New Physics Search via the Higgs Self-Coupling

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We discuss quantum corrections of new physics to the triple coupling of the lightest CP-even Higgs boson in the Two Higgs Doublet Model (THDM) and also in the Minimal Supersymmetric Standard Model (MSSM). In the THDM, quartic contributions of the mass of heavy particles in the loop can appear, which are not absorbed by renormalization of the Higgs boson mass. Such non-decoupling effects on the self-coupling can give corrections of $O(100\%)$, even when all measured Higgs couplings with gauge bosons and fermions are consistent with the Standard Model prediction. In the MSSM, the loop-corrections decouple in such a scenario.

At Linear Colliders (LC’s), the mass generation mechanism will be explored by precise measurements of the Higgs couplings with fermions and gauge bosons via the Higgs production cross section rates and the decay branching ratios. The determination of the structure of the Higgs potential, however, is only possible by measuring the Higgs self-couplings. The trilinear Higgs boson coupling $\lambda_{hhh}$ can be directly measured from the double Higgs boson production processes $e^+e^- \rightarrow Z^* \rightarrow Zh \bar{h}$ and $e^+e^- \rightarrow W^+ \nu W^- \bar{\nu} \rightarrow hh \nu \bar{\nu}$, when the Higgs boson ($h$) is light. At the $e^+e^-$ collider with the energy of 500 GeV (3 TeV) and the integrated luminosity of 1 ab$^{-1}$ (5 ab$^{-1}$), $\lambda_{hhh}$ can be measured by about 20% (7%) accuracy for the Higgs bosons with the mass of 120 GeV.

In this talk, we discuss one-loop corrections to $\lambda_{hhh}$ in the two-Higgs-doublet model (THDM) and in the Minimal Supersymmetric Standard Model (MSSM). The Higgs sector of the MSSM is a special case of the weakly coupled THDM. Some models based on the dynamical electroweak symmetry breaking also yield the strongly coupled THDM as their low-energy effective theory. The $hhh$ coupling in the THDM, in general, differs from that in the Standard Model (SM) at tree-level, depending on parameters of the Higgs sector. Quantum corrections to the Higgs self-coupling, especially their decoupling property, have been studied in the MSSM. In the SM, the leading one-loop contribution of the top quarks ($t$) to the effective self-coupling is expressed by

$$\lambda_{hhh}^{\text{eff}}(\text{SM}) = \frac{3m_h^2}{v} \left[ 1 - \frac{N_c}{3\pi^2} \frac{m_t^4}{v^2 m_h^4} \left\{ 1 + \mathcal{O} \left( \frac{m_t^2}{m_h^2}, \frac{v^2}{m_h^2} \right) \right\} \right], \quad (1)$$
where \( m_h \) (\( m_t \)) is the physical mass of \( h \) (\( t \)), \( N_c \) is the color number of \( t \), and \( p_i \) (\( i = 1-3 \)) represent momenta of the external lines. The non-vanishing \( O(m_t^4) \) term is a striking feature of the one-loop correction to the self-coupling. If a new physics particle has the similar property to the top quarks, the new physics effect on \( \lambda_{hhh} \) can become large due to the quartic mass contribution. We here examine this possibility in the context of the THDM and the MSSM.

The Higgs potential of the CP-conserving THDM is given by

\[
V_{\text{THDM}} = m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - m_3^2 \left( \Phi_1 \Phi_2 + \Phi_2 \Phi_1 \right) + \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1 \Phi_2|^2 + \lambda_5 \left\{ \left( \Phi_1 \Phi_2 \right)^2 + \left( \Phi_2 \Phi_1 \right)^2 \right\} ,
\]

(2)

where we imposed a softly-broken discrete symmetry under \( \Phi_1 \to \Phi_1 \) and \( \Phi_2 \to -\Phi_2 \). Two types of the Yukawa interaction are then possible, so called Model I and Model II. After the diagonalization of the mass matrices, we have two CP-even (\( h, H \)), one CP-odd (\( A \)), and a pair of charged (\( H^\pm \)) Higgs bosons. All coupling constants (\( \lambda_1-\lambda_5 \)) are then related to the input parameters \( m_h, m_H, m_A, m_{H^\pm}, \alpha, \beta, M \) and \( v(\simeq 246 \text{ GeV}) \), where \( \alpha \) is the mixing angle between CP-even bosons, \( \tan \beta = \langle \Phi_2 \rangle / \langle \Phi_1 \rangle \), and \( M(= m_3/\sqrt{\sin \beta \cos \beta}) \) is the soft-breaking scale of the discrete symmetry. The masses of the heavier Higgs bosons (\( H, H^\pm \) and \( A \)) typically have two kinds of origin, as seen by

\[
m_h^2 \simeq M^2 + \lambda_1 v^2, \quad \left( \Phi : H, A, \text{or} \ H^\pm \right)
\]

(3)

which essentially determines the decoupling/non-decoupling property of the heavy Higgs bosons.

At LC, \( \lambda_{hhh} \) will be measured after precision measurements of \( m_h \) and \( g_{hVV}^2 \), so that we can use their experimental information to predict \( \lambda_{hhh}^{\text{eff}} \). Here, we consider a specific scenario: (1) Only one light Higgs boson (\( h \): CP-even, \( m_h = 115 - 160 \text{ GeV} \)) is found. (2) Data for the \( hVV \) couplings as well as for the Higgs decay branching ratios are in good agreement with the SM prediction. This means \( \sin^2(\alpha - \beta) \simeq 1 \) in the context of the THDM. Then, the tree \( hhh \) coupling also takes a same form as the SM, i.e., \( \lambda_{hhh}^{\text{tree}}(THDM) = 3m_h^2/v \). The leading one-loop contribution is calculated, in this case, \( a \)

\[
\lambda_{hhh}^{\text{eff}}(THDM) = \frac{3m_h^2}{v} \left\{ 1 + \frac{m_H^4}{12\pi^2 m_h^2 v^2} \left( 1 - \frac{M^2}{m_H^2} \right)^3 + \frac{m_A^4}{12\pi^2 m_h^2 v^2} \left( 1 - \frac{M^2}{m_A^2} \right)^3 \right\}
\]

\[
\quad + \frac{m_{H^\pm}^4}{6\pi^2 m_h^2 v^2} \left( 1 - \frac{M^2}{m_{H^\pm}^2} \right)^3 - \frac{N_c m_h^4}{3\pi^2 m_h^2 v^2} + \mathcal{O}\left( \frac{p^2 m_h^2}{m_h^2 v^2}, \frac{m_h^2}{m_h^2 v^2}, \frac{m_h^2}{v^2} \right) \right\} .
\]

(4)

The quartic mass terms of the heavier Higgs boson masses appear with a sup-

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\[a\] We note that the top-loop effects on the \( hVV \) (\( VV = ZZ, WW \)) couplings (\( g_{hVV}^2 \)) and the Yukawa coupling can also yield non-decoupling power-like contributions of the top-quark mass, but it turns out that the contribution is at most quadratic (not quartic).
the loop contributions of heavier Higgs bosons. The corrections are small and the typical decoupling behavior is observed for $h$ of mass $m_h$ in the effective self-coupling $\lambda_{hhh}^\text{eff}$ of the SM prediction becomes about 30% (100%) for $m_A = 300$ (400) GeV. The decoupling behavior of the heavier Higgs boson contribution is shown in Fig. 2 as a function of $M$ with $m_A^2 = \lambda v^2 + M^2$. For a given $M$, the heavy Higgs boson contribution reduces rapidly for larger $M \gg \lambda v^2$, though it can still be at a few tens of percent level when $M = 1$ TeV. The momentum dependence in the effective self-coupling $\lambda_{hhh}^\text{eff}(q^2)$ for $h^* \rightarrow hh$, where $q^2$ is the momentum of $h^*$, is shown for $M = 0$ in Fig. 3.

In the MSSM, $\lambda_A v^2$ in Eq. (3) is constrained to be $\lambda_A v^2 \simeq \mathcal{O}(m_{A}^2)$, so that the corrections are small and the typical decoupling behavior is observed for the loop contributions of heavier Higgs bosons. The leading stop-loop effect can be expressed in the limit of $m_A \rightarrow \infty$ for $M_Q = M_U = M_S (\equiv M_g)$ by

$$\lambda_{hhh}^\text{eff}(M_{SSM}) \bigg|_{\alpha = \beta = 0} = 1 + \frac{N_c m_t^2}{8\pi^2 v^2 M_S^2} m_A^2 \left( \frac{3}{2} X_t^2 + \frac{1}{2} X_b^2 - \frac{1}{20} M_S^2 \right),$$

where $M_Q$ and $M_U$ represent the soft-SUSY-breaking masses of left- ($M_Q$) and right- ($M_U$) handed stops, and $m_t X_t$ is the off-diagonal element of the stop mass matrix. The $O(m_t^2)$ terms appear with the suppression factor $(m_t^2/M_S^2)$, so that the effects decouple in the SM-like scenario ($M_S \rightarrow \infty$).

For $\sin^2(\alpha - \beta) = 1$, the top-loop effect is the same as in the SM, being independent of the choice of the Yukawa interaction; either Model I or II. The difference between Model I and II appears in the region of the charged Higgs boson because of the $b \rightarrow s\gamma$ results.
leading stop effect is plotted as a function of $X_t/M_S$ for several values of $M_S$.

In summary, the quantum correction can be $O(100\%)$ in the general THDM due to the quartic mass terms of heavier Higgs bosons, even when all the data before the measurement of $hhh$ coupling are almost SM like. Such large effects may be detected at LC’s. When the Higgs bosons are *weakly coupled*, the loop effects of the heavier Higgs bosons are suppressed in the large mass limit. In the MSSM, the Higgs sector is similar to a weakly coupled THDM, so that the loop effects of the heavier Higgs bosons are small. For the light stop scenarios, the stop-loop contribution can be large, and its correction can exceed 5 %.

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