Search for a heavy Higgs boson decaying to a pair of W bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract

A search for a heavy Higgs boson decaying to a pair of W bosons in the mass range from 200 GeV to 3 TeV is presented. The analysis is based on proton-proton collisions recorded by the CMS experiment at the CERN LHC in 2016, corresponding to an integrated luminosity of $35.9 \text{ fb}^{-1}$ at $\sqrt{s} = 13$ TeV. The decay of the W boson pair is reconstructed in the $\ell\nu\ell'\nu'$ and $\ell v q\bar{q}$ final states. Both gluon fusion and vector boson fusion production of the signal are considered, with a number of hypotheses for their relative contribution investigated. Interference effects between the signal and background are also taken into account. Dedicated event categorizations based on the kinematic properties of associated jets and matrix element techniques are employed to optimise the signal sensitivity. The observed data are consistent with the standard model expectation. Combined upper limits at the 95% confidence level on the product of the cross section and branching fraction exclude a heavy Higgs boson with Standard Model-like couplings and decays in the mass range evaluated. Exclusion limits are also set in the context of two Higgs doublet models.
1 Introduction

The discovery of the Higgs boson by the LHC experiments ATLAS and CMS in 2012 [1, 2] represents a major advancement in particle physics. Studies of the new particle have so far shown consistency with the Standard Model (SM) Higgs mechanism predictions [3–7], the only unknown parameter, the boson’s mass, has been measured to be close to 125 GeV. Nevertheless, in order to determine whether the SM gives a complete description of the Higgs sector, precise measurements of the Higgs boson coupling strengths, CP structure and transverse momentum are required [8, 9]. A complementary and important strategy involves the search for an additional Higgs boson, denoted X, whose existence would prove the presence of beyond-the-SM (BSM) physics in the form of a non-minimal Higgs sector [10, 11]. The search for additional scalar resonances in the full mass range accessible at the LHC remains one of the main objectives of the experimental community.

The search for a high mass Higgs boson has been performed at ATLAS [12–14] and CMS [15, 16] in a number final states, using proton-proton collisions recorded at center-of-mass energies of 7, 8 and 13 TeV, with no significant excess observed. For Higgs boson masses above 200 GeV one of the most sensitive channels is the decay to a pair of W bosons [17]. In this analysis a search is performed in the fully leptonic, $\ell^+\ell^-$, and semi leptonic, $\ell\nu q\bar{q}$, WW final states (with $\ell = e$ or $\mu$) using proton-proton collisions recorded at a center-of-mass energy of 13 TeV by the CMS experiment in 2016, corresponding to an integrated luminosity of 35.9 fb$^{-1}$.

The fully leptonic channel has a clear signature of two isolated leptons and missing-transverse-energy (MET), due to the neutrinos escaping detection. For the semi-leptonic channel, the leptonically decaying boson is reconstructed as a single isolated lepton and MET. The hadronically decaying boson may be sufficiently boosted that its decay products are contained in a single merged jet. Jet substructure techniques are used to identify merged jets with two well defined subjets and to determine the merged jet mass, helping to discriminate vector bosons from QCD jets originating from quarks and gluons. If the hadronic decay products are resolved then the boson decay products may be reconstructed using two quark-jets (a dijet). The search is performed in a wide mass range from 200 GeV up to 3 TeV. Event categories optimised for the gluon fusion (ggF) and vector-boson fusion (VBF) production mechanisms are used to increase the signal sensitivity.

A signal interpretation in terms of a heavy Higgs boson with SM-like couplings and decays is performed. This is motivated by BSM models in which the SM Higgs boson mixes with a heavy EW singlet, which predicts the existence of an additional resonance at high mass with couplings similar to those of the SM Higgs boson [10]. The signal model includes a detailed simulation of the interference between the X signal, the SM Higgs boson off-shell tail and the WW backgrounds. Both ggF and VBF production are considered, with a number of hypotheses for their relative contribution investigated. Additional interpretations based on a number of Two-Higgs-doublet model (2HDM) [11] formulations are performed. The 2DHM, which introduces a second scalar doublet, is incorporated in supersymmetric models [18], axion models [19], and may introduce additional sources of explicit or spontaneous CP violation that explain the baryon asymmetry of the universe [20].

2 The CMS detector

The CMS detector, described in detail in Ref. [21], is a multipurpose apparatus designed to study high transverse momentum ($p_T$) physics processes in proton-proton and heavy-ion collisions. A superconducting solenoid occupies its central region, providing a magnetic field of
3.8 T parallel to the beam direction. Charged-particle trajectories are measured by the silicon pixel and strip trackers, which cover a pseudorapidity region of \(|\eta| < 2.5\). A crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter surround the tracking volume and cover \(|\eta| < 3\). The steel/quartz-fiber Cherenkov hadron forward (HF) calorimeter extends the coverage to \(|\eta| < 5\). The muon system consists of gas-ionization detectors embedded in the steel flux return yoke outside the solenoid, and covers \(|\eta| < 2.4\). The first level of the CMS trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than 4 \(\mu s\), using information from the calorimeters and muon detectors. The high-level trigger processor farm further reduces the event rate to a few hundred Hz before data storage.

3 Data and simulated samples

3.1 Experimental data samples

The 13 TeV proton proton collisions used in this analysis were recorded in 2016 and correspond to a total integrated luminosity of 35.9 fb\(^{-1}\).

The trigger \cite{22} selection used in the \(\ell\nu 2q\) analysis requires the presence of one electron with \(p_T > 25\) GeV and \(|\eta| < 2.1\) passing tight identification and isolation requirements, or one muon with \(p_T > 24\) GeV and \(|\eta| < 2.4\) passing loose identification and isolation requirements.

The events used in the \(2\ell 2\nu\) analysis are triggered by requiring the presence of one or two high transverse momentum electrons or muons. For the single lepton triggers, tight lepton identification criteria are applied and the thresholds for the lepton \(p_T\) are 27(45) GeV for electrons inside(outside) the region \(|\eta| < 2.1\), and 22 GeV for muons. For dielectron triggers, the minimal \(p_T\) are required to be 23 GeV for the leading and 12 GeV for the subleading electron. For dimuon triggers, the minimal \(p_T\) are required to be 17 GeV for the leading and 8 GeV for the subleading muon. The different flavour dilepton triggers require the highest \(p_T\) lepton to have \(p_T > 17\) GeV, and the 2nd highest \(p_T\) lepton to have \(p_T > 8\) GeV if it is a muon or \(p_T > 12\) GeV if it is an electron. The overall trigger efficiency for the combination of the single lepton, the double lepton and \(e\mu\) triggers for selected signal events is measured to be larger than 99%.

3.2 Signal and background simulation

Several event generators are used to optimise the analysis and estimate the expected yields of signal and background events, as well as the associated systematic uncertainties.

The heavy Higgs boson signal samples are generated in the ggF and VBF production modes at next-to-leading order (NLO) in QCD using POWHEG v2 \cite{23–27}, for a number of masses ranging from 200 GeV to 3 TeV. The resonance width is set according to the SM Higgs boson expectation for signal masses up to 1 TeV, above this value the width is set to half the resonance mass. The decay of the signal to a pair of W bosons is handled by JHUGEN v6.2.8 \cite{28}. The simulated signal samples are normalized using cross sections \cite{29, 30} and decay rates \cite{31} computed by the LHC Higgs cross section working group.

The \(W+\text{Jets}\) process is produced at NLO with the MADGRAPH5_AMC@NLO event generator \cite{32}, using the FxFx merging scheme \cite{33} between the jets from matrix element calculations and parton showers, and scaled to the next-to-next-to-leading order (NNLO) cross section computed using FEWZ \cite{34}.

Single top and \(t\bar{t}\) processes are generated using POWHEG v2 \cite{35, 36} and MADGRAPH5_AMC@NLO. The cross sections of the different single top processes are estimated at NLO accuracy \cite{37},
while the tf cross section is computed at NNLO accuracy, with NNLL soft gluon resumma-
tion [38]. For simplicity these processes are collectively referred to as the top background in this analysis.

The WW diboson continuum background is simulated in a number of ways: POWHEG v2 [39] and MADGRAPH5_AMC@NLO are used for WW produced via $q\bar{q}$ ($q\bar{q} \rightarrow WW$), while gluon fusion produced WW ($gg \rightarrow WW$) is generated using MCFM v7.0 [40] and a WW plus 2 jets ($qq \rightarrow qqWW$) sample is produced with POWHEG v2 at LO. The cross section used for normaliz-
ing the WW processes produced via $q\bar{q}$ is computed at NNLO [41]. The leading-order (LO) cross section for $gg \rightarrow WW$ is obtained directly from MCFM. For this process, the difference be-
tween LO and NNLO cross sections is large; a scale factor of 1.4 is theoretically calculated [42] and applied to the $gg \rightarrow WW$ simulation. In order to control the top quark background pro-
cesses, the $2\ell 2\nu$ analysis implements an event categorisation based on jet multiplicity. This approach enhances the importance of logarithms of the jet $p_T$, spoiling the convergence of the fixed-order calculations of the $q\bar{q} \rightarrow WW$ process and requires the use of dedicated resumma-
tion techniques for an accurate prediction of the differential distributions [43, 44]. The $p_T$ of
the jets produced in association with the WW system is strongly correlated with its transverse
momentum, $p_T^{WW}$, especially in the case where only one jet is produced. The simulated $q\bar{q} \rightarrow
WW$ events are therefore reweighted to reproduce the $p_T^{WW}$ distribution from the $p_T$-resummed

calculation.

Drell-Yan (DY) production of Z/γ* is generated using MADGRAPH5_AMC@NLO and scaled to
the NNLO cross section computed using FEWZ. Multiboson processes such as WZ, ZZ, and
VVV ($V=W,Z$) are also simulated with MADGRAPH5_AMC@NLO and normalized to the NLO
cross sections. QCD multi-jet production has been generated with PYTHIA 8.1 [45]. The QCD
samples are enriched in events with muons or electrons with dedicated filters.

All processes are generated using the NNPDF2.3 [46, 47] parton distribution functions (PDF)
for NLO generators, while the LO version of the same PDF is used for LO generators. All the
event generators are interfaced to PYTHIA 8.1 for the showering of partons and hadronization,
and to simulate the underlying event (UE) and multiple parton interactions (MPI) based on the
CUET8PM1 tune [48]. To estimate systematic uncertainties related to the choice of UE and MPI
tune, WW background samples are generated with two alternative tunes which are represen-
tative of the uncertainties on the tuning parameters. The systematic uncertainty associated to
showering and hadronization is estimated by interfacing the same samples with the HERWIG++
2.7 generator [49, 50].

For all processes, the detector response is simulated using a detailed description of the CMS
detector, based on the GEANT4 package [51]. Additional pp interactions are simulated with
via PYTHIA 8.1 overlapped with the event of interest to reproduce the number of interactions
occurring simultaneously within the same bunch crossing (pileup) measured in data.

## 4 Event reconstruction

The particle-flow (PF) algorithm [52] is used to reconstruct the observable particles in the event.
Clusters of energy deposits measured by the calorimeters, charged particle tracks identified in
the central tracking system, and the muon detectors, are combined to reconstruct individual


candidates are reconstructed by combining charged tracks in the muon detector with
tracks reconstructed in the central tracking system [53]. They are required to have $|\eta| < 2.4$. 
Identification criteria based on the number of hits in the tracker and muon systems, the fit quality of the muon track, and the consistency of the trajectory with the primary vertex are imposed on the muon candidates to reduce the misidentification rate.

Electrons are reconstructed from a combination of the deposited energy of the ECAL clusters associated with the track reconstructed from the measurements determined by the inner tracker, and the energy sum of all photons spatially compatible with being bremsstrahlung from the electron track [54]. In this analysis, electron candidates are required to have $|\eta| < 2.5$. Additional requirements are applied to reject electrons originating from photon conversions in the tracker material or jets mis-reconstructed as electrons. Electron identification criteria rely on observables sensitive to the bremsstrahlung along the electron trajectory, the geometrical and momentum-energy matching between the electron trajectory and the associated supercluster, as well as ECAL shower shape observables and compatibility with the primary vertex.

Leptons are required to be isolated from hadronic activity by requiring that the sum of the energy of clusters and $p_T$ of tracks in a cone around the lepton of radius $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.4$, is below a certain fraction of the lepton $p_T$. To mitigate the effect of pile-up on the isolation variable, a correction based on the total event occupancy [55] is applied.

The jet reconstruction uses all PF candidates, except those charged candidates that are not associated to the primary vertex. This requirement mitigates the effect of pile-up for $|\eta| < 2.5$. Particle candidates are clustered using the anti-$k_t$ algorithm [56, 57] with a cone radius of 0.4 (AK4) and 0.8 (AK8). To reduce residual pile-up contamination from neutral PF candidates, a correction based on jet median area subtraction [55] is applied. Jet energy is calibrated using both simulation and data following the technique described in [58]. Only AK4 jets with $p_T > 30$ GeV (20 GeV for b-jets) and $|\eta| < 4.7$ are considered in this analysis. The AK8 jets considered are required to have $p_T > 200$ and $|\eta| < 2.4$. Those AK4 (AK8) Jets which overlap with a well identified and isolated lepton within a distance of $\Delta R = 0.4 (0.8)$ are ignored.

A jet grooming technique is used for AK8 jets to help identify and discriminate between jets from boosted hadronic W decays and jets from quarks and gluons. The AK8 jets are groomed by means of the modified mass drop tagger algorithm [59], also known as the soft-drop algorithm. The soft-drop mass ($m_J$) used in the analysis is computed from the sum of the four-momenta of the jet constituents passing the grooming algorithm, after the application of the pileup mitigation corrections provided by the pileup per particle identification (PUPPI) algorithm [60].

Discrimination between AK8 jets originating from W decays and those originating from gluons and quarks is also achieved by using the $N$-subjettiness jet substructure variable [61]. This observable exploits the distribution of the jet constituents found in the proximity of the subjet axes to determine if the jet can be effectively subdivided into a number $N$ of subjets. The generic $N$-subjettiness variable is defined using the $p_T$-weighted sum of the angular distance $\Delta R_{N,k}$ of the jet constituents $k$ with respect to the axis of the $N^{th}$ subjet:

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}). \quad (1)$$

The normalization factor $d_0$ is defined as $d_0 = \sum_k p_{T,k} R_0$, with $R_0$ the clustering parameter of the original jet. In this analysis, which aims to select $W \rightarrow q\bar{q}$ decays, the variable that best discriminates W boson jets from those from quarks and gluons is the ratio of the 2-subjettiness to the 1-subjettiness: $\tau_{21} = \tau_2 / \tau_1$. The $\tau_{21}$ observable is calculated for the jet before the grooming procedure, and includes the PUPPI algorithm corrections for pileup mitigation.
To identify jets coming from b quarks, a multivariate b tagging algorithm [62, 63] and the combined secondary vertex (CSVv2) algorithm [63, 64] are used in the 2ℓ2ν and ℓν2q analyses respectively. In both analyses, the chosen working point corresponds to about 80% efficiency for real b-jets and to a mis-tagging rate of about 10% for light flavour or gluon jets and of 35 to 50% for c-jets.

The missing transverse energy ($E_T^{\text{miss}}$) is reconstructed as the negative vectorial sum in the transverse plane of all PF candidates applying an extra calibration to propagate the jet energy calibration.

If more than one vertex is reconstructed, the vertex with the largest value of summed physics-object $p_T^2$ is taken to be the primary pp interaction vertex. The physics objects chosen are those that have been defined using information from the tracking detector. These objects include jets, the associated missing transverse momentum, which was taken as the negative vector sum of the $p_T$ of those jets, and charged leptons.

For each event in the fully leptonic channel, at least two high-$p_T$ lepton candidates originating from a single primary vertex are required. Opposite charge dielectron pairs, dimuon pairs and electron-muon (eµ) pairs are accepted. In the semileptonic channel at least one high-$p_T$ lepton candidate, and two AK4 jets or one AK8 jet, originating from a single primary vertex are required.

5 Signal models

A signal interpretation in terms of a heavy Higgs boson with SM-like couplings and decays is implemented in this analysis. Due to the large width of the signal at high mass, interference of the WW continuum and the SM Higgs off-shell tail with the X resonance becomes significant [65]. The MELA matrix-element package [66, 67], based on JHUGEN for Higgs bosons, and on MCFM for the continuum WW background, has been used to estimate the interference of high mass X resonances with the WW continuum and the SM Higgs. The two sources of interference have opposite sign and partially cancel out with the size of the cancellation depending on the signal mass, generally the net effect is non-negligible. Fig. 1 displays the generator level mass of a ggF produced 700 GeV signal and the effects of interference with the $gg \to WW$ continuum and SM Higgs off-shell tail. Production of the X resonance through ggF and VBF is considered in this analysis. A parameter $f_{VBF}$, which is the fraction of the VBF production cross section with respect to the total cross section, is included in the model and a number of hypotheses investigated.

An interpretation in the context of a general Two Higgs Doublet Model (2HDM) is conducted. Various formulations of the 2HDM predict different couplings of the two doublets to right-handed quarks and charged leptons: in the type-1 formulation, all fermions couple to only one Higgs doublet; in the type-2 formulation, the up-type quarks couple to a different doublet than the down-type quarks and leptons. There are five physical Higgs bosons predicted: Two CP-even neutral bosons $h$ and $H$; a neutral CP-odd boson $A$; and two charged bosons $H^\pm$. In most formulations of the 2HDM $h$ corresponds to the SM Higgs boson, and $H$ is an additional high mass CP-even Higgs boson. The 2DHM has two important free parameters, $\alpha$ and $\tan \beta$, which are the mixing angle and the ratio of the vacuum expectation values of the two Higgs doublets, respectively. The quantity $\cos(\beta - \alpha)$ is also of interest, as the coupling of the heavy Higgs boson $H$ to two vector bosons is proportional to this factor. In the decoupling limit, which occurs at $\cos(\beta - \alpha) = 0$, all couplings become SM-like.
Figure 1: Generator level mass of a ggF produced 700 GeV signal (black line) normalized to the SM cross-section. The effects of the interference of the signal with the $gg \to WW$ continuum and the SM Higgs are shown in blue and red respectively. The total interference effect is shown in green.

The Minimal Supersymmetric Standard Model (MSSM) [68, 69], which incorporates a type-2 2HDM, is also considered. At tree level, the whole phenomenology can be described using just two parameters. By convention, these parameters are chosen to be $\tan\beta$ and $m_{A}$, the mass of the pseudoscalar Higgs boson. Two benchmark MSSM scenarios are investigated: the $m_{h}^{\text{mod}+}$ scenario and the hMSSM scenario [70].

Model predictions for the MSSM scenarios are provided by the LHC Higgs Cross Section Working Group [71]. The ggF cross sections have been computed with SusHi_v.1.4.1 [72]. The masses, mixing, branching fractions and the effective Yukawa couplings of the Higgs bosons in the $m_{h}^{\text{mod}+}$ scenario are all calculated with FeynHiggs_v.2.10.2 [73–77]. For the hMSSM scenario the branching fractions are obtained from HDECAY_v.6.40 [78, 79]. The results for the general 2HDM interpretation are obtained using the ggF cross sections computed with SusHi_v.1.5.0 and the branching fractions from 2HDMC_v.1.7.0 [80]. The VBF cross sections are approximated using the BSM Higgs production cross sections for VBF, which are provided for different masses by the LHC Higgs Cross Section Working Group [81], multiplied by $\cos^{2}(\beta - \alpha)$.

6 Selection and categorization

In this analysis a search for a heavy Higgs boson decaying to two $W$ bosons in the $2\ell 2\nu$ and $\ell\nu2q$ final states is performed. At a center-of-mass energy of 13 TeV the ggF cross section for the SM Higgs boson is almost one order of magnitude larger than that for VBF production [82]. However the ggF cross section decreases with $m_{X}$ while the VBF/ggF cross section ratio increases, meaning that the VBF production mechanism becomes more important at higher masses. The main feature distinguishing the two production mechanisms is the presence of associated jets for VBF production. Event categorizations based on the kinematic properties of associated jets and matrix element techniques are employed to optimise the signal sensitivity.
6. Selection and categorization

6.1 $X \rightarrow 2\ell 2\nu$

The $2\ell 2\nu$ analysis selects two oppositely charged leptons in the same flavour and different flavour final states. Leptons must be well identified and isolated to reject fake leptons and leptons coming from decays in flight. Events are categorized according to the lepton flavour composition and the number of AK4 jets with $p_T > 30$ GeV. To suppress the top background, events are required to have no b-tagged AK4 jets with $p_T$ above 20 GeV. The final discriminating variable used in this analysis is the visible mass $m^T_{\ell\ell} = \sqrt{(p_{\ell\ell} + E_T^{\text{miss}})^2 - (\vec{p}_{\ell\ell} + \vec{p}_{T}^{\text{miss}})^2}$. This variable is chosen for its effectiveness in discriminating between different signal mass hypotheses.

6.1.1 Different flavour final state

For the different flavour $e\mu$ channel one of the two leptons is required to have a $p_T$ greater than 25 GeV, the other is required to have $p_T$ greater than 20 GeV. To suppress background processes with three or more leptons in the final state, such as ZZ, WZ, Z$\gamma$, W$\gamma$ or triboson production, events with an additional identified and isolated lepton with $p_T > 10$ GeV are rejected. The dilepton invariant mass $m_{\ell\ell}$ is required to be greater than 50 GeV to reduce the SM Higgs boson contamination. Due to the presence of neutrinos in the final state the $E_T^{\text{miss}}$ is required to be greater than 20 GeV. A minimum $m^T_{\ell\ell}$ requirement of 100 GeV is also applied. The DY$\rightarrow\tau\tau$ background is suppressed by requiring the dilepton transverse momentum $p_{T}^{\ell\ell}$ be greater than 30 GeV and the Higgs transverse mass $m^H_T$ be greater than 60 GeV.

In this channel four exclusive jet categories are defined: a zero jet category, a one jet category, a two jet category and a VBF category. The latter category increases the sensitivity to resonances produced via the VBF mechanism by requiring the presence of exactly two jets with an invariant mass of at least 500 GeV and a separation in pseudorapidity greater than 3.5, dijet events failing this criteria enter the two jet category. Fig. 2 displays the $m^T_{\ell\ell}$ distributions for events passing the $2\ell 2\nu$ different flavour selection in the four jet categories.

6.1.2 Same flavour final state

For the same flavour $e^+e^-$ and $\mu^+\mu^-$ channels both leptons are requested to have a $p_T$ greater than 20 GeV, events with an additional identified and isolated lepton with $p_T > 10$ GeV are rejected. The background rejection cuts described for the $e\mu$ channel are also applied in these channels. To suppress the large DY$\rightarrow e^+e^-$ and DY$\rightarrow \mu^+\mu^-$ backgrounds only those events satisfying the VBF category criteria are considered. For the further reduction of this background, the $m_{\ell\ell}$ and $E_T^{\text{miss}}$ requirements are raised to 120 GeV and 50 GeV respectively. Fig. 2 displays the $m^T_{\ell\ell}$ distributions for events passing the $2\ell 2\nu$ different flavour selection.

6.2 $X \rightarrow \ell\nu 2q$

In the $\ell\nu 2q$ analysis the $W \rightarrow \ell\nu$ candidates are constructed by combining the $E_T^{\text{miss}}$ with a lepton which has $p_T$ greater than 30 GeV and $|\eta| < 2.4$ (2.1) for muons (electrons). Those events containing additional muons(electrons) with $p_T > 10(15)$ GeV passing loose identification requirements are rejected. A $W$ mass constraint is applied to the $\ell\nu$ system to estimate the $p_T$ component of the missing energy. The $W \rightarrow q\bar{q}$ candidates are reconstructed as either high $p_T$ merged jets or as resolved low $p_T$ jet pairs, a mass window cut is applied to suppress the $W$+jets background. If an additional AK4 jet with $p_T > 20$ GeV which is b-tagged is present then the event is rejected to suppress the top background. The $W \rightarrow \ell\nu$ and $W \rightarrow q\bar{q}$ decay candidates are combined into WW resonance candidates, the final discriminating variable is the invariant mass of the WW system $m_{WW}$. 
Figure 2: The $m_\ell^2$ distributions in data and simulation for events in the different flavour (top and middle) and same flavour (bottom) categories of the 2/2ν analysis. The points represent the data and the stacked histograms the expected backgrounds. The open histograms show the sum of the expected ggF and VBF produced signals without considering interference effects and normalized to the SM cross-sections. The shaded area shows the combined statistical and systematic uncertainties on the background estimation. Lower panels show the ratio of data to the expected background.
Events are categorised based on the tagging of VBF and ggF production mechanisms. A VBF category is defined requiring two additional AK4 jets satisfying the same requirements as for the $2\ell 2\nu$ analysis. Those events failing the VBF category criteria are considered for the ggF category. The tagging of ggF candidates is achieved using a kinematic discriminant based on the angular distributions of the Higgs candidate decay products. This is implemented with MELA which uses JHUGEN and MCFM matrix elements to calculate probabilities, defined as the matrix elements squared, for an event to come from either signal or background respectively. A cut on the kinematic discriminant at 0.5 is used to tag ggF candidates. Events failing the requirement enter the untagged category resulting in three production mechanism categories.

### 6.2.1 Boosted final state

For the boosted channel an AK8 jet with soft-drop mass in the mass window $65 \leq m_J \leq 105$ GeV is required. To suppress the background from non-prompt leptons in QCD multijet events the $E_T^{\text{miss}}$ must be greater than 40 GeV. For heavy resonance decays the $p_T$ of the $W$ candidates are expected to be roughly half of the resonance mass. Therefore both the leptonic and hadronic $W$ candidates must satisfy the requirement $p_T^{W}/m_{WW} > 0.4$. Finally a cut on the PUPPI n-subjettiness ratio $\tau_2/\tau_1 \leq 0.4$ is used to identify boosted W candidates (boosted W-tagging). The $m_{WW}$ distributions for events passing the $\ell \nu 2q$ boosted selection in the three production categories are shown in Fig. 3.

### 6.2.2 Resolved final state

For events which do not contain a boosted $W$-tagged jet with $m_J > 40$ GeV, it is attempted to reconstruct a resolved hadronic $W$ decay using two AK4 jets. A kinematic fit is performed to the dijet system using the $W$ mass constraint, in events with greater than two jets the dijet pair with the smallest $\chi^2$ is chosen. The invariant mass of the dijet system must be in the mass window $65 \leq m_{jj} \leq 105$ GeV. To suppress the background from non-prompt leptons in QCD multijet events it is required that the $E_T^{\text{miss}}$ be greater than 30 GeV and the leptonic $W$ transverse mass $m_T^{W}$ be greater than 50 GeV. It is also required that the leptonic and hadronic $W$ candidates satisfy the condition $p_T^{W}/m_{WW} > 0.35$. Further reduction in the QCD multijet background is achieved by requiring the Higgs transverse mass $m_T^{H}$ be greater than 60 GeV. The $m_{WW}$ distributions for events passing the $\ell \nu 2q$ resolved selection in the three production categories are shown in Fig. 3.
Figure 3: The $m_{WW}$ distributions in data and simulation for events in the boosted (left) and resolved (right) production categories of the $\ell\ell q\bar{q}$ analysis. Electron and muon channels are combined. The points represent the data and the stacked histograms the expected backgrounds. The open histograms show the sum of the expected ggF and VBF produced signals without considering interference effects and normalized to the SM cross-sections. The shaded area shows the combined statistical and systematic uncertainties on the background estimation. Lower panels show the ratio of data to the expected background.
7. Background estimation

The dominant backgrounds are modelled by simulation that has been reweighted to account for known discrepancies between data and simulated events. Corrections associated with the description in simulation of the trigger efficiencies, as well as the efficiency for electron and muon reconstruction, identification, and isolation, are extracted from events with leptonic Z decays using a tag-and-probe technique [83]. The b tagging efficiency is measured using data samples enriched in b quarks and corrections for simulation derived [84]. For the $\ell\nu q$ boosted category corrections are applied to the W-tagging efficiency and the soft-drop mass scale and resolution of W jets. These corrections have been measured in an almost pure selection of semileptonic tt events where boosted W bosons produced in the top quark decays are separated from the combinatorial tt background by means of a simultaneous fit to the soft-drop mass [85]. For the normalisation of the major backgrounds data driven estimates using control regions are employed.

7.1 $X \rightarrow 2\ell 2\nu$

The main background processes affecting the $2\ell 2\nu$ analysis are from non-resonant WW and top production. The non-resonant WW background populates the entire phase space in $m_T$ while the high mass signal contribution is concentrated at high values of this variable. Therefore this background is estimated directly in the signal extraction procedure by allowing the WW normalization to float independently in each category.

The estimation of the top background in this analysis is performed using a top enriched control region, defined by inverting the b-veto requirement. It is used to constrain the top normalization which is allowed to float in the signal extraction procedure. The data-driven estimation is performed separately for each of the different flavour and same flavour categories. The $m_T$ distributions in the top control regions of each of the different flavour categories are shown in Fig. 4.

DY production is a significant background in the same-flavour categories. A sub-leading source of background in the different flavour categories comes from DY $\rightarrow \tau \tau$ where each $\tau$ decays leptonically. To correct the DY normalization to that observed in data, control regions are defined using alterations of the signal region selection. For the different flavour channel a DY control region is defined for each jet category by inverting the signal region $m_{HT}$ cut, thus requiring $m_{HT} < 60$ GeV. The invariant mass of the two leptons is restricted to the interval between 50 and 80 GeV to exclude possible contributions from non-prompt leptons and from top. For the same flavour channels the control regions are defined by altering the signal region $m_{\ell\ell}$ cut, requesting $70$ GeV $< m_{\ell\ell} < 120$ GeV to select Z boson events. Discrepancies are observed between the $E_T^{\text{miss}}$ distributions in data and simulation for the same flavour control regions. A linear $E_T^{\text{miss}}$ correction is derived for the simulation by fitting the ratio between data, with minor background subtracted, and the DY prediction. The $m_{\ell\ell}$ distributions in the DY control regions of each of the same flavour categories are shown in Fig. 4.

The instrumental background arising from non-prompt leptons in W+jets production is estimated to be between 2% and 8% of the total background. A data driven estimate is implemented using a looser lepton identification criteria with a relaxed isolation requirement. The efficiency for a jet that satisfies the loose lepton requirements to also satisfy the standard selection is determined using dijet events. Similarly, the efficiency for a prompt lepton that satisfies the loose lepton identification requirements to also satisfy the standard selection is determined using DY events. These efficiencies are then used to weight the data events with the probability for the event to contain a non-prompt lepton and the relative probability for the candidates in
this event to also satisfy the standard selection. Other subleading backgrounds such as WZ, ZZ and triboson production are estimated from simulation.

7.2 \( X \rightarrow \ell v 2q \)

The main backgrounds for the \( \ell v 2q \) analysis are from W+jets and top production, with subdominant contributions from diboson, DY and QCD multijets production.

The majority of the events passing the \( \ell v 2q \) selection come from W+jets and top production. A data-driven estimate of the W+jets and top normalisation using two control regions is employed. A top-enriched control region is defined by reversing the b-veto, requiring events with an additional jet which is b-tagged. Additionally a sideband control region, with a similar background composition to that of the signal region, is defined by adapting the hadronic W candidate mass requirements of the signal selection. In the boosted(resolved) category \( m_J(m_{jj}) \) is required to be outside the signal mass window and within the range \( 40 \leq m_J(m_{jj}) \leq 250 \) GeV.

In the signal extraction procedure the normalization of both the W+jets and top backgrounds are allowed to float free, with the control regions included to help constrain the normalizations. This background estimation procedure is applied independently in each category.

The contamination from diboson events represents 6% and 3% of the total background in the boosted and resolved categories respectively. Production of WW, WZ and ZZ through q\bar{q} annihilation is estimated directly from simulation while the gg→WW and qq→qqWW backgrounds are estimated using MELA.

The DY contamination is suppressed in this analysis due to the second lepton veto. It is estimated directly from simulation and represents between 1% and 2% of the total background.

Contamination from non-prompt leptons in QCD multijet production is estimated from simulation to be between 1% and 2% of the total background. The contribution from this source is largely suppressed in this analysis due to the W candidate \( p_T \), transverse mass and substructure requirements. QCD-enhanced samples are defined through a reversal of these requirements, allowing a test of the multijet simulation. The resolved selection is altered by requiring \( m_W^T < 50 \) GeV, \( m_H^T < 60 \) GeV and \( p_T^W/m_W^T < 0.35 \), while for the boosted selection it is required that \( m_W^T < 50 \) GeV, \( \tau_2/\tau_1 > 0.4 \) and \( p_T^W/m_W^T < 0.4 \). QCD multijet contamination levels of 35% and 14% are attained for the boosted and resolved categories respectively. Subtracting the estimated prompt lepton backgrounds the QCD multijet normalisations are found to agree within 3% with the data, with statistical uncertainties of the order of 10%.

To help verify the background estimation procedure, a fit is performed to the \( m_{WW} \) distributions in the sideband allowing the W+jets and top normalizations to float. The top control region is included in the fit to help constrain the background normalizations. Fig 5 displays the sideband \( m_{WW} \) distributions for the boosted and resolved production categories. A good level of agreement between data and the background prediction is observed.
Figure 4: The $m_T^2$ distributions in data and simulation for events in the top control regions of the $2\ell 2\nu$ different flavour categories (top and middle) and the DY control regions of the $2\ell 2\nu$ same flavour categories (bottom). The points represent the data and the stacked histograms the expected backgrounds. The shaded area shows the combined statistical and systematic uncertainties on the background estimation. Lower panels show the ratio of data to the expected background.
Figure 5: The $m_{WW}$ distributions in data and simulation for events in the sideband control regions of the $l\ell/2q$ boosted (left) and resolved (right) production categories. Electron and muon channels are combined. The points represent the data and the stacked histograms the expected backgrounds. The shaded area shows the combined statistical and systematic uncertainties on the background estimation. Lower panels show the ratio of data to the expected background.
8 Signal extraction and systematic uncertainties

The statistical methodology used to interpret the data and to combine the results from the independent categories has been developed by the ATLAS and CMS collaborations in the context of the LHC Higgs Combination Group. A general description of the methodology can be found in Refs. [86–88].

Systematic uncertainties are represented by individual nuisance parameters with log-normal distributions. All sources are treated as normalization uncertainties, and shape uncertainties where appropriate, and are correlated among the signal and background processes and the different categories. The dominant background normalisations are initially unconstrained and are determined during the fit procedure using control regions. Uncertainties arising from limited statistics in the simulated samples are included for each bin of the discriminant distributions in each category independently.

The theoretical sources of uncertainty considered include the effect of PDFs and \( \alpha_s \), and the effect of missing higher-order corrections via variations of the renormalization and factorization scales. Acceptance uncertainties are evaluated for signal and background by varying PDFs and \( \alpha_s \) within their uncertainties [89], and by varying the factorization and renormalization scales by a factor of two [90]. Depending on the process and the category the PDF uncertainties amount to 1-7%, while that of the renormalization and factorisation scales are 1-18%. The PDF and the renormalization and factorization scales uncertainties on the signal cross-section, computed by the LHC Higgs cross section working group [81], are also considered and amount to 2-16% and 0.2-9% respectively depending on the resonance mass and production mechanism.

Effects due to experimental uncertainties are studied by applying a scaling and/or smearing of certain variables of the physics objects in the simulation, followed by a subsequent recalculation of all the correlated variables. The uncertainty on the measured luminosity is 2.5% for data collected during 2016. The trigger efficiency uncertainties are approximately 1% and 2% for the \( \ell\nu2q \) and \( 2\ell2\nu \) final states respectively. Lepton reconstruction and identification efficiency uncertainties vary between 1-3%, while the muon momentum and electron energy scale uncertainties amount to 0.1-1.0% each. Depending on the process and the category the jet energy scale uncertainties are in the range 1-10%. The \( E_T^{\text{miss}} \) uncertainty is taken into account by propagating the corresponding uncertainties on the leptons and jets and amounts to 0.1-1%. The scale factors correcting the b-tagging efficiency and mistagging rate are varied within their uncertainties with resulting uncertainties of 0.1-5% depending on the process and the category. This systematic uncertainty affects in an anticorrelated way the top quark control regions and the signal regions.

In addition, for each final state there are analysis-specific uncertainties which are now discussed.

8.1 \( X \to 2\ell2\nu \)

A conservative 30% uncertainty on the instrumental background arising from non-prompt leptons in W+jets production is estimated by varying the jet \( p_T \) threshold in the dijet control sample used in the background prediction procedure, and from propagation of the statistical errors on the measured fake lepton probabilities. Uncertainties of 3-10% due to the \( p_T^{\text{WW}} \) reweighting are evaluated by varying the factorization and renormalization scale by a factor two, and by varying the resummation scale. The UE uncertainty for the WW background is estimated by comparing two different UE tunes, while the parton shower modelling uncertainty is estimated by comparing samples interfaced with different parton showers, as described in section 3. The
combined effect is evaluated to be 5-10%. A dedicated nuisance for the linear MET correction in the same flavour DY control region is introduced. The uncertainty is 0.2-1%, estimated with the maximum and minimum best-fit lines of the linear fit used to derive the correction. The categorization of events based on jet multiplicity introduces additional signal uncertainties related to higher order corrections. These uncertainties are associated to the ggF production mode and are evaluated independently following the recipe described in [91] and are about 5% for the 0-jet, 10% for the 1-jet, and 20% for the 2-jet and VBF categories.

8.2 $X \rightarrow \ell\nu 2q$

The diboson and DY production cross sections are each assigned an uncertainty of 10%, based on the level of agreement between theoretical predictions and the cross-section measurements at CMS using 13 TeV data of the WV and DY processes [92–94]. An uncertainty of 10% on the background arising from non-prompt leptons in QCD multijets production is assigned based on the observed level of agreement between data and simulation in QCD-enhanced samples. The impact of the jet energy resolution uncertainty is about 0.3-2% depending on the process and the category. For W tagged jets the soft-drop mass scale and resolution uncertainties have been evaluated to be 0.1-1% and 2-5% respectively. The scale factor correcting the boosted W tagging efficiency has an associated uncertainty of 6%. Since this is measured in $t\bar{t}$ events using jets with a typical $p_T$ of 200 GeV an uncertainty of 1-13% on the extrapolation to the higher $p_T$ regime of the high mass signals is also considered.

A summary of the systematic uncertainties considered in the $\ell\nu 2q$ and 2$\ell 2\nu$ analyses are shown in table 1.

9 Results

No evidence for an excess of events with respect to the SM predictions is observed. Upper exclusion limits at 95% confidence level (CL) on the X cross section times branching fraction of the decay to two W bosons are evaluated for masses between 200 GeV and 3 TeV. A number of hypotheses for $f_{VBF}$ have been investigated by setting $f_{VBF}$ to the SM value, allowing $f_{VBF}$ to float, and by setting $f_{VBF} = 0$ and $f_{VBF} = 1$. The expected and observed exclusion limits for the full combination of the the 2$\ell 2\nu$ and $\ell\nu 2q$ analyses are shown in Fig. 6.

Exclusion limits are also set for neutral heavy Higgs bosons in the context of a type-1 and type-2 2HDM with the assumption that $m_H = m_A$. For compatibility with the constraints given by the measured couplings of the 125 GeV Higgs boson the value of $\cos(\beta - \alpha)$ has been fixed to 0.1. In Fig. 7 expected and observed exclusion limits in the $m_H$-tan $\beta$ plane are shown. The dashed lines mark the expected limits, while the observed exclusion contour is indicated by the colored blue area. The bands surrounding the expected limit indicate the ±1, 2$\sigma$ contours. The exclusion limits are significantly extended with respect to the Run 1 results using diboson final states [95]. In Fig. 8 expected and observed exclusion limits are shown for the $m_h^{mod+}$ and the hMSSM scenarios. For both scenarios the region at low values of $m_A$ and tan $\beta$ is excluded. These results show a large improvement over the previous results from Run 1 and also complement the exclusion limits set by the MSSM $H \rightarrow \tau\tau$ analysis using 13 TeV data [96], which has reduced sensitivity at low values of $m_A$ and tan $\beta$. 
Table 1: Summary of systematic uncertainties, quoted in percent, affecting the normalization of background and signal samples. The numbers shown as ranges represent the uncertainties for different processes and categories. A dash (—) represents uncertainties either estimated to be negligible(<0.1%), or not applicable in the specific analysis category.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$X \to WW \rightarrow 2\ell 2\nu$</th>
<th>$X \to WW \rightarrow \ell\ell 2q$</th>
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<tr>
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<tr>
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<td>1%</td>
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<td>1-2%</td>
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<td>Muon momentum scale</td>
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<td>Jet energy resolution</td>
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<tr>
<td>DY $E_T^{\text{miss}}$ reweighting</td>
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</table>
Figure 6: Expected and observed exclusion limits at 95% CL on the $X$ cross section times branching fraction to WW for a number of $f_{VBF}$ hypotheses. For the SM $f_{VBF}$ (top left) and floating $f_{VBF}$ (top right) cases the red line represents the sum of the SM cross sections for ggF and VBF production, while for the $f_{VBF} = 0$ (bottom left) and the $f_{VBF} = 1$ (bottom right) cases it represents the ggF and VBF production cross sections respectively. The black dotted line corresponds to the central expected value while the yellow and green bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties respectively.
Figure 7: Expected and observed 95% CL upper limits on $\tan \beta$ as a function of $m_H$ for a type-1 (left) and type-2 (right) 2HDM. It is assumed that $m_H = m_A$ and $\cos(\beta - \alpha) = 0.1$. The expected limit is shown as a dashed black line. The dark and bright gray bands indicate the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limit. The observed exclusion contour is indicated by the colored blue area.

Figure 8: Expected and observed 95% CL upper limits on $\tan \beta$ as a function of $m_A$ for the $m_h^{mod+}$ (left) and hMSSM (right) scenarios. The expected limit is shown as a dashed black line. The dark and bright gray bands indicate the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limit. The observed exclusion contour is indicated by the colored blue area.
Summary

A search for a heavy Higgs boson decaying to a pair of W bosons in the mass range from 200 GeV to 3 TeV has been presented. The data analysed were collected by the CMS experiment at the CERN LHC in 2016, corresponding to an integrated luminosity of 35.9 fb$^{-1}$ at $\sqrt{s} = 13$ TeV. Two final states of the W boson pair decay, $\ell\nu\ell'\nu'$ and $\ell q\bar{q}$, and two signal production mechanisms, gluon fusion and vector boson fusion, are considered. Combined upper limits at the 95% confidence level on the product of the cross section and branching fraction have excluded a heavy Higgs boson with Standard Model-like couplings and decays in the mass range evaluated. Exclusion limits have also been set in the context of two Higgs doublet models. For the $m_{h^{mod+}}$ and hMSSM scenarios the regions at low values of $m_A$ and $\tan\beta$ have been excluded.

References


