



# Search for the standard model Higgs boson in the decay channel $H \rightarrow ZZ \rightarrow 4\ell$ in pp collisions at $\sqrt{s} = 7$ TeV

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## Abstract

A search for a Higgs boson in the four-lepton decay channel  $H \rightarrow ZZ$ , with each  $Z$  boson decaying to an electron or muon pair, is reported. The search covers Higgs boson mass hypotheses in the range  $110 < m_H < 600$  GeV. The analysis uses data corresponding to an integrated luminosity of  $4.7 \text{ fb}^{-1}$  recorded by the CMS detector in pp collisions at  $\sqrt{s} = 7$  TeV from the LHC. Seventy-two events are observed with four-lepton invariant mass  $m_{4\ell} > 100$  GeV (with thirteen below 160 GeV), while  $67.1 \pm 6.0$  ( $9.5 \pm 1.3$ ) events are expected from background. The four-lepton mass distribution is consistent with the expectation of standard model background production of  $ZZ$  pairs. Upper limits at 95% confidence level exclude the standard model Higgs boson in the ranges 134–158 GeV, 180–305 GeV, and 340–465 GeV. Small excesses of events are observed around masses of 119, 126, and 320 GeV, making the observed limits weaker than expected in the absence of a signal.

*Submitted to Physical Review Letters*

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\*See Appendix A for the list of collaboration members



The standard model (SM) of electroweak interactions [1–3] relies on a scalar particle, the Higgs boson, associated with the field responsible for the spontaneous electroweak symmetry breaking [4–9]. The existence of the Higgs boson has yet to be established experimentally, while its mass,  $m_H$ , is not fixed by the theory. Direct searches for the SM Higgs boson at the LEP  $e^+e^-$  collider and the Tevatron  $p\bar{p}$  collider have led, respectively, to a lower mass bound of  $m_H > 114.4$  GeV [10], and to an exclusion in the range 162–166 GeV [11], at 95% CL. Indirect constraints from precision measurements favour the mass range  $m_H < 158$  GeV [12] at 95% CL. The inclusive Higgs boson production followed by the decay  $H \rightarrow ZZ$  is expected to be one of the main discovery channels at the CERN proton-proton (pp) Large Hadron Collider (LHC) for a wide range of  $m_H$  values. Using the  $H \rightarrow ZZ$  and the  $H \rightarrow WW$  decay channels, the ATLAS collaboration have excluded at 95% CL the mass ranges 145–206 GeV, 214–224 GeV, and 340–450 GeV [13–15].

In this Letter, an inclusive search in the four-lepton decay channel,  $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$  with  $\ell, \ell' = e$  or  $\mu$ , abbreviated as  $H \rightarrow 4\ell$ , is presented. The analysis is designed for a Higgs boson in the mass range  $110 < m_H < 600$  GeV. It uses pp data from the LHC collected at  $\sqrt{s} = 7$  TeV by the Compact Muon Solenoid (CMS) experiment during 2010 and 2011. The data corresponds to an integrated luminosity of  $4.7 \text{ fb}^{-1}$ . The search relies solely on the measurement of leptons, and the analysis achieves high lepton reconstruction, identification, and isolation efficiencies for a  $ZZ \rightarrow 4\ell$  system composed of two pairs of same-flavour and opposite-charge isolated leptons,  $e^+e^-$  or  $\mu^+\mu^-$ , in the measurement range  $m_{4\ell} > 100$  GeV. One or both of the Z bosons can be off-shell. The background sources include an irreducible four-lepton contribution from direct ZZ production via  $q\bar{q}$  annihilation and gg fusion. Reducible contributions arise from  $Zb\bar{b}$  and  $t\bar{t}$  where the final states contain two isolated leptons and two b jets producing secondary leptons. Additional background of instrumental nature arises from Z + jets events where jets are misidentified as leptons.

Particles produced in the pp collisions are detected in the pseudorapidity range  $|\eta| < 5$ , where  $\eta = -\ln \tan(\theta/2)$  and  $\theta$  is the polar angle with respect to the direction of the proton beam. The CMS detector comprises a superconducting solenoid, providing a uniform magnetic field of 3.8 T in the bore, equipped with silicon pixel and strip tracking systems ( $|\eta| < 2.5$ ) surrounded by a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadronic calorimeter (HCAL) ( $|\eta| < 3.0$ ). A steel/quartz-fiber Cherenkov calorimeter extends the coverage ( $|\eta| < 5$ ). The steel return yoke outside the solenoid is instrumented with gas detectors used to identify muons ( $|\eta| < 2.4$ ). A detailed description of the detector is given in Ref. [16].

Monte Carlo (MC) samples for the SM Higgs boson signal and for background processes are used to optimize the event selection and to evaluate the acceptance and systematic uncertainties. The Higgs boson signals from gluon-fusion ( $gg \rightarrow H$ ), and vector-boson fusion ( $q\bar{q} \rightarrow q\bar{q}H$ ), are generated with POWHEG [17] at next-to-leading-order (NLO) and a dedicated generator from Ref. [18]. Additional samples of WH, ZH, and  $t\bar{t}H$  events are generated with PYTHIA [19]. Events at generator level are reweighted according to the total cross section  $\sigma(pp \rightarrow H)$ , which contains contributions from gluon fusion up to next-to-next-to-leading-order (NNLO) and next-next-to-leading-log taken from Refs. [20–29] and from the weak-boson fusion contribution computed at NNLO in Refs. [22, 30–34]. The total cross section is scaled by the branching fraction  $\mathcal{B}(H \rightarrow 4\ell)$  [22, 35–38]. Interference effects in the  $4e$  and  $4\mu$  channels are calculated with PROPHECY4F [22, 35, 36]. The SM background contribution from ZZ production via  $q\bar{q}$  is generated at NLO with POWHEG, while other di-boson processes (WW, WZ) are generated with PYTHIA with cross sections rescaled to NLO predictions. The  $gg \rightarrow ZZ$  contribution is generated with GG2ZZ [39]. The  $Zb\bar{b}$ ,  $Zc\bar{c}$ ,  $Z\gamma$ , and Z + light jets samples are generated with MADGRAPH [40] with cross sections rescaled to NNLO prediction for inclusive

Z production. The  $t\bar{t}$  events are generated at NLO with POWHEG. The generation takes into account the internal initial state and final state radiation (FSR) effects which can lead to the presence of additional hard photons in an event. All events are processed through a detailed simulation of the CMS detector based on GEANT4 [41] and are reconstructed with the same algorithms that are used for data.

Collision events are selected by the trigger system that requires the presence of a pair of electrons (a pair of muons) with transverse energy (transverse momenta) for the first and second lepton above 17 and 8 GeV respectively. The trigger efficiency within the acceptance of this analysis is greater than 99% for signal in the 4e and 4 $\mu$  channels, and rises from about 97.5% at  $m_H = 120$  GeV to above 99% at  $m_H > 140$  GeV in the 2e2 $\mu$  channel, within the acceptance of this analysis.

Electrons are reconstructed within the geometrical acceptance,  $|\eta^e| < 2.5$ , and with  $p_T^e > 7$  GeV, by combining information from the ECAL and inner tracker [42, 43]. Electron identification selection requirements rely on electromagnetic shower-shape observables and on observables combining tracker and calorimetry information. The selection criteria depend on  $p_T^e$  and  $|\eta^e|$ , and on a categorization according to observables sensitive to the amount of bremsstrahlung emitted along the trajectory in the inner tracker. Muons are reconstructed [44] within  $|\eta^\mu| < 2.4$  and  $p_T^\mu > 5$  GeV, using information from both the inner tracker and the muon spectrometer. The inner track is required to be composed of more than 10 tracker-layer hits to ensure a precise measurement of the momentum. The efficiencies are measured in data, using a tag-and-probe technique [45] based on an inclusive sample of Z events. The measurements are performed in several ranges in  $p_T^\ell$  and  $|\eta|$ . The product of reconstruction and identification efficiencies for electrons in the ECAL barrel (endcaps) vary from about 68% (62%) for  $7 < p_T^e < 10$  GeV to 82% (74%) at  $p_T^e \simeq 10$  GeV, and reach 90% (89%) for  $p_T^e \simeq 20$  GeV. It drops to about 85% in the transition region,  $1.44 < |\eta| < 1.57$ , between the ECAL barrel and endcaps. The muons are reconstructed and identified with efficiencies above  $\sim 98\%$ . Lepton candidates are defined with a loose constraint on their isolation, by requiring the sum of the transverse momenta of tracks  $i$  within a cone around the lepton  $\ell$  of  $\Delta R = \sqrt{(\eta^\ell - \eta^i)^2 + (\phi^\ell - \phi^i)^2} < 0.3$ , where  $\phi$  is the azimuthal angle, to have  $\sum_i p_{T,\text{track}}^i / p_T^\ell < 0.7$ . The lepton isolation efficiency for identified leptons with this very loose definition of isolation is found to be greater than 99%.

We first require a Z candidate formed with a pair of lepton candidates satisfying  $50 < m_{1,2} < 120$  GeV,  $p_T^{\ell_1} > 20$  GeV, and  $p_T^{\ell_2} > 10$  GeV. The  $p_T$  thresholds ensure that the leptons are on the high-efficiency plateau for the trigger. The lepton pair is required to be well isolated using a combination of the tracker, ECAL and HCAL information. The sum of the combined relative isolation  $R_{\text{iso}}$  for the two leptons is required to satisfy  $R_{\text{iso}}^{\ell_1} + R_{\text{iso}}^{\ell_2} < 0.35$ , where for each lepton,  $R_{\text{iso}} = (1/p_T^\ell) \times \left( \sum_i p_{T,\text{track}}^i + \sum_j E_{T,\text{ECAL}}^j + \sum_k E_{T,\text{HCAL}}^k \right)$ , with sums running over the charged tracks  $i$ , and the  $E_T$  from energy deposits in cells  $j$  and  $k$  of the ECAL and HCAL within a cone of radius  $\Delta R < 0.3$ , respectively. The footprint of the lepton is removed from the isolation sum. The combined isolation efficiencies measured with data using the tag-and-probe technique are found to be  $> 99\%$  for muons and between 94% to 99% for electrons. The isolation is made largely insensitive to the number of overlapping pp interactions by correcting for the average energy flow [46] per unit area measured as a function of the number of primary vertices. The ratio of the efficiencies measured with data and with simulated  $Z \rightarrow \ell\ell$  events is found to be consistent with unity. The significance of the signed impact parameter of each lepton relative to the event vertex,  $\text{SIP}_{3\text{D}} = \frac{\text{IP}}{\sigma_{\text{IP}}}$ , where IP is the impact parameter in three dimensions and  $\sigma_{\text{IP}}$  the associated uncertainty, is required to satisfy  $|\text{SIP}_{3\text{D}}| < 4$ . The  $\ell^+\ell^-$  pair with reconstructed mass closest to the nominal Z boson mass is retained and denoted  $Z_1$ . The  $Z_1+X$  dataset thus

defined contains the samples used to estimate reducible and instrumental backgrounds, as well as the ZZ rates. In the next step, a subset of events is identified with at least a third lepton candidate. The  $Z_1 + \ell$  events are used to measure misidentified lepton rates. A subset of events with at least a fourth lepton candidate of any flavour or charge is then identified. Together, the  $Z_1 + \ell$  and  $Z_1 + \ell\ell'$  samples provide ways to estimate the remaining reducible ( $Zb\bar{b}$ ,  $t\bar{t}$ ) and instrumental ( $Z + \text{light jets}$ ) backgrounds. For the signal, we select a second lepton pair, denoted  $Z_2$ , from the remaining same flavour  $\ell^+\ell^-$  combinations, by requiring  $m_{Z_2} > 12 \text{ GeV}$ , with the restriction  $m_{4\ell} > 100 \text{ GeV}$ . For the  $4e$  and  $4\mu$  final states, at least three of the four combinations of opposite-sign pairs must satisfy  $m_{\ell\ell} > 12 \text{ GeV}$ . If more than one  $Z_2$  candidate satisfies all criteria, the ambiguity is resolved by choosing the leptons of highest  $p_T$ . The isolation and impact parameter are used to further suppress the remaining backgrounds. We require for any combination of two leptons  $i$  and  $j$ , irrespective of flavour or charge, that  $R_{\text{iso},i} + R_{\text{iso},j} < 0.35$  and also impose  $|\text{SIP}_{3D}| < 4$  for each of the four leptons.

Finally, to select the four-lepton signal candidates, we require that the  $Z_1$  and  $Z_2$  masses satisfy  $m_{Z_1}^{\text{min}} < m_{Z_1} < 120 \text{ GeV}$  and  $m_{Z_2}^{\text{min}} < m_{Z_2} < 120 \text{ GeV}$ , with  $(m_{Z_1}^{\text{min}}, m_{Z_2}^{\text{min}}) = (50, 12) \text{ GeV}$  defining the baseline selection and  $(m_{Z_1}^{\text{min}}, m_{Z_2}^{\text{min}}) = (60, 60) \text{ GeV}$  defining the high-mass selection. The baseline selection is used to search for the Higgs boson, and the high-mass selection is used to measure the ZZ cross section.

The event yields are found to be in good agreement with the MC background expectation at each step of event selection. The ZZ and Z+X backgrounds dominate after the full event selection. The overall signal detection efficiency for the  $4e$  ( $4\mu$ ,  $2e2\mu$ ) channel is evaluated by MC and increases from  $\approx 21\%$  ( $59\%$ ,  $35\%$ ) at  $m_H = 120 \text{ GeV}$  to  $\approx 35\%$  ( $71\%$ ,  $50\%$ ) at  $m_H = 140 \text{ GeV}$ , reaching a plateau at  $\approx 51\%$  ( $81\%$ ,  $63\%$ ) at  $m_H = 200 \text{ GeV}$ , and then slowly rising to  $\approx 60\%$  ( $83\%$ ,  $72\%$ ) at  $m_H = 350 \text{ GeV}$ . The relative mass resolution estimated from MC signal samples is about 2.1% (1.1%, 1.6%) for  $4e$  ( $4\mu$ ,  $2e2\mu$ ).

The small number of observed events precludes a precise direct evaluation of background by extrapolating from mass sidebands. Instead, we rely on MC to evaluate the number of events expected from the ZZ background. The cross section for ZZ production at NLO, through the dominant process of  $q\bar{q}$  annihilation and through gg fusion, is calculated with MCFM [47–49]. The theoretical uncertainties are computed as a function of  $m_{4\ell}$ , varying both the QCD renormalization and factorization scales and the parton distribution functions (PDF) set following the PDF4LHC recommendations [50–54]. The uncertainties for the QCD and PDF scales for each final state are on average 8%. The number of predicted  $ZZ \rightarrow 4\ell$  events and their uncertainties after the baseline selection are given in Table 1. As a consistency check, an evaluation is made based on a normalization to the measured inclusive single-Z production, a procedure discussed in Refs. [55, 56]. The measured rate of single Z bosons defined in this analysis is used to predict the total ZZ rate; making use of the ratio of the theoretical cross sections for ZZ and Z production, and the ratio of the reconstruction and selection efficiencies for the four-lepton and two-lepton final states. The results are in agreement with the ZZ rates reported in Table 1 within uncertainties.

To estimate the reducible ( $Zb\bar{b}$ ,  $t\bar{t}$ ) and instrumental ( $Z + \text{light jets}$ ) backgrounds, a region well separated from the signal region is defined by relaxing and inverting some selection criteria and verifying that the event rates change according to MC expectation. The event rates measured in the background control region are then extrapolated to the signal region. The control region for Z+X, where X stands for  $b\bar{b}$ ,  $c\bar{c}$ , gluon or light quark jets, is obtained by relaxing the isolation and identification criteria for two additional reconstructed lepton objects (a measured track for muons, or a combination of a track and a cluster of ECAL energy deposits for electrons) indi-

cated as  $\ell_{\text{reco}}\ell_{\text{reco}}$ . The additional pair of leptons must have like sign charge (to avoid signal contamination) and same flavour ( $e^\pm e^\pm, \mu^\pm \mu^\pm$ ), a reconstructed invariant mass  $m_{Z_2}$  either satisfying the baseline selection or the high-mass selection, and  $m_{4\ell} > 100$  GeV. A sample  $Z_1 + \ell_{\text{reco}}$ , with at least one reconstructed lepton object, is also defined for the measurement of the lepton misidentification probability, the probability for a reconstructed object to pass the isolation and identification requirements. The contamination from WZ in this set of events is suppressed by requiring that the imbalance of the measured energy deposition in the transverse plane is below 25 GeV. From the  $Z + \ell_{\text{reco}}\ell_{\text{reco}}$  sample the expected number of Z+X background events in the signal region is obtained by taking into account the lepton misidentification probability for each of the two additional leptons. The number of background events expected in the signal region, normalized to the integrated luminosity, and the associated systematic uncertainties, are given in Table 1 for the baseline selection in the range  $100 < m_{4\ell} < 600$  GeV. The reducible and instrumental background is found to be dominated by Z + light jets. A small residual contamination of  $Zb\bar{b}$  remains at low mass while for the high-mass selection these reducible backgrounds are an order of magnitude smaller and therefore can be neglected. This was verified by performing a measurement of  $Zb\bar{b}$  and  $t\bar{t}$  rates in a dedicated four-lepton background control region, defined by requiring a  $Z_1$  and two additional leptons satisfying an inverted  $\text{SIP}_{3\text{D}}$  requirement, namely  $|\text{SIP}_{3\text{D}}| > 5$ , and with relaxed isolation, charge, and flavour requirements. This ensures a negligible Z + light jets contribution in the four-lepton background control region, while the signal and the ZZ background are absent. To extract background rates, the reconstructed  $Z_1$  mass for the sum of the  $Z_1 + 2e$ ,  $Z_1 + 2\mu$ , and  $Z_1 + e\mu$  final states is fit with a Breit-Wigner function convoluted with a Crystal Ball function [57] for the  $Z_1$  peak from  $Zb\bar{b}$  and Chebychev polynomials for the description of the  $t\bar{t}$  continuum. The extrapolation to the signal region relies on knowledge of, and the distinct features of, the  $\text{SIP}_{3\text{D}}$  distributions for the  $Z_2$  leptons of the  $t\bar{t}$  and  $Zb\bar{b}$  backgrounds. The result is found to be compatible with the MC expectation in the signal region within the systematic uncertainty of 20%.

Systematic uncertainties are evaluated from data for trigger efficiency (1.5%), lepton reconstruction and identification (2–3%), and isolation efficiencies (2%). Systematic uncertainties on energy-momentum calibration (0.5%), and energy resolution are accounted for by their effect on the reconstructed mass distributions. The effect of the energy resolution uncertainties is taken into account by introducing a 30% uncertainty on the width of the signal mass peak. Additional systematic uncertainties arise from limited statistics in the reducible background control regions. All reducible and instrumental background sources are derived from control regions, and the comparison of data with the background expectation in the signal region is independent of the uncertainty on the LHC integrated luminosity of the data sample. This uncertainty (4.5%) [58] enters the evaluation of the ZZ background and in the calculation of the cross section limit through the normalization of the signal. Systematic uncertainties on the Higgs boson cross section (17–20%) and branching fraction (2%) are taken from Ref. [22].

Recent studies [22, 59, 60] show that current Monte Carlo simulations do not describe the expected Higgs boson mass line shape above  $\approx 300$  GeV. These effects are estimated to amount to an additional uncertainty on the theoretical cross section, and hence on the limits, of about 4% at  $m_{\text{H}} = 300$  GeV and 10–30% for  $m_{\text{H}}$  of 400–600 GeV.

The number of candidates observed, as well as the estimated background in the signal region, are reported in Table 1 for the baseline selection. The reconstructed four-lepton invariant mass distribution for the combined  $4e$ ,  $4\mu$ , and  $2e2\mu$  channels with the baseline selection is shown in Fig. 1a and compared to expectations from the backgrounds. The shape of the mass distribution below  $m_{\text{H}} = 180$  GeV reflects the shape of the dominant  $q\bar{q}$  annihilation process [61]. The low mass range is shown in Fig. 1b together with the mass of each candidate and its uncertainty.

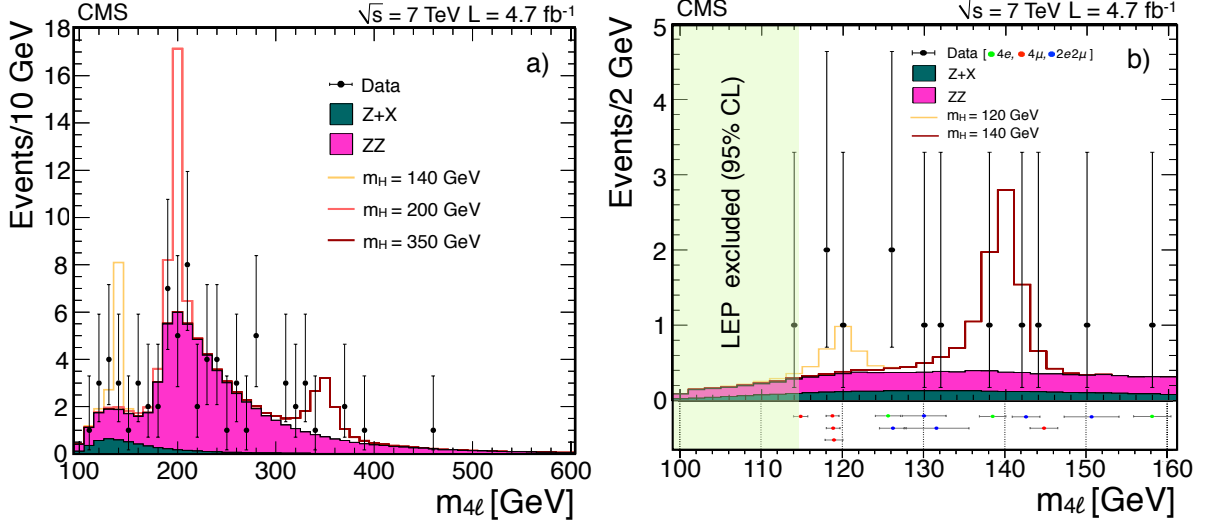


Figure 1: a) Distribution of the four-lepton reconstructed mass for the sum of the 4e, 4 $\mu$ , and 2e2 $\mu$  channels. b) Expansion of the low mass range with existing exclusion limits at 95% CL; also shown are the central values and individual candidate mass measurement uncertainties. Points represent the data, shaded histograms represent the background and unshaded histogram the signal expectations.

The reducible and instrumental background rates are small. These rates have been obtained from data and the corresponding  $m_{4\ell}$  distributions are obtained from MC samples.

The measured distribution is compatible with the expectation from SM direct production of ZZ pairs. We observe 72 candidates, 12 in 4e, 23 in 4 $\mu$ , and 37 in 2e2 $\mu$ , while  $67.1 \pm 6.0$  events are expected from standard model background processes. No hard photon ( $p_T^\gamma > 5$  GeV) was found, outside the isolation veto cone that surrounds each lepton, that could be unambiguously identified as FSR. Thirteen candidates are observed within  $100 < m_{4\ell} < 160$  GeV while  $9.5 \pm 1.3$  background events are expected. We observe 53 candidates for the high-mass selection compared to an expectation of  $51.3 \pm 4.6$  events from background. This high-mass event selection is used to provide a measurement of the total cross section  $\sigma(\text{pp} \rightarrow \text{ZZ} + \text{X}) \times \mathcal{B}(\text{ZZ} \rightarrow 4\ell) = 28.1_{-4.0}^{+4.6}(\text{stat.}) \pm 1.2(\text{syst.}) \pm 1.3(\text{lumi.}) \text{ fb}$ . The measurement agrees with the SM prediction at NLO [47] of  $27.9 \pm 1.9 \text{ fb}$ . The local  $p$ -values, representing the significance of local excesses relative to the standard model expectation, are shown as a function of  $m_H$  in Fig. 2a, obtained either taking into account or not the individual candidate mass measurement uncertainties,

Table 1: The number of candidates observed, compared to background and signal rates for each final state for  $100 < m_{4\ell} < 600$  GeV for the baseline selection. For the Z+X background, the estimations are based on data

Channel	4e	4 $\mu$	2e2 $\mu$
ZZ background	$12.27 \pm 1.16$	$19.11 \pm 1.75$	$30.25 \pm 2.78$
Z+X	$1.67 \pm 0.55$	$1.13 \pm 0.55$	$2.71 \pm 0.96$
All background	$13.94 \pm 1.28$	$20.24 \pm 1.83$	$32.96 \pm 2.94$
$m_H = 120$ GeV	0.25	0.62	0.68
$m_H = 140$ GeV	1.32	2.48	3.37
$m_H = 350$ GeV	1.95	2.61	4.64
Observed	12	23	37

for the combination of the three channels. Excesses are observed for masses near 119 GeV and 320 GeV. The small  $\approx 2\sigma$  excess near 320 GeV includes three events with  $p_T^{4\ell} > 50$  GeV. The most significant excess near 119 GeV corresponds to about  $2.5\sigma$  significance. The significance is less than  $1.0\sigma$  (about  $1.6\sigma$ ) when the look-elsewhere effect [62] is accounted for over the full mass range (for the low-mass range  $100 < m_{4\ell} < 160$  GeV). The local significances change only slightly when including candidate mass uncertainties, instead of using the average mass resolution, e.g. rising to  $2.7\sigma$  around 119 GeV and reaching  $1.5\sigma$  around 126 GeV.

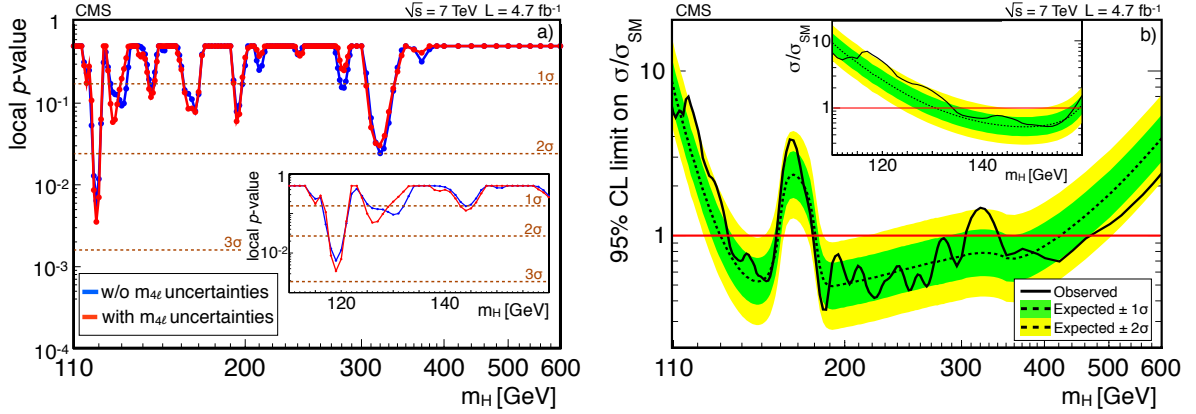


Figure 2: a) The significance of the local excesses with respect to the standard model expectation as a function of the Higgs boson mass, without (blue) or with (red) individual candidate mass measurement uncertainties. b) The observed and the median expected upper limits at 95% CL on  $\sigma(\text{pp} \rightarrow \text{H} + \text{X}) \times \mathcal{B}(\text{ZZ} \rightarrow 4\ell)$ , normalized to the standard model cross section values  $\sigma_{\text{SM}}$ , for a Higgs boson in the mass range 110–600 GeV, using the  $\text{CL}_s$  approach. The insets expand the low mass range.

In absence of a significant clustering of candidates at any given mass, we derive exclusion limits. The exclusion limits for a SM-like Higgs boson are computed for a large number of mass points in the mass range 110–600 GeV, using the predicted signal and background mass distribution shapes. The choice of the step size in the scan between Higgs mass hypotheses is driven by either detector resolution, or the natural width of the Higgs boson. The signal mass distributions shapes are determined using simulated samples for 27 values of  $m_{\text{H}}$  covering the full mass range. The shapes are fit using a function obtained from a convolution of a Breit-Wigner probability density function to describe the theoretical resonance line shape and a Crystal Ball function to account for the detector effects. The parameters of the Crystal Ball function are interpolated for the  $m_{\text{H}}$  points where there is no simulated sample available. The shapes of the background mass distributions are determined by fits to the simulated sample of events, while the normalization is taken from estimates of overall event yields as described above. For each mass hypothesis, we perform an unbinned likelihood fit using the statistical approach discussed in Ref. [63]. We account for systematic uncertainties in the form of nuisance parameters with a log-normal probability density function. The observed and median expected upper limits on  $\sigma(\text{pp} \rightarrow \text{H} + \text{X}) \times \mathcal{B}(\text{H} \rightarrow \text{ZZ}) \times \mathcal{B}(\text{ZZ} \rightarrow 4\ell)$  at 95% CL are shown in Fig. 2b. The limits are calculated relative to the expected SM Higgs boson cross section values  $\sigma_{\text{SM}}$ , using the modified frequentist method  $\text{CL}_s$  [64, 65]. The bands represent the  $1\sigma$  and  $2\sigma$  probability intervals around the expected limit. These upper limits exclude the standard model Higgs boson at 95% CL in the  $m_{\text{H}}$  ranges 134–158 GeV, 180–305 GeV and 340–465 GeV. The limits reflect the dependence of the branching ratio  $\mathcal{B}(\text{H} \rightarrow \text{ZZ})$  on  $m_{\text{H}}$ . The worsening of the limits at high mass arises from the decreasing cross section for the  $\text{H} \rightarrow 4\ell$  signal. By virtue of the



excellent mass resolution and low background, the structure in the measured limits follows the fluctuations of the number of observed events.

In summary, a search for the standard model Higgs boson has been presented in the four-lepton decay modes. Upper limits at 95% confidence level exclude the Higgs boson mass ranges 134–158 GeV, 180–305 GeV, and 340–465 GeV. A major fraction of the explored mass range is thus excluded at 95% CL and the exclusion limits extend beyond the sensitivity of previous collider experiments. Excesses of events are observed at the low end of the explored mass range, around masses of 119 and 126 GeV, and at high mass around 320 GeV. These excesses, although not statistically significant, make the observed limits weaker than expected in the absence of a signal. At low mass, only the region  $114.4 < m_H < 134$  GeV remains consistent with the expectation for the standard model Higgs boson production.

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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- 16: Also at Eötvös Loránd University, Budapest, Hungary
- 17: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 18: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 19: Also at University of Visva-Bharati, Santiniketan, India
- 20: Also at Sharif University of Technology, Tehran, Iran
- 21: Also at Isfahan University of Technology, Isfahan, Iran
- 22: Also at Shiraz University, Shiraz, Iran
- 23: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
- 24: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
- 25: Also at Università della Basilicata, Potenza, Italy
- 26: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 27: Also at Università degli studi di Siena, Siena, Italy
- 28: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 29: Also at University of Florida, Gainesville, USA
- 30: Also at University of California, Los Angeles, Los Angeles, USA
- 31: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 32: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 33: Also at University of Athens, Athens, Greece
- 34: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 35: Also at The University of Kansas, Lawrence, USA
- 36: Also at Paul Scherrer Institut, Villigen, Switzerland
- 37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 38: Also at Gaziosmanpasa University, Tokat, Turkey

- 39: Also at Adiyaman University, Adiyaman, Turkey
- 40: Also at The University of Iowa, Iowa City, USA
- 41: Also at Mersin University, Mersin, Turkey
- 42: Also at Kafkas University, Kars, Turkey
- 43: Also at Suleyman Demirel University, Isparta, Turkey
- 44: Also at Ege University, Izmir, Turkey
- 45: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 46: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 47: Also at Utah Valley University, Orem, USA
- 48: Also at Institute for Nuclear Research, Moscow, Russia
- 49: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 50: Also at Los Alamos National Laboratory, Los Alamos, USA
- 51: Also at Argonne National Laboratory, Argonne, USA
- 52: Also at Erzincan University, Erzincan, Turkey
- 53: Also at Kyungpook National University, Daegu, Korea