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CMS search for Standard Model Higgs: H→W⁺W⁻ and H→ZZ

Giuseppe Codispoti[1,a] on behalf of the CMS Collaboration

Universidad Autónoma de Madrid, 28049 Madrid, Spain.

Abstract. A search for the Standard Model Higgs decaying to W^+W^- and ZZ in pp collisions from LHC at $\sqrt{s}$ = 7 TeV using up to 1.7 fb^{-1} of data recorded by the CMS detector is presented. This search covers a mass range from 110 GeV/c^2 to 600 GeV/c^2. No significant excess above Standard Model background expectations is observed. Upper limits on the production cross section are derived.

1 Introduction

The Standard Model (SM) is a very successful theory in describing almost all phenomena in particle physics observed in past experiments. One of the key remaining questions is the origin of the masses of elementary particles attributed to the spontaneous breaking of electroweak symmetry. The existence of the associated field quantum, the Higgs boson (H), has still to be experimentally established. The discovery or exclusion of the SM Higgs boson is one of the central goals of the CERN Large Hadron Collider (LHC) physics program.

We report on the search for the SM Higgs decaying to W^+W^- and ZZ in pp collisions from LHC at $\sqrt{s}$ = 7 TeV using up to 1.7 fb^{-1} of data recorded by Compact Muon Solenoid (CMS). A full description of the detector as well as of the physics objects and technical challenges to trigger interesting events and extract physics signal from the high luminosity scenario can be found in [1]. The analysis covers a wide mass range hypothesis for the Higgs mass, from 110 GeV/c^2 to 600 GeV/c^2. The main challenge of the search analysis is to distinguish the candidate signal from a wide set of backgrounds showing the very same final states but much higher cross sections. Beside to reducible backgrounds such as Z/W+jets, $t\bar{t}$, single top, QCD hard scattering where jets are misidentified as leptons, we have to deal also with irreducible backgrounds from WW and ZZ production.

2 Higgs decaying in W⁺W⁻

The CMS search for $H \rightarrow W^+W^-$ [2] selects di-bosons candidates where both bosons decay leptonically, yielding an experimental signature of two isolated, high transverse momentum (p_T) oppositely-charged leptons (electrons or muons) and large missing transverse energy (E_T^{miss}) due to undetected neutrinos. Given the large E_T^{miss}, a mass peak cannot be reconstructed and therefore the analysis has a reduced Higgs mass resolution. The zero spin of the Higgs boson gives angular constraints to the final state: the two leptons are expected with moderately small opening angle while the E_T^{miss} with large angle with respect to the

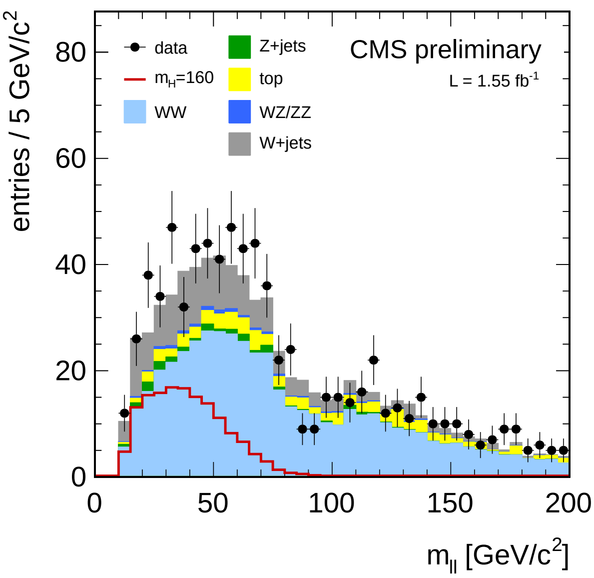

Fig. 1. Di-lepton mass m_{ll} in the $H \rightarrow WW \rightarrow 2\ell 2\nu$ search in the H+0 jet bin for an integrated luminosity of 1.55 fb^{-1}.

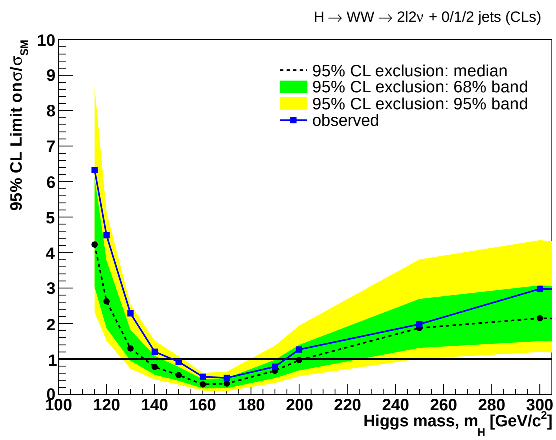

Fig. 2. The expected and observed upper limits at 95% C.L. on σ (pp → H + X) × B($H \rightarrow WW \rightarrow 2\ell 2\nu$) relative to the SM value for an integrated luminosity of 1.55 fb^{-1} using the CLs approach. The results are obtained using a cut-based event selection.

[a] e-mail: giuseppe.codispoti@cern.ch

di-lepton system. Due to different signal sensitivities, the events are separated into three exclusive categories according to the jet multiplicity: H+0 jets, dominated by WW and W+jets backgrounds; H+1 jet, dominated by WW an $t\bar{t}$ background; and H+2 jets where the main background is $t\bar{t}$ and the main production mechanism is Vector Boson Fusion. The W^+W^- non resonant contribution is reduced requiring a small opening angle between the leptons. The remaining background is estimated using side-bands extrapolation for the di-lepton mass distribution (fig. 1) for Higgs masses lower than 200 GeV/c^2 and Monte Carlo (MC) simulation for the high masses, where less statistics is available. The W+jets and QCD hard scattering background is controlled using a control sample of loosely identified leptons extrapolated to the signal region. Backgrounds induced by Z bosons are reduced requiring the di-lepton mass to be outside the Z mass window. The remaining contribution is estimated using the events inside the Z mass window, rescaled using the ratio in/out estimated using simulation. The $t\bar{t}$ background is reduced rejecting events where a jet, considering jets with $p_T > 10$ GeV/c, can be identified as b-quarks. The tagged sample, dominated by $t\bar{t}$ and tW, is used to extrapolate the residual contribution. Results for 1.55 fb^{-1} are shown in figure 2: a SM Higgs is excluded in the mass range from 147 GeV/c^2 to 194 GeV/c^2, a wide sensitivity on the full mass range is exploited in the exclusion plot, even at low masses.

3 Higgs decaying in ZZ

The H → ZZ search involves the study of several final states. The general strategy identifies a first Z that decays into a pair $\ell^+\ell^-$ and distinguish the case when the other decays into $\ell^+\ell^-$ (4ℓ), in two neutrinos ($2\ell 2\nu$) or hadronically ($2\ell 2$q). All the final states provide a strong contribution at the high masses searches. Some of them may contribute also to the low mass search, where one of the two bosons can be off-shell. In particular the 4ℓ channel, despite the low yield, provides very clean final states which can be then carefully inspected for the Higgs signal search. In general a loss of sensitivity is present around m_H = 180 GeV/c^2 due to the rapidly decreasing branching ratio of H → ZZ in the SM.

3.1 The four leptons final state

A clean signature of four well identified leptons belongs to the decay channel $H \to ZZ^{(*)} \to \ell^\pm\ell^\mp\ell'^\pm\ell'^\mp$ with $\ell, \ell' = e, \mu$ [3]. The search relies solely on the measurement of leptons, and the analysis achieves high lepton reconstruction, identification and isolation efficiencies for a $ZZ^{(*)} \to 4\ell$ system composed of two pairs of same flavour and opposite charge isolated leptons, e^+e^- or $\mu^+\mu^-$. On the other hand the small branching ratio associated to this decay channel leads to a low events yield and requires a very careful study of the background. The first step of the analysis requires the identification of the best Z candidate (Z_1) through the two opposite charge matching flavour leptons with closest invariant mass to the nominal Z mass and constrained to 60 GeV/c^2 < m_{Z_1} < 120 GeV/c^2. Then at least two other leptons are required for the second Z (Z_2). Isolation and impact parameter requests, imposing the leptons

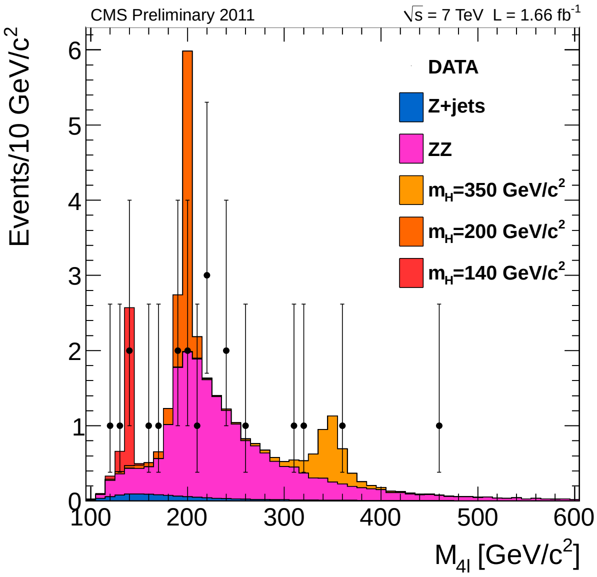

Fig. 3. Distribution of the four-lepton reconstructed mass for the baseline selection in the sum of the 4ℓ channels. Points represent the data, shaded histograms represent the signal and background expectations. The samples correspond to an integrated luminosity of 1.66 fb^{-1}.

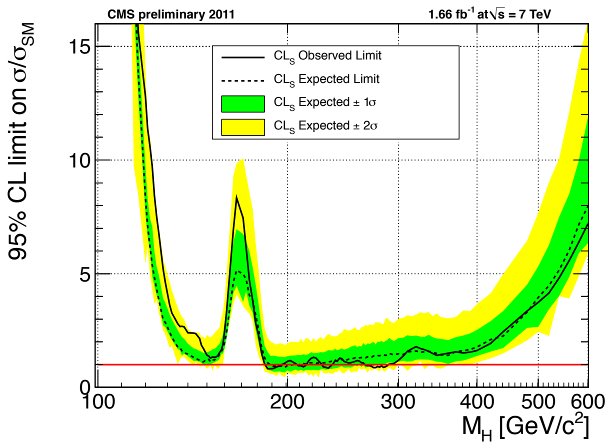

Fig. 4. The expected and observed upper limits at 95% C.L. on σ (pp → H + X) × B(H → ZZ → 4ℓ) relative to the SM value for an integrated luminosity of 1.66 fb^{-1} using the CLs approach. The results are obtained using a shape analysis method.

to be originated from the same primary vertex further reduce the background. A baseline selection, for the analysis in the full mass range imposes 20 GeV/c^2 < m_{Z_2} < 120 GeV/c^2. An high-mass selection, which is used for $m_H > 2\times m_Z$ and the ZZ cross section measurement, requires 60 GeV/c^2 < m_{Z_2} < 120 GeV/c^2. The ZZ background estimation is performed using the MC prediction at Next to Leading Order (NLO) that gives a good description of the mass distribution shape. The MC prediction is then normalized using Z→ $\ell^+\ell^-$ events in data and the expected ratio σ_{ZZ}/σ_Z and acceptance obtained from MC. The fake leptons from Z+jets instrumental background are estimated using a control sample containing the Z_1 plus loosely identified leptons. The $Zb\bar{b}$ and $Zt\bar{t}$ background are estimated removing flavour, charge and isolation request for Z_2 and reversing the impact parameter cut. The invariant mass distribution of the events surviving the selection

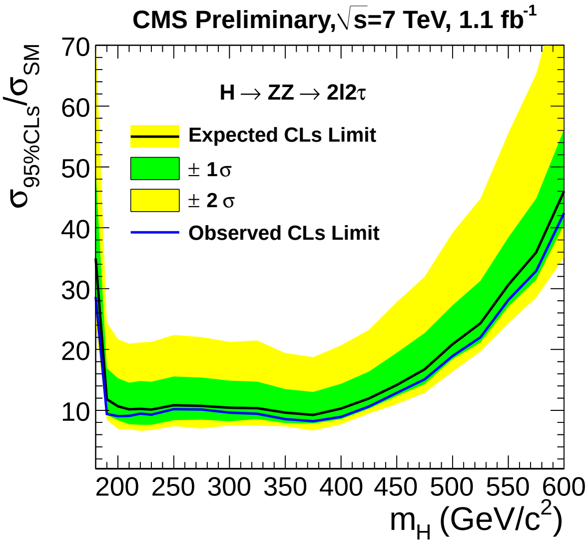

Fig. 5. The expected and observed upper limits at 95% C.L. on σ (pp $\to$ H + X) $\times$ B(H $\to$ ZZ $\to 2\ell 2\tau$) relative to the SM value for an integrated luminosity of 1.1 fb^{-1} using the CLs approach.

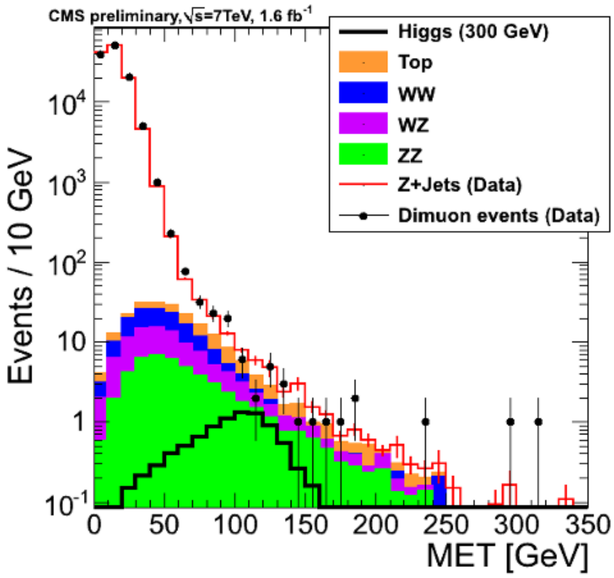

Fig. 6. Missing transverse energy distribution in the H $\to$ ZZ $\to 2\mu 2\nu$ channel at pre-selection level for 1.6 fb^{-1} of data.

is shown in figure 3. Results of the analysis are summarized in the exclusion plot in figure 4.

3.1.1 The two leptons two taus final state

A specific analysis completes the four leptons scenario with the specific case where the secon Z decays in two τ leptons [4]. The analysis is performed on a data sample where 4ℓ events are already discarded. Additional requirements are added in order to be able to reconstruct the 2 τ. Resuls are shown in figure 5.

3.2 The two leptons two neutrinos final state

High branching ratio and good sensibility to the high mass range (250-600 GeV/c^2) characterize the decay channel H $\to$ ZZ$^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$ [5] where the second Z decays in two neutrinos. Two well isolated, close angle, charged leptons come from the decay of the first boosted Z. The second Z decaying in two neutrinos brings to large $E_T^{\rm miss}$, which characterizes the event and provides a good background suppression power as shown in figure 6. The $t\bar{t}$ background is suppressed rejecting b-tagged events. The WZ and ZZ backgrounds are estimated from MC simulation. Residual backgrounds are estimated from data: Z+jets is modeled using photon + jets events and $t\bar{t}$ and WW are estimated events with different flavour leptons ($e\mu$ events). Cuts optimization is performed on the basis of the Higgs mass hypothesis. The dilepton pair is constrained to the Z mass, the $E_T^{\rm miss}$ is requested to be not aligned with jets in order to cope with jet energy mis-measurements. Transverse mass is also used to characterize the sample. Results of this analysis are shown in figure 7.

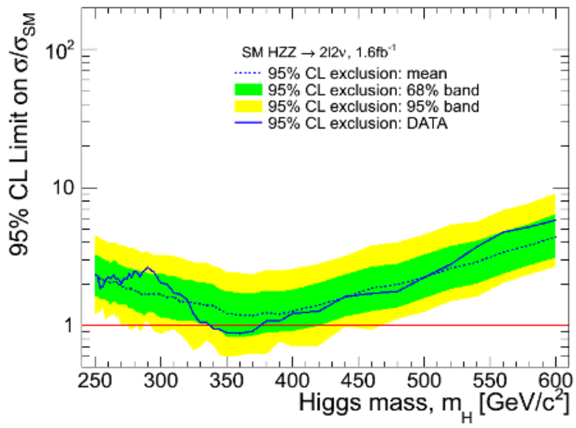

Fig. 7. The expected and observed upper limits at 95% C.L. on σ (pp $\to$ H + X) $\times$ B(H $\to$ ZZ $\to 2\ell 2\nu$) relative to the SM value for an integrated luminosity of 1.6 fb^{-1} using the CLs approach. The results are obtained using a cut-based event selection.

3.3 The two leptons two jets final state

The advantage of the channel where one Z decays hadronically is the fully reconstructable final state with two leptons and two jets [6]. Moreover, the branching fraction of the decay channel H $\to$ ZZ$^{(*)} \to \ell^+\ell^-$ $q\bar{q}$ is about 20 times higher than the 4ℓ channel. This may lead to better sensitivity to SM Higgs boson production at high masses, where kinematic requirements can effectively suppress background. For the analysis we select events containing at least two leptons and two jets compatible with the Z mass hypothesis. Since the final states are fully reconstructed we can perform angular analysis: the initial zero spin of the Higgs bosons constraint the relative angles between the decays product. A dedicated likelihood is used to discriminate signal compatible events. Since Z+jets events involve gluon radiation we can use gluon-jets characteristics to reject them. In order to do this we build a likelihood discriminant based on number of neutral and charged tracks and their transverse momentum distribution. The effectiveness of the gluon-quark likelihood discriminator is tested on photon+jets sample where jets mainly come from quarks. The $t\bar{t}$ background is suppressed requesting small $E_T^{\rm miss}$ and controlled using

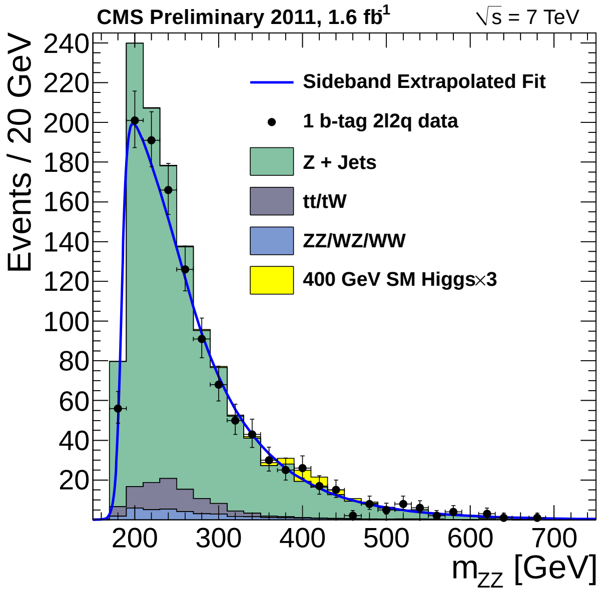

Fig. 8. The m_{ZZ} invariant mass distribution after final selection in the 1 b-tag category of the $H \to ZZ^{(*)} \to 2\ell 2q$ channel. Points with error bars show distributions of data, solid histograms show expectation from simulated events, solid curved line shows prediction of background from sideband extrapolation procedure. The samples correspond to an integrated luminosity of 1.6 fb^{-1}.

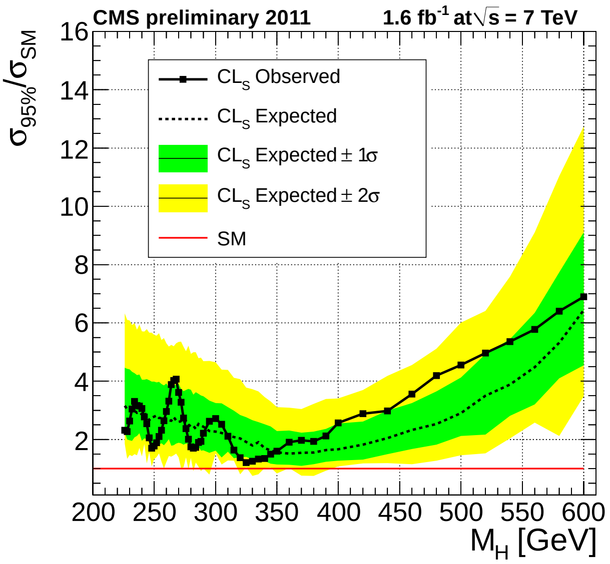

Fig. 9. The expected and observed upper limits at 95% C.L. on σ (pp $\to$ H + X) × B(H $\to$ WW $\to 2\ell 2$q) relative to the SM value for an integrated luminosity of 1.6 fb^{-1} using the CLs approach. The results are obtained using a shape analysis method.

the eμ sample. Finally the presence of b-jets leads to a better characterization of the background. For this reason we divide the data sample in three main categories: 0 b-tag category, were events do not contain jets satisfying the b-tag algorithm; we use the quark-gluon likelihood discriminator to veto gluons events which are studies in a separate category; 1 b-tag category; 2 b-tag category. The background determination is completely data-driven: we use sidebands extrapolation from di-jet mass distribution, where sidebands are defined as (60 GeV/c^2 < m_{jj} < 75 GeV/c^2) ∪ (105 GeV/c^2 < m_{jj} < 130 GeV/c^2). This method better describe data

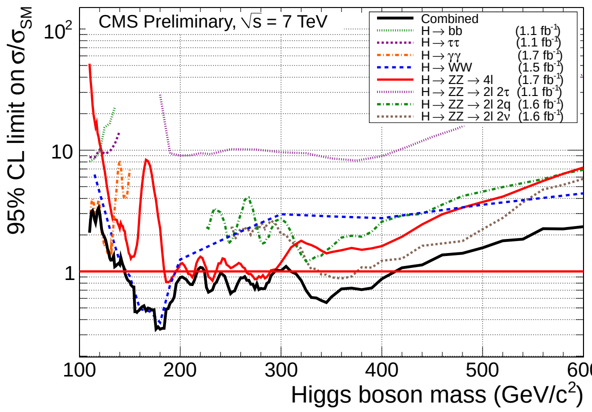

Fig. 10. The observed 95% C.L. upper limits on the signal strength modifier $\mu = \sigma/\sigma_{SM}$ as a function of the SM Higgs boson mass for the eight CMS major analyses and their combination, included the five described in this paper. The limits are obtained with the CLs method.

than the MC simulation based as can be easily seen in figure 8. Results of this analysis are shown in figure 9.

4 Conclusions

A search for the SM Higgs boson decaying into two Z or W bosons has been presented. The analisys is performed with the first 1.6 fb^{-1} of data recorded by CMS in 2011 over a total of almost 5 fb^{-1} and cover a mass range from 130 GeV/c^2 to 440 GeV/c^2. No significant excess is observed thus no evidence of a Higgs boson is found. Combining the results from the different channels [7] we set limits on the Standard Model Higgs production in the ranges 145-216 GeV/c^2, 226-288 GeV/c^2 and 310-400 GeV/c^2. The limits and the contribution of the decay channels illustrated are summarized in figure 10.

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