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# Studies of jet quenching using isolated-photon + jet correlations in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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ABSTRACT

Results from the first study of isolated-photon + jet correlations in relativistic heavy ion collisions are reported. The analysis uses data from PbPb collisions at a centre-of-mass energy of 2.76 TeV per nucleon pair corresponding to an integrated luminosity of 150 $\mu b^{-1}$ recorded by the CMS experiment at the LHC. For events containing an isolated photon with transverse momentum $p_T^{\gamma} > 60$ GeV/$c$ and an associated jet with $p_T^{\text{Jet}} > 30$ GeV/$c$, the photon + jet $p_T$ imbalance is studied as a function of collision centrality and compared to pp data and PYTHIA calculations at the same collision energy. Using the $p_T^{\gamma}$ of the isolated photon as an estimate of the momentum of the associated parton at production, this measurement allows an unbiased characterisation of the in-medium parton energy loss. For more central PbPb collisions, a significant decrease in the ratio $p_T^{\text{Jet}}/p_T^{\gamma}$ relative to that in the PYTHIA reference is observed. Furthermore, significantly more $p_T^{\gamma} > 60$ GeV/$c$ photons in PbPb are observed not to have an associated $p_T^{\text{Jet}} > 30$ GeV/$c$ jet, compared to the reference. However, no significant broadening of the photon + jet azimuthal correlation is observed.

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## 1. Introduction

Parton scatterings with large momentum transfer produce energetic particles which can be used as "probes" to study the strongly interacting medium created in high-energy heavy ion collisions [1,2]. The production of high transverse momentum ($p_T$) partons and photons in "hard" processes occurs over very short time scales, $\tau \approx 1/p_T \lesssim 0.1$ fm/$c$, and thus their yields can be potentially modified by final-state interactions occurring while they traverse the medium. Since the production cross sections of these energetic particles are calculable using perturbative quantum chromodynamics, they have long been recognised as particularly useful "tomographic" probes of the created medium [3–9].

Previously, in PbPb collisions at the Large Hadron Collider (LHC), the effects of the produced medium were studied using back-to-back dijets which were observed to be significantly unbalanced in their transverse momenta [10–12]. The advantage of the large yield of dijets (as compared to photon + jet pairs) is, however, offset by a loss of information about the initial properties of the probes, i.e. prior to their interactions with the medium. Correlating two probes that both undergo energy loss also induces a selection bias towards scatterings occurring at, and oriented tangential to, the surface of the medium. At leading order (LO), photons are produced back-to-back with an associated parton (jet) having close to the same transverse momentum. Furthermore, these photons do not strongly interact with the medium. The yields of isolated photons in PbPb collisions were found to match the expectation based on pp data and the number of nucleon–nucleon collisions, with a modification factor of $R_{AA} = 0.99 \pm 0.31(\text{stat.}) \pm 0.26(\text{syst.})$ [13]. Therefore, photon + jet production has been hailed as the "golden channel" to investigate energy loss of partons in the medium [14,15].

"Prompt photons" are photons produced directly in the hard sub-processes. 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 [13]. This restriction yields "isolated photons" ($\gamma$), which consist mostly of prompt photons produced directly in the initial hard scattering. Background photons from the decays of neutral mesons, such as $\pi^0$, $\eta$, and $\omega$, are suppressed by this isolation requirement, as they are predominantly produced via jet fragmentation.

This Letter describes the first study of the jet energy loss using isolated-photon + jet pairs from PbPb data at a nucleon–nucleon centre-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV. An integrated PbPb luminosity of $\int \mathcal{L}\,dt = 150$ $\mu b^{-1}$ was collected by the Compact Muon Solenoid (CMS) experiment during the 2011 running of the LHC.

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For comparison, a pp reference dataset with $\int \mathcal{L}\,dt \approx 200$ nb$^{-1}$ at $\sqrt{s} = 2.76$ TeV was obtained in 2011.

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 in $\Delta\phi_{J\gamma} = |\phi^{\text{Jet}} - \phi^{\gamma}|$ and the transverse momentum ratio given by $x_{J\gamma} = p_{\text{T}}^{\text{Jet}}/p_{\text{T}}^{\gamma}$. Photons with transverse momentum of $p_{\text{T}}^{\gamma} > 60$ GeV/$c$ are selected in a pseudorapidity range of $|\eta^{\gamma}| < 1.44$, using isolation criteria detailed in Sections 2.2 and 2.3. These photons are then correlated with jets having $p_{\text{T}}^{\text{Jet}} > 30$ GeV/$c$ and $|\eta^{\text{Jet}}| < 1.6$. Parton energy loss due to induced gluon radiation can lead to a shift of the $x_{J\gamma}$ distribution towards lower values. In addition, parton energy loss can cause reconstructed jets to fall below the $p_{\text{T}}^{\text{Jet}} > 30$ GeV/$c$ threshold, leading to a reduction of the fraction of photons with an associated jet.

Section 2 of this Letter begins with a description of the experimental setup as well as the event triggering, selection and characterisation. The Monte Carlo simulation, the photon and jet reconstruction, and the analysis procedure are also described. The results and their systematic uncertainties are presented in Section 3, followed by a summary in Section 4.

## 2. The CMS detector

Particles produced in pp and PbPb collisions are studied using the CMS detector [16]. 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. Photons 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 super-conducting solenoid. In addition to the barrel and endcap detectors, 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 [17]. A set of scintillator tiles, the beam scintillator counters, is mounted on the inner side of each HF for triggering and beam-halo rejection for both pp and PbPb collisions.

### 2.1. Trigger and event selection

Collision events containing high-$p_{\text{T}}$ 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, more refined 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 $p_{\text{T}}^{\gamma} > 40$ GeV/$c$ are stored for further analysis. This HLT selection is fully efficient for events containing a photon with $p_{\text{T}}^{\gamma} > 50$ GeV/$c$ and the analysis presented here includes all photons with $p_{\text{T}}^{\gamma} > 60$ GeV/$c$.

In order to select a pure sample of inelastic hadronic PbPb collisions for analysis, further offline selections were applied to the triggered event sample similar to [11]. Notably among these include requiring a reconstructed event vertex, and requiring at least 3 calorimeter towers in the HF on both sides of the interaction point with at least 3 GeV total deposited energy in each tower. Beam halo events were vetoed based on the timing of the $+z$ and $-z$ BSC signals. Additionally, events containing HCAL noise [18] are rejected to remove possible contamination of the jet sample. Details about this event selection scheme can be found in [10]. The number of events removed by these criteria are shown in Table 1. Analysis of the Monte Carlo (MC) reference, described in Section 2.2, uses identical event selection, except for the calorimeter noise rejection, which is a purely experimental effect.

The online trigger scheme for the pp data at 2.76 TeV is the same as that used for the CMS pp prompt photon analysis at 7 TeV [19]. The pp trigger requires at least one reconstructed electromagnetic cluster with a minimum transverse energy of 15 GeV/$c$. The offline criterion applied to select pp hadronic collision events is similar to previous CMS pp papers [20]. Apart from the trigger and hadronic collision selection the pp analysis uses the same event selections as the PbPb analysis [13].

For the analysis of PbPb events, it is important to determine the degree of overlap between the two colliding nuclei, termed collision centrality. Centrality is determined using the sum of transverse energy reconstructed in the HF. The distribution of this total energy is used to divide the event sample into equal percentiles of the total nucleus–nucleus interaction cross section. These finer centrality bins are then combined into four groups; one containing the 10% most central events (i.e. those which have the smallest impact parameter of the two colliding Pb nuclei and which produce the highest HF energy); two encompassing the next most central 10–30% and 30–50% of the events; and finally one with the remaining 50–100% peripheral events. Centrality can also be characterised using the number of nucleons participating in the interaction, $N_{\text{part}}$ (with $N_{\text{part}} = 2$ for pp). The corresponding $N_{\text{part}}$ values for a given centrality range are determined from a Glauber calculation [21]. Detector effects are accounted for using a GEANT4 simulation [22] of events generated with a multi-phase transport model (AMPT) [23]. A detailed description of the centrality determination procedure can be found in [10].

### 2.2. Monte Carlo simulation

The production of high-$p_{\text{T}}$ photons by LO processes and parton radiation and fragmentation channels with a high-$p_{\text{T}}$ photon in the final state are simulated with PYTHIA [24] (version 6.422, tune Z2). Tune Z2 is identical to the Z1 tune described in [25], except that Z2 uses the CTEQ6LL PDF while Z1 uses CTEQ5L, and the cutoff for multiple parton interactions, $p_{\perp 0}$, at the nominal energy of $\sqrt{s_0} = 1.8$ TeV is decreased by 0.1 GeV/$c$. Modifications to account for the isospin effect of the colliding nuclei, i.e. the correct cross section weighting of pp, pn, and nn subcollisions [26], is used. Events containing isolated photons are selected using the generator-level information of the PYTHIA events. The isolation criterion requires that the total energy within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ surrounding the photon direction be less than 5 GeV. This selection is found to be equivalent to the experimental requirements for isolated photons described in Section 2.3. These events are then processed through the full CMS detector simulation chain using the GEANT4 package. In order to model the effect of the underlying PbPb events, the PYTHIA photon events are embedded into background events generated using HYDJET (version 1.8) [26]. This version of HYDJET is tuned to reproduce event properties such as charged hadron multiplicity, $p_{\text{T}}$ spectra, and elliptic flow measured as a function of centrality in PbPb collisions.

**Table 1**
The impact of the various event-selection criteria on the $\int \mathcal{L}\,dt = 150$ mb$^{-1}$ PbPb data sample. In the third column, the percentages are with respect to the line above. The selections are applied in the sequence listed. Recall that $\Delta\phi_{J\gamma} = |\phi^{\text{Jet}} - \phi^{\gamma}|$.

| Selection | Events remaining | % of previous |
|---|---|---|
| Collision events with a photon of $p_{\text{T}}^{\gamma} > 40$ GeV/$c$ | 252 576 | – |
| HCAL cleaning | 252 317 | 96.76 |
| Isolated photon candidate $p_{\text{T}}^{\gamma} > 60$ GeV/$c$, $\lvert\eta\rvert < 1.44$ | 2974 | 1.18 |
| Jet candidate $p_{\text{T}}^{\text{Jet}} > 30$ GeV/$c$, $\lvert\eta\rvert < 1.6$ | 2198 | 73.91 |
| $\Delta\phi_{J\gamma} > \frac{7}{8}\pi$ | 1535 | 69.84 |

### 2.3. Photon reconstruction and identification

Photon candidates are reconstructed from clusters of energy deposited in the ECAL, following the method detailed in Ref. [13]. The selected photon candidates 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 $p_{\text{T}}^{\gamma} > 60$ GeV/$c$. In addition, photon candidates are dropped if they overlap with any electron tracks, identified by matching tracks coming from the collision vertex with reconstructed ECAL clusters and selecting on $E/p$. The separation of the photon and electron are required to be within a search window of $|\eta^{\gamma} - \eta^{\text{Track}}| < 0.02$ and $|\phi^{\gamma} - \phi^{\text{Track}}| < 0.15$. 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. [13]. The reconstructed photon energy is corrected to account for the material in front of the ECAL and for electromagnetic shower containment. An additional correction is applied to the clustered energy in order to remove the effects from the PbPb underlying event (UE). The size of the combined correction is obtained from the isolated photon PYTHIA + HYDJET sample and varies from 2–10%, depending on centrality and photon $p_{\text{T}}^{\gamma}$. The effect of the corrections on the energy scale is validated by an analysis of the reconstructed Z boson mass observed in $\text{Z} \to \text{e}^{-}\text{e}^{+}$ decays in PbPb data as a function of centrality.

Since the dominant source of neutral mesons is jet fragmentation with associated hadrons, a first rejection of neutral mesons mimicking a high-$p_{\text{T}}$ photon in the ECAL is done using the ratio of hadronic to electromagnetic energy, $H/E$. The $H/E$ ratio is calculated using the energy depositions in the HCAL and the ECAL inside a cone of $\Delta R = 0.15$ around the photon candidate direction [19]. Photon candidates with $H/E < 0.1$ are selected for this analysis. A correction for the contribution from the remaining short-lived neutral mesons is applied later.

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 is used. 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 [13], is used to further reject photon candidates originating from jets. The mean of $\text{SumIso}^{\text{UE-sub}}$ for fragmentation and decay photons is $\approx 20$ GeV, while the distributions of $\text{SumIso}^{\text{UE-sub}}$ for isolated photons are Gaussians centred around 0 and having widths varying from 3.5 GeV for peripheral collisions to 8.5 GeV for the central collision. 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. A downward fluctuation in the UE contribution to $\text{SumIso}^{\text{UE-sub}}$ can inadvertently allow a non-isolated photon to pass the isolation cut. From the PYTHIA + HYDJET sample, the efficiency of this tightened selection is estimated to be 70–85%, depending on centrality and photon $p_{\text{T}}$, and is found not to be dependent on the angular or momentum correlation with the associated jet. The relative efficiency between $\text{SumIso}^{\text{UE-sub}} < 1$ GeV and $\text{SumIso}^{\text{UE-sub}} < 5$ GeV is about 82% (0–10% centrality) and 90% (50–100% centrality).

Photon purities in each centrality interval are estimated using a two-component fit of the shape of the electromagnetic shower in the ECAL, $\sigma_{\eta\eta}$, defined as a modified second moment of the electromagnetic energy cluster distribution around its mean $\eta$ position:

$$\sigma_{\eta\eta}^{2} = \frac{\sum_i w_i(\eta_i - \bar{\eta})^2}{\sum_i w_i},$$
$$w_i = \max\left(0, 4.7 + \ln\frac{E_i}{E}\right), \tag{1}$$

where $E_i$ and $\eta_i$ are the energy and position of the $i$-th ECAL crystal in a group of $5 \times 5$ crystals centred on the one with the highest energy, $E$ is the total energy of the crystals in the calculation, and $\bar{\eta}$ is the average $\eta$ weighted by $w_i$ in the same group [19]. The discrimination is based only on the pseudorapidity (i.e. longitudinal) distribution of the shower, which is aligned with the magnetic field direction. As a result, showers with a wider distribution in the transverse plane, which can originate from photons converted to $\text{e}^{+}\text{e}^{-}$ pairs in the detector material, are not eliminated. The shape of the $\sigma_{\eta\eta}$ distribution for the signal is obtained from photon + jet PYTHIA + HYDJET samples for each $p_{\text{T}}^{\gamma}$ and centrality bin. The shape of the background distribution is extracted from data using a background-enriched set of photon candidates with $10 < \text{SumIso}^{\text{UE-sub}} < 20$ GeV. The estimated photon purity is 74–83% for photon candidates, which are required to have $\sigma_{\eta\eta} < 0.01$.

### 2.4. Jet reconstruction

Jets are reconstructed by clustering particles measured with a particle-flow (PF) algorithm [27], using the anti-$k_{\text{T}}$ sequential recombination algorithm with a distance parameter of $R = 0.3$ [28]. The jets used in the analysis are required to have $p_{\text{T}}^{\text{Jet}} > 30$ GeV/$c$ and $|\eta^{\text{Jet}}| < 1.6$ to ensure high reconstruction efficiency. Jets within $R < 0.3$ around a photon are removed in order not to correlate the photon with itself. Details of the jet reconstruction procedure and its performance can be found in [12]. The small value of $R$, compared to a more typical $R = 0.5$–$0.7$ used to analyse pp events, helps to minimise sensitivity to the UE contribution, and especially its fluctuations. The energy from the UE is subtracted using the same method as employed in [10,12] and originally described in [29]. The jet energy resolution can be quantified using the Gaussian standard deviation $\sigma$ of $p_{\text{T}}^{\text{Reco}}/p_{\text{T}}^{\text{Gen}}$, where $p_{\text{T}}^{\text{Reco}}$ is the UE-subtracted, detector-level jet energy, and $p_{\text{T}}^{\text{Gen}}$ is the generator-level jet energy without any contributions from a PbPb UE. The magnitude of this resolution is determined using PYTHIA + HYDJET simulation propagated through the detector using GEANT4. Compared to direct embedding into PbPb events, this method avoids uncertainties associated with the detector versus MC geometry alignment, which is especially difficult to achieve accurately with

**Table 2**
Parameters of the functional form for the jet energy resolution $\sigma(p_{\mathrm{T}}^{\mathrm{Reco}}/p_{\mathrm{T}}^{\mathrm{Gen}})$ given in Eq. (2), obtained from GEANT4 simulation of PYTHIA pp jets and from PYTHIA jets embedded in HYDJET events for various PbPb centralities (indicated by the % ranges in parentheses). The units of $S$ are $\sqrt{\mathrm{GeV}/c}$ and the units of $N$ are GeV/$c$.

| $C$ | $S$ | $N$ (pp) | $N$ (50–100%) | $N$ (30–50%) | $N$ (10–30%) | $N$ (0–10%) |
|---|---|---|---|---|---|---|
| 0.0246 | 1.213 | 0.001 | 0.001 | 3.88 | 5.10 | 5.23 |

finely segmented pixel trackers. The UE produced by HYDJET with GEANT4 has been checked against the data by observing the energy collected inside randomly oriented cones with the same radius as the distance parameter as the jet algorithm, and is found to match the data well. The dependence of $\sigma$ on $p_{\mathrm{T}}^{\mathrm{Jet}}$ can be parametrised using the expression

$$\sigma\left(\frac{p_{\mathrm{T}}^{\mathrm{Reco}}}{p_{\mathrm{T}}^{\mathrm{Gen}}}\right) = C \oplus \frac{S}{\sqrt{p_{\mathrm{T}}^{\mathrm{Gen}}}} \oplus \frac{N}{p_{\mathrm{T}}^{\mathrm{Gen}}}, \tag{2}$$

where $\oplus$ indicates a sum in quadrature, and the quantities $C$, $S$, and $N$ are fitted parameters (Table 2). The first two terms of the parametrisation are determined from PYTHIA simulation, and the third term, which represents background fluctuations (not corrected for the flow direction), is determined from PYTHIA + HYDJET simulation.

Because the effects of the UE for jets found in PbPb events are subtracted, corrections to the mean reconstructed jet energy are derived from pp data and PYTHIA-only simulation (i.e. without HYDJET) [30]. Studies of the performance of jet reconstruction in PYTHIA + HYDJET events show that no additional centrality-dependent energy correction is needed.

The jet reconstruction efficiency is defined as the fraction of simulated PYTHIA jets which are correctly reconstructed when embedded into a HYDJET event. The efficiency is found to be greater than 90% for jets within the selected $p_{\mathrm{T}}$ and $\eta$ range for all centralities. For the analysis of the pp sample, the same PbPb jet reconstruction algorithm is used. The performance of the jet reconstruction in peripheral PbPb events is found to approach that for the pp simulation.

### 2.5. Analysis procedure

To construct photon + jet pairs, the highest $p_{\mathrm{T}}^{\gamma}$ isolated photon candidate in each selected event is associated with every jet in the same event. The photon + jet pairs constructed in this way contain background contributions that need to be subtracted before using them to study energy loss effects on the jet produced in the same scattering as the photon. The dominant background contributions are photons from meson decays which pass the isolation requirement and the combinatoric background where the leading photon is paired with a jet not originating from the same hard scattering. The combinatoric background includes misidentified jets which arise from fluctuations of the underlying event as well as real jets from multiple hard interactions in the collision.

The background contributions from decay photon and fake jets are estimated separately with methods that are data-driven and are subtracted from the photon + jet pair sample.

The estimation of the yield and the kinematic characteristics of decay photons contained in the isolated-photon sample is based on the shower shape distributions for the analysed ECAL clusters. The ECAL clusters originating from high-$p_{\mathrm{T}}$ meson decays correspond to two photons that are reconstructed as a single wide cluster. Events with a large shower width ($0.011 < \sigma_{\eta\eta} < 0.017$, see Eq. (1)) are used to determine the contributions of the decay photon background to the $\Delta\phi_{J\gamma}$ and $x_{J\gamma}$ observables. The background shape obtained from this procedure is scaled according to the background-photon fraction, which is estimated from a fit of the shower shape distribution. The estimated background contribution fraction (which is equal to 1 − purity) is then subtracted from the yield for the signal events, which have a small shower width ($\sigma_{\eta\eta} < 0.01$).

The background contribution due to photon + jet pairs arising from fake jets or multiple hard scatterings is also subtracted. It is estimated by correlating each isolated highest-$p_{\mathrm{T}}$ photon from the triggered photon + jet sample to jets found in a different event selected randomly from a set of minimum bias PbPb data. The random event used in the pairing is chosen to have the same centrality as the photon + jet candidate event. The fake jet background estimated in this way has a flat distribution in $\Delta\phi_{J\gamma}$. The effect of this background is biggest in the most central events where, on average, approximately 20% of the jets paired with each photon candidate are estimated to be fake jets. The estimated distributions of $\Delta\phi_{J\gamma}$ and $x_{J\gamma}$ for photons paired with fake jets, found using this random pairing of events, are subtracted from the distributions coming from the same-event photon + jet sample to obtain the final results.

## 3. Results

### 3.1. Photon + jet azimuthal correlations

Possible medium effects on the back-to-back alignment of the photon and recoiling jet can be studied using the distribution of the number of photon + jet pairs, $N_{J\gamma}$, as a function of the relative azimuthal angle, $\Delta\phi_{J\gamma}$, normalised by the total number of pairs, $(N_{J\gamma})^{-1}\mathrm{d}N_{J\gamma}/\mathrm{d}\Delta\phi_{J\gamma}$. Fig. 1 shows distributions of $\Delta\phi_{J\gamma}$ for PbPb data in four centrality bins, ranging from peripheral events (50–100%, Fig. 1a) to the most central events (0–10%, Fig. 1d). The PbPb data are compared to PYTHIA + HYDJET simulation and pp data. For both PbPb data and MC distributions, the jet is found to be well aligned opposite to the photon direction, with a clear peak at $\Delta\phi_{J\gamma} = \pi$. The shape of the $\Delta\phi_{J\gamma}$ correlation peak is similar in PbPb data and MC. The apparent excess in the tail of the 0–10% data was investigated and deemed statistically not significant compared to the subtracted background. To study the centrality evolution of the shape, the distributions are fitted to a normalised exponential function:

$$\frac{1}{N_{J\gamma}}\frac{\mathrm{d}N_{J\gamma}}{\mathrm{d}\Delta\phi_{J\gamma}} = \frac{\mathrm{e}^{(\Delta\phi-\pi)/\sigma}}{(1-\mathrm{e}^{-\pi/\sigma})\sigma}. \tag{3}$$

The fit is restricted to the exponentially falling region $\Delta\phi > 2\pi/3$. The results of this fit for PbPb data are shown in Fig. 2, where the width of the azimuthal correlation ($\sigma$ in Eq. (3), denoted $\sigma(\Delta\phi_{J\gamma})$ in Fig. 2) is plotted as a function of centrality and compared to pp and PYTHIA + HYDJET fit results. The resulting $\sigma(\Delta\phi_{J\gamma})$ values in PbPb do not show a significant centrality dependence within the present statistical and systematic uncertainties. For central PbPb collisions, $\sigma(\Delta\phi_{J\gamma})$ is similar to the PYTHIA reference based on the Z2 tune, and comparison with other PYTHIA tunes shows a theoretical uncertainty that is larger than the difference between the data and MC. Comparing the PYTHIA tune Z2 with tune D6T [31,32] shows an 8% difference in $\sigma(\Delta\phi_{J\gamma})$, which is expected because these two tunes differ in their parton shower ordering resulting in a different $\Delta\phi$ correlation. The large statistical uncertainty in the $\sigma(\Delta\phi_{J\gamma})$ extracted from the pp data at 2.76 TeV does not allow

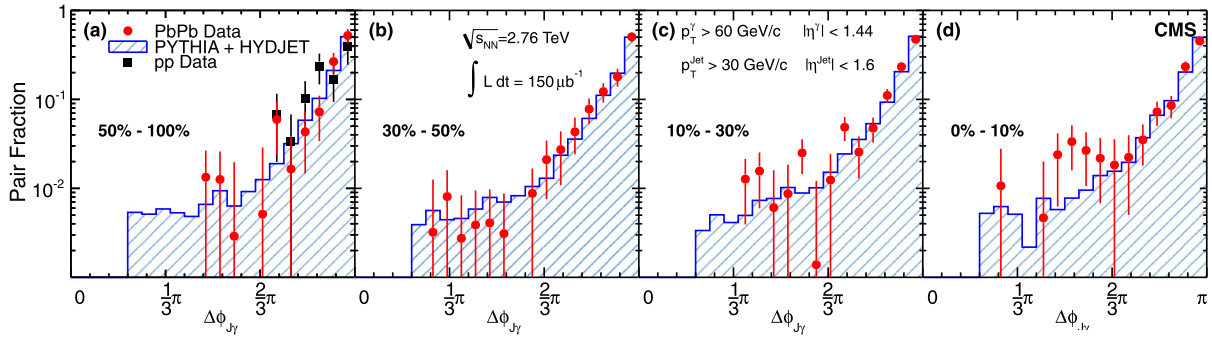


**Fig. 1.** Azimuthal correlation $\Delta\phi_{J\gamma}$ between the photon and associated jet after background subtraction. The area of each distribution is normalised to unity. All panels show PbPb data (filled circles) compared to pp data at 2.76 TeV (filled squares), and to the PYTHIA + HYDJET MC simulation (shaded histogram) in bins of increasing centrality left to right. The error bars on the points represent the statistical uncertainty.

a discrimination between these two PYTHIA tunes. Both the Z2 and D6T tunes matched the shape of the azimuthal dijet correlation measured in pp collisions at 7 TeV [33] at about the 10% level in the region $\Delta\phi > 2\pi/3$. The result that $\sigma(\Delta\phi_{J\gamma})$ is not found to be significantly modified by the medium is consistent with the earlier observation of an unmodified $\Delta\phi$ correlation in dijet events [10].

### 3.2. Photon + jet momentum imbalance

The asymmetry ratio $x_{J\gamma} = p_{\mathrm{T}}^{\mathrm{Jet}}/p_{\mathrm{T}}^{\gamma}$ is used to quantify the photon + jet momentum imbalance. In addition to the jet and photon selections used in the $\Delta\phi_{J\gamma}$ study, we further impose a strict $\Delta\phi_{J\gamma} > \frac{7}{8}\pi$ cut to suppress contributions from background jets. Note that photon + jet pairs for which the associated jet falls below the 30 GeV/$c$ threshold are not included in the $x_{J\gamma}$ calculation. This limits the bulk of the $x_{J\gamma}$ distribution to $x_{J\gamma} \gtrsim 0.5$. Fig. 3 shows the centrality dependence of $x_{J\gamma}$ for PbPb collisions as well as that for PYTHIA + HYDJET simulation where PYTHIA contains inclusive isolated photon processes. The $\langle x_{J\gamma}\rangle$ obtained from PYTHIA tunes Z2 and D6T agree to better than 1%. Overlaid in the peripheral bin is the $\langle x_{J\gamma}\rangle$ for 2.76 TeV pp data, showing consistency to the MC reference. However the poor statistics of the pp data does not allow a significant comparison. Further studies using the 7 TeV high statistics pp data showed a good agreement in $\langle x_{J\gamma}\rangle$ between data and PYTHIA, justifying the use of PYTHIA + HYDJET as an unmodified reference. The dominant source of systematic uncertainty in $\langle x_{J\gamma}\rangle$ is the relative photon + jet energy scale. Its impact on the probability density of $x_{J\gamma}$ is approximately 10% for the intermediate region of $0.6 < x_{J\gamma} < 1.2$. The normalisation to unity causes a point-to-point anticorrelation in the systematic uncertainties, where the upward movement of the probability density at small $x_{J\gamma}$ has to be offset by the corresponding downward movement at large $x_{J\gamma}$. This is represented by the separate open and shaded red systematic uncertainty boxes in Fig. 3. For a given change in the energy scale, all points would move together in the direction of either the open or shaded red box. The $N_{\mathrm{part}}$ dependence of the mean value $\langle x_{J\gamma}\rangle$ is shown in Fig. 4(a).

While the photon + jet momentum ratio in the PYTHIA + HYDJET simulation shows almost no change in the peak location and only a modest broadening, even in the most central PbPb events, the PbPb collision data exhibit a change in shape, shifting the distribution towards lower $x_{J\gamma}$ as a function of centrality. It is important to note that, as discussed above, the limitation of $x_{J\gamma} \gtrsim 0.5$ constrains the degree to which this distribution can shift.

### 3.3. Jet energy loss

To study the quantitative centrality evolution of the energy loss, the average ratio of the jet and photon transverse momenta, $\langle x_{J\gamma}\rangle$, is shown in Fig. 4(a). While the photon + jet mean momentum ratio in the PYTHIA + HYDJET simulation exhibits a roughly centrality-independent value of $\langle x_{J\gamma}\rangle = 0.847 \pm 0.004(\mathrm{stat.}) - 0.859 \pm 0.005(\mathrm{stat.})$, the ratio is $\langle x_{J\gamma}\rangle = 0.73 \pm 0.02(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$ in the most central PbPb data, indicating that the presence of the medium results in more unbalanced photon + jet pairs.

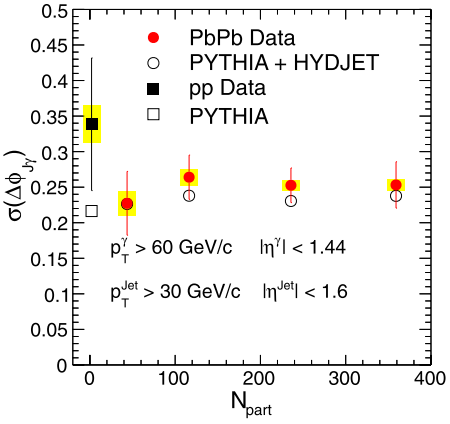


**Fig. 2.** Fitted $\Delta\phi_{J\gamma}$ width ($\sigma$ in Eq. (3)) between the photon and associated jet after background subtraction as a function of $N_{\mathrm{part}}$. The fit range was restricted to $\Delta\phi_{J\gamma} > \frac{2}{3}\pi$. The yellow boxes indicate point-to-point systematic uncertainties and the error bars denote the statistical uncertainty. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

It is important to keep in mind that the average energy loss of the selected photon + jet pairs does not constitute the full picture. There are genuine photon + jet events which do not contribute to the $\langle x_{J\gamma}\rangle$ distribution because the associated jet falls below the $p_{\mathrm{T}}^{\mathrm{Jet}} > 30$ GeV/$c$ threshold. To quantify this effect, Fig. 4(b) shows $R_{J\gamma}$, the fraction of isolated photons that have an associated jet passing the analysis selection. The value of $R_{J\gamma}$ is found to decrease, from $R_{J\gamma} = 0.685 \pm 0.008(\mathrm{stat.}) - 0.698 \pm 0.006(\mathrm{stat.})$ for the PYTHIA + HYDJET reference, as well as pp and peripheral PbPb data, to the significantly lower $R_{J\gamma} = 0.49 \pm 0.03(\mathrm{stat.}) \pm 0.02(\mathrm{syst.}) - 0.54 \pm 0.05(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})$ for the three PbPb bins above 50% centrality.

### 3.4. Systematic uncertainties

Photon purity, reconstruction efficiency, and 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, $\langle x_{J\gamma}\rangle$ and $R_{J\gamma}$.

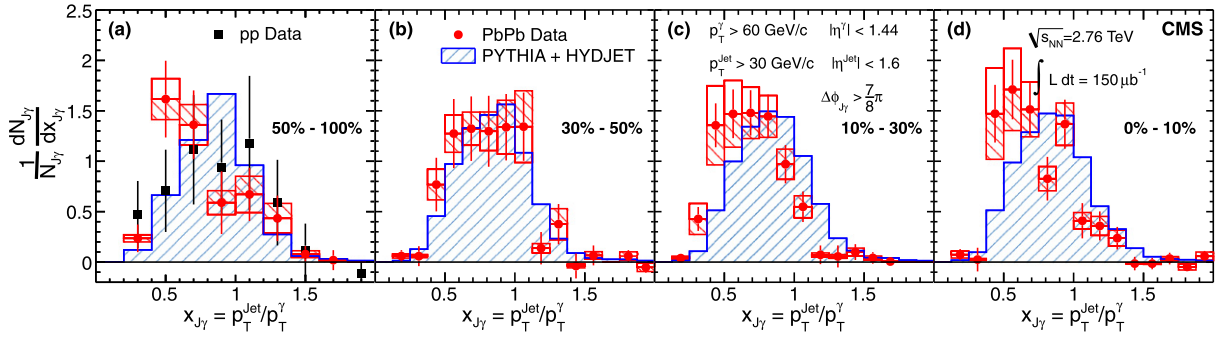


**Fig. 3.** Ratio of $p_T$ between the photon ($p_T^\gamma > 60$ GeV/$c$) and jet ($p_T^{Jet} > 30$ GeV/$c$, $\Delta\phi_{J\gamma} > \frac{7}{8}\pi$) after subtracting background. The area of each distribution is normalised to unity. All panels show PbPb data (filled circles) compared to pp data at 2.76 TeV (filled squares), and to the PYTHIA + HYDJET MC simulation (shaded histogram) in bins of increasing centrality left to right. The error bars on the points represent the statistical uncertainty. See text for an explanation of the open and shaded red systematic uncertainty boxes.

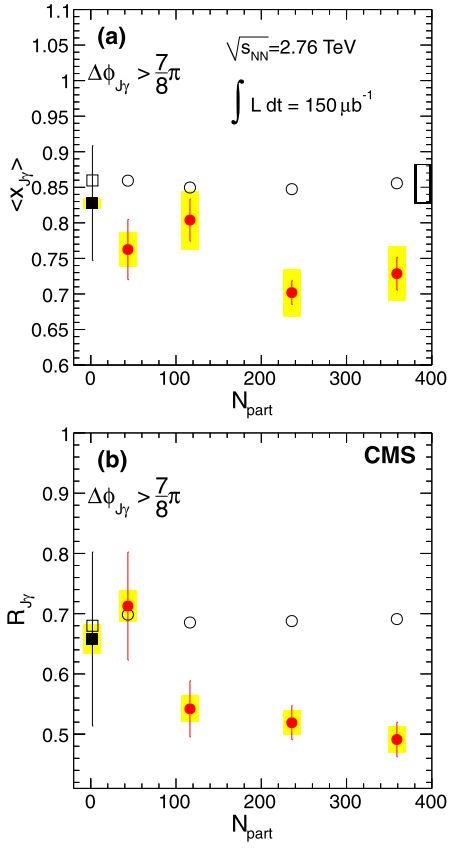


**Fig. 4.** (a) Average ratio of jet transverse momentum to photon transverse momentum as a function of $N_{part}$. The empty box at the far right indicates the correlated systematic uncertainty. (b) Average fraction of isolated photons with an associated jet above 30 GeV/$c$ as a function of $N_{part}$. In both panels, the yellow boxes indicate point-to-point systematic uncertainties and the error bars denote the statistical uncertainty. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

Additionally, the momentum asymmetry observables are also influenced by the relative photon and jet energy calibrations. For the measurement of $\sigma(\Delta\phi)$, the uncertainty due to the photon angular resolution is negligible, less than $10^{-5}$.

The uncertainty in the relative photon + jet energy scale consists of four main contributions. The first one comes from the 2% relative uncertainty of the jet energy scale in the barrel for $30 < p_T^{Jet} < 200$ GeV/$c$, when compared with the ECAL energy scale [30]. The second contribution is the residual data-to-MC energy scale difference in pp collisions, which is not corrected for in this analysis, for which we quote the 2% maximum relative uncertainty applicable in the range $|\eta^{Jet}| < 1.6$. Thirdly, the additional uncertainty for the jet energy scale in the presence of the UE is determined to be 3% for the 30 to 100% and 4% for the 0 to 30% centrality range, using the embedding of PYTHIA isolated photon + jet pairs into HYDJET. The fourth contribution is the effect of heavy ion background on the ECAL energy scale, which is determined from $Z \to e^- e^+$ mass reconstruction, after applying the PbPb ECAL correction. This results in a relative uncertainty of 1.5%, comparable to the pp uncertainty (obtained via $\pi^0$ and $\eta \to \gamma\gamma$).

The absolute photon energy scale uncertainty, estimated to be 1.5% using Z decays as described above, will also affect the threshold of our photon kinematic selection. Similarly, the lower transverse momentum cutoff for jets is sensitive to their absolute energy scale. For CMS, the energy of jets is calibrated by measuring the relative photon + jet energy scale in pp collisions, and therefore the uncertainty in jet energies is the quadrature sum of the uncertainties in the relative jet-to-photon energy scale and the absolute photon energy scale.

The uncertainty of the photon purity measurement using the $\sigma_{\eta\eta}$ template fitting is estimated by (a) varying the selection of sideband regions that is used to obtain the background template and (b) shifting the template to measure the signal template uncertainty. These result in an estimated uncertainty on the photon purity of 12% and 2%, respectively. Systematic effects due to photon reconstruction efficiency are estimated by correcting the data using the efficiency derived from the MC simulation, and comparing the result with the uncorrected distribution. The contribution of non-isolated photons (mostly from jet fragmentation) that are incorrectly determined to be isolated in the detector due to UE energy fluctuations or detector resolution effects is estimated using PYTHIA + HYDJET simulation. The difference of photon + jet observables obtained from generator level isolated photons and detector level isolated photons is taken to be the systematic uncertainty resulting from the experimental criterion for an isolated photon.

The current analysis removes contamination from fake jets purely by subtracting the background estimated from event mixing. A cross-check of this subtraction has been performed using a direct rejection of fake jets via a fake jet discriminant. The discriminant sums the $p_T^2$ of the jet core within $R < 0.1$ around the jet axis and determines the likelihood that the reconstructed jet is not the result of a background fluctuation. Both techniques for fake jet removal agree within 1% for the observables studied. The effect of inefficiencies in the jet finding is estimated by repeating the analysis and weighting each jet with the inverse of the jet finding efficiency as a function of $p_T^{Jet}$.

Tables 3, 4, and 5 summarise the relative systematic uncertainties for $\sigma(\Delta\phi)$, $\langle x_{J\gamma}\rangle$, and $R_{J\gamma}$, respectively, for the pp data and

**Table 3**
Relative systematic uncertainties for $\sigma(\Delta\phi_{J\gamma})$ for pp data and each of the PbPb centrality bins.

| Source | pp | PbPb 50–100% | PbPb 30–50% | PbPb 10–30% | PbPb 0–10% |
|---|---|---|---|---|---|
| $\gamma$ $p_{\mathrm{T}}$ threshold | 3.0% | 3.0% | 3.0% | 2.0% | 1.2% |
| Jet $p_{\mathrm{T}}$ threshold | 1.3% | 1.3% | 0.2% | 0.5% | 2.4% |
| $\gamma$ efficiency | 0.8% | 0.8% | 0.3% | 0.3% | 0.3% |
| Jet efficiency | 0.6% | 0.6% | 0.7% | 0.4% | 0.3% |
| Isolated $\gamma$ definition | 0.7% | 0.7% | 1.6% | 2.0% | 0.5% |
| $\gamma$ purity | 6.8% | 6.8% | 2.7% | 0.5% | 0.9% |
| $e^-$, $e^+$ contamination | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% |
| Fake jet contamination | 0.3% | 0.3% | 0.1% | 0.2% | 1.2% |
| Jet $\phi$ resolution | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% |
| $\sigma$ fitting | 0.3% | 0.3% | 0.1% | 0.1% | 0.1% |
| Total | 7.7% | 7.7% | 4.5% | 3.0% | 3.2% |

**Table 4**
Relative systematic uncertainties for $\langle x_{J\gamma}\rangle$ for pp data and each of the PbPb centrality bins. The uncertainties due to the pp $\gamma$-jet relative energy scale and $\gamma$ purity are common to all of the measurements and are quoted as a correlated uncertainty.

| Source | pp | PbPb 50–100% | PbPb 30–50% | PbPb 10–30% | PbPb 0–10% |
|---|---|---|---|---|---|
| $\gamma$–jet rel. energy scale | 2.8% | 4.1% | 5.4% | 5.0% | 4.9% |
| $\gamma$ $p_{\mathrm{T}}$ threshold | 0.6% | 0.6% | 0.6% | 0.6% | 1.3% |
| Jet $p_{\mathrm{T}}$ threshold | 0.7% | 0.7% | 1.9% | 1.9% | 2.0% |
| $\gamma$ efficiency | $< 0.1\%$ | $< 0.1\%$ | $< 0.1\%$ | 0.1% | 0.2% |
| Jet efficiency | 0.5% | 0.5% | 0.6% | 0.6% | 0.5% |
| Isolated $\gamma$ definition | 0.1% | 0.1% | 0.7% | 0.4% | 2.0% |
| $\gamma$ purity | 2.2% | 2.2% | 1.9% | 2.4% | 2.7% |
| $e^-$, $e^+$ contamination | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% |
| Fake jet contamination | 0.1% | 0.1% | 0.1% | 0.2% | 0.1% |
| Total | 3.7% | 4.8% | 6.2% | 6.0% | 6.4% |
| Correlated (abs., rel.) | 3.6% | 3.6% | 3.6% | 3.6% | 3.6% |
| Point-to-point | 0.9% | 3.2% | 5.1% | 4.8% | 5.3% |

**Table 5**
Relative systematic uncertainties for the fraction of photons matched with jets, $R_{J\gamma}$, for pp data and each of the PbPb centrality bins.

| Source | pp | PbPb 50–100% | PbPb 30–50% | PbPb 10–30% | PbPb 0–10% |
|---|---|---|---|---|---|
| $\gamma$ $p_{\mathrm{T}}$ threshold | 2.0% | 2.0% | 1.9% | 1.3% | 2.1% |
| Jet $p_{\mathrm{T}}$ threshold | 1.4% | 1.4% | 2.3% | 2.6% | 2.7% |
| $\gamma$ efficiency | 0.2% | 0.2% | 0.2% | 0.5% | 0.5% |
| Jet efficiency | 1.5% | 1.5% | 1.7% | 1.8% | 2.1% |
| Isolated $\gamma$ definition | 0.2% | 0.2% | 0.6% | 1.3% | 0.8% |
| $\gamma$ purity | 2.3% | 2.3% | 1.9% | 0.2% | 0.9% |
| $e^-$, $e^+$ contamination | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% |
| Fake jet contamination | 0.4% | 0.4% | 0.8% | 1.0% | 1.4% |
| Total | 3.7% | 3.7% | 4.1% | 3.9% | 4.5% |

for each of the PbPb centrality bins used in the analysis. For $\langle x_{J\gamma}\rangle$, the uncertainties are separated into a correlated component that is common to all centrality bins and a component that represents the point-to-point systematic uncertainty. The common correlated uncertainty is obtained by combining the pp jet energy scale uncertainty with the photon purity uncertainty. This absolute uncertainty of 3.6% was used as the correlated uncertainty for all PbPb centrality bins.

## 4. Conclusions

The first study of isolated-photon + jet correlations in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV has been performed as a function of collision centrality using a dataset corresponding to an integrated luminosity of 150 $\mu b^{-1}$. Isolated photons with $p_{\mathrm{T}}^{\gamma} > 60$ GeV/$c$ were correlated with jets with $p_{\mathrm{T}}^{\mathrm{Jet}} > 30$ GeV/$c$ to determine the width of the angular correlation function, $\sigma(\Delta\phi_{J\gamma})$, the jet/photon transverse momentum ratio, $x_{J\gamma} = p_{\mathrm{T}}^{\mathrm{Jet}}/p_{\mathrm{T}}^{\gamma}$, and the fraction of photons with an associated jet, $R_{J\gamma}$. The PbPb data were compared to both pp data and a PYTHIA + HYDJET MC reference which included the effect of the underlying PbPb event but no parton energy loss. No angular broadening was observed beyond that seen in the pp data and MC reference at all centralities. The average transverse momentum ratio for the most central events was found to be $\langle x_{J\gamma}\rangle_{0-10\%} = 0.73 \pm 0.02(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$. This is lower than the value of 0.86 seen in the pp data and predicted by PYTHIA + HYDJET at the same centrality. In addition to the shift in momentum balance, it was found that, in central PbPb data, only a fraction equal to $R_{J\gamma} = 0.49 \pm 0.03(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})$ of photons are matched with an associated jet at $\Delta\phi_{J\gamma} > \frac{7}{8}\pi$, compared to a value of 0.69 seen in PYTHIA + HYDJET simulation. Due to the hot and dense medium created in central PbPb collisions, the energy loss of the associated parton causes the corresponding reconstructed jet to fall below the $p_{\mathrm{T}}^{\mathrm{Jet}} > 30$ GeV/$c$ threshold for an additional 20% of the selected photons.

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