The Compact Muon Solenoid Experiment
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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.

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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.

Keywords Large Hadron Collider · Compact Muon Solenoid · Higgs Boson

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 conceptualising 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] [3] [4] and measurements on its properties continued thereafter [5]. This paper reports various Higgs boson production processes studied: gluon fusion (ggF), vector boson

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fusion (VBF), and associated production with vector bosons (VH , where $V = Z, W$ bosons) or a pair of top quarks ($t\bar{t}H$). 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 (4ℓ) final state at $\sqrt{s} = 13$ TeV is an important channel in CMS. The analysis was performed to re-discover it at 13 TeV 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 experimental acceptance relevant to lepton kinematics and event topology, is predicted in the standard model to be 2.76 ± 0.14 fb, while observed it is $2.92^{+0.48}_{-0.44}(\text{stat})^{+0.28}_{-0.24}(\text{sys})$ fb [7]. 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) [7]. The Higgs boson anomalous couplings are analyzed using a matrix element likelihood approach to simultaneously analyze the H to 4ℓ 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_{a3} , 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 $\gamma\gamma$, γ +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 data 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.

Fig. 1 Local p-value and significance as a function of the SM Higgs boson mass hypothesis. The observation (red, solid) is compared to the expectation (blue, dashed) in the $H \rightarrow \tau^+\tau^-$ decay channel at $m_H = 125.09$ GeV (left) [11]. In the case of $H \rightarrow b\bar{b}$, the output of the BDT discriminant clearly shows the excess of events over the expected SM background (right) [12].

2.3 $H \rightarrow WW$

This analysis used 15.2 fb^{-1} of luminosity at $\sqrt{s} = 13 \text{ TeV}$. 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 ($\sqrt{s} = 7$ 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 ± 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 $\sqrt{s} = 13 \text{ TeV}$ [11]. Event categories are designed to separately target Higgs boson signal events produced by vector boson or gluon fusion. The τ is reconstructed using the hadron-plus-strips (HPS) algorithm which exploits tracker and calorimeter information corresponding to τ_h decays with an efficiency of about 60%. Most of the τ -lepton energy is carried by neutrinos which reduces the discriminating power of the invariant mass of the di- τ 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 4.9σ as compared to the expected significance of 4.7σ , as shown in Figure 1 (left). The

analysis combined with Run I data (7 and 8 TeV) gives a statistical significance of 5.9σ . 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: $Z(\nu\nu)H$, $W(\mu\nu)H$, $W(e\nu)H$, $Z(\mu\mu)H$, and $Z(ee)H$. The search is performed in data samples corresponding to an integrated luminosity of 35.9 fb^{-1} at $\sqrt{s} = 13\text{ TeV}$. An excess of events is observed in data, as shown in Figure 1 (right), compared to the expectation in the absence of a $Hb\bar{b}$ signal which corresponds to a statistical significance of observed (predicted) $3.3(2.8)\sigma$. The signal strength is measured to be 1.2 ± 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 can be directly probed using Higgs boson production in association with a pair of top quarks ($t\bar{t}H$). 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 $m_H = 125\text{ GeV}$. 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 μ , 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 τ . This channel targets $t\bar{t}H$ production with at least one hadronically decaying τ lepton (τ_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 $\sqrt{s} = 13\text{ TeV}$. The measurements

are being extended for determining Higgs boson properties such as spin, width, couplings, and fiducial cross sections. CMS is measuring differential cross section with better precision in high resolution channels ($H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$). We have seen clear evidence of VH ($H \rightarrow b\bar{b}$) and $H \rightarrow \tau^+\tau^-$ is discovered in a single experiment for the first time. 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 ($H \rightarrow b\bar{b}$) has just started at the LHC.

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