The Triple Higgs Boson Self-Coupling at Future Linear $e^+e^-$ Colliders Energies: ILC and CLIC

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We analyzed the triple Higgs boson self-coupling at future $e^+e^-$ colliders energies, with the reactions $e^+e^- \rightarrow b\bar{b}HH, t\bar{t}HH$. We evaluate the total cross-sections for both $b\bar{b}HH$ and $t\bar{t}HH$, and calculate the total number of events considering the complete set of Feynman diagrams at tree-level. We vary the triple coupling $\kappa \lambda_3H$ within the range $\kappa = -1$ and $+2$. The numerical computation is done for the energies expected to be available at a possible Future Linear $e^+e^-$ Collider with a center-of-mass energy 800, 1000, 1500 GeV and a luminosity 1000 $fb^{-1}$. Our analysis is also extended to a center-of-mass energy 3 $TeV$ and luminosities of 1000 $fb^{-1}$ and 5000 $fb^{-1}$. We found that for the process $e^+e^- \rightarrow b\bar{b}HH$, the complete calculation differs only by 3% from the approximate calculation $e^+e^- \rightarrow ZHH (Z \rightarrow b\bar{b})$, while for the process $e^+e^- \rightarrow t\bar{t}HH$, the expected number of events, considering the decay products of both $t$ and $H$, is not enough to obtain an accurate determination of the triple Higgs boson self-coupling.

KEYWORDS: Total cross-sections; standard model Higgs boson.

1. Introduction

The Higgs boson $^1$–$^3$ plays an important role in the Standard Model (SM) $^4$–$^6$ because it is responsible for generating the masses of all elementary particles (leptons, quarks, and gauge bosons). However, the Higgs-boson sector is the least tested in the SM, in particular the Higgs boson self-interaction.

The search for Higgs bosons is one of the principal missions of present and future high-energy colliders. The observation of this particle is of major importance for the present understanding of fundamental particle interactions. Indeed, in order to accommodate the well established electromagnetic and weak interaction phenomena, the existence of at least one

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isodoublet scalar field to generate fermion and weak gauge bosons masses is required. Despite previous success in explaining the present data, the SM cannot be completely tested before this particle has been experimentally observed and its fundamental properties studied.

The triple and quartic Higgs boson couplings $\lambda_{3H}$ and $\lambda_{4H}$ are defined through the potential:

$$V(H) = \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4,$$

where the triple and quartic couplings of the Higgs field $H$ are given by

$$\lambda_{3H} = \frac{3M_H^2}{M_Z^2} \lambda_0,$$

$$\lambda_{4H} = \frac{3M_H^2}{M_Z^4} \lambda_0.$$

To obtain these expressions we assumed the normalization employed in Ref. $^9$–$^{14}$ where $\lambda_0 = M_Z^2/v$.

In the SM, we obtain $M_H = \sqrt{2\lambda v}$ as the simple relationship between the Higgs boson mass $M_H$ and the self-coupling $\lambda$, where $v = 246$ GeV is the vacuum expectation value of the Higgs boson. The triple vertex of the Higgs field $H$ is given by Eq. (2) and a measurement of $\lambda_{3H}$ in the SM can determine $M_H$. An accurate test of this relationship may reveal the extended nature of the Higgs sector. The measurement of the triple Higgs boson coupling is one of the most important goals of Higgs physics in a future $e^+e^-$ linear collider experiment. This would provide the first direct information on the Higgs potential responsible for electroweak symmetry breaking.

The triple Higgs boson self-coupling can be measured directly in pair-production of Higgs particles at hadron and high-energy $e^+e^-$ linear colliders. Several mechanisms that are sensitive to $\lambda_{3H}$ can be exploited for this task. Higgs pairs can be produced through double Higgs-strahlung of $W$ or $Z$ bosons $^9$–$^{21}$ $WW$ or $ZZ$ fusion $^8,^{22}$–$^{25}$ moreover, through gluon-gluon fusion in $pp$ collisions $^{26}$–$^{29}$ and high-energy $\gamma\gamma$ fusion $^8,^{30}$ at photon colliders. The two main processes at $e^+e^-$ colliders are double Higgs-strahlung and $WW$ fusion:

$$\text{double Higgs-strahlung} : e^+e^- \rightarrow ZHH,$$

$$\text{WW double-Higgs fusion} : e^+e^- \rightarrow \bar{\nu}_e\nu_eHH.$$  

(4)

The $ZZ$ fusion process of Higgs boson pairs is suppressed by an order of magnitude because the electron-$Z$ coupling is small. The more suitable reaction in $e^+e^-$ colliders to measure the triple couplings in the range of the theoretically preferred Higgs mass $O(100$ GeV) is the double Higgs-strahlung process $e^+e^- \rightarrow ZHH$. Operating at center-of-mass energy $\sqrt{s}$ from
The production cross-section (about 0.1-0.2 \( fb \)) if the Higgs boson mass is \( M_H = 120 \text{ GeV} \). When the center-of-mass energy \( \sqrt{s} > 1 \text{ TeV} \), the \( e^+e^- \rightarrow \bar{\nu}_e\nu_eHH \) mode becomes sizeable and it is possible to measure the triple Higgs self-coupling \( \lambda_{3H} \) by using this process. Therefore, in the first stage of the ILC (\( \sqrt{s} < 1 \text{ TeV} \)), \( e^+e^- \rightarrow ZHH \) is the most promising channel to measure the triple Higgs self-coupling \( \lambda_{3H} \). In this process, the final state of two Higgs may be generated by the interchange of a virtual Higgs in such a way that this process is sensitive to the triple coupling \( HHH \) in the Higgs potential. It is necessary to include four-body processes with heavy fermions \( f, e^+e^- \rightarrow f\bar{f}HH \), in which the SM Higgs boson is radiated by a \( b(\bar{b}) \) quark at future \( e^+e^- \) colliders with a c.m. energy in the range of 800 to 1500 GeV, as in the case of the ILC \( 31,32 \) and Compact Linear Collider (CLIC) \( 42 \) machines, in order to know its impact on the three-body channel and also to search for new relations that may have a clear signature of the Higgs boson production.

The Higgs coupling with top quarks, the largest coupling in the SM, is directly accessible in the process where the Higgs boson is radiated off top quarks, \( e^+e^- \rightarrow t\bar{t}HH \). This process depends on the Higgs boson triple self-coupling, which could lead us to obtain the first non-trivial information on the Higgs potential. We are interested in finding regions that could allow the observation of the \( bbHH \) and \( t\bar{t}HH \) processes at future linear \( e^+e^- \) colliders energies: ILC and CLIC. In the process \( e^+e^- \rightarrow bbHH \), the set of figures shown for the \( bbHH \) final state includes the \( ZHH \) process with \( Z \rightarrow bb \). We found that the results for the complete calculation \( e^+e^- \rightarrow bbHH \) and for the approximate \( e^+e^- \rightarrow ZHH \) with an on-shell \( Z \) decay to \( b\bar{b} \), differ only at the 3% level in the examined kinematic range. We consider the complete set of Feynman diagrams at tree-level (Figs. 1 and 2) and use the CALCHEP \( 43 \) packages to evaluate the amplitudes and cross-section of the processes \( e^+e^- \rightarrow bbHH \) and \( e^+e^- \rightarrow t\bar{t}HH \).

This paper is organized as follows: In Sec. 2, we study the triple Higgs boson self-coupling through the processes \( e^+e^- \rightarrow bbHH \) and \( e^+e^- \rightarrow t\bar{t}HH \) at future linear \( e^+e^- \) colliders energies and, finally, we summarize our results in Sec. 3.

### 2. Cross-Section of the Higgs Boson Pairs Production with Triple Self-Coupling

In this section we present numerical results for \( e^+e^- \rightarrow bbHH \) and \( e^+e^- \rightarrow t\bar{t}HH \) with double Higgs boson production. We carry out the calculations using the Standard Model framework at future linear \( e^+e^- \) colliders energies. We use the CALCHEP \( 43 \) packages for calculations of the matrix elements and cross-sections. These packages provide automatic computation of the cross-sections and distributions in the SM as well as their extensions at tree-level. We consider the high energy stage of a possible future linear \( e^+e^- \) collider with \( \sqrt{s} = 800,1000,1500 \text{ GeV} \) and the designed luminosity 1000 \( fb^{-1} \).
2.1 Triple Higgs Boson Self-Coupling Via $e^+e^- \rightarrow b\bar{b}HH, t\bar{t}HH$

In order to illustrate our results for the sensitivity to the $HHH$ triple Higgs boson
self-coupling, we show the $\kappa$ dependence of the total cross-section for $e^+e^- \rightarrow b\bar{b}HH$ in Fig. 3 and for $e^+e^- \rightarrow t\bar{t}HH$ in Fig. 4. We consider one representative value of the Higgs boson mass, $M_H = 130$ GeV, with a center-of-mass energy of $\sqrt{s} = 800, 1000, 1500$ GeV, varying the triple coupling $\kappa \lambda_{3H}$ within the range $\kappa = -1$ and +2. In both cases, the cross-section is sensitive to the value of the triple coupling. The sensitivity to $\lambda_{3H}$ increases with the collider energy, reaching a maximum at $\sqrt{s} \sim 600$ GeV for the $b\bar{b}HH$ channel and at $\sqrt{s} \sim 1200$ GeV for the $t\bar{t}HH$ channel (Figs. 5 and 6). As an indicator of the order of magnitude, in Tables I - III we present the number of events of Higgs bosons expected for several Higgs boson masses, center-of-mass energy and $\kappa$ values and for $1000 fb^{-1}$ luminosity (of course, we have multiplied by the corresponding Branching Ratios to obtain the observable number of events). In particular, if we consider the $H \rightarrow b\bar{b}$ decay for $M_H < 130$ GeV, there is some possibility to detect the $e^+e^- \rightarrow b\bar{b}HH$ process. In this region, the number of events is small but sufficient to detect $e^+e^- \rightarrow b\bar{b}HH \rightarrow b\bar{b}b\bar{b}$, in which the $BR(H \rightarrow b\bar{b}) \sim 0.6$ and the background for 6 b-jet are small.

For the $e^+e^- \rightarrow t\bar{t}HH$ process, the center-of-mass energy $1000$ GeV and $M_H < 130$ GeV is the most favorable, but the Branching Ratios for the four decay modes make this process very small.

For the center-of-mass energy $\sqrt{s}$ from 800 GeV up to about $1$ TeV, the production of $b\bar{b}HH$ and $t\bar{t}HH$ in the intermediate mass range of the $H$ mass is significant and all the final states can be identified without large momentum loss. When the c.m. energy $\sqrt{s}$ exceeds $1$ TeV, the cross-section decreases and therefore in the first stage of a future International Linear Collider ($\sqrt{s} \leq 1$TeV), $e^+e^- \rightarrow b\bar{b}HH$ and $e^+e^- \rightarrow t\bar{t}HH$ are important channels to measure the triple Higgs boson self-coupling.

Finally, we include a contour plot for the number of events of the studied processes as a function of $M_H$ and $\sqrt{s}$ with $\kappa = 0.5, 1 (S.M.), 1.5$ in Figs. 7 and 8. These contours are obtained from Tables I - III.

2.2 Triple Higgs Boson Self-Coupling Via $e^+e^- \rightarrow b\bar{b}HH, t\bar{t}HH$ at CLIC Energies

In this subsection we analyze the triple Higgs self-coupling $\lambda_{3H}$ via the processes $e^+e^- \rightarrow b\bar{b}HH, t\bar{t}HH$ for energies expected at the CLIC. Figs. 9 and 10 show the total cross-section for the double Higgs-strahlung in $e^+e^-$ collisions, $e^+e^- \rightarrow b\bar{b}HH, t\bar{t}HH$ as a function of $M_H$ for the c.m. energy of $\sqrt{s} = 3$ TeV and $\kappa = 0.5, 1 (S.M.), 1.5$. The effects of a variation of the triple coupling by 50% from its SM value are shown in these figures. The production cross-section is of the order of a fraction of a femtobarn ($0.005 fb$ for $b\bar{b}HH$ and $0.008 fb$ for $t\bar{t}HH$) when it is not overly suppressed by phase-space and it is mediated by $s$ channel gauge boson exchange. From these figures, we observe that the total cross-sections of both processes are
Table I. Total production of Higgs boson pairs in the SM for $L = 1000 \, fb^{-1}$ and $\kappa = 0.5$.

| $M_H (GeV)$ | $\sqrt{s} = 800 \, GeV$ | $\sqrt{s} = 1000 \, GeV$ | $\sqrt{s} = 1500 \, GeV$ |
|-------------|-----------------|-----------------|-----------------|
| 110         | 20 (11)         | 16 (18)         | 10 (17)         |
| 130         | 17 (5)          | 14 (11)         | 9 (13)          |
| 150         | 14 (2)          | 12 (6)          | 9 (9)           |
| 170         | 11 (-)          | 11 (4)          | 8 (7)           |
| 190         | 9 (-)           | 10 (2)          | 8 (5)           |

Table II. Total production of Higgs boson pairs in the SM for $L = 1000 \, fb^{-1}$ and $\kappa = 1 (SM)$.

| $M_H (GeV)$ | $\sqrt{s} = 800 \, GeV$ | $\sqrt{s} = 1000 \, GeV$ | $\sqrt{s} = 1500 \, GeV$ |
|-------------|-----------------|-----------------|-----------------|
| 110         | 23 (13)         | 18 (21)         | 12 (19)         |
| 130         | 21 (5)          | 17 (13)         | 11 (14)         |
| 150         | 18 (2)          | 16 (8)          | 10 (11)         |
| 170         | 15 (-)          | 14 (-)          | 10 (8)          |
| 190         | 13 (-)          | 13 (-)          | 10 (6)          |

too small because their order of magnitude is smaller than that for the case of $\sqrt{s} = 800, 1600 \, GeV$, as indicated in Ref.\textsuperscript{37–41}

As in subsection 2.1, we show the $\kappa$ dependence of the total cross-section for $e^+e^- \rightarrow b\bar{b}HH, t\bar{t}HH$ in Figs. 11 and 12. We consider one representative value of the Higgs boson mass, $M_H = 130 \, GeV$, and center-of-mass energy $\sqrt{s} = 3 \, TeV$, varying the triple coupling $\kappa \lambda_3 H$ within the range $\kappa = -1$ and +2. In both cases, the production cross-sections are also too small because their order of magnitude is smaller than that for the case of $\sqrt{s} = 800, 1500 \, GeV$ and $M_H = 130 \, GeV$, as is illustrated in Figs. 3 and 4 of subsection 2.1.

Finally, in Tables IV and V we present the Higgs boson number of events for several Higgs boson masses, $\kappa$ values, luminosities of 1000$fb^{-1}$ and 5000$fb^{-1}$ and center-of-mass energy $\sqrt{s} = 3 \, TeV$ (of course, we have multiplied by the corresponding Branching Ratios to obtain the observable number of events). It is clear from Figs. 9 - 12 and Table IV that it would be difficult to obtain a clear signal of the processes $e^+e^- \rightarrow b\bar{b}HH, t\bar{t}HH$ at energies of a future linear collider such as CLIC, after having considered the background, except for $\sqrt{s} = 3 \, TeV$ and very high luminosity ($L = 5000 \, fb^{-1}$) as is shown in Table V. However,
Table III. Total production of Higgs boson pairs in the SM for $\mathcal{L} = 1000 \, fb^{-1}$ and $\kappa = 1.5$.

| $M_H (GeV)$ | $\sqrt{s} = 800 \, GeV$ | $\sqrt{s} = 1000 \, GeV$ | $\sqrt{s} = 1500 \, GeV$ |
|------------|----------------|----------------|----------------|
| 110        | 28 (15)        | 21 (24)        | 13 (20)        |
| 130        | 26 (6)         | 21 (15)        | 13 (16)        |
| 150        | 23 (3)         | 20 (9)         | 13 (13)        |
| 170        | 20 ( -)        | 18 (5)         | 13 (10)        |
| 190        | 17 ( -)        | 17 (3)         | 13 (8)         |

Table IV. Total production of Higgs boson pairs in the SM for $\sqrt{s} = 3 \, TeV$ and $\mathcal{L} = 1000 \, fb^{-1}$.

| $M_H (GeV)$ | $\kappa = 0.5$ | $\kappa = 1 (SM)$ | $\kappa = 1.5$ |
|------------|----------------|----------------|----------------|
| 110        | 5 ( 7)         | 5 ( 8)         | 5 ( 8)         |
| 130        | 5 ( 6)         | 5 ( 7)         | 5 ( 7)         |
| 150        | 4 ( 5)         | 5 ( 6)         | 5 ( 7)         |
| 170        | 4 ( 4)         | 5 ( 5)         | 5 ( 6)         |
| 190        | 4 ( 4)         | 5 ( 4)         | 6 ( 6)         |

Table V. Total production of Higgs boson pairs in the SM for $\sqrt{s} = 3 \, TeV$ and $\mathcal{L} = 5000 \, fb^{-1}$.

| $M_H (GeV)$ | $\kappa = 0.5$ | $\kappa = 1 (SM)$ | $\kappa = 1.5$ |
|------------|----------------|----------------|----------------|
| 110        | 24 (35)        | 25 (39)        | 27 (42)        |
| 130        | 23 (29)        | 24 (33)        | 26 (37)        |
| 150        | 22 (26)        | 24 (28)        | 27 (33)        |
| 170        | 21 (21)        | 24 (25)        | 27 (30)        |
| 190        | 21 (18)        | 24 (22)        | 28 (28)        |

for the center-of-mass energy of CLIC, the $WW$ double Higgs fusion process,\textsuperscript{7,8,33} which increases with rising $\sqrt{s}$, can be exploited by larger energies and luminosities, and would be the preferred mechanism to measure the triple Higgs self-coupling $\lambda_{3H}$. 
3. Conclusions

e^+e^- linear colliders represent a possible opportunity for triple Higgs boson self-coupling analysis. Therefore, we have analyzed the triple Higgs boson self-coupling at future e^+e^- collider energies with the reactions e^+e^- \rightarrow b\bar{b}HH and e^+e^- \rightarrow t\bar{t}HH. The ILC has access to the triple Higgs boson self-coupling through the double Higgs production processes e^+e^- \rightarrow ZHH and e^+e^- \rightarrow \nu\bar{\nu}HH.\(^7\)-\(^{14}\),\(^{17}\)-\(^{21}\),\(^{33}\) Although the cross section for e^+e^- \rightarrow ZHH with intermediate Higgs boson mass is only about 0.1-0.2 fb for \(\sqrt{s} < 1 \text{ TeV}\), the measurement of the Higgs self-coupling \(\lambda_{3H}\) at e^+e^- colliders can be significantly improved. For example, in Ref.,\(^{33}\) C. Castanier et al. concluded that a precision of about 10% on the total cross-section for e^+e^- \rightarrow ZHH can be achieved, leading to a relative error on \(\lambda_{3H}\) of 18% with the help of high integrated luminosity \(L = 2\,\text{ab}^{-1}\) after performing the detailed simulations of signal and background process at the TESLA.\(^{44}\) Other simulations\(^{17}\)-\(^{20}\) demonstrate that the Higgs self-coupling \(\lambda_{3H}\) can be extracted more accurately by using some discriminating kinematic variables, namely the invariant mass of the HH system and the extraction of the Higgs self-coupling \(\lambda_{3H}\) can be further improved to an accuracy of 8% and even better in multi-TeV e^+e^- collisions.\(^{21}\) Therefore, to determine the triple Higgs boson self-coupling \(\lambda_{3H}\) via the process e^+e^- \rightarrow b\bar{b}HH and due to the cross-section difference of 3% between ZHH(Z \rightarrow b\bar{b}) and b\bar{b}HH, the conclusions for the precision in the determination of \(\lambda_{3H}\) are not significantly modified. That is to say, we expect that the results for the complete computation of the process e^+e^- \rightarrow b\bar{b}HH should not alter the conclusions of the previous computation\(^{17}\)-\(^{20}\),\(^{33}\) and thus the same background analysis for e^+e^- \rightarrow ZHH(Z \rightarrow b\bar{b}) remains valid for e^+e^- \rightarrow b\bar{b}HH. Examination of variables sensitive to the triple Higgs boson vertex and the availability of high luminosity will allow testing of the Higgs potential structure at future linear e^+e^- colliders (in the case of the Minimal Supersymmetric extension of the Standard Model (MSSM) with large \(\tan\beta\), the b\bar{b}HH channel may be significantly enhanced). On the other hand, for the t\bar{t}HH final state, we found a major number of events (Table V) to difference of the b\bar{b}HH channel, but after considering the decay products of both the Higgs boson (H) and the top quark (t) to b quarks, the expected final number of events will be very small. Finally, the study of these processes is important and could be useful to probe the triple Higgs boson self-couplings \(\lambda_{3H}\) given the following conditions: very high luminosity, excellent b tagging performance, and center-of-mass energy in the range \(\sqrt{s} = 800 - 1000 \text{ GeV}\), which is the most favorable colliding energy for b\bar{b}HH and t\bar{t}HH production and for the lightest Higgs boson mass in the range \(M_H = 110 - 130 \text{ GeV}\). In addition, these results have never been reported in the literature before and could be of relevance for the scientific community.
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Fig. 1. Feynman diagrams at tree-level for $e^+e^- \rightarrow b\bar{b}HH$. 
Fig. 2. Feynman diagrams at tree-level for $e^+e^- \rightarrow t\bar{t}HH$. 
Fig. 3. Variation of the cross-section $\sigma(b\bar{b}HH)$ with the modified triple coupling $\kappa\lambda_3 H$ at a collider energy of $\sqrt{s} = 800, 1000, 1500$ GeV and $M_H = 130$.

Fig. 4. The same as in Fig. 3, but for the process $e^+e^- \rightarrow t\bar{t}HH$. 
Fig. 5. The dependence of the cross-section on center-of-mass energy $\sqrt{s}$ for two fixed Higgs masses $M_H = 110, 130$ GeV. The variation of the cross-section for modified triple couplings $\kappa \lambda_3 H$ is indicated by the solid and dot-dashed lines.
Fig. 6. The same as in Fig. 5, but for the process $e^+e^- \rightarrow t\bar{t}HH$. 
Fig. 7. Contour plot for the number of events of the process $e^+e^- \rightarrow b\bar{b}HH$ as a function of $M_H$ and $\sqrt{s}$. The variation of the number of events for modified triple couplings $\kappa\lambda_{3H}$ is indicated for $\kappa = 0.5$, 1(S.M.), 1.5.
Fig. 8. The same as in Fig. 7, but for the process $e^+e^- \rightarrow t\bar{t}HH$.
Fig. 9. The cross-section for the double Higgs-strahlung via $e^+e^- \rightarrow bbHH$, at a c.m. energy of $\sqrt{s} = 3$ TeV as a function of $M_H$ with $\kappa = 0.5, 1, 1.5$. The effects of a variation of the triple coupling by 50% from its SM value are shown.

Fig. 10. The same as in Fig. 9, but for the process $e^+e^- \rightarrow t\bar{t}HH$. 
Fig. 11. Variation of the cross-section $\sigma(b\bar{b}HH)$ with the modified triple coupling $\kappa\lambda_{3H}$ at a collider energy of $\sqrt{s} = 3$ TeV and $M_H = 130$.

Fig. 12. The same as in Fig. 11, but for the process $e^+e^- \rightarrow t\bar{t}HH$. 
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