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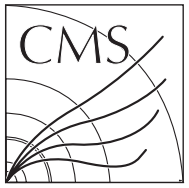

**The Compact Muon Solenoid Experiment**

# Conference Report

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# Search for new resonances decaying into two Higgs bosons at CMS

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**Abstract**

Searches for resonant production via a new boson X which decays either to two Higgs bosons (HH) or to one Higgs boson and a new scalar Y (YH), having a mass $m_{\mathrm{Y}} < m_{\mathrm{X}} - m_{\mathrm{H}}$, are presented. The results are based on proton-proton collision data collected by the CMS experiment at the LHC from 2016 to 2018 at a center-of-mass energy of 13 TeV. The data corresponds to an integrated luminosity of 138 $\mathrm{fb}^{-1}$. The final states considered include a pair of bottom quarks with two W bosons or two photons, and a pair of photons with two $\tau$ leptons. Model independent analyses are performed with a narrow-width approximation for the new boson X in different mass ranges depending on the final states. No evidence for the presence of a signal is observed and corresponding upper limits on the $\mathrm{X} \to \mathrm{HH}/\mathrm{YH}$ production cross section are set. Limits are also obtained on the resonant HH production for resonances with spin-0 and spin-2 assumptions in extra dimensions. Both limits on the resonant HH and YH production are interpreted within the MSSM and NMSSM benchmark scenarios, as well as models in the Extended Higgs Sector. Finally, a combination of the results of these searches is provided together with constraints on different beyond the standard model scenarios.

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PROCEEDINGS OF SCIENCE

# Search for new resonances decaying into two Higgs boson at CMS

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Searches for resonant production via a new boson X which decays either to two Higgs bosons (HH) or to one Higgs boson and a new scalar Y (YH), having a mass $m_{\mathrm{Y}} < m_{\mathrm{X}} - m_{\mathrm{H}}$, are presented. The results are based on proton-proton collision data collected by the CMS experiment at the LHC from 2016 to 2018 at a center-of-mass energy of 13 TeV. The data corresponds to an integrated luminosity of 138 $\mathrm{fb}^{-1}$. The final states considered include a pair of bottom quarks with two W bosons or two photons, and a pair of photons with two $\tau$ leptons. Model independent analyses are performed with a narrow-width approximation for the new boson X in different mass ranges depending on the final states. No evidence for the presence of a signal is observed and corresponding upper limits on the $\mathrm{X} \rightarrow \mathrm{HH/YH}$ production cross section are set. Limits are also obtained on the resonant HH production for resonances with spin-0 and spin-2 assumptions in extra dimensions. Both limits on the resonant HH and YH production are interpreted within the MSSM and NMSSM benchmark scenarios, as well as models in the Extended Higgs Sector. Finally, a combination of the results of these searches is provided together with constraints on different beyond the standard model scenarios.

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*Speaker

## 1. Introduction

The discovery of the Higgs boson, H, in 2012 [1, 2] marked a significant milestone in particle physics. Subsequent measurements of its properties and couplings have advance the understanding of electroweak symmetry breaking and the origin of the mass of elementary particles. After 12 years of the discovery, present data has shown that the measured production and decay modes of the H boson [3, 4] are in agreement with the SM expectations, which is a scalar particle spin-0 and even parity with mass of 125.2 GeV [5, 6].

Despite extensive studies on its properties and couplings, several questions about the Higgs sector remain unanswered. The H boson could serve as a probe to explore new physics beyond the Standard Model (BSM). Various BSM theories, including Warped Extra Dimensions (WED), Extended Higgs Sector (2HDM, 2HDM+S, TRSM), and Supersymmetric Models (MSSM, NMSSM), predict resonant HH/HY production. This report discusses the search for new resonances decaying into a pair of Higgs bosons (HH) and one Higgs boson with a new scalar Y (YH).

## 2. Searches for $X \to HH/YH$ at CMS

The CMS experiment at the LHC is designed to study a wide range of physics phenomena [7], [8]. The data used in these analyses corresponds to an integrated luminosity of 138 $fb^{-1}$, collected during Run 2 (2016-2018) at a center-of-mass energy of 13 TeV. The searches for new resonances are performed in various final states resulting from decay modes of two scalar bosons (HH or YH).

This section describes searches for resonances decaying into two H bosons with a mass of 125 GeV, and one H boson with a new scalar Y in three different final states published by the CMS experiment.

### 2.1 $X \to HH/YH \to \gamma\gamma\tau\tau$

A search for the production of two scalar bosons in the $\gamma\gamma\tau\tau$ final state is presented [9]. Although the H boson decaying into two photons and two tau leptons has small branching fraction, the two photons provide a clear signal that is easy to detect and measure accurately. The additional tau leptons in the event help to better distinguish the signal from background processes. Altogether, there are four different search channels performed in this analysis: resonant HH production via a spin-0 particle, $X^{(0)} \to HH$; resonant HH production via a spin-2 particle, $X^{(2)} \to HH$; resonant $X \to YH$ production, $X \to H(\gamma\gamma)Y(\tau\tau)$; resonant $X \to YH$ production, $X \to H(\tau\tau)Y(\gamma\gamma)$ in low and high mass regions.

For each search channel, a simultaneous maximum likelihood fit is performed to the $m_{\gamma\gamma}$ distributions in data in the corresponding analysis categories. No significant deviation from the background-only hypothesis is observed. This analysis considers a narrow-width approximation for $260 \leq m_X \leq 1000$ GeV. Fig. 1 shows the upper limits on the resonant production cross section as a function of the resonant mass, $m_X$, for the $X^{(0)} \to HH$ and $X^{(2)} \to HH$ searches.

The upper limits on the resonant production cross section for the $X \to H(\gamma\gamma)Y(\tau\tau)$ and $X \to H(\tau\tau)Y(\gamma\gamma)$ are shown in Fig. 2 for the left and middle plots, respectively. The right plot shows the observed upper limits in the 2D $(m_X, m_Y)$ plane. The red-hatched region indicates

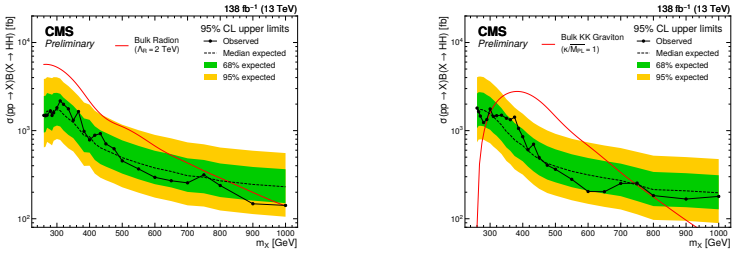


**Figure 1:** Expected and observed 95% CL upper limits on the resonant production cross section, for the spin-0 (left) and spin-2 (right) of the H($\gamma\gamma$)H($\tau\tau$) analysis. The red lines show the theoretical predictions with different energy scales and couplings [9].

masses for which the observed limits are below the maximally allowed limits in the NMSSM taken from [10].

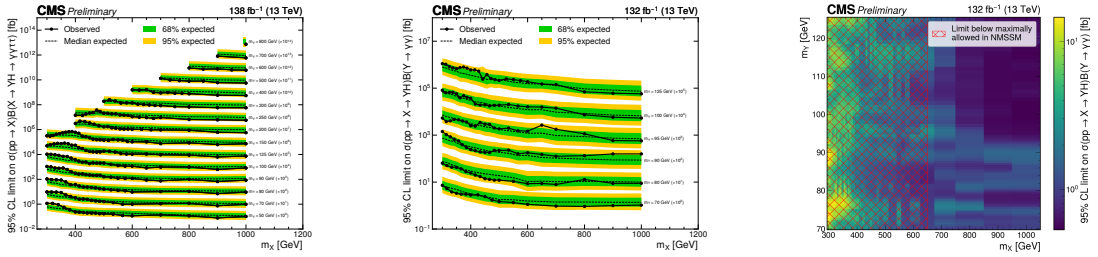


**Figure 2:** Expected and observed 95% CL upper limits on $\sigma(pp \to \mathrm{X} \to \mathrm{YH} \to \gamma\gamma\tau\tau)$ as a function of the resonant mass $m_\mathrm{X}$ and in the 2D $(m_\mathrm{X}, m_\mathrm{Y})$ plane [9].

## 2.2 X → HH → bbWW

A search for Higgs boson pair (HH) production with one Higgs boson decaying to two bottom quarks and the other to two W bosons, in the mass range from 260 to 900 GeV with narrow-width approximation, is presented [11]. The final states considered include at least one leptonically decaying W boson. This HH → bbWW has the second largest combined branching fraction. The two channels of this analysis are characterised by the decay products of the H → WW: single-lepton (SL) and di-lepton (DL) channels.

Furthermore, the events are classified into processes based on the output of multi-class deep neural networks (DNNs), separately trained for the SL and DL cases. In the SL case, the signal extraction is performed by a simultaneous maximum likelihood fit to the distributions of the DNN outputs. In the DL case, the DNN output of the signal category is combined into an unrolled 2D variable with the output of a heavy-mass estimator (HME), a variable that estimates the most likely invariant mass of the HH system.

The distribution in the DNN score (SL case) and the unrolled combination of the DNN score and the HME bin (DL case) are shown in Fig. 3 for the SR, for an assumed resonance mass of $m_\mathrm{X}$ = 400 GeV represented by an open red histogram. No significant deviation from the SM expected

signal is found and upper limits are set on the HH production cross section which will be shown in the combination in Section 3.

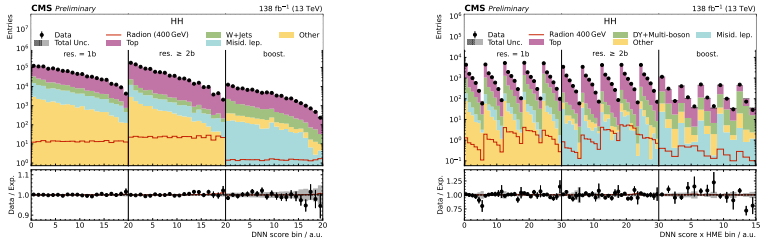


**Figure 3:** Distributions of the DNN output for events in the signal nodes of the SL (left) and DL (right) categories of the H(bb)H(WW) analysis based on merged and resolved jets categories [11].

### 2.3 $X \to HH/YH \to bb\gamma\gamma$

A search for new resonances in the final state with two bottom quarks and two photons is presented [12]. The resonance X decays into either a pair of the H bosons (HH), or the H boson and a new scalar Y (YH). One Higgs boson is reconstructed from a pair of photons and their invariant mass $m_{\gamma\gamma}$ is required to be compatible with the Higgs boson mass. Two pairs of jets, identified as originating from b quarks, are paired to form the other H boson or a new resonance Y of unknown mass.

A BDT training is performed using simulations to separate signal and non-resonant backgrounds $\gamma\gamma$ + jets and $\gamma$ + jets. The resonant backgrounds are from different single Higgs productions. An NN-based discriminant is developed and optimal selection is applied to improve sensitivity on the searches.

For signal extraction, a simultaneous unbinned 2D maximum likelihood fit to the $m_{\gamma\gamma}$ and $m_{jj}$ distributions is performed. In the HH searches, no statistically significant deviations in data are observed with respect to the background-only hypothesis. In the YH searches, $m_{\gamma\gamma}$ and $m_{jj}$ distributions in data are shown in Fig. 4 for the signal hypothesis where the largest excess is observed for $m_X = 650$ GeV and $m_Y = 90$ GeV with a local (global) significance of $3.8\sigma(2.8\sigma)$.

Finally, a model independent analysis is performed with a narrow-width approximation for X in the mass range of 260 to 1000 GeV for the HH decay and 300 to 1000 GeV for the YH decay, covering a mass range of $90 < m_Y < 800$ GeV. Limits will be shown in the combination in Section 3.

## 3. Combination of $X \to HH/YH$ analyses

The analyses searching for the production of the H boson through decays of heavy resonances, performed by the CMS Collaboration using the Run 2 data set, are reviewed in [13]. The analyses cover a wide range of H boson decay modes, in particular, decays into photons, b quarks, $\tau$ leptons, and W bosons. The Y boson is exclusively searched for in b quark final states in resolved and merged topologies. The results are presented as summary plots which show the sensitivity of all channels in direct comparison as shown in Figs. 5, 6, and interpreted in the context of relevant BSM scenarios, as presented in Figs. 7, and 8.

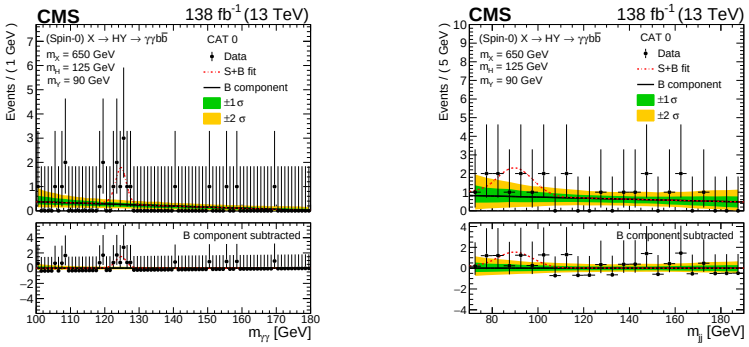


**Figure 4:** Invariant mass distributions of $m_{\gamma\gamma}$ (left) and $m_{\mathrm{jj}}$ (right), with $m_{\mathrm{X}}$ selection corresponding to an YH signal with $m_{\mathrm{X}} = 650$ GeV and $m_{\mathrm{Y}} = 90$ GeV. The distributions are shown for the signal-dominated category (CAT 0) [12].

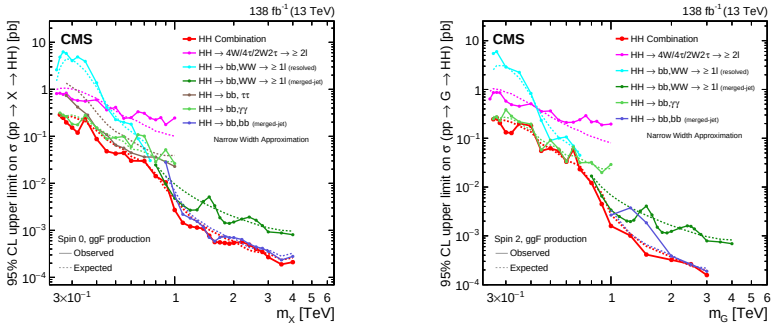


**Figure 5:** Observed and expected 95% CL upper limits on the product of the cross section for the production of a spin-0 resonance X and a spin-2 resonance G, via gluon-gluon fusion and the branching fraction for the corresponding HH decay. The results of the individual analyses are presented and the result of their combined likelihood analysis are shown in the red solid line [13].

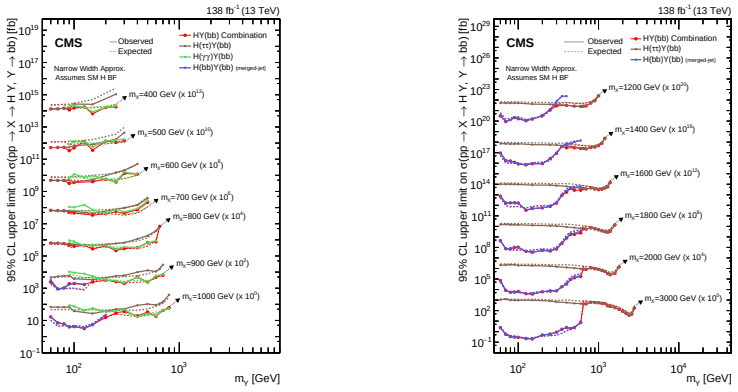


**Figure 6:** Observed and expected upper limits, at 95% CL, on the product of the cross section for the production of a resonance X via gluon-gluon fusion and the branching fraction for the X → Y(bb)H decay. The results derived from the individual analyses and their combined likelihood analysis are shown as functions of $m_{\mathrm{Y}}$ for $m_{\mathrm{X}} \leq 1$ TeV (left), and $m_{\mathrm{X}} \geq 1.2$ TeV (right) [13].

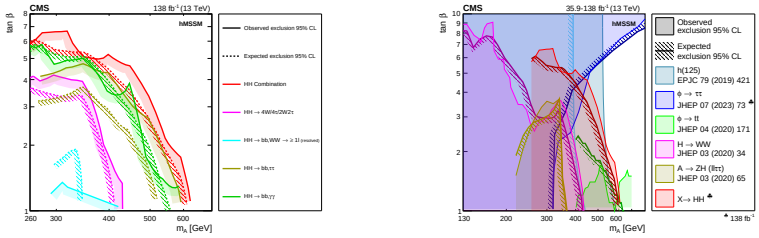


**Figure 7:** Interpretation of the results from the searches for the X → HH decay, in the hMSSM model. In the left part of the figure, the observed and expected exclusion contours at 95% CL, in the ($m_{\mathrm{A}}$, tan$\beta$) plane, from the individual HH analyses and their combined likelihood analysis are shown. In the right part of the figure, a comparison of the region excluded by the combined likelihood analysis with selected results from other searches is shown [13].

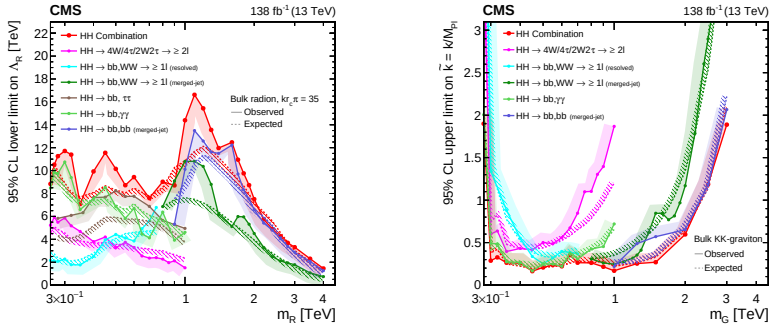


**Figure 8:** Observed and expected limits, at 95% CL, on the parameters of models with Warped Extra Dimensions, as obtained from the X → HH analyses and their combined likelihood analysis. Shown are lower limits (left) on the bulk radion ultraviolet cutoff parameter $\Lambda_{\mathrm{R}}$, as a function of the radion mass $m_{\mathrm{R}}$, and upper limits (right) on the parameter $\tilde{k}$ of the spin-2 bulk graviton G, as a function of $m_{\mathrm{G}}$ [13].

## 4. Summary

This report focuses on resonances decaying into two H bosons, or one H boson and another new resonance, using proton-proton collision data from 2016-2018 at $\sqrt{s}$ = 13 TeV. The results and constraints on various BSM scenarios, including Extended Higgs Sectors, and Warped Extra Dimensions, are presented.

## 5. Acknowledgements

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