Research on Jet Quenching with Isolated-Photon+Jet correlation in Pb-Pb and p-p collisions at collision energy 5.02 TeV

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Abstract. This paper is dedicated on the phenomenon of jet quenching and its quantitative description at $\sqrt{S_{NN}}$=5.02 TeV. Data from collision events with an isolated leading photon, $p_T^\gamma > 40$ GeV, associate jets with p_T^{jet} >30 GeV, are plotted as a function of centrality; result is then matched to reference function in p-p events at the same level of energy to infer some model for parton energy loss in PbPb collisions. The main motivation for this paper is to overcome the difficulties of comparing the theoretical models and experimental data, which are linked with a hypothetical equation for energy loss.

1. Introduction

In the process of collisions of heavy ions, a deconfined medium of quarks and gluons is formed at extremely high temperature and density[10], knowing as the Quark Gluon Plasma (QGP).[9]

Information from the thermodynamical properties (such as temperature, energy or particle densities...) and transport properties (such as viscosity and conductivity) of the QGP can be obtained by comparing the results for a given observable Φ_{AA} measured in nucleus-nucleus(in this study Pb-Pb was measured) collisions to those measured in proton-proton (pp, "QCD vacuum") collisions as a function of centre of-mass energy $\sqrt{S_{NN}}$, transverse momentum p_T, pseudrapidhity y, reaction centrality (impact parameter b), and particle type (mass m).[1] Schematically as follow.

$$R_{AA}(\sqrt{S_{NN}}, p_T, y, m; b) = \frac{hot \quad dense \quad QCD \quad medium}{QCD \quad vaccum} \tag{1}$$

The most interesting phenomenon during QGP formation was "jet quenching". As a result of fragmentation, jets are generated in the opening process of QGP generation[7]. It was discovered at RHIC that the jets are somehow "quenched", after being generated in heavy-ion collision, (experiencing energy loss as it goes through the medium) compare to the jets generated in pp collision. Obviously, this effect is the result of the interaction of the sprays[11].

The QGP medium which only appear in ultra relativistic collision of heavy ions, instead of the pp ones. Therefore, the energy loss of particles in the QGP, ΔE, provides some information about the medium [2].

The impact parameter b (i.e. the distance between centers of two colliding particles) is randomly assigned to the collision models. In general, more particles are produced in collisions with a small

impact parameter meanwhile events with larger impact parameter results in fewer colliding particles. This correlation can be used to make the collision centrality (central dependence) as a part of the total cross section. In addition, central collision are those events with high multiplicity and low average b while peripheral collisions are those with low multiplicity and large average b.Plus, within big collision systems, the difference in the number of particles generated results from energy fluctuations by individual pp collisions is small compared to the impact-parameter-caused difference. Therefore, the charged particle multiplicity, noted as Nch, could serve to restrain the impact parameter. The Glauber model is commonly used to determine the correlation of the multiplicity and the impact parameter. For instance, the 10% highest multiplicity of all the collisions are defined as 0-10% central. One thing to note is that when determining the centralities, the distribution of impact parameters at a certain multiplicity is often assumed to be normal and consistent.

For this paper, only Certain parameters are considered to be related to the energy loss. Derivations from the order of magnitude of the jet energy loss infer that the energy loss is proportional to the quadratic of jet path length L. For the Glauber Model used in this paper, the energy loss formula is given by

$$\Delta E = p_T{}^{jet} - 0.8 \times \left(ln(\frac{p_T{}^{jet}}{p_0}) \right)^2 \times (\frac{L_1}{L_0})^2 \qquad (2)$$

Where p0 and L0 represent the mean value of jet transverse momentum p and jet path length L.

2. Methods

2.1. Introduction of Glauber Model
During ultra relativistic collisions, some conditions such as the geometry of the impact region and the collision parameter b and cannot be obtained through direct observation. However, what could be done is to relate the number of participating and spectating particles through the used of centrality[8]. By dividing the centrality to different percentile range (such as 0-10%) of a collision, the geometries of the impact region can thus be determined with assumed initial nucleon configuration (which is often a Fermi-Dirac distribution) of the two nucleus [3].

2.2. Monte Carlo Analysis
The Monte Carlo method is a geometric approach that implements the nuclear distributions in order to build realistic nuclei to "collide". Several methods can be used to create this distribution all of which are well defined. An example is the two parameter Fermi model that is used to create 197-Au nuclei, where a Woods-Saxon density profile is created from a mean field potential on the nucleons. The equation describes the force felt by each nucleon, and the potential can be utilized to map out a probability function for the radial position of each nucleon[6].

In all methods, a distribution function is sampled from to give each nucleon in the nucleus a certain radial position. The nucleon is then assigned random azimuthal and polar angles that allow the nucleus to be built in a three-dimensional, spherical coordinate system. In order to reduce processing time, the spherical coordinates of each nucleon are converted into cartesian coordinates and saved in the nucleus arrays. When sampling from the radial distribution, the distribute function samples so that no radial position on the sphere is more likely to be chosen than another. The polar angle is obtained from transforming a uniform sample on the interval [-1,1] with the arctangent function and the azimuthal angle is sampled from a flat distribution over range $-\pi$ to π. This gives an even distribut-ion over the entire sphere that prevents oversampling near the poles. In essence, sampling in this fashion is the spherical equivalent to sampling over a uniform function in one dimension. The interaction distance at which two nucleons can be considered to have collided is also needed to run the program. This distance is directly related to the inelastic cross section of the nucleons, itself a function of beam energy. In this paper, however, considering the fact that the participants do not "know".

Since we care only colliding ions, we need to understand the most basic ion collision: proton-proton. If one can accurately model a proton-proton collision, then one can model heavier ion collisions as a conglomeration of many individual proton or neutron collisions. The particle data group gathers large amounts of data about elastic and total proton-proton cross sections from many experiments, and compiles all this data in one compact source. This program pulls the data in real time and fits curves to both elastic and total cross section as a function of beam energy. The proton-proton inelastic cross section is given by the curve of the total cross section minus the elastic cross section. The cross section is converted to a radial distance using the equation that relates area of a circle to radius: Σ pp over inner $= \pi r^2$ This program correlates number of interacting particles ("participants") and binary nucleon-nucleon collisions to the impact parameter, which is simply the distance between the centers of the nuclei during the collision. Because we are assuming every individual nucleon travels straight throughout the collision, the impact parameter can be drawn as the distance between the centers of the nuclei when projected onto a flat plane.

Two jets (see for di-jet phenomenon) are stimulated from the center in each of the events to opposite direction (back to back). Then the for each direction the jets are simulated as a beam, and the number of events that the two triggered jets crosses are counted as L1 L2.

2.3. Operating Process

2.3.1. Setting up the model. The MC Glauber model shall be set up in two steps with the programming operation. First, under the collision of two nucleus, we presume the member nucleons are traveling in a path of an approximated straight line (i.e. the eikonal approximation [4]). This way, they are either participant or spectator.
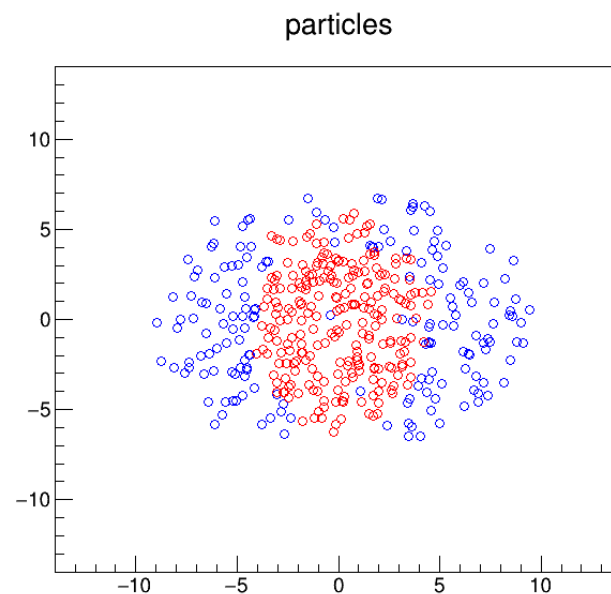

Figure 1. An illustrative example of the PbPb collision simulated in the Monte Carlo Glauber Model drawn in two-dimensional coordinate.

2.3.2. Initialization of nuclei.
Each nucleon's position in the nucleus is assigned according to the Fermi-Dirac Distribution With quantum models as FIG.1. shows, the probability function of the all particle in the nucleus can be approximated to that of single particle. In an approximated spherical nuclei, the distribution of nucleons is thought to be regular and consistent in both azimuthal and polar coordinates as figure 2. The parameters of the probability distribution function used in this experiment is obtained from

nuclear charge density distributions that formerly extracted by electron scattering experiments at low-energy levels.
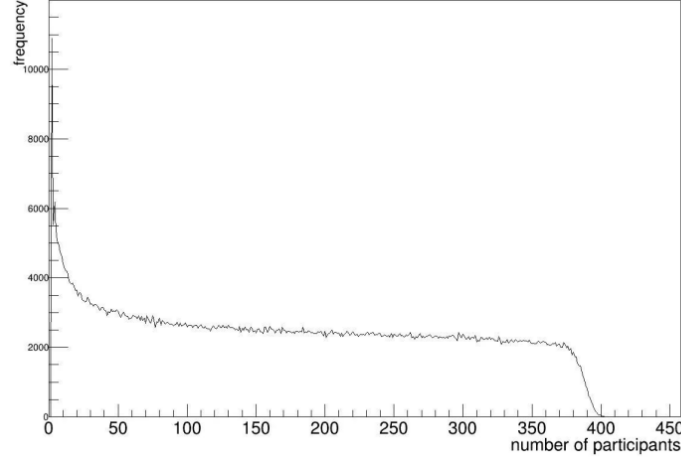

Figure 2. The distribution of number of participants N_{part}. Impact parameter b used in each trial is randomly assigned.

2.3.3. Jet production and L "counting".
As discussed above, the jets can be approximated to rays with certain angle. In practice, we use a set of liner equations to symbolize them on the xy plane. Hence, for every event, we can store the coordinates for the colliding center of the two nucleons (midpoint of the line segment connecting their centers). For each of the coordinates we randomly generate thousands of radian range between -PI to -PI (or slope in Cartesian coordinates) to ensure the jets emit at all direction. Considering the coordinates and slope we get, we can calculate some liner equation for each event. Next, for each equation or jet, we can count how much QGP it goes through by counting the participant nucleons that intersect with the line. This shall be done applying the formula for distance from point to line the to all nucleons, and compare the result with nucleon radius.
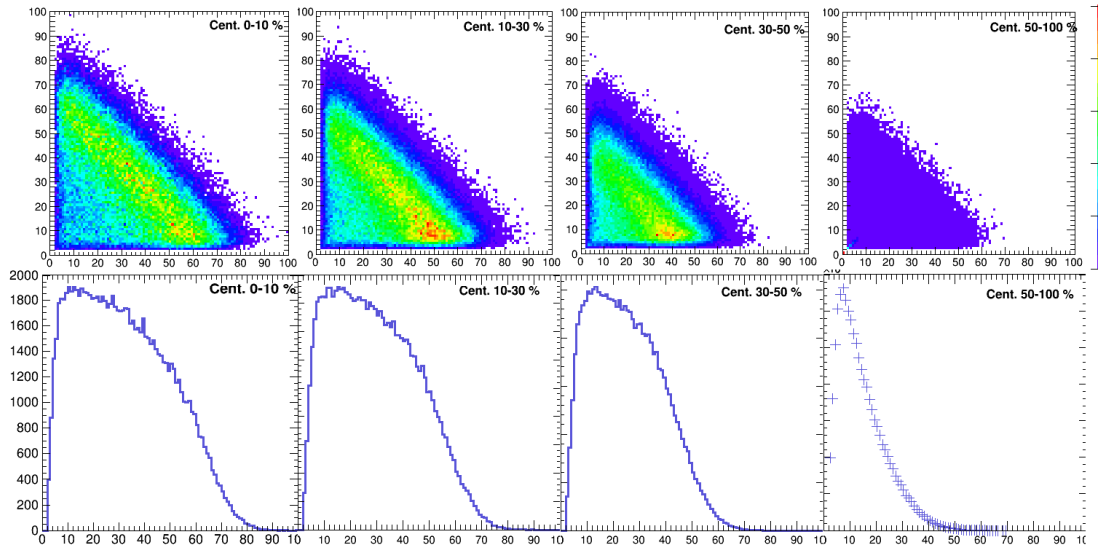

Figure 3. The centrality dependence of L_1 and L_2 for PbPb collision(top). The color of the bins represents the density of jets with respective path lengths. The centrality dependence of the distribution of L_1 for PbPb collision(bottom).

3. Results and Discussion

By inputting the values of the several parameters into the proposed energy loss formula, the centrality dependence of transverse momentum change (equivalent to energy change in magnitude) is calculated. After applying the simulated energy change to a set of pp collisions selected by the CMS detector[5], a histogram of PbPb momentum ratio x_γ^j (simulated) can be plotted together with the x_γ^j ratio of the original photon-jet momentum from pp collision. We can obtain the centrality dependence of x_γ^j and compare it directly to the CMS experimental data as in figure 3 and figure 4. By adjusting the parameters of the energy loss function, the model gradually approaches the experimental data.
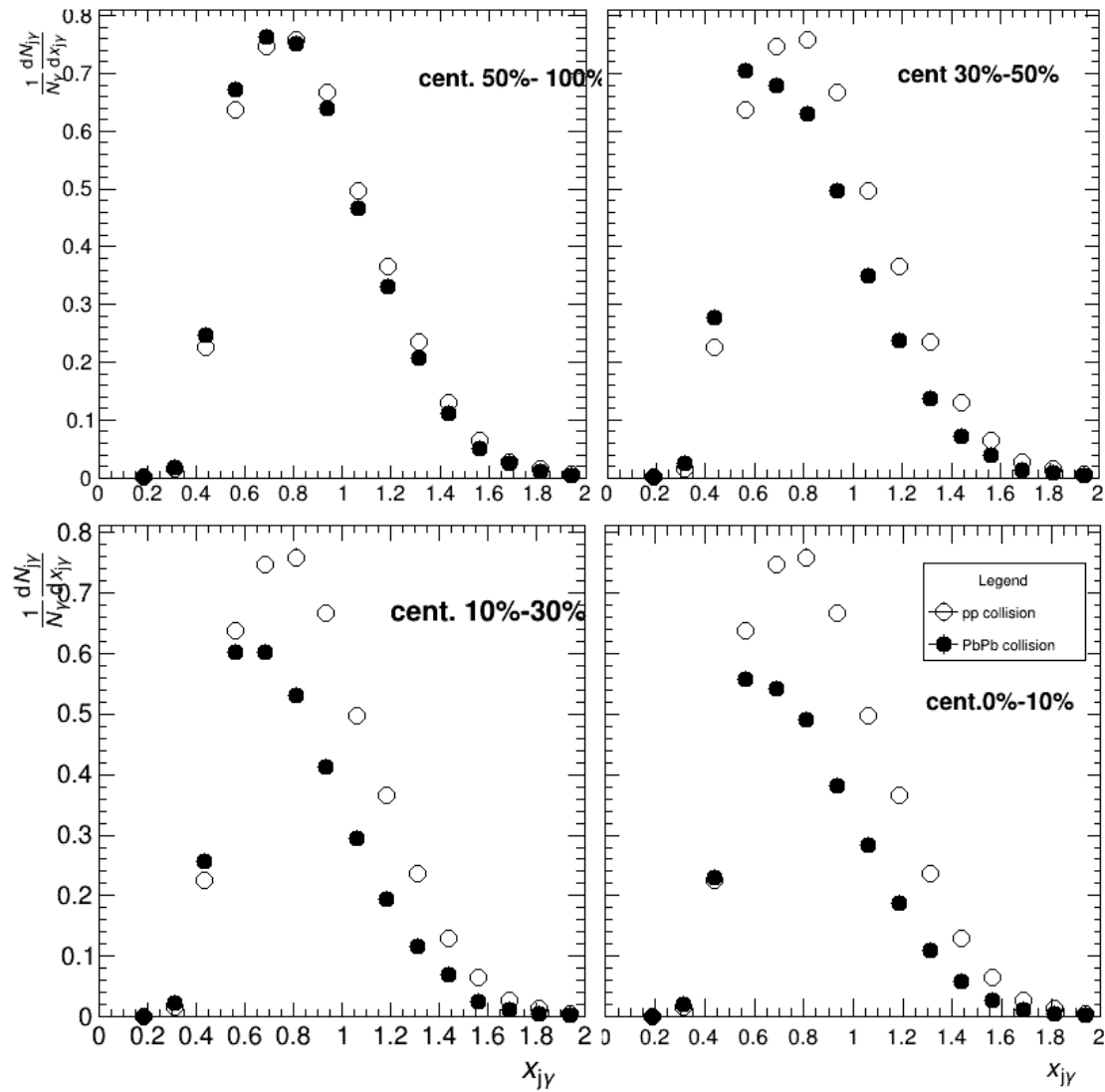

Figure 4. The centrality dependence of x_γ^j of photon+jet pairs normalized by the number of photons for PbPb (full markers) and smeared pp (open markers) data. (Simulation).

In 50-100% centrality, i.e., the most peripheral collisions, the PbPb distribution corresponds with the pp reference data. As the collisions become more and more central (smaller centrality percentile), the PbPb distributions present lower values and smaller integrals. This trend is consistent with the Glauber Model expectations that as the jet path lengths become larger with more central collisions, the energy loss increases. The R_γ^j distributions, the average number of associated jets per photon, as a

function of centrality is shown in withp_T^γ interval($p_T^\gamma >60$GeV/c) (figure 5). In more central collisions, larger suppression of R_γ^j compared to the smeared pp reference data is observed in ($p_T^\gamma >60$GeV/c) selection, corresponding to larger energy loss due to interaction with the QGP. Photon+jet transverse momentum imbalance is calculated with$x_\gamma^j = \dfrac{p_T^j}{p_T^\gamma}$ .In order to subtract the background fluctuations, a selection cut of $\Delta\phi_{j\gamma} > \dfrac{7}{8\pi}$ is applied.
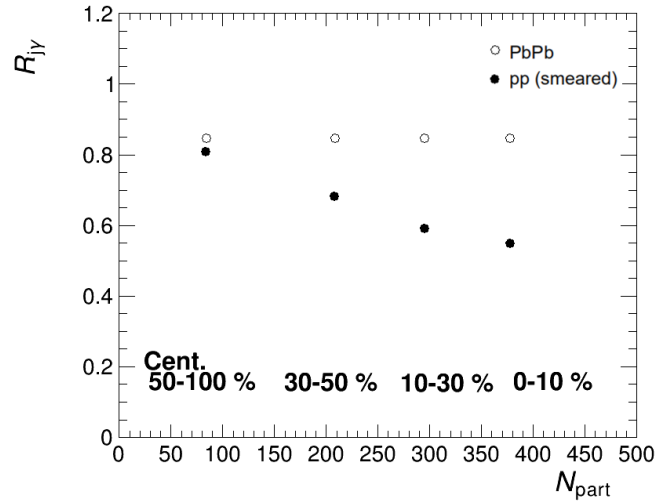

Figure 5. The distribution of R_γ^j as a function of centrality for $p_T^\gamma >60$GeV/c. Smeared pp collision data is implemented as reference.
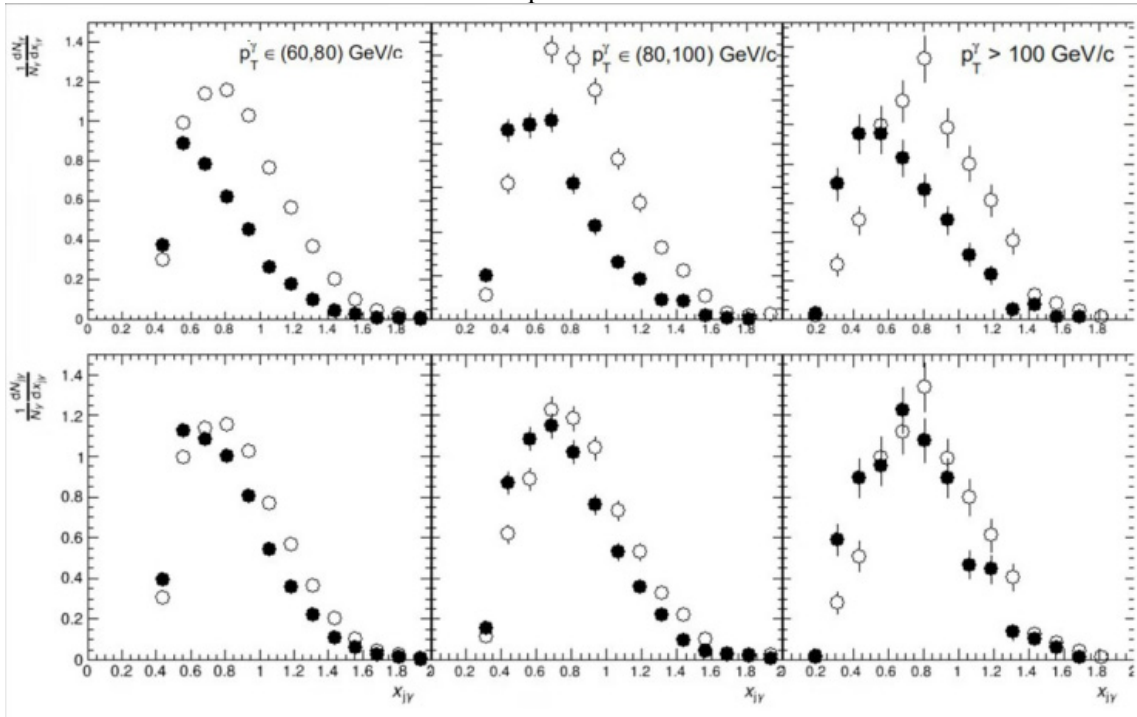

Figure 6. The $x_\gamma^j = \dfrac{p_T^j}{p_T^\gamma}$ distributions of PbPb collisions(markers) in 0-30% (top)and 30-100% centrality(bottom)intervals and five p_T^γ intervals. Smeared pp collision data (markers)is implemented for comparison.

The distributions of x_γ^j with different centrality intervals (0-30% and 30-100%) and p_T^γ selection cuts in PbPb and pp collisions are shown in figure 6. In 0-30% centrality, PbPb collisions present relatively strong modifications with respect to the smeared pp collisions. The distributions shift towards smaller values of x_γ^j and smaller total integrals, whereas in less central collisions (30-100% centrality), distributions that are more consistent between PbPb and pp collisions are observed.

4. Conclusion

This paper studied the correlations of isolated photons with $p_T^\gamma > 40$ GeV/c, $|\eta^{Jet}| < 1.44$ and jets with $p_T^\gamma > 30$ GeV/c , $|\eta^{Jet}| < 1.6$ in pp and PbPb collisions at $\sqrt{S_{NN}} = 5.02$ TeV based on the data collected in the CMS experiment. Monte Carlo Glauber Model is used to compare simulation with experimental data and energy loss formula associated with jet path length is implemented. The $x_\gamma^j = \frac{p_T^j}{p_T^\gamma}$ and R_γ^j of pp and PbPb collisions is studied in different centrality intervals and in different p_T^γ intervals. The difference between PbPb collision data and pp collision data increases as the collisions becomes more central. For intervals with $p_T^\gamma > 60$GeV, the values of R_γ^j are observed to be lower than those of respective pp reference and PbPb collisions tend to have lower x_γ^j and smaller integrals. These results are consistent with the Monte Carlo Glauber Model and previous study at $\sqrt{S_{NN}} = 2.76$ TeV. The results provide new comparisons between Monte Carlo Glauber Model simulation and experimental data from the CMS experiment with various centrality intervals and different selection cuts of isolated-photon and jets.

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