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Higgs self-coupling at the FCC-hh

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The Higgs self-coupling λ governs the shape of the Higgs potential and its precise determination is one of the main goals at future colliders. Here we present a new study based on fast simulations at the FCC-hh, assuming $\sqrt{s}$ = 100 TeV and an integrated luminosity of 30 ab^{-1}. The κ_λ self-coupling modifier is determined from double Higgs production in two channels, the $bb\gamma\gamma$ and the $b\bar{b}\ell\ell + E_T^{miss}$ final states. The $bb\gamma\gamma$ drives the precision, down to 3.6%, while the $b\bar{b}\ell\ell + E_T^{miss}$ achieves an uncertainty of 22%, however being a benchmark measurement for the impact of pile-up. A further study on the resolution of the invariant mass m_{bb} of the two b-jets in $bb\gamma\gamma$ shows that, with an optimal calorimeter and b-tagging algorithm achieving a resolution of 3% on m_{bb}, a precision $\leq$ 2% on κ_λ can be reached.

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1. Introduction

The Higgs boson (H) discovery in 2012 has been a milestone in particle physics and up to now the properties of this boson are in agreement with the Standard Model (SM) predictions within uncertainties [1, 2]. However the shape of the Higgs potential is still largely unknown, due to the loose constraints on the Higgs self-coupling λ obtained up to now. The Higgs self-coupling is mainly measured at the LHC from double Higgs production (HH), which is strongly suppressed in proton-proton collisions (see e.g. diagrams in [2]) and is about 1000 smaller than the single-H gluon-gluon fusion (ggF) process. The strongest constraint on the Higgs self-coupling modifier κ_λ at the time of the workshop, where κ_λ is defined as the ratio λ/λ_{SM}, is set by the ATLAS Collaboration exploiting single Higgs and HH production with the Run 2 data, and is in the range $-0.4 < \kappa_\lambda < 6.3$ at 95% confidence level [3].

Projections at future colliders quote a possible final uncertainty of about 50% at the HL-LHC, of about 33% at FCC-ee and down to 15-30% (4%) for a muon collider at 3 (10) TeV (see [4] for a recent compilation). The FCC-hh is planned as the second stage of the Future Circular Collider project. The first stage will be a high-luminosity e^+e^- collider hosted in a 90.7 km tunnel [5] running as a Higgs, top and electroweak factory. The FCC-hh will be in a second stage due to the needed R&D for the high-field magnets and will be a pp collider at $\sqrt{s}$ around 100 TeV and able to deliver up to 30 ab^{-1} of integrated luminosity for 2 interaction points. It will offer unprecedented potential in the higher energy frontier but also for precision Higgs physics. Due to the higher data sample (about a factor of 10) and the higher cross section (about a factor of 20 for di-Higgs production in ggF channel) compared to the HL-LHC, the HH data sample will be 400 times higher than at the HL-LHC and κ_λ can be measured with 20 times better precision. In addition, detector optimization and the possibility to add rarer channels will have the potential to increase this precision even more.

Previous studies on projections on κ_λ were obtained in [6], based on the $bb\tau\tau$ (hadronic channels), $bb\gamma\gamma$ and $b\bar{b}b\bar{b}$ final states, and quoting a sensitivity on κ_λ in the range 3.4–7.8%, depending on the assumed detector scenario and systematic uncertainties. Here an update based on an improved fast simulation is presented, based on two complementary channels, the $bb\gamma\gamma$ high-resolution final state and the $b\bar{b}\ell\ell + E_T^{miss}$ final state, the latter one being sensitive to pile-up.

2. Event generation, fast simulation and analysis

The study employs fast simulation samples, generated with the Delphes [7] framework, where the Delphes cards are based on a reference detector as described in the FCC-hh conceptual design report [8]. The detector concept is 50 m in overall length and 20 m in diameter with a central solenoid of 4 T and 2 forward solenoids, extending to a pseudorapidity coverage up to $|\eta| < 6$. It would consist of a silicon tracking detector, an electromagnetic calorimeter with LAr, a central hadron calorimeter with Pb/steel and scintillator tiles and an outer muon system with drift chambers. The expected pile-up at FCC-hh is $O(1000)$, however it is assumed that, by the time of the FCC-hh, high granularity of the components, timing detectors and pile-up mitigation algorithms will allow similar or even better performances as for the present LHC detectors. We assume then two detector scenarios, with resolutions and efficiencies on the main objects, and three sets of systematic uncertainties, as in Tables 1 and 2.

	Relative momentum resolution		Efficiency	
Object	Scenario I	Scenario II	Scenario I	Scenario II
Electrons	0.4-1%	0.8-3.0%	76-95%	72-90%
Muons	0.5-3%	1.0-6.0%	90-99%	88-97%%
	Medium b-tagging		80-90%	76-86%
	Mistag rates c-jets		10-20%	

Table 1: Relative momentum resolutions and efficiencies of the relevant objects used for the analysis.

Source of uncertainty	Syst. 1	Syst. 2	Syst. 3	Applies to
b-jet ID / b-jet	0.5%	1%	2%	Signals, MC bkgs.
Lepton ID / lepton	0.5%	1%	2%	Signals, MC bkgs.
γ ID / γ	0.5%	1%	2%	Signals, MC bkgs.
Luminosity	0.5%	1%	2%	Signals, MC bkgs.
Signal cross-section	0.5%	1%	1.5%	Signals, MC bkgs.
Data-driven bkg. est.	-	1%	1%	V+jets
Data-driven bkg. est.	-	-	1%	$t\bar{t}$

Table 2: Overview of systematic uncertainties considered in this study.

Proton-proton collisions at $\sqrt{s}$=100 TeV were generated for the signal samples at 3 different values of κ_λ (1, 2.4, 3.0). The Key4HEP project was used as software framework. Here the ggF di-Higgs signal is targeted (σ = 1.13 pb), where the two Higgs bosons are typically decaying back to back, with one of the Higgs decaying into two b-jets, and the second one into two photons ($bb\gamma\gamma$) or into two leptons plus missing transverse energy ($b\bar{b}\ell\ell + E_T^{miss}$, Fig. 1). The topology of the events allow to distinguish the signal from the overwhelming backgrounds.

2.1 The $b\bar{b}\ell\ell + E_T^{miss}$ channel

The $b\bar{b}\ell\ell + E_T^{miss}$ channel is characterized by two b-jets from one of the Higgs decays, two leptons of opposite sign (either muons or electrons) and missing transverse energy from the other Higgs decay. It includes the signals from $HH \to b\bar{b}WW^*$, $HH \to b\bar{b}\tau\tau$, $HH \to b\bar{b}ZZ^*$, for a total branching ratio of 3.24%. The final state with E_T^{miss} from the neutrinos makes the full reconstruction of one of the Higgs bosons not possible and therefore this is a less sensitive channel compared to the final states $bb\gamma\gamma$, $bb\tau\tau$, $b\bar{b}b\bar{b}$. The background is dominated by top pair production in the dilepton final state, followed by smaller contributions from V+jets, $t\bar{t}Z$, single top and other single-H production modes. A cut-based analysis exploits several kinematic variables to enhance the signal, like for instance a cut on the $m_{lb}^{reco} = \left(\min \frac{m_{l_1 b_1} + m_{l_2 b_2}}{2}, \frac{m_{l_1 b_2} + m_{l_2 b_1}}{2}\right)$ variable to suppress the top background (Fig. 1). Five categories are defined based on the lepton flavour, whether a resonant Z boson is present and on the angle between the leptons and the E_T^{miss} vector. The stranverse mass m_{T2} [9] (Fig. 1) is used in the statistical inference to extract the sensitivity on the signal strength and κ_λ, by using the Combine package [10], from a one-dimensional likelihood fit fixing all other H couplings to their SM values. The obtained precision in this channel, in the detector scenario I and systematics 1, is 22%.

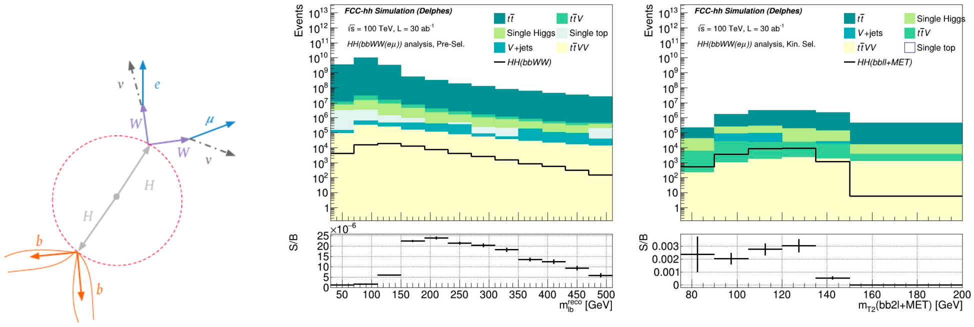

Figure 1: Topology of the event (left) and distributions of two variables used in the $b\bar{b}\ell\ell + E_T^{miss}$ analysis: the m_{lb}^{reco} variable to suppress the top background (middle) and m_{T2} used for the statistical inference (right).

2.2 The $bb\gamma\gamma$ channel

The $bb\gamma\gamma$ final state is characterized by two b-jets and two γ with respective m_{bb} and $m_{\gamma\gamma}$ peaking around 125 GeV. It has a branching ratio of only 0.26%, however it provides one of the best sensitivities due to the high resolution of the $\gamma\gamma$ system. Three deep neural networks (DNNs) are employed to suppress the various backgrounds, which are dominated by resonant single-H production (especially $t\bar{t}H$) and the non-resonant QCD $\gamma(\gamma)$+jets contribution. Some of the variables used are shown in Fig. 2. A first DNN is trained to suppress the $t\bar{t}H$ background based on kinematic variables of the final objects. The events are then split in two m_X regions (<350 and >350 GeV), as the shape of $m_X = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ depends on κ_λ. A second DNN is trained for the signal against the other backgrounds, defining a medium and a high category of the DNN score (>0.6). Finally the events, are divided in a central m_{bb} region around the Higgs mass value and a side-band region. The signal strength modifier is extracted from the eight resulting categories by fitting the $m_{\gamma\gamma}$ distribution. The resulting uncertainty on κ_λ amounts to 3.2% with the scenario I of the detector and statistical uncertainty only and to 3.6% with the systematics 1 assumption.

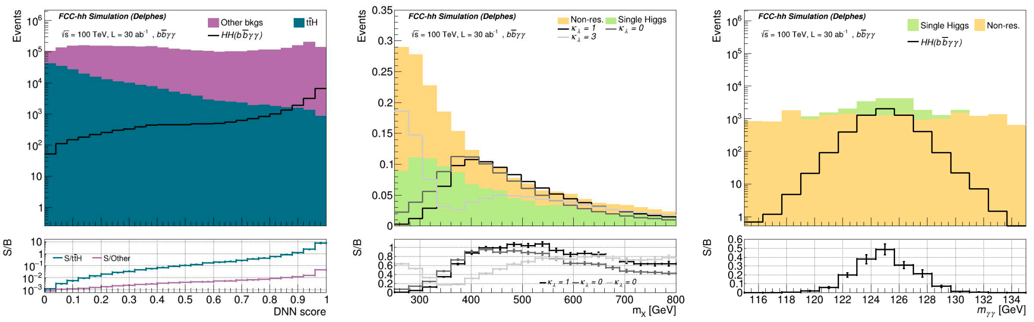

Figure 2: Distributions of variables used in the $bb\gamma\gamma$ analysis: the DNN score used to suppress the $t\bar{t}H$ background (left), the m_X distribution shown here with different κ_λ assumptions (middle) and the $m_{\gamma\gamma}$ distribution used in the statistical inference (right).

The precision on κ_λ is mainly driven by the resolution on the invariant mass m_{bb} of the two b-jets from the Higgs decay. Assuming b-jets regression algorithms and an optimal calorimeter performance at the time of FCC-hh, the statistical precision on κ_λ can be decreased to 2.5%, 2.0% and 1.8%, for an m_{bb} resolution of 10 GeV, 5 GeV or 3 GeV at the Higgs mass value, respectively.

3. Summary

A new study on the prospects to measure the Higgs self-coupling modifier κ_λ at the FCC-hh is shown here, assuming $\sqrt{s}$=100 TeV and 30 ab^{-1} of integrated luminosity, and analyzing fast simulation samples with two final states, $bb\gamma\gamma$ and $b\bar{b}\ell\ell + E_T^{miss}$. The $bb\gamma\gamma$ final state drives the precision, achieving a precision of 3.2% (3.6%) at statistical level (with systematic uncertainties 1, Table 2) and with the most performant detector scenario. With an m_{bb} resolution of 3 GeV at the Higgs mass value, this precision could be improved to below 2%.

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