Very Heavy MSSM Higgs-Boson Production at the Linear Collider

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Abstract

In the Minimal Supersymmetric Standard Model (MSSM) we present the corrections to the heavy neutral CP-even Higgs-boson production in the WW-fusion and Higgs-strahlung channel, $e^+e^- \rightarrow \bar{\nu}\nu H$, taking into account all $\mathcal{O}(\alpha)$ corrections arising from loops of fermions and sfermions. While the $H$ boson shows decoupling behavior at the tree-level, we find non-negligible loop corrections that can enhance the cross section considerably. At a center-of-mass energy of $\sqrt{s} = 1000$ GeV, masses of up to $M_H \lesssim 750$ GeV are accessible at the LC in favorable regions of the MSSM parameter space.
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In the Minimal Supersymmetric Standard Model (MSSM) we present the corrections to the heavy neutral $CP$-even Higgs-boson production in the $WW$-fusion and Higgs-strahlung channel, $e^+e^- \rightarrow \bar{\nu}\nu H$, taking into account all $O(\alpha)$ corrections arising from loops of fermions and sfermions. While the $H$ boson shows decoupling behavior at the tree-level, we find non-negligible loop corrections that can enhance the cross section considerably. At a center-of-mass energy of $\sqrt{s} = 1000$ GeV, masses of up to $M_H < \sim 750$ GeV are accessible at the LC in favorable regions of the MSSM parameter space.

1. INTRODUCTION

Finding the mechanism that controls electroweak symmetry breaking is one of the main tasks of the current and next generation of colliders. The solution may be the Higgs mechanism within the Standard Model (SM), or within its most appealing extension, the Minimal Supersymmetric Standard Model (MSSM) \cite{1}. Contrary to the SM, two Higgs doublets are required in the MSSM, resulting in five physical Higgs bosons \cite{2}. While the discovery of one light Higgs boson might well be compatible with the predictions both of the SM and the MSSM, the discovery of an additional heavy Higgs boson would be a clear signal for physics beyond the SM.

The Higgs sector of the MSSM can be expressed at lowest order in terms of $M_Z$, $M_A$ (the mass of the $CP$-odd Higgs boson), and $\tan \beta = v_2/v_1$, the ratio of the two vacuum expectation values. In the decoupling limit, i.e. for $M_A \gtrsim 200$ GeV, the heavy MSSM Higgs bosons are nearly degenerate in mass, $M_A \approx M_H \approx M_{H^\pm}$. The couplings of the heavy, neutral Higgs bosons to SM gauge bosons are proportional to $(V = Z,W^\pm)$

$$VV\{h,H\} \sim VA\{H,h\} \sim \{\sin, \cos\}(\beta-\alpha), \quad (1)$$

where $\alpha$ is the angle that diagonalizes the $CP$-even Higgs sector. In the decoupling limit one finds $\beta-\alpha \rightarrow \pi/2$, i.e. $\{\sin, \cos\}(\beta-\alpha) \rightarrow \{1,0\}$.

At the LC, the possible channels for heavy, neutral Higgs-boson production are the production via $Z$-boson exchange,

$$e^+e^- \rightarrow Z^* \rightarrow \{Z,A\}H \quad (2)$$

and the $WW$-fusion channel,

$$e^+e^- \rightarrow \bar{\nu}_e W^+ \nu_e W^- \rightarrow \bar{\nu}_e \nu_e H. \quad (3)$$

As a consequence of the coupling structure, in the decoupling limit the heavy Higgs boson can only be produced in $(H,A)$ pairs. This limits the LC reach to $M_H \lesssim \sqrt{s}/2$. Higher-order corrections to the $WW \rightarrow H$ channel from loops of fermions and sfermions, however, involve potentially large contributions from the top and bottom Yukawa couplings and can thus significantly affect the decoupling behavior. The same corrections may also contribute to the Higgs-strahlung channel, $e^+e^- \rightarrow Z^* \rightarrow ZH$. However, while this channel is suppressed with $1/s$, the $WW$-fusion channels rises with $\log s$.

Electroweak loop effects on processes within the MSSM where a single Higgs boson is produced have recently drawn considerable interest in the literature \cite{3–8}, see Ref. \cite{3} for a detailed
overview, also including the SM case. It has been found that the processes $e^+e^- \to \nu_e\bar{\nu}_e A$ [5], $e^+e^- \to Z^+ \to H(Z,A)$ [6], and $e^+e^- \to W^+H^-$ [7,8] only possess a small potential to produce the heavy Higgs bosons with $M_H \approx M_A \approx M_{H\pm} > \sqrt{s}/2$. Recently, the results for the one-loop corrections of fermions and sfermions to the process $e^+e^- \to \nu\bar{\nu}H$ have been presented [3]. This process can be mediated via the WW-fusion and the Higgs-strahlung mechanism, see Fig. 1. In the latter case the Z boson is connected to a neutrino pair, $e^+e^- \to ZH \to \nu\bar{\nu}H$, with $l = e, \mu, \tau$ (where the two latter neutrinos result in an indistinguishable final state in the detector). While the well-known universal Higgs-boson propagator corrections turned out not to significantly modify the decoupling behavior of the heavy $CP$-even Higgs boson, an analysis of the process-specific contributions to the $WWH$ vertex has been missing so far. We summarize in this paper the LC reach for the heavy $CP$-even Higgs boson, including also the effects of beam polarization in our analysis.

![Figure 1](image1.png)

Figure 1. The tree-level diagrams for the process $e^+e^- \to \nu\bar{\nu}H$, consisting of the WW-fusion contribution (left) and the Higgs-strahlung contribution (right).

2. THE CALCULATION

Below we describe the loop corrections that enter the process $e^+e^- \to \nu\bar{\nu}H$ at the one-loop level. The contributions involve corrections to the $WWH$ vertex and the corresponding counter-term diagram, see Fig. 2, corrections to the $W$-boson propagators and the corresponding counter terms, see Fig. 3, and the counter-term contributions to the $\nu\bar{\nu}W$ vertex, see Fig. 4. Furthermore, Higgs propagator corrections enter via the wave-function normalization of the external Higgs boson, see below. There are also $W$-boson propagator corrections inducing a transition from the $W^\pm$ to either $G^\pm$ or $H^\pm$. These corrections affect only the longitudinal part of the $W$ boson and are thus $\propto m_e/M_W$ and have been neglected.

![Figure 2](image2.png)

Figure 2. Corrections to the $WWH$ vertex and the corresponding counter-term diagram. The label $f^\pm$ denotes all (s)fermions, except in the presence of a $f^\pm$, in which case the former denotes only the isospin-up and the latter the isospin-down members of the (s)fermion doublets.

![Figure 3](image3.png)

Figure 3. Corrections to the $W$-boson propagator and the corresponding counter-term diagrams. The labeling is as in Fig. 2.
Figure 4. Counter-term contributions entering via the $e \nu_e W$ vertex.

While the renormalization in the counter terms depicted in Figs. 3 and 4 is as in the SM, the $WWH$ vertex is renormalized as follows,

$$
\Gamma^{(0),CT}_{WWH} = \Gamma^{(0)}_H + \delta Z_e + \frac{1}{2} \frac{\delta M^2_W}{M^2_W} + \delta Z_W + \frac{\delta s_W}{s_W} \sin \beta \cos \beta \sin(\beta - \alpha) \delta \tan \beta + \frac{1}{2} \delta Z_H + \frac{1}{2} \Gamma^{(0)}_H \delta Z_{hh} ,
$$

with $\Gamma^{(0)}_{h,H} = i e M/s_w \{ \sin, \cos \}(\beta - \alpha)$. The counter-terms are given by

$$
\delta Z_{(H,h)} = - \left[ \Re \Sigma_{(H,h,h)}^{(0)}(m^2_{(H,h)}) \right]^{\text{div}},
\delta Z_{hh} = \delta Z_{Hh} = \frac{\sin \alpha \cos \alpha}{\cos 2\alpha} (\delta Z_h - \delta Z_H),
\delta \tan \beta = \frac{\delta \tan \beta \MSbar}{\MSbar} = - \frac{1}{2 \cos 2\alpha} \times \left[ \Re \Sigma_{hh}^{(0)}(m^2_h) - \Re \Sigma_{Hh}^{(0)}(m^2_h) \right]^{\text{div}},
\delta M^2_V = \Re \Sigma^{\tau}_{(V)}(m^2_h), (V = Z, W^\pm),
\delta s_W/s_W = 1 + 1/2 \frac{s^2_W}{s^2_W} \left( \frac{\delta M^2_Z}{M^2_Z} - \frac{\delta M^2_W}{M^2_W} \right),
\delta \tilde{Z}_e = \delta Z_e - \frac{1}{2} \Delta r, = 1 \left\{ 1 + \frac{1}{2} \frac{c^2_W}{s^2_W} \left( \frac{\delta M^2_Z}{M^2_Z} - \frac{\delta M^2_W}{M^2_W} \right) \right\} .
$$

The finite wave-function renormalizations are given in Ref. [3].

The numerical analysis is performed in the $\sigma_H^{\text{enh}}$ ("enhanced cross section") scenario, which is defined by

$$
m_t = 174.3 \text{ GeV}, \ M_{\text{SUSY}} = 350 \text{ GeV}, \ X_t = 2 M_{\text{SUSY}}, \ A_b = A_t, m_\chi = 800 \text{ GeV} \mu = 1000 \text{ GeV}, M_2 = 200 \text{ GeV} ,
$$

which, up to changes in the values for $M_{\text{SUSY}}$ and $\mu$, is the well-known $m_{\tilde{t}}^{max}$ scenario [15].

In Fig. 5 we show the result for the $\sigma_H$ evaluation in the $\sigma_H^{\text{enh}}$ scenario for $\sqrt{s} = 1 \text{ TeV}$. Assuming an integrated luminosity of $O(1 - 2 ab^{-1})$, a cross section of $\sigma_H = 0.01 \text{ fb}$ constitutes a lower limit for which the observation of the heavy Higgs boson could be possible. We first focus on the left column, where the results are given without polarization of the $e^+$ and $e^-$ beams. The upper row shows the tree-level cross section (including the finite wave-function renormalization, Eq. (5)). The middle row shows the $\alpha_{\text{eff}}$ approximation for $\sigma_H$ (which has mostly been used for phenomenological analyses so far), where the outgoing Higgs boson is not on-shell. The lower row presents the result including the one-loop corrections. Two conclusions can be drawn: neglecting the wave function renormalization leads to considerable differences to the case in which the outgoing Higgs boson is on-shell. Instead

$$
\Gamma^{WF} = \Gamma^{(0)}_H \left[ \sqrt{Z_{hh} - 1} + \frac{1}{2} \Gamma^{(0)}_h \sqrt{Z_{hH} Z_{hh}} \right] .
$$

3. NUMERICAL ANALYSIS
of $M_H \lesssim \sqrt{s}/2 = 500$ GeV, now the observation up to $M_H \approx 600$ GeV seems to be possible.

The right column of Fig. 5 shows the yield roughly an enhancement by a factor of 3.

Figure 5. The cross section for $e^+e^- \rightarrow \nu\bar{\nu}H$ is shown in the $\sigma_H^{\text{enh}}$ scenario in the $M_A - \tan\beta$-plane for $\sqrt{s} = 1$ TeV. The different shadings correspond to: white: $\sigma \leq 0.01$ fb, light shaded: $0.01 \text{ fb} \leq \sigma \leq 0.02$ fb, dark shaded: $0.02 \text{ fb} \leq \sigma \leq 0.05$ fb, black: $\sigma \geq 0.05$ fb.

The prospects for observing a heavy Higgs boson beyond the kinematical limit of $M_H \lesssim \sqrt{s}/2$ become even more favorable if polarized beams are used. The cross section becomes enhanced for left-handedly polarized $e^-$ and right-handedly polarized $e^+$. While a 100% polarization results in a cross section enhancement of roughly a factor of 4, more realistic values of 80% polarization for $e^-$ and 60% polarization for $e^+$ [16] would yield roughly an enhancement by a factor of 3.

The right column of Fig. 5 shows the $\sigma_H^{\text{enh}}$ scenario with 100% polarization of both beams. The area in the $M_A - \tan\beta$ plane in which observation of the $H$ boson might become possible is strongly increased in this case. Thus, in the case with beam polarization, taking into account the one-loop corrections, $M_H \lesssim 750$ GeV could be observable at $\sqrt{s} = 1$ TeV.

The question whether this enlarged reach in $M_H$ is due to a special choice of MSSM parameters is analyzed in Figs. 6, 7. We show the results for $\sigma_H$ in the $\mu - M_{\text{SUSY}}$-plane for $M_A$ fixed to $M_A = 600, 700$ GeV (Fig. 6, 7) and $\tan\beta = 4$ with the other parameters chosen as in the $m_{h}^{\text{max}}$ scenario. The $\alpha_{\text{eff}}$ approximation is compared with the one-loop result (including also the finite wave-function renormalization). In the case of unpolarized beams (left columns) the $\alpha_{\text{eff}}$ result shows no region of observability in the $\mu - M_{\text{SUSY}}$-plane for $M_A = 600, 700$ GeV. However, taking the loop corrections into account, $\sigma_H$ becomes large enough to observe $e^+e^- \rightarrow \nu\bar{\nu}H$ in a sizable fraction of the $\mu - M_{\text{SUSY}}$-plane (with $M_{\text{SUSY}} \lesssim 500$ GeV). The situation becomes even more favorable if besides the loop correction also polarization is taken into account. For $M_A = 600$ GeV (Fig. 6) the whole $\mu - M_{\text{SUSY}}$-plane possesses an observable $\sigma_H$, even with $\sigma_H > 0.05$ fb for $M_{\text{SUSY}} \lesssim 500$ GeV.

For $M_A = 700$ GeV, in the case of polarized beams, loop corrections enhance $\sigma_H$ to an observable level for $M_{\text{SUSY}} \lesssim 500$ GeV for nearly all $\mu$ values. Thus, an enhanced cross section, although clearly dependent on the chosen scenario, can be found in large parts of the MSSM parameter space.

4. CONCLUSIONS

We have investigated the production of the heavy $CP$-even MSSM Higgs-boson at a future LC in the process $e^+e^- \rightarrow \nu\bar{\nu}H$, which is dominated by the WW-fusion mechanism at higher energies. We have evaluated all one-loop contributions from fermions and sfermions, and we have implemented the numerically large process-independent Higgs-boson propagator corrections so that the correct on-shell properties of the outgoing Higgs boson are ensured. We find that in favorable regions of the MSSM parameter space...
the genuine loop corrections can drastically enlarge the parameter space for which detection of \( H \) becomes possible. In such a scenario, assuming polarized beams, at \( \sqrt{s} = 1 \) TeV the detection of \( H \) could be possible up to \( M_H \lesssim 750 \) GeV.

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