PHYSICAL REVIEW D **93,** 031301(R) (2016)

Uncovering mass generation through Higgs flavor violation

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(Received 7 August 2015; published 22 February 2016)

A discovery of the flavor-violating decay $h \to \tau\mu$ at the LHC would require extra sources of electroweak symmetry breaking (EWSB) beyond the Higgs in order to reconcile it with the bounds from $\tau \to \mu\gamma$, barring fine-tuned cancellations. In fact, an $h \to \tau\mu$ decay rate at a level indicated by the CMS measurement is easily realized if the muon and electron masses are due to a new source of EWSB, while the tau mass is due to the Higgs. We illustrate this with two examples: a two Higgs doublet model, and a model in which the Higgs is partially composite, with EWSB triggered by a technicolor sector. The first- and second-generation quark masses and Cabibbo-Kobayashi-Maskawa mixing can also be assigned to the new EWSB source. Large deviations in the flavor diagonal lepton and quark Higgs Yukawa couplings are generic. If m_μ is due to a rank 1 mass matrix contribution, a novel Yukawa coupling sum rule holds, providing a precision test of our framework. Flavor-violating quark and lepton (pseudo)scalar couplings combine to yield a sizable $B_s \to \tau\mu$ decay rate, which could be $\mathcal{O}(100)$ times larger than the Standard Model $B_s \to \mu\mu$ decay rate.

DOI: 10.1103/PhysRevD.93.031301

Measurements of Higgs production and decay [1,2] have revealed that most of the electroweak symmetry breaking (EWSB) is due to the vacuum expectation value (VEV) of the Higgs field. In the Standard Model (SM) the Higgs VEV also sources the charged fermion masses. Testing this assumption directly is possible for the third-generation fermions by measuring the Higgs decays to b quarks and tau leptons and by measuring the $t\bar{t}h$ cross section at the LHC. Present measurements indicate that the Higgs is at least partially responsible for the masses of the third-generation fermions. Much less is known about the origin of mass for the first two generations. There is experimental confirmation that the Higgs has a smaller Yukawa coupling to the muon than to the tau [3,4], as expected in the SM. The SM also predicts that the Higgs should not have tree-level flavor-changing decays, e.g., $h \to bs$ or $h \to \tau\mu$. The discovery of such decays would mean that there must be new physics (NP) near the electroweak scale [5–21]. In this paper we point out that flavor-violating Higgs decays can also be understood as a test of fermion mass generation, and we devise a sum rule that can be checked experimentally.

Intriguingly, the CMS Collaboration has obtained the first bounds on $\mathrm{Br}(h \to \tau\mu) < 1.51\%$ at 95% C.L., with a hint of a nonzero signal [22]. The best fit branching fraction is $\mathrm{Br}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$. We will show that the strength of this signal is naturally understood if a second source of EWSB is responsible for the muon mass. This means that there is a whole family of NP models that can lead to large flavor-violating Higgs decays. We also extend this possibility to the quark sector.

Let us first discuss $h \to \tau\mu$ in models in which the Higgs is the only source of EWSB. In an effective field theory, in which the NP particles are integrated out, the Higgs-lepton couplings are [8,18]

$$-\mathcal{L}_{\mathrm{Y}} = \lambda_{ij}(\bar{\ell}^i_L e^j_R)H + \frac{\lambda'_{ij}}{\Lambda^2}(\bar{\ell}^i_L e^j_R)H(H^\dagger H) + \mathrm{H.c.}, \quad (1)$$

where Λ is the NP scale, and we have kept the two leading terms. In Fig. 1(a) the two operators are denoted with a blob corresponding to the exchange of NP states. For example, the latter could be vectorlike leptons of mass Λ which mix with the SM leptons; see Fig. 2(a). [Note that if the only NP states are scalars, then (1) implies the presence of additional EWSB VEVs [23]].

A misalignment of λ_{ij} and λ'_{ij} in flavor space leads to off-diagonal Higgs Yukawa couplings in the mass basis. Using the normalization in [10], we find

$$Y_{\tau\mu} = \frac{v_W^2}{\sqrt{2}\Lambda^2}\langle\tau_L|\lambda'|\mu_R\rangle, \quad (2)$$

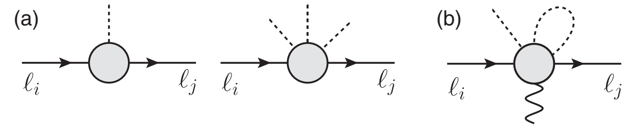

FIG. 1. Contributions to the lepton mass matrix and Yukawa interactions (a) and the electromagnetic dipole (b).

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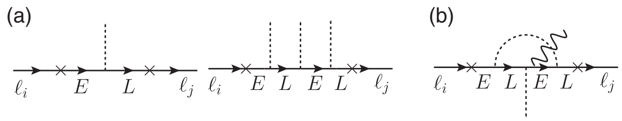

FIG. 2. A realization of Fig. 1 with vectorlike leptons.

and similarly for $Y_{\mu\tau}$, with the Higgs VEV $v_W = 246$ GeV. The CMS measurement [22] gives

$$\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} = (2.6 \pm 0.6) \times 10^{-3}. \quad (3)$$

In the blobs of Fig. 1 at least one NP particle needs to carry electromagnetic charge. Thus, the electromagnetic dipole operators

$$\mathcal{L}_{\text{eff}} = c_{L,R} m_\tau \frac{e}{8\pi^2} (\bar{\mu}_{R,L} \sigma^{\mu\nu} \tau_{L,R}) F_{\mu\nu} \quad (4)$$

are also generated via photon emission from intermediate NP states. Estimating the amplitude in Fig. 1(b) using naïve dimensional analysis (NDA) gives

$$c_L \sim \frac{v_W}{\sqrt{2} m_\tau \Lambda^2} \langle \tau_L | \lambda' | \mu_R \rangle = \frac{Y_{\tau\mu}}{m_\tau v_W}, \quad (5)$$

and similarly for c_R. The bound $\text{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$ (90% C.L.) [24] implies

$$\sqrt{|c_L|^2 + |c_R|^2} < (3.8 \text{ TeV})^{-2}. \quad (6)$$

Comparing with (5), and taking $Y_{\tau\mu} \sim Y_{\mu\tau}$, yields

$$\sqrt{|c_L|^2 + |c_R|^2} \sim \left(\frac{Y_{\tau\mu}}{2.2 \times 10^{-5}} \right) (3.8 \text{ TeV})^{-2}, \quad (7)$$

which generically excludes the observed $h \to \tau\mu$ rate by 4 orders of magnitude [see (3)], as observed in the vectorlike lepton case [18,25]. We conclude that the observed $h \to \tau\mu$ rate can only be explained if either (i) $\tau \to \mu\gamma$ is suppressed by apparently fine-tuned cancellations or (ii) the Higgs is not the only source of EWSB.

Specifically, we will show that the observed $h \to \tau\mu$ rate can be explained in models in which the lepton mass matrix is of the form

$$\mathcal{M}^\ell = \mathcal{M}_0^\ell + \Delta\mathcal{M}^\ell, \quad (8)$$

where a rank 1 matrix $\mathcal{M}_0^\ell$ is due to the VEV of a scalar ϕ (the primary component of the Higgs) and accounts for the bulk of m_τ. The matrix $\Delta\mathcal{M}_\ell$ is due to an additional source of EWSB, can be rank 2 or 3, and accounts for m_e and m_μ. We first focus on the second and third generations. We choose the flavor basis in which $(\mathcal{M}_0^\ell)_{33} \sim m_\tau$ is the only nonzero entry of $\mathcal{M}_0^\ell$, so that generically

$$(\Delta\mathcal{M}^\ell)_{ij} = \mathcal{O}(m_\mu), \qquad i,j = 2,3. \quad (9)$$

The flavor-violating Yukawa couplings are given by

$$v_W Y_{\mu\tau} = -R_Y (\Delta\mathcal{M}^\ell)_{\mu\tau}, \quad (10)$$

and similarly for $Y_{\tau\mu}$. Here $(\Delta\mathcal{M}^\ell)_{\mu\tau} \equiv \langle \mu_L | \Delta\mathcal{M}^\ell | \tau_R \rangle$, while R_Y only depends on the details of the EWSB sector. Taking $(\Delta\mathcal{M}^\ell)_{\mu\tau} \sim (\Delta\mathcal{M}^\ell)_{\tau\mu}$ and $R_Y \sim 1$, the $h \to \tau\mu$ rate (3) corresponds to $(\Delta\mathcal{M}^\ell)_{\mu\tau} \sim (0.45 \pm 0.10)$ GeV, consistent with (9).

If there is more than one contribution to $\mathcal{M}^l$, the $\tau \to \mu\gamma$ constraint is easily satisfied. For instance, if $\Delta\mathcal{M}^\ell$ originates from a radiative or new strong interaction form factor at a NP scale Λ, the dipole operator coefficients (4) generically scale as

$$c_{L,R} \sim \frac{(\Delta\mathcal{M}^\ell)_{\mu\tau,\tau\mu}}{\Lambda^2} \frac{8\pi^2}{m_\tau} \sim \frac{Y_{\tau\mu,\mu\tau}}{m_\tau v_W} \frac{8\pi^2 v_W^2}{\Lambda^2}. \quad (11)$$

Compared to (5), there is an extra factor $8\pi^2 v_W^2/\Lambda^2$. Thus, consistency with $\tau \to \mu\gamma$ can always be achieved for sufficiently large $\Lambda \geq \mathcal{O}(10)$ TeV.

We also consider the analog of (8)–(10) for quarks with the same two sources of EWSB and, therefore, with the same R_Y. It is natural to consider $\Delta\mathcal{M}_{ij}^{u,d} = \mathcal{O}(m_{c,s})$ for $i,j = 2$, 3. Generation of m_c, m_s and V_{cb} then implies

$$(\Delta\mathcal{M}^{u,d})_{22} \approx m_{c,s}, \qquad (\Delta\mathcal{M}^d)_{23} \approx V_{cb} m_b, \quad (12)$$

and $R_Y^2 \Delta\mathcal{M}_{32}^d \lesssim V_{cb} m_b/6$ from the bound on the (Higgs exchange) B_s mixing operator $(\bar{b}_R s_L)(\bar{b}_L s_R)$ [26].

An example of a model that can produce the structure in (8) and the corresponding one in the quark sector is a two Higgs doublet model (2HDM). (In previous 2HDM studies of the $h \to \tau\mu$ signal, m_μ was due to the Higgs VEV [14,15,17,20,23]). The Higgs doublets Φ and Φ' contain the neutral scalars ϕ and ϕ', with VEVs v and v', respectively, where $v_W^2 = v^2 + v'^2$. The field ϕ has a Yukawa coupling $\phi \bar{\ell}_L^3 e_R^3$, whereas ϕ' has couplings to all three families, consistent with (9). Note that a hierarchy in the VEVs, $v \gg v'$, can help explain the mass ratio m_μ/m_τ. The Yukawa coupling structure can, for instance, follow from a symmetry which is horizontal or which distinguishes between new vectorlike leptons and the SM ones [27,28]. The two Higgs doublets would transform differently, equivalent to a Peccei-Quinn (PQ) symmetry that is softly broken by the $m^2 \phi\phi'$ term, as required by vacuum alignment.

The off-diagonal Higgs Yukawa couplings satisfy (10), with R_Y given by

$$R_Y = R_{\alpha\beta} \equiv 2\cos(\alpha - \beta)/\sin 2\beta. \quad (13)$$

Here, the ratio of VEVs is defined as $\tan\beta = v/v'$, and the mixing of ϕ and ϕ' yields the light and heavy Higgs mass

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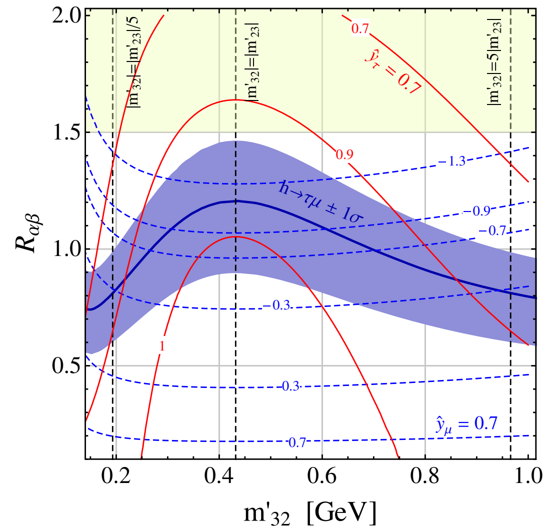

FIG. 3. The region favored by the measurement of $\mathrm{Br}(h \to \tau\mu)$ at the 1σ level (in blue). The dashed vertical lines correspond to $|m'_{32}/m'_{32}| = 1/5, 1, 5$. Contours of $\hat{y}_\mu$ (blue) and $\hat{y}_\tau$ (red) are shown for $\tan\beta = 2$. The yellow region is in conflict with the measurement of the hZZ coupling, for $\tan\beta = 2$.

eigenstates $h = \phi\cos\alpha - \phi'\sin\alpha$, $H = \phi\sin\alpha + \phi'\cos\alpha$. The reduced flavor diagonal Yukawa couplings $\hat{y}_a \equiv Y_{aa}/Y_{aa}^{\mathrm{SM}}$ are given by

$$\hat{y}_a = \cos\alpha/\sin\beta - R_Y(\Delta\mathcal{M}^\ell)_{aa}/m_a, \qquad a = \mu, \tau, \quad (14)$$

valid in the phase convention $m_a \equiv (\mathcal{M}^\ell)_{aa} > 0$.

The 2HDM with tree-level Yukawa couplings provides an exception to the scaling in (11). It satisfies the bound from $\tau \to \mu\gamma$ due to an additional y_τ insertion compared to (5) and heavy Higgs mass suppression [7]. Variations in which the ϕ' Yukawa couplings are radiatively induced would possess the scaling in (11).

Horizontal symmetries may imply that certain ϕ' Yukawa couplings vanish. For example, the charges of a global $U(1)$ symmetry, or a simple Z_3 in the two-generation case, can be chosen such that $\Delta\mathcal{M}^\ell$ only has off-diagonal nonzero entries, m'_{23} and m'_{32}. We refer to this example as the "horizontal" case. We also consider a "generic" case, in which all m'_{ij} can be nonzero.

In the horizontal case, two of the entries in $\mathcal{M}^\ell$ are fixed by m_μ and m_τ, leaving one free parameter, taken to be m'_{32}. The Higgs couplings are fixed by m'_{32} and the angles α, β. Figure 3 shows the region in the $m'_{32} - R_{\alpha\beta}$ plane favored by the CMS result in (3). (A similar range of $R_{\alpha\beta}$ is spanned in the generic case.) The Higgs coupling to weak gauge bosons (g_{hVV}) is modified by a factor $\sin(\beta - \alpha)$. For $R_{\alpha\beta} > 1.5$ and $\tan\beta = 2$, the shift satisfies $|\delta g_{hVV}/g_{hVV}^{\mathrm{SM}}| \gtrsim 20\%$, in conflict with Higgs data. For larger $\tan\beta$, this constraint on $R_{\alpha\beta}$ is weakened.

From Fig. 3, the CMS result requires $R_{\alpha\beta} = \mathcal{O}(1)$, versus the decoupling limit $R_{\alpha\beta} \to 0$. Expanding in v_W^2/m_A^2 and $1/\tan\beta$, with A the neutral pseudoscalar,

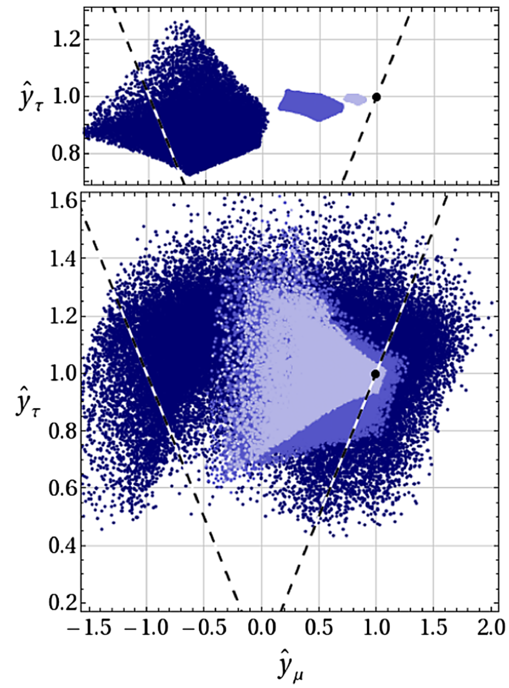

FIG. 4. The reduced Higgs couplings $\hat{y}_\mu$ and $\hat{y}_\tau$ for the horizontal case (top panel), generic case (bottom panel), and SM (black dot). Dark blue, blue and light blue regions reproduce the CMS $\mathrm{Br}(h \to \tau\mu)$ measurement, 1/3 of it and 1/10 of it, respectively, at the 1σ level. The dashed lines satisfy $\hat{y}_\mu/\hat{y}_\tau = \pm 1$.

$$R_{\alpha\beta} \simeq v_W^2/m_A^2 \times (\lambda_3 + \lambda_4 + \cdots) \qquad (15)$$

in the PQ symmetric limit $\lambda_{5,6,7} = 0$ (we use the notation of [29] for the quartic scalar couplings, λ_i). The value $R_{\alpha\beta} \sim 1$ can be obtained with $m_A \sim 500$ GeV and $\lambda_3 \sim \lambda_4 \sim 2$. Such couplings are compatible with electroweak precision constraints and do not develop Landau poles below $\mathcal{O}(30)$ TeV. For smaller $\lambda_{3,4}$ the poles can be pushed beyond M_{GUT} while maintaining $R_{\alpha\beta} \sim 1$, if $\lambda_7 \neq 0$ due to PQ symmetry breaking. In that case, at large $\tan\beta$, $\Delta R_{\alpha\beta} \sim v_W^2/m_A^2 \times (\lambda_7 \tan\beta)$, which could originate, e.g., from a dimension 5 coupling $|\phi|^2\phi\phi' S$ to a PQ charged singlet scalar S, as in the next-to-minimal supersymmetric Standard Model.

Observable $h \to \tau\mu$ is correlated with significant deviations of the flavor diagonal couplings from their SM values, as can already be seen in Fig. 3. Figure 4 shows $\hat{y}_\mu$ versus $\hat{y}_\tau$ for horizontal and generic parameter scans. We take $1/5 < |m'_{32}/m'_{23}| < 5$ in the horizontal case (corresponding to 0.2 GeV $\lesssim m'_{32} \lesssim$ 0.95 GeV in Fig. 3), and $|(\Delta\mathcal{M}^\ell)_{ij}| < 5m_\mu$ for all entries in the generic case. Both scans allow $\lambda_{3,4} \leq 2$, $m_A \geq 400$ GeV, $|\delta g_{hVV}/g_{hVV}^{\mathrm{SM}}| \leq 20\%$, and a heavy Higgs production cross section below 10% of a SM Higgs with the same mass, to be consistent with heavy scalar direct search bounds.

In the horizontal case, the CMS result implies a negative $\hat{y}_\mu$, with $|\hat{y}_\mu|$ typically well below 1, and $|\hat{y}_\tau - 1| \lesssim 25\%$.

The deviations tend to be larger in the generic case. The ratios $|\hat{y}_\mu| < 1$ and $|\hat{y}_\mu/\hat{y}_\tau| < 1$ (versus $\hat{y}_\mu/\hat{y}_\tau \approx 1$ in the type-II 2HDM) are favored in the current, as well as hypothetical future scenarios with a 3× or 10× smaller $h \to \tau\mu$ rate (and scaled 1σ errors).

If the quark Yukawa coupling structure in the 2HDM is analogous to (8), with v' yielding (12), then the off-diagonal quark couplings satisfy $Y_{ct,tc} = \mathcal{O}(m_c/v_W)$, $Y_{bs} \ll Y_{sb} \approx 5\times 10^{-4} R_Y$; see (12) and below. There are new contributions to $B_s \to \mu\mu$, with A exchange being the largest [27]. In the horizontal case, the $\mathrm{Br}(B_s \to \mu\mu)$ measurement [30] constrains $\tan\beta$, e.g., $\tan\beta \lesssim 7$ for $m_A \simeq 500$ GeV. In the generic case much larger values of $\tan\beta$ are allowed. The $B_s \to \mu\mu$ bound has been imposed in Fig. 4. Roughly 80% of the points do not require tuned cancelations in m_μ and $B_s \to \mu\mu$. From (14), the diagonal couplings satisfy $\hat{y}_{c,s} = \cos\alpha/\sin\beta - R_Y$ and $\hat{y}_{t,b} = \cos\alpha/\sin\beta$, up to $\mathcal{O}(m_{c,s}/m_{t,b})$. Thus, while $\hat{y}_{t,b}$ receive modest corrections $\leq 20\%$, $\hat{y}_{c,s}$ tend to be $\mathcal{O}(1)$ suppressed and could even vanish in tuned regions of parameter space. This possibility, given a new source of light quark masses, has been mentioned in [31].

In our next illustration of (8), $\Delta\mathcal{M}_\ell$ is due to technicolor (TC) strong dynamics. The Higgs is a mixture of ϕ and a composite heavy scalar, σ_{TC}. As in the 2HDM, in addition to the heavy Higgs state (H) there is a charged scalar and a neutral pseudoscalar (A) (both also partially composite). The framework is bosonic technicolor (BTC) [32–40], motivated by improved naturalness of EWSB in supersymmetric models. For simplicity, we consider the non-supersymmetric case. We add to the SM a weak doublet and two weak singlet technifermions, $T_R = (U_R, D_R)^T$ and D_L, U_L, and a technicolored scalar [41–43], ξ, all transforming in the fundamental of the confining TC gauge group, e.g., $SU(2)_{\mathrm{TC}}$. TC confinement yields the $SU(2)_L$-breaking condensates $\langle\bar{D}D\rangle, \langle\bar{U}U\rangle$ at a scale $\Lambda_{\mathrm{TC}} \sim 4\pi f_{\mathrm{TC}}$, where f_{TC} is the technipion decay constant. The W and Z masses receive contributions from TC and the Higgs, so that $v_W^2 \simeq f_{\mathrm{TC}}^2 + v^2$, where $\langle\phi\rangle = v$ is a Higgs VEV. The Higgs and precision electroweak phenomenology is viable if $f_{\mathrm{TC}} \lesssim 80$ GeV [40,44], or $\tan\beta \equiv v/f_{\mathrm{TC}} \gtrsim 3$.

The effective operators

$$\frac{h_i^\ell h_j^{e\dagger}}{m_\xi^2}\bar{\ell}_L^i T_R \bar{D}_L e_R^j + \mathrm{H.c.} \tag{16}$$

follow from integrating out the ξ field in the Yukawa couplings $h_i^\ell \xi\bar{\ell}_L^i T_R + h_i^{e\dagger}\xi^*\bar{D}_L e_R^i$. The TC condensates thus yield a rank 1 contribution to $\Delta\mathcal{M}^\ell$. Employing a leading-order chiral Lagrangian, we obtain the lepton masses and dipole coefficients [27]

$$(\Delta\mathcal{M}^\ell)_{ij} = \eta\kappa\frac{4\pi f_{\mathrm{TC}}^3}{2m_\xi^2}h_i^\ell h_j^{e\dagger}; \qquad \frac{c_L}{8\pi^2} = Q_\xi\frac{(\Delta\mathcal{M}^\ell)_{\tau\mu}}{2m_\xi^2 m_\tau}, \tag{17}$$

and similarly for c_R, where $Q_\xi = 1/2$ is the ξ electric charge, $\kappa \sim 1.5$ based on $1/N_c$ scaling from $n_f = 2$ lattice QCD [45], and η accounts for renormalization-group running between $\mu \sim m_\xi$ and $\mu \sim \Lambda_{\mathrm{TC}}$. Given the central value (less 1σ) of the $h \to \tau\mu$ measurement, consistency with the $\tau \to \mu\gamma$ bound requires $\sqrt{R_Y}m_\xi \gtrsim 10(8.7)$ TeV.

The chiral Lagrangian yields $R_Y > \cos\alpha/\sin\beta$ to all orders in the chiral expansion [27], where α is the $\phi - \sigma_{\mathrm{TC}}$ mixing angle. Given that $\cos\alpha \approx 1$ (due to the relatively large σ_{TC} mass) and $\sin\beta = v/v_W \approx 1$, $R_Y > 1$ to good approximation. Using NDA, we obtain $R_Y - 1 \sim 0.2$, with large uncertainty due the poorly known mass and couplings of the σ_{TC}.

Numerical examples consistent with the $\tau \to \mu\gamma$ bound are easily found. For instance, for $h^\ell = h^e$, the CMS result (less 1σ) is obtained for $h_3 \approx 2.1(1.5)$ and $h_2 \approx 0.6(0.6)$ at the matching scale $\mu \sim m_\xi$. Alternatively, for $h_3^\ell = 0$, the signal (less 1σ) is obtained if $h_2^\ell h_2^e \approx 0.6(0.4)$ and $h_2^\ell h_3^e \approx 2.5(1.5)$. In these examples $R_Y = 1.3$, $f_{\mathrm{TC}} = 80$ GeV, $\eta \sim 3$ based on two loop estimates in α_{TC}, and $m_\xi \approx 8.8(7.6)$ TeV, yielding $\mathrm{Br}(\tau \to \mu\gamma)$ at the bound.

The flavor diagonal couplings generically show large deviations from the SM predictions. In the above examples, $\hat{y}_\mu$ is negative with magnitude ranging from ≈0.2 to 0.9, $\hat{y}_\tau \approx 0.9$–1.6, and $|\hat{y}_\mu/\hat{y}_\tau| \approx (0.2$–$0.6)$, well below the SM and type-II 2HDM ratio.

We extend (8) to the quark sector via the colored techniscalar ω with couplings to the quark doublets (h^q) and quark singlets ($h^{u,d}$) analogous to h^ℓ and h^e, respectively [27]. Rank 1 $\Delta\mathcal{M}^{u,d}$ follow in analogy with (16) and (17). Consistency with (12) and with the bound on $\mathrm{Br}(b \to s\gamma)$ requires a scale $m_\omega \gtrsim 5$ TeV, similar to the $\tau \to \mu\gamma$ bounds on m_ξ. In turn, the quark masses and mixings can be obtained with all $h_i^{u,d} \lesssim 1$. The flavor diagonal Yukawa couplings satisfy $\hat{y}_{c,s} \approx 1 - R_Y$ and $\hat{y}_{t,b} \approx 1$, given $\cos\alpha/\sin\beta \approx 1$; see (14).

Our general framework (8) readily extends to three generations [27]. For instance, in the flavor basis of (9), it is natural that $(\Delta\mathcal{M}^\ell)_{1i,i1} = \mathcal{O}(m_e)$. The couplings $Y_{ex,xe}$ ($x = \mu, \tau$) then yield Higgs mediated $\mu \to e\gamma$ rates below the current bound. In the quark sector, with $(\Delta\mathcal{M}^{u,d})_{1i,i1} = \mathcal{O}(m_{u,d})$, consistency of the Higgs mediated flavor-changing neutral currents, e.g., ϵ_K [26], with θ_c, V_{ub} requires $(\Delta\mathcal{M}^d)_{ji} \lesssim (\Delta\mathcal{M}^d)_{ij}/10$ ($[ij] = 13, 23$). These relations could result from horizontal symmetries which address the fermion mass and mixing hierarchies. It is noteworthy that $s \to dg$ dipole operators, with scaling analogous to (11), could play a role in ϵ'/ϵ, bridging the gap between experiment [46–48] and the SM prediction [49,50].

A novel Yukawa coupling sum rule holds if $\Delta\mathcal{M}^\ell$, like $\mathcal{M}_0^\ell$, is rank 1 when neglecting the first generation. This is the case in the BTC example and could be realized more generally in the "rank 1" approach to the fermion mass and mixing hierarchies; see, e.g., [51–58]. The sum rule is given by

$$\hat{y}_\mu \hat{y}_\tau - \hat{y}_{\tau\mu}\hat{y}_{\mu\tau} = \hat{y}_{t,b}(\hat{y}_\mu + \hat{y}_\tau - \hat{y}_{t,b}), \tag{18}$$

where $\hat{y}_{ij} \equiv Y_{ij}/Y_{ii}^{\rm SM}$, and we have substituted $\cos\alpha/\sin\beta \to \hat{y}_{t(b)}$; see (14). It holds up to corrections of $\mathcal{O}(m_c/m_t, m_s/m_b, m_e/m_\mu)$. Remarkably, the sum rule offers a precision test of the rank 1 hypotheses, potentially validating our framework in this case. If $\Delta\mathcal{M}^\ell$ has full rank, (18) holds up to $\mathcal{O}(m_\mu/m_\tau)$ corrections, which can be sizable for large $Y_{\tau\mu,\mu\tau}$ as in (3) [27].

Generation of the CMS $h \to \tau\mu$ result and V_{cb} (12) in our framework can lead to a sizable $B_s \to \tau\mu$ rate via h, A and H tree-level exchanges. The A and H contributions grow as $(\tan\beta)^4$, whereas the A contribution to ${\rm Br}(B_s \to \mu\mu)$ grows as $(\tan\beta)^2$ and tends to interfere destructively with the SM. Thus, large values of the ratio $R_{\tau\mu} \equiv {\rm Br}(B_s \to \tau\mu)/{\rm Br}(B_s \to \mu\mu)_{\rm SM}$ are possible, without tuned cancellations in ${\rm Br}(B_s \to \mu\mu)$. In our 2HDM and BTC examples, at moderate $\tan\beta \lesssim 4$ and for $m_A, m_H \gtrsim 400$ GeV, $R_{\tau\mu} \lesssim 10$ correlates with $\lesssim 50\%$ suppression of ${\rm Br}(B_s \to \mu\mu)$. However, for $\tan\beta \sim 6$–10, easily realized in the 2HDM, much larger $R_{\tau\mu}$ are possible: in the generic (horizontal) case, $R_{\tau\mu}$ can be as large as ∼200 (∼50) accompanied by ∼50% suppression (∼20% enhancement) of ${\rm Br}(B_s \to \mu\mu)$. We estimate that ${\rm Br}(B \to K^{(*)}\mu\tau)$ can be as large as $\mathcal{O}(10^{-7})$ in such cases. The above framework could lead to potentially observable $t \to hc$ decays [27] if, e.g., V_{cb} receives a sizable contribution via $(\Delta\mathcal{M}^u)_{23} = O(V_{cb}m_t)$.

In summary, an observable $h \to \tau\mu$ signal is naturally realized in models where the first- and second-generation masses and Cabibbo-Kobayashi-Maskawa mixing are due to a second source of EWSB. We have focused on the second and third generations, illustrating our framework with a two Higgs doublet model and an example with a partially composite Higgs, where EWSB is triggered by new strong interactions. The flavor diagonal Higgs Yukawa couplings typically show large deviations from the SM. Finally, (pseudo)scalar exchanges can yield ${\rm Br}(B_s \to \tau\mu) \lesssim$ few $\times 10^{-7}$ and significant shifts in ${\rm Br}(B_s \to \mu\mu)$, both potentially detectable at the LHC.

ACKNOWLEDGMENTS

The work of A. L. K. is supported by DOE Grant No. DE-SC0011784. J. Z. is supported in part by the U.S. National Science Foundation under CAREER Grant No. PHY-1151392. The research of L. S. leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Program (FP/2007-2013)/ERC Grant Agreement No. 279972 "NPFlavour." The research of W. A. and S. G. at Perimeter Institute is supported by the Government of Canada through Industry Canada and by the Province of Ontario through the Ministry of Economic Development and Innovation. We would like to thank Radovan Dermisek, Jernej Kamenik and Stefan Pokorski for discussions. We acknowledge support by the Munich Institute for Astro- and Particle Physics (MIAPP) of the DFG cluster of excellence "Origin and Structure of the Universe."

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