Perspectives of Neutral Supersymmetric Higgs Boson Searches
at a 500 GeV e^+e^- Linear Collider

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Abstract

Perspectives of searches for neutral Higgs bosons at a future e^+e^- collider running at \( \sqrt{s} = 500 \) GeV (EE500) are analyzed in the Minimal Supersymmetric Standard Model (MSSM). Full 1-loop diagrammatic calculations of radiative corrections are applied to study prospects for the discovery and identification of Higgs signals as a function of various SUSY parameters. In large parameter regions more than one Higgs boson can be found. However, if only one scalar is discovered, comparison of production rates and decay branching ratios shows that it may be difficult to distinguish the lightest SUSY scalar from the Higgs boson of the Minimal Standard Model (MSM).

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Perspectives of searches for neutral Higgs bosons at a future e⁺e⁻ collider running at √s = 500 GeV (EE500) are analyzed in the Minimal Supersymmetric Standard Model (MSSM). Full 1-loop diagrammatic calculations of radiative corrections are applied to study prospects for the discovery and identification of Higgs signals as a function of various SUSY parameters. In large parameter regions more than one Higgs boson can be found. However, if only one scalar is discovered, comparison of production rates and decay branching ratios shows that it may be difficult to distinguish the lightest SUSY scalar from the Higgs boson of the Minimal Standard Model (MSM).

1. Introduction
The search for Higgs particles is one of the most challenging questions of experimental particle physics. Their discovery would confirm the mechanism used to generate masses in gauge theories and, more generally, the experimental evidence for Higgs boson(s) would be crucial to understanding the mechanism of the SU(2) x U(1) symmetry breaking. Therefore, still more efforts will be devoted to the search for Higgs scalars in the future. Particular attention is given to the search for Higgs bosons with properties predicted by the MSSM. The Higgs sector of the MSSM contains five physical Higgs bosons: one neutral CP-odd scalar, A⁰, two neutral CP-even scalars, H⁰ and h⁰, and two charged scalars, H±. The study of the MSSM is well motivated:

1) The phenomenology of the MSSM Higgs sector is well determined and strongly constrained compared to other extensions of the MSM. At the tree level, all scalar masses and couplings are effectively parametrized in terms of two free parameters. Also, the effect of 1-loop radiative corrections is well understood. It introduces an additional dependence on other parameters, of which the top quark mass is most important.

2) The discovery of the lightest neutral scalar may be the first evidence of supersymmetry in Nature. Owing to the structure of the MSSM, at least one light neutral
Higgs boson is expected: at the tree-level $m_h \leq m_Z$. Radiative corrections can increase $m_h$ by a few tens of GeV (depending mainly on the unknown top and stop masses) shifting its upper bound to 120–130 GeV (for $m_t < 180$ GeV, $m_{	ilde{g}} \approx \mathcal{O}$(TeV) and reasonable choices of other SUSY parameters) [1-8].

(3) Supersymmetric theories, of which MSSM is the simplest realistic example, solve the hierarchy problem and, moreover, can lead to unification of gauge coupling constants at the grand unification scale of about $10^{16}$ GeV [9].

An important issue considered in the paper is the experimental potential of an EE500 collider. Using typical detector sensitivities, the parameter regions are studied where a Higgs boson signature can be detected for a general choice of MSSM parameters. A related question is how the MSSM Higgs bosons can be distinguished from the Higgs boson of the MSM.

It has recently been found and studied [1-8] that a realistic analyses of the MSSM phenomenology has to include 1-loop radiative corrections, which are strongly dependent on the top quark mass. For most choices of SUSY parameters radiative corrections become large already for top masses around the current experimental mass limit of about 113 GeV [10]. Several approaches have been developed to compute corrections to the tree-level approximation:

- the Effective Potential Approach (EPA) [3],
- the Renormalization Group Approach (RGE) [4, 5], and
- the full 1-loop diagrammatic calculation [6, 7].

In this paper the last method is used. This approach is most accurate and can provide a "reference frame" for the other calculations. The diagrammatic 1-loop calculation includes effects which have as yet been neglected (or cannot be included) in the other approximations, such as gauge sector contributions, momentum-dependent effects in 2- and 3-point Green’s functions, and genuine 1-loop corrections to 3-point functions involving gauge and Higgs bosons on external lines. Finally, the full dependence of the physical observables on all soft breaking parameters of the MSSM can be explored using this approach.

2. Method of Calculations

Details of the calculation of the neutral Higgs boson production cross sections in $e^+e^-$ collisions for the reactions $e^+e^- \rightarrow Z^0h^0(H^0)$, $e^+e^- \rightarrow A^0h^0(H^0)$ and of their decay branching ratios have been discussed in Ref. [6]. We recall only main points here.

We use the on-shell renormalization scheme. It introduces ten renormalization constants for the Higgs and gauge boson sectors: $Z_H$, $Z_W$, $Z_2$, $Z_H$, ($i=1,2$), $\delta m_{\tilde{t}}^2$ ($i=1,2,3$) and $\delta v_i$ ($i=1,2$) (the latter are needed in the chosen gauge). We calculate all 2-point Green’s functions in ’t Hooft-Feynman gauge (with $\xi = 1$) and fix the renormalization constants imposing the following conditions on the renormalized self-energies (see Ref. [6] for more details):

$$\hat{\Pi}'_i(0) = \hat{\Pi}^T_{Z^0}(0) = \hat{\Pi}^T_{Z}(p^2 = m_{Z}^2) = \hat{\Pi}^T_W(p^2 = m_{W}^2) = 0,$$
\[ \hat{\nu}_1 = \hat{\nu}_2 = 0 \quad \text{ (tadpoles)}, \]
\[ \hat{\Sigma}_{AA}(p^2 = m_A^2) = \hat{\Sigma}_{AZ}(p^2 = m_A^2) = 0, \]
\[ \delta v_1/v_1 = \delta v_2/v_2, \quad \delta v_i = \frac{\xi}{64\pi^2} (3g_2^2 + g_1^2) v_i \eta, \quad \eta = \frac{2}{d-4} + \gamma - \ln 4\pi. \]  

(1)

In addition, we have calculated the following 3-point Green's functions appearing in expressions for cross sections and branching ratios: \( h(H)ZZ(\gamma), h(H)AZ(\gamma), h(H)AA, Hhh. \) The physical masses are determined as \( m_{ph}^2 = p_0^2, \) where \( p_0^2 \) solves the equation:
\[ \left[ p_0^2 - m_{hH}^2 - \hat{\Sigma}_{hh}(p_0^2) \right] \left[ p_0^2 - m_{hH}^2 - \hat{\Sigma}_{HH}(p_0^2) \right] - \hat{\Sigma}_{hh}(p_0^2) - \hat{\Sigma}_{HH}(p_0^2) = 0, \]

(2)

\( m_{hH}^2 \) being the tree level mass parameters. The usual perturbative determination of physical masses \( m_{(1)}^2 = m_{(0)}^2 + \hat{\Sigma}(m_{(0)}^2) \) is inappropriate because of large radiative corrections [6, 7].

In the calculation of the physical amplitudes, mixing of scalars has to be taken into account. In our approach we use the tree-level angle \( \alpha \) in all expressions. There is no natural way to define "effective" \( \alpha \) for 1-loop Higgs boson couplings. Instead, for each external Higgs boson line two contributions have to be included, as schematically shown in Fig. 1.

Up to some non-leading corrections, the net effect of summing these two terms is equivalent to changing the tree-level angle \( \alpha \) to the effective 1-loop \( \alpha \) used in the EPA. The full amplitude is given by [6]:
\[ \text{Amp} = Z_h^{1/2} \hat{\Gamma}_{hh}^{(n)} + Z_h^{1/2} \frac{\hat{\Sigma}_{hh}(m_h^2)}{m_{hH}^2 - m_{hH}^2 - \hat{\Sigma}_{HH}(m_h^2)} \hat{\Gamma}_{hh}^{(n)}, \]

(3)

where the dots stand for particles coupled to the Higgs bosons.

3. Dependence of the Allowed Mass Ranges on the Supersymmetric Parameters

After inclusion of radiative corrections, the allowed mass ranges for the CP-even scalars depend on \( m_t \) and SUSY parameters. In Fig. 2 the upper limits on \( m_h \) are shown as a function of \( m_A \) for several choices of parameters. Thin and thick lines illustrate those limits for \( m_t = 130 \text{ GeV} \) and \( m_t = 180 \text{ GeV}, \) respectively. Cross-marked lines are plotted assuming all SUSY particles to be heavy (\( \sim 1 \text{ TeV} \)) and no mixing in the sfermion sector (\( A = 0 \)). Dotted lines show the case of light squarks (\( \sim 200 \text{ GeV} \)). Compared to the effect of squarks, the contribution of sleptons is negligible. The top quark and squark masses have the biggest impact on the theoretical upper Higgs mass limit. From the experimental
point of view, the dependence on gaugino masses and on mixing in the squark sector can also be very important: for instance changing $m_{\tilde{g}}$ from 1 TeV (cross-marked) to 200 GeV (dashed) shifts $m_h$ by $O(5 \text{ GeV})$. The shift can be positive or negative, depending on the specified parameter set. Solid lines show the absolute upper bound for $m_h$ obtained by the independent variation of all parameters in the ranges defined in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$m_{\tilde{q}}$ (GeV)</th>
<th>$m_{\tilde{u}}$ (GeV)</th>
<th>$m_{\tilde{g}}$ (GeV)</th>
<th>$\mu$ (GeV)</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>100—1000</td>
<td>100—300</td>
<td>200—1000</td>
<td>—500—500</td>
<td>—1—1</td>
</tr>
</tbody>
</table>

Table 1: Ranges of SUSY parameters used for independent variation in the study of the Higgs boson discovery regions.

The circle-marked lines show the upper bound for $m_h$ for the same set of heavy SUSY parameters, when obtained in the EPA approximation. It is higher by about 5 – 7 GeV. It should be noted that this difference can be particularly important in the study of the accessible mass region at the second phase of the LEP programme at CERN, LEP200. At LEP200, Higgs bosons with masses in the neighborhood of 100 GeV will be detectable.

![Figure 2: Miximal mass of the lighter CP-even MSSM Higgs boson for various values of SUSY parameters.](image)

4. Discovery Potential in the MSSM

We have studied regions of the MSSM parameter space where Higgs bosons can be discovered. A discovery of two Higgs bosons would be unambiguous evidence that the Higgs sector is extended compared to the MSM. Various production mechanisms involving neutral and charged Higgs bosons are expected. While in Ref. [15] the charged Higgs sector
is addressed, here possible reactions with neutral CP-even and CP-odd Higgs bosons are investigated. Two Higgs boson bremsstrahlung and two Higgs pair-production production mechanisms are possible:\[ e^+e^- \rightarrow h^0Z^0, \ H^0Z^0, \ h^0A^0, \ H^0A^0. \]

Depending on the Higgs boson masses, the top quark mass and several other SUSY parameters which are relevant for the effective Higgs boson couplings, the expected cross sections vary largely. This determines which of the above four processes can be observed. In order to study the effect of the variation of the MSSM parameters, a scanning over the mass parameter space \((m_h,m_A)\) and \((m_H,m_A)\) has been performed. With a step size of 5 GeV each mass point has been analyzed separately up to Higgs boson masses of 300 GeV. For each fixed mass combination, the production cross sections of the four reactions are calculated. If for a given mass combination the cross section is larger than the assumed constant sensitivity, this mass point is called a sensitivity point. Regions of sensitivity are determined by linear interpolation between points with sensitivity. For Higgs boson bremsstrahlung and Higgs boson pair-production similar detection sensitivities can be expected. The precise sensitivity depends on the achievable signal efficiency and the reduction of the background. For simplicity, only the two most important experimental parameters have been used:

\[ \text{a)} \quad \text{An estimated sensitivity of 0.01 pb needed for } e^+e^- \rightarrow h^0Z^0 \ (H^0Z^0) \text{ signal, and} \]

\[ \text{b)} \quad \text{a sensitivity of 0.01 pb needed for } e^+e^- \rightarrow h^0A^0 \ (H^0A^0) \text{ signal.} \]

This corresponds to a sensitivity for a signal if more than 300 events are produced, assuming a total luminosity of an EE500 collider of \(\mathcal{L} = 30 \text{ fb}^{-1}\).

The most general version of the MSSM Lagrangian contains a large number of free parameters. In many studies, this number is reduced by imposing additional theoretical assumptions. For example, MSSM parameters are obtained via renormalization group evolution from a broken supergravity models at the Planck scale [4, 5]. Experimental searches for the MSSM particles should not fully rely on such additional constraints, at least when the variation of additional parameters has significant influence on the Higgs boson production and decay rates. Fortunately, most of the SUSY parameters have very small impact on numerical results. We therefore investigate the complete subset of MSSM parameters to which the cross sections are most sensitive and we vary them independently. In order to decrease the number of degrees of freedom in the model, we used some relations and simplifications for less important parameters describing the phenomenology of the Higgs sector. The important parameters taken into account are:

- \((m_h,m_A)\) or \((m_H,m_A)\) – the investigated Higgs bosons mass combination.
- \(m_t\) – the top quark mass.
- \(m_{sq}\) and \(m_{sl}\) – the squark and slepton mass parameters. The parameter \(m_{sq}\) we take common for all three generations of up- and down-, left- and right-type squarks; similarly for \(m_{sl}\).

\[ ^3\text{We do not discuss others possibilities of Higgs boson production, for example: via } W^+W^- \text{ fusion [12],}
\]

\[ \text{via bremsstrahlung off } b\text{-quark } e^+e^- \rightarrow b\bar{b} \rightarrow b\bar{b}h^0 \text{ (significant for large values of } \tan \beta \text{ [13]), or charged Higgs boson production in top decays } e^+e^- \rightarrow t\bar{t} \rightarrow H^+b\bar{t} \text{ [17].} \]
Higgs boson mass is possible. In order to decrease the number of free parameters, we related SU(2) and U(1) gaugino masses by the GUT relation $m_{SU(2)} = \frac{5}{3} \tan^2 \theta_W m_{U(1)}$. Adding this constraint has small impact on numerical results.

- **$m_g$** – the gaugino mass.

- **$\mu$** – the parameter mixing Higgs doublets in the superpotential.

- **$A$** – the mixing parameter in the sfermion sector. We take it common for all sfermions. The mixing is proportional to $Am_{eq}$ for squarks and $Am_{sl}$ for sleptons.

In each plot a maximum of four regions are distinguished in the $(m_h, m_A)$ and $(m_H, m_A)$ plane:

(A) The sensitivity region, where by direct searches a Higgs signal cannot escape detection, independent of the variation of the top quark mass ($113 \leq m_t \leq 180$ GeV) and the SUSY parameters as listed in Table 1.

(B) The non-sensitive region, where the perspectives of direct searches depend on the top quark mass. For fixed $m_h$ and $m_{A}$, searches can have sensitivity or not depending on the specific choice of $m_t$. Supersymmetric particles are assumed to be heavy, with masses fixed and given by the upper values of parameters listed in Table 1.

(C) The additional non-sensitive region, arising when $m_t$ and SUSY parameters are varied simultaneously and independently of each other. SUSY parameters are varied over the ranges listed in Table 1.

(D) The theoretically disallowed region, where $(m_h, m_A)$ or $(m_H, m_A)$ combinations are not allowed, even when varying the top quark masses and SUSY parameters in the ranges given above, requiring $\tan \beta \geq 0.5$.

(E) The non-sensitivity region, where no signal can be found independent of the top quark mass ($113 \leq m_t \leq 180$ GeV) and the SUSY parameters listed in Table 1.

The parameter region in which the lighter CP-even Higgs, $h^0$, can be discovered at an EE500 collider is shown in Fig. 3 (assuming that the top mass does not exceed 180 GeV). The left plot shows the regions (A) to (D) determined if only the sensitivity for $e^+e^- \rightarrow h^0Z^0$ detection is considered, and the right plot shows the change of the regions when, in addition, the sensitivity for $e^+e^- \rightarrow h^0A^0$ is incorporated. In the small region where an $e^+e^- \rightarrow h^0Z^0$ would not be visible, the heavier CP-even Higgs boson could be detected first. Due to this complementary process, the entire parameter space is covered by searches for Higgs boson bremsstrahlung only. The region of almost equal CP-even and CP-odd scalar masses can also be covered by searches for Higgs boson pair-production. Such a signal would be unambiguous evidence of an extension of the MSM.

The upper top mass limit is motivated by recent lineshape analysis of LEP1 data at the $Z^0$ pole (see for example Ref. [14]). Independently of the Higgs boson mass, an upper limit of 185 GeV (95% CL) on the top mass has been given. However, one should be aware of the fact that this limit is based on the calculations of $\Gamma(Z^0 \rightarrow b\bar{b})$ in the MSM, and therefore in the MSSM a variation of this limit with, for example, the charged Higgs boson mass is possible.
5. Distinction between MSSM and MSM Higgs Bosons

There exist different possibilities to unambiguously identify a Higgs boson as a non-minimal one. The observation of two Higgs scalars would be very interesting, since it immediately goes beyond the MSM and gives strong support to multi-doublet Higgs models, particularly to the MSSM. As shown in the previous section, a CP-odd or a second CP-even Higgs boson can be observed at an EE500 collider for some regions of the MSSM parameter space.

Additional possibilities of distinguishing a light Higgs scalar in the MSSM from the MSM are particularly important in regions of the parameter space (large m_A) where only the lighter scalar could be produced via bremsstrahlung off the Z^0. In those regions the distinction between MSSM and MSM could eventually be made on the basis of measurements of the coupling of an observed scalar to the Z^0. However, the cross section for the process e^+e^- → Z^0h^0 is very similar to the MSM Higgs boson production cross section, e^+e^- → Z^0H^0_{MSSM}, for large m_A values [5, 16]. For m_A > 100 GeV the difference is typi-

An EE500 machine also has the potential of discovering the heavier Higgs boson. This is particularly important, since already at LEP200 chances of finding the lighter Higgs boson signal are good if the MSSM is realized in Nature (for LEP200 a similar analysis has been made, but without the study of the additional SUSY parameter dependence [11]). The parameter regions which can be explored at an EE500 collider for the heavier CP-even Higgs boson are shown in Fig. 4 for m_t ≤ 180 GeV. The effects of independent scanning over the SUSY parameters is clearly visible. Some fraction of the parameter space is covered by searches for Higgs boson bremsstrahlung only (left plot). Most of the remaining region can be covered by searches for Higgs boson pair-production up to about m_A + m_h ≤ 400 GeV (right plot).

Figure 3: Regions of the (m_h,m_A) plane which can be explored for the lighter CP-even MSSM Higgs boson. The left plot shows the region which can be explored using sensitivities for e^+e^- → h^0Z^0 only (the line width of region (B) is about its size). In the right plot the sensitivity for e^+e^- → h^0A^0 are also taken into account. We take m_t ≤ 180 GeV and √s = 500 GeV. For details see text.
Another method of identifying the origin of a produced scalar is based on its decay branching fractions. The dominant and most important channel of $h^0$ decay is $h^0 \rightarrow b\bar{b}$. The total contribution of the other channels such as $h^0 \rightarrow c\bar{c}$, $\tau^+\tau^-$, $gg$, $\gamma\gamma$, and eventually $h^0 \rightarrow Z^0\gamma$ is less than 20% (10% for $\tan\beta \geq 3$), and most likely too small to be measured with sufficient precision. Detailed experimental aspects are addressed in Ref. [18]. We assume that MSM and MSSM can be distinguished experimentally if the difference between $\text{BR}(h^0 \rightarrow b\bar{b})$ in both models is larger than 8% as suggested in Ref. [19]. Regions where this condition is fulfilled are shown in Fig. 5 (right plot). Regions (A) to (D) are defined as for the cross section comparison. It can be seen that in the most difficult range $m_A \geq 100$ GeV, even knowledge of $\text{BR}(h^0 \rightarrow b\bar{b})$ at the assumed level is in
better than 3-4%. This means that a high experimental precision is required to identify the Higgs as a MSSM one.

It is important to note that the above comparison of cross sections and branching ratios is independent of the experimental center-of-mass energy and holds also for lower energies (LEP200), or at accelerators running with TeV. The experimental feasibility of measuring these differences depend strongly on the experimental capabilities.

6. Conclusions
We have presented aspects of searches for neutral supersymmetric Higgs bosons at an EE500 collider. Full 1-loop diagrammatic calculations of radiative corrections to the Higgs particle production and decay rates are applied and the dependence of the results on all important model parameters is investigated. Several SUSY parameters, in addition to the top and stop masses, are varied independently. Effects of such scanning over the MSSM parameter space are clearly visible. The maximal mass of the lightest Higgs boson can vary by 10–15 GeV for fixed top and stop quark masses. Even in the most unfavorable parameter combination, at least one MSSM Higgs boson should be observable.

An EE500 collider has good chances of discovering two Higgs particles present in the MSSM. However, in a large part of the parameter space of the MSSM only one CP-even scalar can be found via the bremsstrahlung process $e^+e^- \rightarrow Z^0h^0$. In this case, it will be difficult to assess the origin of a new scalar. Such a scalar could be distinguished from the MSM Higgs boson if its decay branching ratios are measured with a precision better than 3-4%.
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