PROCEEDINGS OF SCIENCE

Searches for heavy Higgs bosons decaying to light Higgs bosons with a mass of 125 GeV

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Searches for Higgs bosons decaying to a pair of Higgs bosons (hh or hA) or for a Higgs boson decaying to Zh/ZA are presented. Different analyses involving Higgs boson decays into bottom-quarks, tau pairs, and diphotons will be summarized in this talk.

The European Physical Society Conference on High Energy Physics
22-29 July 2015
Vienna, Austria

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PoS(EPS-HEP2015)117

1. Introduction

The discovery of a 125 GeV Higgs boson at the ATLAS and CMS experiments in 2012 [1, 2] has since changed the field of Beyond the standard model (BSM) Higgs searches. The valid options for BSM theories have been limited to those which can incorporate a Higgs boson with a mass close to 125 GeV and coupling properties consistent with those measured at the LHC.

Many such BSM models predict the existence of a heavier resonance decaying into final states containing the 125 GeV Higgs boson. An example of such a process is shown in Figure 1, in which an unknown resonance X produced via gluon fusion decays into a pair of Higgs bosons, which each decays to a b-anti b quark pair. For a particular choice of model, X could be a radion [3, 4], graviton [5] or a heavier Higgs boson.

Heavier Higgs bosons are predicted by Two Higgs Doublet Model (2HDM) scenarios [6, 7, 8], in which the addition of a second Higgs doublet leads to 5 physical Higgs bosons, 3 of which are neutral - the pseudoscalar A, and the scalar bosons H and h. Typically such models are expressed in terms of benchmark quantities; commonly used are $\tan\beta$ and α, the ratio of the vacuum expectation values and the mixing angles of the two Higgs doublets respectively. In such a model, either of the scalar H or h bosons can be the 125 GeV SM-like Higgs boson discovered at the LHC. The minimally supersymmetric standard model (MSSM) is an example of a 2HDM motivated by supersymmetry [9]. Depending on the choice of mass hierarchy in such a model, the processes $\mathrm{H} \to \mathrm{hh}$, $\mathrm{A} \to \mathrm{Zh/H}$ or $\mathrm{H/h} \to \mathrm{ZA}$ are possible.

In the following proceedings, several analyses are described in which a heavier resonance decays into a final state containing at least one 125 GeV Higgs boson. The analyses all use the 8 TeV dataset taken by CMS during Run 1 of the LHC, which amounts to up to 19.8 fb^{-1} of data.

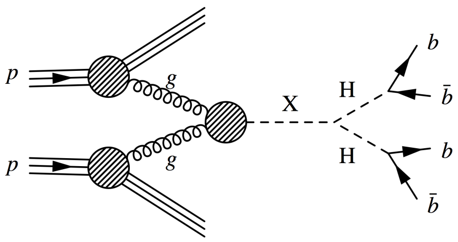

Figure 1: Illustration of an unknown resonance X, produced by gluon-fusion, decaying into a pair of Higgs bosons which each decay into a b-anti b quark pair.

2. Searches in HH/hh final states

2.1 Search for X$\to$ HH $\to \gamma\gamma$bb

The X$\to$ HH $\to \gamma\gamma$bb analysis [10] uses the cut based $\mathrm{H} \to \gamma\gamma$ selection [11] to select the two photons. Two jets are selected to form the bb candidates, and the events are categorised according to whether 0, 1 or 2 of these jets are b-tagged. The 0 b-tagged category has low purity and is used for cross-checks, while the 1 b-tagged (medium purity) and 2 b-tagged (high purity) categories are used as signal regions.

PoS(EPS-HEP2015)117

A range of masses for the candidate particle X is considered between $260 < m_X < 1100\,\mathrm{GeV}$. The optimal variable for signal extraction is different for lower and higher mass signal hypotheses. For a candidate particle with $m_X < 400\,\mathrm{GeV}$, a fit is made to the diphoton mass $m_{\gamma\gamma}$, while applying requirements in windows of the 4-body mass $m_{\gamma\gamma jj}$. The fit is performed to data using a functional form for the background and signal, and an example can be seen in Figure 2 (left) for the medium purity event category and a signal hypothesis of $m_X = 300\,\mathrm{GeV}$. For a candidate particle with mass $m_X > 400\,\mathrm{GeV}$, the 4 body mass $m_{\gamma\gamma jj}$, reconstructed using a kinematic fitting method, is used for the fit for signal extraction.

Model independent limits on cross section times branching fraction for the $X \to HH \to \gamma\gamma bb$ process are set and compared to predictions from radion and graviton models, as can be seen in Figure 2 (right). The analysis excludes a radion with $\Lambda_R = 1\,\mathrm{TeV}$ for masses below 0.97 TeV and the RS1 KK-graviton with masses between 340 and 400 GeV.

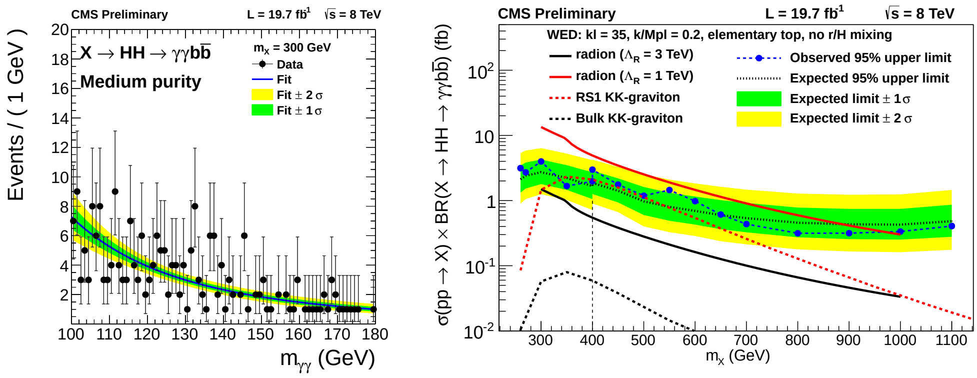

Figure 2: Left: Example of a fit for signal extraction in the medium purity category. The fit is performed to the variable $m_{\gamma\gamma}$ for a signal hypothesis of $m_X = 300\,\mathrm{GeV}$. Right: Expected and observed limit on the cross section times branching fraction for the $X \to HH \to \gamma\gamma bb$ process from the combination of all categories. The limit is compared with predictions for choices of radion and graviton models [10].

2.2 Search for $X \to HH \to bbbb$

This search [12] takes a similar model independent approach considering signal hypothesis masses between $270 < m_X < 1100\,\mathrm{GeV}$ and comparing to radion and graviton models. This analysis is also separated into lower and higher signal masses for the most optimal signal extraction; for the lower masses ($m_X < 450\,\mathrm{GeV}$) the candidate jets are paired requiring a combined invariant mass as close as possible to 125 GeV, whereas for higher masses ($m_X > 450\,\mathrm{GeV}$) jets which have the smallest $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ are paired. The model independent limits for the radion and graviton signal hypotheses are shown in Figure 3. The analysis is able to exclude a radion with $\Lambda_R = 1\,\mathrm{TeV}$ for masses between 300 and 1100 GeV, and a KK-graviton with masses between 380 and 830 GeV.

2.3 Search for $H \to hh \to bb\tau\tau$

The $H \to hh \to bb\tau\tau$ analysis [13] uses the inclusive $H \to \tau\tau$ [14] selection to select a candidate $\tau\tau$ pair, in any of the three most sensitive channels $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$, where τ_h indicates

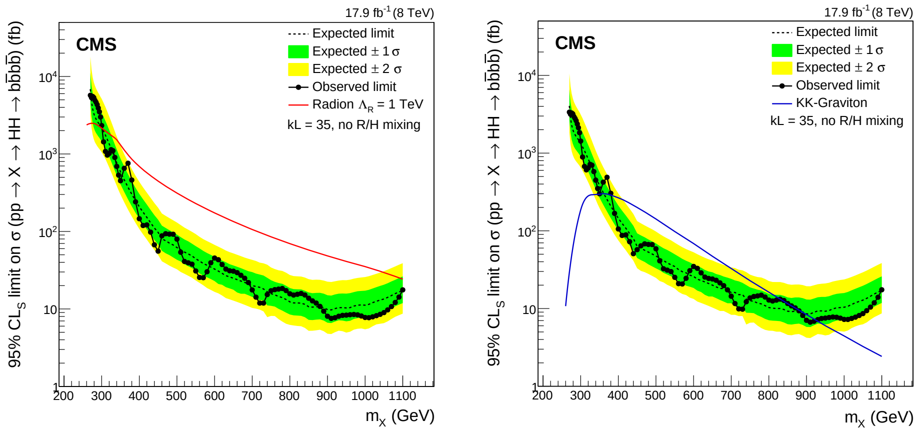

Figure 3: Expected and observed limit on the cross section times branching fraction for the X→ HH → bbbb process for the radion (left) and graviton (right) signal hypotheses [12].

a hadronically decaying tau. Two jets are required to form the candidates from the h → bb decay, and the events are categorised according to whether 0, 1 or 2 of these jets are b-tagged.

A selection is applied on the reconstructed di-tau mass $m_{\tau\tau}$ and di-jet mass m_{jj} in windows around 125 GeV, specifically $70 < m_{jj} < 150$ GeV and $90 < m_{\tau\tau} < 150$ GeV. The signal extraction is performed to the 4-body mass, reconstructed using a kinematic fit and denoted m_H^{kinfit}. An example such distribution, for events in the $\mu\tau_h$ final state in which one of the jets is b-tagged, is shown in Figure 4 (left).

A model independent limit on the H → hh → bb$\tau\tau$ process is shown in Figure 4 (right). Model dependent results in 2HDM and MSSM interpretations are produced for this analysis in combination with the A → Zh → $\ell\ell\tau\tau$ analysis described in section 3.2.

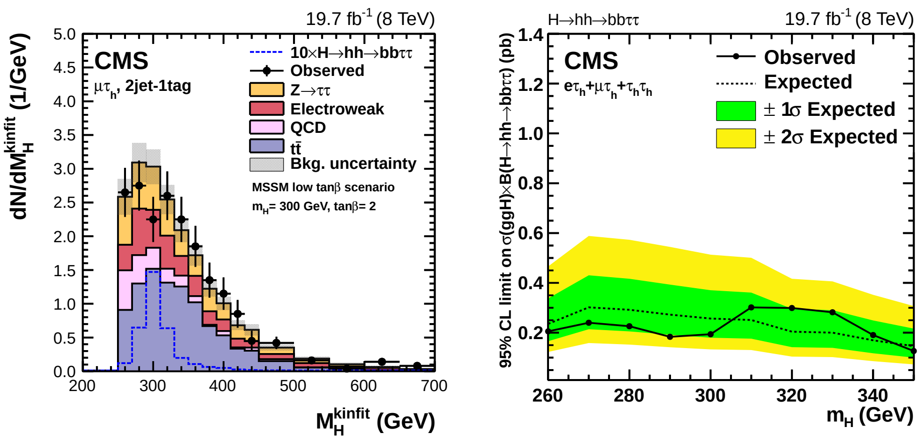

Figure 4: Left: Example 4-body mass distribution as extracted from the kinematic fit. Right: Expected and observed limit on cross section times branching fraction for the H → hh → bb$\tau\tau$ process for the combination of all channels and categories [13].

3. Searches in ZH/Zh/ZA final states

3.1 Search for $\mathrm{A} \to \mathrm{Zh} \to \ell\ell \mathrm{bb}$

For selecting events in a final state containing a Z boson, the clean signatures from $\mathrm{Z} \to \ell\ell$ ($\ell =$e, μ) are used. The candidate bb pair for this analysis [15] is selected using two jets, both of which pass the loose b-tagging working point and one of which passes the medium working point. The 4-body mass $\mathrm{m}_{\ell\ell\mathrm{bb}}$ is reconstructed using a kinematic fitting method. For signal extraction, a 2D fit is performed to the 4-body mass and a BDT discriminator, trained in 3 different ranges of $\mathrm{m_A}$ hypotheses.

The results of this analysis are presented in both model independent and model dependent forms. The model independent limit on cross section times branching fraction for the $\mathrm{A} \to \mathrm{Zh} \to \ell\ell\mathrm{bb}$ process is shown in Figure 5 (left). Model dependent limits are set in type-I and type-II 2HDM scenarios in which $\mathrm{m_H}$ and $\mathrm{m_A}$ are fixed to particular values. The exclusion is expressed in the 2D plane of $\tan\beta$ and $\cos(\beta - \alpha)$. An example of such an exclusion, for a type-II 2HDM with $\mathrm{m_A} = \mathrm{m_H} = 300\,\mathrm{GeV}$ is shown in Figure 5 (right).

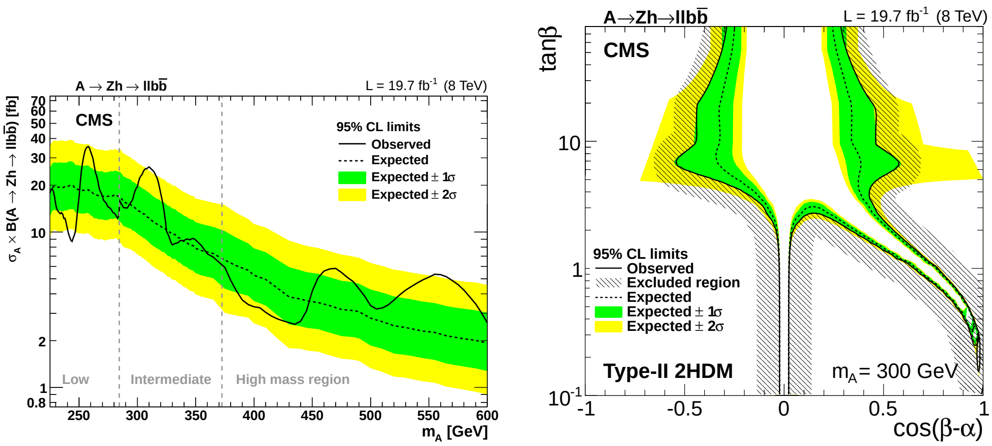

Figure 5: Left: Expected and observed limit on cross section times branching fraction for the $\mathrm{A} \to \mathrm{Zh} \to \ell\ell\mathrm{bb}$ process. Right: Expected and observed limit in a 2HDM type-II scenario in which $\mathrm{m_A} = 300\,\mathrm{GeV}$ [15].

3.2 Search for $\mathrm{A} \to \mathrm{Zh} \to \ell\ell\tau\tau$

In this final state [13] the same approach is made of selecting $\mathrm{Z} \to \ell\ell$ events. For the tau pair the 4 most sensitive final states are used $\mathrm{e}\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, and $\mathrm{e}\mu$ are used. The 4-body mass $\mathrm{m_A}$ is reconstructed by combining the 4-vectors from the Z boson and the $\tau\tau$ candidates and is the variable used for signal extraction. An example of one such distribution is shown in Figure 6 (left) for the $\tau_h\tau_h$ final state using $\mathrm{Z} \to \mathrm{ee}$ decays. A total of 8 different channels are combined for all possible combinations of Z boson and $\tau\tau$ final states.

The model independent limit on cross section times branching fraction for the $\mathrm{A} \to \mathrm{Zh} \to \ell\ell\tau\tau$ process is shown in Figure 6 (right). Model dependent limits are also set in combination with the $\mathrm{H} \to \mathrm{hh} \to \mathrm{bb}\tau\tau$ analysis described in section 2.3. These are set in a low-$\tan\beta$ appropriate MSSM scenario [16] in Figure 7 (left) and in a type-II 2HDM scenario (the same scenario as shown in the previous section) in Figure 7 (right). Note that following the conference further work has produced updated limits, so these figures are modified with respect to those shown in the conference talk.

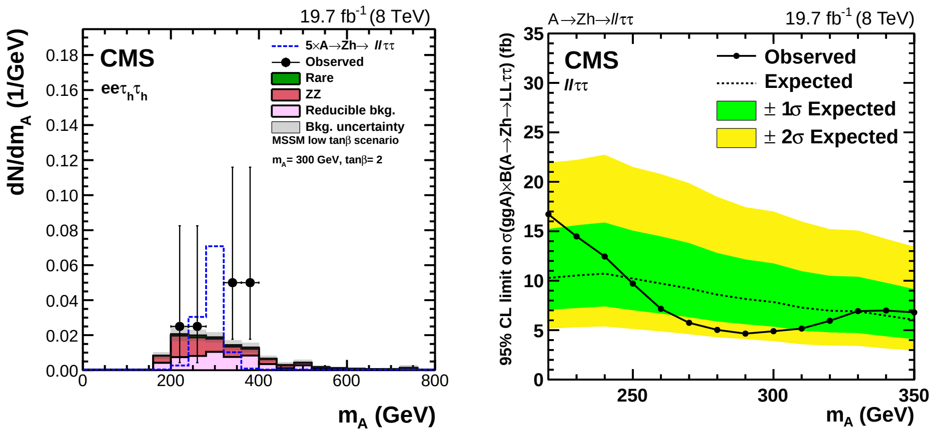

Figure 6: Left: Example 4-body mass distribution for events in the $\tau_h\tau_h$ channel in which the Z boson decays to ee. Right: Expected and observed limit on cross section times branching fraction for the A $\rightarrow$ Zh $\rightarrow \ell\ell\tau\tau$ process for the combination of all channels and categories [13].

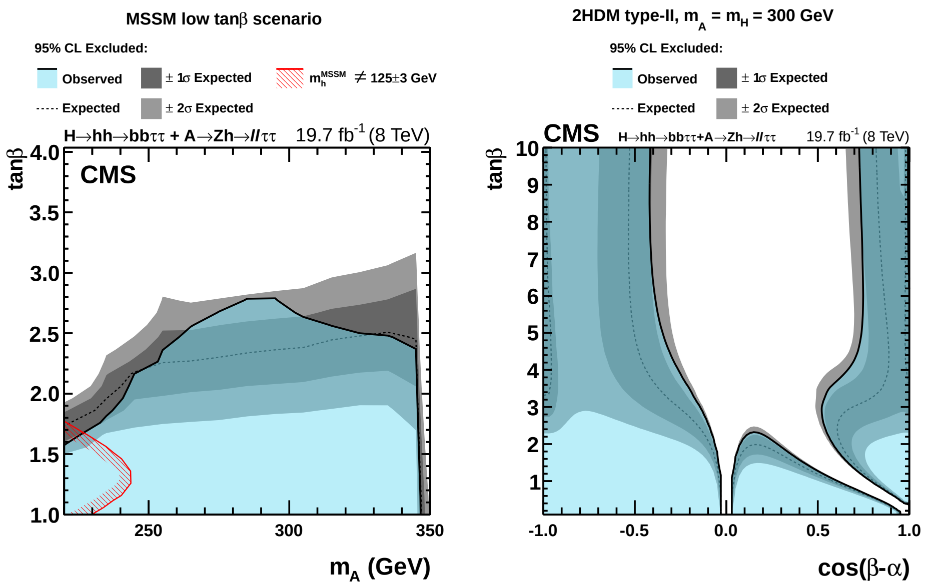

Figure 7: Expected and observed limit in the MSSM low-tanβ scenario (left) and the type-II 2HDM scenario in which $m_A = m_H = 300\,$GeV (right) [13].

Note that a more model independent approach to both A $\rightarrow$ Zh analyses, in which both possible mass hierarchies $m_H > m_A$ and $m_A > m_H$ are considered, is been illustrated in [17]. Interpretations in 2HDM scenarios can also be found in this publication.

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PoS(EPS-HEP2015)117