PROCEEDINGS OF SCIENCE

Search for resonant di-Higgs production at CMS

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The latest results from searches for resonant production of Higgs boson pairs (HH) at the Large Hadron Collider (LHC) with the CMS detector are presented. The searches explore a variety of final states, some of which both in the resolved and boosted topology, and are conducted on data collected at $\sqrt{s}$ =13 TeV in 2016, with an integrated luminosity of 35.9 fb^{-1}.

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1. Introduction

In the quest for new physics, resonant production of Higgs pairs (HH) is a process of interest: many theories beyond the standard model (BSM) predict the existence of heavy particles that can couple to a pair of Higgs bosons, and that could appear as a resonance in the invariant mass of the HH system. This would induce a significant increase of the HH production cross section with respect to the standard model (SM). A schematic representation via gluon-gluon fusion of resonant HH production at the LHC is shown in Fig. 1.

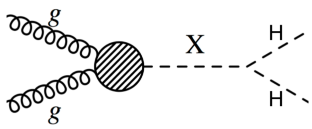

Figure 1: Schematic representation of resonant HH production.

BSM models that predict new resonances are, for instance: Warped Extra Dimensions (WED) [1] that predict spin-0 radions [2] and spin-2 Kaluza-Klein (KK) gravitons [3]; and models with an extended Higgs sector such as the two-Higgs-doublet model [4] that predict a heavy spin-0 resonance potentially decaying into Higgs pairs. The latest searches for resonant HH production on data collected in 2016 at an integrated luminosity of 35.9 fb^{-1} with the CMS detector are presented. The searches explore a variety of final states, depending on the decay modes of the two Higgs bosons: $\text{b}\bar{\text{b}}\text{b}\bar{\text{b}}$ in both the resolved and boosted topology, $\text{b}\bar{\text{b}}\tau\tau$, $\text{b}\bar{\text{b}}\text{VV}$ (V=W,Z), and $\text{b}\bar{\text{b}}\gamma\gamma$.

2. HH $\rightarrow$ $\text{b}\bar{\text{b}}\text{b}\bar{\text{b}}$

Depending on the mass of the new resonance, the two b pairs are treated differently in order to exploit their kinematic topology. Three searches are designed to target different masses. The resolved analysis targets resonance masses m_X <1200 GeV; the semi-resolved one targets m_X up to 2000 GeV; and the fully-merged analysis m_X up to 3000 GeV.

In the resolved search [7], the 4 bjets from the two $\text{b}\bar{\text{b}}$ pairs can be distinguished. Events are selected with 4 jets, with at least 3 of them satisfying the btag requirement. The jets are then paired to form Higgs candidates. Two mass regions are defined for the search, and a boosted Decision Tree (BDT) is trained to correct the bjet energies. The main background is the multijet background and is modelled from data. Upper limits on the production cross section times branching fraction ($\sigma \times BF$) for a spin-2 (spin-0) resonance are shown in Fig. 2 left (right).

In the semi-resolved search [8], one of the two Higgs bosons is Lorentz-boosted and therefore is reconstructed as one hadronic jet, while in the fully-merged search [9] both H $\rightarrow$ $\text{b}\bar{\text{b}}$ systems are reconstructed as a single jet. In the semi-resolved (fully-merged) search, two categories are defined according to the $\Delta\eta$ between the two Higgs candidates from the merged and resolved jets (value of the b-tagging algorithm). In both searches, the discriminating variable is the reduced HH invariant mass ($m_{J_1 J_{2,red}} = m_{J_1 J_2} - (m_{J_1} - m_H) - (m_{J_2} - m_H)$, with $J_2 = jj$ in the case of the semi-resolved

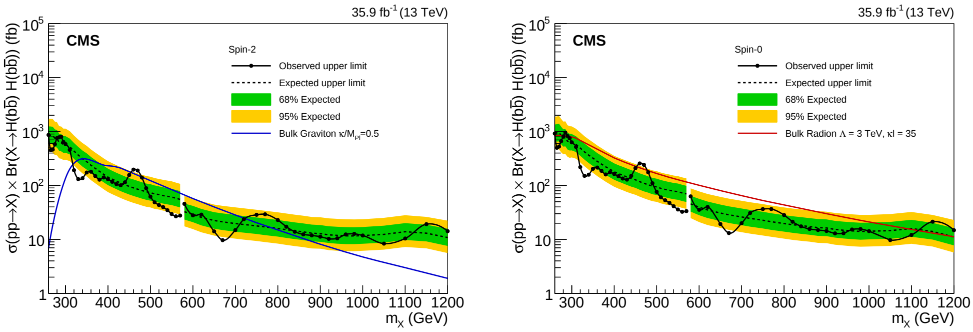

Figure 2: The observed and expected upper limits on the cross section for a spin-2 (left) and spin-0 (right) resonance X → H(b$\bar{b}$)H(b$\bar{b}$) at 95% CL in the resolved search [7].

analysis), and the multijet background is estimated from data. The results from the two searches are combined and upper limits on $\sigma \times BF$ for a spin-2 (spin-0) resonance are shown in Fig. 3 left (right). Below 2 TeV, the sensitivity after combining the two analyses improves by up to 18%(55%) for a graviton (radion) with respect to the fully-merged analysis alone.

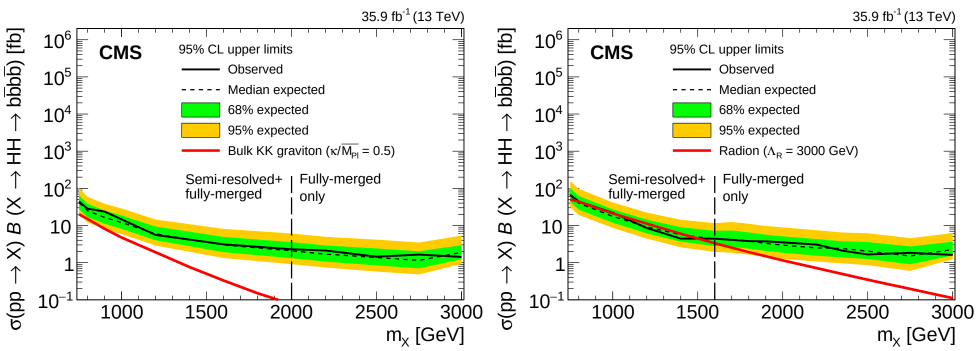

Figure 3: The observed and expected upper limits on the cross section for a spin-2 (left) and spin-0 (right) resonance X → H(b$\bar{b}$)H(b$\bar{b}$) at 95% CL [8] in the semi-resolved and fully-merged search.

3. HH → b$\bar{b}\tau\tau$

In the search for HH production in the b$\bar{b}\tau\tau$ final state [10], events are selected if there is one isolated τ lepton decaying hadronically (τ_{had}) and a second lepton of opposite charge (e, μ, or τ_{had}). The events are then categorised according to the number of bjets. The main background contributions come from t$\bar{t}$, Drell-Yan, and multijet events. A BDT is used to reduce the contribution from t$\bar{t}$. The stranverse mass, defined as the largest mass of the parent particle that is compatible with the kinematic constraints of the event, is used as a discriminating variable between signal and background in a binned Maximum Likelihood (ML) fit.
Upper limits on $\sigma \times BF$ for a spin-0 resonance are shown in Fig. 4 (left) for the b$\bar{b}\tau_\mu\tau_{had}$, b$\bar{b}\tau_e\tau_{had}$, and b$\bar{b}\tau_{had}\tau_{had}$ channels combined. Fig. 4 (right) shows the theoretical interpretation of the search in the context of the hMSSM [5], where the mass of a pseudocalar A in the range 230–360 GeV and values of tanβ up to around 2 are excluded at 95% CL.

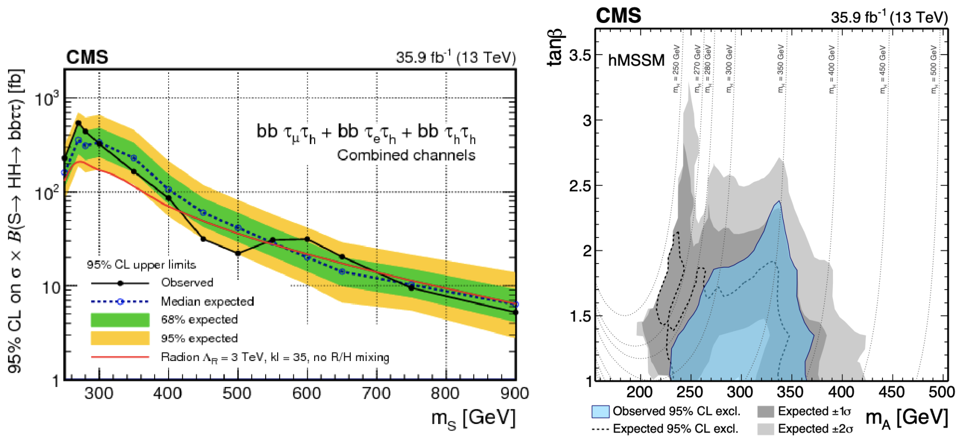

Figure 4: The observed and expected upper limits on the cross section for a spin-0 resonance $X \to H(b\bar{b})H(\tau\tau)$ (left); theoretical interpretation of the search in the context of the hMSSM (right) [10].

4. $HH \to b\bar{b}VV$

Three searches are carried out in the $b\bar{b}VV$ final state. The $b\bar{b}\ell\nu\ell\nu$ search [11] targets either $WW^* \to \ell\nu\ell\nu$ or $ZZ^* \to \ell\ell\nu\nu$ decays. Two isolated and opposite-sign leptons are required together with two b-tagged jets for the event selection. The main background is $t\bar{t}$, which is estimated from simulation. A parametric Deep Neural Network (DNN) is employed to scan over different m_X hypotheses, and the DNN output is used as a final discriminant in a binned ML fit. Upper limits on $\sigma \times BF$ for a spin-2 resonance are shown in Fig. 5 (left).
Another search is conducted in the $b\bar{b}WW^*$ final state, where $WW^* \to qq'\ell\nu$ [12]. The b-quark pair is reconstructed as a single jet, and one isolated lepton nearby a jet of the merged qq' pair from one of the two W bosons is required for event selection. The main background is $t\bar{t}$, which is suppressed by kinematically reconstructing the HH decay chain. Limits are extracted using a two-dimensional (2D) distribution of the m_{bb} and m_{HH} invariant masses. Upper limits on $\sigma \times BF$ for a spin-0 resonance are shown in Fig. 5 (right).

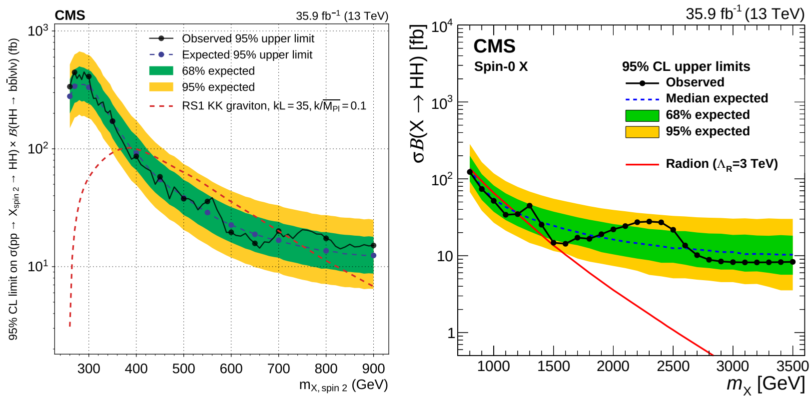

Figure 5: The observed and expected upper limits on the cross section for a spin-2 resonance $X \to H(b\bar{b})H(\ell\nu\ell\nu)$ (left) [11]; and for a spin-0 resonance $X \to H(b\bar{b})H(qq'\ell\nu)$ (right) [12].

The $HH \to b\bar{b}ZZ$ search [13] search is carried out for two different Z decay channels, where one

Z always decays to leptons and the other one either hadronically or to two neutrinos. In the first case, a BDT is trained to discriminate against the multijet background, and a search for an excess of events is performed in the distribution of the BDT output. In the second case, the discriminating variable used in the ML fit is instead the HH transverse mass distribution. Upper limits on $\sigma \times BF$ for a spin-0 resonance decaying to H(b$\bar{\text{b}}$)H(ZZ) are shown in Fig. 6 (left), where an interpretation of the results in the context of an extended Higgs scenario, the N2HDM [6], is also reported.

5. $HH \rightarrow \text{b}\bar{\text{b}}\gamma\gamma$

In the search for HH production in the b$\bar{\text{b}}\gamma\gamma$ final state [14], events with two identified photons and two bjets are selected. The main background comes from events with photons and jets, and is estimated from mass side-bands. Events are classified into categories according to the HH reduced mass ($M_X = m_{jj\gamma\gamma} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$) and the output of a BDT classifier trained to separate signal and background. An excess of events is searched for on the 2D di-photon and di-jet invariant mass. Upper limits on $\sigma \times BF$ for a spin-2 resonance are shown in Fig. 6 (right).

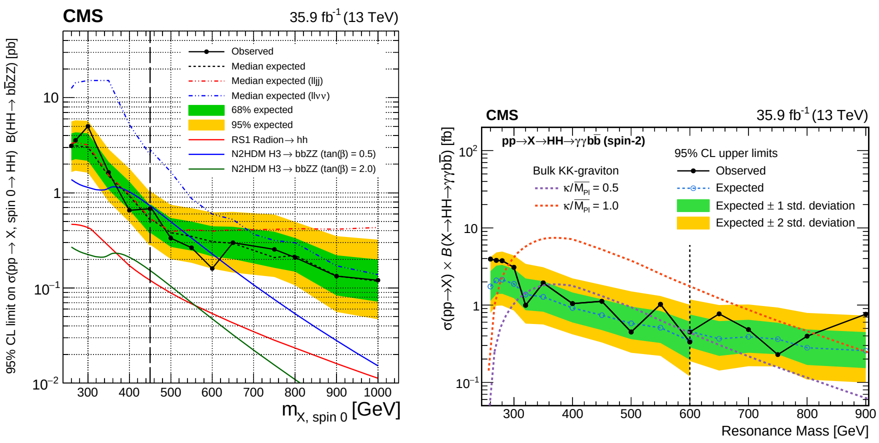

Figure 6: The observed and expected upper limits on the cross section for a spin-0 resonance X → H(b$\bar{\text{b}}$)H(ZZ) (left) [13]; and for a spin-2 resonance X → H(b$\bar{\text{b}}$)H($\gamma\gamma$) [14].

6. Summary

The latest searches for resonant HH production at CMS were presented. Some searches have to cope with a high Higgs branching fraction and large background contributions (e.g. HH → b$\bar{\text{b}}$b$\bar{\text{b}}$) while others with a low branching fraction and small background contributions (e.g. HH → b$\bar{\text{b}}\gamma\gamma$). The large variety of final states explored is crucial for future combinations. No excess of events has been observed so far. In the future, with new searches performed on the full Run 2 dataset, new and more powerful limits on BSM resonances are yet to come.

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