Search for a Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4l$

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Abstract

A search for a Higgs boson in the decay channel $H \rightarrow ZZ^{(*)}$ with each $Z$ boson decaying to an electron or muon pair is presented using pp collisions from the LHC at $\sqrt{s} = 7$ TeV. The data analyzed correspond to an integrated luminosity of $1.66 \pm 0.07$ fb$^{-1}$ recorded by the CMS detector in 2010 and 2011. The search covers Higgs boson mass ($m_H$) hypotheses of $110 < m_H < 600$ GeV/$c^2$ with an expected sensitivity varying between one and five times the standard model cross section at 95% CL over most of the mass range. Twenty one events are observed, while $21.2 \pm 0.8$ events are expected from standard model background processes. Six of the events are below the kinematic threshold of two on-shell $Z$'s ($m_H < 180$ GeV/$c^2$), while $2.8 \pm 0.2$ background events are expected. The events are not clustered in mass excluding interpretation as the standard model Higgs boson. The distribution of events is consistent with the expectation of standard model continuum production of $ZZ^{(*)}$ pairs and the production cross section for $60 < m_Z < 120$GeV/$c^2$ is measured to be in agreement with the predicted value. Upper limits at 95% CL on the cross section $\times$ branching ratio for a Higgs boson with standard model-like decays exclude cross sections from about one to two times the expected standard model cross section for masses in the range $150 < m_H < 420$ GeV/$c^2$. Reinterpreted in the context of the standard model with four fermion families a Higgs boson with a mass in the range 120-520 GeV/$c^2$ is excluded at 95% CL.
# Introduction

The standard model (SM) of electroweak interactions [1–4] predicts the existence of a scalar boson, the Higgs boson, associated to the spontaneous electroweak symmetry breaking [5–10]. The mass $m_H$ of this scalar boson is a free parameter of the theory. The inclusive production of SM Higgs bosons followed by the decay $H \to ZZ^{(*)}$ is expected to be a main discovery channel at the CERN LHC pp collider for a wide range of $m_H$ values.

The direct searches for the SM Higgs boson at the LEP $e^+e^-$ collider have lead to a lower mass bound of $m_H > 114.4$ GeV/$c^2$ (95% CL) [11]. The direct searches by the D0 and CDF experiments at the Tevatron exclude the mass range $158 < m_H < 173$ GeV/$c^2$ (95% CL) [12]. Indirect constraints from precision measurements, which are sensitive to the existence of a Higgs boson through virtual loops, favour the mass range $m_H < 185$ GeV/$c^2$ (95% CL) [13].

In the absence of new physics beyond the SM, the requirement of perturbative unitarity of the theory sets an upper bound on $m_H$ in a range from about 500 to 800 GeV/$c^2$ [14–16]. The mass range $m_H \gg 2 \times m_Z$ remains largely unexplored. Some theories beyond the SM can naturally accommodate, with a minimal extension of the scalar sector, a Higgs boson with SM-like couplings in this high mass range [17].

A search for a SM Higgs boson in the four-lepton decay channel, $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$ with $\ell, \ell' = e$ or $\mu$, in short $H \to 4\ell$, is presented in this paper. The analysis is designed for a hypothetical Higgs boson mass in the range $110 < m_H < 600$ GeV/$c^2$ and uses data collected by the CMS experiment during 2010 and 2011 at the LHC collider, with pp collisions at $\sqrt{s} = 7$ TeV. The same analysis was previously used in Ref. [18] and the results are updated here for an integrated luminosity of $L = 1.66 \pm 0.07$ fb$^{-1}$.

The sample of events with four reconstructed leptons contains an irreducible contribution from $ZZ^{(*)}$ production via $q\bar{q}$ and $gg$ fusion processes. Potential reducible background contributions are from $Zb\bar{b}$ and $H \to W^+bW^-\bar{b}$, with the W undergoing a leptonic decay, where the final states contain two isolated leptons and two $b$ jets giving rise to secondary leptons or misidentified leptons. Reconstructed $4\ell$ events can also arise from instrumental background such as $Z$+jets or $WZ$ + jet(s) or from the production of multiple jets in QCD hard interactions, where jets are misidentified as leptons.

The search for a Higgs boson $4\ell$ signal presented in this paper relies solely on the measurements of leptons. The analysis achieves high lepton reconstruction, identification and isolation efficiencies for a $ZZ^{(*)}$ system, composed of two pairs of same flavour and opposite sign leptons, $ee$ or $\mu\mu$, in the measurement range $m_{4\ell} > 100$ GeV/$c^2$. Additional selection requirements are made that are specifically tailored to suppress contributions from the reducible and instrumental backgrounds, with a minimal reduction in the $ZZ^{(*)}$ efficiencies.

## 2 Detector, Reconstruction and Datasets

A detailed description of the CMS detector and a description of the coordinate system adopted by CMS can be found elsewhere [19]. The detector comprises a superconducting solenoid providing a uniform magnetic field of 3.8 T. The bore of the solenoid is instrumented with various particle detection systems. The inner tracking system is composed of a pixel detector with three barrel layers at radii between 4.4 and 10.2 cm and a silicon strip tracker with 10 barrel detection layers extending outwards to a radius of 1.1 m. Each system is completed by two end caps, extending the acceptance up to $|\eta| < 2.5$. The pseudorapidity $\eta$ is defined as
with a minimum transverse momentum $p_T$ above $\mathcal{O}(10)$ GeV/c, is required for the sample corresponding to the early data taking with instantaneous luminosities in the range $10^{25} - 10^{31}$ cm$^{-2}$s$^{-1}$. The presence of a pair of electrons with $E_{T,1} > 17$ and $E_{T,2} > 8$ GeV, or a pair of muons with $p_{T,1} > 13$ and $p_{T,2} > 8$ GeV/c, is required for a major fraction of the data sample, collected with instantaneous luminosities up to $\sim 2.2 \times 10^{33}$ cm$^{-2}$s$^{-1}$. The trigger is fully efficient for the $4e, 4\mu$ and $2e2\mu$ channels.

The trigger used in this analysis has evolved in response to the rapidly increasing instantaneous luminosity. The presence of at least one charged lepton, either an electron or a muon, with a minimum transverse momentum $p_T$ above $\mathcal{O}(10)$ GeV/c, is required for the sample corresponding to the early data taking with instantaneous luminosities in the range $10^{25} - 10^{31}$ cm$^{-2}$s$^{-1}$. The presence of a pair of electrons with $E_{T,1} > 17$ and $E_{T,2} > 8$ GeV, or a pair of muons with $p_{T,1} > 13$ and $p_{T,2} > 8$ GeV/c, is required for a major fraction of the data sample, collected with instantaneous luminosities up to $\sim 2.2 \times 10^{33}$ cm$^{-2}$s$^{-1}$. The trigger is fully efficient for the $4e, 4\mu$ and $2e2\mu$ channels.

Monte Carlo (MC) data samples for the SM Higgs boson signal and a large variety of electroweak and QCD-induced SM background processes, including full simulation and reconstruction, have been used for the optimization of the event selection prior to the analysis. They are also used in this analysis for comparisons to the measurements, and the evaluation of acceptance corrections and systematic uncertainties. All production cross sections are re-weighted at least to next-to-leading-order (NLO), or beyond where possible. The general multi-purpose MC event generator PYTHIA [25] is used in conjunction with other event generators, for the showering, hadronization, decays and to add the underlying $pp$ event. The processes are processed with a detailed simulation of the CMS detector based on GEANT4 [26]. The Higgs boson samples are generated with POWHEG [27] which incorporates NLO gluon fusion ($gg \to H$) and weak-boson fusion $q\bar{q} \to q\bar{q}H$. The events are re-weighted according to the most recent calculations [28] of the total cross section $\sigma(pp \to H)$ which comprises the gluon fusion contribution from Refs. [29–37] and the weak-boson fusion contribution from Refs. [28, 38–42]. The total cross section is scaled by the branching ratio $B(H \to 4\ell)$ [28, 43–46]. Interference in the $4\ell$ or $4\mu$ channels is taken into account using the Prophecy4f [28, 43, 44] generator tool for precision calculations. Di-boson production ($WW, WZ, ZZ, Z\gamma$) is generated at leading order (LO) with PYTHIA. The $ZZ^{(*)}$ events are re-weighted with a $m_{4\ell}$-dependent K-factor to account for the contributions of NLO diagrams. Both $q\bar{q} \to ZZ^{(*)}$ and $gg \to ZZ^{(*)}$ contributions are evaluated.
with MCFM [47]. Interference effects involving the Higgs boson are neglected. An uncertainty of ±30% is attributed to the gluon-induced contribution. An inclusive Z+jets sample has been generated with MadGraph [48], considering all (five) quark flavours for the initial state parton density functions (PDFs), and gluons, light (d, u, s) and heavy (c, b) quarks for the jets in the final state. A K-factor is used to correct to the NLO cross section. Using a filter that selects events with two b jets or two c jets in the final state, the sample is partitioned in Z + light jets ("Z+jets") and Z + heavy flavour jets (Zb\bar{b}/Zc\bar{c}). A top pair production sample is generated at NLO with POWHEG.

### 3 Event Selection

The selection steps act on loosely isolated (see below) lepton candidates, i.e. electrons within the geometrical acceptance of $|\eta^e| < 2.5$ and with $p_T^e > 7$ GeV/c and muons satisfying $|\eta^\mu| < 2.4$ and $p_T^\mu > 5$ GeV/c. We impose the following sequence of requirements:

1. **First Z**: a pair of lepton candidates of opposite charge and matching flavour ($e^+e^-$, $\mu^+\mu^-$) satisfying $m_{1,2} > 60$ GeV/c$^2$, $p_{T,1} > 20$ GeV/c and $p_{T,2} > 10$ GeV/c; the pair with reconstructed mass closest to the nominal Z boson mass is retained and denoted $Z_1$.

2. **Three or more leptons**: at least another lepton candidate of any flavour or charge.

3. **Four or more leptons and a matching pair**: a fourth lepton candidate with the flavour of the third lepton candidate from the previous step, and with opposite charge.

4. **Choice of the “best 4\ell” and $Z_1, Z_2$ assignments**: retain a second lepton pair, denoted $Z_2$, among all the remaining $\ell^+\ell^-$ combinations with $m_{Z_2} > 12$ GeV/c$^2$ and such that the reconstructed four-lepton invariant mass satisfies $m_{4\ell} > 100$ GeV/c$^2$. For the 4e and 4\mu final states, at least three of the four combinations of opposite sign pairs must satisfy $m_{4\ell} > 12$ GeV/c$^2$. If more than one $Z_2$ combination satisfies all the criteria, the one built from leptons of highest $p_T$ is chosen.

5. **Relative isolation for selected leptons**: for any combination of two leptons $i$ and $j$, irrespective of flavour or charge, the sum of the combined relative isolation $R_{iso,i} + R_{iso,j} < 0.35$.

6. **Impact parameter for selected leptons**: the significance of the impact parameter to the event vertex, SIP$^{3D}$, is required to satisfy $|\text{SIP}_{3D} = \frac{\text{IP}}{\sigma_{IP}}| < 4$ for each lepton, where IP is the lepton impact parameter in three dimensions at the point of closest approach with respect to the primary interaction vertex, and $\sigma_{IP}$ the associated uncertainty.

7. **$Z$ and $Z^{(*)}$ kinematics**: with $60 < m_{Z_1} < 120$ GeV/c$^2$ and $m_{Z_2}^{min} < m_{Z_2} < 120$ GeV/c$^2$, where $m_{Z_2}^{min}$ is defined below.

The first step ensures that the leptons in the preselected events are on the high efficiency plateau for the trigger. Control samples for the Z+jet, Zbb/c\bar{c} and t\bar{t} backgrounds are obtained as subsets of the event sample that remain after the first step. The second step allows for control of the three-lepton event rates which include WZ di-boson production events. The first four steps are designed to reduce the contribution of the instrumental backgrounds from QCD multi-jets and Z + jets, whilst preserving the maximal signal efficiency and the phase space for the evaluation of background systematics. By reducing the number of jets misidentified as leptons, fewer combinatorial ambiguities arise when assigning the leptons to candidate Z bosons. The
The subsequent steps further suppress the reducible backgrounds from $Zb\bar{b}/c\bar{c}$, $t\bar{t}$, and the remaining $WZ + \text{jet(s)}$, and define the phase space for the Higgs boson signal. Requiring all selection criteria with $m_{\text{Z}}^{\text{min}} = 20 \text{ GeV/c}^2$ defines the baseline selection which is used in subsequent analysis, independent of the $m_H$ hypothesis. Requiring all selection criteria with $m_{\text{Z}}^{\text{min}} = 60 \text{ GeV/c}^2$ defines the high-mass selection which is used for the measurement of the $ZZ$ cross section and for the Higgs boson searches at high mass ($m_H > 2 \times m_Z$).

Additional electron identification requirements are imposed [21] which rely on electromagnetic shower shape observables and on observables combining tracker and calorimetry information. The electron identification observables used are: $|\Delta \eta_{\text{in}}| = |\eta_{\text{sc}} - \eta_{\text{extrap}}|$, where $\eta_{\text{sc}}$ is the energy weighted position in $\eta$ of the supercluster and $\eta_{\text{extrap}}$ is the $\eta$ coordinate of the position of closest approach to the supercluster position, extrapolating from the innermost track position and direction; $|\Delta \phi_{\text{in}}| = |\phi_{\text{sc}} - \phi_{\text{extrap}}|$, where $\Delta \phi_{\text{in}}$ is analogous to $\Delta \eta_{\text{in}}$ in azimuthal coordinates; $E_{\text{seed}}/p_{\text{in}}$, where $E_{\text{seed}}$ is the seed cluster energy and $p_{\text{in}}$ the track momentum at the innermost track position; $H/E$ is the ratio of energy deposited in the Hadronic Calorimeter directly behind the ECAL cluster ($H$) and the energy of the electron supercluster ($E$); $\sigma_{\text{mip}}$ is the width of the ECAL supercluster along the $\eta$ direction from an array of $5 \times 5$ crystal cells centered on the highest energy crystal of the related seed cluster. The cuts are dependent on the $p_T$ of the electron candidates to take into account the evolution with $p_T$ of the shape of the distributions for the discriminating variables. The cuts are also dependent on a categorization of the electron candidates according to observables that are sensitive to the amount of bremsstrahlung emitted along the trajectory in the inner tracker: the fraction of radiated energy ($f_{\text{brem}}$) as measured from the innermost and outermost momentum measurements along the electron track, and the ratio $E/p$ between the supercluster energy and the measured track momentum at the interaction vertex. Finally, different cuts are used for $\eta$ regions covered by the ECAL barrel and end caps, and for regions between them. In total, nine electron categories are thus defined. For muons the inner track is required to have at least 10 hits to ensure a good momentum measurement. No further identification requirements are imposed for the reconstructed muons. The lepton identification requirements are chosen to achieve high efficiency within acceptance, such that sufficient rejection power against jets is obtained in the context of the full event selection.

The efficiencies for reconstruction, identification and selection for electrons and muons is measured with data by using a “tag-and-probe” technique based on the sample of inclusive single $Z$ production events. This combines the requirements of a mass constraint from a pair of reconstructed candidates (e.g. tracks for muons, superclusters for electrons) with a tight lepton selection applied on one leg (the “tag”), to ensure sufficient purity. The other leg (the “probe”) is used to measure the efficiency of a given reconstruction algorithm or identification criterion. The efficiency is defined as the ratio of the number of probes satisfying the criterion to the total number of probes. The measurements have been performed in several ranges in $|\eta|$, matching domains with uniform detector and reconstruction performance for the tracker and calorimeters, and in $p_T$ ranges from 7 GeV/c to 100 GeV/c. Efficiencies rising from about 97% for $5 < p_T < 7$ GeV/c to 99% for $p_T > 7$ GeV/c are obtained for muons over the full acceptance. Efficiencies rising from about 95%/90% for at $p_T^e \simeq 10$ GeV/c to a plateau above 97%/95% for $p_T^e \simeq 20$ GeV/c are obtained for electrons in the ECAL barrel/end caps. This drops to about 85% for electrons in the transition region at $1.44 < |\eta| < 1.57$ between the ECAL barrel and end caps. The ratio of the tag-and-probe efficiencies measured with data and with a simulated sample of $Z \rightarrow \ell\ell$ events is found to be consistent with unity.
Figure 1: Comparison between data and MC at an early stage of the event selection where the four lepton combination is chosen, and the lepton pairs are assigned to the $Z_1$ and $Z_2$ bosons. The full selection requirements are applied to the leptons assigned to the $Z_1$. The plots show from left to right the reconstructed mass $m_{Z_1}$, the reconstructed mass $m_{Z_2}$ and the reconstructed four-lepton invariant mass for the (a) 4e, (b) 4$\mu$ and (c) 2e2$\mu$ channels. Points with statistical uncertainties represent the data. Shaded histograms represent the MC expectations. The samples correspond to an integrated luminosity of $L = 1.66 \text{ fb}^{-1}$.

To be considered as candidates for the selection steps up to the choice of the “best 4$\ell'$, the reconstructed leptons must also satisfy a very loose relative “track-only” isolation $R_{\text{track}} < 0.7$ where $R_{\text{track}} = (1/\mathbf{p}_T^i) \times A_{\text{track}}^{i}$ and $A_{\text{track}} = \sum \mathbf{p}_T^i$. The sum runs over the tracks $i$ within a cone of radius $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$ with axis along the lepton candidate direction, excluding a central inner “veto” region of width $\Delta \eta < 0.015$ (e) or $\Delta R < 0.015$ ($\mu$) which contains the lep-
ton candidate track footprint. The isolation cone apex is fixed at the position of the associated event vertex. The lepton isolation efficiency for identified leptons with this very loose $R_{\text{iso}}^{\text{track}}$ is found to be greater than 99% from tag-and-probe studies using the Z resonance, and to be insensitive to event pile-up for the LHC running conditions considered in this analysis. For the leptons chosen to form the 4$\ell$ system in event candidates, the combination of the tracker, ECAL and HCAL information is then used for isolation. The combined lepton $R_{\text{iso}}$ is calculated as $R_{\text{iso}} = (1/p_T^\ell) \times (A_{\text{iso}}^{\text{track}} + A_{\text{iso}}^{\text{ECAL}} + A_{\text{iso}}^{\text{HCAL}})$. The $A_{\text{iso}}^{\text{ECAL}}$ and $A_{\text{iso}}^{\text{HCAL}}$ are sums over the $E_T$ from energy deposits in cells of the ECAL and HCAL respectively, and with geometrical centroids situated within a cone of radius $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$. A central inner veto removes the ECAL (or HCAL) regions containing the footprint of the lepton [21, 22, 24]. The measurements are again performed for different $|\eta|$ ranges covering the geometrical acceptance and $p_T$ ranges up to 100 GeV/c. The combined isolation efficiencies measured for identified leptons with data using tag-and-probe is found to be above 99% everywhere for muons and between 94% and 99% for electrons. The ratio of the tag-and-probe efficiencies measured with data and with the MC sample is found to be everywhere consistent with unity within the uncertainties.

Figure 1 shows a comparison between data and MC after the choice of the “best 4$\ell$” and assignments of the lepton pairs to the $Z_1$ and $Z_2$ bosons, corresponding to step four of the selection, for the reconstructed mass $m_{Z_1}$, the reconstructed mass $m_{Z_2}$ and the reconstructed four-lepton invariant mass, for the 4$e$, 4$\mu$ and 2$e$2$\mu$ channels. In addition to step four requirements, the full selection requirements are applied to the leptons assigned to the $Z_1$. A slight excess of events is observed at this early step of the analysis in the 4$e$ and 4$\mu$ channels, which is visible at low $m_{Z_1}$. This excess is attributed to an underestimate of the instrumental background from the MC samples. A fair agreement with MC expectation is recovered after the application of isolation requirements on the other lepton pair as can be seen in Table 1 which shows the event yields as a function of the selection steps for the baseline selection in the 4$e$, 4$\mu$ and 2$e$2$\mu$ channels. The total number of signal-like events surviving the full baseline selection is very small for the current integrated luminosity. The remaining background according to the MC expectations is composed mostly of the $ZZ^{(*)}$ continuum, with some very small contamination from $Zb\bar{b}$/$Zc\bar{c}$ and WZ+jets, while the Z+jets is suppressed. A very small contamination of $Z\gamma$ ($t\bar{t}$) remains for the 4$e$ (4$\mu$) final states.

The overall signal detection efficiency for a 4$\ell$ system within the geometrical acceptance is evaluated from MC to be rising from about 42% / 72% / 54% at $m_H = 190$ GeV/c$^2$ to about 59% / 82% / 71% at $m_H = 400$ GeV/c$^2$ for the 4$e$ / 4$\mu$ / 2$e$2$\mu$ channels. A fit of the signal mass distribution as obtained from the MC shows a resolution for a Higgs boson mass hypothesis of 150 GeV/c$^2$ in the 4$e$ (4$\mu$, 2$e$2$\mu$) of 2.7(1.6, 2.1) ± 0.1 GeV/c$^2$. Just above the $2 \times m_Z$ threshold, for $m_H = 190$ GeV/c$^2$, the resolution for 4$e$ (4$\mu$, 2$e$2$\mu$) is 3.5(2.5, 2.8) ± 0.1 GeV/c$^2$.

4 Measurement and Control of the Background

The small number of events observed precludes a precise evaluation of the background using mass sidebands. We therefore rely on other methods that use data to estimate the backgrounds and the associated systematic uncertainties. The procedure consists of choosing a wide background control region outside the signal phase space which is populated by relaxing some selection criteria, and verifying that the event rates change according to the MC expectation. The control region for any given background must be chosen carefully since any of the other reducible or instrumental backgrounds might rapidly become dominant if the event selection is relaxed, thus making the extrapolation to the signal phase space difficult.
Table 1: Event yields in the (a) 4ℓ, (b) 4µ and (c) 2e2µ channel for the trigger and the seven event selection steps, (see text) with steps three and four regrouped as “Z⁺ + ℓ⁻ + ℓ⁻⋅” for the choice of the best four leptons and Z₁, Zₐ assignments, and with isolation requirements applied to the leptons assigned to the Z₁. The samples correspond to an integrated luminosity of L = 1.66 fb⁻¹.

(a) Cut QCD tt Zjets ZZ WZ ZZ mH = 200 GeV/c² Total Data
Trigger 1.55 x 10⁴ 2.18 x 10⁴ 4.82 x 10⁴ 2.97 x 10³ 2.64 x 10⁴ 221 49.8 10.2 9.2 5.21 1.48 7.7 x 10² 12
Z⁺ 3.46 74.8 1.05 x 10³ 804 123 51.2 13.9 3.2 1.2 4.85 1.31 5.31 x 10² 5
Isolation 0 0.96 0.29 0.29 0.13 0.89 0.37 0.027 0.61 4.48 1.21 4.77 x 10² 5
IP 0 0 0 0 0 0.29 0.009 4.48 1.21 4.19 x 10² 5
Kinematics 0 0 0 0 0 0 0 1.40 0.29 4.04 1.20 4.19 x 10² 5

(b) Cut QCD tt Zjets ZZ WZ ZZ mH = 200 GeV/c² Total Data
Trigger 4.46 x 10⁴ 4.01 x 10⁴ 5.38 x 10³ 2.51 x 10³ 2.91 x 10⁴ 224 56.4 11.7 15 8.5 4.6 1.89 17.3 x 10² 26
Z⁺ 2.04 x 10³ 1.86 x 10³ 5.04 x 10³ 2.34 x 10³ 6.66 x 10³ 209 49.4 10.8 10.8 7.6 2.2 1.77 8.22 x 10² 17
Isolation 0 0.96 1.02 5.33 0 0.072 7.65 1.89 17.3 x 10² 26
IP 0 0.027 0.44 0.44 0 0.036 7.25 1.77 8.22 x 10² 17
Kinematics 0 0.027 0 0 0 0 0 6.19 1.71 7.06 x 10² 10

(c) Cut QCD tt Zjets ZZ WZ ZZ mH = 200 GeV/c² Total Data
Trigger 2.28 x 10³ 1.75 x 10³ 4.01 x 10³ 4.75 x 10³ 5.58 x 10³ 465 95.0 19.1 100 15.0 5.4 1.97 11.74 x 10² 26
Z⁺ 1.29 x 10³ 3.38 x 10³ 9.46 x 10³ 4.40 x 10³ 5.01 x 10³ 394 84.3 17.6 16.3 7.6 2.2 1.77 8.22 x 10² 17
Isolation 0 5.30 0.88 7.26 0.29 0.13 0.12 0.89 5.31 x 10² 26
IP 0 0 0.15 1.33 0.14 0.072 11.9 2.95 13.1 x 10² 8
Kinematics 0 0 0 0.44 0 0.036 11.3 2.81 11.75 x 10² 8

The number of events N^{B\text{control}} in a given background B expected in the signal region in a four lepton mass range, m_{4\ell} bounded by m₁ and m₂, can be written as:

\[ N^{B\text{control}} [m₁, m₂] = N^{B\text{control}} \times \left( \frac{A^{B\text{signal}}}{A^{B\text{control}}} \right) \times \int_{m₁}^{m₂} \rho^B (m) dm \]  

(1)

where N^{B\text{control}} is the background rate in the control region, A^{B\text{signal}} and A^{B\text{control}} are the signal acceptance in the “signal”-like and “background”-like regions respectively, and \( \rho^B (m) \) is the event density as a function of mass for the background. Two different four-lepton mass ranges are considered: the full mass range \([m₁, m₂] = [100, 600]\) GeV/c², and the mass range \([m₁, m₂] = [f_{\text{min}} (m₁), f_{\text{max}} (m₁)]\). The latter defines the mass window for the cut-and-count method, the simplest of the methods used for the interpretation of the measurements. The functions f^{MC}_⁺ are chosen based on MC simulation of the Higgs boson signal to establish an optimal measurement window for a given central mass hypothesis m₁ (see section 6). It thus takes into account the mass migrations from generated to reconstructed quantities, the mass resolution and the intrinsic width from the resonance Breit-Wigner.

4.1 ZZ(\ast) Continuum

Two different methods have been used to determine N^{ZZ\text{signal}} for the ZZ\text{(*)} di-boson continuum, a normalization to the measured Z rate and an estimate from MC simulation. The former is our reference method for the present low integrated luminosities. A direct measurement from sidebands, e.g. excluding the signal region around a given Higgs boson mass hypothesis, is affected by large statistical uncertainties and will become useful only at higher integrated luminosities.
The method of normalization to the measured Z rate has been discussed in detail in Refs [49–51]. It relies on the measurement of inclusive single Z production which is used to predict the total ZZ rate within the acceptance defined by this analysis, making use of the ratio of the theoretical cross sections for Z and ZZ production, and of the ratio of the reconstruction and selection efficiencies for the 2ℓ and 4ℓ final states. The ZZ\((^{(*)})\) → 4ℓ control region is defined here by the observed single Z inclusive rate for Z → ℓℓ. The ratio of acceptance between the control and the signal region is then given by combining the theoretical cross sections and the selection efficiencies as obtained from MC simulation:

\[
R_{\text{theory}}^c \times R_{\text{MC}}^c = \frac{\sigma_{\text{NLO}}^{qg\rightarrow ZZ\rightarrow 4\ell} + \sigma_{\text{LO}}^{gg\rightarrow ZZ\rightarrow 4\ell}}{\sigma_{\text{NNLO}}^{pp\rightarrow Z\rightarrow 2\ell}} \times \frac{\epsilon_{\text{MC}}^{ZZ\rightarrow 4\ell}}{\epsilon_{\text{MC}}^{Z\rightarrow 2\ell}} .
\]

In this way we obtain the expected number of ZZ events in the full mass region, for either the baseline or the high-mass selection. To obtain the number of events in a given mass region around the hypothetical Higgs boson mass we use an integral of the probability density \(dN/dm_4\ell\) from MC simulation of \(pp \rightarrow ZZ(^{(*)})\) → 4ℓ.

The cross section for ZZ\((^{(*)})\) production at NLO through qq annihilation and gg fusion are calculated with MCFM, while the cross section for the Z at NNLO is calculated with FEWZ 2.0. For each Z boson, the di-lepton invariant mass is required to be greater than 12 GeV/c² to match the generator level cut applied in MC samples. The theoretical uncertainties on the ratio are computed varying for each 4ℓ and 2ℓ final states both the QCD renormalization and factorization scales \((m_Z, m_Z/2, 2m_Z)\) following the PDF4LHC recommendations [52–56]. The combined PDF and QCD scale uncertainties for each final state are 5.75% for ZZ\((^{*)}\) → 4ℓ, 6.32% for Z → 2ℓ and 5.90% for ZZ → 4ℓ/Z → 2ℓ.

The efficiency \(\epsilon_{\text{MC}}\) is defined as the ratio between events passing all the selection criteria and events with the cut at generator level \((m_{ll} > 12\text{ GeV/c}^2)\). These terms are computed with the corresponding MC samples. At the reconstruction level, the ZZ\((^{(*)})\) events must fulfill all the event selection criteria. The selection of Z events follows from the first step of the selection. The rates are extracted through a fit of the di-lepton invariant mass distribution, subtracting the background contribution. Event counts for Z → ℓℓ for an integrated luminosity of 1.18 fb⁻¹ for 2e and for 2µ final states are: \(N_{\text{obs}}^{Z\rightarrow \ell\ell}\) ≃ 4.8 × 10⁵ and \(N_{\text{obs}}^{Z\rightarrow \mu\mu}\) ≃ 5.6 × 10⁵. Statistical uncertainties for such a large number of events are negligible, while for systematic uncertainties we assume a value of 1%, based on the estimate of the amount of background events in the selection used for the Z cross section measurement in CMS.

In a complementary method the estimation of the number of ZZ events in any given mass range \([m_1, m_2]\) is obtained directly from the absolute rate predicted by the MC model simulation:

\[
N_{\text{expect}}^{ZZ}[m_1, m_2] = (\sigma_{\text{NLO}}^{qg\rightarrow ZZ\rightarrow 4\ell} + \sigma_{\text{LO}}^{gg\rightarrow ZZ\rightarrow 4\ell}) \times \epsilon_{\text{MC}}^{ZZ\rightarrow 4\ell} \times \mathcal{L} \times \int_{m_1}^{m_2} \rho_{ZZ}(m) dm \quad (3)
\]

When used for comparisons with data, the method is affected by the full systematic uncertainties on the pp integrated luminosity and the theoretical and acceptance systematic uncertainties within the analysis cuts.

The number of events and relative uncertainties from ZZ\((^{*)}\) → 4ℓ predicted by normalization to the measured Z rate and by the MC model simulation for an integrated luminosity of 1.66 fb⁻¹ in the signal region in a mass range from 100 to 600 GeV/c² with the baseline and high-mass selections are given in Table 2.
Table 2: Number of ZZ background events and relative uncertainties in the signal region in a mass range from 100 to 600 GeV/$c^2$, estimated from normalization to the measured Z rate and from Monte Carlo simulation, for baseline and high-mass event selections

<table>
<thead>
<tr>
<th>channel</th>
<th>Normalization to Z rate</th>
<th>MC model simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{ZZ \rightarrow 4e}$</td>
<td>4.05 ± 0.26</td>
<td>4.07 ± 0.38</td>
</tr>
<tr>
<td>$N_{ZZ \rightarrow 4\mu}$</td>
<td>6.02 ± 0.40</td>
<td>6.23 ± 0.57</td>
</tr>
<tr>
<td>$N_{ZZ \rightarrow 2e2\mu}$</td>
<td>9.87 ± 0.66</td>
<td>10.06 ± 0.93</td>
</tr>
<tr>
<td>high-mass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{ZZ \rightarrow 4e}$</td>
<td>3.67 ± 0.25</td>
<td>3.70 ± 0.34</td>
</tr>
<tr>
<td>$N_{ZZ \rightarrow 4\mu}$</td>
<td>5.22 ± 0.34</td>
<td>5.38 ± 0.48</td>
</tr>
<tr>
<td>$N_{ZZ \rightarrow 2e2\mu}$</td>
<td>8.96 ± 0.59</td>
<td>9.14 ± 0.85</td>
</tr>
</tbody>
</table>

4.2 Reducible and Instrumental Backgrounds

For the measurement of the $Zb\bar{b}/c\bar{c}$ and $t\bar{t}$, a four-lepton background control region is defined by inverting SIP$_{3D}$ and relaxing isolation, charge and flavour requirements for two leptons. In detail, the $Zb\bar{b}/c\bar{c}$ and $t\bar{t}$ control region is defined taking a set of events with a pair of identified leptons with opposite charge and matching flavour ($e^+e^-, \mu^+\mu^-$) that form a good $Z_1$, as requested for the signal selection. For the other pair of leptons the flavour, charge, and isolation requirements are removed. Finally the SIP$_{3D}$ impact parameter cuts are reversed on the two leptons by requiring $|SIP_{3D}| > 5$. Inverting the SIP$_{3D}$ selection cuts for two leptons ensures a negligible $Z+$jets contribution in the four-lepton background control region.

A comparison of the MC expectation with data is shown in Fig. 2 for the sum of the $Z_1+2e$, $Z_1+2\mu$ and $Z_1+e\mu$ final states. The data are compatible with the MC expectation with a very

![Figure 2](image-url)

Figure 2: Distribution of the best reconstructed Z candidate invariant mass for the events in the four-lepton background control region defined by a pair of identified leptons with opposite charge and matching flavour and another pair of leptons with isolation cut relaxed, flavour and charge requirements removed and large impact parameters. Solid points represent the data, shaded histograms represent the MC expectations, the signal and the ZZ background contribute negligibly. The samples correspond to an integrated luminosity of $\mathcal{L} = 1.66$ fb$^{-1}$. 
clean and distinct resonant contribution from \(Z\bar{b}b/c\bar{c}\) and non-resonant contribution from \(t\bar{t}\). Only a very small contamination from \(Z+\text{jets}\) remains. The signal and the \(ZZ\) background are either absent or negligible.

To extract the number of \(t\bar{t}\) and \(Z\bar{b}b/c\bar{c}\) events in the four-lepton signal region, we exploit the knowledge and distinct features of the SIP\(_{3D}\) distribution. The SIP\(_{3D}\) distributions for the \(Z_t\) lepton of the \(t\bar{t}\) and \(Z\bar{b}b/c\bar{c}\) backgrounds are uniform and of similar shapes. This is in sharp contrast with the expected SIP\(_{3D}\) distribution for the signal which is concentrated at low SIP\(_{3D}\) and steeply falling with increasing SIP\(_{3D}\). We measure the functional shape of the SIP\(_{3D}\) distributions for the \(Z_t\) lepton of the \(t\bar{t}\) and \(Z\bar{b}b/c\bar{c}\) backgrounds in data and calculate the acceptance ratio \(R_{\text{SIP}_{3D}} = A_{|\text{SIP}_{3D}|<4}/A_{|\text{SIP}_{3D}|>5}\).

Final factors for estimating the number of events in the signal-like regions include a combinatorial factor to account for relaxing lepton flavors and charges, a factor for the \(Z_t\) selection (baseline or high-mass), and from the relative isolation for the pair of additional leptons. The estimated number of events from the reducible background for the baseline selection, including the full statistical error propagation, are reported in Table 3. For the high-mass selection all the estimated numbers are an order of magnitude smaller and the reducible background can therefore be neglected.

In order to control the \(Z+\text{jets}\) background, a four-lepton background control region is obtained by relaxing the cuts on isolation and identification requirements for two additional leptons. In detail, the control region is defined taking a set of events with a pair of identified leptons with opposite charge and matching flavour (\(e\pm\mu\mp\)) with a reconstructed invariant mass \(m_{Z_1}\) satisfying \(60 < m_{Z_1} < 120\text{ GeV}/c^2\), with transverse momenta of \(p_{T,1} > 20\text{ GeV}/c\) and \(p_{T,2} > 10\text{ GeV}/c\), sum of relative isolation variables \(< 0.35\), and impact parameter \(|\text{SIP}_{3D}| < 4\). An additional pair of reconstructed leptons with like charge (to avoid signal contamination) and matching flavour (\(e^\pm e^\pm, \mu^\pm \mu^\pm\)) is requested with a reconstructed invariant mass \(m_{Z_2}\) either satisfying the baseline selection (\(20 < m_{Z_2} < 120\text{ GeV}/c^2\)) or the high-mass selection (\(60 < m_{Z_2} < 120\text{ GeV}/c^2\)). The reconstructed four-lepton invariant mass is required to satisfy \(m_{4\ell} > 100\text{ GeV}/c^2\). From this set of events the expected number of \(Z+\text{jets}\) in the signal region is obtained taking into account the fake probability, measured from a sample of \(Z_1 + 1\) lepton with no identification or isolation requirements, and where contamination from WZ events is suppressed requiring that the imbalance on the measured energy deposition in the transverse plane be below 25 GeV.

Normalized to the integrated luminosity, the number of events from \(t\bar{t}\), \(Z\bar{b}b/c\bar{c}\) and \(Z+\text{jets}\) expected and the relative error in the signal region in a mass range from \(m_1 = 100\text{ GeV}/c^2\) to \(m_2 = 600\text{ GeV}/c^2\) both for the baseline and high-mass selections is given in Table 3.

## 5 Systematic uncertainties

The main sources of systematic uncertainties on the expected yields are summarized in Table 4. Systematic uncertainties have been evaluated from data for the trigger efficiency as well as for effects from individual lepton reconstruction, identification and isolation efficiencies, and from energy-momentum calibration. Additional systematic uncertainties affecting the derivation of exclusion limits come from the limited statistics in the background control regions which propagate to the background evaluation in the signal region. All major background sources are derived from control regions, and the comparison of the data with the background expectation in the signal region is independent of the uncertainty on the LHC integrated luminosity for
Table 3: Number of background events and relative uncertainties for baseline and high-mass event selections in the signal region in a $m_{4\ell}$ range from 100 to 600 GeV/$c^2$, estimated from data as described in the text. Upper three rows: $t\bar{t}$ and $Zb\bar{b}/c\bar{c}$ estimated from the control region with inverted SIP$_{3D}$, relaxed isolation, charge and flavour requirements for two leptons. Lower three rows: $Z$+jets estimated from the control region with relaxed isolation and identification requirements for two leptons.

<table>
<thead>
<tr>
<th></th>
<th>baseline</th>
<th>high-mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{Zb\bar{b}/c\bar{c},t\rightarrow4e}$</td>
<td>$0.01 \pm 0.01$</td>
<td>-</td>
</tr>
<tr>
<td>$N_{Zb\bar{b}/c\bar{c},t\rightarrow4\mu}$</td>
<td>$0.05 \pm 0.01$</td>
<td>$0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$N_{Zb\bar{b}/c\bar{c},t\rightarrow2e2\mu}$</td>
<td>$0.06 \pm 0.01$</td>
<td>$0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$N_{Z+\text{jets}\rightarrow4e}$</td>
<td>$0.48 \pm 0.08$</td>
<td>$0.20 \pm 0.07$</td>
</tr>
<tr>
<td>$N_{Z+\text{jets}\rightarrow4\mu}$</td>
<td>$0.09 \pm 0.02$</td>
<td>$0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$N_{Z+\text{jets}\rightarrow2e2\mu}$</td>
<td>$0.61 \pm 0.11$</td>
<td>$0.22 \pm 0.07$</td>
</tr>
</tbody>
</table>

the data sample. This uncertainty enters in the calculation of a cross section limit through the normalization of the signal. Also given for completeness in Table 4 is an evaluation of the systematics uncertainties on the Higgs boson cross section and branching ratio [28].

Table 4: Summary of the magnitude of systematic uncertainties in percent. The uncertainties assigned for the lepton reconstruction, identification and isolation apply to the event yields. The uncertainty assigned to the electron energy scale is further propagated through the shape of the expected signal and background reconstructed mass distributions.

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
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</tr>
<tr>
<td>Trigger efficiency</td>
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</tr>
<tr>
<td>Higgs cross section</td>
<td>17-20</td>
</tr>
<tr>
<td>Higgs B.R.</td>
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</tr>
<tr>
<td>Lepton reco/ID eff.</td>
<td>2-3</td>
</tr>
<tr>
<td>Lepton isolation eff.</td>
<td>2</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>3</td>
</tr>
</tbody>
</table>

6 Results

The reconstructed four-lepton invariant mass distributions obtained in the $4e$, $4\mu$, and $2e2\mu$ channels with the baseline selection are shown in Fig. 3, and compared to expectations from the SM backgrounds. Five (ten, six) event candidates are observed in the $4e$ ($4\mu$, $2e2\mu$) final states, satisfying the baseline selection. The reconstructed four-lepton invariant mass distribution obtained with the high-mass selection is shown in Fig. 4 for the combination of the three channels. The reducible and instrumental backgrounds are very small or negligible. In Fig. 3 and 4, the background rates are estimated from data (see below) and the corresponding shapes for the $m_{4\ell}$ distributions are obtained from MC samples. The number of events observed, as well as the background rates in the signal region within a mass range from $m_1 = 100$ GeV/$c^2$ to $m_2 = 600$ GeV/$c^2$, are reported for each final state in Table 5 for the baseline and high-mass selections.

The measured distribution is seen to be compatible with the expectation from SM continuum production of ZZ$(^{(*)}$ pairs. We observe $N_{\text{obs}}^{\text{baseline}} = 21$ events for the baseline selection, in good
Figure 3: Distribution of the four-lepton reconstructed mass for the baseline selection in (a) $4e$, (b) $4\mu$, (c) $2e2\mu$, and (d) the sum of the $4\ell$ channels. Points represent the data, shaded histograms represent the signal and background expectations. The samples correspond to an integrated luminosity of $\mathcal{L} = 1.66 \text{ fb}^{-1}$.

agreement with the expectation of $21.2 \pm 0.8$ events from SM background evaluation. Six of the events are below the kinematic threshold of two on-shell Z’s ($m_{H} < 180 \text{ GeV/c}^{2}$), while $2.8 \pm 0.2$ background events are expected. The probability that the background fluctuates to the observed number of events is $6.5\%$. The events are not clustered at a single mass excluding interpretation as the standard model Higgs boson. However we note that the six events form three mass pairs: two events are close to each of the following masses $122, 142$.
and 165 GeV/c$^2$, respectively. We observe $N_{\text{obs}}^{\text{high mass}} = 14$ events for the high-mass selection compared to an expectation of $18.3 \pm 0.8$ events from SM background evaluations. This corresponds to a 19% probability for the background to fluctuate to a value $\leq N_{\text{obs}}^{\text{high mass}}$. More details on the event kinematics are given in Table 6. The mass $m_{4\ell}$, transverse momentum $p_{T,4\ell}$, and the rapidity $|y_{4\ell}|$ are provided for each of the twenty one events (two from 2010 and nineteen from 2011 data taking periods), surviving the baseline selection. The rapidity is defined as $|y_{4\ell}| \equiv 1/2 \times |\ln [(E_{4\ell} + p_{Z,4\ell})/(E_{4\ell} - p_{Z,4\ell})]| = 1/2 \times |\ln [(1 + \beta \cos \theta)/(1 - \beta \cos \theta)]|$, where $\beta = E_{4\ell}/p_{4\ell}$ and $\theta$ is the angle relative to the $z$ axis. No attempt to recover electromagnetic final state radiation prior to imposing the analysis selection criteria is made. However, a posteriori all selected events were inspected for the presence of direct photons that might originate by inner bremsstrahlung from leptons in the final state. A search for photons with $p_{T,\gamma} > 7$ GeV/c is performed in a cone with axis along the lepton trajectory and of radius $\Delta R < 0.7$. One photon is found with $p_{T,\gamma} = 13.0$ GeV/c in event “M” at $\Delta R = 0.55$ from a muon. Adding the photon to the muon four-momentum shifts the $Z_1$ mass from 77.8 to 91.3 GeV/c$^2$ and the four-lepton mass from 119.0 to 131.9 GeV/c$^2$.

The high-mass event selection and analysis which imposes the presence of two lepton pairs with invariant masses in the range $60 < m_{\ell^+\ell^-} < 120$ GeV/c$^2$ is used to provide a measurement of the total cross section $\sigma(pp \rightarrow ZZ + X) \times B(ZZ \rightarrow 4\ell)$. This measured cross section is obtained via:

$$\sigma(pp \rightarrow ZZ + X) \times B(ZZ \rightarrow 4\ell) = \frac{\sum [N_{\text{obs}}(i_{ch}) - N_{\text{back}}(i_{ch})]}{A_{4\ell} \times \epsilon_{ZZ\rightarrow4\ell} \times L}$$

(4)

Where $i_{ch}$ means $4e$, $4\mu$, $2e2\mu$; $A$ is the acceptance of the detector, the efficiency $\epsilon_{ZZ\rightarrow4\ell}$ is the ratio between the ZZ events that survive the selection cuts and the generated ZZ events within the acceptance of the detector. The fiducial and kinematic acceptance is defined by the fraction...
Table 5: Number of events observed, background and signal rates for each final state in a mass range from $m_1 = 100 \text{ GeV}/c^2$ to $m_2 = 600 \text{ GeV}/c^2$ both for the baseline and high-mass selections. For $ZZ$, $Z$+jets, $t\bar{t}$ and $Zb\bar{b}/c\bar{c}$ the data driven estimations are used, for $WZ$ the Monte Carlo estimation is used.

<table>
<thead>
<tr>
<th></th>
<th>baseline</th>
<th>high-mass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4e</td>
<td>4$\mu$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>4.05 ± 0.26</td>
<td>6.02 ± 0.40</td>
</tr>
<tr>
<td>$Z$+jet</td>
<td>0.48 ± 0.08</td>
<td>0.09 ± 0.02</td>
</tr>
<tr>
<td>$Zb\bar{b}/c\bar{c}$, $t\bar{t}$</td>
<td>0.01 ± 0.01</td>
<td>0.05 ± 0.01</td>
</tr>
<tr>
<td>$WZ$</td>
<td>0.009 ± 0.009</td>
<td>0.009 ± 0.009</td>
</tr>
<tr>
<td>All background</td>
<td>4.54 ± 0.27</td>
<td>6.12 ± 0.40</td>
</tr>
<tr>
<td>$m_{H_1} = 140 \text{ GeV}/c^2$</td>
<td>0.45</td>
<td>0.82</td>
</tr>
<tr>
<td>$m_{H_1} = 200 \text{ GeV}/c^2$</td>
<td>1.20</td>
<td>1.71</td>
</tr>
<tr>
<td>$m_{H_1} = 350 \text{ GeV}/c^2$</td>
<td>0.70</td>
<td>0.93</td>
</tr>
<tr>
<td>Observed</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

of events with four final state leptons satisfying $p_T > 7(e), 5(\mu)$ within $|\eta^e| < 2.5$ and $|\eta^\mu| < 2.4$. The generated $ZZ$ events are the fraction of the PYTHIA MC sample used in the analysis with $60 < m_Z < 120 \text{ GeV}/c^2$.

The total cross section for a pair of Z bosons in the mass range $60 < m_Z < 120 \text{ GeV}/c^2$ is found to be

$$\sigma(pp \rightarrow ZZ + X) \times B(ZZ \rightarrow 4\ell) = 20.8^{+6.8}_{-4.0}(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.9(\text{lumi.}) \text{ fb}.$$ 

The measured cross section agrees within about one standard deviation with the expectation from the SM [47] which predicts $28.32 \pm 1.95 \text{ fb}$. More results on di-boson cross section measurements by the CMS experiment are presented in Ref. [57].

The exclusion limits for a SM-like Higgs Boson are computed for a large number of mass points in the mass range $110-600 \text{ GeV}/c^2$, and 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 17 simulated samples covering the full mass range. The shapes for each simulated sample are fit using a function ($f^\text{MC}$) obtained as a convolution between a Breit-Wigner-like probability density function to describe the theoretical resonance line shape, and a Crystal-Ball function to describe the detector effects. The parameters of the Crystal-Ball function are interpolated for the Higgs boson mass points where there is no simulated sample available. The
Table 6: Properties of the four-lepton combinations satisfying the baseline selection for the Higgs boson search.

<table>
<thead>
<tr>
<th>Event</th>
<th>Run #</th>
<th>Event #</th>
<th>Channel</th>
<th>$m_{Z_1}$ (GeV/c^2)</th>
<th>$m_{Z_2}$ (GeV/c^2)</th>
<th>$m_{4\ell}$ (GeV/c^2)</th>
<th>$p_{T,4\ell}$ (GeV/c)</th>
<th>$y_{4\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>146511</td>
<td>504867308</td>
<td>4\mu</td>
<td>91.4</td>
<td>92.6</td>
<td>201.2</td>
<td>2.9</td>
<td>0.18</td>
</tr>
<tr>
<td>B</td>
<td>147926</td>
<td>368148849</td>
<td>4\mu</td>
<td>101.5</td>
<td>40.0</td>
<td>167.8</td>
<td>43.7</td>
<td>1.45</td>
</tr>
<tr>
<td>C</td>
<td>163334</td>
<td>286336207</td>
<td>2e2\mu</td>
<td>94.5</td>
<td>65.1</td>
<td>162.9</td>
<td>10.4</td>
<td>-0.53</td>
</tr>
<tr>
<td>D</td>
<td>163659</td>
<td>344708580</td>
<td>4e</td>
<td>93.3</td>
<td>28.8</td>
<td>139.3</td>
<td>24.9</td>
<td>0.39</td>
</tr>
<tr>
<td>E</td>
<td>163795</td>
<td>30998576</td>
<td>2e2\mu</td>
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<td>82.3</td>
<td>207.1</td>
<td>5.0</td>
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<td>F</td>
<td>163817</td>
<td>344708580</td>
<td>4e</td>
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<td>2e2\mu</td>
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<td>243.7</td>
<td>11.6</td>
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<td>H</td>
<td>166408</td>
<td>917379387</td>
<td>2e2\mu</td>
<td>88.8</td>
<td>105.3</td>
<td>257.9</td>
<td>29.3</td>
<td>-1.21</td>
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<tr>
<td>I</td>
<td>166438</td>
<td>78213037</td>
<td>4e</td>
<td>94.5</td>
<td>44.6</td>
<td>216.7</td>
<td>22.9</td>
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<td>J</td>
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<td>337493970</td>
<td>4\mu</td>
<td>91.0</td>
<td>93.2</td>
<td>238.5</td>
<td>22.0</td>
<td>0.26</td>
</tr>
<tr>
<td>K</td>
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<td>1491724484</td>
<td>2e2\mu</td>
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<td>93.9</td>
<td>194.6</td>
<td>14.2</td>
<td>0.82</td>
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<tr>
<td>L</td>
<td>167281</td>
<td>480301165</td>
<td>4\mu</td>
<td>90.4</td>
<td>54.8</td>
<td>222.3</td>
<td>42.3</td>
<td>-0.64</td>
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<tr>
<td>M</td>
<td>167284</td>
<td>1038911933</td>
<td>4\mu</td>
<td>77.8</td>
<td>29.7</td>
<td>119.0</td>
<td>43.9</td>
<td>0.58</td>
</tr>
<tr>
<td>N</td>
<td>167675</td>
<td>876568967</td>
<td>4e</td>
<td>92.6</td>
<td>27.1</td>
<td>125.7</td>
<td>15.3</td>
<td>0.07</td>
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<tr>
<td>O</td>
<td>167807</td>
<td>966824024</td>
<td>2e2\mu</td>
<td>90.2</td>
<td>93.4</td>
<td>323.0</td>
<td>40.9</td>
<td>-0.43</td>
</tr>
<tr>
<td>P</td>
<td>171106</td>
<td>141954801</td>
<td>4e</td>
<td>91.0</td>
<td>91.5</td>
<td>190.2</td>
<td>7.5</td>
<td>-0.33</td>
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<tr>
<td>Q</td>
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<td>160966858</td>
<td>4\mu</td>
<td>90.2</td>
<td>88.3</td>
<td>218.9</td>
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<td>R</td>
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<td>4\mu</td>
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<td>87.7</td>
<td>198.8</td>
<td>8.7</td>
<td>1.2</td>
</tr>
<tr>
<td>S</td>
<td>172208</td>
<td>60033190</td>
<td>4\mu</td>
<td>87.7</td>
<td>97.0</td>
<td>308.6</td>
<td>71.1</td>
<td>0.34</td>
</tr>
<tr>
<td>T</td>
<td>172799</td>
<td>60033190</td>
<td>4\mu</td>
<td>90.4</td>
<td>82.2</td>
<td>361.8</td>
<td>6.5</td>
<td>0.52</td>
</tr>
<tr>
<td>U</td>
<td>172208</td>
<td>60033190</td>
<td>4\mu</td>
<td>91.9</td>
<td>85.0</td>
<td>457.9</td>
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<td>-0.52</td>
</tr>
</tbody>
</table>

Mass shapes for the backgrounds are determined by fits to the simulated sample of events, with full detector simulation, and taking into account high-order effects, while the normalization is taken from the overall event yield estimates as described in previous sections.

As a cross check the cut-and-count method has been used. To calculate the exclusion limits, the shapes are integrated in a given mass window, \([m_1, m_2] = [f_{MC_{min}}(m_H), f_{MC_{max}}(m_H)]\), to extract the signal and background yields. The mass window is chosen for each mass point to find the optimal expected limit, computed with a Bayesian approach with flat prior. The resulting mass windows are asymmetric and their width accounts for the mass migrations from generated to reconstructed quantities, the mass resolution and the intrinsic width for a given central mass hypothesis. Similar exclusion limits results are obtained for the cut-and-count method and for the method relying on mass shapes.

The observed and mean expected 95% CL upper limits on Higgs \(\sigma(pp \rightarrow H + X) \times B(ZZ \rightarrow 4\ell)\) from a shape analysis method, obtained for Higgs masses in the range 110-600 GeV/c^2 are shown in Fig. 5. The limits are made using a CLs approach, for the expected ratios to the SM, and in the context of a SM extension by a sequential fourth family of fermions with very high masses (SM4) [58–61]. The bands represent the 1\(\sigma\) and 2\(\sigma\) probability intervals around the expected limit. The expected background yield is small hence the 1\(\sigma\) range of expected outcomes includes pseudo-experiments with zero observed events. The lower edge of the 1\(\sigma\) band therefore corresponds already to the most stringent limit on the signal cross section, as fluctuations below that value are not possible. We account for systematic uncertainties in the form of nuisance parameters with a log-normal probability density function. The exclusion limits extend at high mass beyond the sensitivity of previous collider experiments. The expected limits reflect the dependence of the branching ratio \(B(H \rightarrow ZZ)\) on the Higgs boson mass. The worsening limits at high masses arise from the decreasing signal cross section. The reduced
The results of a search for a standard model Higgs boson produced in pp collisions at $\sqrt{s} = 7$ TeV and decaying in $ZZ$ have been presented in the leptonic Z decay channel $ZZ \rightarrow 4\ell$, with $\ell = e, \mu$. The results are an update, for an integrated luminosity of $\mathcal{L} = 1.66 \pm 0.07$ fb$^{-1}$, sensitivity around $m_H = 160$ GeV/c$^2$ and for the low masses arise from the very small $H \rightarrow ZZ$ branching ratio in these regions. By virtue of the excellent mass resolution and low background the structure in the measured limits follows the distribution of the observed events.

In the current study the exclusion limit is compared to the cross section for on-shell Higgs production and decay in the zero-width approximation, and acceptance estimates are obtained with Monte Carlo simulations that are based on ad-hoc Breit-Wigner distributions for describing the Higgs-boson propagation. Recent analyses show that the use of a QFT-consistent Higgs propagator, also allowing for the degree to which the Higgs-boson is off-shell, dynamical QCD scales and interference effects between Higgs signal and backgrounds will result, at Higgs masses above $\sim 300$ GeV/c$^2$, in a sizeable effect on conventionally defined but theoretically consistent parameters (mass and width) that describe the propagation of an unstable Higgs boson [28, 59, 62]. In this work these effects are not included in the limits calculations, but they are estimated to amount to an additional uncertainty on the theoretical cross section of 10–30% for 400–600 GeV/c$^2$ Higgs masses. The NLO electroweak (EW) radiative corrections in the fourth generation model have been calculated very recently. The NLO EW radiative corrections for Higgs production via heavy-quark loops in gluon-gluon fusion are found to be +12% for Higgs boson mass of 120 GeV/c$^2$ and -13% for 600 GeV/c$^2$ with current parameter settings [63]. The NLO EW radiative corrections in the Higgs boson decay-width for $H \rightarrow WW^{(*)}/ZZ^{(*)} \rightarrow 4f$ appear very large, being about -70% for Higgs boson mass below 200 GeV/c$^2$, and about -25% for 600 GeV/c$^2$ [64]. These corrections however are not taken into account in the current analysis.

7 Conclusions

The results of a search for a standard model Higgs boson produced in pp collisions at $\sqrt{s} = 7$ TeV and decaying in $ZZ^{(*)}$ have been presented in the leptonic Z decay channel $ZZ^{(*)} \rightarrow 4\ell$, with $\ell = e, \mu$. The results are an update, for an integrated luminosity of $\mathcal{L} = 1.66 \pm 0.07$ fb$^{-1}$,
of those presented for the first time by the CMS Collaboration in Ref. [18]. Simple sequential
sets of lepton reconstruction, identification and isolation cuts and a set of kinematic cuts have
been introduced to define a common baseline for the search at any Higgs boson mass $m_H$ in the
range $100 < m_H < 600 \text{ GeV}/c^2$. The instrumental background from Z+jets and the reducible
backgrounds from Zb $\bar{b}$ and t$\bar{t}$, with misidentified primary leptons, are shown to be negligible
over most of the mass, with a small contamination remaining at low mass.

Twenty one events are observed in the 2$e$2$\mu$, 4$e$ and 4$\mu$ channels for an integrated luminosity
of $1.66 \pm 0.07 \text{ fb}^{-1}$, while $21.2 \pm 0.8$ events are expected from standard model background
processes. The distribution of events is compatible with the expectation from the standard
model continuum production of Z boson pairs from $q\bar{q}$ annihilation and $gg$ fusion. No clus-
tering of events is observed in the measured $m_{4\ell}$ mass spectrum. Six of the events are below
the kinematic threshold of two on-shell Z’s ($m_H < 180 \text{ GeV}/c^2$), while $2.8 \pm 0.2$ background
events are expected. The probability that the background fluctuates to the observed number
if events is 6.5%. Using the high-mass selection which contains fourteen events, a total cross
section for a pair of Z bosons in the mass range $60 < m_Z < 120 \text{ GeV}/c^2$ has been measured
to be in agreement with the predicted value. Upper limits obtained at 95% CL on the cross
section $\times$ branching ratio for a Higgs boson with standard model-like decays exclude cross sections
from about one to two times the expected standard model cross section for masses in the
range $150 < m_H < 420 \text{ GeV}/c^2$. Upper limits obtained in the context the standard model with a
fourth fermion family, exclude a Higgs boson with a mass in the ranges 120-520 $\text{ GeV}/c^2$ at 95% CL.
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.


Figure 6: Event yields in the (a) 4e, (b) 4µ and (c) 2e2µ channels as a function of the event selection steps. Black points with uncertainties represent the data, other symbols represent the MC expectations. The samples correspond to an integrated luminosity of \( \mathcal{L} = 1.66 \text{ fb}^{-1} \).