Higgs Boson Measurements in CMS with Run II Data

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Abstract Latest results from the CMS experiment on studies of Higgs boson production are presented. Studies involving the 125 GeV Higgs boson using various Standard Model production and decay modes have been performed using proton proton collisions from data accumulated during the LHC Run II with center-of-mass energy of 13 TeV. Similar datasets have also been used to place constraints on physics beyond the Standard Model involving extended Higgs boson sectors.

1 Introduction

The elucidation of the mechanism of electroweak (EW) symmetry breaking and the discovery of the Higgs boson (H) were one of the main goals before conceptualizing the design of the Compact Muon Solenoid (CMS) [1] experiment at the Large Hadron Collider (LHC). In the standard model (SM), the spontaneous symmetry breaking takes place through a complex scalar field which leads to the existence of a scalar particle—the Higgs boson. The Higgs field generates fermion masses via Yukawa interactions. Although model does not predict the mass of the Higgs boson, \( m_H \), production cross sections and decay probabilities of the Higgs boson are calculated using \( m_H \). In 2012, the ATLAS and CMS Collaborations discovered a Higgs boson [2–4] and measurements on its precise mass and properties continued thereafter [5]. This paper reports various Higgs boson production processes studied: gluon fusion (ggF), vector boson fusion (VBF), and associated production with vector bosons (VH, where \( V = Z, W \) bosons) or a pair of top quarks (ttH). The Higgs boson decays involving bosonic and fermionic modes have been studied using Run II data collected at center-of-mass energy \( \sqrt{s} = 13 \) TeV.

2 Standard Model Higgs Boson in Bosonic Decays

2.1 \( H \rightarrow ZZ \)

The Higgs boson production in the four lepton (4\( \ell \)) final state at \( \sqrt{s} = 13 \) TeV is an important channel in CMS. The analysis was performed to re-discover it at 13 TeV using 38.6 fb\(^{-1}\) of luminosity, and to measure the Higgs boson properties. With significant excess of events the measured signal strength modifier, relative to that of the SM Higgs boson production, is measured as \( \mu = 1.05^{+0.19}_{-0.17} \) in the combined ATLAS and CMS measurement of the Higgs boson mass [6]. The fiducial cross section at \( \sqrt{s} = 13 \) TeV with the corresponding

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experimental acceptance relevant to lepton kinematics and event topology, is predicted in the standard model to be $2.76 \pm 0.14$ fb, while observed it is $2.92^{+0.48}_{-0.44} \text{stat}^{+0.28}_{-0.24} \text{sys}$. The differential cross sections are measured as a function of the Higgs boson transverse momentum ($p_T$), the number of associated jets, and the associated leading jet $p_T$. The mass measurement based upon a 3D fit on the four lepton invariant mass $m_H = 125.26 \pm 0.20 \text{stat} \pm 0.08 \text{sys}$ GeV with the width constrained to $\Gamma_H < 1.10$ GeV at 95% confidence level (CL). The Higgs boson anomalous couplings are analyzed using a matrix element likelihood approach to simultaneously analyze the $H$ to $4\ell$ and associated production with two quark jets. The data collected at a $\sqrt{s} = 13$ TeV in Run II of the LHC are combined with the Run I data, collected at 7 and 8 TeV. No deviations from the standard model are observed and constraints are set on the anomalous HVV contributions, including the CP-violation parameter $f_{\alpha 3}$, details of which are summarized in [8].

2.2 $H \rightarrow \gamma \gamma$

Owing to the excellent mass resolution of the CMS electromagnetic calorimeter, $H \rightarrow \gamma \gamma$ is the most sought channel along with $H \rightarrow 4\ell$. This channel provides a clean final state with relatively small backgrounds. The main SM backgrounds are irreducible $\gamma \gamma$, $\gamma +$jet, and dijet events. The analysis is optimized in various SM production modes, namely, $ggF$, $VBF$, $t\bar{t}H$, and $VH$. In this decay channel, the Higgs boson is re-discovered with Run II integrated luminosity of 35.9 fb$^{-1}$ and the excess of events over the standard model background contributes to $\mu = 1.16^{+0.15}_{-0.14}$. The fiducial cross sections is measured using various requirements on the photons kinematics, their isolation, and the event topology [9]. A fair agreement between data and SM prediction is observed.

2.3 $H \rightarrow WW$

This analysis used 15.2 fb$^{-1}$ of luminosity at $\sqrt{s} = 13$ TeV. The $W^+W^-$ candidates are selected in events with an oppositely charged lepton pair, namely one electron and one muon, and large missing transverse momentum. The analysis has specific categories for gluon fusion production, vector boson fusion, and vector boson associated production with up to two jets, and two or three leptons in the final state. Adding the excess of events in each channel and further combining with Run I data (7 and 8 TeV), the observed (expected) significance is $4.3(4.1)$ $\sigma$ [10]. The cross section times branching fraction is found to be $1.05 \pm 0.26$ over the SM prediction.

3 Standard Model Higgs Boson in Fermionic Decays

3.1 $H \rightarrow \tau^+\tau^-$

The $H \rightarrow \tau^+\tau^-$ analysis was performed using 35.9 fb$^{-1}$ of luminosity collected at $\sqrt{s} = 13$ TeV [11]. Event categories are designed to separately target Higgs boson signal events produced by vector boson or gluon fusion. The hadron-plus-strips (HPS) algorithm based reconstruction concentrates on the hadronic decay modes of a $\tau$. Most of the $\tau$-lepton energy is carried by neutrinos which reduces the discriminating power of the invariant mass of the di-$\tau$ system. The results are extracted via maximum likelihood fits in two-dimensional planes giving an observed significance for Higgs boson decays to $\tau^+\tau^-$ pairs of 4.9 $\sigma$ as compared to the expected significance of 4.7 $\sigma$, as shown in Fig. 1 (left). The analysis combined with Run I data (7 and 8 TeV) gives a statistical significance of 5.9 $\sigma$. This is first observation of $H \rightarrow \tau^+\tau^-$ in a single experiment.

3.2 $H \rightarrow b\bar{b}$

The Higgs boson decaying to $b\bar{b}$ in association with an electroweak vector boson is studied for the following processes: $Z(\nu\nu)H$, $W(\nu\nu)H$, $W(e\nu)H$, $Z(\mu\mu)H$, and $Z(\ell\ell)H$. The search is performed in data samples corresponding to an integrated luminosity of 35.9 fb$^{-1}$ at $\sqrt{s} = 13$ TeV. An excess of events is observed in data, as shown in Fig. 1 (right), compared to the expectation in the absence of a $Hbb$ signal which corresponds to a statistical significance of observed (predicted) $3.3(2.8)$ $\sigma$. The signal strength is measured to be $1.2 \pm 0.4$. 

The combination with Run I data gives a statistical significance of observed (predicted) 3.8(3.8) \sigma with signal strength of 1.06^{+0.31}_{-0.29} \ [12].

3.3 $t\bar{t}H$

The Higgs boson—top quark Yukawa coupling is directly probed using Higgs boson production in association with a pair of top quarks (t\bar{t}H) using 35.9 fb$^{-1}$ of luminosity accumulated at $\sqrt{s} = 13$ TeV. Higgs boson decays involving ZZ*, WW*, and $\tau^+\tau^-$ are included. The event selection corresponds to events where at least one of the top quarks decays leptonically, by selecting events with two electrons or muons of the same charge, or with more than three electrons or muons, and hadronic jets compatible with the hadronization of b quarks. The fitted signal yields are compared with the expectation for a SM Higgs boson having $m_H = 125$ GeV. The observed (expected) best fit signal strength is $1.5^{+0.5}_{-0.5}(1.0^{+0.5}_{-0.4})$, with an observed (expected) significance of $3.3 (2.4) \sigma$ in the background only hypothesis. This result is obtained after combination with Run I data. The observed (expected) 95% CL exclusion limit on $\mu$, using the background only hypothesis, is 2.5(0.8) \ [13].

There is another search for $t\bar{t}H$ in final states with a $\tau$. This channel targets $t\bar{t}H$ production with at least one hadronically decaying $\tau$ lepton ($\tau_H$) in the final state. This channel is sensitive not only to the $H \rightarrow \tau^+\tau^-$ but also to the $H \rightarrow ZZ^*, H \rightarrow WW^*$ decay modes \ [14]. The event selection is similar to that for the multilepton analysis. The signal estimation is performed by extracting the signal rate by means of a maximum likelihood fit to the distribution of discriminating variables in various categories. A combination of multivariate techniques including boosted decision trees (BDT) and matrix element method (MEM) analyses are used to create the discriminating variables.

4 Summary

We have presented latest standard model Higgs boson results from LHC Run II data. Searches for the H(125 GeV) have been performed using the latest techniques which re-establishes its presence at $\sqrt{s} = 13$ TeV. The measurements are being extended for determining Higgs boson properties such as spin, width, couplings, and fiducial cross sections. We have summarized results involving bosonic and fermionic decay channels. CMS is measuring differential cross section with better precision in high resolution bosonic decay channels ($H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$). Analysis involving Higgs bosonic decay channel $H \rightarrow WW$ gives significant excess above $4 \sigma$ standard deviation. The Higgs fermionic decay $H \rightarrow \tau^+\tau^-$ is discovered in a single experiment for the first time. CMS has seen clear evidence of Higgs in another fermionic decay channel VH ($H \rightarrow bb$). The $t\bar{t}H$ production channel is the only possibility to study the top-Higgs coupling, since the Higgs mass is too low for
a Higgs decaying into a pair of top quarks. The analysis using Run II data exploiting multilepton final states gives significant excess above 3 \( \sigma \) standard deviation. New and hybrid analysis techniques mainly consisting of multivariate techniques are consistently used in almost every Higgs boson decay channel. The analysis in boosted Higgs boson decay topologies \( (H \rightarrow bb) \) has just started at the LHC.

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References

1. CMS Collaboration, The CMS experiment at the CERN LHC. JINST 3 S08004 (2008)
2. ATLAS Collaboration, Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Phys. Lett. B 716, 1 (2012). arXiv:1207.7214
3. CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. Phys. Lett. B 716, 30–61 (2012)
4. CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at \( \sqrt{s} = 7 \) and 8 TeV. J. High Energy Phys. 06, 081 (2013)
5. CMS Collaboration, Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV. Eur. Phys. J. C 75, 212 (2015)
6. CMS Collaboration, Combined Measurement of the Higgs boson mass in pp collisions at \( \sqrt{s} = 7 \) and 8 TeV with the ATLAS and CMS experiments. Phys. Rev. Lett. 114, 191803 (2015)
7. CMS Collaboration, Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at \( \sqrt{s} = 13 \) TeV. https://doi.org/10.1007/JHEP11(2017)047. arXiv:1706.09936
8. CMS Collaboration, Constraints on anomalous Higgs boson couplings in production and decay H \( \rightarrow 4l \). https://cds.cern.ch/record/2256097?ln=en
9. CMS Collaboration, Measurement of differential fiducial cross sections for Higgs boson production in the diphoton decay channel in pp collisions at \( \sqrt{s} = 13 \) TeV. https://cds.cern.ch/record/2257530
10. CMS Collaboration, Higgs to WW measurements with 15.2 fb\(^{-1}\) of 13 TeV proton-proton collisions. https://cds.cern.ch/record/2273908
11. CMS Collaboration, Observation of the SM scalar boson decaying to a pair of \( \tau \) leptons with the CMS experiment at the LHC. arXiv:1708.00373, https://cds.cern.ch/record/2264522
12. CMS Collaboration, Evidence for the Higgs boson decay to a bottom quark–antiquark pair. arXiv:1709.07497, https://cds.cern.ch/record/2278170
13. CMS Collaboration, Search for Higgs boson production in association with top quarks in multilepton final states at \( \sqrt{s} = 13 \) TeV. https://cds.cern.ch/record/2256103
14. CMS Collaboration, Search for associated production of a Higgs boson with a top quark pair in final states with a \( \tau \) lepton at \( \sqrt{s} = 13 \) TeV. https://cds.cern.ch/record/2257067