

Projections for HH measurements in the $b\bar{b}ZZ(4l)$ final state with the CMS experiment at the HL-LHC

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Prospects for the study of Higgs boson pair (HH) production in the $HH \rightarrow b\bar{b}4l$ ($l = e, \mu$) channel are studied in the context of the High Luminosity LHC. The analysis is performed using a parametric simulation of the Phase-2 CMS detector response provided by the Delphes software and assuming an average of 200 proton-proton collisions per bunch crossing at a center-of-mass energy of 14 TeV. Assuming a projected integrated luminosity of 3000 fb^{-1} , the expected significance for the nonresonant standard model (SM) HH signal is 0.37σ ; a 95% confidence level (CL) upper limit on its cross section is set to 6.6 times the SM prediction. The statistical combination of five decay channels ($b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $b\bar{b}WW$, $b\bar{b}ZZ$) results in an expected significance for the SM HH signal of 2.6σ and an expected 68% and 95% CL intervals for the self-coupling modifier $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$ of $[0.35, 1.9]$ and $[-0.18, 3.6]$, respectively.

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1. Introduction

The CERN LHC future physics program will target a large range of measurements, including a detailed study of the Higgs boson properties and direct searches for physics beyond the standard model (BSM). The measurement of the Higgs pair production is an important test of the standard model (SM) electroweak symmetry breaking (EWSB) sector, because it allows to extract the Higgs self-coupling (λ_{HHH}), which is directly related to the structure of the Higgs field potential. Furthermore, any possible deviations in the Higgs self-coupling due to BSM effects could open the door to new physics searches and provide important tests of the validity of the SM. Hence, a parametrization of an anomalous coupling $\lambda_{HHH} = \kappa_\lambda \cdot \lambda_{HHH}^{SM}$ has been introduced, where κ_λ is called *self-coupling modifier*.

In hadron colliders such as LHC, the dominant nonresonant HH production mode proceeds through top-quarks loop diagrams in the gluon fusion channel, shown in Figure 1. Their contribution is affected by a destructive interference between the box and the triangle diagrams; consequently, the total SM production rate of the double Higgs process is really small (31.05 fb and 36.69 fb at a center-of-mass energy of 13 TeV and 14 TeV, respectively) [1].

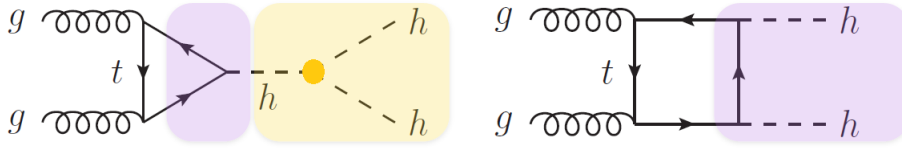


Figure 1: Leading order Feynman diagrams for nonresonant HH production in the SM through the Higgs boson self-coupling (left) and the top-box diagram (right).

Here, a study of the $HH \rightarrow b\bar{b}ZZ^*$ (41) channel in proton-proton collisions at the HL-LHC at a center-of-mass energy of 14 TeV is presented considering the Phase-2 CMS detector. The upgrade programme of the CMS detector, necessary to fully exploit the physics potential of the LHC, has been designed to cope with an instantaneous luminosity up to $\mathcal{L} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and an average number of pileup events up to 200.

In the final section, results obtained from the statistical combination of five decay channels ($b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $b\bar{b}WW$, $b\bar{b}ZZ$) are presented; all these analyses are designed to be orthogonal.

2. The $HH \rightarrow b\bar{b}ZZ^*$ (41) analysis at the HL-LHC

Up to now, the low signal rate of HH events leads to consider mostly final states with a sizable branching ratio. In view of HL-LHC, some rare but clean processes have been re-considered because of the increasing available statistics and the challenging conditions due to the enormous number of pileup events. In this work, the sensitivity to the Higgs self-coupling for $m_H = 125 \text{ GeV}$ is evaluated through the measurement of the nonresonant production of Higgs pairs in the $b\bar{b}ZZ^*$ (41) final state. Despite a small cross section ($\sigma_{b\bar{b}41} = 5.3 \text{ ab}$), the presence of four leptons associated with two b jets leads to a very clean final state topology allowing to maintain a rather good signal selection efficiency and to control the backgrounds.

Monte Carlo samples

Signal events are generated at leading order (LO) with MadGraph5_aMC@NLO [2] accounting for the full m_t dependence, for several values of k_λ ranging from $k_\lambda = -10$ to $k_\lambda = 10$, in steps of 0.5. The single Higgs boson production in gluon (ggH) and vector boson (VBF) fusion, and in associated production with top quarks ($t\bar{t}H$) and vector bosons (VH), is considered as a background for HH production. The main contribution to the background comes from $t\bar{t}(b\bar{b})H(4l)$, $t\bar{t}Z(2l)$, ggH(4l) events, followed by minor contributions from $Z(b\bar{b})H(4l)$, WH(4l) and VBF(H); $t\bar{t}ZZ(4l)$ is found to be negligible. ggH and VBF(H) lead to a significant contribution to the final state $b\bar{b}ZZ(4l)$ mainly because of the large number of pileup events. The background processes are generated at LO with MadGraph5_aMC@NLO, except ggH and VBF(H), generated with POWHEG [3]. All simulated samples are normalised to the expected SM cross section as recommended in [4]: samples production cross sections are summarized in Table 1. Generated signal and background samples are showered and hadronized with Pythia8 [5] and processed with the Delphes fast simulation software [6], used to model the Phase-2 CMS detector and simulate an average number of pileup events of 200.

HH	$t\bar{t}H$	$t\bar{t}Z$	ZH	WH	VBF(H)	ggH
0.0053	0.0761	69.224	0.0183	0.1876	1.1690	15.007

Table 1: Cross section times branching ratio [fb] for the signal and the background processes.

Event selection

At least four identified and isolated muons (electrons) with $|\eta| < 2.8$ and $p_T > 5$ (7) GeV are required in the events, where muons and electrons are selected if passing loose (medium) identification criteria with a relative isolation smaller than 0.7. Z boson candidates are formed from pairs of opposite-charge leptons (l^+l^-) requiring a minimum angular separation between two leptons of 0.02. At least two dilepton pairs are required. The Z candidate with the invariant mass closest to the nominal Z mass is denoted as Z_1 ; then, among the other opposite-sign lepton pairs, the one with the highest p_T is labelled as Z_2 . In order to improve the sensitivity to the Higgs boson decay, Z candidates are required to have an invariant mass in the range [50, 100] GeV (Z_1) and [12, 60] GeV (Z_2), respectively. At least one lepton is required to have $p_T > 20$ GeV and a second is required to have $p_T > 10$ GeV. The four leptons invariant mass, m_{4l} , is requested to be in the range $120 < m_{4l} < 130$ GeV. Two or three identified b jets, reconstructed with the anti- k_T algorithm inside a cone of radius $R = 0.4$, are required; a b-tag medium working point, exploiting the presence of the MIP Timing Detector (MTD), is assumed. Their invariant mass is required to be in the range $90 < m_{b\bar{b}} < 150$ GeV and the angular distance between the two b jets has to be $0.5 < \Delta R_{b\bar{b}} < 2.3$; furthermore, a missing transverse energy (MET) cut is fixed at 150 GeV and $\Delta R_{HH} > 2.0$.

Results

The invariant mass spectrum of the four leptons after the full event selection is shown in Figure 2a. The expected event yields, shown in Table 2, are normalised to an integrated luminosity of 3000 fb^{-1} for the HH signal and the considered background processes. The most sensitive channel

is $b\bar{b}4\mu$, but a sizeable contribution to the sensitivity also comes from the $b\bar{b}2e2\mu$ and $b\bar{b}4e$ final states. The main sources of systematic uncertainty are related to the muon/electron reconstruction, identification and isolation (0.5% in both cases), to the b tagging algorithm (ranging from 1% to 6%) and to the integrated luminosity (1%). The impact of the systematic uncertainties on the analysis is found to be almost negligible. Including all the considered final states, the combined upper limit at the 95% CL on the HH cross section corresponds to 6.6 times the SM prediction, with a corresponding significance of 0.37σ . A scan of the negative log-likelihood as a function of the signal strength $\mu = \sigma_{HH}/\sigma_{HH}^{SM}$ in the $b\bar{b}ZZ^*(4l)$ channel is shown in Figure 2b (orange line), where the presence of a signal with the strength and properties predicted by the SM is assumed.

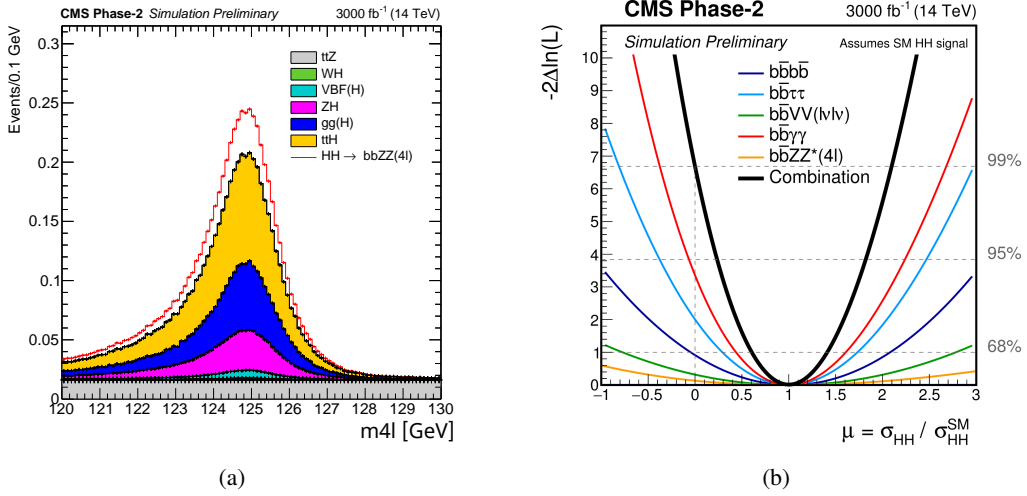


Figure 2: Invariant mass distribution of the four leptons selected at the end of the analysis for the signal (in red) and the considered background processes (a); scan of the negative log-likelihood as a function of the signal strength μ assuming SM HH signal in the five decay channels analysed and their combination (b).

	HH	$t\bar{t}H$	ggH	ZH	WH	VBF	$t\bar{t}Z$
$b\bar{b}4l$	1.0	2.5	1.5	$9.4 \cdot 10^{-1}$	$4.0 \cdot 10^{-2}$	$1.7 \cdot 10^{-1}$	1.6
$b\bar{b}4\mu$	$4.9 \cdot 10^{-1}$	1.3	$6.9 \cdot 10^{-1}$	$4.9 \cdot 10^{-1}$	$2.2 \cdot 10^{-2}$	$1.1 \cdot 10^{-1}$	$8.1 \cdot 10^{-1}$
$b\bar{b}4e$	$8.8 \cdot 10^{-2}$	$2.2 \cdot 10^{-1}$	$5.3 \cdot 10^{-2}$	$6.9 \cdot 10^{-2}$	$2.9 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$	0.0
$b\bar{b}2e2\mu$	$4.2 \cdot 10^{-1}$	1.0	$7.6 \cdot 10^{-1}$	$3.8 \cdot 10^{-1}$	$1.5 \cdot 10^{-2}$	$4.9 \cdot 10^{-2}$	$7.9 \cdot 10^{-1}$

Table 2: Event yields for the signal and the background processes, normalised to 3000 fb^{-1} .

3. Combination results

The statistical combination of five decay channels ($b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $b\bar{b}WW$, $b\bar{b}ZZ$) results in a combined 95% CL upper limit on the SM HH cross section of 0.77 times the SM prediction. The absence of a HH signal, corresponding to $\mu = 0$, is excluded at the 99% (2.6σ) CL. Both systematic and statistical uncertainties are considered. Results for each considered final state are shown in Table 3 and details of each analysis are documented in [7].

Prospects are also studied for the measurement of the trilinear Higgs boson coupling for each final state and their combination (Figure 3a). The expected 68% and 95% confidence level inter-

HH \rightarrow	$b\bar{b}b\bar{b}$	$b\bar{b}\tau\tau$	$b\bar{b}\gamma\gamma$	$b\bar{b}VV(1\nu1\nu)$	$b\bar{b}ZZ^*(4l)$	Combination
Significance (σ)	0.95	1.4	1.8	0.56	0.37	2.6
Limit at 95% CL	2.1	1.4	1.1	3.5	6.6	0.77

Table 3: Significance and 95% CL upper limit for each channel analysed and their combination (in black).

vals for the self-coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ are [0.35, 1.9] and [-0.18, 3.6], respectively. Under the assumption that no HH signal exists, 95% CL upper limits on the SM HH production cross section are derived as a function of κ_λ (Figure 3b): the excluded cross section changes as a function of λ_{HHH} , because it is directly related to variations in the HH kinematic properties.

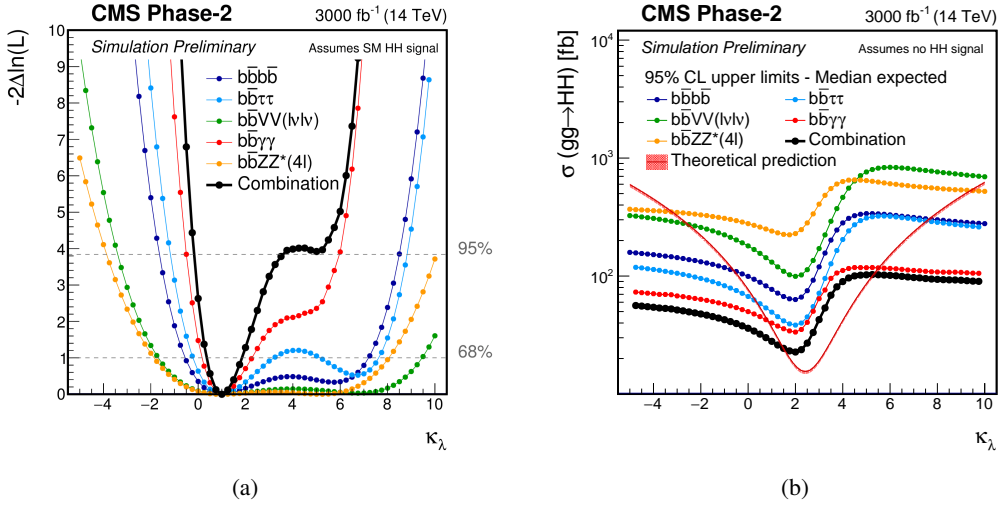


Figure 3: Expected likelihood scan (a) and upper limit at the 95% CL on the HH production cross section (b) as a function of κ_λ assuming SM HH signal and absence of HH signal, respectively. The functions are shown separately for the five decay channels studied and for their combination (in black).

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