PROCEEDINGS OF SCIENCE

Search for non–resonant Higgs bosons pair production in the $bb\tau\tau$ final state at CMS

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A search for the non–resonant production of Higgs boson pairs (HH) via the gluon–gluon and vector boson fusion processes in final states with two bottom quarks and two tau leptons is presented. The search uses data from proton-proton collisions at a center-of-mass energy of $\sqrt{s}$ = 13 TeV recorded with the CMS detector at the LHC, corresponding to an integrated luminosity of 138 fb^{-1}. Events in which at least one tau lepton decays hadronically are considered and multiple machine learning techniques are used to identify and extract the signal. The data are found to be consistent, within uncertainties, with the standard model (SM) background predictions. Upper limits on the HH production cross section and constraints on anomalous Higgs boson couplings are set. The observed (expected) upper limit at 95% confidence level corresponds to 3.3 (5.2) times the SM prediction for the inclusive HH cross section and to 124 (154) times the SM prediction for the vector boson fusion HH cross section. At a 95% confidence level, the Higgs field self–coupling is constrained to be within -1.8 and 8.8 times the standard model expectation, and the coupling of two Higgs bosons to two vector bosons is constrained to be within -0.4 and 2.6.

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1. Introduction

The discovery of the Higgs boson (H) by the ATLAS and CMS Collaborations [1–3] was a major step towards improving the understanding of the mechanism of electroweak symmetry breaking. With the value of the H mass (m_H) now experimentally measured (125.38 ± 0.14 GeV), the structure of the Higgs scalar field potential and the strength of the H self–coupling are precisely predicted in the standard model (SM) but an experimental measurement of this coupling has not been performed yet.

The trilinear self–coupling of the Higgs boson (λ_{HHH}) can be extracted from the measurement of the Higgs boson pair (HH) production cross section. The two main production mechanisms in pp collisions are gluon–gluon fusion (ggF, Fig. 1) and vector boson fusion (VBF, Fig. 2). The ggF diagrams interfere destructively, leading to a small cross section of 31.05 fb. Despite its lower cross section (1.726 fb), the VBF production mode is very interesting because it provides a unique handle to study the coupling of a H to two vector bosons (V) and is easy to identify thanks to its two forward jets being well–separated in pseudorapidity and having a large invariant mass

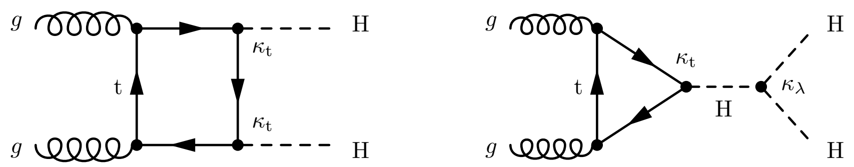

Figure 1: Feynman diagrams depicting leading-order contributions to Higgs boson pair production via gluon-gluon fusion in the SM

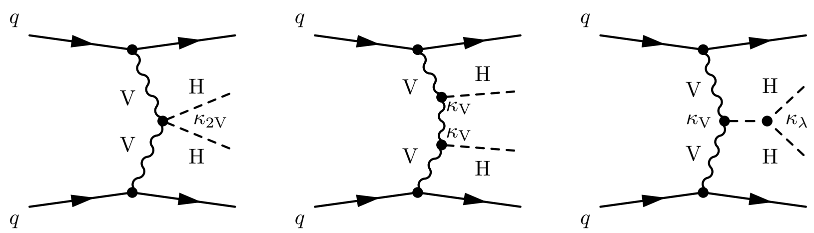

Figure 2: Feynman diagrams depicting leading-order contributions to Higgs boson pair production via vector boson fusion in the SM.

Beyond–the–SM (BSM) physics effects can manifest themselves via anomalous couplings of the H or via new particles that can enter in the quantum loops at production. The experimental signature would be a modification of the HH production cross section and of the event kinematics.

The variation of λ_{HHH} with respect to the SM prediction is parameterized by the coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$, which affects both the ggF and the VBF production mechanisms. Similarly, the variations of the couplings involved in the VBF production are parameterized as κ_V (VVH coupling) and κ_{2V} (VVHH coupling).

The $bb\tau\tau$ final state has intermediate branching fraction (7.3%) and signal purity (τ leptons reconstruction is challenging due to the presence of neutrinos in the final state), and is therefore a quite sensitive channel. Three decay modes of the $\tau\tau$ system are considered in this analysis: $\tau_\mu\tau_h$, $\tau_e\tau_h$, and $\tau_h\tau_h$, where τ_μ, τ_e, and τ_h correspond respectively to the decay of a τ lepton into a muon, an electron, or hadrons, with the associated neutrinos. These account for 87.6% of all the $\tau\tau$ decay modes.

The main sources of backgrounds are $t\bar{t}$ production in the semileptonic channels, and DY ($Z/\gamma^* \to ll$) and QCD multijet events in the fully hadronic channel. The DY and $t\bar{t}$ shapes are taken from Monte Carlo simulations while their yields are corrected from data in dedicated control regions. The estimation of the QCD multijet production is fully data–driven.

The search presented here investigates gluon-gluon and vector boson fusion processes exploiting data from proton–proton collisions at a center–of–mass energy of $\sqrt{s} = 13$ TeV recorded with the CMS detector [4] at the LHC, corresponding to an integrated luminosity of 138 fb^{-1}.

2. Event reconstruction, selection and categorization

The event reconstruction is based on the particle–flow (PF) algorithm, which identifies each individual particle in an event by combining the information from the various elements of the CMS detector, and classifies it into electrons, muons, photons, and charged or neutral hadrons. The contribution of the neutrinos originating in the decays of unstable particles is represented by the missing transverse momentum vector, computed as the negative vector sum of the transverse momenta of all the PF candidates in an event.

The online trigger selections of this analysis require the presence of a pair of hadronically decaying taus ($\tau_h\tau_h$ channel), or a single isolated lepton (electron or muon) or a lepton plus a hadronically decaying tau ($\tau_\mu\tau_h$ and $\tau_e\tau_h$ channels). A VBF di–tau trigger introduced in 2017 targets events containing two hadronically decaying tau leptons and two energetic jets.

Offline reconstructed objects are required to match with trigger objects with an additional threshold on the p_T. The distance between two objects forming a pair must satisfy $\Delta R > 0.5$, where ΔR is the angular separation between the two leptons. The two selected leptons are always required to have opposite electric charge. To reduce $Z/\gamma^* \to ll$ contamination, events with an additional lepton are vetoed.

Finally, events selected with the above described criteria are required to have at least two jets with $p_T > 20$ GeV, within the tracker acceptance and $\Delta R(j, l) > 0.5$, where l represents the leptons selected above. A dedicated deep neural network (DNN) based algorithm (HH–Btag) has been developed to identify b–jets coming from the $HH \to bb\tau\tau$ decay. The two jets satisfying the selections above with the highest HH–Btag score are taken as those originating from the decay of the Higgs boson. Two additional VBF jets are looked for among all the remaining jets. All possible pairs are built and that with the highest invariant mass (m_{jj}) is chosen as the VBF candidate pair.

Events containing a VBF jet pair with high invariant mass and large separation in pseudorapdiity are placed in a "VBF–inclusive" category. To further improve the separation of VBF and ggF events in this category a DNN–based multi–classification approach is employed to create two additional signal categories (*classVBF* for the HH VBF events and *classGGF* for the ggF contribution), as well as three background-enriched ones (*classttH* for $t\bar{t}H$ events, *classTT* for $t\bar{t}$ contamination, and *classDY* for $Z/\gamma^* \to ll$ contribution), used to constrain the systematic uncertainties affecting these processes.

Events without a VBF jet pair are classified in the "boosted" ($\Delta R(b, b < 0.8)$ and "resolved" ($\Delta R(b, b) > 0.8$) categories according to their geometrical separation. The two jets in the boosted category must be distant enough to be reconstructed separately. Events in the resolved category are further split into two categories exploiting the DNN–based b–tagging algorithm developed in CMS, DeepJet [5]. The *res1b* category collects events where only one jet passes the medium working point of DeepJet while the *res2b* one collects the events with two b–tagged jets.

In the resolved and boosted categories an elliptical mass selection on $m_{\tau\tau}$ and m_{bb} is applied to remove significantly outlying background events in regions where no signal overlap is expected. The ellipses parameters are chosen for each category using a random search that minimizes the background acceptance for a signal efficiency larger than 90%.

As an example the di–lepton and di–jet invariant mass distributions in the *res2b* category of the $\tau_h\tau_h$ channel are reported in Fig. 3.

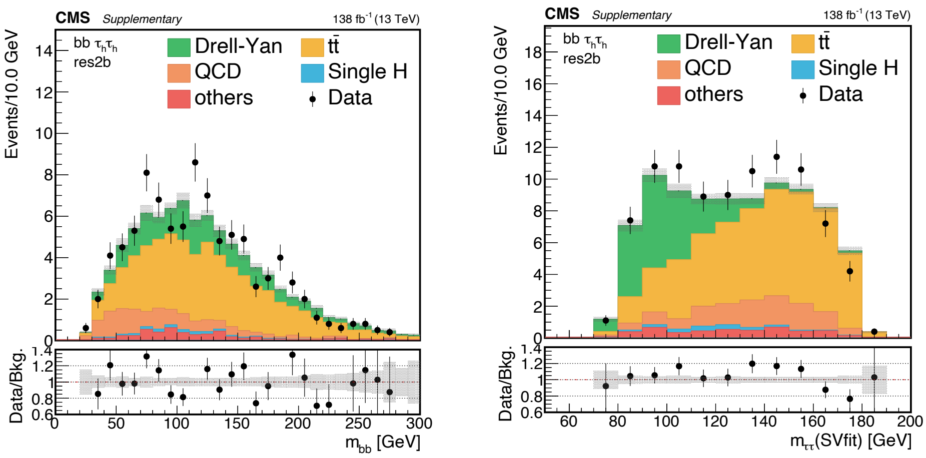

Figure 3: Distributions of the invariant mass of the b-jet pairs (left) and the lepton pairs (right) in the *res2b* category of the $\tau_h\tau_h$ channel [6].

3. Results

A DNN is employed to classify events, in each of the categories described above, as $HH \to bb\tau\tau$ signal or background by assigning a single prediction per event. Information on the b–tagging score of the jets, and the kinematical properties of the HH, $\tau\tau$ and bb systems, are some of the most important input features of this DNN.

A binned maximum likelihood fit of the DNN prediction to the data is performed simultaneously in each of the eight categories per channel per year for a total of 72 distributions fitted simultaneously.

No excess of events is found and 95% confidence level (CL) upper limits on the cross section for HH production are set using the asymptotic modified frequentist method.

Expected (observed) sensitivities for the inclusive (ggF + VBF) HH production cross section as a function of κ_λ are reported in the left part of Fig. 4. Cross sections larger than 5.2 (3.3) $\times\, \sigma_{SM}$ are excluded at 95% CL while κ_λ is constrained at 95% CL in the interval $-1.8 < \kappa_\lambda < 8.8$.

Expected (observed) sensitivities for the VBF HH production cross section are reported as a function of κ_{2V} in right part of Fig. 4. Cross sections larger than 154 (124) $\times\, \sigma_{SM}$ are excluded at 95% CL, while κ_{2V} is constrained at 95% CL in the interval $-0.4 < \kappa_\lambda < 2.6$.

The constraint imposed on the VBF HH production cross section represents the best results published so far for a single channel.

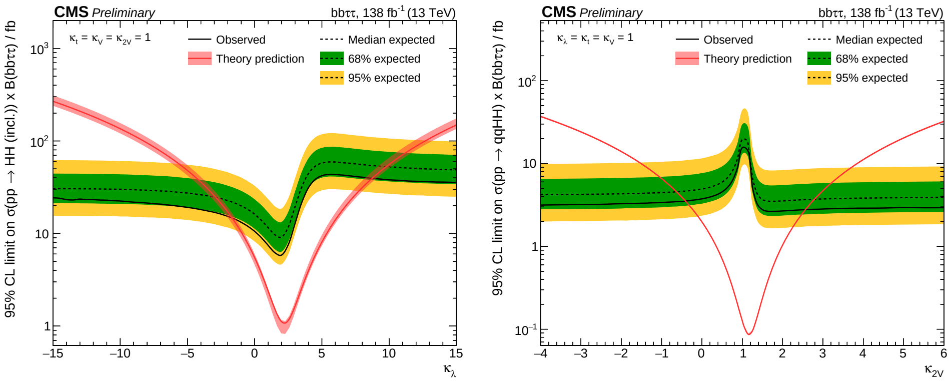

Figure 4: Expected and observed sensitivities for the inclusive (ggF + VBF) and VBF only HH production cross section as a function of the relevant coupling modifier [6].

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