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Measurement of the triple-differential cross section for photon+jets production in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$

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Abstract

A measurement of the triple-differential cross section, $\mathrm{d}^3\sigma/(\mathrm{d}p_\mathrm{T}^\gamma\,\mathrm{d}\eta^\gamma\,\mathrm{d}\eta^\text{jet})$, in photon+jets final states using a data sample from proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ is presented. This sample corresponds to an integrated luminosity of $2.14\,\text{fb}^{-1}$ collected by the CMS detector at the LHC. Photons and jets are reconstructed within a pseudorapidity range of $|\eta| < 2.5$, and are required to have transverse momenta in the range $40 < p_\mathrm{T}^\gamma < 300\,\text{GeV}$ and $p_\mathrm{T}^\text{jet} > 30\,\text{GeV}$, respectively. The measurements are compared to theoretical predictions from the SHERPA leading-order QCD Monte Carlo event generator and the next-to-leading-order perturbative QCD calculation from JETPHOX. The predictions are found to be consistent with the data over most of the examined kinematic region.

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Studies of events produced in proton-proton collisions containing a photon and one or more jets in the final state provide a direct probe of quantum chromodynamics (QCD) [1–5]. The production cross sections, examined for various angular configurations, are sensitive to contributions from the QCD hard-scattering subprocesses and to parton distribution functions (PDFs) of the proton [6, 7]. Measurements of these cross sections serve to constrain PDF models and provide information for improving phenomenological Monte Carlo models, as well as testing the applicability of fixed-order perturbative calculations over a wide range of kinematic regions. Photon+jets (direct photon) events are a major source of background to standard model measurements, most notably for the study of a light, neutral Higgs boson in the decay channel $H \rightarrow \gamma\gamma$ [8], as well as beyond-the-standard-model searches for signatures of extra dimensions [9] and excited quarks [10], among others. Photon+jets events can also be used to calibrate jet energies [11], and to model the missing transverse energy distributions attributed to the presence of noninteracting particles [12].

This Letter presents a measurement of the triple-differential cross section for photon+jets production using a data set collected by the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) from pp collisions at $\sqrt{s} = 7$ TeV. The data correspond to an integrated luminosity of $2.14\,\text{fb}^{-1}$. This measurement spans a transverse momentum range of $40 < p_\text{T}^\gamma < 300$ GeV and $p_\text{T}^\text{jet} > 30$ GeV for photons and jets, respectively. It is performed in four regions of pseudorapidity for the photon ($|\eta^\gamma| < 0.9$, $0.9 \leq |\eta^\gamma| < 1.44$, $1.56 \leq |\eta^\gamma| < 2.1$ and $2.1 \leq |\eta^\gamma| < 2.5$) and two regions of pseudorapidity for the leading-transverse-momentum jet ($|\eta^\text{jet}| < 1.5$ and $1.5 \leq |\eta^\text{jet}| < 2.5$). The dominant mechanisms for direct production of photons with large transverse momentum are the Compton-like gluon scattering process $gq \rightarrow \gamma q$ and the quark-antiquark annihilation process, $q\bar{q} \rightarrow \gamma g$ [13]. The main background for these processes comes from the decay of neutral hadrons, such as π^0 and η mesons, into nearly collinear pairs of photons. This measurement spans an x and Q^2 region of $0.002 \lesssim x \lesssim 0.4$ and $1600 \leq Q^2 \leq 9 \times 10^4$ GeV^2, extending the kinematic regions covered by earlier measurements [14–24]. Measurements of the differential cross sections and ratios of the differential cross sections for different angular configurations are compared to theoretical predictions.

The CMS detector is a general-purpose, hermetic detector providing large solid angle coverage for electromagnetic and hadronic showers, charged particle tracks, and muons. The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, with the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ in the x-y plane. The pseudorapidity is defined by $\eta = -\ln[\tan(\theta/2)]$. A full description of the CMS detector can be found in Ref. [25]. The subdetectors most relevant to this analysis are the electromagnetic calorimeter (ECAL), the hadron calorimeter (HCAL), and the silicon tracker. These detectors are located within a 3.8 T superconducting solenoid of 6 m internal diameter. The ECAL is a homogeneous calorimeter composed of approximately 76 000 lead tungstate crystals with segmentation $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$ (where ϕ is measured in radians), corresponding to a physical area of $22 \times 22\,\text{mm}^2$ at the front face of a crystal in the central barrel region ($|\eta| < 1.5$) and $28.62 \times 28.62\,\text{mm}^2$ in two endcap regions ($1.5 < |\eta| < 3.0$). The HCAL is a brass/scintillator sampling calorimeter with segmentation of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ in the central region ($|\eta| < 1.74$) and $\Delta\eta \times \Delta\phi = 0.09 \times 0.174$ to 0.35×0.174 for forward pseudorapidity ($1.74 < |\eta| < 3.0$). The silicon tracking system, located between the LHC beam pipe and the ECAL, consists of pixel and strip detector elements covering the pseudorapidity range $|\eta| < 2.5$. In the forward region a preshower detector, consisting of two planes of silicon sensors interleaved with 3 radiation lengths of lead, is located in front of the ECAL, covering

the region $1.65 < |\eta| < 2.6$.

Events selected for this analysis are recorded using a two-level trigger system. A level-1 trigger requires a cluster of energy deposited in the ECAL with transverse energy $E_T > 20\,\text{GeV}$. The CMS high-level trigger (HLT) applies a more sophisticated energy clustering algorithm to events passing the level-1 threshold and further requires E_T trigger thresholds from 30 to $135\,\text{GeV}$. These thresholds are raised with increased instantaneous luminosity to prevent saturation of the readout. In addition to these trigger requirements, an offline requirement is imposed to ensure that events have at least one well reconstructed primary vertex within $24\,\text{cm}$ in z of the nominal center of the detector.

Photons deposit most of their energy through electromagnetic showers in the ECAL. They are reconstructed by clustering energy deposits in neighboring crystals according to criteria that are optimized for different regions of pseudorapidity. Each clustering algorithm begins from a seed crystal with large transverse energy. In the barrel region, clusters are formed by summing energies across 5 (35) crystals in the η (ϕ) direction. Clusters in the endcap are formed by combining contiguous 5×5 arrays of crystals and including the corresponding energy in the preshower detector. The full details of these algorithms can be found in Ref. [26]. We apply the same selection criteria used in the measurement of the inclusive photon cross section [27] and provide a summary here. A photon reaching the ECAL without undergoing conversion to an e^+e^- pair deposits most of its energy in a 3×3 crystal matrix. Only a very small fraction of the energy from the resulting shower leaks into the HCAL, hence the ratio of the energy of the photon candidate in the HCAL to the energy in the ECAL, H/E, within a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.15$ around the seed crystal can be used to separate photon showers from electromagnetic components of hadron-initiated showers. For this analysis, a requirement of $H/E < 5\%$ is applied to the photon candidates. To reject electrons, we require that there be no hits in the first two inner layers of the silicon pixel detector that are consistent with an electron track matching the location and energy of the photon candidate in the calorimeter (pixel detector veto). To further improve the purity of the photon candidate sample, an additional requirement is applied based on the second moment of the electromagnetic shower in η, calculated using a 5×5 matrix of crystals around the highest energy crystal in the cluster,

$$\sigma_{\eta\eta}^2 = \frac{\sum (\eta_i - \bar{\eta})^2 \, w_i}{\sum w_i}, \tag{1}$$

where the sum runs over all elements of the 5×5 matrix, and $\eta_i = 0.0174\hat{\eta}_i$, with $\hat{\eta}_i$ denoting the η index of the ith crystal; the individual weights w_i are given by $w_i = \max\left(0, 4.7 + \ln(E_i/E_{5\times5})\right)$ and E_i is the energy of the ith crystal; $\bar{\eta} = \sum \eta_i w_i / \sum w_i$ is the energy-weighted average pseudorapidity. The requirement $\sigma_{\eta\eta} < 0.01$ (0.028) in the barrel (endcaps) further suppresses background from neutral mesons (π^0, η, etc.) that may satisfy the isolation requirements described below as a result of fluctuations in the fragmentation of partons. The combined H/E and shower shape requirements along with the pixel detector veto comprise the photon identification criteria. If multiple photons are reconstructed within the fiducial range of this analysis, only the photon with highest p_T^γ (*leading photon*) is considered.

Jets are reconstructed using the anti-k_T [28] clustering algorithm with distance parameter of 0.5. Inputs for the jet clustering are defined by the particle-flow [29] algorithm, which is a full-event reconstruction technique that aims to reconstruct and identify all stable particles produced in an event through the combination of information from all subdetectors. Jets with $p_T > 30\,\text{GeV}$ are selected for this analysis, and are required to pass data quality requirements designed to remove spurious jets resulting from noise. Since energetic photons are also reconstructed as

jets by the anti-k_T algorithm, any jet that overlaps with the leading photon within a cone of $R < 0.5$ is removed from consideration.

Even after the photon identification criteria are applied, a significant background remains, mostly from neutral mesons that decay to photons that overlap in the ECAL. Templates constructed from signal and background distributions are fitted to data to determine the purity of the selected photon sample. The method exploits the distribution of energy in the vicinity of the photon using the variable $\mathrm{Iso}^\gamma = \mathrm{Iso_{TRK}} + \mathrm{Iso_{ECAL}} + \mathrm{Iso_{HCAL}}$, where $\mathrm{Iso_{TRK}}$ is the sum of the p_T of tracks consistent with the reconstructed vertex in a hollow cone, $0.04 < R < 0.40$, centered around the candidate photon momentum vector extending from the primary vertex to the ECAL cluster. Similarly, $\mathrm{Iso_{ECAL}}$ is the transverse energy deposited in the ECAL in $0.06 < R < 0.40$, and $\mathrm{Iso_{HCAL}}$ is the transverse energy deposited in the HCAL in $0.15 < R < 0.40$. For the $\mathrm{Iso_{TRK}}$ ($\mathrm{Iso_{ECAL}}$) distributions, we do not include energy in a rectangular strip of $\Delta\eta \times \Delta\phi = 0.015\,(0.040) \times 0.040$ to exclude energy associated with the photon in case of conversion [30]. The method takes advantage of differences in the Iso^γ distributions between signal and background. The main contribution to Iso^γ for genuine photons comes from the underlying event and multiple pp interactions in the same bunch crossing (pile-up collisions). The average number of pile-up collisions for data used in this analysis is ∼6. In contrast, Iso^γ for misidentified photons includes additional contributions of energy from jet fragmentation. Hence, the Iso^γ distribution for the background tends to be broader than for signal.
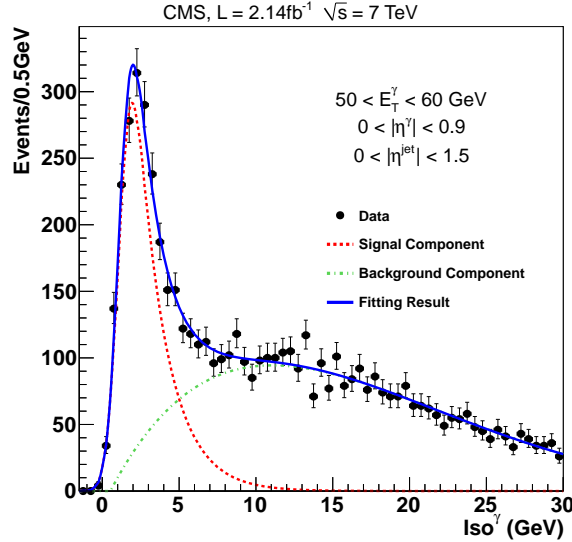

Figure 1: Example of a fit to the Iso^γ distribution using signal and background templates.

The signal template is modeled using Monte Carlo (MC) events generated with PYTHIA 6.424 [31] and parameterized by the convolution of an exponential function with a Gaussian,

$$S(x) = C_S\, e^{\alpha x} \otimes \mathrm{Gaussian}(x, \mu, \sigma), \qquad (2)$$

where $x = \mathrm{Iso}^\gamma$, (μ, σ) and α describe the peak and tail of the signal template, respectively, and C_S normalizes the distribution to unit area. The background template is obtained from data using a background-enriched sample collected from a sideband region, obtained by inverting the shower shape selection requirement and requiring $\sigma_{\eta\eta} > 0.011\,(0.030)$ in the barrel (endcap)

regions. The background distribution is parameterized using an inverse ARGUS function [32],

$$B(x) = \begin{cases} C_B \left[1 - e^{z(x-q_1)}\right] \cdot [1 - q_2(x - q_1)]^{q_3} & ; \ x \geq q_1 \\ 0 & ; \ x < q_1, \end{cases} \tag{3}$$

where $x = \text{Iso}^\gamma$, z describes the shape of the background template in the signal-dominated region, q_1 (q_2, q_3) describe the starting point of the background template (or its shape in the background-dominated region), and C_B normalizes the distribution to unit area.

The signal purity is determined by fitting the signal and background template functional forms to data, $N_S \cdot \text{Iso}_S^\gamma + N_B \cdot \text{Iso}_B^\gamma$, and minimizing an extended χ^2 defined as

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{N_i - (N_S S_i(\vec{p}, \alpha) + N_B B_i(z, \vec{q}))}{\sigma_{N_i}} \right)^2 + \left(\frac{(z - z_{\text{central}})}{\sigma_z} \right)^2, \tag{4}$$

where N_S and N_B are the numbers of signal and background events, n is the number of bins in the templates, N_i the observed number of events for the ith bin with uncertainty σ_{N_i}, S_i and B_i are the per-bin integrals of the corresponding signal and background templates, and z_{central} (σ_z) is the value (uncertainty) of the parameter z determined by the fitting of the background template. The parameters can be categorized into those that most directly model the signal-dominated (μ, σ, z, and q_1) and background-dominated (α, q_2, and q_3) regions. The parameter that describes the peak in the signal template is allowed to vary in the fit to correct for differences between data and MC in the region of low isolation energy. This procedure is validated with data using a photon sample collected from $Z \rightarrow \mu^+ \mu^- \gamma$ events. The parameter that describes the tail of the signal template in the high isolation energy region is shifted by 5% to estimate the uncertainty from the contributions of nonprompt photons, which originate from jet fragmentation. In the low Iso^γ region, the background distribution is constrained by the sideband data, allowing the parameter z to vary based on the value z_{central} with an uncertainty σ_z. An example of the resulting templates is shown in Fig. 1. The purity is determined independently in bins of γ and jet pseudorapidity and as a function of p_T^γ.

The signal purity is defined as the ratio of prompt photons to the total number of selected photons. This is shown as a function of p_T^γ in Fig. 2 for two ranges of η^γ; it increases with the transverse momentum of the photons. The main contribution to the systematic uncertainty in the photon signal purity is due to the modeling the shape of the background template, which is dominated by statistics in the sideband samples. This uncertainty is evaluated by performing pseudo-experiments based on simulated QCD samples to examine variations in the measurement of the purity due to statistical fluctuations in the template models. We also consider a smaller contribution to the systematic uncertainty related to the modeling of the signal template. The systematic uncertainty is evaluated independently for each bin and increases with decreasing photon transverse momentum from 1% to 30%.

The selection efficiency for photons can be factorized into four terms, which are measured independently: $\epsilon_{\text{total}} = \epsilon_{\text{trigger}} \cdot \epsilon_{\text{RECO}} \cdot \epsilon_{\text{ID}} \cdot \epsilon_{\text{PMV}}$. The first factor, $\epsilon_{\text{trigger}}$, is the trigger selection efficiency, and is measured in data using electrons from the decay of Z bosons following a 'tag-and-probe' method [33]. The tag electron is required to match an object reconstructed as an HLT electron, while the probe requirement is relaxed to pass the offline photon selection requirements and a photon HLT path. This efficiency factor is found to be consistent with 100% within its systematic uncertainty. The reconstruction efficiency, ϵ_{RECO}, is measured using simulated events in a photon+jets sample generated with PYTHIA. The same sample is used to determine ϵ_{ID}, the efficiency of the photon identification criteria apart from the pixel detector
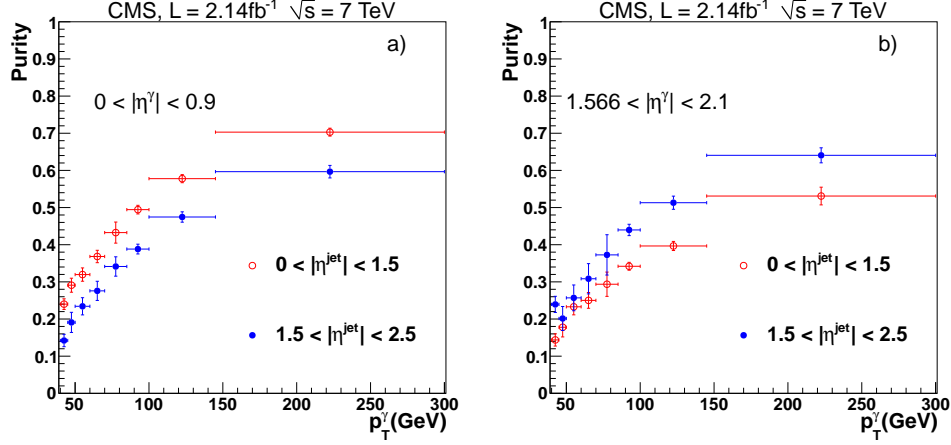
Figure 2: Examples of signal purity as a function of p_T^γ for (a) photons in the barrel and (b) photons in the endcap. In each figure the open (filled) circles correspond to the events with leading jet located in the barrel (endcap). The error bars represent the total statistical and systematic uncertainty in the purity measurement.

veto. The systematic uncertainty is determined from the differences between data and MC simulation by applying similar selections to electrons in a Z-boson-enriched sample. The photon pixel veto efficiency, ϵ_{PMV}, is estimated from data by employing the tag-and-probe technique with final-state-radiation photons in $Z \to \mu^+ \mu^- \gamma$ events. The total photon efficiency as a function of photon transverse momentum in the four photon pseudorapidity ranges is shown in Fig. 3. The variation of total efficiency values in the photon pseudorapidity regions is mainly caused by the pixel veto efficiency contribution.
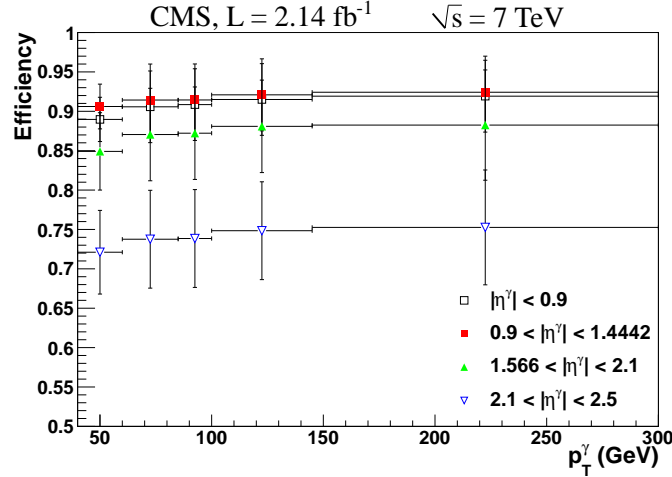

Figure 3: Total efficiency for photon selection as a function of photon transverse momentum (p_T^γ) in four different photon pseudorapidity (η^γ) ranges. The error bars include both statistical and systematic uncertainties and are dominated by the latter.

Figures 4 and 5 show the measurement of the triple-differential cross section $d^3\sigma / (dp_T^\gamma \, d\eta^\gamma \, d\eta^{jet})$ for $|\eta^{jet}| < 1.5$ and $1.5 < |\eta^{jet}| < 2.5$. The measurements are corrected for detector effects due to resolution and calibration by unfolding the spectra using an iterative method [34] and calculated using

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_\mathrm{T}^\gamma \mathrm{d}\eta^\gamma \mathrm{d}\eta^\mathrm{jet}} = \frac{1}{\Delta p_\mathrm{T}^\gamma \cdot \Delta\eta^\gamma \cdot \Delta\eta^\mathrm{jet}} \frac{N_\mathrm{signal}^\gamma \cdot U}{L \cdot \epsilon}, \tag{5}$$

where N^γ is the number of photon candidates in bins of $\Delta p_\mathrm{T}^\gamma, \Delta\eta^\gamma$, and $\Delta\eta^\mathrm{jet}$ with integrated luminosity L; U and ϵ are the unfolding and efficiency corrections, respectively.
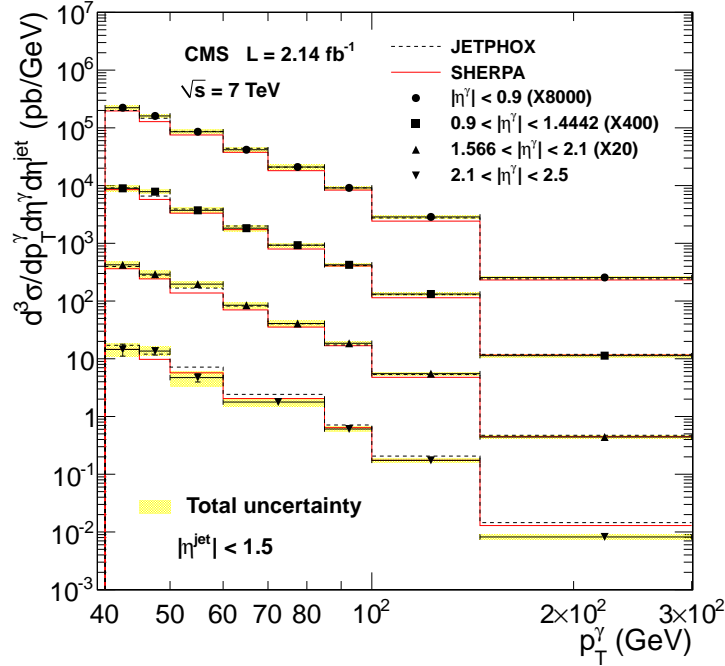

Figure 4: Differential cross sections for $|\eta^\mathrm{jet}| < 1.5$. The measured cross sections (markers) in four different ranges of η^γ are compared with the SHERPA tree-level MC (solid line) and the NLO perturbative QCD calculation from JETPHOX (dashed line). The cross sections for the most central photons are scaled by factors of 20 to 8000 for better visibility. Error bars are statistical uncertainties and the shaded bands correspond to the total experimental uncertainties.

The contributions to the systematic uncertainty in the differential cross section from the determination of photon reconstruction efficiency, unfolding, and the photon purity determination are given in Table 1. The table also shows the total systematic uncertainty obtained by adding all the contributions in quadrature. At low p_T^γ the systematic uncertainty is dominated by the purity determination. This is also the region where the uncertainty is the highest. At high p_T^γ the most significant contribution usually comes from the determination of the reconstruction efficiency.

The measured cross sections are compared to theoretical predictions based on perturbative QCD using the leading order (LO) MC event generator SHERPA (v1.3.1) [35] and the full next-to-leading order (NLO) calculation implemented in JETPHOX (v1.2.2) [36]. The SHERPA generator includes higher-order tree-level matrix elements and parton shower modeling as described in Ref. [37]. It also extends this technique to processes involving prompt photons [38], combining the photon and QCD parton multiplicity tree-level matrix elements with a QCD+QED parton shower using the formalism given in Ref. [37], thus treating photons and jets on an equal footing [38]. This treatment also includes contributions from the photon fragmentation component, permitting a direct comparison with experimental measurements. The predictions from SHERPA agree well with earlier photon measurements from the Tevatron [21]. The photon+jets
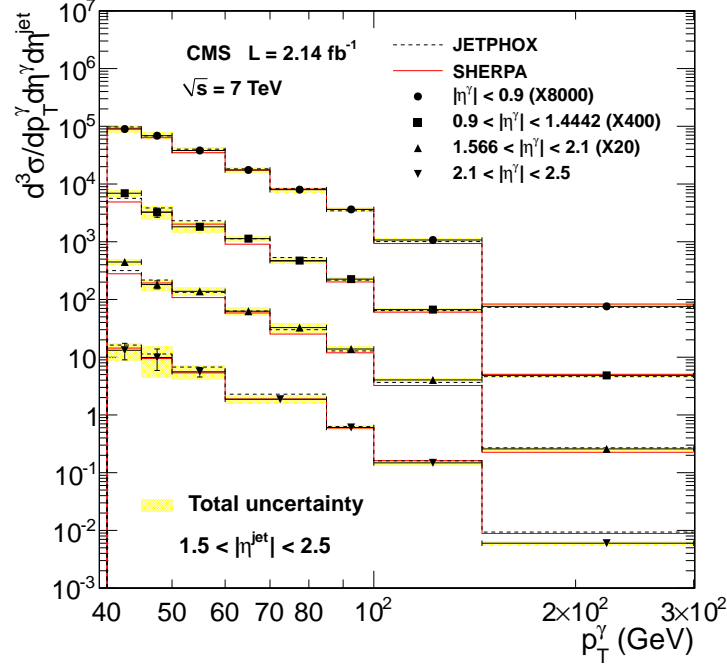
Figure 5: Differential cross sections for $1.5 < |\eta^{\text{jet}}| < 2.5$. The measured cross sections (markers) in four different ranges of η^γ are compared with the SHERPA tree-level MC (solid line) and the NLO perturbative QCD calculation from JETPHOX (dashed line). The cross sections for the most central photons are scaled by factors of 20 to 8000 for better visibility. Error bars are statistical uncertainties and the shaded bands are the total experimental uncertainties.

Table 1: Contributions to the relative systematic uncertainty (in percent) in the cross section measurement from efficiency, unfolding, and purity calculations. The total systematic uncertainty is obtained by adding all the contributions in quadrature. The numbers in the table represent the ranges of uncertainties obtained in different η^γ and η^{jet} bins.

p_T^γ (GeV)	efficiency (%)	unfolding (%)	purity (%)	total (%)
$|\eta^\gamma| < 1.4442$				
40–45	2.5	2.1	$4.9 - 9.3$	$5.9 - 9.9$
45–50	1.2	2.5	$4.9 - 17$	$5.5 - 17$
50–60	4.5	2.6	$4.2 - 13$	$6.7 - 14$
60–70	4.5	2.4	$3.7 - 11$	$6.3 - 13$
70–85	4.5	1.2	$4.6 - 5.7$	$6.6 - 7.4$
85–100	4.5	1.4	$2.2 - 3.1$	$5.2 - 5.6$
100–145	4.5	1.4	$1.8 - 2.5$	$5.0 - 5.4$
145–300	4.5	1.2	$1.4 - 2.6$	$4.9 - 5.3$
$1.556 < |\eta^\gamma| < 2.5$				
40–45	3.0	2.1	$6.9 - 9.9$	$7.8 - 11$
45–50	3.5	2.5	$8.6 - 38$	$9.6 - 38$
50–60	5.0	2.6	$7.2 - 25$	$9.1 - 25$
60–70	5.0	2.4	$7.0 - 12$	$9.0 - 14$
70–85	5.0	$1.2 - 5.0$	$10 - 13$	$11 - 15$
85–100	5.0	$1.4 - 5.0$	$2.8 - 4.6$	$5.9 - 8.0$
100–145	5.0	$1.4 - 4.0$	$2.8 - 6.3$	$5.9 - 8.2$
145–300	5.0	$1.2 - 2.1$	$2.9 - 5.1$	$6.1 - 7.3$

final states are generated with up to three additional jets using SHERPA and the CTEQ6 [39] parton distribution functions (PDFs). Calculations are performed using default choices for renormalization (μ_R) and factorization (μ_F) scales equal to p_T^γ. For JETPHOX the CT10 [40] NLO PDFs are used with $\mu_R = \mu_F = \mu_f = p_T^\gamma/2$, where μ_f defines the fragmentation scale. To model the experimental selection requirements, the hadronic energy around the photon within the $R < 0.4$ cone is required to be less than $5\,\text{GeV}$. The effect due to the choice of theory scales is obtained by independently varying μ_R, μ_F, μ_f by the factors 0.5 and 2.0. The uncertainty in the predictions due to the choice of PDF is determined from the 40 (52) component error sets of CTEQ6M (CT10) and evaluated using the master equations as given by the 'modified tolerance method' recommended in Ref. [41]. Figure 6 shows the ratios of the measured triple-differential cross section to theoretical predictions. The determination of the photon signal purity contributes the main systematic uncertainty affecting this measurement. The central values of the cross section, the statistical uncertainty, and the total systematic uncertainty are summarized in Tables 2 and 3. The predictions from SHERPA and JETPHOX are consistent with data, except for cases of photons measured in the largest η and p_T regions.

Figure 7 shows the ratios of cross sections with different angular orientations between the photon and the leading jet. An earlier study performed by the D0 experiment at the Tevatron [21] restricted the photon to $|\eta^\gamma| < 1.0$, while allowing the jet to be either in the central ($|\eta^{\text{jet}}| < 0.8$) or forward ($1.5 < |\eta^{\text{jet}}| < 2.5$) region. In this study, we consider $|\eta^\gamma| < 0.9$ and $|\eta^{\text{jet}}| < 1.5$ or $1.5 < |\eta^{\text{jet}}| < 2.5$. The advantage of measuring the ratios of cross sections is that uncertainties in the integrated luminosity and reconstruction efficiencies largely cancel.

In conclusion, events with at least one photon and one jet have been studied with a data sample corresponding to an integrated luminosity of $2.14\,\text{fb}^{-1}$ collected in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$. The cross section is measured as a function of the transverse momentum of the photon for various configurations of the leading photon and the leading jet. These measurements are used to determine eight ratios of the triple-differential cross section $\mathrm{d}^3\sigma/(\mathrm{d}p_T^\gamma \, \mathrm{d}\eta^\gamma \, \mathrm{d}\eta^{\text{jet}})$, providing measures of the relative cross sections for photon+jets production in different pseudorapidity regions and, thus, over a wide range of parton momentum fraction. Comparisons of the data to theoretical predictions from SHERPA and JETPHOX are also presented. Although predictions from SHERPA are observed to be lower than those from JETPHOX, the measured cross sections are found to be consistent with both MC predictions within systematic uncertainties over most of the measured kinematic regions. The NLO predictions in QCD and tree-level predictions of SHERPA both fail to describe the data for photons in the highest η and p_T regions within expected variances of either theoretical scale or parton distribution functions.

Table 2: The triple-differential cross sections $\mathrm{d}^3\sigma/(\mathrm{d}p_\mathrm{T}^\gamma\,\mathrm{d}\eta^\gamma\,\mathrm{d}\eta^\mathrm{jet})$ for photons located in the central region with statistical and systematic uncertainties, compared to predictions from JETPHOX and SHERPA. A 2.2% luminosity uncertainty is included in the systematic uncertainty [42]. The final two columns show the ratio of CMS data to JETPHOX (D/J) and SHERPA (D/S), respectively.

p_T^γ	Cross section (pb/GeV)			Ratio	
(GeV)	DATA	JETPHOX	SHERPA	D/J	D/S
$\lvert\eta^\gamma\rvert < 0.9$ and $\lvert\eta^\mathrm{jet}\rvert < 1.5$					
40–45	27.9±1.0±1.8	24.9	24.5	1.12±0.08	1.14±0.08
45–50	20.1±1.0±1.2	18.3	16.0	1.10±0.08	1.26±0.10
50–60	10.70±0.40±0.75	10.8	9.41	0.99±0.08	1.14±0.09
60–70	5.22±0.16±0.35	5.53	4.71	0.94±0.07	1.11±0.08
70–85	2.62±0.09±0.20	2.61	2.26	1.00±0.08	1.16±0.10
85–100	1.14±0.01±0.06	1.14	1.04	1.00±0.06	1.09±0.06
100–145	0.358±0.003±0.020	0.344	0.303	1.04±0.06	1.18±0.07
145–300	0.0320±0.0002±0.0017	0.0302	0.0290	1.06±0.06	1.10±0.06
$\lvert\eta^\gamma\rvert < 0.9$ and $1.5 < \lvert\eta^\mathrm{jet}\rvert < 2.5$					
40–45	11.2±1.0±1.1	12.2	11.6	0.92±0.12	0.97±0.13
45–50	8.59±0.82±1.04	8.52	7.94	1.01±0.16	1.08±0.17
50–60	4.76±0.36±0.43	5.02	4.36	0.95±0.11	1.09±0.13
60–70	2.19±0.14±0.20	2.29	2.17	0.96±0.11	1.01±0.11
70–85	0.998±0.061±0.074	1.04	1.02	0.96±0.09	0.97±0.09
85–100	0.454±0.009±0.027	0.429	0.455	1.06±0.07	1.00±0.06
100–145	0.134±0.002±0.008	0.126	0.116	1.06±0.06	1.15±0.07
145–300	0.0095±0.0001±0.0005	0.0091	0.0104	1.04±0.06	0.91±0.05
$0.9 < \lvert\eta^\gamma\rvert < 1.4442$ and $\lvert\eta^\mathrm{jet}\rvert < 1.5$					
40–45	22.4±1.4±1.9	22.8	21.3	0.98±0.10	1.05±0.11
45–50	19.6±1.0±1.3	16.4	14.4	1.19±0.10	1.36±0.11
50–60	9.32±0.50±0.76	9.82	8.32	0.95±0.09	1.12±0.11
60–70	4.57±0.20±0.58	4.99	4.32	0.92±0.12	1.06±0.14
70–85	2.32±0.10±0.16	2.33	1.99	1.00±0.08	1.17±0.10
85–100	1.06±0.01±0.06	1.03	1.01	1.03±0.06	1.05±0.06
100–145	0.331±0.004±0.018	0.322	0.285	1.03±0.06	1.16±0.07
145–300	0.0283±0.0003±0.0015	0.0298	0.0291	0.95±0.05	0.97±0.05
$0.9 < \lvert\eta^\gamma\rvert < 1.4442$ and $1.5 < \lvert\eta^\mathrm{jet}\rvert < 2.5$					
40–45	17.3±1.3±1.8	14.1	12.2	1.22±0.15	1.42±0.18
45–50	8.1±1.5±1.4	9.62	8.23	0.84±0.21	0.98±0.25
50–60	4.54±0.61±0.66	5.77	5.05	0.79±0.16	0.90±0.18
60–70	2.83±0.18±0.22	2.82	2.27	1.00±0.10	1.25±0.13
70–85	1.18±0.09±0.09	1.33	1.15	0.89±0.10	1.03±0.11
85–100	0.563±0.013±0.034	0.541	0.503	1.04±0.07	1.12±0.07
100–145	0.167±0.003±0.010	0.161	0.151	1.04±0.06	1.11±0.07
145–300	0.0121±0.0002±0.0007	0.0115	0.0127	1.05±0.06	0.96±0.05

Table 3: The triple-differential cross sections $d^3\sigma/(dp_T^\gamma d\eta^\gamma d\eta^{\text{jet}})$ for photons located in forward region with statistical and systematic uncertainties, compared to predictions from JETPHOX and SHERPA. A 2.2% luminosity uncertainty is included in the systematic uncertainty. The final two columns show the ratio of CMS data to JETPHOX (D/J) and SHERPA (D/S), respectively.

p_T^γ	Cross section (pb/GeV)			Ratio	
(GeV)	DATA	JETPHOX	SHERPA	D/J	D/S
1.556 < $|\eta^\gamma|$ < 2.1 and $|\eta^{\text{jet}}|$ < 1.5					
40–45	21.2±2.0±1.9	19.8	18.1	1.07±0.14	1.17±0.15
45–50	14.6±1.4±2.0	14.0	12.1	1.04±0.17	1.21±0.20
50–60	9.82±0.67±0.92	8.38	6.89	1.17±0.14	1.43±0.17
60–70	4.23±0.26±0.39	4.10	3.51	1.03±0.11	1.20±0.13
70–85	2.04±0.11±0.24	2.02	1.77	1.01±0.13	1.15±0.15
85–100	0.928±0.019±0.058	0.868	0.842	1.07±0.07	1.10±0.07
100–145	0.276±0.005±0.017	0.267	0.239	1.04±0.07	1.16±0.08
145–300	0.0221±0.0003±0.0016	0.0236	0.0223	0.94±0.07	0.99±0.07
1.556 < $|\eta^\gamma|$ < 2.1 and 1.5 < $|\eta^{\text{jet}}|$ < 2.5					
40–45	22.3±1.4±1.8	15.8	14.0	1.41±0.14	1.60±0.16
45–50	9.1±1.4±1.1	10.9	9.66	0.83±0.17	0.94±0.19
50–60	6.92±0.68±0.84	6.65	5.39	1.04±0.16	1.28±0.20
60–70	3.13±0.21±0.42	3.15	2.92	0.99±0.15	1.07±0.16
70–85	1.63±0.11±0.25	1.50	1.26	1.09±0.18	1.29±0.22
85–100	0.694±0.017±0.055	0.643	0.596	1.08±0.09	1.16±0.10
100–145	0.202±0.004±0.015	0.183	0.162	1.10±0.08	1.25±0.10
145–300	0.0129±0.0002±0.0008	0.0135	0.0113	0.96±0.06	1.14±0.08
2.1 < $|\eta^\gamma|$ < 2.5 and $|\eta^{\text{jet}}|$ < 1.5					
40–45	14.5±3.4±1.6	17.1	14.5	0.85±0.22	1.00±0.26
45–50	13.6±2.0±1.3	12.0	9.77	1.13±0.20	1.39±0.25
50–60	4.72±0.76±1.19	7.17	5.71	0.66±0.20	0.83±0.25
60–85	1.78±0.16±0.24	2.42	2.05	0.74±0.12	0.87±0.14
85–100	0.607±0.031±0.044	0.713	0.641	0.85±0.08	0.95±0.08
100–145	0.174±0.008±0.015	0.206	0.174	0.84±0.08	1.00±0.10
145–300	0.0082±0.0004±0.0006	0.0145	0.0129	0.56±0.05	0.63±0.06
2.1 < $|\eta^\gamma|$ < 2.5 and 1.5 < $|\eta^{\text{jet}}|$ < 2.5					
40–45	13.2±4.2±1.4	16.2	14.4	0.81±0.27	0.92±0.31
45–50	9.9±4.0±3.7	11.4	9.51	0.87±0.48	1.04±0.57
50–60	5.6±1.0±1.0	6.75	5.36	0.83±0.22	1.04±0.27
60–85	1.87±0.18±0.23	2.29	1.88	0.82±0.13	0.99±0.15
85–100	0.607±0.029±0.051	0.628	0.593	0.97±0.09	1.02±0.10
100–145	0.148±0.006±0.011	0.160	0.161	0.92±0.08	0.92±0.08
145–300	0.0060±0.0003±0.0004	0.0094	0.0088	0.64±0.06	0.68±0.06
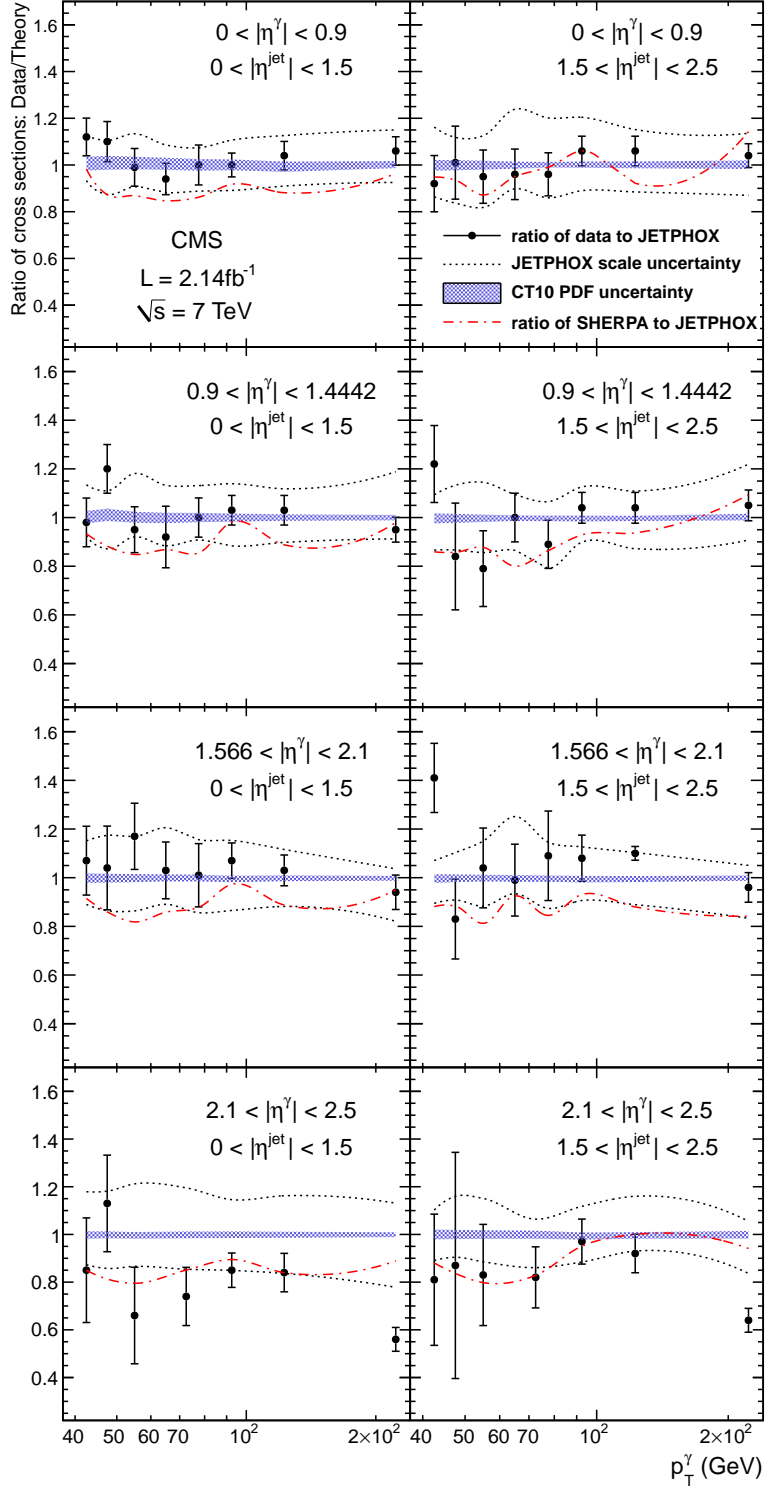
Figure 6: The ratios of the measured triple-differential cross sections to the NLO QCD prediction using JETPHOX with the CT10 PDF set and scales $\mu_{R,F,f} = \frac{1}{2}p_T^\gamma$. The vertical lines on the points show the statistical and systematic uncertainties added in quadrature. The two dotted lines represent the effect of varying the theoretical scales as described in the text. The shaded bands correspond to the CT10 PDF uncertainty. The dash-dotted lines show the ratios of the SHERPA predictions to JETPHOX.

Figure 7: Ratios of the triple-differential cross sections for the various jet orientations with respect to the photon. The error bars on the theoretical predictions correspond to statistical and systematic uncertainties.

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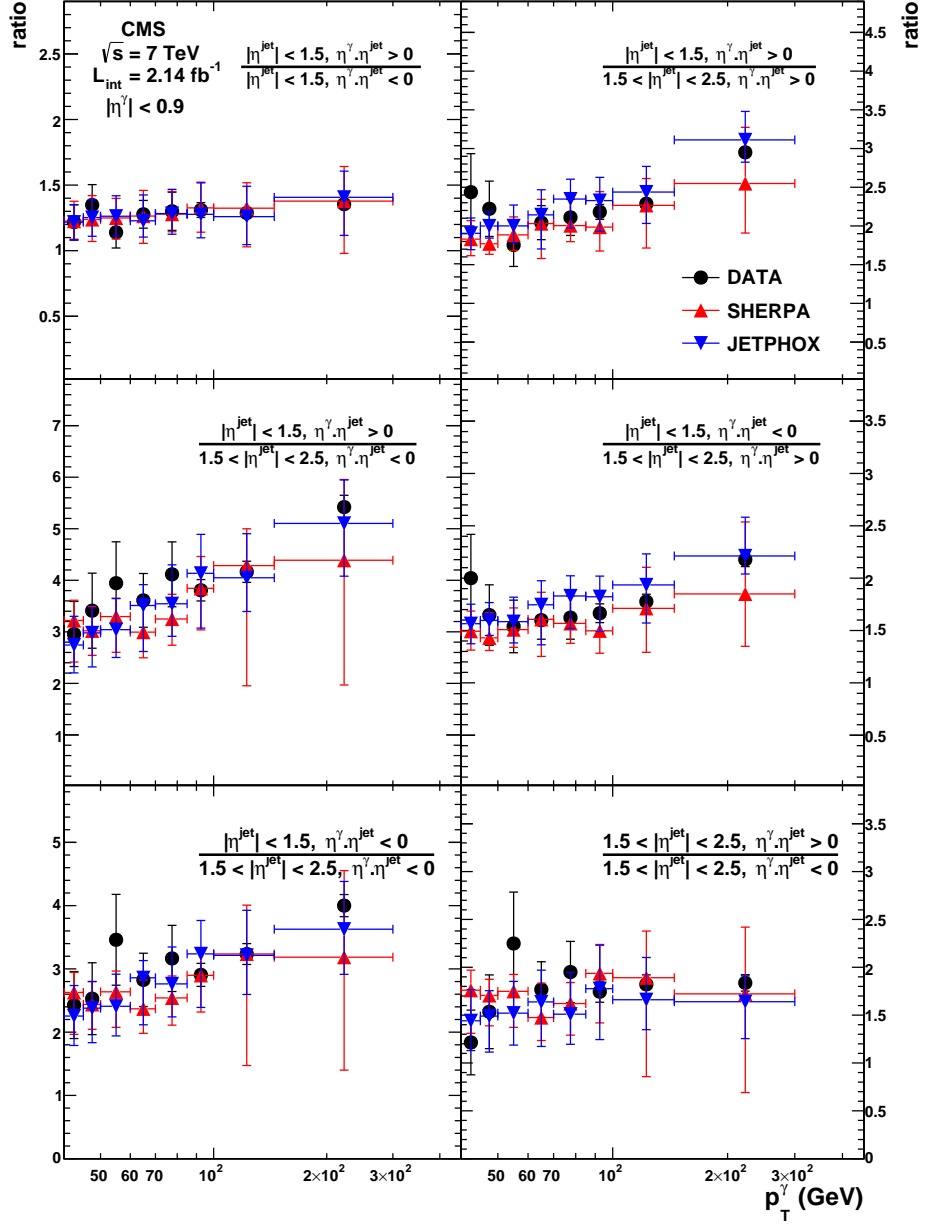
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