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Results on the search for the Standard Model Higgs Boson at CMS

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Abstract

A summary of the results from searches for the Standard Model Higgs Boson in the CMS experiment at LHC with data collected from proton-proton collisions at $\sqrt{s} = 7$ TeV is presented. The Higgs boson is searched in a multiplicity of decay channels using data samples corresponding to integrated luminosities in the range $4.6 - 4.8$. The investigated mass range is $110 - 600$. Results are reported for each channel as well as for their combination.

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Results on the search for the Standard Model Higgs Boson at CMS

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Abstract.

A summary of the results from searches for the Standard Model Higgs Boson in the CMS experiment at LHC with data collected from proton-proton collisions at $\sqrt{s} = 7$ TeV is presented. The Higgs boson is searched in a multiplicity of decay channels using data samples corresponding to integrated luminosities in the range $4.6 - 4.8 \text{ fb}^{-1}$. The investigated mass range is $110 - 600$ GeV. Results are reported for each channel as well as for their combination.

Keywords: CMS, Higgs

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INTRODUCTION

The Compact Muon Solenoid (CMS) detector [1] at the CERN pp Large Hadron Collider (LHC) [2] is a general purpose detector consisting of a pixel and silicon-strip tracker (SST) immersed in a 3.8 T axial magnetic field provided by a superconducting solenoid, a scintillating PbWO_4 crystals electromagnetic calorimeter (ECAL), and a brass-scintillator hadronic calorimeter (HCAL). A forward calorimeter (HF) covers the region at large pseudorapidity to $|\eta| = 5.2$. Muons are measured in layers of three types of gaseous detectors installed in the iron yoke: Drift Tubes (DT), Cathod Strip Chambers (CSC), and Resistive Plate Chambers (RPC). In 2011 the LHC provided pp collisions at a center of mass energy $\sqrt{s} = 7$ TeV, achieving a peak instantaneous luminosity record of $3.5 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, and data equivalent to an integrated luminosity of about 5.6 fb^{-1} were recorded by the CMS apparatus, with an efficiency greater than 90%. The impressive performances of the LHC are confirmed in the ongoing 2012 pp collisions run at $\sqrt{s} = 8$ TeV. Indeed, the same integrated luminosity of 2011 has been collected by CMS after only a few months of data taking. The increasing amount of data, coped with the top level performances and the reliable operations of the detector, are fundamental for developing a broad physics program, where the search for the standard model (SM) Higgs boson represents one of the main goals.

The existence of the Higgs boson is predicted by the standard model of particle physics [3, 4, 5] as a consequence of the mechanism for the origin of mass, the spontaneous electroweak symmetry breaking [6, 7, 8, 9, 10, 11]. Experimental bounds at 95% confidence level (CL) on the Higgs boson mass m_H were established by experiments at LEP ($m_H > 114.4$ GeV) [12] and Tevatron ($m_H \notin [147, 179]$ GeV) [13]. Indirect constraints from precision electroweak measurements give $m_H < 169$ GeV at 95% CL [14].

FIGURE 1. Expected upper limits at 95% CL on σ/σ_{SM} as function of the Higgs boson mass, for the five Higgs boson decay modes investigated in CMS and their combination. The limits are obtained with the asymptotic CLs approximation [16].

At the LHC, the SM Higgs production proceeds mainly via gluon-gluon fusion mechanism [15]. Other production mechanisms with smaller cross sections, like vector boson fusion (VBF) or associated production of the Higgs with a vector boson, play an important role in the search strategy since they provide peculiar final state signatures. The branching fractions of the possible decay modes of the Higgs boson depend strongly on m_H and, together with the signal selection efficiency, the background rejection power of the analysis and the invariant mass resolution of the reconstructed final state, determine the sensitivity of a search channel in a given m_H range.

SM HIGGS BOSON SEARCHES AT CMS

In CMS, five channels have been investigated for evidence of a SM Higgs boson in the m_H range 110 – 600 GeV: $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$, $H \rightarrow bb$, $H \rightarrow WW$, $H \rightarrow ZZ$. The analyses are based on data samples from the 2011 run corresponding to integrated luminosities in the range 4.6 – 4.8 fb^{-1} . The sensitivity of each channel as function of m_H , evaluated as the expected upper limit at 95% CL on the Higgs cross section relative to the SM (σ/σ_{SM}) in the background-only hypothesis, is shown in Fig 1. By combining the five channels, it can be predicted that CMS is able to exclude at 95% CL the m_H range 114.5 – 543 GeV.

The $H \rightarrow \gamma\gamma$ channel. $H \rightarrow \gamma\gamma$ is the most sensitive channel for $m_H < 130$ GeV, thanks to the clean signature (two isolated photons of high transverse energy E_T) and the excellent di-photon invariant mass resolution (about 1 – 2%) dominated by the ECAL energy resolution. The m_H range 110 – 150 GeV has been investigated by the CMS analysis [17]. Prompt $\gamma\gamma$, γ +jet, jet+jet, and Drell-Yan to ee events represent the main background sources. Selected events in data are classified in several categories which are

FIGURE 2. Left: The $m_{\gamma\gamma}$ distribution for data events along with the sum of the polynomial fits to the background affecting the analyzed events categories. Right: Observed upper limit on $\sigma(H \rightarrow \gamma\gamma)$ as a function of the boson mass relative to the SM. The median expected limit along with 1 and 2σ bands (light and dark bands, respectively) are also displayed. The expected limit obtained with a previously published cut-based analysis is shown to demonstrate the improvement in sensitivity.

characterized by decreasing signal to noise ratio (S/N) and are analyzed separately. The class with the best S/N is made by events where two backward-forward jets consistent with VBF topology are reconstructed. The remaining events are classified according to the output of a multivariate analysis (MVA) discriminator, exploiting the kinematics of the di-photon system, the estimated di-photon mass resolution, and the value of a photon-jet discriminator algorithm. The di-photon mass distribution of data events is analyzed to search for evidence of a narrow resonance peak from the Higgs decay over a decreasing background distribution (Fig. 2-left). The background expectation for each category is obtained from a polynomial fit to the invariant mass distribution in data. The observed upper limits at 95% CL are consistent with expectations in the background-only hypothesis (Fig. 2-right) and five m_H ranges are excluded: 110.0 – 111.0 GeV, 117.5 – 120.5 GeV, 128.5 – 132.0 GeV, 139.0 – 140.0 GeV, 146.0 – 147.0 GeV. An excess of events at 2.9σ -level is observed for $m_H \approx 125$ GeV. Accounting for the Look-Elsewhere-Effect (LEE) [18], the significance of the excess decreases to 1.6σ -level in the search mass range.

The $H \rightarrow \tau\tau$ channel. The $H \rightarrow \tau\tau$ channel has been studied in CMS in a multiplicity of final states, with τ 's decaying leptonically or hadronically (τ_h). Signal events are characterized by large missing transverse energy (MET) due to the undetected neutrinos in the final state, that is also reflected in the broad $m_{\tau\tau}$ invariant mass (resolution $\approx 20\%$). The final states $e\mu$, $\mu\mu$, $e\tau_h$, and $\mu\tau_h$ have been considered in the inclusive analysis [19, 20]. In addition, an optimized analysis for the study of the associated WH production with the W boson decaying leptonically [21] investigates the $e\mu\tau_h$ and $\mu\mu\tau_h$ final states, with same-charge leptons and an opposite-charge τ_h . The m_H range 110 – 150 GeV has been considered. The main backgrounds are represented by Drell-Yan to $\tau\tau$ and W +jets events. The observed upper limits at 95% CL are above $3\sigma_{SM}$ and consistent with expectations in the background-only hypothesis.

The $H \rightarrow bb$ channel. The analysis of the $H \rightarrow bb$ decay mode [22] exploits the signature provided by the associated VH production channel, with $V = W, Z$, in order to reject the overwhelming QCD background. Final states with $W \rightarrow l\nu$, $Z \rightarrow ll$ with $l = e, \mu$ and $Z \rightarrow \nu\nu$ have been considered. The m_H range 110 – 135 GeV has been investigated. The analysis requires two jets of high transverse momentum p_t which satisfy a b -tagging identification algorithm, plus one or two isolated leptons of high p_t (or high event MET in case of a $Z \rightarrow \nu\nu$ decay). The di-jet invariant mass resolution for signal events is about 10%. The main backgrounds are represented by W +jets and top-quark events. The observed upper limits at 95% CL are in the range $3.4 - 7.5\sigma_{SM}$ and consistent with expectations in the background-only hypothesis.

The $H \rightarrow WW$ channel. The highest sensitivity analysis of the $H \rightarrow WW$ channel investigates the fully leptonic $2l2\nu$ modes, where $2l = ee, \mu\mu, e\mu$ [23]. Signal events are characterized by two isolated leptons of high p_t and opposite charge, plus high event MET. The m_H range 110 – 600 GeV has been studied. Non-resonant WW , W +jets, Drell-Yan, and top-quark events represent the main backgrounds affecting the channel. Selected events in data are classified into several categories, according to the number of reconstructed jets and the lepton flavours, which are characterized by different background composition and S/B, and are analyzed separately. In order to improve the analysis sensitivity, kinematical variables useful to discriminate signal events from background are used as input to MVA classifiers, trained separately for different boson masses. The distribution of the MVA classifiers is studied in order to search for excess of events with respect to the background expectation. The observed upper limits at 95% CL are consistent with expectations in the background-only hypothesis and the analysis excludes the m_H range 129 – 270 GeV.

Additional final states have been also investigated. In the $lvjj$ analysis [24] the two leading jets reconstructed in the event must have an invariant mass compatible with the W mass and a W mass constraint is applied to reconstruct the longitudinal component of the neutrino. The analysis excludes a SM Higgs boson at 95% CL in the interval 327 – 415 GeV. The dedicated analyses of the associated production modes $WH \rightarrow WWW \rightarrow 3l3\nu$ [25] and VH where $V \rightarrow 2j$ and $H \rightarrow WW \rightarrow 2l2\nu$ [26] set 95% CL upper limits which are above $5\sigma_{SM}$.

The $H \rightarrow ZZ$ channel. The highest sensitivity analysis of the $H \rightarrow ZZ$ channel exploits $4l$ final states ($4l = 4e, 4\mu, 2e2\mu$), where each Z boson decays to a pair of electrons or muons [27]. Signal events have a very distinctive signature: two pairs of same-flavour, opposite-charge, high-pt, and isolated leptons, with invariant masses consistent with a Z -boson. The small background rate (mainly due to non-resonant ZZ and Z +jets events), the high lepton reconstruction efficiency over a large p_t range, and the excellent $4l$ invariant mass resolution (about 2%) make this channel particularly sensitive in the entire 110 – 600 GeV range of m_H . The $4l$ invariant mass distribution of selected data events is analyzed to search for evidence of a narrow resonance peak over a small level of background (see Fig. 3-left). The observed upper limits at 95% CL are consistent with expectations in the background-only hypothesis (Fig. 3-right) and three m_H ranges are excluded: 134 – 158 GeV, 180 – 305 GeV, and 340 – 465 GeV. An excess of events at 2.5σ -level is observed for $m_H \approx 119$ GeV. Accounting for the LEE,

FIGURE 3. Left: The m_{4l} invariant mass distribution for selected data events compared with background expectation and signal expectation for a few m_H hypotheses. Right: Observed upper limit on $\sigma(H \rightarrow ZZ \rightarrow 4l)$ as function of the boson mass relative to the SM. The median expected limit along with 1 and 2 σ bands (light and dark bands, respectively) are also displayed.

the significance of the excess is estimated at 1.5 σ -level in the 100 – 160 GeV search range.

Additional final states, which are particularly sensitive for $m_H > 200$ GeV, have been also analyzed. The $2l2\nu(l = e, \mu)$ analysis [28] requires a ee or $\mu\mu$ pair with a mass consistent with Z boson and large event MET. Assuming that the MET comes entirely from the Z decay, an invariant transverse mass m_T for the diboson pair can be computed, whose distribution in data can be analyzed to search for a broad excess of events on top of the background. The analysis excludes a SM Higgs boson at 95% CL in the interval 270 – 440 GeV. The $2l2q(l = e, \mu)$ analysis [29] studies final states with a lepton pair plus two high- p_t jets with an invariant mass consistent with a Z boson. The analysis sets 95% CL upper limits which for m_H in the range 350 – 400 GeV are at the level of the expected SM cross section. The $2l2\tau(l = e, \mu)$ analysis complements the $4l$ channel [30] and the observed upper limits at 95% CL are in the range 4 – 12 σ_{SM} .

Combination of results

The combination of Higgs boson searches [31] is based on the modified frequentist CLs construction [32]. For each analyzed decay mode, either a total number of selected events or a selected events distribution, depending on the specific analysis technique, has been used as input. Correlations of uncertainties across different channels have been taken into account. The procedure employs the generation of ensembles of pseudo-datasets for 183 Higgs boson mass hypotheses in the range 110 – 600 GeV, with a step size varying from 0.5 GeV at low masses (dictated by the $\gamma\gamma$ and $4l$ channels resolution) to 20 GeV at high masses (dictated by the Higgs boson width). The observed upper limits at 95% CL are consistent with expectations in the background-only hypothesis (Fig. 4-left) except for $m_H \approx 125$ GeV, where the limit is weaker than expected (Fig. 4-right)

FIGURE 4. Left: Observed and expected 95% CL upper limit σ/σ_{SM} as function of the Higgs boson mass. The observed values are shown by the solid line. The dashed line indicates the expected median of results for the background-only hypothesis. The ranges expected to contain 68% and 95% of all observed excursions from the median are shown with dark and light bands, respectively. The mass ranges excluded by LEP, Tevatron and this measurement are shown as hatched areas. Right: Same plot but zoomed in the low mass region.

due to the excess seen in $\gamma\gamma$ and $4l$ channels. The combined significance of the excess is 2.8σ . Accounting for LEE, the significance is 0.8σ in the range 110 – 600 GeV (2.1σ in the range 110 – 145 GeV). The m_H range 127.5 – 600 GeV is excluded at 95% CL (129 – 525 GeV at 99% CL).

Conclusions

The SM Higgs boson has been searched in CMS using five channels and employing data samples from the 2011 pp run at $\sqrt{s} = 7$ TeV corresponding to integrated luminosities in the range 4.6 – 4.8 fb^{-1} . The investigated Higgs masses are in the range 110 – 600 GeV. The combination of the searches excludes a SM Higgs boson at 95% CL in the mass range 127.5 – 600 GeV. An excess of events is seen for $m_H \approx 125$ GeV, with a significance which is not sufficient to claim for observation of a new state. The spectacular performances of the LHC machine have been confirmed in the 2012 run at $\sqrt{s} = 8$ TeV, providing CMS with the same amount of data as in 2011 after only a few months of data taking. The first public results based on the analysis of the entire 2011+2012 data sample have recently confirmed the excess at 125 GeV, with a significance at the level of 5σ [33]. Still additional analysis work has to be done, profiting of the increasing statistics provided by the LHC, in order to clarify the physics properties of the new state.

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