Study of jet energy loss using mono-photon events in Pb+Pb compared to p+p collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Abstract

This analysis uses parametrized data from Pb+Pb collisions at a centre-of-mass energy of 5.02 TeV with an integrated luminosity of 1 nb^{-1} and p+p collisions at a centre-of-mass energy of 5.02 TeV with an integrated luminosity of 50 pb^{-1} based on results from the CMS experiment at the CERN LHC. For each event containing a photon with $p_T > 70$ GeV and an associated jet with $p_T > 30$ GeV, the photon-jet p_T imbalance, $X_{j\gamma}$, is studied for the 10% most central collisions compared to p+p collision data. Using $X_{j\gamma}$ and the rate of mono-photon events R_γ, the sensitivity to two different distributions for the parton energy loss in the quark-gluon plasma (QGP) is studied.

Keywords: QGP, jet, mono-photon

Introduction

Properties of quark-gluon plasma (QGP), a state of matter with high temperature and density, can be studied in collisions of heavy ions at high energies. This paper aims to understand how the properties of the QGP can be explored using photon-jet events created in lead+lead (Pb+Pb) collisions, in comparison to reference distributions from proton+proton (p+p) collisions.

This study characterizes parton energy loss in the QGP through the rate of mono-photon events, in which there is a single photon with no associated jet[2] having transverse momentum $p_T > 30GeV$ at $\Delta\phi_{j\gamma} = |\phi_{jet} - \phi_{photon}| > 3/4\pi$ (A more explicit explanation will be given in event selection part). In Pb+Pb

[1]Authors' names are arranged in alphabetical order.

[2]From now on we call the jet produced with photon as associated jet and the jet blended with it but actually unrelated as noise jet. They together in a single event are called companion jets with this photon.

collisions at the Large Hadron Collider(LHC), the properties of QGP have been studied using back-to-back photon+jet pairs, which were observed to contain highly imbalanced transverse momentum. This is because the colorless photons do not strongly interact with the QGP, while the jets tend to lose energy via the interaction with other color charges when propagating through QGP. The yields of isolated photons in Pb+Pb collisions were found to match the expectation based on p+p data and the number of nucleon-nucleon collisions, with a modification factor of $R_{AA} = 0.99 \pm 0.31(\text{stat.}) \pm 0.26(\text{syst.})$ [1]. Therefore, photon+jet production has been hailed as the golden channel to investigate energy loss of partons in the QGP [2, 3].

Reconstruction of jets is conducted by using the anti-k_t algorithm [4], with input parameter radius R=0.4, and resolution 0.1×0.1. The algorithm scanned jet tower cell by cell, giving the result of reconstruction contains a mix of genuine jets and jet-sized patches, which is later rejected by event selection. While the reconstruction of photon is made through approach called Island algorithm [5]. In order to gain eligible mono-photon events, a cutting method was utilized. Filtered events contain only photons without companion jet in the $\Delta\phi_{j\gamma} > 3/4\pi$ range, where $\Delta\phi_{j\gamma}$ is defined as $\Delta\phi_{j\gamma} = |\phi_{jet} - \phi_{photon}|$.
In the following part, the familiar ratio $X_{j\gamma}$ defined by

$$X_{j\gamma}(p_T) = \frac{p_T(assojet)}{p_T(photon)} \tag{1}$$

is used to quantify the photon+jet momentum imbalance.
The discrimination power of $X_{j\gamma}$ will be compared with the rate of mono photon events, defined as:

$$R_\gamma(p_T) = \frac{dN_{mono\ photon}/dp_T}{dN_{all\ photon}/dp_T}, \tag{2}$$

which is expected to be sensitive to the tail of energy loss. In this equation, the term above represents the number of mono-photon events in a particular p_T range, and the denominator is that of all the events within that range.

Experimental Setup

The parametrized data for this analysis reflect the performance and acceptance of the CMS experiment at the CERN LHC. The central feature of the CMS apparatus is the 6-m internal diameter superconducting solenoid, providing a magnetic field of 3.8 T. Within the solenoid, tracking system consists of silicon pixel and silicon strip detectors, in which tracking of charged particles occurs. Photons are reconstructed in the crystal electromagnetic calorimeter (ECAL), which has a pseudorapidity range of $|\eta| < 1.48$. Meanwhile, the barrel region of the hadron calorimeter (HCAL) has $|\eta| < 1.74$. Apart from above detectors, CMS also contains hadron forward (HF) calorimeters in the purpose of measuring the centrality, which covers the rapidity region $2.9 < |\eta| < 5.2$ [6]. Minimum-biased beam scintillator counters, so called a set of scintillator tiles, are located on the interior wall of HFs and are used for triggering and beam-halo rejection for Pb+Pb and p+p collisions. Collision events are mainly selected by the CMS two-tiered trigger system. With the custom hardware processors, the first level (L1) uses information from the calorimeters and muon detectors to select events. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing.

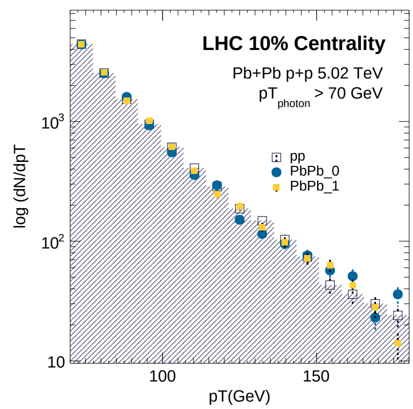
Event Selection and Analysis Technique

The integrated luminosity of the analyzed data sample were 1 nb^{-1} for Pb+Pb collision and 50 pb^{-1} for p+p collision. To filter events in both p+p and Pb+Pb collisions, we selected events with photons that have transverse momentum $p_T > 70GeV$ and pseudo-rapidity $|\eta| < 2.4$. And further, in each selected event, jets with $p_T < 30$ GeV or $|\eta_{jets}| > 2.4$ are rejected for such magnitude is seen as merely the fluctuation of noise, where $\eta = -\ln[\tan\theta/2]$ and θ describes the polar angle between the produced particles and the beam direction. The number of total filtered events now is denoted as N_{events}. The difference in azimuthal angle between photon and its associated jets was calculated as $\Delta\phi_{j\gamma} = |\phi_{jet} - \phi_{photon}|$. Among the remaining events, jets with $\Delta\phi_{j\gamma} < 3/4\pi$ were further eliminated, and only jets beyond this range are viewed as potential associated jets since one should expect them to be emitted back to back from their corresponding partner photons due to momentum conservation. From N_{events}, events with only one photon (no potential jets) were selected as mono-photon events.

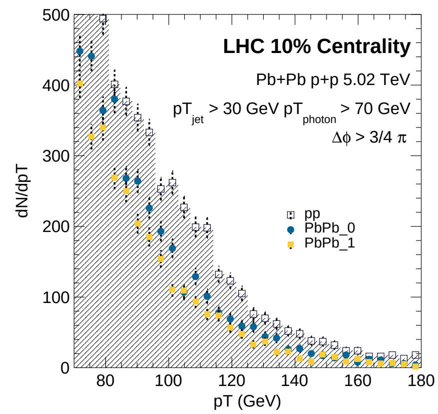
With selected events for both p+p and Pb+Pb collisions, distributions of p_T of jets and of photons, $\Delta\phi_{j\gamma}$, $X_{j\gamma}$ and R_γ were obtained, including background noise. For the purpose of getting more accurate results for $X_{j\gamma}$, we selected a cut of jets with $\Delta\phi$ from $1/2\pi \sim 3/4\pi$ (same width as for the potential associated jet) and use these jets to simulate the underlying background in the range of $3/4\pi \sim \pi$.

Result and Discussion

After filtering the event candidates, the p_T of remaining photons and jets are shown as histograms in Fig. 1a and Fig. 1b respectively, where the percentile represents the centrality, and here only the central-most data are selected. The thresholds of p_T have been labeled in the figures for each case, and the center mass energy in our case is of 5.02 TeV for both Pb+Pb collision and p+p collision (Note that we have two sets of Pb+Pb data, $data_0$ and $data_1$), which is the same for all the following results. The general shapes of them are negative exponential (Note that the former is logarithmic while the other is not), conforming to the expectation of statistical theory.

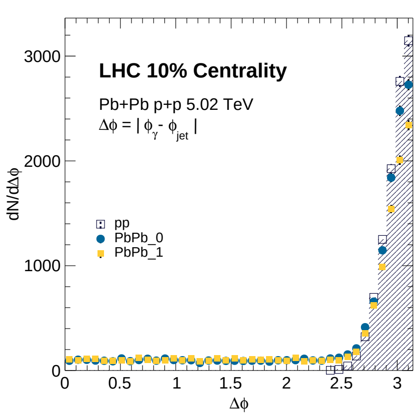


(a) Distribution of p_T for photon

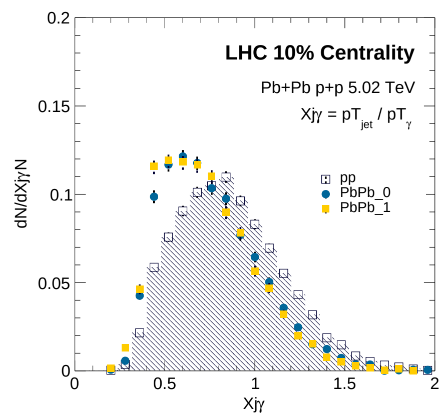


(b) Distribution of p_T for jet

Figure 1: Fig.1a and Fig.1b illustrate the distribution of transverse momentum for photons and jets in all events. The legends have been shown in figures. Uncertainties are indicated by black lines.



(a) Distribution of $\Delta\phi$



(b) Distribution of $X_{j\gamma}$

Figure 2: In Fig.2a, the difference of $\Delta\phi$ between jets and the photon in the same event has been shown. Shown in Fig.2b for selected events are the nomalized distributions of $X_{j\gamma}$, underlying background removed. And all legends have been labeled.

In Fig. 2a, we can see for p+p there does not exist any underlying background. And not surprisingly, there's a peak starting from about $4/5\pi$. This figure proves the validity of setting threshold as $3/4\pi$ in further step.

How much p_T for an associated jet has been absorbed by the QGP is always the main concern. First, let us still use the concept of $X_{j\gamma}$ defined as in Eq.(1).

This observable quantifies the percentage of remaining p_T of jets after they pass through the QGP and here, the p_T of photon is taken as a reference of their original transverse momentum, as shown in Fig. 2b. Our expectation is that 1) there should be a sharp cut for $X_{j\gamma}$ larger than 1 for the case of Pb+Pb collision since QGP is not supposed to enhance the p_T of jets and that 2) the distribution of $X_{j\gamma}$ should gather around 1 due to the absence of QGP. However, the first conjecture seems only roughly correct and the second is almost totally wrong, as suggested by the data (see Fig. 2b). The reason for the failure of the second expectation is mainly due to fermion motion, gluon radiation and the omission of energy beyond the radius of the jet clustering algorithm. The shadow area is the noise back ground for the two Pb data sets, very close to each other.

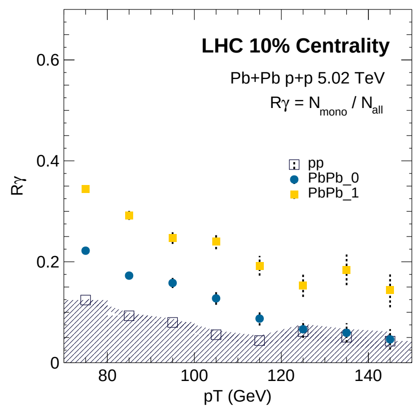


Figure 3: This figure demonstrates the R_γ. All the legends haven been labeled out in the figures.

Finally, we employ the mono-photon rate R_γ defined in Eq.(2). It can be used to describe how likely a photon at a particular p_T will lose its associated jet. For example, in some histogram bin, if such ratio is 1, it means that at this p_T range the associated jet will tend to lose almost all of its energy and be drowned in background. Otherwise, if zero, no jet would be absorbed. From Fig. 3, R_γ is almost always below 0.1 for p+p, indicating that for most photons in this case the associated jet is observed in the experiment. And from the camparison of the two Pb data, we observe that in $data_0$ photons are less likely to lose their jet partner than that in $data_1$. Namely, the two different dataset behave differently concerning large energy loss area, which is not observed as readily in the $X_{j\gamma}$ distribution shown in Fig. 2b.

The systematic uncertainty in this analysis is mainly contributed by photon purity, reconstruction efficiency, isolation, as well as the contamination from $e^\pm$ and fake jets contribute to the systematic uncertainties of the photon+jet azimuthal correlation and the observables related to momentum asymmetry, $x_{J\gamma}$ and R_γ. In addition, the relative photon and jet energy calibrations also interfere to the momentum asymmetry observables.

Conclusion

This analysis uses parametrized data from Pb+Pb collisions at a centre-of-mass energy of 5.02 TeV with an integrated luminosity of 1 nb^{-1} and p+p collisions at 5.02 TeV with an integrated luminosity of 50 pb^{-1}. There are two Pb+Pb samples studied, which have the same average energy loss but have different tails. $Data_0$ has a Gaussian energy loss distribution while $data_1$ is Landau-like. The imbalance degree described by $X_{j\gamma}$ only considers photons that have partners and has omitted the situation of large energy loss for each given initial p_T, and thus is incapable to tell two datasets apart. However, R_γ is designed to describe the tail; as we can see, the significant discrepancy of $data_0$ and $data_1$ in Fig. 3 demonstrate its sensitivity to large energy loss.

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