \_evout\_ controls the possible event-by-event output to an additional external ASCII file with the name of the Root output file appended with \_points\_. If \_evout\_ = 2, then the file stores the transverse positions event-by-event. Its content consists of the blocks

RDS NwAB specA atan2(ycmA,xcmA) specB atan2(ycmB,xcmB)

followed with NwAB lines of the format

x y z c w

The second part of the block is

Nbin

followed with Nbin lines of the format

x y z c w

Above we use the notation RDS for the relative deposited strength in the event, NwAB for the number of wounded objects (nucleons or quarks), specA for the number of spectators from nucleus A and atan2(ycmA,xcmA) for the angle of their center of mass, and specB and atan2(ycmB,xcmB) for analogous quantities for nucleus B, and Nbin for the number of binary collisions. Then x and y are the transverse coordinates of the sources 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 of the given source. The number of blocks is equals to the number of events.

If \_evout\_ = 1, then a simplified output is generated, with the format

NwA NwB Nbin RDS

where NwA and NwB are the numbers of wounded objects in nuclei A and B, respectively. The number of output lines equals to the number of events.

3.4 Reading external nuclear distributions

The user may provide external files with nuclear distributions. We have used two sets of such files. The first one comes from Alvioli et al. [77] for the case of
\(^{16}\text{O}, ^{40}\text{Ca},\) and \(^{208}\text{Pb}.\) They can be obtained from [http://sites.psu.edu/color/](http://sites.psu.edu/color/). The user must create from the downloaded files a single file, for instance running

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

The resulting file `o16.dat` should be placed in the relative subdirectory `nucl`. The files 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. Groups of \(A\) lines, where \(A\) is the mass number of the nucleus, correspond to a single nuclear configuration.

The second case concerns \(^{3}\text{He}\) or \(^{3}\text{H}\) distributions, which are taken from the Green’s function Monte Carlo simulations [93] as provided in [14]. For the user’s convenience the files `he3.plaintext.dat` and `h3.plaintext.dat` are also provided at the GLISSANDO web site. The format of these files is

```
x_1\ y_1\ z_1 \ x_2\ y_2\ z_2 \ x_3\ y_3\ z_3 \ foo \ foo \ foo \ foo \ foo
```

where \((x_i, y_i, z_i)\) are the Cartesian coordinates of the \(i\)th nucleon in a given configuration.

To use the nuclear configurations from external files, the code must be compiled with

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

and executed as

```
./glissando3 [input_file] [output_file] [nucleus_A_file] [nucleus_B_file]
```

When the syntax

```
./glissando3 [input_file] [output_file] [nucleus_A_file]
```

is used, then the distribution of the nucleons in nucleus A is read from an external file, whereas for nucleus B the positions of nucleons are generated randomly. This syntax must also be used for the collisions of nucleus A with the proton or the deuteron.

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3.5 Fixing centrality cuts

We explains how to impose centrality cuts on GLISSANDO 3 simulations and how to properly choose the range for the impact parameter $b$ (a too large range slows down the simulations). The supplied shell script `centrality.sh` implements the following procedure. First, a minimum-bias simulation must be run, with no (or broad-range) values for the $W_0$, $W_1$, $RDS_0$, and $RDS_1$ parameters, as well as $BMIN=0$ and $BMAX$ set to a somewhat larger value than approximately the sum of the radii of the two colliding nuclei. Next, the macro/demo_3/cent.C script should be executed in root. The values of $W_0$, $W_1$, or $RDS_0$, $RDS_1$ corresponding to the desired centrality classes can be read off from the generated file `output/centrality.dat`. Next, the input file must be modified with the proper values for $W_0$, $W_1$ supplied (if centrality is determined by the multiplicity of the wounded objects), or $RDS_0$, $RDS_1$ (if centrality is given by the relative deposited strength RDS), and the code must be rerun (with low statistics). Running `/macro/demo_3/b_dist.C` and looking at the plot `b_dist.pdf` allows us to determine the optimum values for $BMIN=0$ and $BMAX$. We thus should update these parameters in the input file and rerun simulations with full statistics.

The above steps can be simply traced by executing `centrality.sh`.

4 Structure of the code

The structure of the code is provided in the supplied reference manual created with doxygen.

5 Summary

We have presented GLISSANDO 3, with hopes it will continue to be a useful and versatile tool for the heavy-ion community. The authors most welcome suggestions and questions from the users.

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A  Input and output

The input parameters are collected in Table A.1. The hash sign # at the beginning of the line comments it out, in which case a default value of the parameter as set in the code (file functions.h) is used.

| name      | default | description                                                                 |
|-----------|---------|-----------------------------------------------------------------------------|
| ISEED     | 0       | seed for the random number generator, if 0 a random seed is generated       |
| EVENTS    | 10000   | number of generated events                                                  |
| NBIN      | 40      | number of bins for histograms in $\rho$, $x$, 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 $B$                                                  |
| NCS       | 3       | number of partons in the nucleon                                            |
| RWSA      | -1      | 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    | -1      | deformation parameter $\beta_2$, nucleus $A$                               |
| BETA4A    | -1      | deformation parameter $\beta_4$, nucleus $A$                               |
| ROTA_THETA| -1      | rotation parameter (angle $\theta$), -1 - random rotation, nucleus $A$     |
| ROTA_PHI  | -1      | rotation parameter (angle $\phi$), -1 - random rotation, nucleus $A$       |
| RWSB      | -1      | Woods-Saxon radius for the distribution of centers, nucleus $B$ [fm]        |
| AWSB      | 0.459   | Woods-Saxon width, nucleus $B$ [fm]                                         |
| BETA2B    | -1      | deformation parameter $\beta_2$, nucleus $B$                               |
| BETA4B    | -1      | deformation parameter $\beta_4$, nucleus $B$                               |
| ROTB_THETA| -1      | rotation parameter (angle $\theta$), -1 - random rotation, nucleus $B$     |
| ROTB_PHI  | -1      | rotation parameter (angle $\phi$), -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 $A$                    |

Continued on Next Page...
Table A.1 – Continued

| name       | default | description                                                                 |
|------------|---------|-----------------------------------------------------------------------------|
| WFB        | 0       | the w parameter of the Fermi distribution, nucleus B                        |
| CD         | 0.9     | closest allowed distance between centers of nucleons [fm]                   |
| SNN        | -1      | NN (parton-parton) “wounding” cross section [mb]                            |
| SBIN       | -1      | NN (parton-parton) 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         | 1.      | Poisson, Gamma or NegBin parameter for wounded                              |
| Ubin       | 1.      | Poisson, Gamma or NegBin parameter for binary                               |
| Vw         | 2.      | Negative binomial variance, wounded nucleons                                |
| Vbin       | 2.      | 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         | 1.0     | central value of the Gaussian wounding profile                             |
| GAMA       | -1      | central value of the Gamma wounding profile                                 |
| OMEGA      | -1      | relative variance of cross-section fluctuations for the Gamma wounding profile |
| SCALEA     | 1.      | scale parameter for the size of the nucleus (cluster version)              |
| SIGMAA     | 1.      | standard deviation of x,y,z coordinates of nucleons in the alpha cluster    |
| SIGMABISA  | 1.      | standard deviation of x,y,z coordinates of nucleons in the 3He cluster or nucleon no. 9 |
| SCALEB     | 1.      | scale parameter for the size of the nucleus (cluster version)              |
| SIGMAB     | 1.      | standard deviation of x,y,z coordinates of nucleons in the alpha cluster    |
| SIGMABISB  | 1.      | standard deviation of x,y,z coordinates of nucleons in the 3He cluster or nucleon no. 9 |
| QSCALE     | -1      | scale parameter in the parton distribution function, f(r) = r^2 * \(exp(-r/QSCALE)\), QSCALE = 1/(4.27/Sqrt(3/2)) |

Continued on Next Page...
| name  | default | description |
|-------|---------|-------------|
| DS    | -1      | source smearing parameter |
| ECM   | -1      | center of mass energy of the colliding system [GeV] |
| 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 |
| 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 2
A typical output to the console from GLISSANDO3.

user@host: ~/GL3$ ./glissando3
Start: Mon Nov 12 15:36:16 2018

******************************************************************************
GLISSANDO 3 ver. 3.111
ver. 3: http://arxiv.org.abs/xxxx.xxxx
ver. 2: Computer Physics Communications 185 (2014) 1759, arXiv:1310.5475
ver. 1: Computer Physics Communications 180 (2009) 69, arXiv:0710.5731
******************************************************************************
Simulation of nuclear collisions in Glauber models
******************************************************************************
parameters reset from default in input/input.dat:
EVENTS 2000
NUMA 208
NUMB 208
ECM 2760

generates Root output file output/glissando.root

number of events: 2000

208+208 @ sqrt(s_NN)=2760GeV

Woods-Saxon: RA=6.40677fm, aA=0.459fm, dA=0.9fm
Woods-Saxon: RB=6.40677fm, aB=0.459fm, dB=0.9fm

NUCLEON MODEL
mixed model: sig_w=61.9917mb, sig_bin=61.9917mb, alpha=0.12
RDS distribution scale with u=1 (wounded) and u=1 (binary)
gamma wounding profile, G=0.972569, omega=0.586854
source smearing width: 0.4 fm
acceptance window: b_min=0fm, b_max=25fm, Nw_min=2, Nw_max=100000

event: 2000 (100%)

Some quantities for the specified acceptance window
(+/- gives the e-by-e standard deviation):
A+B cross section = 7226.7mb (makes sense for min. bias)
efficiency (accepted/all) = 36.8053%
N_w = 113.994 +/- 114.84
RDS: 93.5426 +/-107.285

Finish: Mon Nov 12 15:37:04 2018
(0h:0m:48s)
******************************************************************************