Study of isolated photon+jet correlation in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Abstract

Measurements of the correlation in isolated photon and jet pairs in pp, pPb and PbPb collisions are presented. The analysis is performed using datasets recorded by the CMS experiment at the LHC from pp and PbPb collisions at 2.76 TeV and pPb collisions at 5.02 TeV. The corresponding integrated luminosities are $150 \mu$b$^{-1}$, $5.3$ pb$^{-1}$ and $30.4$ nb$^{-1}$ for PbPb, pp, and pPb respectively. For events containing an isolated photon with $p_{T}^{\gamma} > 40$ GeV/c and an associated jet with $p_{T}^{\text{jet}} > 30$ GeV/c, the photon+jet transverse momentum balance is studied as a function of collision centrality. The previously published study on PbPb events containing an isolated photon with $p_{T}^{\gamma} > 60$ GeV/c is now compared to the pp collision data and a strong photon+jet momentum imbalance is confirmed. The photon $p_{T}^{\gamma}$ range is extended down to 40 GeV/c and the imbalance is observed over the entire $p_{T}^{\gamma}$ range. In addition, the same observables are studied in pPb collisions and no significant modification is observed, confirming that the PbPb imbalance does not originate from cold nuclear matter effects.
1 Introduction

In relativistic heavy-ion collisions a strongly interacting medium was predicted by lattice Quantum Chromodynamics calculations. Parton scatterings with large momentum transfer can be used as “probes” to study this strongly interacting medium \([1, 2]\), often referred to as the Quark-Gluon Plasma (QGP). These high transverse momentum \((p_T)\) probes, which are created in very short time scales, \(\tau \approx 1/p_T \lesssim 0.1 \text{ fm}/c\), can potentially be modified while they traverse the medium and have been recognized as particularly useful “tomographic” probes \([3–8]\).

Previously, in PbPb collisions at the Large Hadron Collider (LHC), a significant \(p_T\) imbalance was observed in back-to-back jets \([9, 10]\) which is interpreted as resulting from the in-medium parton energy loss, often referred to as “jet-quenching”. On the other hand, the yields of inclusive isolated photons in PbPb collisions were found to match the expectation based on pp data scaled by the number of nucleon-nucleon collisions \([11]\) which show that photons are not modified when passing through the medium. At leading order (LO), photons are produced back-to-back with an associated parton (jet) having close to the same transverse momentum. Therefore, photon+jet production has been hailed as the “golden channel” to investigate energy loss of partons in the medium \([12, 13]\). Measurements of this kind allow an unbiased characterization of the in-medium parton energy loss.

“Prompt photons” which are produced directly in the hard sub-processes are ideal probes which can be used to tag the initial parton energy. Experimentally, events with enriched production of prompt photons are selected using an isolation requirement, namely that the additional energy in a cone of fixed radius around the direction of the reconstructed photon be less than a specified value \([14]\) in order to suppress the large background from the decays of neutral mesons, such as \(\pi^0, \eta,\) and \(\omega\) as they are predominantly produced via jet fragmentation. This restriction yields “isolated photons” (\(\gamma\)), which consist mostly of prompt photons produced directly in the initial hard scattering.

The isolated photon+jet pair analysis is performed in PbPb, pp and pPb data. The goal of this analysis is to characterise possible modifications of jet properties as a function of centrality using isolated-photon+jet events in PbPb collisions. The properties of isolated-photon+jet pairs are studied via the azimuthal angular correlation \(\Delta \phi_{J\gamma} = |\phi_{\text{Jet}} - \phi_{\gamma}|\), the transverse momentum ratio \(x_{J\gamma} = p_T^{\text{Jet}} / p_T^{\gamma}\), and the fraction of photons with an associated jet, \(R_{J\gamma}\). In a previous publication \([15]\), results from PbPb were compared to the prediction from the \textsc{Pythia} \([16]\) simulated event generator due to the lack of statistics of pp collisions available at that time. A significant decrease in the ratio of \(x_{J\gamma}\) relative to that in the \textsc{Pythia} reference was observed, while no significant modification was observed in the azimuthal angular correlation.

In 2013, high statistics pp and pPb data were recorded by the Compact Muon Solenoid (CMS) detector. In this Physics Analysis Summary, isolated-photon+jet pairs from pp and PbPb data at a nucleon-nucleon center-of-mass energy \(\sqrt{s_{NN}} = 2.76\text{ TeV}\) are studied as a function of centrality and isolated photon \(p_T\). The same analysis is also performed with pPb collisions at \(\sqrt{s_{NN}} = 5.02\text{ TeV}\), and compared to a simulated \textsc{Pythia} reference at the same center-of-mass energy to study the possible cold nuclear effects.

2 The CMS detector

Events recorded in pp, pPb, and PbPb collisions are studied using the CMS detector \([17]\). The central tracking system is comprised of silicon pixel and strip detectors that allow for the reconstruction of charged-particle trajectories in the pseudorapidity range \(|\eta| < 2.5\), where
\[ \eta = -\ln[\tan(\theta/2)] \] and \( \theta \) is the polar angle relative to the counterclockwise beam direction. It provides an impact parameter resolution of \( \approx 15 \mu m \) and a \( p_T \) resolution of about 1.5\% for 100 GeV/c particles. Photon candidates used in this analysis are reconstructed using the energy deposited in the barrel region of the PbWO\(_4\) crystal electromagnetic calorimeter (ECAL), which covers a pseudorapidity range of \( |\eta| < 1.479 \), and has a finely segmented granularity of \( \Delta \eta \times \Delta \phi = 0.0174 \times 0.0174 \). The brass/scintillator hadron calorimeter (HCAL) barrel region covers \( |\eta| < 1.74 \) and has a segmentation of \( \Delta \eta \times \Delta \phi = 0.087 \times 0.087 \). Endcap regions of the HCAL and ECAL extend the \( |\eta| \) coverage out to about 3. The calorimeters and tracking systems are located within the 3.8 T magnetic field of the superconducting solenoid. In addition to the barrel and endcap calorimeters, CMS includes hadron forward (HF) steel/quartz-fibre Cherenkov calorimeters, which cover the forward rapidity of \( 2.9 < |\eta| < 5.2 \) and are used to determine the degree of overlap (“centrality”) of the two colliding Pb nuclei [9] in PbPb collisions. An efficient muon system, not used in this analysis, is deployed for the reconstruction and identification of muons up to \( |\eta| = 2.4 \).

### 3 Event Selection

Collision events containing high-\( p_T \) photon candidates are selected online by the CMS two-level trigger system consisting of the Level-1 (L1) and High Level Trigger (HLT). First, events are selected using an inclusive single-photon-candidate L1 trigger with a transverse momentum threshold of 5 GeV/c. Then, photon candidates are reconstructed in the HLT using a clustering algorithm (identical to that used for offline analysis) applied to energy deposits in the ECAL. Events containing a reconstructed photon candidate with \( p_T^\gamma > 40 \) GeV/c are used for further analysis.

In order to select a pure sample of inelastic hadronic pp and pPb collisions for analysis further offline selections were applied to the triggered event sample [18]. Notable among these a reconstructed event vertex and at least 1 calorimeter tower in the HF on both sides of the interaction point with at least 3 GeV total deposited energy in each tower are required. Events containing HCAL noise [19] are rejected to remove possible contamination of the jet sample. For the PbPb analysis, a similar strategy to the pp and pPb analysis is employed as detailed in Ref. [9]. Starting with events containing at least one isolated photon candidate with \( p_T > 40 \) GeV/c, 98.9\%, 99.7\% and 99.8\% of the events in pp, pPb, and PbPb collisions passed these selection criteria.

For the analysis of PbPb collisions, the “centrality” (i.e., the degree of the overlap of the two colliding nuclei) is determined by the total energy from both HF calorimeters. The distribution of this total energy was used to divide the event sample into centrality bins. The most central 30\% of the events (i.e., smallest impact parameter) is denoted as 0–30\%. Based on Glauber simulations, the average number of participating nucleons in a collision (\( N_{\text{part}} \)) in a centrality interval is calculated. Details about centrality determination and \( N_{\text{part}} \) calculations can be found in Ref. [9]. The observables in this paper are presented as a function of centrality and \( N_{\text{part}} \) to study their impact parameter dependence.

### 4 Monte Carlo simulation

The high-\( p_T \) isolated photon production in pp collisions are simulated with PYTHIA [16] (version 6.422, tune Z2 [20]), which was modified to take into account the nucleon content of the colliding nuclei [21]. These events are propagated through the CMS detector using the GEANT4 package [22] to simulate the detector response.
To study the impact of the large underlying events on the reconstruction of jets and photons in PbPb collisions, the PYTHIA sample is embedded in simulated minimum-bias events from HYDJET (version 1.8) [21]. This version of HYDJET was tuned to describe the properties of the PbPb collisions such as the charged hadron multiplicity, $p_T$ spectra and elliptic flow. Similarly, the PYTHIA sample is embedded in HIJING (version 1.383) for the photon reconstruction studies in pPb collisions.

Monte Carlo (MC) events containing isolated photons are selected using the generator-level information of the PYTHIA sub–events. An isolation criterion is applied, requiring that the total energy within a cone of \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4 \) surrounding the photon direction be smaller than 5 GeV.

## 5 Photon reconstruction

Photon candidates are reconstructed from clusters of energy deposited in the ECAL. The algorithms used for pp and pPb are detailed in Ref. [23] while the optimized clustering algorithm used in high multiplicity PbPb collisions can be found in Ref. [11]. The selected photon candidates used in this analysis are restricted to be in the barrel region of the ECAL by requiring a pseudorapidity limit of \( |\eta^\gamma| < 1.44 \) and are also required to have a transverse momentum of \( p_T^\gamma > 40 \text{ GeV}/c \) to maximize statistics while still leaving phase space available for associated jets.

In order to remove electron contamination, photon candidates which match with a track within a search window of \( |\eta^\gamma - \eta^\text{Track}| < 0.02 \) and \( |\phi^\gamma - \phi^\text{Track}| < 0.15 \) are dropped [11]. Anomalous signals caused by the interaction of heavily-ionising particles directly with the silicon avalanche photodiodes used for the ECAL barrel readout are removed, again using the prescription of Ref. [11]. The reconstructed photons are corrected to account for the effects of the material in front of the ECAL as well as energy leakage. For the analysis of PbPb data, an additional correction was applied to account for energy contamination from the PbPb underlying event (UE). The size of the combined correction which was obtained from the isolated photon PYTHIA+HYDJET sample varies from 0–10%, depending on centrality and photon $p_T^\gamma$.

Since the dominant background photon candidates originate from jet fragmentation with associated hadrons, a first rejection of neutral mesons mimicking a high-$p_T$ photon in the ECAL is done using the ratio of hadronic to electromagnetic energy, $H/E$. The $H/E$ ratio is defined as the fraction of hadronic energy to the electromagnetic energy inside a cone of \( \Delta R = 0.15 \) which is computed from the energy deposition in ECAL and HCAL [24]. Photon candidates with $H/E < 0.1$ are selected for this analysis.

To determine if a photon candidate is isolated, the detector activity in a cone of radius $\Delta R = 0.4$ with respect to the centroid of the cluster, not counting the activity of the cluster, is used. In PbPb collisions, the UE-subtracted photon isolation variable $\text{SumIso}^{\text{UE-sub}}$, which is the sum of transverse energy measured in three sub-detectors (ECAL, HCAL, Tracker) minus the expected contribution from the UE to each sub-detector, as described in Ref. [11], is used to further reject photon candidates originating from jets. Candidates with $\text{SumIso}^{\text{UE-sub}}$ smaller than 1 GeV are selected for further study. A tightened isolation criterion for data (as compared to the 5 GeV applied for the MC) is used in order to minimise the impact of random PbPb UE fluctuations. The same isolation algorithm as in pp collisions, detailed in Ref. [25], is employed for the analysis of pPb data.

The fraction of prompt photons within the collection of candidates (the photon purity) is ex-
Jet Reconstruction

6 Jet Reconstruction

Offline jet reconstruction is performed using the CMS “particle-flow” algorithm [26, 27]. By combining information from all sub-detector systems, the particle-flow algorithm identifies stable particles in an event, classifying them as electrons, muons, photons, charged and neutral hadrons. To form jets, those particle-flow objects are clustered using the anti-$k_T$ sequential recombination algorithm provided in the FASTJET framework [28, 29]. A small resolution parameter of $R = 0.3$ is used to minimize the effects of heavy ion background fluctuations in this analysis.

In order to subtract the UE background in PbPb collisions, the iterative algorithm in Ref. [30], using the same implementation as in the PbPb analysis of Ref. [9] is employed. In pp and pPb collisions, jets are reconstructed without UE subtraction. The jet energies are corrected to the energies of final-state particle jets using a factorized multi-step approach [31]. The jet energy corrections are derived using simulated PYTHIA events, as well as dijet and photon+jet collision events in pp and pPb collisions. Jets with $|\eta| < 1.6$, to remain in the well-characterized barrel calorimeter, and corrected $p_T > 30\, \text{GeV}$, to avoid high rates of fake jets from the UE, are selected.
7 Analysis procedure

To form photon+jet pairs, the highest $p_T$ isolated photon candidate passing the selection criteria and within $|\eta| < 1.44$ in each event is associated with all jets in $|\eta| < 1.6$ in the same event. The combinatorial background in PbPb collisions, including misidentified jets which arise from the UE fluctuation as well as jets from multiple hard parton-parton scatterings in the same collisions, need to be subtracted in order to study the energy loss effects on the jets produced in the same scattering as the photon. It is estimated by correlating each leading isolated photon candidate to jets found in a different event selected randomly from a set of minimum bias PbPb data in the same centrality class [15].

The background contribution from decay photon+jets is subtracted from the photon+jet pair sample using a data-driven method. The yields and kinematic characteristics of decay photon+jet background are estimated by events with a larger photon shower width ($0.011 < \sigma_{\eta\eta} < 0.017$), which is dominated by background photons from neutral hadron decays. The estimated background contribution fraction ($1 - \text{photon purity}$) is then subtracted from the yield for the signal events, which have a smaller photon shower width ($\sigma_{\eta\eta} < 0.010$).

In order to compare PbPb collisions with the pp reference, the pp data is smeared to match the jet energy resolution in each of the PbPb centrality classes. The jet energy resolution is calculated from Gaussian fits to the ratio of reconstructed jet $p_T$ to generated jet $p_T$ in a Monte Carlo sample, and the difference in resolution between pp and PbPb is used to smear the pp data. The difference in resolution between pp and PbPb is negligible, so no smearing is applied to the pp data when compared to pPb.

The systematic uncertainties are estimated for each observable using similar procedure as described in Ref. [15]. The total uncertainties were calculated by summing in quadrature of the uncertainties from various sources: (a) photon purity (b) photon energy scale (c) electron contamination (d) photon isolation criteria (e) jet energy resolution (f) jet energy scale and (g) residual jet energy correction.

8 Results

8.1 Photon+jet azimuthal correlation

Possible medium modification of the back-to-back photon and recoiling jet alignment can be studied by comparing the relative azimuthal angle ($\Delta\phi_{J\gamma}$) distributions in pp and PbPb collisions. The shape of the $\Delta\phi_{J\gamma}$ distribution in PbPb collisions is studied in bins of leading photon $p_T$ and event centrality which is shown in Fig. 2. Within the quoted statistical uncertainty, the results in pp and PbPb collisions are consistent with each other. The same study is also performed in pPb collisions and the results are consistent with both PYTHIA+HIJING at $\sqrt{s_{NN}} = 5.02$ TeV and pp data at $\sqrt{s_{NN}} = 2.76$ TeV.

8.2 Photon+jet transverse momentum imbalance

The asymmetry ratio $x_{J\gamma} = p_{TJ}^\text{jet} / p_{T\gamma}^\text{jet}$ is used to quantify the photon+jet transverse momentum imbalance. In addition to the photon and jet selection used in the $\Delta\phi_{J\gamma}$ study, a strict $\Delta\phi_{J\gamma} > \frac{7}{8}\pi$ selection is applied to suppress contribution from background jets as well as photon+2-jets events. Figure 3 shows the centrality and $p_T^\gamma$ dependence of $x_{J\gamma}$ in pp, pPb, and PbPb collisions.
Figure 2: Azimuthal correlation of photons and jets in each $p_T$ bin (from left to right) for pPb (top), peripheral PbPb (middle) and central PbPb (bottom). The pPb data are compared to pp data at 2.76 TeV and PYTHIA+HIJING MC simulation. The PbPb data are compared to smeared pp data. The shaded boxes represent the systematic uncertainty while the lines through the points represent the statistical uncertainty.
collisions as well as PYTHIA+HIJING MC simulation. The pp data is smeared to account for the jet resolution difference in pp and PbPb collisions when compared with PbPb data. A significant modification with respect to the smeared pp reference is observed in 0–30% PbPb collisions. The results in pPb collisions are consistent with pp at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV PYTHIA+HIJING reference. The mean of the $x_{J\gamma}$ as a function of photon $p_T$ is shown in Fig. 4. In the region $p_T^\gamma < 60$ GeV, the $\langle x_{J\gamma} \rangle$ in smeared pp and PbPb collisions are consistent within the quoted uncertainty.

![Figure 3: Distribution of $x_{J\gamma}$ in each $p_T^\gamma$ bin (from left to right) for pPb (top), peripheral PbPb (middle) and central PbPb (bottom). The pPb data are compared to pp data at 2.76 TeV and PYTHIA+HIJING MC simulation and PbPb data are compared to the smeared pp data. On the middle and bottom row, pp data are shown in the background to exhibit the modification of the pp reference by jet energy smearing. The shaded boxes represent the systematic uncertainty while the lines through the points represent the statistical uncertainty.](image)

### 8.3 Fraction of photons with associated jets

Due to the jet $p_T$ threshold of 30 GeV/$c$, the average energy imbalance of the selected photon+jet pairs does not constitute the full picture. There are photon+jet pairs which do not contribute to the $\langle x_{J\gamma} \rangle$ because the associated jets fall below the threshold. To quantify the effect, the fraction of isolated photons that have an associated jet passing the analysis selection $(R_{J\gamma})$ is shown in Fig. 5. The value of $R_{J\gamma}$ in pPb is consistent with pp and PYTHIA+HIJING MC simulation. In the 0–30% central PbPb collisions, the value of $R_{J\gamma}$ is found to be lower than the smeared pp data in all leading photon $p_T$ bins.
Figure 4: Average jet over photon transverse momentum ratio ($\langle x_{J\gamma} \rangle$) of the recoiled jets in (left) pPb, unsmeared pp, and PYTHIA+HIJING, (middle) smeared pp and peripheral PbPb, and (right) smeared pp and central PbPb. The pp results were smeared by the relative jet energy resolution in order to account the underlying event fluctuation when compared to PbPb data. The shaded boxes represent the systematic uncertainty while the lines through the points represent the statistical uncertainty.

8.4 Jet yield ratio

In order to illustrate the medium modification of the associated jet $p_T$ spectra, the ratio of the associated jet yield in PbPb and smeared pp events, $I_{AA}$, is also shown in Fig. 6. The associated yield is suppressed by a factor of two in low $p_T^\gamma$ bins. As $p_T^\gamma$ increases, an excess of jets appears at low $p_T^{jet}$ in central PbPb as the increased phase space at high $p_T^\gamma$ allows the quenched jets to remain above the kinematic cuts.

8.5 Updated pp photon+jet reference

The high statistics pp data taken in 2013 is analyzed and compared to the published PbPb data from Ref. [15] in order to replace the previous Monte Carlo reference. The centrality distribution of $x_{J\gamma}$ for PbPb collisions with $p_T^\gamma > 60$ GeV/c is shown in Fig. 7. When compared to the smeared pp data, the PbPb collision data exhibit a change in shape, shifting the distribution towards lower $x_{J\gamma}$ as a function of centrality.

To study the centrality evolution of the $\Delta\phi_{J\gamma}$ shape in pp and PbPb collisions, the distributions are fitted to a normalized exponential function:

$$\frac{1}{N_{J\gamma}} \frac{dN_{J\gamma}}{d\Delta\phi_{J\gamma}} = \frac{\nu(\Delta\phi-\pi)/\sigma}{(1-e^{-\pi/\sigma})\sigma}. \quad (2)$$

The fit is restricted to the exponentially falling region $\Delta\phi > 2\pi/3$. The results obtained from PbPb collisions and smeared pp data are consistent with each other as shown in Figure 8a. Figures 8b,c show the results $R_{J\gamma}$ and $\langle x_{J\gamma} \rangle$ in pp and PbPb collisions as a function of event centrality. Despite the fact that $R_{J\gamma}$ obtained from PYTHIA+HYDJET MC is slightly higher than that in the pp data, the updated pp reference confirms the observation of away-side jet energy loss that was based on the comparison between PbPb data and PYTHIA+HYDJET reference.
Figure 5: Fraction of photons associated to a jet ($R_{J\gamma}$) as a function of leading photon $p_T$ in (left) pPb, unsmeared pp, and PYTHIA+HIJING, (middle) smeared pp and peripheral PbPb, and (right) smeared pp and central PbPb. The pp results were smeared by the relative jet energy resolution in order to account the underlying event fluctuation when compared to PbPb data. The shaded boxes represent the systematic uncertainty while the lines through the points represent the statistical uncertainty.

9 Conclusions

The study of PbPb photon+jet correlations published in Ref. [15] were compared with pp results using a dataset corresponding to an integrated luminosity of 5.3 pb$^{-1}$ at \( \sqrt{s_{NN}} = 2.76 \) TeV. In addition, the analysis extended the photon $p_T$ range from 60 GeV/c to 40 GeV/c. The photon+jet transverse momentum ratio, $x_{J\gamma} = \frac{p_{T_{Jet}}}{p_{T\gamma}}$, and the fraction of photons with an associated jet, $R_{J\gamma}$, were studied in bins of leading photon $p_T$ and collision centrality. For all $p_T\gamma$ bins, $R_{J\gamma}$ in the 0–30% central PbPb collisions was lower than pp collisions by 0.1 – 0.2, which indicates a larger fraction of jets lost energy and fell below 30 GeV/c. By comparing the yields of jets in PbPb and pp collisions triggered by photons above 80 GeV/c, a shift of the jet spectra toward the lower $p_{T_{Jet}}$ direction was observed.

The pPb collisions using a dataset corresponding to an integrated luminosity of 30.4 nb$^{-1}$ at \( \sqrt{s_{NN}} = 5.02 \) TeV and compared to the PYTHIA+HIJING MC at the same centre-of-mass energy and pp data at \( \sqrt{s_{NN}} = 2.76 \) TeV. No significant modifications in $x_{J\gamma}$ and $R_{J\gamma}$ were observed in those comparisons. This confirms that the observed photon+jet $p_T$ imbalance did not originate from initial-state effects in cold nuclear matter.

References


Figure 6: Ratio of jet yield in PbPb to smeared pp. In the low $p_T^\gamma$ events, the yields in PbPb are smaller than in pp for all $p_T^{\text{jet}}$ bins. As $p_T^\gamma$ increases, yields at low $p_T^{\text{jet}}$ are greater in PbPb than smeared pp. The shaded boxes represent the systematic uncertainty while the lines through the points represent the statistical uncertainty.

Figure 7: Distribution of $x_{J\gamma}$ of photon+jet pairs of pp and PbPb collisions normalized by the number of photon+jet pairs. The momenta of jets in pp were smeared by the relative jet energy resolution to be used as the reference of each centrality bin. The shaded boxes represent the systematic uncertainty while the lines through the points represent the statistical uncertainty.


Figure 8: Comparison of $\Delta\phi_{J\gamma}$ width, $R_{J\gamma}$ and $\langle x_{J\gamma} \rangle$ in pp and PbPb collisions. The PbPb events are divided into 4 centrality bins as in the previous analysis [15]. The momenta of jets in pp were smeared by the relative jet energy resolution to be used as the reference of each centrality bin. The shaded boxes represent the systematic uncertainty while the lines through the points represent the statistical uncertainty.


