Effects of pileup on charged particle production from 44.5 AGeV to 100 AGeV fixed-target Au+Au Collisions

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Abstract

The Relativistic Heavy Ion Collider (RHIC) aims to study the quark-gluon plasma through heavy ion collisions, primarily between collisions of two Au-197 nuclei. When these ions collide, they produce a shower of charged particles, whose counts can be represented as a random sample from the overall particle production distribution. I analyzed data from RHIC consisting of Primary-Track vs Barrel time-of-flight matches across multiple energies of Au+Au collisions. In order to get a clear view of the data, a phenomenon called "pileup" must have its contribution quantified. One form of pileup occurs when two Au+Au collisions occur simultaneously (in the same beam bucket). Since the number of charged particles produced in each collision is independent, this form of pileup can be represented as a convolution of the given particle production distribution with itself. The resulting multiplicity distribution, whose pileup contribution is quantified, can then be split into several centrality classes. These classes allow us to see the average number of collisions, participants, and impact parameters in relation to particle production. Comparisons can then be made between the outcome of nuclear collisions between different types of nuclei and energy levels.

1 Introduction

A "hot-topic" in nuclear physics is the phenomenon known as the quark-gluon plasma (QGP). In the QGP quarks and gluons are incapable of forming into hadrons due to the extremely high temperatures. In this state all quarks and gluons are free particles in a state of matter often called a "perfect fluid" due to its theorized extremely low viscosity. This is the state that the universe was in until one microsecond after the Big Bang. Through studying the QGP physicists hope to gain insights into this time period of the universe.

Particle detectors such as STAR (Solenoid Tracker at RHIC) are able to study the QGP by analyzing particles produced through collisions of atomic nuclei [1]. During these collisions temperatures can reach up to hundreds of thousands of times the temperature of the core of the sun. At this extreme temperature the constituent nucleons melt and the gluons and quarks are briefly liberated. In a broad overview, STAR functions by accelerating 100-120 bunches of $\approx 10^{10}$ ions per beam towards each other. In the case of fixed target collisions, there is only 1 beam employed onto a stationary target. When these bunches overlap or cross over the fixed target, it is known as a "bunch-crossing". These crossings are where nuclear collisions could occur, and allow the detector to use valuable timing information for analysis of the produced particles.

In this paper I will discuss my process of creating a Glauber model [2] [3] to aid in the analysis of fixed target Au+Au collision data to quantify the contribution of in-time pileup in the overall recorded multiplicities.

2 Background

2.1 Glauber Model of Atomic Nuclei

The Glauber model allows for a classical representation of nuclear collisions. The model approximates the nucleus as a "fuzzy" hard sphere. If the nucleus was a true hard sphere, its density of nucleons would be a constant function with a sharp drop off at the spheres radius. Instead, the nuclei's densities are represented by a probability density ρ(r) given by Equation 1, where "r" is distance from the center of the nucleus, "R" is the half-density radius (the distance from the center of the nucleus where the nucleon density is at half the maximum) and “a“ is the skin depth. This equation is also known as the “Woods-Saxon distribution“. This model helps describes the less dense region outside of the hard sphere populated by nucleons as well.

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

For a Au-197 nucleus, the half-density radius is 6.38 fm and the skin depth is 0.535 fm.

Each nucleon's exact position is expressed with spherical coordinates r, θ, ϕ, whose position is given by Equation 2.

$$P(r, \theta, \phi) = \rho(r) r^2 d(cos\theta) d\phi \tag{2}$$

Note that the radial distribution contains an additional factor of r^2 which comes from the Jacobian-determinant of spherical coordinates. In Figure 1 the Woods-Saxon distribution is compared with the true distribution shown on the left panel, with an example Au-197 nucleus on the right.

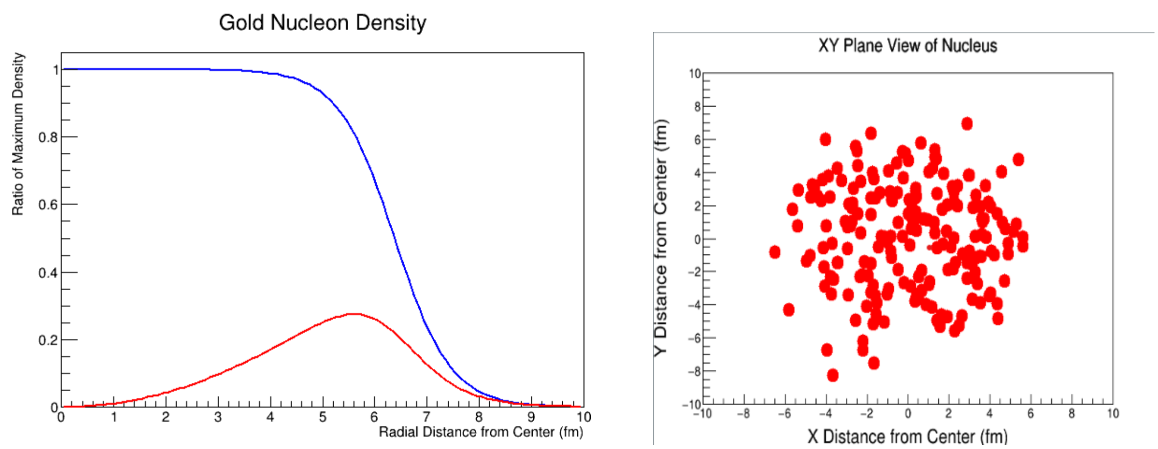

Figure 1: Right: Distribution of Nucleons across radial distances (red) compared to the Woods-Saxon distribution given by Equation 1 (blue). Note that the left side of the distribution is dominated by the effect from r^2 and the right side is dominated by the Woods-Saxon distribution. Left: Generated Au-197 nucleus according to Equation 2 with red dots representing nucleons.

Once one nucleus is generated, another can be generated as well. This next nucleus includes a spatial distance offset with respect to the other nucleus's center. Since the particles can be produced via spherical coordinates I chose to offset the particles on only the x-axis as it wouldn't remove randomness and allows for simplicity.

This offset is known as the impact parameter. During collisions at RHIC and other accelerators, it is impossible to control the impact parameter, but we are able to randomly generate (and keep track of) an impact parameter in my simulation. Observations can then be made based upon impact parameter and how it affects other resulting values.

The total distance between two nucleons of the respective nuclei dictate whether or not a binary nucleon collision is to occur. The collision axis is Z so only the X and Y coordinates (determined from the nucleons spherical coordinates) matters.

The minimum required distance (d) for a collision is given by Equation 3. It is a function of a parameter called cross-section, denoted by σ. Cross section is a value that describes the effective area 2 nucleons cover when they collide and varies based upon the energy and of the colliding nuclei.

$$d = \sqrt{\frac{\sigma}{\pi}} \tag{3}$$

In my simulations I assumed every nucleon to be a proton with constant energy. This assumed that the nucleons share the same cross section. A simulated binary nucleon collision is shown in Figure 2.

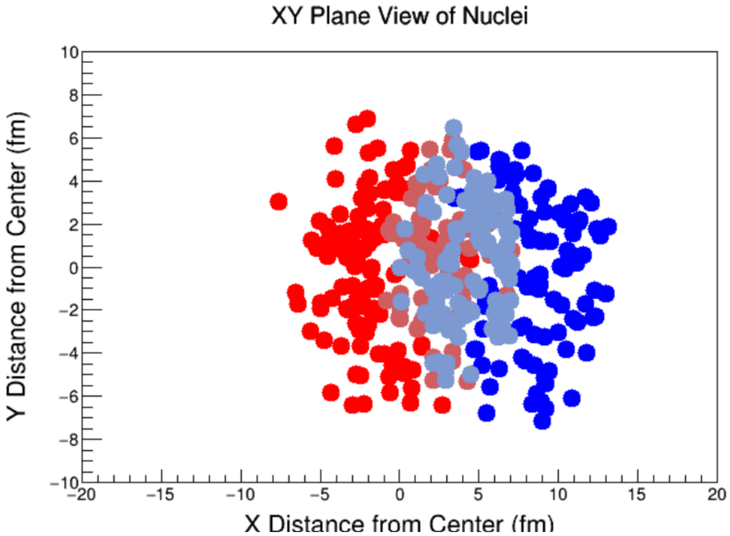

Figure 2: A Au+Au collision at Z=0 with a chosen impact parameter of 6.5 fm. The vibrant red and blue dots represent non-participating nucleons, while the duller blue and red dots are participating nucleons of their respective nuclei.

From a given nuclear collision we can also count the number of participating nucleons and the total number of binary nucleon collisions that occurred. Figure 3 shows a distribution of the number of binary nucleon collisions over 100 thousand simulated Au+Au collisions at 100 GeV beam energy with varying impact parameters. Note that lower numbers of nucleon collisions occur orders of magnitudes more frequently.

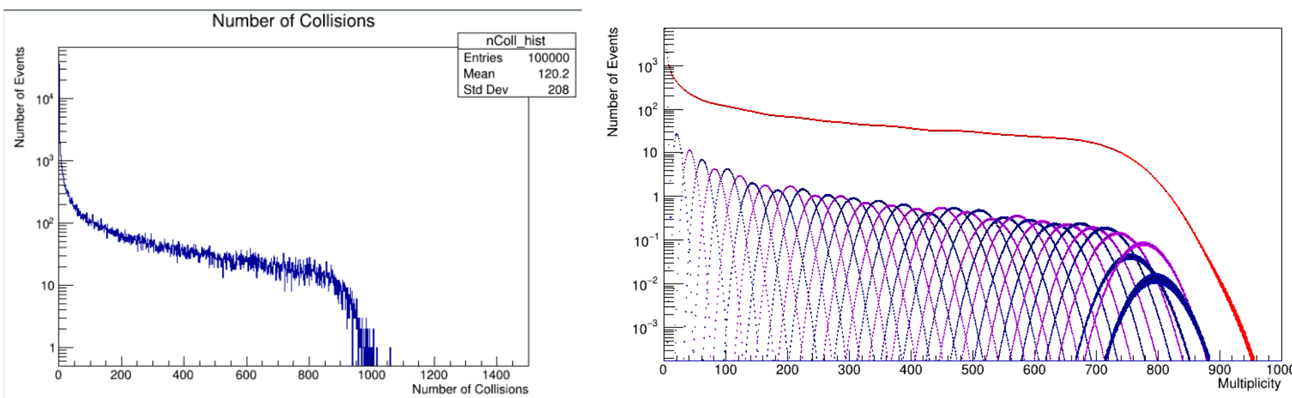

Figure 3: Left: Resulting distribution of number of binary nucleon collisions from 100 thousand simulated Au+Au collisions at 100 AGeV collisions. Right: Multiplicity distribution (red) for $\mu = 0.4$ and k 0.6. Blue and Violet colored distributions show the individual multiplicity distribution calculated from a single N_{coll}

2.2 Particle Production

Every time a binary nucleon collision occurs, energy is released in the form of particles, primarily pions. The number of particles produced is also known as "multiplicity" and can help make inferences about the properties of the collisions. A larger multiplicity implies a lower impact parameter, and thus larger number of participants, N_{part} and collisions, N_{coll}.

The Glauber model approximates every binary nucleon collision to produce energy according to a negative-binomial distribution (NBD) parameterized by μ and k., where μ is the mean and k controls the spread of high-value. Thus it is possible to determine a multiplicity distribution from an N_{coll} distribution for a given μ and k. Figure 3 on the right, shows such a distribution. This is done by calculating the individual multiplicity distributions for a single number of collisions, by sampling from the created NBD N_{coll} many times for every event that had N_{coll} collisions. Due to the central limit theorem, as one samples and increasing number of times from any distribution, the resulting distribution of those samples approaches that of a Gaussian. The overall multiplicity distribution is the sum of all the individual effects.

3 RHIC Data

I was given fixed-target Au+Au collision data. It consisted of a two-dimensional histogram of primary tracks vs their barrel-time-of-flight matched tracks with the z-axis as the number of such events. Figure 4 shows the data I was given for a 100 GeV beam energy run.

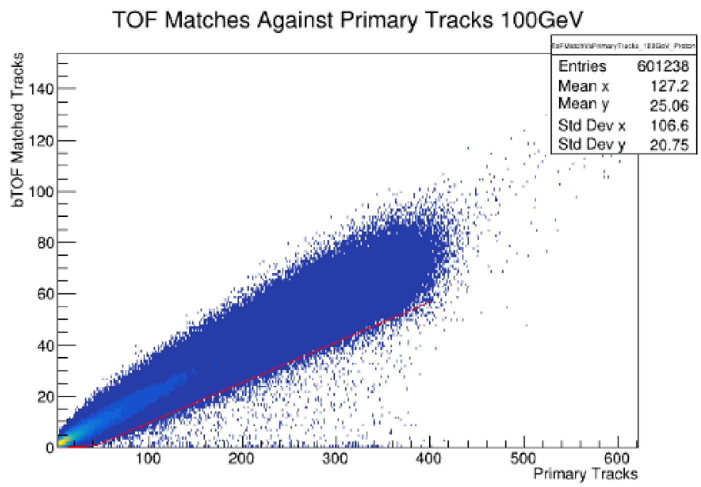

Figure 4: STAR data of a fixed target Au+Au collision consisting of Primary Track vs bTOF matched tracks. The Z axis (color) being the abundance of those events with lighter colors signalling more events. The red line denotes that the area below it was assumed to be all out of time pileup.

3.1 Types of Pileup

Simply stated, pileup is data that is produced through mechanisms that we do not wish to include in our calculations. This data consists of errors in the readings of tracks and improper matchings of them. They can be seen in Figure 4 as the fuzzy edges on the top end of the cone and below cone.

One type of pileup is called out-of-time pileup. These occur because of improper counting of tracks between different bunch crossings. For example, if a given collision occurs near the end of one bunch crossing, some of the tracks produced by that collision may be re-counted in the subsequent bunch crossing. This specific instance of out-of-time pileup would make it appear as if a larger number of primary tracks occurred. In reality the extra tracks from the previous bunch crossing would not be matched by the bTOF due to their not sharing the same vertex as the new nuclear collision. Due to the incorrectly large primary tracks with less matched bTOF tracks, the out of time pileup is seen below and slightly to the right of the cone. It is simple to correct this, as they are in different bunches. By eye, I fit a line to the bottom of the cone (see the red line in Figure 4) and set the content of all the bins below it to zero.

The second type of pileup is in-time pileup. It is harder to quantify due to the pileup occurring within a single bunch crossing, and is the bulk of the discussion for the rest of this paper. It occurs, when 2 nuclei collisions occur simultaneously (less than a nanosecond) apart from each other in a single bunch crossing. At this small of a timescale, the detector does not have the time resolution to distinguish between these two events, and instead considers them as one event producing a multiplicity equal to the sum of their individual nucleus+nucleus collisions.

In-time pileup is visible above the main cone in Figure 4 but more easily understood through its x-projection where only the number of primary tracks and their abundance is considered. Figure 5 shows the x-projection of Figure 4. Near the tail end there is a visible extension of the distribution. This is from the in time pileup and occurs when 2 nuclear collisions produce multiplicities, which when summed together results in a value outside the standard range of the distribution. Though it is also known that in-time pileup occurs within the rest of the distribution as two smaller multiplicity events could result in an observed multiplicity that's unreasonable to expect in the overall distribution.

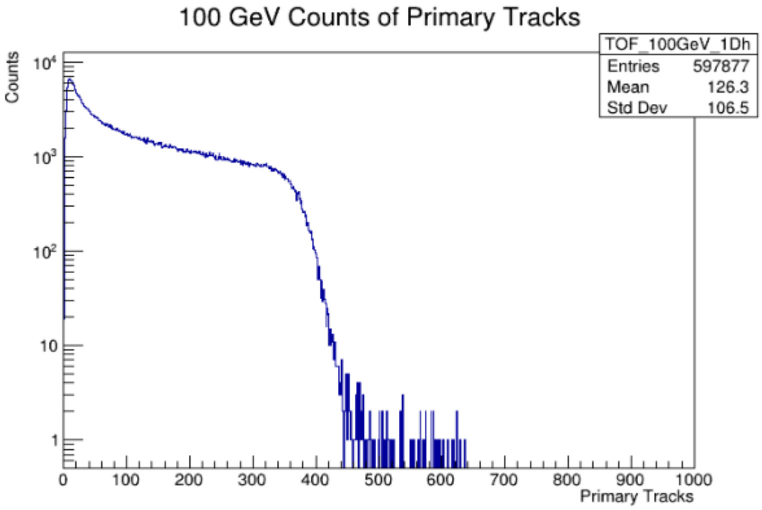

Figure 5: X-projection of the STAR data from Figure 4. Consists of primary tracks vs their respective counts. The "fuzzy" edge of the distribution indicates contribution from in-time pileup throughout the entire distribution.

3.2 Trigger Inefficiencies

Before quantifying the in-time pileup, I needed to account for a seperate phenomenon known as the trigger-inefficiency of the detector. Figure 6 shows that at low multiplicities, the detector saw a far fewer number of events than would be expected for the distribution. This occurs because the detector struggles to overcome its threshold for background when there are very few tracks. Therefore a lot of the actual low multiplicity events are not accounted for.

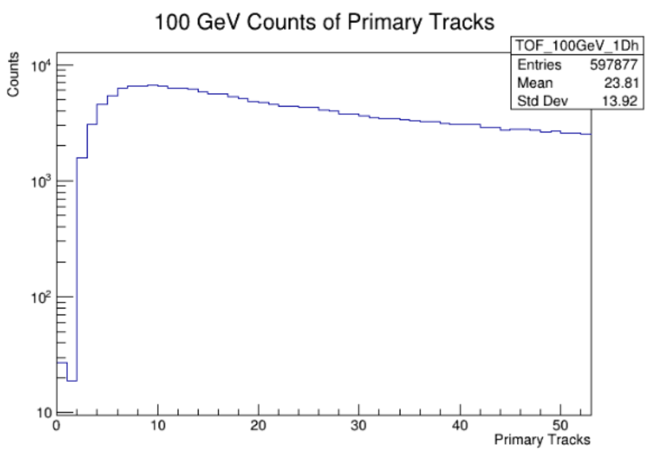

Figure 6: Zoomed in low multiplicity end of 5. The decreasing edge towards lower multiplicites signifies that the detector has trigger inefficiencies that must be accounted for.

In order to remedy this, I used a histogram to represent the ratio of the detector's efficiency in each bin. The process of calculating this histogram is discussed in Section 4. The efficiency histogram can be modeled by a function $-e^{-Ax}+1$, where A is a constant representing the rate at which efficiency increases. But, in reality we have to assume it to have maximum efficiency (=1.0) at some point. In the case of my analysis, I chose the 80 multiplicity to be the first point where I was confident of maximum efficiency. Every multiplicity bin thereafter was also stated to have a efficiency equal to 1.

4 Quantifying the Effect of Pileup

Instead of determining the effect of pileup across the entire distribution, it is more beneficial to see its contribution across different centrality classes. We want to find these centrality classes across the multiplicity distribution that contains no trigger inefficiencies and no pileup.

This was achieved by performing a χ^2 fit between a Glauber model generated multiplicity distribution and the STAR data such as that seen in Figure 5 with in-time pileup subtracted. The Glauber model distribution serves the major purpose of approximating the shape of the data's distribution without trigger inefficiencies. And also serves as the basis of calculating the expected in-time pileup distribution over the entire range. Figure 7 shows the 100 GeV data distribution plotted against the distribution which I found to represent the pileup.

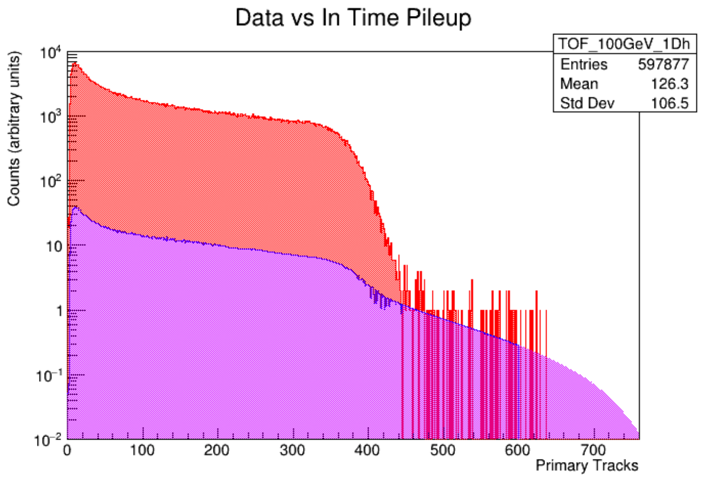

Figure 7: Red region shows the overall multiplicity distribution seen in Figure 5 with the purple region showing the distribution of in-time pileup.

The in-time pileup distribution can be represented as a convolution of the corrected multiplicity distribution with itself. This is because the multiplicity from a single nucleus+nucleus collision can be thought of as a random sample from the overall multiplicity distribution; similar to how the multiplicity of a binary nucleon collision can be thought of as a sample from a negative binomial distribution.

Once the in time pileup distribution is calculated through convolution, it must be multiplied by the efficiency histogram. This accounts for the trigger inefficiencies of the detector only once, as opposed to convolving the data with itself which would account for the trigger inefficiencies twice. The efficiency histogram is simply the data histogram divided by the current simulation histogram we are fitting.

After properly scaling the distribution to represent the in-time pileup of the data, it is subtracted to give a representation of what the data would look like if the in time pileup was correct. This is where the χ^2 calculation is performed, because its important we get a distribution without any inefficiencies or pileup for our centrality calculation. Figure 8 shows the fitted simulation histogram with the centrality cuts. Each cut represents the spread of 5% of the overall multiplicity. The first class is the one furthest to the right and represents the 5% most central, and thus most particle producing collisions. Note they have a greater spread because there was far less of them compared to the less central collisions.

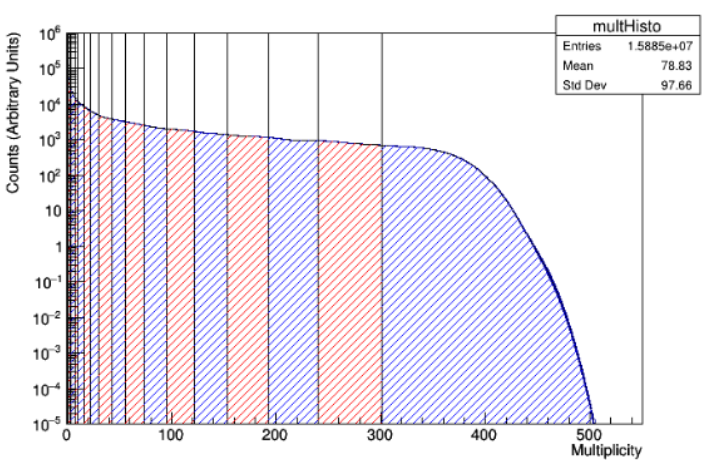

Figure 8: Fitted multiplicity distribution without trigger inefficiencies or in time pileup. Alternating blue and red regions show the different centrality classes, with the five percent most central collisions occurring in the right most blue region.

5 Results

After calculating the centrality cuts I was able to determine the contribution of pileup in each region. Figure 9 compares the resulting contribution between the centrality bins for the 100 GeV and 44.5 GeV data. It is seen that as the collision gets less central, the contribution of pileup decreases. The decrease is linear for most centrality classes, yet the first class has significantly greater in time pileup contribution outside of what that pattern predicts. It is also interesting that 44.5 GeV had a significantly larger amount of in-time pileup compared to 100 GeV

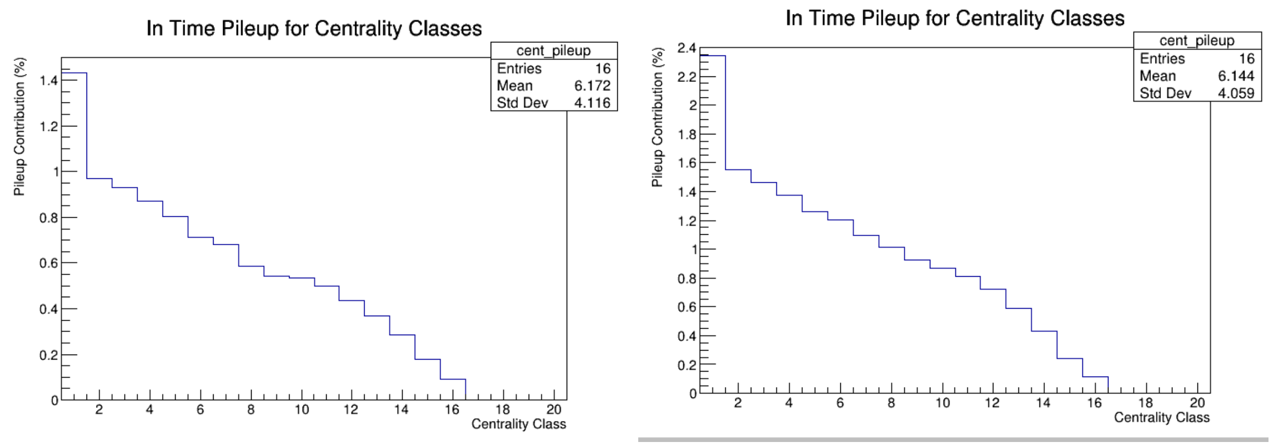

Figure 9: Left: In-time pileup contributions in percentage across the different centrality classes for 100 GeV beam energies. Classes ranging from the most central (1) to the least central (16). Classes above eighty percent were chosen not to be shown due to possible error. Right: Same as left-side but for 44.5 GeV beam energy.

6 Discussion and Conclusion

The large contribution from pileup in the first centrality class is likely due to the lack of statistics in the very high multiplicity regions. In figure 5 it is seen that there is not much in-time pileup visible outside of the main distribution. So the method I used may struggle to properly quantify the contribution in such regions of low statistics.

As for the reason that a factor of 2 difference is seen between the 44.5 AGeV and 100 AGeV is likely due to the luminosity parameter of the beam. This dictates how many ions are in a given beam bucket and at low energies it is possible those at RHIC increased the amount of ions per bucket by a factor of 2, ultimately leading to ≈ 2 times more in-time pileup.

Overall, we saw that there was very little contribution from in-time pileup. Nevertheless it is important to quantify this effect because it can have significant effects on future calculations. These centrality classes will also serve to be beneficial to calculate the average N_{part}, N_{coll} and impact parameter., which allow for comparisons between different types of nuclei collisions and energies.

References

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