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Projections for HH measurements in the bbZZ(4l) final state with the CMS experiment at the HL-LHC

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Summary. — Prospects for the study of Higgs boson pair (HH) production in the HH → $b\bar{b}4l$ (l = e, μ) 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 0.37 σ; 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 2.6 σ and an expected 68% and 95% CL intervals for the Higgs self-coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda^{SM}_{HHH}$ of $[0.35, 1.9]$ and $[-0.18, 3.6]$, respectively.

1. – Introduction

The CERN LHC future physics program will target a large range of measurements, including a detailed study of the Higgs (H) boson properties and direct searches for physics beyond the standard model (BSM). The measurement of the H pair production is an important test of the standard model (SM) electroweak symmetry breaking (EWSB) sector, because it allows to extract the trilinear Higgs coupling (or self-coupling, λ_{HHH}) and reconstruct the shape of the scalar potential, characterizing the scalar sector of the SM. Furthermore, any possible deviations in the H self-coupling due to BSM effects could open the door to new physics searches and provide important tests of the validity of the SM. In fact, BSM physics can produce consequences on the couplings of the H boson with anomalous effects, or can manifest itself with contributions in the quantum loops responsible for the double Higgs production, thanks to modifications to the H self-coupling that can enhance the cross section and modify the kinematic properties of the H bosons pair. Hence, a parametrization of an anomalous coupling $\lambda_{HHH} = \kappa_\lambda \cdot \lambda^{SM}_{HHH}$ has been introduced, where k_λ is called *self-coupling modifier*.

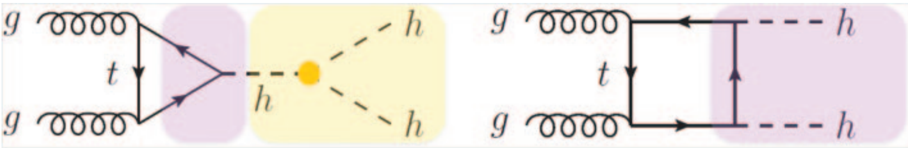


Fig. 1. – Leading-order Feynman diagrams for the SM nonresonant HH production through the Higgs boson self-coupling (left) and the top-box diagram (right).

In hadron colliders such as LHC, the dominant nonresonant HH production mode proceeds through top quarks loop diagrams in the gluon fusion channel (ggF), shown in fig. 1. However, since the two processes have amplitude with the same order of magnitude but interfere destructively, the ggF cross section is considerably reduced. Consequently, the total SM production rate of the HH process, depending on λ_{HHH} and on the top Yukawa coupling y_t, is really small (31.05 fb and 36.69 fb at a center-of-mass energy of 13 TeV and 14 TeV, respectively) [1].

Here, a study of the HH → b$\bar{\text{b}}$ZZ(4l) 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 istantaneous luminosity up to $\mathcal{L} = 5 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ and an average number of overlapping events (pileup) up to 200.

In the final section, results obtained from the statistical combination of five decay channels (b$\bar{\text{b}}$b$\bar{\text{b}}$, b$\bar{\text{b}}\tau\tau$, b$\bar{\text{b}}\gamma\gamma$, b$\bar{\text{b}}WW, b\bar{\text{b}}$ZZ) are presented; all these analyses are designed to be orthogonal thanks to the mutually exclusive requirements in the objects used, or to have a negligible overlap.

2. – The HH → b$\bar{\text{b}}$ZZ(4l) analysis at the HL-LHC

The HH production can be studied in many different final states, since both H bosons present a huge variety of exploitable decay channels. Up to now, the low signal rate of HH events leads to consider mostly final states with a sizable branching fraction, exploiting the presence of two b jets in the final state. However, 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 $m_H = 125$ GeV is evaluated through the measurement of the nonresonant production of H pairs in the b$\bar{\text{b}}$ZZ(4l) final state. Despite a small cross section ($\sigma_{\text{b}\bar{\text{b}}4\text{l}} = 5.3$ 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.

2˙1. *Monte Carlo samples*. – The SM HH → b$\bar{\text{b}}$ZZ(4l) signal events are generated at leading order (LO) with MadGraph5_aMC@NLO [2] accounting for the full m_t dependence and considering only the gluon fusion production mechanism. Moreover, twenty BSM samples corresponding to anomalous λ_{HHH} values, ranging from $k_\lambda = -10$ to $k_\lambda = 10$ in steps of 0.5, are generated. The correspondent cross sections are computed using the parametrization of the HH cross section as a function of the k_λ parameter, without varying the other EFT parameters, fixed to their SM values ($k_t = 1, c_2 = c_g = c_{2g} = 0$). The single H boson production in gluon (ggH) and vector boson (VBF) fusion, and in

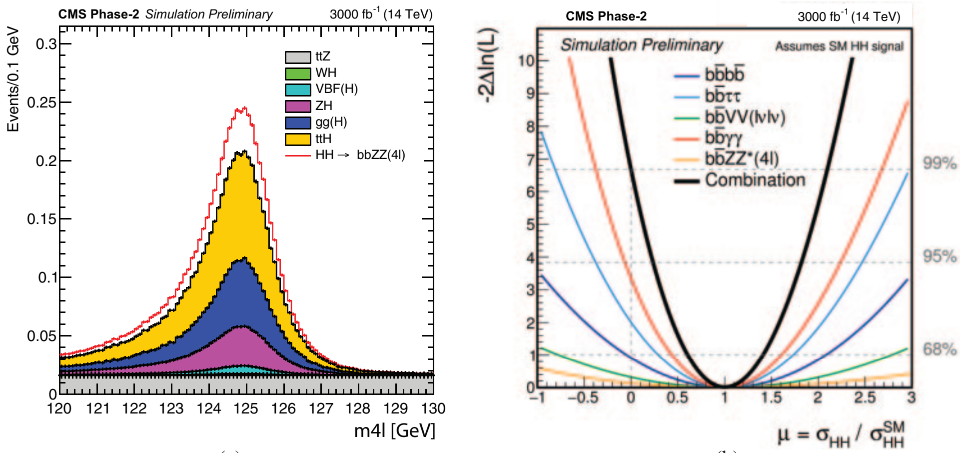
TABLE I. – *Product of the cross section and branching fraction [fb] for the signal and the background processes.*

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

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; $t\bar{t}$ZZ(4l) is found to be negligible. ggH and VBF 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, generated with POWHEG [3]. All simulated samples are normalized to the expected SM cross section as recommended in [4]: samples production cross sections are summarized in table I. 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.

2˙2. *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 (electrons) are selected if they pass 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, taking into account the expected improvement of 20% on the resolution on the $m_{b\bar{b}}$ in the HL-LHC scenario thanks to a proper b jet energy regression [7]. Moreover, the angular distance between the two b jets has to be $0.5 < \Delta R_{b\bar{b}} < 2.3$ and a missing transverse energy (MET) cut is fixed at 150 GeV and $\Delta R_{HH} > 2.0$.

2˙3. *Results.* – The invariant mass spectrum of the four leptons after the full event selection is shown in fig. 2(a). The expected event yields, shown in table II, are normalized 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



(a) (b)

Fig. 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 analyzed and their combination (b).

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 0.37 σ. A scan of the negative log-likelihood as a function of the signal strength $\mu = \sigma_{HH}/\sigma_{HH}^{SM}$ in the b$\bar{\text{b}}$ZZ(4l) channel is shown in fig. 2(b) (orange line), where the presence of a signal with properties predicted by the SM is assumed.

Assuming that a HH signal exists with the properties predicted by the SM, prospects for sensitivity of the analysis to the measurement of the H self-coupling λ_{HHH} are derived. The projected confidence interval on κ_λ corresponds to $[-2.0, 8.0]$ at 68% CL and to $[-3.9, 9.9]$ at 95% CL considering statistical and systematic uncertainties, as shown in fig. 3(a) (orange curve).

Table II. – *Event yields for the signal and the background processes, normalized to 3000 fb^{-1}.*

	HH	t$\bar{\text{t}}$H	ggH	ZH	WH	VBF	t$\bar{\text{t}}$Z
b$\bar{\text{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{\text{b}}$4μ	$4.9 \cdot 10^{-1}$	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{\text{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{\text{b}}$2e2μ	$4.2 \cdot 10^{-1}$	1.0	$7.6 \cdot 10^{-1}$	$3.8 \cdot 10^{-1}$	$1.5 \cdot 10^{-2}$	$4.9 \cdot 10^{-2}$	$7.9 \cdot 10^{-1}$

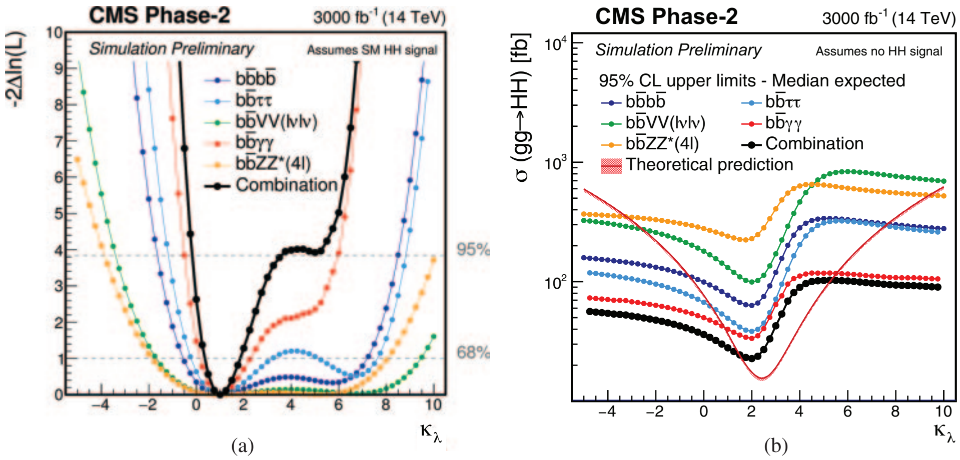


Fig. 3. – Expected likelihood scan (a) and upper limit at the 95% CL on the HH production cross section (b) as a function of κ_λ assuming SM HH signal and absence of HH signal, respectively. The functions are shown separately for the five decay channels studied and for their combination (in black).

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% (2.6 σ) CL. Both systematic and statistical uncertainties are considered. Results for each considered final state are shown in table III and details of each analysis are documented in [8].

The improvement of these results with respect to previous projections, which rely only on the extrapolation of current 2016 Run 2 results to an integrated luminosity of 3000 fb^{-1}, is achieved by the dedicated optimization of the analysis strategies applied to the HL-LHC data set.

Prospects are also studied for the measurement of the trilinear Higgs boson coupling for each final state and their combination (fig. 3(a)). The expected 68% and 95% confidence level intervals for the self-coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$ are [0.35, 1.9] and [−0.18, 3.6], respectively. The likelihood function is characterized by a peculiar structure with two local minima: this is due to the dependence of the total cross section and of the HH kinematic properties on κ_λ, while the relative height of the two minima depends on the capability of each analysis to access differential m_{HH} information. In fact, the total

Table III. – *Signal significance and 95% CL upper limit for each channel analyzed and their combination.*

HH →	$b\bar{b}b\bar{b}$	$b\bar{b}\tau\tau$	$b\bar{b}\gamma\gamma$	$b\bar{b}$VV($l\nu l\nu$)	$b\bar{b}$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

HH cross section has a quadratic dependence on κ_λ with a minimum at $\kappa_\lambda \simeq 2.45$ and a partial degeneracy exists between the $\kappa_\lambda = 1$ and a second κ_λ value. The interplay between the changes in the cross section and in the acceptance as a function of κ_λ affects the exact position of this second minimum.

On the one hand, thanks to the analyses that retain sensitivity on the differential m_{HH} distribution, such as $\mathrm{b\bar{b}b\bar{b}}$ and $\mathrm{b\bar{b}}\tau\tau$, the degeneracy between $\kappa_\lambda = 1$ and other κ_λ values is partially removed by using this information as input to the multivariate methods. On the other hand, exploting a dedicated m_{HH} categorization and good acceptance and purity in the low m_{HH} region in the case of the $\mathrm{b\bar{b}}\gamma\gamma$ channel, a better discrimination of the second minimum is achieved. The combination of the five analyses largely removes the degeneracy, and results in a plateau in the likelihood function for κ_λ values between 4 and 6. Finally, 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 (fig. 3(b)): the excluded cross section changes as a function of λ_{HHH}, because it is directly related to variations in the HH kinematic properties.

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