Accumulating hints for flavor-violating Higgs bosons at the electroweak scale

Andreas Crivellin[1,2,*] and Syuhei Iguro[3,4,5,†]

[1]Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH20138057 Zürich, Switzerland
[2]Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[3]Institute for Theoretical Particle Physics (TTP), Karlsruhe Institute of Technology (KIT), Wolfgang-Gaede-Straße 1, 76131 Karlsruhe, Germany
[4]Institute for Astroparticle Physics (IAP), KIT, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[5]Institute for Advanced Research (IAR), Nagoya University, Nagoya 464–8601, Japan

(Received 22 November 2023; accepted 10 June 2024; published 9 July 2024)

We show that supplementing the Standard Model by only a second Higgs doublet, a combined explanation of $h \to e\tau$, $h \to \mu\tau$, $b \to s\ell^+\ell^-$, the W mass and $R(D^{(*)})$ as well as the excess in $t \to bH^+(130\ \mathrm{GeV}) \to b\bar{b}c$ is possible. While this requires flavor violating couplings, the stringent bounds from, e.g., $\mu \to e\gamma$, $\tau \to \mu\gamma$, $B_s - \bar{B}_s$ mixing, $b \to s\gamma$, low mass dijet, and $pp \to H^+H^- \to \tau^+\tau^-\nu\bar{\nu}$ searches can be avoided. However, the model is very constrained; it inevitably predicts a shift in the SM Higgs coupling strength to tau leptons as well as a nonzero $t \to hc$ rate, as indeed preferred by recent measurements. We study three benchmark points providing such a simultaneous explanation and calculate their predictions, including collider signatures which can be tested with upcoming LHC run-3 data.

DOI: 10.1103/PhysRevD.110.015014

I. INTRODUCTION

The Standard Model (SM) describes the known fundamental constituents of matter and their interactions at subatomic scales. It has been extensively tested and verified by a plethora of measurements [1] and the discovery of the Brout-Englert-Higgs boson [2–5] at the LHC [6,7], which has, in fact, properties [8–11] in agreement with the SM expectations, provided its last missing puzzle piece. However, these results do not exclude the existence of additional scalars, if the SM-Higgs signal strengths are not significantly altered (i.e. the mixing with the new scalars is sufficiently small) and their contribution to the ρ parameter ($\rho = m_Z^2 \cos^2\theta_W / m_W^2$) does not violate the experimental bounds. In fact, several indirect and direct hints suggest the existence of new Higgs bosons (see Ref. [12] for a recent review).

In this article, we consider the simple and motivated option of extending the SM by a single Higgs doublet, i.e. a two-Higgs-doublet model (2HDM); see Ref. [13] for a review. We will focus on flavor-violating signatures motivated by an interesting set of anomalies, i.e. deviations from the SM predictions: nonzero rates of $t \to bH^+(130) \to b\bar{b}c$, $h \to e\tau$, and $h \to \mu\tau$ as well as the deviations from the SM predictions in $b \to s\ell^+\ell^-$, the W mass, and $R(D^{(*)})$. For an explanation, flavor violation is clearly required (except for the W mass), and we will thus consider the 2HDM with generic Yukawa couplings [14–25] as a minimal model with the potential of explaining these measurements. However, there are various bounds from flavor and collider observables which must be respected, such that the model is very constrained and it is *a priori* not clear if a combined explanation is possible.

II. G2HDM

In the 2HDM with generic Yukawa couplings (G2HDM), also called the type-III 2HDM, one can work in the so-called Higgs basis where only one Higgs doublet acquires a nonzero vacuum expectation value (VEV) [26] such that

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+\phi_1+iG^0}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2+iA}{\sqrt{2}} \end{pmatrix}. \qquad (1)$$

Here, G^+ and G^0 are would-be Goldstone bosons, and H^+ and A are the charged Higgs and the CP-odd Higgs boson, respectively, with $v \approx 246$ GeV. The Yukawa couplings can then be written as

*Contact author: andreas.crivellin@psi.ch
†Contact author: igurosyuhei@gmail.com

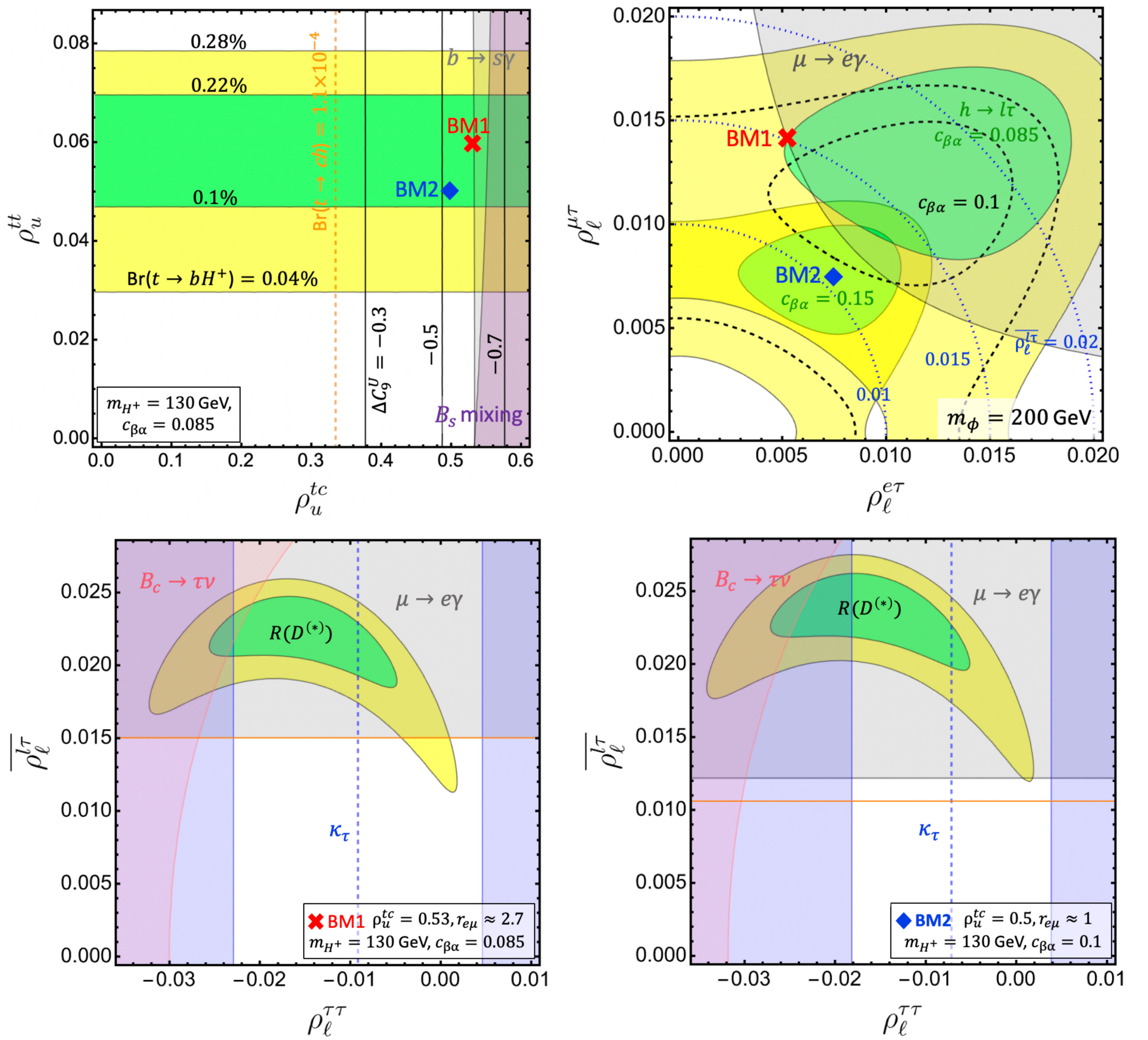

FIG. 1. Upper left: predicted values of ΔC_9^U and preferred regions for $\mathrm{Br}(t \to bH^+)$ in the ρ_u^{tc}-ρ_u^{tt} plane along with constraints from $b \to s\gamma$ (lighter gray) and $B_s - \bar{B}_s$ mixing (darker gray) assuming $\mathrm{Br}(H^+ \to bc) \approx 100\%$. The HL-LHC sensitivity to $\mathrm{Br}(t \to hc)$ is shown for $c_{\beta\alpha} = 0.085$ (orange-dashed line). The red cross and the blue diamond indicate our two benchmark points BM1 and BM2, respectively. Upper right: preferred regions (1σ and 2σ) from $h \to l\tau$ for $c_{\beta\alpha} = 0.085$, $c_{\beta\alpha} = 0.1$ and $c_{\beta\alpha} = 0.15$, in the $\rho_\ell^{e\tau}$-$\rho_\ell^{\mu\tau}$ plane as well as the exclusion region from $\mu \to e\gamma$ which, in a linear approximation, is independent of $c_{\beta\alpha}$. Bottom left (right): preferred regions from $R(D^{(*)})$ (1σ and 2σ) as well as the exclusion region from $\mu \to e\gamma$ (gray), κ_τ (blue), and $B_c \to \tau\nu$ (red) in the $\rho_\ell^{\tau\tau}$-$\overline{\rho_\ell^{l\tau}}$ plane assuming all Yukawa couplings to be real. The up-quark Yukawa couplings are set to the values of BM1 (BM2) given in the upper figures while the benchmark value of $\overline{\rho_\ell^{l\tau}}$ is indicated by the orange line. The current measured central value of κ_τ is shown as a dashed blue line.

$$\mathcal{L}_Y = -\bar{Q}_L^i (H_1 y_d^i + H_2 \rho_d^{ij}) d_R^i - \bar{L}_L^i (H_1 y_\ell^i + H_2 \rho_\ell^{ij}) e_R^i - \bar{Q}_L^i (V^\dagger)^{ij} (\tilde{H}_1 y_u^j + \tilde{H}_2 \rho_u^{jk}) u_R^j, \tag{2}$$

where i, j, and k are flavor indices, and $\tilde{H}_{1,2} = i\tau_2 H_{1,2}^*$ with τ_2 being the second Pauli matrix. We now perform the rotation

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\beta\alpha} & \sin\theta_{\beta\alpha} \\ -\sin\theta_{\beta\alpha} & \cos\theta_{\beta\alpha} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix} \tag{3}$$

to go to the mass eigenstates h and H for the neutral Higgses, where h is SM-like. Furthermore, writing $Q = (V^\dagger u_L, d_L)^T$, where V is the Cabbibo-Kobayashi-Maskawa (CKM) matrix [27,28], we arrive at the mass eigenbasis for the fermions with $y_i^f = \sqrt{2} m_{f_i}/v$ (m_{f_i} denoting the fermion masses).

Note that ρ_f^{ij} is independent of the fermion masses, i.e. contains 9 complex parameters each for $f = u, d, \ell$. The off-diagonal elements of ρ_d are stringently constrained by meson mixing and decays and we will thus disregard them. We will rather consider the minimal scenario where ρ_u^{tt}, ρ_u^{tc}, $\rho_\ell^{\tau\tau}$, $\rho_\ell^{\mu\tau}$, and $\rho_\ell^{e\tau}$ are the only nonzero entries. In addition, we consider $m_{H^\pm}$, m_H, m_A and Higgs mixing parameter $c_{\beta\alpha} \equiv \cos\theta_{\beta\alpha}$ as free parameters (with relevant impact on the phenomenology) while we disregard CP violation in the Higgs potential.

III. PHENOMENOLOGICAL ANALYSIS

We can now consider the preferred size of the relevant free parameters $\rho_u^{tt}, \rho_u^{tc}, \rho_\ell^{\tau\tau}, \rho_\ell^{\mu\tau}, \rho_\ell^{e\tau}$, $c_{\beta\alpha}$, $m_{H,A}$, and m_{H^+}, assuming in the first step that all couplings are real and that the other new Yukawa couplings are negligibly small.

Concerning observables that are only sensitive to the charged Higgs contribution, we first use the excess in $t \to H^+ b \to b\bar{b}c$ to fix $m_{H^+} \approx 130$ GeV. Furthermore, $b \to s\ell^+\ell^-$ favors sizable and negative ΔC_9^U which can be obtained via ρ_u^{tc}, such that for $\mathrm{Br}(H^+ \to c\bar{b}) \approx 100\%$, i.e. $|\rho_\ell^{\ell\tau}|, |\rho_u^{cc}| \ll |\rho_u^{tc}|$, leading to $\rho_u^{tt} \approx 0.06$. However, the possible effect in ΔC_9^U is limited to ≈ -0.6 by the constraints from $b \to s\gamma$ and $B_s - \bar{B}_s$ mixing. This is illustrated in Fig. 1 (upper left). Note that the impact of the neutral Higgs bosons can be disregarded for these observables, such that we can choose two benchmark (BM) points for the couplings ρ_u^{tc}, i.e. $\rho_u^{tc} = 0.53$ and $\rho_u^{tc} = 0.5$ for BM1 and BM2, respectively for $\rho_u^{cc} \approx 0$.

Turning to observables sensitive to lepton couplings, the excesses in $h \to e\tau$ and $h \to \mu\tau$ lead to a preference of nonzero values of $\rho_\ell^{e\tau}$, $\rho_\ell^{\mu\tau}$, and $c_{\beta\alpha}$.[1] This at the same time leads to an effect in $\mu \to e\gamma$ as illustrated in Fig. 1 (upper right). Note the mild dependence on the neutral Higgs masses which we set for definiteness to 200 GeV, and that explaining both $h \to e\tau$ and $h \to \mu\tau$ at the same time is possible with a Higgs mixing of $c_{\beta\alpha} \gtrsim 0.08$. Since the significance of excesses in $h \to e\tau$ and $h \to \mu\tau$ are slightly different, the contours are not symmetric in the $\rho_\ell^{e\tau}$-$\rho_\ell^{\mu\tau}$ plane. To maximize the contribution to $R(D^{(*)})$ while explaining $h \to l\tau$ at 1σ we fixed the $r_{\mu e} \equiv \rho_\ell^{\mu\tau}/\rho_\ell^{e\tau} = 2.7$ and $\overline{\rho_\ell^{l\tau}} \equiv \sqrt{|\rho_\ell^{e\tau}|^2 + |\rho_\ell^{\mu\tau}|^2} \approx 0.015$ (BM1). In a more conservative setup we use and $r_{\mu e} = 1$ and $\overline{\rho_\ell^{l\tau}} = 0.011$ (BM2). Finally, since $|\rho_\ell^{l\tau}| \ll |\rho_u^{tc}|$ the results discussed in the previous paragraph are not affected.

TABLE I. The value of the parameters for BM3 and the corresponding predictions for the observables.

Parameters
$m_{H^+} = 130$ GeV, $m_\phi = 200$ GeV, $c_{\beta\alpha} = 0.1, \rho_u^{tt} = 0.06,$ $\rho_u^{tc} = 0.47, \rho_\ell^{\tau\tau} = -0.01(1 \pm 1.8i), \rho_\ell^{\mu\tau} = 0.01, \rho_\ell^{e\tau} = 0.006$
Predictions
$\mathrm{Br}(t \to b\bar{b}c) = 0.16\%, \Delta C_9^U = -0.47, \mathrm{Br}(h \to \mu\tau) = 0.061\%,$ $\mathrm{Br}(h \to e\tau) = 0.022\%, R(D) = 0.341, R(D^*) = 0.272,$ $\kappa_\tau = 0.91, \chi^2_{\rm SM} - \chi^2_{\rm G2HDM}(\mathrm{ST}, 2023) = 10.4,$ $\mathrm{Br}(\mu \to e\gamma) = 2.0 \times 10^{-13}$, $\Delta C_7 = -0.027, R_{B_s} = 0.03,$ $\mathrm{Br}(B_c \to \tau\bar{\nu}) = 30\%, \mathrm{Br}(t \to ch) = 3.0 \times 10^{-4}$

Let us now consider $R(D^{(*)})$ in the lower panel in Fig. 1 for BM1 (left) and BM2 (right) where we also show the $\mu \to e\gamma$ exclusion region in the $\rho_\ell^{\tau\tau}$-$\overline{\rho_\ell^{l\tau}}$ plane. The red and blue regions are excluded by the $B_c \to \tau\nu$ lifetime and κ_τ, respectively. Note that the minimal deviation of κ_τ from unity is 4% for BM1 since $|\rho_\ell^{\tau\tau}| \gtrsim 5 \times 10^{-3}$ and $c_{\beta\alpha} \gtrsim 0.08$ are necessary to explain $h \to l\tau$ and $R(D^{(*)})$ simultaneously.

Note that the BM1 scenario is on the edge of the current constraints such that it can explain all anomalies as well as possible. However, we found that an explanation of $R_{D^{(*)}}$ is possible only within 2σ level. On the other hand, the BM2 scenario is more conservative with respect to the experimental bounds but is only in agreement with $R(D^{(*)})$ at the boundary of the 2σ level. The reason for this is that $\rho_\ell^{e\tau}$ and $\rho_\ell^{\mu\tau}$ are smaller which reduces the noninterfering effect NP with the SM. Since also an imaginary part of $\rho_u^{tc}\rho_\ell^{\tau\tau}$ leads to an amplitude which does not interfere with the SM in $b \to c\tau\nu$, this can help to explain $R(D^{(*)})$.[2] We can include the imaginary part of $\overline{\rho_\ell^{l\tau}}$ as $\rho_\ell^{\tau\tau}$ into the definition of $\overline{\rho_\ell^{l\tau}}$, i.e. $\overline{\rho_\ell^{l\tau}} = \sqrt{|\rho_\ell^{e\tau}|^2 + |\rho_\ell^{\mu\tau}|^2 + \mathrm{Im}[\rho_\ell^{\tau\tau}]^2}$.[3] Once we consider complex $\rho_\ell^{\tau\tau}$, we can generate an imaginary value of the $h\tau\bar{\tau}$ coupling (for $c_{\beta\alpha} \neq 0$). Since the ATLAS measurement of the SM-Higgs CP properties only starts to constrain this [31], the resulting bound is too weak to be relevant. Therefore, $|\rho_\ell^{\tau\tau}|$ can be bigger than in the case $\rho_\ell^{\tau\tau}$ is real and thus explain $R(D^{(*)})$ with a smaller $|\rho_u^{tc}|$ and hence yield a smaller value of ΔC_7, alleviating the $b \to s\gamma$ bound. The corresponding benchmark point (BM3) is given in Table I which explains $t \to bH^+ \to b\bar{b}c$, $h \to l\tau$, and $R(D^{(*)})$ within 1σ with $\Delta C_9^U \simeq -0.5$ and moderate ΔC_7 and $\mathrm{Br}(\mu \to e\gamma)$.

[1]In principle also $\rho_\ell^{\tau e}$, $\rho_\ell^{\tau\mu}$ could explain $h \to e\tau$ and $h \to \mu\tau$. However, in order to avoid chirally enhanced effects in $\mu \to e\gamma$ it is important that both $\rho_\ell^{\tau e}\rho_\ell^{\mu\tau}$ and $\rho_\ell^{e\tau}\rho_\ell^{\tau\mu}$ are not sizable. Furthermore, to avoid effects in $b \to cl\nu$, we will opt for $\rho_\ell^{l\tau} \neq 0$ and $\rho_\ell^{\tau l} = 0$.

[2]Note that electroweak baryogenesis could be realized with complex Yukawa couplings [29,30].

[3]Note that $\rho_\ell^{\tau\tau}$ does not contribute to $\mu \to e\gamma$. For simplicity we consider the complex $\rho_\ell^{\tau\tau}$ and assume that ρ_u^{tc} remains to be real. However, ρ_u^{tc} could be complex as well without conflicting $\Delta\Gamma_B$.

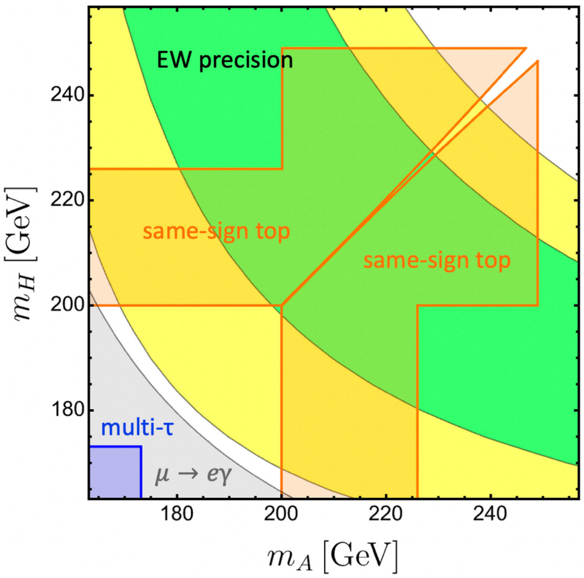

FIG. 2. Preferred regions (green: 1σ; yellow: 2σ) from electroweak precision data along with exclusion regions from multitau and same-sign top searches as well as $\mu \to e\gamma$ in the m_A-m_H plane.

Finally, we consider the impact of varying m_A and m_H in Fig. 2 for BM3. Multitau final state searches exclude the bottom-left[4] part of the m_A-m_H plane and small values of m_A and m_H are also disfavored by $\mathrm{Br}(\mu \to e\gamma)$. Same-sign top searches provide constraints if $m_H, m_A \gtrsim 200$ GeV. However, because of the cancellation between the amplitudes from A and H, $m_H \simeq m_A$ can evade this bound. Furthermore, once $\phi \to W^\pm H^\mp$ becomes kinematically allowed, same-sign top searches lose their constraining power. Note that top associated Higgs production [33] and bottom associated H^+ production [34] as well as lowering the threshold of same-sign top searches [35,36] are crucial to probe this scenario.

IV. CONCLUSIONS AND DISCUSSION

Motivated by the hints for NP in $t \to bH^+$, $b \to s\ell^+\ell^-$, $h \to e\tau$, $h \to \mu\tau$, m_W, and $R(D^{(*)})$ we revisited the model with the minimal particle context that is potentially capable of providing a combined explanation, the 2HDM with generic sources of flavor violation. Even though the model is very predictive and hence constrained, we found a minimal set of parameters (Fig. 3) that can address these deviations from the SM predictions simultaneously without violating any other bounds. For this, a mild mass difference between the charged and additional neutral Higgs boson is necessary to evade the LHC constraint, at the same time improving the EW global fit by shifting the prediction for the W mass. Furthermore, a deviation in the SM Higgs coupling strength to tau leptons κ_τ and a nonzero rate for $t \to hc$ are predicted, both welcomed by current data.

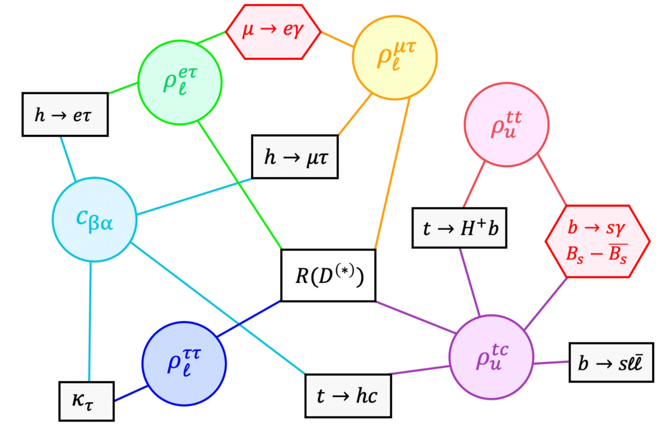

FIG. 3. Diagram showing the correlations between the free parameters (circles) of our model (except the Higgs masses) and the observables. Observables providing strong constraints are shown as red hexagons while the ones pointing toward a NP effect are shown as black rectangles.

While we assumed the other Yukawa coupling to be negligible, $\rho_d^{bb} \approx \mathcal{O}(10^{-2})$ could be helpful to reduce the effect in ΔC_7 while allowing for b-associated production of the new neutral scalars at the LHC. Adding a small ρ_u^{cc} would induce ΔC_9^U [see Eq. (4)] of the Supplemental Material [37].[5] Note that once we give up either $h \to \mu\tau$ or $h \to e\tau$, the $\mu \to e\gamma$ constraint can be relaxed such that $R(D^{(*)})$ could be fully explained. This is because $\rho_\ell^{e\tau}$ or $\rho_\ell^{\mu\tau}$ can be larger and hence the smaller $c_{\beta\alpha}$ is allowed. Then larger $\rho_\ell^{\tau\tau}$ and smaller ρ_u^{tc} can explain $R(D^{(*)})$. While a smaller ρ_u^{tc} would lead to a smaller contribution to ΔC_9^U, a tiny ρ_u^{cc} can already regenerate a sizable value. Note that a smaller ρ_u^{tc} would also be beneficial to avoid tuning the neutral Higgs masses while still avoiding collider constraints. To assess the validity of such a more complicated scenario, a global fit, e.g. with the public tool GAMBIT [38], is desirable for future research.

ACKNOWLEDGMENTS

We are very grateful to Lisong Chen, Marco Fedele, Ulrich Nierste, Teppei Kitahara, Hiroyasu Yonaha, and Martin Lang for enlightening discussions and encouraging this work. The work of A. C. is supported by a professorship grant from the Swiss National Science Foundation (No. PP00P21_76884). S. I. is supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Grant No. 396021762-TRR 257.

[4]Note that the inclusive di-τ resonance search [32] will be able to cover the region where either H or A is lighter than $m_t + m_c$ in future.

[5]It is important to comment that an additional ρ_u^{cc} does not induce $D - \bar{D}$ mixing since H^+ does not couple to an up quark in our setup.

[1] R. L. Workman *et al.* (Particle Data Group Collaboration), Review of particle physics, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).
[2] P. W. Higgs, Broken symmetries, massless particles and gauge fields, Phys. Lett. **12**, 132 (1964).
[3] F. Englert and R. Brout, Broken symmetry and the mass of gauge vector mesons, Phys. Rev. Lett. **13**, 321 (1964).
[4] P. W. Higgs, Broken symmetries and the masses of gauge bosons, Phys. Rev. Lett. **13**, 508 (1964).
[5] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Global conservation laws and massless particles, Phys. Rev. Lett. **13**, 585 (1964).
[6] G. Aad *et al.* (ATLAS Collaboration), Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B **716**, 1 (2012).
[7] S. Chatrchyan *et al.* (CMS Collaboration), Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B **716**, 30 (2012).
[8] J. M. Langford (ATLAS, CMS Collaborations), Combination of Higgs measurements from ATLAS and CMS: Couplings and $\kappa-$ framework, Proc. Sci. LHCP2020 (**2021**) 136.
[9] ATLAS Collaboration, Combined measurements of Higgs boson production and decay using up to 139 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment, Report No. ATLAS-CONF-2021-053, 2021.
[10] A. Tumasyan *et al.* (CMS Collaboration), A portrait of the Higgs boson by the CMS experiment ten years after the discovery, Nature (London) **607**, 60 (2022).
[11] ATLAS Collaboration, A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery, Nature (London) **607**, 52 (2022); Nature (London) **612**, E24 (2022).
[12] A. Crivellin and B. Mellado, Anomalies in particle physics, Nat. Rev. Phys. **6**, 294 (2024).
[13] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Theory and phenomenology of two-Higgs-doublet models, Phys. Rep. **516**, 1 (2012).
[14] W.-S. Hou, Tree level $t \to ch$ or $h \to tc$ decays, Phys. Lett. B **296**, 179 (1992).
[15] D. Chang, W. S. Hou, and W.-Y. Keung, Two loop contributions of flavor changing neutral Higgs bosons to $\mu \to e\gamma$, Phys. Rev. D **48**, 217 (1993).
[16] J. Liu and L. Wolfenstein, Spontaneous *CP* violation in the $SU(2)_L \times U(1)_Y$ model with two Higgs doublets, Nucl. Phys. **B289**, 1 (1987).
[17] T. P. Cheng and M. Sher, Mass matrix ansatz and flavor nonconservation in models with multiple Higgs doublets, Phys. Rev. D **35**, 3484 (1987).
[18] M. J. Savage, Constraining flavor changing neutral currents with $B \to \mu^+\mu^-$, Phys. Lett. B **266**, 135 (1991).
[19] A. Antaramian, L. J. Hall, and A. Rasin, Flavor changing interactions mediated by scalars at the weak scale, Phys. Rev. Lett. **69**, 1871 (1992).
[20] L. J. Hall and S. Weinberg, Flavor changing scalar interactions, Phys. Rev. D **48**, R979 (1993).
[21] M. E. Luke and M. J. Savage, Flavor changing neutral currents in the Higgs sector and rare top decays, Phys. Lett. B **307**, 387 (1993).
[22] D. Atwood, L. Reina, and A. Soni, Probing flavor changing top-charm-scalar interactions in e^+e^- collisions, Phys. Rev. D **53**, 1199 (1996).
[23] D. Atwood, L. Reina, and A. Soni, Phenomenology of two Higgs doublet models with flavor changing neutral currents, Phys. Rev. D **55**, 3156 (1997).
[24] F. J. Botella, G. C. Branco, M. Nebot, and M. N. Rebelo, Flavour changing Higgs couplings in a class of two Higgs doublet models, Eur. Phys. J. C **76**, 161 (2016).
[25] J. Herrero-Garcia, N. Rius, and A. Santamaria, Higgs lepton flavour violation: UV completions and connection to neutrino masses, J. High Energy Phys. 11 (2016) 084.
[26] S. Davidson and H. E. Haber, Basis-independent methods for the two-Higgs-doublet model, Phys. Rev. D **72**, 035004 (2005); Phys. Rev. D **72**, 099902(E) (2005).
[27] N. Cabibbo, Unitary symmetry and leptonic decays, Phys. Rev. Lett. **10**, 531 (1963).
[28] M. Kobayashi and T. Maskawa, *CP* violation in the renormalizable theory of weak interaction, Prog. Theor. Phys. **49**, 652 (1973).
[29] K. Fuyuto, W.-S. Hou, and E. Senaha, Electroweak baryogenesis driven by extra top Yukawa couplings, Phys. Lett. B **776**, 402 (2018).
[30] S. Kanemura and Y. Mura, Electroweak baryogenesis via top-charm mixing, J. High Energy Phys. 09 (2023) 153.
[31] G. Aad *et al.* (ATLAS Collaboration), Measurement of the *CP* properties of Higgs boson interactions with τ-leptons with the ATLAS detector, Eur. Phys. J. C **83**, 563 (2023).
[32] A. Tumasyan *et al.* (CMS Collaboration), Searches for additional Higgs bosons and for vector leptoquarks in $\tau\tau$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2023) 073.
[33] S. Iguro, Conclusive probe of the charged Higgs solution of P_5' and $R_{D^{(*)}}$ discrepancies, Phys. Rev. D **107**, 095004 (2023).
[34] M. Blanke, S. Iguro, and H. Zhang, Towards ruling out the charged Higgs interpretation of the $R_{D^{(*)}}$ anomaly, J. High Energy Phys. 06 (2022) 043.
[35] G. Aad *et al.* (ATLAS Collaboration), Search for heavy Higgs bosons with flavour-violating couplings in multi-lepton plus b-jets final states in pp collisions at 13 TeV with the ATLAS detector, J. High Energy Phys. 12 (2023) 081.
[36] CMS Collaboration, Search for new Higgs bosons through same-sign top quark pair production in association with a jet in proton-proton collisions at $\sqrt{s} = 13$ TeV, Report No. CMS-PAS-TOP-22-010, 2023.
[37] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevD.110.015014 for the details on the contributions of the G2HDM to the relevant observales.
[38] P. Athron, C. Balazs, T. E. Gonzalo, D. Jacob, F. Mahmoudi, and C. Sierra, Likelihood analysis of the flavour anomalies and $g-2$ in the general two Higgs doublet model, J. High Energy Phys. 01 (2022) 037.