

Using the Optical Glauber Monte Carlo Model to Calculate R_{AA} Related Results Produced by the ATLAS Collaboration

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Keywords: R_{AA} , Optical Monte Carlo Model, Quark-Gluon Plasma, Jet Quenching, Energy Loss

Received: January 3, 2020

Accepted: March 7, 2020

Published: March 10, 2020

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ABSTRACT

The energy loss during jet quenching due to the existence of Quark Gluon Plasma (QGP) is calculated by Optical Glauber Monte Carlo model with data collected by ATLAS Collaboration using the LHC detector. An energy loss formula for this situation was modeled and took the form $\Delta p_T = \sqrt{L^3} \cdot \ln p_T \cdot \frac{e + \ln p_T}{30\pi^2}$. The nuclear modification factor, R_{AA} , for jets in a $^{208}\text{Pb} + ^{208}\text{Pb}$ nucleus collision with rapidity interval of $|y| = 2.8$ and the initial transverse momentum of $50 \text{ GeV} \leq p_T \leq 1000 \text{ GeV}$, are compared with various data plots produced by ATLAS Collaboration. R_{AA} results are plotted in different centrality bins, which are defined by the distribution of number of participating nucleons N_{part} . The R_{AA} value was found to slowly increase at lower transverse momenta and flatten out at higher transverse momenta. The model's theoretical calculation results turned out to be similar to the plots produced by the ATLAS Collaboration using data from the LHC with small differences for higher systematic uncertainty events.

1. INTRODUCTION

High energy ultra relativistic heavy-ion collisions between two atomic nuclei in particle accelerators can result in a condensed substance that exhibits fluid-like properties known as Quark Gluon Plasma (QGP) [1], which is mainly constituted of colour charge carriers (e.g. quarks and gluons). Quantum Chromodynamics (QCD) describes the strong interactions between elementary particles such as quark and gluons, which carry colour charges. Unlike in Quantum Electrodynamics (QED), where field lines originating from charged particles spread infinitely throughout space, field lines between interacting quarks only exist in a thin tube between them; this has been determined experimentally and through simulations. Therefore, independent free

quarks can only exist under special circumstances, as the energy required to separate confined quarks found in hadrons would scale indefinitely with the distance of separation, and the energy inputted would make it favourable for the creation of a quark anti-quark pair due to vacuum fluctuations.

To better understand the properties and the compositions of QGP, particle colliders are used both to generate the plasma and to read their signatures through processes similar to scattering experiments, which can be done by observing and measuring properties of hard and soft probes exiting out of the QGP [2]. Jets, like vector-bosons and quarkonia, are a form of hard probes, for their signatures going through QGP are different compared to their signatures when moving through vacuum. Jets produced at nucleon-nucleon collision sites are subjected to energy modifications due to the effects imposed by the QGP. It has been observed that the energies of jets produced in Pb + Pb collisions are lower than those of jets produced in pp collisions; this phenomenon has been termed as jet quenching [3, 4], as the jets' passage through QGP lowers their energies. The energy by which a jet loses is dependent on its initial transverse momentum p_T and the distance through the QGP that the jet travels, which is modeled by the distance through the participating nucleons that the jet penetrates (L). This energy suppression could be observed by comparing the jet p_T distribution in Pb + Pb collisions to the jet yield of pp collisions.

The characterization of the distribution of the number of participating nucleons, N_{part} , achieved by grouping these events into different centrality bins that correspond to different ranges of impact parameters (for example, smaller impact parameters can mean higher numbers of collisions and larger impact parameters can mean smaller numbers of collisions), can categorize data for further calculation regarding N_{part} as shown in Table 1. Figure 1 displays the distribution of N_{part} over 100,000 samples, separated into different centrality bins.

The measurement of the jet yield and nuclear modification factor R_{AA} represents the relationship between the jet energy loss and the initial transverse momenta with respect to different centralities in a collision

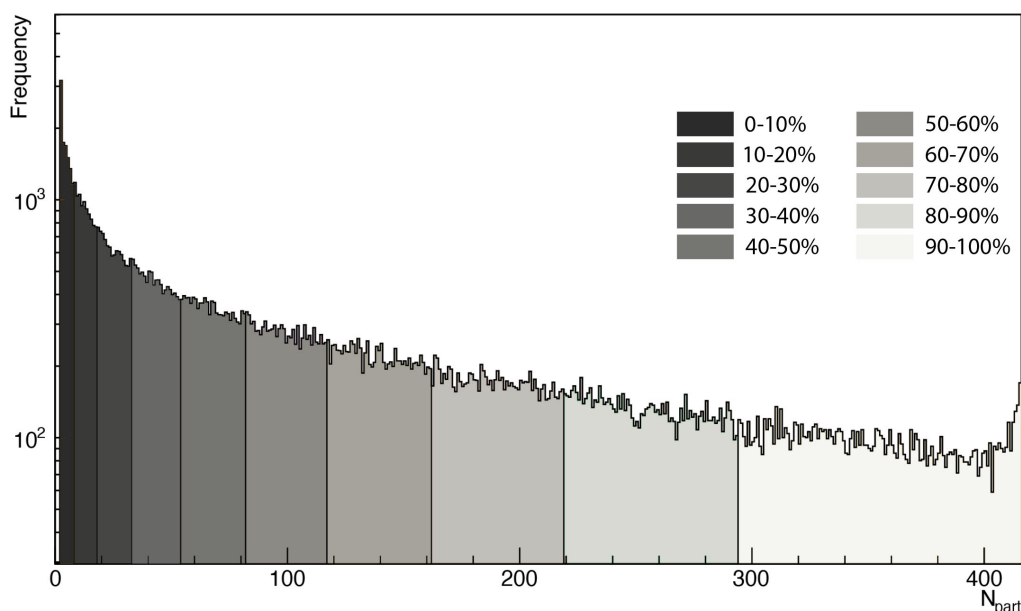


Figure 1. The distribution of the number of participating nucleons (N_{part}) separated into different centrality bins. Starting at the y-axis where the centrality is about 100%, every interval between each vertical colored line categorizes a centrality range of 10%. (From left to right the first centrality range is 90% to 100%; the second range is 80% to 90%, etc. The lowest range is 0% - 10%.) N_{part} has a mode at 2, and the frequency at which each N_{part} occurs gradually decreases as N_{part} increases, until falling to 0 after N_{part} reaches 416, the maximum number of participants for a $^{208}\text{Pb} + ^{208}\text{Pb}$ collision. Note the use of a logarithmic scale for the y-axis.

Table 1. The mean number of participants, “ N_{part} ”, and their uncertainties for different centrality intervals.

Centrality Range	N_{part}
70% - 80%	25
60% - 70%	43
50% - 60%	67.5
40% - 50%	99
30% - 40%	139
20% - 30%	190
10% - 20%	256
0% - 10%	354.5

event. The definition of R_{AA} presented in the paper by the ATLAS Collaboration [5] is given in Equation (1).

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \left. \frac{d^2 N_{\text{jet}}}{dp_T dy} \right|_{\text{cent}}}{\langle T_{AA} \rangle \left. \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \right|_{pp}} \quad (1)$$

In order to incorporate the Optical Glauber Monte Carlo Model, the following interpretation of R_{AA} , given in Equation (2), is used to simplify and optimize the calculations.

$$R_{AA} = \frac{\psi(p_T|_{\text{before}})}{\psi(p_T|_{\text{after}})} \quad (2)$$

where $\psi(p_T)$ is the frequency distribution of transverse momentum, p_T .

Using data provided by the ATLAS Collaboration from the LHC detector, this paper aims to analyze the relationship between p_T and R_{AA} under different centrality ranges, attempt to find a formula for the jet energy loss, and reproduce some of the plots presented in the paper by the ATLAS Collaboration [5] through the use of computer simulations built under the Optical Monte Carlo Model.

2. METHOD

The program setup is based on the Optical Glauber Monte Carlo approach [6-8], which is a simplistic, geometry based method of approximating N_{part} (the number of participating nucleons) and N_{coll} (the number of binary nucleon-nucleon collisions), given an impact parameter b and a certain nucleus radius r of a nucleus-nucleus collision.

Within this model, it is assumed that the velocities of the two colliding lead nuclei are exactly opposite of each other. For the purposes of this project, it was assumed that the protons and neutrons are geometrically identical and that the charge that the protons carry has no effects on the collisions. The initial locations of nucleons are determined by assuming that the density distribution of the nucleons with respect to the distance to the center of the nucleus is rectangular, but disregarding the effects of nuclear charge density and minimum inter-nucleon separation distance. As the experiment using the ATLAS detector at the LHC indicated, the ^{208}Pb nucleus, containing 208 nucleons each with a radius of 0.546 fm, has a radius of 6.62 fm.

The event of a Pb-Pb collision is simulated using the computer program ROOT, which utilizes random number generators to generate the positions of the nucleons in two spheres to simulate two Lead nuclei. The position of each nucleon is determined randomly by selecting arbitrary points within a sphere of radius 6.62 fm; this step is repeated for each of the 208 nucleons in each nucleus. Coordinates of these three-dimensional spherical nuclei, separated by the impact parameter (which is determined randomly given the distribution $d\sigma/db = 2\pi b$), are then projected onto a two-dimensional plane. If the distance between the centers of two arbitrary nucleons is less than the diameter of a nucleon (which is 1.092 fm), they are registered as collided and are participants. If a given nucleon does not collide with any other nucleon in the other nucleus, the nucleon would be regarded to as a spectator. **Figure 2** shows an example of a simulated collision with this model.

This model treats the nuclei collision as numbers of independent binary nucleon-nucleon collisions. The model also assumes that all the nucleons carry ultra-relativistic momentum and that they travel in a straight trajectory according to their initial positions and can collide with multiple nucleons without any path change or deflection. These properties indicate that the inelastic nucleon-nucleon cross section is not disturbed by other collisions made by the same nucleon. Due to the fact that the elastic cross sections do not contribute to a significant amount of energy loss, they are not considered here in this model.

The Optical Glauber Monte Carlo model allows for the derivation of centrality ranges from the N_{part} distribution, which characterize whether the collision is central or peripheral. Dijets, two jets that start at the same position but facing the opposite directions, are produced, initiating at the centers of the nucleon-nucleon collisions going at a random angle θ . It is important to note that, in this model, these jets are infinitely thin and will not be deflected or curved during their contact within the Quark Gluon Plasma. The amount of QGP that each jet goes through is calculated by taking the sum of the total distance of participating nucleons the jet penetrates through (L_1 and L_2 for the distances that the dijet goes through on each side). **Figure 3** shows the distribution of L_1 and L_2 over 4 different centrality bins: 0% - 10%, 20% -

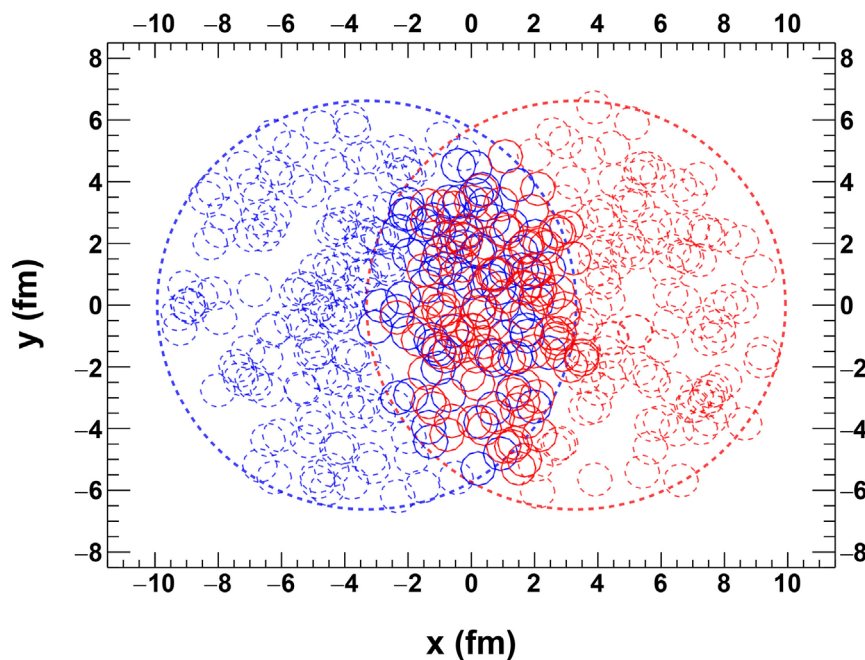


Figure 2. A collision between two randomly generated lead nuclei with an impact parameter of 6.62 fm, projected onto the transverse plane. The origin is the midpoint of the centers of the nuclei. Nucleons from the nucleus on the left are colored in blue, while nucleons from the nucleus on the right are colored in red. Spectator nucleons have dotted edges, while participating nucleons have solid edges. The outline of the nuclei is shown in large dotted circles.

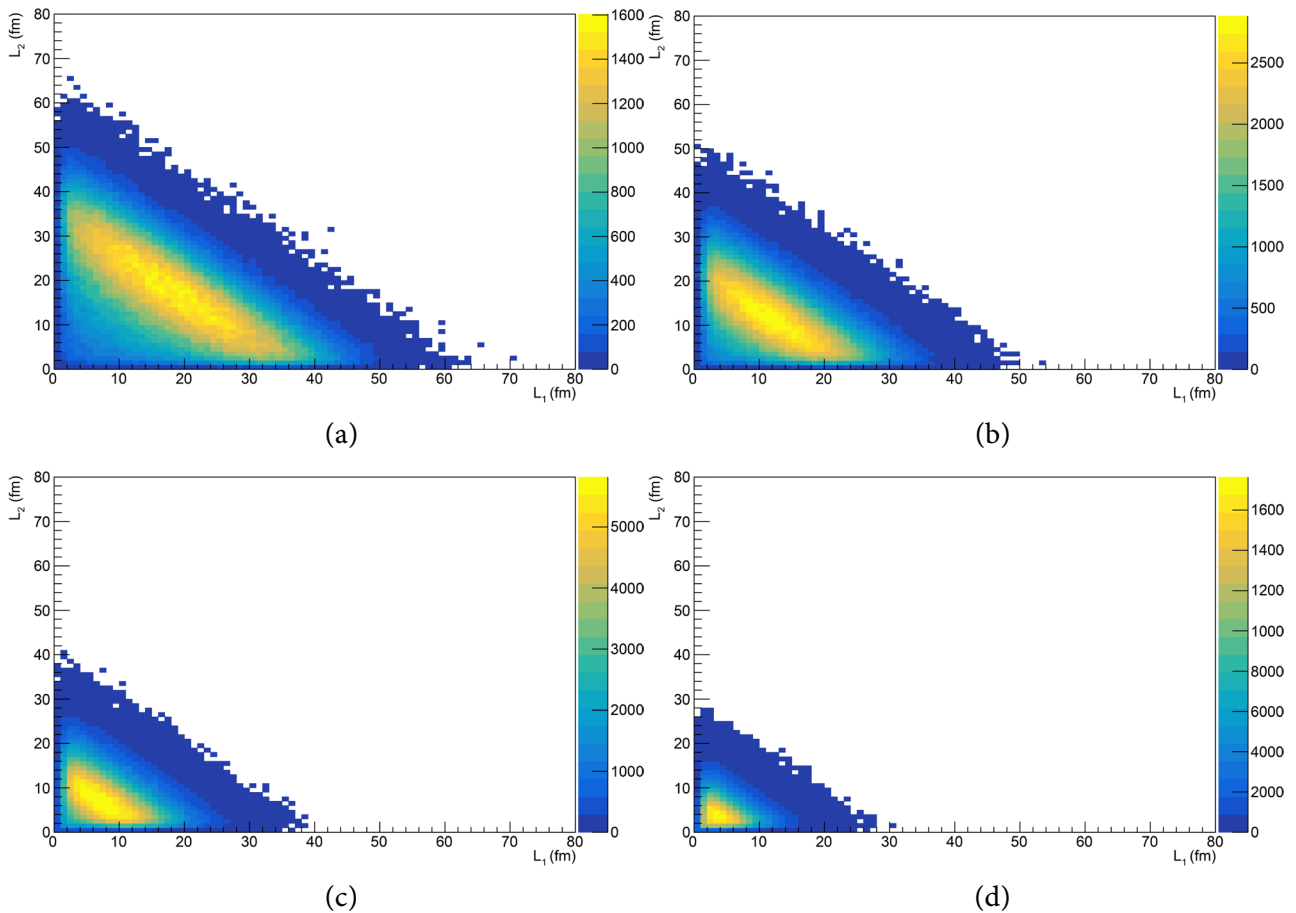


Figure 3. The result of the Jet distance calculation using the Optical Glauber Monte Carlo model bounded within different centrality ranges over 1,000,000 samples each. The right color bar demonstrates the intensity of the distribution at a particular point. (a) Centrality range: 0% - 10%; (b) Centrality range: 20% - 30%; (c) Centrality range: 40% - 50%; (d) Centrality range: 60% - 70%.

30%, 40% - 50%, and 60% - 70%.

However, the model has certain downsides regarding the physics behind it. It assumes that all the nuclei and nucleons are completely spherical, thus disregarding most of the ultra-relativistic and quantum effects. According to experimental data, it is theorized that, during process of jets traveling through the QGP, different kinds of interactions will contribute to an energy loss. At present this process is not completely understood, but many researchers have done numerous works on this energy loss formula [9, 10]. We propose an energy loss formula written in the form as given by Equation (3) in order to compensate for all the above causes. The use of the equation will be demonstrated later in the paper.

$$\Delta p_T = \sqrt{L^3} \cdot \ln p_T \cdot \left(\frac{e + \ln p_T}{30\pi^2} \right) \quad (3)$$

3. RESULTS AND DISCUSSIONS

Equation (3) presents the formula for the energy lost for a jet with transverse momentum p_T traveling through QGP a distance of L . Using this energy loss formula, we produced different graphs of the amount of energy lost based on the initial transverse momentum at different centrality ranges. Figure 4 presents several graphs of energy loss at centrality ranges of 0% - 10%, 20% - 30%, 40% - 50%, and 60% -

70%.

Similar to the results obtained by the ATLAS Collaboration, **Figure 5** shows the nuclear modification factor R_{AA} as a function of Jet p_T for eight centrality ranges. The R_{AA} value is calculated by jets with $|y|=2.8$ and p_T between 50 GeV and 1000 GeV. Following the ATLAS results, we have modified our bins using variable binning to compress higher p_T jet intervals before evaluating R_{AA} . R_{AA} values increase slowly as p_T values increase for all events at different centrality ranges until flattening out at high p_T values. R_{AA} predictions yield by the Optical Glauber Monte Carlo model is fairly close to the actual experimental data collected by the LHC and presented by ATLAS. Most of the data points presented by the model can potentially lie directly on top of the ATLAS data if luminosity uncertainty is considered. This is a proof that the energy loss formula is sufficient to compensate most the ultra-relativistic quantum effects that are not considered in the Optical Glauber Monte Carlo model.

Figure 6 shows a relationship between R_{AA} and N_{part} for p_T range ($100 < p_T < 126$ GeV) of jets with $|y| \leq 2.8$. Compared with data from ATLAS, our paper produced similar results: R_{AA} decreases on a smooth curve as number of participants increases. The model corresponding to the characteristics of the ATLAS results because both of them showed tendency for peripheral collisions to produce higher R_{AA} values

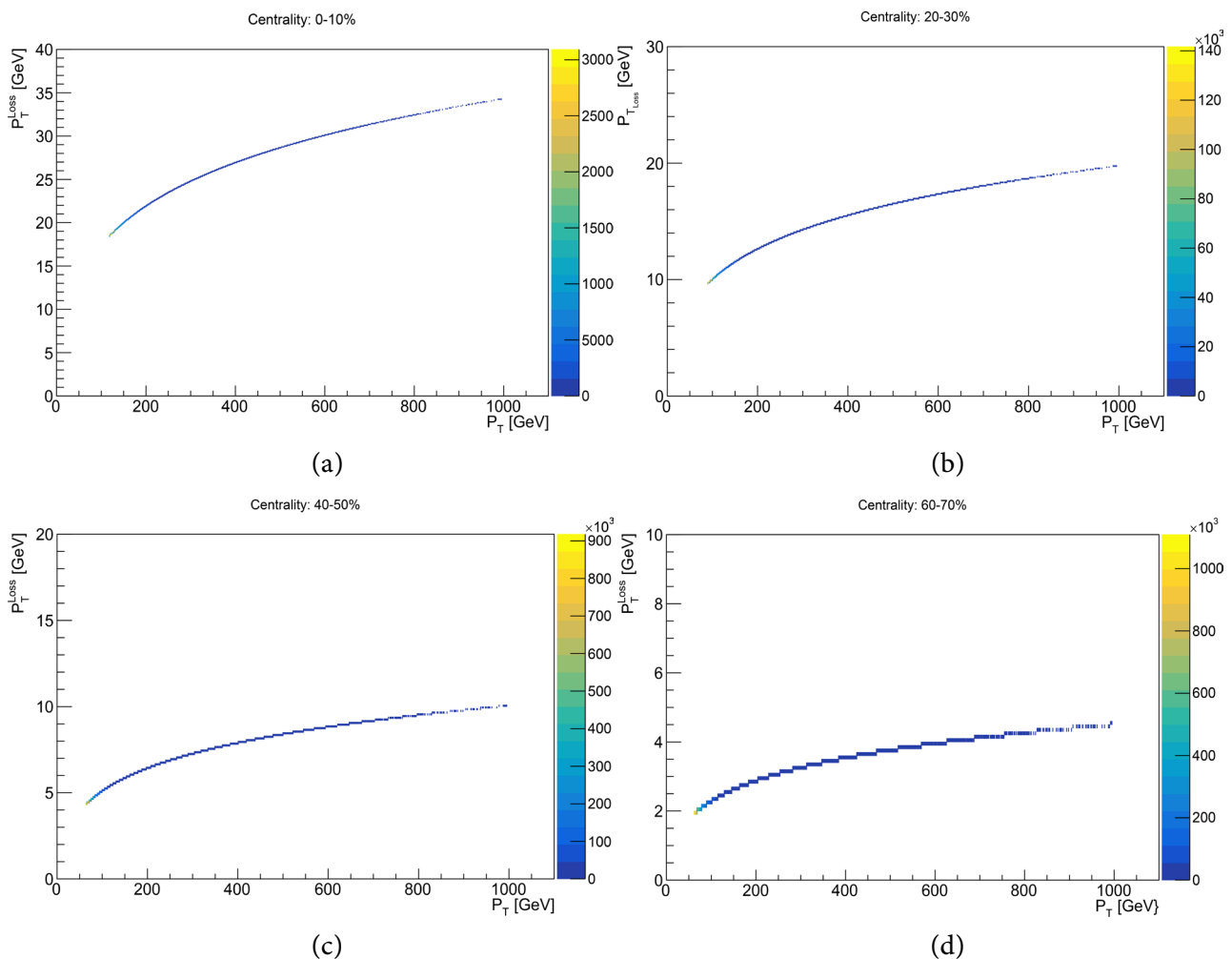
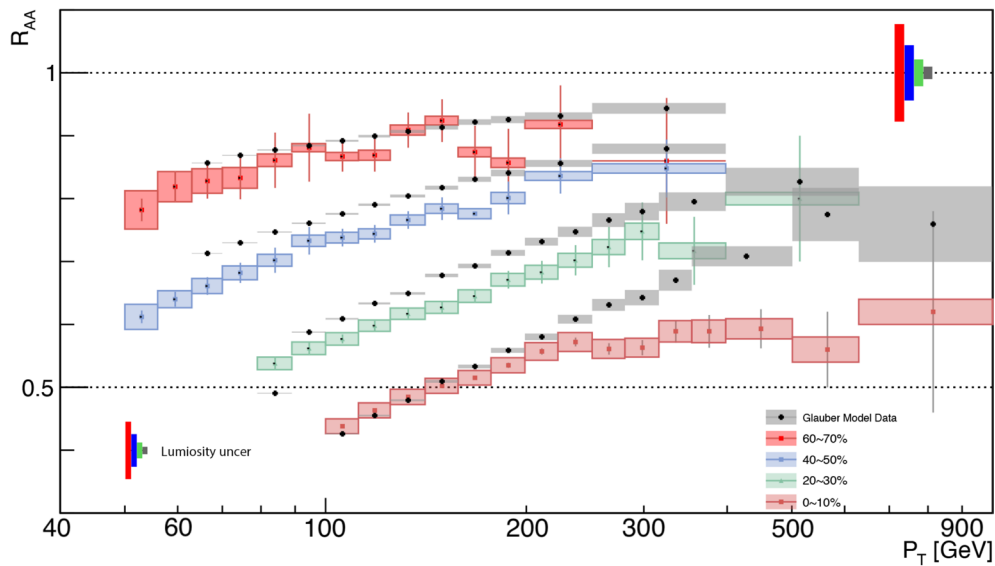
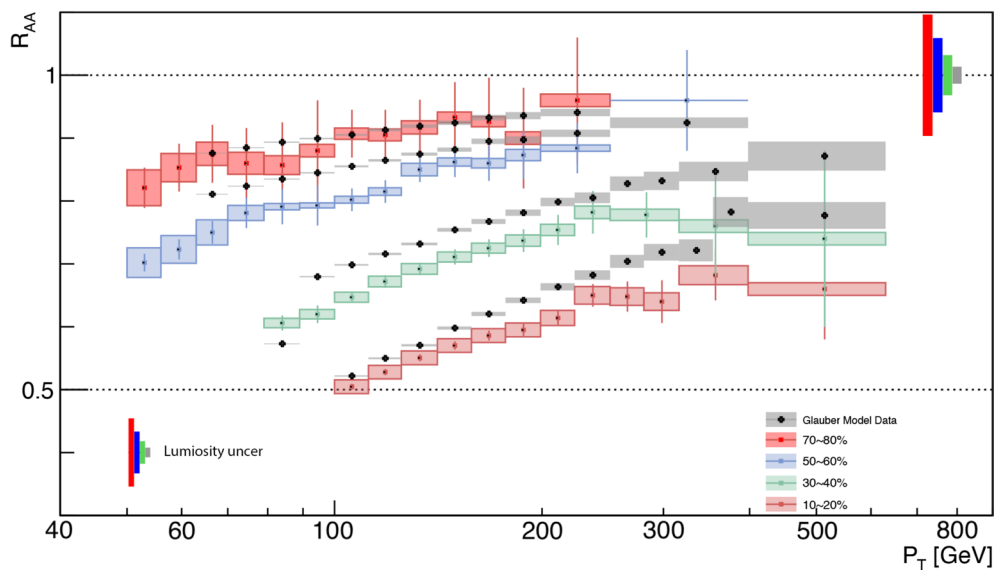


Figure 4. The energy that a jet would lose based on the transverse momentum of the jet and bounded into different centrality, 0% - 10% centrality for the graph above. The right colour bar demonstrates the intensity of the distribution at a particular point. (a) Centrality range: 0% - 10%; (b) Centrality range: 20% - 30%; (c) Centrality range: 40% - 50%; (d) Centrality range: 60% - 70%.



(a)



(b)

Figure 5. Plots reproduced in this project. The colored boxes are results obtained ATLAS Collaboration. The grey box labeled “Glauber Model Data” corresponds to the results according to the name centralities. (a) Centrality intervals 0% - 10%, 20% - 30%, 40% - 50%, and 60% - 70%; (b) Centrality intervals 10% - 20%, 30% - 40%, 50% - 60%, and 70% - 80%.

and central collisions to produce lower R_{AA} values.

The results seem like that both the initial p_T and the amount of QGP will influence the energy loss during the collision. When the initial p_T become higher, the influences of QGP on jets will tend to be constant. Therefore, we predict that the QGP will exert a stronger effect on jets with lower transverse momentum, which means the jets with lower p_T will lose relative more energy than the jets with higher p_T due to the QGP. It is also explicit that the jet energy loss is dependent on the amount of QGP (and subsequently, the number of participants and the impact parameter), and the amount of QGP will become more crucial factor as p_T increases.

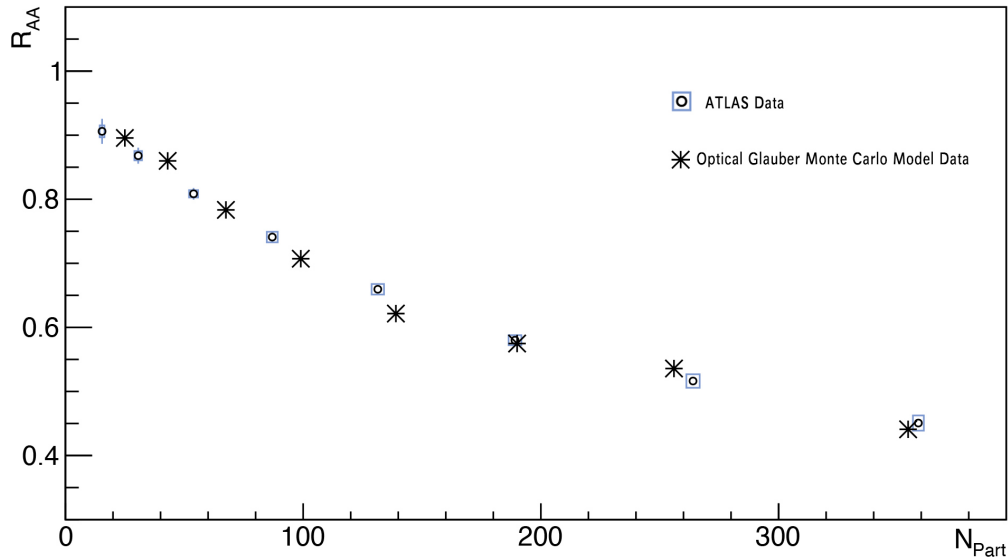


Figure 6. R_{AA} with respect N_{part} to with $100 < p_T < 126$ GeV. The white dots represent data from the ATLAS Collaboration, while the stars represent the data outputted from the Optical Glauber Monte Carlo Model.

4. CONCLUSION

Nuclear Modification Factor (R_{AA}) predictions, calculated using the Optical Glauber Monte Carlo model and random Dijet generation functions with transverse momentum (p_T) data for Pb-Pb nucleon-nucleon collisions at center-of-mass energy of 5.02 TeV provided by the ATLAS detector at the LHC, are consistent with the data yield from ATLAS results. From the plots, one can see that the effects of Quark Gluon Plasma (QGP) on jets vary with p_T and the different centrality ranges, which correspond to the N_{part} . These results represent the success of the Optical Glauber Monte Carlo Model at replicating the actual experimental data. So the Optical Glauber Monte Carlo Model turns out to be a plausible theoretical model for the evaluation of jet quenching.

ACKNOWLEDGEMENTS

We sincerely acknowledge the contribution and instruction by Professor Guntehr Roland for this paper.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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