Testing Higgs Self-Couplings at High-Energy Linear Colliders

M.M. Mühlleitner

Laboratoire de Physique Mathématique et Théorique, UMR5825–CNRS, Université de Montpellier II, F–34095 Montpellier Cedex 5, France

Abstract. In order to verify the Higgs mechanism experimentally, the Higgs self-couplings have to be probed. These couplings allow the reconstruction of the characteristic Higgs potential responsible for the electroweak symmetry breaking. The couplings are accessible in a variety of multiple Higgs production processes. The theoretical analysis including the most relevant channels for the production of neutral Higgs boson pairs at high-energy and high-luminosity e^+e^- linear colliders will be presented in this note.

1. Within the Higgs mechanism [1] the electroweak gauge bosons and fundamental matter particles acquire their masses through the interaction with a scalar field. The self-interaction of the scalar field induces, via a non-vanishing field strength $v = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV, the spontaneous breaking of the electroweak $SU(2)_L \times U(1)_Y$ symmetry down to the electromagnetic $U(1)_{EM}$ symmetry.

To establish the Higgs mechanism experimentally, the self-energy potential of the Standard Model [2], $V = \lambda \left(\Phi^\dagger\Phi - v^2/2\right)^2$, with a minimum at $\langle\Phi\rangle_0 = v/\sqrt{2}$ must be reconstructed. This task requires the measurement of the Higgs self-couplings of the physical Higgs boson H, which can be read off directly from the potential

$$V = \frac{M_H^2}{2}H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4 \tag{1}$$

As evident from Eq. (1), in the SM the trilinear and quadrilinear vertices are uniquely determined by the mass of the Higgs boson, $M_H = \sqrt{2\lambda}v$.

The trilinear self-coupling $\lambda = 6\sqrt{2}\lambda$ in units of $v/\sqrt{2}$ is accessible directly in Higgs pair production at high-energy e^+e^- linear colliders. For c.m. energies up to about 1 TeV, double Higgs-strahlung [3,4]

$$e^+e^- \to ZHH \tag{2}$$

is the most promising process [5]. The process includes the amplitude involving the trilinear Higgs self-coupling and two additional amplitudes due to the standard electroweak gauge interactions, cf. Fig. 1, so that it is a binomial in λ_{HHH}.

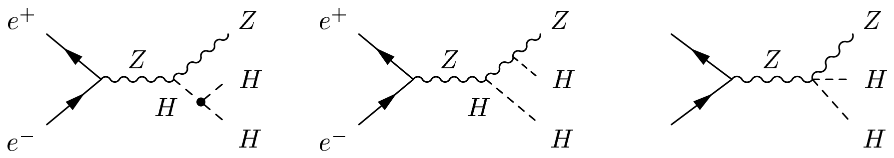

FIGURE 1. Subprocesses contributing to double Higgs-strahlung, $e^+e^- \to ZHH$, in the Standard Model at e^+e^- linear colliders.

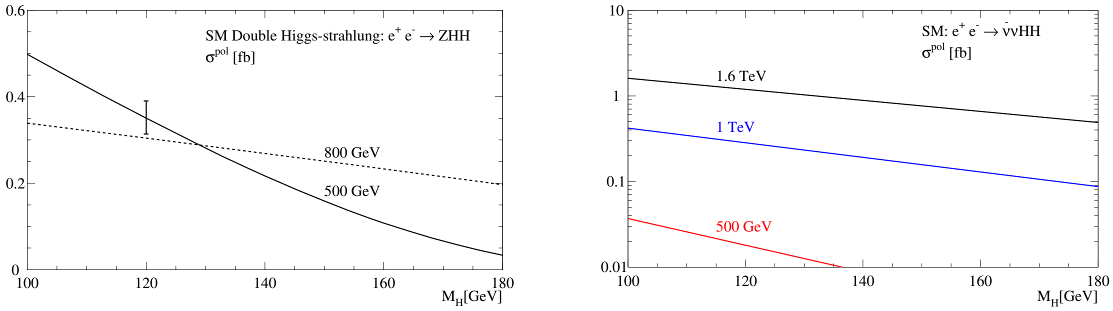

FIGURE 2. (a) The cross section for double Higgs-strahlung, $e^+e^- \to ZHH$, in the Standard Model at two collider energies: $\sqrt{s} = 500$ GeV and 800 GeV. The electron/positron beams are taken oppositely polarized. The vertical bar corresponds to a variation of the trilinear Higgs coupling between 0.8 and 1.2 of the SM value. (b) The cross section for WW double Higgs fusion, $e^+e^- \to \nu_e\bar{\nu}_e HH$, at $\sqrt{s} = 500$ GeV, 1 TeV and 1.6 TeV. The initial beams are polarized.

As evident from Fig. 2a the cross section is very sensitive to the trilinear Higgs self-coupling and amounts up to 0.35 fb for $M_H = 120$ GeV and a c.m. energy of 500 GeV. Scaling with the energy, it decreases to 0.3 fb at $\sqrt{s} = 800$ GeV. Experimental detector simulations of signal and background processes in the SM have demonstrated that the Higgs self-coupling can be extracted with an accuracy of $\sim 20\%$ for $M_H = 120$ GeV at high luminosity $\int \mathcal{L} = 2$ ab^{-1} [6].

The WW double Higgs fusion process [4,7]

$$e^+e^- \to \nu_e\bar{\nu}_e HH \tag{3}$$

which increases with rising $\sqrt{s}$, can be exploited for larger energies, cf. Fig. 2b. [$\sigma = 0.37$ fb for $M_H = 120$ GeV and $\sqrt{s} = 1$ TeV, polarized e^+e^- beams.]

Triple Higgs production is sensitive to the quadrilinear Higgs self-coupling. Due to the suppressed coupling and an additional particle in the final state, the cross section $\sigma(e^+e^- \to ZHHH)$ is only of $\mathcal{O}$(ab) and therefore not measurable at typical linear collider energies and luminosities [5].

2. In the Minimal Supersymmetric Extension of the Standard Model (MSSM) with five physical Higgs particles h, H, A and $H^\pm$ [8], a plethora of trilinear and quadrilinear Higgs self-couplings can be realized. The CP-invariant couplings

	double Higgs − strahlung				triple Higgs − production			
λ	Zhh	ZHh	ZHH	ZAA	Ahh	AHh	AHH	AAA
hhh	×				×			
Hhh	×	×			×	×		
HHh		×	×			×	×	
HHH			×				×	
hAA				×	×	×		×
HAA				×		×	×	×

TABLE 1: The trilinear couplings between neutral CP-even and CP-odd MSSM Higgs bosons, which can generically be probed in double Higgs-strahlung and associated triple Higgs-production, are marked by a cross. [The matrix for WW fusion is isomorphic to the matrix for Higgs-strahlung.]

among the neutral Higgs bosons, λ_{hhh}, λ_{Hhh}, λ_{HHh}, λ_{HHH}, λ_{hAA}, λ_{HAA}, are involved in a large number of processes [5,9]. The double and triple Higgs production processes and the trilinear couplings, that can be probed in the respective process, are listed in Table 1. The system is solvable for all λ's up to discrete ambiguities. However, in practice, not all processes are accessible experimentally so that one has to follow the reverse direction in this case: Comparing the theoretical predictions with the experimental results of the accessible channels, the trilinear Higgs self-couplings can be tested stringently.

The process $e^+e^- \to Zhh$ is sensitive to the trilinear coupling of the light CP-even Higgs boson h,

$$\lambda_{hhh} = 3\cos 2\alpha \sin(\beta + \alpha) + \mathcal{O}(G_F M_t^4/M_Z^2) \tag{4}$$

expressed in the mixing angles α and β, in a large range of the MSSM parameter space, as can be inferred from Fig. 3. It shows the 2σ sensitivity area in the $[M_A, \tan\beta]$ plane for a non-zero coupling at an integrated luminosity of 2 ab^{-1}. The cross section is required to exceed 0.01 fb. The sensitivity areas are significantly smaller for processes involving heavy Higgs bosons H and A in the final state. Details can be found in Ref. [5].

3. In summary. The measurement of the Higgs self-couplings is essential for the reconstruction of the characteristic self-energy potential. The large luminosities, which are available at future high-energy e^+e^- linear colliders, allow the measurement of the trilinear Higgs self-couplings via double Higgs-strahlung and WW double Higgs fusion.

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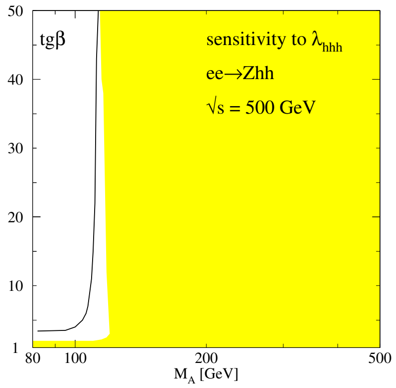

FIGURE 3. MSSM: Sensitivity to the coupling λ_{hhh} of the light CP-even neutral Higgs boson h in the process $e^+e^- \to Zhh$ for a collider energy of 500 GeV (no mixing).

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