Higgs search in $H \to ZZ/WW$ decay channels with the CMS detector

C. Charlot, for the CMS collaboration
Laboratoire Leprince-Ringuet, Ecole Polytechnique and IN2P3/CNRS, Palaiseau, France

Abstract. A prospective analysis for the search of the Standard Model Higgs boson decaying in vector boson pairs is presented with the CMS experiment in the context of the initial luminosity at the CERN LHC pp collider. Monte Carlo data corresponding to an integrated luminosity of up to 1 fb$^{-1}$ are analysed and the expected significance for a Standard Model-like Higgs boson in these channels is established.

1. Introduction

The Standard Model (SM) of electroweak and strong interactions predicts the existence of a single physical Higgs boson, the quantum of the scalar field responsible for electroweak symmetry breaking. Direct searches for the SM Higgs particle at the LEP $e^+e^-$ collider have lead to a lower mass bound of $m_H > 114.4$ GeV/$c^2$ (95% CL) [1]. Ongoing direct searches at the TeVatron pp collider by the D0 and CDF experiments set constraints on the production cross-section for a SM-like Higgs boson in a mass range extending up to about 200 GeV/$c^2$ [2, 3]. A consistency fit including all the measured electroweak observables favours the mass range $m_H < 182$ GeV/$c^2$ (95% CL) [4]. The inclusive production of SM Higgs bosons followed by the decay into di-bosons and subsequently into leptons, $H \to ZZ^{(*)} \to lll'l'$ and $H \to WW^{(*)} \to l\nu l\nu$ with $l, l' = e$ or $\mu$, are expected to be early discovery channels at the CERN LHC pp collider over a wide range of possible $m_H$ values. We present here the analysis strategies for the the Higgs search in di-boson decay channels and leptonic modes in the context of an initial luminosity of 1 fb$^{-1}$. Signal and background datasets obtained with a detailed Monte Carlo simulation of the detector response, including the limited inter-calibration and alignment precision expected at startup, are treated using a complete reconstruction chain. Emphasis is put on the reduction of distinguishable background rates and on methods allowing for a data-driven derivation of experimental and background systematic uncertainties.

2. The CMS detector

A general description of the CMS detector can be found elsewhere [5]. This analysis relies mostly on the tracker and the electromagnetic calorimeter (ECAL), both immersed in a 4 T magnetic field parallel to the $z$ axis, and on the muon spectrometer hosted in the iron magnet return yoke. The CMS tracker is a cylindrical detector equipped with silicon pixel detectors for the innermost part and silicon strip detectors for the outer layers. The tracker acceptance for a minimum of 5 collected hits extends up to pseudorapidities $\eta$ of about $|\eta| < 2.4$. The CMS ECAL is made of quasi-projective PbWO$_4$ crystals with a granularity of approximately $\Delta \eta \times \Delta \phi = 0.0175 \times 0.0175$ in the barrel part ($|\eta| \leq 1.48$) and of approximately $\Delta x \times \Delta y = 1.3R_M \times 1.3R_M$ in the endcaps.
parts. The endcaps are equipped with a preshower device that cover the region $1.6 < |\eta| < 2.6$. The electron reconstruction efficiency varies from 85% to 95% depending on $p_T$ and $\eta$. The muon spectrometer consists of Drift Tubes (DTs), Cathode Strip Chambers (CSCs), and Resistive Plate Chambers (RPCs), which cover the angular region $|\eta| < 2.4$. The muon reconstruction efficiency varies between 95% and 99%.

3. The $WW^{(*)} \rightarrow ll\nu\bar{\nu}$ analysis

The analysis in this channel is performed using either a simple cut based approach and a more involved multi-variate analysis based on a neural network (NN). Events passing leptonic trigger paths with two identified and isolated high-$p_T$ leptons ($e$ or $\mu$) are selected. Standard lepton reconstruction techniques are used, and the identification of electrons is relatively tight to reduce the contamination from $W$+jets processes. The charged isolated leptons identified in this way are combined into all possible pairs requiring leptons of opposite charge and within $|\eta| \leq 2.5$ and $p_T \geq 10$ GeV or at least one lepton with $p_T \geq 20$ GeV. If none or more than one such pair is found the event is rejected so to suppress $WZ$ and $ZZ$ backgrounds. A minimum missing transverse energy of 30 GeV is required in accordance with the presence of two neutrinos in the final state. An event containing any jet with $p_T > 15$ GeV and $|\eta| < 2.5$ is rejected. This cut removes the bulk of the $t\bar{t}$ background. Finally, $m_{\ell\ell} > 12$ GeV is required to select events with leptons coming from fully leptonic $W$ pair decays. Additional variables are used in the final kinematical selection both in the cut based and in the NN analysis: the angle $\Delta\Phi_{\ell\ell}$ between the two leptons in the transverse plane; the invariant mass of the lepton pair ($e^+e^-$ and $\mu^+\mu^-$ final states); the missing transverse energy and the transverse momenta of the harder and the softer lepton. In the NN analysis, following additional variables are used: the separation angle $\Delta\eta_{\ell\ell}$ between the leptons in $\eta$, the transverse mass of both lepton-missing transverse energy pairs, the $\eta$ angle of both leptons, the angle in the transverse plane between the missing transverse energy and the closest lepton and the flavour of the di-lepton final state. Systematic uncertainties play an important role in this analysis where no strong mass peak is expected due to the presence of two neutrinos in the final state. Experimental systematic uncertainties coming from the luminosity measurement, lepton identification and efficiencies, missing transverse energy resolution, jet efficiency and energy scale have been taken into account. The normalization of the two main backgrounds, $t\bar{t}$ and $W^+W^-$ has been addressed using various data driven methods. The overall relative error depends on the final state and on the Higgs mass. It is estimated as about 11% for the signal and 21% for the background. Fig. 1 (left) shows the neural network outputs for the signal and the backgrounds for $m_H = 170$ GeV$/c^2$. The distributions are representative of other mass regions. There is a clear shape difference between signal and background events, although there is no region completely free of background. The vertical line indicate the cut value used.

4. The $ZZ^{(*)} \rightarrow llll'$ analysis

This channel is characterized by the presence of two pairs of isolated primary electrons or muons, with one pair generally resulting from the decay of a $Z$ boson on its mass shell. After the High Level Trigger, the event rates in the lepton paths are still dominated by "fake" leptons coming predominantly from QCD processes. To reduce the contribution of QCD multijets and $Z/W+jet(s)$ at a level comparable or below the contribution of the three main backgrounds, $t\bar{t}$, $Zbb$ and $ZZ^{(*)}$, a set of pre-selection cuts is applied. Events are kept only if at least one combination of two matching pairs is found with an invariant mass greater than 100 GeV$/c^2$. To further suppress the $Z+jet(s)$ contamination, a loose track-based isolation is applied. The major reducible backgrounds then remaining are $Z+jet(s)$, $t\bar{t} \rightarrow W^+bW^-\bar{b}$ and $Zbb$ with fake leptons from jets or semi-leptonic decays of bottom mesons. The final selection incorporates tighter lepton isolation complemented by three-dimensional impact parameter measurements. In order
to best preserve the signal detection efficiency while acting on low $p_T$ lepton candidates to suppress the Zbb background, the isolation criteria for the leptons from the pair of lowest $m_{\ell^+\ell^-}$ is made $p_T$ dependent. The $m_{yy}$ masses observables are finally exploited with very loose cuts to preserve the simplicity of an $m_H$ independent selection for the initial luminosity: it is required a reconstructed "Z" with $50 < m_Z < 100\,\text{GeV}/c^2$ and a "Z*" with $20 < m_Z < 100\,\text{GeV}/c^2$. Contrary to the WW(*) channel, the ZZ(*) decay mode allows in presence of signal for a narrow peak in the four lepton invariant mass distribution as shown in Fig. 1 (right). The Z+jet(s) and $t\bar{t}$ backgrounds are completely eliminated. The Zbb background is considerably reduced and only survives towards low masses.

![CMS Preliminary](image1)

**Figure 1.** left: NN outputs for signal (blue squares) and background (red circles) in the WW(*) channel for $m_H = 170\,\text{GeV}$; right: four lepton invariant mass after baseline selection in the ZZ(*) $\rightarrow 2e2\mu$ channel. Results are for an integrated luminosity of 1 fb$^{-1}$.

5. Results

The same likelihood ratio technique as used at LEP and the Tevatron [6] is used here to evaluate the significance of the experiment to the presence of a Higgs boson signal. The expected significance of an event excess under the assumption of the presence of a Higgs boson is shown in Fig. 2 (left) for the WW(*) channel and for the NN analysis. Systematic uncertainties for the signal and background are taken into account. A SM Higgs boson can be found at 5$\sigma$ in this channel around $m_H = 160\,\text{GeV}$. In the case of the ZZ(*) channel, the uncertainty on the observations is dominated by statistical fluctuations for the considered integrated luminosity. It is found unlikely that an integrated luminosity of 1 fb$^{-1}$ will yield an observation of a mass peak with a significance well above 2$\sigma$. In absence of a significant deviation from the SM expectations, an upper limit on the cross-section for the production of a SM-like Higgs boson can be derived. The results are presented in Fig. 2 (right) for various $m_H$ hypothesis and expressed in terms of the ratio of excluded over Standard Model cross sections $R_{95\%C.L.} = \sigma_{95\%C.L.}/\sigma_{SM}$. Systematic errors on the signal and background are taken into account, with an assumption of their 100% correlation. One can see that there is a fair chance of excluding the SM-like Higgs at 95%C.L. for the mass range $185 - 250\,\text{GeV}/c^2$. From the event counts for signal and background, together with associated systematic errors, it is possible to combine results of expected sensitivity in all di-boson decay channels. The combination of these channels is done using two different approaches, a bayesian calculation and a method based on confidence levels, with different assumptions on the correlation between systematic errors. As a result, combining the di-boson decay modes in the leptonic final states, a SM-like Higgs boson can be excluded at the LHC with 1 fb$^{-1}$ for all masses above $\sim 140\,\text{GeV}/c^2$. Finally, a preliminary evaluation of the combined sensitivity in
Figure 2. left: expected significance as obtained from the NN analysis for the WW\((^*)\) channel; right: expected excluded cross-sections for a SM-like Higgs boson normalized to the SM Higgs boson cross sections. The green (yellow) bands shows the 68% (95%) coverage range. Results are for an integrated luminosity of 1 fb\(^{-1}\).

the case of a 10 TeV initial energy of the LHC has been performed. The dominant effect is the change in cross-sections due to partonic luminosities. Using a simple rescaling of the signal and background yields leads to a loss of about a factor 1.5 in sensitivity going from 14 TeV to 10 TeV. Detailed analyses at 10 TeV involving a complete reevaluation of systematics are ongoing.

6. Conclusions
The CMS experiment is actively preparing for the Higgs search with complete analyses based on detailed Monte carlo simulations and full event reconstruction. The di-boson decay modes with their leptonic final states represent the main discovery channels for integrated luminosities of around 1 fb\(^{-1}\). A SM Higgs can be found at 5\(\sigma\) in the WW\((^*)\) channel around \(m_H = 160\) GeV for an integrated luminosity of 1 fb\(^{-1}\). Due to its lower \(\sigma \times \text{BR}\), the ZZ\((^*)\) channel doesn’t allow for a discovery with such integrated luminosities and 95% confidence level exclusions limits can be set in absence of deviation from SM expectation. Combining both channels, it is found that with an integrated luminosity of 1 fb\(^{-1}\) a SM-like Higgs boson can be excluded at the LHC for all masses above \(\sim 140\) GeV/c\(^2\). In the case of a 10TeV initial energy of the LHC machine, the sensitivity would decrease by a factor of about 1.5.

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