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Abstract

We study the prospects for detecting light charged Higgs scalars ($H^\pm$) at future e^+e^- colliders. Various two-Higgs-doublet models (2HDM) and a general multi-Higgs-doublet model (MHDM) are considered, all of which may contain a $H^\pm$ in the discovery range of LEP2. The potentially troublesome cases of $M_{H^\pm} \approx M_W$ and $M_{H^\pm} \approx M_Z$ are discussed, as well as ways of distinguishing the different models.

1 Introduction

A major constraint on the Higgs sector of the Standard Model (SM) is that the measured value of the parameter $\rho = M_W^2/M_Z^2 \cos^2 \theta_W$ is consistent with 1. A more general model with an arbitrary number of Higgs *doublets* will automatically satisfy this constraint at tree level [1]. Since direct evidence for any Higgs particles is lacking at present, it is interesting and important to explore more general models. One particular form of the Two Higgs Doublet Model (2HDM) has received substantial attention in the literature, mainly due to the fact that it is the structure of the minimal supersymmetric extension (MSSM) of the SM. However, there are two variants of the 2HDM which differ in how the doublets are coupled to the up- and down-type quarks. In [1] these are referred to as Models I and II, with Model II appropriate for the MSSM. The phenomenology of these two types of models can be quite different. We will show, for example, that the charged Higgs bosons $H^\pm$ of Model I can be within the reach of the LEP2 e^+e^- collider ($\sqrt{s} \sim 200$ GeV), while those of the more commonly studied versions of Model II cannot. We say ‘commonly studied’ because we will show that there exists a variant of Model II which could contain a light charged scalar.

In this paper we study the phenomenology of non-minimal Higgs models relevant to high-energy e^+e^- colliders. We consider in particular the general Multi-Higgs-Doublet-Model (MHDM), which has received relatively little attention in the literature. It has been shown that there are significant phenomenological differences between the MHDM and the 2HDM [2]. Particularly important in this respect is the detection of the lightest charged scalar of the MHDM. We note that detection of a charged Higgs boson would provide unambiguous evidence of a non-minimal Higgs sector. In contrast to the 2HDM of, for example, the MSSM, the lightest charged scalar of the MHDM has essentially no theoretical constraint on its mass and could therefore be in the discovery range of LEP2.

For all the charged scalars that we will consider there exists an experimental lower bound from LEP of 41.7 GeV [3], obtained from a lack of signal from the process $e^+e^- \rightarrow \gamma^*, Z^* \rightarrow H^+ H^- \rightarrow \tau \nu_\tau \tau \nu_\tau$. With higher energy colliders, distinguishing between the various models and the special cases of $M_H \approx M_W$ or $M_H \approx M_Z$ pose potential problems. We shall show that the possibility of a large branching ratio for the decay channel $H^\pm \rightarrow cb$ (which is possible in the MHDM but not in the 2HDM) goes some way to overcoming these difficulties.

The remainder of the paper is organised as follows. In the next section we describe the general features of the Higgs sector of 2HDM and MHDM. In Section 3 we discuss existing constraints on the various models and compute some relevant branching ratios. In Sections 4 and 5 we discuss the production of charged Higgs scalars at LEP2 and higher energy e^+e^- colliders respectively. Finally, Section 6 contains our conclusions.

2 The Models

The theoretical structure of the 2HDM is well known [1] and will not be discussed further here. For the MHDM it has been shown [2] that the couplings of the charged scalars to the fermions depend on the three complex parameters X , Y and Z . These originate from the mixing matrix for the charged scalar sector. We will assume, as is conventionally done in the literature, that one of the charged scalars is much lighter than the others and thus dominates the low-energy phenomenology. The relevant part of the Lagrangian is [2]

$$\mathcal{L} = (2\sqrt{2}G_F)(X\bar{U}_L V M_D D_R + Y\bar{U}_R V M_U D_L + Z\bar{N}_L M_E E_R)H^+ + h.c. \quad (1)$$

Here U_L , U_R (D_L , D_R) denote left- and right-handed up (down) type quark fields, N_L is the left-handed neutrino field, and E_R the right-handed charged lepton field. M_D , M_U , M_E are the diagonal mass matrices of the down type quarks, up type quarks and charged leptons respectively. V is the CKM matrix.

The CP conserving 2HDM which is usually considered in the literature [1] contains an important parameter

$$\tan \beta = v_2/v_1 \quad (2)$$

with v_1 and v_2 being real vacuum expectation values (VEVs) of the two Higgs doublets. The Lagrangian has the same form as (1) with $X = Z = \tan \beta$, $Y = \cot \beta$ for Model II and $X = Z = -\cot \beta$, $Y = \cot \beta$, for Model I. In the MHDM X , Y and Z are *arbitrary* complex numbers. It follows that combinations of parameters like XY^* have different values depending on the model under consideration. In particular, we will see in the following section that such a combination appears in loop corrections involving charged scalars, giving rise to important phenomenological differences between the models. For a full review see for example Ref. [2].

As an aside, we note that the most general 2HDM potential includes a CP violating phase resulting in VEVs of v_1 and $v_2 e^{i\theta}$ [1]. In this scenario $\tan \beta = v_2 e^{i\theta}/v_1$, and so (for model II)

$$XY^* = \tan \beta (\cot \beta)^* = e^{2i\theta} \neq 1. \quad (3)$$

However after imposing experimentally desirable natural flavour conservation [4], the phase θ is forced to be either 0 or $\pi/2$ depending on the sign of a parameter in the Higgs potential [5]. The latter value also conserves CP and in this case

$$XY^* = e^{2i\theta} = -1. \quad (4)$$

We will explore the consequences of this below.

3 Constraints and Branching Ratios

Precision measurements of the process $b \rightarrow s\gamma$ impose the severest constraints on the mass of the charged scalar of the 2HDM (Model II). The diagrams which contribute to this decay rate are essentially the same as those for the SM with the $W^\pm$ replaced by $H^\pm$. It has been shown [6] that

$$\text{BR}(b \rightarrow s\gamma) = C \left| \eta_2 + G_W(x_t) + (|Y|^2/3)G_W(y_t) + (XY^*)G_H(y_t) \right|^2 \quad (5)$$

where

$$C = \frac{3\alpha\eta_1^2 \text{BR}(B \rightarrow X_c l \nu)}{2\pi F_{\text{ps}}(m_c^2/m_b^2)} \approx 3 \times 10^{-4}. \quad (6)$$

Here $F_{\text{ps}} \approx 0.5$ is a phase space factor, $\eta_1 \approx 0.66$ and $\eta_2 \approx 0.57$ are QCD correction factors, and the G functions are positive increasing:

$$\begin{aligned} G_W(x) &= \frac{x}{12(1-x)^4} \left[(7-5x-8x^2)(1-x) + 6x(2-3x)\ln(x) \right], \\ G_H(x) &= -\frac{x}{6(1-x)^3} \left[(3-5x)(1-x) + 2(2-3x)\ln(x) \right], \\ F_{\text{ps}} &= 1 - 8x + 8x^3 - x^4 - 12x^2 \ln(x). \end{aligned} \quad (7)$$

The dimensionless parameters x_t and y_t are defined by $x_t = m_t^2/M_W^2$ and $y_t = m_t^2/M_H^2$ with M_H being the mass of the charged Higgs. This calculation is purely 'SM + charged Higgs' and so assumes no SUSY particles in the loops. The CLEO collaboration has recently obtained the limit [7]

$$\text{BR}(b \rightarrow s\gamma) < 5.4 \times 10^{-4} \quad (95\% \text{ cl}). \quad (8)$$

Now in the 2HDM (Model II) with $\tan \beta$ real we have

$$XY^* = \tan \beta (\cot \beta)^* = 1, \quad (9)$$

and so there is a $G_H(y_t)$ contribution to the branching ratio which does not depend on $\tan \beta$. Hence to keep the theoretical branching ratio below the bounds from experiment, the Higgs mass M_H (which appears in G_H) must be constrained. We therefore obtain a lower bound of $M_H > 200$ GeV. However this is *not* the case in 2HDM (Model I). Here $XY^* = -(\cot^2 \beta)$, and so the 2HDM contribution to the decay is $[G_W(y_t)/3 - G_H(y_t)](\cot^2 \beta)$. This is negative for all values of y_t and so no bound on M_H independent of $\tan \beta$ can be found. Hence this $H^\pm$ could be in the range of LEP2.

In the MHDM, the combination XY^* which appears in (5) is an arbitrary complex number. Hence there is the possibility of cancellation between the terms that depend on the MHDM parameters, and therefore no bound on M_H . In addition, we recall

that $XY^* = -1$ in the 2HDM (Model II) with $\tan\beta$ purely imaginary. Therefore the $G_H(y_t)$ contribution is negative and again no mass bound independent of $\tan\beta$ can be obtained. With the expected energy of LEP2 ($\sqrt{s} = 180 \rightarrow 200$ GeV), the $H^\pm$ of the conventional version of the 2HDM (Model II, $\theta = 0$) is inaccessible, while both the lightest $H^\pm$ of the MHDM as well as the charged scalars of the 2HDM (Model II, $\theta = \pi/2$) and 2HDM (Model I, $\theta = \pi/2$, $\theta = 0$) could possibly be found.

We next consider the branching ratios for the decays of the $H^\pm$, which will differ from model to model. In the 2HDM (both Model I and Model II), for Higgs masses in the range of LEP2, the dominant decay modes are to $\tau\nu_\tau$ or cs [1]. In Model II the former is dominant for $\tan\beta > 2$, the latter for $\tan\beta < 1$ with equality around $\tan\beta = 1.4$; in Model I the branching ratios are independent of $\tan\beta$ with the cs and $\tau\nu_\tau$ rates fixed at approximately 65% and 33% respectively. The cb channel never exceeds more than a few percent ($\approx 4\%$ in Model II and $\approx 1\%$ in Model I) due to heavy CKM matrix suppression, although in MHDM it can be significantly enhanced due to the greater freedom in X , Y and Z . Such an enhancement could have two important uses. It could increase the chance of detection if $M_H \approx M_W$ (when $W^\pm$ decays form a large background), and also indicate that any detected $H^\pm$ is from the MHDM rather than from the 2HDM.

The actual calculation of the decay widths for the three channels $H^\pm \rightarrow \tau\nu_\tau$, $H^\pm \rightarrow cb$ and $H^\pm \rightarrow cs$ is straightforward. Note that these are the only channels we need consider for Higgs masses in the energy range of LEP2; decays to lighter fermions are negligible because the charged Higgs-fermion coupling is in proportion to mass, and the tree-level vertices involving two vector bosons ($H^\pm W^\pm Z$, $H^\pm W^\pm \gamma$) are absent [1]. The decay channels $H^\pm \rightarrow tb$ and $H^\pm \rightarrow W^\pm h$ (where h is a light neutral Higgs boson) would of course dominate for much heavier charged scalars.

The Feynman rule for the Higgs – up-type quark – down-type quark vertex is [1, 2]

$$\frac{igV_{ud}}{2\sqrt{2}M_W}[m_d X(1 + \gamma_5) + m_u Y(1 - \gamma_5)] , \quad (10)$$

and that for the Higgs – tau – neutrino vertex is

$$\frac{ig}{2\sqrt{2}M_W}m_\tau Z(1 + \gamma_5) . \quad (11)$$

With these rules we can readily construct the invariant amplitude $-i\mathcal{M}$ and the corresponding decay width. For the lepton decay channel we obtain

$$\Gamma(H^\pm \rightarrow \tau\nu_\tau) \approx \frac{Gm_\tau^2 M_H |Z|^2}{4\pi\sqrt{2}} , \quad (12)$$

and for the quark decay channels we obtain

$$\Gamma(H^\pm \rightarrow ud) \approx \frac{3Gm_d^2 M_H |V_{ud}|^2 |X|^2}{4\pi\sqrt{2}} + \frac{3Gm_u^2 M_H |V_{ud}|^2 |Y|^2}{4\pi\sqrt{2}} . \quad (13)$$

Here we have used the approximations $M_H^2 \gg m_u^2$, m_d^2 , m_τ^2 , and a negligible contribution proportional to $m_d m_u (X^* Y + XY^*)$ has been omitted. Our results agree with those given in [8] after the replacements $|X|$, $|Z| \rightarrow \tan\beta$, $|Y| \rightarrow \cot\beta$.

The next step is to study the variation of the decay widths with the parameters X , Y , Z . Before doing so, however, we note that in the MHDM there are various experimental bounds on these parameters which we must respect:

- (i) for a top quark mass of 180 GeV and a charged scalar mass of below 80 GeV, there is a bound $|Y| \lesssim 0.8$ from considering the $Z \rightarrow b\bar{b}$ vertex [2];
- (ii) the strictest bound on $|XY^*|$ comes from the aforementioned process $b \rightarrow s\gamma$, see Eq. (5). The weakest upper bound is obtained for $\arg(XY^*) = \pi$, and Ref. [2] shows that in this case $|XY| < 4$, again for $m_t = 180$ GeV and $M_H < 80$ GeV. As M_H grows the constraint lessens;
- (iii) there is also a bound $|XZ| < 0.32 M_H^2 \text{ GeV}^{-2}$ which is 648 (2048) for $M_H = 45$ (80) GeV; constraints on $|Z|$, $|X|$ and $|YZ|$ are similarly large [2], and none are relevant for the analysis which follows.

For the calculation of the decay widths we use the following mass values: $m_s = 180$ MeV, $m_c = 1.5$ GeV, $m_b = 5$ GeV, $m_t = 180$ GeV, $m_\tau = 1.8$ GeV. For the CKM matrix elements we take [3] $|V_{cs}| = 0.975$ and $|V_{cb}| = 0.040$.

Figures 1 and 2 show lines of constant branching ratio (BR) in the $|X|$, $|Y|$ plane for the $H^\pm \rightarrow cb$ channel, in the range 20% to 50%. For $M_H = 80$ GeV (which suffers from large $W^\pm$ backgrounds), regions below the curve $|XY| = 4$ are allowed by current experimental data. In Fig. 1 we have set $|Z| = 0$, and in Fig. 2 $|Z| = 0.5$. We see that there is a significant parameter space for large $\text{BR}(H^\pm \rightarrow cb)$, with low values of $|Y|$ and $|Z|$ being more favourable. Table 1 shows the maximum obtainable $\text{BR}(H^\pm \rightarrow cb)$ using input values for $|Y|$ and $|Z|$, and taking $|X|$ ten times larger than the smallest of these.¹ The important point here is that sizeable BRs for the decay

	$ Y = 0.2$	$ Y = 0.5$	$ Y = 0.8$
$ Z = 0.2$	39%	19%	10%
$ Z = 0.6$	21%	37%	28%
$ Z = 1.0$	11%	30%	24%

Table 1: Maximum values of the branching ratio for $H^\pm \rightarrow cb$ assuming $|X| = 10 \min(|Y|, |Z|)$.

$H^\pm \rightarrow cb$ are obtainable, whether we impose ‘naturalness’ or not. This is in contrast to the charged scalars of the various 2HDM which never reach more than $\text{BR} \sim 4\%$ in

¹We assume that ‘naturalness’ requires the parameters to be of the same order of magnitude

the cb channel. Thus a significant $\text{BR}(H^\pm \rightarrow cb)$ signal would be a signature of a MHDM. Furthermore, because the $W^\pm \rightarrow cb$ decay is negligible ($\text{BR} \sim 0.05\%$), there is more chance in the MHDM of overcoming the W^+W^- background when $M_H \approx M_W$.

4 Production of $H^\pm$ at LEP2

If for any of the above models M_H *does* lie in the discovery range of LEP2, how would one search for it? Production in top decay, i.e. $e^+e^- \rightarrow \gamma^*, Z^* \rightarrow t\bar{t} \rightarrow H^+H^-b\bar{b}$, is obviously kinematically forbidden at LEP2. Therefore we must rely on the annihilation process $e^+e^- \rightarrow \gamma^*, Z^* \rightarrow H^+H^-$. This has been studied extensively in the literature for the case of the 2HDM. It is straightforward to show that the $Z H^+H^-$ and γH^+H^- couplings have the same strength in both the 2HDM and MHDM, with respective Feynman rules [1]

$$\frac{-ig \cos 2\theta_W}{2 \cos \theta_W} (p' - p)^\mu \quad \text{and} \quad -ie(p' - p)^\mu, \quad (14)$$

where p', p are the 4-momenta of the H^+, H^- . Therefore the analysis of Ref. [9] is relevant for the MHDM. The production cross section is

$$\sigma_{H^+H^-} = \frac{1}{4} \sigma_0 \beta^3 F(s, M_Z, \Gamma_Z, \theta_W), \quad (15)$$

where $\sigma_0 = 4\pi\alpha^2/3s$, $\beta = \sqrt{1 - 4M_H^2/s}$ and $F(s, M_Z, \Gamma_Z, \theta_W)$ is given by

$$1 - 2C_V C'_V \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} + C_V^2 (C_Z^2 + C_A^2) \frac{s^2}{(s - m_Z^2)^2 + M_Z^2 \Gamma_Z^2}. \quad (16)$$

The couplings C are

$$C_A = \frac{-1}{4 \sin \theta_W \cos \theta_W}, \quad C_V = \frac{1 - 4 \sin^2 \theta_W}{4 \sin \theta_W \cos \theta_W}, \quad C'_V = \frac{-1 + 2 \sin^2 \theta_W}{2 \sin \theta_W \cos \theta_W}. \quad (17)$$

In the calculations which follow we use the parameter values: $M_Z = 91.18$ GeV, $M_W = 80.30$ GeV, $\alpha = 1/128$, $\Gamma_Z = 2.49$ GeV, $\sin^2 \theta_W = 0.225$. From Eqs. (15)-(17) we can compute the expected total number of H^+H^- events. This is shown in Fig. 3 as a function of M_H , where we have assumed an integrated luminosity of 500 pb^{-1} and two values for the collider energy. For $\sqrt{s} = 180$ GeV we expect approximately 350 events for $M_H = 45$ GeV, decreasing to 51 events for $M_H = 80$ GeV. For Higgs masses below M_W there should therefore be no problem in detection, the particle being detected as a peak in the jet-jet mass distribution, for example. Also, the scalar nature of the $H^\pm$ gives rise to a characteristic $\sin^2 \theta$ angular dependence with respect to the beam direction. The potential problem arises when $M_H \approx M_W$. The W^+W^-

production cross section ($\approx 20 \text{ pb}$) is considerably larger than that for H^+H^- (see Fig. 4), and so the $H^\pm \rightarrow cs, \tau\nu_\tau$ decays will be overwhelmed by the much more numerous $W^\pm \rightarrow cs, \tau\nu_\tau$. Table 2 shows the expected number of events for 500 pb^{-1} integrated luminosity and two different values of the collider energy ($\sqrt{s}$).² Clearly

	$\sqrt{s} = 180 \text{ GeV}$	$\sqrt{s} = 200 \text{ GeV}$
W^+W^-	9727	10191
ZZ	0	397
$H^+H^- (M_H = 80 \text{ GeV})$	51	91
$H^+H^- (M_H = 90 \text{ GeV})$	0	35

Table 2: The expected number of W^+W^- , ZZ and H^+H^- events for 500 pb^{-1} integrated luminosity at LEP2.

detection of a $H^\pm$ will be impossible unless use is made of special decay channels. We therefore consider the number of events in particular channels. Using the SM branching ratios for Z decay [3]

$$b\bar{b} = 15.1\%, \quad c\bar{c} = 12.0\%, \quad s\bar{s} = 15.4\%, \quad \tau\bar{\tau} = 3.4\%, \quad \sum_{i=1}^3 \nu_i \bar{\nu}_i = 20.1\%, \quad (18)$$

and for $W^\pm$ [3]

$$cs = 31.8\%, \quad cb = 0.05\%, \quad \tau\nu_\tau = 10.8\%, \quad (19)$$

we show in Table 3 the expected numbers of events for the various decay channels. The H^+H^- numbers are the maximum and minimum values. The actual numbers depend on the parameters of the particular model. We see that exploiting the $H^\pm \rightarrow cb$

	$cbcb$	$cbcs$	$cb\tau\nu_\tau$	$cscs$	$cst\nu_\tau$	$\tau\nu_\tau\tau\nu_\tau$
W^+W^-	0.0	3.1	1.1	983.6	668.1	113.5
H^+H^-	$0 \rightarrow 51$	$0 \rightarrow 51$	$0 \rightarrow 51$	$0 \rightarrow 51$	$0 \rightarrow 51$	$0 \rightarrow 51$

Table 3: The expected number of W^+W^- and H^+H^- ($M_H = 80$ GeV) induced events for 500 pb^{-1} integrated luminosity at LEP2 (180 GeV).

channel is crucial in eliminating the background.³ As we have already discussed, this is not an option for the 2HDM and so in this case the $\tau\nu_\tau$ channel will have to be used. Given the large background, detection appears difficult. For the MHDM the prospects are much better due to the possibility of a significant branching ratio for the

²We ignore below-threshold ZZ production at the lower energy

³It may also be possible to measure the polarization of the τ lepton, which is different for $H^\pm$ and $W^\pm$ decays, see Ref. [10], although this technique requires a large event sample.

cb decay channel. The expected number of $cbcb$ events arising from H^+H^- production is $51 \times [\text{BR}(H^\pm \rightarrow cb)]^2$, while for the mixed decays ($cbcs$, $cb\tau\nu_\tau$) we have similar expressions with an extra factor of two from permutations. In order to isolate these final states b -tagging will be necessary. Since this a standard technique for searching for the SM Higgs at LEP2, the efficiency will be quite high in practice, see for example Ref. [11]. The number of final states N_b containing at least one b quark is given by

$$N_b = N_{H^+H^-} \times \text{BR}_{cb} \times (2 - \text{BR}_{cb}) \quad (20)$$

For example, a $\text{BR}(H^\pm \rightarrow cb)$ of 30% would give $N_b = 26.0$ with 4.5 events containing two b quarks. The background N_b from W^+W^- is 9.7. Note that these numbers correspond to the idealized situation of 100% efficiency for detecting b quarks. However they should still be large enough to provide an observable signal assuming a more realistic tagging efficiency, see Ref. [10]. At the higher collider energy, $\sqrt{s} = 200$ GeV, ZZ production becomes a significant background, particularly if $M_H \approx M_Z$. The corresponding number of events in the various channels is given in Table 4.⁴ For

	$cbcb$	$cbcs$	$cb\tau\nu_\tau$	$cscs$	$cst\nu_\tau$	$\tau\nu_\tau\tau\nu_\tau$
W^+W^-	0.0	3.2	1.1	1030.6	700.0	118.9
ZZ	14.4	0	0	14.7	0	5.4
H^+H^- (80)	$0 \rightarrow 91$	$0 \rightarrow 91$	$0 \rightarrow 91$	$0 \rightarrow 91$	$0 \rightarrow 91$	$0 \rightarrow 91$
H^+H^- (90)	$0 \rightarrow 35$	$0 \rightarrow 35$	$0 \rightarrow 35$	$0 \rightarrow 35$	$0 \rightarrow 35$	$0 \rightarrow 35$

Table 4: The expected number of W^+W^- , ZZ and H^+H^- ($M_H = 80, 90$ GeV) induced events for 500 pb^{-1} integrated luminosity at LEP2 (200 GeV).

$M_H = 80$ GeV, there is an improved chance of detection with a maximum of 91 events. A $\text{BR}(H^\pm \rightarrow cb)$ of 30% for the MHDM would now give $N_b = 46.4$, with a background of 10.2 events from W^+W^- . Again, detection depends on the efficiency of b -tagging. If $M_H = 90$ GeV ($\approx M_Z$), the number of produced H^+H^- pairs is lower (≈ 35), and there is a large background from ZZ decays with $N_b(ZZ) = 110.8$. For the 2HDM the mass regions $M_H \approx M_W$ and $M_H \approx M_Z$ are problematic; in the former case there is no $H^\pm \rightarrow cb$ channel to exploit, and the latter suffers from there being too few $H^\pm$ pairs produced.

If a $H^\pm$ is found then can we infer the underlying Higgs model? As mentioned in Section 3, a sizeable $H^\pm \rightarrow cb$ signal would be a signature of a MHDM. For a mass comfortably below M_W a significant number of pairs will be produced. In this mass range, a branching ratio of 10% would probably be sufficient to produce a large enough N_b to tag, in excess of what could be expected from a 2HDM. For example, if $N_{H^+H^-} = 100$ (corresponding to $M_H \approx 75$ GeV at $\sqrt{s} = 180$ GeV), we find $N_b = 19.0$ compared to a maximum value of $N_b = 7.8$ for any 2HDM.

⁴The $ZZ \rightarrow \tau\nu_\tau\tau\nu_\tau$ number corresponds to $Z \rightarrow \tau\tau$ and $Z \rightarrow \sum_i \nu_i\bar{\nu}_i$.

5 High-Energy e^+e^- Colliders

Prospects for a very-high-energy e^+e^- linear collider have recently been discussed, see for example Ref. [12], with collision energy $\sqrt{s} = 500 \rightarrow 1000$ GeV, and integrated luminosity of the order $1 \rightarrow 10 \text{ fb}^{-1}$. The increased centre-of-mass energy would of course enable heavier H^+H^- pairs to be created, should M_H be beyond the reach of LEP2. We will again focus on the pair production process, although if $\sqrt{s} > 2m_t \approx 350$ GeV and $m_t > M_H + m_b$, an additional production mechanism becomes available, *viz.* $t \rightarrow H^\pm b$. The phenomenology of the 2HDM at these colliders has been extensively studied [12], with the conclusion that the charged Higgs scalar can indeed be detected. For pair production, it has been claimed [9] that a charged Higgs whose decays are dominated by SM fermion or Wh modes, and whose mass is less than $0.4\sqrt{s}$, will be detectable with a luminosity of 10 fb^{-1} . This result holds equally for the MHDM: Fig. 5 shows the expected number of events corresponding to an integrated luminosity of 3 fb^{-1} . Can we detect the charged Higgs when $M_H \approx M_W$ or $M_H \approx M_Z$ at these colliders? Table 5 shows the expected number of charged scalar pairs for two different collider energies and an integrated luminosity of 3 fb^{-1} . The elimination of the large

	$\sqrt{s} = 500 \text{ GeV}$	$\sqrt{s} = 1000 \text{ GeV}$
H^+H^- ($M_H = 80 \text{ GeV}$)	317	89
H^+H^- ($M_H = 90 \text{ GeV}$)	303	88

Table 5: Number of $e^+e^- \rightarrow H^+H^-$ pairs for $\int \mathcal{L} = 3 \text{ fb}^{-1}$.

W^+W^- and ZZ backgrounds (Fig. 4) using kinematical cuts has been discussed in the literature. For example, in Ref. [13] it has been shown that an e^+e^- collider with $\sqrt{s} = 1000$ GeV and integrated luminosity of 10 fb^{-1} can detect a charged Higgs of $M_H \approx M_W$ provided that $\text{BR}(H^\pm \rightarrow \tau\nu_\tau)$ was at least 30%. In this case (*cf.* LEP2) the cb decay channel does not have to be significant for detection. However as we have already stressed, the decay $H^\pm \rightarrow cb$ *does* provide a way of distinguishing 2HDM and MHDM models, and offers an alternative mode of detection for the potentially difficult $M_H \approx M_W$, M_Z mass regions (recall that in the 2HDM this branching ratio peaks at approximately 4%).

There are however two caveats to this discussion. First, if a light h exists then the decay $H^\pm \rightarrow W^\pm h$ needs also to be considered. In 2HDM models the $W^\pm H^\pm h$ coupling depends on $\cos(\beta - \alpha)$, where α is a mixing angle arising from the diagonalization of the CP-odd sector of the Higgs mass matrix. If this factor is not small, the Wh channel can dominate the fermion decay modes [1] (assuming that the $t\bar{b}$ channel is kinematically forbidden). With the expectation that $h \rightarrow b\bar{b}$, this would lead to a new source of b quarks feigning the signal coming from an enhanced MHDM cb channel. However this should not be a problem in practice, since the $W^\pm h$ final state has a very

different topology (dominantly 4-jet) from that of $H^\pm \rightarrow cb$ (dominantly 2-jet). Note that the mere presence of $H^\pm \rightarrow W^\pm h$ in MHDM inevitably reduces its branching ratio $\text{BR}(H^\pm \rightarrow cb)$ somewhat.

The second caveat is that when $H^\pm \rightarrow tb$ is allowed, it usually dominates over all fermion decay modes in both 2HDM and MHDM. The decay $H^\pm \rightarrow W^\pm h$ can compete depending on the value of the suppression factor from the Higgs sector mixing angles (which is $\cos(\beta - \alpha)$ in the 2HDM), and the mass of the neutral h boson; see Ref. [1]. Can we distinguish between the MHDM and 2HDM for this higher mass region, $M_H > m_t + m_b$? In the MHDM, large values of $|Z|$ and small values of $|X|, |Y|$ could enhance $\tau\nu_\tau$ decays to values not attainable in the 2HDM. However asymmetric choices such as $|X| = 0.1, |Y| = 0.1, |Z| = 10$ would be needed and this seems somewhat unnatural. Of course, the discovery of a second charged scalar would provide conclusive proof of a MHDM (notwithstanding the existence of more exotic Higgs sectors containing triplets etc.).

Table 6 shows the various backgrounds to the H^+H^- signal from W^+W^- and ZZ production at $\sqrt{s} = 500$ GeV, assuming an integrated luminosity of 3 fb^{-1} . For the

	$cbcb$	$cbcs$	$cb\tau\nu_\tau$	$cscs$	$cst\nu_\tau$	$\tau\nu_\tau\tau\nu_\tau$
W^+W^-	0.0	7.2	2.4	2284.0	1551.4	263.4
ZZ	27.3	0.0	0.0	27.9	0.0	10.3
$H^+H^-(80)$	$0 \rightarrow 317$	$0 \rightarrow 317$	$0 \rightarrow 317$	$0 \rightarrow 317$	$0 \rightarrow 317$	$0 \rightarrow 317$
$H^+H^-(90)$	$0 \rightarrow 303$	$0 \rightarrow 303$	$0 \rightarrow 303$	$0 \rightarrow 303$	$0 \rightarrow 303$	$0 \rightarrow 303$

Table 6: The expected number of W^+W^- , ZZ and H^+H^- ($M_H = 80, 90$ GeV) induced events for 3 fb^{-1} integrated luminosity at 500 GeV.

case of $M_H = 80$ GeV, a $\text{BR}(H^\pm \rightarrow cb)$ of 20% would produce 114.1 decays containing at least one b quark. The background is 22.6 events, and so the charged scalar could easily be detected. For $M_H \approx M_Z$ there is no particular problem, since the numbers of H^+H^- and ZZ events are comparable, see Fig. 4.

For the 2HDM, $M_H \approx M_W$ is problematic due to an enormous background, although Ref. [13] discusses how this could be reduced. As for the MHDM, the $M_H \approx M_Z$ region does not pose any particular problem since the signal and background cross sections are comparable.

The situation when $M_H \approx m_t \approx 180$ GeV needs special consideration. Here there exists a background from $e^+e^- \rightarrow Z^*, \gamma^* \rightarrow t\bar{t}$. The literature has dealt with this case for the 2HDM (see for example Ref. [12]) and the analysis holds again for the MHDM. The best chance of eliminating the $t\bar{t}$ background is by exploiting the $H^+H^- \rightarrow c\bar{c}s\bar{s}$ channel. Because the $t\bar{t}$ decays primarily to $W^+W^-b\bar{b}$, the process of anti- b -tagging can single out the Higgs bosons. This idea will in general work better for the 2HDM where the $H^\pm$ rarely decays to b quarks.

6 Conclusions

In this paper we have studied the prospects for detection of light charged Higgs scalars of the MHDM and 2HDM at e^+e^- colliders. It is theoretically possible that the masses of these particles lie within the discovery range of LEP2. For the MHDM, with $\sqrt{s} = 180$ GeV, masses from 41.7 GeV (current LEP lower bound) to $M_H < M_W$ will be covered successfully. For $M_H \approx M_W$, detection requires a branching ratio of $> 30\%$ for the $H^\pm \rightarrow cb$ decay, with b -tagging efficiencies around 50%. For $\sqrt{s} = 200$ GeV, a $\text{BR}(H^\pm \rightarrow cb)$ of 20% would be sufficient if $M_H \approx M_W$, but for $M_H \approx M_Z$ too few charged scalars are produced. We have shown that branching ratios of these magnitudes (or greater) are allowed, which is in contrast to the 2HDM. A distinctive signature of the $H^\pm$ would be a $\text{BR}(H^\pm \rightarrow cb) > 10\%$. This would be sufficiently large to distinguish the MHDM from the 2HDM, given at least 100 or so pair production events.

For the $H^\pm$ of the various 2HDM considered (Model I with $\theta = \pi/2$, $\theta = 0$ and Model II with $\theta = \pi/2$) the above comments apply, apart from the $M_H \approx M_W$ and $M_H \approx M_Z$ mass regions. Here detection seems difficult, as there is no significant $H^\pm \rightarrow cb$ decay to exploit.

We have also considered higher energy e^+e^- colliders with increased luminosity. These would enable heavier charged scalars to be produced (should M_H be beyond the LEP2 range), and create more events for the difficult $M_H \approx M_W$ and $M_H \approx M_Z$ regions. For both the 2HDM and MHDM detection is fairly straightforward for $2M_H < 0.8\sqrt{s}$. The only potential problem would be for $M_H \approx M_W$, but Ref. [13] has shown that a sizeable $\tau\nu_\tau$ branching ratio would be sufficient for detection. A significant $H^\pm \rightarrow cb$ channel in the MHDM would provide an alternative signal for this region and would again provide a way of distinguishing between the 2HDM and the MHDM as long as $M_H < m_t + m_b$. If $H^\pm \rightarrow tb$ is allowed then this channel (along with a possible $H^\pm \rightarrow W^\pm h$) generally dominates for both models and thus they would be virtually indistinguishable. However, there does exist an unnatural region of parameter space ($|X|, |Y|$ small and $|Z|$ large) which would produce a higher $\text{BR}(H^\pm \rightarrow \tau\nu_\tau)$ for the MHDM than is ever possible in the 2HDM. This would in principle be a way of distinguishing between the two models.

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References

- [1] J.F. Gunion, H.E. Haber, G.L. Kane and S. Dawson, *The Higgs Hunter's Guide* (Addison-Wesley, Reading, 1990).
- [2] Y. Grossman, Nucl. Phys. **B426** (1994) 355.
- [3] Review of Particle Properties, Phys. Rev. **D50** (1994).
- [4] S.L. Glashow and S. Weinberg, Phys. Rev. **D15** (1977) 1958.
- [5] G.C. Branco, A.J. Buras and J.M. Gerard, Nucl. Phys. **B259** (1985) 306.
- [6] P. Krawczyk and S. Pokorski, Nucl. Phys. **B364** (1991) 10.
- [7] CLEO collaboration: R. Ammaret *et al.*, Phys. Rev. Lett. **71** (1993) 674.
- [8] ALEPH collaboration: Z. Ajaltouni *et al.*, Phys. Lett. **B241** (1990) 626.
- [9] S. Komamiya, Phys. Rev. **D38** (1988) 2158.
- [10] B.K. Bullock, K. Hagiwara and A.D. Martin, Phys. Rev. Lett. **67** (1991) 3055.
- [11] J.E. Augustin, preprint CERN-PPE-94-81 (1994).
- [12] Proceedings of the Munich - Annecy - Hamburg Workshop on 'e⁺e⁻ collisions at 500 GeV', December 1993, ed. P.M. Zerwas, DESY 92-123C (1993).
- [13] J. Alexander, D.L. Burke, C.K. Jung, S. Komamiya, and P.R. Burchat in *Proceedings of the Summer Study on High Energy Physics in the 1990s*, Snowmass 1988, ed. S. Jensen (World Scientific, Singapore, 1989) p. 135.

Figure Captions

- [1] Lines of constant branching ratio for the decay $H^+ \rightarrow c\bar{b}$ with $|Z| = 0$. The experimentally allowed region lies beneath the curve $|XY| = 4$.
- [2] As for Fig. 1 but with $|Z| = 0.5$.
- [3] Expected number of H^+H^- pairs produced with $\int \mathcal{L} = 500 \text{ pb}^{-1}$ at LEP2 as a function of M_H , for $\sqrt{s} = 180$ and 200 GeV.
- [4] Cross sections for the pair production of $W^\pm$, Z and $H^\pm$ at e^+e^- colliders, as a function of $\sqrt{s}$.
- [5] As for Fig. 3, but for $\sqrt{s} = 500$ and 1000 GeV with $\int \mathcal{L} = 3 \text{ fb}^{-1}$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5