A theoretical status of the triple Higgs coupling studies at the LHC

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ABSTRACT

Now that a Higgs boson has been discovered at the LHC, measuring its couplings to other particles is the next important step. In order to probe the electroweak symmetry breaking mechanism at its core it is crucial to reconstruct the scalar potential and hence measure the triple Higgs coupling at the LHC. We present a review of the main Standard Model Higgs boson pair production mechanisms in which the triple Higgs coupling plays a role and present the latest phenomenological analyses in view of a high luminosity LHC. One example of an analysis in the Two-Higgs-Doublet model will also be given as an illustration of an extended Higgs sector.

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1 Introduction

After the discovery in 2012 at CERN [1] of a Higgs boson [2] it is of utmost importance to pin down its properties, notably through couplings measurements. It looks like a Standard Model (SM) Higgs boson so far [3] but there is still the possibility of a beyond-the-SM (BSM) interpretation of the data.

After electroweak symmetry breaking (EWSB), the scalar potential contains triple and quartic Higgs couplings. Their measurements would allow for the reconstruction of the scalar potential. It has been shown that the quartic Higgs coupling is not accessible at current of foreseen collider energies of order 100 TeV [4]. This is the reason why the focus is on the triple Higgs coupling that is accessible through Higgs boson pair production. It has been the focus of early theoretical studies at leptonic [5, 6] and hadronic [7] colliders and a detailed analysis of the $b\bar{b}\gamma\gamma$ search channel in the early 2000s, including a fit to the $m_{HH}$ distributions, has stated that excluding a vanishing triple Higgs coupling would be possible at the LHC with a very high luminosity of 6 ab$^{-1}$ [8].

This review deals with the recent theoretical calculations of the SM production mechanisms and the state-of-the-art phenomenological analyses. Numerous BSM studies have also been performed and one case example will be given in the context of the Two-Higgs-Doublet model (2HDM) of type II.

2 SM Higgs boson pair production at the LHC

2.1 Overview of the main channels

The main production channels for a Higgs boson pair follow the same pattern as for single Higgs production and generic Feynman diagrams are depicted in Fig. 1. In Fig. 2 the total cross section is presented as a function of the center-of-mass energy. All cross sections are $\sim 1000$ times smaller than their single Higgs production counterparts: a high luminosity is required to measure the production of a Higgs boson pair.

![Generic Feynman diagrams](image)

Figure 1: Generic Feynman diagrams contribution to gluon fusion Higgs pair production (up) and VBF production (down). The triple Higgs coupling is highlighted in red.

The gluon fusion mechanism is the largest production channel. It is mediated by loops of heavy quarks (top and bottom in the SM), see Fig. 1 (up). The leading order (LO) cross section was calculated decades ago [9, 10] and the process has been known for long at next-to-leading order (NLO) in QCD in an effective field theory (EFT) approach using the infinite top quark mass approximation [11]. The NLO K-factor is of the order of 2, similar to the single Higgs production case. The major improvement in 2013 came from the extension of this calculation up to the next-to-next-to-leading order (NNLO), providing a $+20\%$ increase of the total cross section [12], see Fig. 2 (right). An improved NLO calculation is also available [13] including the exact real emission. A next-to-next-to-leading logarithmic (NNLL) resummation was performed in Ref. [14] and increases the NLO cross section by 20% to 30%, stabilizing also the scale dependence of the result. The merging to parton showering effects for gluon fusion plus one jet has been done in 2014 [15] leading to a sizable reduction of the uncertainties on the efficiencies of the cuts down to the level of 10%.

The second production channel at the LHC is the vector boson fusion (VBF). The structure of this process is very similar to the single Higgs production case and proceeds at LO via the generic Feynman diagrams depicted in Fig. 1 (down). The LO cross section has been known for a while [9, 10] and recently the NLO QCD corrections have been calculated for the total cross section and the differential distributions [13, 17] and
they increase the LO result by \( \approx 7\% \). The calculation has been implemented in the public code VBFNLO [18]. The approximate NNLO QCD corrections have been obtained using the structure function approach which gives quite good results for the total cross section and they increase the NLO result by less than 1% [19].

The two other channels are of less importance, the double Higgs-strahlung known up to NNLO in QCD [17] and the associated production with a top-antitop pair known up to NLO in QCD [13]. A NLO interface to parton shower for these processes as well as the first two presented has been performed in Ref. [13], allowing for NLO differential predictions in all channels.

2.2 Theoretical uncertainties on the total rates

The gluon fusion channel is affected by sizable uncertainties of three different types: a) the scale uncertainty due to the variation of the renormalization scale \( \mu_R \) and the factorization scale \( \mu_F \) around a central scale \( \mu_0 = M_{HH} \). This provides a rough estimate of the missing higher-order terms and amounts to \( \approx \pm 8\% \) at NNLO at 14 TeV [12], see Fig. 2(right); b) the uncertainty related to the parton distribution function (PDF) and the experimental value of \( \alpha_s(M_Z^2) \). This uncertainty calculated at NLO within the MSTW2008 PDF set [20] at 90% CL is \( \pm 7\% \) at 14 TeV [17]; c) the uncertainty related to the EFT approach (see Ref. [17] for more details), estimated to be of the order of 10% [17] and confirmed by the top mass expansion calculation of Ref. [21]. The total uncertainty amounts to \( \approx 37\% \) at 14 TeV at NLO [17], which can be reduced down to \( \approx 30\% \) using the latest NNLO result.

The VBF channel is a rather clean process and the theoretical uncertainties are rather small. The scale uncertainty, calculated with a variation of \( \mu_R \) and \( \mu_F \) around the central scale \( \mu_0 = Q_{W/Z}^* \) is roughly \( \pm 3\% \) at NLO [17]. The PDF uncertainty is limited and amounts to \( \approx 7\%/ -4\% \) at 14 TeV. There is no EFT uncertainty and the total theory error is \( \approx 8\%/ -5\% \) at 14 TeV [17].

3 Parton level analysis

The Higgs pair production process needs to be measured in order to extract the triple Higgs coupling \( \lambda_{HHH} \). The total rates being quite small, it is required in the parton level analyses that at least one Higgs boson decays in a \( b\bar{b} \) pair because this channel has the highest branching fraction. There are then two main interesting final states: a) \( b\bar{b}\tau\tau \); b) \( b\bar{b}\gamma\gamma \), rather clean but the rates are very small and there is a lot of fake photon identification. These channels are currently used by the experimental collaborations in their projections for the future [22]. All the analyses are based on the gluon fusion production channel at 14 TeV using LO \( gg \rightarrow HH \) matrix elements normalized to the NLO total cross section and boosted topology cuts in addition to standard acceptance cuts. The channel \( HH + 2j \), including VBF production, has started to be investigated [23].
3.1 The $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ channels

The $b\bar{b}\tau\tau$ channel is rather promising. When using a $\tau$ reconstruction efficiency of 80%, $M_{HH} > 350$ GeV and $p_T(H) > 100$ GeV as boosted topology cuts and an optimistic mass window 112.5 GeV $< M_{\tau\tau} < 137.5$ GeV, this results in a significance $S/\sqrt{B} = 2.97$ already at 300 fb$^{-1}$ and 9.37 at 3 ab$^{-1}$ [17], corresponding to 33 and 330 signal events respectively.

The main improvement in 2012 came from the use of the jet substructure analysis presented in Ref. [24]. This technique has been applied in Ref. [25] in addition to the other cuts presented above, obtaining a signal-over-background ratio $S/B \simeq 0.5$ and 95 signal events at 1000 fb$^{-1}$. Adding one jet in the final state enhances the significance and $S/B \simeq 1.5$, and with additional improvements a 60% accuracy on $\lambda_{HHH}$ could be reached at 3 ab$^{-1}$ [26]. This very promising channel hence needs a dedicated analysis by the experimental collaborations to assess the potential difficulties of a realistic experimental environment.

The $b\bar{b}\gamma\gamma$ channel is a clean channel but rather difficult because of the smallness of the signal rates and the large amount of fake photons. Nevertheless it has been found in Ref. [17] that the significance could be $S/\sqrt{B} = 6.46$ at 3 ab$^{-1}$ with 47 signal events when assuming a $b$-tagging efficiency of 70% and including a simulation of the fake photons. This simulation also uses the same boosted topology cuts as above with $|y_{\mu}| < 2$ and an isolation $\Delta R(b,b) < 2.5$ in addition. This promising channel has also been part of a high energy LHC analysis [27].

Using a multivariate analysis could improve the results. It has been found in Ref. [28] that it increases the significance of the signal and would lead to a probe of the triple Higgs coupling at the level of 40% uncertainty at the LHC at 14 TeV using 3 ab$^{-1}$ of data.

3.2 More improvements

Additional improvements could increase the sensitivity of the previous searches. In Ref. [29] it has been advocated to use the ratios $C_{HH}$ of double Higgs production to single Higgs production cross sections to significantly reduce the theoretical uncertainties, down to $\Delta^t C_{HH} \simeq \pm 2\%$ and $\Delta^{PDF} C_{HH} \simeq \pm 2\%$. This is due to the similar structure in the higher-order corrections in both channels.

The semi-leptonic $b\bar{b}W^+W^-$ channel at 14 TeV could be also a valuable channel when using a multivariate analysis with a possible significance $S/\sqrt{S+B} = 2.4$ at 600 fb$^{-1}$ already with 9 signal events [30]. In addition, the $4b$ channel had been thought for long not to be a useful channel, nevertheless it has been reanalyzed recently with a jet substructure analysis and a side-band analysis and found to be interesting with 3 ab$^{-1}$ of data to constrain $\lambda_{HHH} \lesssim 1.2 \times \lambda_{HHH}^{SM}$ at 95% CL [31]. More experimental analyses are obviously required to confirm this promising result.

4 The 2HDM of type II: a case example of a BSM analysis

The study of the triple Higgs coupling in various extensions of the SM has been very active in the past few years. There are many examples, such as with a strong Higgs sector [32], Minimal Supersymmetric SM (MSSM) analyses [33], Next-to-MSSM analyses [34], etc. As a case example we choose here to present the CP-conserving 2HDM in which there are two Higgs doublets leading to five Higgs bosons: 2 CP-even bosons $h$ and $H$, one CP-odd boson $A$ and two charged Higgs bosons $H^\pm$. In the type II version one doublet couples to the up-type fermions while the other couples to the down-type fermions.

A fit using the latest experimental data as well as theoretical constraints, especially tight perturbativity limits, has been presented in Ref. [35]. The triple Higgs coupling of the light $h$ cannot be enhanced compared to the standard $\lambda_{HHH}^{SM}$ (see Fig. 3(left)). Still the triple Higgs couplings between non-standard Higgs bosons can reach $5 \times \lambda_{HHH}^{SM}$ at 2$\sigma$ as exemplified with the case of $\lambda_{AAH}$ in Fig. 3(center). Thanks to the effect of a possible resonant heavier CP-even Higgs boson $H$ it is also possible to greatly enhance $\sigma(gg \rightarrow hh)$ and it could be one detection mode for the heavier Higgs boson $H$ (see Fig. 3(right)). These effects have also been studied in Ref. [36].
5 Outlook

Extracting the triple Higgs coupling and hence measuring the production of a Higgs boson pair is one of the goals of the high luminosity run of the 14 TeV LHC. Great improvements have been made in the calculation of the SM cross sections, now reaching at least the NLO QCD accuracy if not that of the NNLO. The theoretical uncertainty is then reduced down to the level of 30% in the gluon fusion channel and below 10% in the other channels. It is expected that the next coming years will bring major improvements towards a fully differential NLO calculation of the gluon fusion channel including the full quark mass dependance. The parton level analyses, in particular in the $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ channels, have seen good prospects already at 300 fb$^{-1}$ and mostly at 3 ab$^{-1}$. These two channels are now under consideration by ATLAS and CMS.

There has been also a lot of BSM activity in order to pin down potential large effects on the triple Higgs coupling. One example is the 2HDM of type II in which non-standard triple Higgs couplings can reach five times the size of the standard triple Higgs coupling. Light $hh$ pair production can also be greatly enhanced due to a resonant heavier Higgs boson $H$. Lots remain to be done given the vast landscape of BSM physics.

References


