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MULTI-HIGGS BOSON PRODUCTION AND SELF-COUPLING MEASUREMENTS AT HADRON COLLIDERS*

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The Higgs boson is the first fundamental scalar to be discovered. A crucial task following this discovery is to directly measure its couplings to the Standard Model content. These include the self-couplings that can be probed via production of multiple Higgs bosons at hadron colliders. I will be discussing recent phenomenological advancements in this direction, focussing on Higgs boson pair and triple production at the Large Hadron Collider and a Future Circular hadron Collider (FCC).

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1. Introduction

In this paper, I will be discussing ways of measuring the coupling between scalar particles at colliders. Let us consider a set of scalar particles $\mathcal{S}_i$, where, *e.g.*, $i = \{1, 2, 3, 4\}$. Examples of the vertices that we would be interested in appear in figure 1. The relevant Lagrangian would then contain interactions, *e.g.*, of the form of

$$\mathcal{L} \supset \Lambda \sum_{ijk} \lambda_{ijk} \mathcal{S}_i \mathcal{S}_j \mathcal{S}_j + \sum_{ijkl} \lambda_{ijkl} \mathcal{S}_i \mathcal{S}_j \mathcal{S}_j \mathcal{S}_l \,, \tag{1}$$

where λ_{ijk} and λ_{ijkl} are the relevant three- and four-point couplings and Λ is some mass scale characterising the interactions. If one of these particles also happens to couple to the constituents of hadrons, say, $\mathcal{S}_3$, then this would result in direct production, for example, of the final states $\mathcal{S}_1 \mathcal{S}_2$ or $\mathcal{S}_1 \mathcal{S}_2 \mathcal{S}_4$.

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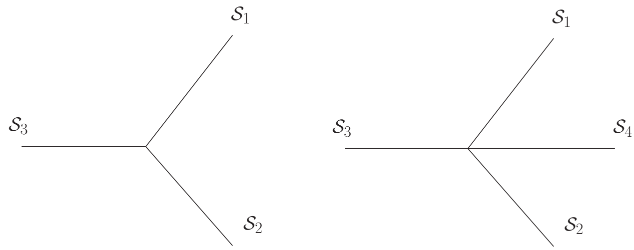

Fig. 1. The vertices representing the coupling between three (left) or four scalars (right), $\mathcal{S}_i$.

Here, I will be focussing on the cases $\mathcal{S}_1 = \mathcal{S}_2 = \mathcal{S}_3 = h$ and $\mathcal{S}_1 = \mathcal{S}_2 = \mathcal{S}_3 = \mathcal{S}_4 = h$, where h is the Higgs boson scalar, and the relevant couplings in this case are the triple Higgs couplings, which will be denoted as λ_3 and the quartic Higgs coupling, which will be denoted as λ_4.

Some comments are appropriate at this point. First of all, in general, the "self-coupling" diagrams are not the only diagrams that would appear in such processes. Moreover, the "interesting" diagrams could be suppressed with respect to the additional diagrams, for example, due to propagator suppression. Additionally, the self-coupling diagrams could appear in loops, and precision measurements could be sensitive to them, for example through their contribution either in gauge boson masses or single scalar production at colliders.

This paper is organised as follows: in the next section, we discuss multi-Higgs boson production, and, in particular, double and triple Higgs boson production at the Large Hadron Collider (LHC) and a future circular hadron collider with the centre-of-mass energy of 100 TeV. I will then briefly discuss indirect constraints on the self-couplings, obtained through precision measurements, and summarise.

2. Multi-Higgs boson production at hadron colliders

2.1. Motivation

Let us begin with reviewing the recipe for the electroweak sector of the Standard Model. One considers an $\mathrm{SU}(2) \times \mathrm{U}(1)$ gauge symmetry and a complex doublet scalar field, H, that "sits" in a potential $\mathcal{V}(H^\dagger H)$, shown in figure 2 and given by

$$\mathcal{V}\left(H^\dagger H\right) = \mu^2 |H|^2 + \lambda |H|^4 \,, \tag{2}$$

where μ and λ are two parameters to be determined. The minima of the potential of Eq. (2) lie on $|H|^2 = v^2/2$. Choosing a particular minimum, $|H| \sim (0, v)/\sqrt{(2)}$ realizes electroweak symmetry breaking, maintaining the

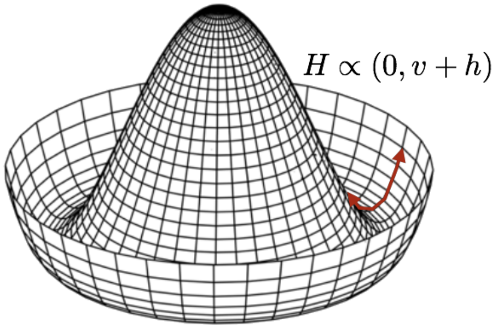

Fig. 2. The "mexican-hat" potential for the Higgs complex SU(2) scalar doublet.

U(1) invariance required by electrodynamics. Excitations about this minimum, *i.e.* $|H| \sim (0, v + h)/\sqrt{2}$ represent the physical scalar Higgs boson. The remaining three degrees of freedom of the complex doublet scalar field, the Goldstone bosons, are "absorbed" by the W and Z gauge bosons that consequently acquire mass. This results in the following potential for the physical scalar, h:

$$\mathcal{V}(h) = \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4 \,, \tag{3}$$

where we have exchanged μ^2 and λ with the physical parameters m_h and v, the Higgs boson mass and the vacuum expectation value respectively. In what follows, we will define $\lambda_3^{\mathrm{SM}} \equiv m_h^2/(2v^2)$ and $\lambda_4^{\mathrm{SM}} \equiv \lambda_3^{\mathrm{SM}}/4$. We may then write deviations of the couplings from the expected values as

$$\mathcal{V}(h) = \frac{1}{2} m_h^2 h^2 + (1 + c_3)\lambda_3^{\mathrm{SM}} h^3 + (1 + d_4)\lambda_4^{\mathrm{SM}} h^4 \,, \tag{4}$$

where c_3 and d_4 parametrize the deviations and we may then define $\lambda_3 \equiv \lambda_3^{\mathrm{SM}}(1 + c_3)$ and, equivalently, for λ_4. Non-zero values of these parameters would signify the presence of new physics in the Higgs potential. Since Higgs bosons couple to initial-state partons, either via vector-boson fusion or gluon fusion, it is evident that these interactions lead to Higgs boson pair or triple production. Consequently, measurements of these processes provide the most direct way to probe the self-couplings.

The cross sections for multi-Higgs boson processes are small for $m_h \simeq 125$ GeV, $\sigma_{hh}(14 \text{ TeV}) \simeq 50$ fb, $\sigma_{hhh}(14 \text{ TeV}) \simeq \mathcal{O}(0.1)$ fb and at 100 TeV these increase to: $\sigma_{hh}(100 \text{ TeV}) \simeq 1800$ fb and $\sigma_{hhh}(100 \text{ TeV}) \simeq 5$ fb [1–7]. Thus, triple Higgs boson production is expected to provide little to no information at the LHC [8–10]. Higgs boson pair production still remains challenging, but some information could be potentially extracted at the LHC. I will be focussing on this first.

2.2. Higgs boson pair production: theoretical aspects

The dominant production mode for Higgs boson pairs proceeds through gluon fusion, through quark loops. Due to the size of the fermion Yukawas, the dominant contribution comes from top quarks running in the loop [1]. The leading-order (LO) diagrams are shown in figure 3. The self-coupling is

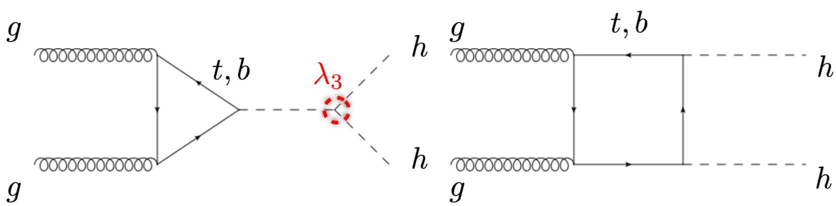

Fig. 3. The dominant leading-order diagrams contributing to Higgs boson pair production via gluon fusion at hadron colliders.

denoted as λ_3 and appears on the diagram on the left, which we will refer to as the "triangle" diagram. The diagram on the right does not contain any self-coupling contributions and will be referred to as the "box" diagram. Due to the fact that the invariant mass of the final state is large, it can probe the structure of the top quark loop, and hence the approximation known as the "Higgs effective theory" (HEFT) does not work well beyond $m_{hh} \sim 2m_t$, where m_{hh} is the Higgs boson pair invariant mass and m_t is the top quark mass. For this reason, one needs to use the full expressions for the loop diagrams, containing the full top mass dependence. It would be interesting to examine the spin structure of these diagrams. With the reference to figure 3, one can write the total matrix element as the sum of the matrix elements for the triangle and the box: $\mathcal{M} = \mathcal{M}_\triangle + \mathcal{M}_\square$. The matrix elements can be expressed in terms of two orthogonal tensors A_1 and A_2, where $A_1 \cdot A_2 = 0$ and $A_1 \cdot A_1 = A_2 \cdot A_2 = 2$, and where A_1 represents a spin-zero ($S_z = 0$) configuration for the incoming gluons and A_2 represents a spin-two ($S_z = 2$) configuration. Due to the intermediate Higgs boson in the triangle diagram propagator, it can only mediate a spin-zero gluon configuration, and hence $\mathcal{M}_\triangle = \alpha_\triangle A_1$ and $\mathcal{M}_\square = \alpha_\square A_1 + \beta_\triangle A_2$, where $\alpha_\triangle$, $\alpha_\square$ and $\beta_\square$ are numerical coefficients. Hence, the squared matrix element at LO is given by

$$|\mathcal{M}|^2 = |\alpha_\triangle|^2 + 2\mathrm{Re}\{\alpha_\triangle \alpha_\square\} + |\alpha_\square|^2 + |\beta_\square|^2 \,, \tag{5}$$

where evidently the interference term only involves spin-zero configurations. With this consideration, calculating the cross section at leading order would give

$$\sigma_{hh}^{\mathrm{LO}}(14~\mathrm{TeV}) \simeq \left[5.22\,(1+c_3)^2 - 25.1\,(1+c_3) + 37.3\right]~\mathrm{fb}\,, \tag{6}$$

where one can see that the triangle squared contribution is sub-dominant with respect to the box squared contribution. Moreover, one notices that the interference is large and negative for the SM point ($c_3 = 0$). This reduces the cross section dramatically compared to the case where the self-coupling is absent ($c_3 = -1$).

Taking into account the fact that at LO one needs to calculate the full one-loop process to obtain reliable results, it is clear that the next-to-leading order (NLO) calculation is a two-loop calculation. This is considerably challenging to perform analytically. A numerical calculation was completed recently [11]. The di-Higgs boson invariant mass distribution, shown in figure 4 taken from [11], clearly demonstrates how essential it is to employ the full two-loop calculation in order to obtain accurate predictions in the whole spectrum. The figure shows the LO, NLO HEFT [2] and NLO "$\mathrm{FT}_{\mathrm{approx}}$" [10] calculations for comparison. The full NLO calculation was matched to a q_{T} resummation accurate to next-to-leading-logarithmic (NLL) level [12]. Despite the failure of the HEFT to describe Higgs boson pair production beyond $m_{hh} \sim 2m_t$, it has been employed to perform various calculations at even higher orders, for example at NNLO [5], predicting a $\mathcal{O}(20\%)$ rise in the cross section, resummed to next-to-next-to-leading-logarithmic accuracy, matched to either NLO or NNLO in the HEFT [13, 14].

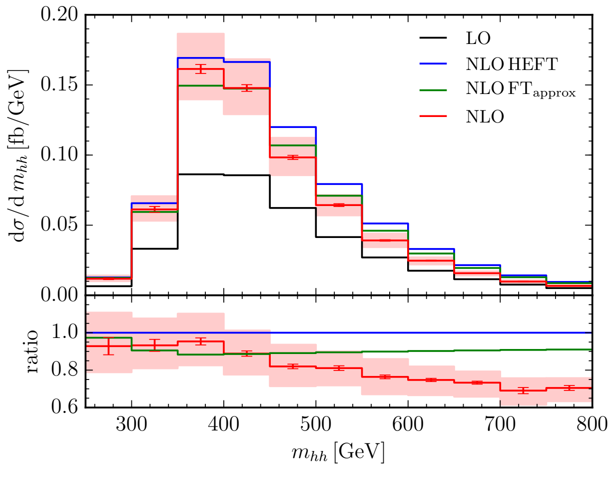

Fig. 4. The di-Higgs boson invariant mass spectrum for various calculations, taken from [11].

2.3. Experimental prospects for Higgs boson pair production

I will only give a brief overview of the experimental prospects for the measurement of Higgs boson pair production at the LHC. Figure 5 shows the branching ratios and the channels being actively explored by the ATLAS and CMS experiments.

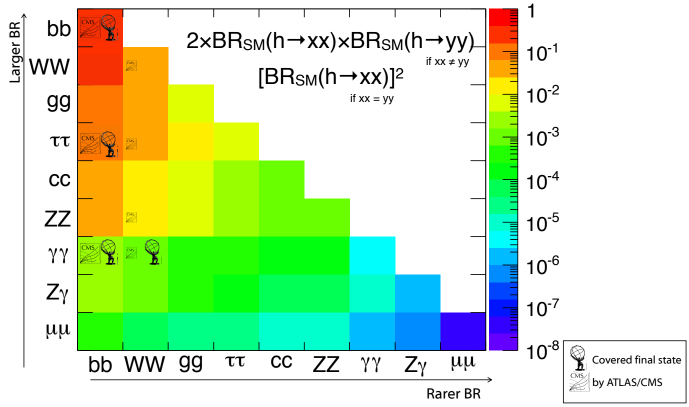

Fig. 5. The Higgs boson pair production branching ratios. The final states that have been explored by the ATLAS and CMS experiments are labelled with the respective symbol [15].

The upshot of the experimental searches is that they will not become sensitive to SM-like Higgs boson pair production until a few hundred inverse femtobarn of data have been collected. In fact, the current limit lies at about $50\times$ the SM cross section, see, *e.g.* [16]. In fact, even at the high-luminosity LHC (HL-LHC), after 3000 fb^{-1} of data has been collected, the prospects are rather bleak, with CMS, *e.g.*, predicting a signal of significance of almost two standard deviations [17] and ATLAS, *e.g.*, predicting constraints at 95% confidence level (C.L.) of $\lambda_3/\lambda_3^{\mathrm{SM}} \in [\sim -1.3, \sim 8.7]$ through the $(b\bar{b})(\gamma\gamma)$ final state [18] and $\lambda_3/\lambda_3^{\mathrm{SM}} \in [\sim -4, \sim 12]$ through $(b\bar{b})(\tau^+\tau^-)$ [19]. This implies that a combination between experiments at the HL-LHC will be essential to maximize the amount of information obtained on this coupling. A study along these lines, exploiting the similarity of the process to Higgs boson single production was considered in Ref. [20]. In that case, my view is that an $\mathcal{O}(1)$ measurement on $\lambda_3/\lambda_3^{\mathrm{SM}}$, or better, will be possible at the end of the HL-LHC lifetime.

For a precise measurement of the triple coupling, one would need to go to an even higher-energy collider, such as the Future Circular hadron–hadron collider (FCC-hh), which is currently foreseen to run at 100 TeV. There, the gluon-fusion-induced cross section for Higgs boson pair production rises to

~ 1.8 pb[1]. Most studies have focussed on the "clean" final state $(b\bar{b})(\gamma\gamma)$ [22–24] and the most recent comprehensive study appears in the FCC-hh report [25]. The study finds that after 30 fb^{-1} of integrated luminosity, the foreseen full data sample of the FCC-hh, the 1σ uncertainty through this channel would be $\sim \pm 3\%$. This was shown to be robust under changes of tagging probabilities.

Additionally, new final states may become available for Higgs boson pair production at 100 TeV. These include, *e.g.*, $hh \to (b\bar{b})(ZZ) \to 4\ell$, $(b\bar{b})(2\ell)$ via either W^+W^- or $\tau^+\tau^-$ [26] or multi-lepton final states such as $hh \to (W^+W^-)(W^+W^-) \to 3\ell jj$ [27].

2.4. Triple Higgs boson production

Triple Higgs boson production will probably be impossible to observe at the LHC, even after the HL-LHC. Even at 100 TeV, the total cross section for triple Higgs boson production via gluon fusion is only ~ 5 fb, rendering a precision measurement challenging there as well. Nevertheless, some information could be potentially obtained with the full FCC-hh dataset, at an integrated luminosity of 30 ab^{-1}. For example, in Refs. [28, 29], the final state $hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$ was investigated. The constraints obtained are rather pessimistic, with Ref. [28] finding, *e.g.* for $\lambda_3 = \lambda_3^{\mathrm{SM}}$, $\lambda_4/\lambda_4^{\mathrm{SM}} \in [\sim -4, \sim 16]$ at 95% C.L. Furthermore, in Ref. [29], the final states $(b\bar{b})(b\bar{b})(\tau^+\tau^-)$ and $(b\bar{b})(\tau^+\tau^-)(\tau^+\tau^-)$ were considered. More recently, the final state $(b\bar{b})(W^+W^-)(W^+W^-)$ was investigated in Ref. [30].

2.5. Summary

We summarise the prospects for the future constraints on the self-couplings through multi-Higgs boson production in Table I.

TABLE I

A summary of the prospects for constraints obtained on the Higgs boson self-couplings.

	HL-LHC (14 TeV, 3000 fb^{-1})	FCC-hh (100 TeV, 30 ab^{-1})
$\delta\lambda_3/\lambda_3^{\mathrm{SM}}$	$\mathcal{O}(1)$	$\mathcal{O}(5\%)$
$\delta\lambda_4/\lambda_4^{\mathrm{SM}}$	—	$\mathcal{O}(1)$–$\mathcal{O}(10)$

[1] A study of vector boson-fusion-induced production at the LHC and beyond can be found in [21].

3. Indirect constraints on Higgs boson self-couplings

For the sake of completeness and without delving into detail, it is worth mentioning the recent studies that focus on indirect constraints on the triple Higgs coupling. These are based on two kinds of measurements: either single Higgs boson production or decay processes or precision measurements obtained through gauge boson masses (*i.e.* propagator effects).

For example, in Refs. [31–33], effects of the triple self-coupling were probed in $gg \to h$, $h \to \gamma\gamma$, $pp \to hZ$ and $pp \to t\bar{t}h$. Constraints obtained with the current LHC datasets are competitive with the direct Higgs boson pair production constraints. The $pp \to t\bar{t}h$ channel is particularly sensitive to the triple coupling and hence expected to provide improved constraints in the future.

Furthermore, there are two approaches based on "precision observables". The first, in Ref. [34], has considered effects on the W-boson mass and the $\sin^2\theta_{\rm eff}$, and the second has considered the effect on the so-called S and T parameters [35]. Both groups have calculated the effects to two loops, and have shown that no quartic contributions appear at this order. Additionally, they have shown that modifying the triple coupling in multiples of the SM value is gauge invariant. The results were again found to be competitive with those coming from the direct Higgs boson pair production, given the current LHC dataset.

4. Conclusions

I have discussed some aspects of multi-Higgs boson production final states at hadron colliders, in particular focussing at the Large Hadron Collider and the proposed Future Circular hadron–hadron collider. These possess rich phenomenology and allow us to probe the Higgs boson self-couplings. I have also briefly touched upon the recent indirect constraint studies that aim to provide complementary information to the self-coupling measurements. Projections for possible constraints obtained either at the end of the lifetime of the high-luminosity LHC or the FCC-hh are given in Table I.

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