

# Measurement of the differential cross section for isolated prompt photon production in $pp$ collisions at 7 TeV

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A measurement of the differential cross section for the inclusive production of isolated prompt photons in proton-proton collisions at a center-of-mass energy of 7 TeV is presented. The data sample corresponds to an integrated luminosity of  $36 \text{ pb}^{-1}$  recorded by the CMS detector at the LHC. The measurement covers the pseudorapidity range  $|\eta| < 2.5$  and the transverse energy range  $25 < E_T < 400 \text{ GeV}$ , corresponding to the kinematic region  $0.007 < x_T < 0.114$ . Photon candidates are identified with two complementary methods, one based on photon conversions in the silicon tracker and the other on isolated energy deposits in the electromagnetic calorimeter. The measured cross section is presented as a function of  $E_T$  in four pseudorapidity regions. The next-to-leading-order perturbative QCD calculations are consistent with the measured cross section.

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## I. INTRODUCTION

The measurement of isolated prompt photon production in proton-proton collisions provides a test of perturbative quantum chromodynamics (pQCD) [1–4]. The cross section measured in  $pp$  collisions also serves as a reference for similar measurements in heavy ion collision data [5]. In addition, isolated prompt photon production represents a background to searches for new phenomena involving photons in the final state, including Higgs boson production [6]. At the Large Hadron Collider (LHC) [7], a significant increase of center-of-mass energy with respect to previous collider experiments [8–13] allows for the exploration of new kinematic regions in the hard scattering processes in hadron-hadron collisions. In high-energy  $pp$  collisions, single prompt photons are produced directly in  $qg$  Compton scattering and  $q\bar{q}$  annihilation, and in the fragmentation of partons with large transverse momentum. Photons are also produced in the decay of hadrons, mainly  $\pi^0$  and  $\eta$  mesons, which can mimic prompt production. This background contamination can be estimated from data using photon identification characteristics, such as electromagnetic shower profile, extra energy surrounding the photon candidate (called “isolation sum” in this article), or kinematic variables of converted photons.

Both the CMS and ATLAS Collaborations have performed measurements of the differential cross section of isolated prompt photon production with data collected in 2010 [14–16]. The CMS Collaboration reported a measurement for photons with  $21 < E_T < 300 \text{ GeV}$  and

$|\eta| < 1.45$  with an integrated luminosity of  $2.9 \text{ pb}^{-1}$  and exploited the electromagnetic shower profile to estimate the background contribution [14]. Here,  $E_T = E \sin\theta$  and  $\eta = -\ln[\tan(\theta/2)]$ , where  $E$  is the photon energy and  $\theta$  is the polar angle of the photon momentum measured with respect to the counterclockwise beam direction. The measurement reported in this paper extends the previous CMS measurement to wider ranges of transverse energy ( $E_T = 25\text{--}400 \text{ GeV}$ ) and pseudorapidity ( $|\eta| < 2.5$ ), corresponding to the kinematic region  $0.007 < x_T < 0.114$ , where  $x_T = 2E_T/\sqrt{s}$ .

The background contribution to isolated photons is estimated with two methods. The “photon conversion method” uses the variable  $E_T/p_T$ , the ratio of the transverse energy measured in the electromagnetic calorimeter to the transverse momentum measured in the tracker for converted photons. The “isolation method” uses the variable ISO, the isolation sum measured in the tracker and the electromagnetic and hadronic calorimeters. The weighted average of the differential cross sections measured with the two methods is reported as a function of  $E_T$  in four intervals of pseudorapidity:  $|\eta| < 0.9$ ,  $0.9 < |\eta| < 1.44$ ,  $1.57 < |\eta| < 2.1$ , and  $2.1 < |\eta| < 2.5$ . The size of the converted-photon sample is limited due to the probability for a photon to convert before reaching the CMS electromagnetic calorimeter and the relatively small conversion reconstruction efficiency. On the other hand, the signal purity obtained with the photon conversion method is very high at low photon  $E_T$ , while the isolation method is less effective at separating signal from background at low photon  $E_T$ . A combination of the cross-section measurements minimizes statistical and systematic uncertainties and yields better overall performance.

This paper is organized as follows. Section II describes the relevant CMS detector components. Sections III, IV, and V list the data and simulation samples, the event

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selections, and the photon identification criteria that are applied in the analysis, respectively. Sections VI and VII detail the methods used to extract the signal photon yield and the estimation of signal efficiency. Section VIII describes the sources of systematic uncertainties on the cross-section measurement and Sec. IX presents the measured differential cross section. Section X discusses the comparison of experimental measurements with next-to-leading-order (NLO) pQCD calculations.

## II. THE CMS DETECTOR

The CMS detector is a general-purpose detector built to explore physics at the TeV scale and is described in detail in Ref. [17]. A brief description of the main components that are relevant to the present analysis is provided here.

The electromagnetic calorimeter (ECAL) consists of nearly 76 000 lead tungstate crystals that provide coverage in pseudorapidity  $|\eta| < 1.479$  in a cylindrical barrel region and  $1.479 < |\eta| < 3.0$  in two endcap regions. The crystals are  $25.8 X_0$  long in the barrel and  $24.7 X_0$  long in the endcaps, where  $X_0$  denotes the radiation length. In the barrel region, the transverse distance from the interaction point to the front face of crystals, with a size of  $22 \times 22 \text{ mm}^2$ , is 1.29 m, corresponding to a granularity of  $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$ . In the endcap region, the front face of the crystals is  $28.62 \times 28.62 \text{ mm}^2$  and the distance from the interaction point to the front face is 3.15 m. Throughout this paper,  $\phi$  is the azimuthal angle measured in radians in the plane transverse to the beam, from the direction pointing to the center of the LHC ring toward the upward direction. A preshower detector consisting of two planes of silicon strip sensors that are interleaved with a total of  $3 X_0$  of lead ( $2 X_0$  in the front and  $1 X_0$  after the first silicon plane) is located in front of the ECAL endcaps, covering  $1.653 < |\eta| < 2.6$ . Avalanche photodiodes are used to detect the scintillation light in the barrel region, while vacuum phototriodes are used in the endcap region. The ECAL has an ultimate energy resolution better than 0.5% for unconverted photons with  $E_T$  above 100 GeV [18]. In 2010 collision data, for  $E_T > 20$  GeV, this resolution is already better than 1% in the barrel [19].

The ECAL is surrounded by a brass/scintillator sampling hadronic calorimeter (HCAL) with a coverage up to  $|\eta| < 3$ . The scintillation light is converted by wavelength-shifting fibres that are read out with hybrid photodiodes. The HCAL is subdivided into towers with a segmentation of  $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$  at central rapidity ( $|\eta| < 1.74$ ) and  $0.09 \times 0.174$  to  $0.35 \times 0.174$  at forward rapidity ( $1.74 < |\eta| < 3$ ).

A silicon tracker is located inside the ECAL. The tracker consists of two main detectors: three barrel layers and two endcap disks per side of silicon pixel detectors, covering the region from 4 cm to 15 cm in radius, and within 49 cm on either side of the nominal collision point along the LHC

beam axis; ten barrel layers and 12 endcap disks per side of silicon strip detectors, covering the region from 25 to 110 cm in radius, and within 280 cm on either side of the nominal collision point along the LHC beam axis. The tracker acceptance extends up to a pseudorapidity of  $|\eta| = 2.5$ . The tracker, ECAL, and HCAL are immersed in a 3.8 T axial magnetic field, which enables the measurement of charged particle momenta over more than 4 orders of magnitude, from less than 100 MeV to more than 1 TeV, by reconstructing their trajectories as they traverse the inner tracking system. With the silicon tracker, the transverse momentum resolution for high-momentum tracks (100 GeV) is around 1–2% up to  $|\eta| = 1.6$ ; beyond this  $\eta$  value it degrades due to the reduced lever arm.

## III. DATA AND SIMULATION SAMPLES

The data sample used in this analysis corresponds to a total integrated luminosity of  $(35.9 \pm 1.4) \text{ pb}^{-1}$  [20] recorded in 2010 with the CMS detector. The simulated samples were generated with PYTHIA version 6.4.20 [21], the CTEQ6L [22] parton distribution functions (PDFs), and the Z2 parameter set [23]. Generated events are passed through the full GEANT4 [24] simulation of the CMS detector and are then reconstructed using the same algorithm as for the data. For the simulation of the signal and background, two sets of samples generated with PYTHIA are used: one containing direct photons produced in  $q\bar{q}$  Compton scattering and  $q\bar{q}$  annihilation, and a second one generated with all  $2 \rightarrow 2$  QCD processes that include photons from initial- and final-state radiation (ISR and FSR), photons from parton showers, and photons from neutral meson decays. Isolated direct photons, ISR and FSR photons, and photons from parton showers are treated as signal, while all other photons are considered to be background. In the simulation, a signal photon must have an isolation sum of less than 5 GeV. The isolation sum is calculated as the sum of the  $E_T$  of all charged and neutral particles, after removing the photon, within a cone of  $R \equiv \sqrt{(\eta - \eta^\gamma)^2 + (\phi - \phi^\gamma)^2} = 0.4$ ,  $\eta^\gamma$  and  $\phi^\gamma$  being the coordinates of the photon. The 5 GeV threshold at the generator level was chosen to ensure greater than 95% efficiency for direct photons and minimize dependence of the efficiency on the variation of underlying event models.

## IV. EVENT SELECTION

Events with high- $E_T$  photons are selected online by a two-level trigger system. At the first level, the  $E_T$  sum of two neighboring ECAL trigger towers, a trigger tower being a  $5 \times 5$  crystal matrix, is required to be above 8 GeV. The events that satisfy this selection are passed on to the second trigger level, the High Level Trigger (HLT). In the HLT, the energy measured in the crystals is clustered using the same clustering algorithm as for the offline photon reconstruction [25,26]. The events having at least one reconstructed electromagnetic cluster with an  $E_T$

TABLE I. Effective integrated luminosity for each photon  $E_T$  range.

$E_T$ (GeV)	Integrated luminosity ( $\text{pb}^{-1}$ )
25–35	$2.4 \pm 0.1$
35–55	$8.2 \pm 0.3$
55–80	$17.6 \pm 0.7$
>80	$35.9 \pm 1.4$

above a programmable threshold ( $E_T^{\text{HLT}}$ ) are accepted. In this analysis,  $E_T^{\text{HLT}}$  of 20, 30, 50, or 70 GeV are used, depending on the run period. Owing to the increase of the LHC instantaneous luminosity and the limited available trigger bandwidth, different rate-reduction factors were applied to the triggers at 20, 30, and 50 GeV. Only data collected without the application of rate-reduction factors are used, therefore the data samples for events with photons with  $E_T < 80$  GeV correspond to smaller effective integrated luminosities, as listed in Table I. Events not coming from  $pp$  collisions, such as those from beam-gas interactions or beam scraping in the transport system near the interaction point, which produce considerable activity in the pixel detector, are removed by requiring a good primary interaction vertex to be reconstructed. Such vertices must have at least three tracks and must be within 24 cm (2 cm) of the nominal center of the detector along (perpendicular to) the beam axis. The efficiency for reconstructing a primary interaction vertex is greater than 99.5% [27]. In addition, at least 25% of the reconstructed tracks in the event are required to satisfy the quality requirements given in Ref. [28].

## V. PHOTON RECONSTRUCTION AND IDENTIFICATION

Photon showers deposit their energy in several crystals in the ECAL. The presence of material in front of the calorimeter may result in photon conversions. Because of the strong magnetic field, the energy deposited in ECAL by converted photons can be spread in  $\phi$ . The energy is therefore clustered at the electromagnetic calorimeter level by building a cluster that is extended in  $\phi$ , thus minimizing the cluster containment variations due to electromagnetic interactions in the tracker material. The threshold for crystals to be included in the cluster is approximately 1 GeV in transverse energy. In the barrel region of ECAL, clusters are formed from the energy sum in a rectangular strip of 5 crystals along  $\eta$  and up to 35 crystals in  $\phi$ . In the endcap region of ECAL, clusters comprise one or more contiguous arrays of  $5 \times 5$  crystals. Endcap cluster positions are extrapolated to the preshower where preshower clusters are built. The total endcap cluster energy is the sum of cluster energies in the endcap crystals and preshower.

Energy corrections are applied to the clusters to take into account the interactions with the material in front of ECAL and shower containment; the corrections are parametrized

as a function of cluster size,  $E_T$ , and  $\eta$ , and are on average 1% [19]. The corrections include the following steps:

- (i) A compensation of the  $\eta$  dependence of the lateral energy leakage since the axes of the truncated-pyramid shaped barrel crystals make an angle of  $3^\circ$  with respect to the vector from the nominal interaction vertex, in both the  $\eta$  and  $\phi$  projections. This correction is applied only to barrel clusters.
- (ii) A correction to compensate for interactions with material in front of ECAL. Since these interactions spread energy mainly in the  $\phi$  direction, this loss can be parametrized as a function of the ratio of the cluster size in  $\phi$  to its size in  $\eta$ .
- (iii) A residual correction that is a function of the cluster  $E_T$  and  $\eta$ , to compensate for variations along  $\eta$  in the amount of material and the dependence on  $E_T$  of the bremsstrahlung and conversion processes.

A photon candidate is built from the energy-corrected cluster, and the photon momentum is calculated with respect to the location of the reconstructed primary interaction vertex. If multiple vertices are reconstructed, the vertex with the largest scalar sum of the transverse momenta of the associated tracks ( $\Sigma p_T$ ) is selected.

The timing of the ECAL signals is required to be consistent with that of collision products [29]. Topological selection criteria are used to suppress direct interactions in the ECAL Avalanche photodiodes [30]. The residual contamination has an effect smaller than 0.2% on the measured cross section over the entire  $E_T$  range considered. Contamination from noncollision backgrounds is estimated to be negligible [31].

Photons are required to have a transverse energy  $E_T > 25$  GeV since above 25 GeV the trigger efficiency is approximately 100% for both the barrel and the endcap photons (Sec. VII). The measurements are performed in four photon pseudorapidity intervals:  $|\eta| < 0.9$  (central barrel),  $0.9 < |\eta| < 1.44$  (outer barrel),  $1.57 < |\eta| < 2.1$  (low- $\eta$  endcaps), and  $2.1 < |\eta| < 2.5$  (high- $\eta$  endcaps). This definition excludes the transition region between the barrel and the endcaps ( $1.44 < |\eta| < 1.57$ ) and the region outside of the tracker coverage ( $|\eta| > 2.5$ ). The central barrel has  $1\text{--}1.5 X_0$  less material in front of the ECAL than the outer barrel, while the low- $\eta$  endcaps have about  $0.5 X_0$  more material than the high- $\eta$  endcaps, which motivates the subdivision of the barrel and the endcaps.

As mentioned in Sec. I, the major source of background comes from the decays of hadrons (such as  $\pi^0 \rightarrow \gamma\gamma$ ) and nonisolated photons produced by the fragmentation of quarks or gluons. The photons from hadron decays tend to produce a wider shower profile since hadrons are massive and give a nonzero opening angle between the photon daughters. In addition, both the decay photons and nonisolated fragmentation photons are accompanied by a number of neutral and charged hadrons that deposit energy in the ECAL and HCAL and leave multiple tracks in the

tracking system. Based on these differences between signal and background, several photon identification variables are used in this analysis:

- (i)  $H/E$ : the ratio of the energy deposited in the HCAL to the energy deposited in the ECAL inside a cone of  $R < 0.15$  centered on the reconstructed photon direction.
- (ii)  $\sigma_{\eta\eta}$ : a modified second moment of the electromagnetic energy cluster about its mean  $\eta$  position. This quantity is computed with logarithmic weights and is defined as

$$\sigma_{\eta\eta}^2 = \frac{\sum_i^{5 \times 5} w_i (\eta_i - \bar{\eta}_{5 \times 5})^2}{\sum_i^{5 \times 5} w_i},$$

$$w_i = \max\left(0, 4.7 + \ln \frac{E_i}{E_{5 \times 5}}\right),$$

where  $E_i$  and  $\eta_i$  are the energy and pseudorapidity of the  $i$ th crystal within a matrix of  $5 \times 5$  crystals centered on the cluster seed and  $E_{5 \times 5}$  and  $\bar{\eta}_{5 \times 5}$  are the energy sum of the matrix and the weighted average of the pseudorapidities of the same group.

- (iii)  $\text{Iso}_{\text{TRK}}$ : the sum of the transverse momenta ( $p_T$ ) of all tracks in a hollow cone  $0.04 < R < 0.4$  drawn around the photon direction. The tracks pointing to a rectangular strip of width  $|\Delta\eta| = 0.015$  centered around the photon position are removed from the sum in order to recover possible photon conversions. In addition, tracks with a transverse (longitudinal) impact parameter above 0.1 (0.2) cm are not included.
- (iv)  $\text{Iso}_{\text{ECAL}}$ : the sum of the  $E_T$  in the individual ECAL crystals located in a hollow cone, with an inner radius of 3.5 crystals and an outer radius of  $R = 0.4$ , drawn around the ECAL cluster. The  $E_T$  deposited in a strip of width  $|\Delta\eta| = 2.5$  crystals centered on the photon position is subtracted from the sum to exclude possible photon conversions.
- (v)  $\text{Iso}_{\text{HCAL}}$ : the sum of the  $E_T$  in the HCAL towers in a hollow cone  $0.15 < R < 0.4$  centered on the ECAL cluster.

The signal photons are expected to have smaller values of  $H/E$ ,  $\sigma_{\eta\eta}$ ,  $\text{Iso}_{\text{TRK}}$ ,  $\text{Iso}_{\text{ECAL}}$ , and  $\text{Iso}_{\text{HCAL}}$  compared to the background photons. The selection criteria for the two methods are slightly different and are described in detail in Sec. VI.

## VI. EXTRACTION OF THE PROMPT PHOTON YIELD

The following subsections describe the details of extracting the photon yield ( $N^\gamma$ ) from the two variables (i)  $E_T/p_T$ , the ratio of the  $E_T$  measured in the ECAL to the  $p_T$  measured in the tracker for converted photons, and (ii) ISO, which is  $\text{Iso}_{\text{TRK}} + \text{Iso}_{\text{ECAL}} + \text{Iso}_{\text{HCAL}}$ .

The photon conversion method relies on the difference in the shape of the  $E_T/p_T$  distributions between the signal and background. For an isolated prompt photon, the sum of the  $p_T$  of the conversion tracks is on average the same as the energy deposited in the ECAL, and thus the  $E_T/p_T$  distribution peaks around one. For photons produced from the decay of  $\pi^0$  and  $\eta$  in jets, the  $p_T$  measured from the conversion electron pairs does not account for the full amount of energy collected in the calorimeter and the  $E_T/p_T$  is, on average, above one.

The isolation method relies on the difference in the shape of the ISO distributions. For a photon signal, only underlying event, pile-up, and detector noise may contribute to the ISO; the ISO distribution falls off quickly at around 5 GeV. For a photon background from neutral hadron decays, the energy of particles that are produced together with  $\pi^0$  or  $\eta$  from the parton fragmentation adds a significant amount of activity around the decay photon and widens the ISO distribution.

In each method, one of these variables is chosen as a discriminating observable. A set of preselection criteria is applied to increase the signal fraction of the photon sample; the signal-region selection criteria are listed in Table II. The number of signal events  $N^\gamma$  is obtained by fitting the distribution of the discriminating observable as the sum of two components: signal and background.

TABLE II. Signal-region and sideband-region preselection criteria for the photon conversion and isolation methods.

Cut	Signal region	Sideband region
Photon conversion method		
$H/E$	$< 0.05$	$< 0.05$
$\text{Iso}_{\text{TRK}}$ (GeV)	$< (2.0 + 0.001E_T)$	$(2.0 + 0.001E_T) - (5.0 + 0.001E_T)$
$\text{Iso}_{\text{ECAL}}$ (GeV)	$< (4.2 + 0.003E_T)$	$< (4.2 + 0.003E_T)$
$\text{Iso}_{\text{HCAL}}$ (GeV)	$< (2.2 + 0.001E_T)$	$< (2.2 + 0.001E_T)$
barrel: $\sigma_{\eta\eta}$	$< 0.010$	0.010–0.015
endcap: $\sigma_{\eta\eta}$	$< 0.030$	0.030–0.045
Isolation method		
$H/E$	$< 0.05$	$< 0.05$
barrel: $\sigma_{\eta\eta}$	$< 0.010$	0.0110–0.0115
endcap: $\sigma_{\eta\eta}$	$< 0.028$	$> 0.038$



The shapes of the component distributions are taken from simulation and are validated by methods based on data.

### A. Photon conversion method

After applying the signal-region preselection criteria in Table II, converted photons are reconstructed by combining the information in the ECAL and the tracker. The ECAL clusters, built and corrected as described in Sec. V, are used as starting points for an inward conversion track search, using the  $E_T$  of subclusters as an initial guess for the electron or positron trajectory [25,32]. The innermost point of the resulting tracks is assumed to be close to the conversion point and used as seed for outward track search of the other arm of the conversion. The pattern recognition includes the average energy loss for electrons passing through the tracker material. Once all tracks have been found and the track collection cleaned with loose selection criteria, pairs of oppositely charged tracks belonging to the same cluster are considered as possible conversion candidates. A vertex fit imposing the condition that these tracks be parallel at the conversion vertex is required to converge with a  $\chi^2$  probability greater than  $5 \times 10^{-4}$ . The latter ensures that only good vertices are retained and random or ill-defined pairs are rejected. Furthermore, since the method is based on the matching between energy-momentum of the conversions, the requirement  $E_T/p_T < 3$  is applied.

In each  $E_T$  bin, the measured  $E_T/p_T$  distribution is fitted using a binned extended maximum likelihood method, with the likelihood defined as

$$-\ln L = (N_s + N_b) - \sum_{i=1}^n N_i \ln(N_s \mathcal{P}_s^i + N_b \mathcal{P}_b^i),$$

where  $N_s$  and  $N_b$  are the numbers of expected signal and background events,  $n$  is the number of bins,  $N_i$  is the number of observed photon candidates in the  $i^{\text{th}}$  bin, and  $\mathcal{P}_s^i$  and  $\mathcal{P}_b^i$  are the signal and background probability density functions integrated over the  $i^{\text{th}}$  bin.

Both the signal shape  $\mathcal{P}_s$  and the background shape  $\mathcal{P}_b$  are extracted from simulations. An alternate background shape is extracted from background-enriched data that are selected by defining a two-dimensional sideband region in the  $\sigma_{\eta\eta} - \text{Iso}_{\text{TRK}}$  plane according to the definitions given in Table II. In this sideband region, photon candidates satisfy loose but fail tight criteria on  $\sigma_{\eta\eta}$  and  $\text{Iso}_{\text{TRK}}$ ; the other requirements are the same as those for the signal region. The comparison between the  $E_T/p_T$  background distributions obtained from simulation and data gives a measure of the discrepancy between simulation and data and is used to quantify the systematic uncertainty related to the modelling of the background shape. More details are found in Sec. VIII A.

An example of the fit to data is shown in Fig. 1 and the photon yield  $N^\gamma$  for each  $E_T$  and  $\eta$  interval is listed in Table III. Because of the lack of converted-photon candidates at large  $E_T$ , photon conversion results are measured for  $E_T < 200$  GeV. Figure 2 shows the measured signal purity, defined as the estimated fraction of true prompt photons over all reconstructed photons that satisfy the selection criteria. The signal purity clearly increases with photon transverse energy, as expected from simulation studies.

### B. Isolation method

Photons are required to satisfy the signal-region preselection criteria listed in Table II. Background from electrons is suppressed by requiring the absence of a short track segment, built from either two or three hits in the silicon pixel detector, consistent with an electron track matching the observed location and energy of the photon candidate (pixel veto requirement). The signal and background component distributions are parametrized with analytic functions. For the signal component, a convolution of exponential and Gaussian functions is used:

$$S(x) = \exp(ax) \otimes \text{Gauss}(\mu, \sigma, x), \quad (1)$$

while for the background the threshold function is used:

$$B(x) = (1 - p_1(x - p_0))^{p_2} \times (1 - e^{p_3(x - p_0)}). \quad (2)$$

Here,  $x$  is the ISO variable. Other parametrizations give a much larger  $\chi^2$  and fail to describe the observed ISO distributions. Using these parametrizations, an unbinned extended maximum likelihood fit to the measured ISO distribution is performed for the region  $-1 < x < 20$  GeV, with the likelihood defined as

$$-\ln L = N_s + N_b - \sum_{i=1}^N \ln(N_s \mathcal{P}_s^i + N_b \mathcal{P}_b^i),$$

where  $N_s$  and  $N_b$  are the expected signal and background yields,  $N$  is the number of observed photon candidates, and  $\mathcal{P}_s^i$  and  $\mathcal{P}_b^i$  are the signal and background probability density functions evaluated with the ISO of photon candidate  $i$ . The signal and background probability density functions are obtained by normalizing the integrals of  $S(x)$  and  $B(x)$  to unity in the fit range, respectively:

$$\mathcal{P}_s^i = \frac{1}{\int_{-1}^{20} S(x) dx} S(x^i),$$

and

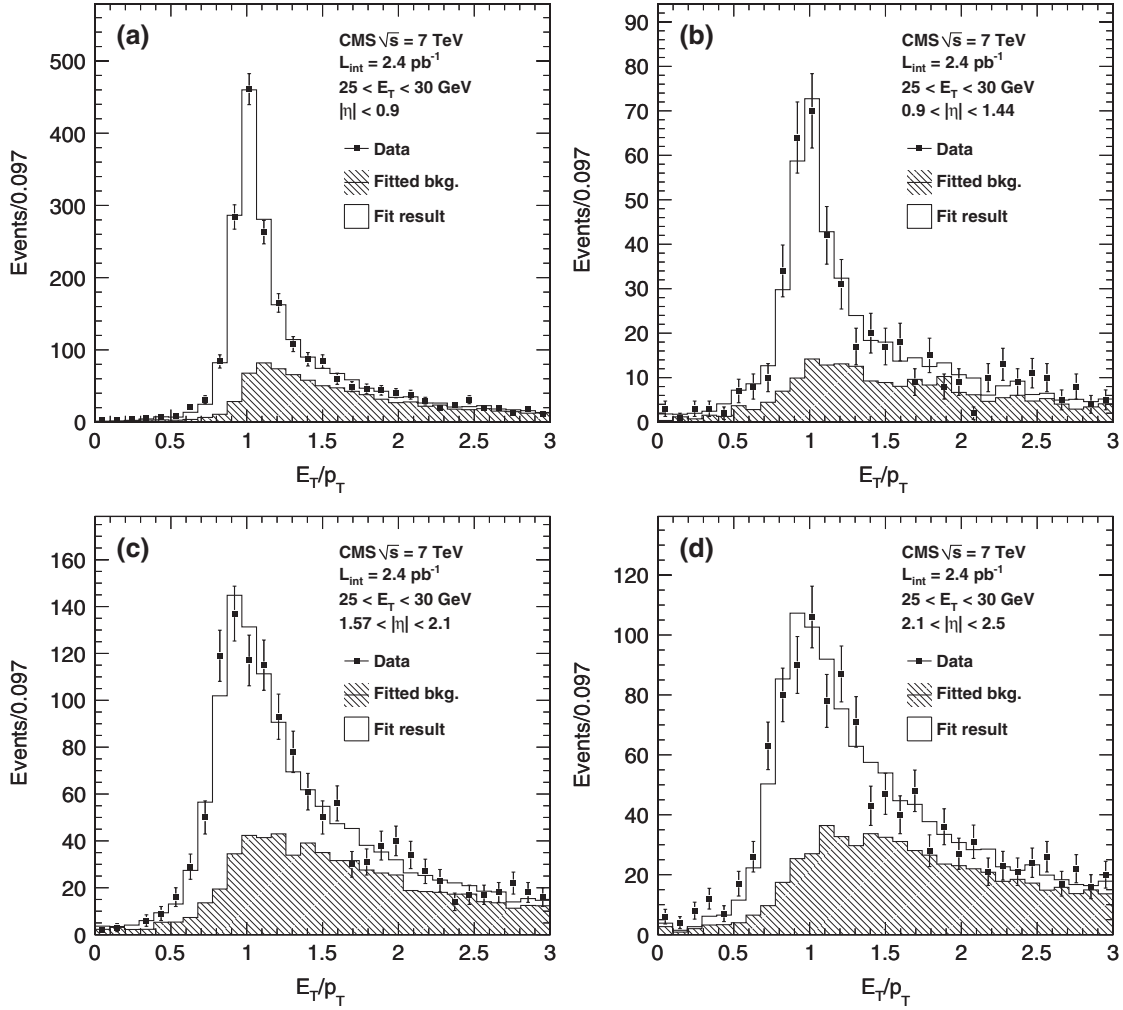


FIG. 1. Measured  $E_T/p_T$  distributions for converted-photon candidates with  $E_T = 25\text{--}30$  GeV, in the four  $\eta$  regions considered. The binned extended maximum likelihood fit result (open histogram) is overlaid in each plot. The fitted component from background is shown by hatched histograms.

TABLE III. Measured signal yield  $N^\gamma$  from the photon conversion method. The uncertainty on the yield is the statistical uncertainty from the extended maximum likelihood fit.

$E_T$ (GeV)	$ \eta  < 0.9$	$0.9 <  \eta  < 1.44$	$1.57 <  \eta  < 2.1$	$2.1 <  \eta  < 2.5$
25–30	$1254 \pm 44$	$275 \pm 26$	$661 \pm 43$	$577 \pm 40$
30–35	$648 \pm 31$	$157 \pm 26$	$280 \pm 31$	$298 \pm 29$
35–40	$1126 \pm 40$	$262 \pm 40$	$618 \pm 39$	$446 \pm 36$
40–45	$711 \pm 49$	$197 \pm 21$	$362 \pm 31$	$268 \pm 26$
45–50	$436 \pm 35$	$115 \pm 13$	$235 \pm 40$	$170 \pm 35$
50–55	$262 \pm 27$	$75 \pm 10$	$183 \pm 26$	$114 \pm 18$
55–60	$444 \pm 27$	$101 \pm 8$	$241 \pm 31$	$142 \pm 17$
60–65	$255 \pm 22$	$56 \pm 5$	$159 \pm 15$	$119 \pm 12$
65–70	$181 \pm 13$	$41 \pm 6$	$104 \pm 13$	$89 \pm 8$
70–80	$254 \pm 18$	$73 \pm 9$	$130 \pm 18$	$93 \pm 14$
80–100	$437 \pm 19$	$98 \pm 8$	$231 \pm 26$	$122 \pm 15$
100–120	$177 \pm 7$	$42 \pm 3$	$61 \pm 8$	$41 \pm 5$
120–200	$134 \pm 6$	$22 \pm 2$	$65 \pm 3$	$22 \pm 5$

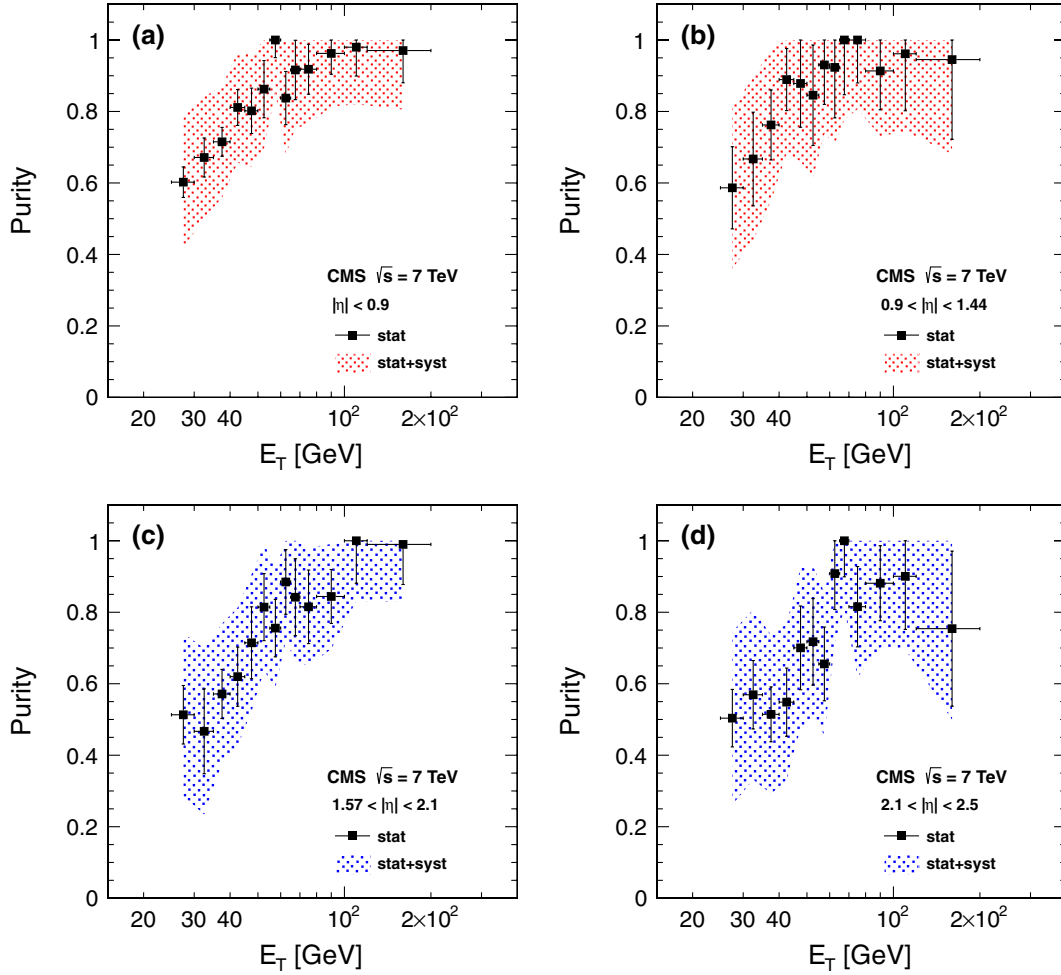


FIG. 2 (color online). Measured signal purity for  $0 < E_T/p_T < 3$  with the photon conversion method in the four  $\eta$  regions. The vertical error bars show the statistical uncertainties, while the shaded areas show the statistical and systematic uncertainties added in quadrature. Estimation of the systematic uncertainties is discussed in Sec. VIII.

$$\mathcal{P}_b^i = \frac{1}{\int_{-1}^{20} B(x) dx} B(x^i),$$

where  $x^i$  is the measured ISO of photon candidate  $i$ .

While fitting the observed ISO distributions in data, the values of the shape parameters in  $\mathcal{P}_s$  and  $\mathcal{P}_b$  are not fixed. The two signal shape parameters  $\mu$  and  $\sigma$  in Eq. (1) and two background shape parameters  $p_1$  and  $p_2$  in Eq. (2) are determined from the fit to data directly, while the exponential tail of the signal  $a$ , the background turn-on power  $p_3$ , and the background starting point  $p_0$  are constrained in the fit.

The constrained values of parameter  $a$  and parameters  $p_0$  and  $p_3$  are obtained first by fitting the simulated signal events with the parametrization in Eq. (1) and simulated background events with the parametrization in Eq. (2),

respectively. Then, the constrained values are further corrected with data-to-simulation scaling factors. A difference between data and simulation is observed due to the imperfect modelling of detector noise, the underlying event, pile-up, and the hadronization process.

To derive the scaling factor for the parameter  $a$ , low-bremsstrahlung electrons from  $Z^0 \rightarrow e^+e^-$  decays are selected as described in Ref. [26]. The amount of bremsstrahlung is obtained from the relative difference between the momentum measured at the last point ( $p_{\text{out}}$ ) on the electron track and the momentum measured at the origin ( $p_{\text{in}}$ ). Here, “low bremsstrahlung” means that the ratio  $(p_{\text{in}} - p_{\text{out}})/p_{\text{in}}$  is less than 0.15. A fit to the electron ISO distribution is performed using the parametrization in Eq. (1); the ratio of the value of  $a$  obtained from electron data to that from electron simulation is taken as the scaling factor for the parameter  $a$  of the photon signal shape.

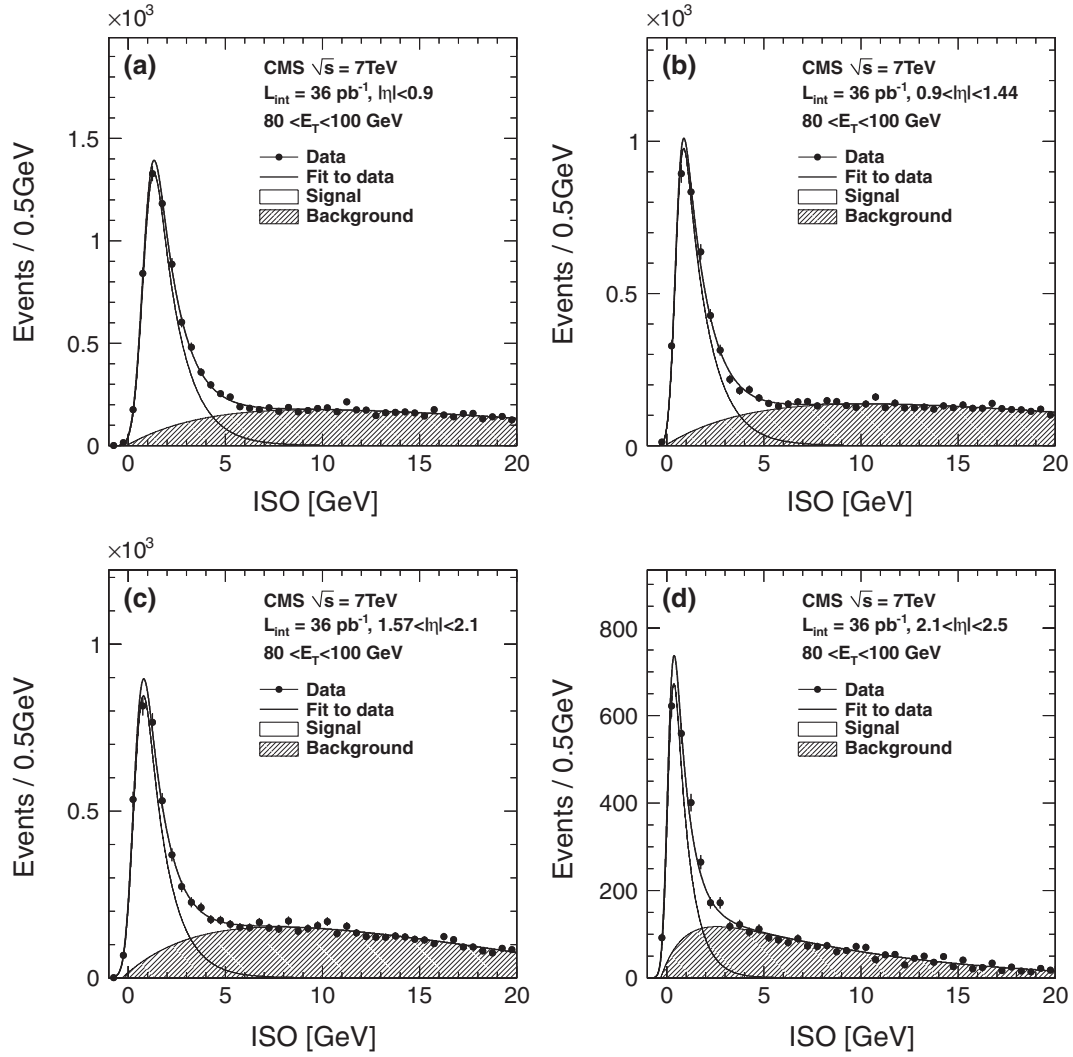


FIG. 3. Measured ISO distributions for candidates with  $E_T = 80\text{--}100$  GeV. The unbinned maximum likelihood fit result (solid line) is overlaid in each plot. The fitted signal and background components are also shown. Imperfections of the fitting model are included as part of the systematic uncertainties.

To derive the scaling factors for the parameters  $p_0$  and  $p_3$ , a background-enriched sample is selected with the sideband-region selection criteria listed in Table II; the contamination of signal in this sideband region is negligible. In this sideband region, photon candidates satisfy the loose but fail the tight criterion on  $\sigma_{\eta\eta}$ ; the other requirements are the same as those for the signal region. Then, fits to the sideband-region ISO distributions in the data and in the simulation, using the parametrization in Eq. (2), are performed to obtain the scaling factor.

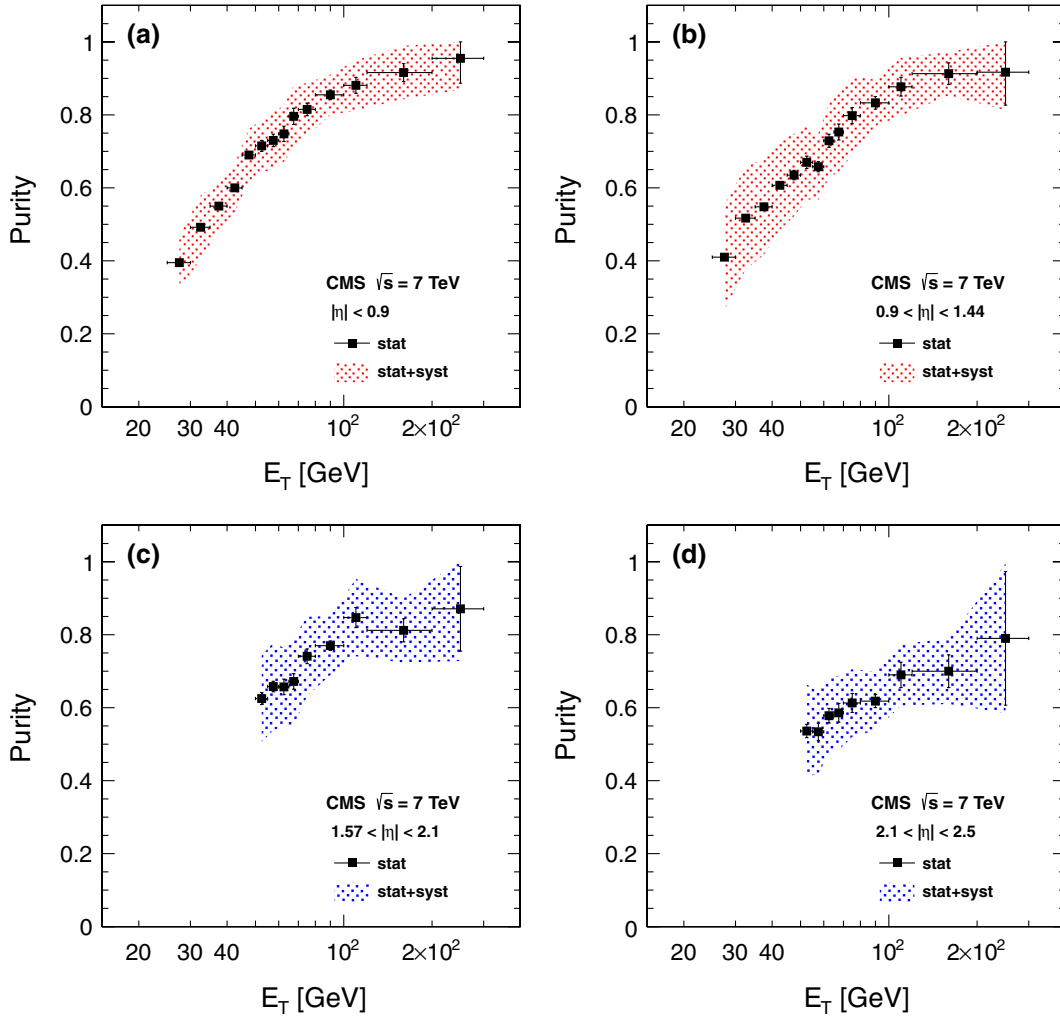
Figure 3 shows the result of the fit for photons with  $E_T = 80\text{--}100$  GeV in the four  $\eta$  intervals. The value of ISO may be negative given that an average value is used

subtract the contribution of detector noise in the computation of  $\text{ISO}_{\text{ECAL}}$  and  $\text{ISO}_{\text{HCAL}}$  variables. Table IV lists the signal yields  $N^\gamma$  for each  $E_T$  and  $\eta$  bin. The results for  $E_T < 50$  GeV in the endcaps are not used in the measurement due to the large systematic uncertainties in the modelling of the background shape. In order to minimize dependence on the model of isolation, the signal yields are quoted for  $\text{ISO} < 5$  GeV. Because the signal and background-enriched samples are small in the highest  $E_T$  bin (300–400 GeV), the value of  $N^\gamma$  is obtained by counting the number of observed photon candidates assuming 100% purity, instead of performing the fit. Such an assumption is justified by the fact that purity increases with  $E_T$ , as shown in Fig. 4.



TABLE IV. Measured signal yield  $N^\gamma$  from the isolation method. The uncertainty on the yield is the statistical uncertainty from the extended maximum likelihood fit.

$E_T$ (GeV)	$ \eta  < 0.9$	$0.9 <  \eta  < 1.44$	$1.57 <  \eta  < 2.1$	$2.1 <  \eta  < 2.5$
25–30	$15951 \pm 209$	$12088 \pm 165$	...	...
30–35	$8193 \pm 151$	$5977 \pm 101$	...	...
35–40	$14813 \pm 179$	$10384 \pm 131$	...	...
40–45	$8568 \pm 121$	$5790 \pm 94$	...	...
45–50	$5548 \pm 92$	$3425 \pm 72$	...	...
50–55	$3400 \pm 71$	$2138 \pm 54$	$2154 \pm 56$	$1298 \pm 44$
55–60	$4906 \pm 115$	$3067 \pm 67$	$3155 \pm 69$	$1747 \pm 77$
60–65	$3280 \pm 92$	$2143 \pm 52$	$2015 \pm 66$	$1209 \pm 42$
65–70	$2397 \pm 67$	$1521 \pm 44$	$1378 \pm 44$	$822 \pm 36$
70–80	$3013 \pm 64$	$1928 \pm 54$	$1812 \pm 50$	$1042 \pm 44$
80–100	$5487 \pm 85$	$3489 \pm 73$	$3193 \pm 54$	$1679 \pm 49$
100–120	$2128 \pm 53$	$1397 \pm 41$	$1210 \pm 39$	$572 \pm 29$
120–200	$1842 \pm 49$	$1111 \pm 36$	$887 \pm 35$	$396 \pm 25$
200–300	$217 \pm 15$	$121 \pm 12$	$81 \pm 11$	$27 \pm 6$
300–400	$44 \pm 7$	$26 \pm 5$	$8 \pm 3$	$1 \pm 1$

FIG. 4 (color online). Measured signal purity for  $\text{ISO} < 5$  GeV with the isolation method in the four  $\eta$  regions. The purity for the bin  $E_T = 300\text{--}400$  GeV is not shown. The vertical error bars show the statistical uncertainties, while the shaded areas show the statistical and systematic uncertainties added in quadrature. Estimation of the systematic uncertainties is discussed in Sec. VIII.

## VII. EFFICIENCY ESTIMATION

The selection efficiency can be factorized into several contributions, corresponding to the different steps of the selection process, and can be expressed as

$$\epsilon = \epsilon_{\text{reco}} \times \epsilon_{\text{id1}} \times \epsilon_{\text{trig}} \times \epsilon_{\text{id2}}.$$

The reconstruction efficiency  $\epsilon_{\text{reco}}$  is defined as the ratio of the number of true prompt photons that are reconstructed to the number of true prompt photons that are generated with true  $E_T$  and  $\eta$  and have a generator-level isolation less than 5 GeV (Sec. III). The value of  $\epsilon_{\text{reco}}$  is 99.8% for all  $E_T$  and  $\eta$  bins and is determined from simulated photon signal events.

The preselection efficiency  $\epsilon_{\text{id1}}$  is defined as the ratio of the number of true prompt photons that are reconstructed and satisfy the preselection requirements in Table II (with additional requirement of  $\text{ISO} < 5$  GeV for the isolation method) to the number of true prompt photons that are reconstructed. The value of  $\epsilon_{\text{id1}}$  is determined from simulated photon signal events first and then multiplied by a data-to-simulation scaling factor. To derive this data-to-simulation scaling factor, a technique called “tag-and-probe” [33] that uses electrons from  $Z^0 \rightarrow e^+e^-$  decays is applied. The simulation predicts a few percent difference in the efficiency  $\epsilon_{\text{id1}}$  between photons and electrons; half of this difference is taken as a systematic uncertainty. In addition, the scaling factor is measured in various time periods that correspond to different average numbers of pile-up events due to multiple  $pp$  interactions in the same bunch crossing. The envelope of the full variation, approximately 3–5% depending on the selection criteria and photon  $E_T$ , is taken as the systematic uncertainty. The derivation of the efficiency scaling factors is described in more detail in Ref. [31].

The trigger efficiency  $\epsilon_{\text{trig}}$  is measured with the tag-and-probe method directly from data and defined with respect to the number of reconstructed electrons satisfying the preselection criteria. The  $\epsilon_{\text{trig}}$  is measured to be  $(99.8 \pm 0.1)\%$  for the barrel and  $(99.0 \pm 0.7)\%$  for the endcaps.

The symbol  $\epsilon_{\text{id2}}$  represents the efficiency of the pixel veto requirement for the isolation method while for the photon conversion method it represents the product of three terms: conversion probability, track reconstruction efficiency, and identification efficiency. While  $\epsilon_{\text{id1}}$  and  $\epsilon_{\text{trig}}$  are calibrated with electrons using the “tag-and-probe” technique,  $\epsilon_{\text{id2}}$  must be measured using a different method as described in Secs. VII A and VII B.

### A. Photon conversion method

The tag-and-probe scaling factor on  $\epsilon_{\text{id1}}$  is on average  $0.963 \pm 0.050$  for the barrel and  $0.990 \pm 0.053$  for the endcap. The uncertainty on the scaling factor is dominated by the uncertainty associated with the number of pile-up

events, the background estimate underneath the  $Z^0$  mass peak, and the difference between photons and electrons observed in the simulation.

For the photon conversion method,  $\epsilon_{\text{id2}}$  cannot be measured from the  $Z^0 \rightarrow e^+e^-$  events and is measured with a different sample. First, a sample is selected in data by applying the  $H/E$  and  $\sigma_{\eta\eta}$  requirements listed in Table II. The ISO distribution of these selected candidates is used to extract the yield,  $N_1$ , of signal photons with  $\text{ISO} < 5$  GeV, using the signal shape from Eq. (1) with the background shape obtained from the simulation. Second, a subsample of these candidates is selected, which, in addition to passing the shower shape selection, also have reconstructed conversion tracks meeting the conversion identification criteria as discussed in Sec. VI A. The signal extraction is performed again on the conversion subsample to obtain an estimate of the number of signal photons,  $N_2$ , that converted and passed the conversion identification selection. The ratio between the extracted number of signal events before and after applying the conversion selection,  $N_2/N_1$ , is used as an estimate of the value of  $\epsilon_{\text{id2}}$ .

In simulation, the  $\epsilon_{\text{id2}}$  depends only weakly on the  $E_T$  of the photon, but varies strongly with  $\eta$ . Because of the relatively small number of events in the conversion subsample, an average value of the  $\epsilon_{\text{id2}}$  for each  $\eta$  bin is extracted and then corrected for the  $E_T$  dependence observed in the simulation. As a cross-check, photon identification criteria and the ISO fit range are varied. The measured  $\epsilon_{\text{id2}}$  is found to be independent of the choice of these parameters.

Figure 5(a) shows the total efficiency  $\epsilon$  for the photon conversion method, after taking into account the scaling factors, as a function of photon  $E_T$  in the four  $\eta$  regions. The value of  $\epsilon$  for the photon conversion method is lower than that for the isolation method because of the probability for a photon to convert before reaching the CMS electromagnetic calorimeter and the relatively small conversion reconstruction efficiency. The conversion probability, estimated at the generator level, is between 20% and 70% in the region of  $|\eta| < 1.44$  and between 65% and 70% in the region of  $1.57 < |\eta| < 2.5$ . The efficiency in the region  $0.9 < |\eta| < 1.44$  is lower than in the other regions because this region covers the area of transition between the tracker barrel and endcap where the largest amount of material, due to cables and services, is located. This region is especially challenging for electron and conversion reconstruction. Uncertainties on the  $\epsilon_{\text{id1}}$ ,  $\epsilon_{\text{id2}}$ , and trigger efficiency  $\epsilon_{\text{trig}}$  are included as sources of systematic uncertainty on the final cross-section measurement in Sec. VIII.

### B. Isolation method

The data-to-simulation scaling factor on  $\epsilon_{\text{id1}}$  measured with the tag-and-probe method varies from  $0.971 \pm 0.073$  to  $0.955 \pm 0.032$  for the barrel and from  $0.998 \pm 0.056$  to

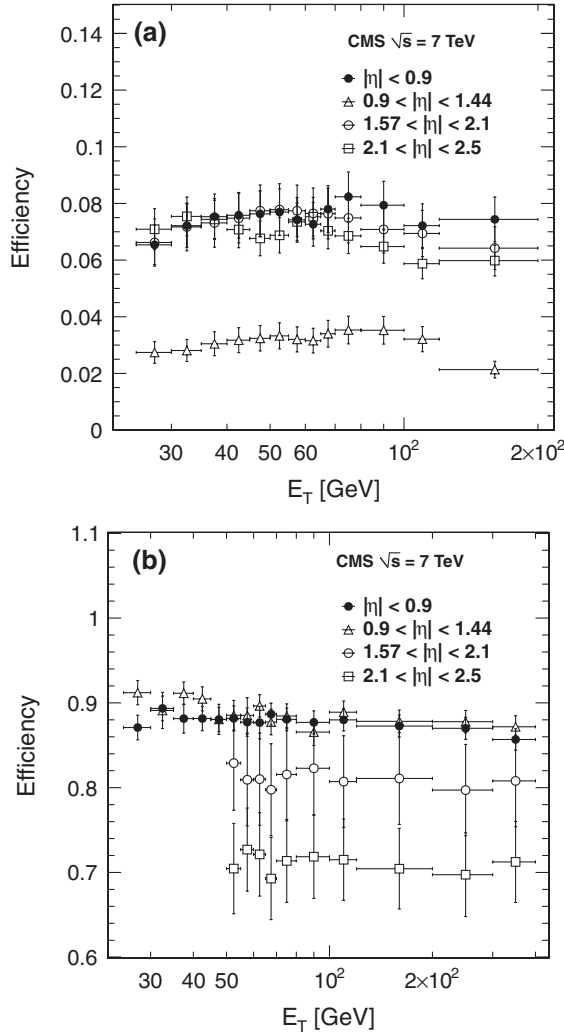


FIG. 5. Measured signal efficiency  $\epsilon$  for the (a) photon conversion and (b) isolation methods in the four  $\eta$  regions. Data-to-simulation scaling factors have been applied. The error bars are dominated by the systematic uncertainties and are 100% correlated between different  $E_T$  bins.

$0.990 \pm 0.056$  for the endcaps, as  $E_T$  increases from 20 GeV to 45 GeV.

In addition, as mentioned in Sec. VIB, a pixel veto requirement is applied in the isolation method to suppress the contribution of electron background. The efficiency of the pixel veto requirement is estimated with the photons from the final-state radiation of muons in  $Z^0$  decays, i.e.,  $Z^0 \rightarrow \mu^+ \mu^- \gamma$  events. The algorithm used in the pixel veto requirement may be affected by the presence of nearby muon tracks leading to a false match to the photon. To reduce this bias, events with photons that are close to the muons are removed and the procedure is validated with simulation. A data-to-simulation scaling factor is measured to be  $0.996 \pm 0.013$  for the barrel and  $0.959 \pm 0.062$  for the endcaps.

Figure 5(b) shows the total efficiency  $\epsilon$  for the isolation method, after taking into account the scaling factors, as a function of photon  $E_T$  in the four  $\eta$  regions. Uncertainties on the  $\epsilon_{id1}$ ,  $\epsilon_{id2}$ , and trigger efficiency  $\epsilon_{trig}$  are included as sources of systematic uncertainty on the final cross-section measurement in Sec. VIII.

## VIII. SYSTEMATIC UNCERTAINTIES

Table V summarizes the systematic uncertainties on the cross section in the four  $\eta$  regions. The major sources of systematic uncertainties include the uncertainties on the shapes of the signal and background and photon identification efficiency. Secs. VIII A and VIII B describe the estimation of these dominant systematic uncertainties that are specific to each method.

In addition to the 4% overall uncertainty on the integrated luminosity, uncertainties on the ECAL energy scale and trigger efficiency are 100% correlated between the photon conversion and isolation methods. The uncertainty on the ECAL energy scale is estimated from the  $Z^0$  mass peak positions to be 0.6% for the barrel and 1.5% for the endcaps [34]. The full analysis procedure is repeated by scaling up and down the photon  $E_T$  according to the uncertainty, which results in an uncertainty of 4% on the photon cross section. The 4% uncertainty is given by the statistical fluctuations in the yield rather than the expected mean size of the effect. The uncertainty on the trigger efficiency is limited by the available sample of  $Z^0 \rightarrow e^+ e^-$  events.

For both methods, systematic uncertainties on the signal and background shapes are obtained by pseudoexperiments. The signal or background distribution is varied in the generated pseudoexperiments according to the uncertainty on the shape parameters. The result of each pseudoexperiment is then fitted using the original fit model. The variation of the fitted yield is assigned as the systematic uncertainty. The uncertainties on the efficiency  $\epsilon_{id1}$  for both methods and  $\epsilon_{id2}$  for the isolation method are dominated by the limited number of  $Z^0 \rightarrow e^+ e^-$  and  $Z^0 \rightarrow \mu^+ \mu^- \gamma$  events available, the pile-up conditions, the background estimate, and the difference between photons and electrons observed in simulation.

The uncertainties due to the bias introduced in the fitting procedure and the amount of electron background result in a less than 6% uncertainty on the measured cross section. The uncertainty due to imperfection of the fitting model is obtained from pseudoexperiments by extracting the difference between observed signal yields and the yields expected under the fitted model. The electron background from  $Z^0 \rightarrow e^+ e^-$  decays is estimated from the product of the integrated luminosity, the production cross section measured in Ref. [35], and the efficiency from simulated  $Z^0$  events multiplied by a data-to-simulation efficiency scaling factor. The contribution of electron background from  $W \rightarrow e \nu$  decays and Drell-Yan

TABLE V. Systematic uncertainties expressed in percent for each source in the four  $\eta$  regions. The ranges, when quoted, indicate the variation over photon  $E_T$ . The unfolding correction is discussed in Sec. IX.

Source	$ \eta  < 0.9$	$0.9 <  \eta  < 1.44$	$1.57 <  \eta  < 2.1$	$2.1 <  \eta  < 2.5$
Common				
Luminosity	4.0		4.0	
Energy scale	4.0		4.0	
Trigger efficiency	0.1		0.7	
Photon conversion method				
Isolation efficiency	5.2	5.2	5.4	5.4
Conversion efficiency	11	11	8.9	8.9
Fit bias	0–4.1	0–6.1	0.1–4.2	0–5.3
Signal shape	1	2.3	3	3.1
Background shape	0.1–4.8	4.1–5.9	0.3–14	6.2–15
Electron background	0.01–0.1	0.02–0.2	0.05–1.1	0.03–0.8
Unfolding correction	4.0	4.0	4.0	4.0
Total	14–18	14–20	12–21	13–23
Isolation method				
Efficiency	3.6–7.6	3.6–7.6	8.6	8.6
Fit bias	0.1–2.9	0.1–2.8	0.1–4.0	1.1–4.7
Signal/background shape	1.8–13	1.6–32	4.9–16	7.0–21
$N^\gamma$ for $E_T = 300\text{--}400$ GeV	4.5	8.3	10	20
Electron background	<0.1	<0.1	<0.1	<0.1
Unfolding correction	2.0	2.0	2.0	2.0
Total	3.8–18	3.9–35	8.7–18	10–23

processes is estimated following the same procedure. The total contribution of electron background is less than 1% and is taken as a systematic uncertainty.

### A. Photon conversion method

A significant source of systematic uncertainty affecting the photon conversion method is the possible mismodelling of the signal and background probability density functions ( $\mathcal{P}_s$  and  $\mathcal{P}_b$ ). To establish the size of this uncertainty, both  $\mathcal{P}_s$  and  $\mathcal{P}_b$  are checked against the data. For the signal distribution, possible differences in the  $E_T/p_T$  distribution are investigated by varying the peak position and the width of the distribution. For each variation, the change in signal yield is computed along with the  $\chi^2$  probability of the fit to data. The weighted variance of these varied signal yields is computed using the  $\chi^2$  probability for each variation as the weight, and is used to set the systematic uncertainty on the signal shape. For the background, an alternate  $\mathcal{P}_b$  is extracted from the observed  $E_T/p_T$  distribution in the sideband (background-enriched) region defined in Table II. The extraction of the signal yield is repeated using this value of  $\mathcal{P}_b$  determined from data, and the size of the difference from the central value is taken as the systematic uncertainty due to background shape. The observed and simulated  $E_T/p_T$  distributions in the sideband region are in good agreement and the shapes of  $E_T/p_T$  distributions are found to be insensitive to the number of pile-up events in the data.

The systematic uncertainty associated with  $\epsilon_{\text{id}2}$  is another significant source of uncertainty. The uncertainty on  $\epsilon_{\text{id}2}$  due to the use of the isolation method to extract the numbers of signal candidates  $N_1$  and  $N_2$  (Sec. VII A) is estimated in several ways, including a comparison of ISO background shapes from data sideband regions and simulation and a comparison of  $\epsilon_{\text{id}2}$  extracted with different photon candidate selections. The statistical uncertainty on the number of candidates used in Sec. VII A to measure the  $\epsilon_{\text{id}2}$  from data is also included in the uncertainty. Finally, the  $\epsilon_{\text{id}2}$  is recomputed by splitting the data sample into statistically independent halves. The final uncertainty on the  $\epsilon_{\text{id}2}$  is chosen to cover the differences seen under each of these variations.

Figure 6 shows the  $E_T$  dependence of each dominant systematic uncertainty listed in Table V for the photon cross section measured with the photon conversion method. The systematic uncertainty associated with signal/background shape in the  $\eta$  region  $|\eta| < 0.9$  increases with photon  $E_T$ , which is different from the other  $\eta$  regions for the following reasons. The size of the systematic uncertainty is mainly driven by the difference between the simulated and observed background distributions with sideband selections; it is a balance between the decreasing number of background events at high  $E_T$  for this comparison (tending to make the uncertainty larger) and increasing purity (tending to make the uncertainty lower). In this  $\eta$  bin the first effect dominates.

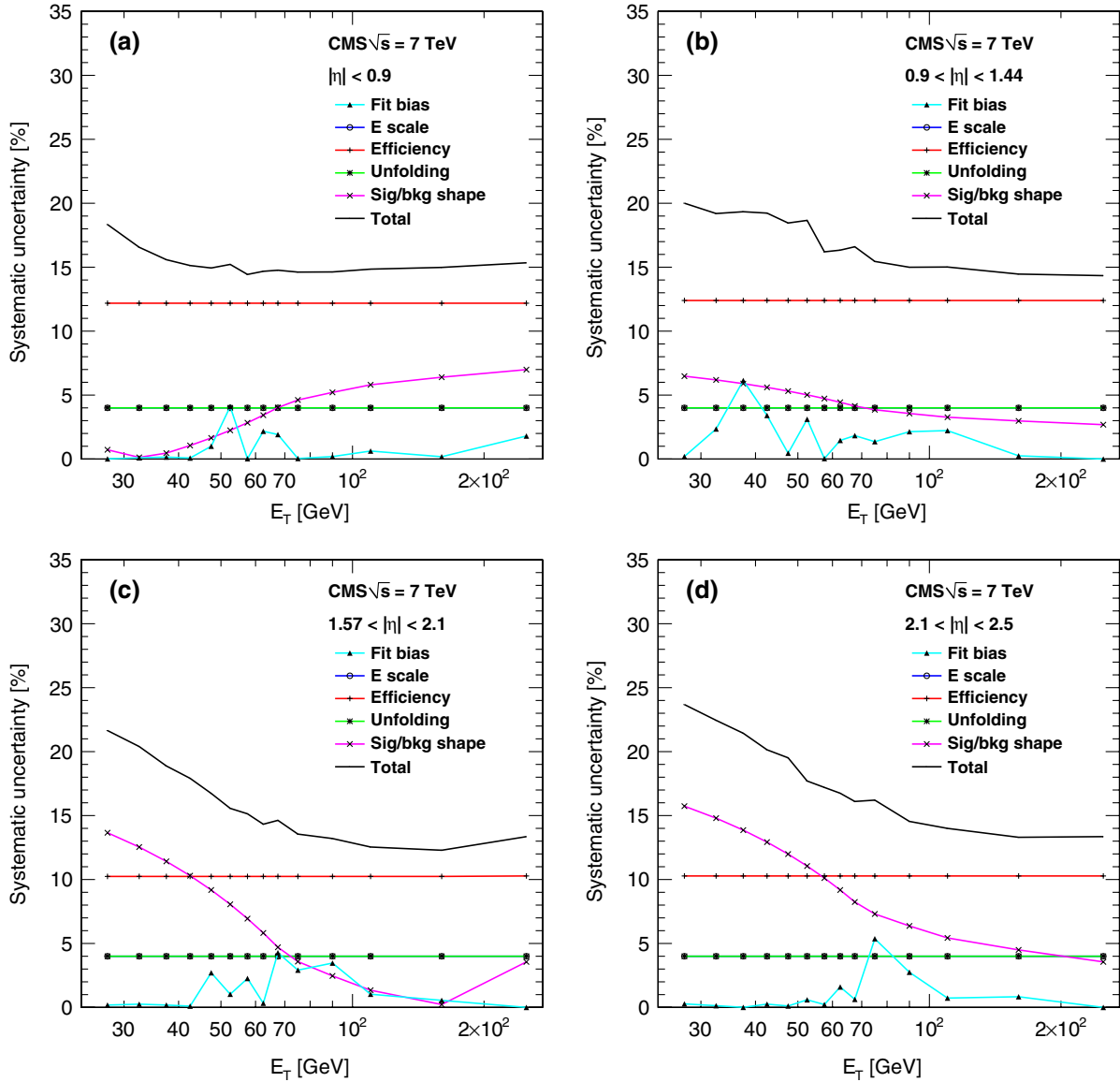


FIG. 6 (color online). Relative systematic uncertainties on the photon cross section measured with the photon conversion method in the four  $\eta$  regions. Systematic uncertainties due to the uncertainties on the fit bias, energy scale, selection efficiency, unfolding correction factors, and signal and background shapes are shown, as well as their total quadrature sum (upper curve).

### B. Isolation method

For the highest- $E_T$  bin in the isolation method (300–400 GeV), the relative systematic uncertainty on  $N^\gamma$  is obtained from the difference between the fitted purity at 200–300 GeV and the assumed 100% purity. For the other  $E_T$  bins, the uncertainties associated with the signal and background shapes arise from the uncertainties on the constrained values of the shape parameters  $a$ ,  $p_0$ , and  $p_3$  in the likelihood fit [Eqs. (1), and (2) in Sec. VIB].

The constrained value of the signal parameter  $a$  is varied by  $\pm 30\%$  to account for the imperfect modelling of pile-up events; the value 30% is the largest data-simulation difference observed among the four  $\eta$  bins in the electron sample. In order to estimate the effect due to the modelling

of nondirect photons in PYTHIA,  $2 \rightarrow 2$  QCD processes that contain ISR, FSR, and parton shower photons are removed in the signal simulation, which results in a 5% change in the constrained value of parameter  $a$ .

The uncertainty on the background shape parameters  $p_0$  and  $p_3$  is mainly driven by the size of background-enriched samples that are selected within the sideband region of  $\sigma_{\eta\eta}$  and that are used to derive the data-to-simulation scaling factors. Because of the large statistical uncertainties on the data-to-simulation scaling factors for higher photon  $E_T$  bins, the difference between the constrained values obtained by applying and not applying the scaling factors is conservatively included as a systematic uncertainty.



The uncertainty on  $N^\gamma$  from the signal and background shapes is determined from pseudoexperiments by varying simultaneously the values of parameters  $a$ ,  $p_0$ , and  $p_3$  according to their uncertainties.

Figure 7 shows the  $E_T$  dependence of each dominant systematic uncertainty listed in Table V for the photon cross section measured with the isolation method. Variations of the systematic uncertainty associated with the signal/background shapes are observed for the following reasons. In general, the uncertainty decreases with photon  $E_T$ , which is expected due to the increase of photon purity. However, the difference between simulated and observed ISO distribution increases with  $E_T$ . For  $E_T < 55$  GeV, only data before the improvement of LHC instantaneous

luminosity are used (Table I) and in this period there are fewer pileup collisions on average. Therefore, a step or a transition in systematic uncertainty is observed at  $E_T = 55$  GeV in Figs. 7(a) and 7(b). In addition, due to the lack of high- $E_T$  photon candidates that satisfy side-band selection criteria, a background-enriched sample with photon  $E_T = 80$ –100 GeV is used to derive the data-to-simulation scaling factors for all the  $E_T$  bins above 80 GeV. Therefore, for three out of four  $\eta$  regions, a discontinuity in the systematic uncertainty is observed at 100 GeV. The systematic uncertainty on the cross section for low- $E_T$  photons in the outer barrel is larger than in the central barrel because of a larger difference between the simulated and observed isolation distributions.

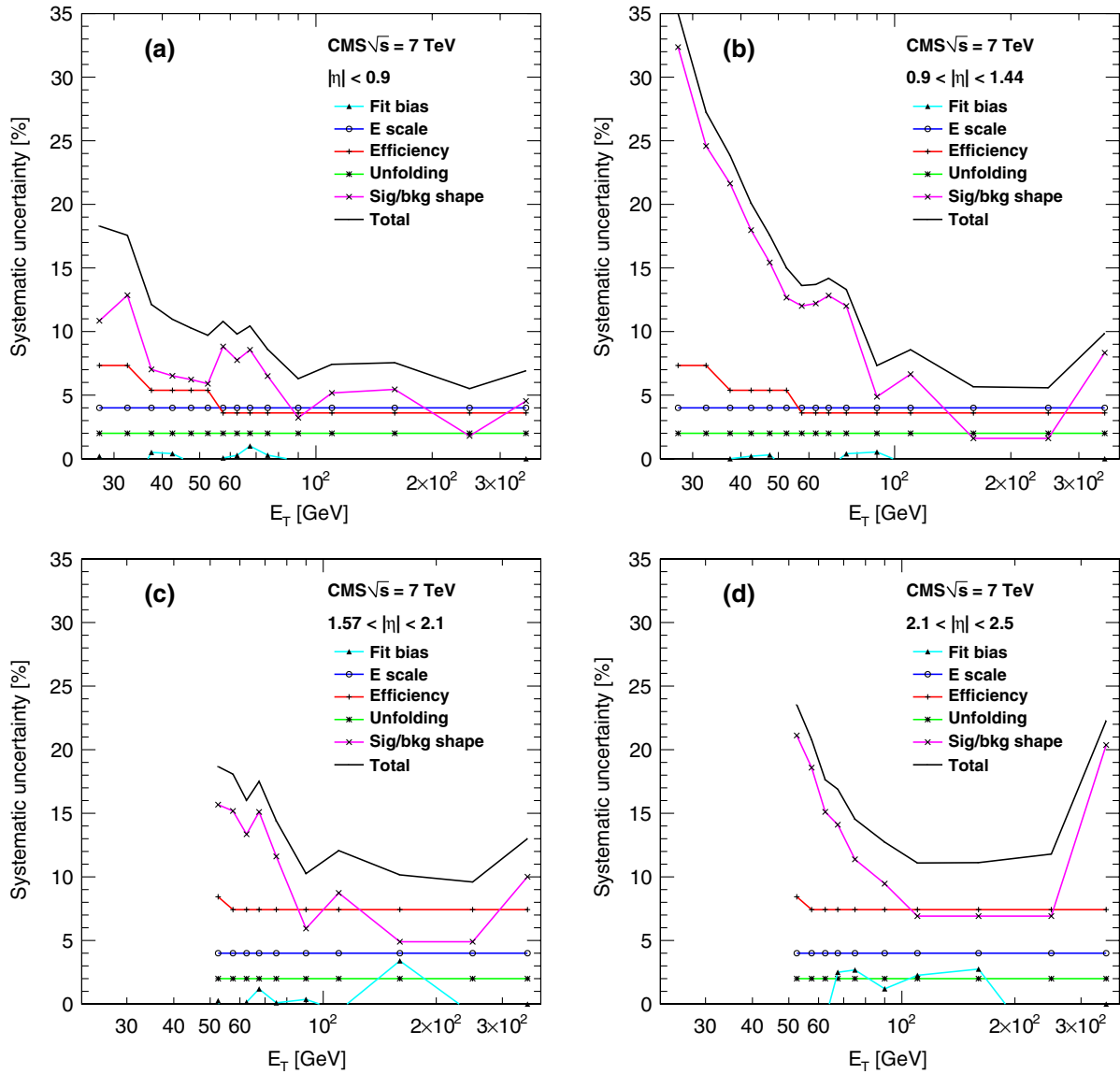


FIG. 7 (color online). Relative systematic uncertainties on the photon cross section measured with the isolation method in the four  $\eta$  regions. Systematic uncertainties due to the uncertainties on the fit bias, energy scale, selection efficiency, unfolding correction factors, and signal and background shapes are shown, as well as their total quadrature sum (upper curve).

## IX. RESULTS

The differential cross section is defined as

$$d^2\sigma/dE_T d\eta = N^\gamma \cdot \mathcal{U} / (L \cdot \epsilon \cdot \Delta E_T \cdot \Delta \eta), \quad (3)$$

where  $N^\gamma$  is the signal photon yield measured from data (Sec. VI),  $L$  is the integrated luminosity,  $\mathcal{U}$  denotes the bin-by-bin unfolding correction factors,  $\epsilon$  is the product of the efficiencies (Sec. VII), and  $\Delta E_T$  and  $\Delta \eta$  are the sizes of the  $E_T$  and  $\eta$  bins.

The  $E_T$  of a photon candidate can be mismeasured because of detector resolution and imperfections in the reconstruction algorithm. The bin-by-bin unfolding correction  $\mathcal{U}$  is applied to account for these effects. The correction is obtained from simulation for each  $E_T - \eta$  bin, by

TABLE VI. Measured isolated prompt photon differential cross section  $d^2\sigma/dE_T d\eta$  in the four pseudorapidity regions. The quoted uncertainties are statistical and systematic, respectively.

	$ \eta  < 0.9$	$0.9 <  \eta  < 1.44$
$E_T$ (GeV)	Cross section (nb/GeV)	Cross section (nb/GeV)
25–30	$(7.83 \pm 0.17^{+0.96}_{-0.96}) \times 10^{-1}$	$(6.69 \pm 0.85^{+1.25}_{-1.33}) \times 10^{-1}$
30–35	$(3.85 \pm 0.14^{+0.46}_{-0.42}) \times 10^{-1}$	$(4.07 \pm 0.46^{+0.67}_{-0.55}) \times 10^{-1}$
35–40	$(2.04 \pm 0.04^{+0.19}_{-0.19}) \times 10^{-1}$	$(1.90 \pm 0.19^{+0.31}_{-0.29}) \times 10^{-1}$
40–45	$(1.25 \pm 0.03^{+0.11}_{-0.11}) \times 10^{-1}$	$(1.42 \pm 0.06^{+0.19}_{-0.19}) \times 10^{-1}$
45–50	$(7.93 \pm 0.22^{+0.63}_{-0.66}) \times 10^{-2}$	$(7.81 \pm 0.48^{+0.96}_{-0.93}) \times 10^{-2}$
50–55	$(4.97 \pm 0.16^{+0.37}_{-0.39}) \times 10^{-2}$	$(5.03 \pm 0.24^{+0.54}_{-0.54}) \times 10^{-2}$
55–60	$(3.49 \pm 0.09^{+0.28}_{-0.28}) \times 10^{-2}$	$(3.46 \pm 0.16^{+0.31}_{-0.34}) \times 10^{-2}$
60–65	$(2.31 \pm 0.09^{+0.17}_{-0.18}) \times 10^{-2}$	$(2.18 \pm 0.12^{+0.18}_{-0.22}) \times 10^{-2}$
65–70	$(1.61 \pm 0.07^{+0.12}_{-0.13}) \times 10^{-2}$	$(1.58 \pm 0.10^{+0.14}_{-0.15}) \times 10^{-2}$
70–80	$(1.05 \pm 0.03^{+0.09}_{-0.08}) \times 10^{-2}$	$(1.09 \pm 0.05^{+0.10}_{-0.10}) \times 10^{-2}$
80–100	$(4.80 \pm 0.12^{+0.30}_{-0.28}) \times 10^{-3}$	$(4.86 \pm 0.24^{+0.37}_{-0.35}) \times 10^{-3}$
100–120	$(1.89 \pm 0.05^{+0.14}_{-0.14}) \times 10^{-3}$	$(2.00 \pm 0.10^{+0.21}_{-0.17}) \times 10^{-3}$
120–200	$(4.07 \pm 0.16^{+0.33}_{-0.29}) \times 10^{-4}$	$(4.06 \pm 0.16^{+0.23}_{-0.23}) \times 10^{-4}$
200–300	$(4.00 \pm 0.29^{+0.27}_{-0.27}) \times 10^{-5}$	$(3.60 \pm 0.39^{+0.20}_{-0.20}) \times 10^{-5}$
300–400	$(8.20 \pm 1.22^{+0.59}_{-0.54}) \times 10^{-6}$	$(7.84 \pm 1.53^{+0.75}_{-0.75}) \times 10^{-6}$
	$1.57 <  \eta  < 2.1$	$2.1 <  \eta  < 2.5$
$E_T$ (GeV)	Cross section (nb/GeV)	Cross section (nb/GeV)
25–30	$(6.39 \pm 0.50^{+1.35}_{-1.35}) \times 10^{-1}$	$(7.40 \pm 0.58^{+1.74}_{-1.70}) \times 10^{-1}$
30–35	$(2.93 \pm 0.34^{+0.59}_{-0.57}) \times 10^{-1}$	$(4.09 \pm 0.38^{+0.91}_{-0.91}) \times 10^{-1}$
35–40	$(1.92 \pm 0.13^{+0.36}_{-0.36}) \times 10^{-1}$	$(1.97 \pm 0.15^{+0.42}_{-0.41}) \times 10^{-1}$
40–45	$(1.18 \pm 0.10^{+0.20}_{-0.20}) \times 10^{-1}$	$(1.22 \pm 0.12^{+0.24}_{-0.24}) \times 10^{-1}$
45–50	$(7.03 \pm 0.69^{+1.13}_{-1.13}) \times 10^{-2}$	$(8.13 \pm 0.94^{+1.54}_{-1.54}) \times 10^{-2}$
50–55	$(5.63 \pm 0.31^{+0.63}_{-0.58}) \times 10^{-2}$	$(5.34 \pm 0.42^{+0.70}_{-0.65}) \times 10^{-2}$
55–60	$(3.72 \pm 0.21^{+0.42}_{-0.34}) \times 10^{-2}$	$(3.10 \pm 0.22^{+0.39}_{-0.34}) \times 10^{-2}$
60–65	$(2.34 \pm 0.14^{+0.24}_{-0.18}) \times 10^{-2}$	$(2.39 \pm 0.12^{+0.27}_{-0.27}) \times 10^{-2}$
65–70	$(1.61 \pm 0.12^{+0.17}_{-0.13}) \times 10^{-2}$	$(1.75 \pm 0.09^{+0.19}_{-0.18}) \times 10^{-2}$
70–80	$(1.07 \pm 0.06^{+0.10}_{-0.09}) \times 10^{-2}$	$(1.03 \pm 0.05^{+0.11}_{-0.11}) \times 10^{-2}$
80–100	$(4.91 \pm 0.14^{+0.35}_{-0.37}) \times 10^{-3}$	$(3.86 \pm 0.18^{+0.33}_{-0.33}) \times 10^{-3}$
100–120	$(1.48 \pm 0.12^{+0.13}_{-0.07}) \times 10^{-3}$	$(1.39 \pm 0.08^{+0.12}_{-0.12}) \times 10^{-3}$
120–200	$(3.68 \pm 0.16^{+0.27}_{-0.27}) \times 10^{-4}$	$(2.29 \pm 0.19^{+0.18}_{-0.18}) \times 10^{-4}$
200–300	$(2.80 \pm 0.39^{+0.30}_{-0.30}) \times 10^{-5}$	$(1.40 \pm 0.30^{+0.26}_{-0.26}) \times 10^{-5}$
300–400	$(2.80 \pm 0.99^{+0.37}_{-0.34}) \times 10^{-6}$	$(5.42 \pm 5.42^{+1.21}_{-1.21}) \times 10^{-7}$

taking the ratio of the generator- to the reconstruction-level photon  $E_T$  spectrum. Direct photons, simulated by PYTHIA as described in Sec. III, are used to derive the correction. The difference in the correction factors obtained by using the  $E_T$  spectrum of direct photons in PYTHIA and by using that of the NLO pQCD predictions [3,4] is taken as a systematic uncertainty. The resulting relative change on the cross section is listed in Table V and shown in Figs. 6 and 7 for the photon conversion and isolation methods, respectively.

After unfolding corrections are applied, the results of the photon conversion and isolation methods are compared for the  $E_T$  bins where both are available. The consistency of the results is quantified by the global  $\chi^2$  divided by the number of  $E_T$  bins; they are 11.8/13, 20.4/13, 12.2/8, and 3.6/8 for the four pseudorapidity intervals, respectively, which indicates a good agreement between the results of the two methods. The results of the two methods are combined using the procedure described in Ref. [36], weighting each method by its corresponding uncertainty in each  $E_T - \eta$  bin. The weights are obtained by inverting the covariance matrix between the two methods, which has elements  $C_{ij} = \rho_{ij}\sigma_i\sigma_j$ , where  $\sigma_i$  and  $\sigma_j$  are the total uncertainties for the two methods and  $\rho_{ij}$  is the correlation coefficient.

Since the value of  $\rho_{ij}$  is not known in data, the following procedure is adopted for combining the results. The systematic uncertainties from trigger efficiency and energy scale are fully correlated because the same procedure is applied to both measurements and they give a lower limit on  $\rho_{ij}$ . The systematic uncertainties due to signal and

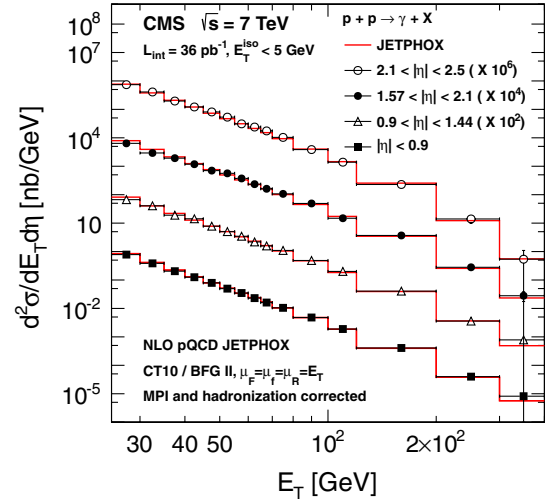


FIG. 8 (color online). Measured isolated prompt photon differential cross sections (markers) as a function of transverse energy in the four pseudorapidity regions and the predictions from JETPHOX 1.3.0 using the CT10 PDFs (histograms). The error bars are the quadrature sums of statistical and systematic uncertainties on the measurements. The cross sections are scaled by the factors shown in the legend for easier viewing.

background shapes as well as to the fitting bias have negligible correlation, as checked from simulation studies; they provide the upper limit on the correlation coefficients  $\rho_{ij}$ . For the remaining sources of uncertainties, the correlation coefficients are varied from zero to one. Each unknown coefficient is varied independently, and for each variation, the resulting value of  $\rho_{ij}$  is used in the combination. The final value of the combined cross section is the mean of the central values obtained for each  $\rho_{ij}$ . For each value of  $\rho_{ij}$  the uncertainty on the combined measurement is evaluated and the final, total uncertainty is conservatively quoted as the mean of the resulting uncertainty distribution plus its standard deviation.

Since the major sources of systematic uncertainties (signal and background shapes) are uncorrelated, the impact on

the final combined result of varying the correlations on the remaining sources is limited to the percent level. The central values and uncertainties generated with this procedure were studied in pseudoexperiments to confirm that they have the desired properties.

Since the conversion method has smaller uncertainty than the isolation method at low  $E_T$ , it receives a higher weight in the combination at low  $E_T$ . The situation is reversed at high  $E_T$ . Table VI lists the final measured cross section with corresponding statistical and systematic uncertainties.

## X. COMPARISON WITH THEORY

The measured differential cross sections are shown in Fig. 8 for the four pseudorapidity ranges considered,

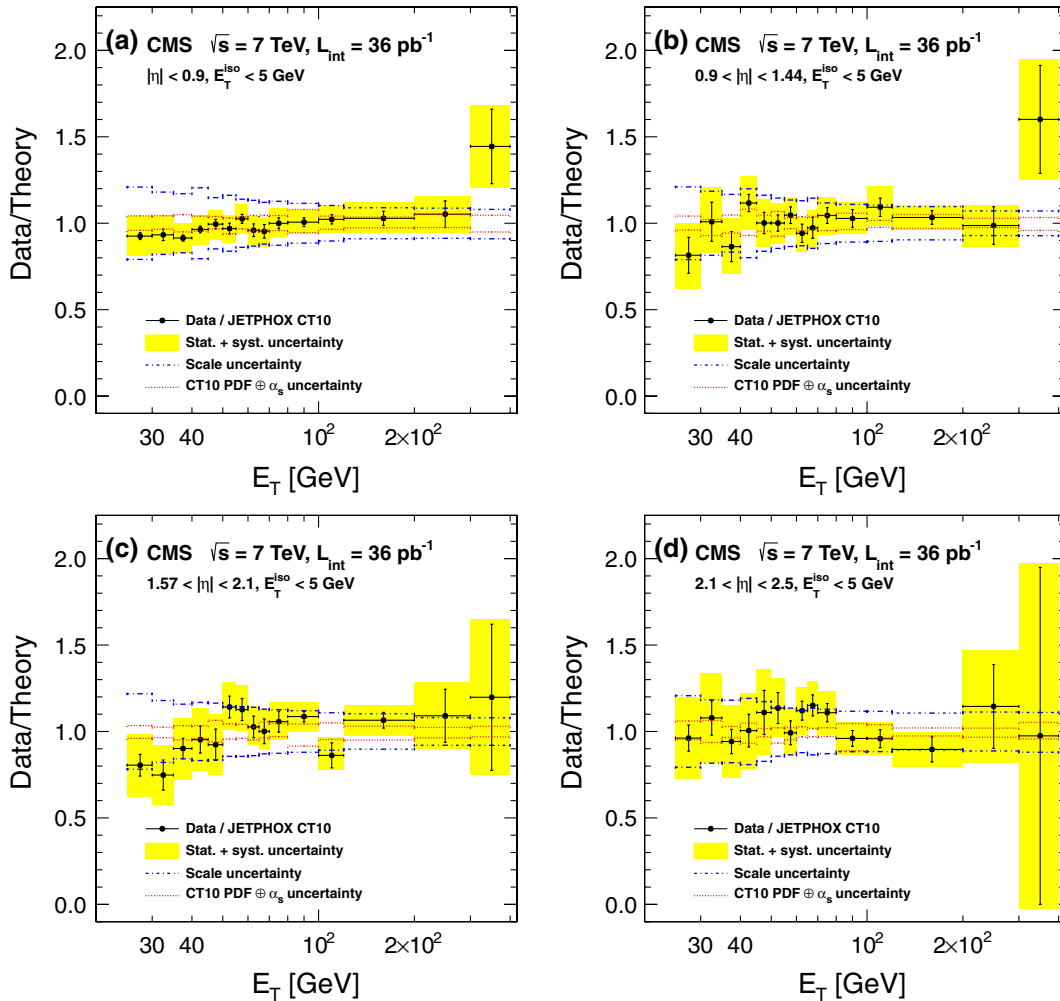


FIG. 9 (color online). Ratios of the measured isolated prompt photon differential cross section to the NLO pQCD predictions from JETPHOX 1.3.0 using the CT10 PDFs. The vertical error bars show the statistical uncertainties, while the shaded areas show the statistical and systematic uncertainties added in quadrature. The 4% luminosity uncertainty on the data is not included. The two sets of curves show the uncertainties on the theoretical predictions due to their dependence on the renormalization, factorization, and fragmentation scales, and on the variation of CT10  $\alpha_s$  and PDFs. A correction to account for extra activity ( $\bar{C} = 0.975 \pm 0.006$ ) is applied to the theoretical predictions, as explained in the text.

together with NLO pQCD predictions from JETPHOX 1.3.0 [3,4] using the CT10 PDFs [37] and the Bourhis, Fontannaz, Guillet (BFG) set II of fragmentation functions [38]. The 4% overall uncertainty on the integrated luminosity is considered separately. The hadronic energy surrounding the photon is required to be at most 5 GeV within  $R < 0.4$  at the parton level. The renormalization, factorization, and fragmentation scales ( $\mu_R$ ,  $\mu_F$ , and  $\mu_f$ ) are all set to the  $E_T$  of photon. To estimate the effect of the choice of theory scales in the predictions, the three scales are varied independently between  $E_T/2$  and  $2E_T$  while keeping the ratio of one scale to the other scales, or vice versa, at most two. Retaining the largest cross-section variation at each  $E_T$  bin, the predictions change by  $\pm 22\%$  to  $\pm 7\%$  with increasing  $E_T$ . The uncertainty on the predictions due to the PDFs is determined from the  $52 + 1$  CT10 PDF sets using the Hessian method [39,40] with a reduction of a factor of 1.645 to obtain the 68% confidence level variation. The uncertainty due to the variation of  $\alpha_s(M_Z)$  values is estimated from the difference between CT10 PDFs with  $\alpha_s(M_Z)$  set to 0.118, and two CT10as sets with  $\alpha_s(M_Z)$  set to  $0.118 \pm 0.001$  corresponding to the 68% confidence level variation. The  $\alpha_s(M_Z)$  uncertainty is added in quadrature with the PDF uncertainty [37]; the combined PDF and  $\alpha_s$  uncertainties are within the ranges of 2.5–8.0%, 1.6–8.2%, 2.4–8.5%, and 1.7–11% in the four  $\eta$  regions, respectively. Finally, using the BFG set I of fragmentation functions instead of the BFG set II yields negligible differences in the predictions.

The theoretical predictions are multiplied by an additional correction factor  $C$  to account for the presence of contributions from the underlying event and parton-to-hadron fragmentation, which tend to increase the hadronic energy inside the isolation cone. Using simulated PYTHIA events,  $C$  is determined as the ratio between the isolated fraction of the total prompt photon cross section at the hadron level and the same fraction obtained after turning off both multiple-parton interactions (MPI) and hadronization. Four different sets of PYTHIA parameters (Z2 [22], D6T, DWT, and Perugia-0 [41]) are considered. The average of  $C$  over all parameter sets,  $\bar{C} = 0.975 \pm 0.006$ , has little  $E_T$  and  $\eta$  dependence. The uncertainty on  $\bar{C}$  is the root mean square of the results obtained with the different PYTHIA parameter sets. The correction reduces the predicted cross section, since the presence of extra activity results in some photons failing the isolation requirements.

Overall, predictions from the NLO pQCD calculations agree with the measured cross sections within uncertainties, as shown in Figs. 8 and 9. However, for photons with lower  $E_T$  in the  $\eta$  regions  $|\eta| < 0.9$ ,  $0.9 < |\eta| < 1.44$ , and  $1.57 < |\eta| < 2.1$ , the cross sections predicted by NLO pQCD tend to be larger than the measured cross sections, similar to the observation in Ref. [15].

## XI. CONCLUSION

A measurement of the differential cross section for the production of isolated prompt photons with  $E_T = 25\text{--}400$  GeV in  $pp$  collisions at  $\sqrt{s} = 7$  GeV has been performed in four intervals of pseudorapidity:  $|\eta| < 0.9$ ,  $0.9 < |\eta| < 1.44$ ,  $1.57 < |\eta| < 2.1$ , and  $2.1 < |\eta| < 2.5$ . Two variables are explored to estimate the prompt photon yield: the ratio of the energy measured in the electromagnetic calorimeter to the momentum measured in the tracker for converted photons, and the isolation measured in the tracker and calorimeters. The differential cross sections obtained with these two methods are combined into one measurement. Predictions from the NLO pQCD are found to agree with the measured cross section within uncertainties, although at low  $E_T$  the predictions tend to be higher than the measured cross section. This measurement probes the kinematic region  $0.007 < x_T < 0.114$ , extends the previous CMS measurement to wider ranges of photon  $E_T$  and pseudorapidity, establishes a benchmark for photon identification and background estimation, and determines the rate of one of the background processes affecting searches for new physics involving photons.

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