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Search for high-mass neutral Higgs bosons using the CMS detector

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We summarize the status of the searches for neutral Higgs bosons with masses greater than 200 GeV based on data collected by the CMS experiment at a center of mass energy of $\sqrt{s} = 13\,\text{TeV}$ in the years 2015 and 2016. The analyzed data corresponds to an integrated luminosity ranging from $2.3\,\text{fb}^{-1}$ to $12.9\,\text{fb}^{-1}$. The tested mass range could be increased with respect to earlier analyses, but no sign for a new heavy neutral resonance has been found in data so far.

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1. Introduction

With the discovery of a Higgs boson with an invariant mass of $m = 125\,\text{GeV}$ announced by the ATLAS and CMS experiment in 2012, the Standard Model (SM) of particle physics was complemented by one missing piece. Whereas in the SM a single massive scalar is enough in order to describe the mass generation of fermions and vector bosons, many theories beyond SM (BSM) predict a more complex Higgs sector featuring more, usually heavier Higgs bosons. In this paper, we present the status of the searches for an additional neutral Higgs boson by the CMS collaboration beyond an invariant mass of $200\,\text{GeV}$. This new resonance can couple to SM particle in a similar way as the SM Higgs boson. Therefore, all the SM Higgs boson search channels, like the decay to a pair of fermions or vector boson, need to be exploited. Furthermore, a heavier Higgs boson can also decay to other Higgs boson such that the SM Higgs boson can be used as probe for an extended Higgs sector.

2. Status after LHC Run-1

In Reference [1], a summary of the results of many high-mass BSM Higgs boson searches performed by the CMS collaboration from LHC Run-1 is presented. Exclusion limits of the different searches have been interpreted consistently in several models for extended Higgs sectors. In Figure 1, the constrained parameter space of a particular two Higgs doublet model as well as the hMSSM is depicted. The different colors represent the 95% confidence level exclusion limits of different BSM Higgs boson searches. One can clearly observe that those different analyses constrain different parts of the parameter space. This originates from the differing coupling structure of the heavy Higgs boson to the up-/down-type fermions, vector bosons, and Higgs bosons in those different models and different areas of the parameter space. These two examples underline the

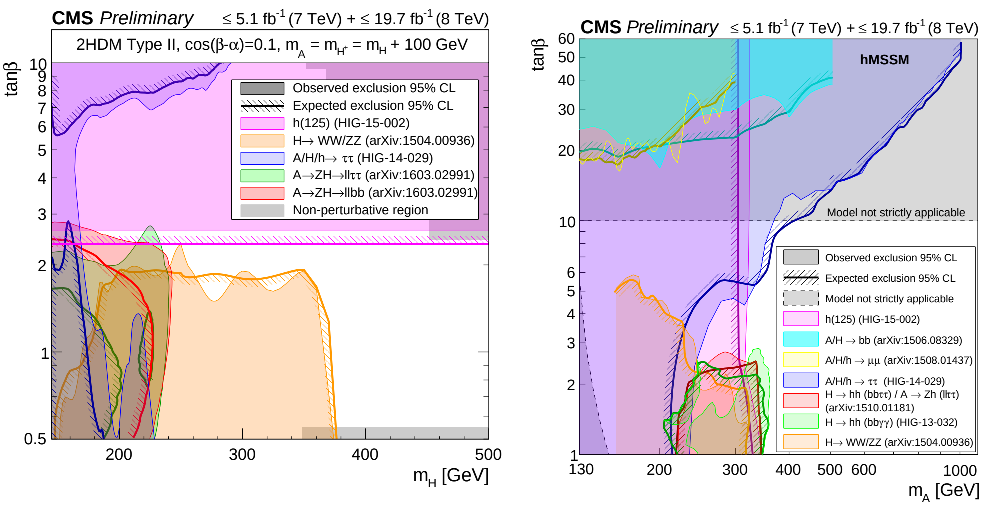

Figure 1: Status of the search for an extended Higgs sector after LHC Run-1 for a generic 2HDM Type-II (left) and the hMSSM (right). Different searches are necessary in order to cover the full parameter space. [1]

importance of a wide search program for this new heavy Higgs boson as pursued within the CMS collaboration.

3. Searches for a heavy Higgs boson decaying to fermions

One of the standard search channels in MSSM models is the decay $H \to \tau\tau$, as very often down-type fermion couplings are enhanced and the di-tau final state provides a rather clean search topology. CMS has performed an update of this analysis based on an integrated luminosity of $2.3\,\text{fb}^{-1}$ at a center of mass energy of $\sqrt{s} = 13\,\text{TeV}$ in Ref. [2]. No excess over the SM-only hypothesis has been found in the mass range from 100 GeV to 3 TeV. The excluded parameter space could be largely increased. More details concerning this analysis can also be found in Ref. [3].

Another very important channel in the sector of searches for heavy Higgs bosons decaying fermionically is the decay into a pair of bottom quarks. CMS presents first results in this search channel at a center of mass energy of 13 TeV and an integrated luminosity of $2.69\,\text{fb}^{-1}$ in Ref. [4]. The search is implemented as a resonance search in the di-jet mass spectrum, requiring two reconstructed b-jet and no further isolated lepton in the event. In order to improve the mass resolution and scale, a special final state radiation recovery mechanism taking into account additional particles outside of the b-jet cone has been developed. The cross section limits are extracted from a maximum likelihood fit to the di-jet mass spectrum, where the background is modelled with an empiric falling function. Figure 2 (left) shows a window of the search range where the dashed line indicates a simulated resonance with $m_X = 750\,\text{GeV}$. In Figure 2 (right), the 95% CL limits on the cross section are depicted for different spin hypotheses. No excess above the background-only hypothesis can be found in a range $m_X = 500\,\text{GeV} - 1.2\,\text{TeV}$. The purple line indicates the expected cross section in a spin-2 graviton model and it demonstrates that the analysis is starting to be sensitive to these models in the low mass region.

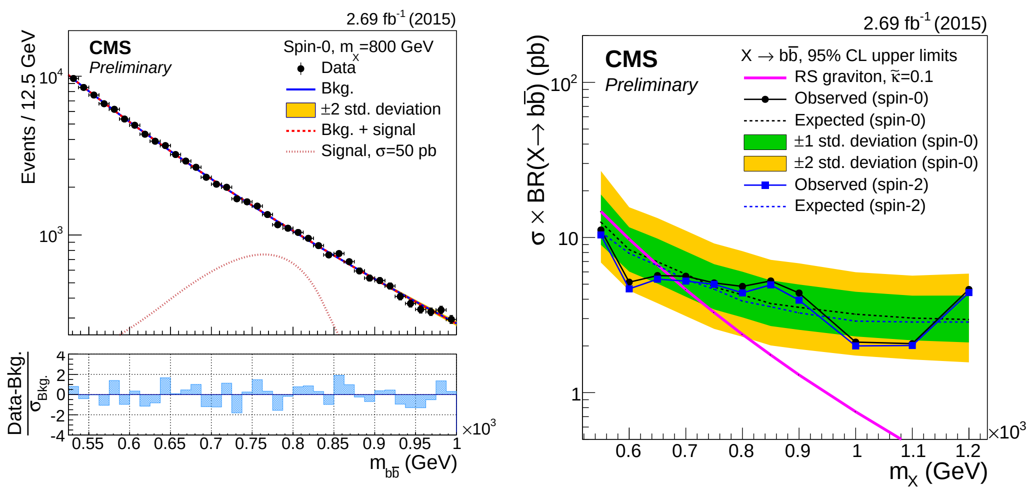

Figure 2: Left: Window of the di-jet mass spectrum with an simulated signal of $m = 750\,\text{GeV}$ overlayed. Right: 95% CL limits on the cross section for the spin-0 and spin-2 hypothesis. [4]

4. Searches for a heavy Higgs boson decaying to vector bosons

The CMS collaboration has already presented a few results on the search for a heavy Higgs boson decaying into four leptons based on the data collected in 2015 [5, 6]. We will focus in the following on the update of the analysis in the four charged lepton final state based on an integrated luminosity of $12.9\,\mathrm{fb}^{-1}$ at a center of mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$ [7]. The search for the high-mass Higgs boson has been divided into the three sub-channels $4e$, 4μ, and $2e2\mu$ and, compared to the SM Higgs boson analysis, into a reduced number of categories (VBF-tagged and untagged). A lot of effort has been invested in order to treat interference effects between ZZ background, the high-mass tail of the SM Higgs boson resonance and a new heavy Higgs boson resonance correctly. It is shown in Ref. [8] that those effects can have a significant impact on the shape and position of the new resonance peak. Figure 3 (left) shows the reconstructed four-lepton mass spectrum. Note that the SM Higgs boson signal as well as the ZZ background are parts of the signal model in this analysis. In order to extract cross section limits, an unbinned likelihood fit to the four-lepton mass has been performed scanning a mass range $m_X \in [130\,\mathrm{GeV}, 3\,\mathrm{TeV}]$ and a resonance width $\Gamma \in [0\,\mathrm{GeV}, m_X]$. VBF and VH production has been considered, where the contribution of the different production mechanism has been modelled in a parameter which has been fixed or kept floating in different fits. Figure 3 (right) shows the cross section limit in the four lepton channel in the floating production mode scenario for different assumptions for the resonance width. Note that the $1/2\sigma$ intervals of the expected limit are only drawn for the zero-width scenario. No significant excess above the background-only hypothesis can be observed in a mass range $m = 130\,\mathrm{GeV} - 3\,\mathrm{TeV}$.

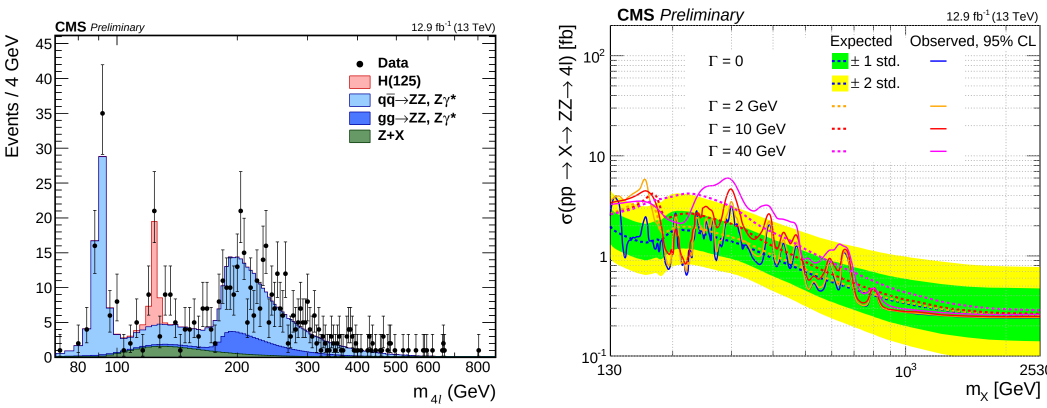

Figure 3: Left: Four-lepton mass spectrum. Right: 95% CL limits on the cross section for different hypotheses on the resonance width. [7]

First results of a resonance decaying into a pair of W bosons extending to the high-mass regime is presented in Ref. [9]. In this analysis, only leptonically decaying W bosons are considered and, in order to reduce the Drell-Yan background, only the mixed flavour channel $e\mu$ is used. The analysis is subdivided into three categories (0-jet, 1-jet, and VBF-tagged). As for the ZZ analysis, interference effects between WW background, SM Higgs boson, and the new resonance has been considered. The signal is extracted using a template shape analysis based on an improved transverse mass observable which takes also into account the longitudinal momentum information of the leptons. Figure 4 (left) shows this transverse mass distribution in the 0-jet category. The cross section limits are shown in Figure 4 (right) assuming the SM width for a high-mass Higgs boson. The observed and expected limits are well in agreement and no significant excess can be found up to $m = 1\,\text{TeV}$.

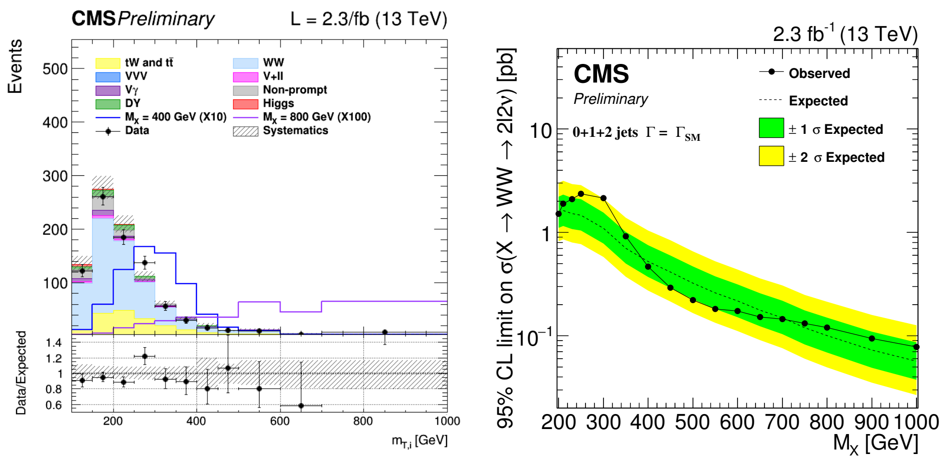

Figure 4: Left: Improved transverse mass observable taking into account the longitudinal momentum information of the lepton. Right: 95% CL limit on the cross section in a mass range up to 1 TeV. [9]

5. Searches for a heavy Higgs boson decaying to SM-like Higgs bosons

With increased collision energy and increasing integrated luminosity, searches for a heavy resonance decaying into two SM Higgs bosons become more and more of relevance. CMS has made updates public on di-Higgs boson searches in several search channels [10, 11, 12]. An overview of the status of the search for double Higgs boson production can be found in Ref. [13]. In the following, we focus on the search for $H \to h(125)h(125) \to bb\tau\tau$ using data corresponding to an integrated luminosity of $12.9\,\text{fb}^{-1}$ at a center of mass energy of 13 TeV [10]. Three different channels have been considered in this search according to the possible decay modes of the tau-lepton ($bbe\tau_h$, $bb\mu\tau_h$, $bb\tau_h\tau_h$). Furthermore, three categories are implemented: Two resolved categories with one or two b-tagged jets ($R = 0.4$) in the event and a new boosted category, which features one b-tagged large jet ($R = 0.8$). After a rough preselection regarding the invariant mass of the di-jet and di-lepton system with respect to the SM Higgs boson mass, the event is kinematically fitted. With the known SM Higgs boson mass, the signal event is highly constrained which can be exploited in order to get a full four-vector reconstruction of the tau leptons. Furthermore, in this way the unknown heavy Higgs boson mass is reconstructed to a precision of about 10%. This observable is also finally used for the signal extraction and limit setting. Figure 5 (left) shows the heavy Higgs boson mass after the kinematic fit in the resolved, 2 b-tag category. The SM background features a falling slope, where it is obvious that a potential signal would appear as a peak on top of the spectrum. In Figure 5 (right) the cross section limit is depicted. Within the 2σ uncertainty, the expected limit follows the observed one such that no significant excess can be found within a mass range of $m = 250 - 900\,\text{GeV}$.

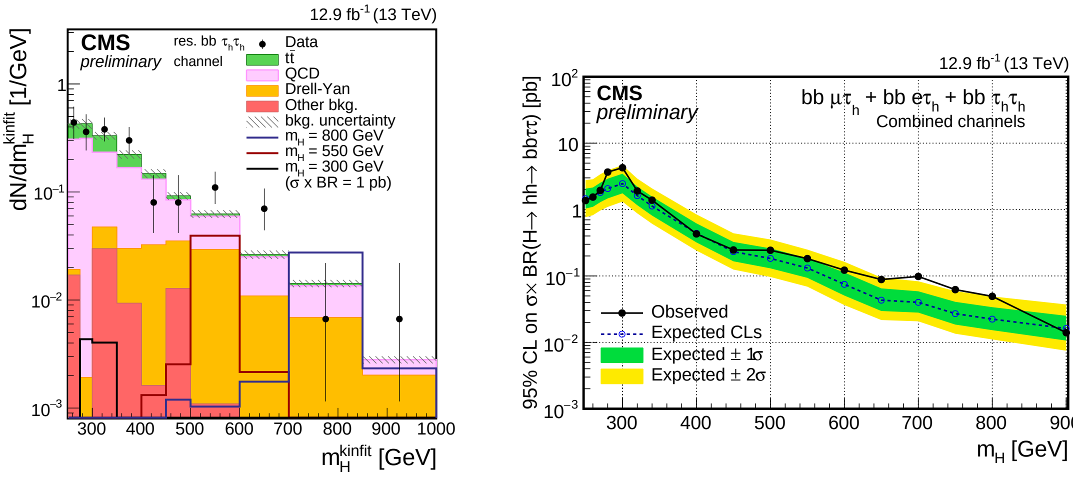

Figure 5: Left: Invariant mass of heavy Higgs after a kinematic fit. Right: 95% CL limit on the cross section in a mass range up to 900 GeV. [10]

6. Conclusions

The CMS collaboration pursues a rich search program for an additional, heavier Higgs boson. Many analyses have been updated using LHC data from 2015 and 2016 up to integrated luminosities of 12.9 fb^{-1}. The tested mass ranges could be significantly enlarged, but up to now no significant excess with respect to the SM-only hypothesis can be reported in all searches.

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