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Search for the standard model Higgs boson decaying to W^+W^- in the fully leptonic final state in pp collisions at $\sqrt{s} = 7$ TeV ☆

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ABSTRACT

A search for the standard model Higgs boson decaying to W^+W^- in pp collisions at $\sqrt{s} = 7$ TeV is reported. The data are collected at the LHC with the CMS detector, and correspond to an integrated luminosity of 4.6 fb^{-1}. The W^+W^- candidates are selected in events with two charged leptons and large missing transverse energy. No significant excess of events above the standard model background expectations is observed, and upper limits on the Higgs boson production relative to the standard model Higgs expectation are derived. The standard model Higgs boson is excluded in the mass range 129–270 GeV at 95% confidence level.

1. Introduction

One of the open questions in the standard model (SM) of particle physics [1–3] is the origin of the masses of fundamental particles. Within the SM, vector boson masses arise by the spontaneous breaking of electroweak symmetry by the Higgs field [4–9]. The existence of the associated field quantum, the Higgs boson, has yet to be established experimentally. The discovery or the exclusion of the SM Higgs boson is one of the central goals of the CERN Large Hadron Collider (LHC) physics program.

Direct searches at the CERN e^+e^- LEP collider set a limit on the Higgs boson mass $m_H > 114.4$ GeV at 95% confidence level (CL) [10]. Precision electroweak data constrain the mass of the SM Higgs boson to be less than 158 GeV at 95% CL [11,12]. The SM Higgs boson is excluded at 95% CL by the Tevatron collider experiments in the mass range 162–166 GeV [13], and by the ATLAS experiment in the mass ranges 145–206, 214–224, 340–450 GeV [14–16]. The $H \to W^+W^- \to 2\ell 2\nu$ final state, where ℓ is a charged lepton and ν a neutrino, was first proposed as a discovery channel at the LHC in [17]. A previous search for the Higgs boson at the LHC in this final state was published by the Compact Muon Solenoid (CMS) collaboration with 36 pb^{-1} of integrated luminosity [18]. This search is performed over the mass range 110–600 GeV, and the data sample corresponds to 4.6 ± 0.2 fb^{-1} of integrated luminosity collected in 2011 at a center-of-mass energy of 7 TeV. A similar search was conducted by the ATLAS Collaboration [14].

2. CMS detector and simulation

In lieu of a detailed description of the CMS detector [19], which is beyond the scope of the Letter, a synopsis of the main components follows. The superconducting solenoid occupies the central region of the CMS detector, providing an axial magnetic field of 3.8 T parallel to the beam direction. Charged particle trajectories are measured by the silicon pixel and strip tracker, which cover a pseudorapidity region of $|\eta| < 2.5$. Here, the pseudorapidity is defined as $\eta = -\ln(\tan\theta/2)$, where θ is the polar angle of the trajectory of the particle with respect to the direction of the counterclockwise beam. The crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL) surround the tracking volume and cover $|\eta| < 3$. The steel/quartz-fiber Cherenkov calorimeter (HF) extends the coverage to $|\eta| < 5$. The muon system consists of gas detectors embedded in the iron return yoke outside the solenoid, with a coverage of $|\eta| < 2.4$. The first level of the CMS trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than 3 μs, 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.

The expected SM Higgs cross section is 10 orders of magnitude smaller than the LHC inelastic cross section, which is dominated by QCD processes. Selecting final states with two leptons and missing energy eliminates the bulk of the QCD events,

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leaving non-resonant diboson production ($pp \to W^+W^-$, WZ, $W\gamma$, ZZ), Drell–Yan production (DY), top production ($t\bar{t}$ and tW), and W + jets and QCD multijet processes, where at least one jet is misidentified as an isolated lepton, as the background sources. Several Monte Carlo event generators are used to simulate the signal and background processes. The POWHEG 2.0 program [20] provides event samples for the $H \to W^+W^-$ signal and the Drell–Yan, $t\bar{t}$, and tW processes. The $q\bar{q} \to W^+W^-$ and W + jets processes are generated using the MADGRAPH 5.1.3 [21] event generator, the $gg \to W^+W^-$ process using GG2WW [22], and the remaining processes using PYTHIA 6.424 [23]. For leading-order generators, the default set of parton distribution functions (PDF) used to produce these samples is CTEQ6L [24], while CT10 [25] is used for next-to-leading order (NLO) generators. Cross section calculations [26] at next-to-next-to-leading order (NNLO) are used for the $H \to W^+W^-$ process, while NLO calculations are used for background cross sections. For all processes, the detector response is simulated using a detailed description of the CMS detector, based on the GEANT4 package [27]. The simulated samples are reweighted to represent the distribution of number of pp interactions per bunch crossing (pile-up) as measured in the data. The average number of pile-up events in data is about ten.

3. W^+W^- event selection

The search strategy for $H \to W^+W^-$ exploits diboson events where both W bosons decay leptonically, resulting in an experimental signature of two isolated, high transverse momentum (p_T), oppositely charged leptons (electrons or muons) and large missing transverse energy (mainly due to the undetected neutrinos), E_T^{miss}, defined as the modulus of the negative vector sum of the transverse momenta of all reconstructed particles (charged or neutral) in the event [28]. To improve the signal sensitivity, the events are separated into three mutually exclusive categories according to the jet multiplicity: $2\ell + E_T^{miss} + 0$ jets, $2\ell + E_T^{miss} + 1$ jet, and $2\ell + E_T^{miss} + 2$ jets. Events with more than 2 jets are not considered. In this way the sensitivity is increased since the signal yields and the signal-to-background ratios are very different among the three categories.

Furthermore, the search strategy splits signal candidates into three final states denoted by: e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$. The bulk of the signal arises through direct W decays to charged stable leptons of opposite charge, though the small contribution proceeding through an intermediate τ lepton is implicitly included. The events are selected by triggers which require the presence of one or two high-p_T electrons or muons. The trigger efficiency for signal events that pass the full event selection is measured to be above 95% in the $\mu^+\mu^-$ final state, and above 98% in the e^+e^- and $e^\pm\mu^\mp$ final states for a Higgs boson mass ~130 GeV. The trigger efficiencies increase with the Higgs boson mass.

Two oppositely charged lepton candidates are required, with $p_T > 20$ GeV for the leading lepton ($p_T^{\ell,max}$) and $p_T > 10$ GeV for the trailing lepton ($p_T^{\ell,min}$). To reduce the low-mass $Z/\gamma^* \to \ell^+\ell^-$ contribution, the requirement on the trailing lepton p_T is raised to 15 GeV for the e^+e^- and $\mu^+\mu^-$ final states. This tighter requirement also suppresses the W + jets background in these final states. Only electrons (muons) with $|\eta| < 2.5$ (2.4) are considered in the analysis. Muon candidates [29] are identified using a selection similar to that described in [18], while electron candidates are selected using a multivariate approach, which exploits correlations between the selection variables described in [30] to improve identification performance. The lepton candidates are required to originate from the primary vertex of the event, which is chosen as the vertex with highest $\sum p_T^2$, where the sum is performed on the tracks associated to the vertex, including the tracks associated to the leptons. This criterion provides the correct assignment for the primary vertex in more than 99% of both signal and background events for the pile-up distribution observed in the data. Isolation is used to distinguish lepton candidates from W-boson decays from those stemming from QCD background processes, which are usually immersed in hadronic activity. For each lepton candidate, a $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ cone of 0.3 (0.4) for muons (electrons) is constructed around the track direction at the event vertex. The scalar sum of the transverse energy of each particle reconstructed using a particle-flow algorithm [28] compatible with the primary vertex and contained within the cone is calculated, excluding the contribution from the lepton candidate itself. If this sum exceeds approximately 10% of the candidate p_T the lepton is rejected, the exact requirement depending on the lepton η, p_T and flavour.

Jets are reconstructed from calorimeter and tracker information using the particle-flow technique [28,31], combining the information from all CMS subdetectors to reconstruct each individual particle. The anti-k_T clustering algorithm [32] with distance parameter $R = 0.5$ is used, as implemented in the FASTJET package [33,34]. To correct for the contribution to the jet energy due to the pile-up, a median energy density (ρ) is determined event by event. Then the pile-up contribution to the jet energy is estimated as the product of ρ and the area of the jet and subsequently subtracted [35] from the jet transverse energy E_T. Jet energy corrections are also applied as a function of the jet E_T and η [36]. Jets are required to have $E_T > 30$ GeV and $|\eta| < 5$ to contribute to the event classification according to the jet multiplicity.

In addition to high momentum isolated leptons and minimal jet activity, missing energy is present in signal events but generally not in background. In this analysis, a *projected* E_T^{miss} variable, defined as the component of E_T^{miss} transverse to the nearest lepton if that lepton is within $\pi/2$ in azimuthal angle, or the full E_T^{miss} otherwise, is employed. A cut on this observable efficiently rejects $Z/\gamma^* \to \tau^+\tau^-$ background events, where the E_T^{miss} is preferentially aligned with leptons, as well as $Z/\gamma^* \to \ell^+\ell^-$ events with mismeasured E_T^{miss} associated with poorly reconstructed leptons or jets. The E_T^{miss} reconstruction makes use of event reconstruction via the particle-flow technique [28]. Since the *projected* E_T^{miss} resolution is degraded by pile-up, a minimum of two different observables is used: the first includes all reconstructed particles in the event [28], while the second uses only the charged particles associated with the primary vertex. For the same cut value with the first observable, the $Z/\gamma^* \to \ell^+\ell^-$ background doubles when going from 5 to 15 pile-up events, while it remains approximately constant with the second observable. The use of both observables exploits the presence of a correlation between them in signal events with genuine E_T^{miss}, and its absence otherwise, as in Drell–Yan events.

Drell–Yan background produces same-flavour lepton pairs (e^+e^- and $\mu^+\mu^-$): thus, the selection requirements designed to suppress this background are slightly different for same-flavour and opposite-flavour ($e^\pm\mu^\mp$) events. Same-flavour events must have *projected* E_T^{miss} above about 40 GeV, with the exact requirement depending on the number of reconstructed primary vertices (N_{vtx}) according to the relation *projected* $E_T^{miss} > (37 + N_{vtx}/2)$ GeV. For opposite-flavour events, the requirement is lowered to 20 GeV with no dependence on the number of vertices. These requirements remove more than 99% of the Drell–Yan background. In addition, requirements of a minimum dilepton transverse momentum ($p_T^{\ell\ell}$) of 45 GeV for both types and a minimum dilepton mass ($m_{\ell\ell}$) of 20 (12) GeV for same- (opposite-) flavour events are applied. Two additional selection criteria are applied only to the same-flavour events. First, the dilepton mass must be outside a 30 GeV window centered on the Z mass, and second, to suppress Drell–Yan events with the Z/γ^* recoiling against a jet, the angle in the transverse plane between the dilepton system and the leading jet must be less than 165 degrees, when the leading jet has $E_T > 15$ GeV.

To suppress the top-quark background, a *top tagging* technique based on soft-muon and b-jets tagging methods [37,38] is applied. The first method is designed to veto events containing muons from b-quarks coming from the top-quark decay. The second method uses b-jet tagging, which looks for tracks with large impact parameter within jets. The algorithm is also applied in the case of 0-jet bin, which can still contain jets with $E_T < 30$ GeV. The rejection factor for top-quark background is about two in the 0-jet category and above 10 for events with at least one jet passing the selection criteria.

To reduce the background from WZ and ZZ production, any event that has a third lepton passing the identification and isolation requirements is rejected. This requirement rejects less than 0.1% of the $H \to W^+W^- \to 2\ell 2\nu$ events, while it rejects 60% of WZ and 10% of the ZZ processes. After the E_T^{miss} requirement ZZ events are dominated by the $ZZ \to 2\ell 2\nu$ process, where there is no 3rd lepton. The $W\gamma$ production, where the photon is misidentified as an electron, is reduced by more than 90% in the dielectron final state by γ conversion rejection requirements.

After applying all selection criteria described in this section, which is referred to as the "W^+W^- selection", 1359, 909, and 703 events are obtained in data in the 0-jet, 1-jet, and 2-jet categories respectively. This sample is dominated by non-resonant W^+W^- events. The signal efficiency at this stage for a Higgs boson with $m_H = 130$ GeV is about 5.5%, where all the electron, muon and tau W decays are considered. The main efficiency loss is due to the lepton selection and the stringent E_T^{miss} requirements. Fig. 1 shows the distributions of the azimuthal angle difference ($\Delta\phi_{\ell\ell}$) between the two selected leptons after the W^+W^- selection, for a SM Higgs boson with $m_H = 130$ GeV and for backgrounds in the 0- and 1-jet categories. The clear difference on the shape between the $H \to W^+W^-$ and the non-resonant W^+W^- processes is due to the spin-0 nature of the Higgs boson. The scale of the figures allows for comparing the background contributions between the 0-jet and the 1-jet channels.

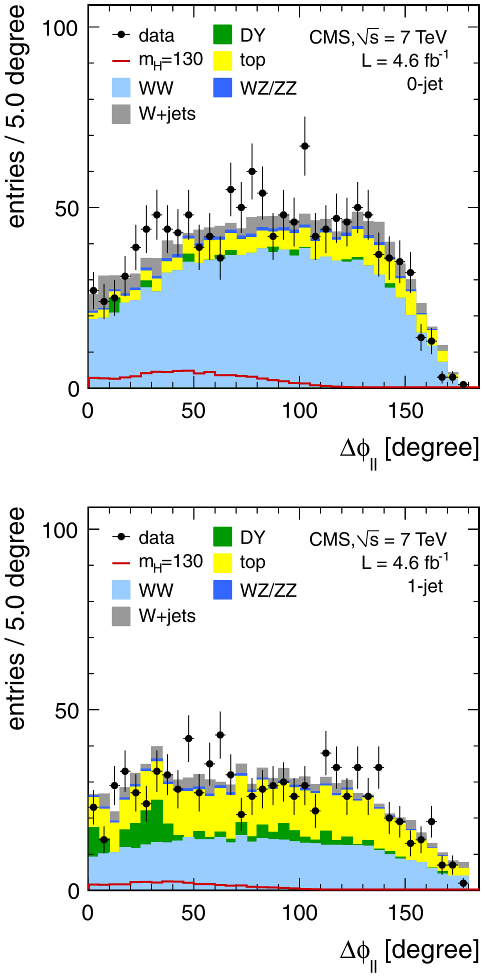

Fig. 1. Azimuthal angle difference between the two selected leptons in the 0-jet (top) and 1-jet (bottom) categories, for a $m_H = 130$ GeV SM Higgs boson and for the main backgrounds at the W^+W^- selection level.

4. $H \to W^+W^-$ search strategy

To enhance the sensitivity to a Higgs boson signal, two different analyses are performed in the 0-jet and 1-jet categories, the first utilizing a cut-based approach and the second using a multivariate technique. As the kinematics of signal events change as a function of the Higgs mass, separate optimizations are performed for different m_H hypotheses. Only the cut-based approach is applied to the 2-jet category, as its relative impact on the sensitivity is limited with the current integrated luminosity.

In the cut-based approach extra requirements, designed to optimize the sensitivity for a SM Higgs boson, are placed on $p_T^{\ell,\max}$, $p_T^{\ell,\min}$, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$ and the transverse mass m_T, defined as $\sqrt{2p_T^{\ell\ell}E_T^{miss}(1-\cos\Delta\phi_{E_T^{miss}\ell\ell})}$, where $\Delta\phi_{E_T^{miss}\ell\ell}$ is the angle in the transverse plane between E_T^{miss} and the transverse momentum of the dilepton system. The cut values, which are the same in both the 0- and 1-jet categories, are summarized in Table 1. The $m_{\ell\ell}$ distribution of the two selected leptons in the 0-jet and 1-jet categories, for a $m_H = 130$ GeV SM Higgs hypothesis and for the main backgrounds, are shown in Fig. 2.

Table 1

Final event selection requirements for the cut-based analysis in the 0-jet and 1-jet bins. The values of $p_T^{\ell,\min}$ in parentheses at low Higgs masses correspond to the requirements on the trailing lepton for the same-flavour final states.

m_H [GeV]	$p_T^{\ell,\max}$ [GeV]	$p_T^{\ell,\min}$ [GeV]	$m_{\ell\ell}$ [GeV]	$\Delta\phi_{\ell\ell}$ [°]	m_T [GeV]
	>	>	<	<	[,]
120	20	10 (15)	40	115	[80, 120]
130	25	10 (15)	45	90	[80, 125]
160	30	25	50	60	[90, 160]
200	40	25	90	100	[120, 200]
250	55	25	150	140	[120, 250]
300	70	25	200	175	[120, 300]
400	90	25	300	175	[120, 400]

In the multivariate approach a boosted decision tree (BDT) is trained for each Higgs boson mass hypothesis [39] and jet category to discriminate signal from background. In addition to the W^+W^- selection, loose m_H dependent requirements on $m_{\ell\ell}$ and m_T are applied to enhance the signal-to-background ratio (BDT selection level).

The multivariate technique uses the following observables in addition to those used in the cut-based analysis: $\Delta R_{\ell\ell} \equiv \sqrt{(\Delta\eta_{\ell\ell})^2 + (\Delta\phi_{\ell\ell})^2}$ between the leptons, the transverse mass of both lepton-E_T^{miss} pairs, and finally the lepton flavours. The BDT training is performed using $H \to W^+W^-$ as signal and non-resonant W^+W^- as background. Extensive studies demonstrate that the inclusion of other processes does not improve the performance, because the kinematic variables within the jet category and

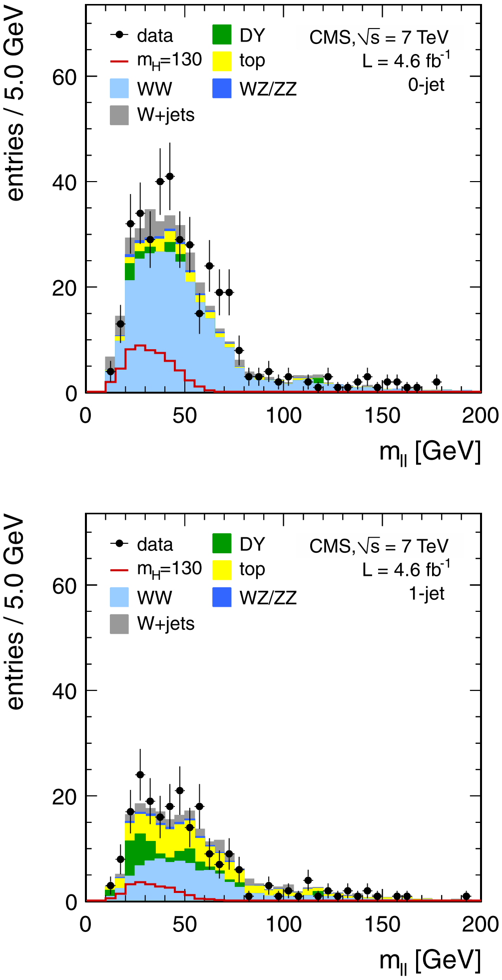

Fig. 2. Dilepton mass in the 0-jet (top) and 1-jet (bottom) categories, for a $m_{\mathrm{H}} = 130$ GeV SM Higgs boson and for the main backgrounds. The cut-based $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ selection, except for the requirement on the dilepton mass itself, is applied.

phase-space region are quite similar among various background processes. The BDT classifier distributions for $m_{\mathrm{H}} = 130$ GeV are shown in Fig. 3 for 0-jet and 1-jet categories. In the analysis, the binned BDT distributions of Fig. 3 are fitted to templates for the signal and backgrounds BDT distributions. The analysis is repeated using both a likelihood approach, where the correlations among the variables are neglected, and a single variable approach based on $m_{\ell\ell}$. We also perform an analysis using a Matrix Element method as previously done in [40], to compute the differential cross section for signal and background hypotheses on an event-by-event basis. At low masses of the Higgs boson, all approaches yield results consistent with those from the BDT analysis, which is chosen as default because of the superior sensitivity in the entire 110–600 GeV mass range.

The 2-jet category is mainly sensitive to the vector boson fusion (VBF) production mode [41–43], whose cross section is roughly ten times smaller than that for the gluon-gluon fusion mode. The VBF channel with a different production mechanism offers the possibility to test the compatibility of an eventual signal with the SM Higgs. The VBF signal can be extracted using simple selection criteria especially in the relatively low background environment of the fully leptonic $\mathrm{W}^+\mathrm{W}^-$ decay mode, providing additional search sensitivity. The $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ events from VBF production are characterized by a pair of energetic forward-backward jets and very little hadronic activity in the rest of the event. Events passing the $\mathrm{W}^+\mathrm{W}^-$ criteria are selected requiring $p_{\mathrm{T}} > 30$ GeV for both leading jets, with no jets above this threshold present in the pseudorapidity region between them. To reject the main background, which stems from top-quark decays, two additional requirements are applied to the two jets, j_1 and j_2: $|\Delta\eta(j_1, j_2)| > 3.5$ and $m_{j_1 j_2} > 450$ GeV. Finally, a m_{H} dependent requirement on the high end of the dilepton mass is applied.

The selection with the requirements described in this section is referred to as the “Higgs selection” for both the cut-based and the multivariate approaches.

5. Background predictions

A combination of techniques are used to determine the contributions from the background processes that remain after the Higgs selection. Where feasible, background contributions are estimated directly from the data itself, avoiding large uncertainties related to the simulation of these sources. The remaining contributions taken from simulation are small.

The W + jets and QCD multijet backgrounds arise from leptonic decays of heavy quarks, hadrons misidentified as leptons, and electrons from photon conversion. The estimate of these contributions is derived directly from data using a control sample of events where one lepton passes the standard criteria and the other does not, but satisfies a relaxed set of requirements (“loose” selection), resulting in a “tight-fail” sample. The efficiency, $\epsilon_{\mathrm{loose}}$, for a jet satisfying the loose selection to pass the tight selection is determined using data from an independent multijet event sample dominated by non-prompt leptons, and parameterized as a function of p_{T} and η of such lepton. The background contamination is then estimated using the events of the “tight-fail” sample weighted by $\epsilon_{\mathrm{loose}}/(1 - \epsilon_{\mathrm{loose}})$. The systematic uncertainties stemming from the efficiency determination dominate the overall uncertainty of this method, which is estimated to be about 36%.

The normalization of the top-quark background is estimated from data as well by counting the number of top-tagged (N_{tagged}) events and applying the corresponding top-tagging efficiency. The top-tagging efficiency ($\epsilon_{\mathrm{top\ tagged}}$) is measured with a control sample dominated by $\mathrm{t\bar{t}}$ and tW events, which is selected by requiring a b-tagged jet. The residual number of top events ($N_{\mathrm{not\ tagged}}$) in the signal region is given by: $N_{\mathrm{not\ tagged}} = N_{\mathrm{tagged}} \times (1 - \epsilon_{\mathrm{top\ tagged}})/\epsilon_{\mathrm{top\ tagged}}$. Background sources from non-top events are subtracted estimating the misidentification probability from data control samples. The main uncertainty comes from the statistical uncertainty in the control sample and from the systematic uncertainties related to the measurement of $\epsilon_{\mathrm{top\ tagged}}$. The uncertainty is about 25% in the 0-jet category and about 10% otherwise.

For the low-mass $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ signal region, $m_{\mathrm{H}} < 200$ GeV, the non-resonant $\mathrm{W}^+\mathrm{W}^-$ contribution is estimated from data. This contribution is measured using events with a dilepton mass larger than 100 GeV, where the Higgs boson signal contamination is negligible, and a simulation is used to extrapolate into the signal region. The total uncertainty is about 10%. For larger Higgs boson masses there is a large overlap between the non-resonant $\mathrm{W}^+\mathrm{W}^-$ and Higgs boson signal, and simulation is used for the estimation.

The $\mathrm{Z}/\gamma^* \to \ell^+\ell^-$ contribution to the $\mathrm{e}^+\mathrm{e}^-$ and $\mu^+\mu^-$ final states is based on extrapolation from the observed number of events with a dilepton mass within ±7.5 GeV of the Z mass, where the residual background on that region is subtracted, using $\mathrm{e}^{\pm}\mu^{\mp}$ events. The extrapolation to the signal region is performed using the simulation and the results are cross-checked with data, using the same algorithm and subtracting the background in the peaking region which is estimated from $\mathrm{e}^{\pm}\mu^{\mp}$ events. The largest uncertainty in the estimate is related to the statistical uncertainty of the control sample and it is about 50%. The $\mathrm{Z}/\gamma^* \to \tau^+\tau^-$ contamination is estimated using $\mathrm{Z}/\gamma^* \to \mathrm{e}^+\mathrm{e}^-$ and $\mu^+\mu^-$ events selected

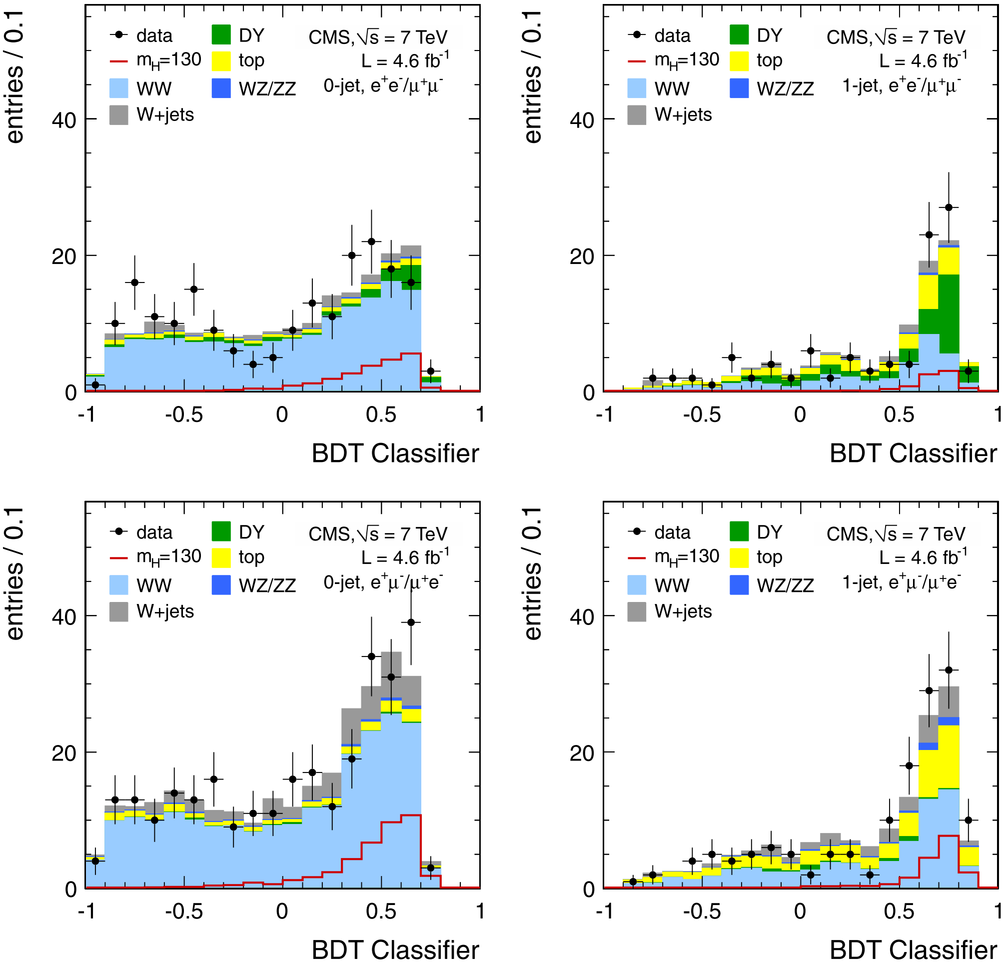

Fig. 3. BDT classifier distributions for signal and background events for a $m_H = 130$ GeV SM Higgs boson and for the main backgrounds at the BDT selection level: (upper-left) 0-jet bin same-flavour final state, (upper-right) 1-jet bin same-flavour final state, (lower-left) 0-jet bin opposite-flavour final state, (lower-right) 1-jet bin opposite-flavour final state.

Table 2
Observed number of events and background estimates for an integrated luminosity of 4.6 fb^{-1} after applying the W^+W^- selection requirements. Only statistical uncertainties on each estimate are reported. The $Z/\gamma^* \to \ell^+\ell^-$ process corresponds to the dimuon and dielectron final states.

	Data	All bkg.	$q\bar{q} \to W^+W^-$	$gg \to W^+W^-$	$t\bar{t} + tW$	W + jets
0-jet	1359	1364.8 ± 9.3	980.6 ± 5.2	58.8 ± 0.7	147.3 ± 2.5	99.3 ± 5.0
1-jet	909	951.4 ± 9.8	416.8 ± 3.6	23.8 ± 0.5	334.8 ± 3.0	74.3 ± 4.6
2-jet	703	714.8 ± 13.5	154.7 ± 2.2	5.1 ± 0.2	413.5 ± 2.7	37.9 ± 3.6

	WZ/ZZ	$Z/\gamma^* \to \ell^+\ell^-$	$W\gamma^{(*)}$	$Z/\gamma^* \to \tau^+\tau^-$
0-jet	33.0 ± 0.5	16.6 ± 4.0	26.8 ± 3.5	2.4 ± 0.5
1-jet	28.7 ± 0.5	39.4 ± 6.4	13.0 ± 2.6	20.6 ± 0.4
2-jet	15.1 ± 0.3	56.1 ± 11.7	10.8 ± 3.6	21.6 ± 2.1

in data, where the leptons are replaced with simulated τ decays, thus providing a better description of the experimental conditions with respect to the full simulation of the process $Z/\gamma^* \to \tau^+\tau^-$. The TAUOLA [44] package is used in the simulation of τ decays to account for τ polarization effects.

Finally, to estimate the $W\gamma^*$ background contribution coming from asymmetric virtual photon decays [45], where one lepton escapes detection, the MADGRAPH generator with dedicated cuts is used. To obtain the normalization scale of the simulated events a control sample of high purity $W\gamma^*$ events with three reconstructed leptons is defined and compared to the simulation prediction. A measured factor of about 1.6 with respect to the leading order cross section is found.

Other minor backgrounds from WZ, ZZ (when the two selected leptons come from different bosons) and $W\gamma$ are estimated from simulation. The $W\gamma$ background estimate is cross-checked in data using the events passing all selection requirements, except that here the two leptons must have the same charge; this sample is dominated by W + jets and $W\gamma$ events.

The number of estimated events for all processes after the W^+W^- selection are summarized in Table 2. The number of events observed in data for the cut-based selection, with the signal and background predictions, are listed in Table 3 for several mass hypotheses.

The templates for the BDT are mainly taken from the simulation and cross-checked in control samples in data. For the W + jets

Table 3

Observed number of events, background estimates and signal predictions for an integrated luminosity of 4.6 fb^{-1} after applying the $H \to W^+W^-$ cut-based selection requirements. The combined statistical and experimental systematic uncertainties on the processes are reported. Theoretical systematic uncertainties are not quoted. The $Z/\gamma^* \to \ell^+\ell^-$ process corresponds to the dimuon, dielectron and ditau final state.

m_H	Data	All bkg.	$pp \to W^+W^-$	Top	W + jets	$WZ + ZZ + W\gamma^{(*)}$	$Z/\gamma^* \to \ell^+\ell^-$	$H \to W^+W^-$
0-jet category								
120	136	136.7 ± 12.7	100.3 ± 7.2	6.7 ± 1.0	14.7 ± 4.7	6.1 ± 1.5	8.8 ± 9.2	15.7 ± 0.8
130	193	191.5 ± 14.0	142.2 ± 10.0	10.6 ± 1.6	17.6 ± 5.5	7.4 ± 1.6	13.7 ± 7.8	45.2 ± 2.1
160	111	101.7 ± 6.8	82.6 ± 5.4	10.5 ± 1.4	3.0 ± 1.5	2.2 ± 0.4	3.4 ± 3.4	122.9 ± 5.6
200	159	140.8 ± 6.8	108.2 ± 4.5	23.3 ± 3.1	3.4 ± 1.5	3.2 ± 0.3	2.7 ± 3.7	48.8 ± 2.2
400	109	110.8 ± 5.8	59.8 ± 2.7	35.9 ± 4.7	5.5 ± 1.8	9.3 ± 1.1	0.2 ± 0.2	17.5 ± 0.8
1-jet category								
120	72	59.5 ± 5.9	27.0 ± 4.7	17.2 ± 1.0	5.4 ± 2.4	3.2 ± 0.6	6.6 ± 2.3	6.5 ± 0.3
130	105	79.9 ± 7.7	38.5 ± 6.6	25.6 ± 1.4	6.5 ± 2.5	4.0 ± 0.6	5.3 ± 2.5	17.6 ± 0.8
160	86	70.8 ± 6.0	33.7 ± 5.5	27.9 ± 1.4	3.2 ± 1.4	1.9 ± 0.3	4.2 ± 1.4	60.2 ± 2.6
200	111	130.8 ± 6.7	49.3 ± 2.2	59.4 ± 2.8	5.2 ± 1.8	2.2 ± 0.1	14.6 ± 5.3	25.8 ± 1.1
400	128	123.6 ± 5.3	44.6 ± 2.2	60.6 ± 2.9	6.2 ± 2.1	3.9 ± 0.5	8.3 ± 3.2	12.2 ± 0.5
2-jet category								
120	8	11.3 ± 3.6	1.3 ± 0.2	5.5 ± 2.8	0.7 ± 0.6	1.8 ± 1.5	1.9 ± 1.4	1.1 ± 0.1
130	10	13.3 ± 4.0	1.6 ± 0.2	6.5 ± 3.2	0.7 ± 0.6	1.8 ± 1.5	2.7 ± 1.9	2.7 ± 0.2
160	12	15.9 ± 4.6	1.9 ± 0.2	8.4 ± 3.9	1.2 ± 0.8	1.8 ± 1.5	2.7 ± 1.9	12.2 ± 0.7
200	13	17.8 ± 5.0	2.2 ± 0.2	9.4 ± 4.2	1.2 ± 0.8	1.8 ± 1.5	3.2 ± 2.1	8.4 ± 0.5
400	20	23.8 ± 6.4	3.5 ± 0.3	14.1 ± 5.8	1.1 ± 0.8	1.9 ± 1.5	3.3 ± 2.1	2.5 ± 0.1

background the nominal shape is derived from the same control sample used to determine the normalization.

6. Efficiencies and systematic uncertainties

The signal efficiency is estimated using simulations. All Higgs production mechanisms are considered: the gluon fusion process, the associated production of the Higgs boson with a W or Z boson, and the VBF process. Since the Higgs p_T spectrum generated by POWHEG is harder than that predicted by more precise calculations [46,47], the Higgs boson p_T distribution is re-weighted to match the prediction from NNLO calculations with a resummation up to next-to-next-to-leading-log accuracy, following the method proposed in [48]. Early phenomenological work on Higgs boson production and decay can be found in Refs. [49–51]. The SM Higgs boson production cross sections are taken from [26,41–43,52–71].

Residual discrepancies in the lepton reconstruction and identification efficiencies between data and simulation are corrected for by data-to-simulation scale factors measured using $Z/\gamma^* \to \ell^+\ell^-$ events in the Z peak region [72], recorded with dedicated unbiased triggers. These factors depend on the lepton p_T and $|\eta|$, and are typically in the range (0.9–1.0).

Experimental effects, theoretical predictions, and the choice of Monte Carlo event generators are considered as sources of uncertainty for both the cut-based and the BDT analyses. For the cut-based analysis the impact of these uncertainties on the signal efficiency is assessed, while for the BDT analysis the impacts on both the signal efficiency and the kinematic distributions are considered. The experimental uncertainties on lepton efficiency, momentum scale and resolution, E_T^{miss} modeling, and jet energy scale are applied to the reconstructed objects in simulated events by smearing and scaling the relevant observables and propagating the effects to the kinematic variables used in the analysis. Separate $q\bar{q} \to W^+W^-$ samples are produced with varied renormalization and factorization scales using the MC@NLO generator [73] to address the shape uncertainty in the theoretical model. The kinematic differences with respect to an alternate event generator are used as an additional uncertainty for $q\bar{q} \to W^+W^-$ (MADGRAPH versus MC@NLO) and top-quark production (MADGRAPH versus POWHEG). The normalization and the shape uncertainty on the W + jets background is included by varying the efficiency for misidentified leptons to pass the tight lepton selection and by comparing to the results of a closure test using simulated samples. For the BDT analysis, the $Z/\gamma^* \to \ell^+\ell^-$ process is modeled using events at low E_T^{miss} to gain statistical power in the extrapolation to the signal region. The effect of the limited amount of simulated events on the shape knowledge is addressed by varying the distribution used to set the limits by the statistical uncertainty in each histogram bin.

The uncertainty on the signal efficiency from pile-up is evaluated to be 0.5%. The assigned uncertainty corresponds to shifting the mean of the expected distribution which is used to reweight the simulation up and down by one interaction. A 4.5% uncertainty is assigned to the luminosity measurement [74].

The systematic uncertainties due to theoretical ambiguities are separated into two components, which are assumed to be independent. The first component is the uncertainty on the fraction of events categorized into the different jet categories and the effect of jet bin migration. The second component is the uncertainty on the lepton acceptance and the selection efficiency of all other requirements. The effect of variations in parton distribution functions and the value of α_s, and the effect of higher-order corrections, are considered for both components using the PDF4LHC prescription [75–79]. For the jet categorization, the effects of higher-order log terms via the uncertainty in the parton shower model and the underlying event are also considered, by comparing different generators. These uncertainties range between 10% and 30% depending on the jet category. The uncertainties related to the diboson cross sections are calculated using the MCFM program [80].

The overall signal efficiency uncertainty is estimated to be about 20% and is dominated by the theoretical uncertainty due to missing higher-order corrections and PDF uncertainties. The uncertainty on the background estimations in the $H \to W^+W^-$ signal region is about 15%, which is dominated by the statistical uncertainty on the observed number of events in the background-control regions.

7. Results

After applying the mass-dependent Higgs selection, no significant excess of events is found with respect to the expected backgrounds, and upper limits are derived on the product of the Higgs

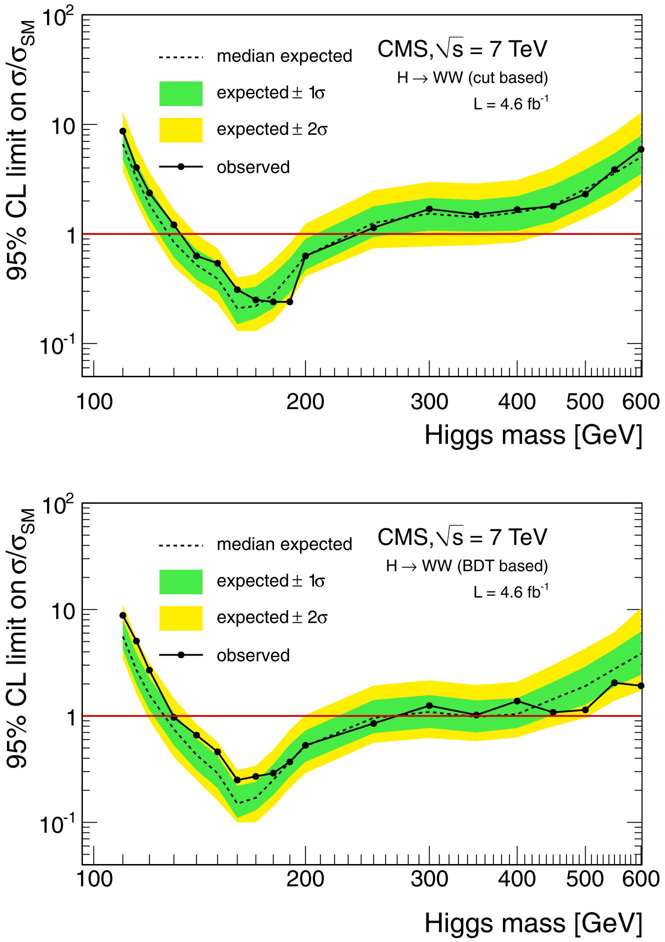

Fig. 4. Expected and observed 95% CL upper limits on the cross section times branching fraction, $\sigma_{\mathrm{H}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-)$, relative to the SM Higgs expectation, using cut-based (top) and multivariate BDT (bottom) event selections. Results are obtained using the CL_s approach.

boson production cross section and the $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ branching fraction, $\sigma_{\mathrm{H}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-)$, with respect to the SM Higgs expectation, $\sigma/\sigma_{\mathrm{SM}}$.

To compute the upper limits the profile modified frequentist construction CL_s [81–83] is used. The likelihood function from the expected number of observed events is modeled as a Poisson random variable, whose mean value is the sum of the contributions from signal and background processes. All the sources of systematic uncertainties are also considered. The 95% CL observed and expected median upper limits are shown in Fig. 4. Results are reported for both the cut-based and the BDT approaches. The bands represent the 1σ and 2σ probability intervals around the expected limit. The *a posteriori* probability intervals on the cross section are constrained by the assumption that the signal and background cross sections are positive definite. The results are also summarized in Table 4.

The cut-based analysis excludes the presence of a Higgs boson with mass in the range 132–238 GeV at 95% CL, while the expected exclusion limit in the hypothesis of background only is 129–236 GeV. With the multivariate analysis, a Higgs boson with mass in the range 129–270 GeV is excluded at 95% CL, while the expected exclusion limit for the background only hypothesis is in the range 127–270 GeV. The observed (expected) upper limits are about 0.9 (0.7) times the SM expectation for $m_{\mathrm{H}} = 130$ GeV.

8. Summary

A search for the SM Higgs boson decaying to $\mathrm{W}^+\mathrm{W}^-$ in pp collisions at $\sqrt{s} = 7$ TeV is performed by the CMS experiment using a data sample corresponding to an integrated luminosity of 4.6 fb^{-1}. No significant excess of events above the SM background expectation is found. Limits on the Higgs boson production cross section relative to the SM Higgs expectation are derived, excluding the presence of the SM Higgs boson with a mass in the range 129–270 GeV at 95% CL.

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Table 4
Expected and observed 95% CL upper limits on the cross section times branching fraction, $\sigma_{\mathrm{H}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-)$, relative to the SM Higgs expectation, in the cut-based and multivariate BDT-based analyses. Results are obtained using the CL_s approach. The 68% and 95% ranges are also given.

Higgs mass	Cut based				BDT based			
	Observed	Expected	68% range	95% range	Observed	Expected	68% range	95% range
110	8.7	6.6	[4.8, 9.3]	[3.7, 13.0]	8.8	5.6	[4.2, 8.0]	[3.5, 11.0]
115	4.0	3.2	[2.3, 4.4]	[1.9, 6.3]	5.1	2.7	[2.0, 3.9]	[1.6, 5.4]
120	2.4	1.9	[1.4, 2.6]	[1.1, 3.7]	2.7	1.6	[1.1, 2.3]	[0.9, 3.2]
130	1.2	0.8	[0.6, 1.2]	[0.5, 1.7]	1.0	0.8	[0.5, 1.1]	[0.4, 1.5]
140	0.6	0.5	[0.4, 0.7]	[0.3, 1.0]	0.7	0.4	[0.3, 0.6]	[0.3, 0.8]
150	0.5	0.4	[0.3, 0.6]	[0.2, 0.7]	0.5	0.3	[0.2, 0.4]	[0.2, 0.6]
160	0.3	0.2	[0.2, 0.3]	[0.1, 0.4]	0.3	0.2	[0.1, 0.2]	[0.1, 0.3]
170	0.3	0.2	[0.2, 0.3]	[0.1, 0.4]	0.3	0.2	[0.1, 0.2]	[0.1, 0.3]
180	0.2	0.3	[0.2, 0.4]	[0.2, 0.6]	0.3	0.3	[0.2, 0.4]	[0.1, 0.5]
190	0.2	0.4	[0.3, 0.6]	[0.2, 0.8]	0.4	0.4	[0.3, 0.5]	[0.2, 0.7]
200	0.6	0.6	[0.5, 0.9]	[0.4, 1.2]	0.5	0.5	[0.4, 0.7]	[0.3, 1.0]
250	1.1	1.3	[0.9, 1.8]	[0.7, 2.5]	0.9	1.0	[0.7, 1.4]	[0.6, 1.9]
300	1.7	1.5	[1.1, 2.1]	[0.8, 3.0]	1.3	1.1	[0.8, 1.6]	[0.6, 2.2]
350	1.5	1.4	[1.1, 2.0]	[0.8, 2.9]	1.0	1.0	[0.7, 1.4]	[0.6, 2.0]
400	1.7	1.6	[1.1, 2.2]	[0.8, 3.1]	1.4	1.0	[0.8, 1.5]	[0.6, 2.1]
450	1.8	1.8	[1.3, 2.8]	[1.0, 4.0]	1.1	1.4	[1.0, 2.1]	[0.8, 3.0]
500	2.3	2.6	[1.8, 3.9]	[1.4, 5.9]	1.1	1.9	[1.3, 2.9]	[1.0, 4.3]
550	3.9	3.6	[2.5, 5.4]	[1.9, 8.5]	2.1	2.8	[1.9, 4.3]	[1.4, 6.1]
600	5.9	5.0	[3.5, 7.9]	[2.8, 12.8]	1.9	3.9	[2.4, 6.2]	[1.7, 10.3]

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