Study of jet quenching with isolated photon+jet correlations in pbpb and pp collisions at $\sqrt{s_{NN}} = 5.02$ tev

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ABSTRACT. In pp and PbPb collisions, azimuthal angle and transverse momentum($p_T$) distributions of jetphoton pairs are recorded with the CMS detector at the CERN LHC at $\sqrt{s_{NN}} = 5.02$ TeV. The modeling technique is based on the Monte Carlo Glauber Model, in which the nucleons are randomly distributed in the nuclei. Distribution of the ratio $\frac{p_T^{\gamma}}{p_T^{jet}}$ is simulated at different centrality intervals, and the reconstructed jets have to pass the cut of $\eta^{jet} < 1.6$ and $p_T^{jet} > 30$ GeV/c. Centrality percentile can be defined by binning the distribution with fractions regarding the total integral. The results from the simulation show that the Monte Carlo Glauber Model is consistent with the resultsof the CMS experimental data in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

KEYWORDS: Quark Gluon Plasma; Jet quenching; Glauber Monte Carlo model

1. Introduction

In relativistic heavy ion collisions, QGP(quark-gluon plasma), a state of matter predicted by QCD that exists at extremely high temperature and/or density is formed. Jets, which is a group of hadrons that come from the hadronization from quarks in heavy ion collisions, are produced in the collisions interact with the QGP and lose certain amount of energy since they are color charge carriers. This process, named “jet quenching”, provides a probe to determine properties of the hot and dense QGP,
which has been observed through the measurements of hadrons with high transverse momentum and of jets.

Though electroweak bosons do not interact with the QGP directly, the jets produced can give insights to the properties of QGP since the electroweak boson $p_T$ closely reflects the initial energy of the associated parton that fragments into the jet. The parton energy loss mechanisms can be understood through the study of correlations in boson-jet events. In this paper, energy loss of PbPb collisions is studied by comparing Glauber MonteCarlo model and experimental data.

In this research, the isolated photon that is selected by the CMS experiment is used. Prompt photon and associated jets are selected by reconstruction with a cone of specific value of radius. The correlations of isolated photons and jets in PbPb and pp collisions are measured at $\sqrt{s_{NN}} = 5.02$ TeV. The azimuthal angle difference $\Delta\phi_{j\gamma} = |\phi^{\text{jet}} - \phi^{\text{isolated photon}}|$, the $p_T$ ratio $x_{j\gamma} = p_T^{\text{jet}} / p_T^{\gamma}$ and the average number of associated jets per photon, $r_{j\gamma}$, are presented. In the end, the results from PbPb collisions are compared with those from pp collisions, with smeared pp data serving as the reference.

2. Analysis methodology

2.1 Monte carlo glauber model

To calculate geometric quantities of ultra-relativistic heavy ion collisions, such as the impact parameter ($b$), number of participating nucleons ($N_{\text{part}}$) and number of binary nucleon-nucleon collisions ($N_{\text{coll}}$), Glauber Models are developed to perform calculations on experimental data (for a complete review, see [2][3]). Basically, Glauber Models involves two approaches—the optical-limit approximation and the Monte Carlo approach[3]. In this paper, the modeling technique is based on the Monte Carlo Glauber Model, in which the nucleons are randomly distributed in the nuclei.

The nucleons are stochastically distributed in three-dimensional coordinates. Then it is assumed that the nucleons move along straight trajectories, which indicates that the longitudinal coordinate is irrelevant to the calculations. The impact parameter $b$ is randomly chosen from the distribution.

$$\frac{dN}{db} \propto b$$

A nucleon-nucleon collision is counted when the distance $d$ between the nucleons satisfies:

$$d \leq \sqrt{r_{NN}/\pi}$$
where $\sigma_{NN}$ is the total inelastic nucleon-nucleon cross-section. At CERN LHC, it is expected that $\sigma_{NN} = 68 \text{mb}$, corresponding to $\sqrt{s_{NN}} = 5.02 \text{ TeV}$.[1] Fig.1 qualitatively visualizes one example of the collisions with impact parameter $b=5\text{fm}$.

The Glauber Model used in this paper is parametric, which means that the parameters in the model can be adjusted through many iterations to increase the correlation between the model and the experimental data. The output of the model is a statistical probability distribution of respective geometric parameters. Physical insights into PbPb collisions can be interpreted from the distribution through comparison with experimental data.

2.2 Centrality

In events with large $b$, i.e., peripheral collisions, we expect large nuclear overlap and a large number of participants, whereas in events with small $b$, i.e., central

![Figure 1: A illustrative example of the PbPb collision simulated in the Monte Carlo Glauber Model drawn in two-dimensional coordinate.](image)

Collisions, we expect small nuclear overlap and a small number of participants. Therefore, it is assumed that the impact parameter $b$ of the collisions is monotonically related to the number of participating nucleons [1]. From the distribution of $N_{\text{part}}$, centrality percentile can be defined by binning the distribution with fractions regarding the total integral[3]. The $N_{\text{part}}$ distribution of the Glauber Model in this research is shown in Fig.2.
Figure. 2 The distribution of number of participants $N_{\text{part}}$. Impact parameter $b$ used in each trial is randomly assigned.

After a large number (10000 in this case) of Monte Carlo trials, for each of the centrality intervals, the mean value of participants (i.e., $<N_{\text{part}}>$) is calculated (Tab.1).

Table 1 Average values of the number of participating nucleons $<N_{\text{part}}>$ for centrality intervals used in analysis of the paper

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$&lt;N_{\text{part}}&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10%</td>
<td>340-416</td>
</tr>
<tr>
<td>10-30%</td>
<td>249-340</td>
</tr>
<tr>
<td>30-50%</td>
<td>167-249</td>
</tr>
<tr>
<td>50-100%</td>
<td>0-167</td>
</tr>
</tbody>
</table>

2.3 Jet path length

In order to calculate the energy loss during jet-quenching, algorithm for jet path length is implemented in the Glauber Model. In the algorithm, the paths in QGP are denoted by $L_1$ and $L_2$, which are calculated as the number of participating nucleons of which the jet encounters in hard scattering, respectively.

The algorithm is aimed to show the distribution of the relationship of $L_1$ and $L_2$ in PbPb collisions. To achieve this outcome, the algorithm generates jets for every nucleon-nucleon collision with random azimuthal angle $\Delta\phi$, and the number of collided nucleons crossed by each of the jets is counted. The results for various centrality intervals are presented in Fig.3.
Since the energy loss of the jets during interactions with the QGP cannot be directly measured from the experiment, energy loss formula needs to be applied to the model.

Certain parameters are considered to be related to the energy loss in jet-quenching: jet path length, as discussed above. 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

$$\Delta E = p_T^{\text{jet}} - 0.8 \times (\ln\left(\frac{p_T^{\text{jet}}}{p_0}\right))^2 \times \left(\frac{L}{L_0}\right)^2$$ \hspace{1cm} (3)

Where $p_0$ and $L_0$ represent the mean value of jet transverse momentum $p_T^{\text{jet}}$ and jet path length $L$, respectively.

Jet reconstruction is done by the CMS particle-flow (PF) algorithm and the anti-$k_T$ algorithm. Reconstructed jets have to pass the cut of $|\eta| < 1.6$ and $p_T^{\text{jet}} > 30 GeV/c$[1].

3. Result

3.1 Centrality dependence

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[1], a histogram of PbPb momentum ratio $x_{\gamma}$ (simulated) can be plotted together with the $x_{\gamma}$ ratio of PbPb collisions.
the original photon-jet momentum from pp collision. We can obtain the centrality dependence of $x_{T_{p}}$ and compare it directly to the CMS experimental data [1].

By adjusting the parameters of the energy loss function, the model gradually approaches the experimental data. Fig. 3 presents the calculations with energy loss formula of:

$$\Delta E = p_{T}^{\gamma} - 0.8 \times (\ln\left(\frac{p_{T}^{\gamma}}{10}\right))^{2} \times \left(\frac{L_{n}}{12.2}\right)^{2}$$

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 expectation that as the jet path lengths become larger with more central collisions, the energy loss increases.

The $R_{\gamma}$ distributions, the average number of associated jets per photon, as a function of centrality is shown in Fig. 4 with $p_{T}^{\gamma}$ interval ($p_{T}^{\gamma} > 60 GeV/c$). In more central collisions, larger suppression of $R_{\gamma}$ compared to the smeared pp reference data is observed in $p_{T}^{\gamma}$ selection, corresponding to larger energy loss due to interaction with the QGP.

### 3.2 Photon+Jet Transverse Momentum Imbalance

Photon+jet transverse momentum imbalance is calculated with $x_{T_{p}} = p_{T}^{\gamma} / p_{T}^{\gamma}$. In order to subtract the background fluctuations [1], a selection cut of $\Delta\phi_{T_{p}} > 7 /$
Figure 4 The centrality dependence of $x_{\gamma}$ of photon+jet pairs normalized by the number of photons for PbPb (full markers) and smeared pp (open markers) data. (Simulation)

Figure 5 The distribution of $R_{\gamma}$ as a function of centrality for $p_T>60\text{GeV/c}$. Smeared pp collision data is implemented as reference.

$(8\pi)$ is applied. The distributions of $x_{\gamma}$ with different centrality intervals (0-30% and 30-100%) and $p_T$ selection cuts in PbPb and pp collisions are shown in Fig.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 $x_{\gamma}$ and smaller total integrals, whereas in less central collisions (30-100% centrality), distributions that are more consistent between PbPb and pp collisions are observed.
Figure 6 The $x_{j\gamma} = p_T^{\gamma}/p_T^{j}$ distributions of PbPb collisions (markers) in 0-30\% (top) and 30-100\% centrality (bottom) intervals and five $p_T^{\gamma}$ intervals. Smeared pp collision data (markers) is implemented for comparison.

4. Conclusions

This paper studied the correlations of isolated photons with $p_T^{\gamma} > 40\text{GeV}/c$ and $|\eta^{\gamma}| < 1.44$ and jets with $p_T^{j} > 30\text{GeV}/c$ and $|\eta^{j}| < 1.6$ in pp and PbPb collisions at $\sqrt{S_{NN}} = 5.02 \text{ TeV}$ 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 $x_{j\gamma} = p_T^{\gamma}/p_T^{j}$ and $R_{j\gamma}$ of pp and PbPb collisions is studied in different centrality intervals and in different $p_T^{\gamma}$ intervals. The difference between PbPb collision data and pp collision data increases as the collisions becomes more central. For intervals with $p_T^{\gamma} > 60\text{GeV}$, the values of $R_{j\gamma}$ are observed to be lower than those of respective pp reference and PbPb collision and to have lower $x_{j\gamma}$ and smaller integrals. These results are consistent with the Monte Carlo Glauber Model previous study at $\sqrt{S_{NN}} = 2.76 \text{ TeV}$. 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.

References

