The impact of the fragmentation processes of spectators on the centrality determination in heavy-ion collisions

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A heavy-ion collision experiment has a wide range of physical observables that are dependent on the initial geometry. Centrality is used to describe the initial geometry of collisions in experiments. Spectator fragments, or pieces of the colliding nuclei that were not involved in the collision, can be used to determine centrality. In this work, we discuss how processes of spectator fragmentation may impact the centrality determination procedure. These effects are demonstrated using the DCM-QGSM-SMM model, which realistically reproduces fragmentation processes, and the published results of the NA61/SHINE experiment.

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Introduction

Physical observables, which is used to study strongly interacting matter formed in relativistic heavy-ion collisions (e.g. collective anisotropic flow, particle yields), depend on the initial collision geometry [1, 2]. The initial collision geometry can be defined by the impact parameter (b), the number of binary nucleon-nucleon collisions (N_{coll}), the number of participating nucleons (N_{part}), and the number of spectator nucleons (N_{spec}), etc. Since these model parameters cannot be measured directly in experiments, the concept of centrality is introduced to map the initial geometry parameters with the experimentally measured observables (so-called centrality estimators). The energy of spectator fragments detected in forward hadron calorimeters can be used as a centrality estimator. The centrality class corresponding to a specific energy range $E_1 - E_2$ is defined by the following formula:

$$C_E = \frac{1}{\sigma_{inel}^{AA}} \int_{E_1}^{E_2} \frac{d\sigma}{dE} dE. \quad (1)$$

where σ_{inel}^{AA} is a total inelastic nucleus-nucleus cross-section and $d\sigma/dE$ is the differential cross-section of a nucleus–nucleus collision. To compare the total energy of spectators detected in a forward hadron calorimeter with the geometric parameters of collisions, a centrality determination method is required. The novel data-driven centrality determination approach based on

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Monte Carlo sampling of spectator fragments was presented in our earlier work [3]. The method is based on the output of the Monte Carlo version of the Glauber model (MC Glauber) [4, 5], which provides information about the geometry properties of collisions: impact parameter b and number of spectators N_{spec}. In order to establish a connection between the initial geometry parameters (b and N_{spec}) with the energy of spectators detected in a forward hadron calorimeter, a large sample of the fragmentation model (e.g. DCM-QGSM-SMM [6, 7]) events has been generated. The model events were run through the entire chain of realistic hadron calorimeter simulations based on the GEANT4 platform and realistic reconstruction algorithms. This sample is used to evaluate steps of the centrality determination procedure described below.

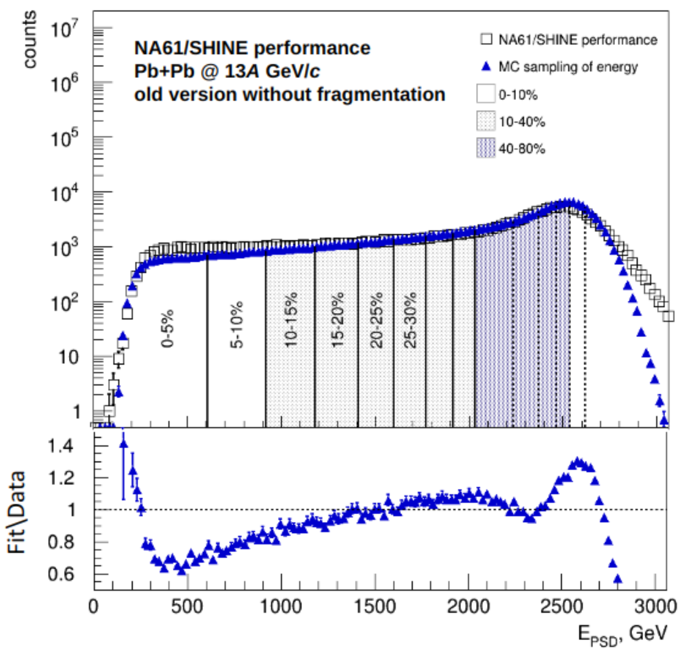

Figure 1. The distribution of the total energy of spectator fragments E_{PSD} in the PSD calorimeter for Pb+Pb collisions at p_{beam} = 13A GeV/c ($\sqrt{s_{NN}}$ = 5.12 GeV). The published NA61/SHINE experimental data [8] are shown by open boxes and the results of the approximation of PSD energy distribution using a Monte-Carlo sampling of spectator fragments [3] are shown by closed triangles. The figure is taken from [3].

Based on the number of spectators (N_{spec}) known from the MC-Glauber model, the total energy of spectators is determined [3]. Using the free parameters μ and k, the energy of the spectators is sampled in accordance with the Gaussian distribution $G(\mu, k)$ [9, 10]. The total energy E_{tot} is proportional to the energy of all detected spectators: $E_{tot} = E_0 + \sum_{i=1}^{N_{spec}} E^i_{spec}$, where N_{spec} is the number of spectator nucleons from MC Glauber model and parameter E_0 describes the offset at low energies due to the contribution of produced particles (participants) in forward rapidity region [3]. The produced total energy E_{tot} distribution can then be fitted to the experimentally measured one E_{exp}. A minimization procedure is applied to find the optimal set of parameters (μ, k, E_0) that result in the smallest fitting criteria χ^2. Centrality classes are defined by cuts on E_{exp} and corresponding parameter values (b, N_{spec} , . . .) for each class are determined from the MC-Glauber model. The validity of the method was verified using published data from the fixed-target NA61/SHINE experiment (SPS, CERN) for Pb+Pb collisions at beam momentum p_{beam} = 13 A GeV/c ($\sqrt{s_{NN}}$ = 5.12 GeV) [8]. The Projectile Spectator Detector (PSD) of NA61/SHINE experiment is a forward hadron calorimeter with the transverse and longitudinal segments assembled of sampling lead/scintillators modules [11]. The acceptance of the PSD allows us to detect projectile spectators and produced particles emitted in forward rapidity region. Figure 1 shows the distribution of the total energy of spectator fragments E_{PSD} in the PSD calorimeter (open boxes) for NA61/SHINE experimental data [8]. The results of the approximation of PSD energy distribution using a Monte-Carlo sampling of spectator fragments with Gaussian approximation for the energy of spectators are shown by closed triangles [3]. The 5% centrality classes defined with Monte-Carlo sampling normalization are indicated with black solid vertical lines. The distribution of the total energy of spectators for the most central events is poorly described in Fig 1 because, the developed algorithm does not account for the fragmentation of spectator matter [3].

This work discusses the implications of including fragmentation processes in a centrality determination method based on Monte Carlo sampling of spectator fragments.

Fragmentation of spectator matter with the DCM-QGSM-SMM model

To evaluate the impact of the fragmentation processes, one can use a theoretical model that includes a description of fragmentation mechanisms. In the present study, the DCM-QGSM-SMM model [6, 7] is used for this purpose. This hybrid model consists of several stages. In the first stage, the initial geometry of collision is determined: the impact parameter b and the initial positions of the nucleons according to the Woods-Saxon distribution. Next, the code executes the DCM (Dubna Cascade Model) portion, which is based on the Boltzmann-Uehling-Uhlenbeck system of relativistic kinetic equations solved via Monte Carlo methods. The DCM is a universal intranuclear cascade model for describing leptonic, hadronic, and nuclear-nuclear interactions and particle production in them. To make this model applicable at high energies, the DCM is hybridized with the QGSM (quark-gluon string) model. QGSM models hadron collisions at energies above 5 GeV, describing binary collisions within the framework of a semi-classical independent quark-gluon jet approach. After the completion of the stage of intranuclear production of cascade particles, the formation of nuclear fragments continues. First of all, the coalescence model is used, which produces high-energy light spectators' fragments such as deuterons, tritons, and helium. The process of

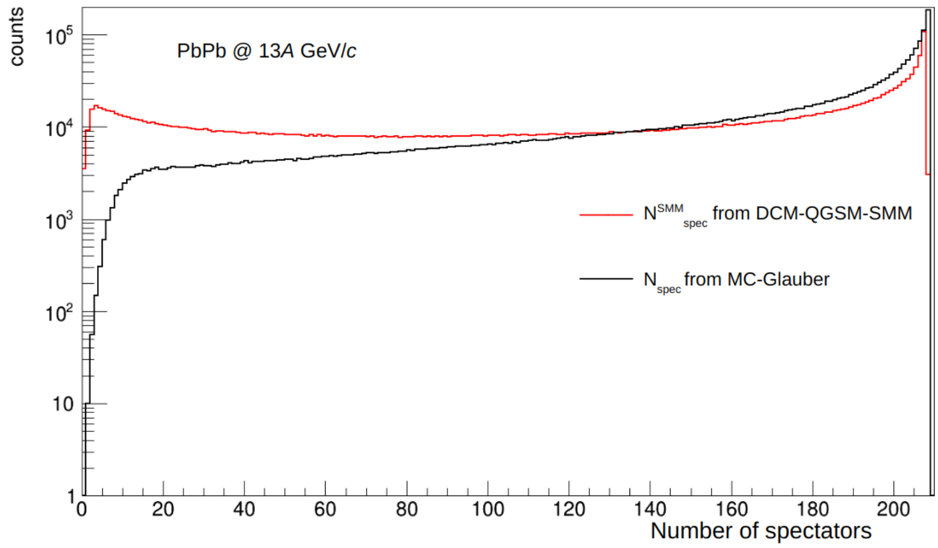

Figure 2. Comparison between the distribution of the number of spectators generated with the MC-Glauber model (black line) and the distribution of the number spectators in the final state, produced with the DCM-QGSM-SMM model (red line).

coalescence occurs through interactions between nucleons born at the cascade stage. Light fragments that are heavier than ^{4}He are inferred using three different concepts: the Fermi breakup, coalescence, and statistical multifragmentation (SMM). The Fermi breakup applies to all fragments with a mass of less than 13 daltons. Some light fragments can combine with cascade nucleons through coalescence. After all cascade particles leave the participants' region, the remaining thermalized nuclear fragments pass through the SMM (statistical multifragmentation) stage. According to SMM, such a thermalized system can allow multiple fragments to be produced. Light fragments formed at this stage can also lead to Fermi break-up if their mass is less than 13. Other unstable fragments can also decay according to decay or light fragment evaporation models [6, 7].

In the first version of the centrality procedure based on the Monte Carlo sampling of spectator fragments [3] the N_{spec}, which is being used in the calculation of the total energy of spectators, was taken from the output of the MC-Glauber model. The total number of spectator nucleons in the final state N_{spec}^{SMM} can be different from the N_{spec} due to the complicated process of the spectator fragments formation, described above. To evaluate the difference between these two values, the hybrid of the MC-Glauber and DCM-QGSM-SMM models is created. In this hybrid, the initial state of the heavy ion collisions is determined in the DCM-QGSM-SMM model. Next, the MC-Glauber and DCM-QGSM-SMM models are applied to the identical events. Therefore, all events have information about initial geometry parameters (e.g. N_{spec}) calculated using the MC-Glauber model and final state parameters (e.g. N_{spec}^{SMM}) modeled using the DCM-QGSM-SMM model. The comparison

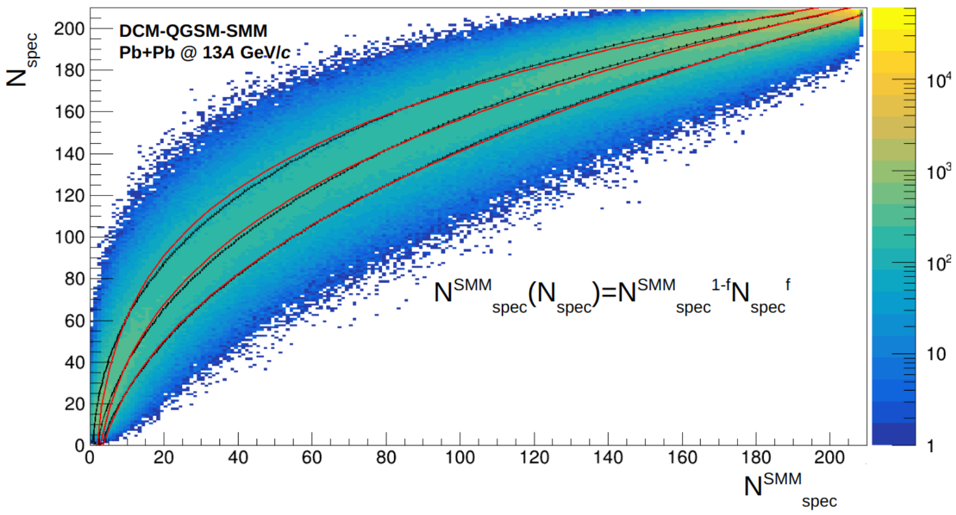

Figure 3. The correlation between N_{spec} generated with the MC-Glauber model and the number of spectators N^{SMM}_{spec} produced with the DCM-QGSM-SMM model. Black lines: mean values and widths of N^{SMM}_{spec} distributions for each N_{spec} slice, red lines: fits of the corresponding black lines.

between N_{spec} and N^{SMM}_{spec} for the Pb-Pb collisions at $p_{beam} = 13$ AGeV/c is shown in the Fig. 2. It can be seen that the main difference between these two distributions occurs in the most central events. Therefore, in the new version of the centrality determination method, the N^{SMM}_{spec} is used to estimate the total energy of the spectators.

Results for the updated centrality determination procedure

Figure 3 shows the correlation between N_{spec} and N^{SMM}_{spec}. Black lines show the mean values and widths of N^{SMM}_{spec} distributions for each N_{spec} slice. The red lines show the result of the fit with power function $N^{SMM}_{spec}(N_{spec}) \sim N^{f}_{spec}$. Finally, it is proposed that the following formula can be used to calculate N^{SMM}_{spec}:

$$N^{SMM}_{spec}(N_{spec}) = A^{1-f} N^{f}_{spec}, \tag{2}$$

where A is the mass of the colliding nuclei and f is a free parameter that should be determined by adjusting the experimental distribution of spectator energy. In summary, the additional step of computing N^{SMM}_{spec} based on N_{spec} known from the MC-Glauber model is introduced in the procedure described in [3].

The validity of the updated procedure for centrality determination in Pb-Pb collisions at $p_{beam} = 13$ AGeV/c has been verified using the same data recorded with the PSD detector of NA61/SHINE experiment [3,8]. The result of the fit of the PSD energy distribution is shown in Fig. 4. The resulting fit parameters are: $\chi^2/NDF = 8.06$, $\mu = 11.84$, $k = 8.15$, $f = 0.22$, fit range: $E^{min}_{PSD} = 200$, $E^{max}_{PSD} = 3000$. The new version of the procedure better reproduces the knee of the most central events, see Fig. 4. However, there

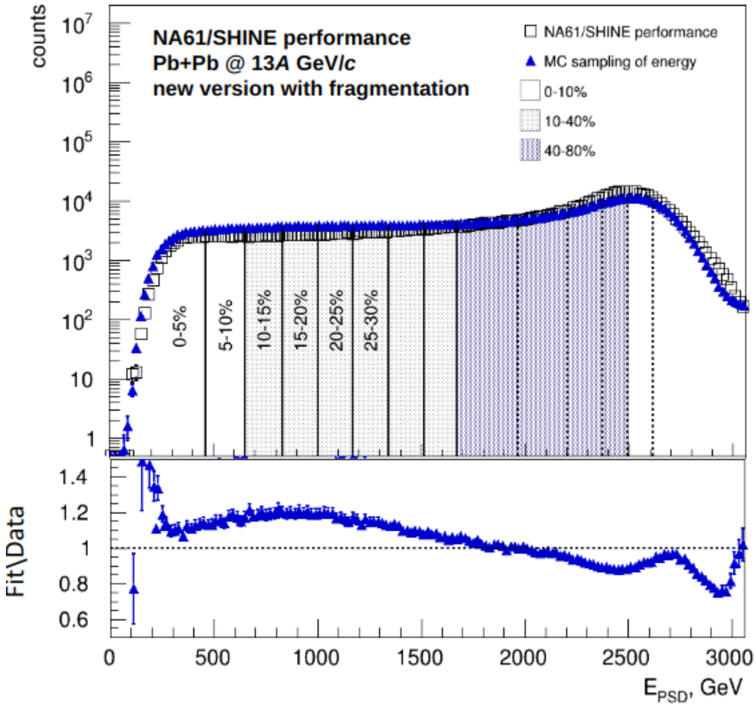

Figure 4. The results of the approximation of PSD energy E_{PSD} distribution using the updated method of Monte-Carlo sampling of spectator fragments.

is still an imbalance between the number of peripheral and central events, which can be seen in the ratio in Fig. 4. The introduction of a more realistic mixture of particles generated in the last phase of Monte Carlo sampling for spectator energy should correct this imbalance.

Conclusions

In conclusion, the DCM-QGSM-SMM model results are used to examine the effects of incorporating the fragmentation processes into the centrality determination method based on the energy of spectators. Using these studies, the method for centrality determination in heavy ion collisions based on Monte Carlo sampling of spectator fragments is improved. The validity of the updated procedure has been verified on the published data of NA61/SHINE experiment for Pb-Pb collisions at $p_{beam} = 13$ AGeV/c ($\sqrt{s_{NN}} = 5.12$ GeV).

Acknowledgments

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