JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE INTEREST PROGRAMME

Study of bulk properties of the medium produced in heavy ion collisions at MPD

Supervisor:

Dr. Alexey Aparin

Student:

Pedro Antonio Nieto Marín,

Universidad Autónoma de Sinaloa

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Abstract

To make an analysis of identified charged particles ($\pi^{\pm}$, $K^{\pm}$ and $p^{\pm}$) formation at midrapidity region of $|\eta| < 0.5$ we calculated centrality classes for Bi+Bi collisions at center-of-mass energies of $\sqrt{S_{NN}} = 7.7,\ 9,\ 9.46\ GeV$ generated by the statistical Monte Carlo generator model: Ultrarelativistic Quantum Molecular Dynamics (UrQMD). We corrected the information about the distance of closest approach (DCA) from the data reconstructed by the TPC in the MpdRoot framework and finally obtained the multiplicity distributions to calculate the centrality classes.

Introduction

The Quark-Gluon Plasma (QGP) has been studied to understand the first instants of the universe (about a microsecond after the Big Bang) and its properties. Large experimental facilities such as LHC and RHIC are looking for physical observables to help us find the phase transition from hadronic matter to the QGP at which the deconfinement of qurks and gluons occurs in the quantum chromodynamics (QCD) phase diagram. The main goal is to form and characterize a state of unconfined quarks and gluons in local thermal equilibrium in the heavy ion collisions to investigate the properties of the hadronic matter and recreate the QGP.

Figure 1 shows a conjecture of the QCD phase diagram showing the transitions between the phases of hadronic matter and QGP. The relationship between chemical potential (μ_B) and temperature (T) are the main parameters to understand the properties of these created matter [1]. Lattice QCD has been of great relevance as the main tool for the theoretical study of phase transitions predictions for more than 40 years, but only at a chemical potential close to zero it has been very successful in predicting observables in very high energy experiments at LHC or RHIC. However, it presents a very big problem in obtaining predictions for a chemical potential greater than zero, which is fundamental if we want to investigate the phase transitions and the critical point.

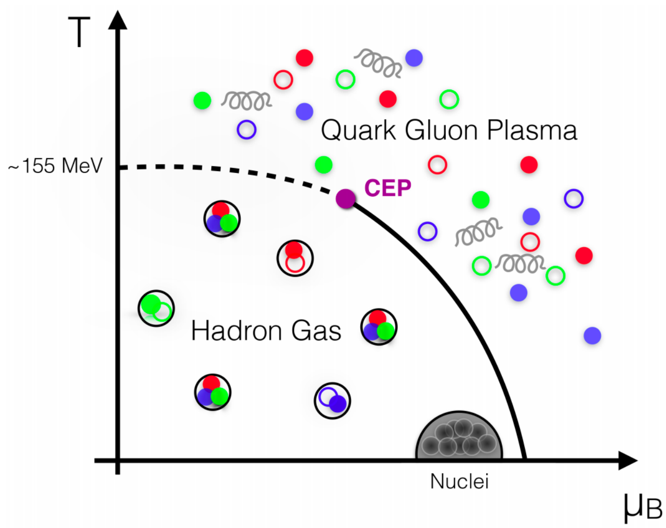

Figure 1: Conjeture of the QCD phase diagram with the temperature (T) on the vertical axis and the chemical potential (μ_B) on the horizontal axis with a hypothetical phase transition and critical end point between the hadron gas and the QGP. Figure taken from [1].

These collisions created in the experiments are the only way to heat and compress nuclear matter at significant temperatures and create a region with very high densities. In these experiments there are only two tools that can be controlled for the study of heavy ion collisions: the species of ions to collide and the center of mass energy. There are certain data that cannot be observed directly in the experiment, so it is very important to do phenomenological studies to learn more about them. The detectors of the experiment are built around the interaction point of the collision and are capable of measuring observables such as particle yields and spectra, event-by-event fluctuations of multiplicity and transverse momentum as well as the corresponding integral distributions.

The international mega-science project "NICA complex" is aimed to study the properties of nuclear matter in the region of the maximum baryonic density [2]. Its main goal is to work on Au+Au collisions in the energy range of $\sqrt{S_{NN}} = 4 - 11$ GeV, relatively low compared to LHC and RHIC. Experimental data on hadron production properties at SPS (CERN) suggest that this transition occurs within the NICA energy range.

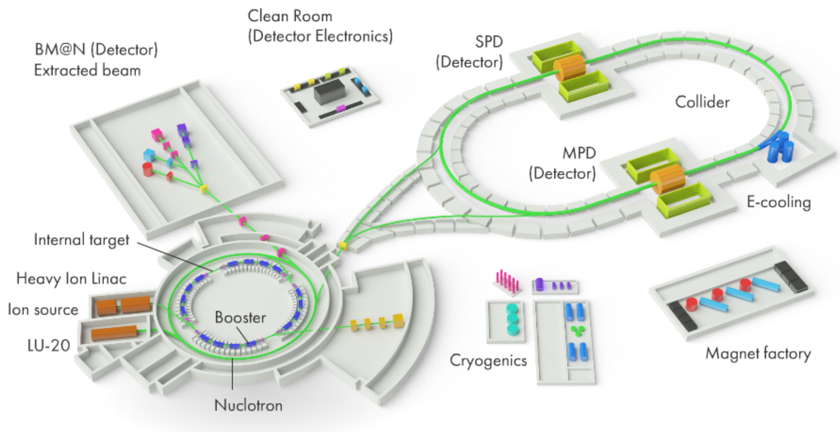

Figure 2: NICA schematic layout

Figure 2 shows a schematic layout of the NICA with the main components:

- **Booster:** The Booster, a superconducting synchrotron, accumulates, cools and further accelerates heavy ions to 600 MeV/n energy. The booster's circumference is 211 meters, its magnetic structure is mounted inside the yoke of the Nuclotron.

- **Nuclotron:** The Nuclotron accelerator having maximum magnetic rigidity of 45 Tm and the circumference of 251.52 m provides the ion acceleration to the experiment energy [3].

- **Spin Physics Detector (SPD):** The SPD is aimed to study the polarized beams of protons and deuterons to study the particle spin physics. Measurements of asymmetries in the lepton pair (Drell-Yan) production in collisions of non-polarized, longitudinally and transversely polarized proton and deuteron beams are suggested to be performed using the SPD.

- **Baryonic Matter at Nuclotron (BM@N):** The BM@N final goal is to perform a research program focused on the production of strange matter in heavy-ion collisions at beam energies between 2 and 6A GeV.

- **Multi-Purpose Detector (MPD):** The global scientific goal of the NICA/MPD project [4] is to explore the phase diagram of strongly interacting matter in the region of highly compressed baryonic matter [5]. The MPD experimental program includes simultaneous measurements of observables that are presumably sensitive to high nuclear density effects and phase transition. The MPD detector consists of many sub-detectors, each with a specific task. Figure 3 shows the barrel in which the main tracker detector is the Time Projection Chamber (TPC) with the internal tracking system (IT). TPC and IT are in charge of determining a precise tracking system, momentum determination and vertex reconstruction. The Time-of-Flight detector (TOF) is crucial for the particle identification and is complemented by the TPC and IT detector with the energy loss measurements. The zero degree calorimeter (ZDC) should provide event centrality and event plane determination, and also measurement of the energy deposited by spectators.

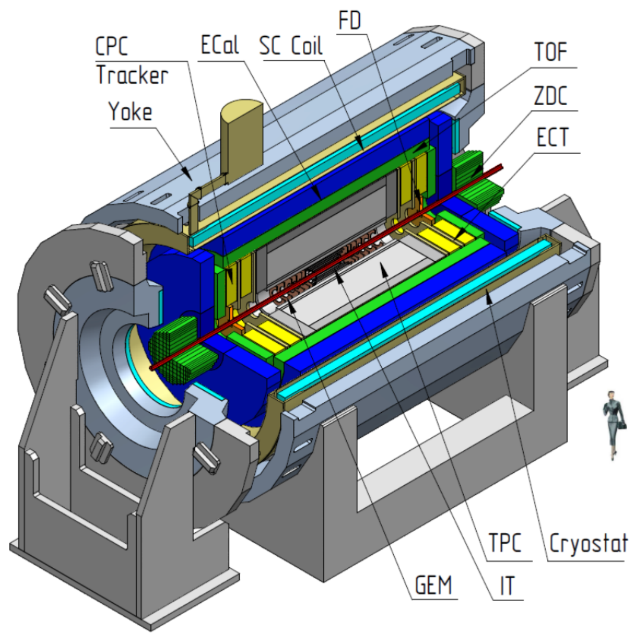

Figure 3: A general view of the MPD detector.

The events classification by centrality of the heavy ion collisions is a key topic of the experiments studying a strongly excited (hot and/or dense) hadronic matter properties. It is crucial to select central collisions to study the most excited nuclear matter. Observables analysis in different centrality intervals allows to study space–time picture of the nuclear–nuclear collisions as well as hadronic matter properties, both of which impossible without centrality data involving. One of the most important observables in the experiment are the multiplicity classes, which are related to the centrality classes by impact parameter ranges (b) of the collisions.

Since the MPD/NICA complex is under development, it is of vital importance to have a simulation framework to generate studies prior to the first collider runs. The MpdRoot framework [6] is based on FairRoot and provides a powerful tool for detector performance studies, development of algorithms for reconstruction and physics analysis of the data. Extended set of event generators for heavy ion collisions are used (UrQMD, LAQGSM, HSD).

In particular, the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) model [7] is a microscopic model used to simulate and study (ultra)relativistic heavy ion collisions of pp, pA and A+A in the energy range from Bevalac and SIS ($\sqrt{S_{NN}} \sim 5$ GeV) up to AGS, SPS and RHIC ($\sqrt{S_{NN}} \sim 200$ GeV). It represents a Monte Carlo solution of a large set of coupled partial integro-differential equations for the time evolution of the various phase space densities of particle species with a microscopic transport theory based on the covariant propagation of all hadrons in classical trajectories.

Project goals

- Correct the DCA values of the reconstructed TPC data from Bi+Bi collisions at center-of-mass energies of $\sqrt{S_{NN}} = 7.7$, 9, 9.46 GeV.
- Get the DCA distributions and make a fit with Gauss function to make primary particles selection in terms of n-sigma.
- Obtain multiplicity distributions with cuts ($|\eta| < 1.5$, $|p_T| < 3$ and primary particles) in the TPC and calculate the centrality classes for each multiplicity range.

Scope of work

We aim to contribute to the studies of bulk properties of this system for incoming run of MPD/NICA. For preliminary results to the first runs on the NICA complex with Bi+Bi heavy ion collisions at low energies, previous studies of first physics are necessary.

Method

For the analysis we used the Monte-Carlo official data from the MPD collaboration which are located at the NICA LHEP computing cluster [8]. Using the available data of UrQMD at the center-of-mass energy of $\sqrt{S_{NN}} = 7.7$, 9, 9.46 GeV for Bi+Bi collisions and statistics of 10^6 events for each energy which are described in [9], [10] and [11] respectively.

DCA correction

The information about the distance of closest approach (DCA) in the current MpdRoot version is based on z-dependent calculations in the 2D transverse plain but is not robust enough for selection of primary tracks. It is necessary to make a correction to the output file of the reconstructed tracks for the new DCA values obtained by 3D helicity fitting method.

For the correction of the DCA values we used the code described in the GitLab of the MpdRoot framework for the flow analysis [12], taking section 1.5 as the starting point for our analysis.

In all steps it was necessary to correct the rootlogon.C macro by changing the line:
"-I$Boost_INCLUDE_DIRS ";** to **"-I$FAIRROOTPATH/include ";

DCA calibration file

Track reconstruction starts from the outermost hits in the TPC, projecting inward assuming an initial primary vertex position at the center of the TPC. It is necessary to obtain the distributions of the DCA values to distinguish primary from secondary particles. The process is divided into 3 parts:

1. Get dca distributions and store them into calibration file.
2. Fit dca distributions via Gauss function to make primary particles selection in terms of n-sigma.
3. Fit p_t dependence of the dca distributions via polynomial function to reduce p_t efficiency loss due to the dca distributions are split into discrete p_t bins

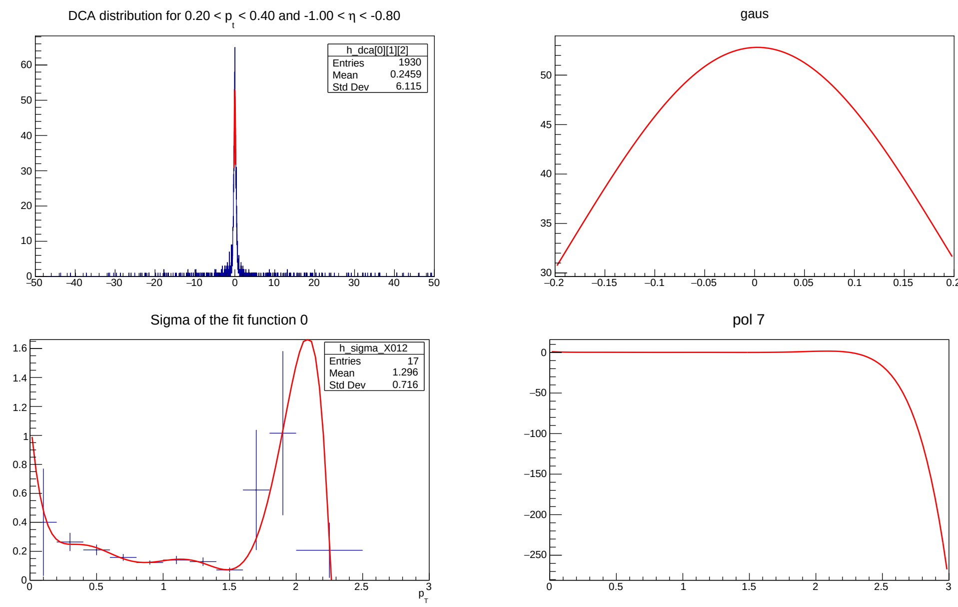

Figure 4: Example of the distribution of DCA values (upper left) with its corresponding fit with the Gaussian function (upper right) and the sigma of the fit function (lower right) with its corresponding fit of the p_T dependence with a polynomial function (lower left) for a small sample of Bi+Bi collisions at $\sqrt{S_{NN}} = 7.7$ GeV.

Centrality calibration file

To obtain the multiplicity distributions, the output files of the reconstructed data with the corrected DCA values of the particle tracks and the output files with the fits with the p_T dependence of the dca distributions (explained in step 3 of the previous section "DCA calibration file") were needed. The macros to get the multiplicity distributions can be found in [13].

Centrality determination

Finally to obtain the centrality classes we use the centrality definition expressed as a function of the multiplicity of charged particles:

$$c = \frac{\int_{N_{max}}^{N_i} \frac{dN_{ev}}{dN_{ch}} dN_{ch}}{\int_{N_{max}}^{0} \frac{dN_{ev}}{dN_{ch}} dN_{ch}} \tag{1}$$

Results

Results for 7.7 GeV

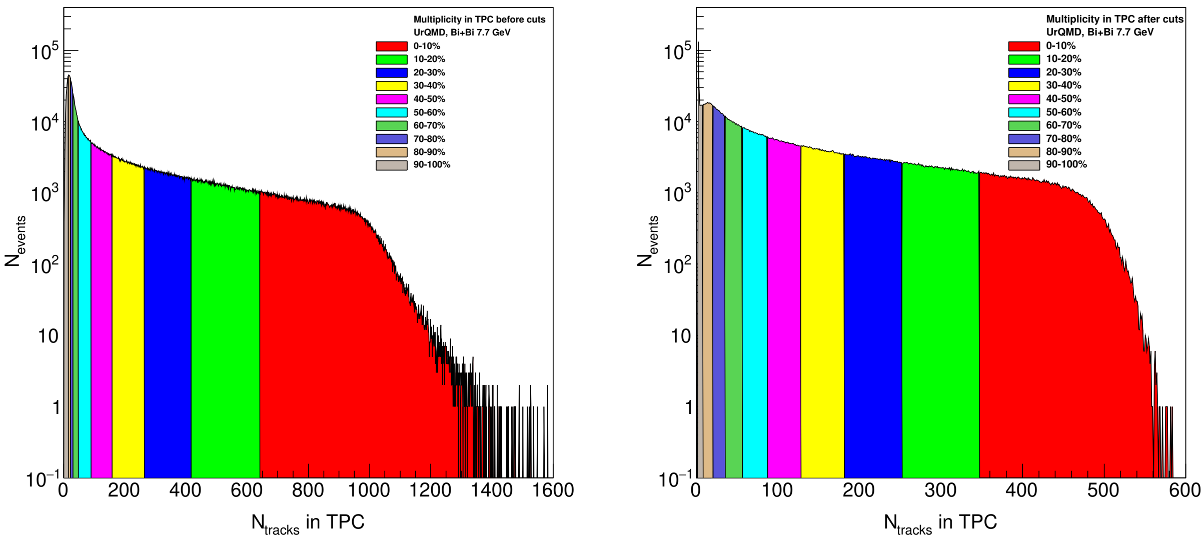

Figure 5: Centrality classes obtained using TPC multiplicity before (left) and after (right) cuts in collisions of Bi+Bi at $\sqrt{S_{NN}} = 7.7$ GeV.

Class %	N_{ch} max	N_{ch} min
0-10	584	346
10-20	346	251
20-30	251	181
30-40	181	127
40-50	127	86
50-60	86	56
60-70	56	34
70-80	34	19
80-90	19	7
90-100	7	0

Table 1: Centrality classes determination for ranges of multiplicity in TPC after cuts in collisions of Bi+Bi at $\sqrt{S_{NN}} = 7.7$ GeV.

Results for 9 GeV

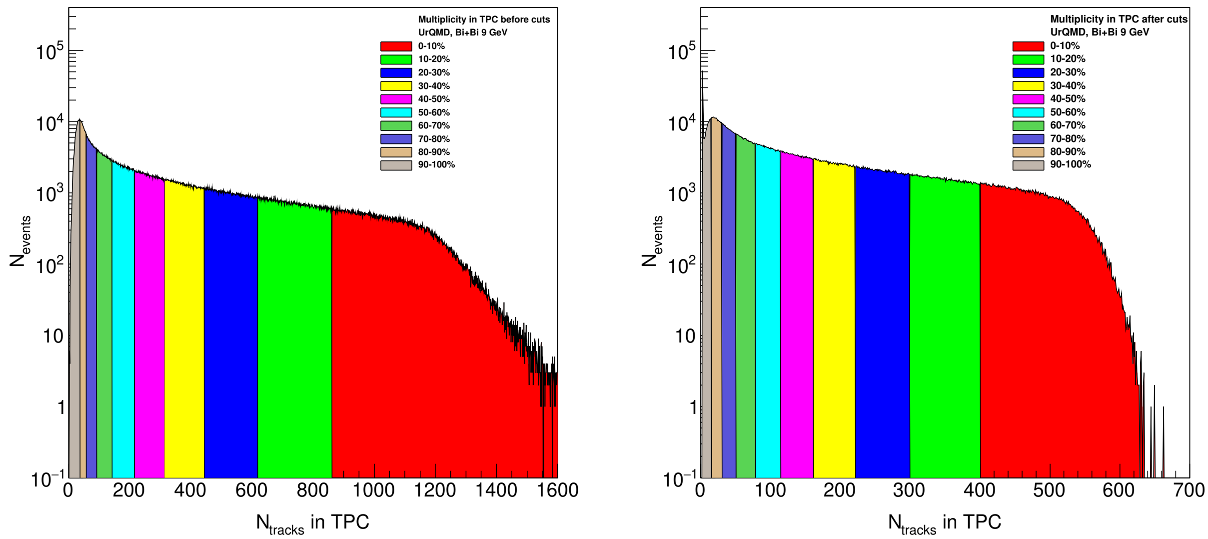

Figure 6: Centrality classes obtained using TPC multiplicity before (left) and after (right) cuts in collisions of Bi+Bi at $\sqrt{S_{NN}} = 9$ GeV.

Class %	N_{ch} max	N_{ch} min
0-10	649	400
10-20	400	298
20-30	298	221
30-40	221	161
40-50	161	114
50-60	114	77
60-70	77	49
70-80	49	30
80-90	30	15
90-100	15	0

Table 2: Centrality classes determination for ranges of multiplicity in TPC after cuts in collisions of Bi+Bi at $\sqrt{S_{NN}} = 9$ GeV.

Results at 9.46 GeV

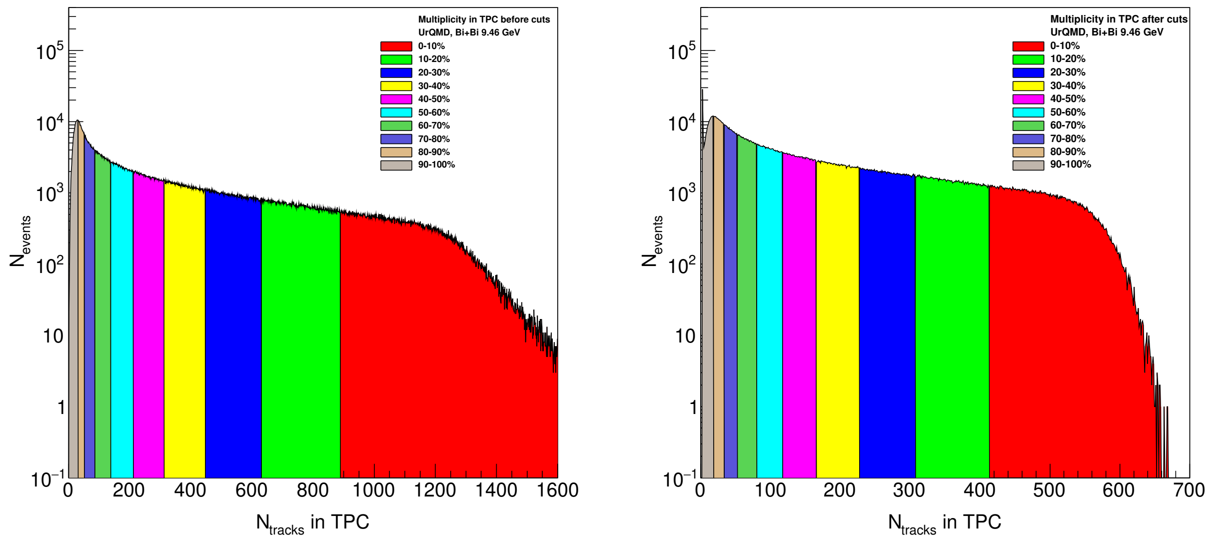

Figure 7: Centrality classes obtained using TPC multiplicity before (left) and after (right) cuts in collisions of Bi+Bi at $\sqrt{S_{NN}} = 9.46$ GeV.

Class %	N_{ch} max	N_{ch} min
0-10	668	412
10-20	412	307
20-30	307	227
30-40	227	164
40-50	164	116
50-60	116	79
60-70	79	52
70-80	52	32
80-90	32	18
90-100	18	0

Table 3: Centrality classes determination for ranges of multiplicity in TPC after cuts in collisions of Bi+Bi at $\sqrt{S_{NN}} = 9.46$ GeV.

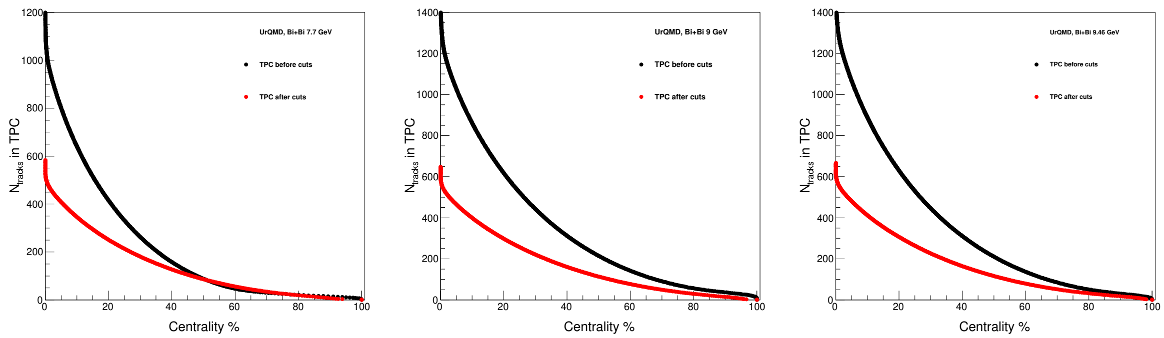

Figure 8: Relation between the multiplicity and the centrality on the TPC before and after cuts in collisions of Bi+Bi at $\sqrt{S_{NN}} = 7.7,\ 9,\ 9.46$ GeV (left to right).

Conclusions

- We corrected the information about the distance of closest approach (DCA) from the Monte Carlo data produced for Bi+Bi collisions in MPD.
- We calculated centrality classes for Bi+Bi collisions at center-of-mass energies of $\sqrt{S_{NN}} = 7.7,\ 9,\ 9.46$ GeV with the corresponding DCA corrections.
- For future work, it is necessary to measure the particle momentum spectra and particle identification efficiency with the corrected DCA values and the centrality classes calculated in this report.

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[13] Github with the macros to launch jobs and get the multiplicity distributions: https://github.com/pedroanietom/NICA-Cluster/tree/main/jobs