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

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Abstract. A search for the Standard Model (SM) Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4l$ 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 analysed correspond to an integrated luminosity of 1.66 ± 0.07 fb^{-1} recorded by the CMS detector in 2010 and 2011. The search covers Higgs boson mass ($m_{\rm H}$) hypotheses of $110 < m_{\rm H} < 600$ GeV/c^2. Twenty-one events are observed, while 21.2 ± 0.8 events are expected from Standard Model (SM) background processes. The events are not clustered in mass excluding interpretation as the SM Higgs boson and its ($4l$) mass distribution is consistent with the expectation of SM continuum production of $ZZ^{(*)}$ pairs. Upper limits at 95% CL on the cross-section $\times$ branching ratio for a SM Higgs boson with SM like decays exclude cross-sections from about once to twice the expected SM cross-section for masses in the range of $150 < m_{\rm H} < 420$ GeV/c^2.

Keywords. CMS; Standard Model Higgs Boson.

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1. Introduction

The wide-purpose compact muon solenoid (CMS) experiment is designed to be effective in detecting the Higgs boson, the last particle of the Standard Model (SM) which has not yet been discovered. More details about CMS can be found in ref. [1].

The SM of electroweak interactions predicts the existence of a scalar boson, the Higgs boson, associated with the spontaneous electroweak symmetry breaking. The mass $m_{\rm H}$ of this scalar boson is a free parameter of the theory. Direct searches for the SM Higgs boson at the LEP e^+e^- collider [2] have led to a lower mass bound of $m_{\rm H} > 114.4$ GeV/c^2 (95% CL) and the D0 and CDF experiments [3] at the Tevatron exclude the mass range $158 < m_{\rm H} < 173$ GeV/c^2 (95% CL). Indirect constraints from precision measurements, which are sensitive to the existence of a Higgs boson through virtual loops, favour the mass range $m_{\rm H} < 185$ GeV/c^2 (95% CL). In the absence of new physics beyond the SM, the requirement of perturbative unitarity of the theory sets an upper bound on $m_{\rm H}$

in a range of about 500 to 800 GeV/c^2. The mass range $m_{\mathrm{H}} \gg 2 \times m_{\mathrm{Z}}$ 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. The current search [4] for a Higgs boson in $4l$ signal presented in this paper relies solely on the measurements of leptons and it achieves high efficiency for leptons reconstruction, identification, isolation, triggers and skimming compatible with optimization of the analysis for a $H \to ZZ^{(*)} \to 4l$ system, in the measurement range of $m_{4l} > 100$ 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. Event selection

Electrons within the geometrical acceptance of $|\eta^e| < 2.5$ with $p_{\mathrm{T}}^e > 7$ GeV/c and muons satisfying $|\eta^\mu| < 2.4$ and p_{T}^μ >5 GeV/c are considered. The tracker isolation should be less than 0.7 for all leptons. It is a scalar sum of p_{T} of all tracks around lepton track, within the inner veto cone radius (0.015) and cone radius (0.3), where cone radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Then, event selection starts by reconstructing first Z, i.e., a pair of lepton candidates of opposite charge and matching flavour ($l^+l^-(l = e/\mu)$), satisfying $m_{1,2} > 60$ GeV/c^2, $p_{\mathrm{T},1} > 20$ GeV/c and $p_{\mathrm{T},2} > 10$ GeV/c and at least another lepton candidate of any flavour or charge. Then, a fourth lepton candidate is considered with the flavour of the third lepton candidate from the previous step, and with opposite charge. Now, 'best $4l$' and Z_1, Z_2 are assigned by retaining a second lepton pair (Z_2), among all the remaining l^+l^- combinations with $m_{Z_2} > 12$ GeV/c^2 and $m_{4l} > 100$ GeV/c^2. For the $4e$ and 4μ final states, at least three of the four combinations of opposite sign pairs must satisfy m_{ll} >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. The sum of the combined relative isolation $R_{\mathrm{iso},j} + R_{\mathrm{iso},i} < 0.35$, for any combination of two leptons i and j, irrespective of flavour or charge, where $R_{\mathrm{iso}} = (1/p_{\mathrm{T}}^l) \times \left(\sum_i p_{\mathrm{T,track}}^i + \sum_j E_{\mathrm{T,ECAL}}^j + \sum_k E_{\mathrm{T,HCAL}}^k\right)$ and ECAL, HCAL are electromagnetic and hadronic calorimeters [1] respectively. The significance of the impact parameter to the event vertex, SIP$_{\mathrm{3D}}$, is required to satisfy $|\mathrm{SIP}_{\mathrm{3D}} = \frac{\mathrm{IP}}{\sigma_{\mathrm{IP}}}| < 4$ 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 σ_{IP} is the associated uncertainty. Z and $Z^{(*)}$ kinematics with $60 < m_{Z_1} < 120$ GeV/c^2 and $m_{\mathrm{Z}}^{\mathrm{min}} < m_{Z_2} <$ 120 GeV/c^2, where $m_{\mathrm{Z}}^{\mathrm{min}} \equiv 20$ GeV/c^2 for baseline analysis and $m_{\mathrm{Z}}^{\mathrm{min}} \equiv 60$ GeV/c^2 for high mass analysis.

3. Measurement and control of backgrounds

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 Monte Carlo (MC) expectation. The number of events $N^{\mathrm{B}}_{\mathrm{expect}}$ from a given background B expected in the signal region in a four-lepton mass range, m_{4l}, bounded by m_1 and m_2, can be obtained as

$$N^{\mathrm{B}}_{\mathrm{expect}}\,[m_1, m_2] = N^{\mathrm{B}}_{\mathrm{control}} \times \left(\frac{A^{\mathrm{B}}_{\mathrm{signal}}}{A^{\mathrm{B}}_{\mathrm{control}}}\right) \times \int_{m_1}^{m_2} \rho^{\mathrm{B}}(m)\,\mathrm{d}m, \tag{1}$$

where $N^{\mathrm{B}}_{\mathrm{control}}$ is the background rate in the control region, $A^{\mathrm{B}}_{\mathrm{signal}}$ and $A^{\mathrm{B}}_{\mathrm{control}}$ are the signal acceptance in the 'signal'-like and 'background'-like regions, respectively, and $\rho^{\mathrm{B}}(m)$ is the event density as a function of mass for the background.

(a) *$ZZ^{(*)}$ continuum:* Two different methods have been used to determine $N^{\mathrm{ZZ}}_{\mathrm{expect}}$ for the $ZZ^{(*)}$ diboson continuum, a normalization to the measured Z rate and an estimate from MC simulation.
(b) *Reducible backgrounds ($Zb\bar{b}/Zc\bar{c}/t\bar{t}$):* Tag a good Z, add two leptons l_3, l_4, relax opposite charge requirement, remove relative isolation and $\mathrm{SIP}_{3\mathrm{D}} > 5$.
(c) *Instrumental backgrounds (Z+jets, W+jets, QCD):* Tag a good Z, add two same-sign same-flavour leptons l_3, l_4, relax ID and remove relative isolation.

4. Results

The reducible and instrumental backgrounds are very small or negligible. The measured distribution is seen to be compatible with the expectation from SM continuum production of $ZZ^{(*)}$ pairs. We observe $N^{\mathrm{baseline}}_{\mathrm{obs}} = 21$ and $N^{\mathrm{highmass}}_{\mathrm{obs}} = 14$ events as shown in figure 1.

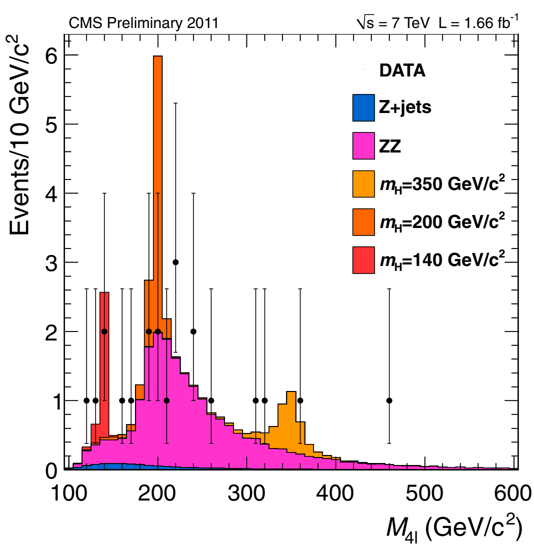

Figure 1. Distribution of the four-lepton reconstructed mass for the sum of the 4l channels in the high-mass selection. Points represent the data, shaded histograms represent the signal and background expectations.

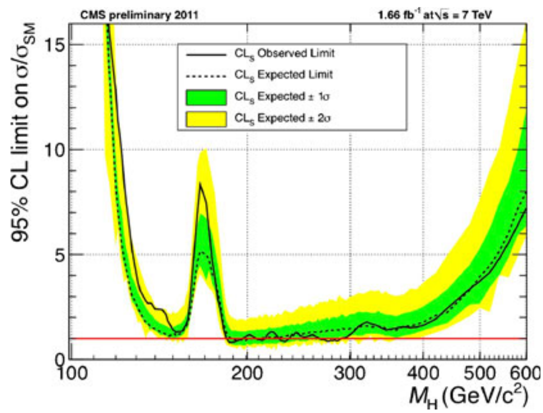

Figure 2. The mean expected and the observed upper limits at 95% CL on $\sigma(pp \to H + X) \times \mathcal{B}(ZZ \to 4l)$ for a Higgs boson in the mass range of 120–600 GeV/c^2, for an integrated luminosity of 1.66 fb^{-1} are shown. The results are obtained using a shape analysis method.

This observation is in good agreement with the expectation of 21.2 ± 0.8 (baseline) and 18.3 ± 0.8 (high mass) events from SM background evaluation. Six of the events are below the kinematic threshold of two on-shell Zs ($m_{\rm H} < 180$ GeV/c^2), while 2.8 ± 0.2 background events are expected. The probability that the background fluctuates to the observed number of events is 6.5% (baseline) and 19% (high mass). The events are not clustered at a single mass excluding interpretation as the SM Higgs boson. The high-mass event selection and analysis which imposes the presence of two lepton pairs with invariant masses in the range of $60 < m_{l^+l^-} < 120$ GeV/c^2 is used to provide a measurement of the total cross-section, i.e., $\sigma(pp \to ZZ + X) \times \mathcal{B}(ZZ \to 4l) = 20.8^{+6.8}_{-4.0}$ (stat.) $\pm$ 0.5(syst.) $\pm$ 0.9(lumi.) fb.

The measured cross-section agrees within about one standard deviation with the expectation from the SM which predicts 28.32 ± 1.95 fb.

The observed and mean expected 95% CL upper limits on Higgs $\sigma(pp \to H + X) \times \mathcal{B}(ZZ \to 4l)$ from a shape analysis method, obtained for Higgs masses in the range 110–600 GeV/c^2 are shown in figure 2. Upper limits obtained at 95% CL on the cross-section$\times$branching ratio for a Higgs boson with SM-like decays exclude cross-sections from about once to twice the expected SM cross-section for masses in the range of $150 < m_{\rm H} < 420$ GeV/c^2.

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