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The measurement of nuclear modification factor for inclusive jets in Pb+Pb collisions at $\sqrt{S_{NN}} = 5.02$ TeV using an estimated energy-loss formula

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ABSTRACT. *In this paper, a new model for energy loss of inclusive jets in Quark-Gluon Plasma(QGP) is proposed. The predicted yield and nuclear modification factor, R_{AA}, for inclusive jet production are comparedwith those from other models such as SCET and LBT as well as the 0.49 nb^{-1} of Pb+Pb data at $|y|< 2.8$ TeV and 25 pb^{-1} of pp data from the ATLAS detector at the LHC. Jets are reconstructed by Glauber MC model and are measured over the transverse momentum range of 40–1000GeV in six rapidity intervals covering $|y|< 2.8$. In the simulated collisions of nucleons based on Glauber model, it is assumed that distance that jet travel through QGP can represent the influence exerted by QGP. The energy-loss formula is composed of three parts: the function of the original transverse momentum P_t, the distance that jets propagate through QGP and fluctuations.*

KEYWORDS: *Heavy ion collision; Quark-Gluon plasma; nuclear modification factor; GlauberMC Model.*

1. Introduction

In relativistic heavy-ion collision experiment, when two beams of particles withrelative light speed collide with each other, a great amount of energy released will accumulate in a small space instantaneously that the deconfinement phase transition of hadronic matter can occur, producing a hot and dense medium call Quark-Gluon Plasma(QGP) [4]-[6]. Products of the hard scattering of quarks and gluons in these medium evolve as parton showers that go through QGP. Parton showers lose their energy mainly through two processes: collisional energy loss and radioactive energy loss,

ISSN 2616-7433 Vol. 1, Issue 07: 118-127, DOI: 10.25236/FSST.2019.010715

giving rise to lower-energy jets. This phenomenon is called “Jet quenching” [4]. However, many physics properties such as the energy loss or the number of participant particles can not be determined by experiments directly. The Glauber model was developed to describe the process of collisions. In order to quantitatively assess the quenching effects, the magnitude of the inclusive jet suppression in nuclear collisions relative to pp is quantified by the nuclear modification factor R_{AA}, defined as:

$$R_{AA} = \frac{\frac{1}{N_{evt}} \frac{d^2 N_{jet}}{d_{pT} dy}\Big|_{cent}}{< T_{AA} > \frac{d^2 \sigma_{jet}}{d_{pT} dy}\Big|_{pp}} \tag{1}$$

where N_{jet} and σ_{jet} are the jet yield in Pb+Pb collisions and the jet cross-section in pp collisions,respectively, both measured as a function of transverse momentum, P_t, and rapidity, y, and N_{evt} and $< T_{AA} >$ is the total number of Pb+Pb collisions within a chosen centrality interval and mean nuclear thickness function [2].

Another equivalent definition for R_{AA}, which is used in our model, is:

$$R_{AA} = \frac{N_{PbPb}}{N_{PP}} \tag{2}$$

Where N_{PbPb} denotes the number of Pb particles whose jets suffer from suppression in QGP produced, while N_{pp} is the number of proton particles which are not influenced by QGP. Therefore, their ratio quantifies the influence to the inclusive jets by QGP.

2. Methodology

2.1 Glauber MC model

Glauber MC model is an efficient theoretical method to estimate the geometric quantities which can not be determined by experiments directly such as the number of participant nucleons and impact parameter theoretically in high-energy scattering[1][2]. Furthermore, it is even possible to simulate the experimentally observable quantities such as the charged particle multiplicity and utilize the the centrality cuts to analyse the real data. One important approximation involves in Glauber model is the optical limit: Collisions are ultra-relativistic. Energy involved in the collision is so high that nucleon deflection, as well as electromagnetic interaction, can be ignored. Therefore, the differences between the neutron and proton are not considered. In addition, the motion of a single nucleon is independent with that of nucleus, which means the total cross section can be obtained by superposition of many scattered cross sections of nucleons. The main idea of the Glauber model is to simplify a 3D scattering process down to a 2D

ISSN 2616-7433 Vol. 1, Issue 07: 118-127, DOI: 10.25236/FSST.2019.010715

process, a feasible approximation when the process is ultra-relativistic and the nuclei are relativistically contracted due to Lorentz contraction on the direction of their momentum vector. Different from previous studies, in which either fermi- or Wood-Saxon distribution are used, we have implemented a uniform nucleon distribution in the sphere of Lead nucleus with radius of 6.38 fm.

In our model, we firstly generate the position vectors of 416 nucleons in two Pb nuclei stochastically in three-dimensional coordinate system according to the nuclear density distribution. And then, a random distribution can be obtained using the distribution, $\frac{d\sigma}{db} = 2\pi b$, where σ is the density and b represents the impact parameter. Under the relativistic effect, the position vectors of each nucleon is projected into X-Y coordinate system(FIG. 1).

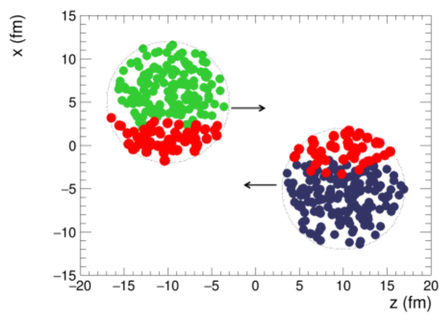


Figure.1 Pb-Pb nuclei are moving along the beam axis. The arrows represent the directions of motion for each nucleus.

Rather than treating the nucleus-nucleus collision as a complex system, the GMC model breaks it into many independent nucleon-nucleon events. That is, the nucleons follow straight-line trajectories and the inelastic nucleon-nucleon collisional cross-section is assumed to be independent with the preceding nucleon collision event. Number of participants and number of collisions are then calculated by comparing the distance between the nucleons and the radius of nucleon. If:

$$d_{NN} < \sqrt{\frac{\sigma_{inel}^{NN}}{\pi}} \quad (3)$$

Where d_{NN} is the distance between two random nucleons and $\sigma_{\text{inel}}^{\text{NN}}$ the total inelastic nucleon-nucleon cross-section, then it counts as an valid collision(FIG. 2).

ISSN 2616-7433 Vol. 1, Issue 07: 118-127, DOI: 10.25236/FSST.2019.010715

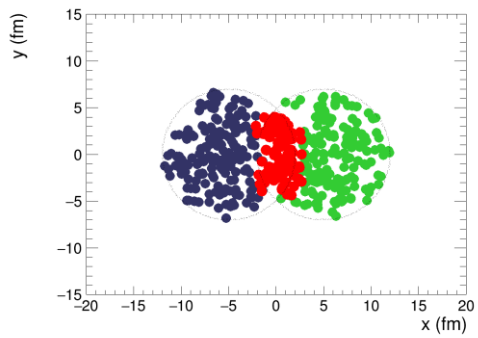


Figure.2 Glauber Monte Carlo collision event (Pb+Pb at $\sqrt{S_{NN}} = 5.02$ *TeV with impact parameter* $b = 10$ *fm viewed in the transverse plane). The red disk represent participant particles.*

Any nucleons which experience the collision for a certain impact parameter is termed as participant particles while the other are called spectator particles.

For each collision of a pair of nucleons, we assume a jet is produced in the collision center and propagates through the QGP in a random generated direction. By comparing the distance between each nucleon which is penetrated by the jet and the collision center, the furthest distance that a single jet crosses through QGP is determined and denoted as L1. The distance that the paired jet crosses through QGP is denoted as L2. The relationship between the numebr of collision and that of participants is given in FIG. 3.

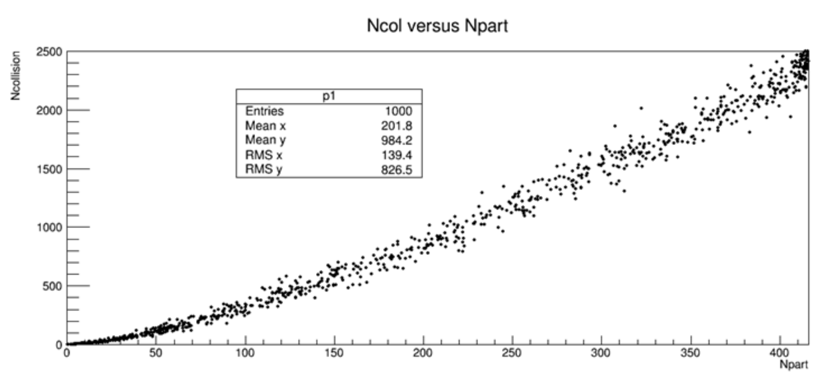


Figure.3 The figure depicts the relationship between the number of participants and number of collisions. A strong positive correlation can be observed.

Unfortunately, neither N_{part} nor N_{coll} can be directedly measured in an RHIC

ISSN 2616-7433 Vol. 1, Issue 07: 118-127, DOI: 10.25236/FSST.2019.010715

experiment. Means values of such quantities can be extracted for classes of N_{evt} measured events via a mapping procedure, which is done by defining 'centrality classes' in both the measured and calculate distribution and then connecting the means values from the same centrality class in the two distributions. The underlying assumption of centrality class is that the impact parameter b is monotonically related to particle multiplicity. One can expect low multiplicity with a large number of spectator particles at mid-rapidity for large b events, or "peripheral" events, and high multiplicity with a small number of spectator particles for small b events, or "central" events. To define the centrality classes, the distribution of N_{part} for different impact parameters is obtained in Fig. 4 and one can measure the total integral. Once the integral is known, the centrality classes are defined as binning the distribution based upon the fraction of total integral(FIG. 4). The centrality intervals used in this measurement are indicated in Table 5 along with their respective calculations of N_{part}.

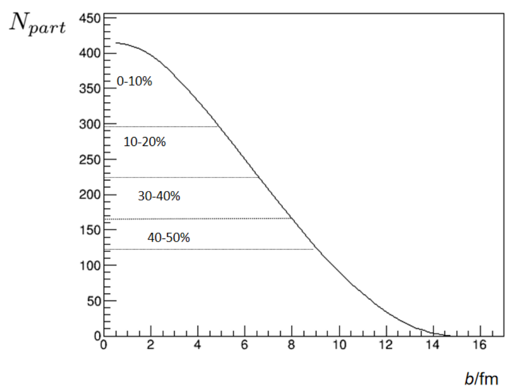


Figure.4 An example of the correlation of impact parameter with Glauber calculated quantities(N_{part}). The plotted distribution and various values are illustrative and not actual measurements.

Table 1 The ten centrality intervals and each's corresponding range of number of participant particles.

Centrality range	N_{part}
0-10%	416-296
10-20%	221-296
20-30%	167-221
30-40%	122-167
40-50%	88-122
50-60%	59-88

ISSN 2616-7433 Vol. 1, Issue 07: 118-127, DOI: 10.25236/FSST.2019.010715

60-70%	37-59
70-80%	18-37
80-90%	6-18
90-100%	0-6

2.2 Energy-loss formula

Drawing on conclusions from the previous experiments [2], one can expect the energy loss for a jet when travelling trough QGP is dependent of the original transverse energy(P_t), which is the pp transverse momentum, and centrality, or L1. Thus we postulate the energy formula of the form:

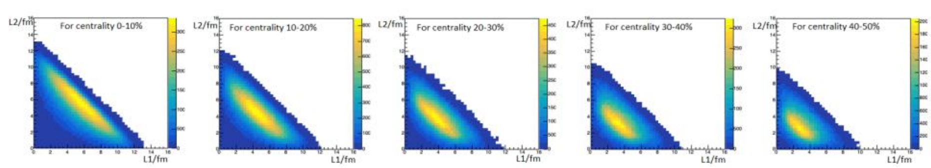
$$\Delta E_{loss} = f_1(P_t) f_2(L1)\varepsilon \quad (4)$$

where $f_1(P_t)$ and $f_2(L1)$ are independent functions of P_t and L1 respectively, and ε is the fluctuation term including any other factors and it is assumed to follow a statistical distribution, e.g. Poisson's distribution.

By comparing the nuclear modification factor obtained from the with the experimental data, this formula can be adjusted and optimized.

3. Results

The relationship between L1 and L2 is presented in the two panels of figure 5, each showing five centrality intervals. In general, the L1 and L2 shows strong negative correlation. That is, as L1 increases, L2 decreases. And the total distribution is for all centrality cuts is symmetric with respect to line $y = x$, and that is because the direction is randomly assigned. As the centrality interval increases from 0-10% to 90-100%, the distribution of L1 and L2 shifts inward, which means the free mean path of jet through QGP decreases.



ISSN 2616-7433 Vol. 1, Issue 07: 118-127, DOI: 10.25236/FSST.2019.010715

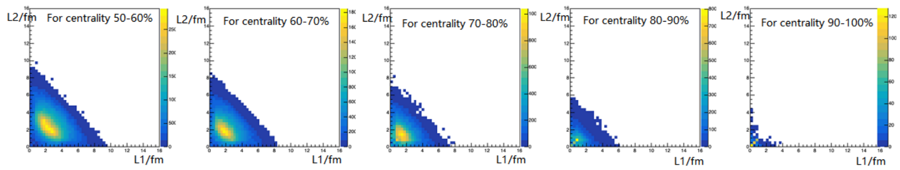


Figure.5 The relationship between L1 and L2 for different centrality intervals. A strong negative correlation between L1 and L2 can be observed. As centrality interval moves from 0-10% to 90-100%, or as the number of participants is decreasing, the L1 and L2 moves inward.

The energy-loss formula is given as followed:

$$f_1(P_t) = \cos(\frac{1}{1000}(P_t - 1500))e^{\frac{p_t - 1500}{1000}} \quad (5)$$

$$f_2(L1) = L1^2 \quad (6)$$

$$\varepsilon = 1 \quad (7)$$

By applying the energy-loss furmula, the distribution of energy loss for jets with $|y| < 2.8$ is given is figure 6. As the original transverse momenum increases, the energy loss increases but with a slower slope.

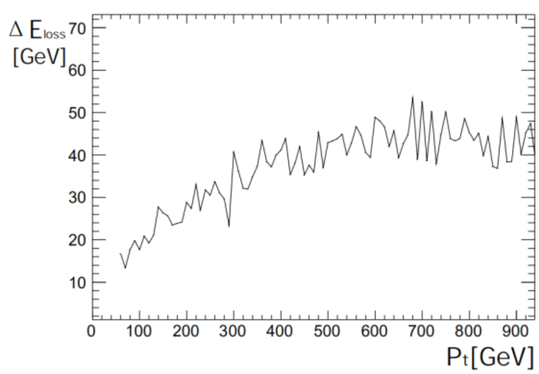


Figure.6 The predicted energy loss versus the original transverse momentum.

In FIG. 7, the nuclear modification evaluated as a function of jets P_t is presented and compared with experimental data separately in four panels, each showing two centrality intervals. A clear suppression of jet production in central Pb+Pb collisions relative to pp collisions is observed. R_{AA} is observed to grow slowly (quenching decreases) with

ISSN 2616-7433 Vol. 1, Issue 07: 118-127, DOI: 10.25236/FSST.2019.010715

increasing jet P_t .When centrality cut goes from 0-10% to 70-80%, or as participant particles decrease, an upward for predicted line can be observed, with the largest values of R_{AA} in the most peripheral collisions and the smallest values of R_{AA} in the most central collisions.

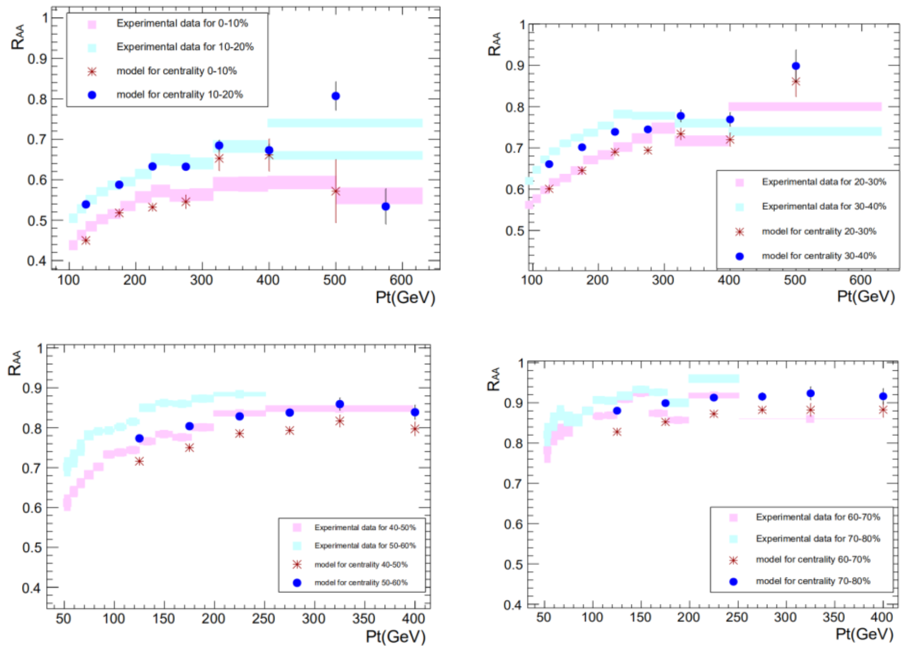


Figure.7 The relationship between the R_{AA} and transverse momentum is shown in the four panels in this figure within the centrality from 0% to 80%, each showing two cnetrality intervals. The general trend is that, as P_t increases, the R_{AA} increases but with decreasing slope.

A comparison of the R_{AA} values with theoretical predictions is provided in Figure 8. The R_{AA} values obtained as a function of jet P_t are compared with four predictions where theory calculations are available: the Linear Boltzmann Transport model (LBT) [7], one calculation using

The Soft Collinear Effective Theory approach (SCETG) [9], and the Effective Quenching model (EQ)[8].

ISSN 2616-7433 Vol. 1, Issue 07: 118-127, DOI: 10.25236/FSST.2019.010715

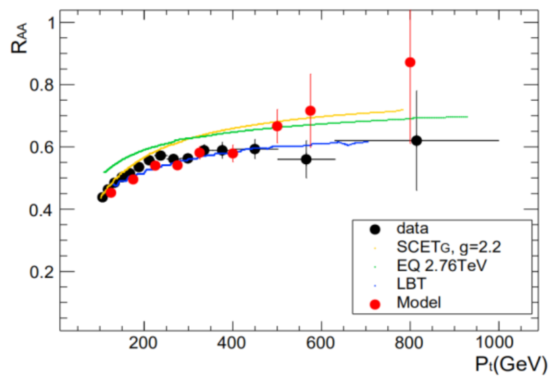


Figure.8 R_{AA} values as a function of jet P_t for the 0-10% centrality interval with theory predictions.

4. Conclusions

Pb-Pb collision at $\sqrt{S_{NN}} = 5.02$ Tev is simulated by applying Glauber model. For each collision, a jet is assumed to occur. Ten centrality cuts ranges are determined and an estimated energy-loss formula is proposed, which can predict the energy loss when jet propagates through the Quark-Gluon Plasma. Measurements of jet yield and nuclear modification factor based on the energy-loss formula are performed for each centrality intervals and compared with the data from Atlas and other models. The predicted magnitude of R_{AA} increases with increasing jet transverse momentum but when it reaches large enough transverse momentum the increasing rate slows down, which is in accordance with the experimental data.

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