Searches for additional Higgs bosons at CMS ^{*}

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Abstract

Description of a broad range of analyses about additional Higgs bosons in the context of Beyond Standard Model (BSM) physics performed at the CMS experiment at LHC.

Keywords: BSM, Higgs, CMS, LHC

1. Introduction

There are various indications for the physics Beyond Standard Model (BSM), which is a natural look for New Physics, as can be seen in Fig. 1, where last results from ATLAS and CMS are reported [1]. The discovered Higgs boson with a mass of 125 GeV theorized by the Standard Model (SM), can be the first member of an Extended Higgs Sector, as predicted by several BSM extensions.

Different searches are possible. *Direct searches* for additional Higgs bosons are possible from the decays of neutral and charged Higgs bosons. *Indirect searches* come from the interpretation of measured mass and couplings of light Higgs bosons in the extensions of the Standard Model. The analyses that will be presented have been performed at CMS experiment [2], mostly using the data collected during 2016. Among the possible analyses it will be described the decay of Higgs boson predicted by the SM in two pseudo scalars Higgs boson in different final states, the double Higgs production in BSM scenarios in different final states, the MSSM Higgs boson analyses, the charged and the invisible Higgs boson analyses and the Lepton Flavor Violation analysis.

Figure 1: The measured results for couplings and BSM for the combination of ATLAS and CMS are reported together with their uncertainties, as well as the individual results from each experiment [1].

2. Theoretical scenarios

The possible theoretical scenarios in which additional Higgs bosons are possible are the following:

- **Higgs singlet:** an additional Higgs singlet with an extra scalar H with a not negligible width at high m_H is introduced. This model includes two doublets and a singlet. There are 7 physical states,

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where one could be the SM Higgs boson (scalar) and another is a pseudo scalar a [3].

- **Higgs doublet:** an additional Higgs doublet is introduced. This model has 5 physical Higgs bosons and can be of different types according to the coupling to the leptons and to the quarks. The possible models are MSSM [4], NMSSM [5], hMSSM [6] and Two Higgs Doublet Model (2HDM) [7].
- **Higgs triplet:** this model is based on isospin-conserving implementation of Higgs triplets based on scalar content ($H^{\pm\pm}$) [8], [9].

3. $h_{125\text{GeV}} \rightarrow aa$ exotic decays

3.1. $h_{125} \rightarrow aa \rightarrow 4\mu$

This analysis studies the decay of the two pseudo scalars in a pair of oppositely charged muons. The analysis has been developed in a way to be model independent. Several SM processes can mimic this signal: bb , in which both b-quarks decay to a pair of muons via double semi-leptonic decay or resonances; *Prompt double J/Ψ* , which is an irreducible background; *EWK to 4 muons* from the electroweak $pp \rightarrow 4\mu$ process [10].

3.2. $h_{125} \rightarrow aa \rightarrow \mu\mu\tau\tau$

The di-muon pair has excellent mass resolution, di-tau pair has reasonable mass resolution and backgrounds are low. The reducible background for this analysis is represented by the events where at least one jet is misidentified as a lepton. Indeed it is used the fake rate technique. The analysis can be interpreted in the 2HDM+S type 3 scenario, which is the most sensitive scenario with large $\tan\beta$ [11].

3.3. $h_{125} \rightarrow aa \rightarrow b\bar{b}\tau\tau$

This analysis has a low signal acceptance due to trigger threshold, but the final state has a good sensitivity. The technique used to estimate the background is the fake rate, where are counted the events passing the identification and the isolation requirements. The most sensitive scenario is 2HDM+S type-3, with $\tan\beta = 2$ [12].

3.4. $h_{125} \rightarrow aa \rightarrow \mu\mu b\bar{b}$

For this analysis is valid the same theoretical scenario of previous analyses. The events are restricted in the mass range $20 \leq m_{\mu\mu} \leq 70$ GeV and the trigger is based on opposite sign and isolated di-muons events. The dominant background is Drell-Yan in di-lepton final state. The signal and background are obtained making a different fit of $m_{\mu\mu}$ from data [13].

3.5. $h_{125} \rightarrow aa \rightarrow 4\tau$

In this analysis two tau leptons decay into muons the other in any final state. The trigger indeed fires if there is a muon with high transverse momentum and isolated. The signal region is defined as $m_{\tau\mu\tau_X} \geq 4$ GeV. The background estimation is based on $\tau\mu\tau_X$ misidentification [13].

The results of all these analyses are summarized in the following diagram (Fig. 2), where the exclusion limits on the production cross-section are reported for each final state:

Figure 2: Expected and observed 95% CL exclusion limits for various exotic h boson decay searches performed with data collected at 8 and 13 TeV with the CMS detector.

4. Double Higgs production analyses

The double Higgs production process looks for a resonance decaying in two SM Higgs bosons in different theoretical scenario, already described. Four final states have been investigated at 13 TeV in CMS, keeping a trade off between the branching ratio and the purity.

4.1. $X \rightarrow hh \rightarrow b\bar{b}\tau\tau$

There are two possible analyses: one where the resonant candidate has a mass up to 1 TeV [14], the other from 1 TeV up to 4 TeV, called *boosted* analysis [15]. Both analyses look for a $h \rightarrow \tau\tau$ candidate in semileptonic ($e\tau_h, \mu\tau_h$) and fully hadronic ($\tau_h\tau_h$) final states, and a $h \rightarrow b\bar{b}$ candidate, using different categorization according to the number of b-jets in the event and applying a cut on Higgs boson masses. The main background is the $t\bar{t}$, which has been estimated with a BDT discrimination for *low mass* analysis and with a data driven technique for *boosted* analysis.

4.2. $X \rightarrow hh \rightarrow bbbb$

Also for this final state there are two different approaches: one where the resonant candidate has a mass up to 1 TeV, called *resolved* analysis [16], the other from 1 TeV up to 3 TeV, called *boosted* analysis [17]. The *resolved* analysis requires the presence of at least 3 b-jets at trigger level and that the di-jet systems should be compatible with Higgs boson mass. Two categories are defined according to the resonance mass, low and high mass regions, and the background is estimated from sideband regions in the (m_{h1}, m_{h2}) plane. The *boosted* analysis requires the presence of a jet with high transverse momentum at trigger level. Two categories are defined according to the b-tagging working points and the background is estimated from different control regions.

4.3. $X \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$

This analysis should provide the best sensitivity among the double Higgs production analyses, thanks to the high branching ratio of the $h \rightarrow b\bar{b}$ candidate and good significance from b-tagging information, and thanks to high trigger and selection efficiency for $h \rightarrow \gamma\gamma$ candidate. The main background is due to the non-resonant photons produced via QCD. The background estimation is based on BDT categorization and on the purity of the reduced 4-body mass. The final results have been performed in the $(m_{bb}, m_{\gamma\gamma})$ plane [18].

4.4. $X \rightarrow hh \rightarrow bbWW$

This analysis studies the two leptons and two neutrinos final state with opposite sign, excluding the tau lepton. This final state has a low branching ratio and large $t\bar{t}$ and Drell-Yan backgrounds. To estimate the background a Deep Neural Network (DNN) has been trained, using the parametrized learning information. The final results have been performed in the $(m_{jj}, \text{DNN output})$ plane [19].

The results of double Higgs analyses are summarized in the following diagram (Fig. 3), where the exclusion limits on the production cross-section of a resonance are reported:

5. MSSM Higgs analyses

5.1. $A/H/h \rightarrow \tau\tau$

This analysis targets the gluon fusion and b-associated production modes, so the events are separated into no b-tag and b-tag categories. Moreover the final states $e\tau$ and $\mu\tau$ are categorized according to the transverse mass. The total transverse mass, a new variable, is used as discriminating variable to extract signal.

Figure 3: Expected and observed 95% CL exclusion limits for different double Higgs final states performed with data collected at 13 TeV with the CMS detector.

The backgrounds have been estimated with the fake factor method in order to estimate the contribution from jet $\rightarrow \tau_h$ fakes [20].

5.2. $A/H \rightarrow b\bar{b}$

This analysis looks for the b-associated production mode. The main challenge is due to the huge QCD multi jet processes. So a dedicated b-tag trigger has been developed. The QCD background has been modeled with a data driven technique. The big challenge is to fit a large mass range [21].

5.3. $A/H/h \rightarrow t\bar{t}$

This analysis requires the presence of a same sign dilepton pair. This channel is very clean for new physics to show up, because of the very low background from SM. Different signal regions (SR) have been determined in terms of the lepton p_T , number of jets and bjets, H_T , M_T , such that various backgrounds/signals populate different regions. The fake rate technique has been applied in different SR. A possible interpretation is in terms of a heavy scalar with $M_H > 2m_{top}$ produced in association with top quarks [22].

5.4. $A/H \rightarrow \mu\mu$

This analysis requires the presence of a pair of oppositely charged muons with high transverse momentum and invariant mass $m_{\mu\mu} > 60$ GeV. Requiring $E_T^{miss} < 35$ GeV a high signal sensitivity has been obtained. A linear combination of two functions for the expected signal and background has been then used in an unbinned likelihood fit to the data. No evidence of MSSM Higgs bosons production has been observed in the mass range between 115 and 300 GeV [23].

6. Charged Higgs boson analyses

6.1. $H^+ \rightarrow \tau \nu$

The search for charged Higgs bosons in decays of $H^\pm \rightarrow \tau^\pm \nu_\tau$ has been performed in the fully hadronic final state. This analysis can be interpreted in the 2HDM scenario. The main backgrounds can be estimated using the fake rate technique. The observation agrees with the standard model prediction. Limits on the charged Higgs boson cross section times branching fraction have been set for the mass range between 180 GeV and 3 TeV [24].

6.2. $H^+ \rightarrow c\bar{b}$

The search for a light charged Higgs boson H^+ decaying to $c\bar{b}$ in top quark pair events using the CMS detector at the LHC have been performed. It is the first search for a charged Higgs boson in this decay mode. The final state then consists of four jets (three b quark jets), one lepton (electron or muon), and missing transverse energy. The main observable used in the analysis is the invariant mass of two jets, one of which is identified as a b quark jet. The dijet pair is selected from at least four jets in an event by a dedicated kinematic fitter and a maximum likelihood fit has been performed on m_{jj} . No signal for the presence of a charged Higgs boson has been observed and upper limits have been set at 95% confidence level from 1.1–0.4% for the charged Higgs boson mass in the range 90–150 GeV. This channel is enhanced and dominant in the flipped 2HDM scenario [25].

6.3. $H^+ \rightarrow cs$

The search for a light charged Higgs boson, originating from the decay of a top quark and subsequently decaying into a charm quark and a strange antiquark, has been performed. The decays lead to a final state comprising an isolated lepton, at least four jets and large missing transverse energy. The main background is the $t\bar{t}$ process. A kinematic fit with both top mass constraint has been used to reconstruct di-jet mass. No significant deviation has been observed in the data with respect to the standard model predictions, and model-independent upper limits have been set on the branching fraction, ranging from 1.2 to 6.5% for a charged Higgs boson with mass between 90 and 160 GeV [26].

6.4. $H^+ \rightarrow tb$

The search for a charged Higgs boson has been performed in top quark decays for $m_{H^\pm} < m_t - m_b$ and in the direct production $pp \rightarrow t(b)H^\pm$ for $m_{H^\pm} > m_t - m_b$. The final states considered are $\mu\tau_h$, di-lepton and lepton

plus jets. The main backgrounds are $t\bar{t}$, electroweak processes and jets faking a τ_h . The number of b jets and the H_T variable have been used as input for exclusion limits. No signal has been observed and 95% confidence level and upper limits have been set on the charged Higgs boson production. The combination of all considered decay modes and final states is used to set exclusion limits in the $m_{H^\pm} - \tan\beta$ parameter space in different MSSM benchmark scenarios [27].

6.5. $H^+ \rightarrow W^+ Z$

The search for charged Higgs bosons produced via vector boson fusion and decaying into W and Z bosons has been performed. The event selection requires three leptons (electrons or muons), two jets with large pseudorapidity separation and high dijet mass, and missing transverse momentum. The main irreducible background is WZ and the backgrounds with at least one fake lepton has been estimated with a fake rate technique. The transverse mass has been used for signal extraction. The observation agrees with the standard model prediction. Limits on the vector boson fusion production cross section times branching fraction for new charged physical states have set as a function of mass from 200 to 2000 GeV and interpreted in the context of Higgs triplet models [28].

6.6. $H^{\pm\pm} \rightarrow W^\pm W^\pm$

The first observation of electroweak production of same-sign W boson pairs in proton-proton collisions has been performed. Events are selected by requiring exactly two leptons (electrons or muons) of the same charge, moderate missing transverse momentum, and two jets with a large rapidity separation and a large dijet mass. The main background is due to the jets misidentified as leptons and a fake rate method in QCD control region has been used. In the signal region a two-dimensional fit on m_{jj} and m_{ll} has been done. The observed significance of the signal is 5.5 standard deviations, where a significance of 5.7 standard deviations is expected based on the standard model. Bounds are given on the structure of quartic vector boson interactions and on the production of doubly charged Higgs bosons [29].

6.7. $H^{\pm\pm} \rightarrow 3l/4l$

The search for a doubly-charged Higgs boson, $H^{\pm\pm}$ has been performed. The search considers final states with three lepton final states coming from the associated production and the four lepton final states coming

from the pair production plus hadronic taus. The contributions from fake objects are estimated using the *tight-to-loose* method measuring the efficiency for a fake object that passes the loose ID to also pass the tight ID in a di-jet control region. The analysis categories are separated by the number of taus associated to the $H^{\pm\pm}$. Lower bounds on the doubly-charged Higgs boson mass have been set for a variety of assumptions on its branching ratio to charged lepton pairs [30].

7. Invisible Higgs analyses

These analyses take into account different production modes: the gluon fusion, the vector boson fusion and the associated production [31] in which Higgs boson decays in invisible final states. The gluon fusion analysis requires no leptons in the final state and at least one energetic jet (from ISR, or hadronic decays of a W or Z boson), and large missing transverse energy. Different control regions are considered requiring di-muon, di-electron, single-muon, single-electron, and γ +jets. For the vector boson fusion the final state is characterized by the presence of two jets with large $\Delta\eta_{jj}$ and large m_{jj} , a large missing transverse energy well separated from any jets. The vector boson plus jets backgrounds are determined through a simultaneous maximum likelihood fit across 4 control regions and signal region, due to its big contribution. For the associated production the leptons from Z boson decay are expected to be isolated from hadronic activity. A MVA classifier has been employed to increase the sensitivity, using a set of 12 variables to train a multiclass BDT.

The upper limits on production cross section of each analysis and of the combined analyses are reported in Fig. 4.

8. Other BSM Higgs analyses

For completeness other two BSM Higgs analyses have to be only mentioned: the search for a new scalar resonance decaying to a pair of Z bosons, which has clean signature and manageable background, where the same strategy used for SM Higgs boson analysis has been used [32]; and the search for lepton flavour violating decays of the Higgs boson to $\mu\tau$ and $e\tau$, where a cut based and BDT analysis has been used to obtain the results reported in Fig. 5 [33].

9. Conclusion

A rich program of searches for Higgs bosons in the context of BSM has being pursued since Run-1. Direct

Figure 4: Observed and expected 95% CL upper limits on $\sigma B(H \rightarrow inv)/\sigma_{SM}$ for both individual production process, as well as their combination, assuming a SM Higgs boson with a mass of 125 GeV.

search of new physics is possible through the production of additional Higgs bosons decaying in Standard Model particles, but BSM Higgs bosons are still hiding. Many more BSM Higgs physics results still to come from full Run2 data taking.

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Figure 5: Constraints on the flavour violating Yukawa couplings from BDT results.

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