Charged Higgs Boson Discovery Potential at a 500 GeV e^+e^- Linear Collider

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Abstract

The discovery potential for charged Higgs bosons has been studied with full-statistics background simulations for $\sqrt{s} = 500$ GeV and $\mathcal{L} = 10 \text{ fb}^{-1}$. For the hadronic decay channels $H^+H^- \rightarrow c\bar{s}c\bar{s}$, $t\bar{b}t\bar{b}$, a microvertex detector is crucial for establishing a signal over the $e^+e^- \rightarrow t\bar{t}$ background. A combination with a search in the channels $H^+H^- \rightarrow c\bar{s}\tau^-\nu$, $\tau^+\nu\tau^-\bar{\nu}$ allows detection sensitivity for charged Higgs bosons up to a mass of about 210 GeV, independent of the charged Higgs decay modes. Sensitivity regions in the m_A - $\tan\beta$ parameter space of the Minimal Supersymmetric extension of the Standard Model (MSSM) are given.

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Abstract

The discovery potential for charged Higgs bosons has been studied with full-statistics background simulations for $\sqrt{s} = 500$ GeV and $\mathcal{L} = 10 \text{ fb}^{-1}$. For the hadronic decay channels $H^+H^- \rightarrow c\bar{s}c s$, $t\bar{b}t b$, a microvertex detector is crucial for establishing a signal over the $e^+e^- \rightarrow t\bar{t}$ background. A combination with a search in the channels $H^+H^- \rightarrow c\bar{s}\tau^-\nu$, $\tau^+\nu\tau^-\bar{\nu}$ allows detection sensitivity for charged Higgs bosons up to a mass of about 210 GeV, independent of the charged Higgs decay modes. Sensitivity regions in the m_A - $\tan\beta$ parameter space of the Minimal Supersymmetric extension of the Standard Model (MSSM) are given.

1 Introduction

Although the Standard Model [1] provides a precise description of existing data on electroweak interactions, the Higgs boson [2], an essential ingredient of the model, has not been observed. It is quite possible that the actual scalar sector in nature has more than one doublet of Higgs bosons or has Higgs bosons in other multiplets. This is expected in many theories that go beyond the Standard Model. A discovery of charged Higgs bosons would be unambiguous evidence that the electroweak symmetry-breaking sector of the Standard Model consists of at least two Higgs doublets. Evidence for a minimum of two Higgs doublets is particularly important since it will be experimentally difficult to distinguish the neutral Higgs boson of the Minimal Standard Model from a neutral Higgs boson in an extended Higgs sector.

The theoretical framework of this study is the Standard Model, where two Higgs doublets generate the spontaneous electroweak symmetry breaking [3]. The Higgs sector of a two-doublet model contains five physical Higgs bosons: one neutral CP-odd scalar, A^0 ; two neutral CP-even scalars, H^0 and h^0 ; and two charged scalars, $H^\pm$. The masses of the Higgs bosons, the mixing angle α between the two neutral scalar Higgs fields, and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$, are free parameters.

The LEP experiments at CERN have raised the lower limit on the charged Higgs mass from about 20 GeV [4] to about 43 GeV [5], independent of the charged Higgs decay modes. In the following years, the next phase of the LEP machine (LEP200) running at a center-of-mass energy around 200 GeV and assuming a total luminosity of $\mathcal{L} = 500 \text{ pb}^{-1}$ has the potential to significantly increase in the charged Higgs sensitivity up to about 70 GeV [6]. Around 80 GeV, much irreducible W^+W^- arises and the signal cross section drops fast near the kinematic production limit. In the framework of the Minimal Supersymmetric Standard Model (MSSM), $m_{H^\pm} > m_W$ is required and searches at LEP for charged Higgs bosons will not be possible. Radiative corrections, which are very important in the neutral Higgs sector, change this mass relation by at most a few

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GeV, which exceptions in some special parameter regions [7]. Thus, in this model, charged Higgs boson searches have to wait for the e^+e^- collider generation beyond LEP200 [6]. Such a machine with $\sqrt{s} = 500$ GeV, referred to as EE500, has been studied in this paper.

Compared to a previous study [8] where no sensitivity for charged Higgs bosons in the hadronic channels for the important decay $H^+ \rightarrow t\bar{b}$ was achieved, this study emphasizes the use of a microvertex detector and improves techniques in hadronic decay channels for both cases $m_{H^\pm} \leq m_t$ and $m_{H^\pm} > m_t$. In particular the channel $H^+H^- \rightarrow t\bar{t}\bar{b}b$ has been studied. Sensitivities for the production processes $H^+H^- \rightarrow c\bar{s}\tau^-\nu$ and $\tau^+\nu\tau^-\bar{\nu}$ have been included in the interpretations. Possible Supersymmetric charged Higgs decays, for example, $H^+ \rightarrow \tilde{t}\tilde{b}$ [9], where $\tilde{t}$ and $\tilde{b}$ are the Supersymmetric partners of the top and bottom quarks, are not considered.

Most of the techniques to search for non-minimal Higgs bosons at LEP1 can be applied to the search for the Higgs bosons at the EE500. The feasibility of these techniques to remove the background have been well studied at LEP1. These techniques are described in Refs. [10], [11], and [12] in increasing detail, and similar techniques are also reported in Ref. [5]. This paper deals with improved methods needed for the discovery of charged Higgs bosons at the EE500, and it may serve as a guide for future searches.

In the general two-doublet model, the produced rate for charged Higgs boson pair-production depends only on the charged Higgs mass, unlike, for example, neutral Higgs boson pair-production. Figure 1 shows the production diagram and the expected number of pair-produced charged Higgs bosons as a function of the charged Higgs boson mass for a total luminosity of 10 fb^{-1} . The cross section is given by [13]:

$$\sigma(e^+e^- \rightarrow H^+H^-) \approx 95(1 - 4m_{H^\pm}^2/s)^{3/2} \quad [\text{fb}]. \quad (1)$$

Figure 1: Left: Diagram for $e^+e^- \rightarrow H^+H^-$ production. Right: Expected number of H^+H^- events for $\sqrt{s} = 500$ GeV and $\mathcal{L} = 10 \text{ fb}^{-1}$.

The decay modes of the Higgs boson determine the signatures in the detector. Charged Higgs bosons are expected to decay predominantly into the heaviest kinematically accessible fermion pair if it is not Cabbibo-suppressed. Figure 2 shows the predicted branching ratios [14] of $H^+ \rightarrow c\bar{s}$ and $H^+ \rightarrow \tau^+\nu$ for a heavy top quark, $m_t > m_{H^\pm}$. If the top quark were lighter than the charged Higgs boson, the reaction $H^+ \rightarrow t\bar{b}$ would be dominant, and thus the following reactions are most important:

$$e^+e^- \rightarrow H^+H^- \rightarrow c\bar{s}c\bar{s}, \bar{t}b\bar{t}b, c\bar{s}\tau^-\nu, \tau^+\nu\tau^-\bar{\nu}.$$

Figure 2: Branching ratios of charged Higgs bosons in the two-doublet Higgs model for $m_t > m_{H^\pm}$.

Indirect limits on the charged Higgs boson mass from results on radiative decays of B mesons are under discussion. A limit has been set on the branching ratio, $\text{BR}(b \rightarrow s\gamma) < 5.4 \times 10^{-4}$ at 95% CL [15]. The existence of charged Higgs bosons would increase this branching ratio compared to the MSM. Based on calculations in Refs. [16, 17], the branching ratio limit translates into an upper mass limit on the charged Higgs boson mass. For a top mass of 180 GeV, charged Higgs masses below 400 GeV are excluded. However, it has been pointed out [18] that still big uncertainties plague the theoretical determination of the $\text{BR}(b \rightarrow s\gamma)$ value in the MSM, and additional Supersymmetric particles can completely cancel the contribution of the charged Higgs boson. Thus, the indirect bound on the charged Higgs mass can vanish.

The rest of this paper is organized as follows: The simulations of signal and background are described (Section 2). The reaction $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{s}c\bar{s}$ is studied for a heavy top mass (Section 3). The method of tagging b-quarks with a microvertex detector is outlined (Section 4). The reaction $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{s}c\bar{s}$ is investigated for $m_{H^\pm} \approx m_t$ where b-tagging is applied to reduce the $t\bar{t}$ background (Section 5). The reaction $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{s}c\bar{s}$ is investigated for $m_{H^\pm} = 140$ GeV and $m_t = 180$ GeV (Section 6). The reaction $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{t}b\bar{b}$ is studied, where b-tagging is applied to reduce $t\bar{t}$ background (Section 7). A combined Higgs mass sensitivity is given in Section 8. An interpretation in the framework of the MSSM is given, including the effects of radiative corrections (Section 9).

2 Signal and Background Simulations for the EE500

The signal reactions have been generated with 2000 events in each investigated channel. In all figures, the number of signal events is normalized to the expected rate. The simulated background processes and their cross sections for $\sqrt{s} = 500$ GeV and $\mathcal{L} = 10 \text{ fb}^{-1}$ are summarized in Fig. 3. In addition to background processes which have been well studied at the Z^0 resonance (LEP1), the reaction $e^+e^- \rightarrow W^+W^-$ is important because its final states $c\bar{s}c\bar{s}$, $cs\tau\nu$, and $\tau^+\nu\tau^-\bar{\nu}$ are identical to those of pair-produced charged Higgs bosons. The W^+W^- decay branching ratios into hadrons and leptons are summarized in Table 1. The W^+W^- background gives the largest contribution to 4-jet events. Less important is the background from Z^0Z^0 decays because of the smaller Z^0Z^0 production rate, even though about 50% of Z^0Z^0 decays lead directly to 4-jet events (Table 2).

Figure 3: Diagrams of background reactions and their expected cross sections for $\sqrt{s} = 500$ GeV.

W^+W^- Branching Ratios	BR (in %)
$W^+W^- \rightarrow \tau^+\nu\tau^-\bar{\nu}$	1.1
$W^+W^- \rightarrow qq\tau\nu$	14
$W^+W^- \rightarrow q\bar{q}q\bar{q}$	47

Table 1: W^+W^- branching ratios into $\tau^+\nu\tau^-\bar{\nu}$, $qq\tau\nu$, and $q\bar{q}q\bar{q}$, where $q\bar{q}=c\bar{s},u\bar{d}$.

Z^0Z^0 Branching Ratios	BR (in %)
$Z^0Z^0 \rightarrow b\bar{b}b\bar{b}$	2.3
$Z^0Z^0 \rightarrow c\bar{c}b\bar{b}$	4.0
$Z^0Z^0 \rightarrow c\bar{c}c\bar{c}$	1.7
$Z^0Z^0 \rightarrow q\bar{q}q\bar{q}$	49

Table 2: Z^0Z^0 branching ratios. Here q indicates the summation over all quark flavors.

Further reactions, such as dimuon events from $e^+e^- \rightarrow \mu^+\mu^-$, are easily identified and are not a serious background to any Higgs signal under investigation. The 2-photon processes are characterized by large missing energy along the beam direction and can therefore be largely removed.

The reaction $e^+e^- \rightarrow t\bar{t}$ is a serious background because of the similarity with hadronic Higgs decays. About 7000 such events are expected taking for example $m_t = 140$ GeV. For top masses larger than about 120 GeV no toponium state is formed and the decay $t \rightarrow W^+\bar{b}$ dominates [19]. Subsequently, the $W^\pm$ decays and multijet final states are expected. No attempt has been made to reconstruct the $W^\pm$ mass in the top decay. Background of radiative returns to produce an on-shell Z^0 in the reaction $e^+e^- \rightarrow \gamma Z^0$ (as a subset of $e^+e^- \rightarrow f^+f^-$) is negligible after preselections are applied.

All processes have been generated with PYTHIA [20], except $e^+e^-f^+f^-$ which was generated with DIAG36 [21]. After generation detector effects are simulated. For the detector simulation a 4π -detector configuration is chosen with excellent spatial and energy resolutions. A central silicon microvertex detector with two layers, $|\cos\theta| < 0.9$, and intrinsic impact parameter resolution (at 90°) of $10 \mu\text{m}$ has been included in the simulations where only the r - ϕ information is used.

The detector effects of hadronic events can be studied efficiently with a parame-

tric detector simulation which takes the detector geometry and intrinsic resolutions into account. Most important for the Higgs search in the multi-jet channels are the energy and spatial resolutions in the central part of the detector ($|\cos \theta| < 0.7$) because of the approximate $\sin^2 \theta$ distribution of the production angle for the signal. Typical resolutions are approximated by smearing single particle energies and directions as listed in Table 3. The resulting resolutions are in agreement with measurements at the Z^0 resonance. For hadronic events an energy resolution of about 10% at $\sqrt{s} = 91$ GeV is reproduced and about 7% energy resolution is expected at $\sqrt{s} \approx 500$ GeV.

Particle	Energy Resolution (in %)	Spatial Resolution
e, γ	$\Delta E/E \approx 5/\sqrt{E}$	$\Delta\phi, \Delta\theta \approx 10$ mrad
Single Hadrons	$\Delta E/E \approx 55/\sqrt{E} + 5$	$\Delta\phi, \Delta\theta \approx 150$ mrad/ $\sqrt{E}$

Table 3: Smearing used for the simulation of detector effects in the EE500 Higgs search. E is the energy in GeV of electrons, photons, or single hadrons.

3 The $H^+H^- \rightarrow c\bar{s}cs$ Channel for a Heavy Top

In this section top quark production is assumed to be kinematically excluded, $2m_t > \sqrt{s}$. With this assumption an important decay mode is $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{s}cs$, whose signature is typically a 4-jet event. A selection based on event topology is applied, and a peak in the reconstructed charged Higgs mass distribution is expected. In order to improve the jet energy resolution, the total event energy is rescaled to the center-of-mass energy $\sqrt{s} = 500$ GeV. It has to be emphasized that Initial State Radiation (ISR) is included in the simulations. Its effect is a reduction of the mean center-of-mass energy and an increase of the energy imbalance if a hard photon escapes undetected near the beampipe. A hadronic event sample is defined using the following cuts:

$$E_{\parallel}/E_v < 0.40, \quad E_{\perp}/E_v < 0.60, \quad 0.84 < E_v/\sqrt{s} < 1.04, \quad N_{cl} \geq 40, \quad (2)$$

where $E_{\parallel}$ is the energy imbalance along the beam direction, $E_{\perp}$ the transverse energy imbalance, E_v the total calorimetric energy and N_{cl} the number of calorimetric clusters. In order to distinguish the signal from the main background due to $e^+e^- \rightarrow q\bar{q}$ decays, use is made of their different topological properties. Energy deposits in the detector are clustered into jets. The clustering method is explained for example in Refs. [11, 12]. Events with 4 and 5 jets ($y_{cut} = 0.02$) are selected. The 5 jet events are transformed into 4-jet events by combining the two jets with the minimum invariant mass. The cut $T < 0.86$ is applied on the event thrust, since the hadronic Higgs boson events are expected to be wider than the background from the reaction $e^+e^- \rightarrow q\bar{q} \rightarrow$ hadrons. The strong background reduction when all previous preselection cuts are applied is summarized in Table 4.

Channel	cscs	qq	WW	ZZ	eeZ	eW ν
Generated Events (in 1000)	2	125	70	6	60	50
After Preselection (in 1000)	1	1.6	0.14	0.1	0	0.01

Table 4: Effect of preselection on expected signal and background.

Cuts on the following variables are applied to further reduce the background:

- $\Delta m_{\text{rec}} = |m_{H^+}^{\text{rec}} - m_{H^-}^{\text{rec}}|$, where $m_{H^\pm}^{\text{rec}}$ are the reconstructed Higgs boson masses. The four jets can be combined into 2-jet pairs in three possible ways. In order to select the combination most likely to come from charged Higgs boson production and decay, the fact that $m_{H^+} = m_{H^-}$ is used. The combination with minimum Δm_{rec} is chosen and mainly $e^+e^- \rightarrow q\bar{q}$ events with $\Delta m_{\text{rec}} \geq 10$ GeV are rejected.
- $|\cos \theta_p| \leq 0.7$ is required, where $\cos \theta_p$ is the polar production angle of the Higgs.

Further cuts have proven to be useful at LEP1 in order to increase the sensitivity for a charged Higgs signal [11, 12]. A few examples, especially to reduce further $e^+e^- \rightarrow q\bar{q}$ background are listed below. They are not applied and may serve in a later analysis.

- $|\cos \theta_d| \leq 0.7$ can be required, where $\cos \theta_d$ is the decay angle of the jets in the Higgs rest frame, which is largely independent of the center-of-mass energy. The good simulation of this variable for LEP1 data (L3 experiment) and the effect of this cut is illustrated in Figure 4 (from [11, 12]). Smaller decay angles are expected for a QCD background compared to Higgs events.

Figure 4: Distribution of the decay angle for L3 data ($\sqrt{s} = 91$ GeV), simulated background and Higgs boson signal in the $c\bar{c}s$ channel.

- In order to exploit the back-to-back production of Higgs bosons it can be required that $\Delta \cos \theta_p \equiv |\cos \theta_p(H^+) + \cos \theta_p(H^-)| \leq 0.3$.
- $\psi_{\text{pl}} \geq 0.7$ rad can be required, where ψ_{pl} is the angle between the $H^+ \rightarrow c\bar{s}$ decay plane and the $H^- \rightarrow \bar{c}s$ decay plane. For the signal the ψ_{pl} distribution is expected to be flat, for the QCD background it is peaked at small angles.
- Cuts could also be applied on the variables $\sum M_{\text{jet}}^{\text{rec}}$, $E_{\text{jet}}^{\text{max}}/\sqrt{s}$ and $E_{\text{jet}}^{\text{min}}/\sqrt{s}$, where $\sum M_{\text{jet}}^{\text{rec}}$ is the sum of the jet masses, $E_{\text{jet}}^{\text{max}}/\sqrt{s}$, $E_{\text{jet}}^{\text{min}}/\sqrt{s}$ are the fractions of energies carried by the highest and lowest energy jets, respectively.

The background from the reactions $e^+e^- \rightarrow Z^0 Z^0$ and W^+W^- is reduced by rejection of events where Z^0 and $W^\pm$ masses can be reconstructed. For this purpose a mass- χ^2 is defined: $\chi_{\text{VV}}^2 = (m_1^{\text{rec}} - m_V)^2/\sigma_1^2 + (m_2^{\text{rec}} - m_V)^2/\sigma_2^2$, where $V = Z^0$ or $W^\pm$, and $\chi_{\text{VV}}^2 > 4$ is required. The normalized distribution of the reconstructed Higgs boson mass,

$0.5 \times (m_{H^+}^{\text{rec}} + m_{H^-}^{\text{rec}})$, and the remaining background are shown in Fig. 5. Using kinematic constraints on the visible energy, a Higgs mass resolution of about 2.8 GeV is obtained. For $m_t > 250$ GeV, in a mass window of ± 3 GeV, two, thirteen, and seven background events remain for $m_{H^\pm} = 140, 180$, and 210 GeV, respectively. A constant signal efficiency of about 15% is expected up to Higgs masses close to the kinematic production limit (approaching the kinematic limit the efficiency decreases, since the selection of the correct jet-jet combination is more difficult). The sensitivity is usually expressed as a ‘ σ effect’ of the ratio of expected signal over background events ($\sigma = \# \text{signal} / \sqrt{\# \text{background}}$). For example, the expected signal efficiency and number of background events corresponds to a 13σ effect at $m_{H^\pm} = 180$ GeV with $\text{BR}(H^+ \rightarrow c\bar{s}) = 0.5$ ($\mathcal{L} = 10 \text{ fb}^{-1}$).

Figure 5: Sensitivity for an $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{s}c\bar{s}$ signal. Open histograms show the simulated signal and solid histograms show the $q\bar{q}$, W^+W^- , Z^0Z^0 background after all cuts are applied (bin size 2 GeV). Left: $m_{H^\pm} = 140, 180$, and 210 GeV, with $2m_t > \sqrt{s}$. Right: Fit to reconstructed mass for mean value and its expected resolution. The number of expected background events and signal efficiency is given.

Beamstrahlung (BS) effects have been studied. Unlike in the pessimistic (and now considered unrealistic) estimation of large beamstrahlung from ‘Palmer G’ type [22], in this study beam parameters of the 1992 design of the NLC [23] are used. The beam energy spectrum of electrons and positrons after BS is obtained with the program BEAM-SPEC [24]. The spectrum has been applied both to signal and background simulations. It has been found that the Higgs mass resolution obtained by rescaling is largely insensitive to BS effects. An example for $m_{H^\pm} = 180$ GeV is given. The final mass resolution of

2.8 GeV degrades to 3.1 GeV if BS is taken into account. With identical selection cuts, the sensitivity decreases with BS from a 13σ to a 9σ effect, mainly due to the Δm_{rec} cut. Overall, the effect of beamstrahlung is visible in the selection, but found to have little effect of the detectability of a H^+H^- signal in the hadronic channels investigated. Also for low-multiplicity signals, it has been found that BS can be controlled [25].

A separate study including BS has been devoted to smaller Higgs boson masses. While for masses of 140, 180, and 220 GeV identical selections are used, a Higgs boson mass of 100 GeV requires modification of the selection. Two cuts are important: First, lower Higgs masses lead to events with smaller thrust values. The thrust cut has been released, requiring $T < 0.92$. Second, the very strong χ_{VV}^2 rejection for W^+W^- and Z^0Z^0 events would also remove Higgs bosons with masses smaller than 140 GeV. The χ_{VV}^2 cut is released to give sensitivity for a 100 GeV Higgs. Four W^+W^- and five Z^0Z^0 background events remain in addition to four $q\bar{q}$ events. Most of the W^+W^- and Z^0Z^0 background is still removed by event-shape cuts. The selection efficiency is about 10%, which corresponds to a 7.5σ effect for the signal. It is important to point out that the two particular cases $m_{H^\pm} = m_W$ and $m_{H^\pm} = m_Z$ require a different analysis and are not considered in this case study. The applied rejection of W^+W^- and Z^0Z^0 background would also reject such a charged Higgs signal. The event-shape of signal and background would also be the same, and about 50% of W^+W^- decays have identical quark content. In these two cases, use must be made of the different initial spin values of signal and background. Sensitivity curves are given for charged Higgs masses in the range $100 < m_{H^\pm} < 230$ GeV in the general two-doublet model (Section 8), and in the MSSM (Section 9).

4 Tagging of b-quarks

The possibility of distinguishing b-flavored jets from jets resulting from lighter quarks is referred to as ‘b-tagging’. A simple method for b-tagging [26, 27] is used to exploit the possibilities of a microvertex detector, details of its application for non-minimal Higgs searches with the L3 detector can also be found in Ref. [6].

The underlying idea of using higher accuracy in tracing particles close to the interaction point is based on the fact that a larger number of B hadrons are produced in b-jets than in jets resulting from other quarks. The B hadrons have a long lifetime ($\tau_B = 1.3$ ps), which gives a larger number of detectable secondary vertices. Compared to LEP1 or LEP200, the identification of a secondary vertex becomes better at an EE500 collider, since the mean decay length increases with increasing energy.

Typical impact parameters of b-jets are about $200 \mu\text{m}$ for $b\bar{b}$ events at LEP1 and similar values are expected at the EE500 collider. Compared to these values the resolution of tracking systems with a microvertex detector are much smaller. This resolution will allow a very efficient tagging of secondary vertices from B decays.

In order to pursue this method of b-tagging, the number of tracks carrying lifetime information, N_i , is defined, where $i = 1, \dots, N_{\text{jet}}$, and N_{jet} is the number of reconstructed jets in an event. First, several auxiliary parameters are defined. The average cross projection, $\overline{\chi_j}$, for the N tracks in the jet:

$$\overline{\chi_j} = \frac{1}{N} \sum_i \vec{\chi}_{i,j} \cdot \hat{J} \quad (i \neq j), \quad (3)$$

where $\vec{\chi}_{i,j}$ is the coordinate of the interception point of track i and track j in the r - ϕ plane, and $\hat{J}$ is the jet direction, see Fig. 6 (from [26]); $\Delta\phi_{i,j} > 2.5^\circ$ is required in the summation. The transverse momentum of a track with respect to the jet axis, p_T , the impact parameter of a track, δ , and the polar angle of the track, θ .

Figure 6: Schematic view of the definition of the impact parameter, δ_i , and the cross projection, $\chi_{i,j}$. All variables are defined in the r - ϕ plane.

A track carrying lifetime information is defined by:

- $\bar{\chi} > 150 \mu\text{m}$. Events with B hadrons have many more track combinations which contribute more than about $200 \mu\text{m}$, while for track pairs from the interaction point small $\bar{\chi}$ values are obtained.
- $p_T > 1 \text{ GeV}$: this assures good tracking resolution and small multiple scattering.
- $\delta > 40 \mu\text{m}$, and $\delta > (250 - 70 \times p_T) \mu\text{m}$ with p_T in GeV. The impact parameter is large for a track resulting from B-meson decay, and a selection cut well above the expected resolution is chosen.
- $\theta > 25^\circ$: this requirement assures that the track lies within the microvertex detector acceptance.

The b-tagging presented here allows a strong separation of a signal from background events. This method is used in two complementary cases:

- 1) As anti-b-tagging in the $c\bar{s}c\bar{s}$ channel (no b-quarks) to reject $t\bar{t}$ background (2 b-quarks), and
- 2) as b-tagging in the $t\bar{t}b\bar{t}b$ channel (4 b-quarks) to also reject $t\bar{t}$ background.

5 The $H^+H^- \rightarrow c\bar{s}c\bar{s}$ Channel for $m_{H^\pm} = m_t = 180 \text{ GeV}$

The same preselection as in Section 3 is applied. For $m_t = 180 \text{ GeV}$ about 6000 $e^+e^- \rightarrow t\bar{t}$ events are expected. As shown in the upper left plots of Fig. 7, the $t\bar{t}$ background (hatched region) is very significant. This background can be reduced (lower plot) if b-tagging is applied to reject events with large probabilities of b-quark content.

Figure 7: Upper left: Sensitivity for an $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{c}s$ signal with $m_{H^\pm} = m_t = 180$ GeV. Open histograms show the simulated signal and solid histograms show the $q\bar{q}$, W^+W^- , Z^0Z^0 background after all cuts are applied, the $t\bar{t}$ background is hatched (bin size 2 GeV). The upper plot shows signal and background without b-tagging, while in the lower plot sensitivity is much improved with b-tagging. Upper right: $m_{H^\pm} = m_t = 180$ GeV. Fit to the reconstructed mass for the mean value and its expected resolution. The number of expected background events and the signal efficiency are given. Lower left: Number of tracks coming from a secondary vertex per event (tracks with lifetime information). More tracks are expected for the $t\bar{t}$ background than for the $c\bar{c}s$ signal. Only loose cuts are applied on the number of clusters, the parallel energy imbalance, the event thrust, and the thrust angle. A cut rejecting events with $N_{\text{tracks}} \geq 4$ results in 86% signal efficiency and a reduction factor of 2.4 for $t\bar{t}$ background.

A cut on the number of tracks with lifetime information, rejecting events with $N_{\text{tracks}} \geq 4$, results in 86% signal efficiency and a reduction factor of 2.4 for $t\bar{t}$ background. The distribution of N_{tracks} is shown in Fig 7 (lower plot). The number of tracks with lifetime information is largest for top decays ($t\bar{t} \rightarrow W^+W^-b\bar{b}$) because of the larger probability of finding B hadrons in such events. Also some fraction of the Z^0Z^0 background is rejected, since more than 10% of the 4-quark decay modes contain at least one $b\bar{b}$ pair. The upper right plot of Fig. 7 shows the reconstructed Higgs mass with a Gaussian fit. The simulated Higgs mass of 180 GeV is well reconstructed. A mass resolution of 3.2 GeV is obtained. The selection efficiency is 12% with twenty background events.

6 The $H^+H^- \rightarrow c\bar{c}s$ Channel for $m_{H^\pm} = 140$ GeV, $m_t = 180$ GeV

In the $c\bar{c}s$ channel, the mass combination $m_{H^\pm} = m_t$ has the least sensitivity. If $m_{H^\pm}$ differs from m_t , for example $m_{H^\pm} = 140$ GeV and $m_t = 180$ GeV, higher sensitivities can be obtained. Using the same techniques as in the previous section, the selection efficiency is 14%, while four background events remain. A mass resolution of 2.7 GeV is obtained. The corresponding plots are shown in Fig. 8.

Figure 8: Sensitivity for an $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{c}s$ signal with $m_{H^\pm} = 140$ GeV and $m_t = 180$ GeV. Open histograms show the simulated signal and solid histograms show the $q\bar{q}$, W^+W^- , Z^0Z^0 background after all cuts are applied, the $t\bar{t}$ background is hatched (bin size 2 GeV). Left: The upper plot shows signal and background without b-tagging, while in the lower plot b-tagging is applied, rejecting events with $N_{\text{tracks}} \geq 4$. Right: Fit to the reconstructed mass for the mean value and its expected resolution. The number of expected background events and the signal efficiency are given.

7 The $H^+H^- \rightarrow t\bar{t}b\bar{b}$ Channel

As in the cscs channel, events with large hadronic activity are expected and a topological event-shape selection is applied. The event selection concentrates on the reaction

$$e^+e^- \rightarrow H^+H^- \rightarrow t\bar{t}b\bar{b} \rightarrow W^+W^-b\bar{b} \rightarrow \text{multijets}.$$

Compared with the cscs channel, the background can be reduced further with a harder hadronic selection. The thrust cut has been tightened, requiring $T < 0.78$ and very large hadronic activity is required, $N_{\text{cl}} \geq 90$. A slightly weaker cut on the visible energy is useful, $0.7 < E_v/\sqrt{s} < 1.1$. The strong background rejection with this preselection is listed in Table 5. A looser cut is applied on the maximum allowed mass difference of the reconstructed Higgs masses, $|m_1^{\text{rec}} - m_2^{\text{rec}}| < 20$ GeV, because of the larger uncertainty in the reconstruction of the multijet system.

Channel	tbtb	qq	tt	WW	ZZ	eeZ	eW ν
Generated Events (in 1000)	2	125	7	70	6	60	50
After Preselection (in 1000)	0.9	0.3	0.3	0.01	0.02	0	0

Table 5: Effect of preselection on expected signal and background.

Similar selections to those used in the cscs channel are applied to further reduce W^+W^- and Z^0Z^0 background. The remaining background consists mostly of $t\bar{t}$ background. This background can be reduced through b-tagging because of more b-quarks in the signal compared to the background. The parton content of the H^+H^- signal and pure hadronic $t\bar{t}$ decays is compared in Table 6. A larger number of tracks coming from

	Signal	Background
Quark Content	b bcs b bcs	bcs bcs

Table 6: Final state partons (for $t \rightarrow W^+\bar{b} \rightarrow c\bar{s}\bar{b}$) with enhanced b-content for the signal.

secondary vertices are expected for the signal as shown in Fig. 9. The figure also shows that no signal is expected without b-tagging, consistent with the findings of the previous study [8]. If b-tagging is applied by a cut on the number of tracks with lifetime information, rejecting events with $N_{\text{tracks}} \leq 10$, almost the entire background is removed. A Higgs mass reconstruction becomes possible. A fit to the reconstructed masses yields a good reproduction of the simulated Higgs mass with a resolution of 16 GeV. Typically four background events remain with about 4% selection efficiency. An example for $m_{H^\pm} = 180$ GeV and 100% decay $H^+H^- \rightarrow t\bar{t}b\bar{b}$ is given. Using the same σ definition as before (also for this small number of background events), the expected signal efficiency and the number of background events correspond to a 7σ effect ($\mathcal{L} = 10 \text{ fb}^{-1}$).

8 Combined H^+H^- Sensitivity in the 2-Doublet Model

In the framework of the Standard Model with two Higgs doublets, the three charged Higgs decay branching fractions can be parametrized as a function of $\text{Br}(H^+ \rightarrow \tau^+\nu)$ for $m_{H^\pm} < m_t$, and 100% branching ratio $H^+ \rightarrow t\bar{b}$ is assumed otherwise. While the H^+H^- production cross section is a function of the charged Higgs mass alone, the branching fraction $\text{Br}(H^+ \rightarrow \tau^+\nu)$ can vary from about 0 to 1, depending on the unknown parameter $\tan\beta$, as shown in Fig 2.

The detailed studies for $H^+H^- \rightarrow t\bar{t}b\bar{b}$ lead to a selection efficiency of 4% with four background events. In the cscs channel, $m_{H^\pm} = m_t$ with the least sensitivity is taken

Figure 9: Upper left: Sensitivity for an $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{t}b\bar{b}$ signal with $m_{H^\pm} = 180$ and $m_t = 140$ GeV. Open histograms show the simulated signal and solid histograms show the $q\bar{q}$, W^+W^- , Z^0Z^0 background after all cuts are applied, the $t\bar{t}$ background is hatched (bin size 4 GeV). The upper plot shows the signal and background without b-tagging: no sensitivity can be obtained, while in the lower plot with b-tagging the signal is clearly visible and only few background events remain. Upper right: Fit to the reconstructed mass for the mean value and its expected resolution. The number of expected background events and the signal efficiency are given. Lower left: Number of tracks coming from a secondary vertex per event (tracks with lifetime information). The most tracks are expected for the $t\bar{t}b\bar{b}$ signal. Only loose cuts are applied on the number of clusters, the parallel energy imbalance, the event thrust, and the thrust angle. A cut rejecting events with $N_{\text{tracks}} \leq 10$ results in 41% signal efficiency and a reduction factor of 10, 50, 99, and 12 for $t\bar{t}$, $q\bar{q}$, W^+W^- and Z^0Z^0 backgrounds, respectively.

having 12% efficiency with twenty background events. For the $c\bar{s}\tau\nu$ and $\tau\nu\tau\nu$ channels at $\sqrt{s} = 500$ GeV, sensitivities are estimated according to techniques outlined in Ref. [6]. Typical efficiencies for $H^+H^- \rightarrow c\bar{s}\tau^-\nu$ are 6% with about ten expected background events. This corresponds to a sensitivity ($\sigma = \sqrt{\text{\#signal}/\text{\#background}}$) in agreement with the study [8] where about 20% efficiency with 85 background events are achieved. For the reaction $e^+e^- \rightarrow H^+H^- \rightarrow \tau^+\nu\tau^-\bar{\nu}$ 12% efficiency with also about ten background events is estimated. These numbers rely on that fact that beamstrahlung can be controlled with the new machine design also for low-multiplicity signals [25] as pointed out before. For large $\tan\beta$, in addition to searches in the $\tau\nu\tau\nu$ channel, a signal can possibly be detected from $t \rightarrow H^+\bar{b}$ decays as investigated in detail in Ref. [28].

The numbers of background events are small, especially for $e^+e^- \rightarrow H^+H^- \rightarrow t\bar{t}b\bar{b}$, consequently for all channels Poisson statistics has been used to determine the detection sensitivity. The sensitivities expressed as discovery cross section are listed for all channels in Table 7 assuming a total luminosity of $\mathcal{L} = 10 \text{ fb}^{-1}$. These cross sections decrease slower than linear with increasing luminosity due to a raise of background events.

Channel	$t\bar{t}b\bar{b}$	$c\bar{s}\bar{c}s$	$c\bar{s}\tau\nu$	$\tau^+\nu\tau^-\bar{\nu}$
Number of Signal Events Needed	10	16	13	13
Discovery Cross Section (in fb)	25	13	22	11

Table 7: Number of signal events needed for a 99.73% CL effect (3σ) over the background using Poisson statistics. The discovery cross sections are calculated from the expected signal efficiencies.

Based on the above sensitivities, regions where a signal can be discovered in the $\text{Br}(H^+ \rightarrow \tau^+\nu)$ vs. $m_{H^\pm}$ parameter space are shown in Fig. 10 for $m_t = 140$ and 180 GeV. Independent of the charged Higgs decay modes a charged Higgs boson can be discovered up to a mass of $m_{H^\pm} = 210$ GeV with $\mathcal{L} = 10 \text{ fb}^{-1}$ as a 3σ effect. Owing to the rapid increase of expected Higgs events for lower Higgs masses near the kinematic production limit, already for $m_{H^\pm} = 200$ GeV, more than a 5σ effect is expected. For a 210 GeV Higgs boson, the sensitivity can also be increased to more than 5σ with $\mathcal{L} = 30 \text{ fb}^{-1}$. For $\sqrt{s} = 1000$ GeV and $\mathcal{L} = 50 \text{ fb}^{-1}$, the 3σ sensitivity mass range can be approximately doubled.

Figure 10: Combined sensitivity range. Left: $m_t = 140$ GeV. Right: $m_t = 180$ GeV. For $m_{H^\pm} \leq m_t$, sensitivity will be obtained by searches in the channels $c\bar{s}\bar{c}s$, $c\bar{s}\tau^-\nu$, and $\tau^+\nu\tau^-\bar{\nu}$. The three overlapping regions are shown as a function of the charged Higgs branching fraction into leptons. For $m_{H^\pm} > m_t$, $H^+H^- \rightarrow t\bar{t}b\bar{b}$ is dominant. Independent of the decay modes, sensitivity for a discovery can be obtained up to about $m_{H^\pm} = 210$ GeV at 99.73% CL (3σ effect).

9 Interpretation in the Minimal Supersymmetric Standard Model

In the MSSM, the sensitivity for charged Higgs bosons can be translated into a sensitivity region in the m_A - $\tan\beta$ plane. The calculations [29] include radiative corrections, and in addition to the charged Higgs decay modes mentioned above, the decay $H^+ \rightarrow W^+h^0$, where h^0 is the lightest Higgs boson in the MSSM. No pure Supersymmetric decay modes are considered.

As is well known, the effects of radiative corrections in the MSSM are large. In good approximation, these effects are characterized by m_t and $m_{\tilde{t}}$, where $m_{\tilde{t}}$ is the mass of the Supersymmetric partner of the top (Experimental aspects of additional Supersymmetric parameters are discussed in Ref. [30]). Radiative corrections vanish for $m_t = m_{\tilde{t}}$, and they are large when both masses are large and different. In this approximation the amount of radiative corrections is proportional to:

$$m_t^4 \ln(m_{\tilde{t}}/m_t). \quad (4)$$

The different 3σ discovery regions are presented in Fig. 11 (taking $\mathcal{L} = 30 \text{ fb}^{-1}$) for the case of no radiative corrections ($m_t = m_{\tilde{t}}$), and with $m_{\tilde{t}} = 1 \text{ TeV}$. Plots are shown for $m_t = 140$ and 180 GeV . It is important to note that for no, or small radiative corrections and large top mass, the decay $H^+ \rightarrow W^+h^0$ is dominant in a significant parameter space. This channel has not been studied, and no sensitivity is obtained in the parameter region around $m_A = 140 \text{ GeV}$ and $\tan\beta \approx 1$. The figures show the mass region $60 \leq m_A \leq 220 \text{ GeV}$ where the lower mass corresponds to a charged Higgs mass of 100 GeV . For the ordinate the range $0.5 \leq \tan\beta \leq 15$ is chosen, where a lower bound on $\tan\beta$ around 1 is given in the context of Supergravity models, and no major changes are seen for $\tan\beta$ values larger than 15.

10 Conclusions

At a future e^+e^- collider with $\sqrt{s} = 500 \text{ GeV}$, a large discovery potential for charged Higgs bosons is expected after about one year of data-taking ($\mathcal{L} = 10 \text{ fb}^{-1}$). Detector performances known from LEP detectors result in good background reduction. Full hermeticity of the detector is essential in the pure hadronic channels in order to achieve high resolution of reconstructed Higgs masses. Mass resolutions of about 3 and 16 GeV can be achieved in the $c\bar{s}c\bar{s}$ and $t\bar{t}b\bar{b}$ channels, respectively. Beamstrahlung with beam parameters of the 1992 NLC design has a small effect on the Higgs boson detectability and its mass resolution. In the $c\bar{s}\tau^-\nu$ and $\tau^+\nu\tau^-\bar{\nu}$ channels hermeticity is important in order to suppress background resulting from incomplete event detection. Suggested detectors with higher spatial and energy resolutions [31] will probably reduce the needed total luminosity compared to the established detector designs of today. A critical parameter is the hadronic energy resolution. The tagging of b-quarks has been studied with a conservative microvertex detector simulation (r - ϕ plane only) and found to be efficient for the reduction of $t\bar{t}$ background. In the $c\bar{s}c\bar{s}$ channel, anti-b-tagging can significantly reduce $t\bar{t}$ background, while in the $t\bar{t}b\bar{b}$ channel b-tagging is essential for finding a signal.

In the Standard Model with two Higgs doublets, charged Higgs bosons cannot escape detection for a combined search in the $c\bar{s}c\bar{s}$, $c\bar{s}\tau^-\nu$, $\tau^+\nu\tau^-\bar{\nu}$ and $t\bar{t}b\bar{b}$ channels with a 3σ effect ($m_{H^\pm} = 210 \text{ GeV}$) and a 5σ effect ($m_{H^\pm} = 200 \text{ GeV}$). A search in the $t\bar{t}b\bar{b}$ channel is most difficult due to the complexity of the event topology and the similarity

Figure 11: Combined sensitivity range in the MSSM ($\mathcal{L} = 30 \text{ fb}^{-1}$) for $m_{\tilde{\tau}} = 1 \text{ TeV}$ (upper plots) and $m_{\tilde{\tau}} = m_t$ (lower plots). Left: $m_t = 140 \text{ GeV}$ and right: $m_t = 180 \text{ GeV}$. For $m_{H^\pm} \leq m_t$, sensitivity will be obtained by searches in the three channels $c\bar{s}c\bar{s}$, $c\bar{s}\tau^-\nu$, and $\tau^+\nu\tau^-\bar{\nu}$. For $m_{H^\pm} > m_t$, $H^+H^- \rightarrow t\bar{t}b\bar{b}$ is important. Sensitivity for a discovery can be obtained up to about $m_A = 210 \text{ GeV}$ at 99.73% CL (3σ effect). A small region remains without sensitivity, since the reaction $H^+ \rightarrow W^+ h^0$ has not been studied.

with $t\bar{t}$ background. This decay channel is expected to be dominant if kinematically allowed, and the obtained sensitivity sets the upper mass limit on the charged Higgs boson reach.

In the MSSM, a good coverage of the $m_A - \tan\beta$ parameter space can be obtained up to about $m_A = 200$ GeV (3σ effect) with a few years of running ($\mathcal{L} = 30 \text{ fb}^{-1}$). In summary, an e^+e^- collider is an ideal and surely in the hadronic channels a unique machine to detect and study charged Higgs bosons.

Interest in future simulations are for more detailed studies of the effects of machine design and beamstrahlung, four-fermion background, microvertex developments for b-tagging, dependence of detection sensitivities on other detector types, the particular case $m_{H^\pm} = m_W$, the additional decay mode $H^+ \rightarrow W^+h^0$ and pure Supersymmetric Higgs decays. Fine-tuning of the selection cuts will probably improve the given sensitivities of all signatures investigated.

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