DCPT/02/124
IPPP/02/62
LMU 13/02
MPI-PhT/2002-72
LC-TH-2002-019
hep-ph/0211384

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 $\mathcal{CP}$-even Higgs-boson production in the WW-fusion and Higgs-strahlung channel, $e^+e^- \to \bar{\nu}\nu\, H$, 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.

*talk given by S. Heinemeyer at the "RADCOR 2002 – Loops & Legs 2002", Kloster Banz, Germany, September 2002

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In the Minimal Supersymmetric Standard Model (MSSM) we present the corrections to the heavy neutral $\mathcal{CP}$-even Higgs-boson production in the WW-fusion and Higgs-strahlung channel, $e^+e^- \to \bar\nu\nu\, H$, 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.

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) [1]. Contrary to the SM, two Higgs doublets are required in the MSSM, resulting in five physical Higgs bosons [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 $\mathcal{CP}$-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 α is the angle that diagonalizes the $\mathcal{CP}$-even Higgs sector. In the decoupling limit one finds $\beta - \alpha \to \pi/2$, i.e. $\{\sin,\cos\}(\beta-\alpha) \to \{1,0\}$.

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

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

and the WW-fusion channel,

$$e^+e^- \to \bar\nu_e W^+\, \nu_e W^- \to \bar\nu_e \nu_e H\,. \quad (3)$$

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 $WW \to H$ 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, $e^+e^- \to Z^* \to ZH$. 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 [3–8], see Ref. [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 $e^+e^- \to \bar{\nu}\nu H$ 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, $e^+e^- \to ZH \to \bar{\nu}_l\nu_l H$, 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 $\mathcal{CP}$-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 $\mathcal{CP}$-even Higgs boson, including also the effects of beam polarization in our analysis.

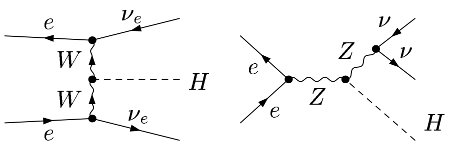

Figure 1. The tree-level diagrams for the process $e^+e^- \to \bar{\nu}\nu H$, consisting of the WW-fusion contribution (left) and the Higgs-strahlung contribution (right).

2. THE CALCULATION

Below we describe the loop corrections that enter the process $e^+e^- \to \bar{\nu}\nu H$ at the one-loop level[1]. 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 $e\nu_e W$ 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.

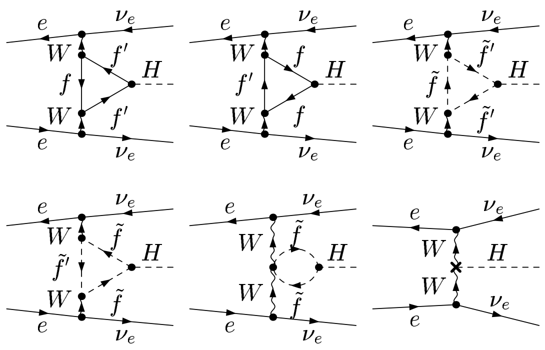

Figure 2. Corrections to the WWH vertex and the corresponding counter-term diagram. The label $\overset{(\sim)}{f}$ denotes all (s)fermions, except in the presence of a $\overset{(\sim)}{f}{}'$, in which case the former denotes only the isospin-up and the latter the isospin-down members of the (s)fermion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

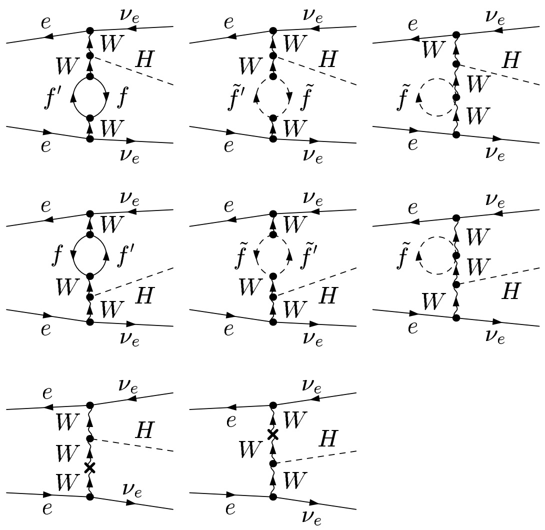

Figure 3. Corrections to the W-boson propagator and the corresponding counter-term diagrams. The labeling is as in Fig. 2.

[1] We focus on the description of the loop corrections to the WW-fusion channel. However, the same corrections are taken into account for the Higgs-strahlung process.

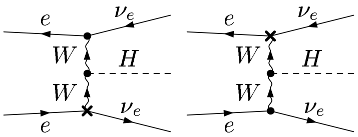

Figure 4. Counter-term contributions entering via the $e\,\nu_e\,W$ vertex.

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,

$$\Gamma^{(0),\mathrm{CT}}_{WWH} = \Gamma^{(0)}_H \Bigg[1 + \delta\tilde{Z}_e + \frac{1}{2}\frac{\delta M_W^2}{M_W^2} + \delta Z_W + \frac{\delta s_W}{s_W} - \sin\beta\,\cos\beta\,\frac{\sin(\beta-\alpha)}{\cos(\beta-\alpha)}\delta\tan\beta + \frac{1}{2}\delta Z_H + \frac{1}{2}\frac{\Gamma^{(0)}_h}{\Gamma^{(0)}_H}\delta Z_{hH} \Bigg],$$

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

$$\begin{aligned}
\delta Z_{\{H,h\}} &= -\left[\mathrm{Re}\,\Sigma'_{\{HH,hh\}}(m^2_{\{H,h\}})\right]^{\mathrm{div}}, \\
\delta Z_{hH} &= \delta Z_{Hh} = \frac{\sin\alpha\,\cos\alpha}{\cos 2\alpha}(\delta Z_h - \delta Z_H), \\
\delta\tan\beta &= \delta\tan\beta^{\overline{\mathrm{MS}}} = -\frac{1}{2\cos 2\alpha}\times \\
&\quad \left[\mathrm{Re}\,\Sigma'_{hh}(m_h^2) - \mathrm{Re}\,\Sigma'_{HH}(m_H^2)\right]^{\mathrm{div}}, \\
\delta M_V^2 &= \mathrm{Re}\,\Sigma^T_V(M_V^2)\,, (V = Z, W^\pm), \\
\frac{\delta s_W}{s_W} &= \frac{1}{2}\frac{c_W^2}{s_W^2}\left(\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\right), \\
\delta\tilde{Z}_e &= \delta Z_e - \frac{1}{2}\Delta r, \\
&= \frac{1}{2}\Bigg\{\frac{c_W^2}{s_W^2}\left(\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\right) \\
&\quad - \left(\Sigma^T_W(0) - \delta M_W^2\right)/M_W^2\Bigg\}. \qquad (4)
\end{aligned}$$

$\delta\tilde{Z}_e$ incorporates the charge renormalization and Δr (which is due to the parametrization of the Born cross section with G_μ), see [3]. The gauge-boson field-renormalization constants, $\delta Z_{\{W,Z,\gamma Z\}}$, drop out in the result for the complete S-matrix element.

In order to ensure the correct on-shell properties of the outgoing Higgs boson, which are necessary for the correct normalization of the S-matrix element, furthermore a finite wave-function normalization has to be incorporated [9]:

$$\Gamma^{\mathrm{WF}} = \Gamma^{(0)}_H\left[\sqrt{\hat{Z}_H} - 1 + \frac{1}{2}\frac{\Gamma^{(0)}_h}{\Gamma^{(0)}_H}\sqrt{\hat{Z}_H}\;\hat{Z}_{hH}\right]. \quad (5)$$

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

The evaluation of the Feynman diagrams and the further calculations have been done using the packages *FeynArts*, *FormCalc*, and *LoopTools* [10–12]. The Higgs-boson sector evaluations have been performed with *FeynHiggs*2.0 [13, 14]. The resulting Fortran code will be made available at `www.hep-processes.de`.

3. NUMERICAL ANALYSIS

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

$$\begin{aligned}
m_t &= 174.3\ \mathrm{GeV},\ M_{\mathrm{SUSY}} = 350\ \mathrm{GeV}, \\
X_t &= 2M_{\mathrm{SUSY}},\ A_b = A_t, m_{\tilde{g}} = 800\ \mathrm{GeV} \\
\mu &= 1000\ \mathrm{GeV}, M_2 = 200\ \mathrm{GeV}\ , \qquad (6)
\end{aligned}$$

which, up to changes in the values for M_{SUSY} and μ, is the well-known $m_h^{\max}$ scenario [15].

In Fig. 5 we show the result for the σ_H evaluation in the σ_H^{enh} scenario for $\sqrt{s} = 1$ TeV. Assuming an integrated luminosity of $\mathcal{O}(1 - 2\,\mathrm{ab}^{-1})$, a cross section of $\sigma_H = 0.01$ 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 α_{eff} approximation for σ_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[2]. Two conclusions can be drawn: neglecting the wave function renormalization leads

[2]The neglected higher-order corrections (e.g. from bosonic loops and initial state radiation) can in priciple be sizable, see e.g. Fig. 3 in Ref. [16]. However, they constitute corrections to the Born matrix element, i.e. they contain the WWH coupling and thus show the decoupling for

to considerable differences to the case in which the outgoing Higgs boson is on-shell. Secondly, the loop corrections, Figs. 2 - 4, lead to a strong enhancement of the H production cross section. Instead of $M_H \lesssim \sqrt{s}/2 = 500$ GeV, now the observation up to $M_H \approx 600$ GeV seems to be possible.

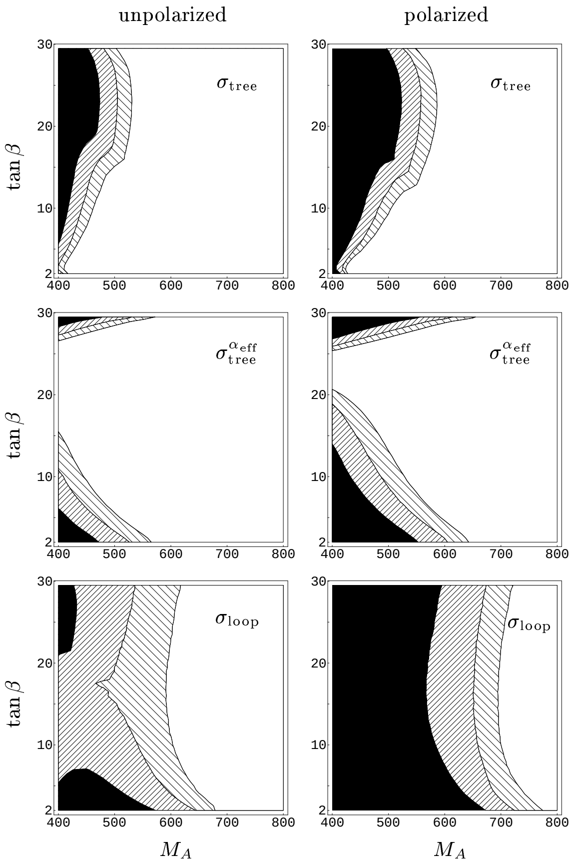

Figure 5. The cross section for $e^+e^- \to \bar\nu\nu\, H$ is shown in the $\sigma_H^{\rm enh}$ scenario in the $M_A - \tan\beta$-plane for $\sqrt{s} = 1$ TeV. The different shadings correspond to: white: $\sigma \leq 0.01$ fb, light shaded: 0.01 fb $\leq \sigma \leq 0.02$ fb, dark shaded: 0.02 fb $\leq \sigma \leq 0.05$ 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^+ [17] would yield roughly an enhancement by a factor of 3. The right column of Fig. 5 shows the $\sigma_H^{\rm enh}$ 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 σ_H in the $\mu - M_{\rm SUSY}$-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 $m_h^{\rm max}$ scenario. The $\alpha_{\rm eff}$ approximation is compared with the one-loop result (including also the finite wave-function renormalization). In the case of unpolarized beams (left columns) the $\alpha_{\rm eff}$ result shows no region of observability in the $\mu - M_{\rm SUSY}$-plane for $M_A = 600, 700$ GeV. However, taking the loop corrections into account, σ_H becomes large enough to observe $e^+e^- \to \bar\nu\nu\, H$ in a sizable fraction of the $\mu - M_{\rm SUSY}$-plane (with $M_{\rm SUSY} \lesssim 500$ 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 $\mu - M_{\rm SUSY}$-plane possesses an observable σ_H, even with $\sigma_H > 0.05$ fb for $M_{\rm SUSY} \lesssim 500$ GeV. For $M_A = 700$ GeV, in the case of polarized beams, loop corrections enhance σ_H to an observable level for $M_{\rm SUSY} \lesssim 500$ GeV for nearly all μ 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 $\mathcal{CP}$-even MSSM Higgs-boson at a future LC in the process $e^+e^- \to \bar\nu\nu\, H$, which is dom-

the M_A values considered here. Therefore the neglected corrections would not substantially change the contours shown in this section.

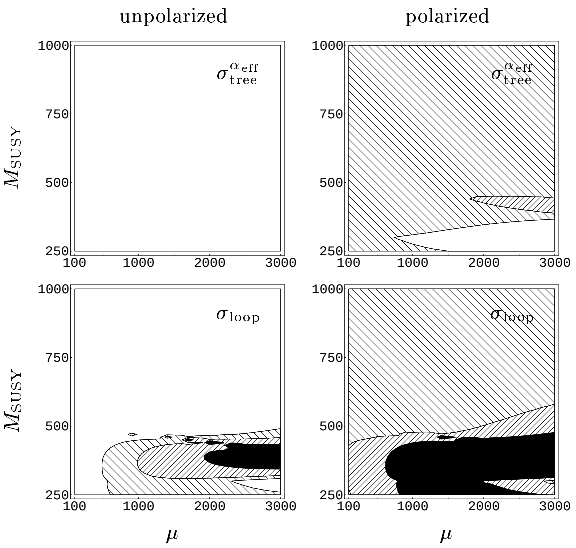

Figure 6. The cross section for $e^+e^- \to \bar{\nu}\nu\, H$ is shown in the $m_h^{\rm max}$ scenario for $M_A = 600$ GeV and $\tan\beta = 4$ in the $\mu - M_{\rm SUSY}$ plane for $\sqrt{s} =$ 1 TeV. The color coding is as in Fig. 5.

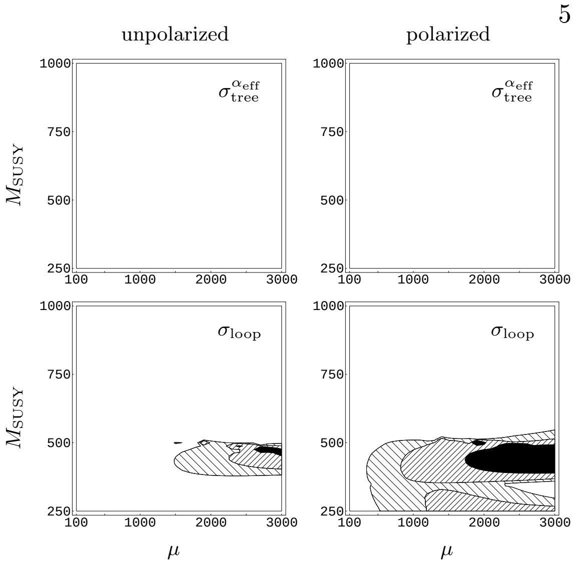

Figure 7. The cross section for $e^+e^- \to \bar{\nu}\nu\, H$ is shown in the $m_h^{\rm max}$ scenario for $M_A = 700$ GeV and $\tan\beta = 4$ in the $\mu - M_{\rm SUSY}$ plane for $\sqrt{s} =$ 1 TeV. The color coding is as in Fig. 5.

inated 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.

Acknowledgements: S.H. thanks the organizers of "RADCOR 2002 – Loops & Legs 2002" for the invitation and the inspiring atmosphere.

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