

# Triple Higgs Boson Self-Coupling in a $\gamma\gamma$ Collider

**A. Gutiérrez-Rodríguez**

Facultad de Física, Universidad Autónoma de Zacatecas.  
Apartado Postal C-580, 98060, Zacatecas, México.

**Javier Peressutti and O. A. Sampayo**

Instituto de Física de Mar del Plata (IFIMAR) CONICET, UNMDP. Departamento de Física, Universidad Nacional del Mar del Plata  
Funes 3350, (7600) Mar del Plata, Argentina.

E-mail: alexgu@fisica.uaz.edu.mx

## Abstract.

We analyzed the double production and the triple self-coupling of the standard model Higgs boson at future  $\gamma\gamma$  collider energies, with the reactions  $\gamma\gamma \rightarrow t\bar{t}HH$ . We evaluated the total cross section for  $t\bar{t}HH$  and calculated the total number of events considering the complete set of Feynman diagrams at tree-level and for different values of the triple coupling  $\kappa\lambda_{HHH}$ . The numerical computation was done for the energy which is expected to be available at a possible Future Linear  $\gamma\gamma$  Collider with a center-of-mass energy  $500 - 3000$  GeV and luminosities of 1000 and  $5000$  fb $^{-1}$ . We found that the number of events for the process  $\gamma\gamma \rightarrow t\bar{t}HH$ , taking into account the decay products of both  $t$  and  $H$ , is enough to obtain relevant information about the triple Higgs boson self-coupling.

## 1. Introduction

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 interactions. Indeed, in order to accommodate the well established electromagnetic and weak interaction phenomena, the existence of at least one isodoublet scalar field to generate fermion and weak gauge bosons masses is required. Despite repeated 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 [1, 2, 3]  $\lambda$  and  $\tilde{\lambda}$  are defined through the potential

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

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  $v = 246$  GeV is the vacuum expectation value of the Higgs boson. The triple vertex of the Higgs field  $H$  is given by the coefficient  $\lambda_{HHH} = \frac{3M_H^2}{M_Z^2}$ . 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 future  $e^+e^-$  linear collider can not only be designed to operate in  $e^+e^-$  collision mode, but can also be operated as a  $\gamma\gamma$  collider. This is achieved by using Compton backscattered photons in the scattering of intense laser photons on the initial  $e^+e^-$  beams. The design of the photon linear collider and physics opportunities are described in references [4, 5] and the possibility of measuring the  $HHH$  coupling is discussed in Refs. [2, 6, 7].

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  $\lambda_{HHH}$  can be exploited for this task. Higgs pairs can be produced through double Higgs-strahlung of  $W$  or  $Z$  bosons [3, 8, 9],  $WW$  or  $ZZ$  fusion [2, 10, 11, 12] as well as through gluon-gluon fusion in  $pp$  collisions [13, 14, 15] and high-energy  $\gamma\gamma$  fusion [2, 6] at photon colliders. In  $\gamma\gamma$  collisions, double Higgs production is possible in several reactions at the tree level, and one process,  $\gamma\gamma \rightarrow HH$ , at the one-loop level:

$$\begin{aligned} WW \text{ double Higgs-fusion} & : \gamma\gamma \rightarrow WWHH, \\ \text{double Higgs-fermion} & : \gamma\gamma \rightarrow f\bar{f}HH, \\ \text{one-loop level} & : \gamma\gamma \rightarrow HH. \end{aligned} \tag{2}$$

As was studied in Ref. [2] the reaction  $\gamma\gamma \rightarrow WWHH$  is free from any background except incorrect combinatorial of jets; for  $M_H < 150 \text{ GeV}$ , the main branching is four  $b$ -jets (with an invariant mass peak at  $M_H$ ) plus jets from two additional  $W$  bosons, up to four, and/or a large missing energy. 8-jet events can be detected in total: For  $M_H > 150 \text{ GeV}$ , the signature includes up to twelve quark jets with the invariant mass peaking at  $M_W$  and  $M_H$ .

In the case of the process  $\gamma\gamma \rightarrow f\bar{f}HH$ , the important contribution happens when the considered fermion is a quark-top since the Higgs-fermion coupling is proportional to the fermion mass.

The study of the four-body processes with quark top  $t$ ,  $\gamma\gamma \rightarrow t\bar{t}HH$ , in which the SM Higgs boson is radiated by a  $t(\bar{t})$  quark at future  $\gamma\gamma$  colliders [4, 5] with a c.m. energy in the range of 500 to 3000  $\text{GeV}$ , as in the case of the DESY TeV Energy Superconducting Linear Accelerator (TESLA) machine [16], is necessary in order to know its impact on other 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  $\gamma\gamma \rightarrow t\bar{t}HH$ . Consequently, this process can be used to probe the  $t-\bar{t}-H$  Yukawa coupling directly. 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  $t\bar{t}HH$  processes at the next generation of high energy  $\gamma\gamma$  linear colliders.

This paper is organized as follows: In Sec. 2, we study the triple Higgs boson self-coupling through the processes  $\gamma\gamma \rightarrow t\bar{t}HH$  at next generation linear  $\gamma\gamma$  colliders. Finally, we summarize our results in Sec. 3.

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

To illustrate our results we present the Higgs boson number of events in Tables 1-2 (of course we have to multiply for the corresponding Branching Ratios to obtain the observable number of events) for several Higgs boson masses, center-of-mass energy and  $\kappa$  values and for a luminosity of  $1000 \text{ fb}^{-1}$  and  $5000 \text{ fb}^{-1}$ .

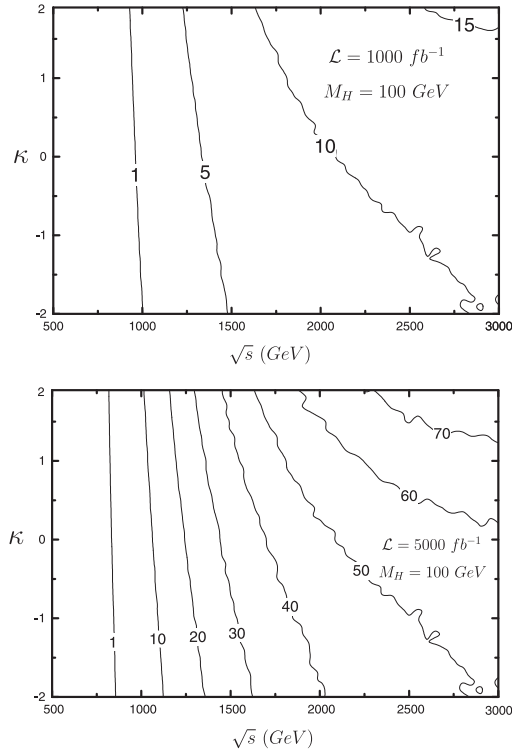
We also include a contours plot for the number of events of the studied processes in the  $(\sqrt{s}, \kappa)$  plane with  $M_H = 100 \text{ GeV}$  and  $1000 fb^{-1}$ ,  $5000 fb^{-1}$  in Fig. 1. These contours are obtained from Tables 1-2.

**Table 1.** Total production of Higgs boson pairs in the SM for  $\mathcal{L} = 1000 \text{ (5000)} \text{ } fb^{-1}$  and  $\kappa = 2$ .

Higgs Production	$\gamma\gamma \rightarrow t\bar{t}HH, \quad \kappa = 2$					
$M_H(GeV)$	$\sqrt{s} = 800 \text{ GeV}$	$\sqrt{s} = 1000 \text{ GeV}$	$\sqrt{s} = 1500 \text{ GeV}$	$\sqrt{s} = 2000 \text{ GeV}$	$\sqrt{s} = 2500 \text{ GeV}$	$\sqrt{s} = 3000 \text{ GeV}$
100	- (-)	2 (10)	8 (40)	13 (65)	15 (75)	16 (80)
120	- (-)	- (-)	4 (20)	7 (35)	9 (45)	10 (50)
140	- (-)	- (-)	2 (10)	4 (20)	6 (30)	7 (35)

**Table 2.** Total production of Higgs boson pairs in the SM for  $\mathcal{L} = 1000 \text{ (5000)} \text{ } fb^{-1}$  and  $\kappa = 1$ .

Higgs Production	$\gamma\gamma \rightarrow t\bar{t}HH, \quad \kappa = 1$					
$M_H(GeV)$	$\sqrt{s} = 800 \text{ GeV}$	$\sqrt{s} = 1000 \text{ GeV}$	$\sqrt{s} = 1500 \text{ GeV}$	$\sqrt{s} = 2000 \text{ GeV}$	$\sqrt{s} = 2500 \text{ GeV}$	$\sqrt{s} = 3000 \text{ GeV}$
100	- (-)	1 (5)	7 (35)	11 (55)	13 (65)	13 (65)
120	- (-)	- (-)	4 (20)	6 (30)	8 (40)	8 (40)
140	- (-)	- (-)	2 (10)	3 (15)	4 (20)	5 (25)



**Figure 1.** Contour plot for the number of events of the process  $e^+e^- \rightarrow t\bar{t}HH$  as a function of  $\sqrt{s}$  and  $\kappa$ . The variation of the number of events for modified triple couplings  $\kappa\lambda_{HHH}$  is indicated for  $\mathcal{L} = 1000 fb^{-1}, 5000 fb^{-1}$  and  $M_H = 100 \text{ GeV}$ .

### 3. Conclusions

As a possible option of the International Linear Collider (ILC), the feasibility of physics opportunities of high energy physics photon-photon interaction has been considered in Ref. [17]. In the high energy photon linear collider, high energy photon beams are generated by inverse Compton scattering between the electron and the laser beams. The  $\gamma\gamma$  collider represents a possible opportunity for the triple Higgs boson self-coupling analysis. Therefore, we have analyzed the triple Higgs boson self-coupling at future  $\gamma\gamma$  collider energies with the reaction  $\gamma\gamma \rightarrow t\bar{t}HH$  and considering the complete set of Feynman diagrams at tree-level and in the frame work of the standard model.

We found that for the process  $\gamma\gamma \rightarrow t\bar{t}HH$ , the complete calculation at tree level gives a production cross-section of the order of a fraction of a femtobarn, i.e., 0.015 fb, 0.010 fb and 0.007 fb for  $M_H = 100, 120, 140$  GeV, respectively, and at the end of the examined energy range. These values are, however, larger than the production cross-section for  $e^+e^- \rightarrow b\bar{b}HH$  and  $e^+e^- \rightarrow t\bar{t}HH$  [18]. The number of events obtained considering the decay products of both  $t$  and  $H$  is enough to obtain relevant information about the triple Higgs self-coupling. Moreover, this process can be used to probe the  $t - \bar{t} - H$  Yukawa coupling.

Finally, the study of this process is important and could be useful to probe the triple Higgs boson self-couplings  $\lambda_{HHH}$  using a  $\gamma\gamma$  collider with very high luminosity and high center-of-mass energy. 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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