Higgs searches in CMS

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Abstract. These proceedings report the results on the Higgs searches at the CMS experiment with data collected during the 2011 LHC run at 7 TeV, corresponding to an integrated luminosity of about 5 fb$^{-1}$. The search for the standard model Higgs boson has been narrowed to a mass window of just 16 GeV. In the searches beyond the standard model no significant deviation is found, and limits on the Higgs boson mass are set for several physics scenarios.

1. Introduction
The discovery of the mechanism for electroweak symmetry breaking is one of the goals of the physics programme at the Large Hadron Collider (LHC). Here we report on several Higgs boson searches carried out in proton-proton collisions at $\sqrt{s} = 7$ TeV using the Compact Muon Solenoid (CMS) detector [1] at the LHC. The analysed data recorded in 2011 correspond to an integrated luminosity up to 5 fb$^{-1}$, depending on the search channel. The standard model (SM) of Particle Physics describes very precisely the experimental measurements up to now, but one of its key ingredients has not yet been observed: the Higgs boson, which is at the source of the electroweak symmetry breaking and provides a mechanism to assign mass to particles. It is clear, however, that the SM theory breaks at larger scales, and some major open points are the unification of couplings, hierarchy problem, dark matter issue and neutrino masses. Theories have been proposed that attempt to answer some of these open questions such as supersymmetry (SUSY) or other beyond the standard model (BSM) scenarios, and are currently under experimental test. The latest Higgs searches results in the following scenarios are reported: standard model, an extension to the standard model that includes a fourth generation of fermions, a fermiophobic Higgs boson, and beyond the standard model Higgs searches.

2. Standard model Higgs
In the $H \rightarrow \gamma \gamma$ analysis [2] a search is made for a narrow peak in the diphoton mass distribution in the range 110-150 GeV, on a large irreducible background from QCD production of two photons. To enhance the sensitivity of the analysis, candidate diphoton events are separated into mutually exclusive categories of different expected signal-to-background ratios, based on the properties of the reconstructed photons and by the presence of two jets satisfying criteria aimed at selecting events in which a Higgs boson is produced through the vector boson fusion (VBF) process. The analysis uses multivariate techniques for the selection and classification of the events. The limit set on the cross section of a Higgs boson decaying to two photons relative to the SM expectation is shown in Figure 1 (left). The median expected limit on the cross section obtained in the previously reported analysis [3] of the same dataset is also shown. The use of multivariate techniques has increased the sensitivity by about 20% across the entire mass
range. The analysis of the data excludes at 95% confidence level (CL) a standard model Higgs boson decaying into two photons in the mass ranges 110-111, 117.5-120.5, 128.5-132.0, 139-140 and 146-147 GeV. The largest excess of events above the expected standard model background is observed for a Higgs boson mass hypothesis of 125 GeV with a local significance of 2.9 standard deviations.

In the $H \rightarrow ZZ \rightarrow 4\ell 2\nu$ decay mode [4] a search is made for a narrow four-lepton mass peak in the presence of a small continuum background. Since there are differences in the reducible background rates and mass resolutions between the subchannels $4e$, $4\mu$, and $2e2\mu$, they are analysed separately. The main background source is an irreducible four-lepton contribution from direct ZZ production via $q\bar{q}$ and gluon-gluon processes. The low mass range is shown in Figure 1 (right) together with the mass of each candidate and its uncertainty. Upper limits at 95% CL exclude the Higgs boson mass ranges $134-158$ GeV, $180-305$ GeV, and $340-465$ GeV. Excesses of events are observed at the low end of the explored mass range, around masses of 119 and 126 GeV.

The decay channel $H \rightarrow ZZ \rightarrow 2\ell 2\nu$ [5] is especially sensitive in the high-mass range 250-600 GeV. Events with a lepton pair ($ee$ or $\mu\mu$ are selected, with mass consistent with that of an on-shell Z boson, and large missing transverse energy is asked for, assuming that it is due to the undetected neutrinos from a $Z \rightarrow \nu\nu$ decay. No significant excess is found above the background expectation, and the Higgs boson mass range 270-440 GeV is excluded at 95% CL.

Figure 1. Left: The 95% CL limit on $\sigma/\sigma_{SM}$ for a Higgs boson decaying to two photons, relative to the SM expectation. The symbol $\sigma$ denotes the production cross section times the relevant branching fractions. The background only expectations are represented by their median (red line) and by the 68% and 95% CL bands. The expected limit obtained in the earlier analysis of the same dataset is shown for comparison. Right: Distribution of the four-lepton mass for the $4\ell$ channels.

The decay mode $H \rightarrow WW$ is highly sensitive to a SM Higgs boson in the mass range around the WW threshold of 160 GeV. With the development of tools for lepton identification and missing transverse energy reconstruction optimised for pileup conditions it is possible to extend the sensitivity down to 120 GeV. The most sensitive analysis in the low mass region is based on the final state in which both W bosons decay leptonically, resulting in a signature with two isolated, oppositely charged leptons (electrons or muons) and large missing transverse energy due to the undetected neutrinos [6]. To further improve the signal sensitivity, the events are separated into three mutually exclusive categories according to the jet multiplicity. Its main backgrounds are irreducible non-resonant WW production and reducible W+jets processes, where a jet has been misidentified as a lepton. Some categories are also contaminated by top-quark decays and Drell-Yan production. The event selection in the two-jet category is optimised for the VBF
production mechanism. After applying the analysis selection, the resultant sample is dominated by non-resonant WW events, as it can be seen in Figure 2 (left), where $\Delta\phi_{ll}$ is shown, for the 0-jet category. To enhance the sensitivity to a Higgs boson signal, a multivariate technique is used after the analysis selection. A boosted decision tree (BDT) is trained for each Higgs boson mass hypothesis and jet category to discriminate signal from background. The expected and observed 95% CL upper limits are shown in Figure 2 (right). The presence of the SM Higgs boson with a mass in the range 129-270 GeV is excluded at 95% CL.

Figure 2. Left: Distribution of the azimuthal angle difference between the two selected leptons ($\Delta\phi_{ll}$) for the zero-jet category in the $H \rightarrow WW$ search. The signal expected from a Higgs boson with a mass $m_H = 130$ GeV is shown superimposed. Right: The 95% CL limit on $\sigma/\sigma_{SM}$ for a Higgs boson decaying, via a W boson pair, to two leptons and two neutrinos, relative to the SM expectation.

The $H \rightarrow \tau\tau$ search is performed using the final-state signatures $e\mu$, $\mu\mu$, $e\tau_h$, and $\mu\tau_h$ [7, 8], where electrons and muons arise from leptonic $\tau$-decays and $\tau_h$ denotes hadronic $\tau$-decays. Each of these categories is further divided into three exclusive sub-categories according to the nature of the associated jets, and a broad excess in the reconstructed $\tau\tau$ mass distribution is searched for. In addition, a search for $H \rightarrow \tau\tau$ is performed for a Higgs boson produced in association with a W boson [9]. No significant excess of events over background expectations is observed, and 95% CL upper limits are set.

For $m_H < 135$ GeV, the decay $H \rightarrow bb$ has one of the largest branching fractions, but the signal is overwhelmed by QCD production of bottom quarks. The analysis [10] is therefore designed to search for a dijet resonance in events where a Higgs boson is produced at high transverse momentum and in association with a W or Z boson, which largely suppresses the QCD background. Five independent search channels are explored, depending on the decay of the vector boson. An upper limit of 6 to 13 times greater than the predicted SM value is set at 95% CL in the mass range $100 < m_H < 140$ GeV.

The combination [11] of the SM Higgs boson searches requires simultaneous analysis of the data from all individual search channels, accounting for all statistical and systematic uncertainties and their correlations. The combination is repeated for 183 Higgs boson mass hypotheses in the range 110-600 GeV. The overall statistical methodology used in the combination was developed by the CMS and ATLAS collaborations in the context of the LHC Higgs Combination Group. Figure 3 (left) shows the 95% CL upper limits on the signal strength
The best fit values are shown in Figure 7 (right). The expected excluded mass range in the absence of the standard model Higgs boson is 114.5-543 GeV at 95% CL. The observed results exclude the standard model Higgs boson in the mass range 127.5-600 GeV at 95% CL. An excess of events above the expected standard model background is observed at the low end of the explored mass range. The largest excess, with a local significance of 2.8 standard deviations, is observed for a Higgs boson mass hypothesis of 125 GeV. More data are required to ascertain the origin of the observed excess.

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For an extension of the standard model including a fourth generation of fermions (SM4), the SM4 Higgs boson is excluded in the mass range 120-600 GeV at 95% CL.

3. Minimal supersymmetric standard model Higgs
In the minimal supersymmetric standard model (MSSM), the standard scalar Higgs boson is substituted by three neutral \( \phi = (h, H, A) \) and two charged (\( H^\pm \)) Higgs particles, and all decays to down-type fermions are enhanced by a factor of \( \tan \beta \). For relatively high \( \tan \beta \) the \( \text{BR}(\phi \to \tau \tau) \) is about 10% which is much lower than the corresponding branching ratio of the b-decay mode. Neutral MSSM Higgs bosons are searched in the \( \tau\tau \) final state, which is preferred for its clear signature in the two leptons final states (electrons or muons) and in the lepton plus a hadronic decaying \( \tau \) final state. The dilepton channel was searched in dimuons and in electron-muon final states. The hadronic \( \tau \) is reconstructed in 1 and 3 prongs. To extract the \( \tau\tau \) mass a kinematic fit is applied to the measured components, including the missing energy, with an improvement of about 20% on the measured mass [12]. In Figure 4 (left) is shown the exclusion plot for the neutral MSSM Higgs mass versus \( \tan \beta \). For \( \tan \beta = 20 \) Higgs masses up to 300 GeV are excluded. The charged MSSM Higgs bosons are searched in the top decays \( t \to bH^\pm \) with the tau final states \( H^\pm \to \tau \nu \). The \( t\bar{t} \) production yields with tau final states are modified by Higgs diagrams if the Higgs mass is lower than the top mass. The Higgs particle is searched in isolated \( \tau \) decays plus b-jets and possibly an isolated lepton in the final state, depending on the second top decay chain in the \( t\bar{t} \) events. Results from this analysis [13] on
BR(t → bH⁺) are shown in Figure 4 (right). Values of BR(t → bH⁺) > 4% are excluded for all the possible Higgs mass values.

4. Light pseudoscalar Higgs
The presence of a light pseudoscalar CP-odd Higgs is predicted within the next to minimal supersymmetric extension to the standard model. This search [14] has been performed in the sidebands of the Υ → μμ decays, namely 5.5 < m_{μμ} < 9 GeV and 11.5 < m_{μμ} < 14 GeV. A special high level trigger conceived for charmonium states studies was set up and this analysis has been performed with a data sample corresponding to a luminosity of 1.3 fb⁻¹. Results are shown in Figure 5 with no excess found in the dimuon spectrum. An upper limit on the cross section \( \sigma(pp → a → μμ) \) below 5 pb is set for all the masses in the two search intervals.
5. Doubly charged Higgs
These exotic Higgs bosons are predicted within the type II see-saw model and are related to the presence of a light neutrino mass. $H^{++}$ decay to two same charged leptons and obviously do not have any physical background in the SM. They are produced in pairs or together with a single charged Higgs through the processes $Z/\gamma \rightarrow H^{++}H^{--}$ and $W^{+} \rightarrow H^{++}H^{-}$ (charge conjugates included), giving final states with four or three leptons, same charge resonant. No excess is observed in the CMS data [15]. In Figure 6 (left) are shown the mass limits for the different leptonic final states and four benchmark points of the see-saw mechanism.

6. Fermiophobic Higgs
In the Fermiophobic model the gluon-gluon process of Higgs production is forbidden and the production cross section is suppressed by an order of magnitude, with the VBF and the Higgs-strahlung (VH) becoming the two most important contributions to Higgs production. On the other hand, the diphoton decay $H \rightarrow \gamma\gamma$ is enhanced by another order of magnitude. This analysis [16] is based on the selection of two high transverse momentum photons and three tag classes with electron, muon or dijets in the final states, corresponding to different decays in the associate production. The results are presented in Figure 6 (right) and show a small excess at 126 GeV, which is diluted when the diphoton channel is combined [11] with $H \rightarrow WW$ and $H \rightarrow ZZ$. Two intervals of Higgs mass are excluded at 95% CL, $110 < m_H < 124$ GeV and $128 < m_H < 136$ GeV.

Figure 6. Left: Limits on the mass of the doubly charged Higgs bosons for different final states. Right: The 95% CL upper limits on the signal strength parameter $\sigma/\sigma_{FP}$ for the fermiophobic Higgs boson hypothesis, as a function of the Higgs boson mass. It includes the three explored Higgs boson decay modes.

7. Conclusions
The observed results exclude the standard model Higgs boson in the mass range 127.5-600 GeV at 95% CL, and an excess of events above the expected standard model background is observed at the low end of the explored mass range, making the observed limits weaker than expected in absence of a signal. The largest excess, with a local significance of 2.8 standard deviations, is observed for a Higgs boson mass hypothesis of 125 GeV. In addition, a broad program of BSM
Higgs bosons searches has been presented. Model independent inclusive searches together with well defined new physics scenarios have been probed during 2011 with a luminosity of about 5 fb$^{-1}$. A large fraction of the MSSM Higgs parameters are constrained by the $H \rightarrow \tau \tau$ analysis. A small excess on the $H \rightarrow \gamma \gamma$ decay is noted, compatible with a statistical fluctuation. No evidence for new BSM Higgs bosons is observed.

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