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Charged Higgs Boson Physics at Future Linear Colliders

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The search and study of heavy Higgs bosons is an important part of the anticipated physics program of a high energy e^+e^- linear collider. This paper reviews the expected sensitivity of e^+e^- collisions from 0.5 up to 3 TeV in the study of the physics of charged Higgs bosons in supersymmetric scenarios.

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1. Introduction

The study of an extended Higgs sector appears particularly adapted to the capabilities of a lepton collider of sufficient energy and luminosity. e^+e^- and $\mu^+\mu^-$ collisions provide us with pair production of H^+H^- and H^0A^0 bosons. If photon collisions are available in a $\gamma\gamma$ collider setup, scans of the H^0 and A^0 peaks can also be performed [1]. In this paper we focus on the study of charged Higgs bosons at an e^+e^- linear collider in supersymmetric scenarios. Since the heavy Higgs states generally decouple from the other Supersymmetric particles, most of, if not all, the results derived for the Minimal Supersymmetric extension of the Standard Model (MSSM) can be also applied to a non-Supersymmetric extended Higgs sectors, such as that of the two-Higgs doublet model (2HDM) or the Higgs triplet model [2]. In the decoupling limit, with $M_A >> M_Z$ and the masses of the heavy Higgs particles much larger than those of the other states, the fundamental quantities to be determined in the charged Higgs study are the masses and the widths of these Higgs states and their decay branching fractions. The mass of one of the heavy Higgs bosons, generally taken to be the CP-odd A^0 state, is a fundamental theory parameter. The A^0, H^0 and $H^\pm$ bosons are almost degenerate in mass in the decoupling limit and this needs to be verified experimentally. The heavy Higgs decay branching ratios are sensitive to another fundamental theory parameter, the ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta = v_2/v_1$. The total width of the heavy Higgs states is also important for determining $\tan\beta$. Finally, in SUSY models the contribution of sparticle loops may induce CP-violating asymmetries in the decay of charged Higgs bosons, which can be searched for at a linear collider. From an experimental point of view, the large jet multiplicity and event complexity of processes such as $e^+e^- \to H^+H^- \to t\bar{b}t\bar{b}$ and $W^+h^0W^-h^0$ make them excellent benchmarks for the detector granularity and its ability to perform accurate kinematic reconstruction and jet flavour tagging in an high particle density environment.

2. Charged Higgs Production and Simulation Studies

Charged Higgs production in e^+e^- collisions proceeds mostly through s-channel pair production, $e^+e^- \to H^+H^-$. The production cross section at a given $\sqrt{s}$ energy depends on the charged Higgs mass and $\tan\beta$. Typical values range between $\sim$20 fb for $M_{H^\pm}$ = 250 GeV at $\sqrt{s}$ = 0.8 TeV and 0.5 fb for $M_{H^\pm}$ = 1140 GeV at $\sqrt{s}$ = 3 TeV, due to the P-wave suppression near threshold (see Figure 1). The single boson production $e^+e^- \to H^-\tau^+\nu_\tau$ + c.c. [3, 4] and $e^+e^- \to H^-t\bar{b}$ + c.c. [5] processes, which give access to charged Higgs production beyond the kinematic limit for pair production, have also been considered. Their cross sections scale as $\tan^2\beta$. However, at $\mathcal{O}$(0.01 fb) they are too small to be exploitable in the interesting region $M_{H^\pm} > \sqrt{s}/2$. Production of charged Higgs bosons in t decays, $t \to H^+b$ has also been studied at a linear collider, using also the fact that the polarisation of the tau leptons from the subsequent $H^\pm \to \tau^\pm\nu_\tau$ decay is opposite to that of those originating from $W^\pm \to \tau^\pm\nu_\tau$ for isolating the signal [6]. However, the Tevatron [7, 8], and soon the LHC, data are closing the region of interest for this process.

In the mass range of interest for a linear collider, the main decay processes are $H^+ \to t\bar{b}$, $H^+ \to \tau^+\bar{\nu}_\tau$ and $H^+ \to W^+h^0$. The $t\bar{b}t\bar{b}$ final state is dominant and it has been considered for most of the searches and mass measurement studies. Simulation studies of charged Higgs bosons have been performed at 0.5 TeV for $M_{H^\pm}$= 140 and 180 GeV [9], at 0.8 TeV for $M_{H^\pm}$= 200 and

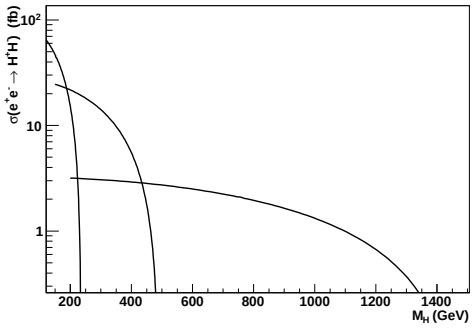

Figure 1: Higgs pair production: cross section for $e^+e^- \to H^+H^-$ at $\tan\beta = 20$ as a function of $M_{H^\pm}$ for $\sqrt{s}$ = 0.5, 1.0 ad 3.0 TeV.

300 GeV [10, 11] and at 3.0 TeV for $M_{H^\pm}$= 700 [12, 13], 900 [14] and 1140 GeV. The SM $t\bar{b}\bar{t}b$ irreducible background is small, with a production cross section of 3.2 fb at 0.8 TeV and 1.2 fb at 3 TeV and a flat distribution in the tb invariant mass. The event reconstruction starts with the identification of two top quarks in events with large jet multiplicity and no significant missing energy. At energies below 1 TeV the boost of the top is small and the decay $t \to W^+b$ can be explicitly reconstructed. At multi-TeV energies and $M_{H^\pm}$ of 0.7 - 1.2 TeV, the top quark boost is such that it can be reconstructed as a single jet. Jet flavour tagging is essential since the four b jets are a distinctive signature of the $WbbWbb$ final state. Once the four-parton final state is reconstructed, the t and b pair which minimises the mass difference between the two tb systems is selected. Given the large jet multiplicity, the four b tags and the need to reject leptonic W decays for an accurate t energy measurement, the reconstruction efficiency is of the order of just a few percent.

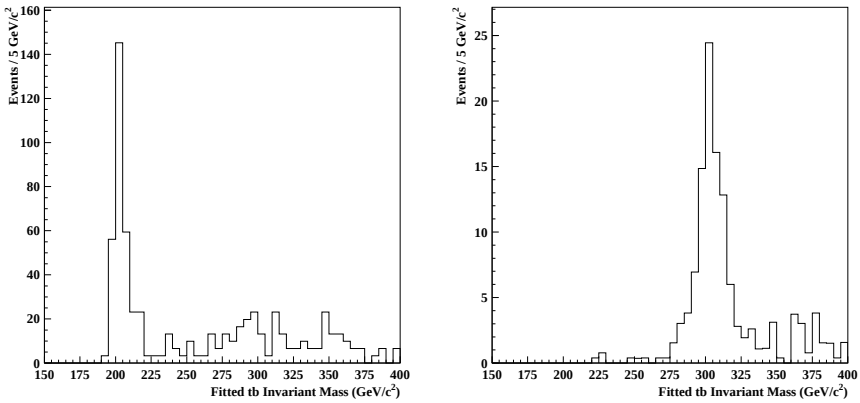

Figure 2: Mass reconstruction: tb invariant mass after kinematic fitting for signal events with $M_{H^\pm}$ = 200 GeV (left) and 300 GeV (right) at $\sqrt{s}$ = 0.8 TeV (from [10]).

The tb invariant mass resolution is 16 GeV for $M_{H^\pm}$ = 180 GeV at $\sqrt{s}$ = 0.5 TeV [9], 17 GeV for $M_{H^\pm}$ = 300 GeV at $\sqrt{s}$ = 0.8 TeV [10], 55 GeV for $M_{H^\pm}$ = 700 GeV [12, 13] and 72 GeV for $M_{H^\pm}$

= 1140 GeV, both at $\sqrt{s}$ = 3.0 TeV. The mass resolution is due to the finite jet energy resolution, to missing energy from escaping neutrinos and to confusion in the association of individual particles to jets, due to the large multiplicities. This mass resolution can be improved by applying a kinematic fit to the reconstructed hadronic final states. Kinematic fits applied in simulation studies impose energy and transverse momentum $p_x = p_y = 0, E \pm |p_z| = \sqrt{s}$, accounting for beamstrahlung photons radiated along the beam axis and an equal boson mass condition $M_{j1j2} = M_{j3j4}$. This improves the mass resolution by a factor of $\sim$2 to 8.5 GeV for $M_{H^\pm}$ = 300 GeV at $\sqrt{s}$ = 0.8 TeV (see Figure 2) [10], 25 GeV for $M_{H^\pm}$ = 700 GeV at $\sqrt{s}$ = 3.0 TeV [12, 13] and 45 GeV for $M_{H^\pm}$ = 1140 GeV. However, these resolutions are larger than the expected $H^\pm$ natural width at these masses.

3. Discovery Reach and Present Predictions

Since the SM background is small and flat at large values of the tb invariant mass, a significant signal of charged Higgs pair production can be established at an e^+e^- linear collider, even with small cross sections and the sensitivity extends almost to the kinematical threshold for pair production by combining different decay final states, irrespective of the value of $\tan\beta$. At $\sqrt{s}$ = 3 TeV, the $e^+e^- \to H^+H^-$ process is observable for charged Higgs boson masses up to 1.25 TeV (see Figure 3) and exceeds the sensitivity of the process $e^+e^- \to H^0A^0$ which drops below 1 TeV at $\tan\beta \sim$ 5 [12]. This sensitivity can be compared to the expectations for the heavy Higgs mass values of new physics models within the constraints offered by previous searches, low energy data and, possibly, astrophysical data, such as relic dark matter density. There have been extensive efforts to determine the regions of new physics model parameter space most likely to be realised in nature given these data. Most of these efforts concern some specific implementation of the supersymmetric extension of the Standard Model. The constraints most relevant here are those from the light Higgs boson mass limits, rare B decay rates and dark matter relic density. Given the large number

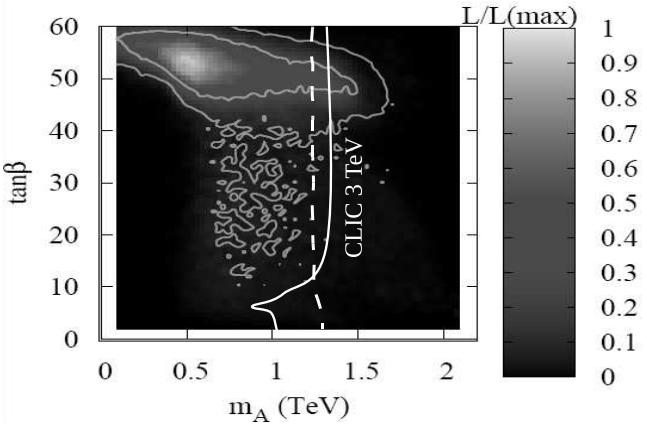

Figure 3: Likelihood marginalised to the M_A - $\tan\beta$ plane with the contour for the anticipated sensitivity to H^+H^- (dashed line) and H^0A^0 (continuous line) pair production at a 3 TeV linear collider (plot modified from [15], sensitivity contours from [12])

of parameters of the MSSM, these studies are best performed in constrained versions, where the gaugino and sfermion masses are assumed to be unified at the GUT scale. This is generally known as the constrained MSSM (cMSSM). The physical masses are calculated using the renormalisation group equations (RGEs) from a set of five fundamental parameters: the universal scalar, m_0, and gaugino, $m_{1/2}$, masses, $\tan\beta$, the universal trilinear coupling, A_0 and the sign of the coupling μ. Different statistical techniques have been employed. A sampling of the full five-parameter space was performed in the study of ref. [15] using a Markov chain Monte Carlo method [16] and taking into account limits from particle searches, $\Omega_\chi h^2$ and low-energy constraints. Of particular interest here is the two-dimensional map of the M_A - $\tan\beta$ plane obtained, which is shown in Figure 3 where the sensitivity of a 3 TeV linear collider to $H^\pm$ and H^0A^0 pair production is superimposed. Variants of the cMSSM either add further constraints or relax them. In mSUGRA there are fixed relations between the bi-linear and trilinear couplings parameters and the scalar mass and the additional condition that the gravitino mass is equal to the scalar mass, $m_{3/2} = m_0$, thus reducing the number of free parameters to just three [17]. In the non-universal Higgs mass model (NUHM) the supersymmetric contributions to the Higgs masses are allowed a different value [18]. In this model, predictions for the M_A-$\tan\beta$ parameters have been obtained in the study of ref. [19]. A recent frequentist analysis, based on LEP-2 limits, electro-weak and flavour data, $g-2$ and $\Omega_\chi h^2$ results, considers all these models and determines likelihood functions for SUSY observables. The 95 % C.L. interval for the charged Higgs boson mass is found to be in the range $350 < M_{H^\pm} < 750$ GeV for the cMSSM and in the range $100 < M_{H^\pm} < 600$ GeV for the non-universal Higgs mass extension [20]. A similar study in the mSUGRA model finds the interval $600 < M_{H^\pm} < 1200$ GeV, again at 95 % C.L. [21]. These results show that present data place only a very loose constrain on the masses of the heavy Higgs particles and highlight the interest in pursuing detailed studies for charged Higgs bosons at the LHC and at future lepton colliders over a broad mass range up to, and possibly beyond, 1 TeV.

3.1 Mass Determination

The mass $M_{H^\pm}$ is determined by a fit to the two-parton invariant mass distribution after kinematic fitting. The signal peak can be modelled by a Breit-Wigner function convoluted with a Gaussian resolution term. In general, the experimental resolution is larger than the $H^\pm$ natural width. Alternatively, a template method, as that adopted in the study of ref. [12], can be used to build a χ^2 for the mass fit. The SM background is essentially flat below this peak in the mass region of interest. The residual $H^0A^0 \to b\overline{b}b\overline{b}$ contribution gives a peaking background in the signal region, since the masses of the charged and heavy neutral Higgs bosons are expected to be almost degenerate. However, the $e^+e^- \to H^+H^-$ cross section is larger than that for $e^+e^- \to H^0A^0$ and the t tagging reduces this background. The invariant mass distributions for signal and background at $\sqrt{s}$ of 0.8 TeV and 3.0 TeV are shown in Figure 4.

3.2 Decay Studies

Modes other than the dominant tb decay have also been studied. In particular, the study of [12] has considered the leptonic decay $H^+ \to \tau^+\nu_\tau$ in the mixed channel $tb\tau\nu$. Signal events can be selected using the standard reconstruction of the hadronic decay and the transverse mass of $H^+ \to \tau^+\nu_\tau$. The reconstruction efficiency, around 0.045, is comparable to that of the fully hadronic

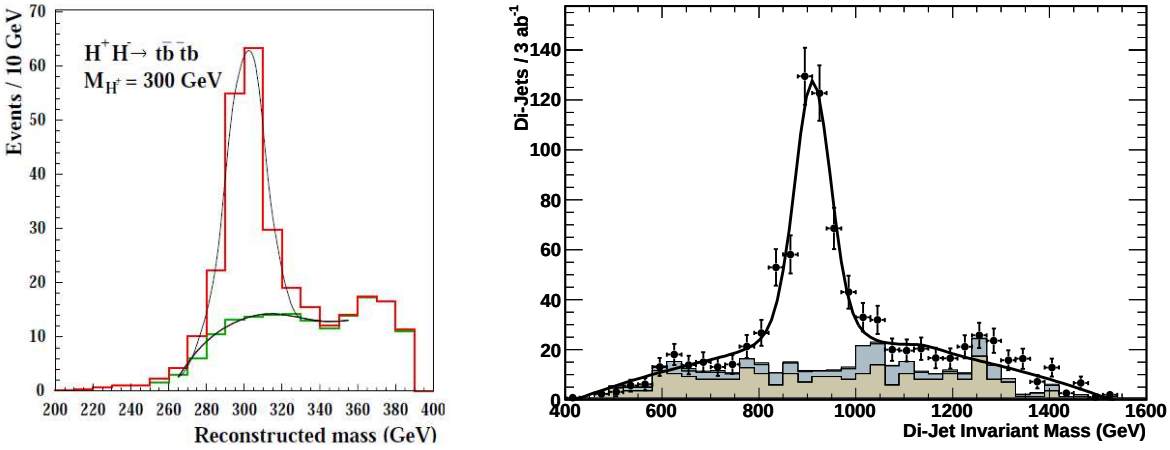

Figure 4: Mass reconstruction: tb invariant mass for signal and background events reconstructed at $\sqrt{s}$ = 0.8 TeV (left) (from [11]) and 3.0 TeV (right).

Table 1: Summary of the results on the reconstruction efficiency and the determination of $M_{H^\pm}$ at various centre-of-mass energies.

$M_{H^\pm}$ (GeV)	$\sqrt{s}$ (TeV)	$\int \mathscr{L}$ (ab^{-1})	Final State	Selection Efficiency	$\delta M/M$	Ref.
145	0.5	0.5	cs	0.15	0.006	[9]
200	0.8	0.5	tb	0.02	0.002	[10, 11]
300	0.8	0.5	tb	0.04	0.004	[10, 11]
702	3.0	3.0	tb	0.02	0.007	[12]
880	3.0	3.0	tb	0.05	0.008	[14]
906	3.0	3.0	tb	0.07	0.006	Preliminary
1136	3.0	3.0	tb	0.05	0.007	Preliminary

mode. The determination of $\tan\beta$ will be essential to constrain phenomenology and to relate the extended Higgs sector to cosmology through dark matter. The precision of a linear collider is expected to provide essential inputs [22]. It is possible to constrain $\tan\beta$ by determining the H^0, A^0, H^+ widths and decay branching ratios $H^0, A^0 \to b\bar{b}$, $\tau^+\tau^-$, $H^+ \to t\bar{b}$, $\tau\nu$. In particular, the determination of the charged Higgs bosons decay yields to tb and cs hadronic and to $\tau\nu_\tau$ leptonic final states offers a good opportunity to determine $\tan\beta$ as long as its value is not too large [23, 12]. At very large values of $\tan\beta$ complementary sensitivity is provided by the determination of the boson width as shown in Figure 5.

In presence of CP violation, the scalar h^0 and H^0 bosons and the pseudo-scalar A^0 are mixed, In this case the A^0 is no longer a mass eigenstate and the $H^\pm$ mass should be used instead of M_A for parametrising the MSSM [24]. CP violation in the new physics sector can manifest itself in decay

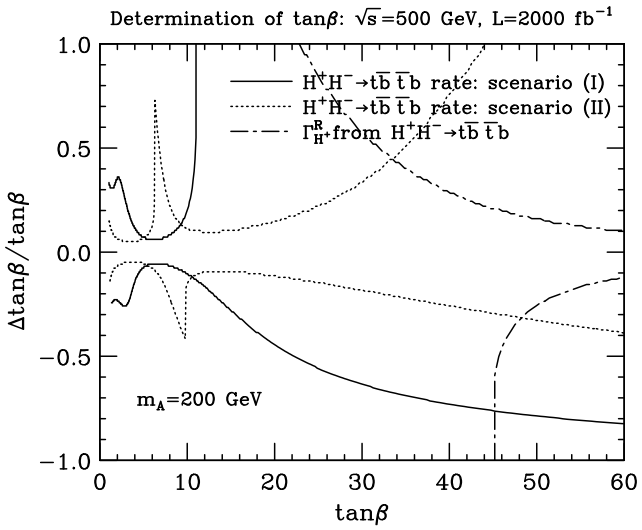

Figure 5: $\tan\beta$ determination with $H^{\pm}$: accuracy as a function of $\tan\beta$ for $M_{H^{\pm}}$ = 200 GeV (from [23])

rate asymmetries such as

$$\delta^{CP}_{ff'} = \frac{\Gamma(H^+ \to f\bar{f}') - \Gamma(H^- \to \bar{f}f')}{\Gamma(H^+ \to f\bar{f}') + \Gamma(H^- \to f\bar{f}')} \tag{3.1}$$

In particular, in MSSM CP asymmetries are expected to be mostly due to squark loops in $H^+ \to t\bar{b}$ decays [26, 25, 27]. The size of these asymmetries scale inversely with $\tan\beta$ from 0.20 to 0.02 for $5 < \tan\beta < 30$. δ^{CP} can be determined using quark-anti quark tagging in hadronic top decays adopting a vertex charge algorithm for b and c jets and lepton charge in semileptonic t decays. The analysis is quite challenging due to the limited quark charge separation power and the small statistics. With typical cross sections of $\mathcal{O}$(1 fb) and few ab^{-1} of integrated luminosity, a sensitivity to deviations of δ^{CP} from zero at the level of $\sim$0.10 should be feasible.

4. Conclusions

A lepton collider of sufficiently high energy and luminosity can provide good accuracy in the determination of the mass (better than 1%), production cross section and decay branching fractions of charged Higgs bosons, through pair production virtually up to the kinematic limit. The accuracy afforded by an e^+e^- linear collider will be essential for the interpretation of the nature of a non-minimal Higgs sector and understand its role in relation to relic dark matter. The study of the heavy Higgs sector is one of the important drivers towards high energy and high luminosity performance for a linear collider. At present the input from the LHC data is essential to define the machine and detector requirements. The ongoing activity in simulation studies for the ILC at 1 TeV and CLIC at 3 TeV will help clarifying requirements and physics potential based on realistic simulation and reconstruction including accelerator effects.

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