Search for nonresonant Higgs boson pair production in the 4 leptons plus 2 b jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search for nonresonant pair-production of Higgs bosons (HH) with one Higgs boson decaying into four leptons and the other into a pair of b quarks is presented. The analyzed data correspond to an integrated luminosity of 137 $fb^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV collected with the CMS detector during the years 2016 to 2018. An upper limit of 30 at 95% confidence level (CL) is set on the signal strength modifier $\mu$, defined as the ratio of the observed double-Higgs boson production rate in the $HH \rightarrow ZZ^* bb \rightarrow 4\ell b\bar{b}$ decay channel to the standard model (SM) expectation. Possible modifications of the SM Higgs trilinear coupling are investigated and constrained to be within the observed (expected) range $-9(-10.5) < k_\lambda < 14(15.5)$ at 95% CL.
1 Introduction

The discovery of the Higgs boson (H) by the ATLAS and CMS Collaborations [1, 2] was the first experimental proof of the predicted mechanism of the electroweak symmetry breaking. The measurements of the H boson properties performed by both collaborations were found to be compatible with the standard model (SM) predictions [3–5]. The measurement of the H boson self-coupling provides an independent test of the SM by probing the Higgs scalar field potential [6]. A measurement of the H boson trilinear coupling can be obtained by measuring the production of pairs of H bosons (HH) at the LHC.

By exploiting different decay channels, studies of pair production of H bosons allow different regions of the parameter space of the anomalous couplings and of the nonresonant invariant mass spectrum to be probed. A combination of different decay channels is therefore needed to obtain the best possible sensitivity on the HH production.

A wide variety of HH decay channel combinations has been studied by the ATLAS [7–10] and CMS [11–17] Collaborations. The Higgs to four-lepton (H → ZZ* → 4ℓ) decay channel, where ℓ is either an electron or a muon, is the rarest observed so far at the LHC but it has the largest signal-to-background ratio. The analysis presented in this note searches for HH pairs where one Higgs decays to a Z boson pair, that in turn decays into 4ℓ, and the other to a pair of b jets (bb). The final state exhibits a clear signature granted by 4ℓ decay mode and also by the high branching fraction of the bb decay channel, partially compensating for the small branching fraction of the 4ℓ channel.

The HH SM production cross section has been computed at NNLO in quantum chromodynamics (QCD), including NNLL corrections and finite top quark mass effects at NLO. Its value is σ_{HH} = 31.05^{+2.2\%}_{-5.0\%}(QCD scale) ± 2.1\%(PDF) ± 2.1\%(α_S) ± 2.7\%(top) fb in proton-proton (pp) collisions at 13 TeV for a H boson mass of 125 GeV [18–21]. Considering the branching fraction B(HH → ZZ*bb → 4ℓbb), the exclusive cross section is reduced to approximately 4.5 ab in the SM. Beyond the Standard Model (BSM) physics can significantly modify the cross section and the kinematic properties of H boson pair production, such as the HH invariant mass distribution. In order to provide constraints on these effects, we use the electroweak chiral lagrangian model [22, 23], an effective field theory (EFT) based approach that extends the SM with dimension-6 operators, in an equivalent way as done in [24] but at NLO in QCD. This approach results in five operators relevant for the HH production, of which we select the modifier of the Higgs trilinear coupling λ_{HHH} (k_λ = λ_{HHH}/λ_{SM}) to perform scans of the allowed variations based on the results of the analysis.

2 The CMS detector

The CMS detector features a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and end cap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system. The particle-flow algorithm aims to reconstruct and identify each individual particle in an event with an optimized combination of information from the various elements of the CMS detector. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [25].
3 Datasets

Proton-proton data collected by the CMS experiment in 2016, 2017, and 2018, at a center-of-mass energy of 13 TeV, are used for the analysis. Data-taking conditions vary year by year, and the samples used correspond to a total integrated luminosity of 137 fb$^{-1}$. The primary triggers require the presence of a pair of loosely isolated leptons, whose exact requirements depend on the data taking year. Triggers requiring a triplet of low transverse momentum ($p_T$) leptons, as well as isolated single-electron and single-muon triggers, help to recover efficiency. The overall trigger efficiency for events that satisfy the $4\ell$ selection described below is greater than 98%.

Signal samples of the SM $ggHH \rightarrow ZZ^*b\bar{b} \rightarrow 4\ell b\bar{b}$ process are generated at NLO in QCD using the POWHEG V2 [26–28] generator with the implementation described in [22, 23]. Using the same model, BSM signal samples with alternative values of $k_\lambda$ in integer steps between $-10$ and 10 are generated. Alternative samples using MadGraph5_aMCatNLO [29] at leading order (LO) with EFT description of the fermion loops are also used to cross-check the main samples.

Single SM Higgs-boson production processes constitute the main background for this analysis. Descriptions of the H boson production are obtained using the POWHEG V2 generator for the six main production modes: gluon fusion ($ggH$), vector boson fusion (VBF) [30], and associated production ($WH, ZH, bbH, \text{and } t\bar{t}H$ [31]). In the case of $ggH$, $WH$ and $ZH$ the MiNLO extension of POWHEG is used [32, 33] to increase the accuracy in the two jet phase space. The description of the decay of the H boson to four leptons is obtained using the JHU GEN generator [34]. In the case of $WH, ZH, bbH, \text{and } t\bar{t}H$, the H boson is allowed to decay to $H \rightarrow ZZ \rightarrow 2\ell 2X$ so that 4-lepton events where two leptons originate from the decay of associated $Z$, $W$ bosons or top quarks are also taken into account. Showering of parton-level events is then performed by allowing QCD emissions at all energies in the shower and vetoing them afterwards according to the POWHEG internal scale.

Several backgrounds include genuine nonresonant $ZZ^*$ events. Production of $ZZ^*$ via quark-antiquark annihilation is generated at NLO using MadGraph5_aMCatNLO up to one extra parton, with appropriate settings to merge jet multiplicities. As this simulation covers a large range of $ZZ$ invariant masses, dynamical QCD factorization and renormalization scales have been chosen. NNLO/NLO k-factors, as well as additional NLO electroweak corrections [35], are applied to the Monte Carlo sample differentially as a function of $m(ZZ^*)$.

The $gg \rightarrow ZZ^*$ process is simulated at LO with MCFM [36, 37]. In order to match the $gg \rightarrow H \rightarrow ZZ^*$ transverse momentum spectra predicted at NLO, the showering for MCFM samples is performed with different settings, allowing only emissions up to the parton-level scale. An exact calculation beyond the NLO does not exist for the $gg \rightarrow ZZ^*$ background, but it has been shown [38] that the soft collinear approximation is able to describe the background cross section and the interference term at NNLO. The NNLO k-factor for the signal is obtained as a function of $m(ZZ^*)$ using the HNNLO v2 Monte Carlo program [39–41]. Triboson production with at least one Z boson with leptonic decays is generated at the NLO using MadGraph5_aMCatNLO, using similar settings as in the previous samples.

The contribution of $Z+jets$ is estimated from data-driven techniques as described in Sec 5. Other small backgrounds, such as $t\bar{t}Z$, are considered as well, from the simulation.

The PYTHIA 8 [42, 43] package is used for parton showering, hadronization and the underlying event simulation, with parameters set by the CUETP8M1 tune [44] for the 2016 data taking period and the CP5 tune [45] for the 2017 and 2018 data taking periods. The NNPDF set of parton distribution functions (PDFs) [46] is used (NNPDF3.0 for the 2016, NNPDF3.1 for 2017 and 2018).
The detector response is simulated using a detailed description of the CMS detector implemented in the GEANT4 package [47, 48]. The simulated events are reconstructed using the same algorithms as used for the data. The simulated samples include additional interactions in the same and neighboring bunch crossings, referred to as pileup. Simulated events are weighted to match the pileup distribution observed in the data, this procedure is performed for each year separately.

4 Event reconstruction and selection

The final state should consist of at least two pairs of opposite-charged isolated leptons and at least two jets. The 4l selection is similar to that used in the CMS $H \rightarrow ZZ^* \rightarrow 4\ell$ measurement described in [4].

Events are reconstructed using a particle-flow algorithm [49] that reconstructs and identifies each individual particle with an optimized combination of all subdetector information.

The primary interaction vertex from which the Higgs boson candidates arise is identified using the same method as in [4].

Electrons are identified using a multivariate classifier, which includes observables sensitive to bremsstrahlung along the electron trajectory, the geometrical and energy-momentum compatibility between the electron track and the associated energy cluster in the ECAL, the shape of the electromagnetic shower, and variables that discriminate against electrons originating from photon conversions [50]. The charged, neutral hadrons and photon components of the isolation variable described below are also included as input variables in the electron multivariate classifier.

Muons are reconstructed by combining information from the silicon tracker and the muon system [51]. The muons are selected from the reconstructed muon track candidates by applying minimal requirements on the track in both the muon system and silicon tracker, and taking into account compatibility with small energy deposits in the calorimeters.

In order to further suppress electrons from photon conversions and muons originating from in-flight decays of hadrons, the three-dimensional impact parameter significance normalised to its uncertainty is required to be less than four.

Muons are required to be isolated from other particles in the event. The relative isolation is defined as

$$R_{iso} = \frac{\sum \text{charged hadrons} \ p_T + \max(0, \sum \text{neutral hadrons} \ p_T + \sum \text{photons} \ p_T - \Delta \beta)}{p_T^{\ell}},$$

(1)

where the sums run over the charged, neutral hadrons and photons, in a cone defined by $\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3$ around the lepton trajectory. To minimize the contribution of charged particles from pileup to the isolation calculation, charged hadrons are included only if they originate from the primary vertex. The correction factor, $\Delta \beta$, gives an estimate of neutral particles energy deposit from pileup vertices. Muons with $R_{iso} < 0.35$ are considered isolated. A similar requirement is not applied to electrons since isolation information is included in the multivariate classifier.

The efficiency of the lepton reconstruction and selection is measured in bins of $p_T^{\ell}$ and $\eta^{\ell}$ using the tag-and-probe technique. The measured scale factors are used to correct the simulation. Scale and smearing corrections are applied to leptons in bins of $p_T^{\ell}$ and $\eta^{\ell}$ using the $J/\psi$ meson...
and Z boson leptonic decays.

Final-state radiation (FSR) is recovered following an algorithm described in [4].

Jets are reconstructed from particle-flow candidates using the anti-\(k_T\) clustering algorithm [52], as implemented in the FASTJET package [53], with a distance parameter of 0.4. In order to ensure a good reconstruction efficiency and to reduce the instrumental background as well as the contamination from pileup, loose identification criteria based on the multiplicities and energy fractions carried by charged and neutral hadrons are imposed on jets [54]. Only jets in the tracker fiducial region (\(|\eta| < 2.4\)) are considered.

Jet energy corrections are extracted from data and simulated events to account for the effects of pileup, uniformity of the detector response, and residual differences between the jet energy scale in the data and in the simulation. The jet energy scale calibration [55–57] relies on corrections parameterized in terms of the uncorrected \(p_T\) and \(\eta\) of the jet. In order to ensure that jets are well measured and to reduce the pileup contamination, all jets must have a corrected \(p_T\) larger than 20 GeV. The CMS DeepCSV algorithm is employed as b quark jet identification algorithm. It combines impact parameter significance, secondary vertex and jet kinematics information to provide a final output discriminator [58] whose score is computed with a Deep Neural Network technique. Data to simulation b tagging correction factors are applied to simulated events as a function of jet \(p_T\), \(\eta\) and flavour.

A signal event must contain at least two Z candidates, each formed from pairs of isolated electrons or muons of opposite charges. Only reconstructed electrons (muons) with a \(p_T > 7\) (5) GeV are considered. Among the four leptons, the highest \(p_T\) lepton must have \(p_T > 20\) GeV, and the second-highest \(p_T\) lepton must have \(p_T > 12\) (10) GeV if it is an electron (muon). All leptons are required to be separated by \(\Delta R(\ell_1, \ell_2) > 0.02\), and electrons are required to be separated from muons by \(\Delta R(e, \mu) > 0.05\).

Within each event, all permutations of leptons giving a valid pair of Z candidates are considered. For each ZZ candidate, the lepton pair with the invariant mass closest to the nominal Z boson mass is denoted \(Z_1\) and is required to have a mass greater than 40 GeV. The other dilepton candidate is denoted \(Z_2\). The \(m_{Z_2}\) is required to be greater than 12 GeV and less than 120 GeV. All pairs of oppositely charged leptons that can be built from the ZZ candidate, regardless of flavor, are required to satisfy \(m_{\ell\ell'} > 4\) GeV to suppress backgrounds from hadron decays. If more than one ZZ candidate survives the selection, the one with the highest value of the scalar sum of transverse momentum of leptons is retained.

In order to search for H boson pair production, in addition to the ZZ selections, events are required to have at least 2 jets. The jets are required to be separated from the leptons of the ZZ candidate by \(\Delta R(\text{lepton}, \text{jet}) > 0.3\) and to have \(p_T > 20\) GeV. At this stage, no other requirements on the value of the invariant mass or b tagging score of the jets are required. The \(b\bar{b}\) candidate is formed using the two highest b tagger score jets, following a study performed on simulated HH \(\rightarrow 4\ell b\bar{b}\) events.

We define as the 4\(\ell\) signal region the events passing the further requirement of \(115\ \text{GeV} < m(4\ell) < 135\ \text{GeV}\), while the remaining events define the 4\(\ell\) control region. The expected yields in the signal region after the above selection are presented in Table 1. Figure 1 shows the \(m(4\ell)\) and \(m(b\bar{b})\) distributions in signal, estimated background components, and data.
5. Background Estimation

Table 1: Expected yields in the 4ℓ signal region plus at least two jets after selection. Others contains contributions from TTW, WWZ, WZZ and ZZZ, processes.

<table>
<thead>
<tr>
<th>Final state</th>
<th>Signal</th>
<th>tZ</th>
<th>tH</th>
<th>bbH</th>
<th>ZZ</th>
<th>ggH-VBF</th>
<th>ZH</th>
<th>WH</th>
<th>others</th>
<th>Z+X</th>
<th>Total expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4µ</td>
<td>0.054</td>
<td>0.56</td>
<td>0.67</td>
<td>0.16</td>
<td>3.72</td>
<td>11.89</td>
<td>0.70</td>
<td>0.88</td>
<td>0.04</td>
<td>3.87</td>
<td>22.38</td>
<td>29</td>
</tr>
<tr>
<td>4e</td>
<td>0.028</td>
<td>0.35</td>
<td>0.38</td>
<td>0.07</td>
<td>1.43</td>
<td>5.93</td>
<td>0.37</td>
<td>0.45</td>
<td>0.02</td>
<td>2.64</td>
<td>11.60</td>
<td>12</td>
</tr>
<tr>
<td>2e2µ</td>
<td>0.079</td>
<td>0.92</td>
<td>0.88</td>
<td>0.19</td>
<td>4.93</td>
<td>15.07</td>
<td>0.94</td>
<td>1.12</td>
<td>0.11</td>
<td>7.22</td>
<td>31.36</td>
<td>33</td>
</tr>
</tbody>
</table>

Figure 1: m(4ℓ) (left) and m(bb̄) (right) distributions. The m(bb̄) plot is done considering only events in the mass window: 115 GeV < m(4ℓ) < 135 GeV.

5 Background Estimation

5.1 Irreducible background

The irreducible background to the HH signal is estimated from MC simulations. One of the main contributions is represented by the production of single H bosons decaying into ZZ, whose description is provided using the POWHEG v2 generator. For the gluon fusion H production mode, NNLO parton shower weights are applied. Another large contribution is given by the q ¯q → ZZ∗ process, which is generated at NLO and then reweighted with NNLO/NLO k-factors to account for the higher order of the cross section used. Additional NLO electroweak corrections are applied. The gg → ZZ∗ contribution too is estimated from MC by reweighting the MC with NNLO k-factors. Other backgrounds, such as ttZ and ttW are also estimated from the MC simulation.

5.2 Reducible background

The reducible background (Z + X) originates from processes which contain one or more non-prompt leptons (leptons which are not originating from the primary vertex). The main sources of non-prompt leptons are non-isolated electrons and muons coming from decays of heavy-flavour mesons, mis-reconstructed jets (usually originating from light-flavour quarks) and electrons from γ conversions.

The rate of these background processes is estimated by measuring the f_e and f_µ probabilities for misidentified electrons and muons which do pass looser selection criteria to also pass the final selection criteria in selected samples of Z(ℓℓ) + e + 2jets and Z(ℓℓ) + μ + 2jets events. The misidentification rates are evaluated using the tight requirement |M_{inv}(ℓ_1 ℓ_2) − M_Z| < 7 GeV,
to reduce the contribution from asymmetric conversions of photons populating low masses. The misidentification rates are measured in bins of the transverse momentum of the loosely identified lepton and separately for the barrel and the endcap region.

Two control samples are obtained as subsets of $Z + 2$ jet events which pass the first step of the selection, requiring an additional pair of loose leptons of same flavour and opposite charge passing the impact parameter selection. The first control sample is obtained by requiring that the two loose leptons, which do not form the $Z_1$ candidate, do not pass the final identification and isolation criteria (2P2F region). The second control sample is obtained by requiring one of the four leptons not to pass the final identification and isolation criteria, while the other three leptons do (3P1F region).

The prediction of the reducible background in the signal region can be written as [4]:

$$N_{Z^X}^{SR} = \sum f_i \left( N_{3P1F}^{Z} - N_{3P1F}^{bkg} - N_{3P1F}^{ZZ} \right) + \sum f_i \frac{f_j}{(1 - f_i)(1 - f_j)} N_{2P2F}$$

(2)

where $N_{2P2F}$ is the observed number of events in the first control sample, $N_{3P1F}$ is the observed number of events in the second control sample and $f_i$ are the estimated lepton misidentification rates.

6 Multivariate analysis

To better discriminate signal and background events and to improve the sensitivity of the analysis, a boosted decision tree (BDT) discriminator is trained using simulated events in the $4\ell$ signal region, using the TMVA tool of the ROOT analysis package [59].

Several sets of variables were studied and the optimal set was found by maximizing the area under the Receiver Operating Characteristics (ROC) curve for each resulting discriminator. The optimized set contains ten variables, namely: the $p_T$ of the four leptons; the $\Delta R$ between the reconstructed $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow bb$ systems; the two $b$ tagging scores, the $p_T$ and the invariant mass of the two jets with the highest value of $b$ tagging score.

The BDT is trained separately for each data taking year and for each of the leptonic final states ($4\mu$, $4e$, and $2e2\mu$) for a total of nine independent discriminators. Detailed studies were performed on the discrimination ranking, variable correlations and possible discriminator over-training. Figure 2 shows the inclusive BDT discriminator distribution for the signal, estimated background components, and data for the three different leptonic final state ($4\mu$, $4e$, and $2e2\mu$) and data taking years.

7 Systematic Uncertainties

Experimental uncertainties considered for the measurement arise from different sources: the uncertainty on the integrated luminosity ($2.3 - 2.6\%$), the uncertainty on the lepton identification and reconstruction efficiency (ranging from $1$ to $15.5\%$ on the overall event yield for the different final states).

The uncertainties in the jet energy scale (JES) and jet energy resolution (JER) are accounted for by changing the jet response by one standard deviation for each source [60]. The effects on the signal acceptance are also accounted for. Uncertainties on the scale factors are provided as a function of the jet $p_T$, $\eta$ and hadron flavour. The above uncertainties apply equally to all
Figure 2: Inclusive BDT distributions for signal, estimated background components, and data for the three different leptonic final state ($4\mu$, $4e$, and $2e2\mu$) and data taking years.

Table 2: Summary of experimental systematic uncertainties. The effect of b tagging SF, JEC and JES is propagate to the shape of the BDT distribution, thus those uncertainties are treated as shape uncertainties.

<table>
<thead>
<tr>
<th>Experimental uncertainties</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.6%</td>
<td>2.3%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Leptons ID and reco eff</td>
<td>1.6 ± 15.5%</td>
<td>1.1 ± 12.1%</td>
<td>1.0 ± 11%</td>
</tr>
<tr>
<td>b tagging SF</td>
<td>shape</td>
<td>shape</td>
<td>shape</td>
</tr>
<tr>
<td>JEC</td>
<td>shape</td>
<td>shape</td>
<td>shape</td>
</tr>
<tr>
<td>JER</td>
<td>shape</td>
<td>shape</td>
<td>shape</td>
</tr>
<tr>
<td>Z+X uncertainties</td>
<td>30 ± 41%</td>
<td>30 ± 38%</td>
<td>30 ± 37%</td>
</tr>
</tbody>
</table>

simulated signal and backgrounds. The JES, JER and b tagging scale factors uncertainties are considered as shape uncertainties, in particular JES uncertainties, together with the statistical uncertainties of the last bin of the BDT, have the highest impact on the analysis. All the other uncertainties are considered as log-Normal distributed uncertainties on the normalisation. The experimental uncertainties originating from the reducible background estimation, described in Section 5.2, are also considered. The main contribution comes from the mismatch in the composition of backgrounds between the samples where the misidentification rate is derived and where it is applied. The summary of the experimental systematic uncertainties is reported in Table 2. Theoretical uncertainties arise from the choice of PDF set, the uncertainty on $\alpha_s$, the renormalization and factorization QCD scale ($\langle 61 \rangle$). These uncertainties affect both signal and background processes. For the HH signal [62], in addition to the uncertainty sources just described, also an uncertainty related to missing finite top-quark mass effects gives a contribution. An additional uncertainty of 10% on the k-factor is used for the $gg \rightarrow ZZ^*$ prediction and of 0.1% for the $qq \rightarrow ZZ^*$ prediction. All experimental uncertainties are considered uncorrelated while all theoretical uncertainties are considered correlated among the three years. The summary of theory systematic uncertainties is reported in Table 3.
Table 3: Summary of theory systematic uncertainties.

<table>
<thead>
<tr>
<th>Theory uncertainties</th>
<th>PDF and $\alpha_s$</th>
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</thead>
<tbody>
<tr>
<td>HH</td>
<td>$m_{top}$ unc HH</td>
</tr>
<tr>
<td>HH</td>
<td>PDF set ggH</td>
</tr>
<tr>
<td>HH</td>
<td>$\alpha_s$ ggH</td>
</tr>
<tr>
<td>HH</td>
<td>PDF set and $\alpha_s$ VBFH</td>
</tr>
<tr>
<td>HH</td>
<td>PDF set and $\alpha_s$ ZH</td>
</tr>
<tr>
<td>HH</td>
<td>PDF set and $\alpha_s$ WH</td>
</tr>
<tr>
<td>HH</td>
<td>PDF set and $\alpha_s$ bbH</td>
</tr>
<tr>
<td>HH</td>
<td>PDF set and $\alpha_s$ ttH</td>
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<td>HH</td>
<td>PDF set and $\alpha_s$ qqZZ</td>
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<td>HH</td>
<td>PDF set and $\alpha_s$ ttW</td>
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<td>HH</td>
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<td>QCD scale</td>
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<td>VVV</td>
</tr>
<tr>
<td>QCD scale</td>
<td>ggZZ</td>
</tr>
<tr>
<td>Electroweak corrections</td>
<td>qqZZ</td>
</tr>
<tr>
<td>Electroweak corrections</td>
<td>ggZZ</td>
</tr>
</tbody>
</table>
8 Results

The results are extracted with a multi-dimensional binned maximum likelihood fit to the BDT distribution in data. Shape templates for the BDT score for signal are obtained from the simulated samples and for backgrounds from both simulated samples and data as described in Section 6. Uncertainties are treated as nuisance parameters for which log-normal a priori distributions are assumed and template shape variations are taken into account via continuous template morphing, where indicated in Table 2.

Upper limits on the production cross section of a pair of H bosons times the branching fraction $B(HH \rightarrow 4\ell b\bar{b})$ are computed using the modified frequentist approach for confidence levels (CL$_s$), taking the profile likelihood as a test statistic [63–66] in the asymptotic approximation. The limits are subsequently compared to the theoretical predictions assuming SM branching fractions for H boson decays.

The observed (expected) upper limit on the signal strength modifier $\mu$, defined as the ratio of the double-H boson rate in the $4\ell b\bar{b}$ channel to the Standard Model (SM) expectation, is 30 (37) at 95% CL, as is shown in Fig. 3 (left).

Upper limits are also set for different hypotheses of anomalous H boson self-coupling, as a function of $k_A$, assuming the other BSM couplings ($k_t$, $c_2$, $c_{2g}$ and $c_g$) equal to their SM values. The result is shown in Fig. 3 (right) and the exclusion is compared to the theoretical prediction for the cross section (red line). The analysis constrains $k_A$ to be within the observed (expected) range $-9(-10.5) < k_A < 14(15.5)$ at 95% CL.

![Figure 3](image)

Figure 3: Left: upper limit on the signal strength at 95% CL for each year and for the combination. Right: Expected and observed 95% CL upper limits on the SM-like HH production cross section times $B(HH \rightarrow 4\ell b\bar{b})$ obtained for different values of $k_A$. The green and yellow bands represent, respectively, the one and two standard deviation extensions around the expected limit.

9 Summary

A search for nonresonant H boson pair production in the 4-lepton $b\bar{b}$ final state is presented. This search uses a data sample collected in proton-proton collisions at $\sqrt{s} = 13$ TeV by the CMS
detector during the years 2016 to 2018 that corresponds to an integrated luminosity of 137 fb$^{-1}$. The results are found to be compatible with the SM expectations, and an upper limit of 30 at the 95% CL is set on the signal strength modifier $\mu$, defined as the observed double-H boson rate in the $4\ell b\bar{b}$ channel divided by the Standard Model (SM) expectation. Possible modifications of the SM Higgs trilinear coupling are investigated and constrained to be within the observed (expected) range $-9(-10.5) < k_\lambda < 14(15.5)$ at 95% CL.

References


[40] M. Grazzini, “NNLO predictions for the Higgs boson signal in the $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4l$ decay channels”, *JHEP* 02 (2008) 043, doi:10.1088/1126-6708/2008/02/043, arXiv:0801.3232.


