Measurement of isolated photon production in pp and PbPb collisions at root s(NN)=2.76 TeV

Journal Article

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Measurement of isolated photon production in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV ☆

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ABSTRACT

Isolated photon production is measured in proton–proton and lead–lead collisions at nucleon–nucleon centre-of-mass energies of 2.76 TeV in the pseudorapidity range $|\eta| < 1.44$ and transverse energies E_T between 20 and 80 GeV with the CMS detector at the LHC. The measured E_T spectra are found to be in good agreement with next-to-leading-order perturbative QCD predictions. The ratio of PbPb to pp isolated photon E_T-differential yields, scaled by the number of incoherent nucleon–nucleon collisions, is consistent with unity for all PbPb reaction centralities.

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1. Introduction

Prompt photons with high transverse energy (E_T) in hadronic collisions are produced directly from the hard scattering of two partons. At lowest order in perturbative QCD calculations, three partonic mechanisms produce prompt photons in hadronic collisions: (i) quark–gluon Compton scattering $qg \rightarrow \gamma q$, (ii) quark–antiquark annihilation $q\bar{q} \rightarrow \gamma g$, and (iii) collinear fragmentation of a final-state parton into a photon. Prompt photons from (i) and (ii) are called "direct"; those from (iii) are called "fragmentation". Measured photon production cross sections provide a direct test of perturbative quantum chromodynamics (pQCD) [1], and constrain the proton [2] and nuclear [3] parton distribution functions (PDFs). In the case of nuclear collisions, jets are significantly suppressed [4,5] but direct photons as well as W and Z bosons [6,7] are unaffected by the strongly interacting medium produced in the reaction. Thus, these electroweak particles constitute particularly "clean" probes of the initial state of the collision. In particular, the direct comparison of production cross sections of such probes in pp and nuclear collisions allows one to estimate possible modifications of the nuclear parton densities with respect to a simple incoherent superposition of nucleon PDFs.

However, the measurement of prompt photon production is complicated by the presence of a large background coming from the electromagnetic decays of neutral mesons (mostly $\pi^0, \eta \rightarrow \gamma\gamma$)

produced in the fragmentation of hard-scattered partons. Since high-transverse-momentum (p_T) neutral mesons are produced inside a jet, they are surrounded by significant hadronic activity from other parton fragments. Thus, γ backgrounds from these decays are typically suppressed by imposing isolation requirements on the reconstructed photon candidates. The isolation requirements also significantly suppress the fragmentation photon component, while removing very few of the photons arising from direct processes. Since the annihilation contribution is relatively small at the Large Hadron Collider (LHC), the result is an isolated photon sample dominated by quark–gluon Compton photons [2]. In heavy-ion collisions, the hard scattering that produces an isolated photon is superimposed on the considerable activity arising from multiple parton–parton scatterings (underlying event) occurring simultaneously. A subtraction of the underlying event is therefore necessary before applying isolation criteria.

In this Letter, a measurement of the isolated photon production in pp and PbPb collisions at nucleon–nucleon centre-of-mass energies $\sqrt{s_{NN}} = 2.76$ TeV with the Compact Muon Solenoid (CMS) detector [8] is reported. This constitutes the first measurement of isolated photon production in heavy-ion collisions (though inclusive single photon production has been measured previously at RHIC [9] and SPS [10] energies). Sections 2 and 3 describe the detector and triggers used in the analysis, while the Monte Carlo (MC) simulation and the PbPb reaction centrality determination are discussed in Sections 4 and 5. The photon reconstruction and identification methods used in pp collisions follow very closely those described in the studies at $\sqrt{s} = 7$ TeV [11]. The improvements introduced in order to adapt the photon reconstruction and isolation

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to the high-multiplicity PbPb environment are discussed in Section 6. The photon signal extraction and corrections are discussed in Section 7. The theoretical pQCD calculations from the JETPHOX program [1] are presented in Section 8. Finally, the measured isolated photon E_T spectra in pp and PbPb collisions are compared to the theory and to each other in Section 9.

2. The CMS detector

Final-state particles produced in the pp and PbPb collisions are measured and reconstructed in the CMS detector, consisting of several sub-detector systems [8]. The central tracking system comprises silicon pixel and strip detectors that allow for the reconstruction of the trajectories of charged particles in the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the counterclockwise beam direction. CMS uses a right-handed coordinate system, in which the z axis runs along the beam, the y axis is directed upwards, and the x axis lies in the accelerator plane and points towards the center of the LHC ring. Electromagnetic (ECAL) and hadron (HCAL) calorimeters are located outside the tracking system and provide coverage for $|\eta| < 3$. In the central ("barrel") pseudorapidity range $|\eta| < 1.44$ considered in this analysis, the ECAL and HCAL calorimeters are finely segmented with a granularity of 0.0174×0.0174 and 0.087×0.087, respectively, in η and azimuthal angle ϕ (in radians). 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 a hadron forward (HF) steel/quartz-fibre Cherenkov calorimeter, which covers the forward rapidities $3 < |\eta| < 5.2$ and is used to determine the degree of overlap ("centrality") of the two colliding Pb nuclei. A set of scintillator tiles, the beam scintillator counters (BSC), is mounted on the inner side of the HF for triggering and beam-halo rejection for both pp and PbPb collisions.

3. Data samples, triggers and event selection

The results presented here are based on inclusive photon samples collected in pp and PbPb collisions at 2.76 TeV with minimum-bias and photon triggers. The total data sample corresponds to an integrated luminosity of 231 nb^{-1} and 6.8 μb^{-1} for pp and PbPb, respectively. Note that the PbPb-equivalent luminosity of the PbPb measurement, $\mathcal{L}_{pp\text{-}equiv} = A^2 \times \mathcal{L}_{PbPb} = 294$ nb^{-1} (where $A = 208$ is the nuclear mass number for Pb), is close to that of the pp data. For online event selection, CMS uses a two-level trigger system: a level-1 (L1) and a high level trigger (HLT). The trigger and event selection used for the pp analysis are described elsewhere [11]. PbPb events used in this analysis are selected by requiring a L1 electromagnetic cluster with $E_T > 5$ GeV and an HLT photon with $E_T > 15$ GeV, where E_T values do not include offline corrections for the calorimeter energy response. The efficiency of the photon trigger in PbPb collisions is shown in Fig. 1 for photon candidates with $|\eta^\gamma| < 1.44$. The efficiency is greater than 98% for photon candidates with corrected transverse energy $E_T^\gamma > 20$ GeV in both pp and PbPb collisions.

In addition to the photon-triggered data sample, a minimum-bias (MB) PbPb event sample is collected using coincidences between trigger signals from the $+z$ and $-z$ sides of either the BSC or the HF. The minimum-bias trigger and event selection efficiency in PbPb collisions is $(97 \pm 3)\%$ [4].

To select a pure sample of inelastic hadronic PbPb collisions, the contamination from electromagnetic ("ultra-peripheral") collisions and non-collision beam background are removed following the prescriptions in Ref. [4]. Events are preselected if they contain a reconstructed vertex made of at least two tracks with vertex z
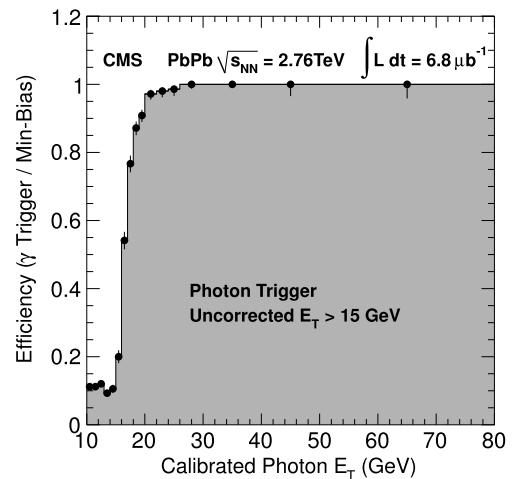

Fig. 1. Efficiency for the photon trigger as a function of the corrected photon transverse energy in PbPb collisions at 2.76 TeV, measured with the minimum-bias sample. Error bars represent the statistical uncertainty.

position $|z| < 15$ cm and an offline HF coincidence of at least three towers with energy greater than 3 GeV on each side of the interaction point. To further suppress the beam-gas and beam-scraping events, the length of pixel clusters along the beam direction is required to be compatible with particles originating from the event vertex.

Offline selection of pp and PbPb events for further analysis requires a photon candidate, defined as described in Section 6, in the pseudorapidity range $|\eta^\gamma| < 1.44$ and with a corrected transverse energy $E_T^\gamma > 20$ GeV, defining the phase space of the measurement.

4. Monte Carlo simulation

In order to study the photon selection efficiency and electron rejection in PbPb collisions, $\gamma + $ jet, dijet, and W $\rightarrow$ eν events are simulated using the PYTHIA Monte Carlo (MC) generator (version 6.422, tune D6T) [12], modified to take into account the isospin of the colliding nuclei [13]. These simulated PYTHIA events, propagated through the CMS detector using the GEANT4 package [14] to simulate the detector response, are embedded in actual MB PbPb events in order to study the effect of the underlying event on the photon reconstruction and isolation. The embedding is done by mixing the simulated digital information with the recorded MB PbPb data. These mixed samples (denoted "PYTHIA + DATA") are used for signal shape studies, and for energy and efficiency corrections.

In order to determine whether a given photon is isolated at the generator level, an isolation cone of radius

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$$

around its direction in pseudorapidity and azimuth is defined. A photon is considered to be isolated if the sum of the E_T of all the other final state particles produced from the same hard scattering inside the isolation cone is smaller than 5 GeV. The GEANT4 simulation is used to determine the isolated photon energy and efficiency corrections.

5. PbPb centrality determination

For the analysis of PbPb events, it is important to determine the overlap or impact parameter of the two colliding nuclei, usually called the reaction "centrality". Centrality is determined with
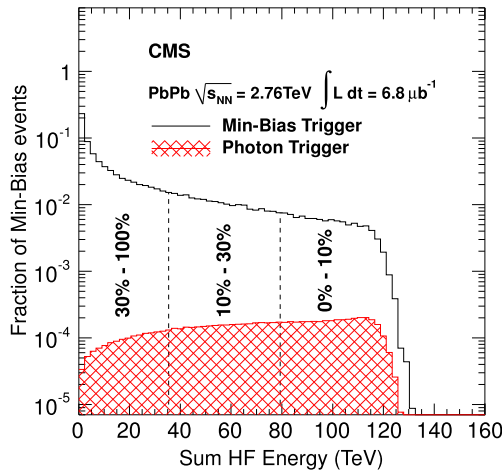
Fig. 2. Probability distribution of the total HF energy for minimum-bias PbPb collisions (black open histogram). The three regions separated by the vertical dotted lines correspond to the centrality ranges used in this analysis. Also shown is the HF energy distribution for the subset of events passing the HLT photon trigger (cross-hatched histogram), which is about 3.3% of all minimum-bias events.

Table 1

Energy correction factors for the background energy contribution found using the $\gamma +$ jet PYTHIA + DATA sample for each centrality interval and photon E_T. The reconstructed E_T of photon candidates with $|\eta^\gamma| < 1.44$ is multiplied by this factor to get the corrected transverse energy E_T^γ.

Photon E_T (GeV)	PbPb centrality		
	0–10%	10–30%	30–100%
20–25	0.90	0.94	0.99
25–30	0.91	0.95	0.99
30–40	0.92	0.95	0.99
40–50	0.94	0.96	0.99
50–80	0.95	0.97	0.99

the minimum-bias sample using the total sum of energy signals from the HF. The PbPb MB data sample is divided into three percentile ranges of the total inelastic cross section: 0–10% (most central, small impact parameter), 10–30% (mid-central), and 30–100% (peripheral, large impact parameter). The distribution of the HF energy, along with the intervals defining the three event classes, are shown in Fig. 2. Details of the centrality determination are described in Ref. [4]. The intervals can be correlated with geometrical properties of the collision using a Glauber model simulation [15]. The two most commonly used quantities are N_{part}, the total number of nucleons in the two Pb nuclei that experience at least one collision, and N_{coll}, the total number of inelastic nucleon–nucleon collisions. The variable N_{part} is often used to quantify the reaction centrality, with $N_{part} = 2$ corresponding to a single nucleon–nucleon interaction and $N_{part} = 2 \times 208$ corresponding to a head-on PbPb collision where all nucleons participate. The variable N_{coll} quantifies the total number of incoherent nucleon–nucleon collisions at a given centrality, and since this is directly proportional to the high-p_T particle production yields, N_{coll} is used to normalize the PbPb yields for comparison with the same observables for hard processes measured in pp collisions. As can be seen in Fig. 2, the centrality distribution associated with hard processes, such as high-E_T photon production (cross-hatched histogram), has a more pronounced contribution from central collisions than for minimum-bias events (solid line).

6. Photon reconstruction and identification

The photon reconstruction algorithm and isolation requirements in pp collisions are detailed in Ref. [16]. The reconstruction in PbPb collisions is very similar, although some modifications are introduced in order to deal with the large background of particles produced in the collision. ECAL "superclusters" are reconstructed in the barrel region of the electromagnetic calorimeter using the "island" energy-clustering algorithm [17]. The first step of the algorithm is a search around the seeds, which are defined as cells (reconstructed hits) with a transverse energy above a threshold of 0.5 GeV. Starting from a seed position, adjacent cells are examined, scanning first in the ϕ and then in the η direction. Cells are added to the cluster until the cell under consideration satisfies one of three conditions; the corrected energy deposit in the cell is zero, the energy in the cell is larger than in the adjacent cell which

was already added to the cluster, or the cell is already part of a different island cluster. In the second step, the island clusters are merged into superclusters. The procedure is seeded by searching for the most energetic cluster above a transverse energy threshold ($E_T > 1$ GeV) and then collecting all the other nearby clusters that have not yet been used in a narrow η-window ($\Delta \eta = 0.07$), and a much wider ϕ-window ($\Delta \phi = 0.8$). A photon candidate is constructed from a "supercluster" (conglomerate of energy deposits) with uncalibrated $E_T > 8$ GeV, and its energy is corrected to account for the material in front of the ECAL and for electromagnetic shower containment. The direction of the photon is also recalculated with respect to the primary vertex. An additional energy correction is applied to remove the background contribution from the underlying PbPb event. This correction is obtained from the $\gamma +$ jet PYTHIA + DATA sample and listed in Table 1 for the 3 centrality intervals. The underlying PbPb activity also worsens the photon energy resolution to a maximum of 9% for the lowest E_T bin in the 0–10% central events, as shown in Fig. 3.

Anomalous signals caused by the interaction of heavily ionizing particles directly with the silicon avalanche photodiodes used for the ECAL barrel readout are removed by the following requirements: (i) the signal should be consistent in time (within 3 ns) with a photon from the collision; (ii) the sum of the energy in the four adjacent cells surrounding the central cell should be at least 10% of the central cell energy. These two selections are satisfied by 99.7% of the photon signal candidates.

The selected photon candidates are required to be in the ECAL barrel within the pseudorapidity interval $|\eta^\gamma| < 1.44$, to not match with any electron candidates in a search window of $|\eta^\gamma - \eta^{Track}| < 0.02$ and $|\phi^\gamma - \phi^{Track}| < 0.15$ with respect to the associated electron candidate track, and to have $E_T^\gamma > 20$ GeV. A first rejection of neutral mesons mimicking a high-E_T photon candidate in the ECAL is done using the H/E ratio defined as the ratio of hadronic energy to electromagnetic energy inside a cone of $\Delta R = 0.15$, computed from the energy depositions in the HCAL and the ECAL [11]. Photon candidates with $H/E < 0.2$ are selected for this analysis.

To measure the isolation of a given photon candidate in a PbPb event, the detector activity in a cone of radius $\Delta R = 0.4$ with respect to the centroid of the cluster is used. Calorimeter-based isolation variables Iso_{ECAL} and Iso_{HCAL} are calculated by summing over the ECAL and HCAL transverse energy, respectively, measured inside the cone, while a track-based isolation variable Iso_{Track} is measured by summing over the transverse momentum of all tracks with $p_T > 2$ GeV/c inside the cone. The total ECAL energy associated with the photon candidate is excluded in the Iso_{ECAL} calculation. In order to remove the contribution of hadronic activity from the underlying PbPb event background falling inside the isolation cone for each centrality, the average value of the energy deposited per unit area in the η–ϕ phase space ($\langle UE \rangle$) is estimated within a rectangular region $2\Delta R$-wide and centered on η^γ in the η-direction and 2π wide in the ϕ-direction, excluding the isolation cone. The UE-subtracted isolation variables
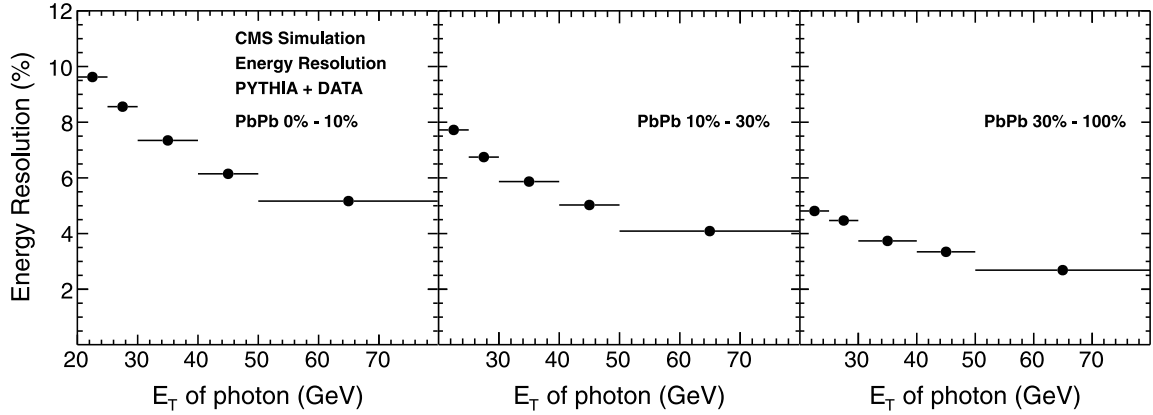
Fig. 3. Relative energy resolution of reconstructed photons as a function of photon transverse energy, determined using γ + jet PYTHIA + DATA sample for three centrality intervals. The horizontal bars indicate the bin width.

Table 2
Efficiencies of the isolated photon identification at each step: clustering, anomalous signal removal, H/E selection, and isolation requirement. Numbers in each row are the efficiencies relative to the previous step. The selections are more efficient for high E_T^γ photons and for more peripheral events. The intervals given indicate the E_T^γ-dependent variations of the efficiencies.

Isolated photon identification	PbPb centrality		
	0–10%	10–30%	30–100%
Supercluster reconstruction	96–99%	97–99%	97–99%
Anomalous signal removal	99–100%	99–100%	99–100%
$H/E < 0.2$	96–99%	98–99%	99–100%
SumIso$^{\text{UE-sub}} < 5$ GeV	82–84%	86–88%	96–97%
Total	77–82%	83–86%	92–95%

Iso$^{\text{UE-sub}}$ = Iso $- \pi (\Delta R)^2 \langle \text{UE} \rangle$ are used to further reject photon candidates originating from jets. The sum of the isolation variables (SumIso$^{\text{UE-sub}}$ = Iso$^{\text{UE-sub}}_{\text{ECAL}}$ + Iso$^{\text{UE-sub}}_{\text{HCAL}}$ + Iso$^{\text{UE-sub}}_{\text{Track}}$) is required to be smaller than 5 GeV. The efficiency of the isolated photon identification criteria in PbPb collisions, which is obtained from the PYTHIA + DATA sample, is summarized in Table 2.

7. Signal extraction, corrections, and systematic uncertainties

The selection criteria described above yield a relatively pure sample of isolated photons. However, there are still non-prompt photons, such as those from isolated π^0s that are carrying a large fraction of the parent fragmenting parton energy, which can pass the isolation cuts. Those remaining backgrounds are estimated using a two-component fit of the shape of the electromagnetic shower in the ECAL and separated from the signal on a statistical basis, as described below.

The topology of the energy deposits can be used as a powerful tool to distinguish the signal from the background by making use of the fine η segmentation of the electromagnetic calorimeter. The shower shape is characterized by a transverse shape variable $\sigma_{\eta\eta}$, defined as a modified second moment of the electromagnetic energy cluster distribution around its mean η position:

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

where E_i and η_i are the energy and position of the i-th crystal in a group of 5×5 crystals centered on the one with the highest energy, E is the total energy of the crystals in the calculation and $\bar{\eta}$ is the average η weighted by w_i in the same group [18,11]. Isolated photons tend to have a smaller mean value of $\sigma_{\eta\eta}$ and

a narrow distribution, while photons produced in hadron decays tend to have larger $\sigma_{\eta\eta}$ mean and a wider $\sigma_{\eta\eta}$ distribution.

The isolated prompt photon yield is estimated with a binned maximum likelihood fit to the $\sigma_{\eta\eta}$ distribution with the expected signal and background components for each E_T^γ interval. The signal and background component shapes used in the pp analysis are described in [11]. In the PbPb analysis, the signal component shape for each E_T^γ and centrality bin is obtained from γ + jet PYTHIA + DATA samples, and the background component shape is extracted from data using a background-enriched SumIso sideband ($6 <$ SumIso$^{\text{UE-sub}} < 11$ GeV) sample while keeping all other selection criteria unchanged.

Fig. 4 illustrates the results of the two-component fit of the shower-shape distribution measured in pp and PbPb collisions. The remaining background contribution from electrons passing all the photon selection criteria, estimated from a sample enriched in isolated electrons found by reversing the electron-veto requirement described in Section 6, is also subtracted to extract the raw signal yields (N_{raw}^γ). Typically, the contribution due to electron contamination in PbPb collisions is 3–6% for different E_T intervals. A bin-by-bin correction for the energy smearing (U), which amounts to 1.00–1.08 for different E_T^γ and centrality bins, is also applied to the raw signal yields to obtain the number of isolated photons. The E_T-differential photon yield per event is defined as

$$\frac{dN_{\text{PbPb}}^\gamma}{dE_T^\gamma} = \frac{N_{\text{raw}}^\gamma}{U \times \epsilon \times f_{\text{cent}} \times N_{\text{MB}} \times \Delta E_T^\gamma}, \quad (2)$$

where N_{MB} is the number of sampled minimum-bias PbPb events, f_{cent} is the fraction of PbPb events in each centrality bin, and ϵ is the efficiency of the isolated photon identification (Table 2). For pp collisions we normalize the yields by the integrated luminosity ($\mathcal{L}_{\text{pp}}$) to obtain the E_T-differential cross section $d\sigma_{\text{pp}}^\gamma/dE_T^\gamma$:

$$\frac{d\sigma_{\text{pp}}^\gamma}{dE_T^\gamma} = \frac{N_{\text{raw}}^\gamma}{U \times \epsilon \times \mathcal{L}_{\text{pp}} \times \Delta E_T^\gamma}. \quad (3)$$

The systematic uncertainties of the measured photon spectra are summarized in Table 3. The total systematic uncertainties are 22–30% for PbPb and 14–16% for pp collisions. The systematic uncertainty of the photon yield $dN_{\text{PbPb}}^\gamma/dE_T^\gamma$ in PbPb collisions is dominated by the uncertainty on the background modeling. Since the transverse shape variable $\sigma_{\eta\eta}$ may be correlated with the number of particles in the isolation cone (characterized by SumIso$^{\text{UE-sub}}$), non-prompt photons from PYTHIA + DATA samples are used to examine the possible difference between the $\sigma_{\eta\eta}$ distribution in the SumIso$^{\text{UE-sub}}$ signal and in the sideband regions.
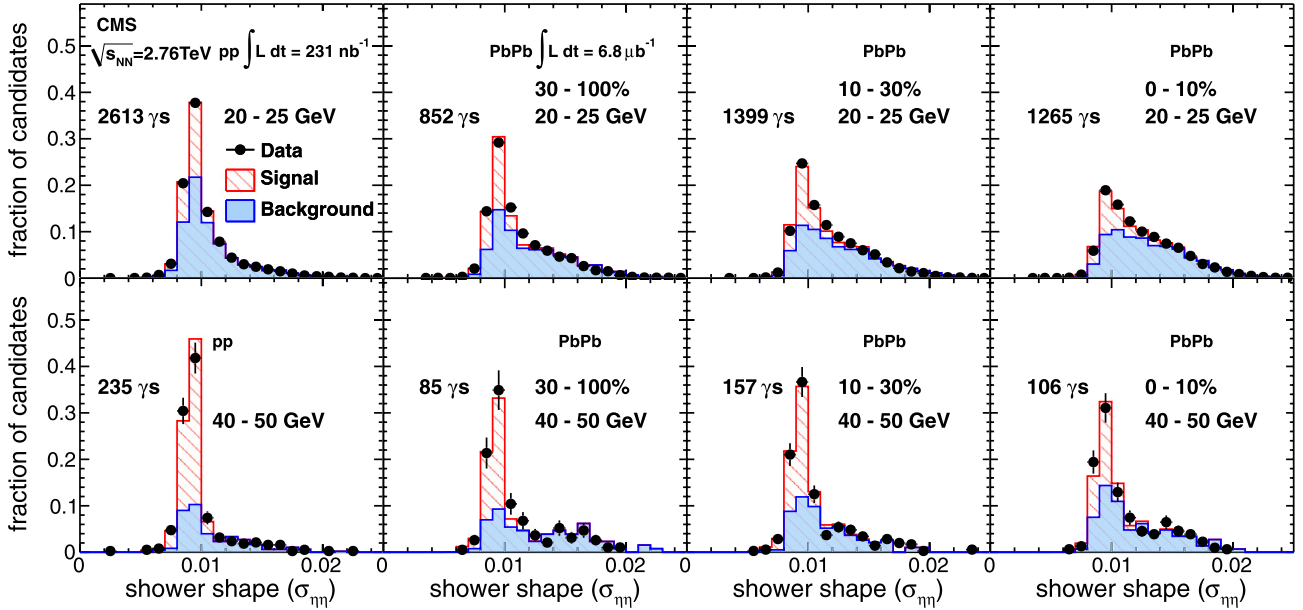
Fig. 4. Measured shower-shape $\sigma_{\eta\eta}$ distribution for photon candidates with $E_T^\gamma = 20$–25 GeV and 40–50 GeV in pp (2 left plots) and PbPb collisions for 3 different centrality ranges. The extracted numbers of isolated photons are shown in the figure. The fit result (red line), signal (red-hatched histogram) and background components (blue shaded histogram) are also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

Table 3

Summary of the contributions to the estimated systematic uncertainties on the isolated photon spectra measured in pp and PbPb collisions and their total. The nuclear overlap function T_{AA} is defined in Section 9. The intervals indicate the E_T^γ-dependent variations of the uncertainties.

Source	pp	PbPb centrality		
		0–10%	10–30%	30–100%
Efficiency	1–5%	5–9%	5–7%	5–6%
Signal modeling	3–5%	1–5%	3–5%	1–4%
Background modeling	9–13%	15–23%	14–16%	12–21%
Electron veto	1%	3–6%	3–5%	3–5%
Photon isolation definition	2%	7%	5%	2%
Energy scale	3–6%	9%	9%	9%
Energy smearing	1%	4%	4%	4%
Shower-shape fit	3%	5%	5%	5%
Anomalous signal cleaning	1%	1%	1%	1%
N_{MB}	–	3%	3%	3%
Luminosity	6%	–	–	–
Total without T_{AA}	14–16%	23–30%	22–25%	23–28%
T_{AA}	–	4%	6%	12%
Total	14–16%	23–30%	23–26%	26–31%

Systematic checks are performed using the differences in the mean and width seen in the MC to vary the background component shape in the fit. The estimated uncertainty is in the range of 12–23%, where the given interval indicates the E_T^γ and centrality-dependent variations of the uncertainty. The uncertainty due to the $\sigma_{\eta\eta}$ distribution of isolated photons is estimated by comparing the distributions of electrons from MC and data. Given the small number of $Z \rightarrow e^+e^-$ events in the PbPb data sample, $Z \rightarrow e^+e^-$ events from the 2010 pp run at $\sqrt{s} = 7$ TeV are mixed with MB PbPb data. The differences in the measured mean and width from those obtained in the MC($Z \rightarrow e^+e^-$) + PbPb data are used to vary the $\sigma_{\eta\eta}$ distributions of isolated photons. Such systematic changes result in a final propagated uncertainty of 1–5% in the isolated photon yield. The uncertainty due to the energy scale propagates to an uncertainty of 9% in the final spectra. The uncertainty due to the energy smearing correction is obtained by varying the assumed isolated photon differential cross section at low photon E_T (used to obtain

the unfolding correction factors) by ±50%, and is found to be 4%. The uncertainty of the two-component fit is checked by using different binning widths in the fit, and is found to be 5%. A 3–6% uncertainty is associated with the electron contamination subtraction. The difference between experimental and theoretical photon isolation definitions as described in Section 8 due to the detector response and underlying event is estimated to be 2–7%. The uncertainty of N_{MB} due to the MB selection efficiency is 3% in PbPb collisions, and a 6% uncertainty is quoted for the integrated luminosity in pp collisions.

8. Theoretical calculations

The isolated photon spectra measured in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are compared with next-to-leading-order (NLO) pQCD predictions obtained using JETPHOX 1.2.2, which reproduces well the measured pp data at $\sqrt{s} = 7$ TeV [11,16]. The inclusive photon spectrum in pp collisions is computed using the CT10 [19] parton distribution functions. The same spectrum in PbPb collisions is computed using the NLO EPS09 [20] PDFs, which include nuclear modifications of the proton PDFs. The reduction of photon emission due to isospin effects in nuclear compared to proton collisions (the relative population of u and d quarks is not identical in a single proton and in a lead nucleus, with 126 neutrons and 82 protons) is accounted for in the calculations. For both systems the BFG-II set [21] of parton-to-photon fragmentation functions is used, and the default renormalization, factorization, and fragmentation scales (μ_R, μ_F, and μ_f) are all set to the photon E_T. The parton-level isolation, summing over the transverse energy of all partons inside a cone of radius $\Delta R = 0.4$, is required to be smaller than 5 GeV. In order to estimate the dependence of the predictions on the choice of theoretical scales, the μ_i scales are varied by a factor of 2 below and above their default values, keeping the ratio between any two scales less than or equal to 2. The uncertainty linked to the choice of the proton PDF is ±(7–5)% and it is smaller than the theoretical scale uncertainty which varies within ±(15–10)% in the measured p_T range, as found in [11]. The uncertainty on the predictions due to nuclear PDFs is estimated using the 30 eigenvalues of the EPS09 PDF set. In addition, the PbPb

Table 4

Isolated photon cross sections for $|\eta^\gamma| < 1.44$ in bins of E_T^γ for pp collisions and PbPb collisions (for 3 centrality intervals and for the full range) at $\sqrt{s_{NN}} = 2.76$ TeV. The first uncertainty is statistical and the second one is systematic (including T_{AA} uncertainties in the PbPb case).

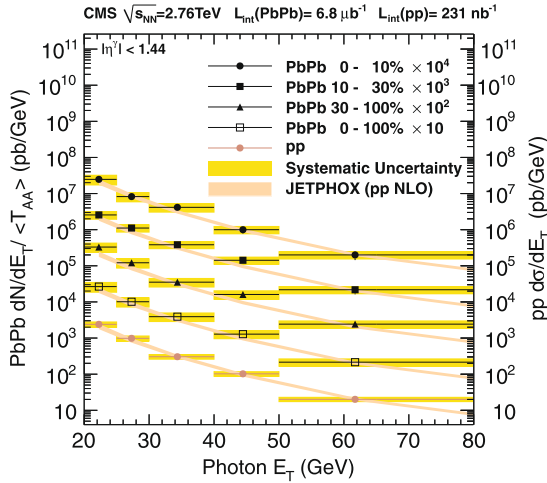| E_T (GeV)	pp $d\sigma_{pp}^\gamma/dE_T^\gamma$ (pb/GeV)	PbPb $dN_{PbPb}^\gamma/dE_T^\gamma/\langle T_{AA}\rangle$ (pb/GeV)			
		0–10%	10–30%	30–100%	0–100%
20–25	$2400 \pm 140 \pm 400$	$2480 \pm 240 \pm 740$	$2560 \pm 210 \pm 620$	$3310 \pm 280 \pm 950$	$2660 \pm 140 \pm 810$
25–30	$983 \pm 74 \pm 159$	$830 \pm 120 \pm 240$	$1110 \pm 120 \pm 250$	$1220 \pm 170 \pm 350$	$1013 \pm 75 \pm 292$
30–40	$305 \pm 30 \pm 45$	$416 \pm 54 \pm 110$	$383 \pm 46 \pm 85$	$353 \pm 60 \pm 94$	$391 \pm 31 \pm 105$
40–50	$102 \pm 12 \pm 15$	$100 \pm 22 \pm 23$	$142 \pm 21 \pm 32$	$161 \pm 30 \pm 43$	$128 \pm 14 \pm 33$
50–80	$20.1 \pm 2.6 \pm 2.8$	$20.0 \pm 5.7 \pm 4.6$	$21.8 \pm 5.5 \pm 5.0$	$24.3 \pm 4.9 \pm 5.6$	$21.5 \pm 3.4 \pm 5.0$

Fig. 5. Isolated photon spectra measured as a function of E_T^γ for 0–10%, 10–30%, 30–100%, 0–100% PbPb collisions (scaled by T_{AA}) and pp collisions at 2.76 TeV, scaled by the factors shown in the figure for easier viewing. The horizontal bars indicate the bin width. The total systematic uncertainty (bottom row of Table 3) is shown as a yellow box at each E_T bin. The results are compared to the NLO JETPHOX calculation (see text) with its associated scale and PDF uncertainties (added in quadrature) shown as a pink band. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

Fig. 6. Nuclear modification factor R_{AA} as a function of the photon E_T measured in the 0–10% most central PbPb collisions at 2.76 TeV. The vertical error bars indicate the statistical uncertainty and the horizontal bars reflect the bin width. The total systematic uncertainties without the T_{AA} uncertainty (see Table 3) are shown as yellow filled boxes. The T_{AA} uncertainty, common to all points, is indicated by the left box centered at unity. The curves show the theoretical predictions, obtained with JETPHOX for various nuclear PDFs described in the text. The uncertainty from the EPS09 PDF parameters is shown as the red dashed lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

spectrum is computed using two alternative nuclear PDF sets: nDS [22] and HKN07 [23]. When data are compared to pp NLO predictions, the proton PDF and the scale uncertainties are added in quadrature.

9. Results

In order to compare the cross sections for any high-p_T particle produced in PbPb and pp collisions, a scaling factor, the nuclear overlap function T_{AA}, is needed to provide proper normalization. This factor, equal to the number of nucleon–nucleon (NN) collisions, N_{coll}, normalized by the pp inelastic cross section, can be interpreted as the NN-equivalent integrated luminosity at any given PbPb centrality. The LHC Collaborations use a common nucleon–nucleon inelastic cross section of $\sigma = 64 \pm 5$ mb at 2.76 TeV, based on a fit of the existing data for total and elastic cross sections in proton–proton and proton–antiproton collisions [24]. In units of mb^{-1}, the average values of T_{AA} are 23.2 ± 1.0, 11.6 ± 0.7, 1.45 ± 0.18, and 5.66 ± 0.35 for the centrality ranges 0–10%, 10–30%, 30–100%, and 0–100%, respectively. These numbers are computed with a Glauber model [15] using the same parameters as in [4]. The quoted uncertainties are derived by varying the Glauber model parameters and the MB trigger and event selection efficiency within their uncertainties. The measured E_T^γ-differential isolated photon cross sections in pp and the T_{AA}-scaled yields in PbPb collisions, including both statistical and systematic uncertainties, are listed in Table 4.

Fig. 5 shows the pp cross sections and the PbPb T_{AA}-scaled yields compared to the JETPHOX predictions obtained with the CT10
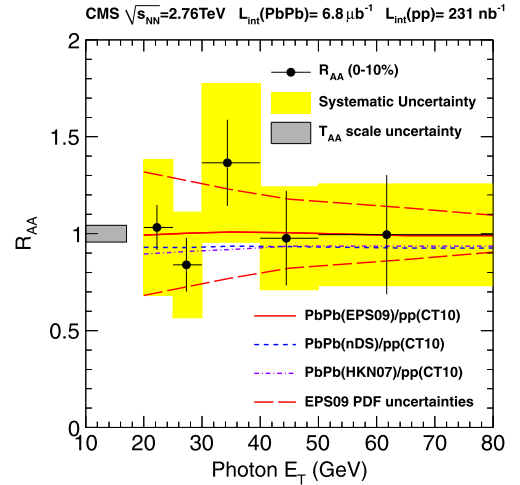
PDF, described in Section 8. The data are plotted at the true centre of the E_T^γ distributions in each bin [25]. The pp and PbPb data are consistent with the NLO calculation at all transverse energies within the quoted statistical and systematic uncertainties.

The nuclear modification factor (R_{AA}) for isolated photon production in PbPb collisions,

$$R_{AA} = dN_{PbPb}^\gamma/dE_T^\gamma / \left(T_{AA} \times d\sigma_{pp}^\gamma/dE_T\right), \qquad (4)$$

is computed from the measured PbPb scaled yield for each centrality and the pp differential cross section. Fig. 6 displays R_{AA} as a function of the isolated photon E_T for the 0–10% most central PbPb collisions. The ratio is compatible with unity within the experimental uncertainties for all E_T values. This confirms the validity of the T_{AA} scaling expectation for perturbative cross sections in nucleus–nucleus collisions at the LHC, as found previously for Z-boson production [6]. Changes in the isolated photon yields in PbPb collisions compared to pp due to modifications of the nuclear parton densities are relatively small in this high-E_T range, according to the JETPHOX calculations. Fig. 6 shows that the calculated NLO ratios of the PbPb to pp isolated photon spectra obtained with the central values of the EPS09, nDS and HKN07 nuclear PDFs differ at most by $\pm 10\%$. The band of uncertainty obtained from the 68% confidence level variation of the EPS09 nuclear parton distribution parameters (red dashed lines) is fully consistent with the measured nuclear modification factor at all transverse energies.
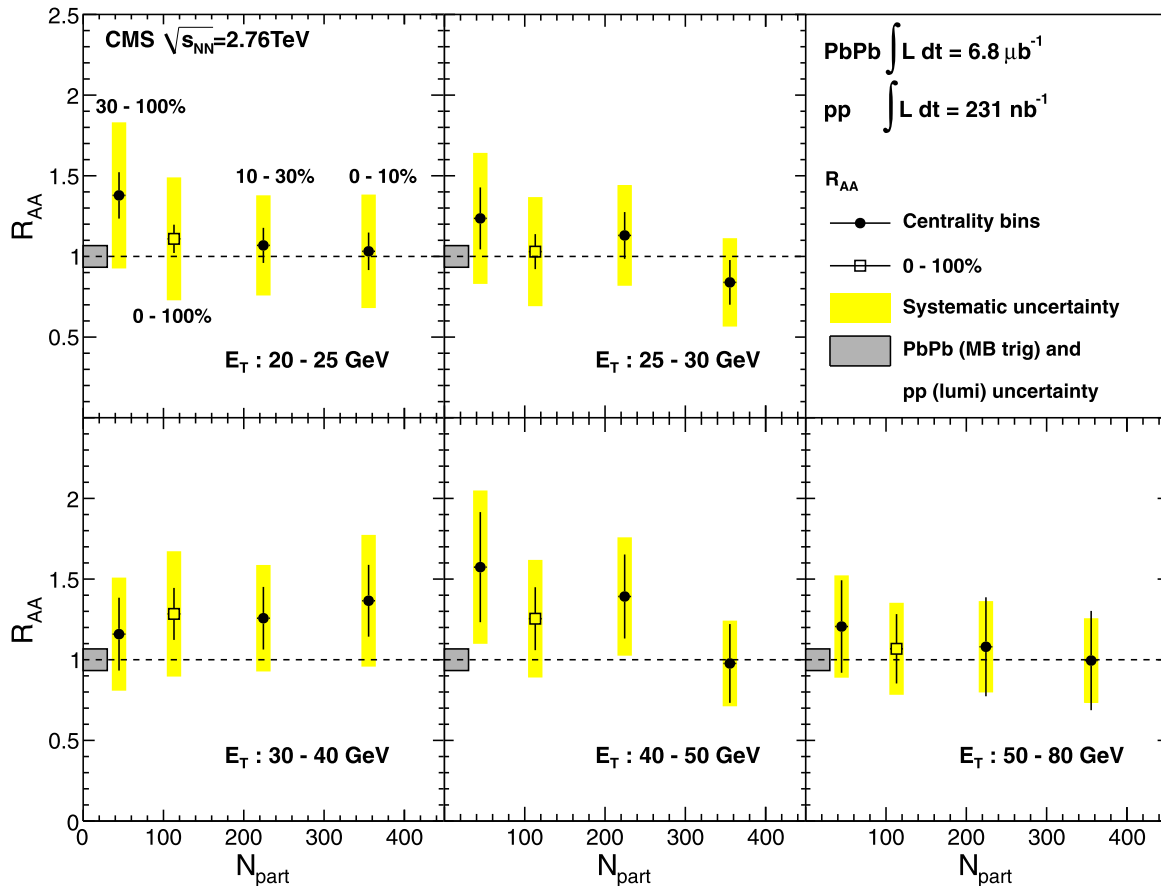
Fig. 7. The measured nuclear modification factor R_{AA} as a function of PbPb centrality (given by the number of participating nucleons, N_{part}) for five different photon transverse energy intervals. The error bars on each point indicate the statistical uncertainty. The systematic uncertainties are shown as yellow boxes, including the centrality dependent T_{AA} uncertainty. The common uncertainties related to event selection efficiency and pp integrated luminosity are shown as grey hatched boxes around unity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

In order to investigate the centrality dependence of the isolated photon production yields in PbPb compared to pp collisions, Fig. 7 plots the R_{AA} as a function of N_{part} for various E_T bins. Within the uncertainties, the measured nuclear modification ratio is consistent with unity, not only for minimum-bias PbPb collisions, but also for central collisions and all photon transverse energies. With improved statistical accuracy and/or reduced systematic uncertainties, isolated photon production yields in PbPb collisions at the LHC could be used to better constrain the nuclear PDFs by including the measurement in standard global fits of parton densities [20,22,23], as discussed in [3].

10. Summary

In summary, the isolated photon spectra at midrapidity ($|\eta^\gamma| < 1.44$) have been measured as a function of transverse energy in pp and PbPb collisions at nucleon–nucleon centre-of-mass energies of 2.76 TeV. The measured spectra are well reproduced by NLO perturbative QCD calculations with recent parton distribution functions for the proton and nucleus. No modification is observed in the E_T^γ spectra measured in PbPb collisions at various centralities with respect to the pp differential cross sections scaled by the corresponding nuclear overlap function. The result confirms the T_{AA} scaling of perturbative cross sections in PbPb compared to pp collisions. It is consistent with the expectation that nuclear parton densities are not significantly modified compared to the proton PDF in the explored kinematic range, dominated by high-p_T photons produced in parton–parton scatterings in the large-Q^2

and moderate parton fractional momentum x region of the nuclear PDFs [20]. Isolated photons are found to be unaffected by the produced strongly interacting medium, in sharp contrast to the large quenching effects observed for jets [4]. The measurement presented here establishes isolated photon production as a valuable perturbative probe of the initial state in heavy-ion collisions and provides a baseline for the study of in-medium parton energy loss in γ + jet events.

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