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Search for the production of $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{W}^{\mp}$ events at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

A search for the production of events containing three W bosons predicted by the standard model is reported. The search is based on a data sample of proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the CMS experiment at the CERN LHC and corresponding to a total integrated luminosity of $35.9\,\mathrm{fb}^{-1}$. The search is performed in final states with three leptons (electrons or muons), or with two same-charge leptons plus two jets. The observed (expected) significance of the signal for $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{W}^{\mp}$ production is 0.60 (1.78) standard deviations, and the ratio of the measured signal yield to that expected from the standard model is $0.34^{+0.62}_{-0.34}$. Limits are placed on three anomalous quartic gauge couplings and on the production of massive axion-like particles.

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*See Appendix A for the list of collaboration members

1 Introduction

According to the standard model (SM), events with three W bosons ($W^{\pm}W^{\pm}W^{\mp}$, labeled WWW in the following) are produced in proton-proton (pp) collisions at the CERN LHC. The process is sensitive to triple and quartic gauge couplings (QGC), so the observation and study of this process provides an important test of the electroweak sector of the SM. Figure 1 shows examples of lowest-order Feynman diagrams for WWW production. The analysis presented here focuses on the electroweak production of WWW events. The associated production of the Higgs (H) boson with a W boson, where the H boson decays to $W^{+}W^{-}$, is considered to be part of the signal production, whereas other processes such as the production of $t\bar{t}W^{\pm}$ are considered to be background processes. The nonresonant WWW production cross section is calculated to be 216 ± 9 fb [1] and, after including the contribution of $WH \rightarrow WWW^{*}$ with one off-shell W boson [2], the total theoretical electroweak production cross section is 509 ± 13 fb. In this paper, the label WWW includes both types of production.

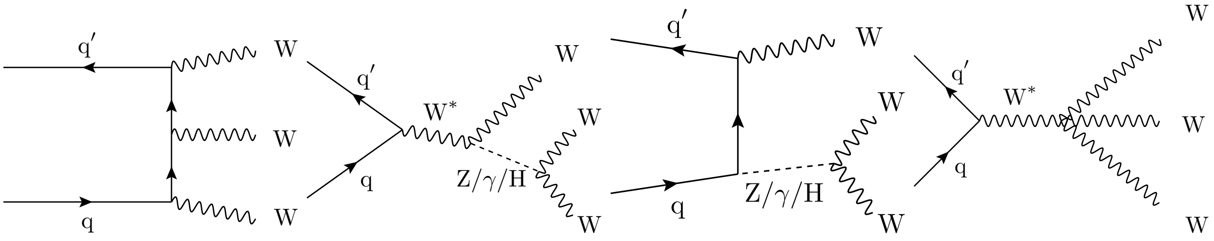

Figure 1: Tree-level Feynman diagrams for WWW production

A search for WWW production in 8 TeV pp collision data [3] and evidence for the production of three massive gauge bosons in 13 TeV pp collisions [4] were reported by the ATLAS Collaboration.

The analysis presented in this paper is performed with a sample of pp collisions at a center-of-mass energy of 13 TeV produced by the LHC and recorded with the CMS detector in 2016; the integrated luminosity for this sample is 35.9 fb^{-1}.

Events containing three W bosons can be classified by the expected number of charged leptons (electrons or muons only) in the final state: 41.7% contain no leptons, 42.4% contain one lepton, 9.6% have two leptons with opposite-sign (OS) charge, 4.8% have two same-sign (SS) leptons, and 1.6% of all events contain three leptons (3ℓ). These branching fractions include the contributions from leptonic decays of τ leptons to electrons or muons and neutrinos. Large backgrounds from the production of events with multiple jets, W bosons and jets, Drell-Yan lepton pairs and jets, and $t\bar{t}$ final states preclude the isolation of a signal except for categories of events with two SS leptons (with the third W boson decaying hadronically) and with three leptons. This search exploits these two event categories.

Certain new physics processes could lead to an excess of events over the SM prediction. These include, for example, processes with anomalous triple gauge couplings (aTGCs) [5] and anomalous QGCs (aQGCs) [5–8]. Since this analysis cannot improve the constraints already placed on aTGCs by recent diboson searches [9–14], it focuses on aQGCs. The production of massive, axion-like particles (ALPs) [15–24] is also considered. In the absence of a signal beyond the SM, limits are placed on aQGCs and on the production of ALPs in association with W bosons.

2 The CMS detector

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 solenoid volume are 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 endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [25]. The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μs. The high-level trigger processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [26].

3 Data and simulated event samples

The data are collected using dilepton triggers that select either two electrons, two muons, or one electron and one muon. These triggers require the leptons to have a high transverse momentum p_{T} and to satisfy loose isolation requirements. The dielectron trigger requires $p_{\mathrm{T}} > 23\,(12)\,\mathrm{GeV}$ for the leading (subleading) electron. The dimuon trigger requires $p_{\mathrm{T}} > 17\,(8)\,\mathrm{GeV}$ for the leading (subleading) muon. Finally, for the electron+muon trigger, the leading lepton must have $p_{\mathrm{T}} > 23\,\mathrm{GeV}$ and the subleading lepton must have $p_{\mathrm{T}} > 12\,\mathrm{GeV}$ if it is an electron, or $p_{\mathrm{T}} > 8\,\mathrm{GeV}$ if it is a muon. Data recorded using prescaled single electron and single muon triggers with p_{T} thresholds of 8 and 17 GeV, respectively, are utilized for studies of background rates. Events with contributions from beam halo processes or anomalous noise in the calorimeter are rejected using dedicated filters [27].

Samples of simulated events are used to optimize the event selection, to estimate some of the SM background processes, and to interpret the results in terms of WWW production. The MADGRAPH5_aMC@NLO 2.2.2 generator [28] is used in the next-to-leading-order (NLO) mode with FxFx jet matching [29] to generate triboson events, both the signal (WWW including WH) and the triboson background processes (such as WWZ). The same generator is used in the leading-order (LO) mode with the MLM jet matching [30] to generate SM $\mathrm{t\bar{t}}$, $\mathrm{t\bar{t}}$+X ($\mathrm{X} = \mathrm{W}, \mathrm{Z}, \mathrm{H}$), W+jets, Z+jets, W$\gamma$, and $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$ events. Events from other diboson (including WZ) and single top quark processes are generated at NLO with POWHEG 2.0 [31–34]. The most precise cross section calculations available are used to normalize the simulated samples, and usually correspond to either NLO or next-to-NLO accuracy [2, 28, 35–42].

The MADGRAPH5_aMC@NLO event generator is used in the NLO mode to simulate events following the model for photophobic, axion-line particles according to the model described in Ref. [24]. The aQGC samples are generated using MADGRAPH5_aMC@NLO 2.2.2 in the LO mode and the reweighting prescription of Ref. [43].

The NNPDF3.0 [44] parton distribution functions (PDFs) are used for all samples. Parton showering, hadronization, and the underlying event are modeled by PYTHIA 8.205 [45] with parameters set by the CUETP8M1 tune [46]. Additional pp collisions due to multiple interactions in the same or adjacent beam crossings, known as pileup, are also simulated, and the simulated distribution of pileup interactions is reweighted to match the one observed in data. The response of the CMS detector is simulated with the GEANT4 [47] package. The simulated events are reconstructed using the same software as the real data.

4 Event reconstruction

The CMS event reconstruction is based on the particle-flow (PF) algorithm [48], which combines information from the tracker, calorimeters, and muon systems to identify charged and neutral hadrons, photons, electrons, and muons, known as PF candidates.

Each event must contain at least one pp interaction vertex. The reconstructed vertex with the largest value of summed physics-object p_{T}^2 is taken to be the primary vertex (PV). The physics objects are the objects reconstructed by a jet finding algorithm [49–51] applied to all charged particle tracks associated with the vertex and also the corresponding missing transverse momentum ($p_{\mathrm{T}}^{\text{miss}}$).

Electrons and muons are identified by associating a track reconstructed in the silicon detectors with either a cluster of energy in the ECAL [52] or a track in the muon system [53], as appropriate. To be selected for this analysis, electron and muon candidates must satisfy $p_{\mathrm{T}} > 10\,\text{GeV}$ and $|\eta| < 2.4$. Electrons with $1.4 < |\eta| < 1.6$, which corresponds to the transition region between the barrel and endcap regions of the ECAL, are discarded. Several working points are defined, which differ according to the identification criteria chosen including the requirements on the three-dimensional impact parameter b and relative isolation I_{rel}. The impact parameter is the distance between the PV and the point of closest approach of the lepton track; $b < 0.015\,\text{cm}$ is required for all lepton candidates. This requirement is tightened to $b < 0.010\,\text{cm}$ for electrons in the SS category. The relative isolation of a lepton with p_{T}^{ℓ} is defined as

$$I_{\text{rel}} = \left(\sum p_{\mathrm{T}}^{\mathrm{c}} + \max \left[\sum p_{\mathrm{T}}^{\mathrm{nc}} - p_{\mathrm{T}}^{\mathrm{PU}}, 0 \right] \right) \Big/ \, p_{\mathrm{T}}^{\ell}.$$

In this expression, $\sum p_{\mathrm{T}}^{\mathrm{c}}$ is the scalar p_{T} sum of charged particles from the PV in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the lepton direction, and $\sum p_{\mathrm{T}}^{\mathrm{nc}}$ is the equivalent p_{T} sum for the neutral hadrons and the photons. The lepton momentum itself is not included in $\sum p_{\mathrm{T}}^{\mathrm{c}}$. The total neutral component contains contributions from pileup, estimated using $p_{\mathrm{T}}^{\mathrm{PU}} = \rho A_{\text{eff}}$ where the average p_{T} flow density ρ is calculated in each event using the jet area method [54], are subtracted. The effective area A_{eff} is the geometric area of the lepton isolation cone multiplied by an η-dependent factor that accounts for the residual dependence of the isolation on the pileup. Electrons are required to satisfy $I_{\text{rel}} < 0.03\,(0.05)$ for the SS (3ℓ) category, and muons must satisfy $I_{\text{rel}} < 0.03\,(0.07)$. These leptons are referred to as "tight" leptons. For "loose" electrons and muons used in the estimation of the nonprompt-lepton background, $I_{\text{rel}} < 0.4$ is required. For "rejection" electrons and muons, used to remove background events where extra leptons are present in either the SS or 3ℓ category, $I_{\text{rel}} < 0.4$ is required. For electrons in the SS category, the background contribution coming from a mismeasurement of the track charge is not negligible. The sign of this charge is inferred using three different observables; requiring all three to agree reduces this background contribution [52].

Events containing τ leptons decaying into charged hadrons are rejected by requiring no isolated tracks aside from selected electrons and muons. An isolated track is a charged PF lepton (charged PF hadron) with $p_{\mathrm{T}} > 5\ (10)\,\text{GeV}$, $|\eta| < 2.4$, and a longitudinal distance to the PV of $|d_z| < 0.1\,\text{cm}$; it must be isolated in the sense that $I_{\text{rel}} < 0.2\,(0.1)$ and $I_{\text{rel}} < 8\,\text{GeV}/p_{\mathrm{T}}^{\text{track}}$. Any isolated track or lepton that matches a selected lepton candidate within $\Delta R < 0.01$ is discarded.

PF candidates are clustered into jets using the anti-k_{T} jet clustering algorithm [49] with a distance parameter $R = 0.4$, implemented in the FASTJET package [50, 51]. Jets must pass loose selection criteria based on the fractions of neutral and charged energy in the jet, and on the relative amount of electromagnetic and hadronic energy. Jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 5$ are selected unless they are within $\Delta R < 0.4$ of a selected lepton or isolated track. Jet energies are corrected for contributions from pileup and to account for nonuniform detector response [55]. The loose working point of the combined secondary vertex (CSVv2) b tagging algorithm [56] is used to identify jets containing the decay of a heavy-flavor hadron. For this working point, the efficiency to select b quark jets is above 80% and the rate for tagging jets originating from the hadronization of gluons, and u, d, and s quarks is about 10%. In order to apply the CSVv2 b tagging algorithm, the jet must be reconstructed within $|\eta| < 2.4$.

The vector missing transverse momentum $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is defined as the negative vector p_{T} sum of all PF particle candidates. The magnitude of $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is denoted $p_{\mathrm{T}}^{\text{miss}}$. Corrections to jet energies due to the nonuniformity in the detector response are propagated to $p_{\mathrm{T}}^{\text{miss}}$ [57].

5 Search strategy and event selection

The event selection criteria are designed to maximize the signal significance in the two final states used in the analysis: two SS leptons and at least two jets (SS category), and three leptons (3ℓ category). Cross sections for background processes are much larger than the signal cross section, so stringent requirements must be applied in order to achieve sensitivity to WWW production.

The SS category contains signal events with the two SS W bosons decaying leptonically and the third W boson decaying hadronically. Correspondingly, the selection requires exactly two tight, high-p_{T} SS leptons and at least two high-p_{T} jets. This category is divided into two signal regions (SRs): "m_{jj}-in" includes the events in which the invariant mass of the two jets closest in ΔR is compatible with the W boson mass, $65 < m_{\mathrm{jj}} < 95\,\mathrm{GeV}$; "$m_{\mathrm{jj}}$-out" includes the remaining events. The m_{jj}-in SR is expected to contain more signal events and fewer background events than the m_{jj}-out region. The m_{jj}-out region still contains a sizable number of WWW events, from off-shell W bosons from WH production, for example. It is therefore is considered a signal region. The main background contribution is called the lost-lepton background and stems from three-lepton events with one lepton not selected due to an inefficiency (e.g., the isolation requirement) or because it falls outside the detector acceptance. Most of this background contribution comes from WZ production and a smaller contribution from $\mathrm{t\bar{t}Z}$ events. The rejection of events with an extra lepton or isolated track reduces this background contribution considerably. A smaller background contribution comes from the production of genuine SS lepton pairs, mainly through $\mathrm{W^{\pm}W^{\pm}}$+ jets and $\mathrm{t\bar{t}W^{\pm}}$ production. This contribution is reduced by requiring the two highest-p_{T} jets not have a large invariant mass m_{JJ} or large η separation and by excluding events with b-tagged jets. Another background contribution comes from events with one or more nonprompt leptons, such as those from semileptonic decays of heavy-flavor hadrons which arise mainly in W+jets and $\mathrm{t\bar{t}}$+jets production. The stringent lepton identification requirements are designed to suppress this contribution as much as possible. Additional requirements that $p_{\mathrm{T}}^{\text{miss}}$ be substantial and that the dilepton mass not be small further suppress this contribution. In the $\mathrm{e^{\pm}}\mu^{\pm}$ channel, a requirement $m_{\mathrm{T}}^{\text{max}} > 90\,\mathrm{GeV}$ is placed to reduce the contribution from the lost-lepton background from WZ production; $m_{\mathrm{T}}^{\text{max}}$ is the largest transverse mass obtained from $p_{\mathrm{T}}^{\text{miss}}$ and any lepton in the event. Background contributions from events containing misidentified or converted photons and from events with a lepton charge misassignment are minor. The details of the event selection for the SS category are listed in Table 1. There are six SRs defined according to the value of m_{jj} (m_{jj}-in or m_{jj}-out) and the flavors of the leptons: $\mathrm{e^{\pm}e^{\pm}}$, $\mathrm{e^{\pm}}\mu^{\pm}$, or $\mu^{\pm}\mu^{\pm}$.

Table 1: Event selection criteria for the SS category, which contains events with two same-sign leptons and at least two hadronic jets.

Variable	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Signal leptons	2 tight same-sign leptons with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$		
Additional leptons	No additional rejection lepton		
Isolated tracks	No (additional) isolated tracks		
Jets	At least two jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$		
b-tagged jets	No b-tagged jet		
Dijet mass (closest ΔR)	$65 < m_{\mathrm{jj}} < 95\,\mathrm{GeV}$ (m_{jj}-in) OR $\lvert m_{\mathrm{jj}} - 80\,\mathrm{GeV}\rvert \geq 15\,\mathrm{GeV}$ (m_{jj}-out)		
Dijet mass (leading jets)	$<400\,\mathrm{GeV}$		
$\Delta\eta$ of two leading jets	<1.5		
$p_{\mathrm{T}}^{\mathrm{miss}}$	$>60\,\mathrm{GeV}$	$>60\,\mathrm{GeV}$	$>60\,\mathrm{GeV}$ if m_{jj}-out
$m_{\ell\ell}$	$>40\,\mathrm{GeV}$	$>30\,\mathrm{GeV}$	$>40\,\mathrm{GeV}$
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_{\mathrm{Z}}\rvert > 10\,\mathrm{GeV}$	—	—
$m_{\mathrm{T}}^{\mathrm{max}}$	—	$>90\,\mathrm{GeV}$	—

The 3ℓ category contains signal events with all three W bosons decaying leptonically, so exactly three charged leptons are required. The fact that the total charge of the three leptons is ±1 means that there can be zero, one, or two same-flavor, opposite-sign (SFOS) lepton pairs; three SRs are designated 0 SFOS, 1 SFOS, 2 SFOS accordingly. The background sources are similar to those in the SS category. The contribution from three prompt-lepton final states (mostly WZ production) is suppressed by requiring the invariant masses of all SFOS pairs to be incompatible with the Z boson mass and with low-mass resonances. Additional reduction is achieved through the following requirements: if exactly one SFOS lepton pair is found, the transverse mass m_{T} calculated from the third lepton and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{T}}^{\mathrm{3rd}}$, must be larger than 90 GeV; and, for events with no SFOS pairs, $m_{\mathrm{T}}^{\mathrm{max}}$ is required to be larger than 90 GeV. These m_{T} requirements reduce the three-lepton background contributions, which originate mostly from WZ production.

Background contributions from nonprompt leptons and converted or misidentified photons are reduced by requiring large $p_{\mathrm{T}}^{\mathrm{miss}}$, large p_{T} of the three-lepton system $p_{\mathrm{T}}(\ell\ell\ell)$, and a large azimuthal separation $\Delta\phi\left(\vec{p}_{\mathrm{T}}(\ell\ell\ell), \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$ between $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and the transverse momentum vector of the three-lepton system, $\vec{p}_{\mathrm{T}}(\ell\ell\ell)$. The nonprompt-lepton background from $\mathrm{t\bar{t}}$ production is further reduced by rejecting events with more than one jet or with any b-tagged jets. Background contributions from photon conversions in which the photon is radiated in a Z boson decay are suppressed by requiring that the three-lepton invariant mass $m_{\ell\ell\ell}$ is not close to the Z boson mass. The details of the 3ℓ selection requirements are presented in Table 2.

For these event selection criteria, about one third of the selected signal events originate from resonant H boson production.

6 Background estimation

The background sources for the SS and 3ℓ categories are essentially the same. Four such sources are considered: lost leptons, two or three leptons from W decays, nonprompt leptons, and "other" minor sources. The lost-lepton background contributions come from final states with one or more Z bosons: WZ, $\mathrm{t\bar{t}Z}$, and ZZ. This contribution is estimated using a three-lepton control region (CR) with at least one SFOS pair compatible with the decay of a Z boson. The background processes in which the SS lepton pair or all three leptons stem from the decay of

Table 2: Event selection criteria for the 3ℓ category, which contains events with exactly three leptons.

Variable	0 SFOS	1 SFOS	2 SFOS
Signal leptons	3 tight leptons with $p_{\mathrm{T}} > 25/20/20\,\mathrm{GeV}$ and charge sum = $\pm 1\mathrm{e}$		
Additional leptons	No additional rejection lepton		
Jets	At most one jet with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 5$		
b-tagged jets	No b-tagged jets		
$p_{\mathrm{T}}(\ell\ell\ell)$	—	$>60\,\mathrm{GeV}$	$>60\,\mathrm{GeV}$
$\Delta\phi\left(\vec{p}_{\mathrm{T}}(\ell\ell\ell), \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$		>2.5	
$p_{\mathrm{T}}^{\mathrm{miss}}$	$>30\,\mathrm{GeV}$	$>45\,\mathrm{GeV}$	$>55\,\mathrm{GeV}$
$m_{\mathrm{T}}^{\mathrm{max}}$	$>90\,\mathrm{GeV}$	—	—
$m_{\mathrm{T}}^{\mathrm{3rd}}$	—	$>90\,\mathrm{GeV}$	—
SF lepton mass	$>20\,\mathrm{GeV}$	—	—
Dielectron mass	$\lvert m_{\mathrm{ee}} - m_{\mathrm{Z}}\rvert > 15\,\mathrm{GeV}$	—	—
m_{SFOS}	—	$\lvert m_{\mathrm{SFOS}} - m_{\mathrm{Z}}\rvert > 20\,\mathrm{GeV}$ and $m_{\mathrm{SFOS}} > 20\,\mathrm{GeV}$	$\lvert m_{\mathrm{SFOS}} - m_{\mathrm{Z}}\rvert > 20\,\mathrm{GeV}$ and $m_{\mathrm{SFOS}} > 20\,\mathrm{GeV}$
$m_{\ell\ell\ell}$		$\lvert m_{\ell\ell\ell} - m_{\mathrm{Z}}\rvert > 10\,\mathrm{GeV}$	

a W boson, such as from the $\mathrm{t\bar{t}W^{\pm}}$ process, are estimated from simulation and validated in an appropriate CR. Background yields from nonprompt leptons are calibrated using a CR in which one lepton passes the "loose" identification requirements but fails the "tight" requirements (as discussed in Section 4). The other background contributions are predicted using simulated event samples that are validated using the data. The following sections provide the details of the background estimations.

6.1 Lost-lepton and three-lepton background

The background predictions for both the SS and the 3ℓ categories rely on the selection of a pair of leptons consistent with a Z boson decay. This background type is expected to contribute from about one third to over 90% of the total background yields, depending on the SR.

Simulation suggests that about two thirds of the lost-lepton events in the SRs of the SS category are present because a lepton does not pass the p_{T} and η requirements. The remaining lost leptons are rejected by identification and isolation requirements. For the SS category, events with three leptons are selected. The additional third lepton must have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$. Among those three leptons, an SFOS lepton pair that satisfies $\lvert m_{\mathrm{SFOS}} - m_{\mathrm{Z}}\rvert < 10\,\mathrm{GeV}$ is required. All other SS selection criteria listed in Table 1 are imposed, except for the selection on m_{jj} in order to retain a sufficient number of events. In these events, the jets stem from initial-state radiation and have similar kinematic distributions in both the SRs and CRs, so the extrapolation from the CR to the SR is reliable. The background estimates for the m_{jj}-in and the m_{jj}-out SRs are fully correlated.

For the 3ℓ category, the CRs are defined in a similar fashion. All selection criteria stated in Table 2 are retained, but the requirement $\lvert m_{\mathrm{SFOS}} - m_{\mathrm{Z}}\rvert > 20\,\mathrm{GeV}$ is inverted so that there is at least one SFOS lepton pair compatible with a Z boson decay. Many events are selected for the 1 and 2 SFOS CRs, but for the 0 SFOS SR no corresponding CR exists. The results are extrapolated for the 1 SFOS and 2 SFOS regions to the 0 SFOS region.

The transfer factors needed to relate the yields in the CRs to the background contributions in the SRs are calculated using the simulation. The observed yields in these CRs agree well with the yields predicted using the simulation. Corrections to this extrapolation due to differences between the lepton reconstruction efficiencies in data and simulation are applied, and corresponding uncertainties are evaluated. The modeling of the m_{SFOS} distribution and its associated uncertainty for the SS category is tested using the mass spectrum in the CR. For the 3ℓ category, in order to ensure no overlap with the SRs, this test is performed after inverting at least one of the SR requirement on $p_{\mathrm{T}}^{\mathrm{miss}}$, $\Delta\phi\left(\vec{p}_{\mathrm{T}}(\ell\ell\ell), \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right)$, $p_{\mathrm{T}}(\ell\ell\ell)$, or $m_{\mathrm{T}}^{\mathrm{3rd}}$. This validation region has also only a small non-3ℓ contamination. The uncertainty due to limited knowledge of the VZ (V = W or Z) and $\mathrm{t\bar{t}Z}$ cross sections and their relative contribution in both SRs and CRs is estimated using events from the SS CRs, but after the requirement of no b-tagged jets is removed. The spectrum of the b-tagged jet multiplicity in simulation is fitted to the one observed in data, and the result of that fit is used to assess the uncertainty due to the relative contribution of VZ versus $\mathrm{t\bar{t}Z}$. For the SS category, an additional uncertainty due to the m_{jj} modeling is evaluated by comparing the observed and predicted yields of all CRs. Experimental uncertainties, such as the uncertainty on the jet energy corrections (JECs), are taken into account. A correction for the non-3ℓ contamination of the CRs is applied. This contamination is small, and stems mostly from nonprompt leptons or leptons from photon misidentified as electrons. The contamination is estimated from simulation, and a 50% relative uncertainty is assigned based on the validation study reported in Section 6.4. Uncertainties associated with the CR-to-SR transfer factors are included also. The impact of all these uncertainties is discussed in Section 7.

For the 0 SFOS SR no corresponding CR exists, so the following strategy is used: since the observed and predicted yields agree well in the 1 and 2 SFOS CRs, the central value for this background type in the 0 SFOS SR is taken from simulation, and the relative systematic uncertainty of the 1 SFOS SR prediction is added to the statistical uncertainty in the simulated yield.

A summary of the lost-lepton and three-lepton background estimation is reported in Table 3. All CRs are mutually exclusive and do not overlap with any of the SRs.

Table 3: Lost-lepton and three-lepton background contributions. The number of events in the data control regions (CRs) and the non-3ℓ contribution, which are estimated from simulation, are reported together with the control-to-signal region transfer factor ($TF_{\mathrm{CR}\rightarrow\mathrm{SR}}$). The last column reports the prediction of the lost-lepton and three-lepton background contributions to the signal regions, together with the statistical and systematic uncertainties.

Channel		Data (CR)	Non-3ℓ (CR)	$TF_{\mathrm{CR}\rightarrow\mathrm{SR}}$	Background estimate
SS m_{jj}-in	$\mathrm{e}^{\pm}\mathrm{e}^{\pm}$	6	0.01 ± 0.01	$0.134^{+0.053}_{-0.066}$	$0.80^{+0.48}_{-0.32}\,(\mathrm{stat})^{+0.32}_{-0.40}\,(\mathrm{syst})$
	$\mathrm{e}^{\pm}\mu^{\pm}$	13	0.26 ± 0.13	$0.103^{+0.024}_{-0.024}$	$1.31^{+0.48}_{-0.37}\,(\mathrm{stat})^{+0.30}_{-0.30}\,(\mathrm{syst})$
	$\mu^{\pm}\mu^{\pm}$	50	1.04 ± 0.58	$0.062^{+0.011}_{-0.012}$	$3.02^{+0.50}_{-0.43}\,(\mathrm{stat})^{+0.54}_{-0.60}\,(\mathrm{syst})$
SS m_{jj}-out	$\mathrm{e}^{\pm}\mathrm{e}^{\pm}$	6	0.01 ± 0.01	$0.600^{+0.140}_{-0.144}$	$3.60^{+2.15}_{-1.43}\,(\mathrm{stat})^{+0.84}_{-0.86}\,(\mathrm{syst})$
	$\mathrm{e}^{\pm}\mu^{\pm}$	13	0.26 ± 0.13	$0.382^{+0.067}_{-0.064}$	$4.86^{+1.79}_{-1.36}\,(\mathrm{stat})^{+0.85}_{-0.82}\,(\mathrm{syst})$
	$\mu^{\pm}\mu^{\pm}$	50	1.04 ± 0.58	$0.090^{+0.014}_{-0.014}$	$4.39^{+0.73}_{-0.63}\,(\mathrm{stat})^{+0.67}_{-0.68}\,(\mathrm{syst})$
3ℓ	0 SFOS	—	—	—	$0.47^{+0.20}_{-0.19}\,(\mathrm{syst})$
	1 SFOS	34	1.01 ± 0.53	$0.095^{+0.019}_{-0.017}$	$3.14^{+0.66}_{-0.55}\,(\mathrm{stat})^{+0.62}_{-0.55}\,(\mathrm{syst})$
	2 SFOS	155	2.74 ± 1.37	$0.066^{+0.009}_{-0.009}$	$10.10^{+0.89}_{-0.82}\,(\mathrm{stat})^{+1.30}_{-1.30}\,(\mathrm{syst})$

6.2 Background due to nonprompt leptons

The background contribution from nonprompt leptons is usually relatively small. However, because of the limited knowledge of this process, the associated uncertainty can have a significant impact on the result. The source of this background contribution is W+jets and $\mathrm{t\bar{t}}$ events in which one or two leptons come from W boson decays and another lepton comes either from a heavy-flavor hadron decay or from misidentified light hadrons. The background contribution is estimated using the tight-to-loose (TL) method [58]. The implementation used in this analysis is similar to the one used in searches for supersymmetric particles [59] and accounts for the kinematic properties and flavor of the parent parton of the nonprompt lepton. The TL method uses two CRs: the measurement region, which is used to extract the TL ratio ϵ_{TL}; and the application region (AR), where ϵ_{TL} is applied to estimate the contribution from the nonprompt-lepton background to the SRs. The ϵ_{TL} measurement region is defined by events containing exactly one loose lepton. To enrich this region with nonprompt leptons, events with $p_{\mathrm{T}}^{\text{miss}} < 20\,\mathrm{GeV}$ and $m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\ell}, \vec{p}_{\mathrm{T}}^{\text{miss}}) < 20\,\mathrm{GeV}$ are selected. To select events with kinematic properties similar to those in W+jets and $\mathrm{t\bar{t}}$ events, the presence of at least one jet with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$, $|\eta| < 2.4$ and $\Delta R(\vec{p}_{\mathrm{T}}^{\ell}, \vec{p}_{\mathrm{T}}^{\text{jet}}) > 1$ is required. The TL ratio is defined as the fraction of events in the measurement region in which the loose lepton also passes the tight lepton selection; and ϵ_{TL} is computed as a function of $p_{\mathrm{T}}^{\text{corr}}$ and $|\eta|$. Here, $p_{\mathrm{T}}^{\text{corr}}$ is p_{T}^{ℓ} plus the fraction of the p_{T} sum of objects in the isolation cone exceeding the isolation threshold value defined in Section 4. The quantity $p_{\mathrm{T}}^{\text{corr}}$ is better correlated with the parent parton p_{T} than is p_{T}^{ℓ}. The ϵ_{TL} measurement is corrected for the contribution of prompt leptons in the measurement region. This contribution is taken from simulation, but its normalization is taken from data in the measurement region sideband satisfying $p_{\mathrm{T}}^{\text{miss}} > 30\,\mathrm{GeV}$ and $80 < m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\ell}, \vec{p}_{\mathrm{T}}^{\text{miss}}) < 120\,\mathrm{GeV}$. Uncertainties in the extrapolation from the sideband to the measurement region are evaluated; they are dominated by the JEC uncertainty.

The ARs are defined similarly to the SRs, with the difference that one of the leptons only passes the loose but not the tight selection defined in Section 4. Nonprompt leptons are the main contribution to these regions; small contributions from prompt lepton events are estimated with simulations and subtracted. The background contribution is estimated by weighting each event by $\epsilon_{\mathrm{TL}}/(1-\epsilon_{\mathrm{TL}})$, where ϵ_{TL} is the probability that the lepton fails the tight selection, and summing all the event weights.

The performance of the TL method is evaluated in simulation by comparing the prediction of the TL method in the SR with the actual yield of nonprompt-lepton background; they agree within the statistical precision of this test. The statistical uncertainty of the test is assigned as an additional systematic uncertainty. The results of the nonprompt-lepton background estimation with its systematic uncertainties are given in Table 4.

6.3 Irreducible backgrounds

The third important background process for this search is irreducible, namely, two or three charged leptons originating from W boson decays. This background process is similar to the signal process and is estimated using Monte Carlo simulations. For the SS category, the simulation predicts that 49% of this background process comes from $\mathrm{t\bar{t}V}$ production (mostly $\mathrm{t\bar{t}W^{\pm}}$), 47% from $\mathrm{W^{\pm}W^{\pm}}$+ jets, and 4% from double-parton scattering (DPS) $\mathrm{W^{\pm}W^{\pm}}$. For the 3ℓ category, the irreducible background process comes almost completely from $\mathrm{t\bar{t}W^{\pm}}$ production. The uncertainty for this background process is based on the relevant cross section measurements by the CMS Collaboration: for $\mathrm{t\bar{t}W^{\pm}}$ production the uncertainty is 22% [60] and for $\mathrm{W^{\pm}W^{\pm}}$+ jets it is 20% [61]. The estimation of this background process is verified in certain validation

Table 4: Nonprompt-lepton background estimates. The data in the application regions (AR), the prompt yields (AR) from simulations, and the predicted nonprompt-lepton background are reported. The uncertainties in the prediction are split into statistical and systematic components.

Channel		Data (AR)	Prompt yield (AR)	Background estimate
SS m_{jj}-in	$\mathrm{e}^{\pm}\mathrm{e}^{\pm}$	8	3.2 ± 2.2	$0.89 \pm 0.53\,(\mathrm{stat}) \pm 0.63\,(\mathrm{syst})$
	$\mathrm{e}^{\pm}\mu^{\pm}$	16	1.7 ± 0.3	$0.92 \pm 0.26\,(\mathrm{stat}) \pm 0.43\,(\mathrm{syst})$
	$\mu^{\pm}\mu^{\pm}$	57	2.9 ± 0.5	$0.82 \pm 0.11\,(\mathrm{stat}) \pm 0.36\,(\mathrm{syst})$
SS m_{jj}-out	$\mathrm{e}^{\pm}\mathrm{e}^{\pm}$	4	1.1 ± 0.5	$0.47 \pm 0.32\,(\mathrm{stat}) \pm 0.28\,(\mathrm{syst})$
	$\mathrm{e}^{\pm}\mu^{\pm}$	32	2.8 ± 0.5	$1.60 \pm 0.31\,(\mathrm{stat}) \pm 0.64\,(\mathrm{syst})$
	$\mu^{\pm}\mu^{\pm}$	36	3.2 ± 0.5	$0.59 \pm 0.11\,(\mathrm{stat}) \pm 0.25\,(\mathrm{syst})$
3ℓ	0 SFOS	17	0.7 ± 0.3	$0.97 \pm 0.25\,(\mathrm{stat}) \pm 0.22\,(\mathrm{syst})$
	1 SFOS	2	0.8 ± 0.3	$0.07^{+0.08}_{-0.07}\,(\mathrm{stat})^{+0.11}_{-0.07}\,(\mathrm{syst})$
	2 SFOS	6	2.0 ± 0.5	$0.30 \pm 0.18\,(\mathrm{stat}) \pm 0.25\,(\mathrm{syst})$

regions in which the dominant contribution comes from the $\mathrm{t\bar{t}W^{\pm}}$ process. The validation regions, however, are not as pure as those defined for the lost-lepton or nonprompt-lepton backgrounds. For the $\mathrm{t\bar{t}W^{\pm}}$ contribution, the validation region is defined by requiring events to contain two tight SS leptons, ≥4 jets, ≥1 b-tagged jets and $60 < m_{\mathrm{jj}} < 100\,\mathrm{GeV}$. For the $\mathrm{W^{\pm}W^{\pm}}$+ jets contribution, the validation region is constructed by requiring two tight SS leptons, ≥2 jets, 0 b-tagged jets, $m_{\mathrm{JJ}} > 400\,\mathrm{GeV}$, and $|\Delta\eta_{\mathrm{JJ}}| > 1.5$. The observed yields and the estimates based on simulations agree within the statistical power of the test.

6.4 Other backgrounds

Other remaining background yields are expected to be very small. They originate from either a charge misassignment for one of the leptons or from events containing a photon that is either misidentified as an electron, or that converts to an $\ell^{+}\ell^{-}$ pair with one of the leptons being lost. These contributions are estimated using simulation and are validated with data. The background yields due to lepton charge misassignment are validated in a dielectron sample with $|m_{\ell\ell} - m_{\mathrm{Z}}| < 10\,\mathrm{GeV}$ by comparing the events yields when the two electrons have either the equal or opposite electric charge. The background contribution due to events with leptons originating from photons is validated in a three-lepton validation region enriched in $\mathrm{Z}\gamma$ production. The selection is similar to the 3ℓ SR selection (Table 2), but at least one SFOS lepton pair with $|m_{\mathrm{SFOS}} - m_{\mathrm{Z}}| < 20\,\mathrm{GeV}$ is required. Also the requirement on $m_{\ell\ell\ell}$ is dropped and the one on $p_{\mathrm{T}}(\ell\ell\ell)$ is inverted. A 50% relative uncertainty is assigned to these background sources. Within this uncertainty, the agreement between data and simulation in these validation regions is satisfactory.

7 Systematic uncertainties

Systematic uncertainties are associated with the background estimations, the signal contribution, and the theoretical predictions. The systematic uncertainties of the estimated background contributions are discussed in Section 6 and a detailed summary is provided in Table 5.

The experimental uncertainties for the signal include JECs [55, 62], lepton energy resolution, lepton efficiency data-to-simulation correction factors [52, 53], b tagging correction factors [56], trigger efficiencies, pileup, and integrated luminosity [63] uncertainties. The lepton reconstruction efficiencies and trigger efficiencies are measured with a tag-and-probe method [64] applied

Table 5: Summary of typical systematic uncertainties in estimated background contributions. The ranges indicate variations across different signal regions.

Uncertainty	Lost-lepton/ three-lepton	Nonprompt leptons	$\gamma \to \ell$	Charge mis-assignment	Irreducible
Control data sample size	11–46%	15–43%	—	—	—
Simulation statistical uncertainty	14–25%	—	—	—	4–18%
Lepton reconstruction	<1%	—	—	—	<1%
Lepton energy resolution	<1%	<1%	—	—	<1%
m_{jj} modeling (SS only)	7.3%	—	—	—	—
Jet energy scale	1–7%	—	—	—	—
m_{SFOS} extrapolation	5-8%	—	—	—	—
$\mathrm{t\bar{t}Z/WZ}$ fraction	<1%	—	—	—	—
ϵ_{TL} measurement	—	21–43%	—	—	—
Validation of TL ratio method	—	22–25%	—	—	—
b tagging	<1%	—	—	—	2–4%
Cross section measurement	—	—	—	—	14–22%
Trigger	—	—	—	—	1%
Pileup	1–8%	—	—	—	—
Integrated luminosity	—	—	—	—	2.5%
Other uncertainties	—	—	50%	50%	—

to $\mathrm{Z} \to \ell^+\ell^-$ events. Table 6 summarizes the systematic uncertainties for the signal process.

The theoretical uncertainty for the predicted signal cross section is obtained from Ref. [1]. Uncertainties in the signal acceptance from the renormalization (μ_{R}) and factorization (μ_{F}) scales are evaluated [65–67]. Parametric (PDF and α_S) uncertainties are estimated using the PDF4LHC prescription [68] with the NNPDF3.0 set [44]. The impact of the systematic uncertainties on the signal is small compared to those of the background estimations.

Table 6: Summary of systematic uncertainties for the signal process.

Uncertainty	Typical size
Simulation statistical uncertainty	12–33%
Cross section calculation (normalization)	6%
$\mu_{\mathrm{R}}/\mu_{\mathrm{F}}$ (acceptance only)	1–13%
PDF (acceptance only)	1–4%
α_S	1%
Lepton reconstruction efficiency	2–3%
Lepton energy resolution	0–2%
Jet energy scale	1–7%
b tagging scale factor	1–3%
Trigger	3–5%
Pileup	0–4%
Luminosity	2.5%

8 Results and interpretations

This section firstly presents the event yields in the nine nonoverlapping categories used to obtain the measured value of the production cross section. Secondly, contributions to the yield originating from aQGCs are considered. Finally, a possible signal from a specific beyond-the-

SM model, photophobic axion-like particle production [24], is investigated.

8.1 Cross section measurement

The data in all SRs, together with the predicted background yields and expected signal yields, are provided in Table 7. The WH $\rightarrow$ WWW* process contributes about one third of the expected signal yield. A graphical representation is given in Fig. 2.

Table 7: Numbers of observed events for all signal regions, including predicted background contributions and expected signal yields. The uncertainties presented include both the statistical and systematic uncertainties.

	m_{jj}-in			m_{jj}-out			3ℓ		
	$\mathrm{e}^\pm\mathrm{e}^\pm$	$\mathrm{e}^\pm\mu^\pm$	$\mu^\pm\mu^\pm$	$\mathrm{e}^\pm\mathrm{e}^\pm$	$\mathrm{e}^\pm\mu^\pm$	$\mu^\pm\mu^\pm$	0 SFOS	1 SFOS	2 SFOS
Lost/three ℓ	$0.8^{+0.6}_{-0.5}$	$1.3^{+0.6}_{-0.5}$	$3.0^{+0.7}_{-0.7}$	$3.6^{+2.3}_{-1.6}$	$4.9^{+1.9}_{-1.5}$	$4.4^{+0.9}_{-0.9}$	$0.5^{+0.2}_{-0.2}$	$3.1^{+0.8}_{-0.7}$	$10.1^{+1.3}_{-1.2}$
Irreducible	$0.3^{+0.1}_{-0.1}$	$1.0^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.3}$	$1.3^{+0.2}_{-0.2}$	$3.7^{+0.4}_{-0.4}$	$3.9^{+0.4}_{-0.4}$	$0.2^{+0.0}_{-0.0}$	$0.1^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$
Nonprompt ℓ	$0.9^{+0.7}_{-0.7}$	$0.9^{+0.8}_{-0.8}$	$0.8^{+0.6}_{-0.6}$	$0.6^{+0.6}_{-0.5}$	$1.8^{+1.4}_{-1.4}$	$0.8^{+0.5}_{-0.5}$	$1.0^{+0.6}_{-0.5}$	$0.1^{+0.1}_{-0.1}$	$0.3^{+0.2}_{-0.2}$
Charge flips	$0.2^{+0.2}_{-0.2}$	$0.4^{+0.3}_{-0.2}$	<0.1	$0.4^{+0.3}_{-0.3}$	$0.5^{+0.3}_{-0.3}$	<0.1	$0.2^{+0.1}_{-0.1}$	<0.1	<0.1
$\gamma \rightarrow$ nonprompt ℓ	$0.2^{+0.1}_{-0.1}$	$0.1^{+0.1}_{-0.1}$	<0.1	$2.2^{+2.1}_{-2.1}$	$0.4^{+0.5}_{-0.4}$	<0.1	<0.1	<0.1	<0.1
Background sum	$2.4^{+1.0}_{-0.8}$	$3.7^{+1.1}_{-1.0}$	$5.6^{+1.0}_{-1.0}$	$8.1^{+3.2}_{-2.8}$	$11.3^{+2.5}_{-2.2}$	$9.1^{+1.2}_{-1.1}$	$1.8^{+0.6}_{-0.6}$	$3.3^{+0.8}_{-0.7}$	$10.4^{+1.3}_{-1.2}$
WWW signal	$0.3^{+0.1}_{-0.1}$	$1.8^{+0.3}_{-0.3}$	$2.4^{+0.3}_{-0.3}$	$0.4^{+0.2}_{-0.2}$	$1.3^{+0.3}_{-0.3}$	$1.5^{+0.4}_{-0.4}$	$1.8^{+0.4}_{-0.4}$	$1.5^{+0.3}_{-0.3}$	$0.7^{+0.3}_{-0.3}$
Total	$2.7^{+1.0}_{-0.8}$	$5.5^{+1.1}_{-1.0}$	$7.9^{+1.0}_{-1.0}$	$8.5^{+3.2}_{-2.7}$	$12.6^{+2.5}_{-2.2}$	$10.6^{+1.3}_{-1.2}$	$3.6^{+0.7}_{-0.7}$	$4.8^{+0.9}_{-0.8}$	$11.1^{+1.3}_{-1.2}$
Observed	0	3	10	4	10	18	2	2	10

A profile maximum likelihood method is used following the procedures set by the LHC Higgs Combination Group [69] to extract the expected and observed significances of this analysis to the SM WWW production process. The signal strength is constrained to be non-negative. The systematic uncertainties are treated as nuisance parameters and are profiled in the maximum likelihood fit. Using the significance as metric, the most sensitive categories among those shown in Fig. 2 are 0 SFOS, m_{jj}-in $\mathrm{e}^\pm\mu^\mp$, 1 SFOS, and m_{jj}-in $\mu^\pm\mu^\mp$. For quantifying the absence of a signal, the modified frequentist $\mathrm{CL_s}$ statistic [70, 71] is used and asymptotic formulae [72] are used for quantifying the significance of an excess.

The expected significance for the combined SS and 3ℓ categories is 1.78 standard deviations (s.d.) assuming the SM production of WWW events, whereas the observed significance is 0.60 s.d. The corresponding expected and observed p-values for the null hypothesis are 0.038 and 0.274. The best fit for the observed signal strength, defined as the ratio of the observed signal to the theoretically predicted one, is $0.34^{+0.62}_{-0.34}$. It follows that the measured cross section is

$$\sigma(\mathrm{pp} \rightarrow \mathrm{W^\pm W^\pm W^\mp}) = 0.17^{+0.32}_{-0.17}\,\mathrm{pb}.$$

The uncertainties include both statistical and systematic components. Assuming the presence of background only, the observed (expected) 95% confidence level (CL) upper limit on the cross section is 0.78 (0.60) pb.

8.2 Limits on anomalous quartic gauge couplings

The interaction of four gauge bosons depicted in Fig. 1 exists in the SM and contributes to the production of the WWW final state. New physics beyond the SM could be manifested as an apparent change in the coupling constant associated with the four-boson vertex, i.e., in an aQGC. A description based on aQGCs is appropriate when the mass scale for new physics

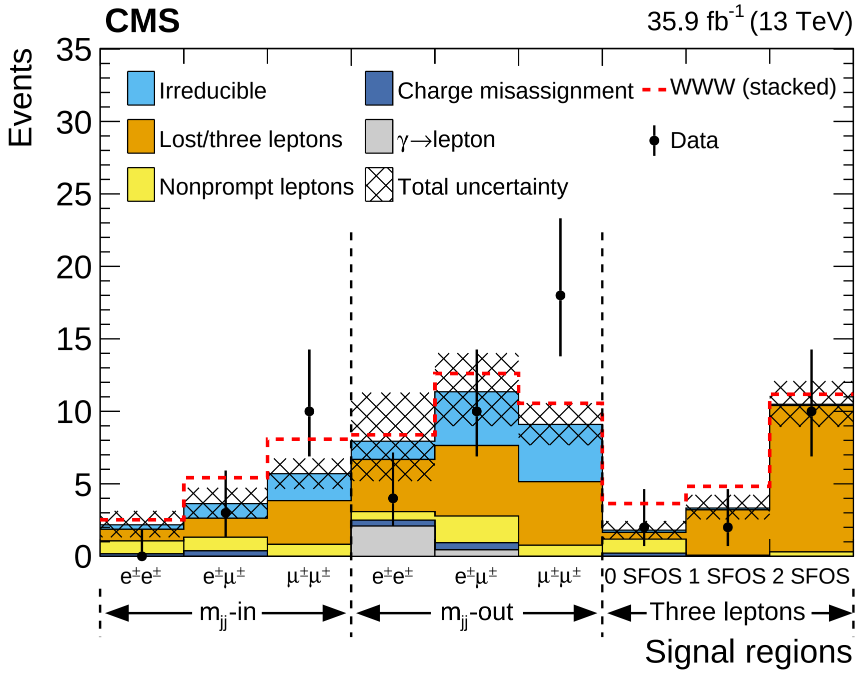

Figure 2: Comparison of the observed numbers of events to the predicted yields in the nine signal regions. The WWW signal shown is stacked on top of the total background and is based on the SM theoretical cross section.

Λ is much higher than the energy scale of the given process, in this case, WWW production characterized by the squared invariant mass of the three W bosons, $\hat{s}_{\mathrm{WWW}}$.

Anomalous couplings can be handled theoretically by extending the SM Lagrangian with the operator product expansion [8]:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j + \cdots,$$

where $\mathcal{O}$ represents the higher-order dimension-6 and dimension-8 operators with Wilson coefficients c_i and f_j, respectively. The operators $\mathcal{O}_i$ are constructed from SM fields and respect gauge invariance. The coefficients are unknown and are treated as free parameters to be determined by the data. The coefficients for all dimension-6 operators, which represent aTGCs, are taken to be zero. The following dimension-8, CP-conserving operators can be included in the non-SM part of the Lagrangian [8, 73]:

$$\begin{aligned}
\mathcal{O}_{\mathrm{S},0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]\left[(D^\mu\Phi)^\dagger D^\nu\Phi\right], & \mathcal{O}_{\mathrm{S},1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right]\left[(D_\nu\Phi)^\dagger D^\nu\Phi\right],\\
\mathcal{O}_{\mathrm{M},0} &= Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right]\left[(D_\beta\Phi)^\dagger D^\beta\Phi\right], & \mathcal{O}_{\mathrm{M},1} &= Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right]\left[(D_\beta\Phi)^\dagger D^\mu\Phi\right],\\
\mathcal{O}_{\mathrm{M},6} &= \left[(D_\mu\Phi)^\dagger\hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right], & \mathcal{O}_{\mathrm{M},7} &= \left[(D_\mu\Phi)^\dagger\hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right],\\
\mathcal{O}_{\mathrm{T},0} &= Tr\left[W_{\mu\nu}W^{\mu\nu}\right]Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right], & \mathcal{O}_{\mathrm{T},1} &= Tr\left[W_{\alpha\nu}W^{\mu\beta}\right]Tr\left[W_{\mu\beta}W^{\alpha\nu}\right],\\
\mathcal{O}_{\mathrm{T},2} &= Tr\left[W_{\alpha\mu}W^{\mu\beta}\right]Tr\left[W_{\beta\nu}W^{\nu\alpha}\right].
\end{aligned}$$

The Lagrangian including dimension-8 anomalous coupling terms is:

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + &\frac{f_{\mathrm{S},0}}{\Lambda^4}\mathcal{O}_{\mathrm{S},0} + \frac{f_{\mathrm{S},1}}{\Lambda^4}\mathcal{O}_{\mathrm{S},1} + \frac{f_{\mathrm{M},0}}{\Lambda^4}\mathcal{O}_{\mathrm{M},0} + \\ &\frac{f_{\mathrm{M},1}}{\Lambda^4}\mathcal{O}_{\mathrm{M},1} + \frac{f_{\mathrm{M},6}}{\Lambda^4}\mathcal{O}_{\mathrm{M},6} + \frac{f_{\mathrm{M},7}}{\Lambda^4}\mathcal{O}_{\mathrm{M},7} + \\ &\frac{f_{\mathrm{T},0}}{\Lambda^4}\mathcal{O}_{\mathrm{T},0} + \frac{f_{\mathrm{T},1}}{\Lambda^4}\mathcal{O}_{\mathrm{T},1} + \frac{f_{\mathrm{T},2}}{\Lambda^4}\mathcal{O}_{\mathrm{T},2},\end{aligned}$$

where the coefficients $f_{x,n}/\Lambda^4$ have dimension TeV $^{-4}$. No form factors for enforcing unitarity are employed in this analysis. When looking for evidence of anomalous couplings, WWW production as predicted in the SM is taken as a background process. Interference effects between the SM and the anomalous contribution to WWW production are taken into account.

Since $\hat{s}_{\mathrm{WWW}}$ cannot be measured directly, the kinematic quantity S_{T} is employed, which is the sum of the p_{T} of the leptons and the jets, and $p_{\mathrm{T}}^{\mathrm{miss}}$. The presence of aQGCs would be manifested as an excess of events at high S_{T}. Since non-WWW background events and SM WWW events appear at low S_{T}, a requirement of $S_{\mathrm{T}} > S_{\mathrm{T}}^{\mathrm{min}}$ is imposed. The value for $S_{\mathrm{T}}^{\mathrm{min}}$ is chosen to optimize the expected limits on the anomalous coupling $f_{\mathrm{T},0}/\Lambda^4$ for which this analysis is most sensitive. For the SS and 3ℓ categories, the values are $S_{\mathrm{T}}^{\mathrm{min}} = 2.0$ and 1.5 TeV, respectively. There is little sensitivity to the operators involving Higgs doublet terms.

The event selection is the same as described in Section 5, except that the restriction on m_{JJ} for the leading two jets is removed in order to retain sensitivity to aQGCs. The numbers of events expected in the SM are very small: 0.22 ± 0.10 events in the SS category (mainly $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$+jets events) and less than 0.01 event in the 3ℓ category. The systematic uncertainty assigned to the predicted background yields is 30% but the predicted limits on anomalous couplings are insensitive to this uncertainty. Furthermore, a reduction of the signal yield by 25%, as might be induced by higher-order corrections to the production cross section [74], increases the allowed range of anomalous couplings by about 11%.

No events are selected when the event selection criteria are imposed on the data. In the absence of any indication for anomalous couplings, limits are set as summarized in Table 8. When calculating the limit on one anomalous coupling, the others are taken to be zero.

Table 8: Limits on three anomalous quartic couplings at 95% CL.

Anomalous coupling	Allowed range (TeV^{-4})	
	Expected	Observed
$f_{\mathrm{T},0}/\Lambda^4$	[-1.3, 1.3]	[-1.2, 1.2]
$f_{\mathrm{T},1}/\Lambda^4$	[-3.7, 3.7]	[-3.3, 3.3]
$f_{\mathrm{T},2}/\Lambda^4$	[-3.0, 2.9]	[-2.7, 2.6]

8.3 Limits on photophobic axion-like particle models

Since the discovery of a H boson [75–77], searches for extended scalar sectors have been of high interest [78, 79]. For example, pseudoscalar particles like the quantum chromodynamics axion, which solve the strong CP problem [15–18], can also be candidates for dark matter [80–82]. Other examples address the hierarchy problem via relaxation mechanisms through the relaxion field [83]. An ALP can have a variety of couplings to SM gauge bosons. Recently, theoretical studies have been extended to include couplings to gauge bosons besides photons [20–23]. Generally speaking, if the ALPs are sufficiently light, branching fractions to photons are expected to be large.

In this study, photophobic ALPs [24] are considered whose mass is large enough that their dominant decay mode is $a \to WW$. In this scenario, the WWW final state results from the production of Wa followed by $a \to WW$. The WWW channel has the largest product of production cross section and branching fraction for $m_a \gtrsim 2m_W$, [24]. For $m_a \lesssim 2m_W$, the branching fraction falls off rapidly; the interpretation for $m_a < 200\,\mathrm{GeV}$ is left for future analyses. The model has one free parameter, $1/f_a$, which fully determines the couplings of the ALP of mass m_a to SM particles. In this context, as for aQGCs discussed in Section 8.2, the SM production of WWW is treated as a background to new physics.

The acceptance of the model for the SRs follows an expected pattern: when $m_a = 200\,\mathrm{GeV}$, the acceptance is similar to that estimated for the SM WWW signal process. As m_a increases, the acceptance rises because the events are more centrally produced and the decay products more often fall within the fiducial region.

There is no evidence for an excess of events (Table 7). Limits on the production of the Wa final state and on the parameter $1/f_a$ are placed using the methods described in Section 8.1 for the SM production of WWW. The limits are displayed as a function of m_a in Fig. 3 (left) for $\sigma(\mathrm{pp} \to \mathrm{Wa})\mathcal{B}(\mathrm{a} \to \mathrm{WW})$ and in Fig. 3 (right) for $1/f_a$.

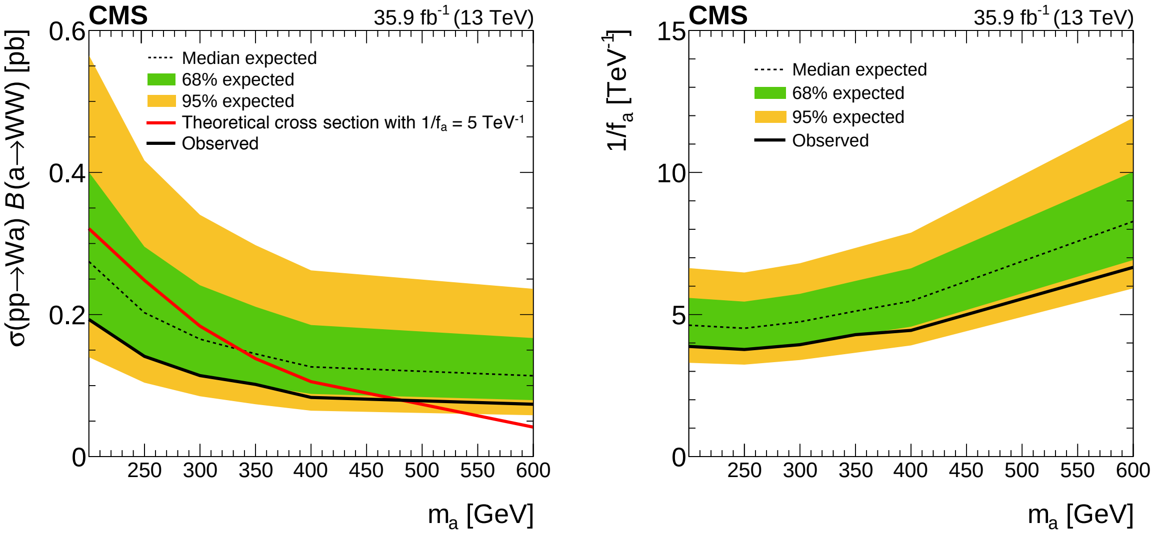

Figure 3: (left) Expected and observed 95% CL upper limits on the product of the cross section and branching fraction $\sigma(\mathrm{pp} \to \mathrm{Wa})\mathcal{B}(\mathrm{a} \to \mathrm{WW})$ as a function of ALP mass. The red line corresponds to the theoretical prediction for $1/f_a = 5\,\mathrm{TeV}^{-1}$. (right) Expected and observed 95% CL upper limits on the photophobic ALP model parameter $1/f_a$ as a function of ALP mass.

9 Summary

A search for $\mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{W}^{\mp}$ production using proton-proton collision data at a center-of-mass energy of 13 TeV was presented. Events with either two same-sign leptons (electrons or muons) and two jets or with three leptons with total charge ±1 were selected. The data were collected with the CMS experiment and correspond to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$. The dominant sources of standard model backgrounds include nonprompt leptons, three-lepton events such as those from the process $\mathrm{WZ} \to 3\ell\nu$, as well as $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$+ jets and $\mathrm{t\bar{t}W}^{\pm}$ production. Predictions for these backgrounds were derived or validated using data in dedicated control regions. The observed (expected) significance for $W^{\pm}W^{\pm}W^{\mp}$ production is 0.60 (1.78) standard deviations and the ratio of measured signal yield to that expected from the standard model is $0.34^{+0.62}_{-0.34}$, which corresponds to a measured cross section of $0.17^{+0.32}_{-0.17}$ pb.

New physics processes that could lead to an excess of events were considered. Limits on anomalous quartic gauge couplings are set, for example; $-1.2 < f_{T,0}/\Lambda^4 < 1.2\,\text{TeV}^{-4}$ at 95% confidence level. Limits are also set on the production of axion-like particles in association with a W boson: mass points between $m_a = 200$ and 480 GeV are excluded for the parameter value $1/f_a = 5\,\text{TeV}^{-1}$.

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