

Resolving the W boson mass in the lepton specific two Higgs doublet model*

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Abstract: In 2022, the collider detector at Fermilab (CDF) collaboration reported the W -boson mass ($M_W = 80.4335 \pm 0.0094$ GeV), which deviates from the standard model (SM) prediction ($M_W^{\text{SM}} = 80.357 \pm 0.006$ GeV) by $\sim 7\sigma$. In contrast, the CMS collaboration obtained $M_W = 80.3602 \pm 0.0099$ GeV, which was very close to the SM global electroweak fit value of ~ 80.357 GeV. Motivated by this situation, we reassess the W -boson mass within the lepton-specific two Higgs doublet model (LS-2HDM). To this end, we perform random scans (generated with SARAH 4.13.0 and evaluated with SPheno 4.0.3) and confront the results with up-to-date theoretical and experimental constraints. The scan enforces vacuum stability, perturbative unitarity, and perturbativity; electroweak precision observables via the oblique parameters (S, T, U); LEP bounds on $H^\pm$; rare B -meson decays; lepton flavor universality (LFU) in Z and τ decays; and 13 TeV LHC searches for additional Higgs bosons. Viable points are further tested with HiggsTools (HiggsSignals + HiggsBounds). In the LS-2HDM, if h_1 is the SM-like Higgs at $m_{h_1} \simeq 125$ GeV with $|\cos(\beta - \alpha)| \lesssim 0.06$, $17 \lesssim \tan\beta \lesssim 39$, $144 \lesssim m_{h_2} \lesssim 414$ GeV, and $435 \lesssim m_{A, H^\pm} \lesssim 685$ GeV, the model reproduces the 2024 CMS W -boson mass within 3σ . Solutions near the 2022 CDF value ($M_W = 80.4335 \pm 0.0094$ GeV) survive; however, after applying all constraints, including HiggsTools, they approach it at best within $\lesssim 2\sigma$. Our findings emphasize that LS-2HDM favors the CMS results consistently with the current experimental results. Although one can theoretically accommodate the CDF results in this model, up-to-date electroweak precision bounds on oblique parameters (S, T, U) with the SM-like Higgs and LFU constraints exclude these solutions. Our results for W -boson mass can only be as close as about 2σ to the CDF results.

Keywords: W -boson, lepton-specific two Higgs doublet model, CDF, CMS

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I. INTRODUCTION

The standard model (SM) has withstood rigorous testing and has successfully been used to explain various phenomena in particle physics. However, recent measurements of the W -boson mass at the collider detector at Fermilab (CDF) revealed substantial discrepancies between experimental observations and theoretical predictions within the SM framework. The CDF reported a precise measurement of the W -boson mass using the 8.8 fb^{-1} dataset from $p\bar{p}$ collisions with a center-of-mass energy of 1.96 TeV as [1]

$$M_W^{\text{CDF}} = 80.4335 \pm 0.0094 \text{ GeV}, \quad (1)$$

which deviates from the SM prediction of $M_W^{\text{SM}} = 80.357 \pm 0.006$ GeV by 7σ [2–13]. Such a notable discrepancy suggests the potential existence of new physics phenomena, thereby necessitating a comprehensive exploration of physics beyond the standard model (BSM).

The W -boson mass result from the CMS experiment in 2024, following almost a decade of research, has considerably eased the strain in the literature created by the CDF measurement. With the value of $M_W = 80.3602 \pm 0.0099$ GeV, the CMS collaboration obtained a value very close to the global electroweak fit prediction of the SM of ~ 80.357 GeV [14]. This new measurement largely resolves the long-standing tension displayed by CDF, moderating the anomaly that first put the SM at risk. However, the values of CDF and CMS disagree with each

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other: their central values differ by ~ 73 MeV (some 5σ). Therefore, when these two experimental results are considered together, a more conservative view about the need for new physics is appropriate.

The inclusion of BSM particles might induce quantum corrections accountable for the deviation observed in the W -boson mass, and therefore, they have sparked a growing interest in exploring new physics BSM, mostly by altering the oblique parameters S , T , and U . These approaches include a broad range of theoretical frameworks, including effective field theory methods [15–21], supersymmetric (SUSY) models [22–28], leptoquark models [29–31], gravitational approaches [32, 33], little Higgs models [34], and extensions of the SM involving additional scalar singlets [35–38] or triplets [39–41]. In addition, models featuring vector-like leptons have been explored [42–47] alongside investigations from the viewpoint of neutrino masses and seesaw mechanisms [48, 49], and other theoretical approaches [50–62]. Furthermore, the two Higgs doublet models (2HDM) have been attracting a considerable interest by providing a simple extension of SM [63–83]. The Higgs bosons in its spectrum can interfere with the SM particles and yield some deviations in W -boson mass, lepton flavor universality (LFU) [84–86], and muon $g-2$ [87–89] through their radiative contributions. Among these efforts, certain studies specifically target the W -boson mass discrepancy while addressing the dark matter problem by employing an approach that considers both issues within their framework [34, 35, 42, 45, 53, 55, 59, 63]. This anomaly seems to attract considerable attention from several theoretical approaches, among which 2HDMs are an important class. Although 2HDMs are widely used in understanding the W -boson mass anomaly, their parameter space is limited by experimental data from several experiments [84–86, 90–96]. Therefore, motivated by these theoretical and experimental efforts within 2HDM frameworks, an exploratory investigation aimed at reconciling the W -boson mass discrepancy by scanning possible solutions within the 2HDM parameter space is conducted in this study.

This study focuses on investigating the effect of the parameter space of 2HDM on the W -boson mass. Two crucial considerations are utilized in our analyses: theoretical limitations and compatibility with the current experimental data. Theoretical limitations arise from constraints related to the stability of the scalar potential and perturbativity. The predictions of 2HDMs must also align with the outcomes of various experiments, including those involving rare decays of B -meson, Z -boson decay, tau-lepton decay, and observations from the large hadron collider (LHC). The HiggsTools framework is utilized to explore the implications of different types of 2HDMs within these theoretical and experimental limitations [97]. Among the several types of 2HDMs, some models can

achieve stronger motivations by distinguishing the SM fermions based on their assigned Z_2 symmetries. For example, the lepton-specific 2HDM (LS-2HDM) assigns a Z_2 symmetry for the SM fermions such that the quarks interact with one Higgs doublet, whereas the leptons interact with another doublet. Thus, a mass hierarchy can be imposed between the quarks and leptons. This discrimination between the quarks and leptons yield different results in the production of the heavy Higgs bosons in the collider experiments [96]. Therefore, the current strong limits from the recent CMS findings on scalar masses of the 2HDM can be modified considerably. For example, the production of the extra Higgs bosons in pp collisions within the LS-2HDM framework is suppressed with the $\tan\beta$ parameter, and they can escape from the detection while significantly contributing to the gauge boson masses and LFU processes at the loop level. Despite its different behaviours, there are still possible experimental tests and limits for the models such as those in the LS-2HDM class [98].

The following steps are implemented in this work. Scalar sector mass spectra consistent with both theoretical and experimental requirements are obtained. Subsequently, the implications on LFU are explored by considering the processes involving the tau-lepton and Z -boson. These analyses further constrain the parameter space of the LS-2HDM. Then, we examine the consistency of the LS-2HDM with both the CDF and CMS W -boson mass measurements under all theoretical and experimental constraints. We show that once the electroweak oblique parameter bounds (S, T, U) and SM-like Higgs boson requirement are imposed, all solutions within about 1σ deviation of the CDF W -boson mass are excluded. The closest viable points lie at $\lesssim 2\sigma$, whereas the CMS value is readily accommodated.

In addition, this comprehensive investigation of the LS-2HDM discusses the implications of both recent measurements. The motivation of our study is to explain the potential excess reported by CDF in the W -boson mass in terms of the LS-2HDM parameter space and to verify if such solutions are in agreement with the CMS measurement. To this end, the LS-2HDM parameter space is scanned systematically, incorporating theoretical consistency conditions (such as scalar potential stability and perturbativity) and available experimental constraints (such as rare B -meson decays, Z -boson and tau-lepton data, and LHC searches). Subsequently, parameter space regions that can explain the CDF and CMS experiment W -mass measurements are evaluated, and the model consistency with each result is commented on. In the following sections, the stabilizing effect of the CMS measurement on LS-2HDM literature is emphasized. Further, we will demonstrate that our findings are in agreement with both experimental results.

The remainder of this work is organized as follows:

Section II summarizes LS-2HDM, focusing on its Higgs sector and Yukawa interactions. Section III outlines the theoretical and experimental constraints used in this analysis, and provides a detailed discussion of their impacts on the parameter space. Section IV explores the parameter space of the LS-2HDM systematically and provides the potential solutions. Finally, Section V offers discussions and concluding remarks.

II. LEPTON-SPECIFIC 2HDM

2HDMs are obtained by extending the scalar sector of the SM with the addition of a second scalar doublet possessing the same quantum numbers as the SM Higgs doublet. The gauge group of the 2HDMs is identical to that of the SM. In 2HDMs, eight scalar fields are introduced, and following a spontaneous symmetry breaking process similar to that of the SM, three of these fields confer masses of the gauge bosons while the remaining five fields undergo mixing, thereby resulting in five distinct physical scalar bosons. These additional degrees of freedom present in the 2HDM have far-reaching implications for the Higgs boson phenomenology. The scalar doublets of 2HDMs are given as

$$\Phi_1 = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad \text{and} \quad \Phi_2 = \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_7 + i\phi_8 \end{pmatrix}, \quad (2)$$

where ϕ_3 and ϕ_7 develop non-zero vacuum expectation values (VEVs) as $\langle \phi_3 \rangle = v_1 / \sqrt{2}$ and $\langle \phi_7 \rangle = v_2 / \sqrt{2}$ satisfying $v_{SM} = \sqrt{v_1^2 + v_2^2}$. The particle content of 2HDMs in the scalar sector are two CP-even ($h_{1,2}$), one CP-odd (A), and two charged ($H^\pm$) Higgs bosons. For a comprehensive review of 2HDMs, please refer to Refs. [99–103] and the citations therein.

In 2HDMs, the addition of a second scalar doublet in the Yukawa sector leads to Yukawa couplings that lack flavor-diagonal properties, which results in the emergence of tree-level FCNC processes severely constrained from the experiments. To resolve this issue, a viable approach is introducing a discrete symmetry to the scalar and Yukawa potentials [104]. The application of this symmetry limits interactions between the additional scalar doublet and fermions, suppresses flavor-changing neutral currents at the tree-level, and establishes the model as a viable approach to satisfy experimental constraints. One important example of this discrete symmetry is the Z_2 symmetry [104–107], which is described as

$$\begin{aligned} \Phi_1 &\rightarrow -\Phi_1 \quad \text{and} \quad \Phi_2 \rightarrow \Phi_2, \\ D_j &\rightarrow D_j, \quad U_j \rightarrow U_j \quad \text{and} \quad E_j \rightarrow -E_j, \end{aligned} \quad (3)$$

where E_j represents right-handed leptons, and U_j and D_j

represent right-handed up-type and down-type quarks, respectively. 2HDMs with this choice of Z_2 symmetry are often referred to as LS-2HDM. Under Z_2 symmetry, the tree level potential of the LS-2HDM becomes

$$\begin{aligned} V_{\text{tree}} &= m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - (m_3^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) \\ &+ \frac{\lambda_1}{2} |\Phi_1|^4 + \frac{\lambda_2}{2} |\Phi_2|^4 \\ &+ \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}], \end{aligned} \quad (4)$$

where $m_{1,2}$ correspond to the mass terms of the scalar potentials, and $\lambda_{1,\dots,5}$ refers to the self-couplings. In Eq. (4), the term involving m_3^2 arises from a combination of scalar doublets and violates the Z_2 symmetry, thereby resulting in soft symmetry breaking. The expressions for the masses of extra scalar bosons at the tree level are obtained from Eq. (4) as

$$\begin{aligned} m_{H^\pm}^2 &= \frac{1}{2} \left(m_3^2 \frac{1}{\sin\beta \cos\beta} - \lambda_3 v_{SM}^2 \right), \\ m_{h_{1,2}}^2 &= \frac{1}{4} m_3^2 \left(\tan\beta + \cot\beta \mp \frac{2}{\sin 2\alpha} \right) + \lambda_1 \cos^2 \beta v_{SM}^2 \\ &+ \lambda_2 \sin^2 \beta v_{SM}^2 \mp \frac{\lambda_3 \sin\beta \cos\beta v_{SM}^2}{\sin 2\alpha} \mp \frac{\lambda_5 \sin\beta \cos\beta v_{SM}^2}{\sin 2\alpha}, \\ m_A^2 &= \frac{1}{2} \left(m_3^2 \frac{1}{\sin\beta \cos\beta} - \lambda_3 v_{SM}^2 + \lambda_4 v_{SM}^2 \right). \end{aligned} \quad (5)$$

where $\sin\alpha$ represents the mixing angle of CP-even Higgs bosons and $\tan\beta = v_2/v_1$ represents the ratio of the VEVs of the doublets. In addition to these expressions in the tree-level, radiative corrections to scalar masses must also be considered. These corrections can be calculated through a one-loop improved scalar potential described as [108, 109]

$$V = V_{\text{tree}} + V_{\text{loop}}, \quad (6)$$

where the loop potential is described as

$$V_{\text{loop}} = \frac{1}{64\pi^2} \sum_{\alpha} n_{\alpha} m_{\alpha}^4 \left[\log \left(\frac{m_{\alpha}^2}{\mu^2} \right) - \frac{3}{2} \right]. \quad (7)$$

with

$$n_{\alpha} = (-1)^{2s_{\alpha}} Q_{\alpha} C_{\alpha} (2s_{\alpha} + 1), \quad (8)$$

where μ represents the renormalization scale, m_{α} represents the masses of particles contributing at loop-level, s_{α} represents the spin of the particles, $Q_{\alpha} = 1(2)$ for neutral

(charged) particles, $C_\alpha = 3(1)$ for quarks (leptons), and α runs over all particles that couple to the scalars at the tree level. Furthermore, the Yukawa Lagrangian under Z_2 symmetry can be written as [109]

$$\mathcal{L}_Y = -Y_e^{ij} \bar{L}_i \Phi_1 E_j - Y_u^{ij} \bar{Q}_i \Phi_2^C U_j - Y_d^{ij} \bar{Q}_i \Phi_2 D_j + \text{h.c.}, \quad (9)$$

where $Y_{e,u,d}^{ij}$ represent the Yukawa couplings, and L_i and Q_i represent the $SU(2)_L$ doublets for leptons and quarks, respectively. Similar to the Yukawa couplings in the SM, the effective Yukawa couplings for the LS-2HDM are obtained as indicated in Table 1. The mass of the top quark is primarily determined by Φ_2 , and therefore, the value of $\tan\beta$ is constrained as $v_2 > v_1$. If $v_2 \gg v_1$ and $\tan\beta \gg 1$, the Yukawa coupling of the CP-odd Higgs boson with quarks becomes negligibly small, while its coupling with leptons increases.

Table 1. Effective Yukawa couplings for LS-2HDM.

$Y_u^{h_1}, Y_d^{h_1}, Y_l^{h_1}$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
$Y_u^{h_2}, Y_d^{h_2}, Y_l^{h_2}$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
Y_u^A, Y_d^A, Y_l^A	$\cot\beta$	$-\cot\beta$	$\tan\beta$

III. THEORETICAL AND EXPERIMENTAL CONSTRAINTS

The theoretical and experimental constraints on the parameter space of the LS-2HDM are investigated to determine the allowed parameter regions for our analysis. First, theoretical limitations on the scalar potential of the LS-2HDM are considered. The scalar potential given in Eq. (4) and (7) should adhere to the vacuum stability and perturbativity conditions; this limits the self couplings as [110]

$$\lambda_i < 4\pi \quad (i = 1, \dots, 5). \quad (10)$$

In order to provide unitarity at tree level, self couplings must satisfy the relations [110] given by

$$\begin{aligned} 3(\lambda_1 + \lambda_2) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2} &< 16\pi, \\ \lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4|\lambda_5|^2} &< 16\pi, \\ \lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4|\lambda_5|^2} &< 16\pi, \\ \lambda_3 + 2\lambda_4 \pm 3|\lambda_5| &< 8\pi, \\ \lambda_3 \pm \lambda_4 &< 8\pi, \\ \lambda_3 \pm |\lambda_5| &< 8\pi. \end{aligned} \quad (11)$$

Furthermore, to ensure that the scalar potential of the LS-

2HDM is finite, free of flat directions, and stable at large field values, the following conditions are imposed:

$$\begin{aligned} \lambda_{1,2} &> 0, \\ \lambda_3 &> -\sqrt{\lambda_1 \lambda_2}, \\ \lambda_3 + \lambda_4 - |\lambda_5| &> -\sqrt{\lambda_1 \lambda_2}, \end{aligned} \quad (12)$$

Besides the aforementioned theoretical constraints, LS-2HDM is subject to stringent experimental constraints as well. It is evident that the predictions of LS-2HDM should align with a wide range of experimental observations, including precision measurements of the electroweak sector and collider searches for new particles and phenomena. First, the constraint on the charged scalar boson mass is determined from the large electron-positron collider (LEP) data as $m_{H^\pm} > 80$ GeV [111]. As discussed in the previous section, due to the significant influence of m_{h_1} on m_t , h_1 is identified as the SM-like Higgs boson, and its mass is fixed at $m_{h_1} \simeq 125 \pm 2$ GeV [112, 113] because the theoretical calculations of the Higgs boson mass involve about 2 GeV uncertainty [114, 115]. Moreover, experimental data from electroweak precision measurements to the W -boson mass in BSM models are used to determine the oblique parameters S , T , and U , and they are constrained as [116]

$$\begin{aligned} S &= -0.04 \pm 0.10, \\ T &= 0.01 \pm 0.12, \\ U &= -0.01 \pm 0.09, \end{aligned} \quad (13)$$

The expressions of these parameters are presented in Section IV.D.

In addition, limitations from rare B -meson decays such as $B_s \rightarrow \mu^+ \mu^-$ and $B_s \rightarrow X_s \gamma$ should be considered because they are sensitive probes for extra scalars of BSM. In the LS-2HDM framework, these decay processes receive contributions from scalar states via loops, limiting the model parameter space. Therefore, the following bounds on the rare B -meson decay branching ratios are applied to the parameter space [91, 117, 118].

$$\begin{aligned} 1.95 \times 10^{-9} &\leq \text{BR}(B_s \rightarrow \mu^+ \mu^-) \leq 3.43 \times 10^{-9} \quad (2\sigma) \\ 2.99 \times 10^{-4} &\leq \text{BR}(B_s \rightarrow X_s \gamma) \leq 3.87 \times 10^{-4} \quad (2\sigma) \end{aligned} \quad (14)$$

Finally, the parameters of LS-2HDM that estimate m_W within the 3σ vicinity of the CDF result given in Eq. (1) are considered in this study.

Following these considerations, the constraints on the parameters of LS-2HDM can be summarized into the following four groups.

G1 Theoretical constraints:

• The self couplings should satisfy the ranges given in Eqs. (10), (11), and (12).

G2 Experimental constraints:

- $m_{H^\pm} \geq 80$ GeV,
- $-0.14 \leq S \leq 0.06$, $-0.11 \leq T \leq 0.13$, $-0.1 \leq U \leq 0.08$, (1σ) ,
- $1.95 \times 10^{-9} \leq \text{BR}(B_s \rightarrow \mu^+ \mu^-) \leq 3.43 \times 10^{-9} (2\sigma)$,
- $2.99 \times 10^{-4} \leq \text{BR}(B_s \rightarrow X_s \gamma) \leq 3.87 \times 10^{-4} (2\sigma)$.

G3 h_1 is chosen to be an SM-like Higgs boson with

- $m_{h_1} = 125.0 \pm 2$ GeV.

G4 Constraint on W -boson mass reads

- $80.4053 \leq M_W^{\text{LS-2HDM}} \leq 80.4617$ GeV (3σ CDF).

G5 Constraint on W -boson mass reads

- $80.3305 \leq M_W^{\text{LS-2HDM}} \leq 80.3899$ GeV (3σ CMS).

The constraints are labeled for brevity in further discussions. The constraint on the Higgs boson in G3 is applied only on its mass in the first step of our analyses. We employ these constraints only to explore the regions where the deviation in M_W can be realized within the allowed ranges reported by the CDF and CMS collaborations. However, in the second step, we perform further analyses and employ HiggsTools (HiggsSignals and HiggsBounds) [97] to ensure the consistency of the Higgs boson solutions beyond its mass.

IV. EXPLORING THE PARAMETER SPACE

The parameter space of the LS-2HDM is explored by performing a random scan of potential parameters using SPheno 4.0.3, generated via SARAH 4.13.0 [119, 120]. In these scans, solutions satisfying the electroweak symmetry breaking condition ($v_1^2 + v_2^2 \approx v_{\text{SM}}^2$) are accepted. To ensure that the results of our random parameter scans are consistent with current measurements of the W -boson mass, the range of the self couplings are chosen as

$$\begin{aligned}
 0 &\leq \lambda_{1,2} \leq \pi, \\
 0 &\leq \lambda_3 \leq 4\pi, \\
 -2\pi &\leq \lambda_{4,5} \leq 0, \\
 -5 &\leq m_3^2 \leq 5 \text{ TeV}^2, \\
 1.2 &\leq \tan\beta \leq 40.0.
 \end{aligned} \tag{15}$$

For determining the ranges of the parameters, we stay in the intervals allowed by perturbativity. The constraints from perturbativity are applied in a straightforward manner to the couplings by following the condition given in

Eq. (10). However, this is not straightforward for the $\tan\beta$ parameter. To adjust the range for this parameter, we consider the couplings of the Higgs bosons to the SM fermions. To maintain the top quark Yukawa coupling perturbative at all energy levels from M_Z to some high energies, $\tan\beta$ should be bounded from below at about 0.3 [121]. In our scans, we lift this lower bound to 1.2 to ensure the fields in Φ_2 form the SM-like Higgs boson. Similarly, one can also place an upper bound by following the perturbativity of the gauge couplings as well as the Yukawa couplings, which disfavors the solutions with $\tan\beta \gtrsim 30$ [122, 123]. These bounds have been obtained in a general manner. As mentioned before, the behaviour of the Higgs bosons may differ in LS-2HDM from the other types of 2HDMs, and therefore, we place an upper limit on $\tan\beta$ at 40. Besides these constraints, we restrict the parameters further for practical reasons to optimize our scans to explore CDF and CMS compatible M_W solutions. After successively applying the constraints listed in the previous section, the solutions and their respective color coding in plots will be used throughout the rest of this work.

A. Mass spectrum of LS-2HDM

The mass spectrum of the LS-2HDM is analyzed by imposing the aforementioned groups of constraints from theoretical and experimental considerations. The correlation between the masses of the LS-2HDM scalars and $\tan\beta$ are illustrated in Fig. 1. As shown in Fig. 1 (top-left), solutions satisfying the theoretical constraints specified by G1 do not introduce further limitations on m_{h_2} . The green points in this plot represent solutions that meet both theoretical and experimental constraints specified in groups G1 and G2 within the ranges of $1.6 \lesssim \tan\beta \lesssim 40.0$ and $70 \lesssim m_{h_2} \lesssim 600$ GeV, respectively. It is evident that the application of G2 does not result in a significant reduction of the parameter space. The yellow points indicate solutions that additionally fulfill the condition $m_{h_1} = 125 \pm 2$ GeV (G1, G2, and G3). Although the application of G3 does not restrict the range of $\tan\beta$, it does reduce the number of solutions in the parameter space and imposes the condition $m_{h_2} \gtrsim 126$ GeV. The solutions indicated by the blue points in Fig. 1 (top-left) depict the parameter space that fulfills all four constraints outlined by groups G1, G2, G3, and G4, *i.e.*, it additionally satisfies restrictions from M_W^{CDF} , which limits the mass of the CP-even scalar boson as $150 \lesssim m_{h_2} \lesssim 430$ GeV. The solutions indicated by the red points depict the parameter space that fulfills G1, G2, G3, and G5. The condition G5 does not restrict the range of the parameter space. The region between the vertical dashed lines in Fig. 1 (top-left) corresponds to the case where h_2 is the SM-like Higgs boson, which does not satisfy G4, *i.e.*, the W -boson mass condition. Therefore, the selection of h_1 as the SM-like Higgs boson, as specified in constraint G3, is clarified.

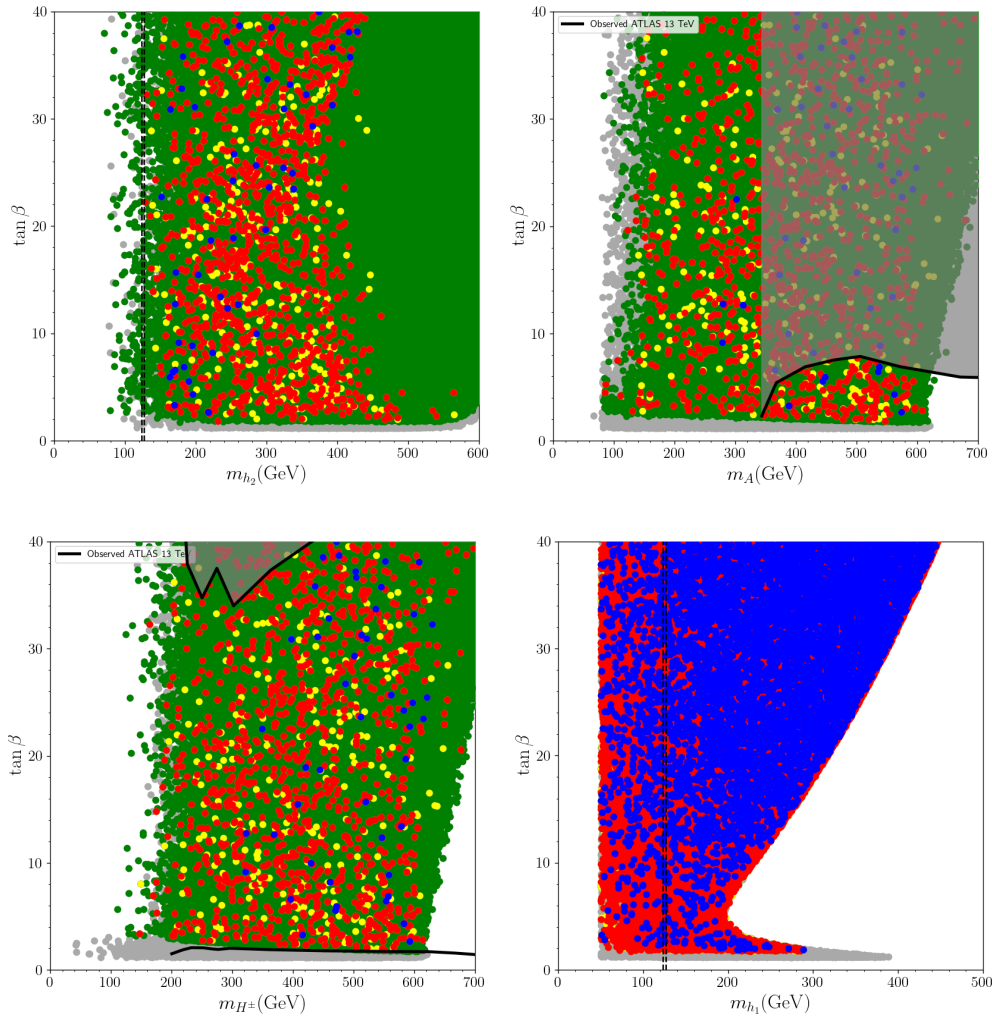


Fig. 1. (color online) Relationship between $\tan\beta$ and the mass of the LS-2HDM scalars for m_{h_2} (top-left), m_A (top-right), $m_{H^\pm}$ (bottom-left), and m_{h_1} (bottom-right). Color coding of solutions are described in detail in the previous text: Green points satisfy conditions G1 and G2; yellow points satisfy conditions G1, G2, and G3; blue points satisfy conditions G1, G2, G3, and G4; and red points satisfy conditions G1, G2, G3, and G5. Solid black lines indicate ATLAS 13 TeV analysis observation limits and gray shaded areas are excluded by these analysis [92, 93]. In the $\tan\beta$ vs. m_{h_1} plot (bottom-right), condition G3 is not applied. Dashed vertical lines represent the SM-like Higgs mass.

There are a few solutions satisfying the G5 condition. It is possible to find solutions compatible with the W -boson mass measured by CMS (represented by red points) in almost every region of the parameter space, and therefore, the G5 condition is not emphasized in the following sections.

In addition, the relationship between m_A and $\tan\beta$ is depicted in Fig. 1 (top-right) with the experimental constraints from the ATLAS 13 TeV results [92], where m_A spans the full $80 \leq m_A \leq 700$ GeV range. It is observed that the application of constraints G1 and G2 imposes limitations as $80 \leq m_A \leq 600 + 4.1 \tan\beta$ GeV. Moreover, adding the condition outlined as G3 reduces the number of solutions within the aforementioned regions. However, imposing the W -mass constraints described as G4 require $270 \leq m_A \leq 610$ GeV. The black line indicates the upper

exclusion limit from the ATLAS 13 TeV analysis [92], and it eliminates the majority of the solutions in the parameter space. Consequently, using solutions satisfying all constraints outlined as G1, G2, G3, and G4 and imposing limits from the ATLAS 13 TeV model independent scalar mass analysis, the mass of the CP-odd scalar boson and $\tan\beta$ are restricted as $340 \text{ GeV} \leq m_A \leq 630 \text{ GeV}$ and $\tan\beta \leq 8.0$, respectively. However, these experimental analyses are performed for cases in which the heavy Higgs bosons considerably interact with the quarks and leptons at any value of $\tan\beta$. The models in the LS-2HDM class may not exhibit such a feature because interactions between the quarks and these heavy Higgs bosons are suppressed by a large $\tan\beta$. In this context, even though the ATLAS analyses result in an exclusion, the solutions accumulate in the faded region in the top-left

plot of Fig. 1 can still be consistent with the experiments. For the charged scalars of LS-2HDM, the variation of $m_{H^\pm}$ on the $\tan\beta$ – $m_{H^\pm}$ plane is given in Fig. 1 (bottom-left). After applying constraints G1 and G2, the remaining solutions are bounded as $110 \text{ GeV} \lesssim m_{H^\pm} \lesssim 605 + 3.8 \tan\beta \text{ GeV}$. However, after applying G3, the lower bound on $m_{H^\pm}$ increases to 150 GeV. After adding cuts from G4, the acceptable solutions satisfy $320 \lesssim m_{H^\pm} \lesssim 630 \text{ GeV}$, and number of valid solutions are reduced. The exclusion limits from ATLAS 13 TeV [93] requires $\tan\beta \gtrsim 2.0$.

Thus far, the CP-even scalar boson h_1 has been identified as the SM-like Higgs boson, and this requirement was described as condition G3. To explore the behavior of m_{h_1} , we remove condition G3, allowing m_{h_1} to vary without this constraint. In this case, the relationship between $\tan\beta$ and m_{h_1} is presented in Fig. 1 (bottom-right). It is observed that m_{h_1} exhibits a distinct behavior in two specific regions of $\tan\beta$. For $\tan\beta \lesssim 5$, m_{h_1} shows

an inverse proportionality to $\tan\beta$, ranging from $50 \lesssim m_{h_1} \lesssim 288 \text{ GeV}$, where upper limit arises from condition G4. Conversely, for $\tan\beta \gtrsim 5$, m_{h_1} demonstrates a direct proportionality to $\tan\beta$, with values in the range of $50 \lesssim m_{h_1} \lesssim 450 \text{ GeV}$. This contrasting behavior in the low and high $\tan\beta$ regions is evident from Eq. (5).

Moreover, an analysis conducted by ATLAS at 13 TeV established an upper limit on m_{h_2} through various channels, including the decay modes of h_2 into two tau-leptons, two W -bosons, or two Z -bosons [92, 94, 95]. To investigate these limitations, the variation of the cross-sections $\sigma(gg \rightarrow h_2 \rightarrow \tau\tau)$, $\sigma(gg \rightarrow h_2 \rightarrow WW)$, and $\sigma(gg \rightarrow h_2 \rightarrow ZZ)$ with respect to m_{h_2} are depicted in Fig. 2. As shown in Fig. 2 (top-left), as m_{h_2} increases, the production cross-section in channel $\sigma(gg \rightarrow h_2 \rightarrow \tau\tau)$ decreases exponentially. According to the restrictions outlined in Ref. [92], nearly half of the solutions that satisfy criteria G4 are excluded, and the allowed parameter range necessitates $m_{h_2} \gtrsim 200 \text{ GeV}$, along with $\sigma(gg \rightarrow h_2 \rightarrow \tau\tau) \lesssim$

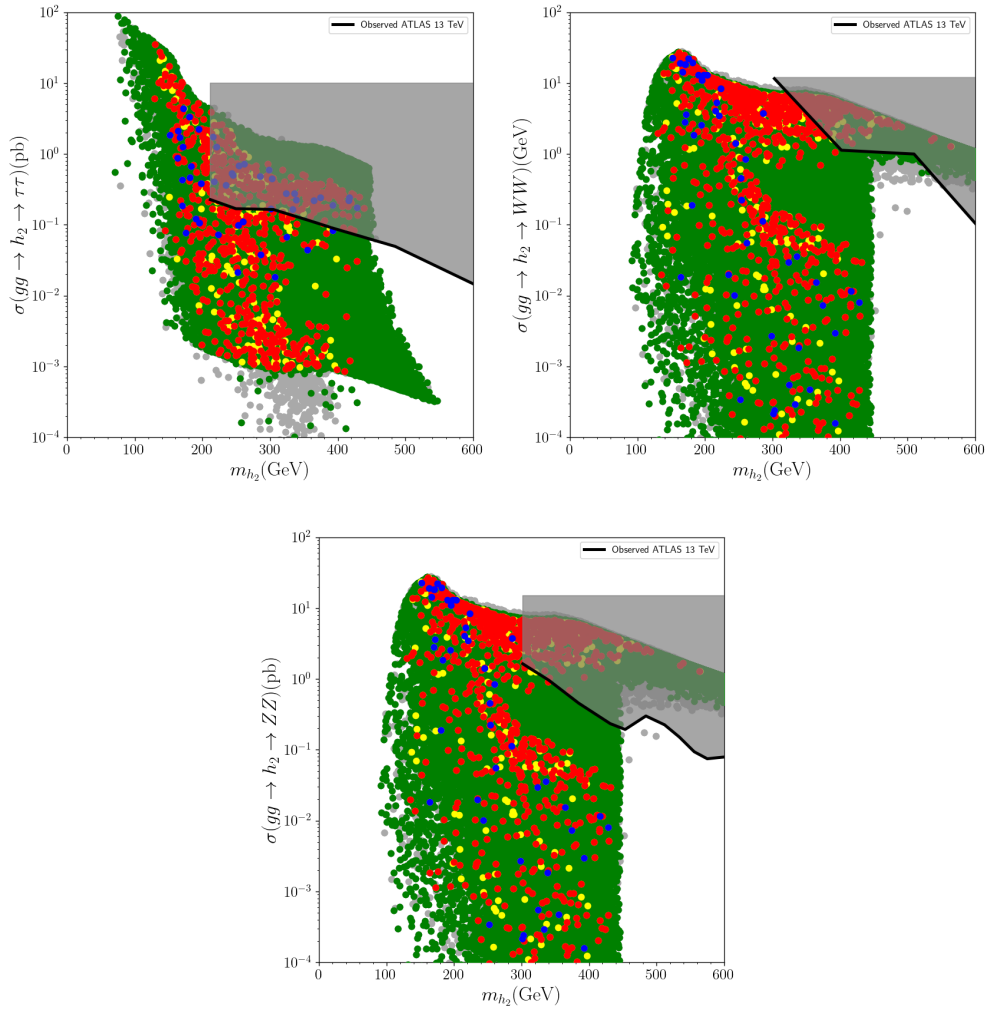


Fig. 2. (color online) Variation of the cross-sections $\sigma(gg \rightarrow h_2 \rightarrow \tau\tau)$ (top-left), $\sigma(gg \rightarrow h_2 \rightarrow WW)$ (top-right), and $\sigma(gg \rightarrow h_2 \rightarrow ZZ)$ (bottom) with respect to m_{h_2} . The color scheme is the same as that in Fig. 1, and the black shaded areas are excluded by Refs. [92, 94, 95]

2×10^{-1} pb. Fig. 2 (top-right) clearly indicates that the $\sigma(gg \rightarrow h_2 \rightarrow WW)$ value decreases with an increase in m_{h_2} , as expected. The solutions that satisfy G4 remain unaffected by the constraint reported in Ref. [94]. For $m_{h_2} \gtrsim 450$ GeV, solutions with $\sigma(gg \rightarrow h_2) \simeq 1.0$ pb and $\text{BR}(h_2 \rightarrow WW) \simeq 1.0$ can be obtained. A similar behavior can be seen in Fig. 2 (bottom), where the dependence of $\sigma(gg \rightarrow h_2 \rightarrow WW)$ on m_{h_2} is plotted, and the production cross-section decreases with an increase in m_{h_2} . No solution satisfying the G4 condition is excluded by the constraints outlined in Ref. [95]. For m_{h_2} below 300 GeV, the cross-section for the decay channel $\sigma(gg \rightarrow h_2 \rightarrow ZZ)$ remains above 1 pb. After considering these findings from Fig. 2, the mass of the heavier CP-even scalar boson is restricted as $150 \lesssim m_{h_2} \lesssim 400$ GeV.

B. Lepton flavor universality in Z boson decay

Another set of constraints on the solutions arises from decay processes involving Z-boson and τ -lepton. Although such processes can yield LFU in SM because of the mass hierarchy among fermion families, the experimental measurements reveal results beyond the SM predictions. In this context, new contributions to LFU can be utilized through processes involving the extra Higgs bosons. Their contributions are displayed in Fig. 3. The couplings of Z-boson with fermions and extra Higgs bosons can be given as [85]

$$-\mathcal{L} = \frac{g}{\cos \theta_W} Z^\mu \left\{ \bar{f} \gamma_\mu ((T_3(f_L) - Q(f_L) \sin^2 \theta_W) \delta g_L) P_L + ((T_3(f_R) Q(f_R) \sin^2 \theta_W) + \delta g_R) P_R \right\} f + i \left(-\frac{1}{2} + \sin^2 \theta_W \right) H^+ \overleftrightarrow{\partial}_\mu H^- + A \overleftrightarrow{\partial}_\mu H \}. \quad (16)$$

where contributions from the new physics can be seen through $\delta g_{R,L}$, which can be calculated as

$$\begin{aligned} \delta g_L^{2\text{HDM}} &= k \left[-\frac{1}{2} B_Z(r_A) - \frac{1}{2} B_Z(r_{h_2}) - 2C_Z(r_A, r_{h_2}) + \sin^2 \theta_W (B_Z(r_A) + B_Z(r_{h_2}) + \tilde{C}_Z(r_A) + \tilde{C}_Z(r_{h_2})) \right], \\ \delta g_R^{2\text{HDM}} &= k \left[2C_Z(r_A, r_{h_2}) - 2C_Z(r_{H^\pm}, r_{H^\pm}) + \tilde{C}_Z(r_{H^\pm}) - \frac{1}{2} \tilde{C}_Z(r_A) - \frac{1}{2} \tilde{C}_Z(r_{h_2}) + \sin^2 \theta_W (B_Z(r_A) + B_Z(r_{h_2}) + 2B_Z(r_{H^\pm}) + \tilde{C}_Z(r_A) + C_Z(r_{H^\pm}, r_{H^\pm})) \right], \end{aligned} \quad (17)$$

with $k = m_f^2 \tan^2 \beta / 16\pi^2 v^2$, where m_f represents fermion masses, Λ represents the cut-off scale, μ represents the

renormalization scale, and $r_\phi = m_\phi^2 / m_Z^2$ ($\phi = A, h_2, H^\pm$). The loop functions employed in Eq. (17) are calculated as

$$\begin{aligned} B_Z(r) &= -\frac{1}{2} (\ln \Lambda^2 + \log(4\pi)) - \frac{1}{4} + \frac{1}{2} \log r, \\ \tilde{C}_Z(r) &= -\frac{1}{2} (\ln \Lambda^2 + \log(4\pi)) - \frac{1}{2} - r(1 + \log r) + r^2 (\log r \log(1 + r^{-1}) - \text{dilog}(-r^{-1})) - \frac{i\pi}{2} (1 - 2r + 2r^2 \log(1 + r^{-1})), \\ C_Z(r_1, r_2) &= C_Z\left(\frac{m_{\phi_1}^2}{m_Z^2}, \frac{m_{\phi_2}^2}{m_Z^2}\right) = C_{00}(0, 0, m_Z^2, m_{\phi_1}^2, m_{\phi_2}^2), \\ C_{00} &= \frac{1}{4} \left(\ln \Lambda^2 + \log(4\pi) - \ln\left(\frac{m_Z^2}{\mu^2}\right) \right) + \frac{3}{8} - \frac{r_1^2 \ln r_1}{4(r_1 - 1)(r_1 - r_2)} + \frac{r_2^2 \ln r_2}{4(r_2 - 1)(r_1 - r_2)}. \end{aligned} \quad (18)$$

The deviation from LFU in the models can be parametrised with $\delta g_{R,L}$ as

$$\delta_{ll} = \frac{2g_L^e \text{Re}(\delta g_L^{\text{LS-2HDM}}) + 2g_R^e \text{Re}(\delta g_R^{\text{LS-2HDM}})}{g_L^{e^2} + g_R^{e^2}}, \quad (19)$$

where $l = \mu, \tau$. Throughout this analysis, the lepton universality in the Z-boson decay are investigated through the partial decay width of the Z-boson into leptons, which can be summarized with the relevant experimental measurements [84, 85] as

$$\begin{aligned} \frac{\Gamma_{Z \rightarrow \mu^+ \mu^-}}{\Gamma_{Z \rightarrow e^+ e^-}} &= 1.0009 \pm 0.0028, \\ \frac{\Gamma_{Z \rightarrow \tau^+ \tau^-}}{\Gamma_{Z \rightarrow e^+ e^-}} &= 1.0019 \pm 0.0032. \end{aligned} \quad \Rightarrow \quad \begin{cases} \delta_{\mu\mu} = \frac{\Gamma_{Z \rightarrow \mu^+ \mu^-}}{\Gamma_{Z \rightarrow e^+ e^-}} - 1 = (9 \pm 28) \times 10^{-4}, \\ \delta_{\tau\tau} = \frac{\Gamma_{Z \rightarrow \tau^+ \tau^-}}{\Gamma_{Z \rightarrow e^+ e^-}} - 1 = (19 \pm 32) \times 10^{-4}, \end{cases} \quad (20)$$

where $\delta_{\mu\mu}$ and $\delta_{\tau\tau}$ represent parameters defined to measure the deviation from LFU.

To understand the impact of LS-2HDM on lepton universality, such as the loop-induced contributions to the Z-boson decay widths, it is essential to explore the precise measurements of lepton universality ratios provided in Eq. (20) within the framework of LS-2HDM. To this end, the distribution of solutions that satisfy constraints outlined as G1, G2, G3 and G4 are plotted on δ_{ll} and $\tan \beta$ plane in left for $\delta_{\mu\mu}$ and in right for $\delta_{\tau\tau}$, in Fig. 4.

Figure 4 shows that the dependence of δ_{ll} on $\tan \beta$ is quadratic as indicated in Eq. (17) in both positive or negative directions depending on the scalar masses of the LS-

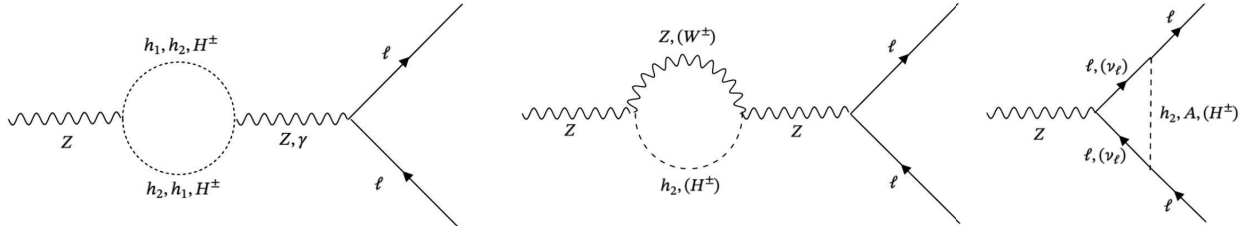


Fig. 3. Diagrams illustrating the contributions to LFU from the new Higgs bosons through decays of Z -boson.

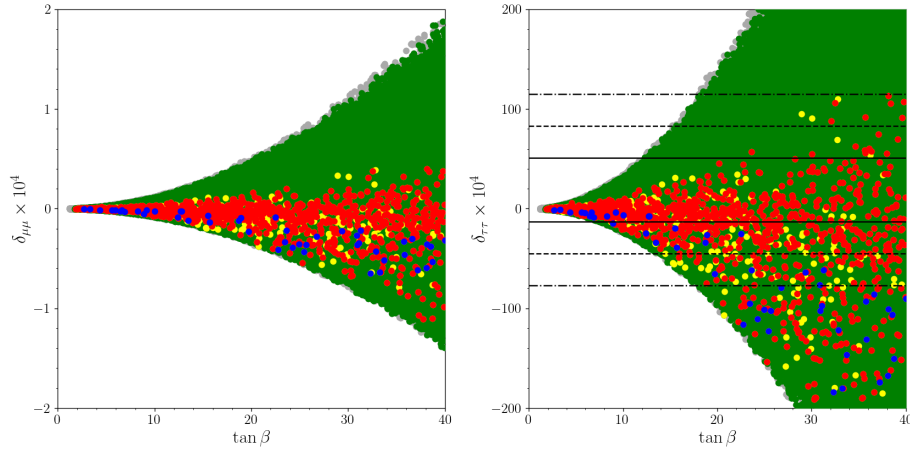


Fig. 4. (color online) Variation of $\delta_{\mu\mu}$ with respect to $\tan\beta$ (left) and $\delta_{\tau\tau}$ with respect to $\tan\beta$ (right). Color coding of the plots is the same as Fig. 1. The solid, dashed, and dash dotted lines indicate deviations from the current limits by Eq. (20) within 1σ , 2σ , and 3σ , respectively. For $\delta_{\mu\mu}$ (left), all solutions lie within 1σ vicinity.

2HDM. Further, Fig. 4 (left) demonstrates that the deviation of $\delta_{\mu\mu}$ from the LFU lies within 1σ level and increases with $\tan\beta$. The value of $\delta_{\mu\mu}$ must be negative to satisfy the boson mass constraint given by G4. In addition, Fig. 4 (right) demonstrates that $\delta_{\tau\tau}$ displays a greater sensitivity to $\tan\beta$ because of the contribution of m_τ^2 . The contribution can be either positive or negative; however, if the parameter space is restricted by G4, $\delta_{\tau\tau}$ is negative with a few exceptions. The majority of solutions satisfying all constraints (G1, G2, G3, and G4) are observed to fall within a 3σ deviation from the observed

value of $\delta_{\tau\tau} = 1.0019$.

To exemplify the behaviour of $\delta_{\tau\tau}$ we listed three benchmark points in Table 2. These points are selected to be consistent all constraints applied so far, and they yield possible minimum values for $\cos(\beta - \alpha)$ for each vicinity of the experimental measurements on LFU. The last two rows in the table show the accommodation of the W -boson mass in terms of the differences and uncertainty with respect to CDF and CMS results, respectively. These solutions indicate that heavy Higgs bosons should weigh in the mass range from 250 GeV to ~ 500 GeV. These

Table 2. Properties of solutions selected from Fig. 4 (right). All masses are given in the GeV unit. $1\sigma, 2\sigma, 3\sigma$ are the deviations from value of $\delta_{\tau\tau}$ (1.0019). All points are selected to yield the possible minimum values for $\cos(\beta - \alpha)$.

$\delta_{\tau\tau}$	$-12.9518 \times 10^{-4} (\leq 1\sigma)$	$-34.1836 \times 10^{-4} (\leq 2\sigma)$	$-63.6799 \times 10^{-4} (\leq 3\sigma)$
$\tan\beta$	12.774	13.45	29.332
m_{h_1}	126.901	125.808	126.263
m_{h_2}	261.613	234.808	364.553
m_A	350.786	558.726	451.389
$m_{H^\pm}$	393.202	578.161	500.79
m_3^2	-4327.4	-4004.4	-4518.6
$ \cos(\beta - \alpha) $	0.0497	0.0455	0.0591
$M_W^{\text{LS-2HDM}} - M_W^{\text{CDF}}$	-0.0309 (3.28 σ)	-0.0241 (2.56 σ)	-0.0227 (2.41 σ)
$M_W^{\text{LS-2HDM}} - M_W^{\text{CMS}}$	0.0424 (4.61 σ)	0.0492 (5.35 σ)	0.0506 (5.50 σ)

solutions with the blue points in the left panel of Fig. 4 reveal that the CDF compatible solutions yield large deviations in LFU processes, and one can accommodate CDF results only up to about 2σ consistently.

C. Lepton flavor universality in tau decay

The deviations from LFU can be tested in decays of τ -lepton. The recent analyses [91] consider pure leptonic and semi-hadronic decay processes. The QCD sector remains intact in LS-2HDM, and the new Higgs bosons interfere these processes through the electroweak and Yukawa interactions. Therefore, we consider only the pure leptonic decays to calculate the deviations from LFU. The relevant diagrams are displayed in Fig. 5. The deviation in τ decays can be analysed by considering the ratio of the gauge couplings of different lepton families as

$$\begin{aligned} \left(\frac{g_\tau}{g_\mu}\right) &= 1 + \delta_{\text{loop}}, & \left(\frac{g_\tau}{g_e}\right) &= 1 + \delta_{\text{tree}} + \delta_{\text{loop}}, \\ \left(\frac{g_\mu}{g_e}\right) &= 1 + \delta_{\text{tree}}, \end{aligned} \quad (21)$$

where δ_{loop} and δ_{tree} represent the contributions to SM value from the loop and tree level processes. In LS-2HDM, these contributions are calculated as [85, 86, 90]

$$\begin{aligned} \delta_{\text{tree}} &= \frac{m_\tau^2 m_\mu^2}{8m_{H^\pm}^4} t_\beta^4 - \frac{m_\mu^2}{m_{H^\pm}^2} t_\beta^2 \frac{g(m_\mu^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}, \\ \delta_{\text{loop}} &= \frac{1}{16\pi^2} \frac{m_\tau^2}{v^2} t_\beta^2 \left[1 + \frac{1}{4} \left(H(m_{H^\pm}^2/m_{H^\pm}^2) + s_{\beta-\alpha}^2 H(m_{h_2}^2/m_{H^\pm}^2) + c_{\beta-\alpha}^2 H(m_{h_1}^2/m_{H^\pm}^2) \right) \right], \end{aligned} \quad (22)$$

where

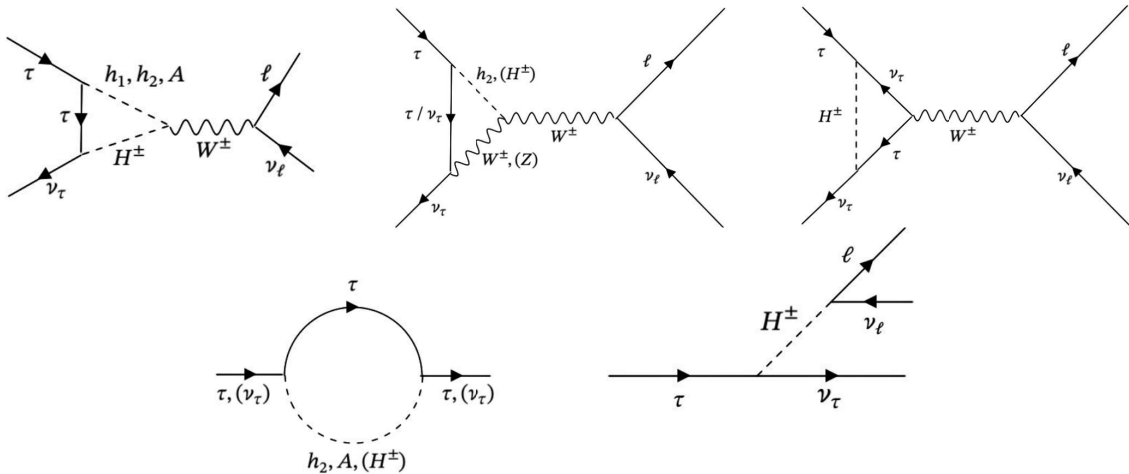


Fig. 5. Diagrams illustrating the contributions to LFU from the new Higgs bosons through decays of τ .

$$f(x) \equiv 1 - 8x + 8x^3 - x^4 - 12x^2 \ln(x),$$

$$g(x) \equiv 1 + 9x - 9x^2 - x^3 + 6x(1+x) \ln(x),$$

$$H(x) \equiv \ln(x)(1+x)/(1-x), \quad (23)$$

and $t_\beta = \tan\beta$, $s_{\beta-\alpha} = \sin(\beta-\alpha)$, and $c_{\beta-\alpha} = \cos(\beta-\alpha)$ are defined for brevity. Using pure leptonic processes, HFLAV collaboration obtained the values of ratios given in Eq. (22) as [91]

$$\begin{aligned} \left(\frac{g_\tau}{g_\mu}\right) &= 1.0009 \pm 0.0014, & \left(\frac{g_\tau}{g_e}\right) &= 1.0027 \pm 0.0014, \\ \left(\frac{g_\mu}{g_e}\right) &= 1.0019 \pm 0.0014. \end{aligned} \quad (24)$$

These averages define ranges for the loop and tree-level contributions as

$$\delta_{\text{loop}} = 0.0009 \pm 0.0014 \quad \text{and} \quad \delta_{\text{tree}} = 0.0019 \pm 0.0014, \quad (25)$$

and these limits will be considered for further analysis.

To examine the relationship between solutions satisfying all four constraints, they are plotted in the δ_{loop} and δ_{tree} versus $\tan\beta$ planes in Fig. 6 (left and right), respectively. Fig. 6 shows that applying constraints reduces the number of solutions and restricts them in the negative plane. In addition, all solutions shown in red in Fig. 6 (left) lie within 2σ vicinity of the HFVAL average value of δ_{loop} given in Eq. (25). Remarkably, for solutions with $\tan\beta \lesssim 20$, this proximity is confined within the 1σ range. For δ_{tree} , solutions meeting all constraints are clustered just below zero, when confined within a 1σ to 2σ window of the average value, as observed in Fig. 6 (right). Finally, it is apparent from Fig. 6 that with increasing

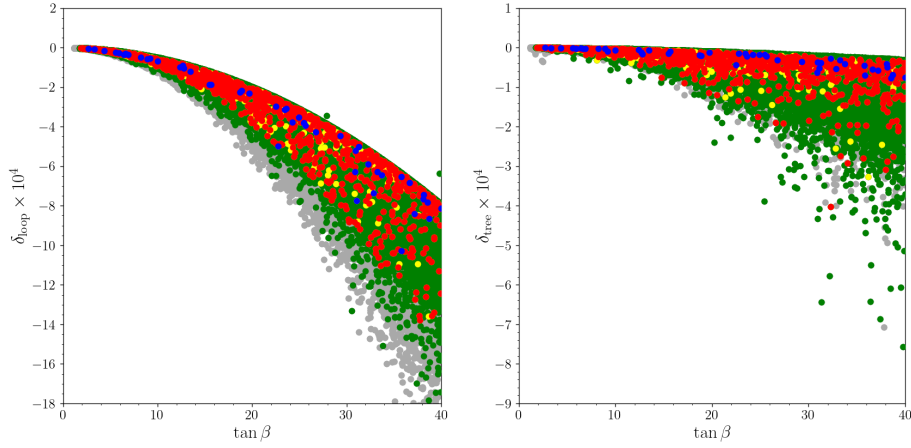


Fig. 6. (color online) δ_{loop} vs. $\tan\beta$ (left), and δ_{tree} vs. $\tan\beta$ (right). Color coding is the same as Fig. 1. All solutions lay within the 1σ vicinity of HFLAV results.

$\tan\beta$, loop contributions to the ratios from LS-2HDM become more significant in comparison to those at the tree level.

D. W -boson mass in LS-2HDM

Based on the main motivation of our study, the new scalar states alter the W -boson mass through loops because they are non-trivially charged under the SM gauge group in 2HDMs. Their contributions can be analyzed through the self-energies of the gauge bosons. These scalar states can arise these contributions through their interactions with W -boson, and the mixing among them. These contributions are illustrated in Fig. 7. Although one can constrain these contributions by fitting the W -boson mass with CDF and/or CMS measurements, the results from the analyses over oblique parameters should be applied and satisfied. These oblique parameters can be defined by considering the self-energies of the W -boson, Z -boson, and contributions to mixing these gauge bosons yielding $Z\gamma$ processes [124–126]. In addition, the contributions to W -boson mass can be written in terms of these oblique parameters as [127]

$$M_W^2 = M_W^{\text{SM}2} \left(1 + \frac{s_W^2}{c_W^2 - s_W^2} \Delta r' \right), \quad (26)$$

with the loop contributions to the two-point function

$$\Delta r' = \frac{\alpha}{s_W^2} \left(-\frac{1}{2}S + c_W^2 T + \frac{c_W^2 - s_W^2}{4s_W^2} U \right), \quad (27)$$

which represents the measure of deviations from SM, and where $s_W = \sin\theta_W$ and $c_W = \cos\theta_W$ with θ_W is the weak angle. In Eq. (27), S , T , and U represent oblique parameters, which contain the effects of incorporating additional scalar bosons contributions through loops within the LS-2HDM framework to M_W . These parameters are defined based on precision measurements in electroweak physics, and in SM, $S = T = U = 0$ serves as the reference point. The explicit form of the S , T , and U parameters are given as [126]

$$\begin{aligned} S = \frac{1}{\pi m_Z^2} \{ & -\mathcal{B}_{22}(m_Z^2; m_{H^\pm}^2, m_{H^\pm}^2) + \sin^2(\beta - \alpha) \mathcal{B}_{22}(m_Z^2; m_{h_2}^2, m_A^2) \\ & + \cos^2(\beta - \alpha) [\mathcal{B}_{22}(m_Z^2; m_{h_1}^2, m_A^2) + \mathcal{B}_{22}(m_Z^2; m_Z^2, m_{h_2}^2) \\ & - \mathcal{B}_{22}(m_Z^2; m_Z^2, m_{h_1}^2) - m_Z^2 \mathcal{B}_0(m_Z^2; m_Z^2, m_{h_2}^2) \\ & + m_Z^2 \mathcal{B}_0(m_Z^2; m_Z^2, m_{h_1}^2)] \}, \end{aligned} \quad (28)$$

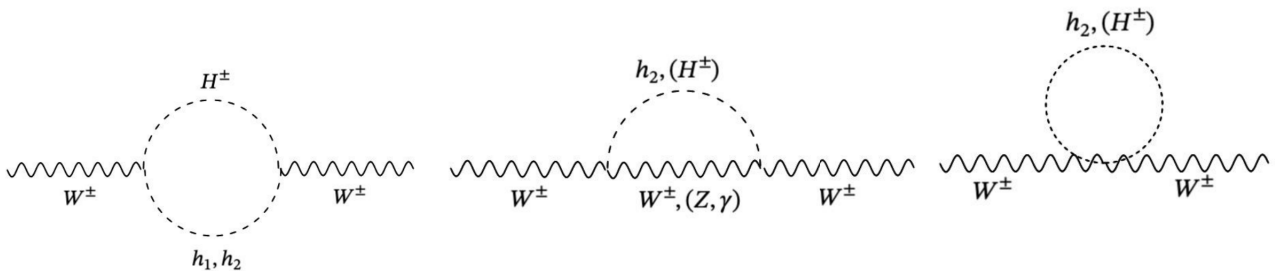


Fig. 7. Diagrams illustrating the contributions to W -boson mass from the new Higgs bosons.

$$T = \frac{1}{16\pi s_W^2 m_W^2} \left\{ \mathcal{F}(m_{H^\pm}^2, m_A^2) + \sin^2(\beta - \alpha) [\mathcal{F}(m_{H^\pm}^2, m_{h_2}^2) - \mathcal{F}(m_A^2, m_{h_2}^2)] + \cos^2(\beta - \alpha) [\mathcal{F}(m_{H^\pm}^2, m_{h_1}^2) - \mathcal{F}(m_A^2, m_{h_1}^2)] \right. \\ \left. + \mathcal{F}(m_W^2, m_{h_2}^2) - \mathcal{F}(m_W^2, m_{h_1}^2) - \mathcal{F}(m_Z^2, m_{h_2}^2) + \mathcal{F}(m_Z^2, m_{h_1}^2) + 4m_Z^2 B_0(0; m_Z^2, m_{h_2}^2) - 4m_Z^2 B_0(0; m_Z^2, m_{h_1}^2) \right. \\ \left. - 4m_W^2 B_0(0; m_W^2, m_{h_2}^2) + 4m_W^2 B_0(0; m_W^2, m_{h_1}^2) \right\}, \quad (29)$$

$$S + U = \frac{1}{\pi m_W^2} \left\{ \mathcal{B}_{22}(m_W^2; m_{H^\pm}^2, m_A^2) - 2\mathcal{B}_{22}(m_W^2; m_{H^\pm}^2, m_{H^\pm}^2) + \sin^2(\beta - \alpha) \mathcal{B}_{22}(m_W^2; m_{H^\pm}^2, m_{h_2}^2) + \cos^2(\beta - \alpha) \right. \\ \left. \times [\mathcal{B}_{22}(m_W^2; m_{h_1}^2, m_{H^\pm}^2) + \mathcal{B}_{22}(m_W^2; m_W^2, m_{h_2}^2) - \mathcal{B}_{22}(m_W^2; m_W^2, m_{h_1}^2) + m_W^2 \mathcal{B}_0(m_W^2; m_W^2, m_{h_2}^2) \right. \\ \left. - m_W^2 \mathcal{B}_0(m_W^2; m_W^2, m_{h_1}^2)] \right\}, \quad (30)$$

where

$$\mathcal{B}_{22}(q^2; m_1^2, m_2^2) \equiv \mathcal{B}_{22}(q^2; m_1^2, m_2^2) - \mathcal{B}_{22}(0; m_1^2, m_2^2), \\ \mathcal{B}_0(q^2; m_1^2, m_2^2) \equiv \mathcal{B}_0(q^2; m_1^2, m_2^2) - \mathcal{B}_0(0; m_1^2, m_2^2), \quad (31)$$

are loop functions arising from two-point loop integrals given as

$$B_{22}(q^2; m_1^2, m_2^2) = \frac{1}{4}(\Delta + 1) \left[m_1^2 + m_2^2 - \frac{1}{3}q^2 \right] \\ - \frac{1}{2} \int_0^1 dx X \ln(X - i\epsilon), \\ B_0(q^2; m_1^2, m_2^2) = \Delta - \int_0^1 dx \ln(X - i\epsilon), \quad (32)$$

where

$$X \equiv m_1^2 x + m_2^2(1 - x) - q^2 x(1 - x), \quad \Delta \equiv \frac{2}{4 - d} + \ln 4\pi - \gamma. \quad (33)$$

Shorthand notation $\mathcal{F}$ in Eq. (29) is defined as

$$\mathcal{F}(m_1^2, m_2^2) \equiv \frac{1}{2} (m_1^2 + m_2^2) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \left(\frac{m_1^2}{m_2^2} \right), \quad (34)$$

which satisfy the relation

$$\mathcal{F}(m_1^2, m_2^2) = \mathcal{F}(m_2^2, m_1^2) \text{ and } \mathcal{F}(m^2, m^2) = 0. \quad (35)$$

As seen from the equation used to calculate the oblique parameters, mass differences among Higgs bosons and their mixing can be restricted directly. Their effects on mass differences are shown in Fig. 8 in correlation with mass differences among the Higgs boson. Further,

the bottom-right panel displays possible correlation between the S and T parameters. The color coding is the same as in Fig. 1. The vertical and horizontal dashed lines indicate solutions with $S, T, U = 0$ as referred to SM. Based on the plots, solutions satisfying the constraints G1, G2, and G3 (yellow points) yield the mass difference between the charged and CP-odd Higgs bosons between about -40 and 150 GeV. There is a slight increase in T and S parameters with increasing mass difference between these Higgs bosons. The correlation of the U parameter is observed to be sharper than that of the other oblique parameters. The CDF-compatible solutions for W -boson mass (blue points) are realized for large T -parameter ($\sim 0.1 - 0.13$), whereas they are accumulated in both positive and negative neighborhoods of the SM values (horizontal dashed line). Further, we display the T and S parameters with respect to each other to explore if there is any possible numerical correlation between them. Our scatter plots do not reveal any specific interval for these parameters with respect to each other because our scans have several free parameters that can help fitting these parameters in any region consistently. If we pick up a point (say from red points), for such a point increasing S values lead to an increase in the T -parameter.

The restrictions on mass differences from the oblique parameters also constrain the deviation in W -boson mass realized in our analyses. Figure 9 display favored mass differences among Higgs bosons by the desired deviation in W -boson mass compatible with oblique parameters. The color coding is the same as that in Fig. 1. The horizontal dashed line at around zero indicates the CMS result, while the upper horizontal dashed line represents the CDF result. As seen from the top-left plane, the blue and red points do not prefer any specific value for $\tan\beta$. They restrict the mass difference between two CP-even Higgs bosons (top-right plane) at ~ 300 GeV by CDF (blue points), and at ~ 440 by CMS (red points) from the upper. The mass difference favoured by blue and red points can

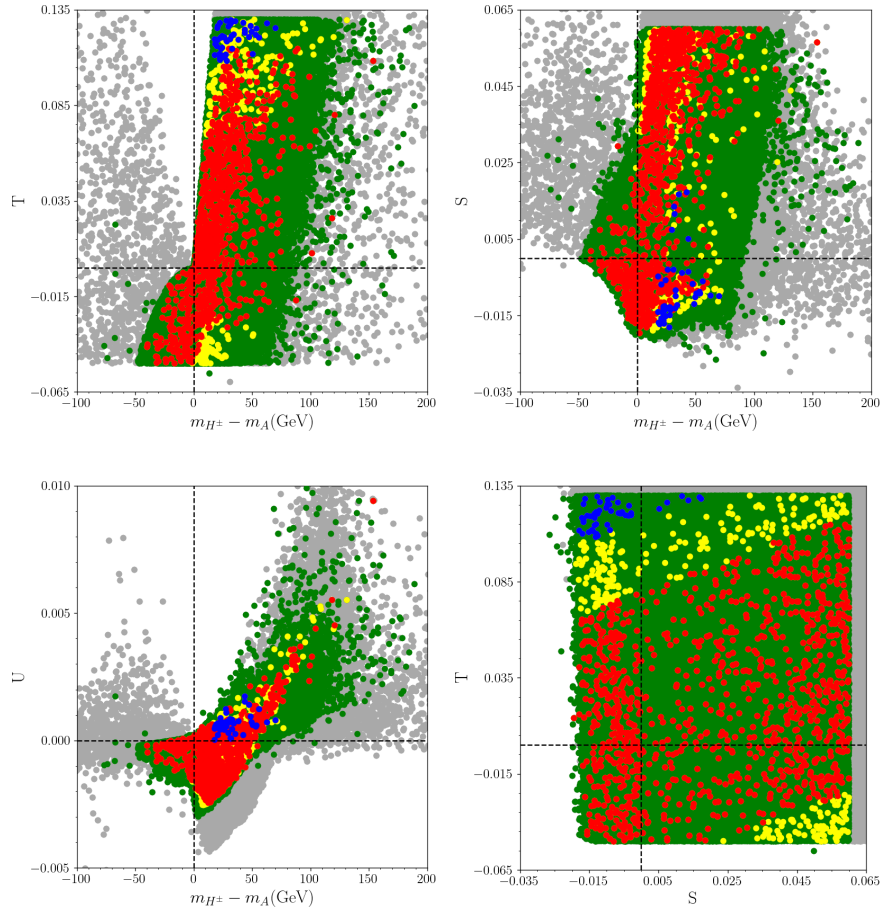


Fig. 8. (color online) Oblique parameters in correlation with mass differences among the Higgs boson. The bottom-right panel also displays possible correlation between S and T parameters. The color coding is the same as in Fig. 1. The vertical and horizontal dashed lines indicate the solutions with $S, T, U = 0$ as referred to SM.

be as large as ~ 480 GeV for mass difference $m_A - m_{h_2}$. The main impact from the W -boson mass together with consistent oblique parameters is seen in the mass difference between the charged and CP-odd Higgs bosons as shown in the bottom-right plane. To accommodate the desired deviation in W -boson mass requires $10 \lesssim m_{H^\pm} - m_A \lesssim 75$ GeV by CDF and $-40 \lesssim m_{H^\pm} - m_A \lesssim 160$ GeV by CMS.

Graphical representations reveal that the LS-2HDM scenario can generate a range of deviations in the mass of W from small to large values, which depends on the choice of appropriate parameters. One observes that the value ΔM_W exhibits variation, which encompasses both the SM expectation and experimental deviations in the CDF measurements. The findings confirm that the LS-2HDM model has the capability to maintain the W -boson mass in approximate ranges of the SM, as upheld by a zero or insignificant ΔM_W ; e.g., $\Delta M_W \approx 0.003$ GeV, in alignment with CMS findings. When all other theoretical and experimental constraints are applied except for the oblique-parameter bounds (S, T, U), the LS-2HDM can yield solutions compatible with the CDF W -boson mass

within about 1σ . For example, one can obtain $\Delta M_W \sim 0.07$ GeV. However, once current constraints on S , T , and U are included, the deviation from the CDF value cannot be reduced below about 2σ .

E. Further analysis

In previous sections, we explored the deviations in the W -boson mass by comparing several experimental and theoretical results, and we found that the LS-2HDM accommodates the CMS value and approaches the CDF value only up to about 2σ once the current (S, T, U), SM-like Higgs, and LFU constraints are imposed. Despite a large variety of constraint sets in our analyses, these solutions need to be considered in further analyses. The properties of the SM-like Higgs boson play an important role in these analyses. Thus far, we have considered only a consistent mass range for the SM-like Higgs boson. A first step to investigate the features of the SM-like Higgs boson within the LS-2HDM framework is considering the mixing among doublets, which is parametrized with $\cos(\beta - \alpha)$. We display the possible $\cos(\beta - \alpha)$ values in our analyses in Fig. 10 in correlation with the SM-like

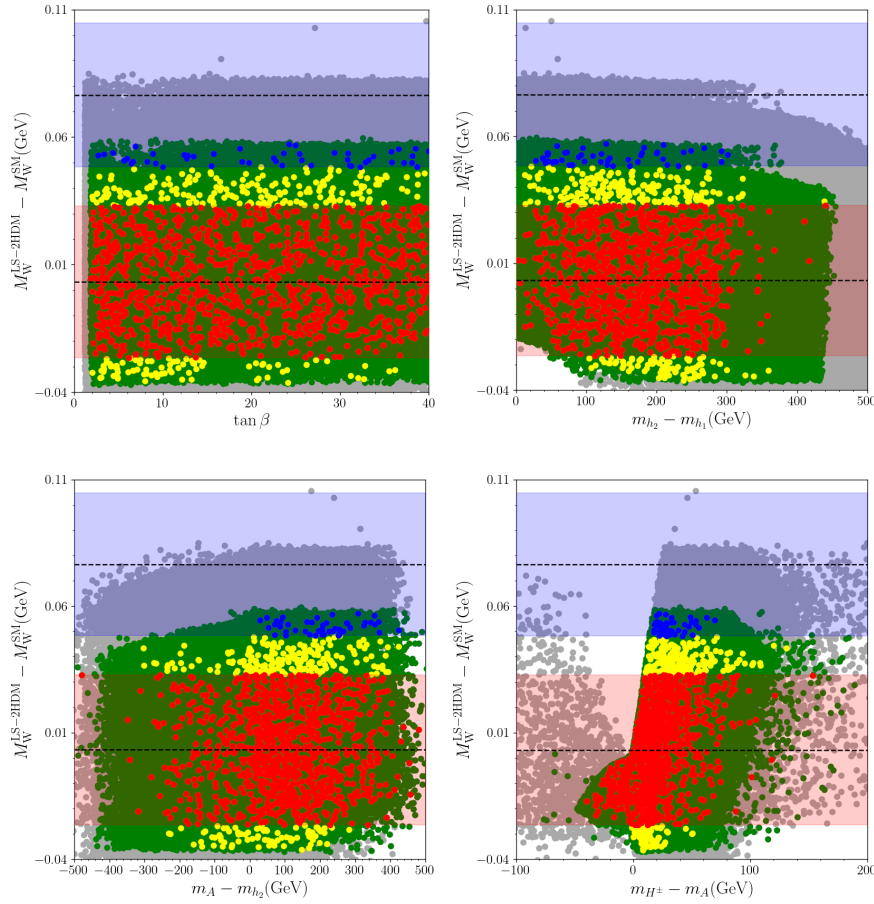


Fig. 9. (color online) Solutions satisfying conditions G1, G2, G3, G4, and G5 plotted in the ΔM_W versus $\tan\beta$ (top-left), $m_{h_2} - m_{h_1}$ (top-right), $m_A - m_{h_2}$ (bottom-left), and $m_{H^\pm} - m_A$ (bottom-right). Color coding of the points is the same as in Fig. 1. The blue region is the 3σ uncertainty range of the M_W value measured by the CDF experiment, and the red region is the 3σ uncertainty range of the M_W value measured by the CMS experiment; the dashed lines indicate the corresponding published central values for the two measurements.

Higgs boson mass, deviation in W -boson mass, and oblique parameters. The color coding is the same as in Fig. 1. The dashed lines in the top-left panel indicate the experimental bounds on the SM-like Higgs boson mass, whereas those in the top-right panel show the CMS and CDF measurements on W -boson mass from bottom to top. The dashed lines in the bottom planes show the solutions with $S, T = 0$ referring to the SM. The top-left panel shows that a consistent mass for the SM-like Higgs boson can be realized in any value of $\cos(\beta - \alpha)$. The boundaries for this parameter reveals the SM-like Higgs boson formation. For example, when $\cos(\beta - \alpha) \simeq 1$, the SM-like Higgs boson is mostly formed by the fields in Φ_1 , whereas those in Φ_2 mostly form the SM-like Higgs boson when $\cos(\beta - \alpha) \sim 0$. The intermediate values of $\cos(\beta - \alpha)$ correspond to the mixing in the SM-like Higgs boson in which all scalar fields actively take part. The top-right panel shows that the desired deviation can be accommodated in the W -boson mass over the entire range of $\cos(\beta - \alpha)$, and the bottom panels show that these solu-

tions can be consistent with the oblique parameters.

Although we strictly subject our solutions to the experimental and theoretical constraints, it does not mean that the resultant blue and red solutions are fully consistent. The first theoretical constraint on the composition of the SM-like Higgs boson arises from the perturbativity limit, especially from the effective Yukawa coupling with the top quark. The heavy mass for the top quark can be accommodated with a large coupling. In this context, a consistent SM-like Higgs boson should be formed by the doublet that directly interacts with the top quark. In our setup, the suitable candidates for the SM-like Higgs boson are those resided in Φ_2 . Besides the perturbativity limit, if the SM-like Higgs boson is formed by fields in Φ_1 , then it would contradict with some other experimental results that examine the effective coupling between the SM-like Higgs boson and gauge bosons as well as with the SM fermions. The most comprehensive approach for checking consistency in the SM-like Higgs boson from its mass is to run the HiggsTools package [97]. This pack-

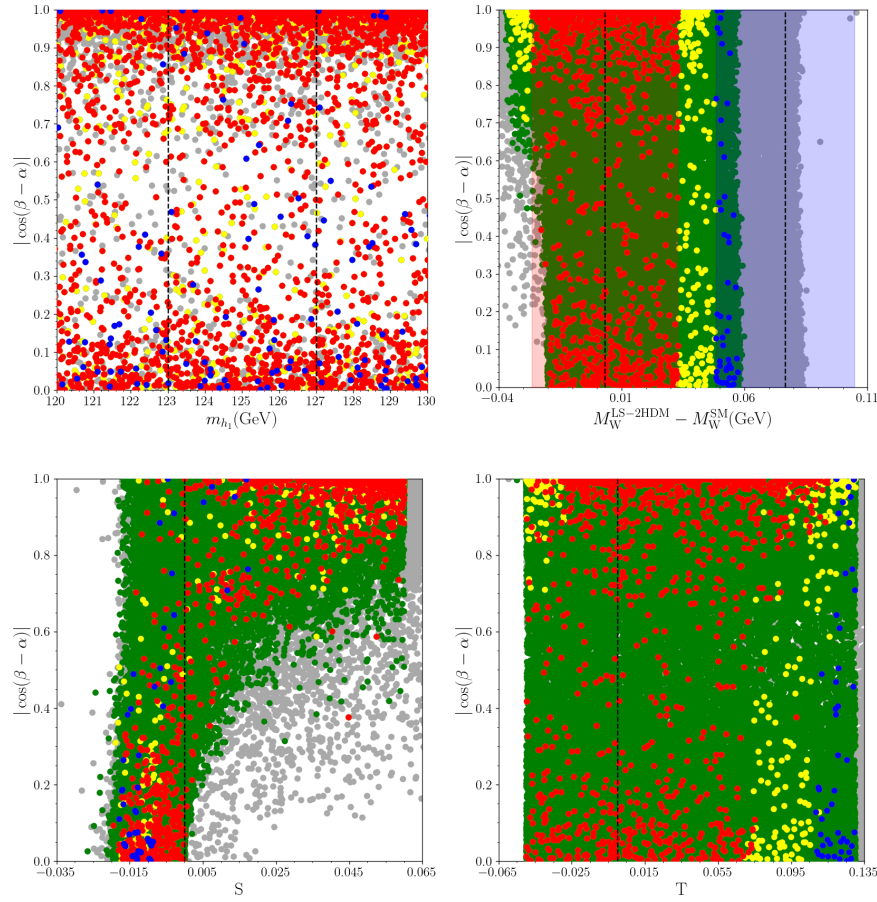


Fig. 10. (color online) Plots for $\cos(\beta - \alpha)$ in correlation with the SM-like Higgs boson mass, deviation in W -boson mass, and the oblique parameters. The color coding is the same as in Fig. 1. The dashed lines in the top-left panel indicate experimental bounds on the SM-like Higgs boson mass, while those in the top-right panel show the CMS and CDF measurements on W -boson mass from the bottom to the top. The dashed lines in the bottom planes show solutions with $S, T = 0$ referring to SM.

age checks the mixing of the SM-like Higgs boson and its couplings to the SM particles, and it confronts the results with a large set of distinct experimental results in terms of its production and decay modes. Based on the discussion about the effective coupling between the SM-like Higgs boson and top quark, one can expect solutions forming the SM-like Higgs boson with the fields in Φ_2 to survive after the HiggsTools run, which corresponds to $\cos(\beta - \alpha) \simeq 0$.

The effect from the consistency of the SM-like Higgs boson goes beyond this expectation such that only ten points survive out of ~ 1000 (red and blue points in total in the previous plots). We exemplify these surviving solutions with six benchmark points in Table 3. Points 1 and 2 exemplify the solutions which lead to the W -boson mass compatible with the CDF results. These solutions accommodate the CP-odd and charged Higgs boson masses at ~ 500 – 600 GeV. Interestingly, these points indicate that the CDF results rather imply a relatively large mass difference between these two Higgs bosons at ~ 15 – 20 GeV. The heavy CP-even Higgs boson weigh around 250 GeV in these solutions. The consistent SM-

like Higgs boson mass is realized at about 124 GeV, which is consistent with the observations within the theoretical uncertainties in the Higgs boson mass calculation. Point 1 among these solutions also implies a 1σ deviation from LFU in $\delta_{\tau\tau}$, whereas Point 2 leads to a 2σ deviation. Points 3, 4, 5, and 6 in Table 3 represent the solutions compatible with the CMS measurements. These solutions can include a slightly heavier SM-like Higgs boson mass (~ 125 GeV). These points indicate that the charged and CP-odd Higgs bosons nearly degenerate in mass. These solutions can be realized with relatively $\tan\beta$ as shown in Point 3. Despite relatively $\tan\beta$ (~ 32), the muon anomalous magnetic moment (Δa_μ) lies in ranges consistent with the recent measurements [128, 129]. Point 3 can lead to compatible new physics contributions to Δa_μ , while predictions in Points 4, 5, and 6 more or less coincide with the SM prediction.

Before concluding, we present the possible limitations in the parameter space of LS-2HDM in Table 4. Although we generate solutions by varying the couplings, we express the ranges for masses and mass differences to

Table 3. Comparison of parameters across all points. All points passed from HiggsTools.

Parameters	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
$M_W^{\text{LS-2HDM}}$	80.4142	80.4032	80.3786	80.3704	80.3540	80.3684
$M_W^{\text{LS-2HDM}} - M_W^{\text{CMS}}$	0.054 (5.87 σ)	0.0429 (4.67 σ)	0.0184 (1.86 σ)	0.0102 (1.03 σ)	-0.0062 (0.63 σ)	0.0082 (0.83 σ)
$M_W^{\text{LS-2HDM}} - M_W^{\text{CDF}}$	-0.0193 (2.05 σ)	-0.0303 (3.22 σ)	-0.0549 (5.84 σ)	-0.0631 (6.71 σ)	-0.0795 (8.46 σ)	-0.0651 (6.92 σ)
m_{h_1}	124.139	124.228	125.7700	124.1860	124.7140	125.9400
m_{h_2}	252.081	246.601	144.5190	244.6180	233.2980	160.6120
m_A	560.419	618.417	435.2390	536.0650	582.1850	532.8540
$m_{H^\pm}$	582.554	633.576	443.2380	540.5340	579.4030	535.4250
$m_{h_2} - m_{h_1}$	127.9420	122.3730	18.7490	120.4320	108.5840	34.6720
$m_{H^\pm} - m_A$	22.1349	15.1589	7.9990	4.4690	-2.7820	2.5710
$m_A - m_{h_2}$	308.3379	371.8160	290.7200	291.4470	348.8870	372.2420
$m_{H^\pm} - m_{h_1}$	458.4149	509.3480	317.4680	416.3480	454.6890	409.4850
$\tan\beta$	24.2350	15.36	32.4200	20.4000	17.8040	23.7880
$ \cos(\beta - \alpha) $	0.0707	0.0446	0.0285	0.0464	0.0598	0.0442
λ_1	2.7537	1.1050	0.4953	1.0403	2.2846	0.7583
λ_2	0.1264	0.1257	0.1304	0.1263	0.1273	0.1307
λ_3	10.12	12.303	6.1309	8.6155	10.2310	9.0426
λ_4	-4.9746	-5.9280	-3.0126	-3.9144	-4.5980	-4.3505
λ_5	-4.1400	-5.3019	-2.7808	-3.7557	-4.7046	-4.2599
m_3^2	-2598.6000	-3955.5000	-642.4600	-2918.4000	-3008.1000	-1077.6000
$B_s \rightarrow \mu^+ \mu^-$	3.072×10^{-9}	3.073×10^{-9}	3.072×10^{-9}	3.073×10^{-9}	3.073×10^{-9}	3.072×10^{-9}
$B_s \rightarrow X_s \gamma$	3.149×10^{-4}	3.148×10^{-4}	3.149×10^{-4}	3.149×10^{-4}	3.148×10^{-4}	3.149×10^{-4}
$\delta_{\mu\mu}$	-3.920×10^{-5}	-1.954×10^{-5}	-3.718×10^{-5}	-2.037×10^{-5}	-1.890×10^{-5}	-3.162×10^{-5}
$\delta_{\tau\tau}$	-1.108×10^{-3}	-5.526×10^{-3}	-1.051×10^{-2}	-5.760×10^{-3}	-5.344×10^{-3}	-8.941×10^{-3}
g_τ/g_μ	0.9996	0.9998	0.9992	0.9997	0.9998	0.9996
g_τ/g_e	0.9996	0.9998	0.9992	0.9997	0.9998	0.9995
g_μ/g_e	1.0000	1.0000	0.9999	1.0000	1.0000	1.0000
S	-0.0162	-0.0165	-0.0181	-0.0145	-0.0151	-0.0180
T	0.128	0.1013	0.0405	0.0231	-0.0169	0.0161
U	0.0006	0.0004	0.0004	0.0002	-0.0000	0.0001
Δa_μ	2.722×10^{-12}	1.206×10^{-12}	1.527×10^{-11}	2.026×10^{-12}	1.790×10^{-12}	6.926×10^{-12}

provide comparable values with the other studies. CDF and CMS analyses reveal different ranges for the deviation in W -boson mass, and these ranges do not overlap. Therefore, we display two sets of ranges. The first two columns display the minimum and maximum ranges when the CDF results are imposed, while the last two columns show limits for the case of CSM results.

V. CONCLUSIONS

In this study, the LS-2HDM parameter space is investigated to obtain a parameter space where the W -boson mass measured by CDF and CMS experiments is confronted within the framework of LS-2HDM. To this

end, both theoretical and experimental constraints are applied to the parameter space. Consequently, only a limited range of parameter values remains viable within the LS-2HDM framework, most of which are found to be compatible with the reported measurements of LFU tau-lepton and Z -boson decays. Among these, the electroweak precision constraints encoded in the oblique parameters (S, T, U) play a crucial role. Enforcing the current global fits excludes solutions that would otherwise realize the CDF 1σ region, whereas the charged-Higgs mass and rare B -decay bounds have a comparatively weak effect. Furthermore, assuming h_1 to be the SM-like Higgs boson reduced the number of solutions consider-

Table 4. Constraints on model parameters that satisfy all four aforementioned groups of limitations and HiggsTools. All masses are given in GeV.

Parameter	Min. Val. (CDF)	Max. Val. (CDF)	Min. Val. (CMS)	Max. Val. (CMS)
m_{h_1}	124.139	124.228	123.668	125.940
m_{h_2}	246.601	252.081	144.519	413.886
m_A	560.419	618.417	435.239	671.085
$m_{H^\pm}$	582.554	633.576	443.238	685.670
$\tan\beta$	15.36	24.235	17.804	38.741
$ \cos(\beta - \alpha) $	0.039	0.071	0.023	0.060
m_3^2	-3955.5	-2598.6	-4926.5	-642.46
$m_{h_2} - m_{h_1}$	122.373	127.942	18.749	290.218
$m_A - m_{h_2}$	308.338	371.816	253.406	372.242
$m_{H^\pm} - m_A$	15.159	22.135	-11.121	15.588

ably. In our scans, we required consistency with the current (S, T, U), SM-like Higg, and LFU constraints, and then, we tested compatibility with the CDF and CMS M_W determinations. Within the feasible solutions, the LS-2HDM easily predicts the CMS measurement, while the predicted W -boson mass approach the CDF value only to about 2σ once all constraints are imposed. The available parameter space of LS-2HDM obtained through this analysis is summarized in Table 4. Within these ranges, LS-2HDM can be effectively utilized for making predictions.

It is important to note that imposing the ($M_W^{\text{LS-2HDM}} - M_W^{\text{CMS/CDF}}$) condition directly on the masses may not always be convenient for determining restrictions on parameters. Using additional parameters related to masses, such as mass differences employed in this analysis results in stronger limits. We observe that the current constraints on oblique parameters can directly bound the mass differences such that consistent solutions can accommodate CDF measurements for the W -boson mass only up to about 2σ , and it is further tightened by requiring h_1 to be SM-like and the LFU constraints. This discrepancy between h_1 being SM-like and M_W^{CDF} might be a sign of an inconsistency that requires further investigations.

To ensure a comprehensive analysis, six solutions were selected, with two estimating M_W^{CDF} within 2σ and the remaining four predicting M_W^{CMS} within 1σ . These se-

lected solutions were used as benchmarks, and their predictions were provided. To comprehensively conclude this analysis, all solutions satisfying the conditions outlined in Table 4 were tested using the HiggsTools package, which incorporated the most recent constraints. With the addition of the new value of the W -boson mass derived by CMS in 2024 in the model, the LS-2HDM has a parameter space that accommodates the CMS measurement and approaches the CDF value of about 2σ ; however, it does not resolve the CDF and CMS tension within a single framework.

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DATA AVAILABILITY STATEMENT

Data sets generated during the current study are available from the corresponding author on reasonable request.

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