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Citation: Sirunyan, A. M. et al. "Evidence for the Associated Production of a Single Top Quark and a Photon in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV." Physical Review Letters 121, 22 (November 2018): 221802 © 2018 CERN for the CMS Collaboration

As Published: <https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.121.221802>

Publisher: American Physical Society

Persistent URL: <http://hdl.handle.net/1721.1/119375>


Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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Evidence for the Associated Production of a Single Top Quark and a Photon in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

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 (Received 8 August 2018; published 29 November 2018)

The first evidence of events consistent with the production of a single top quark in association with a photon is reported. The analysis is based on proton-proton collisions at $\sqrt{s} = 13$ TeV and recorded by the CMS experiment in 2016, corresponding to an integrated luminosity of 35.9 fb^{-1} . Events are selected by requiring the presence of a muon (μ), a photon (γ), an imbalance in transverse momentum from an undetected neutrino (ν), and at least two jets (j) of which exactly one is identified as associated with the hadronization of a b quark. A multivariate discriminant based on topological and kinematic event properties is employed to separate signal from background processes. An excess above the background-only hypothesis is observed, with a significance of 4.4 standard deviations. A fiducial cross section is measured for isolated photons with transverse momentum greater than 25 GeV in the central region of the detector. The measured product of the cross section and branching fraction is $\sigma(pp \rightarrow t\gamma j)\mathcal{B}(t \rightarrow \mu\nu b) = 115 \pm 17(\text{stat}) \pm 30(\text{syst}) \text{ fb}$, which is consistent with the standard model prediction.

DOI: [10.1103/PhysRevLett.121.221802](https://doi.org/10.1103/PhysRevLett.121.221802)

The study of top quark production in association with a photon is an important test of the standard model (SM) description of top quark interactions with gauge bosons, and plays an important role in the search for physics beyond the SM. The cross section for single top quark production in association with a photon is sensitive to the top quark charge, and to its electric and magnetic dipole moments [1,2].

The cross section for the production of a top quark-antiquark pair and an associated photon ($t\bar{t} + \gamma$) has been measured by the CDF Collaboration at the Fermilab Tevatron in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV [3], and by the ATLAS and CMS Collaborations in proton-proton (pp) collisions at the CERN LHC at 8 TeV [4,5]. All measurements are consistent with SM predictions.

The SM predicts three different mechanisms for the production of a single top quark in association with a photon at the LHC: t -channel, s -channel, and tW production, where the largest contribution comes from the t channel. This Letter presents first evidence for single top quark production in association with a photon in the t channel. The data were collected in 2016 by the CMS experiment at $\sqrt{s} = 13$ TeV and correspond to an integrated luminosity of 35.9 fb^{-1} . One of the distinctive

signatures of the signal is the presence of a forward light-flavor energetic jet in the final state that arises from the spacelike nature of the W boson propagator. The search targets events with a top quark, a photon, and at least one additional light-flavor jet, ($t\gamma j$) where the top quark decays into a W boson and a b quark, followed by the W boson decay into a muon and a neutrino. Figure 1 shows representative Feynman diagrams for the process $t\gamma j$ including the leptonic decay of the W boson produced in the top quark decay.

This analysis focuses on the muon decay channel since it enables a good signal selection efficiency with low background contamination. The final state includes possible contributions from $W \rightarrow \tau\nu_\tau$ where the τ lepton decays to $\mu\nu_\mu\nu_\tau$. The kinematic and topological properties of the signal are exploited through a multivariate technique to discriminate against the background processes. The background can be divided into two types: events which contain a genuine photon, such as $t\bar{t} + \gamma$, $W\gamma + \text{jets}$, and $Z\gamma + \text{jets}$ and events in which the photon candidate arises from a misidentified jet, such as $t\bar{t}$, $W + \text{jets}$, and $Z + \text{jets}$ processes.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections, are contained within the superconducting solenoid volume. Extensive forward calorimetry complements the coverage provided by the barrel and end cap detectors. Muons are detected in gas-ionization detectors embedded in the steel

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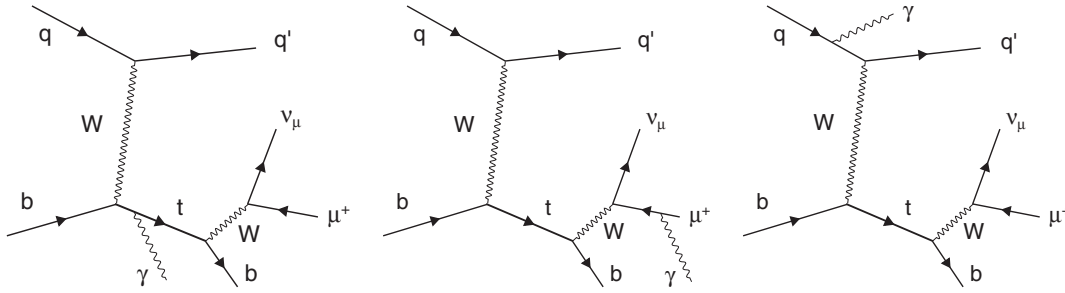


FIG. 1. Representative t -channel Feynman diagrams for single top quark production in association with a photon, including the leptonic decay of the W boson produced in the top quark decay.

flux-return yoke outside the solenoid. Online event selection is accomplished via the two-tiered CMS trigger system [6]. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables used in this analysis, can be found in Ref. [7].

Simulated samples for the $t\gamma j$ signal are generated at next-to-leading order (NLO) using the MADGRAPH5_AMC@NLO v 2.2.2 event generator [8], with a minimum transverse momentum requirement of $p_T > 10$ GeV and a pseudorapidity requirement of $|\eta| < 2.6$ for the associated photon. The angular separation between the photon and all other particles is required to be $\Delta R > 0.05$, where $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and ϕ is the azimuthal angle in radians. The NNPDF3.0 [9] parton distribution functions (PDFs) are used and the top quark mass is set to 172.5 GeV. After these requirements, an inclusive cross section of $2.95 \pm 0.13 \pm 0.03$ pb is obtained, where the first uncertainty is associated with the renormalization and factorization scales and the second uncertainty with the PDFs. These uncertainties are derived using the SYSCALC program [10].

Samples of simulated events for the production of $t\bar{t} + \gamma$, $W + \text{jets}$, $W\gamma + \text{jets}$, Drell-Yan events, $Z\gamma + \text{jets}$, and diboson $+ \gamma$ are generated at NLO using MADGRAPH5_AMC@NLO. Single top quark events in t , s , and tW channels, as well as $t\bar{t}$ events, are generated with the NLO POWHEG v2 event generator [11–14]. The overlaps between the $t\gamma j$ signal sample and the tj inclusive sample, and between $V\gamma + \text{jets}$ and $V + \text{jets}$ samples are removed, where V is a W or Z boson.

Showering and hadronization for all of the simulated samples are implemented with PYTHIA v8.212 [15,16] with the underlying event tune CUETP8M1 [17]. To match the generated events with PYTHIA v8.212 parton shower, the FxFx [18] and the MLM [19] prescriptions are used.

The CMS detector response for all simulated samples is modeled using GEANT4 v9.4 [20]. The simulated samples include the presence of additional pp interactions in the same or neighboring bunch crossings (pileup). The distribution of pileup events in simulation is weighted to match that observed in data.

The particle-flow (PF) algorithm [21] is used for the identification and reconstruction of individual particles in

an event using a combination of information from all subdetectors. It identifies each reconstructed particle as a muon, an electron, a photon, a neutral or a charged hadron. Data samples are selected based on a single-muon trigger, requiring a muon with $p_T > 24$ GeV and $|\eta| < 2.4$. Events are required to have a well-reconstructed primary vertex which is identified as the one with the largest value of summed particle p_T^2 [22]. The simulated events are weighted in order to reproduce the reconstruction and trigger efficiencies in data.

Jets are reconstructed from the PF candidates using the anti- k_T algorithm [23] with a distance parameter $R = 0.4$, implemented in the FASTJET package [24]. Corrections are applied to the jet energy to subtract the contribution from pileup interactions. Jets are tagged as associated to the hadronization of b quarks (b jets) using secondary vertex algorithm, which combines the secondary vertex and track-based lifetime information [25]. The working point chosen for the algorithm, corresponds to a b tagging efficiency of 70%, and misidentification rates of 1% and 15% for light quark jets and c jets, respectively [25]. Events are required to have at least two jets with $p_T > 40$ GeV, one of which must be b -tagged with $|\eta| < 2.5$ and another must lie within the range $|\eta| < 4.7$.

Events are required to contain exactly one isolated muon with $p_T > 26$ GeV and $|\eta| < 2.4$. The isolation is calculated from the reconstructed charged and neutral PF candidates and is corrected for pileup effects [26]. In order to reduce the contribution of background processes with multiple leptons in the final state, events containing additional muon candidates satisfying loose selection criteria or containing electron candidates are rejected [26].

Photon candidates are built from clusters of high-energy deposits in the ECAL. Photon identification depends on isolation and shower shape variables which reflect the energy dispersion in η , and is described in detail in Ref. [27]. The effects of pileup on the isolation variables are accounted for [28].

A conversion-safe electron veto algorithm [27] is used to reject electrons. It discards events containing a track with an energy deposit in the innermost layer of the pixel detector which is not connected to a reconstructed conversion vertex from a photon cluster in the ECAL. Events

are required to have exactly one isolated photon candidate with $p_T > 25$ GeV and $|\eta| < 1.44$.

The missing transverse momentum p_T^{miss} is defined as the negative vector sum of the momenta of all reconstructed PF objects in the transverse plane. The magnitude of p_T^{miss} is required to be larger than 30 GeV.

In order to select well-isolated objects, the photon is required to be separated from the b jet, the light-flavor jet, and any muon candidates by $\Delta R(X, \gamma) > 0.5$, where X stands for μ , b jet, or light-flavor jet. The angular separation between the muon candidate and jets is required to satisfy $\Delta R(\mu, \text{jets}) > 0.3$. The signal region is defined as the region where all the requirements described above are satisfied.

The top quark is reconstructed using the muon, the b jet candidate, and p_T^{miss} where the transverse momentum of the neutrino, which escapes detection, is assumed to be equal to p_T^{miss} . The longitudinal component of the neutrino momentum is obtained by constraining the invariant mass of the muon and the neutrino to the W boson mass, resulting in a quadratic equation. When the two solutions are real, the one with smaller absolute value is taken, while when the solutions are complex the real part is taken [29]. The top quark momentum is reconstructed by combining the momenta of the b jet and of the reconstructed W boson.

The backgrounds from $W\gamma$ + jets, $Z\gamma$ + jets, diboson + γ , s , and tW channel single top quark with a photon production are estimated using simulation. The contribution of the misidentified photon background is estimated from the measurement of the p_T -dependent probability for a jet to be reconstructed as a photon using the method described in Refs. [30,31]. The misidentification probability is calculated based on the near independence of the shower shape and photon isolation variables, which permits the factorization of the misidentification probability and hence its estimation outside the signal region.

Several sources of uncertainties are considered in this estimation. The first comes from the definition of the sideband region and is due to possible correlations between the photon shower shape and photon isolation, that are assumed to be independent. The second source is due to the small contribution of genuine photons in the sideband region, which is estimated from simulation. The last source of uncertainty arises from the limited number of events available in the various photon p_T bins considered in the estimation of the background from misidentified jets.

The uncertainties in the lepton trigger, reconstruction, and identification efficiencies are evaluated using Drell-Yan events [26,32,33]. The uncertainties from the photon selection efficiency and photon energy scale are obtained using $Z \rightarrow e^+ + e^-$ events. The photon energy scale uncertainty is found to be 1% [34,35]. The uncertainty from pileup modeling is evaluated by varying the total pp inelastic cross section by 4.6% [36] and reweighting the simulation accordingly. The uncertainties in the jet energy resolution and jet energy scale (JES) [37,38], and p_T^{miss} are

TABLE I. Event yields after the event selection in data and for each SM contribution. The expected yields are presented with their statistical and systematic uncertainties combined.

Process	Event yield
$t\bar{t} + \gamma$	1401 ± 131
$W\gamma$ + jets	329 ± 78
$Z\gamma$ + jets	232 ± 55
Misidentified photon	374 ± 74
$t\gamma$ (s and tW channel)	57 ± 8
$VV\gamma$	8 ± 3
Total background	2401 ± 178
Expected signal	154 ± 24
Total SM prediction	2555 ± 180
Data	2535

also considered. The b jet identification and misidentification corrections are applied as a function of the p_T and η of the jet [25]. The systematic uncertainty in the integrated luminosity is estimated to be 2.5% [39]. The uncertainties in the $W\gamma$ + jets, $Z\gamma$ + jets, $VV\gamma$, and single top quark contributions are based on the CMS measurements from Refs. [31,40,41,42], respectively. Several sources of uncertainties in the signal modeling are taken into account. The uncertainty from the variations of renormalization and factorization scales is estimated by comparing the simulated samples with scales halved and doubled with respect to the initial value. The uncertainty from the PDF choice is evaluated using the replicas of the NNPDF3.0 PDF set. The uncertainty from parton shower modeling and hadronization is obtained by comparing the results derived from PYTHIA v8.212 and HERWIG++ v2.3 [43].

After the selection, the total number of observed events is 2535 of which 2401 ± 178 events are expected from the SM background in absence of $t\gamma$ signal, where the uncertainty includes both the statistical and systematic components. The expected number of signal events from the SM is 154 ± 24 . The dominant background is $t\bar{t} + \gamma$, and amounts to 55% of the total background yield. Event yields in data and simulation for all background processes are presented in Table I where the $t\bar{t} + \gamma$ yield and its uncertainty are predicted from simulation.

The SM prediction for the signal is much smaller than the background, so it is important to optimize the separation between signal and background events. A multivariate classification approach, based on a boosted decision tree (BDT) [44,45], is used. The BDT input variables in decreasing order of importance are (i) η of the light-flavor jet, (ii) $\cos \theta$, which is the cosine of the angle between the muon candidate and the light-flavor jet in the top quark rest frame, (iii) η of the muon candidate, (iv) ΔR (light-flavor jet, γ), (v) reconstructed top quark mass $m_{\mu b}$, (vi) jet multiplicity, (vii) transverse mass of the reconstructed W boson, and (viii) muon charge. The distributions of some of the most important BDT input variables for data and SM

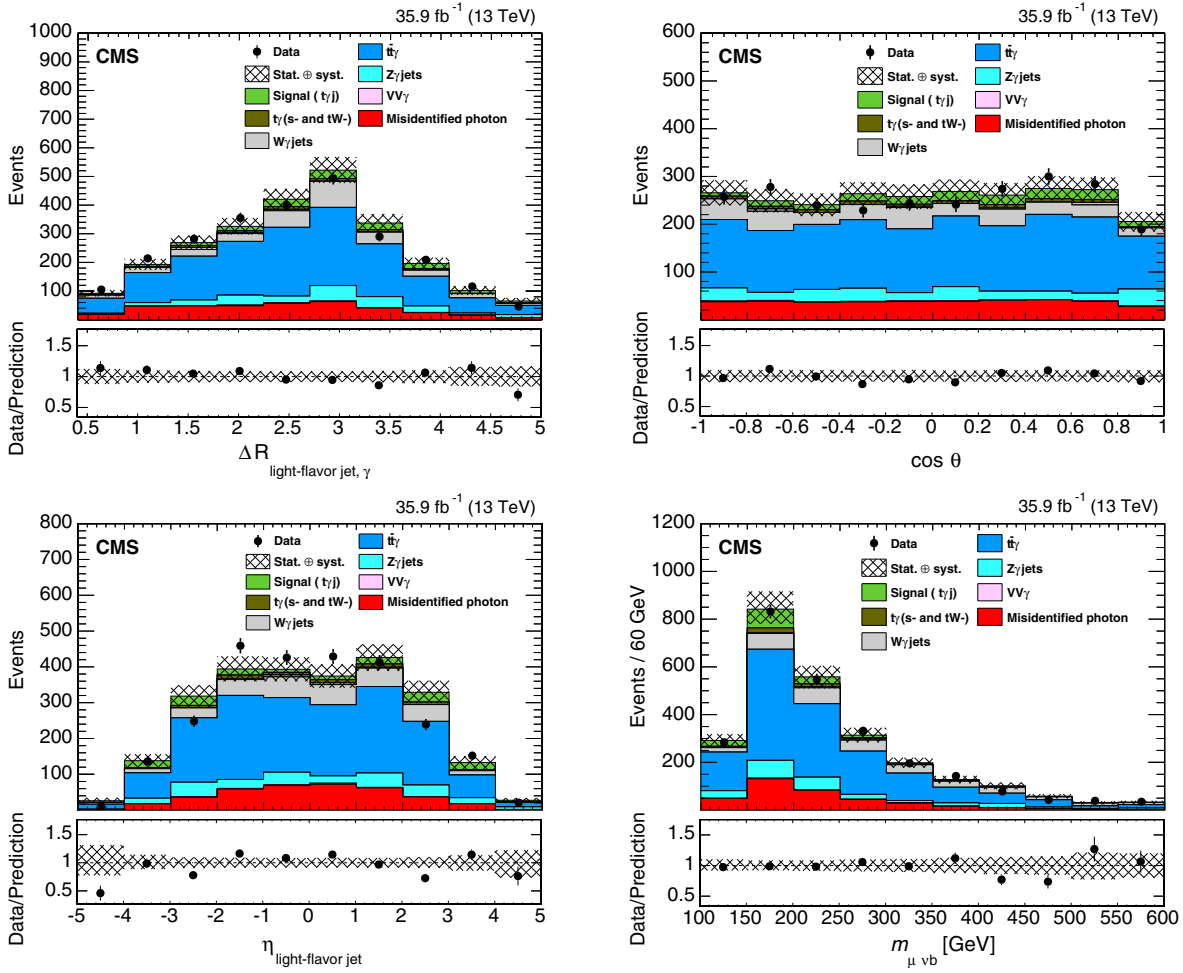


FIG. 2. Distributions of some of the input variables to the BDT: $\Delta R(\text{light jet}, \gamma)$ (upper left), $\cos \theta$ (upper right), η of the light-flavor jet (lower left), and $m_{\mu\nu b}$ (lower right) after the final event selection in data (points), and the SM prediction (filled histograms). The hatched band shows the statistical and systematic uncertainties in the estimated signal and background yields, and the vertical bars on the points represent the statistical uncertainties of the data. The ratios of the data to the SM predictions are shown in the bottom panels.

predictions after the event selection are presented in Fig. 2, where the hatched band indicates the overall uncertainty on the SM predictions. It includes a sizable statistical component besides the systematic uncertainties, which are all propagated to the final results.

The BDT is trained to distinguish signal from background and provides a single discriminant value for every event. The BDT output distribution in data is parametrized as

$$F(x) = C_{\text{sig}} S_{\text{sig}}(x) + C_{\bar{t}\bar{\gamma}} S_{\bar{t}\bar{\gamma}}(x) + C_{W\gamma j} S_{W\gamma j}(x) + C_{Z\gamma j} S_{Z\gamma j}(x) + C_{\text{misid}} S_{\text{misid}}(x) + C_B S_B(x), \quad (1)$$

where x is the BDT output, $S_{\text{sig}}(x)$, $S_{W\gamma j}(x)$, $S_{Z\gamma j}(x)$, $S_{\text{misid}}(x)$, and $S_B(x)$ are the normalized distributions (templates) for the signal, $\bar{t}\bar{\gamma}$, $W\gamma$ + jets, $Z\gamma$ + jets, the misidentified photon background, and the sum of all other backgrounds which includes single top quark production and $VV\gamma$, respectively. The quantities C_{sig} , $C_{\bar{t}\bar{\gamma}}$,

$C_{W\gamma j}$, $C_{Z\gamma j}$, C_{misid} , and C_B are the corresponding normalizations from which C_{sig} and $C_{\bar{t}\bar{\gamma}}$ are left free in the fit, while the other terms are constrained by their associated uncertainties. The different templates, $S(x)$, are taken from simulation except for $\bar{t}\bar{\gamma}$ and misidentified photons. The distribution $S_{\text{misid}}(x)$ is obtained with the method described above, calculating the yield as a function of BDT output. The template $S_{\bar{t}\bar{\gamma}}(x)$ is estimated from data using a control region defined by requiring exactly two b -tagged jets, while keeping all other selection criteria the same as for the signal region. The requirement of two b -tagged jets ensures a high contribution from $\bar{t}\bar{\gamma}$, while suppressing the contributions from all other processes. The uncertainty in the difference of shape between events with two b -tagged and one b -tagged jet is calculated using simulation and accounted for as a systematic uncertainty. In addition, $S_{W\gamma j}(x)$ is validated in data, in a control region enriched in $W\gamma$ + jets events, via the substitution of the signal b jet requirement by a b jet veto.

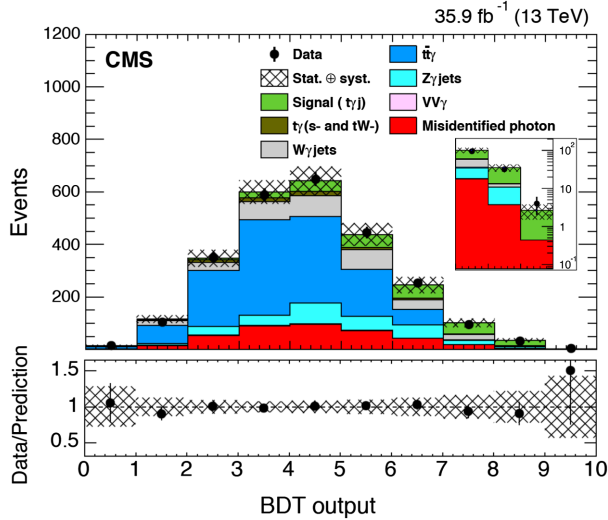


FIG. 3. The BDT output distribution for data and SM predictions after performing the fit. The inset presents a closeup of the last three bins plotted on log scale. The hatched band shows the statistical and systematic uncertainties in the estimated signal and background yields, and the vertical bars on the points represent the statistical uncertainties of the data. The ratio of the data to the SM prediction is shown in the bottom panel.

In order to extract the signal cross section and $t\bar{t} + \gamma$ background normalization, a simultaneous binned likelihood fit is performed on the BDT distribution in the signal region and the $t\bar{t} + \gamma$ control region. Including events from the $t\bar{t} + \gamma$ control region in the fit is useful to constrain the $t\bar{t} + \gamma$ background normalization. Each source of systematic uncertainty is included as a nuisance parameter in the likelihood function. The normalizations of backgrounds except for $t\bar{t} + \gamma$ are left free to vary within the systematic uncertainties. A profile likelihood ratio test statistic is constructed by generating pseudodata for the background-only and for the signal-plus-background hypotheses. The BDT output distribution for data and SM prediction after the fit is shown in Fig. 3.

All of the systematic uncertainties affect both the normalization of backgrounds and shape of the BDT discriminant, except those associated with the integrated luminosity, photon energy scale, p_T^{miss} , and background rates that only affect the normalization. The shape uncertainties have Gaussian constraints, while rate uncertainties have log-normal forms. The main systematic uncertainties in the signal cross section arise from the JES, signal modeling, normalization of $Z\gamma + \text{jets}$, and b tagging and mistagging rates, and amount to 12%, 9%, 8%, and 7%, respectively. The impact of the uncertainty from each source is calculated by performing the fit with all other nuisance parameters fixed to their fitted values. The number of signal and $t\bar{t} + \gamma$ events after the fit are 220 ± 63 and 1221 ± 121 , which both agree with the expected yields within the uncertainties.

An excess of events above the expected background is observed at a p value [46] of 4.27×10^{-6} , which

corresponds to a significance of 4.4 standard deviations. The median expected significance is 3.0, and the 68% and 95% confidence level ranges for the expected significance are [1.5, 4.0] and [0, 8.7], respectively. A fiducial product of the cross section and branching fraction of $\sigma(pp \rightarrow t\bar{t}\gamma)\mathcal{B}(t \rightarrow \mu\nu b) = 115 \pm 17(\text{stat}) \pm 30(\text{syst}) \text{ fb}$ is measured in the phase space defined by the photon transverse momentum $p_{T,\gamma} > 25 \text{ GeV}$, $|\eta_\gamma| < 1.44$, and $\Delta R(X, \gamma) > 0.5$, where X stands for μ , b jet, light-flavor jet. The expected SM product of the cross section and branching fraction within this fiducial phase space is $81 \pm 4 \text{ fb}$, in agreement with the measurement. This is the first experimental evidence for single top quark production in association with a photon.

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 centres 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: BMFWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); 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 INSF (Iran).

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