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Evidence for the Higgs Boson Decay to a Z Boson and a Photon at the LHC

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(Received 8 September 2023; accepted 27 November 2023; published 11 January 2024)

The first evidence for the Higgs boson decay to a Z boson and a photon is presented, with a statistical significance of 3.4 standard deviations. The result is derived from a combined analysis of the searches performed by the ATLAS and CMS Collaborations with proton-proton collision datasets collected at the CERN Large Hadron Collider (LHC) from 2015 to 2018. These correspond to integrated luminosities of around 140 fb^{-1} for each experiment, at a center-of-mass energy of 13 TeV. The measured signal yield is 2.2 ± 0.7 times the standard model prediction, and agrees with the theoretical expectation within 1.9 standard deviations.

DOI: 10.1103/PhysRevLett.132.021803

Since the discovery of the Higgs boson [1–3] by the ATLAS [4] and CMS [5] Collaborations in 2012, a detailed program of measurements [6–8] has confirmed its couplings and other properties to be mostly consistent with those predicted by the standard model (SM). However, there are several rare Higgs boson decay channels, including $H \to Z\gamma$ [9–11], that have not been observed. These channels provide probes for possible contributions arising from physics beyond the SM (BSM physics). During LHC Run 2 (2015–2018), large data samples of proton-proton collisions at $\sqrt{s} = 13$ TeV were collected by the two experiments, improving the sensitivity to such decays.

In the SM, the $H \to Z\gamma$ decay is expected to have a relatively small branching fraction of $(1.5 \pm 0.1) \times 10^{-3}$ for a Higgs boson mass (m_H) close to 125 GeV [12,13]. As the $H \to Z\gamma$ decay occurs via loop diagrams, with examples given in Fig. 1, it is sensitive to modifications in several BSM scenarios that would cause the branching fraction to be enhanced compared with the SM value. Examples include models where the Higgs boson is a composite state [14], a pseudo Nambu-Goldstone boson [15], or a neutral scalar originating from a different source [16,17]. Branching fractions deviating from the SM value are also expected for models with additional colorless charged scalars, leptons, or vector bosons that couple to the Higgs boson, because of their contributions via loop corrections [18–20].

This Letter reports the first evidence for $H \to Z\gamma$ decay obtained from a combination of ATLAS [21] and CMS [22] searches for this channel. The analyses are based on the Run 2 datasets collected by the ATLAS and CMS experiments, corresponding to integrated luminosities of 139 and 138 fb^{-1}, respectively, at a center-of-mass energy of 13 TeV. Previous $H \to Z\gamma$ searches by the ATLAS and CMS Collaborations used the datasets collected at $\sqrt{s} = 7$ and 8 TeV, and partial datasets collected at $\sqrt{s} = 13$ TeV [23–25].

The ATLAS detector [4] is a multipurpose particle detector with cylindrical geometry. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic sampling calorimeters, and a muon spectrometer with three toroidal superconducting magnets, providing nearly 4π coverage in solid angle. The CMS apparatus [5] is a nearly hermetic, multipurpose detector. Contained within a 3.8 T superconducting solenoid are an all-silicon inner tracker, a crystal electromagnetic calorimeter, and a brass-scintillator hadron calorimeter. Gas-ionization muon detectors are embedded in the flux-return yoke outside the solenoid.

The ATLAS and CMS $H \to Z\gamma$ analyses share many features. In both, the Z boson is reconstructed through its decays into electron or muon pairs ($Z \to \ell^+\ell^-$, $\ell = e$ or μ), requiring a dilepton mass above 50 GeV. The leptons provide a clean signature and ensure a high trigger

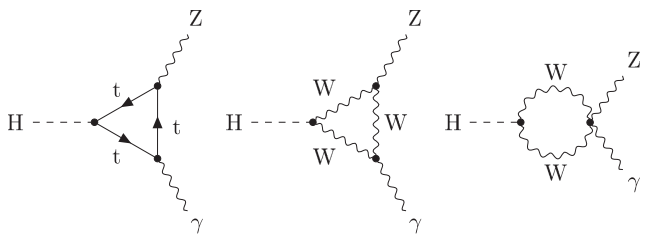


FIG. 1. Examples of Feynman diagrams for $H \to Z\gamma$ decay.

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efficiency and good invariant mass resolution for the final-state products of the Higgs boson decay. The photon candidate is reconstructed from energy clusters in the electromagnetic calorimeters. It must satisfy identification criteria and be isolated from other event activity. The dominant backgrounds arise from Drell-Yan production in association with a photon or a jet misidentified as a photon. In both analyses, the production of the SM Higgs boson signal is modeled with the POWHEG BOX v2 Monte Carlo event generator [26–31].

After the reconstruction and selection of $H \to Z\gamma$ candidate events, the signal is identified as a narrow resonant peak at m_H in the $Z\gamma$ invariant mass ($m_{Z\gamma}$) distribution, calculated as the invariant mass of the $\ell^+\ell^-\gamma$ system. The $m_{Z\gamma}$ resolution is improved by dedicated final-state radiation corrections to the momenta of muons with nearby photons, and via kinematic fits for the dilepton mass of the Z boson candidate using a Breit-Wigner line shape to model the Z boson resonance, convolved with a Gaussian response function for the leptons [32,33]. The resulting $m_{Z\gamma}$ resolution is 1.4–2 GeV, depending on the final state and event topology.

To enhance the sensitivity, both analyses assign events to categories with different signal-to-background ratios by exploiting the kinematic features of different Higgs boson production modes. The ATLAS analysis assigns each event to one of six categories, including a category targeting the vector-boson fusion (VBF) topology, which requires the presence of at least two jets and a selection on the output score of a dedicated boosted decision tree (BDT). The remaining five categories target other Higgs boson production modes, which are defined with different lepton flavors and kinematic properties of the momentum of the $Z\gamma$ system transverse to the beam direction [34].

The CMS analysis assigns each event to one of eight categories, including a category with additional leptons targeting the production of Higgs bosons associated with either a weak vector boson or a top quark pair, and three categories defined by the output score of a dedicated BDT targeting the VBF topology. The other four categories are defined by the output score of another BDT exploiting the differences between the kinematic properties of $H \to Z\gamma$ signal events and background events.

Simultaneous signal-plus-background fits across the analysis categories are performed to the $Z\gamma$ invariant mass distribution, with analytic signal and background functions. The signal models are from Crystal Ball [35] and Gaussian functions, and the background models are based on exponential functions, power law functions, Laurent series, and Bernstein polynomials. Experimental and theoretical uncertainties affecting the expected number of signal events, the shape of the $Z\gamma$ invariant mass distribution from the $H \to Z\gamma$ signal process, and the background models are considered as constrained nuisance parameters. The Higgs boson production cross sections and $H \to Z\gamma$ branching fraction used to normalize the signal are common to both experiments. In both analyses, the parameters of the analytic background functions are determined from the data. Both the ATLAS and CMS analyses measure the signal strength (μ) defined as the ratio of the Higgs boson production cross section times $H \to Z\gamma$ branching fraction to the SM prediction.

The statistical treatment of the data is based on the standard LHC data modeling and handling toolkits: RooFit [36], RooStats [37], and HistFactory [38]. The confidence intervals of the signal strength are determined via the profile-likelihood-ratio test statistic [39]. The likelihood function used to define the test statistic is the product of the likelihood functions of the ATLAS and CMS analyses, adapted to have common constraint terms for the nuisance parameters representing the correlated uncertainties. The main differences between the likelihood functions of the two analyses are the background models. In each category of the ATLAS analysis, the chosen background model is the one that minimizes the presence of "spurious" signal, i.e., the extracted signal yields in signal-plus-background fits to background-only templates of $m_{Z\gamma}$ [1]. The spurious-signal yield is introduced as an additional nuisance parameter in the likelihood function, which modifies the expected signal yield. In the CMS analysis, a discrete profiling method [40] is used to determine the background model directly in the fit to the data. For each category, this method introduces an additional discrete nuisance parameter that selects the best background model among a large set of alternative models. The discrete nuisance parameter is profiled in the final fit.

The experimental uncertainties from the ATLAS and CMS analyses are considered uncorrelated. While some components of the experimental systematic uncertainties could be correlated due to the similar simulation software and calibration techniques, these are expected to be much smaller than the uncorrelated components. Among the theoretical uncertainty sources, the one associated with missing higher orders in the perturbative calculations of the gluon-gluon fusion cross section (renormalization and factorization scale uncertainties) [41–43], and the ones in the $H \to Z\gamma$ branching fraction prediction [13] are correlated. In the CMS analysis, a small number of modifications are made to facilitate the combination. In particular, for consistency, the scale and branching fraction uncertainties are reevaluated. These changes have a minor impact on the CMS result. In the ATLAS analysis, the decomposition of the scale uncertainties in terms of independent sources is modified, which has a negligible impact on the observed signal strength. The uncertainties associated with missing higher orders in the calculations for the other Higgs boson production modes, with the choice of parton distribution functions (PDFs) [44,45], with the value of the strong-force coupling constant (α_s), and with the modeling of the underlying event and parton shower are not correlated because of their different implementations in the two

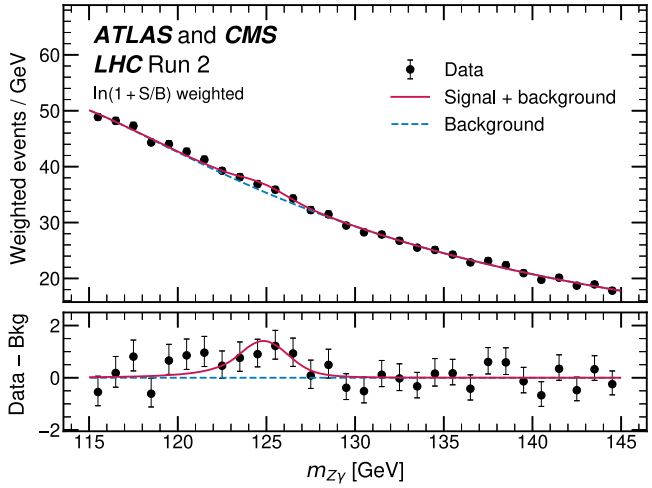


FIG. 2. The $Z\gamma$ invariant mass distribution. Events from all categories in the ATLAS and CMS analyses are shown. As different ranges in $m_{Z\gamma}$ are used in the two analyses, only the common subrange is visualized here. The data (points with error bars) in each category are weighted by $\ln(1 + S/B)$, where S and B are the observed signal and background yields in that category, in the 120–130 GeV interval. The S and B values are derived from the fit to data. The error bars are invisible because of their small values. The fitted signal-plus-background (background) probability density functions (pdfs) in each category are also weighted in the same way and summed, and represented by a red solid (blue dashed) line. The lower panel shows the background-subtracted results with the same data and pdfs.

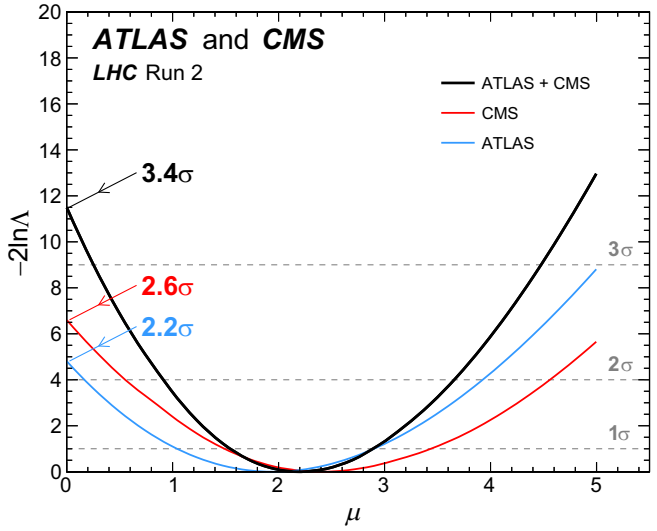


FIG. 3. The negative profile log-likelihood test statistic, where Λ represents the likelihood ratio as a function of the signal strength μ derived from the ATLAS data (blue line), the CMS data (red line), and the combined result (black line). The different Higgs boson masses assumed by ATLAS and CMS have a negligible impact on the results.

analyses. However, approximate correlation strategies were investigated for the integrated luminosity [46–50], scale, and PDF uncertainties; they are found to have a negligible impact and are not adopted in the following results. One difference between the ATLAS and CMS analyses is the assumed value of m_H taken to be 125.09 GeV [51] in the former and 125.38 GeV [52] in the latter. The results of the combination are determined for both m_H values, and the different mass assumptions have a negligible impact within the precision reported in this Letter.

The $Z\gamma$ invariant mass distribution observed in data is shown in Fig. 2. To demonstrate the sensitivity of this likelihood analysis, the events in each category are weighted by $\ln(1 + S/B)$, where S and B are the observed signal and background yields in that category in the range $120 < m_{Z\gamma} < 130$ GeV, as determined by the minimization of the test statistic. The negative log-likelihood ratio as a function of the signal strength is shown in Fig. 3. The observed (expected) signal strength at the 68% confidence level is $\mu = 2.0^{+1.0}_{-0.9}$ (1.0 ± 0.9) for the ATLAS analysis, $\mu = 2.4^{+1.0}_{-0.9}$ $(1.0^{+1.0}_{-0.9})$ for the CMS analysis, and $\mu = 2.2 \pm 0.6(\text{stat})^{+0.3}_{-0.2}(\text{syst}) = 2.2 \pm 0.7$ $[1.0 \pm 0.6(\text{stat}) \pm 0.2(\text{syst}) = 1.0 \pm 0.6]$ for their combination. Expressed in standard deviations σ, the observed (expected) local significance, with respect to the $\mu = 0$ hypothesis of no $H \to Z\gamma$ signal, is 2.2σ (1.2σ) for the ATLAS analysis, 2.6σ (1.1σ) for the CMS analysis, and 3.4σ (1.6σ) for their combination. The uncertainties in the $H \to Z\gamma$ branching fraction and the background modeling are the largest systematic uncertainties. Assuming SM Higgs boson production cross sections, the measured branching fraction for $H \to Z\gamma$ decay is $(3.4 \pm 1.1) \times 10^{-3}$. In contrast to the signal strength measurement, the uncertainty in the SM branching fraction prediction is not included in this fit. The uncertainties in the results are dominated by the statistical fluctuations of data.

The combined result is compatible with the measured signal strengths from individual categories with a p-value greater than 12%. The p-value for compatibility with the SM hypothesis ($\mu = 1$) is about 6%, and the observed local significance with respect to the SM is 1.9σ. The goodness of fit of the model to the data is evaluated with a likelihood-ratio test [53], and has a p-value greater than 90%. Tabulated results are provided in the HEPData record for this analysis [54].

In summary, a combined analysis of ATLAS and CMS searches for the Higgs boson decay to a Z boson and a photon, where the Z boson decays into an electron or muon pair, is presented. The results are based on the 13 TeV proton-proton collision data recorded by the ATLAS and CMS experiments at the CERN LHC, amounting to integrated luminosities of 139 and 138 fb^{-1}, respectively. Evidence for $H \to Z\gamma$ decay is established, with an observed significance of 3.4 standard deviations. The observed signal yield is 2.2 ± 0.7 times the SM prediction. The measured $H \to Z\gamma$ branching fraction is $(3.4 \pm 1.1) \times 10^{-3}$. The result agrees with the SM prediction within 1.9 standard deviations.

ATLAS thanks CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. ATLAS acknowledges the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; ANID, Chile; CAS, MOST, and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF, and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, USA. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; PRIMUS 21/SCI/017 and UNCE SCI/013, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU, and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex, and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales, and Aristeia programs co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014–2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya, and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide, and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [55]. CMS congratulates 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 and other centers 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, FRFCU, MoST, and NSFC (China); Ministerio de Ciencia, Tecnología e Innovación (MINCIENCIAS) (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); General Secretariat for Research and Innovation (GSRI) (Greece); NKFIH (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); MES and NSC (Poland); FCT (Portugal); Ministry of Education, Science and Technological Development (MESTD) (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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