Observation of $WZ\gamma$ production and constraints on new physics scenarios in proton-proton collisions at $\sqrt{s} = 13$ TeV

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A measurement of the $WZ\gamma$ triboson production cross section is presented. The analysis is based on a data sample of proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV recorded with the CMS detector at the LHC, corresponding to an integrated luminosity of 138 fb^{-1}. The analysis focuses on the final state with three charged leptons, $\ell^{\pm}\nu\ell^{+}\ell^{-}$, where $\ell = e$ or μ, accompanied by an additional photon. The observed (expected) significance of the $WZ\gamma$ signal is 5.4 (3.8) standard deviations. The cross section is measured in a fiducial region, where events with an ℓ originating from a tau lepton decay are excluded, to be 5.48 ± 1.11 fb, which is compatible with the prediction of 3.69 ± 0.24 fb at next-to-leading order in quantum chromodynamics. Exclusion limits are set on anomalous quartic gauge couplings and on the production cross sections of massive axionlike particles.

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I. INTRODUCTION

The discovery of the Higgs boson at the CERN LHC [1–3] experimentally confirmed the principle of electroweak (EW) symmetry breaking [4–6] and the mechanism through which the W and Z bosons acquire mass. Following that, many studies have been conducted on physics scenarios beyond the standard model (BSM) as well as the precision measurement of known standard model (SM) processes. Most of those studies show good agreement with the SM [7–11], motivating BSM searches in previously unexplored event topologies as well as precision measurements of rare SM processes. The CMS Collaboration has observed the combined production of three massive gauge bosons at $\sqrt{s} = 13$ TeV [12]. Recently, also at 13 TeV, $W\gamma\gamma$ production has been observed by the ATLAS and CMS Collaborations [13,14], and $Z\gamma\gamma$ and $WW\gamma$ production has been observed by CMS [14,15]. An observation of $WZ\gamma$ production in 13 TeV proton-proton (pp) collisions has been reported by the ATLAS Collaboration [16].

Multiboson production processes are sensitive to contributions with triple gauge couplings (TGCs) and quartic gauge couplings (QGCs). Many BSM models alter these couplings between the gauge bosons. These contributions can be parametrized through anomalous couplings, which can be described in an effective field theory [17]. As one example, the $WZ\gamma$ process is sensitive to potential anomalous TGCs and QGCs (aQGCs). In addition, the study of $WZ\gamma$ production can be used to search for an axionlike particle (ALP) [18–23]. The axion is a hypothesized pseudoscalar particle, predicted by the Peccei-Quinn [24,25] solution of the strong charge-conjugation-parity problem in quantum chromodynamics (QCD). The axion is also a candidate for dark matter. At the LHC, certain types of photophobic ALPs, denoted a, can be explored in $Z\gamma$ final states [26]. Figure 1 shows representative Feynman diagrams at leading order (LO) for $WZ\gamma$ production through QGCs, TGCs, multiperipheral interaction, and an ALP, from left to right, respectively.

This paper reports the measurement of the $WZ\gamma$ production fiducial cross section in pp collisions at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 138 fb^{-1}, recorded with the CMS detector at the LHC. Both the W and the Z bosons are identified via their leptonic decays. Limits on aQGCs, as well as constraints on the ALP model, are also presented. Tabulated results are provided in HEPData [27].

II. THE CMS DETECTOR

The central feature of the CMS [28] 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 (HCAL), each composed of a barrel and two end cap sections, reside within the solenoid volume. Forward calorimeters extend the coverage provided by the barrel

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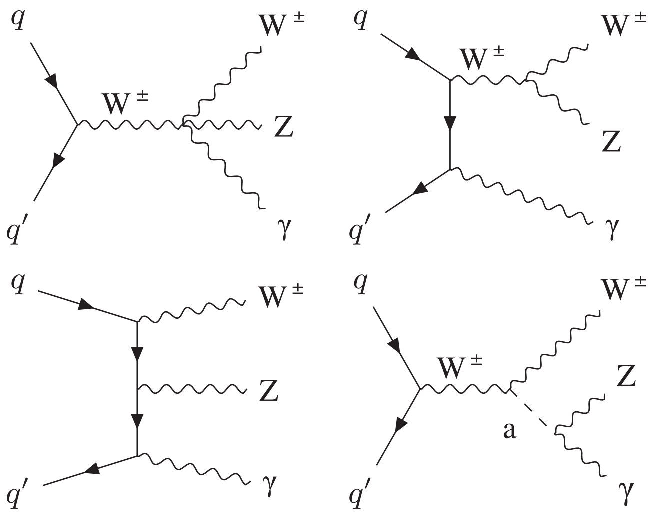

FIG. 1. Feynman diagrams for $WZ\gamma$ production at LO, including production through a QGC vertex (upper left), a representative diagram for TGC production (upper right), and a multiperipheral interaction (lower left). The lower right diagram shows the $WZ\gamma$ production including an ALP, denoted a, which decays to a Z boson and a photon.

and end cap detectors up to pseudorapidities of $|\eta| = 5$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-level trigger system [29]. The first level (L1), composed of specialized hardware processors, uses information from the calorimeters and muon detectors to select events of interest with a maximum rate of 100 kHz. A high-level trigger processor farm decreases this rate to 1 kHz before storage. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, is reported in Ref. [28].

III. SIGNAL AND BACKGROUND SIMULATION

The $WZ\gamma$ signal is modeled using a sample of inclusive $\ell^{\pm}\nu\ell^{+}\ell^{-}\gamma$ events, where $\ell = e$ or μ, simulated with the MadGraph5_aMC@NLO v2.6.5 [30] Monte Carlo (MC) event generator at next-to-LO (NLO) in QCD. Electrons or muons produced via τ decays are included, and the invariant mass of the opposite-charge same-flavor lepton pairs is required to be greater than 4 GeV. The backgrounds are divided into several categories. (i) The top quark backgrounds, which include $t\bar{t}W/t\bar{t}\gamma$ simulated at NLO with the FxFx jet matching scheme [31], $t\bar{t}Z/tZq$ simulated at NLO using MadGraph5_aMC@NLO v2.6.5, and tW production simulated using the POWHEG v2.0 [32–35] generator. (ii) $V\gamma$ ($V = W$ or Z) backgrounds are simulated at NLO with the FxFx jet matching scheme using MadGraph5_aMC@NLO v2.6.5. (iii) VV backgrounds including WZ/ZZ are simulated at NLO using POWHEG v2.0 [36], and the gluon-gluon induced ZZ production is simulated at LO using the MCFM v7.0 generator [37]. (iv) VVV backgrounds including WWW, WWZ, WZZ, ZZZ, $ZZ\gamma$, and $Z\gamma\gamma$ are simulated using MadGraph5_aMC@NLO v2.6.5 at NLO.

The simulation of the aQGC events is performed with MadGraph5_aMC@NLO 2.6.5 at LO. The matrix element reweighting feature in MadGraph5_aMC@NLO provides each event with additional weights corresponding to different theoretical hypotheses, e.g., choice of parameters. This feature sets the size of the coefficients of any anomalous coupling operators probed in the analysis [38]. The simulation of ALP events is performed with MadGraph5_aMC@NLO 2.6.5, using the model from Ref. [26].

The Pythia generator, configured with the CP5 tune, performs parton showering, hadronization, and simulates the underlying event [39]. The next-to-NLO NNPDF3.1 [40] parton distribution functions (PDFs) are employed in the simulation, and the CMS detector response is simulated with the Geant4 package [41,42]. The simulated events include additional pp interactions in the same and neighboring bunch crossings, referred to as pileup (PU). Simulated events are weighted to match the PU distribution from data, with an average PU of approximately 23, 33, and 32 interactions per bunch crossing during the 2016, 2017, and 2018 data-taking periods, respectively.

IV. OBJECTS RECONSTRUCTION AND EVENT SELECTION

A. Objects reconstruction

A particle-flow (PF) algorithm [43] is used to reconstruct particles in the event. It combines all subdetector information to reconstruct individual objects and identify them as charged or neutral hadrons, photons, or leptons (PF candidates). The primary vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Sec. 9.4.1 of Ref. [44].

Muons are reconstructed using the information in the muon system and the inner tracker within $|\eta| < 2.5$ with transverse momentum $p_{\mathrm{T}} > 15$ GeV. The muon momenta are obtained from the curvature of the corresponding tracks [45]. Muon candidates are required to satisfy additional identification (ID) criteria, including a minimum number of hits in the muon system and the inner tracker, the quality of the combined fit to a track, the number of matched muon-detector planes, and the consistency between the track and the PV. The relative isolation is defined as the sum of the charged hadrons and neutral particles in a geometrical cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ centered on the muon trajectory, relative to the muon p_{T}:

$$\mathrm{Iso} = \left(\sum p_{\mathrm{T}}^{\mathrm{charged}} + \max\left[0, \sum p_{\mathrm{T}}^{\mathrm{neutral}} + \sum p_{\mathrm{T}}{}^{\gamma} - \frac{1}{2} p_{\mathrm{T}}^{\mathrm{PU}}\right]\right) \Big/ p_{\mathrm{T}},$$

where ϕ is the azimuthal angle, $\sum p_{\mathrm{T}}^{\mathrm{charged}}$ is the scalar p_{T} sum of charged hadrons originating from the PV, and $\sum p_{\mathrm{T}}^{\mathrm{neutral}}$ and $\sum p_{\mathrm{T}}^{\gamma}$ are the respective scalar p_{T} sums of neutral hadrons and photons. For PU mitigation [46], $p_{\mathrm{T}}^{\mathrm{PU}}$ is assumed to be half of the scalar p_{T} sum deposited in the isolation cone by charged particles not associated with the PV. The factor of 0.5 corresponds approximately to the ratio of neutral to charged hadrons produced in the hadronization of PU interactions. Three muon selection definitions are used based on the cut-based tight and loose IDs from [45]. The "tight" ("veto") selection is defined by using a high (low) purity working point of the cut-based ID, with the Iso required to be $< 0.15(0.4)$ for "tight" ("veto") muons. The "loose" working point is defined by using the high purity working point of the cut-based ID, and the isolation variable is required to be between 0.15 and 0.4.

Electron candidates are reconstructed within $|\eta| < 2.5$ with $p_{\mathrm{T}} > 15$ GeV. This involves combining the information from energy clusters deposited in the ECAL and the trajectories fitted in the tracker [47]. About 35% of electrons radiate more than 70% of their initial energy before reaching the ECAL, thus the total energy is evaluated by adding back all bremsstrahlung photons compatible with originating from the electron track, which is implemented through "superclustering" algorithms [47]. To reduce contamination, e.g., from electrons originating in jets, the electron candidates are required to fulfill additional ID criteria based on the following variables: the relative amount of energy deposited in the HCAL; a match of the trajectory in the inner tracker with that in the supercluster of the ECAL; the number of missing hits in the inner tracker; the consistency between the track and the PV; and $\sigma_{i\eta i\eta}$ [47], a shower shape variable that quantifies the spread in η of the electromagnetic shower in the ECAL. Electron candidates identified as originating from photon conversion are rejected. Three working points are defined according to the ID efficiency [47]. A "tight" working point is used to select electrons in the final state, defined by the CMS cut-based medium ID [47]. A much less restrictive working point is used to perform the additional electron veto, referred to as "veto," defined by the cut-based veto ID. A third working point with an efficiency located between tight and veto, referred to as "loose," defined by the cut-based loose ID, is used to select electron candidates from data to mimic the jet-induced electron background. The relative isolation variable for electrons is defined similarly as for muons, with the exception that the contribution from PU effects is estimated using the effective area approach [47]. The isolation requirement applied to electrons is included in the cut-based ID.

Photons are identified as ECAL energy clusters not linked to the extrapolation of any charged-particle trajectory to the ECAL [47]. They are required to have $p_{\mathrm{T}} > 20$ GeV and be within $|\eta| < 2.5$, while the transition region between the barrel and end cap ECALs of $1.444 < |\eta| < 1.566$ is excluded, because the reconstruction of a photon object in this region is not optimal. Photons located in the barrel region, $|\eta| < 1.444$, and the end cap region, $1.566 < |\eta| < 2.5$, will be referred to as γ_{barrel} and γ_{endcap}, respectively. An isolation requirement using a similar definition as described above is applied with $\Delta R = 0.3$. The cut-based medium ID [47] is used to select "tight," promptly produced, photons. The loose photon criteria is defined by inverting the $\sigma_{i\eta i\eta}$ and the isolation requirements for the tight selection. The PU suppression is performed in a similar way as for electrons. An additional veto is applied on electrons reconstructed as photons.

Jets are reconstructed using PF objects and the anti-k_{T} jet clustering algorithm [48] with a distance parameter of 0.4. The energies of charged hadrons are determined from a combination of their momenta measured in the tracker and the matching of ECAL and HCAL energy deposits, corrected for the response of the calorimeters to hadronic showers. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. To reduce the contamination from PU, charged PF candidates with $|\eta| < 2.4$ are excluded from jet clustering when they are associated with PU vertices [46], in a process called "charged hadron subtraction" [43]. The contribution from neutral PU particles to the jet energy is corrected based on the projected area of the jet on the front face of the calorimeter. Additional ID criteria on the energy fractions of charged and neutral components, as well as a veto on overlaps with leptons ($\Delta R > 0.4$), are applied to jet candidates. A standard "tight" working point is adopted in the analysis. Corrections are applied to the jet energy as a function of jet η and p_{T} to account for detector response nonlinearities, contributions from PU, and residual differences between the jet energy scale in data and simulation [49]. The b quark jet ID uses the tight working point [48] of the deep machine learning version of the combined secondary vertex b tagging algorithm DeepCSV [50], which combines the information from displaced tracks with the information from secondary vertices associated with the jet and on the possible presence of a soft muon in the event from the semileptonic decay of the b quark.

The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is computed as the negative weighted vector p_{T} sum of all the PF candidates in an event, and its magnitude is denoted as $p_{\mathrm{T}}^{\mathrm{miss}}$ [51]. The $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event. A "tag-and-probe" procedure [52] is used to measure factors that correct for data-to-simulation differences in the trigger, reconstruction, and selection efficiencies.

B. Event selection

Collision events are collected using a combination of triggers [53] that require the presence of one or two electrons or muons. The p_T threshold of the single-lepton trigger is 27 (24) GeV for electrons (muons); for the double-lepton triggers with same-flavor leptons, the p_T thresholds of the leading and subleading leptons are 23 (17) and 12 (8) GeV. For the double-lepton triggers with different-flavor leptons, the p_T threshold of the leading lepton is 23 GeV, regardless of the flavor, whereas the p_T threshold of the subleading lepton is 12 or 8 GeV depending on the data-taking period. The combination of these triggers leads to a nearly 100% trigger efficiency in the phase space considered by this study. In 2016 and 2017, partial mistiming of signals in the forward region of the ECAL end cap detectors ($2.75 < |\eta| < 3$) resulted in L1 triggers being wrongly associated with the previous bunch crossing [54]. Since rules for L1 triggers forbid two consecutive bunch crossings to trigger the detector, events with mistimed signals can self veto, which can lead to a decrease in the L1 trigger efficiency. This effect is not included in the simulation, instead a correction is implemented using a factor that represents the probability of the event not having mistimed signals.

A selected event in the $WZ\gamma$ signal region (SR) is required to have exactly three isolated leptons, following the tight working points introduced in Sec. IVA. The leptons can be electrons or muons, and they can be direct W or Z boson decay products, or come from an intermediate τ lepton decay. The leading and subleading leptons in p_T used to reconstruct the Z boson candidate are referred to as ℓ_{Z1} and ℓ_{Z2}, respectively. The remaining lepton, associated with the W boson, is referred to as ℓ_W. The p_T requirements on the leptons are $p_T^{\ell_{Z1}} > 25$ GeV, $p_T^{\ell_{Z2}} > 15$ GeV, and $p_T{}^{\ell_W} > 25$ GeV. A Z boson candidate with invariant mass satisfying $|m_{\ell_{Z1}\ell_{Z2}} - m_Z| < 15$ GeV is required to be reconstructed from two opposite-sign charge and same-flavor (OSSF) leptons among the three tight leptons. If there is more than one combination of OSSF leptons satisfying the Z boson candidate requirement, the one with invariant mass closest to the Z boson mass is chosen. The highest p_T photon satisfying the tight selection with $p_T^\gamma >$ 20 GeV is chosen as the signal photon. The invariant mass of the three leptons, $m_{\ell\ell\ell}$, is required to be larger than 100 GeV to reduce the contribution from $Z\gamma$ production in which the photon converts and produces an additional electron. The invariant mass of any same-flavor lepton pair, $m_{\ell\ell}$, is required to be larger than 4 GeV to avoid low-mass resonances. The invariant mass of the photon and the lepton associated with the W boson, $m_{\gamma\ell_W}$, is required to be outside the interval (75, 105) GeV when ℓ_W is an electron, to reduce the contribution from Z boson events with electrons. Due to the presence of neutrinos in the W boson decay, the selected events are required to have $p_T^{\text{miss}} > 30$ GeV. Events with a fourth lepton satisfying the veto working point are rejected to reduce the VV and VVV backgrounds. To reduce contributions from top quark processes, events with a b-tagged jet with $p_T^b > 30$ GeV and $|\eta^b| < 2.4$ are vetoed. The region used for aQGC constraints is the same as the SR, with the exception that $p_T^\gamma > 60$ GeV.

Control regions (CRs) are defined to constrain or to validate the background models. A CR enriched in events with nonprompt leptons is obtained by inverting the b jet veto and Z boson mass window, $|m_{\ell_{Z1}\ell_{Z2}} - m_Z| > 15$ GeV. The photon requirement is also removed and the remaining selections are the same as for the SR. Similarly, a second CR enriched in events with nonprompt photons is defined by requiring only two tight OSSF leptons with a veto on the presence of a third loose lepton. Also, the SR p_T^{miss} requirement, the b jet veto, and Z boson mass window selection are inverted, and at least one tight photon with $p_T > 20$ GeV is required.

The ZZ CR is defined by inverting the fourth lepton veto in the SR definition. A fourth lepton with $p_T > 15$ GeV satisfying the tight working point is required, and the requirements on the photon are removed. The p_T^{miss} requirement is also inverted. Two pairs of OSSF leptons are required, each having $|m_{\ell\ell} - m_Z| < 15$ GeV. The normalization of the simulated samples used to model the ZZ background is constrained using this CR.

The selection on $m_{\gamma\ell_W}$ is not required in the three CRs. A summary of all the selection criteria for the various regions is shown in Table I.

V. BACKGROUND ESTIMATION

The dominant backgrounds to $WZ\gamma$ production in the SR stem from nonprompt photon, nonprompt lepton, and ZZ production. The former two contributions arise from misidentified objects that are not direct products of the hard scattering, and are usually produced during the subsequent parton shower and hadronization. The probabilities of nonprompt objects passing the ID requirements are typically low, however, the contributions can still be significant because of the large rate of heavy-quark jets at the LHC. These nonprompt objects are typically not modeled well in simulation. Consequently, we estimate their contributions directly from data. The contribution of ZZ production comes from two parts. In one, a Z boson decays into an electron-positron pair and either one of them is misidentified as a photon, denoted by $e \to \gamma$. Alternatively, one of the four final-state leptons is not within the acceptance or does not pass the ID requirements, while the photon is produced from final-state radiation. The ZZ contribution is estimated using simulation, as introduced in Sec. III, which will be constrained in the SR through a simultaneous fit with the ZZ CR.

The background from nonprompt photons arises mainly from events with a jet misidentified as a photon,

TABLE I. Summary of the event selections in the SR, nonprompt CRs, and the ZZ CR. The nonprompt CRs are used to validate and constrain the nonprompt lepton and photon contributions, and the ZZ CR is used to constrain the ZZ contribution. A "…" indicates that no requirement is placed on the corresponding observable. The aQGC SR is the same as the SR with the exception that $p_T^\gamma > 60$ GeV.

Region	N_ℓ	N_γ	N_{OSSF}	N_{btag}	p_T^{miss} [GeV]	$p_T\{\ell_{Z1}, \ell_{Z2}, \ell_W, \ell_4\}$ [GeV]	$\min(m(\ell\ell'))$ [GeV]	$\lvert m(\ell_{Z1}, \ell_{Z2}) - m_Z \rvert$ [GeV]	$m(\ell_{Z1}, \ell_{Z2}, \ell_W)$ [GeV]	$m(\ell_W, \gamma)$ [GeV]
SR	$=3$	≥ 1	≥ 1	$=0$	>30	$>\{25, 15, 25, -\}$	>4	<15	>100	<75 or >105
ZZ CR	$=4$	…	≥ 1	$=0$	<30	$>\{25, 15, 25, 15\}$	>4	<15	>100	…
Nonprompt ℓ CR	$=3$	…	≥ 1	>0	>30	$>\{25, 15, 25, -\}$	>4	>15	>100	…
Nonprompt γ CR	$=2$	≥ 1	$=1$	>0	<30	$>\{25, 15, -, -\}$	>4	>15	…	…

e.g., $WZ+$jets or $tZ+$jets. The method of Refs. [55,56] used to estimate this background includes measuring and applying a per-event extrapolation factor in data, which varies as a function of p_T^γ. The measurement of the extrapolation factor is performed by extracting the fraction of jets misidentified as photons in a region with two or more tight leptons, of which two form a Z boson candidate. The fraction of nonprompt photons is determined via a template fit to the photon $\sigma_{i\eta i\eta}$ distribution, where values are typically small for prompt photons and large for nonprompt photons. The prompt template is taken from simulation, and the nonprompt template from a sideband region of the photon isolation variable. The resulting factors are used to weight events in the application regions: events selected with the same lepton requirements as the nominal SR or nonprompt CR, but with the photon candidate required to pass the loose selection and fail the tight.

The background from nonprompt leptons is mainly comprised of ttZ and ttW production as well as other jet-enriched processes with jets misidentified as leptons. The estimation of nonprompt leptons is performed in a similar fashion to that for the nonprompt photons, with the exception that nonprompt leptons produced via τ decays are estimated using simulation. The extrapolation factor is defined as $\mathrm{W}_\alpha = f_\ell/(1 - f_\ell)$, where f_ℓ is the lepton misidentification rate, defined as the ratio of the number of events with leptons passing the tight working point to the total number of events with leptons passing the tight or loose working points. The f_ℓ is measured as a function of the η and p_T of the leptons and is performed in a dijet-enriched region. The events are required to have only one electron or muon passing the tight or loose working point, at least one tight jet and small p_T^{miss}. In addition, a combination of single-lepton triggers with a minimal p_T of 8 GeV is required. The contribution from prompt leptons, i.e., leptons from $W+$jets and $Z+$jets, is subtracted from both the numerator and denominator using simulation when calculating f_ℓ. To estimate the nonprompt lepton background, these factors are applied as weights to events in three application regions, defined by those events that satisfy the full analysis selection, with the exception that one, two, or three of the leptons pass the loose working point but fail the tight one. The event weight is calculated by multiplying the factors corresponding to each lepton in events that pass the loose selection but fail the tight selection. The final contribution of nonprompt leptons is obtained by summing contributions from the three categories. The possible overlap between the three application regions is removed.

Other backgrounds, including top quark and multiboson production, are estimated from MC simulation as mentioned in Sec. III and are normalized using their most precise theoretical cross sections. The possible double counting between the different background categories is removed.

VI. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties that affect the measurements arise from experimental sources, such as detector effects and the methods used to compute higher-level quantities, e.g., efficiencies, and from variations in theoretical inputs, such as the choice of the renormalization (μ_R) and factorization (μ_F) scales and the choice of the PDFs. Each systematic uncertainty is quantified by evaluating its effect on the normalization and shape of relevant kinematic variables in the signal and background categories, and is propagated to the final distributions on a bin-by-bin basis. The log-normal distribution, recommended [57] for implementing multiplicative corrections, is used to model the dependence of the event yields on the systematic uncertainties.

The systematic uncertainties in the measurement of the integrated luminosity are 1.2%, 2.3%, and 2.5% for the 2016, 2017, and 2018 data-taking periods, respectively [58–60]. Accounting for correlations, the overall uncertainty for the 2016–2018 period is 1.6%. The effect of mismodeling the PU is estimated by varying the total inelastic cross section used in the reweighting procedure by ±4.6% [46]. This uncertainty is treated as fully correlated among different data-taking years. The uncertainties in the correction factors accounting for the ECAL mistiming in

2016 and 2017 MC events vary by 1%–4%, and are treated as correlated across different processes and bins but uncorrelated between the 2016 and 2017 datasets. The systematic uncertainties in the trigger efficiency are measured to be ≈1% and are correlated among the three data-taking years, and the uncertainty related to the limited samples for this measurement is smaller than 0.4% and is uncorrelated among the three years. The uncertainties in the lepton and photon ID and isolation efficiency scale factors are ≈2% and are correlated among different data-taking years. The systematic uncertainty in the electron (photon) momentum correction is ≈2(3)% and is correlated across different processes and data-taking years, whereas the uncertainty in the muon momentum correction is negligible.

The uncertainties in the jet energy scale (JES) and jet energy resolution (JER) are calculated from simulated events by rescaling and spreading the jet p_{T} [49], and propagating the bin-by-bin effects in the variables. The uncertainties in the event yield due to the JES and JER amount to 1%–4%. The JES uncertainty components are considered to be either fully correlated or fully uncorrelated across the different data-taking years, depending on the underlying source, while the JER is treated as uncorrelated across the different years. Both JER and JES uncertainties are treated as correlated across processes.

An overall systematic uncertainty in the nonprompt photon background estimate is defined as the sum in quadrature of the systematic uncertainties from several distinct sources. An uncertainty arising from the choice of the isolation variable sideband is evaluated by estimating the nonprompt photon fraction with a set of alternative choices of the isolation sideband. A nonclosure uncertainty is defined by performing the template fits using simulated events and comparing the results with the known fractions. The uncertainty arising from the choice of the prompt template is assessed by comparing nonprompt fractions obtained from two different choices of prompt template, specifically $WZ\gamma$ or $Z\gamma$. The nonclosure uncertainty in the end cap region is larger than in the barrel region and increases as the photon p_{T} increases. The overall systematic uncertainty in the nonprompt photon background is 12%–22%, dominated by the nonclosure effect. Similarly, the dominant uncertainty in the nonprompt lepton estimate is associated with the nonclosure, which is calculated by comparing two yields, one from the $\gamma +$ jets events and the other from the $\gamma +$ jets events where the nonprompt lepton rates are applied to events with a lepton that passes the loose, but fails the tight working point. The other requirements of the main event selection are applied. The uncertainty associated with the nonprompt lepton background is 30% for both electrons and muons and is correlated across the data-taking years. Additionally, the statistical uncertainty from the extrapolation factor calculation is included.

The uncertainties related to the limited number of simulated events, or to the limited number of events in data CRs, affect the signal and background predictions. They are uncorrelated across different processes, and across bins of a single distribution.

Theoretical uncertainties arise from the choice of μ_{R} and μ_{F}, as well as the choice of PDFs. The uncertainty due to missing higher orders in QCD is estimated through independent changes in the μ_{R} and μ_{F} scales up and down by a factor of 2 relative to their nominal value in each event, under the condition that $1/2 \leq \mu_{\mathrm{R}}/\mu_{\mathrm{F}} \leq 2$. Those changes are propagated to the weights of the MC events. The maximal difference with respect to the nominal yield obtained using the central event weights is taken as the measure of uncertainty. The uncertainties in the PDFs are estimated by combining the expectations from all of the contributions in the NNPDF3.1 set of PDFs, according to the procedure described in Ref. [61]. For the signal, the scale uncertainty is 5%–9% and the PDF uncertainty is 3%–5%, depending on the value of $m_{Z\gamma}$.

All the above systematic uncertainties are applied to both the measured signal rate relative to the SM prediction (signal strength) and to the search for BSM physics. All systematic uncertainties, except those arising from the trigger and lepton ID efficiencies, are assumed to be correlated between the electron and muon channels. A summary of the contributions to the total uncertainty in the signal strength is given in Table II.

VII. RESULTS AND INTERPRETATIONS

This section presents the measured signal strength, its corresponding significance, and the production cross section of the $WZ\gamma$ process. Limits on the aQGCs are also determined. Finally, the results are interpreted in the context of a photophobic ALP production model. These results have been determined using the CMS statistical analysis tool Combine [57]. In order to avoid bias, all of the observed results and any sensitive distributions were blinded until all of the analysis methods were frozen.

TABLE II. Summary of the relative contributions of related groups of uncertainties to the value of the signal strength in the measurement of the SM $WZ\gamma$ signal.

Uncertainty source	$\Delta\mu/\mu_{\mathrm{obs}}$
Statistical	17%
Theory	7.6%
Nonprompt-background estimation	6.6%
Photon related	5.5%
Electron related	4.1%
Integrated luminosity	1.7%
Pileup	<1%
Muon related	<1%

TABLE III. The number of events in data and predictions after the combined fit for the relevant processes in the SR and CRs. All analysis uncertainties are included.

Process	SR	Nonprompt ℓ CR	Nonprompt γ CR	ZZ CR
$WZ\gamma$ signal	60.8 ± 3.5	0.66 ± 0.09	0.20 ± 0.04	0.017 ± 0.008
VV	12.99 ± 0.32	1.86 ± 0.12	0.164 ± 0.017	1016 ± 12
$V\gamma$	1.8 ± 0.9	4.7 ± 2.1	438 ± 27	0.011 ± 0.006
VVV	1.6 ± 0.4	0.36 ± 0.11	0.011 ± 0.007	0.10 ± 0.04
Top	3.3 ± 0.6	227 ± 15	27.0 ± 5.9	0.30 ± 0.04
Nonprompt ℓ	12.9 ± 2.8	1792 ± 34	<0.01	<0.01
Nonprompt γ	15.8 ± 2.2	<0.01	195 ± 19	<0.01
Total prediction	109 ± 5	2027 ± 33	660 ± 21	1016 ± 12
Observed	108	2029	658	1017

A. Measurement of $WZ\gamma$ production

The SM $WZ\gamma$ signal extraction is performed using a simultaneous binned likelihood fit in one-dimensional distributions in $m_{Z\gamma}$ (SR and nonprompt photon CR) and $m_{\ell\ell\ell}$ (nonprompt lepton CR and ZZ CR). The CRs are included in the fits to constrain the dominant backgrounds. The data in the SR and all CRs, together with the background and signal yields after the fit to data, are presented in Table III. The distributions after the combined fit in each region are shown in Fig. 2.

The $WZ\gamma$ signal normalization is allowed to vary without an external constraint in the fit. The normalization of ZZ (gluon-gluon and quark-antiquark induced ZZ are considered together) is allowed to vary freely since it is well constrained from the data in the CR. The nonprompt photon and nonprompt lepton backgrounds are derived directly from the observed events, and hence they are fixed to their yields and constrained within the related uncertainties. Systematic uncertainties are included as nuisance parameters in the likelihood fit. All of the fitted nuisance parameters are consistent with their nominal values. All the other background processes are fixed to their SM cross sections, subject to the uncertainties described in Sec. VI. The measured signal strength is $\mu^{\mathrm{SR}}_{\mathrm{obs}} = 1.47 \pm 0.15(\mathrm{syst}) \pm 0.11(\mathrm{theo}) \pm 0.25(\mathrm{stat}) = 1.47 \pm 0.31$. Considering the background-only hypothesis, this corresponds to an observed (expected) significance of 5.4 (3.8) standard deviations.

B. Fiducial cross section measurement

The leptonic $WZ\gamma$ production cross section measurement is performed in a fiducial phase space region based on particle-level quantities, which is designed to emulate the selection performed at the reconstruction level. The lepton selected at the generator level is “dressed” by adding the four-momenta of any photons with $\Delta R(\ell,\gamma) < 0.1$ to the four-momentum of the lepton. Three dressed leptons (electrons or muons) with $p_{\mathrm{T}} > 15$ GeV and $|\eta^{\ell}| < 2.5$ are required, with at least one OSSF pair to reconstruct a Z boson candidate. In cases where multiple OSSF lepton combinations are possible, the pair with the invariant mass closest to the Z boson mass is selected. The mass of the Z boson candidate is required to be within the interval of 60 to 120 GeV. The photon candidate is required to have $p_{\mathrm{T}} > 15$ GeV, $|\eta^{\gamma}| < 2.5$, and a separation from each lepton of $\Delta R(\ell,\gamma) > 0.3$. A photon isolation selection is also applied, which requires the total scalar p_{T} sum of all stable particles within a cone size $\Delta R = 0.4$ around the photon direction to be less than 50% of the photon p_{T}. Events where an electron or muon originates from a tau lepton decay are excluded. The fiducial cross section is extracted using the same fitting strategy as the fit used to determine the signal significance, with the following exception: events that pass the SR selection but fail the fiducial selection are regarded as a background. The predicted SM cross section for this $WZ\gamma$ fiducial region, obtained using the MadGraph5_aMC@NLO 2.6.5 event generator in NLO, is $\sigma_{\mathrm{SM}} = 3.69 \pm 0.15(\mathrm{PDF}) \pm 0.19(\mathrm{scale})$ fb. The measured fiducial cross section is $\sigma_{\mathrm{obs}} = 5.48 \pm 0.57(\mathrm{syst}) \pm 0.10(\mathrm{theo}) \pm 0.95(\mathrm{stat}) = 5.48 \pm 1.11$ fb, where the theoretical uncertainties include those from the renormalization and factorization scale variations, PDFs, and parton shower modeling in all simulated samples. The measured value is compatible with the SM prediction.

C. Limits on anomalous quartic gauge couplings

The effects of BSM physics can be parametrized in a generic way through a collection of linearly independent higher-dimensional operators in an effective field theory [17]. Reference [62] proposes nine independent charge-conjugate and parity-conserving dimension-eight effective operators by assuming the $\mathrm{SU}(2) \times \mathrm{U}(1)$ symmetry of the EW gauge field, including a Higgs doublet to incorporate the presence of an SM Higgs boson. The presence of nonzero aQGCs would enhance the production of events with large $WZ\gamma$ mass. The operators that can be constrained using the $WZ\gamma$ channel are those containing only the SU(2) field strength and the U(1) field strength, $\mathcal{L}_{\mathrm{T},0} - \mathcal{L}_{\mathrm{T},7}$.

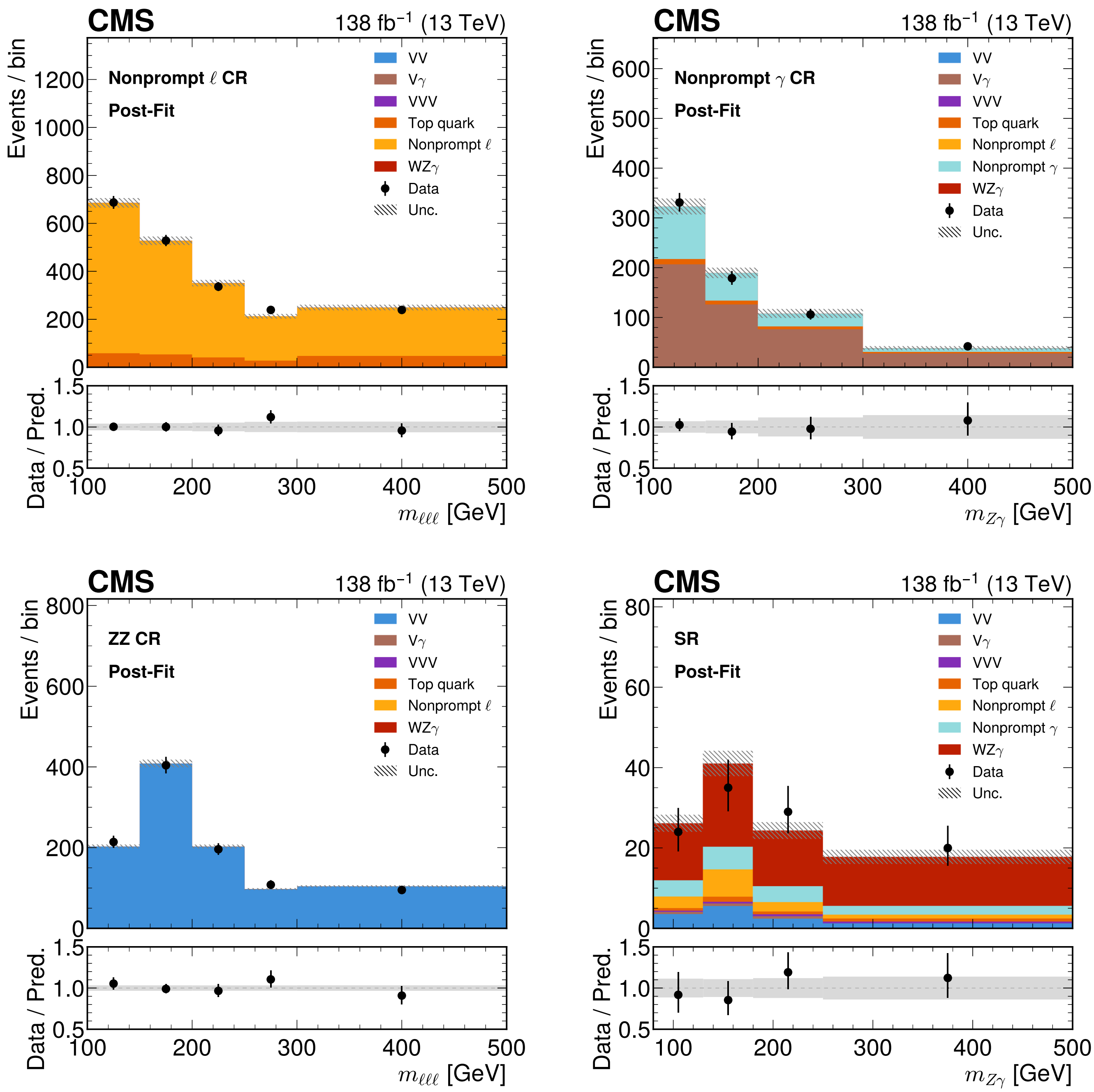

FIG. 2. The distributions of the variables used in the simultaneous fit for the nonprompt ℓ CR (upper left), nonprompt γ CR (upper right), ZZ CR (lower left), and SR (lower right) after the fit to the data. The black points with error bars represent the data and their statistical uncertainties, whereas the shaded band represents the total uncertainties. The bottom panel in each figure shows the ratio of the number of events observed in data to that of the total SM prediction. The last bin of each plot has been extended to include the overflow contribution.

The Wilson coefficient of the operator $\mathcal{L}_{\mathrm{T,X}}$ is denoted by $F_{\mathrm{T,X}}/\Lambda^4$, where Λ is the unknown scale of BSM physics.

A simulation that includes the effects of the nonzero aQGCs in addition to the SM $WZ\gamma$ process is performed, including the interference between the two. To utilize the sensitivity of the invariant mass of the triboson system, the invariant mass of the three leptons and the photon, $m_{\ell\ell\ell\gamma}$, is used for the aQGCs study. In order to obtain a continuous prediction for the aQGCs signal as a function of the anomalous coupling strength, a quadratic function is used to fit the ratio of aQGC and SM yields in the last bin of the $m_{\ell\ell\ell\gamma}$ distribution. The one-dimensional 95% confidence level (CL) limits are calculated using the asymptotic properties of the profile likelihood ratio, using the

TABLE IV. Exclusion limits at the 95% CL for each aQGC coefficient, assuming all other coefficients are set to zero. Unitarity bounds corresponding to each operator are also listed.

Operators	Observed limits [TeV^{-4}]	Expected limits [TeV^{-4}]	Unitarity bound [TeV]
$F_{T,0}/\Lambda^4$	[−2.60, 2.60]	[−2.52, 2.52]	1.32
$F_{T,1}/\Lambda^4$	[−3.28, 3.24]	[−3.18, 3.14]	1.48
$F_{T,2}/\Lambda^4$	[−7.15, 7.05]	[−6.95, 6.85]	1.35
$F_{T,5}/\Lambda^4$	[−2.54, 2.56]	[−2.46, 2.50]	1.55
$F_{T,6}/\Lambda^4$	[−3.18, 3.22]	[−3.08, 3.14]	1.61
$F_{T,7}/\Lambda^4$	[−6.85, 7.05]	[−6.65, 6.85]	1.71

procedure described in Sec. 3.2 of Ref. [63], with all the other aQGC parameters, except for the coefficient being probed, set to zero. No significant excess of events with respect to the SM prediction is observed, and the 95% CL observed and expected limits are summarized in Table IV. A unitarity bound is defined as the scattering energy at which the aQGC coupling strength set equal to the observed limit would result in a scattering amplitude that violates unitarity. The value of the unitarity bound is determined using the VBFNLO 2.7.1 framework [64]. These constraints are of comparable order to those from other analyses [14,55].

D. Limits on photophobic axionlike particle models

In this analysis, a specific model called photophobic ALPs was studied [26,65], whose leading couplings to SM EW gauge bosons do not involve a pair of photons. In this scenario, the $WZ\gamma$ final state results from the production of Wa followed by $a \to Z\gamma$. The invariant mass, $m_{\ell_{Z1}\ell_{Z2}\gamma}$, is used for the ALPs search. In this case, the SM $WZ\gamma$ contribution is regarded as a background whose normalization is determined in the simultaneous fit. Since no significant excess of events relative to the SM prediction is observed, the CL$_s$ criterion [66,67] with the asymptotic approximation [68] is used to evaluate 95% CL upper limits. The results are shown in Fig. 3.

There is only one free parameter f_a that directly determines the couplings between ALPs and vector bosons, which subsequently affects the cross section times branching fraction in the case with $\sigma\mathcal{B} \propto 1/f_a^2$. The limits in Fig. 3 (upper) can be directly reinterpreted as limits in the $1/f_a - m_a$ plane. The limits on $1/f_a$ are shown in Fig. 3 (lower), providing some of the tightest limits for mass values in the range of $m_a = 200$–400 GeV, and also offering the first constraints set on this model for masses between $m_a = 110$–200 GeV compared with the previous results in Ref. [65].

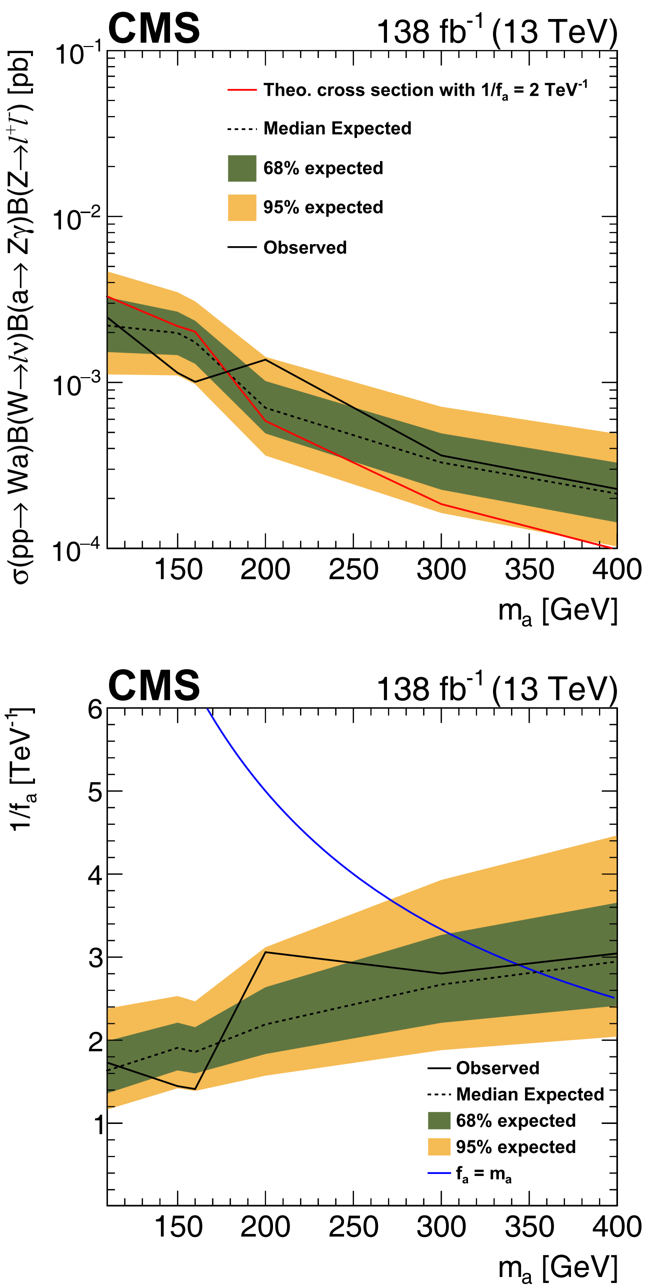

FIG. 3. Expected and observed 95% upper limits on the product of the cross section and branching fraction $\sigma(pp \to Wa)\mathcal{B}(W \to \ell^+\nu_\ell)\mathcal{B}(a \to Z\gamma)\mathcal{B}(Z \to \ell^+\ell^-)$ as a function of the ALP mass from 110 to 400 GeV (upper). The red line corresponds to the theoretical prediction for $1/f_a = 2$ TeV^{-1}. Expected and observed 95% upper limits on the photophobic ALP model parameter $1/f_a$ as a function of ALP mass reinterpreted from $1/f_a = 2$ TeV^{-1} (lower). The blue line indicates the point at which the energy scale of f_a matches that of the ALP mass. The model may not be valid in the region where $m_a > f_a$, as discussed in Ref. [22].

VIII. SUMMARY

A measurement of the production of $WZ\gamma$ with both W and Z bosons decaying leptonically has been presented. Results are based on the data collected in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV by the CMS detector during 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. Events are selected by requiring an identified photon, missing transverse momentum, as well as three identified leptons, of which two correspond to an on-shell Z boson. The observed significance for the SM signal is 5.4 standard deviations, while a significance of 3.8 standard deviations is expected based on the SM prediction. The measured fiducial cross section of leptonic $WZ\gamma$ production is $\sigma_{pp\to\ell^{\pm}\nu\ell^{+}\ell^{-}\gamma} = 5.48 \pm 1.11$ fb, with prompt $\ell = e$ or μ, which is compatible with the prediction of 3.69 ± 0.24 fb at next-to-leading order in quantum chromodynamics. Constraints are placed on anomalous quartic gauge couplings in terms of dimension-eight operators in effective field theory, which are of comparable order to analyses of other final states. Upper limits on the production cross section times branching fraction of photophobic ALPs, denoted a, are set as a function of the ALP mass. Equivalent limits for the ALP mass and coupling parameters are reported, including some of the most stringent constraints for mass values between $m_a = 200$–400 GeV, as well as the first interpretation for masses between $m_a = 110$–200 GeV.

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DATA AVAILABILITY

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy [69].

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