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Search for the standard model Higgs boson in the $H \to ZZ \to 2\ell 2\nu$ channel in pp collisions at $\sqrt{s}$ = 7 TeV

The CMS Collaboration*

Abstract

A search for the standard model Higgs boson in the $H \to ZZ \to 2\ell 2\nu$ decay channel, where $\ell = e$ or μ, in pp collisions at a center-of-mass energy of 7 TeV is presented. The data were collected at the LHC, with the CMS detector, and correspond to an integrated luminosity of 4.6 fb^{-1}. No significant excess is observed above the background expectation, and upper limits are set on the Higgs boson production cross section. The presence of the standard model Higgs boson with a mass in the 270–440 GeV range is excluded at 95% confidence level.

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*See Appendix A for the list of collaboration members

1 Introduction

The standard model (SM) of particle physics [1–3] accommodates essentially all relevant experimental data. One of the remaining questions is the origin of mass for fundamental particles. Within the SM, vector boson masses arise from the spontaneous breaking of electroweak symmetry [4–9]. The existence of the associated field quantum, the Higgs boson, has yet to be experimentally established. The discovery or exclusion of the SM Higgs boson is one of the main goals of the physics programme at the CERN Large Hadron Collider (LHC).

To date, experimental searches for the SM Higgs boson have yielded null results. Limits at 95% confidence level (CL) on its mass (m_{H}) have been placed by experiments at the Large Electron-Positron Collider (LEP), $m_{\mathrm{H}} > 114.4\,\mathrm{GeV}$ [10], the Tevatron, $m_{\mathrm{H}} \notin (162\text{–}166)\,\mathrm{GeV}$ [11], and ATLAS, $m_{\mathrm{H}} \notin (145\text{–}206), (214\text{–}224)$, and $(340\text{–}450)\,\mathrm{GeV}$ [12–14]. The primary production mechanism for the Higgs boson at the LHC is through gluon fusion [15–26] with a small contribution from vector boson fusion (VBF) [27–29].

A search for the SM Higgs boson is presented in the $\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\nu$ channel (where ℓ refers to either e or μ), which is especially sensitive in the high-mass range 250–600 GeV. Results are reported from a data sample corresponding to an integrated luminosity of $4.6\,\mathrm{fb}^{-1}$ recorded in 2011 by the Compact Muon Solenoid (CMS) experiment at $\sqrt{s} = 7\,\mathrm{TeV}$.

2 CMS Detector and Simulations

A detailed description of the CMS detector can be found in Ref. [30]. The key components of the detector include a silicon pixel and a silicon strip tracker, embedded in a 3.8 T solenoidal magnetic field, used to measure the momentum of charged particles. The silicon pixel and strip tracking system covers the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln\left[\tan\left(\theta/2\right)\right]$, and θ is the polar angle of the trajectory of the particle with respect to the beam direction. It is surrounded by a crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadron calorimeter (HCAL). The ECAL and HCAL extend to a pseudorapidity range of $|\eta| < 3.0$. A steel/quartz-fiber Cherenkov forward detector (HF) extends the calorimetric coverage to $|\eta| < 5.2$. The calorimeters are surrounded by the muon system, used to identify muons and measure their momentum. The muon system consists of gas detectors placed in the steel return yoke of the magnet.

The largest background to the SM Higgs boson signal consists of events in which a Z boson is produced in association with jets (Z + jets). The Z + jets cross section is five orders of magnitude larger than the expected production cross section for the signal. The other major backgrounds are top-quark production ($\mathrm{t\bar{t}} \to 2\ell 2\nu 2\mathrm{b}$ and $\mathrm{tW} \to 2\ell 2\nu\mathrm{b}$, and the diboson production ($\mathrm{WZ} \to 3\ell\nu$, $\mathrm{ZZ} \to 2\ell 2\nu$, and $\mathrm{WW} \to 2\ell 2\nu$).

Several Monte Carlo event generators are used to simulate the signal and background processes. The $\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\nu$ signal and top-quark background events are generated by using the next-to-leading order (NLO) program POWHEG 2.0 [31]. The Z + jets and diboson backgrounds are simulated by using the MADGRAPH 5.1.3 generator [32]. The diboson backgrounds are also simulated using the PYTHIA 6.4.22 generator for evaluating certain systematic uncertainties. For events generated using POWHEG and MADGRAPH generators, parton showering is simulated by using PYTHIA with the Z2 tune which differs from the Z1 tune described in Ref. [33] as it uses the CTEQ6 [34] parametrization for the parton distribution functions instead of the CTEQ5 [35] parametrization. The signal events are reweighted so that the transverse momentum (p_{T}) distribution of the Higgs boson agrees with the next-to-next-to-leading order (NNLO) and next-to-next-to-leading log (NNLL) prediction [36, 37]. The total cross section is taken from Ref. [38] and is scaled by the $\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\nu$ branching ratio [39–44]. The parton distribution functions (PDF) are modeled through the CTEQ6L [34] parametrization at leading order and the CT10 parametrization [45] at NLO. The NLO contribution to the $\mathrm{qq} \to \mathrm{ZZ}$ process is taken into account by reweighting the transverse momentum of the visible Z boson to match the prediction from the MCFM 6.0 program [46]. A correction of 12% of the leading order $\mathrm{qq} \to \mathrm{ZZ}$ cross section is included to account for the $\mathrm{gg} \to \mathrm{ZZ}$ process [47]. The detector response to the simulated events is modeled with GEANT4 [30, 48] and reconstruction and analysis are performed by using the same software used for data.

3 Event Selection

For Higgs boson masses considered in this analysis, the Z bosons from $\mathrm{H} \to \mathrm{ZZ}$ decay are typically produced with a substantial p_{T}. Events are therefore selected to have two well-identified, isolated, opposite-charge leptons of same flavour ($\mathrm{e}^+\mathrm{e}^-$ or $\mu^+\mu^-$) with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ that have an invariant mass within 30 GeV window centred on the Z mass. The p_{T} of the dilepton system is required to be greater than 55 GeV. In the electron channel, these events are collected by using dielectron triggers, with thresholds of $p_{\mathrm{T}} > 17\,\mathrm{GeV}$ and $p_{\mathrm{T}} > 8\,\mathrm{GeV}$ for the leading and the other electron, respectively. The muon channel relies on a combination of single- and double-muon triggers. As instantaneous luminosity increased, the thresholds on the double-muon triggers changed from a requirement of $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ for each of the two muons to $p_{\mathrm{T}} > 17\,\mathrm{GeV}$ and $p_{\mathrm{T}} > 8\,\mathrm{GeV}$ on the leading and the other muon, respectively. The threshold for the single-muon trigger increased from $p_{\mathrm{T}} > 17\,\mathrm{GeV}$ to $p_{\mathrm{T}} > 24\,\mathrm{GeV}$. The trigger efficiency for signal, for events selected through the full set of offline requirements is measured by using Z decays in data, and ranges from 95% to 97% in the muon channel and exceeds 99% in the electron channel.

Muon candidates are reconstructed by using two algorithms, one in which tracks in the silicon tracker are matched to energy deposits in the muon detectors and another in which a combined fit is performed to signals in both the silicon tracker and the muon system [49]. The muon candidates for analysis are required to be successfully reconstructed through both algorithms. Other identification criteria based on the number of measurements in the tracker and in the muon system, the fit quality of the muon track, and its consistency with the origin from the primary vertex are also imposed on the muon candidates to reduce the misidentification rate.

Electron reconstruction also involves two algorithms [50], one in which energy clusters in the ECAL are matched to signals in the silicon tracker and another in which tracks in the silicon tracker are matched to ECAL clusters. The electron candidates used in the analysis can be reconstructed by either algorithm. More identification criteria based on the distribution of the shower in the ECAL, a matching of the trajectory of an electron track with the cluster in the ECAL, and consistency with origin of the track from the primary vertex are imposed on the electron candidates to reduce the misidentification rate. Electron candidates with an ECAL cluster in the transition region between ECAL barrel and endcap ($1.4442 < |\eta| < 1.566$) are rejected. Additional requirements are imposed to remove electrons produced in photon conversions in the detector material.

Leptons produced in the decay of Z bosons are expected to be isolated from hadronic activity in the event. The sum of scalar transverse momentum depositions in the calorimeters and the transverse momenta of tracks in a cone of radius 0.3 in η–ϕ space around each lepton, where ϕ is the azimuthal angle, is corrected by the contribution from the lepton and the ratio of this corrected sum divided by the lepton p_{T} is required to be smaller than 15% (10%) for muons (electrons). To correct for the contribution to the isolation sum from pile-up interactions (overlapping minimum-bias events from other concurrent proton-proton collisions), a median energy density (ρ) is determined event by event [51]. Then the pile-up contribution to the isolation sum is estimated as the product of ρ and the area of the cone in which the isolation sum is computed, and it is subtracted from the isolation sum to make it largely insensitive to pile-up. The combined reconstruction, identification and isolation efficiency is measured in data by using Z decays and ranges between 90% and 97% for muons, and between 70% and 90% for electrons, depending on the p_{T} and η of the leptons.

The high instantaneous luminosity delivered by the LHC provides an average of about 10 pile-up interactions per bunch crossing, leading to events with several possible primary vertices. The vertex with largest value of $\sum p_{\mathrm{T}}^2$ for the associated tracks is chosen to be the reference vertex. According to simulation, this requirement provides the correct assignment for the primary vertex in more than 99% of both signal and background events.

The presence of a large imbalance in transverse momentum in an event ($E_{\mathrm{T}}^{\mathrm{miss}}$) is a fundamental feature of the signal. The value of $E_{\mathrm{T}}^{\mathrm{miss}}$ is the modulus of the $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ vector computed as the negative of the vector sum of the transverse momenta of all reconstructed objects identified through the particle-flow algorithm, which aims to reconstruct all particles produced in a collision event by combining information from all sub-detectors [52]. A large $E_{\mathrm{T}}^{\mathrm{miss}}$ threshold is imposed to suppress the bulk of the Z+jets background, which contains little genuine $E_{\mathrm{T}}^{\mathrm{miss}}$. The region of large $E_{\mathrm{T}}^{\mathrm{miss}}$ is populated by Z+jets events in which the $E_{\mathrm{T}}^{\mathrm{miss}}$ is largely due to jet mismeasurement. To suppress the background with $E_{\mathrm{T}}^{\mathrm{miss}}$ arising from mismeasurement of jets, events are removed if the angle in the azimuthal plane between the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest jet with transverse energy $E_{\mathrm{T}} > 30\,\mathrm{GeV}$ is smaller than 0.5 radians. For events having no jets with $E_{\mathrm{T}} > 30\,\mathrm{GeV}$, this requirement is imposed between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest jet with $E_{\mathrm{T}} > 15\,\mathrm{GeV}$. Jets are reconstructed from particle-flow candidates [52, 53] by using the anti-$\mathrm{k_T}$ clustering algorithm [54] with a distance parameter R of 0.5, as implemented in the FASTJET package [55, 56].

Top-quark decays are characterized by the presence of jets originating from b quarks (bjets), which are tagged on the basis of impact parameters of tracks in a jet, relative to the primary vertex [57, 58]. The top-quark background is suppressed by applying a veto on events having a b tagged jet with transverse energy greater than 30 GeV that lies within the tracker volume ($|\eta| < 2.4$). To further suppress the top-quark background, a veto is applied on events containing a "soft muon" with $p_{\mathrm{T}} > 3\,\mathrm{GeV}$, which is typically produced in the leptonic decay of a b quark. The soft-muon veto along with the b-jet veto reduces the top-quark background by a factor of six. To reduce the WZ background in which both bosons decay leptonically, any event with a third lepton (e or μ) with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and passing the identification and isolation requirements is rejected.

4 Analysis Strategy

The search for the SM Higgs boson is performed by using a transverse mass (M_{T}) variable as the final discriminant in searching for an excess of events from the presence of the signal. The transverse mass is defined as follows:

$$M_{\mathrm{T}}^2 = \left(\sqrt{p_{\mathrm{T}}(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{{E_{\mathrm{T}}^{\mathrm{miss}}}^2 + M(\ell\ell)^2} \right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{\mathrm{miss}})^2.$$

where $p_{\mathrm{T}}(\ell\ell)$ and $M(\ell\ell)$ are the transverse momentum and invariant mass of dilepton system, respectively.

Two approaches are considered: a "cut-based" and a "shape-based" analysis. The same set of event selection criteria is used by both the analyses, except for requirements on the $E_{\mathrm{T}}^{\mathrm{miss}}$ and M_{T} variables. In both cases, requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ and M_{T} vary with the Higgs mass hypothesis, but are typically more relaxed for the shape-based analysis.

In the cut-based analysis, the Higgs boson search is performed by looking for an excess of events above the standard model background expectation after applying selection criteria that are tuned for a given Higgs boson mass hypothesis. The $E_{\mathrm{T}}^{\mathrm{miss}}$ and M_{T} selection listed in Table 1 was optimized by using a genetic algorithm for rectangular cuts optimization, GARCON [59], with the expected 95% CL limit on the cross section normalized to the standard model Higgs boson cross section as a figure of merit. Optimization was performed on six m_{H} points, and a smooth-fit interpolation for the cut values was performed to provide optimal cut values for every explored Higgs mass point.

In the shape-based analysis, the Higgs boson search is performed by using a binned likelihood fit to the M_{T} distribution obtained after applying the selection given in Table 1. The range of M_{T} is varied as a function of m_{H} to ensure that the expected signal distribution is fully contained. The shape-based analysis is found to have the best expected signal sensitivity and is considered as the main result in the paper.

Table 1: Higgs boson mass-dependent selection for $E_{\mathrm{T}}^{\mathrm{miss}}$ and M_{T} variables in the cut-based and shape-based analyses.

m_{H} (GeV)	250	300	350	400	500	600
Cut-based analysis selection						
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 70	> 79	> 95	> 115	> 150	> 161
M_T (GeV)	[222, 272]	[264, 331]	[298, 393]	[327, 460]	[382, 605]	[452, 767]
Shape-based analysis selection						
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 70	> 80	> 80	> 80	> 80	> 80
M_T (GeV)	[180, 300]	[250, 350]	[250, 400]	[250, 450]	[250, 600]	[250, 750]

5 Background Estimation

For both types of analyses, the ZZ and WZ backgrounds are modeled using Monte Carlo simulation, and are normalized to their respective NLO cross sections. The remaining backgrounds are estimated using control samples in data.

The Z+jets background is simulated from a control sample of events with a single photon produced in association with jets ($\gamma +$ jets). This obviates the need for using less reliable Monte Carlo simulation of the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution arising from mismeasurement of jets. The $\gamma +$ jets cross section is much larger than $\mathrm{Z} +$ jets. The jets must have a minimum E_{T} of 15 GeV to reduce contamination from processes that have a photon produced in association with genuine $E_{\mathrm{T}}^{\mathrm{miss}}$, such as $\mathrm{W}(\ell\nu) + \gamma$, $\mathrm{W}(\ell\nu)$+jets, where the jet is mismeasured as a photon, and $\mathrm{Z}(\nu\nu) + \gamma$ events. The kinematics and overall normalization of $\gamma +$ jets events are matched to $\mathrm{Z} +$ jets in data through an event-by-event reweighting as a function of the boson p_{T}, and the number of jets with $E_{\mathrm{T}} > 30\,\mathrm{GeV}$, to account for the dependence of the $E_{\mathrm{T}}^{\mathrm{miss}}$ on the associated hadronic activity. Residual differences from pile-up are taken into account by reweighting events according to the number of reconstructed vertices. This procedure yields an accurate model of the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in Z+jets events, as shown in Fig. 1, which compares the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution of the reweighted γ+jets events along with other backgrounds to the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution of the dilepton events in data. To compute the M_{T} for each γ+jets event, the value of $\vec{p}_{\mathrm{T}}(\ell\ell)$ is defined as the photon $\vec{p}_{\mathrm{T}}$ and the value of $M(\ell\ell)$ term is chosen according to a probability density function constructed from the measured dilepton invariant mass distribution in Z+jets events.

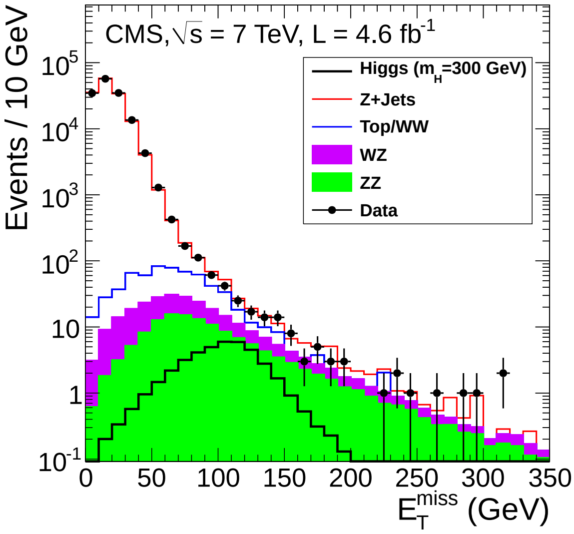

Figure 1: The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in data compared to the background simulation. The dielectron and dimuon channels are combined. Contributions from ZZ, WZ, non-resonant background and Z+jets background are stacked on top of each other. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in signal events for $m_{\mathrm{H}} = 300\,\mathrm{GeV}$ is also shown.

The background processes that do not involve a Z resonance (non-resonant background) are estimated by using a control sample of events with dileptons of different flavor ($\mathrm{e}^{\pm}\mu^{\mp}$) that pass the full analysis selection. This background consists mainly of leptonic W decays in $\mathrm{t\bar{t}}$, tW decays and WW events. Small contributions from single top-quark events produced from s-channel and t-channel processes, W+jets events in which the W boson decays leptonically and a jet is mismeasured as a lepton, and $\mathrm{Z} \to \tau\tau$ events in which τ leptons produce light leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ are included in this estimate of the non-resonant background. This method cannot distinguish between the non-resonant background and a possible contribution from $\mathrm{H} \to \mathrm{WW} \to 2\ell 2\nu$ events, which are treated as part of the non-resonant background estimate.

The non-resonant background in the $\mathrm{e}^{+}\mathrm{e}^{-}$ and $\mu^{+}\mu^{-}$ final states is estimated by applying a scale factor (α) to the selected $\mathrm{e}^{\pm}\mu^{\mp}$ events:

$$N_{\mu\mu} = \alpha_{\mu} \times N_{\mathrm{e}\mu}, \qquad N_{\mathrm{ee}} = \alpha_{\mathrm{e}} \times N_{\mathrm{e}\mu}.$$

This α factor is computed from the sidebands (SB) of the Z peak ($40 < M(\ell\ell) < 70\,\mathrm{GeV}$ and $110 < M(\ell\ell) < 200\,\mathrm{GeV}$) by using the following relations:

$$\alpha_{\mu} = \frac{N_{\mu\mu}^{\mathrm{SB}}}{N_{\mathrm{e}\mu}^{\mathrm{SB}}}, \qquad \alpha_{\mathrm{e}} = \frac{N_{\mathrm{ee}}^{\mathrm{SB}}}{N_{\mathrm{e}\mu}^{SB}},$$

where $N_{\mathrm{ee}}^{\mathrm{SB}}$, $N_{\mu\mu}^{\mathrm{SB}}$, and $N_{\mathrm{e}\mu}^{\mathrm{SB}}$ are the number of events in the Z sidebands in a top-enriched sample of $\mathrm{e}^+\mathrm{e}^-$, $\mu^+\mu^-$, and $\mathrm{e}^\pm\mu^\mp$ final states, respectively. Such samples are selected by requiring $E_{\mathrm{T}}^{\mathrm{miss}}$ $>70\,\mathrm{GeV}$ and a b-tagged jet in the events. The measured values of α with the corresponding statistical uncertainties are $\alpha_\mu = 0.58 \pm 0.02$ and $\alpha_{\mathrm{e}} = 0.42 \pm 0.02$.

Since the M_{T} distribution obtained for the non-resonant background is based on a small sample of $\mathrm{e}^\pm\mu^\mp$ events scaled by α, this distribution is smoothed [60] for use in the shape-based analysis.

6 Systematic Uncertainties

Systematic uncertainties include experimental uncertainties on the selection and measurement of the reconstructed objects, theoretical uncertainties on the signal and background processes which are derived from Monte Carlo simulation, and uncertainties on backgrounds determined from control samples in data. These are summarised in Table 2.

The theoretical uncertainties on the predicted signal are evaluated by changing the parton distribution functions and the QCD renormalization and factorization scales [38, 45, 61–64]. The theoretical uncertainties on the NLO cross sections of the ZZ and WZ backgrounds are estimated by the same procedure of changing the parton distribution functions and the QCD renormalization and factorization scales by using the program MCFM 6.0.

The cross section for on-shell Higgs boson production and decay is calculated in the zero-width approximation. Recent studies show that current Monte Carlo simulation does not describe the correct Higgs-boson line shape for $m_{\mathrm{H}} \gtrsim 300\,\mathrm{GeV}$. These effects are estimated to correspond to an additional uncertainty of 10–30% on the theoretical cross section for $400 < m_{\mathrm{H}} < 600\,\mathrm{GeV}$ [38, 65, 66].

Various factors contribute to the experimental uncertainties that apply to processes derived from Monte Carlo simulation. These include uncertainties on the trigger efficiency and lepton selection efficiencies. The effect of lepton momentum scale and jet energy scale is also taken into account and is propagated to the evaluation of $E_{\mathrm{T}}^{\mathrm{miss}}$. The uncertainty on the b jet veto is estimated by measuring the b-tagging efficiency in data from fully leptonic $\mathrm{t\bar{t}}$ decays [58]. The uncertainty due to the modeling of pile-up is evaluated by shiftng the mean of the distribution of the number of pile-up interactions up and down by one.

The uncertainty on the estimate of the non-resonant background is dominated by the statistical uncertainty of the $\mathrm{e}^\pm\mu^\mp$ control sample. The uncertainty on the prediction of the Z+jets background is affected by any residual contamination of the γ+jets control sample from processes involving a photon and genuine $E_{\mathrm{T}}^{\mathrm{miss}}$. Consequently, this method provides only an upper bound on the prediction. To account for this contamination, the Z+jets background prediction is changed from zero to the estimate obtained from the γ+jets control sample in the limit-setting procedure. This is achieved by taking half of the estimate from the γ+jets control sample as the central value for the Z+jets background and assigning a 100% systematic uncertainty to this value. Since Z+jets contributes to only 10–15% of the total background, the large uncertainty on this background does not have a significant impact on the overall performance of the analysis.

In the shape-based analysis, the difference in the M_{T} distribution with respect to an alternate Monte Carlo generator (MADGRAPH versus PYTHIA) is used as an uncertainty in the modeling of the ZZ, WZ backgrounds. The uncertainty on the M_{T} distributions arising from the limited number of Monte Carlo simulated events is taken into account by scaling all the bins up and down by the respective statistical uncertainties. This is done in a correlated manner to obtain two bounding distributions, within which the nominal distribution is changed. For the non-resonant background, where the nominal M_{T} distribution is obtained by smoothing the M_{T} distribution of $\mathrm{e}^{\pm}\mu^{\mp}$ events, the bounding distributions are taken from simulation to account for any possible bias introduced by smoothing. The uncertainty for signal is assigned by reweighting the p_{T} spectrum of the Higgs boson to the one obtained from changing the renormalization and factorization scales in the NNLO+NNLL calculation [36, 37].

Table 2: Summary of systematic uncertainties on event yields of signal and background processes. Ranges refer to uncertainties that depend on the hypothesised value of m_{H}.

Source	Uncertainty [%]
Luminosity	4.5
PDF for Higgs production (gluon-fusion)	8.2–10.4
PDF for Higgs production (VBF)	3.8–7.6
PDF for $\mathrm{qq} \to \mathrm{ZZ}$	4.8
PDF for $\mathrm{qq} \to \mathrm{WZ}$	5.5
QCD scale for Higgs production (gluon-fusion)	7.6–11.1
QCD scale for Higgs production (VBF)	0.4–2
QCD scale for $\mathrm{gg} \to \mathrm{ZZ}$	20
QCD scale for $\mathrm{qq} \to \mathrm{ZZ}$	6.2
QCD scale for $\mathrm{qq} \to \mathrm{WZ}$	8.5
Higgs boson line shape	10–30
Trigger	1 (for ee), 2 (for $\mu\mu$)
Lepton identification and isolation	2
Lepton momentum scale	5 (for ee), 2 (for $\mu\mu$)
Jet energy scale	1–1.5
bjet Veto	1–1.2
Pile-up	1–3
Non-resonant background	15–100
Z+jets	100

7 Results

The event yields for the cut-based analysis, as a function of m_{H}, and the estimated backgrounds for the 4.6 fb^{-1} dataset are listed in Table 3. The M_{T} distributions for the shape-based analysis based on the selections described in Table 1 for $m_{\mathrm{H}} = 300$ and 400 GeV hypotheses are shown in Fig. 2. No significant excess of events is observed over the expectation from the SM background and limits are set on the production cross section of the standard model Higgs boson as a function of m_{H}.

The median expected and observed 95% CL upper limits on the cross section $\sigma \times BR(\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\nu)$ for $250 < m_{\mathrm{H}} < 600$ GeV by using the cut- and the shape-based approaches are shown in Fig. 3. The measured ratio R of the 95% CL upper limit cross section σ to the SM Higgs boson production cross section σ_{SM} as a function of m_{H} is shown in Fig. 4. These results are obtained by using the $\mathrm{CL_s}$ method [67–69]. For the cut-based analysis the SM Higgs boson is excluded in the mass range 310–465 GeV at 95% confidence level, while the expected exclusion limit in the background-only hypothesis is 305–470 GeV. For the shape-based analysis the SM

Table 3: Background estimates, signal predictions, and observed number of events for an integrated luminosity of 4.6 fb^{-1} after the cut-based selection. The uncertainties include the statistical and systematic components (in that order). The results for signal contain only the systematic uncertainties as the statistical uncertainties are negligible. For the non-resonant background, the 68% upper limit is quoted in the case where the background prediction is zero.

m_H (GeV)	ZZ	WZ	Top/WW/ W+jets/Z→ $\tau\tau$	Z+Jets	Total Background	Expected Signal	Data
250	$36.0 \pm 0.2 \pm 2.6$	$24.0 \pm 0.3 \pm 2.0$	$65.0 \pm 3.8 \pm 5.8$	15.0 ± 15.0	$140.0 \pm 3.8 \pm 16.0$	22.0 ± 2.2	142
300	$23.0 \pm 0.2 \pm 1.7$	$13.0 \pm 0.2 \pm 1.1$	$18.0 \pm 1.1 \pm 3.0$	6.3 ± 6.3	$60.0 \pm 1.1 \pm 7.3$	21.0 ± 2.1	64
350	$16.0 \pm 0.1 \pm 1.1$	$7.0 \pm 0.2 \pm 0.6$	$2.0 \pm 0.1 \pm 1.0$	4.1 ± 4.1	$29.0 \pm 0.3 \pm 4.4$	21.0 ± 2.5	26
400	$12.0 \pm 0.1 \pm 0.9$	$4.6 \pm 0.1 \pm 0.4$	< 1.1	2.7 ± 2.7	$19.0 \pm 0.2 \pm 2.9$	17.0 ± 2.0	18
500	$7.5 \pm 0.1 \pm 0.5$	$2.0 \pm 0.1 \pm 0.2$	< 1.1	1.4 ± 1.4	$11.0 \pm 0.1 \pm 1.5$	7.4 ± 1.3	14
600	$3.9 \pm 0.1 \pm 0.3$	$0.8 \pm 0.1 \pm 0.1$	< 1.1	0.6 ± 0.6	$5.3 \pm 0.1 \pm 0.7$	2.9 ± 0.7	5

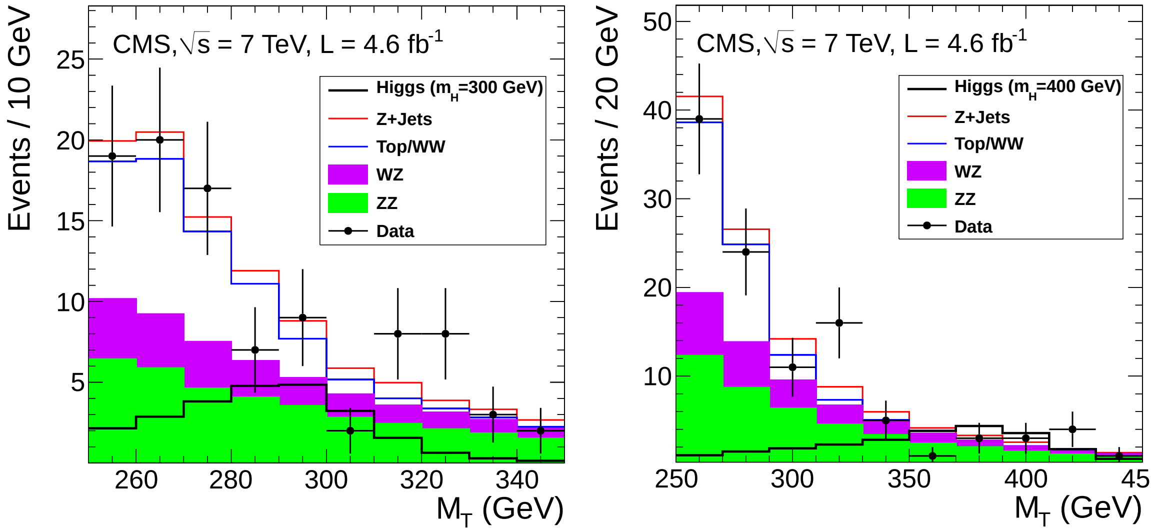

Figure 2: The M_T distribution for events passing m_H selections for 300 GeV (left) and 400 GeV (right). The dielectron and dimuon channels are combined.

Higgs boson is excluded in the mass range 270–440 GeV at 95% confidence level while the expected exclusion limit for the background-only hypothesis is 290–490 GeV.

8 Summary

A search for the standard model Higgs boson has been performed in the decay channel $H \to ZZ \to 2\ell 2\nu$ in pp collisions at $\sqrt{s} = 7$ TeV, using a data sample corresponding to an integrated luminosity of 4.6 fb^{-1}. No significant excess is found above the background expectation. The presence of the SM Higgs boson is excluded for 270 GeV $< m_H <$ 440 GeV at 95% CL.

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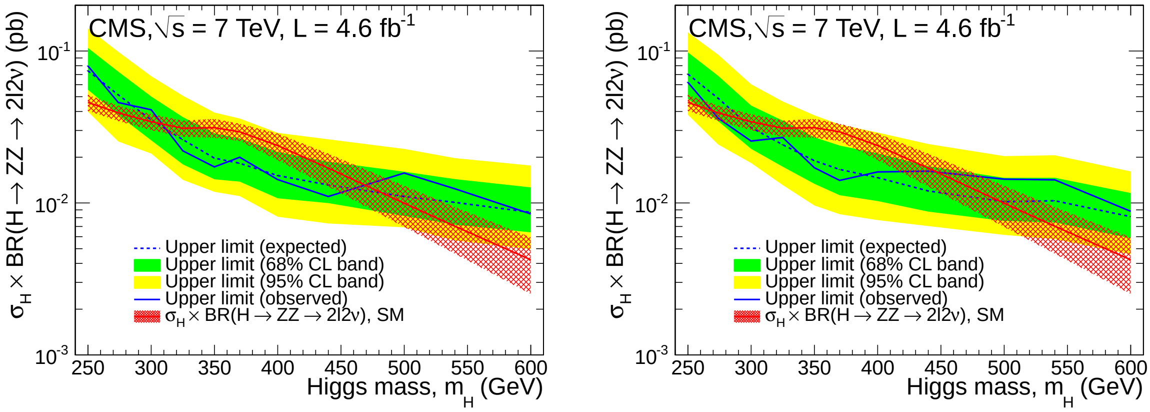

Figure 3: The median expected and observed 95% CL upper limits on the cross section $\sigma \times BR(H \to ZZ \to 2\ell 2\nu)$ for the Higgs boson masses in the range $250 - 600$ GeV for the cut-based (left) and shape-based (right) analyses.

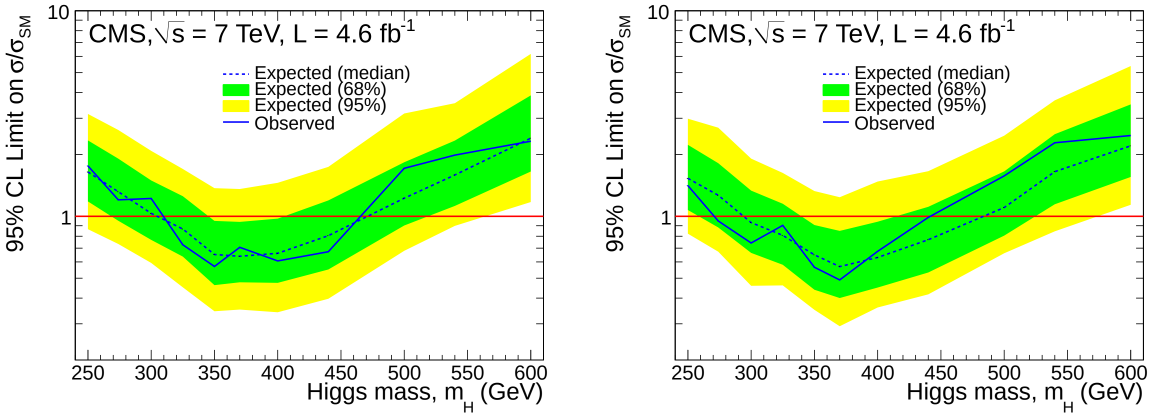

Figure 4: The ratio R of the 95% CL cross section upper limit σ to the SM Higgs boson production cross section σ_{SM} as a function of the Higgs boson mass m_{H} for the cut-based (left) and shape-based (right) analyses.

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