Studying the Triple Higgs Self-Coupling Via $e^+e^- \rightarrow b\bar{b}HH, t\bar{t}HH$
at Future Linear $e^+e^-$ Colliders

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Abstract

We study the triple Higgs self-coupling at future $e^+e^-$ colliders energies, with the reactions $e^+e^- \rightarrow b\bar{b}HH$ and $e^+e^- \rightarrow t\bar{t}HH$. We evaluate the total cross section of $b\bar{b}HH$, $t\bar{t}HH$ and calculate the total number of events considering the complete set of Feynman diagrams at tree-level. The sensitivity of the triple Higgs coupling is considered in the Higgs mass range $110 - 190$ GeV, for the energy which is expected to be available at a possible Next Linear $e^+e^-$ Collider with a center-of-mass energy $800,1000,1500$ GeV and luminosity $1000$ fb$^{-1}$.

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I. INTRODUCTION

In the Standard Model (SM) [1] of particle physics, there are three types of interactions of fundamental particles: gauge interactions, Yukawa interactions and the Higgs boson self-interaction. The Higgs boson [2] plays an important role in the SM; it is responsible for generating the masses of all the 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 isodoblete scalar field to generate fermion and weak gauge bosons masses is required. Despite numerous successes in explaining the present data, the SM cannot be completely tested before this particle has been experimentally observed and its fundamental properties studied.

In the SM, the profile of the Higgs particle is uniquely determined once its mass \( M_H \) is fixed [3]; the decay width and branching, as well as the production cross sections, are given by the strength of the Yukawa couplings to fermions and gauge bosons, which is set by the masses of these particles. However, the Higgs boson mass is a free parameter with two experimental constraints.

The SM Higgs boson has been searched by LEP in the Higgs-strahlung process, \( e^+e^- \rightarrow HZ \), for c.m. energies up to \( \sqrt{s} = 209 \text{ GeV} \) and with a large collected luminosity. In the summer of 2002, the final results of the four LEP collaborations were published and some changes were made with respect to the original publication. Especially, the inclusion of more statistics, the revision of backgrounds, and the reassessment of systematic errors. When these results are combined, an upper limit \( M_H \geq 114.4 \text{ GeV} \) is established at the 95% confidence level [4]. However, in the absence of additional events with respect to SM predictions, this upper limit was expected to be \( M_H > 115.3 \text{ GeV} \) due to a 1.7\( \sigma \) excess [compared to the value 2.9\( \sigma \) reported at the end of 2000] of events for a Higgs boson mass in the vicinity of \( M_H = 116 \text{ GeV} \) [4].

The second constraint comes from the accuracy of the electroweak observables measured at LEP, SLAC Large Detector (SLC), and the Fermilab Tevatron, which provide sensitivity to \( M_H \). The Higgs boson contributes logarithmically, \( \propto \log(\frac{M_H}{M_W}) \), to the radiative corrections to the \( W/Z \) boson propagators. The status, as found in Summer 2002, is summarized in Reference [5]. When taking into account all available data, (i.e. the \( Z^0 \)-boson pole LEP and SLC data, the measurement of the \( W \) boson mass and total width, the top-quark mass and the controversial NuTeV result) one obtains a Higgs boson mass of \( M_H = 81^{+12}_{-33} \text{ GeV} \), which leads to a 95% confidence level upper limit of \( M_H < 193 \text{ GeV} \) [5].

A detailed study of the Higgs potential represents a conclusive test of the symmetry breaking and mass generation mechanism. After discovering of an elementary Higgs boson and testing its couplings to quarks, leptons and gauge bosons, a further proof of the Higgs mechanism will be the experimental evidence that the Higgs field potential has the properties required for breaking the electro-weak symmetry.

The trilinear and quartic Higgs boson couplings [7–9] \( \lambda \) and \( \tilde{\lambda} \) are defined through the
potential

\[ V(\eta_H) = \frac{1}{2} M_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \tilde{\lambda} \eta_H^4, \]  

(1)

where \( \eta_H \) is the physical Higgs field. 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 \( v = 246 \text{ GeV} \) is the vacuum expectation value of the Higgs boson. The trilinear vertex of the Higgs field \( H \) is given by the coefficient \( \lambda_{HHH} = \frac{3M_H^2}{M_Z^2} \) and \( M_H \) can be determined to \( O(100\text{GeV}) \) accuracy. 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 that is responsible for electroweak symmetry breaking.

The trilinear Higgs 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 \( \lambda_{HHH} \) can be exploited for this task. Higgs pairs can be produced through double Higgs-strahlung of \( W \) or \( Z \) bosons \([6,8–10]\), \( WW \) or \( ZZ \) fusion \([7,8,11–13]\); moreover, through gluon-gluon fusion in \( pp \) collisions \([14–16]\) and high-energy \( \gamma\gamma \) fusion \([7,8,17]\) at photon colliders. The two main processes at \( e^+e^- \) colliders are double Higgs-strahlung and \( WW \) fusion:

\[
\text{double Higgs-strahlung} : \, e^+e^- \rightarrow ZHH \\
\text{WW double-Higgs fusion} : \, e^+e^- \rightarrow \bar{\nu}_e \nu_e HH.
\]  

(2)

The \( ZZ \) fusion process of Higgs pairs is suppressed by an order of magnitude because the electron-\( Z \) coupling is small. However, the process \( e^+e^- \rightarrow ZHH \) has been studied \([6,8–10]\) extensively. This three-body process is important because it is sensitive to Yukawa couplings. The inclusion of 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 \([18–21]\) with a c.m. energy in the range of 800 to 1500 GeV, as in the case of DESY TeV Energy Superconducting Linear Accelerator (TESLA) machine \([22]\), is necessary in order to know its impact on three-body mode processes and also to search for new relations that could 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, \( e^+e^- \rightarrow t\bar{t}HH \), followed by the process \( e^+e^- \rightarrow b\bar{b}HH \). This processes 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 \( b\bar{b}HH \) and \( t\bar{t}HH \) processes at the next generation of high energy \( e^+e^- \) linear colliders. We consider the complete set of Feynman diagrams at tree-level (Figs. 1, 2) and use the CALCHEP \([23]\) packages to evaluate the amplitudes and cross section.

At the linear collider, the triple Higgs coupling \( \lambda_{HHH} \) can be accessed by studying multiple Higgs production in the reactions \( e^+e^- \rightarrow b\bar{b}HH \) and \( t\bar{t}HH \) that are sensitive to the triple Higgs vertex. The first process is more relevant at lower values of the center-of-mass energy \( \sqrt{s} \), and for the Higgs boson masses in the range \( 110 \leq M_H \leq 190 \text{ GeV} \). The second process is more relevant at collision energies above 1 TeV and ensures sensitivity to the triple Higgs vertex for intermediate range Higgs masses.
This paper is organized as follows: In Sec. II, we study the triple Higgs self-coupling through the processes $e^+e^− → b\bar{b}HH$ and $e^+e^− → t\bar{t}HH$ at next generation linear $e^+e^−$ colliders. In Sec. III, we give our conclusions.

II. DOUBLE HIGGS PRODUCTION CROSS SECTION IN THE SM AT NEXT GENERATION LINEAR POSITRON-ELECTRON COLLIDERS

In this section we present numerical results for $e^+e^− → b\bar{b}HH$ and $e^+e^− → t\bar{t}HH$ with double Higgs production. We carry out the calculations using the framework of the Standard Model at next generation linear $e^+e^−$ colliders. We use CALCHEP [23] 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. Both $e^+e^− → b\bar{b}HH$ and $e^+e^− → t\bar{t}HH$ processes are studied, including a complete set of Feynman diagrams. We consider the high energy stage of a possible Next Linear $e^+e^−$ Collider with $\sqrt{s} = 800, 1000, 1500$ GeV and design luminosity $1000 \, fb^{-1}$.

For the SM parameters, we have adopted the following: the Weinber angle $\sin^2 \theta_W = 0.232$, the mass ($m_b = 4.5$ GeV) of the bottom quark, the mass ($m_t = 175$ GeV) of the top quark, and the mass ($m_{Z^0} = 91.2$ GeV) of the $Z^0$, taking the mass $M_H$ of the Higgs boson as input [24].

A. Triple Higgs Self-Coupling Via $e^+e^− → b\bar{b}HH$

To illustrate our results of the sensitivity to the $HHH$ triple Higgs self-coupling, we show the $\kappa$ dependence of the total cross-section for $e^+e^− → b\bar{b}HH$ in Fig. 3. We consider one representative value of the Higgs mass $M_H = 130$ GeV with the center-of-mass energy of $\sqrt{s} = 800, 1000, 1500$ GeV and varying the trilinear coupling $\kappa\lambda_{HHH}$ within the range $\kappa = -1$ and $+2$. Clearly, the cross-section is sensitive to the value of the trilinear couplings. Since the $b\bar{b}HH$ cross-section and its sensitivity to $\lambda_{HHH}$ decrease with increasing collider energy, a linear collider operating at 800 GeV offers the opportunity for a precise measurement of $\lambda_{HHH}$ for $M_H \leq 130$ GeV.

Fig. 4 shows the total cross-section as a function of the center-of-mass energy $\sqrt{s}$ for one value of the Higgs mass $M_H = 110$ GeV and for several values of $\kappa$. We observe in this figure that the total cross-section of $b\bar{b}HH$ is of the order 0.04 fb for Higgs mass $M_H = 110$ GeV and $\kappa = 1.5$. The cross sections are at the femtobarn fraction level and they quickly drop with the increase of the center-of-mass energy. Under these conditions, it would be very difficult to extract any useful information about the Higgs self-coupling from the studied process unless the $e^+e^−$ machine works with very high luminosity.

The cross-section for $e^+e^− → b\bar{b}HH$ as function of the center-of-mass energy, with $M_H = 130$ GeV and $\kappa = 0.5, 1(S.M.), 1.5$ is presented in Fig. 5. The cross-sections are shown for unpolarized electron and positron beams. As in Fig. 4, the cross-section is at the femtobarn fraction level and decreases with rising energy. However, the cross-section increases with rising self-coupling in the vicinity of the SM value.

We observe in Figs. 4 and 5 that the cross-section decreases as energy increases. At some given energy, the maximum total cross-section value is $\sigma_{max}^{Tot}$, depending on the Higgs
mass. Since fermion chirality is conserved at the $Z^0$ -- fermion vertex, the cross section may increase by practically twice when electrons and positrons are polarized. Our conclusion is that for Higgs masses in the intermediate mass range and rising self-coupling in the vicinity of the SM value, a visible number of events would be produced as illustrated in Tables I-III.

For center-of-mass energies of 800-1500 $GeV$ and high luminosity, the possibility of a detailed study of the triple Higgs boson self-coupling via the process $b\bar{b}HH$ is promising as shown in Tables I-III. Thus, a high-luminosity $e^+e^-$ linear collider is a very high precision machine in the context of Higgs physics. This precision would allow the determination of the complete profile of the SM Higgs boson, in particular if its mass is smaller than $\sim 130 GeV$.

| $M_H$ (GeV) | $\sqrt{s} = 800 GeV$ | $\sqrt{s} = 1000 GeV$ | $\sqrt{s} = 1500 GeV$ |
|------------|---------------------|---------------------|---------------------|
| 110        | 20                  | 16                  | 10                  |
| 130        | 17                  | 14                  | 9                   |
| 150        | 14                  | 12                  | 9                   |
| 170        | 11                  | 11                  | 8                   |
| 190        | 9                   | 10                  | 8                   |

Table I. Total production of Higgs pairs in the SM for $L = 1000 fb^{-1}$, $m_b = 4.5 GeV$ and $\kappa = 0.5$.

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

Table II. Total production of Higgs pairs in the SM for $L = 1000 fb^{-1}$, $m_b = 4.5 GeV$ and $\kappa = 1(SM)$.

| $M_H$ (GeV) | $\sqrt{s} = 800 GeV$ | $\sqrt{s} = 1000 GeV$ | $\sqrt{s} = 1500 GeV$ |
|------------|---------------------|---------------------|---------------------|
| 110        | 28                  | 21                  | 13                  |
| 130        | 26                  | 21                  | 13                  |
| 150        | 23                  | 20                  | 13                  |
| 170        | 20                  | 18                  | 13                  |
| 190        | 17                  | 17                  | 13                  |
Table III. Total production of Higgs pairs in the SM for $\mathcal{L} = 1000 \text{ fb}^{-1}$, $m_b = 4.5 \text{ GeV}$ and $\kappa = 1.5$.

In Fig. 6, we also include a contour plot for the number of events of the studied process, as a function of $M_H$ and $\sqrt{s}$ with $\kappa = 0.5, 1(S.M.), 1.5$. These contours are obtained from Tables I-III.

B. Triple Higgs Self-Coupling Via $e^+e^- \rightarrow t\bar{t}HH$

As in the case of the process $e^+e^- \rightarrow b\bar{b}HH$, in this subsection we show the sensitivity of the triple Higgs coupling $\kappa \lambda_{HHH}$ via the process $e^+e^- \rightarrow t\bar{t}HH$ in the range of $-1 \leq \kappa \leq 2$ at tree-level (Fig. 7). Solid (short-dashed, dot-dashed) lines are the results of the cross-sections of the process $e^+e^- \rightarrow t\bar{t}HH$ for $\sqrt{s} = 800, 1000, 1500 \text{ GeV}$ and $M_H = 130 \text{ GeV}$. At $\sqrt{s} = 1500 \text{ GeV}$, the cross-section is dominant as illustrated in this figure, where $\kappa = 1$ stands for the Standard Model.

Figs. 8 and 9 show the total cross-section as a function of the center-of-mass energy $\sqrt{s}$ for two representative values of the Higgs mass $M_H = 110, 130 \text{ GeV}$, respectively, and for several values of $\kappa$. We observe in this figure that the total cross-section of $t\bar{t}HH$ is of the order of 0.025 and 0.018 fb for Higgs masses $M_H = 110, 130 \text{ GeV}$, and $\kappa = 1.5$. The cross-sections are at the femtobarn fraction level, and they quickly drop with the increase of the center-of-mass energy. Under these conditions (similar to the $e^+e^- \rightarrow b\bar{b}HH$ process), it would be very difficult to extract any useful information about the Higgs self-coupling from the studied process unless the $e^+e^-$ machine works with very high luminosity.

We observe in Figs. 8 and 9 that the cross section decreases with energy. At some given energy, the total cross sections has its maximum value of $\sigma_{\text{tot}}^{\text{max}}$ depending on the Higgs mass. Since fermion chirality is conserved at the $Z^0 - \text{fermion}$ vertex, the cross section may increase by practically twice when electrons and positrons are polarized.

For center-of-mass energies of 800-1500 GeV and high luminosity, the possibility of observing the process $t\bar{t}HH$ are promising as shown in Tables IV-VI. Thus, a high-luminosity $e^+e^-$ linear collider is a very high precision machine in the context of Higgs physics. This precision would allow the determination of the trilinear Higgs boson self-coupling of the SM, in particular if its mass is smaller than $\sim 130 \text{ GeV}$.

| $M_H(\text{GeV})$ | $\sqrt{s} = 800 \text{ GeV}$ | $\sqrt{s} = 1000 \text{ GeV}$ | $\sqrt{s} = 1500 \text{ GeV}$ |
|-------------------|-----------------------------|-----------------------------|-----------------------------|
| 110               | 11                          | 18                          | 17                          |
| 130               | 5                           | 11                          | 13                          |
| 150               | 2                           | 6                           | 9                           |
| 170               | -                           | 4                           | 7                           |
| 190               | -                           | 2                           | 5                           |

Table IV. Total production of Higgs pairs in the SM for $\mathcal{L} = 1000 \text{ fb}^{-1}$, $m_t = 175 \text{ GeV}$ and $\kappa = 0.5$. 

6
Total Production of Higgs Pairs $e^+e^-\rightarrow ttHH \quad \kappa = 1(SM)$

| $M_H$(GeV) | $\sqrt{s} = 800$ GeV | $\sqrt{s} = 1000$ GeV | $\sqrt{s} = 1500$ GeV |
|------------|---------------------|---------------------|---------------------|
| 110        | 13                  | 21                  | 19                  |
| 130        | 5                   | 13                  | 14                  |
| 150        | 2                   | 8                   | 11                  |
| 170        | -                   | -                   | 8                   |
| 190        | -                   | -                   | 6                   |

Table V. Total production of Higgs pairs in the SM for $\mathcal{L} = 1000$ fb$^{-1}$, $m_t = 175$ GeV and $\kappa = 1(SM)$.

Total Production of Higgs Pairs $e^+e^-\rightarrow ttHH \quad \kappa = 1.5$

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

Table VI. Total production of Higgs pairs in the SM for $\mathcal{L} = 1000$ fb$^{-1}$, $m_t = 175$ GeV and $\kappa = 1.5$.

In Fig. 10, we include a contour plot for the number of events of the studied process as a function of $M_H$ and $\sqrt{s}$ with $\kappa = 0.5, 1(S.M.), 1.5$. These contours are obtained from Tables IV-VI.

Although 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 $e^+e^-\rightarrow ttHH$, the coupling to bottom quarks is also accessible in the reaction where the Higgs is radiated by a $b(\bar{b})$ quark, $e^+e^-\rightarrow b\bar{b}HH$. For $M_H \lesssim 130$ GeV, the Yukawa coupling can be measured with a precision of less than 5% at $\sqrt{s} = 800$ GeV with a luminosity of $\mathcal{L} = 1000$ fb$^{-1}$.

Finally, the measurement of the trilinear Higgs self-coupling, which is the first non-trivial test of the Higgs potential, is possible in the double Higgs production processes $e^+e^-\rightarrow b\bar{b}HH$ and in the $e^+e^-\rightarrow ttHH$ process at high energies. Despite their smallness, the cross sections can be of any practical use for the scientific community.

### III. CONCLUSIONS

An analysis of triple Higgs couplings will provide a crucial test of the Higgs mechanism of electro-weak symmetry breaking by directly accessing the shape of the Higgs field potential.
When the study of the $e^+e^- \rightarrow b\bar{b}HH$ and $e^+e^- \rightarrow t\bar{t}HH$ processes can be performed with high accuracy, $e^+e^-$ linear colliders represent a possible opportunity for triple Higgs couplings analysis. Examination of variables sensitive to the triple Higgs vertex and the availability of high luminosity will allow test the Higgs potential structure at Future Linear $e^+e^-$ Collider. Finally, the study of these processes is important and could be useful to probe the triple Higgs self-coupling $\lambda_{HHH}$ given the following conditions: very high luminosity, excellent $b$ tagging performances, center-of-mass large energy and intermediate range Higgs mass.

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**FIGURE CAPTIONS**

**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 trilinear coupling $\kappa\lambda_{HHH}$ at a collider energy of $\sqrt{s} = 800, 1000, 1500 \text{ GeV}$ and $M_H = 130$. The variation of the cross section for modified trilinear couplings $\kappa\lambda_{HHH}$ is indicated by the solid and dot-dashed lines.

**Fig. 4** The energy dependence of the cross-section with the center-of-mass energy $\sqrt{s}$ for a fixed Higgs mass $M_H = 110 \text{ GeV}$. The variation of the cross-section for modified trilinear couplings $\kappa\lambda_{HHH}$ is indicated by the solid and dot-dashed lines.

**Fig. 5** The same as in Fig. 4, but for $M_H = 130 \text{ GeV}$.

**Fig. 6** Contours 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 trilinear couplings $\kappa\lambda_{HHH}$ is indicated for $\kappa = 0.5, 1(S.M.), 1.5$.

**Fig. 7** The same as in Fig. 3, but for the process $e^+e^- \rightarrow t\bar{t}HH$.

**Fig. 8** The same as in Fig. 4, but for the process $e^+e^- \rightarrow t\bar{t}HH$.

**Fig. 9** The same as in Fig. 5, but for the process $e^+e^- \rightarrow t\bar{t}HH$.

**Fig. 10** The same as in Fig. 6, but for the process $e^+e^- \rightarrow t\bar{t}HH$. 
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