Measurements of triple-differential cross sections for inclusive isolated-photon+jet events in pp collisions at √s = 8 TeV

CMS Collaboration

Abstract Measurements are presented of the triple-differential cross sections for inclusive isolated-photon+jet events in pp collisions at √s = 8 TeV as a function of photon transverse momentum (pTγ), photon pseudorapidity (ηγ), and jet pseudorapidity (ηjet). The data correspond to an integrated luminosity of 19.7 fb−1 that probe a broad range of the available phase space, for |ηγ| < 1.44 and 1.57 < |ηγ| < 2.50, |ηjet| < 2.5, 40 < pTγ < 1000 GeV, and jet transverse momentum, pTjet > 25 GeV. The measurements are compared to next-to-leading order perturbative quantum chromodynamics calculations, which reproduce the data within uncertainties.

1 Introduction

Direct photons produced in the hard scattering of partons in proton–proton collisions are sensitive probes of the perturbative regime of quantum chromodynamics (pQCD) [1,2] and provide useful constraints on the parton distribution function (PDF) of gluons [3–5]. At leading order in pQCD, direct photons are produced mainly through quark–gluon scattering (qg → qγ) with smaller contributions from quark antiquark annihilation (q̅q → γγ). Photons can also be produced via fragmentation of the final state partons. These latter photons are typically accompanied by other partons, and their contributions can be experimentally suppressed by requiring the photons to be isolated from other energy depositions in the calorimeters. A good understanding of isolated photon production also indirectly impacts all jet measurements at the LHC, because photon+jet events are commonly used to determine the absolute jet energy-scale. This process also constitutes a main background in important standard model (SM) processes, such as H → γγ, as well as in searches for physics beyond the SM.

This paper presents measurements of the triple-differential inclusive isolated-photon+jet cross sections using data collected by the CMS experiment during the 2012 run at √s = 8 TeV corresponding to an integrated luminosity of 19.7 fb−1. Measurement of the cross section as a function of different combinations of photon and jet pseudorapidities in the range of |η| < 2.5 allows for the exploration of parton collisions at different values of momentum transfer squared (Q2) and parton momentum fraction (x). Given the photon transverse momentum range of pTγ = 40–1000 GeV, the measurement probes Q2 = (pTγ)2 in the range 103–106 GeV2, and xT = 2pTγ/√s in the range 0.01–0.25, where xT is an approximation to the parton momentum fraction when both photon and jet are produced centrally. This measurement is complementary to previous ones [6–11] in the coverage of the Q2 − x phase space. The cross section can be written as:

\[
\frac{d^3\sigma}{dp_T^\gamma d|\eta^\gamma| d|\eta^{\text{jet}}|} = \frac{1}{\Delta p_T^\gamma \Delta |\eta^\gamma| \Delta |\eta^{\text{jet}}|} \sum U_{ij} \frac{N_i p_i}{\epsilon_i L_i} \tag{1}
\]

where Ni is the number of candidate events, pi is the signal purity, εi is the detection efficiency, L′i is the effective integrated luminosity, ΔpTγ, Δ|ηγ|, and Δ|ηjet| are the bin size in pTγ, |ηγ|, and |ηjet| in the ith data bin. Ui,j is the coefficient of the unfolding matrix between the true quantity in bin j and measured quantities in bin i.

The paper is organized as follows. Section 2 provides a brief introduction to the CMS detector. Selection and reconstruction of events, with attention focused on issues of triggering, photon reconstruction, selections and efficiency, are detailed in Sect. 3. Section 4 describes the extraction of the signal photons from the energy depositions that originate from neutral meson decays, the unfolding, and the measurement of differential cross sections. The results of the measurement, along with comparison with theoretical predictions, are reported in Sect. 5. Finally, the summary is presented in Sect. 6.
2 The CMS detector

A detailed description of the CMS detector, together with definitions of the coordinate system and relevant kinematic variables, is presented in Ref. [12]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and plastic scintillator hadronic calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

3 Event reconstruction and selection

The particle-flow algorithm [13] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The identification and energy measurement of muons, electrons, photons, hadronic jets as well as the missing transverse momentum come from particle-flow objects. In addition, the isolations of identified leptons and photons are measured using the $p_T$ of particle-flow charged hadrons, photons, and neutral hadrons. Jets are reconstructed using the anti-$k_T$ algorithm with a distance parameter of $\Delta R = 0.5$ [14], where $R$ determines the size of the jet in $\eta$–$\phi$ space and $\phi$ is measured in radians. Corrections are applied to the jet energy as functions of jet $\eta$ and $p_T$ to account for contributions from additional inelastic proton-proton interactions in the same or neighboring bunch crossings (pileup), and for the nonuniform and nonlinear response of the detectors [15]. Jets are further required to have at least minimal energy depositions in the tracker, HCAL, and ECAL to reject spurious jets associated with calorimeter noise as well as those associated with muon and electron candidates that are either mis-reconstructed or isolated [16]. Jets have typical energy resolutions of 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [13].

Photons are selected from clusters of energy measured in the ECAL with a small corresponding energy deposition in the HCAL. For the reconstruction of the endcap photons, the depositions of energy in the preshower detector are also included. The calorimeter signals are calibrated and corrected for changes in the detector response over time. The energy resolution of isolated photons is about 1% in the barrel section of the ECAL for unconverted photons (photons that did not convert to electrons before reaching the ECAL) in the tens of GeV energy range. The remaining barrel photons in the similar energy range have a resolution of about 1.3% up to a pseudorapidity of $|\eta| = 1.0$, rising to about 2.5% at $|\eta| = 1.4$. In the endcaps, the resolution of unconverted photons is about 2.5%, while the remaining endcap photons have a resolution between 3 and 4% [17].

Muons are identified by tracks in the muon spectrometer matched to tracks in the silicon tracker. Quality requirements are placed on the silicon tracker and muon spectrometer track measurements as well as on the matching between them. Matching muon spectrometer tracks to tracks measured in the silicon tracker results in a relative $p_T$ resolution of 1.3–2.0% for muons in the momentum range $20 < p_T < 100$ GeV in the barrel ($|\eta| < 1.2$) and better than 6% in the endcaps ($1.2 < |\eta| < 2.4$) [18].

Events selected for this analysis are recorded using a two-level trigger system [19]. A hardware based level-1 trigger requires a cluster of energy deposited within the ECAL above a pre-defined $p_T$ threshold. This threshold is $p_T > 20$ or 22 GeV, and is raised to 30 GeV at high luminosity to keep trigger rates at manageable levels. The CMS high-level trigger (HLT) applies a more complicated ECAL energy clustering algorithm than that of level-1, and requires additional $p_T$ trigger thresholds ranging from 30 to 150 GeV. HLT triggers with thresholds below 90 GeV have additional loose calorimetric identification requirements, based on the electromagnetic (EM) shower, and are prescaled such that only a fraction of events satisfying the trigger requirements are recorded. Since the trigger rates for lower $p_T$ threshold triggers are controlled by applying larger prescale factors, the effective luminosity is smaller for the lower $p_T$ regions. Triggers are combined for different $p_T$ ranges to maximize the number of events without loss of efficiency.

Samples of simulated events used for signal and background studies are described below. Events from both photon+jet production and QCD multijet production with enhanced EM content are generated using PYTHIA version 6.426 [20], and passed through the full CMS detector simulation implemented in Geant4 [21]. The EM-enriched QCD sample is generated by applying a filter that is designed to enhance the production efficiency of fake photons from jets with EM fluctuations. The filter accepts events having photons, electrons, or neutral hadrons with: (i) a $p_T > 15$ GeV within a small region, and (ii) no more than one charged particle in a cone of $\Delta R = \sqrt{\Delta\eta^2 + (\Delta\phi)^2} < 0.2$. Samples for reconstruction efficiency studies of inclusive $Z/\gamma^* \rightarrow e^+e^-$ and $Z/\gamma^* \rightarrow \mu^+\mu^-$ are generated using MADGRAPH 5.1.5.11 [22]. For generation purposes, the CTEQ6L [23] parton distribution functions are used along with underlying event tune Z2* [24] for all MC samples. All the samples include simulation of the multiple pp interactions taking place in each bunch crossing, which are weighted to produce the pileup distribution observed in data. Events selected with the single-photon trigger are chosen offline by requiring at least one photon candidate with
\(p_T^\gamma > 40\) GeV. Photon candidates must either be in the barrel (\(|\eta| < 1.44\)) or endcap (\(1.57 < |\eta| < 2.50\)) detector regions. The leading jet is required to be separated from the photon candidate by \(\Delta R > 0.5\), pass the jet identification requirements, and have \(p_T^{\text{jet}} > 25\) GeV and \(|\eta| < 2.5\). Therefore, dijet events where a photon is radiated in a parton shower are included.

The dominant background originates from the decays of neutral hadrons, such as \(\pi^0\) and \(\eta\) mesons, into photon pairs with small angular separation. To separate signal photons from this background, photons are selected by requiring a narrow transverse shower shape in the ECAL (in the \(\eta\) coordinate), no matching reconstructed track candidates (except for electron tracks from photon conversion), and minimal energy measured in the HCAL region matched to the ECAL shower. Photon candidates are further required to be isolated from nearby particle-flow candidates, such as charged hadrons and photons, after removing those consistent with pileup [17]. A photon candidate is defined as isolated from charged hadrons.

### Table 1 Summary of uncertainties in the estimated purity for photons in the barrel (endcap) region

| Sources                        | Barrel photons (%) | Endcap photons (%) |
|-------------------------------|-------------------|-------------------|
| Statistical                   | 0.5–18.7          | 0.8–9.2           |
| Signal template shape         | 0.2–3.7           | 0.3–7.3           |
| Background template shape     | 0.4–5.2           | 1.3–88.7          |
| Residual bias                 | 0.01–4.7          | 0.05–10.1         |
| Total systematic              | 0.6–7.8           | 1.5–89.3          |

Fig. 1 An example fit of candidate boosted-decision-tree distribution with a composite template (blue histogram). The signal (background) template is shown by the green (red) solid (hatched) region. The bottom panel shows the mean of the fit values for 500 templates varied within the signal and background shape uncertainties (F) subtracted from data (D) divided by the data

Fig. 2 Purity estimates as a function of \(p_T^\gamma\) for different photon and jet pseudorapidity regions. The values are offset by 0.3, 0.6 and 0.9 for \(0.8 < |\eta| < 1.5\), \(1.5 < |\eta| < 2.1\), and \(2.1 < |\eta| < 2.5\) respectively. The total uncertainties are shown as error bars.
Fig. 3 Measured triple-differential cross section distributions as a function of $p_T$ in different bins of $|\eta^{3d}|$ for photons in the barrel region. Note that the distributions are multiplied by a factor of $10^2$, $10^4$, and $10^6$ for $0.8 < |\eta^{3d}| < 1.5$, $1.5 < |\eta^{3d}| < 2.1$, and $2.1 < |\eta^{3d}| < 2.5$ respectively. The statistical (systematic) uncertainties are shown as error bars (color bands).

Fig. 4 Measured triple-differential cross section distributions as a function of $p_T$ in different bins of $|\eta^{3d}|$ for photons in the endcap region. Note that the distributions are multiplied by a factor of $10^2$, $10^4$, and $10^6$ for $0.8 < |\eta^{3d}| < 1.5$, $1.5 < |\eta^{3d}| < 2.1$, and $2.1 < |\eta^{3d}| < 2.5$ respectively. The statistical (systematic) uncertainties are shown as error bars (color bands).

Table 2 Summary of the uncertainties in the measured cross section values for photons in the barrel (endcap) region

| Sources       | Barrel photons (%) | Endcap photons (%) |
|---------------|--------------------|--------------------|
| Statistical   | 1–20               | 1–10               |
| Purity        | 1–9                | 3–66               |
| Efficiency    | 1–9                | 5–11               |
| Luminosity    | 3                  | 3                  |
| Unfolding     | 0–5                | 0–1                |
| Total systematic | 4–12              | 6–66               |

if the sum of the $p_T$ of the charged hadron particle-flow candidates in a cone of radius $\Delta R < 0.3$ around its direction is less than 5 GeV. To limit correlations of the selected photon candidate’s shower energy with other photon quantities, an area in the vicinity of the photon candidate is eliminated in the calculation of the photon isolation (calculated similarly to charged hadron isolation but from the $p_T$ sum of the photon particle-flow candidates), leading to smaller correlation overall. Because of the pileup subtraction, the final photon isolation may be negative as calculated. Final photon candidates are required to have less than 0.0 GeV for $|\eta| < 1.44$, $-0.5 \text{ GeV}$ for $1.5 < |\eta| < 2.1$, and $-1.0 \text{ GeV}$ for $2.1 < |\eta| < 2.5$.

Several quantities related to the shape of the EM shower are then used in a boosted-decision-tree (BDT) [25] to discriminate between direct photons and photons from hadronic activity. These quantities include the transverse width of the cluster in the $\eta$ and $\phi$ coordinates in the ECAL, the calorimetry-based likelihood of this shower to come from a conversion, the pseudorapidity of the cluster, and the average pileup energy density of the event. Simulated samples of photons originating from photon+jet events, where the reconstructed photons are matched to the generated photon, are used as training samples for the signal. Samples of sim-
Simulated QCD multijet events selected at generation level as containing electromagnetically decaying final particles are used for background training. The background contribution is estimated from electrons misidentified as photons is determined from simulated photon+jet events. To validate the efficiency, large samples of $Z \rightarrow e^+e^-$ events in data and simulation are compared. Since the electrons at CMS are reconstructed by pairing ECAL energy depositions with the tracks in the tracker, electron showers can be reconstructed as photons to validate photon selection and identification. The trigger efficiency is measured to be approximately 100 (97)% with an uncertainty of $\approx 3$ (2)% for barrel (endcap) events above the corresponding trigger thresholds. To maintain well-defined trigger efficiencies and effective luminosities, the bins for the cross section are chosen so that maximum efficiency is maintained for each trigger with a separate threshold. The photon selection efficiencies for the offline preselection and isolation criteria are estimated to be $84 \pm 3.4, 83 \pm 6.2, 81 \pm 6.5$, and $88 \pm 10.1$% in $|\eta| < 0.8, 0.8 < |\eta| < 1.44, 1.56 < |\eta| < 2.1$, and $2.1 < |\eta| < 2.5$ respectively for all bins in $p_T^{\gamma}$. The statistical uncertainty in these efficiencies is negligible, and the total uncertainty is mainly due to differences between the electron and photon efficiencies observed in the simulation.

### 4 Experimental measurement

The purity of the selected candidate events is measured bin by bin in photon $p_T^{\gamma}$ and $|\eta|$. In each bin, a data-based template for the BDT output is defined for the background, and a simulation-based template is defined for the signal. The final purity is estimated using a binned maximum likelihood method [26]:

$$F(x) = f_{\text{sig}}S(x) + (1 - f_{\text{sig}})B(x).$$

Here $x$ is the BDT output, $F(x)$ denotes the fit template, $S(x)$ denotes the unity normalized signal template distribution, and $B(x)$ denotes the unity normalized background template distribution. The $f_{\text{sig}}$ parameter describes the signal purity.
log-likelihood defined as, present in the data and is obtained by maximizing the likelihood, which is equivalent to minimizing the negative of the log-likelihood defined as,

$$-\log L(f_{\text{sig}}; x_1, x_2, \ldots x_N) = -\sum_N \log F(x_i | f_{\text{sig}}).$$  

(3)

In the above equation, \( L(f_{\text{sig}}; x_1, x_2, \ldots x_N) \) is the likelihood function as a function of the \( f_{\text{sig}} \) parameter, \( x_i \) represent the individual observed values, and \( N \) represents the total number of data points. The template shape uncertainties are not treated as nuisance parameters, but are characterized using sample experiments as detailed in Sects. 4.1 and 4.2 below.

4.1 Signal templates

Signal templates are obtained using photon+jet simulated events. Because the signal template is obtained from simulation, a data control sample is used to estimate potential differences between data and simulation. Samples of \( Z/\gamma^{*} \rightarrow \mu^{+}\mu^{-}\gamma \) events are obtained by selecting events in which there are two muons and a photon candidate that is produced via final-state radiation from one of the muons. Requiring that the dimuon mass be less than the mass of the on-shell \( Z \) boson allows for the reconstruction of a mass peak in the three-body mass \( (m_{\mu^{+}\mu^{-}\gamma}) \) distribution. The sample of events in the peak of the distribution, \( 80 < m_{\mu^{+}\mu^{-}\gamma} < 100 \text{ GeV} \), is enriched with photons, though some background under the peak remains. The remaining background in the BDT distribution is estimated using the sidebands, which are obtained by inverting the \( m_{\mu^{+}\mu^{-}\gamma} \) criteria, and subtracted. The resulting distribution for data photons is then compared to the response in the simulation in the limited range of \( p_T^\gamma \) available. The difference is assigned as a systematic uncertainty in the signal shape for all \( p_T^\gamma \), in separate bins of \( \eta' \).

4.2 Background templates

The background BDT templates are obtained using a data sideband in pileup-corrected particle-flow photon isolation. Except for the photon isolation constraint, the sideband data is required to pass the same requirements as the signal. Sideband optimization is performed using simulations to select a photon isolation region with sufficient amount of data and minimum correlations between this quantity and the output of the BDT that is used to fit for the final purity. Using a mixture of simulated events containing both dijets and photon+jets, a range of isolation windows are examined. For
Fig. 7 Ratio of triple-differential cross sections as a function of $p_T^\gamma$ measured in data over the corresponding GamJet NLO theoretical prediction (obtained with the CJ15 PDFs) in different bins of $|\eta^\gamma|$ for $1.56 < |\eta^\gamma| < 2.1$. Error bars on the data are statistical uncertainties, and blue bands represent the systematic uncertainties.

Each bin of $\eta^\gamma$ and $p_T^\gamma$, a range of sideband windows are used to generate background templates by varying the candidate photon isolation constraint to an upper bound determined by data set size (nominally 4.5–5 GeV). Based on the observed data sample size, template shapes are generated randomly from the simulated shapes and then are used to perform a fit to a separate mixture of simulation with a known signal fraction. Based on these generated shapes, the bias between the known signal fraction and the signal fraction from the fit is determined using 500 trials, and the central value of this distribution is taken as the bias induced by the residual correlations. Background shapes are estimated separately for the different pseudorapidity and $p_T$ regions. The uncertainty in the correction for the bias and the difference between the final selected data template and the simulated shape are the systematic uncertainties in the background shape.

4.3 Fit and systematic uncertainties

In each bin of $|\eta^\gamma|$, $|p_T^{\text{jet}}|$, and $p_T^\gamma$ the purity is estimated by a simultaneous fit to the BDT output using the previously defined signal and background templates. An example fit are shown in Fig. 1. The uncertainty in this measured purity is estimated from sample distributions generated by varying the signal and background fit templates within their respective uncertainties. For the signal template, where the uncertainty contribution is from differences between simulation and detector response, the shapes of sample distributions are obtained by simultaneous variations across different bins of the BDT template. On the other hand, the source of background template shape uncertainty is the data sideband statistical uncertainty, which is uncorrelated across different bins of the BDT distribution. Therefore, the sample distributions for the background template are created by allowing the adjacent bins to vary independently of each other. The purity estimated in each bin and the associated uncertainty is shown in Fig. 2. The signal purity is lower at larger photon rapidities, where the selection criteria are less effective at separating direct photon signals from photons from meson decays because of the smaller opening angle between the daughter photons.

The residual bias caused by correlations is minimized, but not completely eliminated, using the sideband optimization process described in Sect. 4.2. To compensate for this residual bias, a correction is applied based on the estimated bias from the simulation. The correction applied to correct for resid-
Fig. 8 Ratio of triple-differential cross sections as a function of \( p_T^\gamma \) measured in data over the corresponding GamJet NLO theoretical prediction (obtained with the CJ15 PDFs) in different bins of \(|\eta^\gamma|\) for \( 2.1 < |\eta^\gamma| < 2.5 \). Error bars on the data are statistical uncertainties, and blue bands represent the systematic uncertainties.

4.4 Unfolding

The cross section measurements are unfolded within the fiducial volume of acceptance and phase space, which are as defined previously in this paper. With the excellent energy resolution of the ECAL, and the width of the selected bins, bin-to-bin migrations are small, but still corrected in the final result. The response matrix is determined from the true generator level \( p_T^\gamma \) and the smeared values obtained from the simulation. The D’Agostini iterative unfolding method, implemented in the RooUnfold [27] package, is used to unfold the detector effects. A systematic uncertainty in this unfolding, due to the input \( p_T^\gamma \) distribution, is obtained by reweighting the input distribution to resemble the spectrum observed in data, reproducing the response matrix, and taking the difference between the unfolded results from the reweighted response matrix to the unreweighted one. The final (small) uncertainty from this procedure is propagated to the final cross section result.

5 Comparisons with theory

The measured cross sections are compared with next-to-leading order (NLO) predictions using the modified version of the GamJet [28,29] package. The recent CJ15 [30] parton distribution functions are used as input to this prediction, and uncertainties are assigned based on the deviation from the 24 pairs of varied PDFs supplied with the CJ15 set. A tolerance factor of 1, assuming that all of the datasets used in the PDF calculation are statistically compatible and the experimental uncertainties are Gaussian, is used for the theoretical prediction. Set II of Bourhis–Fontannaz–Guillet (BFG) [31] fragmentation functions are applied to the matrix element calculations to estimate the photon production via...
parton fragmentation. Although contributions from fragmentation photons are included in these predictions, an isolation criterion requiring less than 4 GeV of hadronic energy within a cone of radius $\Delta R < 0.2$ around the photon direction is utilized, removing a large fraction of them. The central values of the renormalization, fragmentation, and PDF scales are set to $p_T^\gamma$. The scale uncertainty is quantified by varying each of the scales by factors of 0.5 and 2.0 independently, and the largest variation is taken as the systematic uncertainty. In general, the scale (PDF) uncertainty is dominant in the low (high) photon pseudorapidity bins, with the total uncertainty ranging from 10 to 25% in most cases, and as high as 70% in some $p_T^\gamma$ bins in the high $|\eta^{\text{jet}}|$ region.

The measured triple-differential cross sections are shown in Figs. 3 and 4. A summary of the uncertainty in the measured cross sections from different sources is reported in Table 2. Comparison between data and theory, along with the respective uncertainties, are provided in Figs. 5, 6, 7, and 8. The measurements are in good agreement with the NLO pQCD predictions from GamJet except in the regions of low $p_T^\gamma$ for endcap photons, where differences of up to 60% are observed between central values of the data and theoretical predictions.

6 Summary

Measurements of the triple-differential inclusive isolated-photon+jet cross section were performed as a function of photon transverse momentum ($p_T^\gamma$), photon pseudorapidity ($\eta^\gamma$), and jet pseudorapidity ($\eta^{\text{jet}}$). The measurements were carried out in pp collision at $\sqrt{s} = 8$ TeV using 19.7 fb$^{-1}$ of data collected by the CMS detector covering a kinematic range of $|\eta^{\gamma}| < 1.44$ and $1.57 < |\eta^\gamma| < 2.50$, $|\eta^{\text{jet}}| < 2.5$, $40 < p_T^\gamma < 1000$ GeV, and jet transverse momentum, $p_T^{\text{jet}}$, >25 GeV. The photon purity was estimated using a combination of templates from data and simulation, based on a multivariate technique. The measured cross sections are in good agreement with the next-to-leading order perturbative quantum chromodynamics (pQCD) prediction, and the experimental uncertainties are comparable or smaller than the theoretical ones. These measured cross sections, in different combinations of photon and jet pseudorapidities, probe pQCD over a wide range of parton momentum fractions. Inclusion of such gluon-sensitive data into the global parton distribution function (PDF) fit analyses has the potential to constrain the gluon PDFs, particularly in the regions where the measured uncertainties are smaller than the uncertainty bands of theoretical predictions.

Acknowledgements We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CA, MoST, and NSF (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSH and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC Ki (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds voor de Jonge Wetenschappers onderzoekers en de Jonge Artiesten van de Kunsten (FRIA-Belgium); the Agentschap voor Innovatief Onderzoek, Technologie en Geschiedenis der Wetenschappen (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science – EOS” – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z181100004218803; the Ministry of Education, Youth and Sports (Czech Republic); GA and SGS (Czech Republic); the Academy of Sciences, the New National Excellence Program UNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 125106, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/ 07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, grant no. 3.2989.2017 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors’ comment: Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as written in its document “CMS data preservation, re-use and open access policy” (https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid =6032&filename=CMSDataPolicyV1.2.pdf&version=2).]

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit.
to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP3.

References

1. J.M. Campbell, R.K. Ellis, C. Williams, Direct photon production at next-to-next-to-leading order. Phys. Rev. Lett. 118, 222001 (2017). https://doi.org/10.1103/PhysRevLett.118.222001. arXiv:1612.04333

2. X. Chen et al., Isolated photon and photon+jet production at NNLO QCD accuracy. Submitted to: JHEP (2019). arXiv:1904.01044

3. D. d’Enterria, J. Rojo, Quantitative constraints on the gluon distribution function in the proton from collider isolated-photon data. Nucl. Phys. B 860, 311 (2012). https://doi.org/10.1016/j.nuclphysb.2012.03.003. arXiv:1202.1762

4. L. Carminati et al., Sensitivity of the LHC isolated-gamma+jet data to the parton distribution functions of the proton. EPL 101, 61002 (2013). https://doi.org/10.1209/0295-5075/101/61002. arXiv:1212.5511

5. J.M. Campbell, J. Rojo, E. Slade, C. Williams, Direct photon production and PDF fits reloaded. Eur. Phys. J. C 78, 470 (2018). https://doi.org/10.1140/epjc/s10052-018-5944-4. arXiv:1802.03020

6. ATLAS Collaboration, Measurement of the inclusive isolated prompt photon cross section in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector. JHEP 08, 005 (2016). https://doi.org/10.1007/JHEP08(2016)005. arXiv:1605.03495

7. ATLAS Collaboration, Dynamics of isolated-photon plus jet production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. Nucl. Phys. B 875, 483 (2013). https://doi.org/10.1016/j.nuclphysb.2013.07.025. arXiv:1307.6795

8. CMS Collaboration, Measurement of the triple-differential cross section for photon+jet production in proton-proton collisions at $\sqrt{s} = 7$ TeV. JHEP 06, 009 (2014). https://doi.org/10.1007/JHEP06(2014)009. arXiv:1311.6141

9. D0 Collaboration, Measurement of the differential cross section of photon plus jet production in pp collisions at $\sqrt{s} = 1.96$ TeV. Phys. Rev. D 88, 072008 (2013). https://doi.org/10.1103/PhysRevD.88.072008. arXiv:1308.2708

10. ATLAS Collaboration, Measurement of the production cross section of an isolated photon associated with jets in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. Phys. Rev. D 85, 092014 (2012). https://doi.org/10.1103/PhysRevD.85.092014. arXiv:1203.3161

11. D0 Collaboration, Measurement of the differential cross section for the production of an isolated photon with associated jet in pp collisions at $\sqrt{s} = 1.96$ TeV. Phys. Lett. B 666, 435 (2008). https://doi.org/10.1016/j.physletb.2008.06.076. arXiv:0804.1107

12. CMS Collaboration, The CMS experiment at the CERN LHC. JINST 3, S08004 (2008). https://doi.org/10.1088/1748-0221/3/08/S08004

13. CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector. JINST 12, P10003 (2017). https://doi.org/10.1088/1748-0221/12/10/p10003. arXiv:1706.04965

14. M. Cacciari, G.P. Salam, G. Soyez, The anti-$k_T$ jet clustering algorithm. JHEP 04, 063 (2008). https://doi.org/10.1088/1126-6708/2008/04/063. arXiv:0802.1189

15. CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 7 TeV. JINST 12, P02014 (2017). https://doi.org/10.1088/1748-0221/12/02/P02014. arXiv:1607.03663

16. CMS Collaboration, Jet algorithms performance in 13 TeV data. CMS Physics Analysis Summary CMS-PAS-JME-16-003, CERN (2017)

17. CMS Collaboration, Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV. JINST 10, P08010 (2015). https://doi.org/10.1088/1748-0221/10/08/P08010. arXiv:1502.02702

18. CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV. JINST 7, P10002 (2012). https://doi.org/10.1088/1748-0221/7/10/P10002. arXiv:1206.4071

19. CMS Collaboration, The CMS trigger system. JINST 12, P01020 (2017). https://doi.org/10.1088/1748-0221/12/01/P01020. arXiv:1609.02366

20. T. Sjostrand, S. Mrenna, P. Skands, pythia 6.4 physics and manual. JHEP 05, 026 (2006). https://doi.org/10.1088/1126-6708/2006/05/026. arXiv:hep-ph/0603175

21. GEANT4 Collaboration, Geant4—a simulation toolkit. Nucl. Instrum. Methods A 506, 250 (2003). https://doi.org/10.1016/S0168-9002(03)01368-8

22. F. Maltoni, T. Stelzer, MadEvent: automatic event generation with MadGraph. JHEP 02, 027 (2003). https://doi.org/10.1088/1126-6708/2003/02/027. arXiv:hep-ph/0208156

23. J. Pumplin et al., New generation of parton distributions with uncertainties from global QCD analysis. JHEP 07, 012 (2002). https://doi.org/10.1088/1126-6708/2002/07/012. arXiv:hep-ph/0201195

24. CMS Collaboration, Study of the underlying event at forward rapidity in pp collisions at $\sqrt{s} = 0.9, 2.76,$ and $7$ TeV. JHEP 04, 072 (2013). https://doi.org/10.1007/JHEP04(2013)072

25. B.P. Roe et al., Boosted decision trees as an alternative to artificial neural networks for particle identification. Nucl. Instrum. Methods 543, 577 (2005). https://doi.org/10.1016/j.nima.2004.12.018

26. W. Verkerke, D.P. Kirkby, The RooFit toolkit for data modeling. In: Computing in High Energy and Nuclear Physics (CHEP03): Proceedings, La Jolla, USA, March, 2003, pp. Note: eConf C030324.186 (2003) MOLT007 (2003). arXiv:physics/0306116

27. G. D’Agostini, Probability and measurement uncertainty in physics: a Bayesian primer (1995). arXiv:hep-ph/9512295

28. H. Baer, J. Ohnemus, J.F. Owens, A calculation of the direct photon-plus jet cross section in the next-to-leading-logarithm approximation. Phys. Lett. B 234, 127 (1990). https://doi.org/10.1016/0370-2693(90)92015-B

29. H. Baer, J. Ohnemus, J.F. Owens, Next-to-leading-logarithm calculation of direct photon production. Phys. Rev. D 42, 61 (1990). https://doi.org/10.1103/PhysRevD.42.61

30. A. Accardi et al., Constraints on large-$x$ parton distributions from new weak boson production and deep-inelastic scattering data. Phys. Rev. D 93, 114017 (2016). https://doi.org/10.1103/PhysRevD.93.114017. arXiv:1602.03154

31. L. Bourhis, M. Fontannaz, J.P. Guillet, Quarks and gluon fragmentation functions into photons. Eur. Phys. J. C 2, 529 (1998). https://doi.org/10.1007/s100520005138. arXiv:hep-ph/9704447
National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece
K. Kousouris, I. Papakrivopoulos, G. Tsiopolitis

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F. A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók, M. Csanad, N. Filipovic, P. Major, M. I. Nagy, G. Pasztor, O. Surányi, G. I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horváth, Hunyadi, F. Sikler, T. Vámi, V. Veszpremi, G. Vesztergombi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z. L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISC), Bangalore, India
S. Choudhury, J. R. Komaragiri, P. C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati, C. Kar, P. Mal, K. Mandal, A. Nayak, S. Roy Chowdhury, D. K. Sahoo, S. K. Swain

Panjab University, Chandigarh, India
S. Bansal, S. B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, A. Mehta, K. Sandeep, S. Sharma, J. B. Singh, A. K. Virdi, G. Walia

University of Delhi, Delhi, India
A. Bhardwaj, B. C. Choudhary, R. B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj, M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, D. Bhowmik, S. Dey, S. Dutt, S. Dutta, S. Ghosh, M. Maity, K. Mondal, S. Nandan, A. Purohit, P. K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar, M. Sharan, B. Singh, S. Thakur

Indian Institute of Technology Madras, Madras, India
P. K. Behera, A. Muhammad

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, D. K. Mishra, P. K. Netrakanti, L. M. Pant, P. Shukla, P. Suggisetti

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M. A. Bhat, S. Dugad, G. B. Mohanty, N. Sur, Ravindra Kumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guhain, Sa. Jain, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Duba, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, E. Eskandari Tadavani, S. M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Nasiri, F. Rezaei Hosseinabadi, B. Safarzadeh, M. Zeinali
Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D. M. Morse, T. Orimoto,
A. Tishelman-charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, O. Charaf, T. Gunter, K. A. Hahn, N. Odell, M. H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D. J. Karmgard, K. Lannon, W. Li, N. Loukas,
N. Marinelli, F. Meng, C. Mueller, Y. Musienko, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne,
A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L. S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, T. Y. Ling, W. Luo, B. L. Winer

Princeton University, Princeton, USA
S. Cooperstein, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange,
M. T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland,
C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V. E. Barnes, S. Das, L. Gutay, M. Jones, A. W. Jung, A. Khatiwada, B. Mahakud, D. H. Miller, N. Neumeister,
C. C. Peng, S. Piperov, H. Qiu, J. F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y. T. Duh, J. L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han,
O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiariito, J. P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan,
R. Kunnawalkam Elayavalli, S. Kyriacou, I. Lafflote, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur,
S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, USA
A. G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A & M University, College Station, USA
O. Bouhali, C. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang,
T. Kamon, S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Dadov, F. De Guio, P. R. Dudero, S. Kunori, K. Lamichhane, S. W. Lee, T. Mengke, S. Muthumuni,
T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, J. D. Ruiz Alvarez,
P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu
University of Virginia, Charlottesville, USA
M. W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang,
E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P. E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin-Madison, Madison, WI, USA
J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber\textsuperscript{75}, M. Grothe, M. Herndon, A. Hervé,
U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W. H. Smith,
N. Woods

\textsuperscript{†} Deceased

1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at University of Chinese Academy of Sciences, Beijing, China
7: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’,
   Moscow, Russia
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Fayoum University, El-Fayoum, Egypt
10: Now at British University in Egypt, Cairo, Egypt
11: Now at Helwan University, Cairo, Egypt
12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at Ilia State University, Tbilisi, Georgia
17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
19: Also at University of Hamburg, Hamburg, Germany
20: Also at Brandenburg University of Technology, Cottbus, Germany
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
24: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
25: Also at Institute of Physics, Bhubaneswar, India
26: Also at Shoolini University, Solan, India
27: Also at University of Visva-Bharati, Santiniketan, India
28: Also at Isfahan University of Technology, Isfahan, Iran
29: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
30: Also at ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC
   DEVELOPMENT, Bologna, Italy
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
33: Also at Kyung Hee University, Department of Physics, Seoul, Korea
34: Also at International Islamic University, of Malaysia, Kuala Lumpur, Malaysia
35: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
36: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
37: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
38: Also at Institute for Nuclear Research, Moscow, Russia
39: Now at National Research Nuclear University 'Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
41: Also at University of Florida, Gainesville, USA
42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
43: Also at California Institute of Technology, Pasadena, USA
44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
46: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy
47: Also at University of Belgrade, Belgrade, Serbia
48: Also at National and Kapodistrian University of Athens, Athens, Greece
49: Also at Riga Technical University, Riga, Latvia
50: Also at Universität Zürich, Zurich, Switzerland
51: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
52: Also at Adiyaman University, Adiyaman, Turkey
53: Also at Istanbul Aydin University, Istanbul, Turkey
54: Also at Mersin University, Mersin, Turkey
55: Also at Piri Reis University, Istanbul, Turkey
56: Also at Ozyegin University, Istanbul, Turkey
57: Also at Izmir Institute of Technology, Izmir, Turkey
58: Also at Marmara University, Istanbul, Turkey
59: Also at Kafkas University, Kars, Turkey
60: Also at Istanbul University, Istanbul, Turkey
61: Also at Istanbul Bilgi University, Istanbul, Turkey
62: Also at Hacettepe University, Ankara, Turkey
63: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
64: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
65: Also at Monash University, Faculty of Science, Clayton, Australia
66: Also at Bethel University, St. Paul, USA
67: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
68: Also at Purdue University, West Lafayette, USA
69: Also at Beykent University, Istanbul, Turkey
70: Also at Bingol University, Bingol, Turkey
71: Also at Sinop University, Sinop, Turkey
72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
73: Also at Texas A&M University at Qatar, Doha, Qatar
74: Also at Kyungpook National University, Daegu, Korea
75: Also at University of Hyderabad, Hyderabad, India