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# A theoretical review of triple Higgs coupling studies at the LHC in the Standard Model

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After the discovery of a Higgs boson at the LHC, the next important step is to measure its couplings to fermions and bosons to unravel its true nature. In order to ultimately test the shape of the scalar potential that triggers the electroweak symmetry breaking, it is crucial to measure the triple Higgs coupling at the LHC. We review the theoretical predictions of the main Standard Model Higgs pair production mechanisms that are needed for such a measurement and present the latest developments in the phenomenological analyses in view of a high luminosity LHC.

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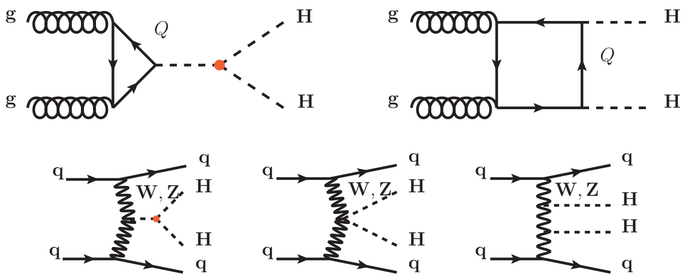


**Figure 1:** Generic Feynman diagrams contribution to gluon fusion Higgs pair production (up) and VBF production (down). The triple Higgs coupling is highlighted in red.

## 1. Introduction

After the discovery of a bosonic particle in 2012 at CERN [1] which has the properties of a Higgs boson [2], the next important task is to perform a detailed study of this boson to pin down its exact nature. The LHC data in 2013 seem to favor a Standard Model (SM) Higgs boson so far [3], but there is still room left for a beyond-the-SM (BSM) interpretation. A measurement of the Higgs boson self-couplings would allow for the reconstruction of the scalar potential triggering the electroweak symmetry breaking (EWSB) mechanism and is the ultimate test of the SM.

After EWSB, the scalar potential contains triple and quartic Higgs couplings. It has been shown in the last decade that the quartic Higgs coupling is not accessible at current of foreseen collider energies of order 100 TeV [4], leading to the focus on the triple Higgs coupling which can be probed through the production of a Higgs boson pair. The early studies focused first on leptonic colliders [5, 6] before the first study at the LHC which gave the theoretical predictions for the main production mechanisms [7]. A comprehensive analysis of the $b\bar{b}\gamma\gamma$ search channel, including a fit to the $m_{HH}$ distributions, stated later on 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 will present the recent improvements in the theoretical predictions of the main production mechanisms and in the phenomenological analyses compared to these early studies. Only the SM case will be presented but numerous BSM studies have also been performed.

## 2. SM Higgs boson pair production at the LHC

The main production channels for a Higgs boson pair follow the same pattern as for single Higgs production. The main channel is the gluon fusion production which is known up to next-to-next-to-leading order (NNLO) in QCD in an effective field theory (EFT) approach [9], then followed by the vector boson fusion (VBF) channel known exactly up to next-to-leading order (NLO) in QCD [10, 11] and even up to NNLO in a structure function approach [12], see Fig. 1 for generic Feynman diagrams. The two other channels are of less importance, the double Higgs-strahlung known up to NNLO in QCD [10] and the associated production with a top-antitop pair known up to NLO in QCD [11].

The pattern of these four channels is depicted in Fig. 2 where the total cross section is presented as a function of the center-of-mass energy. The important common feature of all these channels is the smallness of the cross sections: compared to single Higgs boson production they are three

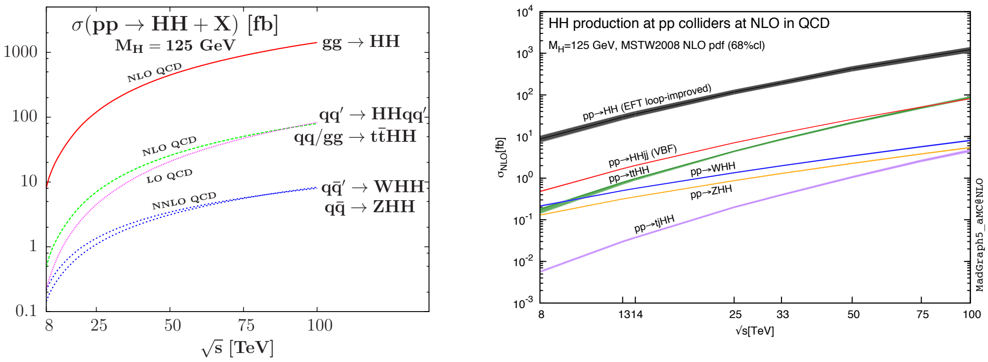


**Figure 2:** The total hadronic cross section of the main production channels of a Higgs boson pair $HH$ (in fb) as a function of the center-of-mass-energy $\sqrt{s}$ (in TeV). Taken from Ref. [10] (left) and Ref. [11] (right).

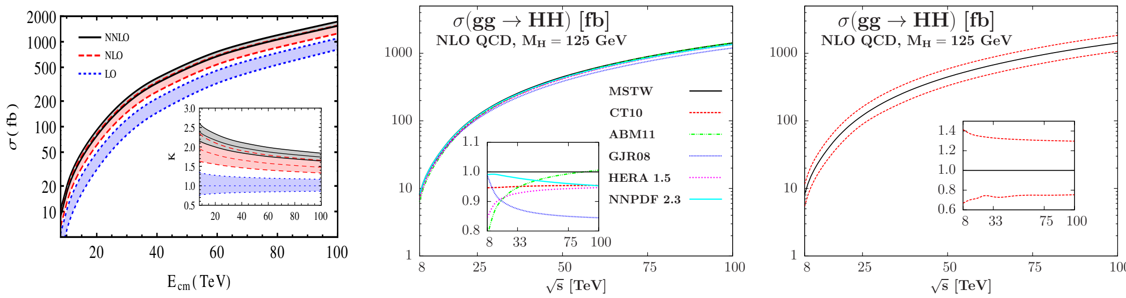


**Figure 3:** Left: the total hadronic cross section $\sigma(gg \to HH)$ at the LHC (in fb) as a function of $\sqrt{s}$ (in TeV) up to NNLO in QCD from Ref. [9], including the scale uncertainty. Center: the same at NLO using different PDF sets, from Ref. [10]. Right: the same at NLO including the total theoretical uncertainty, from Ref. [10].

orders of magnitude smaller and that explains how challenging the measurement of Higgs boson pair production at the LHC is. A high luminosity will be required to perform such a measurement.

### 2.1 The gluon fusion channel

The gluon fusion mechanism provides the largest production channel. It is mediated by loops of heavy quarks that are in the SM mainly top quarks, see Fig. 1 (up). The bottom loop contribution amounts to less that 1% at leading order (LO). The LO cross section was calculated decades ago [13, 14] and the process has been known for long at NLO in QCD in an EFT approach using the infinite top quark mass approximation [15]. 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 NNLO order, providing a +20% increase of the total cross section [9], and is depicted in Fig. 3 (left). At 14 TeV one has $\sigma^{\rm NLO}(gg \to HH) = 33.9$ fb and $\sigma^{\rm NNLO}(gg \to HH) = 40.2$ fb [9]. A next-to-next-to-leading logarithmic (NNLL) resummation was performed in Ref. [16] and increases the NLO cross section by 20% to 30%, stabilizing also the scale dependence of the result.

The gluon fusion channel is affected by sizable uncertainties, divided in three categories: *a)* the scale uncertainty which is due to the variation of the renormalization scale $\mu_R$ and the factorization scale $\mu_F$ around a central scale $\mu_0 = M_{HH}$, and viewed as a rough estimate of the missing higher-order terms. This amounts to $\simeq \pm 18\%$ at NLO at 14 TeV [10] and $\simeq \pm 8\%$ at NNLO [9]; *b)* the uncertainty related to the parton distribution function (PDF) and the experimental value of $\alpha_s(M_Z^2)$, reflected in the spread of the predictions using different PDF sets, see Fig. 3 (center). The uncertainty calculated within the MSTW2008 PDF set [17] at 90% CL is $\pm 7\%$ at 14 TeV [10]; *c)* the uncertainty related to the EFT approach (see Ref. [10] for more details), estimated to be of the order of 10% [10] and confirmed by the top mass expansion calculation of Ref. [18]. The total uncertainty amounts to $\pm 37\%$ at 14 TeV at NLO [10], which can be reduced down to $\pm 30\%$ using the latest NNLO result.

### 2.2 The vector boson fusion channel

The VBF channel is the second largest production channel at the LHC. 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 [13, 19] and recently the NLO QCD corrections have been calculated for the total cross section and the differential distributions [10, 11] and they increase the LO result by $\simeq 7\%$. The calculation has been implemented in the public code `VBFNLO` [20]. 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% [12].

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 [10]. The PDF uncertainty is limited and amounts to $\simeq +7\%/-4\%$ at 14 TeV. There is no EFT uncertainty and the total theory error is $\simeq +8\%/-5\%$ at 14 TeV [10].

### 2.3 Interface to parton shower

The beginning of the year 2014 has seen progresses in the interface between the hard cross section calculations and the parton showering effects. Gluon fusion production plus one jet has been merged to parton shower in an `HERWIG++` implementation [21], leading to a sizable reduction of the theoretical uncertainties on the efficiencies of the cut, now at the level of 10% [22].

In Ref. [11] a NLO interface to parton shower was performed for all main processes in the `MadGraph5_aMC@NLO` framework [23], allowing for NLO differentials predictions in all channels. In particular, an improved NLO calculation has been performed for the gluon fusion mechanism in which the real emission is calculated exactly.

## 3. Parton level analysis

In order to extract the triple Higgs coupling $\lambda_{HHH}$, first the Higgs pair production process needs to be measured. In Ref. [10] it has been shown that the cross section which is the most sensitive to $\lambda_{HHH}$ is the VBF production. Increasing the center-of-mass energy reduces the sensitivity of the total cross section to the triple Higgs coupling. 50% accuracy on the total cross section leads to a 50% accuracy on $\lambda_{HHH}$ at 14 TeV.

Due to the smallness of the total cross sections, in the parton level analyses it is required that at least one Higgs boson decays in a $b\bar{b}$ pair because this channel has the highest branching fraction. There are then three 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; *c)* semi-leptonic $b\bar{b}W(\to \ell\nu)W(\to 2j)$, rather difficult because of the missing energy. The fully leptonic channel is not promising [10] while the other channels are currently used by the experimental collaborations in their projections for the future [24]. All the analyses are based on the gluon fusion production channel at 14 TeV using LO $gg \to HH$ 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 [25].

### 3.1 The $b\bar{b}\tau\tau$ channel

This 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$^{-1}$ [10]. This corresponds respectively to 33 and 330 signal events.

The major improvement has come from the use of the jet substructure analysis [26]. Defining a large cone size for the jet (a "fat jet") and then working backward through the jet in order to separate the softer subjets helps to distinguish the signal from the large QCD backgrounds. This has been applied successfully in addition to the cut strategy presented above and one obtains a signal-over-background ratio $S/B \simeq 0.5$ and 95 signal events at 1000 fb$^{-1}$ [27]. Adding one jet in the final state enhances the significance and $S/B \simeq 1.5$, and then with kinematic bounding variables a 60% accuracy on the triple Higgs coupling could be reached at 3 ab$^{-1}$ [28]. This is hence a very promising channel that needs a dedicated analysis by the experimental collaborations as these results represent what could be achieved in an ideal situation.

### 3.2 The $b\bar{b}\gamma\gamma$ channel

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. [10] 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 simulating the fake photons with `DELPHES` [29]. This simulation also uses the same boosted topology cuts of the previous section with $|\eta_H| < 2$ and an isolation $\Delta R(b,b) <$ 2.5 in addition. This channel is then also very promising and it has been part of a high energy LHC analysis [30].

Using a multivariate analysis could improve the results. It was found in Ref. [31] 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.

### 3.3 The semi-leptonic $b\bar{b}W^+W^-$ channel

Whereas the fully leptonic $b\bar{b}W^+W^-$ channel seems to be hopeless, the semi-leptonic channel could trigger interesting results. In Ref. [32] a parton level analysis was presented, that relies on a jet substructure analysis improved with a boosted decision tree and specific cuts to this channel such as a cut on the hadronically decaying $W$ boson $m_{W_h} >$ 65 GeV. The analysis has obtained a promising result of $S/\sqrt{S+B} = 2.4$ at 600 fb$^{-1}$ already with 9 signal events. More detailed analyses are required to assess the potential of this search channel in a more realistic experimental environment.

### 3.4 More improvements

There are additional improvements that can increase the sensitivity of the previous searches. One example is the use of ratios $C_{HH}$ of double Higgs production to single Higgs production cross sections [33]. Owing to the similar structure in the higher-order corrections in both channels, this leads to a substantial reduction of the theoretical uncertainties with $\Delta^{\mu} C_{HH} \simeq \pm 2\%$, $\Delta^{\rm PDF} C_{HH} \simeq \pm 2\%$. This would lead to a very promising confidence interval of $\simeq +30\%/-20\%$ on the triple Higgs coupling when combining the three previous search channels.

An analysis in the $4b$ search channel, which had been thought for long not a useful channel, has been recently released. Using a jet substructure analysis and a side-band analysis, it was found that at the LHC at 14 TeV with 3 ab$^{-1}$ of data it may be possible to constraint $\lambda_{HHH} < 1.2 \times \lambda_{HHH}^{\rm SM}$ at 95% CL [34]. More experimental analyses are obviously required to confirm this result.

## 4. Outlook

The production of a Higgs boson pair is one of the goals of the high luminosity run of the LHC at 14 TeV, in order to extract the triple Higgs coupling. The past two years have seen major improvements in the theoretical knowledge on the SM Higgs boson pair production and the main channels have now reached the NLO or even NNLO QCD accuracy. The theoretical uncertainty is of the order of 30% in the gluon fusion channel and less than 10% in the other production channels.

The parton level analyses, notably 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$^{-1}$, triggering the experimental collaborations to perform a detailed study. Major theoretical improvements are expected in the coming years towards a fully differential NLO calculation of the gluon fusion channel including the full quark mass dependance.

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