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Full Text

Lepton-Specific Two-Higgs Doublet Model: Experimental Constraints and Implications for 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 arise from precision electroweak data, direct searches for Higgs bosons, the muon anomalous magnetic moment, and various 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 $h \to 4\tau$ 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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I. 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 some 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 will examine 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, and 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 $h \to 4\tau$ 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 present our conclusions.

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 [?]

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

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

where i, j are generation indices, Y_e, Y_u and Y_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

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

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

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 [?]

$$\mathcal{L}_{\text{int}} = \frac{g m_e^i}{2 m_W \cos\beta}(\cos\alpha \bar{e}_i e_i H - \sin\alpha \bar{e}_i e_i h) + \frac{g m_q^i}{2 m_W \sin\beta}(\sin\alpha \bar{q}_i q_i H + \cos\alpha \bar{q}_i q_i h) + \frac{g m_u^i}{2 m_W \tan\beta}\bar{u}_i \gamma_5 u_i A - \frac{g m_d^i}{2 m_W} \cot$$

Obviously, for large $\tan\beta$ the lepton Yukawa couplings are greatly enhanced relative to the SM prediction. One can also verify that the couplings of ZZh and ZZH are given by

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

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** is valid in the Higgs sector, which requires $\lambda_i < 4\pi$ ($i = 1, \dots, 5$).
2. The **S-matrix** satisfies all relevant tree-unitarity constraints, which implies that the quartic couplings λ_i satisfy [?]

$$|\lambda_1+\lambda_2| < 8\pi, \quad |\lambda_3| < 8\pi, \quad |\lambda_3+\lambda_4| < 8\pi, \quad |\lambda_3+2\lambda_4| < 8\pi, \quad |\lambda_1+\lambda_2+2\lambda_3+2\lambda_4| < 16\pi, \quad \sqrt{(\lambda_1-\lambda_2)^2}$$

3. The **scalar potential** in Eq. (2) is finite at large field values and contains 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. The **lower mass bound** on the charged Higgs bosons: $m_{H^\pm} > 92$ GeV [?].
5. The **constraints from LEP searches** for neutral Higgs bosons. 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 $e^+e^- \to H_i A$ with $H_i A \to 4b, 4\tau, 2b2\tau, 6b, 6\tau$ [?], comparing them with LEP data. We also consider constraints from $e^+e^- \to ZH_i$ by looking for a peak in the M_{H_i} recoil mass distribution of the Z-boson [?] and the constraint $\Gamma(Z \to H_i A) < 5.8$ MeV when $m_A + m_{H_i} < m_Z$ [?].

6. The **constraints from LEP searches** for a light Higgs boson via the Yukawa process $f\bar{f} \to S$ with $f = b, \tau$ and S denoting a scalar [?]. These constraints can limit the $f\bar{f}S$ coupling versus m_S and thus constrain the parameters of the L2HDM.

7. The **constraints from the 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 its fitted value is 80.398 ± 0.025 GeV [?]. We use the formula in [?] for the calculation and consider the effect of a different top quark mass (in our calculation we take $m_t = 171.3$ GeV). We also subtract the contribution from the SM Higgs boson to avoid double-counting the contribution from the Higgs sector.

8. The **constraints from $Z\tau^+\tau^-$ 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 prediction for this coupling at the Z-pole is given by $g_V^{\rm SM} = -0.03712$ and $g_A^{\rm SM} = 0.50127$ [?], with fitted values -0.03676 ± 0.00064 and 0.50111 ± 0.00064 respectively [?]. We use the formula in [?] for our calculation.

9. The **constraints from τ 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% to 1.21% [?]. We use the formula in [?] for our calculation.

10. The **constraints from the muon anomalous magnetic moment** a_μ. Now both the theoretical prediction and the experimental measured value of a_μ have reached remarkable precision, but a significant deviation still exists: $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.5 \pm 8.8) \times 10^{-10}$ [?]. In our analysis we require the L2HDM to account for this difference at the 2σ level. Note that in the L2HDM, a_μ receives additional contributions from one-loop diagrams induced by the Higgs bosons and also from two-loop Barr-Zee diagrams mediated by A, h and H [?]. If the Higgs bosons are not too light, the contributions from the Barr-Zee diagrams dominate. To account for the a_μ discrepancy, one needs a light A along with large $\tan\beta$ to enhance the effects of the Barr-Zee diagram involving the τ-loop. The CP-even Higgs bosons are typically preferred to be heavy since their contribution to a_μ is negative.

11. Since the CP-odd Higgs A can be quite light and the decays $h, H \to AA$ may open up with large widths, we require the width of any Higgs boson in the L2HDM to be smaller than its mass (otherwise the Higgs boson may be too broad).

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

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

With 10^{12} random samplings, we obtain the allowed parameter space shown in Figs. 1-2. Fig. 1 shows that the allowed parameter space features a light A ($m_A < 80$ GeV) and large $\tan\beta$ ($\tan\beta < 130$), which mainly arises from the explanation of the a_μ discrepancy. Among the surviving samples displayed in Fig. 1, about 95% satisfy $m_A < 30$ GeV and about 70% satisfy $m_A < 20$ GeV, meaning that a very light A is highly preferred by the constraints.

Fig. 2 shows the allowed parameter space projected in the planes of m_h and m_H versus $m_{H^\pm}$. Three features should be noted. First, all Higgs bosons are lighter than 350 GeV (lighter than 250 GeV for about 90% of the surviving samples), which is mainly due to the unitarity requirement and the a_μ constraint. Second, h and H can be as light as 58 GeV because the LEP2 bound is relaxed significantly due to the weakened ZZh and ZAH couplings from the sizable mixing angle α and the opening of the new decay modes $H, h \to 4\tau$ [**?**]. Third, the values of both m_h and m_H are close to $m_{H^\pm}$, which helps reduce the L2HDM contribution to precision electroweak observables 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 the 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 could still explain a_μ; but such large $\tan\beta$ is disfavored by the $Z\bar{\tau}\tau$ 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 any 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. IMPLICATIONS FOR HIGGS PHENOMENOLOGY

Eq. (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. Consequently, 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. Therefore, the phenomenology of h is of primary importance and will be studied in the following.

Fig. 3 shows the branching ratio of $h \to AA$ versus m_h. Here we have considered all decay modes of h including $h \to VV, AZ, \tau\bar{\tau}, b\bar{b}, t\bar{t}$. This figure shows that for most of the allowed parameter space (about 99%), $h \to \tau\bar{\tau}\tau\bar{\tau}$ is the dominant decay mode. This will make detection of h difficult at the LHC because the lightness of A (note $m_A < 20$ GeV for about 70% of surviving samples) will make the τ leptons from its decay highly collimated [?], which is usually regarded as a difficult scenario for Higgs discovery at the LHC in the next-to-minimal supersymmetric model [?]. Another reason for the detection difficulty of h 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 challenging.

We note that in the L2HDM, $A \to \mu^+\mu^-$ is the second-largest decay mode of A. Thus AA production can give multi-muon signals, like 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. Note that some authors have considered the channels $h \to 2\mu + 2\tau$ [?] 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 all these studies did not consider the worse case of a broad h. We also verified that the branching ratio of $h \to \gamma\gamma$ is usually suppressed to less than 10^{-6} and thus too small for detection.

H A Associated Production at LHC Furthermore, we examine other complementary new channels for detecting the Higgs sector of the L2HDM. First, we consider associated HA production at the LHC. The cross section for this process is shown in Fig. 4, from which one can see that for $m_H < 140$ GeV the cross section exceeds 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 will be needed to analyze the signal and backgrounds in order to detect this process at the LHC. Second, we note that A is always lighter than the Z boson in the allowed parameter space and thus may be produced from Z decays. Therefore we investigate the decay $Z \to \tau\bar{\tau}A$ and find its branching ratio ranges 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 have examined various direct and indirect constraints on the lepton-specific two-Higgs doublet model and studied the properties of the Higgs bosons in the allowed parameter space. We found that the allowed space contains 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 $h \to 4\tau$, which may make Higgs discovery difficult at the LHC. We also examined 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 [**?**].

Note: Figure translations are in progress. See original paper for figures.