PROSPECTS FOR DOUBLE HIGGS PRODUCTION

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Abstract
A concise review of the double Higgs production channel at the LHC and at future hadron and lepton machines is presented.

1 Introduction

Double Higgs production is one example of scattering process that can disclose key information on the electroweak symmetry breaking dynamics, in particular its underlying symmetries and strength. It is one of the few channels that can give direct access to the quartic couplings among two Higgs bosons and a pair of gauge bosons or of top quarks, as well as to the Higgs trilinear self-coupling.

Due to the small cross section, the precision achievable at the LHC on these couplings is quite limited. The large increase in cross section at high-energy hadron machines and the improved precision possible at future lepton
colliders could overcome the LHC limitations providing an ideal environment to test this process.

In the absence of light new states, the new-physics effects can be parametrized via low-energy effective Lagrangians. Two formulations are useful for the study of Higgs physics. The first one, the “linear” Lagrangian, is based on the assumption that the Higgs is part of an SU(2)\_L doublet, as in the SM. In the second, more general formulation, SU(2)\_L × U(1)\_Y is non-linearly realized, hence the name of “non-linear” Lagrangian, and the physical Higgs is a singlet of the custodial symmetry, not necessarily part of a weak doublet. The run 1 LHC indicates that the couplings of the newly discovered boson are close to the values predicted for the SM Higgs. This clearly motivates the use of the linear Lagrangian for future studies. Indeed, small deviations from the SM are naturally expected if the Higgs boson belongs to a doublet, provided the new states are much heavier than the weak scale. The non-linear formulation is still useful, however, when large deviations in the Higgs couplings are allowed. This is especially true for double Higgs production, from which additional couplings not accessible via single Higgs processes can be extracted.

In the linear Lagrangian, the operators can be organized as

\[ \mathcal{L}_{\text{lin}} = \mathcal{L}_{\text{SM}} + \Delta \mathcal{L}_6 + \Delta \mathcal{L}_8 + \ldots \]  

(1)

The lowest-order terms coincide with the usual SM Lagrangian \( \mathcal{L}_{\text{SM}} \), whereas \( \mathcal{L}_n \) contains the deformations due to operators of dimension \( n \), with \( n > 4 \). For our purposes it is sufficient to focus on the operators involving the Higgs boson. The ones in \( \Delta \mathcal{L}_6 \) relevant for double Higgs production are (for simplicity we only include the CP-conserving operators)

\[ \Delta \mathcal{L}_6 \supset \frac{\mathcal{H}}{2v^2} \left[ \partial_\mu (H^\dagger H) \right]^2 + \frac{\mathcal{H}}{v^2} g_u H^\dagger H \tau_L H^c u_R - \frac{\mathcal{H}}{v^2} \frac{m_h^2}{2v^2} (H^\dagger H)^3 \]

\[ + \frac{\mathcal{H}}{m_W^2} \frac{g_s^2 H^\dagger H G_{\mu \nu}^a G^{a \mu \nu}}{2} , \]  

(2)

where \( H \) denotes the Higgs doublet, \( v = 246 \text{ GeV} \) and \( m_h = 125 \text{ GeV} \) is the Higgs mass. The linear Lagrangian relies on a double expansion. The first one is an expansion in derivatives, in which higher-order terms are suppressed by additional powers of \( E^2/m_\ast^2 \). To derive this estimate we assumed that the new dynamics can be broadly characterized by a single mass scale \( m_\ast \), at which new states appear, and by one coupling strength \( g_\ast \) (this is the so called SILH.
power counting\[4\]). The second expansion is in powers of the Higgs doublet: each extra insertion is weighted by a factor $1/f \equiv g_*/m_*$. In order to be under control, the linear Lagrangian requires $E^2/m^2 < 1$ and $v/f < 1$.

In the case of the non-linear Lagrangian, the relevant operators are

$$
\mathcal{L} \supset \left( m_W^2 W_\mu W^\mu + \frac{m_Z^2}{2} Z_\mu Z^\mu \right) \left( 1 + 2 c_V \frac{h}{v} + c_{2V} \frac{h^2}{v^2} \right) - c_3 \frac{m_h^2}{2v} h^3

- m_t \bar{t} \left( 1 + c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right) + \frac{g^2}{4\pi^2} \left( c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G^a_{\mu\nu} G^{a\mu\nu},
$$

where $h$ denotes the physical Higgs field (with vanishing expectation value). With respect to the linear parametrization, the operators in Eq. (3) effectively resum all the corrections of order $v^2/f^2$. The non-linear Lagrangian only relies on the derivative expansion, but not on the expansion in powers of the Higgs field. When the linear and non-linear parametrizations are both valid, the coefficients of the two effective Lagrangians are related by

$$
c_t = 1 - \tau_H/2 - \tau_u, \quad c_{2t} = -(\tau_H + 3\tau_u)/2, \quad c_3 = 1 - 3\tau_H/2 + \tau_6, \quad c_g = c_{2g} = \tau_g \left( 16\pi^2/g^2 \right), \quad c_V = 1 - \tau_H/2, \quad c_{2V} = 1 - 2\tau_H.
$$

Notice that single operators in the linear Lagrangian induce correlated modifications in different Higgs vertices. For instance the $O_u$ operator, which gives a modification of the top Yukawa, also generates a new quartic interaction $tthh$.

2 Double Higgs at hadron colliders

Double Higgs production at hadron colliders is mainly due to three processes: Gluon Fusion (GF), Vector Boson Fusion (VBF) and $tthh$ associated production. In the following we will focus on the GF and VBF channels, for which dedicated analyses at high-energy colliders exist. The $tthh$ channel, for which only LHC studies are currently available\[5\], can provide some information on the Higgs trilinear coupling, but it seems not competitive with the GF channel.

2.1 Gluon fusion

The GF channel is the dominant production mode at hadron colliders. The NNLO SM cross section at the 14 TeV LHC is $\sigma_{SM} \simeq 37$ fb, while it becomes $\sigma_{SM} \simeq 1.5$ pb at a 100 TeV collider. The relatively small cross sections imply
that only a few final states are relevant. In spite of the small branching fraction \((BR \simeq 0.264\%)\) the \(hh \rightarrow \gamma\gamma b\bar{b}\) channel has been recognized as the most promising one due to the clean signal and small backgrounds \([6, 3]\). Other channels, whose exploitation is more difficult due to the large backgrounds, have been also considered, among which \(hh \rightarrow b\bar{b}\tau^{+}\tau^{-}\), \(hh \rightarrow b\bar{b}WW^{*}\) and \(hh \rightarrow b\bar{b}b\tau\). Due to the larger cross section these channels could be relevant for an analysis of the high-energy tail of the kinematic distributions, where boosted jet techniques could enhance the signal reconstruction efficiency.

The GF channel is sensitive to several new-physics effects. In the non-linear formalism, it depends on the Higgs self-coupling \((c_{3})\), on the top couplings \((c_{t}, c_{2t})\) and on the contact interactions with the gluons \((c_{g}, c_{2g})\). It is thus a privileged channel to test the non-linear Higgs couplings \((c_{3}, c_{2t}, c_{2g})\) that cannot be directly accessed in single-Higgs processes. Interestingly, the various new physics effects affect in different ways the kinematic distributions (in particular, the Higgs-pair invariant mass \(m_{hh}\)). An exclusive analysis taking into account the \(m_{hh}\) distribution can thus be used to disentangle the various coefficients in the effective Lagrangian \([3]\). This is relevant at high-energy colliders, where the sizable cross section allows to reconstruct the \(m_{hh}\) distribution, it is instead of limited applicability at the LHC due to the small number of signal events.

To conclude the discussion we report in table 1 the precision on the determination of the Higgs trilinear coupling \(\tau_{6}\) for three benchmark scenarios: 14 TeV LHC with \(L = 300 \text{fb}^{-1}\) integrated luminosity (LHC14), high-luminosity LHC with \(L = 3 \text{ab}^{-1}\) (HL-LHC) and a future 100 TeV \(pp\) collider with \(L = 3 \text{ab}^{-1}\) (FCC100). It is important to stress that the precision on the \(\tau_{6}\) coefficient is affected by the uncertainty on the other parameters in the effective Lagrangian and in particular on the top Yukawa, \(\tau_{u}\) (the result in table 1 was derived by assuming \(\Delta \tau_{u} \simeq 0.05\)). With no uncertainty on \(\tau_{u}\), the Higgs trilinear coupling could be extracted at FCC100 with precision \(\Delta \tau_{6} \simeq 0.18\).

| \(\tau_{6}\) | LHC14 \([-1.2, 0.1]\) | HL-LHC \([-1.0, 1.8] \cup [3.5, 5.1]\) | FCC100 \([-0.33, 0.29]\) | Reference |
|---|---|---|---|---|
| \(\Delta c_{2V}\) | \([-0.18, 0.22]\) | \([-0.08, 0.12]\) | \([-0.01, 0.03]\) | Azatov et al. \([3]\) |

Table 1: Estimated precision on the Higgs trilinear coupling \(\tau_{6}\) and \(\Delta c_{2V} = c_{2V} - 1\) at hadron machines. The table reports the 68% probability intervals.
2.2 Vector boson fusion

The VBF channel is sensitive to the Higgs self-coupling $c_3$ and, more importantly, to the single and double Higgs coupling to the vector bosons ($c_V, c_{2V}$). Analogously to $W W$ scattering, a modification of the Higgs coupling to the gauge fields spoils the cancellation present in the SM, so that the VBF amplitude grows at high energy as $\mathcal{A} \sim s/v^2(c_V^2 - c_{2V})$. The tail of the distribution is thus particularly sensitive on $c_V$ and $c_{2V}$. The Higgs trilinear, on the contrary, affects the $m_{hh}$ distribution mostly at threshold and has a limited impact.

The small cross section forces to consider Higgs decay channels with large branching fractions. The most relevant final state is $hh \rightarrow 4b$. Estimates of the precision achievable on $c_{2V}$ are given in table 2 for three benchmark scenarios.

### Table 2: Expected 68% CL precision on the Higgs trilinear coupling $c_3$ and on the $c_{2V}$ coupling at future lepton colliders.

| COM Energy | Precision | Process | Reference |
|------------|-----------|---------|-----------|
| ILC        |           |         |           |
| 500 GeV    | $\Delta c_3 \sim 104\%$ | DHS     | ILC TDR, Volume 2 [10] |
| $[L = 500 fb^{-1}]$ | | | |
| 1 TeV     | $\Delta c_3 \sim 28\%$ | VBF     | ILC TDR, Volume 2 [10] |
| $[L = 1 ab^{-1}]$ | | | |
| 1.4 TeV   | $\Delta c_3 \sim 24\%$ | DHS     | Contino et al. [11] |
| $[L = 1.5 ab^{-1}]$ | | | |
| CLIC       |           |         |           |
| 3 TeV     | $\Delta c_3 \sim 12\%$ | VBF     | P. Roloff (CLICdp Coll.) [12] |
| $[L = 2 ab^{-1}]$ | | | |

3 Double Higgs at lepton colliders

The main channels for double Higgs production at lepton colliders are Double Higgs-Strahlung (DHS) and Vector Boson Fusion (VBF). The DHS channel is dominant for center of mass energies below $s \lesssim 1$ TeV, while above this threshold the VBF cross section becomes the largest one [13].

Both production channels are sensitive to deviations in the Higgs trilinear coupling and in the double Higgs coupling to vector bosons. The expected precision on the determination of $\Delta c_3$ and $\Delta c_{2V}$ for different benchmark scenarios are listed in table 2. In order to obtain a fair determination of these
parameters a center of mass energy $s \gtrsim 1$ TeV and an integrated luminosity $L \gtrsim 1$ ab$^{-1}$ are necessary. With these minimal requirements a precision of the order $20 - 30\%$ can be achieved. Further improvements in the collider energy could significantly boost the precision on $c_{2V}$, up to a $\sim 3\%$ accuracy, since the effects mediated by this coupling are enhanced at high $m_{hh}$. The deviations in the Higgs trilinear coupling, on the contrary, affect mostly the distribution at threshold, hence an improvement in the precision at higher energies is mainly related to the luminosity increase. The precision on $c_3$ and $c_{2V}$ that can be obtained at lepton machines with $s \gtrsim 1$ TeV is roughly comparable to the one estimated for a 100 TeV hadron collider (see the FCC$_{100}$ column in table [1]).

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