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Trilinear Higgs boson coupling variations for di-Higgs production with full NLO QCD predictions in Powheg

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Abstract. The couplings of the Higgs boson to other particles are increasingly well measured by the ATLAS and CMS experiments. The Higgs boson trilinear self-coupling however is still largely unconstrained, mainly due to the low cross-section for Higgs boson pair production. We present inclusive and differential results for the NLO QCD corrections to Higgs boson pair production with the full top-quark mass dependence, where the Higgs trilinear coupling is varied to non-SM values. The fixed-order calculation is supplemented by parton showering within the Powheg-BOX-V2 event generator, and both Pythia8 and Herwig7 parton-shower algorithms are implemented in a preliminary study of shower effects.

1. Introduction

Impressive experimental constraints have been set on the Higgs boson couplings to vector bosons and heavy fermions \cite{1, 2, 3, 4}. The Higgs potential, in contrast, leaves more room for New Physics. In particular, the Higgs boson trilinear self-coupling $\lambda$ can be experimentally constrained by exclusion limits on Higgs boson pair production $pp \rightarrow hh$ \cite{5, 6}, where the best limit on $\kappa_\lambda = \lambda/\lambda_{\text{SM}}$ is currently given by ATLAS with $-5.0 < \kappa_\lambda < 12.0$ at 95\% confidence level. Higher-order corrections to Higgs pair production were first calculated in the heavy top-quark mass limit (HTL) $m_t \rightarrow \infty$, where the top-quark degrees of freedom are integrated out \cite{7, 8, 9, 10}. The NLO QCD corrections with the full top-quark mass dependence were only computed more recently \cite{11, 12, 13}. The latter are based on numerical evaluations of the two-loop contribution to $gg \rightarrow hh$. For non-SM values of the Higgs couplings, results were computed at NLO QCD in the full theory for a class of extensions of the SM in Ref. \cite{14}.

In the following, an implementation of the full NLO QCD corrections into the Powheg-BOX-V2 event generator \cite{15, 16, 17} is presented. In this framework, the Higgs trilinear self-coupling can be varied, as well as the top-Higgs Yukawa coupling. Total cross-sections are computed for $\sqrt{s} = 13, 14$ and 27 TeV at the (HE-)LHC. Differential results are shown for $\sqrt{s} = 14$ TeV. The fixed-order calculation is then matched to both Pythia8 \cite{18} and Herwig7 \cite{19, 20} parton showers. For a more detailed description, the reader is referred to Ref. \cite{21}.

2. Description of the calculation

The calculation is based on the setup presented in Ref. \cite{22} for the case of the SM. The leading-order amplitude has been computed analytically. The real-emission contributions were
implemented using an interface [23] between the Powheg-BOX and GoSam [24, 25], where the reduction of the one-loop amplitude has been performed with Ninja [26], using master integrals from golem95C [27, 28], OneLOop [29] and VBFNLO [30, 31]. The two-loop amplitude for the full virtual contribution was adapted from Refs. [11, 12], which used an extension of the GoSam package to two loops [32]. There, the integral reduction was performed with REDuze2 [33], and the integrals were numerically evaluated with SecDec3 [34]. For a faster convergence, the integration was performed within a Quasi-Monte-Carlo implementation using a rank-1 shifted lattice rule [35, 36]. The integrals were computed with 16 dual NVIDIA Tesla K20X GPUs.

The top-quark and Higgs masses have been set to $m_t = 173$ GeV and $m_h = 125$ GeV. Thus, the integrals depend only on the two Mandelstam invariants $\hat{s}$ and $\hat{t}$.

A grid for the two-loop amplitude was constructed in both variables using 5291 pre-sampled phase-space points. We split the amplitude in two contributions: diagrams containing the trilinear Higgs coupling are called triangle-like, and those that do not are called box-like (see Fig. 1 for two diagrams at NLO QCD).

At any order in QCD, the squared matrix-element can thus be written as a second-order polynomial in $\lambda$:

$$M_\lambda \equiv |M_\lambda|^2 = M_B^* M_B + \lambda (M_T^* M_T + M_B^* M_B) + \lambda^2 M_T^* M_T.$$  

The two-loop amplitude for an arbitrary value of $\lambda$ can be reconstructed from the squared matrix-element computed for three different values of $\lambda$. In our case, we chose $\kappa_\lambda = \lambda_{BSM}/\lambda_{SM} \in \{-1, 0, 1\}$. A new grid is generated at runtime for the user-defined value of $\lambda$, where the amplitude for each pre-sampled phase-space point is calculated as:

$$M_\lambda = M_0 \cdot (1 - \lambda^2) + \frac{M_1}{2} \cdot (\lambda + \lambda^2) + \frac{M_{-1}}{2} \cdot (-\lambda + \lambda^2).$$

The grid produced for the two-loop amplitude is fed to an interpolation framework, which interfaces the result at any phase-space point $M_\lambda(\hat{s}, \hat{t})$ to Powheg.

3. Total and differential cross-sections for variations of the trilinear coupling

The results given below are produced using the PDF4LHC15_nlo_30_pdfas sets [37, 38, 39, 40] interfaced to Powheg via LHAPDF6 [41], with the corresponding value of $\alpha_s$. The top-quark mass is renormalised in the on-shell scheme and is set to $m_t = 173$ GeV, as in the virtual amplitude. The mass of the Higgs boson is fixed to $m_h = 125$ GeV, and the top-quark and Higgs widths are set to zero. Jets are clustered using the anti-$k_T$ algorithm [42] as implemented in FastJet [43, 44], with a jet distance parameter of $R = 0.4$ and a minimum transverse momentum requirement of $p_T = 20$ GeV. The central renormalisation and factorisation scales are set to $\mu_R = \mu_F = \mu_0 = m_{hh}/2$. Scale uncertainties are estimated by 3-point variations $\mu_R = \mu_F = c \mu_0$, with $c \in \{0.5, 1.0, 2.0\}$. 

Figure 1. Triangle-like (left) and box-like (right) diagrams contribute to the full amplitude. The former contain the Higgs self-coupling, while the latter do not.
Total cross-sections for Higgs pair production at the (HE-)LHC are shown in Table 1, for centre-of-mass energies of $\sqrt{s} = 13, 14$ and 27 TeV and different values of the Higgs self-coupling $\kappa_\lambda = \lambda_{\text{BSM}}/\lambda_{\text{SM}}$. They are accompanied by their relative scale uncertainties, which are of the order $\mathcal{O}(10^{-20})$. Notably, the $K$-factors at 14 TeV show a sizeable dependence on the trilinear coupling $\kappa_\lambda$. In the HTL at NLO QCD, Ref. [45] suggested a variation of the $K$-factors with $\kappa_\lambda$ of the order $\mathcal{O}(2-3\%)$. In the full theory, the $K$-factors are found to vary between $1.56$ and $2.15$ for values of the trilinear coupling in the range $-5 \leq \kappa_\lambda \leq 12$, see Fig. 2.

| $\lambda_{\text{BSM}}/\lambda_{\text{SM}}$ | $\sigma_{\text{NLO}@13\text{TeV}}$ [fb] | $\sigma_{\text{NLO}@14\text{TeV}}$ [fb] | $\sigma_{\text{NLO}@27\text{TeV}}$ [fb] | K-factor@14TeV |
|-------------|-----------------|-----------------|-----------------|----------------|
| -1          | $116.71^{+16.4}_{-14.3}\%$ | $136.91^{+16.4}_{-13.9}\%$ | $504.9^{+14.1}_{-11.8}\%$ | 1.86           |
| 0           | $62.51^{+13.8}_{-13.7}\%$  | $73.64^{+13.5}_{-13.4}\%$  | $275.29^{+13.2}_{-11.3}\%$ | 1.79           |
| 1           | $27.84^{+11.6}_{-12.9}\%$  | $32.88^{+13.5}_{-12.5}\%$  | $127.7^{+11.5}_{-10.4}\%$ | 1.66           |
| 2           | $12.42^{+14.1}_{-12.0}\%$  | $14.75^{+12.0}_{-11.8}\%$  | $59.10^{+10.2}_{-9.7}\%$  | 1.56           |
| 2.4         | $11.69^{+13.9}_{-12.3}\%$  | $13.79^{+13.5}_{-12.5}\%$  | $53.67^{+11.4}_{-10.3}\%$ | 1.65           |
| 3           | $16.25^{+16.4}_{-15.3}\%$  | $19.07^{+17.1}_{-14.1}\%$  | $69.84^{+14.0}_{-12.1}\%$ | 1.90           |
| 5           | $81.74^{+20.0}_{-15.6}\%$  | $95.22^{+19.7}_{-11.6}\%$  | $330.61^{+14.1}_{-13.6}\%$| 2.14           |

Table 1. Total cross-sections for Higgs boson pair production at NLO QCD at (HE-)LHC for centre-of-mass energies of $\sqrt{s} = 13, 14$ and 27 TeV. The scale uncertainties are given in percent.

![Figure 2](image.png)

**Figure 2.** The dependence of the $K$-factor on the trilinear Higgs self-couplings $\kappa_\lambda$ is given at $\sqrt{s} = 14$ TeV in the full theory.

In Fig. 3, distributions of the invariant mass $m_{hh}$ of the Higgs boson pair system are displayed for different values of $\kappa_\lambda$. They exhibit a characteristic dip around $m_{hh} \sim 350$ GeV for values of the trilinear coupling around $\kappa_\lambda = 2.4$. This value of the trilinear self-coupling corresponds to a maximally destructive interference between triangle-like and box-like diagrams. For $\kappa_\lambda = 1$, the maximal destructive interference happens at the $hh$ production threshold and therefore does not manifest itself as a dip, while for $\kappa_\lambda$ values larger than $\sim 3$ the triangle-type contributions start to dominate.
Figure 3. Distributions of the Higgs boson pair invariant mass $m_{hh}$ for various values of $\kappa_\lambda$ at $\sqrt{s} = 14\text{ TeV}$. The uncertainty bands are from scale variations as described in the text.

Note that since the contributions can be separated in triangle- and box-like diagrams, the top-Higgs Yukawa coupling $y_t$ can be simultaneously varied within the same code. A non-SM value of $y_t$ yields in Eq. (1):

$$|\mathcal{M}_\lambda|^2 = y_t^4 \left[ \mathcal{M}_B^* \mathcal{M}_B + \frac{\kappa_\lambda}{y_t} (\mathcal{M}_B^* \mathcal{M}_T + \mathcal{M}_T^* \mathcal{M}_B) + \left( \frac{\kappa_\lambda}{y_t} \right)^2 \mathcal{M}_T^* \mathcal{M}_T \right]. \quad (3)$$

The cross-section can be computed by setting $\kappa_\lambda$ in the code to the desired value of the ratio $\kappa_\lambda/y_t$, and rescaling the result by an overall factor $y_t^4$. For example, $\sigma(y_t=1.2, \kappa_\lambda = 1) = (1.2)^4 \sigma(y_t=1, \kappa_\lambda = 1/1.2)$. Fig. 4 shows the distribution of $m_{hh}$ for values of the top-Higgs Yukawa coupling that are still not experimentally excluded [4].

Figure 4. The distribution of the Higgs boson pair invariant mass $m_{hh}$ for values of the top-Higgs Yukawa coupling $y_t \in \{0.8, 1, 1.2\}$.

4. Parton-shower matched results
We now consider NLO distributions matched to a parton shower. The Les Houches Events (LHE) [46] files produced by Powheg are used as input to the Pythia8.235 and Herwig7.1.4
parton showers. In the case of Herwig7, both the default angular-ordered \( \tilde{q} \) and the dipole showers are compared. The radiation-regulating \( h_{damp} \) parameter in Powheg is set to \( h_{damp} = 250 \) GeV. Multiple-parton interactions and hadronisation are switched off. The default tunes are used for both parton showers.

Fig. 5 displays the transverse momentum of the Higgs boson pair \( p_T^{hh} \) and the separation between the two Higgs bosons \( \Delta R^{hh} = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2} \). Considering first the distribution of \( p_T^{hh} \), both Herwig7 parton showers (PH7-\( \tilde{q} \) and PH7-dipole) generate similar results and reproduce the fixed-order NLO prediction in the far-\( p_T^{hh} \) range. In contrast, Pythia8 agrees with Herwig7 only for small transverse momenta, while it produces much harder radiation in the tail of the distribution. The same comments apply to the \( \Delta R^{hh} \) observable in the region \( 0 < \Delta R^{hh} < \pi \) where shower contributions are important. Large parton-shower matching uncertainties in Higgs boson pair production have already been discussed in Ref. [47].

**Figure 5.** The transverse momentum \( p_T^{hh} \) of the Higgs boson pair and the separation between the two Higgs bosons \( \Delta R^{hh} \) are shown for the fixed-order NLO calculation and three parton showers, in the \( \kappa_\lambda = 1 \) case.

5. Conclusion

We have presented a new program package for Higgs boson pair production at NLO QCD with full top-quark mass dependence. In this package, the trilinear Higgs self-coupling can be varied explicitly. Within the same code, simultaneous variations of the top-Higgs Yukawa coupling can also be produced. The public code for the Powheg-BOX-V2 event generator can be found at the website http://powhegbox.mib.infn.it in the User-Processes-V2/ggHH subdirectory. In addition, approximations related to the heavy top limit (HTL) can be enabled for comparison purposes. We have found that the full \( m_t \)-dependent NLO QCD corrections lead to \( K \)-factors which exhibit a sizeable dependence on the value of the trilinear Higgs self-coupling, which is not present in the HTL. We have compared fixed-order predictions at NLO QCD to parton-shower matched results. Both the Pythia8 and Herwig7 (\( \tilde{q} \) and dipole) parton showers can be matched directly to LHE files produced by Powheg. Full particle-level events can be produced with our framework, including Higgs boson decays and hadronisation.

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