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# Search for Higgs boson pair production with one associated Vector boson at CMS

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A search for Higgs boson pair production (HH) associated with a vector boson V (W or Z boson) is presented. The search is based on 138 $\mathrm{fb}^{-1}$ of proton-proton (pp) collisions at a center-of-mass energy of 13 TeV, collected with the CMS detector at the LHC. The processes in this search include pp $\to$ ZHH and pp $\to$ WHH productions. All hadronic decays and leptonic decays of W and Z bosons involving electrons, muons, and neutrinos are utilized. Higgs bosons are searched for in the $b\bar{b}b\bar{b}$ channel. An observed (expected) upper limit at 95% confidence level (CL) is set at 294 (124) times the cross section from the standard model prediction of the pp $\to$ VHH process. Constraints are also set on the modifier of the Higgs boson trilinear self-coupling $\kappa_\lambda$, and on the coupling $\kappa_{\mathrm{VV}}$ of two Higgs bosons with two vector bosons. The observed (expected) confidence intervals of these coupling modifiers at 95% CL are $-37.7 < \kappa_\lambda < 37.2$ ($-30.1 < \kappa_\lambda < 28.9$) and $-12.2 < \kappa_{\mathrm{VV}} < 13.5$ ($-7.64 < \kappa_{\mathrm{VV}} < 8.90$). In addition, a 95% CL upper limit is set at 43 (22) times the cross section of the pp $\to$ VHH process when $\kappa_\lambda = 5.5$ and other couplings are set to standard model predictions.

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## 1. Introduction

The production of a pair of Higgs bosons (HH) is a rare process that provides unique access to certain couplings. Of particular interest is the trilinear self-interaction coupling $\lambda_{\mathrm{HHH}}$, whose SM prediction is designated by $\lambda_{\mathrm{HHH,SM}}$. The coupling modifier for this interaction is $\kappa_\lambda = \lambda_{\mathrm{HHH}}/\lambda_{\mathrm{HHH,SM}}$. This coupling will provide a model-independent probe of the shape of the scalar potential, which could be related to models of the strong first-order phase transition necessary for baryogenesis [1].

Another two SM-predicted couplings that can enhance some HH production channels involving vector bosons V, where V denotes either a W or Z boson. The coupling of two vector bosons with a single Higgs boson (VVH) and with two Higgs bosons (VVHH) are both predicted by the SM. Their coupling modifiers relative to the SM are $\kappa_{\mathrm{V}}$ and $\kappa_{\mathrm{VV}}$, respectively. Measurements of single Higgs boson production in the ATLAS and CMS Collaborations have constrained $\kappa_{\mathrm{W}}$ and $\kappa_{\mathrm{Z}}$ separately with a precision of $6-8\%$, and measured values are compatible with the SM within that precision [2, 3]. However, no process arising from either VVHH coupling has been observed yet.

This poster presents a search for VHH production using a data set comprising 138 fb$^{-1}$ of proton-proton (pp) collisions collected during 2016 - 2018 with the CMS detector [4]. The total SM cross section for VHH is 0.865 fb, or approximately half the cross section of VBF HH production. However, unlike the other production channels, the VHH production has constructive interference when the coupling modifiers are positive, leading to a significant enhancement in the cross section for VHH production.

## 2. Analysis strategy

Events are analyzed in four distinct channels, each targeting a specific decay of a W and/or Z boson ($Z \to \nu\nu$, $W \to l\nu$, $Z \to ll$, and $Z/W \to q\bar{q}/q\bar{q}'$). These four channels are referred to as the MET channel, the 1-lepton channel (1L), the 2-lepton channel (2L), and the fully hadronic channel (FH), respectively. Beyond the selections following the triggers, there is a dedicated selection applied in each channel to eliminate reducible backgrounds (e.g., QCD multi-jet events in MET and 1L channels, and $t\bar{t}$ events in the 2L channel).

In all channels with four small-radius jets (resolved), there exist three possible combinations for reconstructing the two Higgs boson candidates, the variable $D_{\mathrm{HH}} = |m_{\mathrm{JJ},1} - r \times m_{\mathrm{JJ},2}|/\sqrt{1+r^2}$ is computed, where $m_{\mathrm{JJ},1}$, $m_{\mathrm{JJ},2}$ are the Higgs boson candidate masses and r = 1.05 is a scale factor to bring sub-leading Higgs boson candidate to the generator mass on average. The pairing with the smallest value of $D_{\mathrm{HH}}$ is selected.

All the channels are combined to maximize the sensitivity for enhanced SM coupling strengths, particularly on $\kappa_\lambda$ and $\kappa_{\mathrm{VV}}$. A BDT is trained to categorize events according to the signal kinematics with enhanced-$\kappa_\lambda$ kinematics ($\kappa_\lambda = 20$ in training) and enhanced-$\kappa_{\mathrm{VV}}$ kinematics ($\kappa_\lambda = 0$ in training). Separate BDT training is required for each channel while the same procedure is implemented. Signal (SR), control (CR) and sideband (SB) regions are defined using $r_{\mathrm{HH}}$, a one-dimensional distance from where both masses are exactly 125 GeV.

In the large-radius jet (boosted) analysis in the MET and 1L channels, events are divided into three regions using $D_{b\bar{b}}$ (ParticleNet scores [5]) of each Higgs candidate jet: high-purity (HP), low-purity regions (LP) and failing region (FR). These regions are considered $\kappa_{\mathrm{VV}}$-enriched by construction because the two large-radius jets tend to have $\Delta\phi \sim \pi$.

Machine learning scores are used as observable in all SRs and CRs. For the leptonic channels, BDTs are used to separate signal-like events from background-like events. In the FH channel, the signal-vs-background classifier adapts a neural network discriminant that contains a Hierarchical Combinatoric ResNet that considers the four Higgs boson candidate jets, and a Multi-head Attention Block that considers the kinematic variables associated with additional jets. In the SB regions, the observable are kinematic variables with significant systematic uncertainties that can be constrained with a fit to data. The observable in all small-radius leptonic SBs and in the $t\bar{t}$ CR is the reconstructed $p_T(\mathrm{V})$. In the large-radius SBs, the mass of the sub-leading large radius jet is the observable.

The backgrounds are estimated from MC simulations. However, the statistical precision of MC samples is sometimes insufficient in the signal region to directly measure with selected MC events. In practice, BDTs are trained among the inverted and signal regions and the BDT output scores are used to produce a reweighting function. The ratio of MC events between the signal region and the inverted region is evaluated as a function of the BDT scores that are transformed to have equally filled bins in the nominal background. Moreover, the parameterization is performed using a first- or second-order polynomial to provide a smooth reweighting function. MC events in the inverted region is finally reweighted to mimic background processes in the signal region.

## 3. Results

A binned maximum likelihood fit considering the systematic uncertainties as nuisance parameters is performed simultaneously to the machine learning scores in all SRs, CRs, SBs and all channels. The upper limits on the VHH cross section at 95% CL are extracted both with the SM couplings and with scans on the coupling modifiers. The upper limits on the VHH cross section are observed (expected) to be 294 (124) times of the SM prediction. The upper limits as functions of $\kappa_\lambda$, $\kappa_{\mathrm{VV}}$, and $\kappa_{\mathrm{V}}$ are compared to theoretical predictions, from which the constraints are made, as shown in Figure 1.

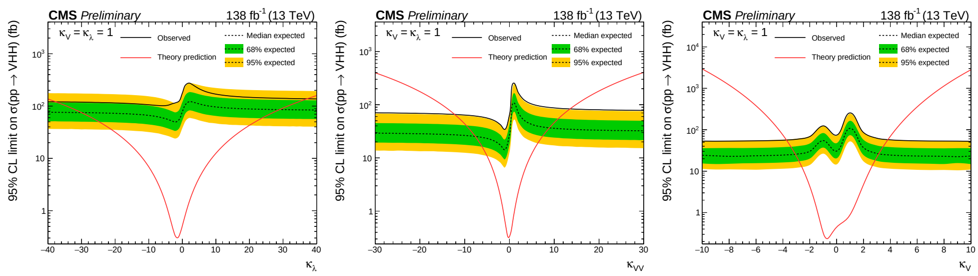


**Figure 1:** Upper 95% CL limits on signal cross section scanned over the $\kappa$ parameter of interest while fixing the other two to their SM-predicted couplings. The x-axis is the scanned $\kappa$ parameter, and the y-axis is the 95% CL upper limit on signal cross section. The scans over $\kappa_\lambda$, $\kappa_{\mathrm{VV}}$, and $\kappa_{\mathrm{V}}$ are shown left, center, and right, respectively.

The SM VHH cross section limits are shown in Figure 2 with $\kappa_\lambda = \kappa_{\mathrm{V}} = \kappa_{\mathrm{VV}} = 1$. Also, shown are the limits where $\kappa_\lambda = 5.5$ when other coupling modifiers are set to unity. In the region of $4 < \kappa_\lambda$

< 7, the ggF and VBF HH production cross sections (and corresponding HH analysis sensitivity) drops due to maximal destructive interference. Thus, the VHH expected limit is comparable to the $b\bar{b}\tau\tau$ cross section limits in this range on the equivalent data set [6], which is typically the second most sensitive channel HH searches after $b\bar{b}\gamma\gamma$ in this range of $\kappa_\lambda$.

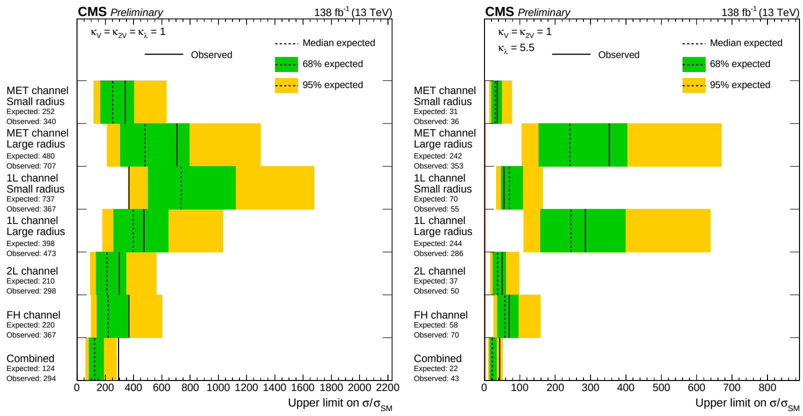


**Figure 2:** The left plot shows the VHH cross section limits per channel and combined for SM-sized couplings, while results with $\kappa_\lambda = 5.5$ and $\kappa_{VV} = \kappa_V = 1.0$ are shown on the right. The latter is a relatively sensitive region for VHH, where the primary HH production cross sections are near minimal because of destructive interference.

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