

# GLISSANDO 3

## the known software tool with new possibilities

Grzegorz Stefanek<sup>1</sup>, Piotr Bożek<sup>2</sup>, Wojciech Broniowski<sup>1,3</sup>, Maciej Rybczyński<sup>1</sup>

<sup>1</sup>Jan Kochanowski University, Kielce, Poland

<sup>2</sup>AGH University of Science and Technology, Kraków, Poland

<sup>3</sup>Institute of Nuclear Physics, Kraków, Poland



### Introduction

Variants of the Glauber model, in particular the wounded-nucleon model and its extensions, have become a basic tool in modeling the early stage of relativistic heavy-ion collisions. The Glauber model approach provides initial conditions for the subsequent hydrodynamic evolution. That way the features of nuclei structure, such as distributions of nucleons in nuclei, the nucleus deformation, the nucleon-nucleon correlations, as well as NN cross section show up indirectly in the measured observables.

GLISSANDO [1] is a Glauber Monte-Carlo generator for initial stages of relativistic heavy-ion collisions. Several models were implemented in GLISSANDO: the wounding-nucleon model, the binary collisions model, the mixed model, and the model with hot-spots. The nucleon-nucleon wounding profile defined by the probability density of inelastic nucleon-nucleon collision at the impact parameter  $b$  can be represented in GLISSANDO by hard-sphere, gaussian or gamma approximations with different fluctuations of cross section measured by scaled variance  $\omega$ . The program generates, among others, the variable-axes (participant) two- and three-dimensional profiles of the density of sources in the transverse plane and their Fourier components.

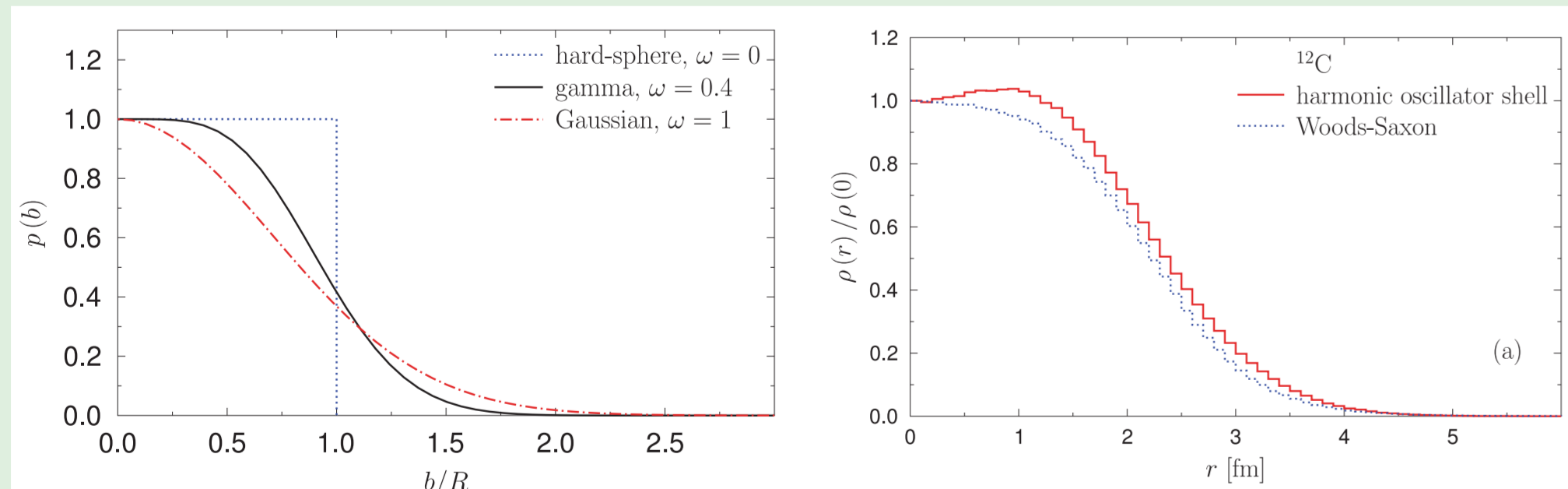
### GLISSANDO - new features

The main features implemented in the previous version GLISSANDO 2 [2] incorporate:

- parametrization of shape of all typical nuclei including light nuclei  $3 \leq A \leq 16$  (a harmonic oscillator shell model density) especially useful in applications for the NA61 experiment [3]
- inclusion of the deformation of the colliding nuclei according the deformed Woods-Saxon density. The deformation effects are relevant for the collisions of deformed Au and U nuclei recently used at RHIC
- possibility of using correlated distributions of nucleons in nuclei
- possibility of overlaying distributions of the produced particles which depend on the space-time rapidity
- inclusion of the negative binomial overlaid distribution in addition to the Poissonian and Gamma distributions (different NN wounding profiles - Fig.1)
- inclusion of core-corona effect

The new features implemented in GLISSANDO 3 [4] include:

- state-of-the art nucleon-nucleon inelastic cross sections and their impact-parameter profiles
- implementation of the wounded quark model (generally wounded parton) model
- possibility of colliding  $^3\text{He}$  and  $^3\text{H}$ , with the distributions from external files
- inclusion of  $\alpha$ -clustered structure of  $^7\text{Be}$ ,  $^{12}\text{C}$ , and  $^{16}\text{O}$  nuclei
- possibility of studying the effect of the proton fluctuations in the framework of the wounded parton model



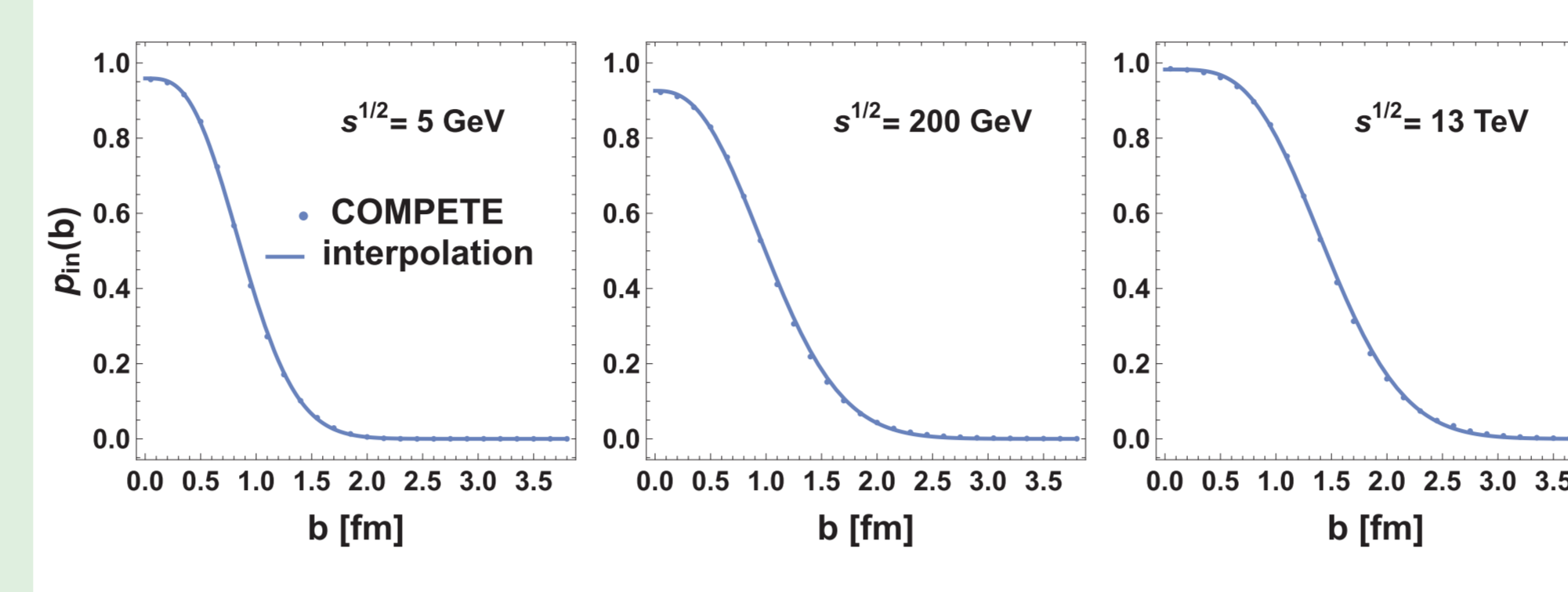
**Fig.1 Left:** Nucleon-nucleon wounding profile function  $p(b)$  for hard-sphere, Gaussian and gamma profiles. Gamma approximation with parameter  $\omega = 0.4$  corresponds to the shape of profile function which reproduces well the TOTEM [5] data on elastic differential cross section measure in proton-proton interactions at  $\sqrt{s_{NN}} = 7000$  GeV. **Right:** The comparison between nuclear density productions given by harmonic oscillator shell model and Woods-Saxon parametrization for  $^{12}\text{C}$  nucleus.

### Inelastic cross sections and inelasticity profiles

The new measurements of the total, elastic and differential elastic cross section make possible new parametrizations of proton-proton and proton-antiproton scattering amplitudes. The COMPETE model used by the COMPAS group parametrizes these amplitudes in very accurate way. In GLISSANDO 3 this parametrization of the data is used as the most complete one. The inelastic profile is simply parametrized by the function:

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

where  $\Gamma(a, z)$  is the incomplete Euler  $\Gamma$  function and  $G(s)$  and  $\omega(s)$  are suitably adjusted parameters such that COMPETE results are reproduced (see Fig.2). The values from the fit are represented with the interpolation functions (Eq.4 in [4]).



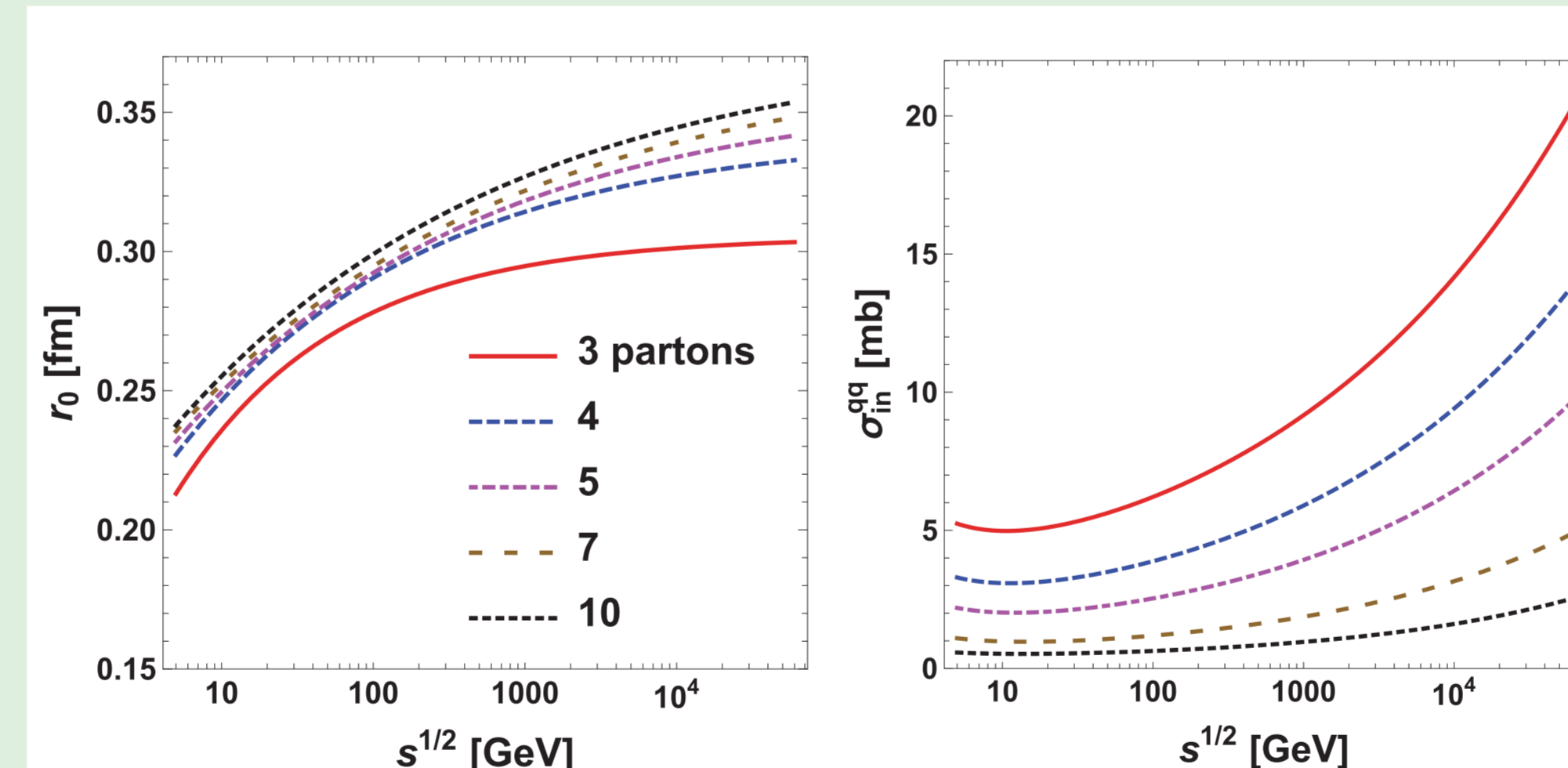
**Fig.2** The inelastic profile as a function of the impact parameter for three sample pp collision energies  $\sqrt{s_{NN}}$ . The points indicate the COMPETE model parametrization, whereas the lines show the interpolation described in the text ([4]).

The use of realistic NN inelasticity profile, as opposed to sometimes used hard-sphere in older software, is phenomenologically important. It leads to proper elastic differential cross section in proton-proton collisions (Fig.2) and it yields sizable effects in standard observables in ultra-relativistic nuclear collisions. In particular, the effect on ellipticity of the fireball can be significant (10%-20% reduction for peripheral A-A collisions as discussed in [6]).

### Wounded partons

In the wounded quark model the valence quarks play the role of elementary scatterers. In the approach implemented in GLISSANDO 3 the multiplicity of produced charged hadrons ( $dN_{ch}/d\eta$ ) is linearly scaled with the number of wounded quarks in a given reaction and centrality class ( $Q_w$ ).

The implementation of the model, described in [7], based on assumption that the nucleons consists on  $p=3$  partons and brings two parameters:  $r_0(s;p)$  which control size of the nucleon built of partons as well as  $\sigma_{\text{in}}^{\text{qq}}$  which is the parton-parton inelastic cross section. The values of parameters are chosen in such a way that the resulting NN collision profile reproduces the COMPETE parametrization. The dependence of these parameters on the energy and the number of partons is shown on Fig.3.

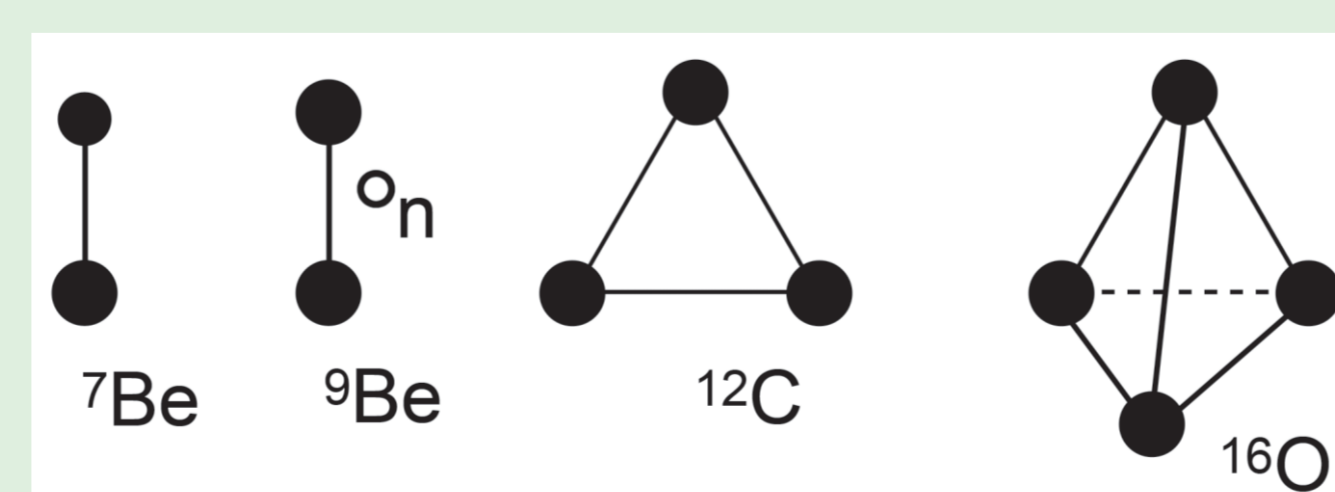


**Fig.3** The energy dependence of the two parameters of the wounded parton model implementation in GLISSANDO 3 for various number of partons  $p$  ([4]).

With chosen parametrization the NN inelasticity profile is the same, within a few percent, if one uses nucleons or partons as elementary scatterers.

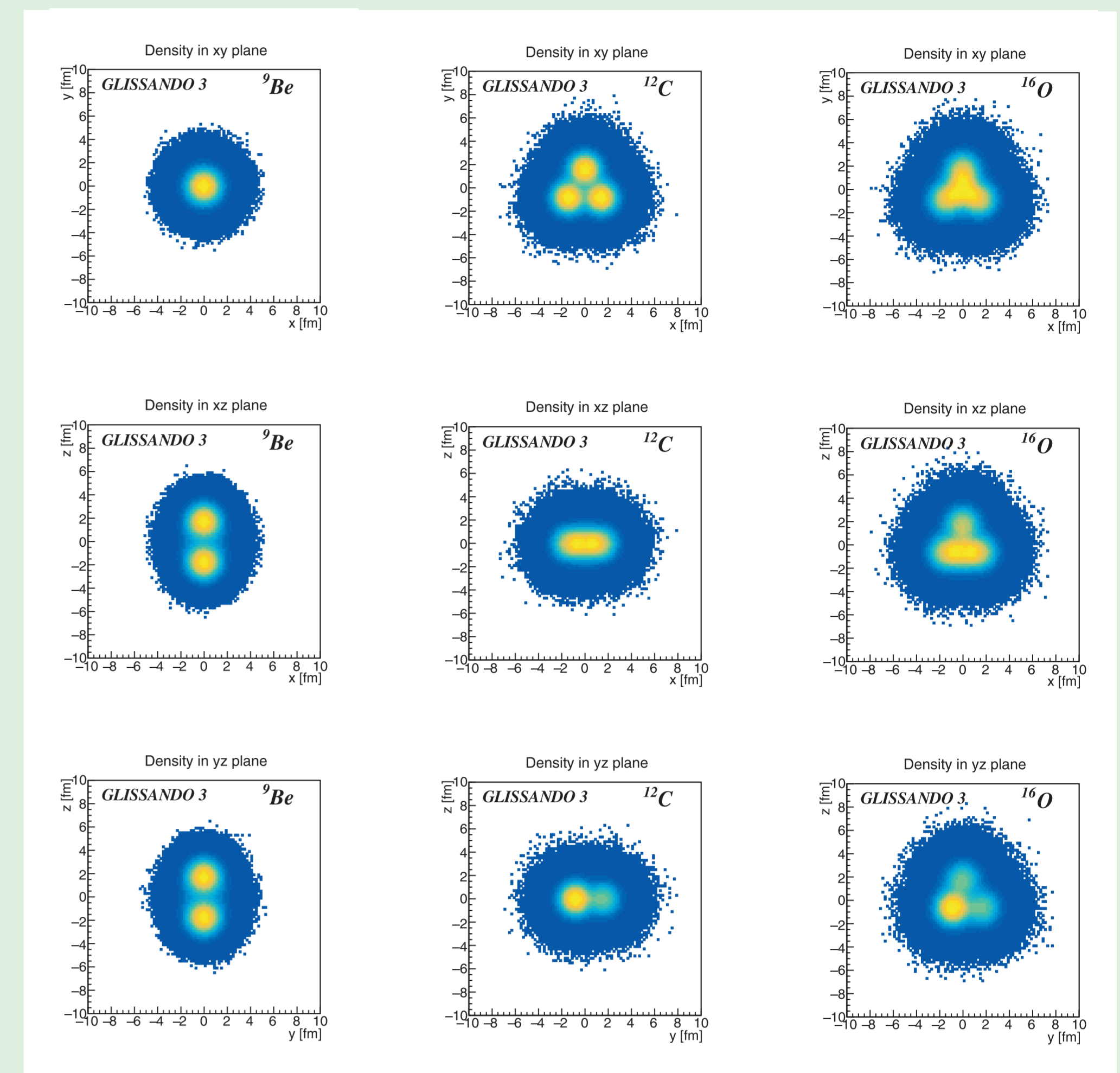
### Reactions with light clustered nuclei

GLISSANDO 3 offers a possibility to collide nuclei whose structure exhibits clustering. Specifically, it was implemented  $^7\text{Be}$  as  $\alpha + ^3\text{He}$ ,  $^9\text{Be}$  as  $2\alpha + \text{neutron}$ ,  $^{12}\text{C}$  as  $3\alpha$ , and  $^{16}\text{O}$  as  $4\alpha$  (Fig.4).



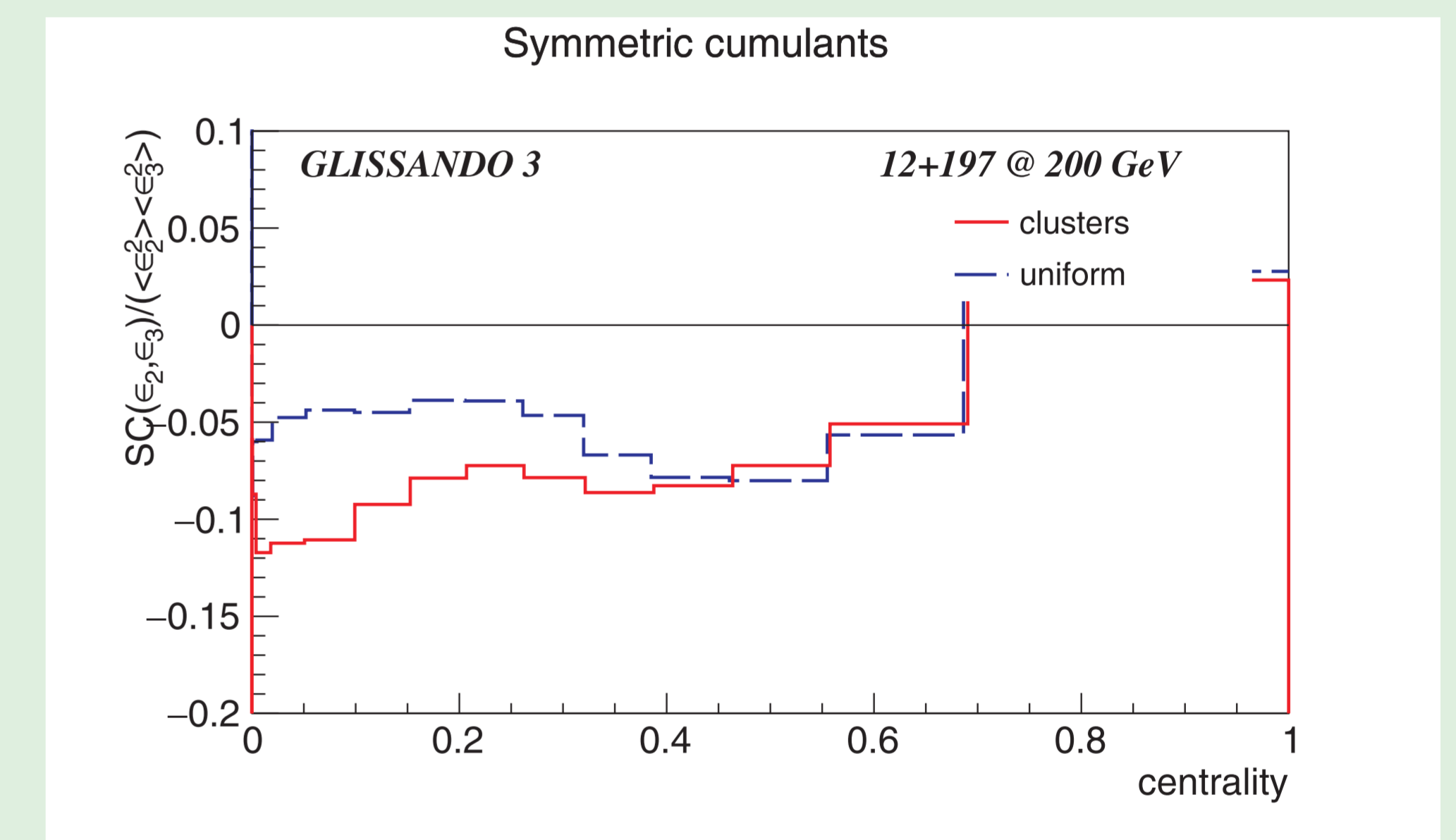
**Fig.4** The cartoon of the geometry of light clustered nuclei. The bigger filled blobs represent  $\alpha$  cluster, the smaller filled blob the  $^3\text{He}$  cluster, and the empty blob the extra neutron in  $^9\text{Be}$  ([4]).

The geometric parameters are adjusted in such a way that the one-body nuclear distributions are matched. The positions of clusters are first arrange like on Fig.4 and the distribution of the centers of nucleons in each cluster is randomly generated according the Gaussian distribution. The positions of the nucleons are generated sequentially, switching between subsequent clusters, until all the nucleons are placed.



**Fig.5** The density profiles of light clustered nuclei  $^9\text{Be}$ ,  $^{12}\text{C}$ ,  $^{16}\text{O}$ .

There are many physical studies which can be done with light clustered nuclei, for example looking for clusterization signatures in harmonic flow patterns. 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) is shown in Fig.6.



**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  $SC(a, b) = \langle a^2 b^2 \rangle - \langle a^2 \rangle \langle b^2 \rangle$  ([4]).

The Monte-Carlo models provide the positions of point-like sources (wounded objects) in the transverse plane. Physically, the sources should have transverse size, which is accomplished by smoothing them with a Gaussian form:

$$\Delta(x, y; x_i, y_i) = \frac{1}{\pi \sigma^2} \exp\left[-\frac{(x - x_i)^2 + (y - y_i)^2}{\sigma^2}\right]$$

Smearing width  $\sigma$  is necessary in forming the initial condition for subsequent hydrodynamic evolution. It also increases the size of the fireball and reduces the eccentricities, which are its basic characteristics. The effect is particularly relevant for small systems and especially for light clustered nuclei.

### References

- [1] W.Broniowski, M.Rybczynski, P.Bozek, Comput. Phys. Commun. 180, 69 (2009).
- [2] M.Rybczynski, G.Stefanek, W.Broniowski, P.Bozek, Comput. Phys. Commun. 185, 1759 (2014).
- [3] <https://na61.web.cern.ch/na61/xc/index.html> and publications there
- [4] P. Bozek, W.Broniowski, M.Rybczynski, G.Stefanek, Comput. Phys. Commun. 245 (2019) 106850; arXiv:1901.04484 [nucl-th].
- [5] G.Antchev *et al.*, Europhys. Lett. 95, 41001 (2011).
- [6] G.Antchev *et al.*, Europhys. Lett. 101, 21002 (2013).
- [7] M.Rybczynski, W.Broniowski, Phys. Rev. C 84 (2011) 064913.
- [7] P. Bozek, W.Broniowski, M.Rybczynski, Phys. Rev. C 94, 014902 (2016).