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Lepton non-universality at LEP and charged Higgs

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Abstract: A recent analysis of the LEP data shows an interesting deviation from lepton universality in W boson decays. An excess at the level of 2.8 σ is found in the tau mode branching ratio with respect to the other two modes. It is suggested that this seeming lepton non-universality might stem from pair production of charged Higgs bosons almost degenerate with W, that preferentially decay to heavy fermions. It is shown that the deviation can be reduced to 1.4 σ in two Higgs doublet model I without any conflict with the existing direct or indirect constraints. This conclusion is largely independent of $\tan\beta$, the ratio of Higgs vacuum expectation values. This scenario can be tested at the forthcoming international linear collider.

Keywords: Higgs Physics, LEP HERA and SLC Physics, Beyond Standard Model.

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Contents

1. Introduction

In a non-abelian gauge theory, the gauge interaction of a fermion is fixed by its representation under the gauge group, up to an overall gauge coupling. The charged current interaction in the Standard Model (SM) is described by an SU(2) group, under which the three flavors of left-handed leptons transform as doublets. An obvious consequence is the lepton universality in the W boson interactions. This has been tested in muon decay, leptonic and semi-leptonic tau decays, and leptonic meson decays (for a review, see [1]; updated results can be found in [2, 3]), showing no evidence of deviation from it.

In contrast, recent LEP data on leptonic branching fractions of the W boson appears to bear a small but intriguing discrepancy from lepton universality [4, 5]. An excess of 2.8 standard deviations is found in the branching ratio of the tau mode with respect to the other two leptonic modes.

If one takes this number seriously and attempts to give an account of it with modification to the SM, a possibility may be to alter the model in such a way that an (effective) W-lepton-neutrino vertex becomes flavor-dependent. Indeed, there has been a class of models taking this approach [6], the last of which was devised to explain the above discrepancy. This model has two SU(2) gauge groups. The first and the second family fermions are charged under one group, and the third the other. Mixing of the gauge bosons of different groups can lead to flavor-dependent lightest W boson couplings to leptons. Tuning the model parameters, one can accommodate the measured leptonic branching ratios. One immediate problem of this idea, however, is that it is likely to affect the aforementioned muon and tau decay rates mediated by W exchange, thereby spoiling their agreement with lepton universality. Another class of models that can give rise to non-universal charged current interaction are those involving a low scale seesaw mechanism [7], although they were not conceived for reconciling the leptonic W branching ratios.

As the difficulty with non-universal charged current interaction is rather evident, this work takes a different approach. It is speculated that the apparent excess of tau mode decay rate is in fact due to pair production of charged Higgs bosons, which dominantly decay to $\tau\nu$ or cs. The LEP measurements of the W boson decay rates are performed by counting the final state fermions. Thus, if a charged Higgs boson decays, its decay products may well appear to be coming from a W decay.

To mimic a W boson, a charged Higgs boson should be light enough to be produced at LEP. Furthermore, its mass should be around m_W to give a meaningful alteration in the number of tau mode events, since the charged Higgs pair production rate rapidly decreases as $m_{H^\pm}$ increases. The following section will elaborate on this. Throughout this paper, the charged Higgs mass is assumed to be slightly above the W mass. This helps to avoid disturbing the W mass measurements at the pair threshold as well. Instantly, this somewhat low $m_{H^\pm}$ raises doubts about its compatibility with the available search results. Particle search is a model-dependent task, and one should first specify in which context the charged Higgs is introduced. Note that this low $m_{H^\pm}$ is hard to be achieved in the minimal supersymmetric standard model (MSSM) due to the tree-level relation, $m_{H^\pm}^2 = m_W^2 + m_A^2$, in conjunction with the CP-odd Higgs mass lower bound, $m_A > 93$ GeV [8]. Thus a remaining natural choice is a general two Higgs doublet model (2HDM) which allows for $m_{H^\pm} \approx m_W$. For this $m_{H^\pm}$, the pair production cross section of charged Higgs turns out to be below 1% of that of W, at LEP energies. This kind of small peak hiding behind a much larger background resonance is extremely difficult to discriminate [9]. In fact, branching ratio independent charged Higgs mass limit from LEP, is lower than m_W.[1]

The two Higgs doublets H_1 and H_2 in 2HDM have eight real degrees of freedom. Three of them are eaten by the W and Z bosons to be their longitudinal components. The remaining five form the lighter CP-even neutral Higgs h^0, the heavier CP-even neutral Higgs H^0, the CP-odd neutral Higgs A^0, and the charged Higgs $H^\pm$, in the case of CP-conserving Higgs sector. Henceforth, CP-invariance in the Higgs sector will be assumed. The five Higgs boson masses in 2HDM can be changed independently of one another except that they are subject to the condition, $m_h \leq m_H$, following from their definitions. The Higgs potential has a large enough number of free parameters for this, unlike the Higgs sector of MSSM where many of the parameters are constrained by supersymmetry.

In the presence of more than one Higgs doublets, flavor changing neural current (FCNC) interactions are in general mediated by Higgs bosons at tree level. In order to avoid this danger, one typically makes assumptions on the way how Higgs doublets couple to fermions. This work follows [11] in classifying models with different assumptions. In Model I, only one Higgs doublet, say H_2, couples to quarks and charged leptons. Models III, IV, and II are obtained from Model I by coupling H_1, instead of H_2, to the down-type quarks, the charged leptons, and both, respectively. These models can be implemented by adopting a discrete symmetry for example [12]. They are summarized in

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[1] A neutral Higgs analogy had been discussed in [10] where the Higgs is assumed to be degenerate with the Z boson.

Models	I		II		III		IV	
	couples to	A_f	couples to	A_f	couples to	A_f	couples to	A_f
$\begin{pmatrix} u \\ d \end{pmatrix}$	H_2	$\cot\beta$	H_2	$\cot\beta$	H_2	$\cot\beta$	H_2	$\cot\beta$
	H_2	$-\cot\beta$	H_1	$\tan\beta$	H_1	$\tan\beta$	H_2	$-\cot\beta$
$\begin{pmatrix} \nu \\ l \end{pmatrix}$	H_2	$-\cot\beta$	H_1	$\tan\beta$	H_2	$-\cot\beta$	H_1	$\tan\beta$

Table 1: For each model, the Higgs doublet that couples to each type of fermion is shown, and the coefficients A_f in the charged Higgs Yukawa interaction terms written in (1.1) are given. This table is an excerpt from [11].

table 1.

The interactions between charged Higgs and fermions are given by

$$\mathcal{L} = \frac{g}{\sqrt{2}m_W} H^+ [V_{ij} m_{u_i} A_u \overline{u}_{Ri} d_{Lj} + V_{ij} m_{d_j} A_d \overline{u}_{Li} d_{Rj} + m_l A_l \overline{\nu}_L l_R] + \text{h.c.}, \tag{1.1}$$

where g is the SU(2) gauge coupling, V_{ij} is an element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, and the coefficient A_f for $f = u, d, l$ should be chosen from table 1 according to the given model. The parameter $\tan\beta$ appearing in this table is defined by

$$\tan\beta \equiv v_2/v_1, \tag{1.2}$$

with $v_{1,2}$ being the vacuum expectation values of $H_{1,2}$ respectively. This interaction Lagrangian is important in two respects. First, it causes the decay $H^\pm \to \tau\nu_\tau$. It should have a suitable branching fraction such that the tau mode excess in W decays can be attributed to charged Higgs. Having $\mathcal{B}(H^\pm \to \tau\nu_\tau)$ within a right range is also crucial for escaping from the charged Higgs direct search at LEP. Second, those processes that provide constraints on the model such as FCNC, $t \to H^+ b$, and $Z \to b\overline{b}$, are influenced by the above Yukawa interactions.

The main idea has been outlined up to this point. The remaining task is then twofold: to evaluate how much excess of tau production can be ascribed to the charged Higgs contribution, and to examine whether or not a variety of experiential constraints can be satisfied. This is to be performed for each of the four models listed in table 1 with $\tan\beta$ as a tunable parameter. Here in advance, it is noted that only Model I survives the constraints that will be discussed in section 3. This leads to $\mathcal{B}(H^\pm \to \tau\nu_\tau) \simeq 0.7$, which will be used in the following section. It will be shown that the lepton non-universality can be alleviated to a large extent without violating any constraint. In particular, the additional tau mode branching fraction due to charged Higgs, is largely determined as a function of $m_{H^\pm}$ independent of $\tan\beta$, by the direct search and the $b \to s\gamma$ constraints.

The paper is organized as follows. Section 2 contains the main result of this paper, which reveals that a sizeable fraction of the observed lepton non-universality can be resolved by pair production of charged Higgs nearly degenerate with the W boson. In section 3, it is shown that the current direct and indirect constraints are consistent with this mass of charged Higgs. Section 4 presents discussions on how to test this scenario at future experiments. Finally, the conclusion is given in section 5.

Experiment	$\mathcal{B}(W \to e\nu_e)$ [%]	$\mathcal{B}(W \to \mu\nu_\mu)$ [%]	$\mathcal{B}(W \to \tau\nu_\tau)$ [%]
ALEPH	$10.78 \pm 0.29^*$	$10.87 \pm 0.26^*$	$11.25 \pm 0.38^*$
DELPHI	$10.55 \pm 0.34^*$	$10.65 \pm 0.27^*$	$11.46 \pm 0.43^*$
L3	$10.78 \pm 0.32^*$	$10.03 \pm 0.31^*$	$11.89 \pm 0.45^*$
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48
LEP	10.65 ± 0.17	10.59 ± 0.15	11.44 ± 0.22

Table 2: Summary, copied from [5], of W branching fractions derived from W-pair production cross sections measurements up to 207 GeV centre-of-mass energy. All results are preliminary with the exception of those indicated by *.

2. Leptonic branching fractions of W boson

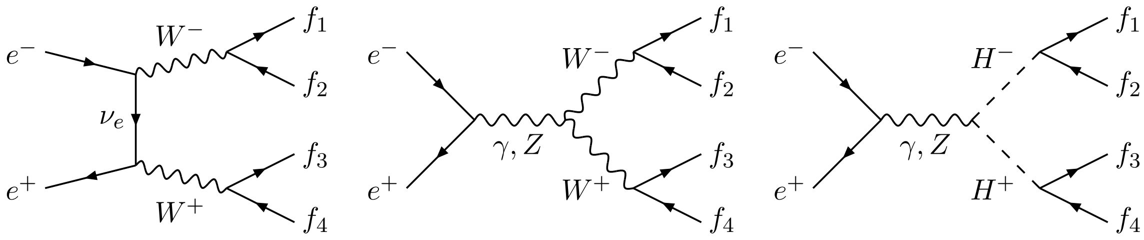
The leptonic branching fractions of W boson has been measured from partial cross sections of $WW \to 4f$ by the four experiments at LEP [4] without the assumption of lepton universality. Part of a table summarizing the result in the latest report [5] is quoted in table 2. Interestingly enough, all the four experiments show a tendency that $\tau\nu_\tau$ mode has a larger branching fraction than the other two modes, albeit with an error bar not much shorter than the difference. A ratio between the tau fraction and the average of electron and muon fractions is given by

$$\left.\frac{\mathcal{B}(W \to \tau\nu_\tau)}{[\mathcal{B}(W \to e\nu_e) + \mathcal{B}(W \to \mu\nu_\mu)]/2}\right|_{\mathrm{LEP}} = 1.077 \pm 0.026, \tag{2.1}$$

under the assumption of partial lepton universality. The departure from complete lepton universality is at the level of 2.8 standard deviations. It may be explained away by a statistical fluctuation which would be gone with sufficient amount of data. Alternatively, the present work takes an interesting possibility that this apparent lepton non-universality stems from physics beyond the minimal Standard Model.

The leptonic W branching fractions were measured from the W-pair production process followed by decays into four fermions. In the SM, the tree-level diagrams for this process are given by figures 1(a) and 1(b). The final state fermions can be $(f_1, f_2) = (e, \overline{\nu}_e), (\mu, \overline{\nu}_\mu), (\tau, \overline{\nu}_\tau), (d, \overline{u}), (s, \overline{c})$ with equal weight, where d and s quarks should include CKM mixing, and (f_4, f_3) can be one conjugate of these states. Now, suppose that there is a charged Higgs boson whose mass is close to the W boson mass. Then, the graph in figure 1(c) produces four fermions as well but with different weights, since a charged Higgs decays preferentially to $(f_1, f_2) = (\tau, \overline{\nu}_\tau), (s, \overline{c})$. If one counts the number of final state leptons for each flavor to measure its branching fraction, the excess of tau final state caused by charged Higgs decay may appear as a higher branching fraction of $W \to \tau\nu_\tau$.

It is straightforward to estimate how much difference this charged Higgs contamination can make. The result differs depending on which modes are considered. The $qql\nu$ modes are most statistically significant. Comparing only $qq\tau\nu$ and $qq\mu\nu$ for example, one has the



(a) (b) (c)

Figure 1: Tree-level Feynman graphs for W-pair production within the SM [(a), (b)], and charged Higgs pair production in 2HDM [(c)], each followed by subsequent decays to four fermions.

ratio of apparent branching fractions,

$$\left.\frac{\mathcal{B}(W \to \tau\nu_\tau)}{\mathcal{B}(W \to \mu\nu_\mu)}\right|_{\text{appar}} = \frac{\sigma_{WW}^{qq\tau\nu} + \sigma_{HH}^{qq\tau\nu}}{\sigma_{WW}^{qq\mu\nu}} = 1 + \frac{\sigma_{HH}}{\sigma_{WW}} \frac{\mathcal{B}(H^\pm \to \tau\nu_\tau)}{\mathcal{B}(W \to \mu\nu_\mu)} \frac{\mathcal{B}(H^\pm \to qq)}{\mathcal{B}(W \to qq)} \approx 1.02. \tag{2.2}$$

For numerical estimation, the charged Higgs mass is taken to be 81 GeV and the center-of-mass energy 200 GeV. For this energy, the charged Higgs pair production cross section is $\sigma_{HH} = 0.14$ pb (from the second of [13]), and the W pair production cross section is $\sigma_{WW} = 17$ pb (from the second of [4]). As for the branching fractions, $\mathcal{B}(W \to qq) = 6/9$, and $\mathcal{B}(W \to \mu\nu_\mu) = 1/9$ were used, in addition to $\mathcal{B}(H^\pm \to qq) = 0.3$ and $\mathcal{B}(H^\pm \to \tau\nu_\tau) = 0.7$ which will be justified in the next section. One may do a similar calculation with only $\tau\nu\tau\nu$ and $\mu\nu\mu\nu$ modes to get a higher value,

$$\left.\frac{\mathcal{B}(W \to \tau\nu_\tau)}{\mathcal{B}(W \to \mu\nu_\mu)}\right|_{\text{appar}} = \sqrt{1 + \frac{\sigma_{HH}}{\sigma_{WW}} \left(\frac{\mathcal{B}(H^\pm \to \tau\nu_\tau)}{\mathcal{B}(W \to \mu\nu_\mu)}\right)^2} \approx 1.15, \tag{2.3}$$

although a leptonic channel cross section is much smaller than a semi-leptonic one, thereby making less significant contribution to the average. From these estimates, one may envisage a possibility that a few per cent out of the seeming 8% deviation of (2.1) from unity, is accommodated by the charged Higgs contribution to four fermion production.

The charged Higgs and W-pair production cross sections, however, are different functions of the center-of-mass energy, as are shown in figure 2. Therefore, one should do a more careful analysis taking into account other factors. Fortunately, the DELPHI collaboration (the first of [4]) provides detailed data for each of the ten different channels including the number of selected events, the background cross section, and the efficiency matrix, as well as luminosity. The luminosity and number of events are presented as functions of $\sqrt{s}$ from 161 GeV to 207 GeV. Using these data, one can perform a maximum likelihood fit. The likelihood is defined as

$$L = \prod_{s,i} \frac{e^{-\mu_s^i} (\mu_s^i)^{N_s^i}}{(N_s^i)!}, \tag{2.4}$$

where s denotes the squared center-of-mass energy, i runs over the ten channels, $jjjj$, $jje\nu$, $jj\mu\nu$, $jj\tau\nu$, $\tau\nu\tau\nu$, $e\nu\tau\nu$, $\mu\nu\tau\nu$, $e\nu e\nu$, $e\nu\mu\nu$, and $\mu\nu\mu\nu$, and N_s^i is the number of selected events in channel i at $\sqrt{s}$. The expected number of events μ_s^i in channel i at $\sqrt{s}$,

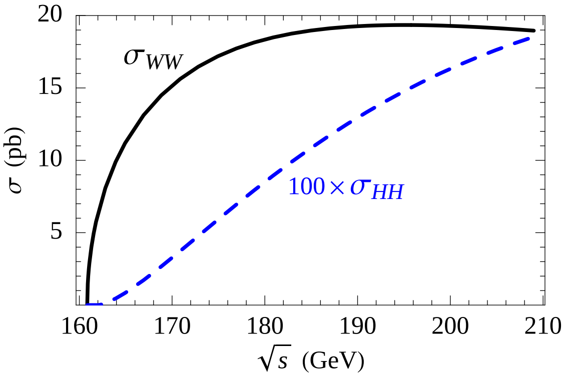


Figure 2: The W boson pair production cross section σ_{WW} (the solid curve) and the charged Higgs pair production cross section σ_{HH} multiplied by 100 for $m_{H^\pm} = 81$ GeV (the dashed curve), from tree-level calculations, as functions of the center-of-mass energy available at LEP.

is written as

$$\mu_s^i = \left(\sum_j \epsilon_s^{ij} \sigma_s^j + \sigma_{\mathrm{bg},s}^i \right) \mathcal{L}_s, \tag{2.5}$$

where ϵ_s^{ij} is the efficiency matrix, $\sigma_{\mathrm{bg},s}^i$ is the background cross section, and $\mathcal{L}_s$ is the luminosity. One can express the channel cross section σ_s^j as a function of $\sigma_{WW,s}$ and the three leptonic W branching fractions, and use the data in the aforementioned reference for the other variables. As before, the subscript s attached to a symbol is a reminder of the relevant center-of-mass energy.

Performing a fit within the SM, one finds at the maximum of L,

$$\mathcal{B}(W \to e\nu_e) = 10.79, \quad \mathcal{B}(W \to \mu\nu_\mu) = 10.67, \quad \mathcal{B}(W \to \tau\nu_\tau) = 11.49. \tag{2.6}$$

These results are slightly different from but close enough to those by DELPHI which is reproduced in table 2. The small variances may have come from the fact that the efficiency matrix and the background cross sections at $\sqrt{s} = 200$ GeV are used for the other values of $\sqrt{s}$ as well. Combining the above three numbers leads to

$$\left. \frac{\mathcal{B}(W \to \tau\nu_\tau)}{[\mathcal{B}(W \to e\nu_e) + \mathcal{B}(W \to \mu\nu_\mu)]/2} \right|_{\text{SM fit}} = 1.071. \tag{2.7}$$

Having tested that a reliable estimation can be made using the available data, one may proceed to do the same fit including charged Higgs contributions. This time, the following three channel cross sections should be modified as

$$\begin{aligned}
\sigma_s^{qq\tau\nu} &= \sigma_{WW,s} \cdot 2\mathcal{B}(W \to qq)\mathcal{B}(W \to \tau\nu_\tau) + \sigma_{HH,s} \cdot 2\mathcal{B}(H^\pm \to qq)\mathcal{B}(H^\pm \to \tau\nu_\tau), \\
\sigma_s^{\tau\nu\tau\nu} &= \sigma_{WW,s} \cdot \mathcal{B}^2(W \to \tau\nu_\tau) + \sigma_{HH,s} \cdot \mathcal{B}^2(H^\pm \to \tau\nu_\tau), \\
\sigma_s^{qqqq} &= \sigma_{WW,s} \cdot \mathcal{B}^2(W \to qq) + \sigma_{HH,s} \cdot \mathcal{B}^2(H^\pm \to qq),
\end{aligned} \tag{2.8}$$

where each first term is the usual W boson contribution and second charged Higgs. Charged Higgs decays to muon and electron modes are ignored due to the small Yukawa couplings,

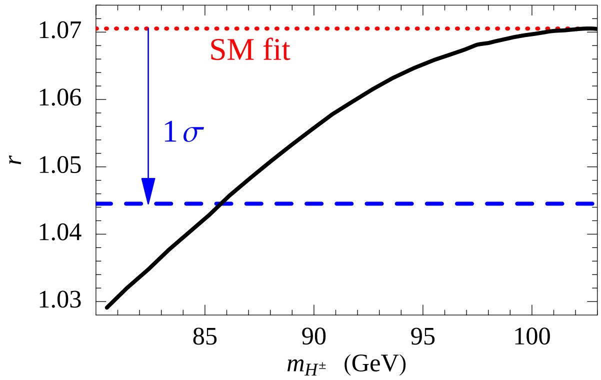


Figure 3: Fit result of $r \equiv 2\mathcal{B}(W \to \tau\nu_\tau)/[\mathcal{B}(W \to e\nu_e)+\mathcal{B}(W \to \mu\nu_\mu)]$ using the DELPHI data, as a function of $m_{H^\pm}$. The Model I branching fractions, $\mathcal{B}(H^\pm \to qq) = 0.3$ and $\mathcal{B}(H^\pm \to \tau\nu_\tau) = 0.7$, are used. The length of the vertical arrow is one standard deviation from (2.1).

and the other modes are assumed to have $\mathcal{B}(H^\pm \to qq) = 0.3$ and $\mathcal{B}(H^\pm \to \tau\nu_\tau) = 0.7$ as for (2.2) and (2.3). For $\sigma_{HH,s}$, the tree-level cross section shown in figure 2 is used. With the charged Higgs contributions included, a likelihood fit results in

$$\mathcal{B}(W \to e\nu_e) = 10.84, \quad \mathcal{B}(W \to \mu\nu_\mu) = 10.73, \quad \mathcal{B}(W \to \tau\nu_\tau) = 11.12. \tag{2.9}$$

Recall that these are not the apparent branching fractions of the W boson, but the real ones excluding contaminations from charged Higgs decays. Thus, their ideal values should coincide with one another. The tau mode excess, then, decreases to

$$\left.\frac{\mathcal{B}(W \to \tau\nu_\tau)}{[\mathcal{B}(W \to e\nu_e) + \mathcal{B}(W \to \mu\nu_\mu)]/2}\right|_{\text{2HDM fit}} = 1.031. \tag{2.10}$$

Comparing this and (2.7), one can notice that the deviation from unity has been diminished by 4%, a value in between the estimates from (2.2) and (2.3).

It is reasonable to guess that approximately the same amount of reduction can be made for each of the four experiments. This would reduce the overall ratio to

$$\left.\frac{\mathcal{B}(W \to \tau\nu_\tau)}{[\mathcal{B}(W \to e\nu_e) + \mathcal{B}(W \to \mu\nu_\mu)]/2}\right|_{\text{LEP,2HDM}} \simeq 1.037 \pm 0.026, \tag{2.11}$$

of which the departure from unity is 1.4 σ. This is a noticeable, if not complete, amelioration from the original 2.8 σ in (2.1).

Remember that this prediction is a function of $m_{H^\pm}$ and $\mathcal{B}(H^\pm \to \tau\nu_\tau)$, and $m_{H^\pm}$ has been assumed to be 81 GeV so far. A remark is in order on how the result depends on these parameters. Once one assumes that the charged Higgs mass is close to the W boson mass and imposes the charged Higgs direct search limit and $b \to s\gamma$ constraint, $\mathcal{B}(H^\pm \to \tau\nu_\tau)$ is almost uniquely determined, as will be discussed in the next section. The remaining dependence on $m_{H^\pm}$ is shown in figure 3. The vertical axis, labeled r, is the ratio in (2.10) from the fit using the DELPHI data for a given value of $m_{H^\pm}$. The ratio worsens as the charged Higgs gets heavier, and eventually for $m_{H^\pm} = 103$ GeV, coincides with the SM fit in (2.7), marked by the dotted horizontal line. Obviously, a light charged Higgs is favored for lepton-universality. To reduce the ratio by at least 1-σ (= 0.026), one should require that

$$m_{H^\pm} < 85.7 \text{ GeV}. \tag{2.12}$$

It can be checked that this inequality holds for any value of $\mathcal{B}(H^\pm \to \tau\nu_\tau)$. This justifies the assumption of $m_{H^\pm} \approx m_W$ made above.

3. Constraints from data

3.1 $B \to X_s\gamma$

One of the most stringent lower limits on the charged Higgs mass has been given by the process $b \to s\gamma$. One will see that this constraint, combined with the direct search limit from LEP, almost determines the type of 2HDM that can be used for the present purpose.

In order to notice different behaviors among models, leading logarithmic approximation should be enough here. The weak effective Hamiltonian for the $B \to X_s\gamma$ mode reads

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1\ldots6,7\gamma,8g} C_i(\mu) Q_i(\mu) + \text{h.c.}, \tag{3.1}$$

where operators with non-vanishing Wilson coefficients at the matching scale are

$$\begin{aligned} Q_2 &= \bar{s}_L \gamma_\mu c_L \; \bar{c}_L \gamma^\mu b_L, \\ Q_{7\gamma} &= \frac{e}{16\pi^2} \, m_b \, \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R, \\ Q_{8g} &= \frac{g_s}{16\pi^2} \, m_b \, \bar{s}_L \sigma_{\mu\nu} G^{\mu\nu} b_R. \end{aligned} \tag{3.2}$$

In the SM, the Wilson coefficients at the matching scale μ_W are given by

$$C_2^{\text{SM}}(\mu_W) = 1, \qquad C_{7\gamma,8g}^{\text{SM}}(\mu_W) = F_{7,8}^{(1)}(x), \tag{3.3}$$

and in 2HDM, there are additional charged Higgs contributions [14],

$$C_2^{H^\pm}(\mu_W) = 0, \qquad C_{7\gamma,8g}^{H^\pm}(\mu_W) = \frac{A_u^2}{3} F_{7,8}^{(1)}(y) + A_u A_d F_{7,8}^{(2)}(y), \tag{3.4}$$

with the notations, $x \equiv m_t^2/m_W^2$ and $y \equiv m_t^2/m_{H^\pm}^2$. Definitions of $F_{7,8}^{(1,2)}$ can be found in [14]. After performing renormalization group running of these Wilson coefficients down to the m_b scale [15], one has the ratio of branching fractions in 2HDM and in the SM,

$$\frac{\mathcal{B}(B \to X_s\gamma)}{\mathcal{B}_{\text{SM}}(B \to X_s\gamma)} = \left| \frac{C_{7\gamma}^{\text{SM}}(m_b) + C_{7\gamma}^{H^\pm}(m_b)}{C_{7\gamma}^{\text{SM}}(m_b)} \right|^2 = \left| 1 + 0.69 A_u A_d + 0.14 A_u^2 \right|^2, \tag{3.5}$$

where it is assumed that $m_{H^\pm} = 85.7$ GeV from (2.12).

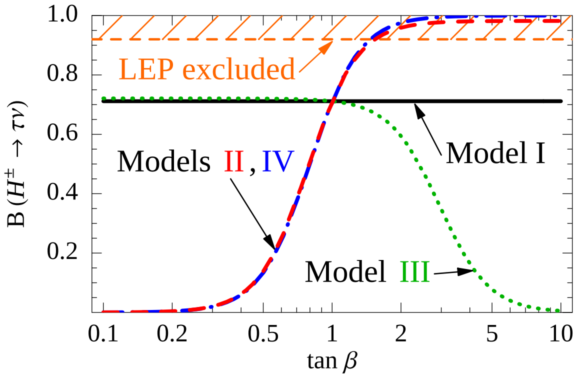


Figure 4: The branching fraction $\mathcal{B}(H^\pm \to \tau\nu_\tau)$ as a function of $\tan\beta$ for each of the Models I–IV, with the parameters, $m_c = 0.67$ GeV, $m_s = 0.07$ GeV, $V_{cs} = 1$, and $m_\tau = 1.777$ GeV. The running quark masses are from [17]. The hatched range of $\mathcal{B}(H^\pm \to \tau\nu_\tau)$ is excluded by the charged Higgs direct search at LEP for $m_{H^\pm} = 85.7$ GeV. This is an update of a plot in [11].

From table 1, it is obvious that Models II and III lead to at least 180% excess of $\mathcal{B}(B \to X_s\gamma)$ with respect to the SM result for any value of $\tan\beta$ because of the term proportional to $A_u A_d$. This is in gross conflict with the data, and thus these two models are excluded from consideration. However, for the remaining two models, sizes of both A_u and A_d are inversely proportional to $\tan\beta$. Indeed, the difference in branching fraction made by charged Higgs contributions is reduced below the current experimental error [16] provided that

$$\tan\beta \gtrsim 4. \tag{3.6}$$

This is the case even for $m_{H^\pm} = 81$ GeV. Consequently, one can conclude that Models I and IV are consistent with $\mathcal{B}(B \to X_s\gamma)$ for moderately high $\tan\beta$ [11, 14]. This behavior of charged Higgs decoupling from quarks for high $\tan\beta$, will be crucial for evading low energy constraints discussed later.

3.2 Direct searches

H^+H^- pair production at LEP. The four experiments at LEP have performed direct searches for charged Higgs by pair production thereof [13], described by figure 1(c). The resulting lower bound on the charged Higgs mass varies rather significantly depending on the branching fraction $\mathcal{B}(H^\pm \to \tau\nu_\tau)$. Examining the exclusion plots, one can notice that $m_{H^\pm} = 85.7$ GeV is not excluded by the data at 95% confidence level provided that

$$\mathcal{B}(H^\pm \to \tau\nu_\tau) < 0.92. \tag{3.7}$$

The branching fraction for each model as a function of $\tan\beta$ is presented in figure 4. Among the four models shown in the plot, only Models I and IV were allowed by $b \to s\gamma$ for $\tan\beta \gtrsim 4$ in the previous subsection. The figure shows that Model IV leads to $\mathcal{B}(H^\pm \to \tau\nu_\tau) \gtrsim 0.99$ for this range of $\tan\beta$. As a result, the only remaining possibility is Model I in which

$$\mathcal{B}(H^\pm \to \tau\nu_\tau) \simeq 0.7. \tag{3.8}$$

For this value, the current charged Higgs mass lower bound is

$$m_{H^\pm} > 80.7 \ \ \text{GeV} \tag{3.9}$$

at 95% confidence level. This is the reason why 81 GeV is used in this paper as a representative value of $m_{H^\pm}$ that maximizes charged Higgs effects.

Note that the branching fraction in (3.8) is independent of $\tan\beta$, a property not shared by the other three models. This makes it easier to avoid a plethora of low energy constraints involving the charged Higgs Yukawa couplings to fermions by raising $\tan\beta$. As $\tan\beta$ increases, $\mathcal{B}(H^\pm \to \tau\nu_\tau)$ does not grow, so that the requirement (3.7) remains obeyed. Neither does it decrease, so that sufficient tau production can be achieved. Nevertheless, one cannot raise $\tan\beta$ all the way to infinity since the lifetime of charged Higgs grows like $\tan^2\beta$. If its decay vertex is far away from the place of e^+e^- collision, it may not look like a W boson decay. For $\tan\beta = 100$, the decay length is about 7 nm, which is negligible compared to the detector dimensions. Therefore, one may forget about it for a reasonable value of $\tan\beta$.

The main background hindering the charged Higgs searches is due to W-pair production given by figures 1(a) and 1(b). Because of this, these searches cannot be very sensitive for $m_{H^\pm}$ around m_W. In a sense, the present work is exploiting this fact the other way around in order to use charged Higgs as a source of background of the W boson production.

W-pair production cross section at LEP. If the four fermion final state from a charge Higgs pair is confused with that from a W-pair, then the W-pair production cross section will appear to have an excess. However, this excess is smaller than the current error. The length of error bar of σ_{WW} measured at LEP ranges between 0.21 pb and 0.7 pb [4, 5], depending on $\sqrt{s}$. This is larger than σ_{HH} plotted in figure 2, from which one can read that $\sigma_{HH} \lesssim 0.2$ pb for the center-of-mass energies available at LEP.

Angular distribution of W-pair production at LEP. The angular distribution of W-pair production can place a constraint on the charged Higgs contamination as the two have different angle dependences. The LEP measurements of the differential cross section $d\sigma_{WW}/d\cos\Theta_{W^-}$, though, are selecting only $qqe\nu$ and $qq\mu\nu$ final states for this purpose since from a jet, it is hard to tell the charge of the W boson which decayed into the jet [4, 5]. A charged Higgs seldom decays to $e\nu$ or $\mu\nu$, and hence its contribution to the observed $d\sigma_{WW}/d\cos\Theta_{W^-}$ is negligible.

Anomalous triple-gauge-boson couplings of W at LEP. Although the analysis of $d\sigma_{WW}/d\cos\Theta_{W^-}$ discards $qqqq$, $qq\tau\nu$, and $\tau\nu\tau\nu$ events, triple-gauge-boson coupling measurements make use of them [18]. Thus, one should check whether or not the charged Higgs contribution affects them excessively. It is convenient to follow the convention from [19], as in the above references for experimental data. The latest analysis by the L3 collaboration (the second of [18]) reports the six parameters given in table 3. The results are for the W-pair data.

	g_1^Z	κ_γ	λ_γ
SM	1.0	1.0	0.0
L3	$0.966^{+0.034}_{-0.032} \pm 0.015$	$0.910^{+0.074}_{-0.066} \pm 0.039$	$-0.024^{+0.035}_{-0.033} \pm 0.017$
2HDM	1.006	0.956	−0.000
	g_5^Z	κ_Z	λ_Z
SM	0.0	1.0	0.0
L3	$0.00 \pm 0.13 \pm 0.05$	$0.924^{+0.059}_{-0.056} \pm 0.024$	$-0.088^{+0.060}_{-0.057} \pm 0.023$
2HDM	0.000	1.009	0.009

Table 3: The triple-gauge-boson couplings g_1^Z, κ_γ, λ_γ, g_5^Z, κ_Z, and λ_Z, given in the SM, and their one-parameter fit results from the L3 experiment (the second of [18]). Each row labeled 2HDM shows the fit results including four fermion production due to charged Higgs pair for $m_{H^\pm} = 81$ GeV.

One may estimate the influence of charged Higgs pair on these parameters using an ideal experiment. Imagine an angular distribution measurement with 100% efficiency. For infinite integrated luminosity, one could replace the variables in the likelihood function of (2.4), with the differential cross sections, as

$$N_a^i = \frac{d\sigma^i_{WW}[(\Theta,\Omega,\overline{\Omega})_a]}{d\cos\Theta \, d\Omega \, d\overline{\Omega}} + \frac{1}{(4\pi)^2}\frac{d\sigma^i_{HH}(\Theta_a)}{d\cos\Theta}, \qquad \mu_a^i(\Psi) = \frac{d\sigma^i_{WW}[(\Theta,\Omega,\overline{\Omega})_a;\Psi]}{d\cos\Theta \, d\Omega \, d\overline{\Omega}}. \tag{3.10}$$

Here, N_a^i corresponds to the observed number of events in which the W or charged Higgs pair decays into a set i of four fermions for a set a of angles. The angle Θ is between e^- and W^- or H^- momentum directions in the e^+e^- center-of-mass frame, and Ω ($\overline{\Omega}$) is the direction of f_1 (f_4) momentum in the W^- (W^+) rest frame. The expected number $\mu_a^i(\Psi)$ is expressed as a function of a given set of couplings Ψ. By maximizing the likelihood function, one obtains the values in the table labeled 2HDM, for which the charged Higgs mass is taken to be 81 GeV. The difference of each coupling from its SM value is much smaller than or comparable to the error. Therefore, one can conclude that $m_{H^\pm} \approx m_W$ is compatible with the triple-gauge-boson coupling measurements. This should not be a surprise given that this mass of charged Higgs is allowed by the direct search discussed above which already incorporates angular distribution information of the final state fermions.

***W* mass and width measurements at LEP.** If the charged Higgs is not exactly degenerate with the W boson, its invariant mass distribution will be distorted, thereby disturbing the W mass and width measurements from direct reconstruction. This effect, though, is negligible due to the small production rate of charged Higgs pair. Using the same method as for checking the anomalous triple-gauge-boson couplings, one can estimate the shifts made by additional charged Higgs peak, in the W mass and width determined from Breit-Wigner distribution fit. The shifts are smaller than the current errors [5], for $m_{H^\pm}$ between 81 GeV and 85 GeV.

$t \to H^+ b$ at CDF. Since the charged Higgs boson mass in consideration is smaller than $m_t - m_b$, it can be produced in the top quark decay. A recent charged Higgs branching ratio

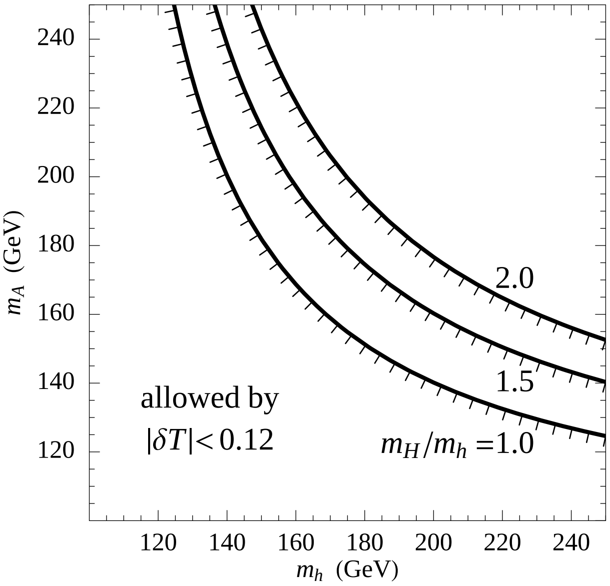


Figure 5: Constraints on m_h and m_A from δT, with the ratio m_H/m_h fixed at 1.0, 1.5, and 2.0, respectively. The charged Higgs mass is assumed to be 81 GeV. For a given m_H/m_h, some value of $\alpha - \beta$ leads to $|\delta T| < 0.12$, the current 1-σ range, in the lower left part of the corresponding curve.

independent analysis at CDF [20] indicates that the mass of $m_{H^\pm} = 81$ GeV is consistent with the data provided

$$\mathcal{B}(t \to H^\pm b) \lesssim 0.75. \tag{3.11}$$

For Model I, one can translate the above bound into the condition, $\tan\beta \gtrsim 0.5$, assuming that the top quark decays only to W^+b or H^+b. If a more sophisticated analysis tightens the upper bound on the branching fraction, $\tan\beta$ may need to be increased by a factor of a few.

3.3 Indirect constraints

***S*, *T*, and *U*.** Extended Higgs sector leads to additional oblique corrections to gauge boson propagators, which can be characterized by three parameters, S, T, and U [21]. Since these corrections arise from gauge couplings of the Higgs bosons, constraints on the S, T, and U parameters are not satisfied simply by increasing $\tan\beta$, unlike constraints on flavor changing processes. In order to estimate the additional effects, one can define δS, δT, and δU relative to some reference Standard Model, following [22]. Their expressions in 2HDM are available in [22, 23]. They depend on the difference between β and the CP-even neutral Higgs mixing angle α, and the Higgs masses, $m_{H^\pm}$, m_h, m_H, and m_A.

The fit result of T using the electroweak data is that $T = -0.17 \pm 0.12$ for 117 GeV of Higgs mass [24]. This error bar is used in the requirement $|\delta T| < 0.12$, which leaves the allowed region for $m_{H^\pm} = 81$ GeV on the (m_h, m_A) plane displayed in figure 5. At each point on the plane, m_H is determined by a given value of m_H/m_h, and $\alpha - \beta$ is chosen such that it minimizes $|\delta T|$. This optimal value of δT is used to draw the three exclusion plots, for m_H/m_h fixed at 1.0, 1.5, and 2.0, respectively. There appears a tendency that δT increases as neutral Higgs bosons get heavier. It is known that the size of correction to T grows with the mass split between charged Higgs and neutral Higgs bosons [25]. Nevertheless, it is clear that there is plenty of allowed parameter space with light enough h^0 or A^0.

The constraint from δS is not so severe as the one from δT. The influence on δU is completely negligible compared to those on T and S.

FCNC processes and CP violation. Flavor and CP violating processes supply important constraints on 2HDM. As was the case for $B \to X_s\gamma$, however, charged Higgs contributions to these processes get suppressed as $\tan\beta$ increases, even if $m_{H^\pm} \approx m_W$.

The first FCNC constraint to check is neutral meson mixing. Using the expressions in [11], one finds that for $\tan\beta \gtrsim 4$, the value of ΔM_{B_d} approaches the SM result within 10%. The latter agrees with the data up to hadronic uncertainties of about 20%. Therefore, the ΔM_{B_d} constraint can be obeyed. As for B_s–$\overline{B_s}$ mixing, it is usual to consider the ratio $\Delta M_{B_s}/\Delta M_{B_d}$ of mass splittings of B_s and B^0 mesons as hadronic uncertainties can be reduces in this way. Since the top quark contribution dominates in the box graphs for both types of mixings, the ratio is the same as in the SM, which is in agreement with the recent measurements [28]. In this model, the CKM matrix is the only source of flavor and CP violation, and hence $\sin 2\beta$ measured from $B \to J/\psi K$ is unchanged either. In the case of ΔM_K, its theoretical prediction is highly uncertain due to long distance effects, and the constraint should be safe for $\tan\beta$ consistent with B^0–$\overline{B^0}$ mixing.

It can also be expected that increasing $\tan\beta$ to an appropriate extent can make CP violation observables such as ϵ_K [11, 26, 27], and ϵ'/ϵ_K [11, 27] compatible with experiments. The same conclusion holds for other flavor changing processes such as $K_L \to \mu^+\mu^-$ [11] and $K^+ \to \pi^+\nu\overline{\nu}$ [11, 26]. Recently Belle announced an evidence of purely leptonic decay $B^- \to \tau\overline{\nu}$ [29], which can be mediated by a charged Higgs in addition to a W^- boson [30]. For $\tan\beta \gtrsim 1$, the branching fraction of this decay coincides with its SM value within 1%, while the data still has around 30% of error.

A_b and R_b. Constraints on 2HDM from A_b and R_b in the $Z \to b\bar{b}$ process have been studied in [23]. It was shown that Model I with $m_{H^\pm} = 81$ GeV for $\tan\beta \gtrsim 2$ was consistent with the then measured value, $R_b = 0.21642 \pm 0.00073$. This is because charged Higgs decouples from fermions for high $\tan\beta$. The error has been reduced by 10% by now [24], but the conclusion should not change very much. The data on A_b is not as constraining as R_b.

μ, τ, π, and K decay. Universality of W boson couplings to lepton charged currents has been thoroughly tested in leptonic decays of muon and tau. In contrast to the apparent disagreement observed at LEP, these decay modes show a perfect agreement with lepton universality with much smaller errors. A summary of this fact using recent data can be found in [3], which states that

$$(g_\mu/g_e)_\tau = 0.9999 \pm 0.0021, \tag{3.12}$$

$$(g_\tau/g_e)_{\tau\mu} = 1.0004 \pm 0.0022, \tag{3.13}$$

where $g_{e,\mu,\tau}$ are W boson couplings to electron, muon, and tau currents, respectively. The first ratio was derived from tau decay rates, and the second tau and muon decay rates, as indicated by the subscript outside each pair of parentheses. This observation will be maintained if charged Higgs exchange does not make more than 0.4% of difference in a decay rate.

In Model I, the decay rate of $\tau \to \mu\nu\nu$ is roughly reduced by a factor $(1 - 2\cot^2\beta\, m_\mu^2/m_{H^\pm}^2)$ [31]. Requiring that this decay rate does not change more than 0.4%, for $m_{H^\pm} =$ 81 GeV, leads to $\tan\beta \gtrsim 0.03$, and $\tau \to \mu\nu\nu$ is virtually unaffected for values of $\tan\beta$ compatible with $b \to s\gamma$. Changes in other modes are even less significant due to smaller lepton Yukawa couplings. As a consequence, leptonic tau and muon decay constraints can remain satisfied, which is also true of pion, kaon, and semi-leptonic tau decays for the same reason.

It should be emphasized that this property of the present approach is different than a class of models which have flavor-dependent effective W boson couplings to charged currents. As mentioned earlier, a model has been proposed [6] that is claimed to account for the observed differences in leptonic W decay rates. In this model, the effective W-τ-ν_τ coupling is enhanced by 3.4% relative to that of W-μ-ν_μ or W-e-ν_e through mixing of different SU(2) gauge bosons that selectively couple to different flavors. Although this renders the W branching fractions consistent with (2.1), it decreases the ratio of $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\mu \to e\nu\nu)$ by 7% from its SM value, thereby conflicting with (3.13).

4. Test at future experiments

The defining character of this scenario is the existence of a charged Higgs boson, with its mass close to m_W, that couples very weakly to fermions. Therefore, its test can be reduced to charged Higgs search. The preferred way is pair production via gauge interactions since charged Higgs Yukawa couplings may be tiny for high $\tan\beta$. Although the LEP experiments still allow the $m_{H^\pm}$ considered in this work, a similar analysis should be able to rule out $m_{H^\pm} \approx m_W$ with higher luminosity at a future e^+e^- machine such as the international linear collider (ILC), in spite of the large background from W-pairs.

Apart from the higher luminosity, ILC offers an interesting possibility of utilizing polarized electron and positron beams. The pair production cross sections of charged Higgs and W are shown in table 4. They are tree-level values at $\sqrt{s} = 500$ GeV for right-handed polarized electron and left-handed polarized positron beams. The charged Higgs mass is assumed to be 81 GeV. One can notice that the beam polarizations can improve the signal-to-background ratio.

An indirect test is to measure the decays of pair-produced W bosons into different quark flavors. This may be considered as a background suppression method in charged

e^-/e^+ polarization	σ_{HH} [pb]	σ_{WW} [pb]	σ_{HH}/σ_{WW} [%]
0%/ 0%	0.10	7.13	1.4
80%/ 0%	0.05	1.47	3.3
90%/ 0%	0.04	0.76	5.4
80%/60%	0.06	0.65	8.7
90%/60%	0.06	0.37	15.0

Table 4: Pair production cross sections of charged Higgs and W, and their ratio, at $\sqrt{s} = 500$ GeV for different right-handed electron and left-handed positron beam polarizations. The charged Higgs mass is assumed to be 81 GeV.

Higgs search. If the charged Higgs is the reason for the apparent excess in $\mathcal{B}(W \to \tau\nu_\tau)$, it should also cause the same kind of excess in $\mathcal{B}(W \to cs)$.

Rejection of the W boson background in an hadronic environment such as LHC should not be as easy as at ILC.

5. Conclusion

A resolution is proposed of the possible lepton non-universality observed at the W-pair production experiments at LEP. Introduction of a charged Higgs boson with $m_{H^\pm} =$ 81 GeV, within the framework of 2HDM, could reduce the 2.8 σ of deviation down to 1.4 σ. In this way, the excessive tau mode decay rate is attributed to the pair production of charged Higgses, which decay preferentially to $\tau\nu$ among the three lepton flavors.

This can be achieved without conflict with the existing direct or indirect constraints. In particular, charged Higgs direct search at LEP in combination with $b \to s\gamma$ singles out one viable type of 2HDM out of the four that are free of tree-level FCNC interactions. This, in turn, determines what fraction of the tau production can be ascribed to charged Higgs, without $\tan\beta$ dependence. Another point to note is that this approach does not spoil other lepton universality tests from muon, tau, and meson decays.

This scenario can be tested at ILC by charged Higgs direct search.

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