Monte Carlo Study of $\sqrt{s_{NN}} = 3$ GeV Au+Au and Au+Al Fixed Target Collisions at STAR

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Abstract—*A Monte Carlo study was carried out for Au+Au and Au+Al fixed target collisions with $\sqrt{s_{NN}} = 3$ GeV at STAR. The purpose was to comprehend similarities and differences between them, and then analyze the possibility of developing a trigger to distinguish in real time these types of events with the TOF detector at STAR. At first, Glauber modeling was applied for these types of collisions. Then 100,000 events for both Au+Au and Au+Al were randomly generated using the UrQMD package and analyzed, returning promising results for the trigger implementation. These results indicate that a TOF multiplicity trigger of 20 has an approximate efficiency of 50% in the selection of Au+Au collisions for events with an impact parameter up to 13 fm. Finally, to carry on later studies for this trigger, UrQMD generated events were run through GSTAR in order to recreate with more detail the environment of STAR.*

Index Terms—*Monte Carlo study, Glauber Model, GSTAR, UrQMD.*

I. Introduction

The STAR detector (for Solenoidal Tracker at RHIC) is one of the experiments at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory (BNL). The main objective of STAR is to study the formation and characteristics of the quark gluon plasma (QGP), a state of matter that exists at high energy densities. Studying the QGP will bring a better understanding of the universe in its early moments [1].

One way of doing this is colliding the nuclei of gold atoms together at high energies. It often happens that some of these gold nuclei collide with the aluminum beam pipe, creating fixed target collisions with lower energies and interesting properties. This inspires an attempt to study fixed target collisions, and led to the present study for a future fixed-target program for both Au+Au and Au+Al collisions. It is of great importance to be able to differentiate between Au+Au and Au+Al collisions in real time, using the capacity of the STAR detector.

STAR consists of many types of detectors. The ones of interest for this study were the Time Projection Chamber (TPC), the Time of Flight detector (TOF) and the End Cap Calorimeter (EEMC). In particular, the TOF detector is of interest because of its fast response capacity for the development of event triggers, i.e. detecting in real time whether a collision of interest between nuclei occurred or not [2]. Since Au+Au collisions can produce higher multiplicities than Au+Al, this can be used to discriminate between the two, up to a certain impact parameter.

II. Proposed Fixed Target

Fig. 1 shows the proposed specifications for a gold fixed target that is intended to be mounted at STAR. It is a small sheet of gold that will be placed inside the aluminum beam pipe. The plan is to use low beam energies, $\sqrt{s_{NN}} \approx 3$ GeV. The side of the detector (west or east) on which the target will be installed is not fully determined yet, so there might be a last minute modification.

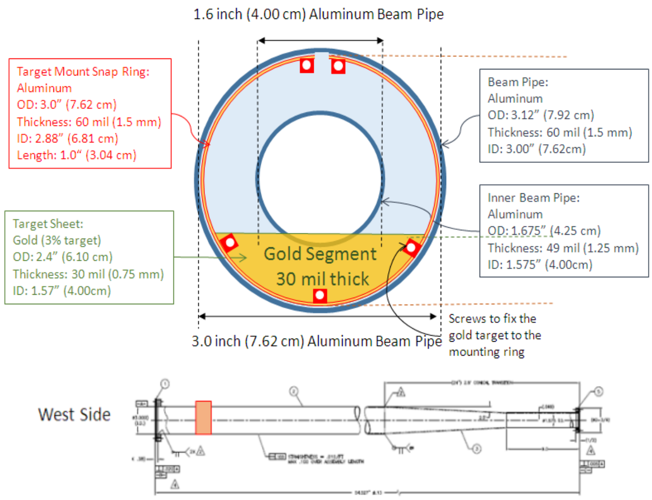

Fig. 1. Proposed gold fixed target specifications [3].

III. Study Review

The study presented here followed a logical sequence of events with the purpose of analyzing and comparing simulated Au+Au and Au+Al fixed target collisions, where $\sqrt{s_{NN}} = 3$ GeV, for subsequent trigger development studies for the selection of Au+Au and the rejection of Au+Al. It can be divided into three man sections:

1) *Glauber model*: Model used initially to comprehend nuclear collisions and their centrality, some similarities and differences between Au+Au and Au+Al collisions, and to get familiarized with certain analysis tools, such as ROOT.

2) *UrQMD simulations*: Virtual recreation of many events using the Monte Carlo simulation package UrQMD (Ultra-relativistic Quantum Molecular Dynamic), accompanied of a preliminary analysis of certain types of particles and the geometric detection capabilities of the TOF, TPC and EEMC detectors in STAR.

3) *GSTAR simulations*: A robust simulation of the environment of STAR and its detectors, with the need of detailed inputs from an event generator (in this case UrQMD) and the coordinates of the fixed targets.

IV. THE GLAUBER MODEL FOR AU+AU AND AU+AL COLLISIONS

As mentioned before, the Glauber Model was used to model collisions among nuclei. Specifically, the Glauber Monte Carlo (GMC) approach was used since it is relatively simple to apply. In a few words, this model intends to estimate the total number of binary collisions N_{coll} and the total number of participants N_{part} (nucleons that are responsible for collisions) given an impact parameter. The Woods-Saxon density function was used to model the random spatial distribution of nucleons inside nuclei. Finally, the inelastic nucleon-nucleon cross section was used to determine N_{part} and N_{coll}. This whole process was applied for both Au+Au and Au+Al events.

A. The Impact Parameter

The impact parameter, denoted as b, is defined as the distance in the transverse plane (XY plane) between the centers of the two nuclei participating in a collision, as can be seen in Fig. 2.

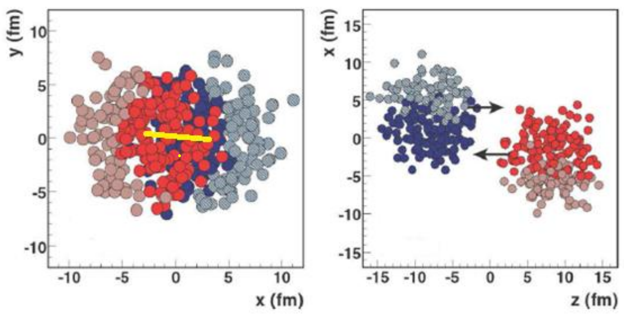

Fig. 2. GMC Au+Au event viewed in the transverse plane (left) and along the beam axis (right) where the highlighted particles are the participating nucleons and the yellow line is the impact parameter [4].

In nuclear collisions, the occurrence of head-on collisions is rare, while peripheral collisions are more likely. Therefore, the impact parameter in GMC calculations is chosen from the linear distribution $2\pi r$, so the coordinates of the centers of both the nuclei colliding follow a uniform spatial distribution. Nevertheless, for each event its impact parameter will be of interest as long as at least one nucleon-nucleon collision takes place. Fig. 3 shows the histograms of these impact parameters for Au+Au and Au+Al collisions where both nuclei were modeled with the Woods-Saxon distribution.

B. The Woods-Saxon Distribution

The Woods-Saxon density function was used to model the radial distribution of the nucleons inside a nucleus.

$$\rho(r) = \rho_0 \frac{1 + \omega(r / R)^2}{1 + e^{\frac{r-R}{a}}} \quad [5]$$

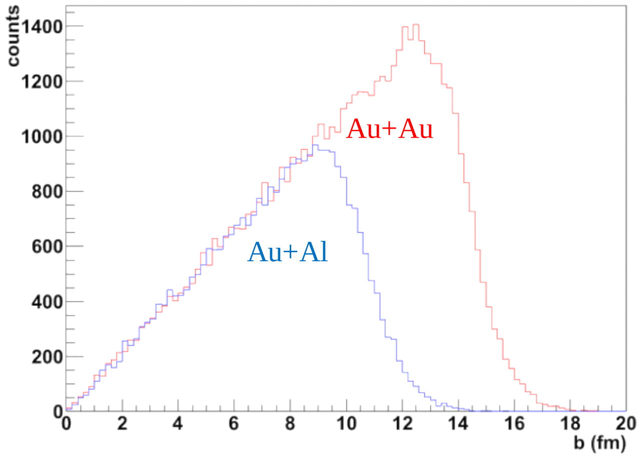

Fig. 3. Impact parameter histograms for Au+Au (red) and Au+Al (blue).

Where the parameter ρ_0 is the nucleon density in the center of the nucleus, R corresponds to the nuclear radius, ω characterizes deviations from a spherical shape and a is the skin depth. Table 1 shows the respective values for gold and aluminum, while Fig. 4 their respective plots.

TABLE 1
PARAMETER VALUES FOR AU AND AL [6]

Element	R	ω	a
^{197}Au	6.38 fm	0	0.535 fm
^{27}Al	3.07 fm	0	0.519 fm

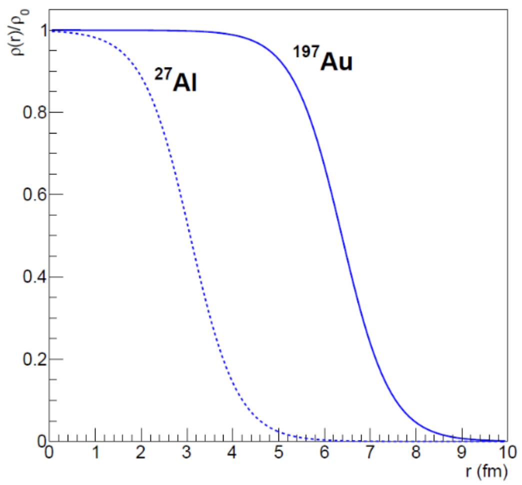

Fig. 4. The Woods-Saxon radial density functions for Au and Al [7].

In the GMC approach, the radial distance from the center of the nucleus is randomly drawn from the normalized distribution $4\pi r^2 \rho(r) / \rho_0$.

C. The Inelastic Nucleon-Nucleon Cross Section

To determine if a binary collision between two nucleons occurred, the following condition must be satisfied [8]:

$$d \leq \sqrt{\sigma_{inel}^{NN} / \pi}$$

Where d is the distance in the transverse plane between the centers of the two nucleons of interest (with a spatial location randomly generated from the Woods-Saxon function), and σ_{inel}^{NN} is the total inelastic nucleon-nucleon cross-section, which varies with $\sqrt{s_{NN}}$. In this particular GMC study, $\sqrt{s_{NN}} = 3$ GeV for both Au+Au and Au+Al collisions. Therefore, $\sigma_{inel}^{NN} = 30$ mb [9].

Fig. 5 shows that both N_{part} and N_{coll} are significantly greater for Au+Au than for Au+Al. This is because there are more nucleons that can participate in each event. It is important to mention that for both Au+Au and Au+Al, N_{coll} is larger than N_{part}. The reason is that a single nucleon can be involved in several collisions.

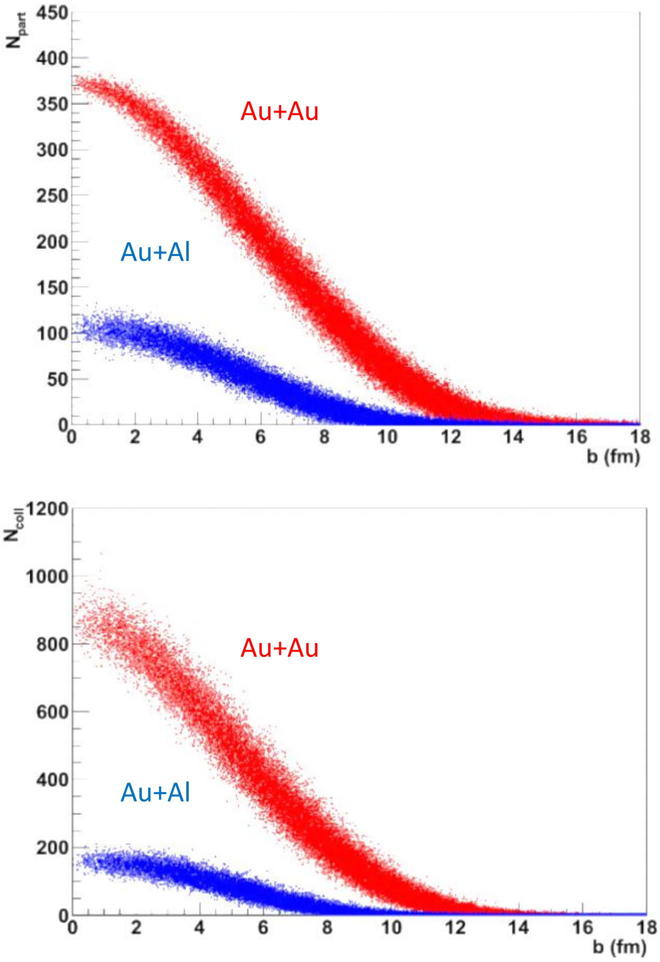

Fig. 5. N_{part} (upper) and N_{coll} (lower) as a function of *b*, for both Au+Au (red) and Au+Al (blue) collisions.

V. Preliminary Analysis of UrQMD Simulations

Once a general view of nuclear collisions was acquired through GMC simulations, the next step was to simulate a large number of Au+Au and Au+Al fixed target collisions with the desired beam-energy. For that, the fully integrated Monte Carlo simulation package UrQMD (Ultra-relativistic Quantum Molecular Dynamic) was used. It is specially designed to recreate the environment of STAR and return many useful individual properties for all the particles involved in any specified number of events. The ones of interest for this study were: particle id, momentum and charge, for particle and motion identification. In this case 100,000 events were simulated for both Au+Au and Au+Al collisions with $\sqrt{s_{NN}} = 3$ GeV.

Particle Analysis

An initial simple particle analysis was made. Table 2 shows the frequency of appearance of each type of particle detected through the overall 100,000 simulated events.

Pion multiplicity plots and top 10 % centrality cuts (most central events) were made, as shown in Fig. 6. As expected, far more pions were created on Au+Au collisions.

TABLE 2
TYPES OF PARTICLES

Particle	Au+Au	Au+Al
p	37.559997 %	39.294079 %
n	53.700681 %	55.291444 %
π^+	2.125303 %	1.416714 %
π^0	2.673547 %	1.738475 %
π^-	3.084127 %	1.864481 %
γ	0.128150 %	0.061396 %
K^+	0.154026 %	0.068847 %
K^0	0.188438 %	0.081023 %
K^-	0.006088 %	0.002432 %
λ	0.134528 %	0.061933 %
η	0.054786 %	0.037930 %
Σ^+	0.050428 %	0.022384 %
Σ^0	0.067448 %	0.030174 %
Σ^-	0.072234 %	0.028668 %
Ξ^0	0.000107 %	0.000008 %
Ξ^-	0.000112 %	0.000013 %

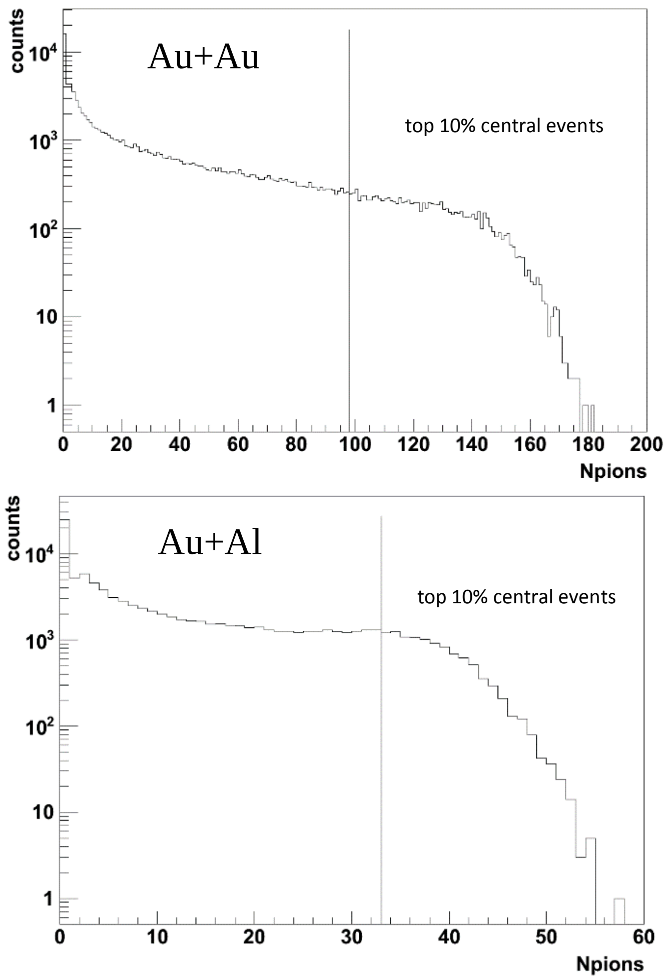

Fig. 6. Pions created from Au+Au (upper) and Au+Al (lower) collisions with a 10% centrality cut at 98 for Au+Au and 33 for Au+Al.

Preliminary Detector Analysis

An early study was made to determine the behavior of the TOF, TPC and EEMC detectors. The range of detection for each of these was modeled using geometric cuts in terms of pseudorapidity η, a spatial coordinate describing the angle between a particle's momentum and the beam axis.

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

In this case, the objective was to study a proposed fixed target located in (0, 0, -200) cm, meaning the collisions occur inside the left side of the beam pipe. Fig. 7 shows that for the TOF $0 \leq \eta \leq 1.5902$, for the TPC $0 \leq \eta \leq 1.7$ and for the EEMC $1.7 < \eta \leq 2.6794$ [10].

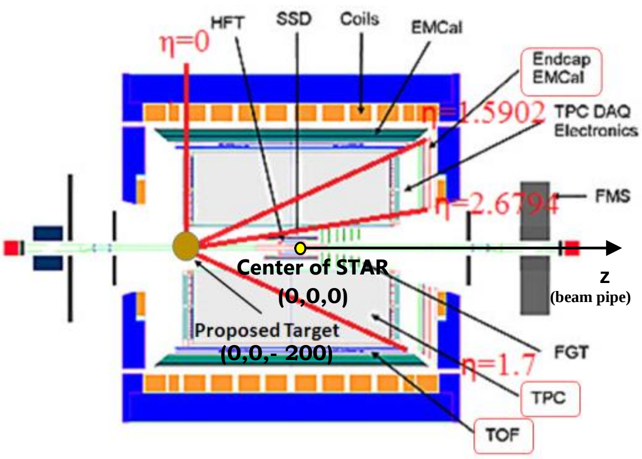

Fig. 7. STAR detector with the respective geometric cuts for the EEMC, the TPC and the TOF [11].

Besides these η cuts for each detector, charge and transverse momentum p_T were also taken into account. It was assumed that in order to spot a particle with any of the detectors, it needed to be charged and have a $p_T \geq 200$ MeV/c. Therefore, all the particles that were analyzed at least satisfied both of this requirements.

Fig. 8 shows the overall η distribution of the 100,000 simulated events of Au+Au and Au+Al collisions. Both have a peak at $\eta \approx 4$ (spectators), but Au+Au also has another peak at $\eta \approx 0$. This means that an important amount of particles will be detected by neither the EEMC, the TPC nor the TOF, but also means that the left side of both the TOF and the TPC will play an important role in particle detection. As can be seen, most charged particles are protons, but almost all the remaining few particles will be detected by the sensors.

Fig. 9 shows the impact parameter distributions for Au+Au and Au+Al collisions, as well as their respective top 10% central events. They are similar to the ones generated with the Glauber model. In this case, it was assumed that a collision occurred if there was at least a pion created in it.

Fig. 10 shows the acceptance of charged particles N_{ch} for each detector as a function of b. As expected, for large impact parameters, the number of particles detected tends to decrease (because most of the particles are spectators). For Au+Al, the number of detected charged particles is substantially less than for Au+Au events.

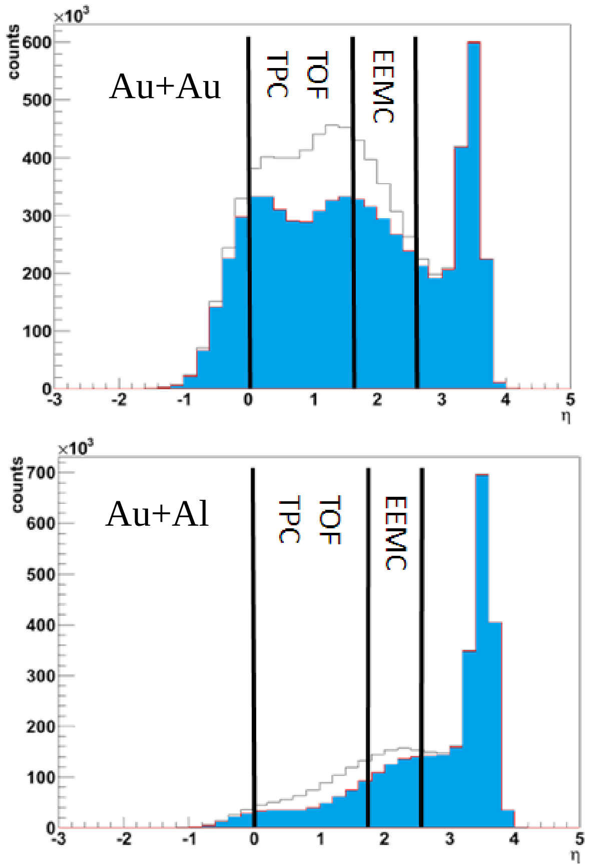

Fig. 8. Pseudorapidity (η) distribution and detection ranges of particles for Au+Au (upper) and Au+Al (lower), where protons appear in blue.

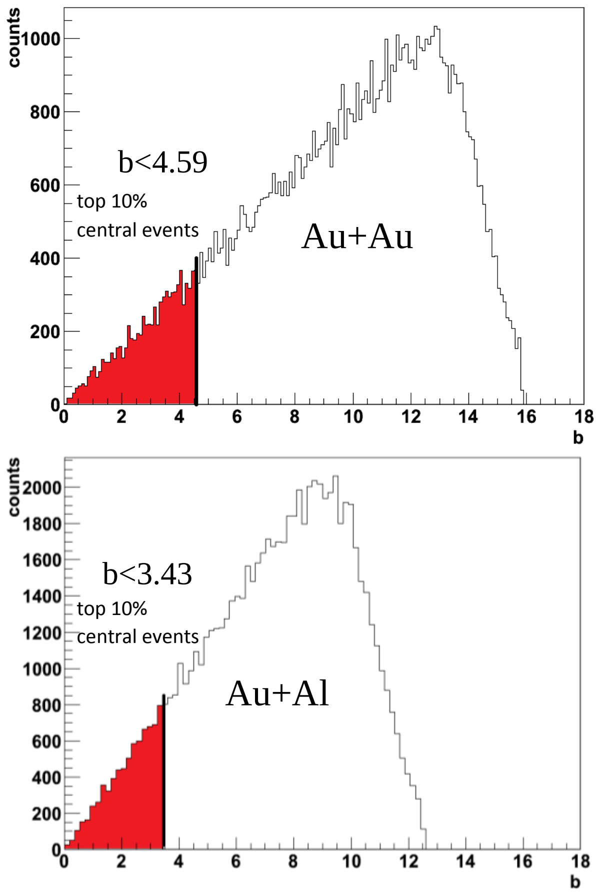

Fig. 9. Impact parameter histograms for Au+Au (upper) and Au+Al (lower), with their respective 10% centrality cut at $b = 4.59$ and $b = 3.43$.

Fig. 11 shows the number of protons N_p and the total number of charged particles N_{ch} detected only by the TOF, also as a function of b. The separation between Au+Au and Au+Al multiplicities is good enough to design a trigger.

In this study, 5 different multiplicity triggers were tested. Their efficiencies are shown in Table 3. The priority of the trigger is to only detect Au+Au events, so Au+Al collisions must be eliminated almost entirely from the readings. In this case, a trigger that might work fine is the one with $N_{ch} \approx 20$, granting an approximate access to events with $b \lesssim 13$ fm.

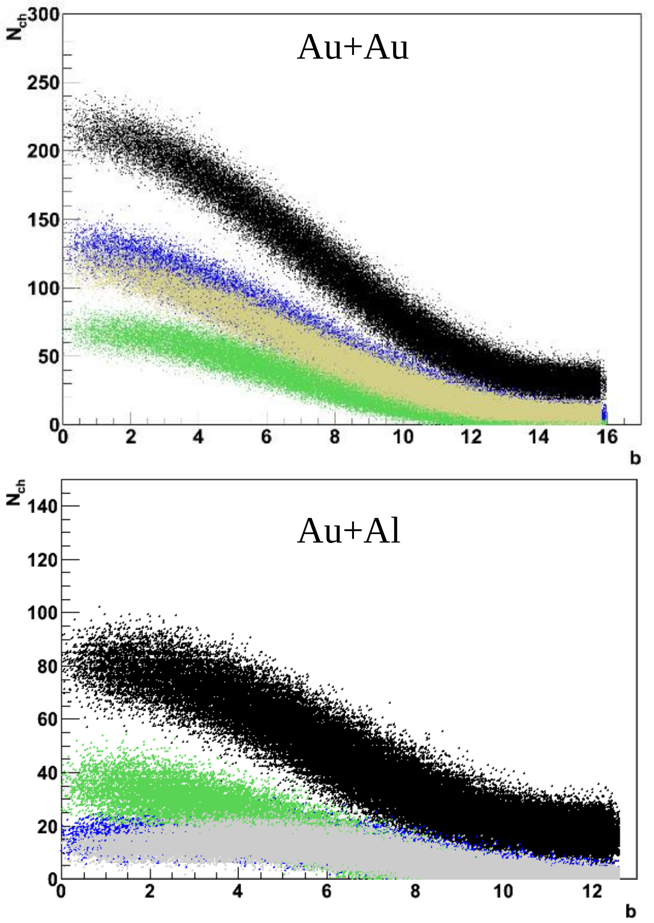

Fig. 10. Total number of particles (black), number of particles detected by the EEMC (green), by the TPC (blue) and by the TOF (gold or silver) per Au+Au (lower) or Au+Al (upper) event as a function of *b*.

TABLE 3
SELECTION AND REJECTION EFFICIENCIES

Trigger (N_{ch})	Au+Au selection efficiency (%)	Au+Al rejection efficiency (%)
30	39.08	100.00
25	43.93	99.99
20	49.80	99.59
15	57.59	94.39
10	71.43	76.80

VI. GSTAR SIMULATIONS

GSTAR is a framework to run STAR simulations using GEANT. It recreates all the physical and geometric properties of STAR. In order to work properly, it uses input from an event generator, in this case from UrQMD output files with major modifications.

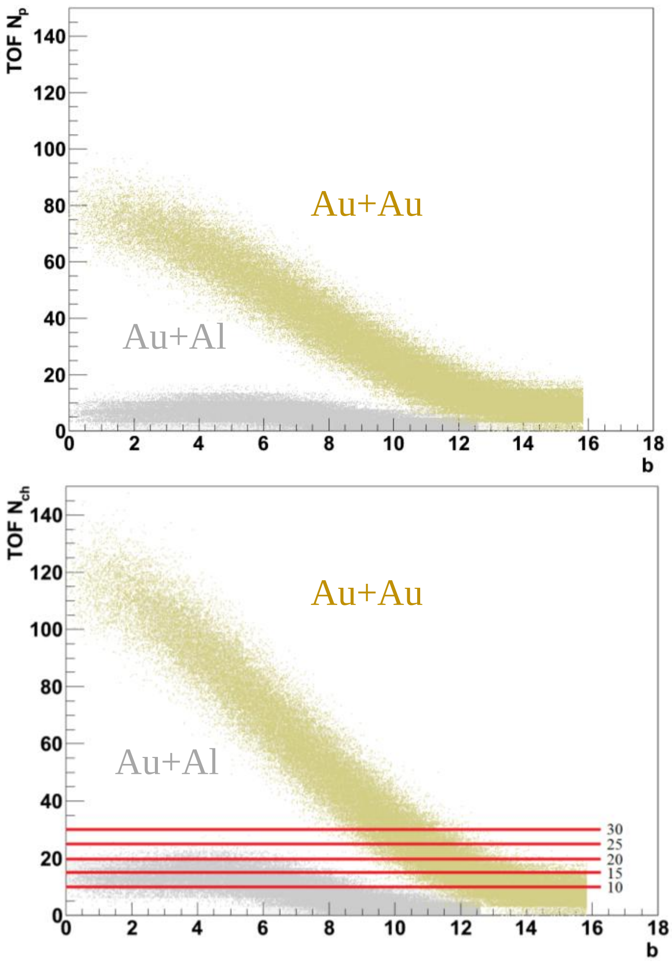

Fig. 11. Number of particles detected per event by the TOF detector for Au+Au (gold) and Au+Al (silver) as a function of the impact parameter. At the top appear protons, and at the bottom all charged particles with different multiplicity triggers.

All tracks and vertices for each event must be specified with detail. Fig. 12 shows the new TX format used [12] for its input files and a small example.

EVENT: event_id n_tracks n_vertices

VERTEX: x y z t vertex_id process parent_track n_daughters

TRACK: ge_pid px py pz track_id start_vertex stop_vertex eg_pid

EVENT: 37 6 2

VERTEX: 1.49.50 -197.40 32.00 0.00 1 0 0 3

TRACK: 170 1.132769 1.398853 0.004712 1 1 0 1

TRACK: 170 1.519299 4.129333 -0.013055 2 1 0 1

TRACK: 170 4.005101 11.310058 -0.144499 3 1 0 1

VERTEX: -2.80 -197.40 60.00 0.00 2 0 0 3

TRACK: 170 46.249561 23.769043 -0.072606 8 2 0 1

TRACK: 170 11.140220 11.062716 -0.030142 9 2 0 1

TRACK: 170 1.004740 4.283729 0.009215 10 2 0 1

Fig. 12. Example of a GEANT input file.

Vertex Coordinates for the Fixed Targets

As seen above, it was necessary to specify the space-time coordinates for each vertex. In this study, it was assumed that $t = 0$ for every single vertex. Spatial coordinates were extracted from equivalent random uniform distributions within certain ranges. For Au+Al, the aluminum beam-pipe was a cylinder with $3.81^2 \text{ cm}^2 \leq x^2 + y^2 \leq 3.96^2 \text{ cm}^2$, $-200 \text{ cm} \leq z \leq -150 \text{ cm}$ (i.e. $\emptyset_{in} = 7.62 \text{ cm}$, $\emptyset_{out} = 7.92 \text{ cm}$), while the gold fixed target was modeled as a flat quasi-semicircular disk with $x^2 + y^2 \leq 3.05^2 \text{ cm}^2$, $y \leq -2 \text{ cm}$, $z = -200 \text{ cm}$.

GEANT Simulations

Once the respective .tx files were created for 100, 000 Au+Au and Au+Al fixed target events generated with UrQMD, the next step was to run these files through the GEANT simulator in order to see how the STAR detector would react with these collisions. In Fig. 13, the particle trajectories of an event can be seen in red when processed by GEANT.

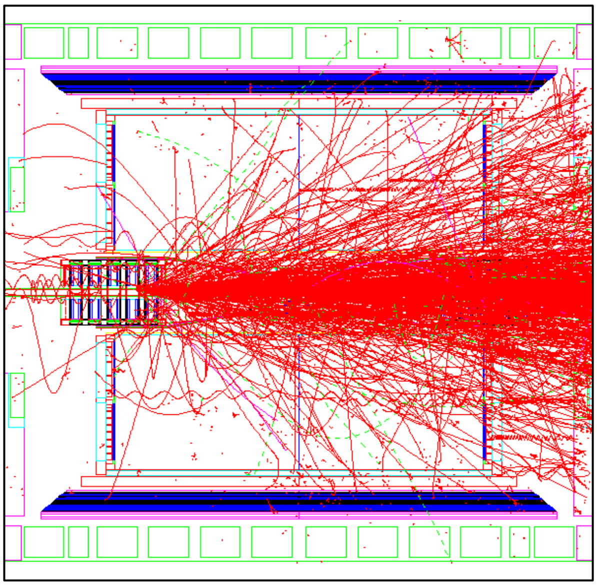

Fig. 13. UrQMD simulated fixed target Au+Al event in the STAR detector.

The GEANT simulator creates binary output files with the .fz format. These .fz files were processed with the bfc.C (Big Full Chain) macro in order to reconstruct the chains with the information of the tracks detected by the simulator of STAR and store it into .root files [13]. These .root files were created for both the 100, 000 Au+Au and Au+Al simulated events.

VII. Conclusion

The preliminary geometric analysis of the UrQMD generated events, with $\sqrt{s_{NN}} = 3 \text{ GeV}$, indicates that a trigger for Au+Au selection and Au+Al rejection with the TOF detector might be implemented with a multiplicity cut around 20, granting access to events with $b \lesssim 13 \text{ fm}$. This trigger has approximately a 50% efficiency, which turns out to be a good level. This study indicates that mounting the proposed gold target at STAR is a project with a good chance of delivering interesting results.

VIII. Future Work

The extraction of the data stored in the .root files with the information of how the sensors would have actually detected the UrQMD events still has to be done. Then, these data must be compared to the analysis presented in this study. Also, a study of the sub regions of the TOF and their specific role on these fixed target collisions might be useful for the trigger. Additionally, other multiplicity cuts should be proposed and tested depending on the centrality of the events desired to be analyzed. Finally, if all the data are consistent, it is recommended to mount the proposed gold target and start making tests at STAR.

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