Search for a Standard Model Higgs Boson in the Decay Channel $H \rightarrow ZZ^{(*)} \rightarrow 4l$

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 presented using $4.71 \pm 0.21$ fb$^{-1}$ of integrated luminosity recorded by the CMS detector in pp collisions from the LHC at $\sqrt{s} = 7$ TeV. The search covers Higgs boson mass hypotheses of $110 < m_H < 600$ GeV/$c^2$. Seventy-two events are observed with $4\ell$ invariant mass $m_{4\ell} > 100$ GeV/$c^2$ (with thirteen below 160 GeV/$c^2$), while $67.1 \pm 6.0$ (9.5 $\pm$ 1.3) events are expected from standard model background processes. Their $4\ell$ mass distribution is consistent with the expectation of standard model continuum production of $ZZ^{(*)}$ pairs, with no significant excess at any mass in the range under study. Upper limits at 95% CL on the product of the cross section and branching ratio exclude the standard model Higgs boson in the ranges $134 < m_H < 158$ GeV/$c^2$, $180 < m_H < 305$ GeV/$c^2$ and $340 < m_H < 465$ GeV/$c^2$. 

The CMS Collaboration
The standard model (SM) of electroweak interactions [1–4] predicts the existence of a scalar particle, the Higgs boson, associated with spontaneous electroweak symmetry breaking [5–10]. The mass, \( m_{\text{H}} \), of the Higgs boson is a free parameter of the theory. Direct searches for the SM Higgs boson at the LEP \( e^+e^- \) collider have led to a lower mass bound of \( m_{\text{H}} > 114.4 \text{ GeV}/c^2 \) (95% CL) [11]. Direct searches at the Tevatron exclude the mass range 158 < \( m_{\text{H}} < 173 \text{ GeV}/c^2 \) [12].

Indirect constraints from precision measurements alone favour the mass range \( m_{\text{H}} < 158 \text{ GeV}/c^2 \) [13]. In the absence of new physics, the requirement of perturbative unitarity of the theory sets an upper bound on \( m_{\text{H}} \) of \( \approx 1 \text{ TeV}/c^2 \). The production of SM Higgs bosons followed by the decay \( H \rightarrow ZZ^{(*)} \) is expected to be the main discovery channel at the CERN LHC pp collider for a wide range of \( m_{\text{H}} \) values.

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 range 110 < \( m_{\text{H}} < 600 \text{ GeV}/c^2 \), using data collected by the CMS experiment during 2010 and 2011 at the LHC collider at \( \sqrt{s} = 7 \text{ TeV} \), corresponding to an integrated luminosity of \( 4.71 \pm 0.21 \text{ fb}^{-1} \). The search relies solely on the measurement of leptons, and the analysis achieves high lepton reconstruction, identification and isolation efficiencies for a \( 4\ell \) system composed of two pairs of same flavour and opposite charge isolated leptons, \( e^+e^- \) or \( \mu^+\mu^- \), in the measurement range \( m_{4\ell} > 100 \text{ GeV}/c^2 \). The background sources comprise an irreducible \( 4\ell \) contribution from \( ZZ^{(*)} \) continuum production. Reducible background 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, and instrumental backgrounds from Z+jets or multiple jet events where jets are misidentified as leptons.

Particles produced in the pp collisions are detected in the pseudorapidity range \( |\eta| < 3 \), 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). The steel return yoke outside the solenoid is instrumented with gas detectors used to identify muons in the range \( |\eta| < 2.4 \). A detailed description of the detector is given in Ref. [14].

Monte Carlo (MC) samples for the SM Higgs boson signal and for background processes are used to optimize the event selection and for the evaluation of acceptance corrections and systematic uncertainties. All events are processed through a detailed simulation of the CMS detector based on GEANT4 [15] and fully reconstructed. The MC Higgs signals from \( gg \rightarrow H \), \( q\bar{q} \rightarrow q\bar{q}H \) are generated with POWHEG [16] at next-to-leading-order (NLO) and the dedicated generator from Ref. [17]. Additional samples of \( WH, ZH \) and \( t\bar{t}H \) events are generated with PYTHIA [18]. The Higgs boson is forced to decay to two Z-bosons, that can be on or off-shell and are forced to decay via \( Z \rightarrow 2\ell \). 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-NLO (NNLO) and next-next-to-leading-log taken from Ref. [19–28] and from the weak-boson fusion contribution computed at NNLO in Ref. [21, 29–33]. The total cross section is scaled by the branching ratio \( B(H \rightarrow 4\ell) \) [21, 34–37]. Interference effects in the \( 4e \) and \( 4\mu \) channels are taken from Prophecy4f [21, 34, 35]. The SM continuum contribution from \( ZZ^{(*)} \) production via \( q\bar{q} \) is generated at NLO with POWHEG, while other di-boson processes (WW, WZ, Z\gamma) are generated with PYTHIA and MADGRAPH [38]. The \( gg \rightarrow ZZ \) contribution is generated with \( gg2ZZ \) [39]. The Z+jets samples, namely \( Zb\bar{b} \), Zc\bar{c} and Z+light jets, are generated with MadGraph. The \( t\bar{t} \) events are generated at NLO with POWHEG.
Collision events are selected by the trigger system that requires the presence of a pair of electrons with transverse energies \( E_{T,1}^e > 17 \) and \( E_{T,2}^e > 8 \) GeV, or a pair of muons with transverse momenta \( p_{T,1}^\mu > 17 \) and \( p_{T,2}^\mu > 8 \) GeV/c. The trigger is found fully efficient for signal in the 4e, 4\( \mu \) and 2e2\( \mu \) channels within the acceptance of this analysis.

Leptons are reconstructed within the geometrical acceptance of \( |\eta^\ell| < 2.5 \) and with \( p_T^\ell > 7 \) GeV/c for electrons and \( |\eta^\ell| < 2.4 \) and \( p_T^\mu > 5 \) GeV/c for muons. The reconstruction of electrons combines information from the ECAL and inner tracker [40, 41]. Muons are reconstructed through a fit performed on hits collected in both the inner tracker and the outer muon spectrometer [42]. Electron identification selection requirements rely on electromagnetic shower shape observables and on observables combining tracker and calorimetry information. The selection criteria depend on \( p_T^\ell \) and \( |\eta^\ell| \), and on a categorization according to observables sensitive to the amount of bremsstrahlung emitted along the trajectory in the inner tracker. For muons the inner track is required to have more than 10 hits to ensure a good measurement of the momentum. The efficiencies are measured in data, using a standard “tag-and-probe” technique based on an inclusive sample of single-Z events. The measurements have been performed in several ranges in \( |\eta| \). The product of reconstruction and identification efficiencies is \( \sim 98\% \) for muons. Efficiencies for electrons in the ECAL barrel [end caps] vary from about 68\% [62\%] for \( 7 < p_T^e < 10 \) GeV/c to 82\% [74\%] at \( p_T^e \approx 10 \) GeV/c, and reach 90\% [89\%] for \( p_T^e \approx 20 \) GeV/c. They drop to about 85\% for electrons in the transition region of \( 1.44 < |\eta| < 1.57 \) between the ECAL barrel and end caps. Lepton candidates are defined with a loose constraint on their isolation, by requiring the sum of the transverse momenta of tracks within a cone of \( \Delta \eta = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3 \) around the lepton \( \ell \) 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 isolation is found to be greater than 99\%. In a first selection step, we require a first Z candidate formed with an \( e^+e^- \) or \( \mu^+\mu^- \) pair of lepton candidates satisfying \( 50 < m_{1,2} < 120 \) GeV/c\(^2\), \( p_{T,1} > 20 \) GeV/c and \( p_{T,2} > 10 \) GeV/c. This provides the \( Z + X \) datasets from which samples are defined to estimate reducible and instrumental backgrounds and the \( ZZ^{(*)} \) rates, thereby ensuring 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 \( R_{\text{iso,1}} + R_{\text{iso,2}} < 0.35 \), where for each lepton, \( R_{\text{iso}} = (1/p_T^\ell) \times (\sum_i p_{T,\text{track}}^i + \sum_j E_{T,\text{ECAL}}^j + \sum_k E_{T,\text{HCAL}}^k) / \sum_i p_{T,\text{track}}^i \), 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 \( \Delta \rho < 0.3 \), 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 \( > 99\% \) everywhere for muons and between 94\% to 99\% for electrons. The isolation is made largely insensitive to event pile-up by correcting for the average energy flow measured in random isolation cones. The ratio of the efficiencies measured with data and with simulated \( Z \to \ell\ell \) events is found to be consistent with unity. The significance of the signed impact parameter of each lepton relative to the event vertex, \( \text{SIP}_{3D} \), is required to satisfy \( |\text{SIP}_{3D} = |p_{\ell,\text{IP}}| \) < 4, where IP is the impact parameter in three dimensions and \( v_{\ell,\text{IP}} \) the associated uncertainty. The pair with reconstructed mass closest to the nominal Z boson mass is retained and denoted \( Z_1 \).

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 (Z\( b\bar{b} \), \( t\bar{t} \)) and instrumental (Z+light jets) backgrounds. We select a second lepton pair, denoted \( Z_2 \), from the remaining same flavour \( \ell^+\ell^- \) combinations, by requiring \( m_{Z_2} > 12 \) GeV/c\(^2\), with the restriction \( m_4 \ell > 100 \) GeV/c\(^2\). For
the 4e and 4μ final states, at least three of the four combinations of opposite sign pairs must satisfy \(m_{\ell\ell} > 12 \text{ GeV}/c^2\). If more than one \(Z_2\) combination satisfies all the criteria, the ambiguity is resolved by choosing the leptons of highest \(p_T\). The isolation and the impact parameter are then 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 \(|\text{SIP3D}| < 4\) for each of the four leptons.

Finally, to define the kinematic phase space for the Higgs boson search, we require that the \(Z_1\) and \(Z_2\) masses satisfy \(m_{Z_1}^{\text{min}} < m_{Z_1} < 120 \text{ GeV}/c^2\) and \(m_{Z_2}^{\text{min}} < m_{Z_2} < 120 \text{ GeV}/c^2\), with \((m_{Z_1}^{\text{min}}, m_{Z_2}^{\text{min}}) = (50,12)\) defining the baseline selection and \((m_{Z_1}^{\text{min}}, m_{Z_2}^{\text{min}}) = (60,60)\) defining the high-mass selection. The baseline selection is used for all \(m_H\) hypotheses. The high-mass selection is used to measure the ZZ cross section.

The event yields are found to be in good agreement with SM MC expectation at each step of event selection. The overall signal detection efficiency is evaluated from MC and increases from \(
\approx 49\% [78\%, 61\%] \) at \(m_H = 190 \text{ GeV}/c^2\) to \(
\approx 59\% [82\%, 71\%] \) at \(m_H = 400 \text{ GeV}/c^2\) for the 4e [4μ, 2e2μ] channels. The mass resolution from a fit to MC samples for \(m_H\) of 150 \text{ GeV}/c^2 in the 4e [4μ, 2e2μ] is 2.7 [1.6, 2.1] ± 0.1 \text{ GeV}/c^2. Just above the 2 \times m_Z threshold, for \(m_H = 190 \text{ GeV}/c^2\), the resolution for 4e [4μ, 2e2μ] is 3.5 [2.5, 2.8] ± 0.1 \text{ GeV}/c^2.

The small number of events observed precludes a direct evaluation of background by extrapolating from mass sidebands to some given final states, at least three of the four combinations of opposite sign pairs must have like charge (to avoid signal contamination) and matching flavour and \(m_\ell\) masses satisfy \(m_{\ell\ell}^{\text{min}} < m_{\ell\ell} < 120 \text{ GeV}/c^2\) and \(m_{\ell\ell}^{\text{min}} < m_{\ell\ell} < 120 \text{ GeV}/c^2\), with \((m_{\ell\ell}^{\text{min}}, m_{\ell\ell}^{\text{min}}) = (50,12)\) defining the baseline selection and \((m_{\ell\ell}^{\text{min}}, m_{\ell\ell}^{\text{min}}) = (60,60)\) defining the high-mass selection. The baseline selection is used for all \(m_H\) hypotheses. The high-mass selection is used to measure the ZZ cross section.

The number of events and uncertainties from \(ZZ^*\) channels is obtained from MC, and cross-checked through an evaluation based on a normalization to inclusive single-Z production, a procedure discussed in Refs [43–45]. The measured rate of single Z bosons is used to predict the total ZZ rate defined in this analysis, making use of the ratio of the theoretical cross sections for ZZ and Z production, and of the ratio of the reconstruction and selection efficiencies for the 4 \(\ell\) and 2 \(\ell\) final states. The cross section for ZZ(*) production at NLO through \(q\bar{q}\) annihilation and gg fusion are calculated with MC@NLO [46–48]. The theoretical uncertainties are computed as a function of \(m_4\), varying both the QCD renormalization and factorization scales \((m_Z, m_2; 2, m_2)\) and the parton distribution functions (PDF) set following the PDF4LHC recommendations [49–53]. The combined scale-dependent QCD and PDF uncertainties for each final state are on average 7.7%. The number of events and uncertainties from ZZ(*) \(\rightarrow 4\ell\) for the baseline selection are given in Table 1.

To estimate the reducible (Zb\(\bar{b}\), t\(\bar{t}\)) and instrumental (Z+light jets) backgrounds, a broad phase space region is chosen, well separated from the signal region, by relaxing 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 back 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 criteria on isolation and identification for two additional leptons \(\ell\ell\). The additional pair of leptons must have like charge (to avoid signal contamination) and matching flavour \((e^\pm e^\pm, \mu^\pm \mu^\pm)\) and a reconstructed invariant mass \(m_{\ell\ell}\) either satisfying the baseline selection or the high-mass selection, and \(m_4 > 100 \text{ GeV}/c^2\). From this set of events the expected number of Z+X background events in the signal region is obtained taking into account the lepton misidentification probability, measured from a sample of \(Z_1 + 1\) lepton with no identification or isolation requirements on the third lepton. The contamination from WZ in this set of events is suppressed by requiring that the imbalance on the measured energy deposition in the transverse plane is below 25 GeV. Normalized to the integrated luminosity, the number of background events expected in the signal region and the associated systematic uncertainties are given in Table 1 for the baseline selection in the range 100 < \(m_4\) < 600 GeV/c^2. The 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 can therefore be neglected. This was verified by performing a measurement of Zb\bar{b} and t\bar{t} in a dedicated four-lepton background control region, defined by requiring a Z_1 and two additional leptons satisfying inverted SIP_{3D} requirements, namely |SIP_{3D}| > 5, and with relaxed isolation, charge and flavour requirements. This ensures a negligible Z+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 for the Z_1 peak from Zb\bar{b} and Chebychev polynomials for the uniform t\bar{t} spectrum. The extrapolation to the signal region relies on knowledge and distinct features of the SIP_{3D} distributions for the Z_2 leptons of the t\bar{t} and Zb\bar{b} backgrounds. The result is found to be compatible with 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%), isolation efficiencies (2%), energy-momentum calibration (0.5%), and energy resolution (30%). Additional systematic uncertainties on exclusion limits arise from limited statistics in the reducible background regions that are propagated to the signal region. 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%) enters for the evaluation of the ZZ^{(*)} continuum 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 ratio (2%) are taken from Ref. [21]. The uncertainty in the lepton energy scale and resolution is accounted for by its effect on the expected signal and background reconstructed mass distributions.

Recent studies [21, 54, 55] show that current Monte Carlo simulations do not describe the correct Higgs boson mass line shape above \approx 300 GeV/c^2. These effects are estimated to amount to an additional uncertainty on the theoretical cross section of 10–30% for m_H of 400 – 600 GeV/c^2 included in the calculations of the limits.

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 SM backgrounds. The low mass range is shown in Fig. 1b together with the mass of each candidate and its uncertainty. 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 number of events observed, as well as the background rates in the signal region are reported in Table 1 for the baseline selection.

The measured distribution is seen to be compatible with the expectation from SM continuum production of ZZ^{(*)} pairs. We observe 72 event candidates, 12 in 4e, 23 in 4\mu and 37 in 2e2\mu final states, while 67.1 ± 6.0 events are expected from standard model background processes. Thirteen of the candidates are observed within 100 < m_{4\ell} < 160 GeV/c^2 while 9.5 ± 1.3 background events are expected. We observe 52 candidates for the high-mass selection compared to an expectation of 51.3 ± 4.6 events from SM background. The significance of the local excesses relative to the standard model expectation as a function of m_H is shown in Fig. 2a, obtained both without or with individual candidate mass measurement uncertainties, for the combination of the three channels. An inset expands the low mass range. Excesses are observed for masses near 120 GeV/c^2 and 320 GeV/c^2. The small \approx 2\sigma excess near 320 GeV/c^2 includes three events with p_T^{4\ell} > 50 GeV/c. The most significant excess near 120 GeV/c^2 corresponds to about 2.5\sigma
also shown are the central values and individual candidate mass measurement uncertainties.

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 99% 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 results correspond to an integrated luminosity of 4.71 fb$^{-1}$.

[2.7$\sigma$] significance not including [including] candidate mass uncertainties. The significance is less than 1.0$\sigma$ [about 1.6$\sigma$] when the look-elsewhere effect is accounted for over the full mass range [for the range $100 < m_{4l} < 160$ GeV/c$^2$]. Hence, the data do not reveal a significant clustering of events at any given mass.

The high-mass event selection is used to provide a measurement of the total cross section $\sigma(pp \rightarrow ZZ + X) \times B(ZZ \rightarrow 4\ell) = 28.1^{+4.6}_{-4.2}$ (stat.) $\pm 1.2$ (syst.) $\pm 1.3$ (lumi.) fb. The measurement agrees within one standard deviation with the SM prediction [46] of $27.9 \pm 1.9$ fb.

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/c$^2$, using the predicted signal and background shapes. The choice of the spacing between Higgs mass hypotheses is driven by either detector resolution, or the natural width of the resonance, depending on which dominates. The signal shape is determined using simulated samples for 17 values of $m_{H}$ covering the full mass range. The shapes for each simulated sample 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 $m_{H}$ points where there is no simulated sample available. The mass shapes for the backgrounds are determined by fits to the simulated sample of events, while the normalization is taken from estimates of overall event yields as described above. As a cross check of the mass shape method, it is verified that consistent exclusion limits are obtained with a cut-and-count method integrating the signal and background yields in $m_{H}$ dependent mass windows.
Table 1: Number of candidates observed, compared to background and signal rates for each final state for $100 < m_H < 600 \text{ GeV}/c^2$ for the baseline selection. For the $Z+X$ background, data driven estimations are used.

<table>
<thead>
<tr>
<th>Baseline</th>
<th>$4e$</th>
<th>$4\mu$</th>
<th>$2e2\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>$12.27 \pm 1.16$</td>
<td>$19.11 \pm 1.75$</td>
<td>$30.25 \pm 2.78$</td>
</tr>
<tr>
<td>Z+X</td>
<td>$1.67 \pm 0.55$</td>
<td>$1.13 \pm 0.55$</td>
<td>$2.71 \pm 0.96$</td>
</tr>
<tr>
<td>All background</td>
<td>$13.94 \pm 1.28$</td>
<td>$20.24 \pm 1.83$</td>
<td>$32.96 \pm 2.94$</td>
</tr>
</tbody>
</table>

Observed $m_H = 120 \text{ GeV}/c^2$ | 0.25  | 0.62  | 0.68  |
Observed $m_H = 140 \text{ GeV}/c^2$ | 1.32  | 2.48  | 3.37  |
Observed $m_H = 350 \text{ GeV}/c^2$ | 1.95  | 2.61  | 4.64  |

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 mean expected and observed upper limits at 95% CL on $\sigma(pp \rightarrow H + X) \times B(ZZ \rightarrow 4\ell)$ for a Higgs boson in the mass range 110-600 GeV/$c^2$, using the CLs approach. The insets expand the low mass range. The results correspond to an integrated luminosity of 4.71 fb$^{-1}$.

The observed and mean expected upper limits on $\sigma(pp \rightarrow H + X) \times B(H \rightarrow ZZ) \times B(ZZ \rightarrow 4\ell)$ at 95% CL from an analysis based on the shape of the mass distributions are shown in Fig. 2b. An inset expands the low mass range. The limits are calculated relative to the expected SM values, using a CLs approach. The bands represent the 1$\sigma$ and 2$\sigma$ probability intervals around the expected limit. We account for systematic uncertainties in the form of nuisance parameters with a log-normal probability density function. The upper limits exclude the standard model Higgs boson at 95% CL in the ranges $134 < m_H < 158 \text{ GeV}/c^2$, $180 < m_H < 305 \text{ GeV}/c^2$ and $340 < m_H < 465 \text{ GeV}/c^2$. The exclusion limits extend beyond the sensitivity of previous collider experiments. The expected limits reflect the dependence of the branching ratio $B(H \rightarrow ZZ)$ on $m_H$. The worsening of the limits at high mass arises from the decreasing cross section for the $H \rightarrow 4\ell$ 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 Higgs boson has been presented in the four-lepton decay modes. A major fraction of the mass range $110 < m_H < 600 \text{ GeV}/c^2$ is excluded at 95% CL. At low
mass, only the region $114.4 < m_H < 134 \text{ GeV/c}^2$ remains possibly consistent with expectations of the standard model.

References


[12] CDF and D0 Collaboration, “Combined CDF and D0 Upper Limits on Standard Model Higgs Boson Production with up to 8.2 fb$^{-1}$ of Data”, arXiv:1103.3233.


