# Determination of Centrality Classes and Trigger Analysis for 200 GeV $^{2}H$-$^{197}Au$ Collisions

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At RHIC, $^{2}H$-$^{197}Au$ collisions at 200 GeV were measured. The particle multiplicity was fit using a Glauber simulation where $^{197}Au$ was modeled using a Woods Saxon density distribution, and $^{2}H$ was modeled according to the Hulthén form of the wave function. From the best fit, centrality classes were determined and used to analyze trigger efficiencies. The minimum bias trigger was written with a goal efficiency of 85% for the total inelastic cross section, and a central event trigger was written with the goal of recording an unbiased set of the 0-5% most central events. Due to the difficulties of predicting centrality and observing nucleons from $^{2}H$ along the beam axis, neither of the triggers achieved the goal efficiencies.

## I. INTRODUCTION

High energy nuclear experiments at the Relativistic Heavy Ion Collider (RHIC) are searching for phase transitions in nuclear matter. Heavy ion collisions at sufficiently high energies are predicted to deconfine quarks from protons and neutrons [1]. Immediately after these collisions, quarks and gluons are able to move beyond the normal shell of a hadron in a hot, dense state of matter called the Quark Gluon Plasma (QGP). The QGP is considered to be the state the universe existed in immediately following the big bang.

To search for the QGP, collisions of heavy ions ($^{197}Au$-$^{197}Au$) are compared to proton-proton (p-p) collisions as well as collisions involving light and heavy ions (ex. $^{2}H$-$^{197}Au$). P-p collisions have been studied for years and are generally considered to not produce a QGP. Furthermore, the production of rare particles and other observable quantities are well understood in p-p collisions. In collisions between light and heavy ions, a QGP is also not predicted to form, and observables are well described as a superposition of p-p collisions, called the Glauber model (see section B) [2]. For heavy ion collisions, evidence of the QGP is obtained by observing differences between the Glauber model predictions and experimental data.

Due to theoretical requirements, the QGP is only predicted to form in nuclear collisions where many nucleons directly collide [1]. More nucleons are typically involved in collisions when the center of two nuclei collide at a small impact parameter–a central collision. However, a precise cutoff value for central collisions is difficult to define because of the uncertainty in nucleon position within a nucleus. Collision centrality is therefore defined as a percentage relative to all recorded nuclear collision events, see FIG. 1. Typically, the top 5% or 10% most central collisions are relevant for QGP studies, but the exact range of collisions to be considered depends on the quantity of interest. In this paper, centrality classes are determined for collisions of $^{2}H$-$^{197}Au$ at 200 GeV.

### A. Experimental Setup

Ions were accelerated at RHIC and collided in the Solenoidal Tracker at RHIC (STAR), located at Brookhaven National Laboratory. The STAR detector specializes in tracking particles output from a heavy ion collision event [3]. FIG. 2 shows the event display for a $^{2}H$-$^{197}Au$ collision. The number of tracks output from a single event is defined as the particle multiplicity. For low particle multiplicity events, the STAR detector may completely miss the tracks. The full distribution of particle multiplicity for all $^{2}H$-$^{197}Au$ events will later be fit and used to determine collision centrality.

Data for the 200 GeV $^{2}H$-$^{197}Au$ experiment was taken continuously from 28 June to 7 July 2021. Because of the large size of the STAR detector, over 1200 tons and three stories tall [3], background is constantly present from internal detector decays and cosmic rays. Data is not constantly saved, so collisions are only recorded if an event trigger is passed [5]. A trigger is a series of hardware and software requirements that define when to record data. Typically, a trigger will require the observation of particles in the beam directions and tracks from produced particles. Since $^{2}H$ only has two nucleons, triggers have more difficulty observing forward moving particles than in a heavy ion collision. This difficulty, combined with the detector inefficiency for low multiplicity events, can lead to low trigger efficiencies.

The trigger that recorded the most data for the $^{2}H$-$^{197}Au$ experiment, with the fewest requirements, was the minimum bias trigger. The percentage of the true number of events that a trigger records is defined as the trigger efficiency. For this experiment, the minimum bias trigger was set with a goal efficiency of 85%. A central trigger was also written in an attempt to record an unbiased view of the 0-5% most central events.

### B. Nuclear Models

To fit the observed particle multiplicity, an accurate model of the nuclear collisions is needed. Collisions involving heavy ions at the RHIC accelerator range in energy from approximately 3 to 200 GeV. This energy is significantly larger than the mass difference between protons and neutrons (≈1 MeV)

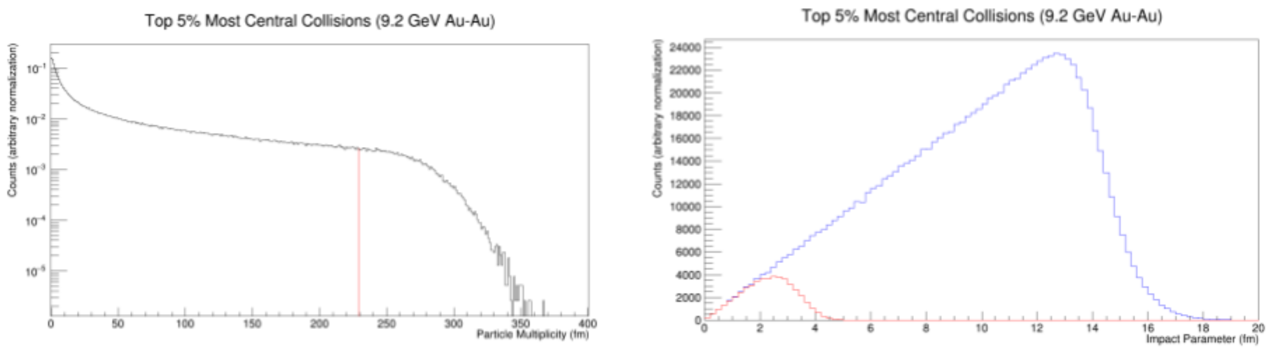



FIG. 1: Here is data from a Glauber simulation of $^{197}Au$-$^{197}Au$ collisions at 9.2 GeV. Collision centrality would ideally be defined as a percentage relative to the full distribution of impact parameters in the data set. So, the 0-5% most central collisions would simply be the lowest 5% of impact parameters in the distribution. However, the impact parameter is not an experimentally observable quantity in high energy nuclear physics, so collision centrality is approximated by the number of particles produced–called particle multiplicity. The figure shows the 0-5% highest multiplicity events, and projects this cut into the impact parameter distribution. While the approximation is not perfect, it is an accurate way to gauge highly central events.

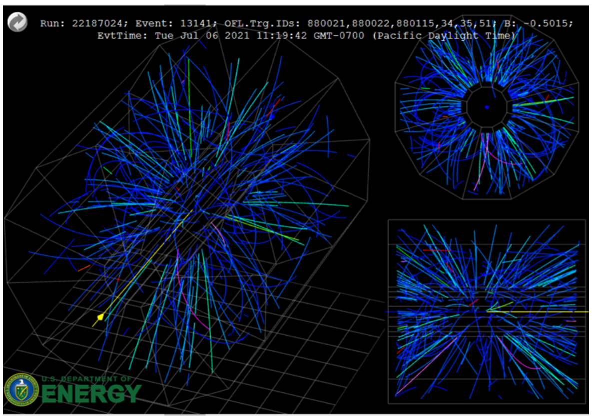


FIG. 2: Event display for a $^2H$-$^{197}Au$ collision at 200 GeV. The track color is related to the charge of a particle. For a full description of the particle identification process used at STAR, see [4].

which allows protons and neutrons to be approximated as equivalent, and referred to collectively as nucleons [2]. The collision energy is also much greater than the nucleon-nucleon binding energy (≈8 MeV), so inter-nucleon potentials can be ignored. Therefore, heavy ion collision are considered to be a superposition of p-p collisions in the simplest model, called the Glauber model.

While nucleon identity and local potentials are not considered in the model, the spatial position of a nucleon must be addressed. For spherical nuclei, including $^{197}Au$, the nucleon density is described by a Woods Saxon distribution as shown in FIG. 3. The Woods Saxon distribution is given mathematically in equation 1.

$$\rho(r) = \frac{\rho_0}{1 + e^{\frac{r-R}{a}}} \tag{1}$$

The distribution is described by three parameters: $\rho_0$ is the normalization constant, $R$ is the nuclear radius, and $a$ is the nuclear skin depth. The skin depth describes how thick the edge of the nucleus is. For $^{197}Au$, the parameters used were $\rho_0 = 1.0$, $R = 6.38$ fm, and $a = 0.535$ fm. The density distribution is then turned into a probability density function (PDF), and from the PDF, random radii are drawn for all 197 nucleons. For each nucleon, the azimuthal and polar angles are drawn according to a uniform sphere.

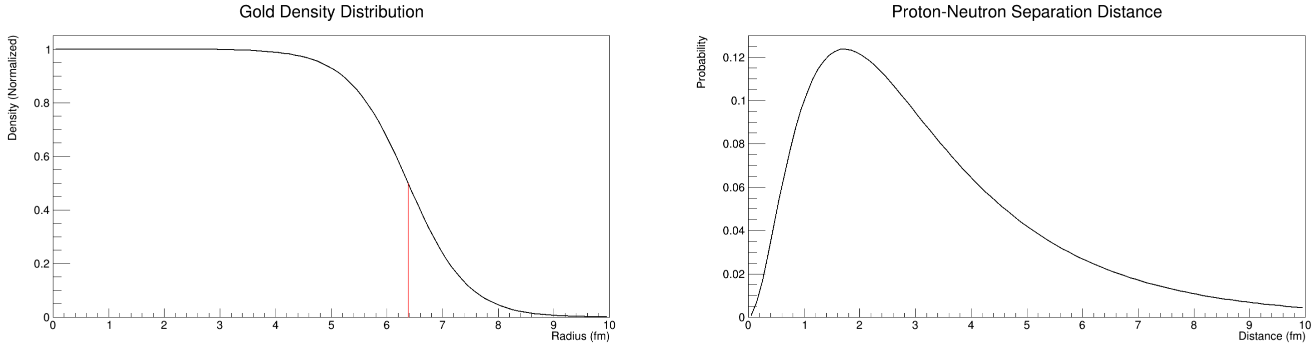
A $^2H$ nucleus (deuteron), made up of one proton and one neutron, is shaped like a dumbbell. Since it is non-spherical, a deuteron cannot be described by a Woods Saxon distribution, and to include deuteron in the Glauber simulation, a second nuclear model needed to be implemented. The deuteron was modeled according to the Hulthén form of the wave function, which describes the separation distance between the two nucleons. The wave function is given in equation 2.

$$\phi(r) = \frac{1}{2\pi} * \frac{\sqrt{ab(a+b)}}{b-a} * \frac{e^{-ar} - e^{-br}}{r} \tag{2}$$

For deuteron, $a = 0.228 fm^{-1}$ and represents the attractive portion of the inter-nucleon potential, while $b = 1.18 fm^{-1}$ and represents the repulsive portion of the potential. Note, the parameter $a$ in (1) and (2) are different physical values, but it is standard notation to label both as $a$. The PDF corresponding to the Hulthén form of the wave function is shown in FIG. 3. To create the nuclear model, a random separation distance, $r$, was drawn from the PDF. One nucleon was placed at $\frac{1}{2} * r$ and the other at $-\frac{1}{2} * r$. Then, the deuteron was randomly oriented in space.

### C. Collision Centrality

With the above models for $^2H$ and $^{197}Au$ nuclei, nuclear collisions can be simulated. A high energy collision is described by several parameters, the most important of which




(a) (b)

FIG. 3: In panel (a), the Woods Saxon density distribution for $^{197}Au$ is shown. The red line shows the nuclear radius in the distribution. In panel (b), the PDF for nucleon separation distance in deuteron, as described by the Hulthén form of the wave function, is shown.

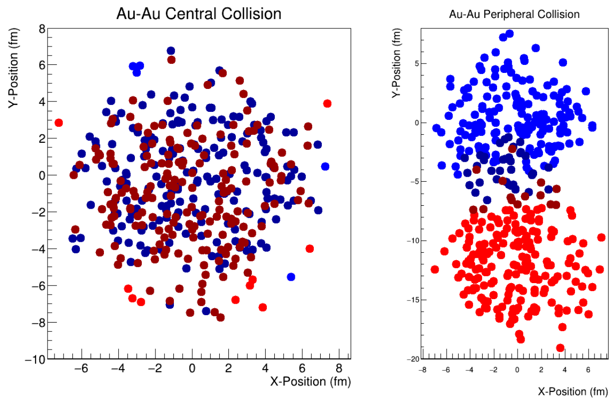



FIG. 4: On the left, a central $^{197}Au$-$^{197}Au$ collision is shown with one nucleus in red and one in blue. The darker nucleons are involved in the nuclear collision (participant nucleons), while the lighter nucleons continue along the beam and are not involved in the collision (spectator nucleons). On the right, a peripheral $^{197}Au$-$^{197}Au$ collision is also shown. Often, the central collisions are the collisions of interest because of their relation to the QGP.

are: the distance between the center of masses of the colliding objects (b, impact parameter) and the interaction region ($\sigma$, cross section). The p-p cross section, which is used as the nucleon-nucleon cross section in the Glauber model, is energy dependent. For 200 GeV collisions, $\sigma = 41.9mb$, where $mb$ is the unit millibarn.

In nuclear collisions, the magnitude of the impact parameter is important for the quality of statistics and the search for the QGP. Refer to the introduction for a thorough discussion of the impact parameter definition. A central collision occurs at a small impact parameter (roughly 2 fm or less for 200 GeV $^2H$-$^{197}Au$), and a peripheral collision occurs at a large impact parameter (roughly 6 fm or more). Examples of both central and peripheral collisions are shown in FIG. 4.

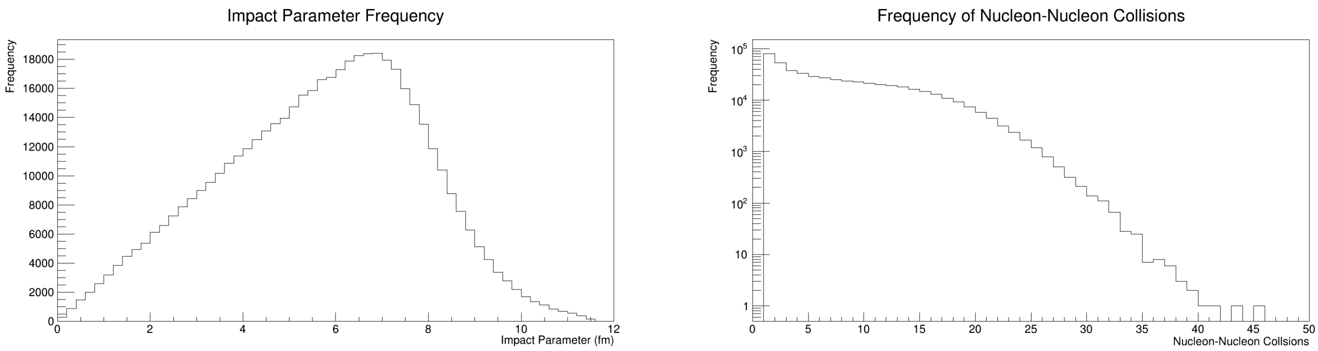
### D. Glauber Simulation

The Monte Carlo Glauber simulation uses random nuclei, modeled by the Woods Saxon and Hulthén form, collided at random impact parameters to simulate the observed particle multiplicity. Impact parameters are drawn from a linear PDF where central collisions are much more rare than peripheral collisions. For the 200 GeV $^2H$-$^{197}Au$ Glauber simulation, $10^6$ individual nuclear collisions were modeled. Collisions where no nucleon-nucleon collisions occurred were dropped from the data-set because only collisions that produce particles can be observed in the STAR detector. All collisions that produce particles are included in the total inelastic cross section of the simulation. This leads to a characteristic impact parameter frequency distribution shown in FIG. 5 (a).

In the Glauber simulation, the number of individual nucleon-nucleon collisions, determined from the nucleon-nucleon cross section, is calculated for every nuclear collision. A frequency distribution for the number of nucleon-nucleon collisions is shown in FIG. 5 (b). P-p collisions, modeled by the negative-binary distribution in equation 3, can be superimposed according to the number of nucleon-nucleon collisions in order to fully model the nuclear collision. The resulting distribution can then be fit to the observed particle multiplicity by varying the k and $\mu$ parameters of the negative-binary (N is the particle multiplicity) as well as the collision hardness (x). Collision hardness is an additional shape parameter that describes the particle production contribution from bulk nucleon processes and individual nucleon collisions (0 is pure bulk process and 1 is only nucleon collisions).

$$f(N;k,\mu) = \frac{(N+\mu)! * (\frac{k}{\mu})^N}{N!\mu! * (\frac{N}{\mu}+1)^{N+\mu}} \tag{3}$$

Differences between the best fit and observed particle multiplicity are common for peripheral collisions. To gauge this difference, the ratio between the number of experimentally measured events and the best fit line is calculated, which is referred to as the trigger efficiency. A 100% efficient trigger




(a)

(b)

FIG. 5: The distribution of impact parameters for the 200 GeV $^2H$-$^{197}Au$ Glauber model is plotted in panel (a). The distribution shape is characteristic for all Glauber models. The frequency rises linearly according to the PDF before dropping off exponentially at large impact parameters. For very peripheral events, nucleon-nucleon collisions only occur if density fluctuations along the nuclear skin happen to overlap. In panel (b), the distribution of the number of nucleon-nucleon collisions for the 200 GeV $^2H$-$^{197}Au$ Glauber simulation is shown. Here, the characteristic horse's back shape is smeared because of the small number of nucleons in deuteron.

would have the same number of events as the fitted model in every bin. Trigger efficiency was calculated in each centrality class for both the minimum bias and central trigger data. The efficiency is also reported as a total percentage for the minimum bias data set.

## II. RESULTS

The Glauber simulation was fit to minimum bias particle multiplicity data for 200 GeV $^2H$-$^{197}Au$ collisions. The fit was performed over a multiplicity range of 12 to 60. The lower cutoff was placed to avoid detector inefficiencies in peripheral collisions. The upper cutoff was placed because of the lack of data points for the most central collisions. In this highest multiplicity region, the fit becomes dominated by statistical noise.

The best fit parameters were k = 2.037, $\mu$ = 1.769, and x = 0.2750 which yielded a $\chi^2_{DOF}$ = 0.805. The best fit is shown in FIG. 6. This is an accurate fit of the data which shows the Hulthén form of the deuteron wave function successfully modeled the minimum bias particle multiplicity. The large separation between the best fit and observed data for low multiplicity events highlights the inefficiency of the detector and trigger for peripheral events.

From the best fit, five percent centrality classes were determined and are listed in Table 1. Centrality classes above the 10-15% range span only 1-2 bins in particle multiplicity because of the small multiplicity range in $^2H$-$^{197}Au$ collisions.

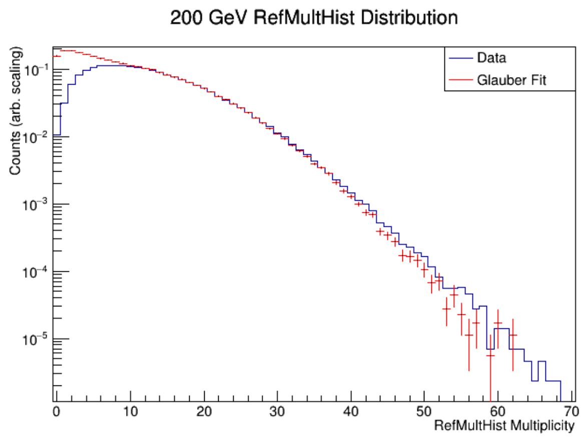
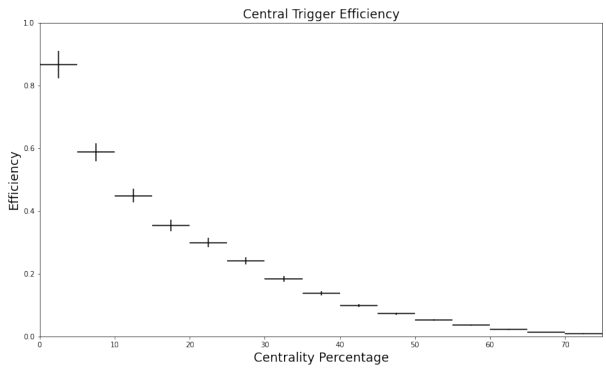



FIG. 6: The particle multiplicity distribution is shown in blue and the best fit from the Glauber simulation is shown in red.

| Centrality | Multiplicity | Centrality | Multiplicity |
|---|---|---|---|
| 0-5 % | 85-26 | 5-10 % | 25-22 |
| 10-15 % | 21-19 | 15-20 % | 18-17 |
| 20-25 % | 16 | 25-30 % | 15-14 |
| 30-35 % | 13 | 35-40 % | 12-11 |
| 40-45 % | 10 | 45-50 % | 9 |
| 50-55 % | 8 | 55-60 % | 7 |
| 60-65 % | 6 | 65-70 % | 5 |

For each centrality class, the efficiency of the minimum bias and central triggers were calculated and are shown in FIG. 6. The central trigger did not achieve the goal of an unbiased record of the 0-5% most central events. The efficiency was significantly below 100% in the top centrality class, and there was large efficiency in less central classes. This shows that the understanding of centrality in $^2H$-$^{197}Au$ collisions is in-



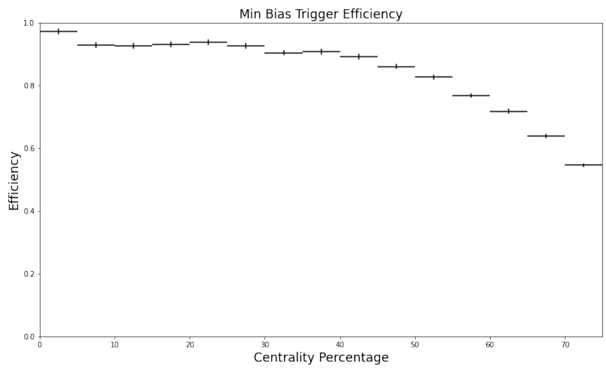




FIG. 7: In both plots, the horizontal lines represent the 5% bin ranges and the vertical line represents uncertainty in the efficiency. The uncertainty comes from varying the normalization of the central trigger data, minimum bias data, and Glauber fit. Efficiency is only shown up to the 65-70% centrality bin because the lowest multiplicity bins contain more than 5% of the data.

complete.

The minimum bias trigger efficiency started to fall below the goal efficiency of 85% in the 50-55% centrality class, and the trigger became more inefficient at even more peripheral events. The minimum bias trigger had a total efficiency of 68.97%, which is well below the goal efficiency. This highlights the difficulty in triggering for $^2H$-$^{197}Au$ events, which can likely be attributed to the lack of nucleons in the deuteron beam direction. For the most peripheral events, the STAR detector inefficiency also becomes a limiting factor for the trigger.

## III. CONCLUSION

High energy $^2H$-$^{197}Au$ collisions at 200 GeV were measured at STAR. To run the Glauber simulation, a new model was introduced for deuteron which used the Hulthén form of the wave function to describe the nucleon-nucleon separation distance. The standard Woods Saxon model was used for $^{197}Au$. The simulation successfully fit observed particle multiplicity, and centrality classes were determined from the fit. The best fit was then used to analyze trigger efficiency for the minimum bias and central event triggers. The minimum bias trigger had low efficiency at peripheral events and did not reach the target goal of 85%. The central event trigger was not successful in recording all of the 0-5% most central events.

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