Lepton-Specific Two-Higgs Doublet Model: Experimental Constraints and Implication on Higgs Phenomenology postprint

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Full Text

Preamble

Lepton-Specific Two-Higgs Doublet Model: Experimental Constraints and Implication on Higgs Phenomenology

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Abstract

We examine various direct and indirect constraints on the lepton-specific two-Higgs doublet model and scrutinize the properties of the Higgs bosons in the allowed parameter space. These constraints come from precision electroweak data, direct searches for Higgs bosons, the muon anomalous magnetic moment, as well as theoretical consistency requirements. We find that in the allowed parameter space, the CP-odd Higgs boson A is rather light ($m_A < 30$ GeV with

95% probability), composed predominantly of the leptonic Higgs and decaying dominantly into $\tau^+\tau^-$; while the SM-like Higgs boson h (responsible largely for electroweak symmetry breaking) decays dominantly via the mode $h \to 4\tau$ with a large decay width, which will make Higgs discovery more difficult at the LHC. However, this scenario predicts a branching ratio $\mathrm{Br}(Z \to \tau^+\tau^- A)$ ranging from 10^{-5} to 10^{-4}, which may be accessible at the GigaZ option of the ILC.

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Introduction

The phenomenological success of the Standard Model (SM) has significantly limited the possibility of new physics except for the Higgs sector, which remains untested. There are numerous speculations on possible extensions of the Higgs sector, among which the simplest is to introduce one more Higgs doublet. Compared with the SM, such simple two-Higgs doublet models usually have much more complicated Higgs phenomenology. In the SM, a single Higgs doublet is responsible for electroweak symmetry breaking and the Higgs couplings with fermions and gauge bosons are completely determined by their masses, leaving little guesswork in determining the discovery channels for the Higgs boson [**?**]. In two-Higgs doublet models, however, the addition of new scalars and the modification of Higgs interactions significantly complicate Higgs discovery at the LHC [**?**]. Given the imminent running of the LHC, phenomenological studies of various such models are urgently important.

In this paper we focus on a special two-Higgs doublet model called the lepton-specific two-Higgs doublet model (L2HDM) [**?**]. Since this model is arguably well-motivated from fundamental theory and also has phenomenological virtues (e.g., it can provide a natural explanation for the leptonic cosmic ray signals reported by PAMELA and ATIC [**?**]), it has attracted much attention [**?**, **?**]. We check various constraints on the model parameters and then scrutinize the properties of the Higgs bosons in the allowed parameter space. These constraints come from precision electroweak data, direct searches for Higgs bosons, the muon anomalous magnetic moment, as well as theoretical consistency requirements. Our main observation is that in the allowed parameter space, the CP-odd Higgs boson A must be light ($m_A < 30$ GeV with 95% probability), composed predominantly of the leptonic Higgs and decaying dominantly into $\tau\bar{\tau}$; while the SM-like Higgs boson h (responsible largely for electroweak symmetry breaking) decays dominantly via the mode $h \to 4\tau$ with a decay width usually exceeding several tens of GeV, which may make Higgs discovery more difficult at the LHC.

This paper is organized as follows. In Sec. II we recapitulate the L2HDM. In Sec. III we examine various constraints on the parameter space and study the properties of the Higgs bosons in the allowed parameter space. Finally, in Sec. IV we give our conclusion.

II. The Lepton-Specific Two-Higgs Doublet Model

The L2HDM is a special two-Higgs doublet model in which one Higgs doublet ϕ_1 couples only to leptons while the other doublet ϕ_2 couples only to quarks. Both Higgs doublets contribute to electroweak symmetry breaking: $v^2 = v_1^2 + v_2^2 = (246\ \text{GeV})^2$, with v_1 and v_2 being respectively the vacuum expectation values of ϕ_1 and ϕ_2; whereas their relative contributions can be quite different and can be parameterized by the ratio $\tan\beta = v_2/v_1$. Thus for large $\tan\beta$ the lepton Yukawa couplings can be greatly enhanced.

The Yukawa interactions and the Higgs potential are given by [?]:

$$\mathcal{L}_{\text{Yukawa}} = Y_e^{ij}\bar{\ell}_i\phi_1 e_j + Y_u^{ij}\bar{q}_i\phi_2^c u_j + Y_d^{ij}\bar{q}_i\phi_2 d_j + \text{h.c.}$$

$$V = m_1^2\phi_1^\dagger\phi_1 + m_2^2\phi_2^\dagger\phi_2 + m_3^2(\phi_1^\dagger\phi_2 + \text{h.c.}) + \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \Big[\frac{\lambda_5}{2}(\phi_1^\dagger\phi_2$$

where i, j are generation indices, $Y_{e,u,d}$ are 3×3 Yukawa matrices, q_i and ℓ_i denote respectively the left-handed quark and lepton fields, u_i and d_i denote respectively the right-handed up- and down-type quark fields, e_i denotes the right-handed lepton fields, and m_i^2 and λ_i are free parameters.

Just like the usual two-Higgs doublet model [?], the spectrum of the Higgs sector includes three massless Goldstone modes, which become the longitudinal modes of $W^\pm$ and Z bosons, and five massive physical states: two CP-even states h and H, a pseudoscalar A, and a pair of charged states $H^\pm$. These states are related to the doublets ϕ_1 and ϕ_2 by:

$$\phi_1 = \begin{pmatrix} G^+\cos\beta - H^+\sin\beta \\ \frac{1}{\sqrt{2}}(v_1 + H\cos\alpha - h\sin\alpha + iG^0\cos\beta - iA\sin\beta) \end{pmatrix}$$

$$\phi_2 = \begin{pmatrix} G^+\sin\beta + H^+\cos\beta \\ \frac{1}{\sqrt{2}}(v_2 + H\sin\alpha + h\cos\alpha + iG^0\sin\beta + iA\cos\beta) \end{pmatrix}$$

where α is the mixing angle that diagonalizes the mass matrix of the CP-even Higgs fields. Due to the constraint $v_1^2 + v_2^2 = (246\ \text{GeV})^2$, the eight free parameters in the potential, i.e., λ_i $(i = 1, \ldots, 5)$ and m_i^2 $(i = 1, 2, 3)$, reduce to seven. In our analysis we choose the following seven parameters as the input parameters of the L2HDM: m_h, m_H, m_A, $m_{H^\pm}$, $\tan\beta$, $\sin\alpha$, λ_5, where m_h, m_A, m_H, and $m_{H^\pm}$ are the masses of the corresponding physical states. Throughout this paper, we use H (h) to denote the Higgs boson with ϕ_2^0 (ϕ_1^0) as its dominant component, which means that we choose $\cos^2\alpha > 1/2$.

The interactions of the physical Higgs states with fermions are then given by [?]:

$$\mathcal{L}_{hff} = \frac{\cos\alpha}{\cos\beta}\frac{m_e^i}{v}\bar{e}_i e_i h - \frac{\sin\alpha}{\sin\beta}\frac{m_q^i}{v}\bar{q}_i q_i h + \frac{i\gamma_5 m_e^i \tan\beta}{v}\bar{e}_i e_i A - \frac{i\gamma_5 m_u^i \cot\beta}{v}\bar{u}_i u_i A + \frac{i\gamma_5 m_d^i \cot\beta}{v}\bar{d}_i d_i A$$

$$\mathcal{L}_{Hff} = \frac{\sin\alpha}{\cos\beta}\frac{m_e^i}{v}\bar{e}_i e_i H + \frac{\cos\alpha}{\sin\beta}\frac{m_q^i}{v}\bar{q}_i q_i H$$

$$\mathcal{L}_{H^\pm f\bar{f}'} = \frac{\sqrt{2}m_u^i}{v}\cot\beta\,\bar{u}_i(m_u^i P_L - m_d^j P_R)d_j H^+ + \frac{\sqrt{2}m_e^i}{v}\tan\beta\,\bar{\nu}_i P_R e_i H^+ + \text{h.c.}$$

where $v = 246$ GeV. Obviously, for large $\tan\beta$ the lepton Yukawa couplings are greatly enhanced relative to the SM prediction. One can also check that the couplings of ZZh and ZZH are given by:

$$g_{ZZh} = \frac{g^2 v}{2\cos^2\theta_W}\sin(\beta-\alpha), \quad g_{ZZH} = \frac{g^2 v}{2\cos^2\theta_W}\cos(\beta-\alpha)$$

which satisfy the sum rule $g_{ZZh}^2 + g_{ZZH}^2 = g_{ZZh}^{\text{SM}2}$. For large $\tan\beta$ (as required by experimental constraints, as shown below), the coupling g_{ZZh} dominates over g_{ZZH}, so h is usually called the SM-like Higgs boson.

III. Constraints on the L2HDM

We note that both theoretical consistency and electroweak data constrain the parameter space of the L2HDM. In our study we consider the following theoretical constraints:

(1) **Perturbativity**: The Higgs sector must remain perturbative, requiring $\lambda_i < 4\pi$ $(i = 1, \dots, 5)$.

(2) **Tree-level unitarity**: The S-matrix must satisfy all relevant tree-unitarity constraints, which implies that the quartic couplings λ_i satisfy [**?**]:

$$|\lambda_1 + \lambda_2| < 8\pi, \quad |\lambda_1 - \lambda_2| < 8\pi, \quad |\lambda_3 + \lambda_4| < 8\pi$$

$$|\lambda_3| < 8\pi, \quad |\lambda_4| < 8\pi, \quad |\lambda_3 + 2\lambda_4| < 8\pi$$

$$3(\lambda_1 + \lambda_2) + 2\lambda_3 + 2\lambda_4 < 16\pi$$

(3) **Vacuum stability**: The scalar potential must be finite at large field values and contain no flat directions, which translates into the bounds [**?**]:

$$\lambda_{1,2} > 0, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2}$$

On the experimental side, we consider the following constraints:

(4) **Charged Higgs mass bound**: $m_{H^\pm} > 92$ GeV [?].

(5) **LEP neutral Higgs searches**: We compute signals from Higgsstrahlung production $e^+e^- \to ZH_i$ $(H_i = h, H)$ with $H_i \to 2b, 2\tau, 4b, 4\tau, 2b2\tau$ [?, ?] and from associated production $e^+e^- \to H_iA$ with $H_iA \to 4b, 4\tau, 2b2\tau, 6b, 6\tau$ [?], comparing them with LEP data. We also consider constraints from $e^+e^- \to ZH_i$ by searching for a peak in the M_{H_i} recoil mass distribution of the Z boson [?] and the constraint $\Gamma(Z \to H_iA) < 5.8$ MeV when $m_A + m_{H_i} < m_Z$ [?].

(6) **LEP light Higgs searches via Yukawa process**: Constraints from $e^+e^- \to f\bar{f}S$ with $f = b, \tau$ and S denoting a scalar [?]. These constraints limit the $f\bar{f}S$ coupling versus m_S and thus constrain L2HDM parameters.

(7) **W boson mass**: The L2HDM Higgs sector can shift the W boson mass through radiative corrections. We require the corrected W boson mass to lie within the 2σ range of the global-fit value. The SM prediction for the W boson mass is 80.363 GeV for $m_t = 173$ GeV and $m_H = 111$ GeV [?], and the fitted value is 80.398 ± 0.025 GeV [?]. We use the formula in [?] for our calculation, taking $m_t = 171.3$ GeV and subtracting the SM Higgs contribution to avoid double-counting.

(8) $Z\tau^+\tau^-$ **coupling**: For large $\tan\beta$, the L2HDM Higgs sector can give sizable radiative corrections to the $Z\tau^+\tau^-$ coupling. We calculate these corrections and require the corrected coupling to lie within the 2σ range of its fitted value. The SM predictions for the vector and axial-vector couplings at the Z-pole are $g_V^{\rm SM} = -0.03712$ and $g_A^{\rm SM} = -0.50127$ [?], with fitted values $g_V^{\rm fit} = -0.03876 \pm 0.00064$ and $g_A^{\rm fit} = -0.50111 \pm 0.00064$ [?]. We use the formula in [?] for our calculation.

(9) **Tau leptonic decay**: We require the L2HDM correction to the branching ratio $\mathrm{Br}(\tau \to e\bar{\nu}_e\nu_\tau)$ to be in the range $[-0.80\%, 1.21\%]$ [?], using the formula in [?].

(10) **Muon anomalous magnetic moment** a_μ: Both the theoretical prediction and experimental measurement of a_μ have reached remarkable precision, but a significant deviation still exists: $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.5 \pm 8.8) \times 10^{-10}$ [?]. The L2HDM can contribute to a_μ through loop diagrams involving $H^\pm$ and A.

With these constraints, we scan the L2HDM parameter space in the ranges:

$$1 < \tan\beta < 200, \quad 92 \text{ GeV} < m_{H^\pm} < 350 \text{ GeV}, \quad -\frac{\sqrt{2}}{2} < \sin\alpha < \frac{\sqrt{2}}{2}, \quad |\lambda_i| < 4\pi$$

[Figure 2: see original paper] shows the same as Fig. 1, but projected in the planes of m_h and m_H versus $m_{H^\pm}$. Both m_h and m_H are close to the value of $m_{H^\pm}$, which helps reduce the L2HDM contribution to precision electroweak data such as m_W and $Z\bar{\tau}\tau$ couplings at the Z-pole. For $m_{H^\pm} > 250$ GeV, the data require $\sin(\beta-\alpha) \approx 1$ [**?**], and in this case h has little effect on the data so that it can deviate significantly from $m_{H^\pm}$.

In summary, the above results indicate that the preferred parameter space of the L2HDM is $37 < \tan\beta < 80$, $m_A < 30$ GeV, and the other Higgs bosons lighter than 250 GeV. Note that this favored region is obtained by considering all constraints (1-11) simultaneously, rather than any individual constraint. For example, for $\tan\beta > 200$, our results indicate that the CP-odd Higgs boson A as heavy as 120 GeV can still explain a_μ; but such large $\tan\beta$ is disfavored by $Z\bar{\tau}\tau$ coupling at the Z-pole or by τ leptonic decay. Another point we should address is that in the L2HDM, the processes $B \to X_s\gamma$ and $\Upsilon \to A\gamma$ cannot impose further constraints [**?**]. The reason is that in the surviving parameter space, $\tan\beta$ must be larger than 37 and, consequently, the couplings of the bottom quark with $H^\pm$ and h are suppressed, as shown in Eq. (8). Finally, we emphasize that in contrast to the L2HDM, which has a large parameter space to account for the a_μ discrepancy without conflicting with other experimental data, the popular type-II 2HDM finds it very difficult to do so [**?**]. This is one of the virtues of the L2HDM.

IV. Implication on Higgs Phenomenology

Equation (8) indicates that the lepton couplings of A, H, and $H^\pm$ are enhanced by large $\tan\beta$, while quark couplings are suppressed. Since the allowed parameter space has large $\tan\beta$, the couplings of the τ lepton with A, H, and $H^\pm$ are larger than the top quark couplings. Therefore these scalars decay dominantly into τ leptons rather than top quarks (if kinematically allowed). Moreover, a light A can change the phenomenology of other Higgs bosons by opening new decay modes like $h, H \to AZ$ and $H^\pm \to AW^\pm$. As discussed earlier, in the case of large $\tan\beta$ and small α, h is the SM-like Higgs boson, mainly responsible for electroweak symmetry breaking and coupling to weak gauge bosons like the SM Higgs.

The phenomenology of h is therefore of primary importance. The dominant decay mode $h \to 4\tau$ makes Higgs discovery challenging at the LHC. Another reason for the detection difficulty is that for more than 80% of the allowed parameter space, the width of h is found to be larger than 10 GeV. Such a broad width will smear the peak of the invariant mass distribution of h-decay products and make detection more difficult.

We note that in the L2HDM, $A \to \mu^+\mu^-$ is the second-largest decay mode of A. Thus AA production can give a multi-muon signal, similar to the scenario proposed in [**?**]. Unfortunately, in the L2HDM the branching ratio of $A \to \mu^+\mu^-$ is of order 10^{-3}, which makes the channel $h \to 4\mu$ quite hopeless at the LHC.

Some authors have considered channels like $h \to 2\mu + 2\tau$ [?] and diffractive Higgs production $pp \to pp + h$ followed by $h \to 2\mu + 2$ jets [?] as well as $h \to 4\tau$ [?] to detect such an h, but these studies did not consider the challenging case of a broad h. We also checked that the branching ratio of $h \to \gamma\gamma$ is usually suppressed to less than 10^{-6} and thus too small for detection.

[Figure 4: see original paper] shows the same as Fig. 1, but displaying the cross section of HA associated production at the LHC versus m_H. For $m_H < 140$ GeV the cross section is larger than 100 fb. The dominant decay of H in this case is found to be $H \to AA$, with a branching ratio larger than 80%, so the main signal of this process is 6τ. Due to the lightness of A, great efforts are needed to analyze the signal and backgrounds to detect this process at the LHC.

Secondly, we note that A is always lighter than the Z boson in the allowed parameter space and thus may be produced from Z decays. We investigate the decay $Z \to \tau\bar{\tau}A$ and find its branching ratio ranging from 10^{-5} to 10^{-4} for $m_A < 40$ GeV (corresponding to 98% of the allowed parameter space). Such a large rate is within the sensitivity of the GigaZ option at the proposed International Linear Collider [?].

V. Conclusion

We examined various direct and indirect constraints on the lepton-specific two-Higgs doublet model and then studied the properties of the Higgs bosons in the allowed parameter space. We found that the allowed space has a very light CP-odd Higgs boson A ($m_A < 30$ GeV with 95% probability) which is composed predominantly of the leptonic Higgs and decays dominantly into $\tau^+\tau^-$. The SM-like Higgs boson h decays dominantly via the mode $h \to 4\tau$, which may make Higgs discovery difficult at the LHC. We also checked other possibilities for testing the Higgs sector of this model and found that the decay $Z \to \tau^+\tau^- A$ has a branching ratio ranging from 10^{-5} to 10^{-4}, which may be accessible at the GigaZ option of the ILC.

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[29] For $m_A < 10$ GeV, the constraint from LEP searches for Higgs bosons is still strong and in this case, the lower mass bound of h is 86 GeV [**?**].