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Can we have a second light Higgs boson in the $U(1)$ model?

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Abstract. *Our theoretical model predicts the existence of a light-mass CP-even Higgs boson ($\mathscr{H}_1$) and a light-mass pseudo-scalar boson ($\mathscr{A}$). The mass ranges for these particles are determined by the cubic coupling, μ_4, at the electroweak energy scale. These light Higgs bosons can produce flavor-changing neutral currents, which play a significant role in meson mixing processes. Specifically, when $m_{\mathscr{A}} = s_\alpha m_{\mathscr{H}_1}$, the contributions to flavor mixing can either completely cancel each other out or, conversely, become extremely large.*

Keywords: extended Higgs sector; light scala; Higgs bosson ankmalies; beyond Standard Model.
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1. Introduction

While the Standard Model (SM) successfully describes particle physics up to the TeV scale, a more fundamental theory is likely needed for a complete understanding of nature. The LHC has yet to uncover clear evidence for physics beyond the SM, and the discovered 125 GeV Higgs boson aligns with SM predictions [1, 2]. However, an intriguing possibility is an extended Higgs sector containing an additional light Higgs boson accessible to collider experiments. This could lead to deviations in the properties of the 125 GeV Higgs boson compared to SM expectations. Higgs boson below 125 GeV was first searched at LEP [3, 4], which hints at the possibility of an additional scalar boson at 96 GeV. Recent CMS results combining data from Run I and full Run II data [5] have indicated a local excess of 2.9 σ in diphoton final states at 95.4 GeV. ATLAS also observed a slight excess at 95.4 GeV with a local significance of about 1.7 σ [6] based on Run II data. The intriguing scenario has been the subject investigations [7–11].

In this work, we focus on the alternative $U(1)_X$ model [12], which posits a scenario with non-universal quark families. Anomaly cancellation within this model provides a compelling explanation for the observed correlation between the number of fermion families and the number of colors. Furthermore, this theory can be embedded into a broader framework of grand unification [13–17] or E_6 [18].

The Higgs sector contains two Higgs doublets and one singlet Higgs. This singlet couples the two Higgs doublets via quartic scalar couplings, Λ_i, and the cubic scalar coupling, μ_4, as detailed in [12]. In our previous work [19], we assume that μ_4 is of the order of the $U(1)_X$ symmetry breaking scale. This led to all new Higgs bosons, including CP-even Higgs, CP-odd Higgs, and singly charged Higgs, being heavy. What if μ_4 is of the order of the electroweak scale? Could this scenario allow for light Higgs boson?

To explore this possibility, the remainder of this work is organized as follows. Section 2 reviews the model, including the diagonalization of scalars and the identification of fermion couplings to scalars. Section 3 investigates flavor-changing phenomenology induced by light Higgs fields. Finally, Section 4 concludes the work.

2. Brief review of the model

2.1. *Particle content and symmetries*

We propose an alternative electroweak gauge group, $SU(2)_L \times U(1)_X \times U(1)_N$, where anomalies are not canceled for each family. The inclusion of $U(1)_N$ is necessary to ensure anomaly cancellation, leading to the breaking of $U(1)_N \times U(1)_X$ down to the SM hyper-charged $U(1)_Y$ group at high energy scales. We concentrate on the $U(1)_X$ version with non-universal quark families. All lepton doublets and one quark doublets share the same X charge, denoted as x, while the remaining quark doublets carry an opposite X charge, $-x$. This model successfully addresses the number of fermion families through anomaly cancellation [12]. The fermion spectrum of the model and their $SU(3)_C \times SU(2)_L \times U(1)_X$ assignments are:

$$\begin{aligned}
l_{aL} &= \begin{pmatrix} \nu_{aL} \\ e_{aL} \end{pmatrix} \sim (1,2,x,-\frac{1}{2}-x), \quad e_{aR} \sim (1,1,x,-1-x), \\
q_{\alpha L} &= \begin{pmatrix} u_{\alpha L} \\ d_{\alpha L} \end{pmatrix} \sim (3,2,-x,\frac{1}{6}+x), \quad q_{3L} = \begin{pmatrix} u_{3L} \\ d_{3L} \end{pmatrix} \sim (3,2,x,\frac{1}{6}-x), \\
u_{\alpha R} &\sim (3,1,-x,\frac{2}{3}+x), \quad d_{\alpha R} \sim (3,1,-x,-\frac{1}{3}+x), \\
u_{3R} &\sim (3,1,x,\frac{2}{3}-x), \quad d_{3R} \sim (3,1,x,-\frac{1}{3}-x),
\end{aligned} \tag{1}$$

and three right-handed neutrinos, $\nu_{aR} \sim (1,1,x,-x)$, are presented, required for anomaly cancellation.

The scalar sector of the model requires two $SU(2)_L$ Higgs doublets, H, Φ, and an electrically neutral $SU(2)_L$ scalar singlet χ. The scalar content of the model with their corresponding $SU(3)_C \times SU(2)_L \times U(1)_X \times U(1)_N$ assignments are given by:

$$H = \begin{pmatrix} H_1^+ \\ H_2^0 \end{pmatrix} \sim (1,2,0,\frac{1}{2}), \quad \Phi = \begin{pmatrix} \Phi_1^+ \\ \Phi_2^0 \end{pmatrix} \sim (1,2,-2x,\frac{1}{2}+2x), \quad \chi \sim (1,1,-2x,2x).$$

To achieve symmetry breaking and generate masses for fermions, the scalar fields have the vacuum expectation values (VEVs) as follows

$$\langle\chi\rangle = \Lambda/\sqrt{2}, \quad \langle H\rangle = (0, v_1/\sqrt{2}), \quad \langle\Phi\rangle = (0, v_2/\sqrt{2}). \tag{2}$$

To be consistent with the SM, the VEVs must satisfy the conditions: $v_1, v_2 \ll \Lambda$, and $v^2 = v_1^2 + v_2^2 = (246\text{GeV})^2$.

2.2. *Revised scalar mass spectrum*

Let us revisit the scalar mass spectrum. The scalar potential takes the following form:

$$\begin{aligned} V \;=\; & \mu_1^2 H^\dagger H + \mu_2^2 \Phi^\dagger\Phi + \mu_3^2 \chi^\dagger\chi + \mu_4[(\Phi^\dagger H)\chi + H.c.] \\ & + \lambda_1 (H^\dagger H)^2 + \lambda_2(\Phi^\dagger\Phi)^2 + \lambda_3(\chi^\dagger\chi)^2 \\ & + \lambda_4(H^\dagger H)(\chi^\dagger\chi) + \lambda_5(\Phi^\dagger\Phi)(\chi^\dagger\chi) \\ & + \lambda_6(H^\dagger H)(\Phi^\dagger\Phi) + \lambda_7(H^\dagger\Phi)(\Phi^\dagger H), \end{aligned} \tag{3}$$

where $\Lambda_{1,2,3,4,5,6,7}$ are dimensionless, while $\mu_{1,2,3,4}$ have a mass dimension. The necessary conditions for this potential to be bounded from below are as follows:

$$\mu_{1,2,3}^2 < 0, \quad \lambda_{1,2,3} > 0, \quad |\mu_{1,2}| \ll |\mu_3|, \tag{4}$$

$$\lambda_4 > -2\sqrt{\lambda_1\lambda_3}, \quad \lambda_5 > -2\sqrt{\lambda_2\lambda_3}, \quad \lambda_6 + \lambda_7\Theta(-\lambda_7) > -2\sqrt{\lambda_1\lambda_2}., \tag{5}$$

where $\Theta(x)$ is the heaviside step function. This implies that there are no constraints on the cubic coupling μ_4 arising from the potential's boundless. On the other hand, expanding the scalar fields around their vacuum expectation values as follows,

$$H = \begin{pmatrix} H_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + S_1 + iA_1) \end{pmatrix}, \tag{6}$$

$$\Phi = \begin{pmatrix} \Phi_1^+ \\ \frac{1}{\sqrt{2}}(v_2 + S_2 + iA_2) \end{pmatrix}, \tag{7}$$

$$\chi = \frac{1}{\sqrt{2}}(\Lambda + S_3 + iA_3), \tag{8}$$

we obtain the following tree-level constraints:

$$\left(2\lambda_1 v_1^2 + (\lambda_6 + \lambda_7)v_2^2 + 2\mu_1^2\right) v_2 + \left(\sqrt{2}\mu_4 v_2 + \lambda_4 v_1 \Lambda\right)\Lambda = 0 \quad , \tag{9}$$

$$\left(2\lambda_2 v_2^2 + (\lambda_6 + \lambda_7)\, v_1^2 + 2\mu_2^2\right) v_1 + \left(\sqrt{2}\mu_4 v_1 + \lambda_5 v_2 \Lambda\right)\Lambda = 0 \quad , \tag{10}$$

$$2\left(\lambda_3\Lambda^2 + \mu_3^2\right)\Lambda + \left(\lambda_4 v_1^2 + \lambda_5 v_2^2\right)\Lambda + \sqrt{2}\mu_4 v_1 v_2 = 0. \tag{11}$$

One of the solutions of the system of equations given in (9, 10) is given as follows:

$$\mu_1 = -\lambda_1 v_1^2 - \frac{\lambda_6+\lambda_7}{2} v_2^2, \quad \sqrt{2}\mu_4 v_2 = -\lambda_4 v_1 \Lambda, \tag{12}$$

$$\mu_2 = -\lambda_2 v_2^2 - \frac{\lambda_6+\lambda_7}{2} v_1^2, \quad \sqrt{2}\mu_4 v_1 = -\lambda_5 v_2 \Lambda. \tag{13}$$

The last two conditions in Eqs.(12, 13) lead to the following constraint on μ_4 :

$$\mu_4^2 \sim \lambda_4\lambda_5\Lambda^2. \tag{14}$$

Recall that the SM Higgs boson is a CP-even scalar with a mass given by $m_H = \sqrt{2\lambda}v$, where Λ is the SM Higgs self-coupling and $v = (\sqrt{2}G_F)^{\frac{1}{2}} \simeq 246$ GeV is the Higgs VEV. The experimentally measured Higgs boson mass, $m_H \simeq 125$ GeV [20], implies that the self Higgs coupling $\Lambda \simeq 0.13$.

In our model, we have seven quartic couplings: three self-couplings, $(\lambda_1, \lambda_2, \lambda_3)$, and four mixed couplings, $(\lambda_4, \lambda_5, \lambda_6, \lambda_7)$, which satisfy the constraints given in (5). Assuming the self-coupling values are larger than the mixed coupling values, such as $\Lambda_{4,5,6,7} \sim 0.1\lambda_{1,2,3}$, we obtain:

$$|\mu_4| < \frac{\Lambda}{100}. \tag{15}$$

This suggests that the cubic coupling μ_4 can be naturally suppressed at the electroweak symmetry breaking scale or even below the electroweak symmetry breaking scale.

Let us reconsider the scalar mass spectrum in the limit: $\mu_4, v_1, v_2 \ll \Lambda$. First, we consider charged scalar fields. In the basis $H_1^\pm, \Phi_1^\pm$, the squared matrix is given by

$$M_c^2 = \frac{1}{2}\begin{pmatrix} -\lambda_7 v_2^2 - \sqrt{2}\mu_4\Lambda\frac{v_2}{v_1} & \lambda_7 v_1 v_2 + \sqrt{2}\mu_4\Lambda \\ \lambda_7 v_1 v_2 + \sqrt{2}\mu_4\Lambda & -\lambda_7 v_1^2 - \sqrt{2}\mu_4\Lambda\frac{v_1}{v_2} \end{pmatrix}. \tag{16}$$

This matrix provides the massless charged scalar fields, $\mathscr{G}^\pm = \cos\alpha H_1^\pm + \sin\alpha\Phi_1^\pm$, corresponding to the SM charged Goldstone bosons, and massive charged scalar fields, $\mathscr{H}^\pm = -\sin\alpha H_1^\pm + \cos\alpha\Phi_1^\pm$, with mass squared given by:

$$m_{\mathscr{H}^\pm}^2 = -\frac{(\sqrt{2}\Lambda\mu_4 + \lambda_7 v_1 v_2)(v_1^2+v_2^2)}{2v_1v_2} = -\frac{\sqrt{2}}{\sin 2\alpha}\mu_4\Lambda - \frac{\lambda_7}{2}\left(v_1^2+v_2^2\right), \tag{17}$$

where $\tan\alpha = \frac{v_2}{v_1}$.

There are three neutral CP-odd scalars: A_1, A_2, A_3. In this basis, the squared mass matrix has the form:

$$M_{\text{CP-odd}}^2 = \frac{\mu_4}{\sqrt{2}}\begin{pmatrix} -\frac{v_2}{v_1}\Lambda & \Lambda & -v_2 \\ \Lambda & \frac{v_1}{v_2}\Lambda & v_1 \\ -v_2 & v_1 & \frac{-v_1v_2}{\Lambda} \end{pmatrix}, \tag{18}$$

This matrix provides a CP-odd massive scalar field, $\mathscr{A}$, and two Goldstone bosons, $\mathscr{G}_Z, \mathscr{G}_{Z'}$. These fields can be expressed as linear combinations of the original fields A_1, A_2, A_3:

$$\begin{aligned} \mathscr{A} &= \cos\alpha_1\cos\alpha_2 A_1 - \sin\alpha_2 A_2 + \cos\alpha_2\sin\alpha_1 A_3, \\ \mathscr{G}_Z &= \cos\alpha_1\sin\alpha_2 A_1 - \cos\alpha_2 A_2 + \sin\alpha_2\sin\alpha_1 A_3, \\ \mathscr{G}_{Z'} &= \sin\alpha_1 A_1 - \cos\alpha_1 A_3. \end{aligned} \tag{19}$$

The angles α_1 and α_2 are related to the parameters v_1, v_2, and Λ as follows

$$\tan\alpha_1 = \frac{v_1}{\Lambda}, \quad \tan\alpha_2 = \frac{\cos\alpha_1}{\tan\alpha}. \tag{20}$$

The mass of the CP-odd scalar field, $\mathscr{A}$, is given by:

$$m_{\mathscr{A}}^2 = -\frac{\mu_4[\Lambda^2(v_1^2+v_2^2)+v_1^2v_2^2]}{\sqrt{2}\Lambda v_1 v_2} = -\frac{\sqrt{2}\mu_4\Lambda}{\sin 2\alpha} - \frac{\mu_4}{\sqrt{2}\Lambda}v_1v_2. \tag{21}$$

The CP-even scalar fields, S_1, S_2, S_3, mix via a following matrix

$$M^2_{\text{CP-even}} = \begin{pmatrix} 2\lambda_1 v_1^2 - \frac{\tan\alpha}{\sqrt{2}}\mu_4\Lambda & (\lambda_6+\lambda_7)v_1v_2 + \frac{\mu_4\Lambda}{\sqrt{2}} & \frac{1}{\sqrt{2}}\mu_4 v_2 + \lambda_4 v_1\Lambda \\ (\lambda_6+\lambda_7)v_1v_2 + \frac{\mu_4\Lambda}{\sqrt{2}} & 2\lambda_2 v_2^2 - \frac{1}{\sqrt{2}\tan\alpha}\mu_4\Lambda & \frac{\mu_4 v_1}{\sqrt{2}} + \lambda_5 v_2\Lambda \\ \frac{1}{\sqrt{2}}\mu_4 v_2 + \lambda_4 v_1\Lambda & \frac{\mu_4 v_1}{\sqrt{2}} + \lambda_5 v_2\Lambda & -\frac{\mu_4}{\sqrt{2}\Lambda}v_1v_2 + 2\lambda_3\Lambda^2 \end{pmatrix}. \tag{22}$$

In the limit $\mu_4 < v_1, v_2 \ll \Lambda$, we have three massive scalar fields which can be written as

$$\begin{aligned} \mathscr{H}_1 &= (\sin\alpha_3)S_1 - (\cos\alpha_3)S_2, \\ \mathscr{H}_2 &= \cos\beta\,(\cos\alpha_3 S_1 + \sin\alpha_3 S_2) + (\sin\beta)S_3, \\ \mathscr{H}_3 &= -\sin\beta\,(\cos\alpha_3 S_1 + \sin\alpha_3 S_2) + (\cos\beta)S_3, \end{aligned} \tag{23}$$

where

$$\tan\alpha_3 = \frac{\lambda_5}{\lambda_4}\tan\alpha, \qquad \tan 2\beta = -\tan\alpha_1\sqrt{\frac{\lambda_4^2}{\lambda_3^2} + \frac{\lambda_5^2}{\lambda_3^2}\tan^2\alpha}. \tag{24}$$

Their masses are given respectively by

$$\begin{aligned} m^2_{\mathscr{H}_1} &\simeq 2\,(\lambda_1+\lambda_2-\lambda_6-\lambda_7)\,\frac{v_1^2 v_2^2}{v_1^2+v_2^2} \\ m^2_{\mathscr{H}_2} &\simeq \frac{2}{v_1^2+v_2^2}\left\{\lambda_1 v_1^4 + \lambda_2 v_2^4 + (\lambda_6+\lambda_7)\,v_1^2 v_2^2\right\} - \frac{1}{2\lambda_3}\left(\lambda_4^2 v_1^2 + \lambda_5^2 v_2^2\right), \\ m^2_{\mathscr{H}_3} &\simeq 2\lambda_3\Lambda^2 + \mathscr{O}(v_1^2, v_2^2). \end{aligned}$$

In this model, we explore the possibility of a second light Higgs boson in addition to the SM Higgs boson. The model predicts two neutral CP-even scalar Higgs bosons with masses at the electroweak scale. Among them one can be identified with the SM Higgs boson, while the other can be a light 95 GeV Higgs boson. Mixing CP-even components can lead to flavor-changing neutral currents (FCNC) at the tree level in the quark sector. However, quark FCNC imposes strong constraints on new physics [19, 21–25]. To address whether a second light Higgs boson can exist in the $U(1)$ model, we must carefully consider the FCNC effects in meson physics and estimate the new physics contribution to the properties of SM-like Higgs boson.

2.3. Probing SM-like Higgs coupling properties

The couplings of the scalar fields to a pair of fermions are derived from the Yukawa Lagrangian

$$\begin{aligned} \mathscr{L}_{\text{Yuk}} &= h^e_{ab}\bar{l}_{aL}He_{bR} + h^\nu_{ab}\bar{l}_{aL}\tilde{H}\nu_{bR} + \frac{1}{2}f^\nu_{ab}\bar{\nu}^c_{aR}\nu_{bR}\chi \\ &\quad + h^d_{\alpha\beta}\bar{q}_{\alpha L}Hd_{\beta R} + h^u_{\alpha\beta}\bar{q}_{\alpha L}\tilde{H}u_{\beta R} + h^d_{33}\bar{q}_{3L}Hd_{3R} + h^u_{33}\bar{q}_{3L}\tilde{H}u_{3R} \\ &\quad + h'^d_{\alpha 3}\bar{q}_{\alpha L}\Phi d_{3R} + h'^u_{3\beta}\bar{q}_{3L}\tilde{\Phi}u_{\beta R} + H.c. \end{aligned} \tag{25}$$

where $\tilde{H} = i\sigma_2 H^*$, $\tilde{\Phi} = i\sigma_2\Phi^*$. We characterize Higgs coupling properties using a series of Higgs coupling strength modifier parameters, κ_i, defined as the ratios of the Higgs boson couplings to particles i to their corresponding SM values. For the coupling of two light neutral Higgs bosons, $\mathscr{H}_1$ and $\mathscr{H}_2$, to a pair of leptons, we have:

$$\begin{aligned}\kappa^l_{\mathscr{H}_1} &= \frac{g_{\mathscr{H}_1 ll}}{g^{SM}_{hll}} \simeq \tan\alpha,\\ \kappa^l_{\mathscr{H}_2} &= \frac{g_{\mathscr{H}_2 ll}}{g^{SM}_{hll}} \simeq \cos\beta\frac{\cos\alpha_3}{\cos\alpha}.\end{aligned} \tag{26}$$

Assuming $\mathscr{H}_2$ is the SM-like Higgs boson and given the limit $\Lambda \gg v_1, v_2$, we obtain $\cos\beta \simeq 1$. To ensure consistency with SM Higgs boson properties, we impose the constraint that $\cos\alpha$ must be close to the $\cos\alpha_3$. As a result, we obtain $\Lambda_4 \simeq \lambda_5$, which indicates that the interaction between the two Higgs doublets and the singlet is symmetric and the mass hierarchy:

$$m^2_{\mathscr{H}_1} < m^2_{\mathscr{H}_2} \ll m^2_{\mathscr{H}_3}. \tag{27}$$

Thus, $\mathscr{H}_1, \mathscr{H}_2$ can be identified as a light 95 GeV Higgs boson and 125 GeV Higgs boson, respectively, while $\mathscr{H}_3$ is a heavy state. It is important to note that if $\mathscr{H}_1$ is identified as the 125 GeV SM-like Higgs boson, it would impose a stringent constraint of $\tan\alpha = \frac{v_2}{v_1} = 1$. This condition appears unnatural and could pose significant challenges when considering phenomenological implications related to meson oscillations and decays, as discussed in [19].

In the limit $\Lambda_4 \simeq \lambda_5$, the model predicts FCNC associated with the light 95 GeV Higgs boson, $\mathscr{H}_1$, and the CP-odd scalar field, $\mathscr{A}$. These FCNC interactions are given by:

- FCNCs associated with $\mathscr{H}_1$:

$$\mathscr{L}^{\mathscr{H}_1}_{\text{FCNC}} = -\frac{g}{2m_W}\left\{\Gamma_{\bar{u}_i u_j \mathscr{H}_1}\bar{u}_{iL}u_{jR} + \Gamma_{\bar{d}_i d_j \mathscr{H}_1}\bar{d}_{iL}d_{jR}\right\}\mathscr{H}_1 + H.c., \tag{28}$$

where

$$\begin{aligned}\Gamma_{\bar{u}_i u_j \mathscr{H}_1} &= -\frac{2}{\sin 2\alpha}\sum_{k=1}^{3}\sum_{\beta=1}^{2}(V^u_L)^\dagger_{i3}(V^u_L)_{3k}m_{u_k}(V^u_R)^\dagger_{k\beta}(V^u_R)_{\beta j},\\ \Gamma_{\bar{d}_i d_j \mathscr{H}_1} &= -\frac{2}{\sin 2\alpha}\sum_{k=1}^{3}\sum_{\beta=1}^{2}\left(V^d_L\right)^\dagger_{i\beta}\left(V^d_L\right)_{\beta k}m_{d_k}\left(V^d_R\right)^\dagger_{k3}\left(V^d_R\right)_{3j}.\end{aligned} \tag{29}$$

- FCNCs associated with $\mathscr{A}$:

$$\mathscr{L}^{\mathscr{H}_1}_{\text{FCNC}} = -\frac{g}{2m_W}\left\{\Gamma_{\bar{u}_i u_j \mathscr{H}_1}\bar{u}_{iL}u_{jR} + \Gamma_{\bar{d}_i d_j \mathscr{H}_1}\bar{d}_{iL}d_{jR}\right\}\mathscr{A} + H.c., \tag{30}$$

where

$$\begin{aligned}\Gamma_{\bar{u}_i u_j \mathscr{A}} &\simeq -\frac{i}{\cos\alpha}\sum_{k=1}^{3}\sum_{\beta=1}^{2}(V^u_L)^\dagger_{i3}(V^u_L)_{3k}m_{u_k}(V^u_R)^\dagger_{k\beta}(V^u_R)_{\beta j},\\ \Gamma_{\bar{d}_i d_j \mathscr{A}} &\simeq -\frac{i}{\cos\alpha}\sum_{k=1}^{3}\sum_{\beta=1}^{2}\left(V^d_L\right)^\dagger_{i\beta}\left(V^d_L\right)_{\beta k}m_{d_k}\left(V^d_R\right)^\dagger_{k3}\left(V^d_R\right)_{3j}.\end{aligned} \tag{31}$$

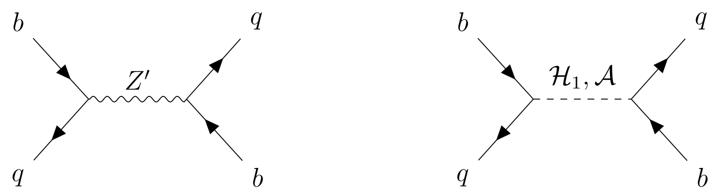

Fig. 1. The left and right Feynman diagrams present for B-meson oscillations Δm_{B_q} mediated by new gauge boson Z' and new scalar bosons $\mathscr{H}_1, \mathscr{A}$, respectively. Here, q denotes d, s

Assuming that the left-handed quark mixing matrix V_L^d is the CKM matrix (V_{CKM}), V_L^u is a unit matrix, and the right-handed quarks do not mix, we obtain

$$\begin{aligned}\Gamma_{\bar{u}_i u_j \mathscr{H}_1(\mathscr{A})} &= 0, \quad \text{and} \quad \Gamma_{\bar{d}_i d_j \mathscr{H}_1(\mathscr{A})} = 0 \quad \text{if} \quad j \neq 3, \\ \Gamma_{\bar{d}_i d_3 \mathscr{H}_1,} &= -2\frac{m_b}{\sin 2\alpha}\left\{(V_{CKM})^\dagger_{i1}(V_{CKM})_{13} + (V_{CKM})^\dagger_{i2}(V_{CKM})_{23}\right\}, \\ \Gamma_{\bar{d}_i d_3 \mathscr{A},} &= -i\frac{m_b}{\cos\alpha}\left\{(V_{CKM})^\dagger_{i1}(V_{CKM})_{13} + (V_{CKM})^\dagger_{i2}(V_{CKM})_{23}\right\}. \end{aligned} \tag{32}$$

Additionally, we have the contribution of FCNCs coupled to the Z' new gauge bosons [19],

$$\mathscr{L}_{q-Z'} = gL^q_{ij}\bar{q}_{iL}\gamma^\mu q_{jL}Z' + (L \to R). \tag{33}$$

Here,

$$L_{ij} = -4x\frac{\tan\theta_W}{\sin 2\theta}\left(V_L^q\right)^\dagger_{i3}\left(V_L^q\right)_{3j}, \quad \text{with} \quad q = u, d, \tag{34}$$

and $\tan\theta_W = \frac{g_Y}{g}$, $\tan\theta = \frac{g_N}{g_X}$. The FCNCs mediated by the gauge boson Z', as presented in Eq.(34), can contribute to both, $K - \bar{K}$ and $B_{s,d} - \bar{B}_{s,d}$ meson oscillations. In contrast, FCNCs involving (pseudo) scalar fields, contribute solely to $B_{s,d} - \bar{B}_{s,d}$ oscillations if the mixing matrix for the right-handed quark is assumed to be a unit matrix. With this assumption, the new physics contribution to $\Delta m^{\text{NP}}_{B_{d,s}}$ is given by

$$\begin{aligned}\Delta m^{\text{NP}}_{B_d} &= \Delta m^{Z'}_{B_d} + \Delta m^{\text{scalars}}_{B_d} \\ &\simeq \frac{2}{3}\frac{g^2}{m^2_{Z'}}\text{Re}(L^2_{13})m_{B_d}f^2_{B_d} \\ &+ \frac{5}{48}\left(\frac{m_K}{m_b + m_d}\right)^2\frac{g^2}{m_W^2}\frac{1}{(\cos\alpha)^2}\left\{\frac{m_b^2}{(m_{\mathscr{H}_1}\sin\alpha)^2} - \frac{m_b^2}{m^2_{\mathscr{A}}}\right\}\text{Re}(\mathscr{V}^2_{13})m_{B_d}f^2_{B_d}, \\ \Delta m^{\text{NP}}_{B_s} &= \Delta m^{Z'}_{B_s} + \Delta m^{\text{scalars}}_{B_s} \\ &\simeq \frac{2}{3}\frac{g^2}{m^2_{Z'}}\text{Re}(L^2_{23})m_{B_s}f^2_{B_s} \\ &+ \frac{5}{48}\left(\frac{m_K}{m_s + m_b}\right)^2\frac{g^2}{m_W^2}\frac{1}{(\cos\alpha)^2}\left\{\frac{m_b^2}{(m_{\mathscr{H}_1}\sin\alpha)^2} - \frac{m_b^2}{m^2_{\mathscr{A}}}\right\}\text{Re}(\mathscr{V}^2_{23})m_{B_s}f^2_{B_s},\end{aligned} \tag{35}$$

where f_{B_d}, f_{B_s} are decay constants of B_d and B_s mesons, respectively. $\mathscr{V}_{i3},\ i=1,2$ are defined as follows:

$$\mathscr{V}_{i3}=\left\{(V_{CKM})^{\dagger}_{i1}(V_{CKM})_{13}+(V_{CKM})^{\dagger}_{i2}(V_{CKM})_{23}\right\},\quad i=1,2. \tag{36}$$

3. Flavor-changing phenomenology

Firstly, we easily observe that for the particular option $m_{\mathscr{A}}=s_\alpha m_{\mathscr{H}_1}$, the scalar contributions to meson difference masses $\Delta m_{B_s,B_d}$ have vanished, leaving only the Z' gauge boson contribution, which was studied in detail [12]. Besides, the condition of mixing angle $s_\alpha\leq 1$ translates to an upper limit of CP-odd scalar mass $m_{\mathscr{A}}\leq m_{H_1}=95$ GeV. This upper limit of $m_{\mathscr{A}}$ is consistent with the current search of ALTAS for light-CP odd Higgs bosons in the mass range $20-90$ GeV [26]. On the one hand, from this bound of CP-odd scalar mass, we can get the quite suppressed following constraint; for instance, by fixing $v_1\sim 100$ GeV, $\Lambda\sim 5$ TeV, we have $|\mu_4|\leq 0.95$ GeV. We comment that this limit of $|\mu_4|$ is much smaller compared with electroweak scales $v_{1,2}\sim\mathscr{O}(10^1-10^2)$ GeV

Otherwise, for the $m_{\mathscr{A}}\neq s_\alpha m_{\mathscr{H}_1}$ scenario, the model may consist of a dangerous light scalar contribution to $\Delta m_{B_s,B_d}$, which in principle is larger than the Z' contribution since the scalar contributions are proportional. $\Delta m^{\text{scalars}}_{B_q}\sim 1/m^2_{\mathscr{H}_1,\mathscr{A}}\sim\mathscr{O}\left(\frac{1}{10^4}\right)\gg\Delta m^{Z'}_{B_q}\sim\frac{1}{m^2_{Z'}}\sim\mathscr{O}\left(\frac{1}{10^6}\right)$ $(q=s,d)$, thus making the model to face dangerous large FCNCs. To explore this in detail, we define the ratios between these two contributions based on Eq. (36) as follows

$$\begin{aligned}\epsilon_{B_q} &= \frac{\Delta m^{\text{scalars}}_{B_q}}{\Delta m^{Z'}_{B_q}}\\ &= \frac{5m_b^2}{32c_\alpha^2}\frac{\text{Re}[\mathscr{V}^2_{i3}]}{\text{Re}[L^2_{i3}]}\left(\frac{m_{B_q}}{m_b+m_q}\right)^2\left(\frac{m_{Z'}}{m_W}\right)^2\left(\frac{1}{(m_{\mathscr{H}_1}s_\alpha)^2}-\frac{1}{m^2_{\mathscr{A}}}\right)\\ &= \frac{5m_b^2}{32c_\alpha^2}\frac{\text{Re}[\mathscr{V}^2_{i3}]}{\text{Re}[L^2_{i3}]}\left(\frac{m_{B_q}}{m_b+m_q}\right)^2\left(\frac{1}{(95s_\alpha)^2}-\frac{1}{k\left[\frac{\sqrt{2}\Lambda^2}{s_{2\alpha}}+\frac{v_1v_2}{\sqrt{2}}\right]}\right),\end{aligned} \tag{37}$$

where we used $m_{\mathscr{H}_1}=95$ GeV and expressed $m_{\mathscr{A}}$ in Eq. (21) in term of factor $k=-\mu_4/\Lambda$. It is important to note that the room for new physics (NP) contributions to Δm_{B_q} can be generally estimated by combining in quadrature the relative uncertainties in both SM and experiment for Δm_{B_q} [19], which reads

$$\frac{\Delta m^{\text{NP}}_{B_q}}{\Delta m^{\text{exp}}_{B_q}}=\frac{\Delta m^{Z'}_{B_q}+\Delta m^{\text{scalars}}_{B_q}}{\Delta m^{\text{exp}}_{B_q}}=\begin{cases}[\text{-0.1295,-0.0145}] & \text{for}\quad q=d\\ [\text{-0.1050,-0.0082}] & \text{for}\quad q=s\end{cases}, \tag{38}$$

where numerical experimental values of $\Delta m^{\text{exp}}_{B_s}=17.765(6)\ \text{ps}^{-1}$, $\Delta m^{\text{exp}}_{B_d}=0.5065(19)\ \text{ps}^{-1}$ [27]. Eq. (38) can translate the following constraint of ϵ_{B_q}

$$\epsilon_{B_q}=\begin{cases}\frac{\Delta m^{\text{exp}}_{B_q}}{\Delta m^{Z'}_{B_q}}\times[\text{-0.1295,-0.0145}]-1 & \text{for}\quad q=d\\ \frac{\Delta m^{\text{exp}}_{B_q}}{\Delta m^{Z'}_{B_q}}\times[\text{-0.1050,-0.0082}]-1 & \text{for}\quad q=s.\end{cases}, \tag{39}$$

Here, $\Delta m_{B_q}^{Z'}$ depends on parameters including Λ, v_1, x, which are extensively studied in Refs. [12, 19]. In those works, the authors investigated whether these parameter spaces satisfy constraints $\Delta m_W^2 = m_W^2|_{\rm exp} - m_W^2|_{\rm SM}$ with $m_W^{\rm exp}$ being the experimental value for the SM W boson mass measured by CDF and CMS collaborations. For instance, with CDF measurement, Ref. [12] found $x = -1/2, \Lambda \sim 5$ TeV, $v_1 \in [0, 55]$ GeV, Eq. (39) gives

$$\epsilon_{B_s} \in [-1.099, -1.0077], \quad \epsilon_{B_d} \in [-1.1609, -1.018]. \tag{40}$$

Since Λ is fixed in this case, we have numerically checked and obtained the minimum of $\epsilon_{B_s} \geq -0.94, \epsilon_{B_d} \geq -0.95$, which conflicts with the limits in Eq. (40) and therefore we can rule out this scenario. On the other hand, for another parameter range for CDF measurement obtained in [12], namely $x = 1/2, \Lambda \in [4.5, 8.5]$ TeV, $v_1 \in [0, 185]$ GeV, Eq. (39) gives [1]

$$\epsilon_{B_s} \in [-1.2865, -1.006], \quad \epsilon_{B_d} \in [-1.4647, -1.0147]. \tag{41}$$

It suggests that the ratios ϵ_{B_q} are very tightly constrained, and the size of scalar contributions to Δm_{B_q} must be comparable with Z' contribution. To compare these limits with the corresponding theoretical estimation, we plot Fig. 2.

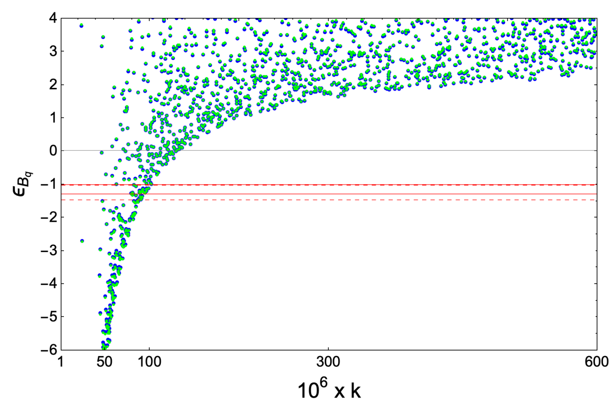

Fig. 2. The figure shows the relationship between predicted ratios ϵ_{B_q} based on Eq. (37) and $k = -\mu_4/\Lambda$ for parameter space $x = 1/2, \Lambda \in [4.5, 8.5]$ TeV, $v_1 \in [0, 185]$ GeV [12,21]. The blue and green points correspond to predicted ϵ_{B_s} and ϵ_{B_d}, whereas the solid and dashed red lines present constraints for ϵ_{B_s} and ϵ_{B_d} given in Eq. (41), respectively.

We see that in Fig. 2, the predicted ϵ_{B_q} can satisfy the above constraints of ϵ_{B_q} in Eq. (41) if k is very small $k \in [75, 100] \times 10^{-6}$. This can be explained due to the fact that ϵ_{B_q} depend on both terms $m_{Z'}^2/m_W^2$ and $1/(m_{\mathscr{H}_1} s_\alpha)^2 - 1/m_{\mathscr{A}}^2$, as can be seen in Eq. (37). For tiny small value $k \sim [75, 100] \times 10^{-6}$, i.e $\mu_4 \sim [-10^{-1}, -10^{-2}]$ GeV leading $m_{\mathscr{A}} \sim m_{\mathscr{H}_1} s_\alpha$, the latter term will be significantly degenerated, which has order 10^{-4}, whereas $m_{Z'}^2/m_W^2 \sim \mathscr{O}(10^3 - 10^4)$, thus these two terms can be canceled, making $\epsilon_{B_q} \sim \mathscr{O}(1)$. When k is large enough, $m_{\mathscr{A}}$ increases, causing the degeneration to disappear, and term $m_{Z'}^2/m_W^2$ will be the dominant one, leading ϵ_{B_q} to increase very high. We want to emphasize that if we assume very suppressed $k \sim 10^{-6}$, ϵ_{B_q} will not be lower

[1] It is important to note that there is correlation between satisfied ranges v_1 and Λ, as shown in Fig. 2 of Ref. [12].

because $m_{\mathscr{A}} \ll m_{\mathscr{H}_1}$, thus the condition for degeneration between these two masses is evaded, and ϵ_{B_q} cannot be at order $\mathscr{O}(1)$.

In general, this suggests that the model with $x = 1/2, \Lambda \in [4.5, 8.5]$ TeV, $v_1 \in [0, 185]$ GeV fulfilling CDF W boson mass, can contain 95 GeV Higgs boson satisfying constraints of ϵ_{B_q} in Eq. 41 if there exists parameter spaces that cause very degeneration between $m_{\mathscr{A}}$ and $m_{\mathscr{H}_1} s_\alpha$ such as $|m_{\mathscr{A}} - m_{\mathscr{H}_1} s_\alpha| \sim \mathscr{O}(10^{-4})$ or $m_{\mathscr{A}} = m_{\mathscr{H}_1} s_\alpha$. For remaining parameter space $x = -1/2$, $\Lambda \sim 5$ TeV, $v_1 \sim [0, 55]$ GeV, the model will suffer remarkably large FCNC induced by light scalar fields $\mathscr{H}_1, \mathscr{A}$, forcing the model to violate tight constraints in Eq. (40) and will be ruled out.

In addition, inspired by the very recent result of CMS for $m_W^{\text{CMS-2024}} = 80.3602 \pm 0.0099$ GeV [28], the Ref. [19] revised constraint of $\Delta m_W^2 = m_W^2|_{\text{CMS}} - m_W^2|_{\text{SM}}$ and explored that there are four choices of $x = \pm 1/2, \pm 1/6$ with specific ranges for v_1, Λ. In particular, from Eq. (39) and each parameter space, we obtain corresponding constraints for ϵ_{B_q} listed in Table 1 The scalar

Table 1. The constraints for ϵ_{B_q} for four different parameter spaces. Here, we also want to emphasize that v_1 and Λ are correlated, as shown in Fig. 1 of Ref. [19].

Parameter spaces	Constraints for ϵ_{B_s}	Constraints for ϵ_{B_d}
$x = \frac{1}{2}, \Lambda \in [4.3, 28.1]$ TeV, $v_1 \in [0, 246]$ GeV	$[-4.0925, -1.0076]$	$[-6.0152, -1.0208]$
$x = \frac{1}{6}, \Lambda \in [13.2, 39.3]$ TeV, $v_1 \in [0, 246]$ GeV	$[-7.0385, -1.0630]$	$[-10.8497, -1.1318]$
$x = -\frac{1}{2}, \Lambda \in [1, 16.7]$ TeV, $v_1 \in [0, 204]$ GeV or $\Lambda \in [1, 5.4]$ TeV, $v_1 \in [220, 246]$ GeV	$[-2.1089, -1.0007]$ or $[-1.1105, -1.001]$	$[-2.7773, -1.0019]$ or $[-1.1769, -1.0024]$
$x = -\frac{1}{6}, \Lambda \in [1, 5.7]$ TeV, $v_1 \in [0, 108]$ GeV or $\Lambda \in [1.5, 16.7]$ TeV, $v_1 \in [141, 246]$ GeV	$[-1.1991, -1.0056]$ or $[-2.0539, -1.0058]]$	$[-1.1989, -1.0128]$ or $[-2.7431, -1.0129]$

contribution to Δm_{B_q} can be larger than the Z' one by several times, compared to Eqs. (40,41) . The predicted ϵ_{B_q} are plotted as the function of $k = -\mu_4/\Lambda$ in Fig. 3 and Fig. 4.

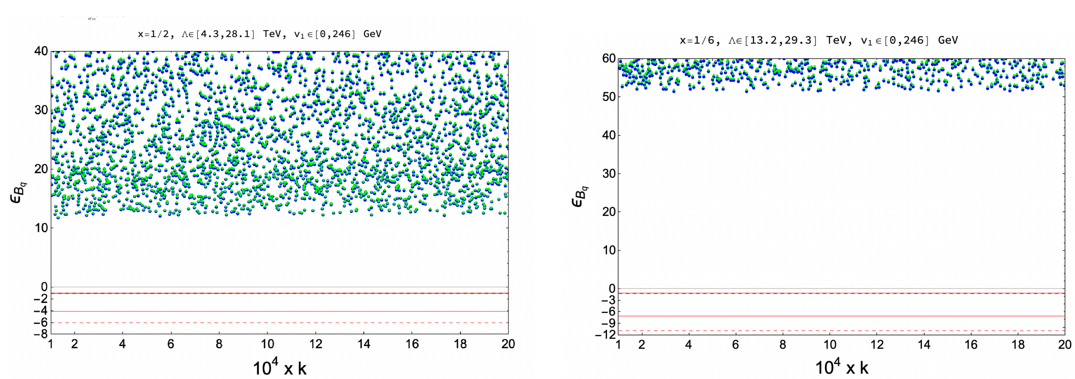

Fig. 3. The left and right panels show the relationship between predicted ratios ϵ_{B_q} ($q = s, d$) based on Eq. (37) and $k = -\mu_4/\Lambda$ for parameter spaces with $x = 1/2$ and $x = 1/6$, shown in the first column of Table 1, respectively. The blue and green points correspond to predicted ϵ_{B_s} and ϵ_{B_d}, whereas the solid (dashed) red lines in two panels present constraints for ϵ_{B_s} (ϵ_{B_d}) given the second and third columns in Table 1.

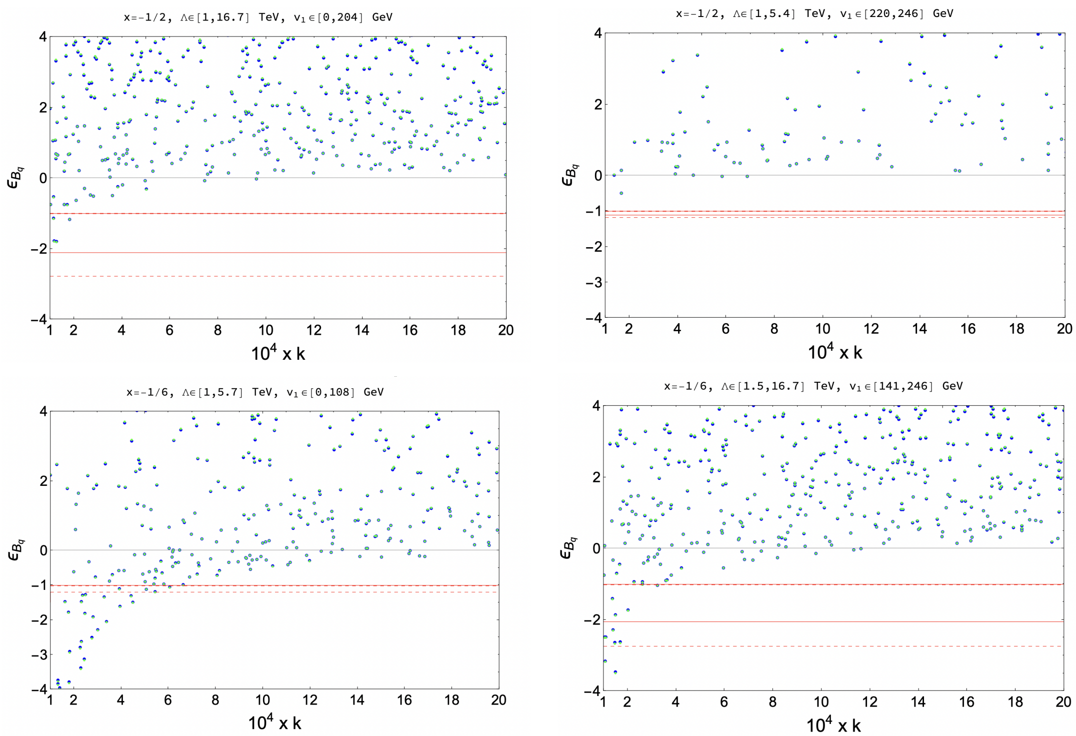

Fig. 4. The top and bottom panels show the relationship between predicted ratios ϵ_{B_q} ($q = s,d$) based on Eq. (37) and $k = -\mu_4/\Lambda$ for parameter spaces with $x = -1/2$ and $x = -1/6$, shown in the first column of Table 1, respectively. The blue and green points correspond to predicted ϵ_{B_s} and ϵ_{B_d}, whereas the solid (dashed) red lines in two panels present constraints for $\epsilon_{B_s}(\epsilon_{B_d})$ given the second and third column in Table 1.

The panels in Fig. 3 illustrate the considerable size scalar contributions in which ϵ_{B_q} are predicted larger than those in Fig. 2 for all values of k. In particular, we get $\epsilon_{B_q} \geq 12$, $\epsilon_{B_q} \geq 50$ for $x = 1/2$ and $x = 1/6$, respectively, due to large Λ; thus, the term $m^2_{Z'}/m^2_W$ in Eq. (37) influences mostly ϵ_{B_q}. As a result, CMS parameter spaces with $x = 1/2$ and $x = 1/6$ will face considerably large FCNC contributions induced by light scalar bosons, making the existence of 95 GeV Higgs bosons questionable in such scenarios.

Otherwise, since parameter spaces with $x = -1/2$ and $x = -1/6$ include distinct ranges, as shown in Table 1, we plot four different panels in Fig .4. We see that the top left and bottom right ones have a few points at small $k \sim [1,2]\times 10^{-4}$ satisfying limits of ϵ_{B_q} in Table 1, whereas the bottom left panel with $x = -1/6$ and relative lower $\Lambda \sim [1,5.7]$ TeV includes fulfilled points for a little bit larger $k \sim [2,6]\times 10^{-4}$. The latter can be explained because in this case, Z' gauge boson mass $m_{Z'}$ can be at electroweak scale $m_{Z'} \sim O(10^2)$ GeV leading to the ratio $m^2_{Z'}/m^2_W \sim \mathscr{O}(10^1 - 10^2)$, while the term $\frac{5m_b^2}{32c_\alpha^2}\frac{m^2_{B_q}}{(m_b+m_q)^2}\frac{\mathrm{Re}[\mathscr{V}^2_{i3}]}{\mathrm{Re}[L^2_{i3}]} \sim \frac{10^4}{v_1^2 x_2} \sim \mathscr{O}(10^2 - 10^3)$ for $x = -1/6$ and v_1 small. The product of these two terms will have comparable order with $1/(m_{\mathscr{H}_1} s_\alpha)^2 - 1/m^2_{\mathscr{A}} \sim 10^{-4}$ due to small $k \sim 10^{-4}$, hence this results that ϵ_{B_q} can be at order $\mathscr{O}(1)$. However, searches for $m_{Z'}$ have pointed out that the lower bound for $m_{Z'}$ should be at TeV scale $m_{Z'} \geq \mathscr{O}(1)$ TeV [20]; therefore, we can ignore the result of the bottom left panel.

4. Conclusion

In this work, we have reanalyzed the scalar sector of the $U(1)_X$ model [12, 19], and the results indicate that the minimum conditions leading to the cubic constant μ_4 can exist at the electroweak scale. This finding opens the possibility of studying the mass spectrum of the CP-even Higgs bosons. Specifically, the model predicts the existence of two light CP-even Higgs bosons: the first one $\mathscr{H}_2$ is identified as the SM-like Higgs boson with 125 GeV mass, and the other one is a lighter Higgs boson $\mathscr{H}_1$, which can be a 95 GeV Higgs boson [5, 6, 29, 30]. Additionally, we have found evidence for the existence of pseudoscalar Higgs bosons $\mathscr{A}$ at the electroweak scale. Unlike the SM-like Higgs boson, the pseudoscalar Higgs $\mathscr{A}$ and 95 GeV Higgs bosons $\mathscr{H}_1$ can affect FCNC, which significantly impacts the constraints of B meson mixing systems. In the case where $m_{\mathscr{A}} = m_{\mathscr{H}_1} s_\alpha$, the contributions to FCNC from the scalar and pseudoscalar Higgs bosons can cancel each other out. Otherwise, both these Higgs bosons can suffer large FCNC.

Specifically, with the parameter spaces satisfying the experimental constraints of the CDF collaboration on the mass of the SM W boson, the model with $x = -1/2$ faces a large FCNC, except in the case $x = 1/2$ if there exists a very slight mass separation between the light Higgs and the pseudoscalar. For the parameter spaces satisfying the CMS experimental constraints on the W-boson mass, the models with $x = 1/2, 1/6$ are not flavored due to dangerous large FCNC, while the model with $x = -1/2, -1/6$ predicts some small parameter spaces for μ_4 in which we can expect a 95 GeV Higgs boson.

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Conflict of interest

The authors have no conflict of interest to declare.

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