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# Measurement of the Higgs Self-Coupling in the HH $\rightarrow$ VVbb channel at the FCC-hh Collider

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The measurement of the Higgs self-interaction is an important test of the Standard Model (SM) electroweak symmetry breaking sector. Sensitivity to the Higgs self-coupling for m$_H$ = 125 GeV is evaluated through the measurement of the non-resonant di-Higgs production final states in proton-proton collisions at a future hadron collider with a center-of-mass energy of 100 TeV. The parton-level generation of the signal and the backgrounds is performed by using MadGraph5_aMC@NLO; then, the Delphes framework is used for a fast parametrization of the FCC-hh detector response. The considered decay channels are $HH \rightarrow VVb\bar{b}$, where $V = Z,W$. For the non-resonant SM signal in an ideal detector parametrization, a precision of O(10%-20%) on the SM cross-section can be estimated in the $b\bar{b}ZZ(4l)$ and $b\bar{b}WW(l\nu jj)$, respectively, corresponding to a precision of O(14%-40%) on the Higgs trilinear coupling.

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## 1. Introduction

After the discovery of the Higgs boson and the completion of the LHC physics programme in the mid-2030s, a lot of profound questions will remain, such as the complete understanding of the Higgs sector or the searching for physics phenomena Beyond the Standard Model (BSM). New machines are needed to open the door to the next phase of experimental exploration and investigate them more deeply. In this context, CERN is coordinating an international Future Circular Collider (FCC) collaboration of hundreds of institutions from all over the world, born to discuss the project for the most powerful circular collider and develop enabling technologies for the post-LHC era, according to the requests from the theoretical and experimental physics community.

A 100 TeV hadron collider is under consideration by the high-energy physics community [1], running at an energy significantly beyond that of the LHC and a luminosity comparable to that of the LHC. It would be housed in a 100 km tunnel in the area of Geneva, employing the LHC ring as a step of pre-acceleration and allowing different physics programmes (with $pp$, $e^+e^-$ and $ep$ collisions or with heavy ions beams). With a similar machine, the production rate of particles like Higgs bosons and top quarks and the cross-section of many processes will increase by a large factor, allowing for exploration of rare channels. The cross-section for the Higgs boson pair production, for example, will increase by about 40 times with respect to the LHC at 14 TeV. Consequently, precise measurements of the Higgs self-coupling and the study of its interactions with other SM particles to uncharted energy scales will be feasible.

One of the most clear Higgs benchmark channel for FCC-hh is the measurement of the Higgs boson pair production (Figure 1) [1, 2, 3, 4]. In particular, the measurement of the Higgs self-coupling ($\lambda_3$) is crucial, because it could provide unique information about the structure of the Higgs potential and probe several aspects of electroweak symmetry breaking mechanism. Furthermore, any possible deviations in 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. In fact, sizable corrections to $\lambda_3$ are predicted in BSM scenarios, leading, in some case, to large deviations in multi-Higgs production processes but not in other observables. We introduce a parametrization of an anomalous coupling, $\lambda_3 = k_\lambda \lambda_3^{SM}$, where $k_\lambda$ is called *self-coupling modifier*.

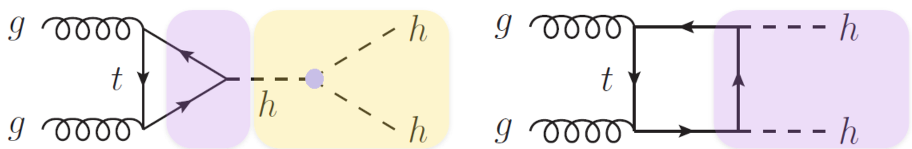


**Figure 1:** Leading order Feynman diagrams for non-resonant di-Higgs production in the SM through the Higgs boson self-coupling (left) and the top-box diagram (right).

Many efforts are already on-going to provide a Conceptual Design Report (CDR) for a FCC-hh by the end of 2018 and define the features of the detector, focusing on the most interesting physics signals. Here, we consider two different analyses related to the di-Higgs production through rare final states [5]: $HH \to b\bar{b}ZZ \to b\bar{b}4l$ and $HH \to b\bar{b}WW \to b\bar{b}l\nu jj$.

## 2. $HH \to b\bar{b}ZZ \to b\bar{b}4l$

The $b\bar{b}ZZ(4l)$ decay mode is categorized as a rare but clean process. Since the cross-section is really small ($\sigma_{b\bar{b}4l} = 178$ ab), at least one of the Higgs bosons is required to decay to a pair of $b$-quarks: the presence of two $b$-jets increases the statistics thanks to the high brancing ratio of $H \to b\bar{b}$ (58%). The final state is easier to reconstruct than others and the request of four leptons in association with two $b$-jets allows good background rejection and high signal efficiency. The main backgrounds processes are $t\bar{t}(b\bar{b})H(4l)$, $gg(H)+b\bar{b}$, $Z(b\bar{b})H(4l)$ and $t\bar{t}Z(2l)$, followed by minor negligible contributions such as $4l+b\bar{b}$ continuum, $t\bar{t}(bl\nu_l bl\nu_l)H(ll)$ and $t\bar{t}ZZ(4l)$. All the samples have been simulated using Madgraph [6] and Pythia8 [7]; then the parametrization of the detector effects and resolutions has been implemented with a pile-up 0 scenario in Delphes [8].

**Event selection** The signal and the backgrounds are studied using an optimized cut-flow based analysis, focusing on the selection of the Higgs peak from four leptons followed by the request of two b-jets. Events are required to have exactly four identified and isolated muons (electrons) with $p_T > 5$ (7) GeV and $|\eta| < 4.0$. At least two di-lepton pairs are required: $Z$ boson candidates are formed from pairs of opposite-charge leptons ($l^+l^-$). 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 $Z_2$. To improve the sensitivity to the Higgs boson decay, the $Z_1$ and $Z_2$ invariant masses have to be in the [40, 120] GeV and [12, 120] GeV ranges, 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 angular distance between two leptons is required to be $\Delta R(l_i, l_j) > 0.02$. The four leptons invariant mass, $m_{4l}$, is requested to be in the range $120 < m_{4l} < 130$ GeV. At least two identified $b$-jets, reconstructed with the anti-$k_T$ algorithm inside a cone of radius $R = 0.4$, are required. Their invariant mass is required to be in the range $80 < m_{b\bar{b}} < 130$ GeV and the angular distance between the 2 $b$-jets has to be $0.5 < \Delta R_{b\bar{b}} < 2$. These cuts are particularly effective to reject the $t\bar{t}H$ background. The percentage of events passing the full analysis chain in the signal and considered background samples is shown in Figure 2 (left).

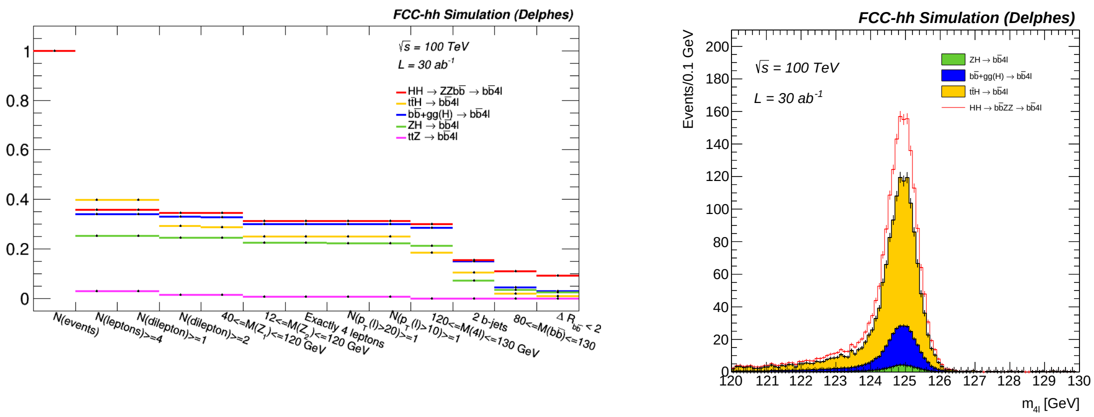


**Figure 2:** Cutflow table showing the percentage of events passing each step of the analysis applied to the signal and the considered backgrounds (left). Invariant mass distribution of the four leptons selected at the end of the analysis (right).

**Results** The invariant mass spectrum of the four leptons after the full event selection is shown in Figure 2 (right). The event yield, normalised to an integrated luminosity of 30 ab$^{-1}$, is $N_S = 489$ for the signal sample, $N_{ttH} = 1162$ for the $t\bar{t}H$ background, $N_{bbH} = 317$ for the $gg(H) + b\bar{b}$ sample, $N_{ZH} = 52$ and $N_{ttZ} = 179$ for the $ZH$ and the $t\bar{t}Z$ process respectively. The expected precision on the SM cross-section, denoted as $r$, is 10% and on the Higgs self-coupling modifier $k_\lambda$ is 14%. Both values are computed at 68% CL without considering systematics. Assuming a 1% systematic uncertainty on the signal and the backgrounds the precision on $r$ and $k_\lambda$ becomes 11% and 15% respectively, while with a 3% systematic uncertainty it worsens to 17% and 24%.

## 3. $HH \to b\bar{b}WW \to b\bar{b}l\nu jj$

To reach a compromise between signal efficiency and background reduction, one $W$ boson is required to decay hadronically and the other one leptonically ($\sigma_{b\bar{b}l\nu jj} = 62$ fb). The dominant backgrounds are $t\bar{t}$ and multi-jet background, with smaller contributions from Drell-Yan and single top-quark production. The samples have been simulated with 50 pile-up interactions per event.

**Event selection** The signal is identified using a boosted decision tree (BDT), trained to obtain the best separation from the dominant background $t\bar{t}$. The variables used in the BDT definition are: the angular separation $\Delta R$ between the two leptons; $p_T$, $\Delta R$ and invariant mass of both the two $W$ bosons and the two $b$-jets system; the transverse mass of the two $W$ system; $p_T$ of neutrino; the transverse mass of the $W$ which decays hadronically.

A set of preliminary cuts is applied to improve the performance of the BDT in the event selection, requiring an invariant mass of the two b-jets system in the range $80 < m_{b\bar{b}} < 180$ GeV, $p_T(WW)$>150 GeV and $\Delta R(b\bar{b})$ smaller than 2.0.

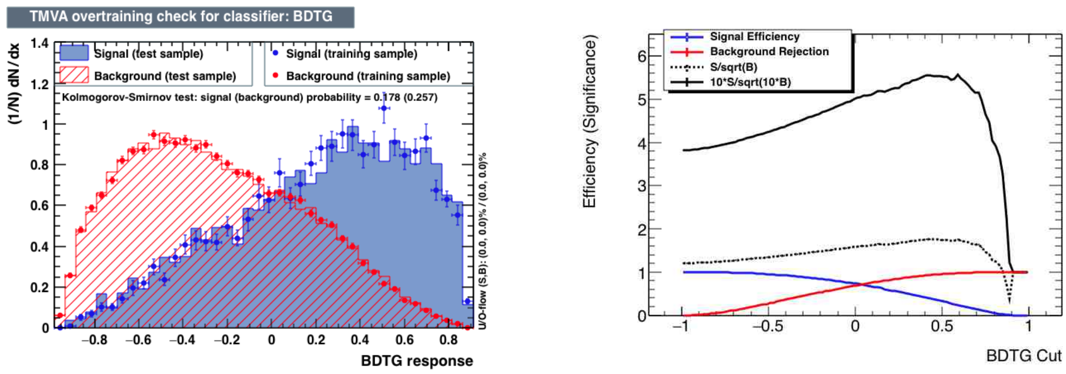


**Figure 3:** BDT response in the training of the signal and background samples (left). Efficiency as a function of the applied cut on the BDT response for two reference integrated luminosity values (right).

**Results** With a BDT cut of 0.51, as seen in Figure 3 (left), a statistical significance of 1.7 $\sigma$ corresponding to a signal efficiency of 0.22 and a background rejection uncertainty of 0.98 is obtained. The output BDT distribution for the signal and background is shown in Figure 3 (right). For an integrated luminosity of 30 ab$^{-1}$, the precision on the SM cross-section is 20% and the sensitivity to the trilinear coupling is about 40%.

## 4. Conclusions

The goal of these studies is to evaluate the sensitivity to the self-coupling of the Higgs boson for $m_H = 125$ GeV through the measurement of the non-resonant di-Higgs production final states at the 100 TeV FCC collider. So far, the analyses show that a precision of about 14% and 40% on the trilinear self-coupling in the $b\bar{b}ZZ(4l)$ and $b\bar{b}WW(l\nu jj)$, respectively, can be reached.

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