

Flavor-violating Higgs and top decays in the type 1B flavorful two-Higgs-doublet model with a twist

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We study flavor-violating decays of the SM-like Higgs boson and rare top decays in the type 1B realization of the flavorful two-Higgs-doublet model with a twist, focusing on $h \rightarrow sb$, $h \rightarrow db$, $h \rightarrow uc$, $h \rightarrow \mu\tau$, $h \rightarrow e\tau$, $h \rightarrow e\mu$, $t \rightarrow ch$, and $t \rightarrow uh$. We present the relevant amplitude and branching-ratio formulae, include one-loop vertex corrections, and impose constraints from Higgs signal-strength measurements, electroweak precision tests, meson mixing, $B \rightarrow X_s \gamma$, direct HFV searches, and CLFV constraints, including $\mu - e$ conversion. The surviving parameter space favors $\text{BR}(h \rightarrow sb) \gg \text{BR}(h \rightarrow db)$, $\text{BR}(t \rightarrow ch) \gg \text{BR}(t \rightarrow uh)$, and $\text{BR}(h \rightarrow \mu\tau) \gg \text{BR}(h \rightarrow e\tau) \sim \text{BR}(h \rightarrow e\mu)$ in the lepton sector. One-loop effects usually preserve these hierarchies, but can modify individual channels through different mechanisms: sizable destructive tree-loop interference can reduce $h \rightarrow sb$ enough to yield rare $\text{BR}_{\text{IL}}(h \rightarrow db) > \text{BR}_{\text{IL}}(h \rightarrow sb)$ points, whereas the large relative corrections found in rare top decays mainly reflect strong SM-like alignment suppressing the tree-level amplitudes.

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I. INTRODUCTION

The discovery of the Higgs boson by ATLAS and CMS Collaborations completed the particle content of the Standard Model (SM), leaving the observed pattern of fermion masses and flavor mixing as an open question [1,2]. Higgs interactions therefore remain a direct probe of the flavor puzzle. In a generic two-Higgs-doublet model (2HDM), the presence of several Yukawa matrices leads to tree-level flavor-changing neutral currents (FCNCs). The traditional solution is natural flavor conservation, in which each fermion species couples to only one scalar doublet [3,4]. Yukawa alignment provides another well-known way to suppress scalar FCNCs [5]. These ideas underlie much of the conventional 2HDM classification and phenomenology [6].

The absence of large observed FCNCs is compatible with a structured scalar flavor sector. Controlled scalar flavor violation can arise if the nonstandard Yukawa couplings are

correlated with fermion masses and mixing. Early examples include the Cheng-Sher ansatz and top-specific scalar flavor violation [7–9]. Branco-Grimus-Lavoura constructions provide another important class in which scalar FCNC couplings are controlled by Cabibbo-Kobayashi-Maskawa (CKM) matrix elements [10–12]. These examples motivate extended Higgs sectors with structured flavor violation.

Flavorful two-Higgs-doublet models follow this philosophy. The flavor-locked flavorful 2HDM showed that characteristic Higgs signatures can be compatible with flavor data when the Yukawa sector is organized by a controlled flavor structure [13]. The flavorful two-Higgs-doublet model with a twist introduced several twisted Yukawa realizations, including the type 1B case studied here [14]. The Type 1B flavorful two-Higgs-doublet model (F2HDM) has a nonstandard flavor structure, approximate protection of first-second generation transitions, and in the implementation considered here a CKM matrix generated in the down sector, distinguishing it from the ordinary natural-flavor-conserving type I 2HDM.

The experimental situation makes Higgs and top-flavor violation especially relevant. Direct LHC searches for charged-lepton-flavor-violating Higgs decays have reached subpercent sensitivity in $h \rightarrow \mu\tau$ and $h \rightarrow e\tau$, while $h \rightarrow e\mu$ is constrained even more strongly [15–17]. Charged-lepton flavor violation in heavy-particle decays, including Higgs, Z, and top decays, is a broad probe of new flavor

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dynamics [18]. Top-Higgs FCNC interactions are likewise well motivated because SM top-FCNC branching fractions are extremely small [19]. Top-FCNC decays have also been analyzed in several $U(1)$ -extended BSM frameworks, including flavor-dependent $U(1)$ and $B-L$ -type models [20,21]. LHC searches for $t \rightarrow Hq$ in $H \rightarrow b\bar{b}$, $H \rightarrow \gamma\gamma$, and multilepton final states now probe branching fractions at the per-mille level or below [22–24].

On the theory side, Higgs flavor violation has been studied in effective-coupling approaches, general 2HDMs, aligned 2HDMs, and flavorful Higgs frameworks [25–30]. Collider signatures of flavorful Higgs bosons can differ substantially from those of natural-flavor-conserving 2HDMs [31]. Rare top decays have also been proposed as direct probes of flavorful Higgs sectors [32]. Related flavor-dependent Higgs-sector studies have investigated rare Higgs decays, top-FCNC channels, charged-lepton-flavor violation, and electroweak precision constraints in $U(1)_F$ -type models [33]. These studies provide the context for a joint numerical analysis of Higgs and top-flavor violation in a type 1B F2HDM.

In this work we analyze the channels $h \rightarrow sb$, $h \rightarrow db$, $h \rightarrow uc$, $h \rightarrow \mu\tau$, $h \rightarrow e\tau$, $h \rightarrow e\mu$, $t \rightarrow ch$, and $t \rightarrow uh$, using the charge-conjugate convention specified below. The final sample is obtained after Higgs, electroweak, flavor, and low-energy selections. The numerical results identify $h \rightarrow sb$, $t \rightarrow ch$, $h \rightarrow db$, and $h \rightarrow \mu\tau$ as the leading channels in the numerical setup used here, reveal a structured flavor pattern, and show that the down-sector Higgs FCNC rates are much more stable at tree level than the texture- and alignment-sensitive tree-level $t \rightarrow ch$ and $h \rightarrow \mu\tau$ modes. We also examine one-loop vertex effects in Higgs-mediated FCNC decays and rare top decays.

The paper is organized as follows. Section II describes the type 1B F2HDM. Section III defines the observables and numerical procedure. Section IV presents the numerical results. Section V gives the conclusions.

II. THE TYPE 1B F2HDM

We work in the type 1B realization of the flavorful two-Higgs-doublet model with a twist [14]. This model is different from the ordinary natural-flavor-conserving type I two-Higgs-doublet model. In the type 1B F2HDM, the two scalar doublets have a nonstandard flavor assignment: Φ_1 gives the dominant contribution to fermion masses of the first two generations, whereas Φ_2 gives fermion masses dominantly of the third generation. Consequently, the two doublets couple to different fermion species dominantly, and tree-level flavor-changing neutral Higgs couplings are generically present.

The type 1B assignment used here is

	u	d	ℓ	
First two generations	Φ_1	Φ_1	Φ_1	(1)
Third generation	Φ_2	Φ_2	Φ_2	

understood as a texture assignment distinct from a natural-flavor-conserving zero pattern. The small entries controlled by the approximate $U(2)^5$ flavor structure and by the $O(1)$ coefficients populate both doublets in a way that reproduces fermion masses and the CKM matrix.

A. Scalar sector

The scalar sector contains two scalar doublets $\Phi_a \sim (2, +1/2)$ under $SU(2)_L \times U(1)_Y$,

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \frac{v_a + \rho_a + i\eta_a}{\sqrt{2}} \end{pmatrix}, \quad a = 1, 2, \quad (2)$$

with

$$v^2 = v_1^2 + v_2^2, \quad \tan \beta = \frac{v_2}{v_1}. \quad (3)$$

We restrict the scalar sector to the commonly used charge-parity (CP)-conserving softly broken Z_2 -type scalar-potential form. The Z_2 breaking is retained only through the quadratic soft term m_{12}^2 , while the hard-breaking quartic terms are not included. The scalar potential is

$$\begin{aligned} V(\Phi_1, \Phi_2) = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.c.}] \\ & + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) \\ & + \left[\frac{\lambda_5}{2} (\Phi_2^\dagger \Phi_1)^2 + \text{H.c.} \right]. \end{aligned} \quad (4)$$

All scalar-potential parameters in Eq. (4) are taken real in the CP-conserving numerical implementation. The neutral CP-even states are obtained from

$$\begin{pmatrix} h \\ H \end{pmatrix} = Z^h \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}, \quad (5)$$

with analogous rotations for the CP-odd and charged sectors. The reduced light-Higgs vector coupling is

$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\text{SM}}} = \frac{v_1 Z_{11}^h + v_2 Z_{12}^h}{v}. \quad (6)$$

The alignment preselection used below is expressed in terms of this quantity. The alignment-distance variable used in the plots is

$$|\cos(\beta - \alpha)| \equiv \sqrt{\max(0, 1 - \kappa_V^2)},$$

which follows the convention $\kappa_V = \sin(\beta - \alpha)$ for an SM-like light Higgs. The sign of the soft term in Eq. (4) follows the project convention $-m_{12}^2(\Phi_1^\dagger \Phi_2 + \text{H.c.})$.

B. Yukawa Lagrangian and type 1B texture

The two-doublet notation used in this work is $\Phi_{1,2}$. In the mass-parameter notation of Ref. [14], the doublet associated with the dominant third-generation masses is denoted by ϕ , while the other doublet is denoted by ϕ' . For the type 1B assignment in Eq. (1), these conventions are related by

$$\phi \equiv \Phi_2, \quad \phi' \equiv \Phi_1, \quad v = v_2, \quad v' = v_1,$$

and the corresponding Yukawa matrices are related by

$$\begin{aligned} \lambda^u &= Y_2^u, & \lambda^d &= Y_2^d, & \lambda^e &= Y_2^e, \\ \lambda'^u &= Y_1^u, & \lambda'^d &= Y_1^d, & \lambda'^e &= Y_1^e. \end{aligned}$$

With $\tilde{\phi}^{(\prime)} = i\sigma_2(\phi^{(\prime)})^*$, the Yukawa part of the flavorful two-Higgs-doublet Lagrangian is written as

$$\begin{aligned} -\mathcal{L}_Y \supset & \sum_{i,j} [\lambda_{ij}^u (\bar{q}_i u_j) \tilde{\phi} + \lambda_{ij}^d (\bar{q}_i d_j) \phi + \lambda_{ij}^e (\bar{\ell}_i e_j) \phi + \text{H.c.}] \\ & + \sum_{i,j} [\lambda_{ij}'^u (\bar{q}_i u_j) \tilde{\phi}' + \lambda_{ij}'^d (\bar{q}_i d_j) \phi' \\ & + \lambda_{ij}'^e (\bar{\ell}_i e_j) \phi' + \text{H.c.}] \end{aligned} \quad (7)$$

Together with the mapping above, Eq. (7) serves as the notation bridge between the ϕ, ϕ' mass-parameter convention and the Φ_1, Φ_2 texture notation used below.

The type 1B flavor assignment is represented by the following flavor-basis Yukawa textures. Up to independent

$O(1)$ coefficients, the first doublet carries the light-generation texture, while the second doublet carries the rank-one third-generation texture [14]:

$$Y_1^u \sim \frac{\sqrt{2}}{v_1} \begin{pmatrix} m_u & m_u & m_u \\ m_u & m_c & m_c \\ m_u & m_c & m_c \end{pmatrix}, \quad Y_2^u \sim \frac{\sqrt{2}}{v_2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_t \end{pmatrix} \quad (8)$$

$$Y_1^d \sim \frac{\sqrt{2}}{v_1} \begin{pmatrix} m_d & \lambda m_s & \lambda^3 m_b \\ m_d & m_s & \lambda^2 m_b \\ m_d & m_s & m_s \end{pmatrix}, \quad Y_2^d \sim \frac{\sqrt{2}}{v_2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix} \quad (9)$$

$$Y_1^e \sim \frac{\sqrt{2}}{v_1} \begin{pmatrix} m_e & m_e & m_e \\ m_e & m_\mu & m_\mu \\ m_e & m_\mu & m_\mu \end{pmatrix}, \quad Y_2^e \sim \frac{\sqrt{2}}{v_2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}. \quad (10)$$

Here λ denotes the Cabibbo-sized expansion parameter in the down sector, and the symbol $\sim$ indicates the parametric texture form. The explicit scan uses independent coefficients O_{ij}^u , O_{ij}^d , and O_{ij}^e to realize these textures while exactly reconstructing the physical fermion masses.

Using this mapping and rotating the fermions into mass eigenstates, we define

$$m_{qq'}^u = \frac{v}{\sqrt{2}} \langle q_L | \lambda^u | q'_R \rangle, \quad m_{qq'}'^u = \frac{v'}{\sqrt{2}} \langle q_L | \lambda'^u | q'_R \rangle, \quad q, q' = u, c, t, \quad (11)$$

$$m_{qq'}^d = \frac{v}{\sqrt{2}} \langle q_L | \lambda^d | q'_R \rangle, \quad m_{qq'}'^d = \frac{v'}{\sqrt{2}} \langle q_L | \lambda'^d | q'_R \rangle, \quad q, q' = d, s, b, \quad (12)$$

$$m_{\ell\ell'}^e = \frac{v}{\sqrt{2}} \langle \ell_L | \lambda^e | \ell'_R \rangle, \quad m_{\ell\ell'}'^e = \frac{v'}{\sqrt{2}} \langle \ell_L | \lambda'^e | \ell'_R \rangle, \quad \ell, \ell' = e, \mu, \tau. \quad (13)$$

In each charged-fermion sector these mass parameters obey $m_{ij}^f + m_{ij}'^f = m_{f_i} \delta_{ij}$. The charged-fermion texture coefficients are denoted as O_{ij}^u , O_{ij}^d , and O_{ij}^e ; the flavor label is a superscript and the matrix element is a subscript.

The explicit primed mass matrices $M_f' \equiv (m_{ij}'^f)$ used to reconstruct the charged-fermion Yukawa sector are [14]

$$M_u' = \begin{pmatrix} m_u + O_{11}^u \frac{m_t^2}{m_t} & \frac{(O_{13}^u m_u)(O_{32}^u m_c)}{m_t} \left(1 + O_{12}^u \frac{m_c}{m_t}\right) & O_{13}^u m_u \\ \frac{(O_{23}^u m_c)(O_{31}^u m_u)}{m_t} \left(1 + O_{21}^u \frac{m_c}{m_t}\right) & m_c + O_{22}^u \frac{m_t^2}{m_t} & O_{23}^u m_c \\ O_{31}^u m_u & O_{32}^u m_c & O_{33}^u m_c \end{pmatrix}, \quad (14)$$

$$M_d' = \begin{pmatrix} m_d - O_{31}^d m_d V_{td}^* \left(1 + O_{11}^d \frac{m_s}{m_b}\right) & O_{32}^d m_s V_{td}^* \left(1 + O_{12}^d \frac{m_s}{m_b}\right) & -V_{td}^* m_b \left(1 + O_{13}^d \frac{m_s}{m_b}\right) \\ O_{31}^d m_d V_{ts}^* \left(1 + O_{21}^d \frac{m_s}{m_b}\right) & m_s - O_{32}^d m_s V_{ts}^* \left(1 + O_{22}^d \frac{m_s}{m_b}\right) & -V_{ts}^* m_b \left(1 + O_{23}^d \frac{m_s}{m_b}\right) \\ O_{31}^d m_d & O_{32}^d m_s & O_{33}^d m_s \end{pmatrix}, \quad (15)$$

$$M'_\ell = \begin{pmatrix} m_e + O_{11}^\ell \frac{m_e^2}{m_\tau} & \frac{(O_{13}^\ell m_e)(O_{32}^\ell m_\mu)}{m_\tau} \left(1 + O_{12}^\ell \frac{m_\mu}{m_\tau}\right) & O_{13}^\ell m_e \\ \frac{(O_{23}^\ell m_\mu)(O_{31}^\ell m_e)}{m_\tau} \left(1 + O_{21}^\ell \frac{m_\mu}{m_\tau}\right) & m_\mu + O_{22}^\ell \frac{m_\mu^2}{m_\tau} & O_{23}^\ell m_\mu \\ O_{31}^\ell m_e & O_{32}^\ell m_\mu & O_{33}^\ell m_\mu \end{pmatrix}. \quad (16)$$

Together with Eqs. (11)–(13), these matrices determine the Yukawa couplings used in the charged-fermion FCNC analysis.

In the numerical realization used below, the CKM matrix is generated in the down sector,

$$V_{Lu} \simeq I, \quad V_{Ru} \simeq I, \quad V_{Ld} \simeq V_{\text{CKM}}, \quad V_{Rd} \simeq I. \quad (17)$$

Equation (17) is the basis choice and numerical ansatz used in the scan. The texture by itself does not fix this rotation pattern. With our fermion-rotation convention,

$$V_{\text{CKM}} = V_{Lu}^\dagger V_{Ld}.$$

Thus $V_{Lu} \simeq I$ implies $V_{Ld} \simeq V_{\text{CKM}}$, while $V_{Rd} \simeq I$ is an additional simplifying assumption. In this section we specify the type 1B texture and the corresponding mass-basis Yukawa definition. The conversion of these mass-basis matrices into the numerical input basis used for the scan is part of the numerical procedure.

III. OBSERVABLES AND NUMERICAL PROCEDURE

A. Decay channels and charge-conjugate convention

The numerical analysis considers the flavor-violating Higgs channels $h \rightarrow \mu\tau$, $h \rightarrow e\tau$, $h \rightarrow e\mu$, $h \rightarrow sb$, $h \rightarrow db$, and $h \rightarrow uc$, together with the top-FCNC channels $t \rightarrow ch$ and $t \rightarrow uh$.

Throughout the paper, the shorthand notation for neutral Higgs decays includes the charge-conjugate final states. We define

$$\text{BR}(h \rightarrow sb) \equiv \text{BR}(h \rightarrow s\bar{b}) + \text{BR}(h \rightarrow \bar{s}b), \quad (18)$$

$$\text{BR}(h \rightarrow db) \equiv \text{BR}(h \rightarrow d\bar{b}) + \text{BR}(h \rightarrow \bar{d}b), \quad (19)$$

$$\text{BR}(h \rightarrow uc) \equiv \text{BR}(h \rightarrow u\bar{c}) + \text{BR}(h \rightarrow \bar{u}c), \quad (20)$$

and, for charged-lepton channels,

$$\text{BR}(h \rightarrow \mu\tau) \equiv \text{BR}(h \rightarrow \mu^-\tau^+) + \text{BR}(h \rightarrow \mu^+\tau^-), \quad (21)$$

$$\text{BR}(h \rightarrow e\tau) \equiv \text{BR}(h \rightarrow e^-\tau^+) + \text{BR}(h \rightarrow e^+\tau^-), \quad (22)$$

$$\text{BR}(h \rightarrow e\mu) \equiv \text{BR}(h \rightarrow e^-\mu^+) + \text{BR}(h \rightarrow e^+\mu^-). \quad (23)$$

The same charge-conjugate convention is used when comparing tree-level and one-loop quantities for the quark channels.

B. Amplitudes and decay widths

For the quark-Higgs channels, we parametrize the amplitude in a chiral form-factor basis,

$$\mathcal{M}(h \rightarrow f_i \bar{f}_j) = \bar{u}_i(p_i)[G_L^{h,ij} P_L + G_R^{h,ij} P_R]v_j(p_j), \quad (24)$$

where $f_i \bar{f}_j = s\bar{b}, d\bar{b}, u\bar{c}$ for the explicitly calculated directions. The one-loop form factors are decomposed schematically as

$$G_X^{h,ij} = g_{X,\text{tree}}^{h,ij} + \Delta g_{X,\text{tri}}^{h,ij}, \quad X = L, R, \quad (25)$$

where $\Delta g_{X,\text{tri}}$ denotes the one-loop vertex contribution.

For top-FCNC decays, we use

$$\mathcal{M}(t \rightarrow q_i h) = \bar{u}_{q_i}(p_q)[G_L^{tq_i} P_L + G_R^{tq_i} P_R]u_t(p_t), \quad (26)$$

with

$$G_X^{tq_i} = g_{X,\text{tree}}^{tq_i} + \Delta g_{X,\text{tri}}^{tq_i}, \quad q_i = u, c, \quad X = L, R. \quad (27)$$

With this convention, the two-body decay width for a neutral scalar decay into two fermions is

$$\begin{aligned} \Gamma(h \rightarrow f_i \bar{f}_j) &= \frac{N_c \lambda^{1/2}(m_h^2, m_i^2, m_j^2)}{16\pi m_h^3} [(m_h^2 - m_i^2 - m_j^2) \\ &\quad \times (|G_L|^2 + |G_R|^2) - 4m_i m_j \text{Re}(G_L G_R^*)], \end{aligned} \quad (28)$$

where $N_c = 3$ for quark final states and $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$. The charge-conjugate branching ratio is

$$\text{BR}(h \rightarrow f_i f_j) = \frac{\Gamma(h \rightarrow f_i \bar{f}_j) + \Gamma(h \rightarrow \bar{f}_i f_j)}{\Gamma_h^{\text{tot}}}. \quad (29)$$

For the top decay in Eq. (26),

$$\begin{aligned} \Gamma(t \rightarrow q_i h) &= \frac{\lambda^{1/2}(m_t^2, m_q^2, m_h^2)}{16\pi m_t^3} [(m_t^2 + m_q^2 - m_h^2)(|G_L|^2 \\ &\quad + |G_R|^2) + 4m_t m_q \text{Re}(G_L G_R^*)]. \end{aligned} \quad (30)$$

The branching ratio is

$$\text{BR}(t \rightarrow q_i h) = \frac{\Gamma(t \rightarrow q_i h)}{\Gamma_t^{\text{tot}}}. \quad (31)$$

The total widths Γ_h^{tot} and Γ_t^{tot} are the widths used in the corresponding numerical normalization.

C. One-loop vertex corrections

For the explicitly calculated quark-Higgs and top-Higgs FCNC channels, we compare the tree-level amplitude with the one-loop vertex contribution shown by category in Figs. 1(a) and 2. We write the amplitude as

$$\mathcal{M}_{\text{1L}} = \mathcal{M}_{\text{tree}} + \mathcal{M}_{\text{loop}}. \quad (32)$$

The corresponding rate-level expression is

$$\text{BR}_{\text{1L}} = \text{BR}_{\text{tree}} + \Delta\text{BR}_{\text{int}} + \text{BR}_{\text{loop}^2}, \quad (33)$$

where $\Delta\text{BR}_{\text{int}}$ is proportional to $2\text{Re}(\mathcal{M}_{\text{tree}}^* \mathcal{M}_{\text{loop}})$, and $\text{BR}_{\text{loop}^2}$ is proportional to $|\mathcal{M}_{\text{loop}}|^2$. We define

$$\delta_{\text{1L}} \equiv \frac{\text{BR}_{\text{1L}} - \text{BR}_{\text{tree}}}{\text{BR}_{\text{tree}}}. \quad (34)$$

D. Parameter scan and constraints

The numerical scan uses the parameter ranges and preselection requirements summarized in Table I. The scalar sector is sampled in $\tan\beta$, m_{12}^2 , and the quartic couplings $\lambda_{1,\dots,5}$ appearing in Eq. (4). This softly broken Z_2 -type scalar-potential choice removes hard Z_2 -breaking quartic terms, reduces the number of independent scalar-sector parameters, and keeps the flavor nonuniversality studied here in the Yukawa texture rather than in additional scalar-potential structures. The scan further imposes an SM-like light-Higgs mass window, heavy non-SM scalar masses above the TeV scale, a charged-pseudoscalar mass-splitting requirement, and an alignment preselection before the full set of phenomenological constraints is applied.

We impose the following theoretical and phenomenological constraints in the numerical pipeline. Theoretical constraints on the scalar sector are imposed following the standard 2HDM perturbativity, tree-level unitarity, and bounded-from-below criteria, translated to the scalar-potential convention of Eq. (4) [6].

a. Perturbativity. The scalar quartic couplings are required to satisfy $\max |\lambda_i^{\text{eff}}| < 4\pi$. The reconstructed Yukawa matrices are also required to remain perturbative, $\max |Y_{a,ij}^f| \leq \sqrt{4\pi}$.

b. Tree-level scalar unitarity. The largest eigenvalue entering the scalar two-body scattering matrix is required to be smaller than 8π .

c. Bounded-from-below and vacuum stability. Our scalar potential uses $\lambda_1(\Phi_1^\dagger \Phi_1)^2 + \lambda_2(\Phi_2^\dagger \Phi_2)^2$, while the convention of Ref. [6] uses $(\lambda_1^B/2)(\Phi_1^\dagger \Phi_1)^2 + (\lambda_2^B/2)(\Phi_2^\dagger \Phi_2)^2$.

The correspondence is $\lambda_1^B = 2\lambda_1$, $\lambda_2^B = 2\lambda_2$, while $\lambda_{3,4,5}^B = \lambda_{3,4,5}$ up to the harmless $\Phi_1^\dagger \Phi_2$ versus $\Phi_2^\dagger \Phi_1$ complex-conjugation convention. For the CP -conserving scalar potential in Eq. (4), the bounded-from-below conditions become

$$\begin{aligned} \lambda_1 &> 0, & \lambda_2 &> 0, \\ \lambda_3 + 2\sqrt{\lambda_1 \lambda_2} &> 0, & \lambda_3 + \lambda_4 - |\lambda_5| + 2\sqrt{\lambda_1 \lambda_2} &> 0. \end{aligned} \quad (35)$$

d. Higgs signal strengths. The Higgs signal-strength selection uses the global one-sigma condition

$$\Delta\chi_{\text{HS}}^2 \equiv \chi_{\text{HS}}^2 - \chi_{\text{HS,min}}^2 \leq 1, \quad (36)$$

where χ_{HS}^2 is the HiggsSignals chi-square and $\chi_{\text{HS,min}}^2$ is the minimum value in the generated scan. Numerically, the 50000-point sample gives $\chi_{\text{HS,min}}^2 = 149.872$, so the applied cut is $\chi_{\text{HS}}^2 \leq 150.872$.

e. Electroweak precision constraints. We require the obtained S, T, U values to lie within the current experimental 1σ ranges quoted in the Review of Particle Physics [34]:

$$\begin{aligned} S &= -0.04 \pm 0.10, & T &= 0.01 \pm 0.12, \\ U &= -0.01 \pm 0.09. \end{aligned} \quad (37)$$

The three intervals are applied independently in the numerical scan.

f. Neutral-meson mixing. Neutral-meson mixing constraints are imposed using the observable-specific two-sided 95% probability intervals reported in Table 3 of the model-independent analysis of Ref. [35]:

$$\begin{aligned} 0.63 &\leq \frac{\Delta M_{B_s}}{\Delta M_{B_s}^{\text{SM}}} \leq 2.07, & 0.53 &\leq \frac{\Delta M_{B_d}}{\Delta M_{B_d}^{\text{SM}}} \leq 2.05, \\ 0.51 &\leq \frac{\Delta M_K}{\Delta M_K^{\text{SM}}} \leq 2.07, & 0.66 &\leq \frac{\epsilon_K}{\epsilon_K^{\text{SM}}} \leq 1.31. \end{aligned} \quad (38)$$

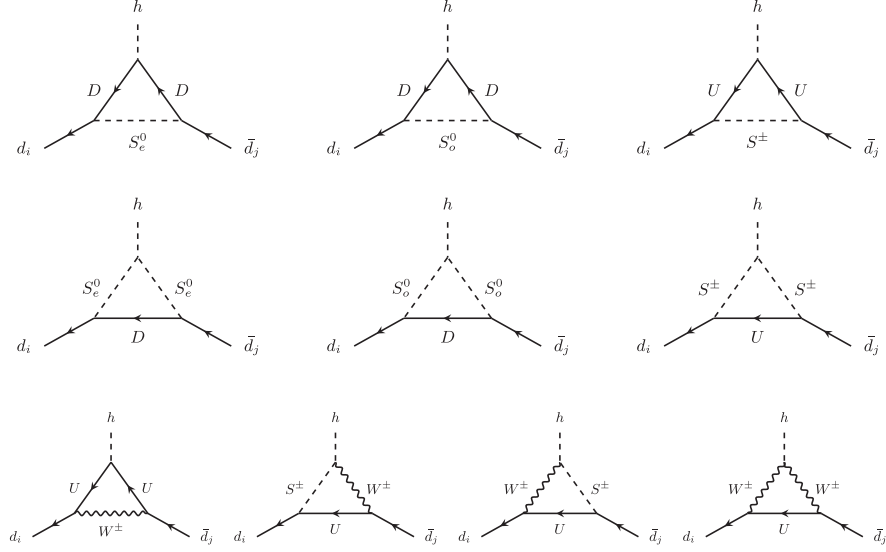
The four conditions are applied independently. The B_s and B_d ratios constrain neutral-meson mixing in the $b \leftrightarrow s$ and $b \leftrightarrow d$ sectors, respectively, while ΔM_K and ϵ_K probe the dispersive and CP -violating components of K^0 - $\bar{K}^0$ mixing. For ΔM_K , we use the short-distance ratio returned by FlavorKit rather than imposing the experimental mass-splitting uncertainty directly, owing to the sizable long-distance contribution to kaon mixing.

g. $B \rightarrow X_s \gamma$. The radiative B -decay constraint is imposed using the inclusive reference interval [36] as

$$2.99 \times 10^{-4} \leq \text{BR}(B \rightarrow X_s \gamma) \leq 3.87 \times 10^{-4}. \quad (39)$$

h. Charged-lepton flavor and $\mu - e$ conversion constraints. The lepton-sector Higgs-flavor-violating (HFV) branching ratios are required to satisfy the current direct 95% C.L. limits

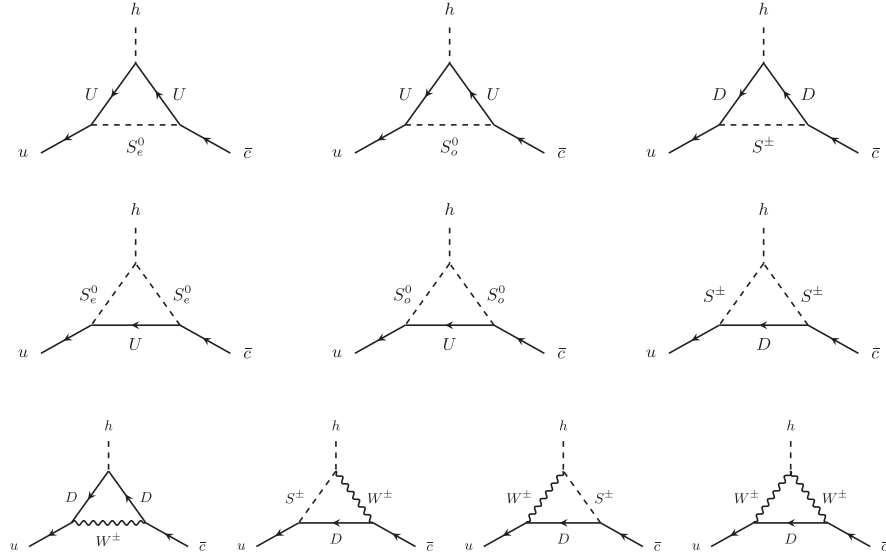
$h \rightarrow d_i \bar{d}_j$ one-loop triangle categories, $d_i d_j = sb, db$



$$S_e^0 = \{h, H\}, S_o^0 = \{A, G^0\}, S^\pm = \{H^\pm, G^\pm\}, U = \{u, c, t\}, D = \{d, s, b\}$$

(a) Down-sector Higgs FCNC channels $h \rightarrow d_i \bar{d}_j$ with $d_i d_j = sb, db$.

$h \rightarrow u \bar{c}$ one-loop triangle categories

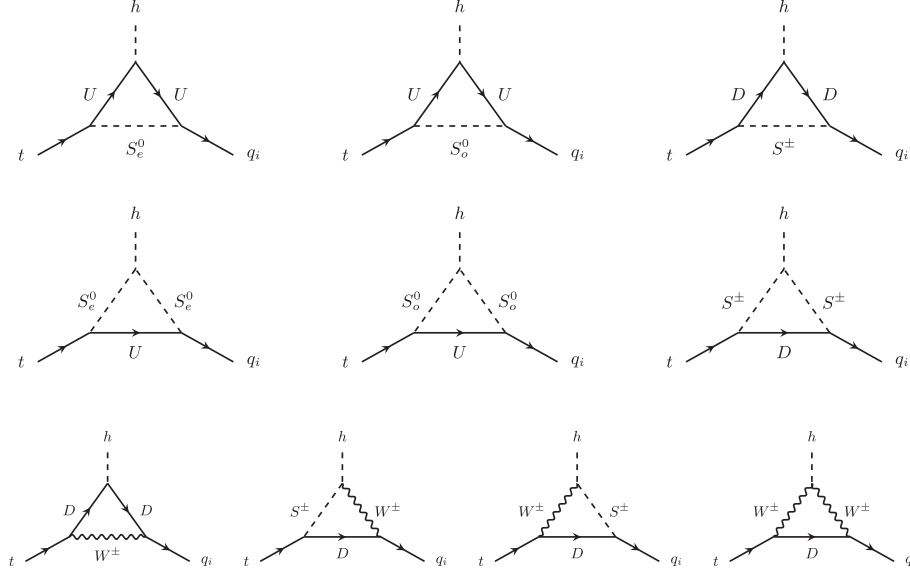


$$S_e^0 = \{h, H\}, S_o^0 = \{A, G^0\}, S^\pm = \{H^\pm, G^\pm\}, U = \{u, c, t\}, D = \{d, s, b\}$$

(b) Up-sector Higgs FCNC channel $h \rightarrow u \bar{c}$.

FIG. 1. One-loop triangle categories for the Higgs FCNC channels. The notation is $S_e^0 = \{h, H\}$, $S_o^0 = \{A, G^0\}$, and $S^\pm = \{H^\pm, G^\pm\}$, with $U = \{u, c, t\}$ and $D = \{d, s, b\}$.

$t \rightarrow q_i h$ one-loop triangle categories, $q_i = u, c$



$$S_e^0 = \{h, H\}, S_o^0 = \{A, G^0\}, S^\pm = \{H^\pm, G^\pm\}, U = \{u, c, t\}, D = \{d, s, b\}$$

FIG. 2. One-loop triangle categories for the top-FCNC channels $t \rightarrow q_i h$ with $q_i = u, c$. The notation is the same as in Fig. 1(a).

$$\begin{aligned} \text{BR}(h \rightarrow e\mu) &< 4.4 \times 10^{-5}, \quad \text{BR}(h \rightarrow e\tau) < 2.0 \times 10^{-3}, \\ \text{BR}(h \rightarrow \mu\tau) &< 1.5 \times 10^{-3}. \end{aligned} \quad (40)$$

These entries correspond to the observed limits for $h \rightarrow e\mu$ [17], $h \rightarrow e\tau$ [16], and $h \rightarrow \mu\tau$ [15], respectively. The $\mu - e$ conversion constraints are imposed as [37–39]

$$\begin{aligned} \text{CR}_{\text{Al}} &< 7.0 \times 10^{-13}, \quad \text{CR}_{\text{Ti}} < 4.3 \times 10^{-12}, \\ \text{CR}_{\text{Au}} &< 7.0 \times 10^{-13}. \end{aligned} \quad (41)$$

i Additional CLFV observables. Radiative and three-body charged-lepton-flavor-violation (CLFV) observables are evaluated as auxiliary predictions outside the independent sample-reducing cut-flow. In the surviving sample, these observables remain below their corresponding current experimental limits. The largest ratios of the predicted values to the corresponding experimental upper bounds are approximately 3.2×10^{-2} for $\mu \rightarrow e\gamma$ and 5.2×10^{-4} for $\tau \rightarrow 3\mu$, with smaller ratios in the other radiative and three-body CLFV channels. Top-FCNC and Higgs-FCNC quantities are evaluated for interpretation outside the selection cuts.

After all imposed selections, the final sample is fixed for the numerical analysis below.

E. Computational workflow

The model implementation and SPheno interface are generated with SARAH 4.15.4 [40]. The particle spectrum, low-energy observables, and lepton-sector HFV Higgs

rates are evaluated with SPheno 4.0.6 [41,42]. In particular, the neutral-meson-mixing observables are computed using the SARAH-generated SPheno/FlavorKit routines [43]. Higgs signal-strength constraints are evaluated with the HiggsSignals functionality used in the HiggsTools 1.1.3 run [44,45]. The FCNC one-loop vertex corrections are obtained using FeynArts 3.12, FormCalc 9.10, and LoopTools 2.16 [46–48], with SARAH-matched $G_{H^\pm ud}^{L,R}$ conjugations.

The numerical chain proceeds as follows. Scalar-sector points satisfying the theoretical and Higgs-sector preselection requirements are first generated. The charged-fermion Yukawa textures are then reconstructed in the mass and gauge bases according to the type 1B flavor structure, with the CKM rotation assigned to the down sector. The Higgs signal-strength selection is applied next, followed by the precision, flavor, and flavor-violating observable requirements. The final branching-ratio distributions and hierarchy observables are then assembled using the conventions of Sec. III A.

IV. NUMERICAL ANALYSIS

The scan ranges and observable definitions were described in Sec. III. In this section we focus on the numerical consequences for the surviving type 1B F2HDM sample.

A. Cut-flow and final sample

Starting from 50000 generated points in the parameter region summarized in Table I, 6790 points pass the global

TABLE I. Input parameter ranges and preselection requirements for the type 1B F2HDM scan.

Parameter or requirement	Range or selection
$\tan\beta = v_2/v_1$	$1 \leq \tan\beta \leq 30$
m_{12}^2	$(2.5 \times 10^5, 1.0 \times 10^6) \text{ GeV}^2$
λ_1	$0 \leq \lambda_1 \leq 3$
λ_2	$0.06 \leq \lambda_2 \leq 0.13$
$\lambda_{3,4,5}$	$-5 \leq \lambda_{3,4,5} \leq 5$
Light-Higgs mass	$124 \text{ GeV} < m_h < 126 \text{ GeV}$
Heavy-scalar masses	$m_H, m_A, m_{H^\pm} > 1 \text{ TeV}$
Charged-pseudoscalar splitting	$ m_A - m_{H^\pm} < 200 \text{ GeV}$
Alignment proxy	$ \kappa_V ^2 > 0.95$
O_{ij}^u	$0.1 \leq O_{ij}^u \leq 10$
O_{ii}^d	$0.01 \leq O_{ii}^d \leq 10$
$O_{12,21}^d, O_{13,31}^d$	$0.01 \leq O_{ij}^d \leq 6$
$O_{23,32}^d$	$0.01 \leq O_{23,32}^d \leq 1$
O_{ij}^e	$1 \leq O_{ij}^e \leq 10$
Texture-factor phases	0

HiggsSignals condition $\Delta\chi_{\text{HS}}^2 \leq 1$. Within this subset, the meson-mixing constraints reduce the sample to 1094 points, the $B \rightarrow X_s\gamma$ selection to 552 points, and the electroweak precision selection to 542 points. The direct HFV and μ - e conversion constraints do not further reduce this sample, leaving

$$N_{\text{final}} = 542. \quad (42)$$

These points form the constrained surviving sample used in the following analysis; the corresponding cut-flow is shown in Fig. 3.

One-loop rate update and branching-ratio convention. Before discussing the hierarchy and parameter dependences, we specify the rate convention used in the numerical plots. The surviving sample is defined by the cut-flow above; the one-loop vertex corrections are then evaluated on this fixed sample and are not used as additional selection cuts. For the Higgs-mediated FCNC decays and rare top decays we use the rate definition of Sec. III C, namely the tree-level contribution plus the tree-loop interference and the squared one-loop amplitude. Thus, unless explicitly stated otherwise, the quoted rates for $h \rightarrow sb$, $h \rightarrow db$, $h \rightarrow uc$, $t \rightarrow ch$, and $t \rightarrow uh$ below refer to the one-loop-updated branching ratios BR_{IL} .

For the lepton-sector HFV Higgs channels, the numerical rates are those obtained from the SPHeno loop calculation in the workflow of Sec. III E. Tree-level quantities are shown separately only when the text explicitly discusses tree-level stability. With this convention, the hierarchy plots in Figs. 4–6 and the parameter-driver plots in Figs. 7–9 can be read as the corrected-rate phenomenology of the final 542-point sample. The detailed size and interpretation of the relative one-loop shifts are discussed later in Sec. IV D.

B. Branching-ratio hierarchy

The eight flavor-violating channels considered in this work display a pronounced hierarchy in the surviving sample, with the ordering quoted in the rate convention of each channel. The numerically largest rates are carried by $h \rightarrow sb$, $h \rightarrow \mu\tau$, $h \rightarrow db$, and $t \rightarrow ch$; the up-sector Higgs-FCNC mode $h \rightarrow uc$, the electron-flavor HFV Higgs modes, and $t \rightarrow uh$ are much smaller.

As shown in Fig. 4, the median rates in this convention are approximately 8.43×10^{-4} for $h \rightarrow sb$, 2.59×10^{-5} for

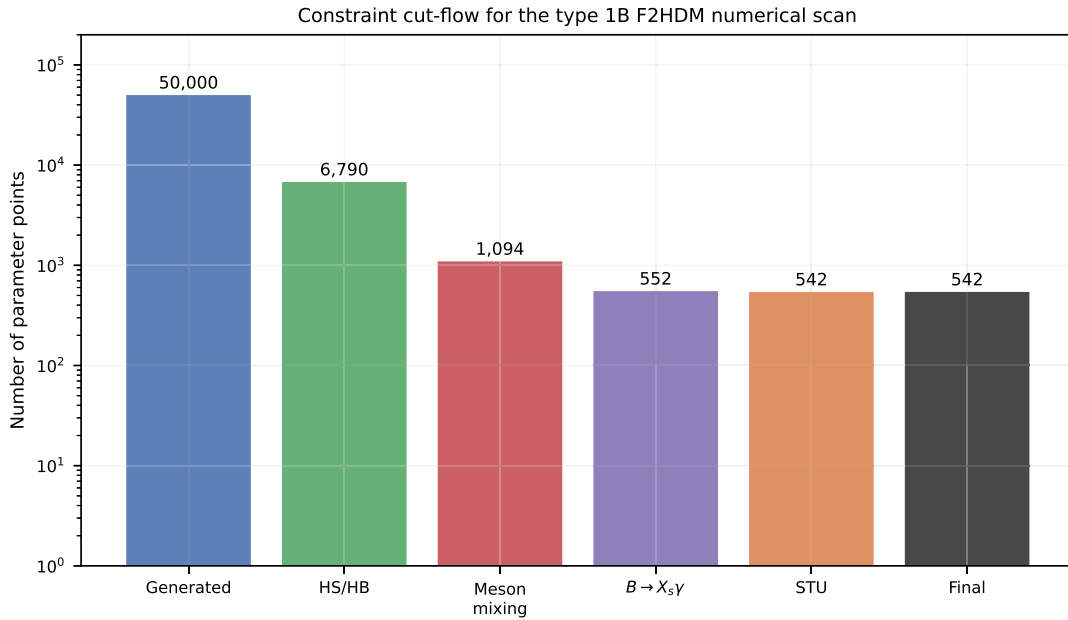
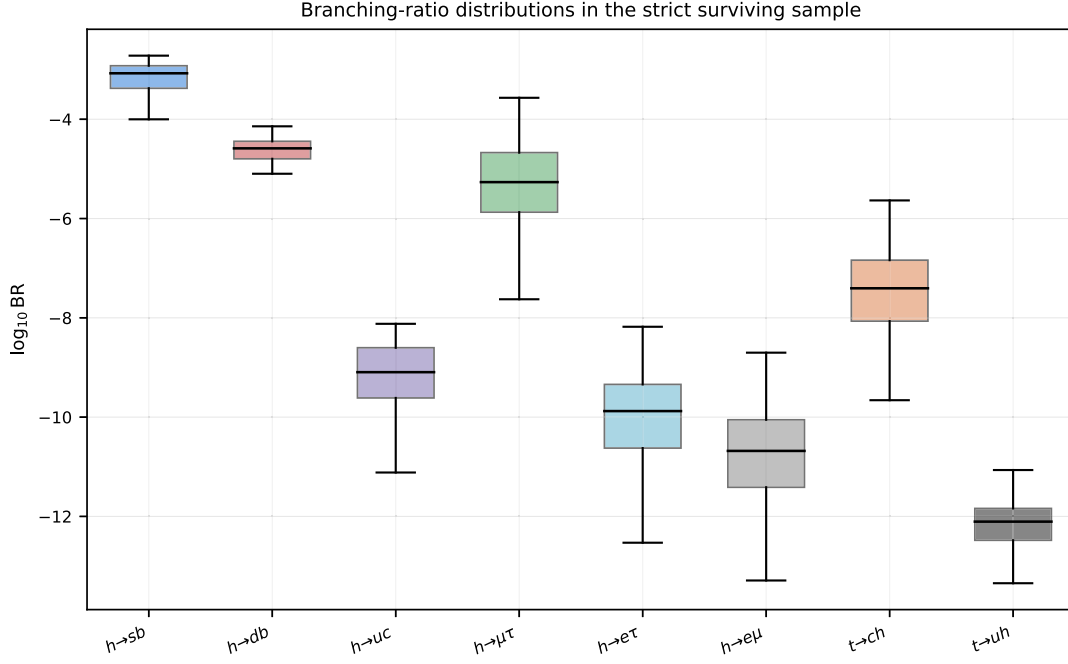
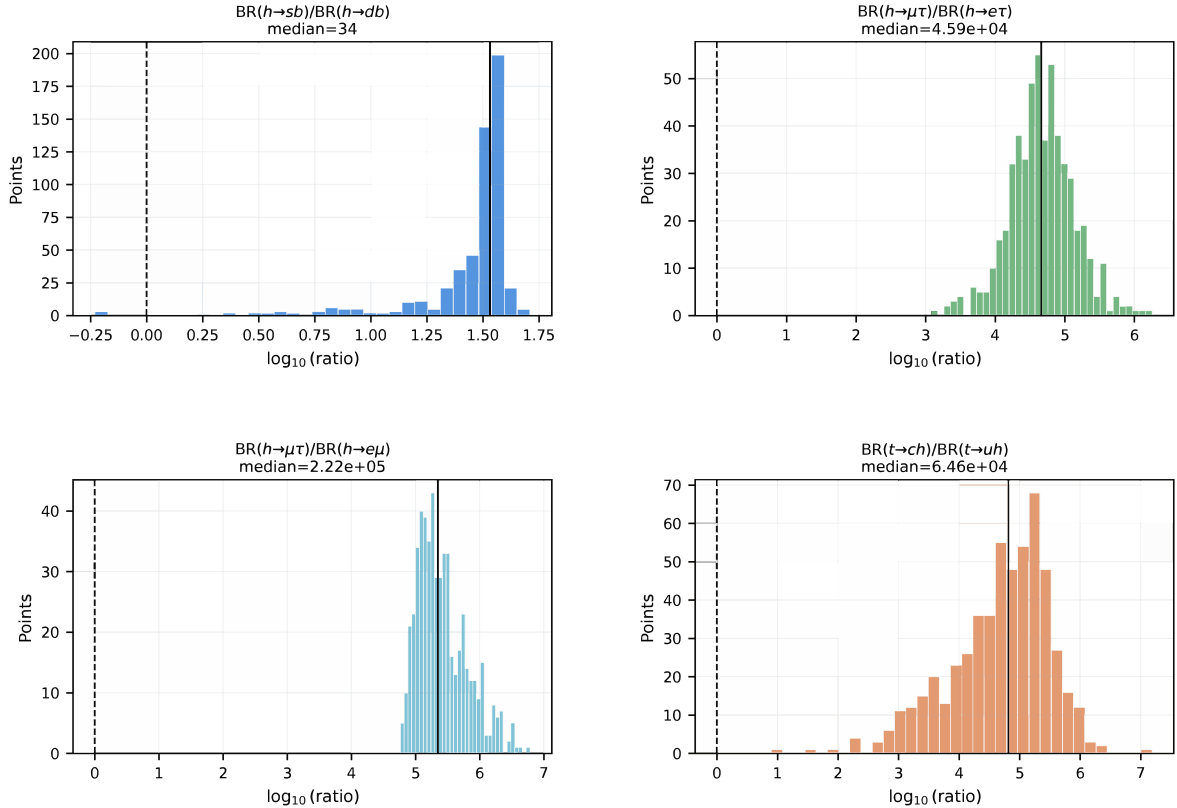


FIG. 3. Cut-flow for the type 1B F2HDM numerical scan after the Higgs, flavor, and electroweak selections.

FIG. 4. Overview of the flavor-violating rates for the eight channels, shown as $\log_{10}$ BR.

$h \rightarrow db$, 8.04×10^{-10} for $h \rightarrow uc$, 5.41×10^{-6} for $h \rightarrow \mu\tau$, 3.93×10^{-8} for $t \rightarrow ch$, and 7.85×10^{-13} for $t \rightarrow uh$. The corresponding maximum branching ratios are 1.91×10^{-3} for $h \rightarrow sb$, 7.20×10^{-5} for $h \rightarrow db$, 7.57×10^{-9} for

$h \rightarrow uc$, 2.70×10^{-4} for $h \rightarrow \mu\tau$, 6.68×10^{-9} for $h \rightarrow e\tau$, 2.01×10^{-9} for $h \rightarrow e\mu$, 2.32×10^{-6} for $t \rightarrow ch$, and 8.59×10^{-12} for $t \rightarrow uh$. The resulting qualitative pattern is that the two down-sector Higgs-FCNC modes satisfy

FIG. 5. Hierarchy-ratio distributions in the type 1B F2HDM sample. The dashed black vertical line marks unit ratio, i.e., $\log_{10}(\text{ratio}) = 0$, while the solid black vertical line marks the median of each distribution.

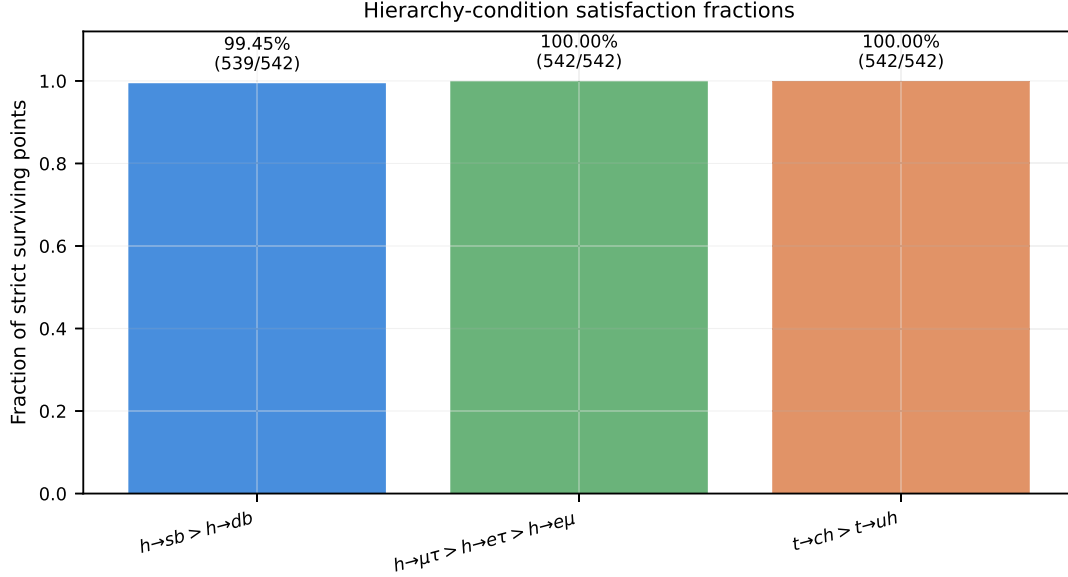


FIG. 6. Fractions of points satisfying the down sector, lepton sector, and top-sector hierarchy conditions.

$$\text{BR}(h \rightarrow sb) \gg \text{BR}(h \rightarrow db),$$

while the up-sector Higgs-FCNC mode $h \rightarrow uc$ is much smaller than the down-sector modes in the final sample. The lepton hierarchy is

$$\text{BR}(h \rightarrow \mu\tau) \gg \text{BR}(h \rightarrow e\tau), \quad \text{BR}(h \rightarrow e\mu).$$

For the top channels the ordering is $\text{BR}(t \rightarrow ch) \gg \text{BR}(t \rightarrow uh)$, with a median ratio $\text{BR}(t \rightarrow ch)/\text{BR}(t \rightarrow uh) \simeq 6.46 \times 10^4$.

The hierarchy distributions in Figs. 5 and 6 show stable down sector, lepton, and top patterns across the final sample. The median ratio $\text{BR}(h \rightarrow sb)/\text{BR}(h \rightarrow db)$ is about 34.0 after the one-loop rate update, and the down-sector condition holds for $539/542 = 99.45\%$ of the

sample. The lepton and top-hierarchy conditions hold for all final points, with median $\text{BR}(t \rightarrow ch)/\text{BR}(t \rightarrow uh) \simeq 6.46 \times 10^4$. The three points with $\text{BR}_{\text{IL}}(h \rightarrow db) > \text{BR}_{\text{IL}}(h \rightarrow sb)$ are discussed in Sec. IV F.

C. Parameter drivers and low-energy correlations

To identify monotonic parameter dependences we use Spearman's rank coefficient,

$$\rho_S(X, Y) = \text{corr}[\text{rank}(X), \text{rank}(Y)], \quad (43)$$

usually with $Y = \log_{10} \text{BR}$. We use the alignment proxy κ_V defined in Sec. II A. We also use the effective texture combination

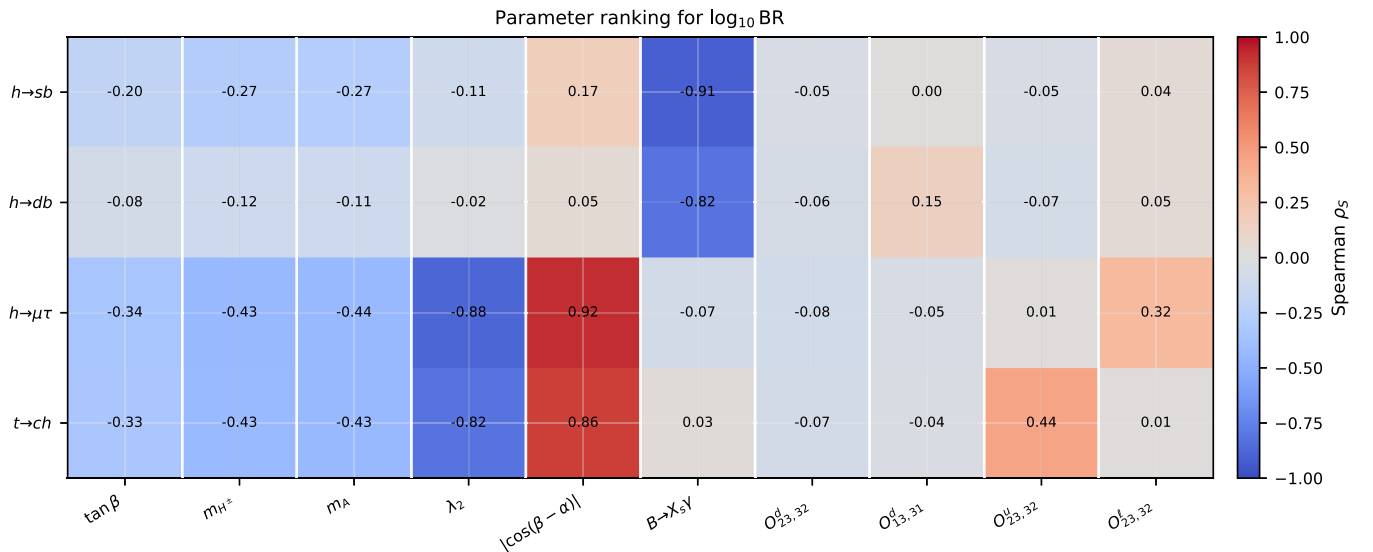
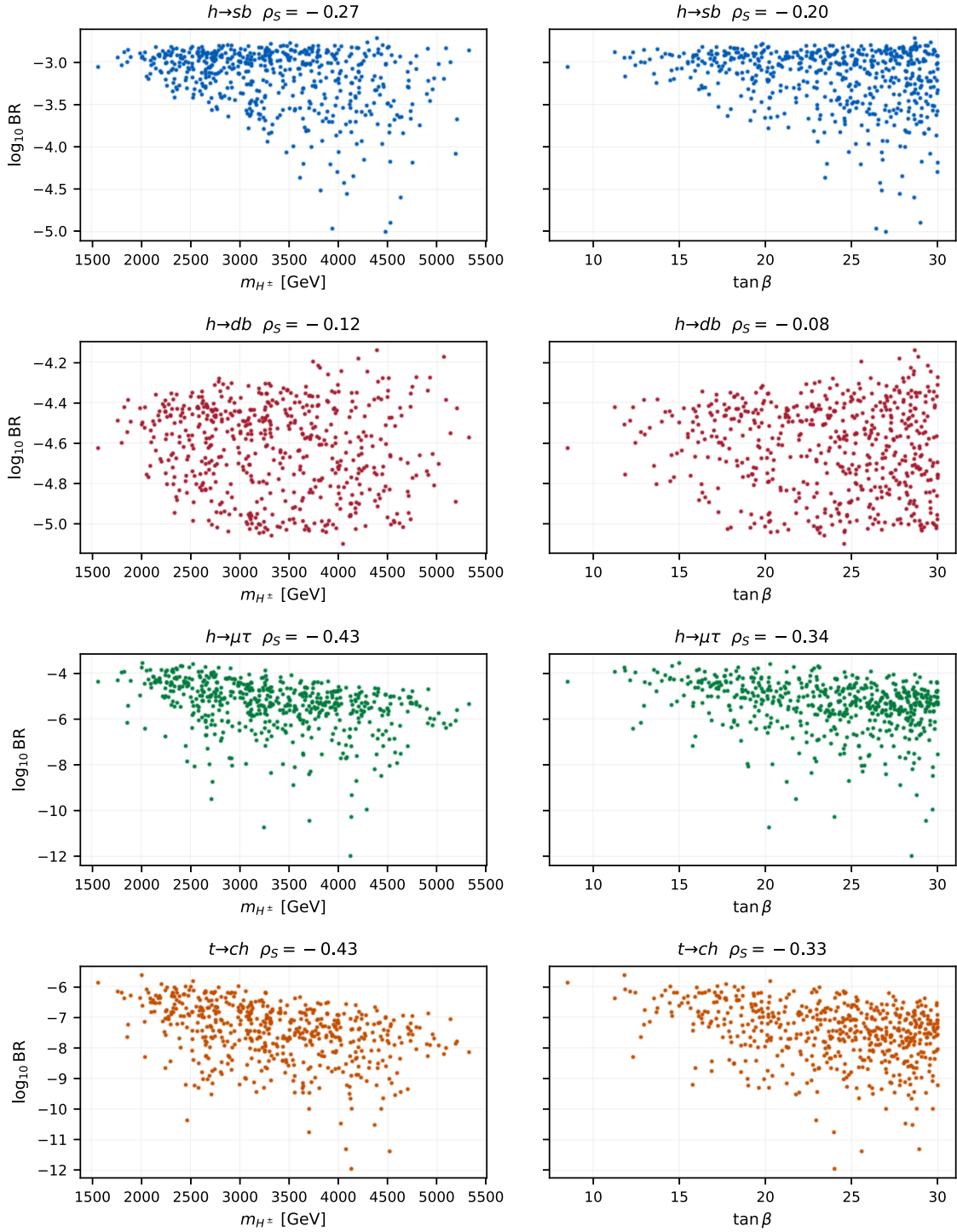


FIG. 7. Spearman-rank driver analysis for the main flavor-violating rates.

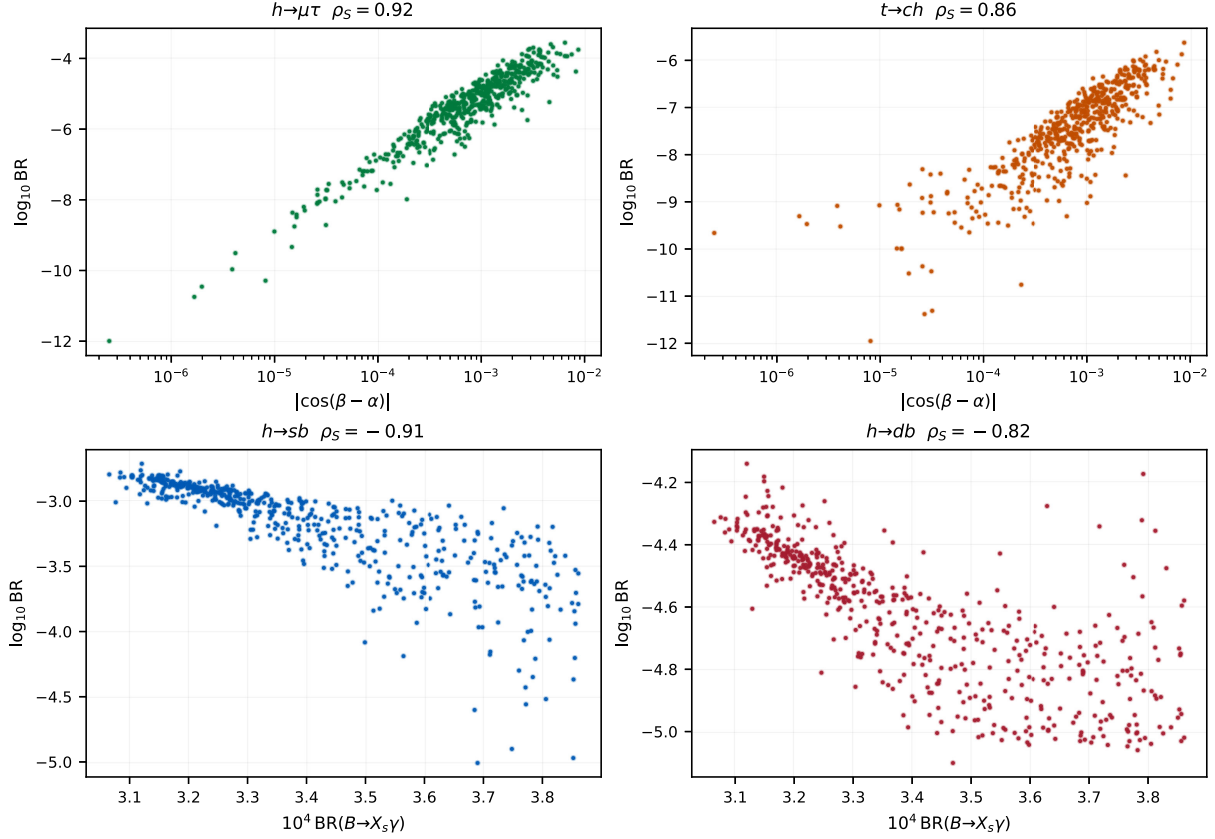
FIG. 8. Dependence of the main flavor-violating rates on $m_{H^\pm}$ and $\tan\beta$.

$$O_{\text{eff}}^{f,ij} = \sqrt{\frac{|O_{ij}^f|^2 + |O_{ji}^f|^2}{2}}, \quad f = u, d, \ell, \quad (44)$$

which is a derived quantity.

The driver ranking in Fig. 7 shows that $h \rightarrow sb$ and $h \rightarrow db$ are shaped mainly by the constrained down-sector

structure and by low-energy flavor selections, with no dominant single $O(1)$ texture entry. Numerically, $\rho_S(O_{\text{eff}}^{d,23}) = -0.055$ for $h \rightarrow sb$ and $\rho_S(O_{\text{eff}}^{d,13}) = 0.151$ for $h \rightarrow db$, while the strongest monotonic correlation in the two down-sector rates is with $\text{BR}(B \rightarrow X_s \gamma)$, $\rho_S = -0.909$, and -0.819 , respectively. The $h \rightarrow \mu\tau$ rate remains strongly alignment controlled, with $\rho_S(|1 - \kappa_V|) = 0.916$, and the

FIG. 9. Alignment and $B \rightarrow X_s \gamma$ correlations for the main flavor-violating rates.

$t \rightarrow ch$ rate also has a positive alignment correlation, $\rho_S(|1 - \kappa_V|) = 0.862$.

Figure 8 shows that the down-sector Higgs-FCNC rates in the final sample retain only mild direct monotonic dependence on $m_{H^\pm}$ and $\tan\beta$ once the stronger flavor selections are imposed; for example $\rho_S(\tan\beta, \log_{10} \text{BR}) = -0.200$ for $h \rightarrow sb$ and -0.075 for $h \rightarrow db$. The $h \rightarrow \mu\tau$ and $t \rightarrow ch$ rates are more visibly alignment controlled, with additional negative correlations with λ_2 in the driver ranking. The alignment panels in Fig. 9 show that $h \rightarrow \mu\tau$ remains strongly alignment controlled, while the $t \rightarrow ch$ rate has a positive alignment correlation and a compressed absolute range. The same figure also shows the strong $B \rightarrow X_s \gamma$ correlation in the down-sector channels.

TABLE II. One-loop relative-correction quantiles for the quark and top-FCNC channels in the strict surviving sample.

Channel	Min	5%	Median	95%	Max
$t \rightarrow ch$	-0.956	-0.248	-0.0927	3.07	3.06×10^4
$t \rightarrow uh$	-0.91	-0.0931	1.11	485	2.74×10^7
$h \rightarrow uc$	-0.716	49.7	4.09×10^3	2.14×10^6	4.25×10^{10}
$h \rightarrow sb$	-0.993	-0.906	-0.444	-0.0473	0.252
$h \rightarrow db$	-0.828	-0.78	-0.422	0.0485	0.624

D. One-loop vertex effects

Having fixed the corrected-rate convention above, we now quantify the size of the vertex effects in Higgs-mediated FCNC decays and rare top decays. The relative quantities in Table II are computed with the triangle categories shown in Figs. 1(a) and 2.

For $t \rightarrow ch$, very large positive relative corrections occur in the one-loop rate comparison. These large ratios are primarily denominator effects caused by very small tree-level rates near the alignment region; the corresponding absolute physical branching ratios remain small. For this channel the relative correction can be written as

$$\delta_{\text{IL}} = \frac{|\mathcal{M}_{\text{tree}} + \mathcal{M}_{\text{loop}}|^2 - |\mathcal{M}_{\text{tree}}|^2}{|\mathcal{M}_{\text{tree}}|^2} = 2\text{Re}\left(\frac{\mathcal{M}_{\text{loop}}}{\mathcal{M}_{\text{tree}}}\right) + \left|\frac{\mathcal{M}_{\text{loop}}}{\mathcal{M}_{\text{tree}}}\right|^2.$$

Near the alignment region, the tree-level tch coupling is strongly suppressed, so $\text{BR}_{\text{tree}}(t \rightarrow ch)$ becomes very small.

Figure 10 illustrates this denominator effect in more detail. In panel (a), the largest values of δ_{IL} appear close to the alignment region. Panel (b) shows that the same region contains very small tree-level $t \rightarrow ch$ branching ratios.

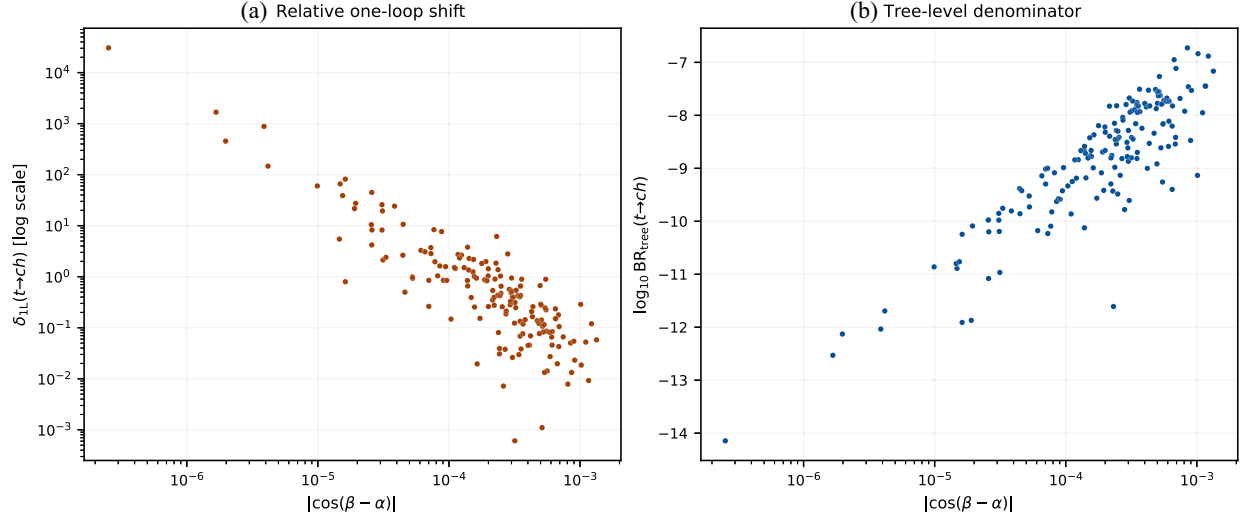


FIG. 10. Alignment dependence in the $t \rightarrow ch$ channel: (a) δ_{1L} on a logarithmic scale and (b) $\log_{10} \text{BR}_{\text{tree}}$ as functions of $|\cos(\beta - \alpha)|$.

The corresponding one-loop-updated branching ratio is shown in Fig. 9(b), where the absolute $t \rightarrow ch$ rate remains small and compressed. The large values of δ_{1L} should therefore be interpreted as relative ratios in tree-suppressed regions, not as evidence for a parametrically large absolute one-loop-induced $t \rightarrow ch$ branching ratio. For $h \rightarrow sb$ and $h \rightarrow db$, the median one-loop relative corrections are negative, $\delta_{1L} \simeq -0.444$ and -0.422 , respectively, indicating a net suppression in the down-sector channels.

E. Tree-level stability and CKM-down origin

A striking feature of the surviving sample is the different width of the tree-level branching-ratio distributions. The tree-level quantiles in Table III show that $h \rightarrow sb$ and $h \rightarrow db$ are locked into narrow bands, while representative up-sector Higgs and top-FCNC rates span several orders of magnitude.

The down-sector central 5–95% intervals are $[1.46, 1.57] \times 10^{-3}$ for $h \rightarrow sb$ and $[4.14, 4.64] \times 10^{-5}$ for $h \rightarrow db$. In contrast, the corresponding intervals are 1.08×10^{-10} to 7.17×10^{-7} for $t \rightarrow ch$ and 3.51×10^{-16} to 5.35×10^{-12} for $h \rightarrow uc$.

The stability can be traced directly to the mass-basis reconstruction in Sec. II B. In the down-sector matrix of Eq. (15), the entries relevant for $h \rightarrow sb$ contain

$$(M'_d)_{23} = -V_{ts}^* m_b \left(1 + O_{23}^d \frac{m_s}{m_b} \right), \quad (M'_d)_{32} = O_{32}^d m_s. \quad (45)$$

The dependence on O_{23}^d is suppressed by m_s/m_b , so the leading structure is the fixed CKM-weighted term $-V_{ts}^* m_b$; the opposite-chirality-related entry is only m_s -sized. Similarly, for $h \rightarrow db$,

$$(M'_d)_{13} = -V_{td}^* m_b \left(1 + O_{13}^d \frac{m_s}{m_b} \right), \quad (M'_d)_{31} = O_{31}^d m_d. \quad (46)$$

The leading fixed term $-V_{td}^* m_b$ dominates over the scanned O^d -dependent pieces. This explains why the down-sector tree-level branching ratios are only weakly sensitive to the scanned O^d factors and form narrow bands. Their remaining variation is tied to the fixed CKM factors, mass reconstruction, Higgs mixing/alignment, and the surviving flavor and electroweak constraints.

This behavior contrasts with $t \rightarrow ch$, $h \rightarrow uc$, and the lepton-sector $h \rightarrow \mu\tau$ rate. In Eq. (14), the relevant up-sector off-diagonal entries are controlled by the scanned O^u texture factors and by alignment-dependent Higgs mixing; the fixed CKM-weighted m_b leading term is a special

TABLE III. Tree-level branching-ratio quantiles for the main channels in the strict surviving sample.

Channel	Minimum	5th percentile	Median	95th percentile	Maximum
$h \rightarrow sb$	1.37×10^{-3}	1.46×10^{-3}	1.54×10^{-3}	1.57×10^{-3}	1.57×10^{-3}
$h \rightarrow db$	3.81×10^{-5}	4.14×10^{-5}	4.49×10^{-5}	4.64×10^{-5}	4.66×10^{-5}
$t \rightarrow ch$	7.17×10^{-15}	1.08×10^{-10}	4.65×10^{-8}	7.17×10^{-7}	2.71×10^{-6}
$h \rightarrow \mu\tau$	1.04×10^{-12}	1.91×10^{-8}	5.27×10^{-6}	8.26×10^{-5}	2.65×10^{-4}

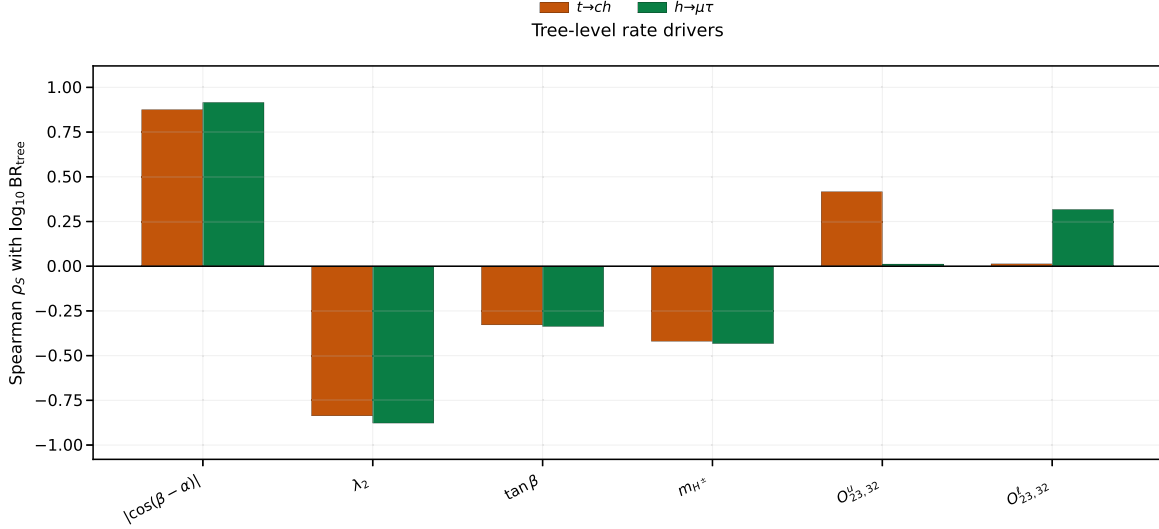


FIG. 11. Spearman correlations for representative tree-level Higgs and top-FCNC branching ratios in the final sample.

feature of the down-sector entries. In Eq. (16), the relevant lepton-sector entries are controlled by $O_{23}^\ell m_\mu$ and $O_{32}^\ell m_\mu$. Consequently, the non-down-sector flavor-violating rates remain more sensitive to scanned texture entries, alignment, and accidental cancellations among Higgs-doublet contributions.

The broad non-down-sector distributions are visible in the driver plot of Fig. 11 and the λ_2 -alignment scatter plot of Fig. 12. These channels reflect their direct sensitivity to the scanned up- and lepton-sector textures, the alignment limit, and accidental cancellations among Higgs-doublet contributions.

F. Rare hierarchy inversion in $h \rightarrow db$ versus $h \rightarrow sb$

A small group of three points satisfies $\text{BR}_{\text{IL}}(h \rightarrow db) > \text{BR}_{\text{IL}}(h \rightarrow sb)$ after the one-loop rate is applied. All three

inversion points retain the tree-level ordering $\text{BR}_{\text{tree}}(h \rightarrow sb) > \text{BR}_{\text{tree}}(h \rightarrow db)$, as summarized in Table IV. We define

$$K_{sb} = \frac{\text{BR}_{\text{IL}}(h \rightarrow sb)}{\text{BR}_{\text{tree}}(h \rightarrow sb)}, \quad K_{db} = \frac{\text{BR}_{\text{IL}}(h \rightarrow db)}{\text{BR}_{\text{tree}}(h \rightarrow db)}. \quad (47)$$

The inversion appears as a correction-factor inversion and is traced to destructive tree-loop interference in the down-sector channels. In the final sample, the inverted points have $K_{sb} \simeq (6.5 - 8.2) \times 10^{-3}$ and $K_{db} \simeq 0.34 - 0.47$, with median values $K_{sb} = 7.1 \times 10^{-3}$ and $K_{db} = 0.41$. Thus K_{db}/K_{sb} is large enough to overcome the underlying tree-level hierarchy even though the tree-level branching ratios keep $h \rightarrow sb$ above $h \rightarrow db$. Schematically,

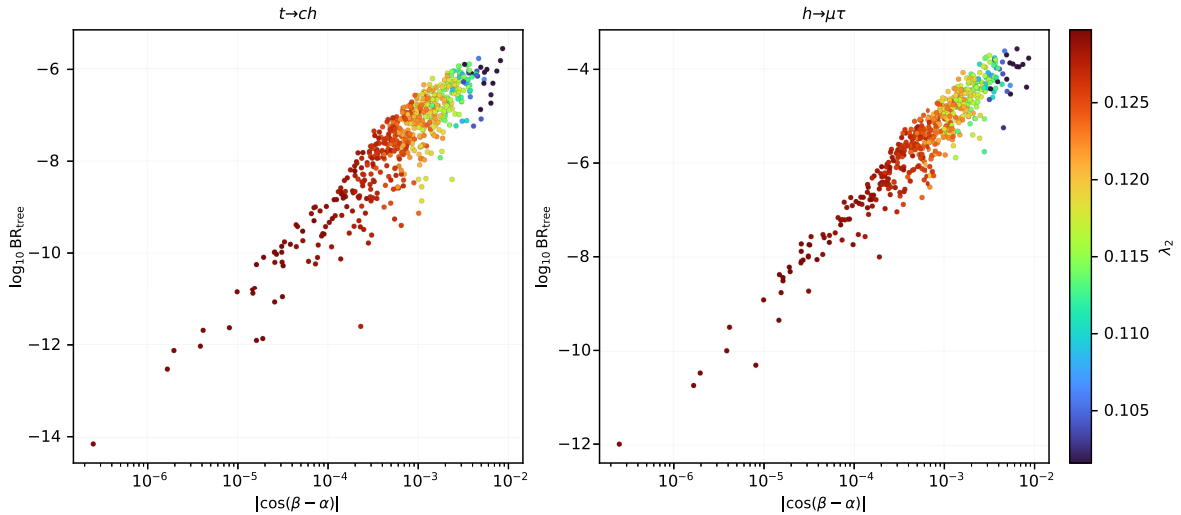

 FIG. 12. Correlation of λ_2 and the alignment proxy with the loop-level $h \rightarrow \mu\tau$ rate and representative tree-level FCNC rates.

TABLE IV. Summary of the rare $h \rightarrow db > h \rightarrow sb$ hierarchy-inversion points after applying one-loop rates in the strict surviving sample.

Quantity	Inversion points
Number of inversion points	3
Inversion fraction	0.55%
Median tree ratio $\text{BR}_{\text{tree}}(h \rightarrow sb)/\text{BR}_{\text{tree}}(h \rightarrow db)$	34.2
Median one-loop ratio $\text{BR}_{\text{1L}}(h \rightarrow sb)/\text{BR}_{\text{1L}}(h \rightarrow db)$	0.592
Median $K_{sb} = \text{BR}_{\text{1L}}(h \rightarrow sb)/\text{BR}_{\text{tree}}(h \rightarrow sb)$	7.08×10^{-3}
Median $K_{db} = \text{BR}_{\text{1L}}(h \rightarrow db)/\text{BR}_{\text{tree}}(h \rightarrow db)$	0.412
Median K_{db}/K_{sb}	57.5
All inversion points keep tree-level $h \rightarrow sb > h \rightarrow db$	yes

$$K_q = \frac{|\mathcal{M}_{\text{tree}}^q + \mathcal{M}_{\text{loop}}^q|^2}{|\mathcal{M}_{\text{tree}}^q|^2} = 1 + \delta_{\text{int}}^q + R_{\text{loop}}^q, \quad q = sb, db, \quad (48)$$

with

$$\begin{aligned} \delta_{\text{int}}^q &= \frac{2\text{Re}[(\mathcal{M}_{\text{tree}}^q)^* \mathcal{M}_{\text{loop}}^q]}{|\mathcal{M}_{\text{tree}}^q|^2}, \\ R_{\text{loop}}^q &= \frac{|\mathcal{M}_{\text{loop}}^q|^2}{|\mathcal{M}_{\text{tree}}^q|^2}, \\ C_{\text{int}}^q &\equiv \frac{\text{Re}[(\mathcal{M}_{\text{tree}}^q)^* \mathcal{M}_{\text{loop}}^q]}{|\mathcal{M}_{\text{tree}}^q| |\mathcal{M}_{\text{loop}}^q|}, \quad q = sb, db. \end{aligned} \quad (49)$$

The small K_{sb} values therefore indicate a near cancellation in the total $h \rightarrow sb$ amplitude, while the corresponding $h \rightarrow db$ rates are suppressed less severely.

Figure 13 shows that the three inverted points lie in the region with strongly negative C_{int}^{sb} , while C_{int}^{db} is less extreme. The enlarge panel resolves the three surviving inverted points individually. The presence of these three inversion points

shows that the destructive-interference mechanism survives the stringent meson-mixing constraints.

G. Lepton-sector HFV tree-level and one-loop comparison

In the final sample, Fig. 14 compares the tree-level and SPHeno one-loop branching ratios for the three lepton-sector HFV Higgs channels. The points lie close to the equal-rate line, showing that the one-loop corrections are generally small over the surviving parameter space.

H. Experimental prospects and interpretation

The hierarchy found in Sec. IV B is a model hierarchy in the surviving type 1B parameter sample; LHC observability requires separate detector-level information. The channel $h \rightarrow sb$ can reach the 10^{-3} level in branching ratio, but its experimental reconstruction is challenging because the final state is embedded in ordinary hadronic Higgs decays and requires flavor-sensitive strange- and bottom-jet information. A direct collider interpretation would therefore need a dedicated analysis with realistic b -tagging, possible

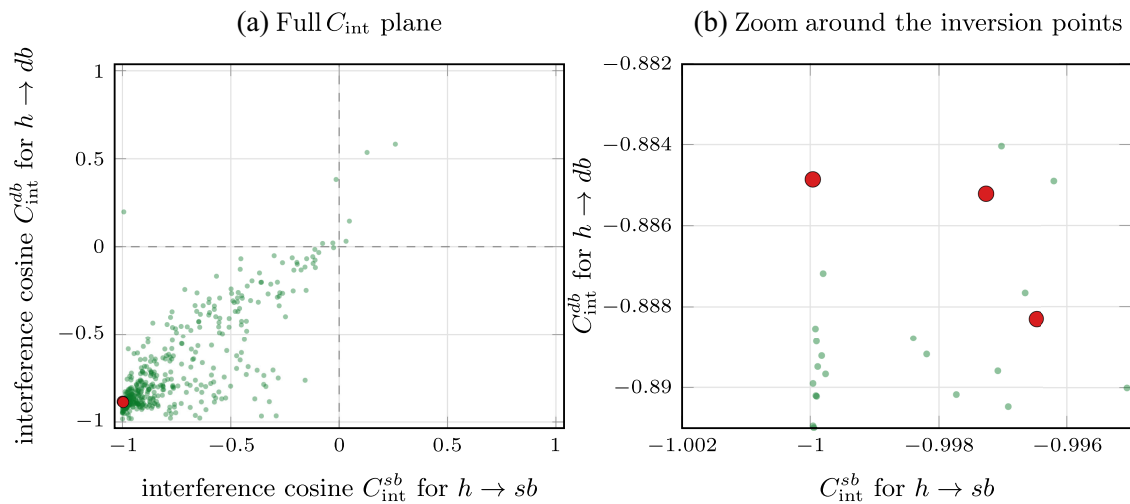


FIG. 13. Interference-cosine projection of the rare hierarchy inversion. Panel (a) shows the full C_{int}^{sb} - C_{int}^{db} plane, and panel (b) enlarges into the inversion region. Green points show noninverted points, while red points show the three points with $\text{BR}_{\text{1L}}(h \rightarrow db) > \text{BR}_{\text{1L}}(h \rightarrow sb)$, after summing the charge-conjugate final states.

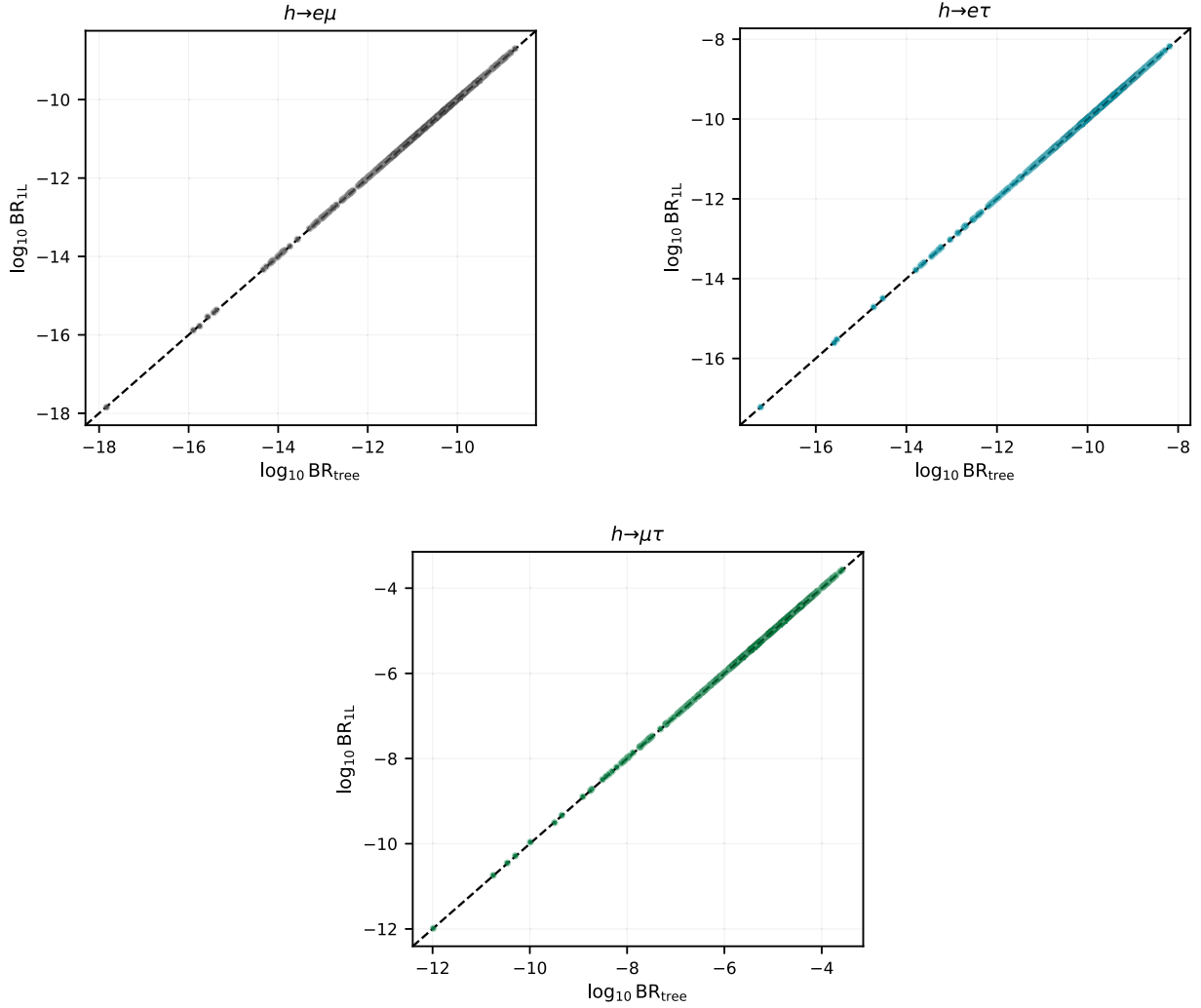


FIG. 14. Comparison of the tree-level and SPheno one-loop branching ratios for the lepton-sector HFV channels in the 542-point final sample. The dashed diagonal line in each panel denotes $BR_{1L} = BR_{tree}$.

strange-tagging, or strange-enriched categories, and detector-level efficiencies.

The lepton-sector HFV mode $h \rightarrow \mu\tau$ is experimentally cleaner. The limits in Table V show 10^{-3} -level sensitivity in $h \rightarrow e\tau$ and $h \rightarrow \mu\tau$, and a stronger 10^{-5} -level bound in $h \rightarrow e\mu$. The values obtained in the surviving sample are below current bounds but can lie in a range relevant for improved Run-3 and high-luminosity LHC analyses. By

contrast, $h \rightarrow e\tau$ and $h \rightarrow e\mu$ are typically much smaller in this type 1B realization.

For top-Higgs FCNCs, current direct limits reach the 10^{-4} level. Both the tree-level texture hierarchy and the loop-corrected rates emphasize $t \rightarrow ch$ over $t \rightarrow uh$ in the surviving sample. Future reinterpretations should combine the model-specific flavor structure with realistic top reconstruction, Higgs decay modes, flavor tagging, and

TABLE V. Current direct experimental upper limits or direct-limit status for the flavor-violating channels considered in this work.

Channel	Direct bound/status	Source
$h \rightarrow e\mu$	$BR < 4.4 \times 10^{-5}$ at 95% C.L.	CMS [17]
$h \rightarrow e\tau$	$BR < 2.0 \times 10^{-3}$ at 95% C.L.	ATLAS [16]
$h \rightarrow \mu\tau$	$BR < 1.5 \times 10^{-3}$ at 95% C.L.	CMS [15]
$t \rightarrow uh$	$BR < 2.6 \times 10^{-4}$ at 95% C.L.	ATLAS [24]
$t \rightarrow ch$	$BR < 3.4 \times 10^{-4}$ at 95% C.L.	ATLAS [24]
$h \rightarrow sb, h \rightarrow db, h \rightarrow uc$	No dedicated process-specific direct upper limit is currently available; present constraints on quark-flavor Higgs couplings are indirect or analysis dependent.	[26,29]

correlations with the low-energy constraints. Thus the most promising phenomenological targets depend on both rate size and experimental accessibility: $h \rightarrow sb$ is numerically large but experimentally difficult, $h \rightarrow \mu\tau$ is cleaner, and $t \rightarrow ch$ provides the leading top-flavor probe in this numerical analysis.

V. CONCLUSIONS

We have studied flavor-violating Higgs and top decays in the type 1B flavorful two-Higgs-doublet model with a twist. Generation-dependent doublet assignments make the Yukawa sector neither natural-flavor-conserving nor aligned, so tree-level scalar FCNCs arise. They are organized by the approximate $U(2)^5$ texture and, in our implementation, by a CKM matrix generated in the down sector. Unlike a generic 2HDM with tree-level FCNCs, where off-diagonal Yukawa couplings are often treated as more freely parametrized, type 1B ties them to these assignments and the CKM-down mass reconstruction, yielding correlated flavor hierarchies.

After imposing Higgs, electroweak, meson-mixing, $B \rightarrow X_s \gamma$, HFV, and CLFV constraints (including μ - e conversion), the surviving sample exhibits $\text{BR}(h \rightarrow sb) \gg \text{BR}(h \rightarrow db)$, $\text{BR}(h \rightarrow \mu\tau) \gg \text{BR}(h \rightarrow e\tau), \text{BR}(h \rightarrow e\mu)$, and $\text{BR}(t \rightarrow ch) \gg \text{BR}(t \rightarrow uh)$. The leading channels are $h \rightarrow sb$, $t \rightarrow ch$, $h \rightarrow db$, and $h \rightarrow \mu\tau$. The tree-level rates for $h \rightarrow sb$ and $h \rightarrow db$ are narrowly distributed and CKM-controlled by the fixed $-V_{ts}^* m_b$ and $-V_{td}^* m_b$ terms, whereas $t \rightarrow ch$ and $h \rightarrow \mu\tau$ vary by orders of magnitude because of texture and alignment sensitivity. Approximate first-second-generation protection suppresses $h \rightarrow uc$ and $h \rightarrow e\mu$. Radiative and three-body CLFV observables remain below current limits and are not used as additional sample-reducing cuts.

We also included one-loop vertex effects, including the loop-amplitude-squared contribution to the rates. Large relative corrections in $t \rightarrow ch$ occur when alignment suppresses the tree-level coupling, although the absolute branching ratio remains small. Rare points with $\text{BR}_{\text{IL}}(h \rightarrow db) > \text{BR}_{\text{IL}}(h \rightarrow sb)$ arise from strong destructive tree-loop interference that suppresses $h \rightarrow sb$ more strongly than $h \rightarrow db$. The overall pattern nevertheless remains $h \rightarrow sb$ as the largest quark-HFV mode, $h \rightarrow \mu\tau$ as the cleanest lepton-HFV mode, and $t \rightarrow ch$ as the leading top-flavor probe.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX: REPRESENTATIVE K^0 - $\bar{K}^0$ MIXING CONTRIBUTIONS

The meson-mixing observables are evaluated using the SARAH-generated SPheno/FlavorKit routines [43]. Representative contributions to K^0 - $\bar{K}^0$ mixing are shown in Fig. 15.

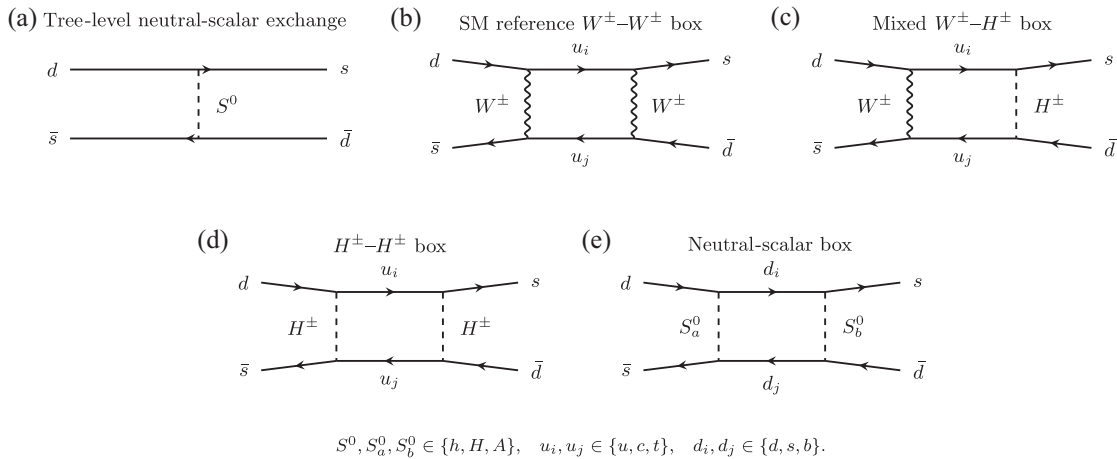


FIG. 15. Representative contributions to K^0 - $\bar{K}^0$ mixing entering the SPheno/FlavorKit evaluation: (a) tree-level neutral-scalar exchange, (b) SM reference $W^\pm$ - $W^\pm$ box, (c) mixed $W^\pm$ - $H^\pm$ boxes, (d) $H^\pm$ - $H^\pm$ boxes, and (e) neutral-scalar boxes. The mixed $W^\pm$ - $H^\pm$ panel represents both boson orderings, and sums over internal flavors are implicit. Additional Goldstone-boson and neutral-gauge contributions present in the generated Wilson coefficients are not displayed separately. The diagrams are representative rather than an exhaustive graphical enumeration.

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