Uncovering Mass Generation Through Higgs Flavor Violation

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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 1st and 2nd generation quark masses and CKM 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 $m_\mu$ 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 $B_s \to \mu\mu$ decay rate, which could be $\mathcal{O}(100)$ times larger than the SM $B_s \to \mu\mu$ decay rate.

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 $tth$ cross section at the LHC. Present measurements indicate that the Higgs is at least partially responsible for the masses of the 3rd 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 source of EWSB is responsible for the muon mass. There is no evidence for 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 1st and 2nd generation quark masses and CKM 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 $m_\mu$ 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 $B_s \to \mu\mu$ decay rate, which could be $\mathcal{O}(100)$ times larger than the SM $B_s \to \mu\mu$ decay rate.

where $\Lambda$ 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 $\Lambda$ 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 $\lambda_{ij}$ and $\lambda'_{ij}$ in flavor space leads to off-diagonal Higgs Yukawa couplings in the mass basis. Using the normalization in [10], we find

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

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

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

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

$$\mathcal{L}_{\text{eff}} = c_{L,R} m_\tau \frac{e}{8\pi^2} \langle \tilde{\tau}_{L,R} \sigma_{\mu\nu} \tau_{L,R} \rangle F_{\mu\nu},$$

are relevant. In order to comply with the data, large values of $|\lambda_{ij}|$, $|\lambda'_{ij}|$, and $m_\tau$ are required. The latter can be accommodated by adding a technicolor sector, while the other bounds require large NP vevs. These are precisely the conditions assumed in [23]. A possible realization of these would be a composite Higgs model with a rank-1 mass matrix contribution generating the muon mass, and 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 $B_s \to \mu\mu$ decay rate, which could be $\mathcal{O}(100)$ times larger than the SM $B_s \to \mu\mu$ decay rate.

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

Figure 2: A realization of Fig. 1 with vectorlike leptons.
are also generated via photon emission from intermediate NP states. Estimating the amplitude in Fig. 1 b) using naive dimensional analysis (NDA) gives
\[
c_L \sim \frac{v_W}{\sqrt{2} m_{\tau} \Lambda^2} \langle \tau L \mid \lambda' \mid \mu R \rangle = \frac{Y_{\tau \mu}}{m_{\tau} v_W},
\]
and similarly for $c_R$. The bound $\text{Br}(\tau \rightarrow \mu \gamma) < 4.4 \cdot 10^{-8}$ \cite{24} implies
\[
\sqrt{|c_L|^2 + |c_R|^2} < (3.8 \text{ TeV})^{-2}.
\]
Comparing with (5), and taking $Y_{\tau \mu} \sim Y_{\mu \tau}$, yields
\[
\sqrt{|c_L|^2 + |c_R|^2} \approx \frac{Y_{\tau \mu}}{2.2 \cdot 10^{-5}} (3.8 \text{ TeV})^{-2},
\]
which generically excludes the observed $h \rightarrow \tau \mu$ rate by four orders of magnitude (see (3)), as observed in the vectorlike lepton case \cite{18, 25}. We conclude that the observed $h \rightarrow \tau \mu$ rate can only be explained if either (i) $\tau \rightarrow \mu \gamma$ 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 $h \rightarrow \tau \mu$ rate can be explained in models in which the lepton mass matrix is of the form
\[
\mathcal{M}_e = \mathcal{M}_0^e + \Delta \mathcal{M}_e,
\]
where a rank 1 matrix $\mathcal{M}_0^e$ is due to the vev of a scalar $\phi$ (the primary component of the Higgs), and accounts for the bulk of $m_\tau$. The matrix $\Delta \mathcal{M}_e$ is due to an additional source of EWSB, can be rank 2 or 3, and accounts for $m_\tau$ and $m_\mu$. We first focus on the 2nd and 3rd generations. We choose the flavor basis in which $(\mathcal{M}_0^\ell)_{33} \sim m_\tau$ is the only non-zero entry of $\mathcal{M}_0^\ell$, so that generically
\[
(\Delta \mathcal{M}_e)_{ij} = \mathcal{O}(m_\mu), \quad i,j = 2,3.
\]
The flavor violating Yukawa couplings are given by
\[
v_W Y_{\tau \mu} = -R_Y (\Delta \mathcal{M}_e)_{\mu \tau},
\]
and similarly for $Y_{\tau \mu}$. Here $(\Delta \mathcal{M}_e)_{\mu \tau} \equiv \langle \mu L | \Delta \mathcal{M}_e | \tau R \rangle$, while $R_Y$ only depends on the details of the EWSB sector. Taking $(\Delta \mathcal{M}_e)_{\mu \tau} \sim (\Delta \mathcal{M}_e)_{\tau \mu}$ and $R_Y \sim 1$, the $h \rightarrow \tau \mu$ rate (3) corresponds to $(\Delta \mathcal{M}_e)_{\mu \tau} \sim (0.45 \pm 0.10) \text{ GeV}$, consistent with (9).

If there is more than one contribution to $\Delta \mathcal{M}_e$ the $\tau \rightarrow \mu \gamma$ constraint is easily satisfied. For instance, if $\Delta \mathcal{M}_e$ originates from a radiative or new strong interaction form factor at a NP scale $\Lambda$ the dipole operator coefficients (4) generically scale as
\[
c_{L,R} \sim \frac{(\Delta \mathcal{M}_e)_{\mu \tau, \tau \mu}}{\Lambda^2} \frac{8\pi^2}{m_{\tau}} \sim \frac{8\pi^2 v_W^2}{\Lambda^2}.
\]
Compared to (5), there is an extra factor $8\pi^2 v_W^2 / \Lambda^2$. Thus, consistency with $\tau \rightarrow \mu \gamma$ can always be achieved for sufficiently large $\Lambda \geq \mathcal{O}(10) \text{ TeV}$.

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 $\Delta M_{ij}^{u,d} = \mathcal{O}(m_s, s)$ for $i,j = 2,3$. Generation of $m_e$, $m_s$ and $V_{cb}$ then implies
\[
(\Delta M_{u,d})_{22} \approx m_c, s, \quad (\Delta M_{d})_{23} \approx V_{cb} m_b,
\]
and $R_Y (\Delta M_{d})_{32} \lesssim V_{cb} m_b / 6$ from the bound on the (Higgs exchange) $B_s$ mixing operator ($B_R S_L \langle \bar{b}_R s_L \rangle$) \cite{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 $h \rightarrow \tau \mu$ signal, $m_\mu$ was due to the Higgs vev \cite{14, 15, 17, 20, 23}. The Higgs doublets $\Phi$ and $\Phi'$ contain the neutral scalars $\phi$ and $\phi'$, with vevs $v$ and $v'$, respectively, where $v^2 = v^2 + v'^2$. The field $\phi$ has a Yukawa coupling $\phi \bar{\ell}_R \ell_R$, whereas $\phi'$ 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 $m_\mu / m_\tau$. The Yukawa coupling structure can, for instance, follow from a symmetry which is horizontal, or which distinguishes between new vector like leptons and the SM ones \cite{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
\[
R_Y = R_{\alpha \beta} = 2 \cos(\alpha - \beta) / \sin 2\beta.
\]
Here, the ratio of vevs is defined as $\tan \beta = v / v'$, and the mixing of $\phi$ and $\phi'$ yields the light and heavy Higgs mass eigenstates $h = \phi \cos \alpha - \phi' \sin \alpha$, $H = \phi \sin \alpha + \phi' \cos \alpha$. The reduced flavor diagonal Yukawa couplings $\tilde{y}_a = Y_{aa} / Y_{33}$ are given by
\[
\tilde{y}_a = \cos \alpha / \sin \beta - R_Y (\Delta M_{e})_{aa} / m_a, \quad a = \mu, \tau,
\]
valid in the phase convention $m_a = (\mathcal{M}_e)_{aa} > 0$.

The 2HDM with tree level Yukawa couplings provides an exception to the scaling in (11). It satisfies the bound from $\tau \rightarrow \mu \gamma$ due to an additional $y_\tau$ insertion compared to (5) and heavy Higgs mass supression \cite{7}. Variations in which the $\phi'$ Yukawa couplings are radiatively induced would possess the scaling in (11).

Horizontal symmetries may imply that certain $\phi'$ 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 $\Delta \mathcal{M}_e$ only has off-diagonal nonzero entries, $m_{33}$ 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 non-zero.

In the horizontal case, two of the entries in $\mathcal{M}_e$ are fixed by $m_\mu$ and $m_\tau$, leaving one free parameter, taken to be $m_{32}$. The Higgs couplings are fixed by $m_{32}$ and the angles $\alpha, \beta$. Fig. 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 $|\delta g_{hVV}/g_{hVV}^{SM}| \gtrsim 20\%$, 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,

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

(15)

in the PQ symmetric limit $\lambda_{5,6,7} = 0$ (we use the notation of [29] for the quartic scalar couplings, $\lambda_i$). 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 $O(30)$ TeV. For smaller $\lambda_{3,4}$ the poles can be pushed beyond $M_{\text{GUT}}$ 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 $|\phi|^2 \phi S$ to a PQ charged singlet scalar $S$, as in the NMSSM.

 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. Fig. 4 shows $\tilde{y}_\mu$ vs. $\tilde{y}_\tau$ for “horizontal” and “generic” parameter scans. We take $1/5 < |m_{12}^T/m_{23}^T| < 5$ in the horizontal case (corresponding to 0.2 GeV $\lesssim m_{12}^T \lesssim 0.95$ GeV in Fig. 3), and $|\Delta M_{\ell\ell}^{(T)}| < 5m_{\mu}$ for all entries in the generic case. Both scans allow $\lambda_{3,4} \lesssim 2$, $m_A \gtrsim 400$ GeV, $|\delta g_{hVV}/g_{hVV}^{SM}| \lesssim 20\%$, and a heavy Higgs production cross section below 10% of a SM Higgs with same mass.

Figure 3: The region favored by the measurement of $\text{Br}(h \to \tau\mu)$ at the 1σ level (in blue). The dashed vertical lines correspond to $|m_{12}^T/m_{23}^T| = 1/5, 1, 5$. Contours of $\tilde{y}_\mu$ (blue) and $\tilde{y}_\tau$ (red) are shown for $\tan\beta = 2$. The yellow region is in conflict with the measurement of the $hZZ$ coupling, for $\tan\beta = 2$.

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



to be consistent with heavy scalar direct search bounds.

In the horizontal case, the CMS result implies a negative $\tilde{y}_\mu$, with $|\tilde{y}_\mu|$ typically well below 1, and $|\tilde{y}_\tau - 1| \lesssim 20\%$. The deviations tend to be larger in the generic case. The ratios $|\tilde{y}_\mu| < 1$ and $|\tilde{y}_\mu/\tilde{y}_\tau| < 1$ (vs. $\tilde{y}_\mu/\tilde{y}_\tau \approx 1$ in the type-II 2HDM) are favored in the current, as well as hypothetical future scenarios with a $3 \times$ or $10 \times$ smaller $h \to \tau\mu$ rate (and scaled $1\sigma$ errors).

If the quark Yukawa coupling structure in the 2HDM is analogous to (8), with $v'$ yielding (12), then the off-diagonal Higgs couplings satisfy $Y_{ct,c} = \mathcal{O}(m_c/v')$, $Y_{bs,b} \ll Y_{sb} \approx 5 \cdot 10^{-3}R_Y$, 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 $\text{Br}(B_s \to \mu\mu)$ measurement [30] constrains $\tan\beta$, e.g. $\tan\beta \lesssim 7$ for $m_A \sim 500$ 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 $m_\mu$ and $B_s \to \mu\mu$. From (14), the diagonal couplings satisfy $\hat{y}_{c,s} = \cos\alpha/\sin\beta - R_Y$ and $\hat{y}_{s,b} = \cos\alpha/\sin\beta$, up to $O(m_{c,s}/m_{t,b})$. Thus, while $\hat{y}_{s,b}$ receive modest corrections $\lesssim 20\%$, $\hat{y}_{c,s}$ tend to be $O(1)$ 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), $\Delta M_\ell$ is due to technicolor (TC) strong dynamics. The Higgs is a mixture of $\phi$ and a composite heavy scalar, $\sigma_{TC}$. 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 scalar). 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], $\xi$, all transforming in the fundamental of the technical chiral expansion gauge, e.g., $SU(2)_T$. TC confinement yields the $SU(2)_L$ breaking condensates $\langle D\xi \rangle$, $\langle UU \rangle$ at a scale $\Lambda_{TC} \sim 4\pi f_{TC}$, where $f_{TC}$ is the technipion decay constant. The $W$ and $Z$ masses receive contributions from TC and the Higgs, so that $v_W^2 \simeq f_{TC}^2 + v^2$, where $\langle \phi \rangle = v$ is a Higgs vev. The Higgs and precision electroweak phenomenology is viable if $f_{TC} \lesssim 80$ GeV [40, 44], or $\tan \beta \equiv v/f_{TC} \gtrsim 3$.

The effective operators

$$\frac{h_L^T h_L^\dagger}{m_\xi^2} \frac{f_{TC}}{\xi} T_R D_L e_i^R + \text{h.c.}, \quad (16)$$

follow from integrating out the $\xi$ field in the Yukawa couplings $h_L^T \xi D_L e_i^R + h^\dagger \xi^* D_L e_i^R$. The TC condensates thus yield a rank 1 contribution to $\Delta M^\xi$. Employing a leading order chiral Lagrangian, we obtain the leptonic masses and dipole coefficients [27],

$$(\Delta M^\xi)_{ij} = \eta \kappa \frac{4\pi f_{TC}^4}{2m_\xi^2} h_i^T h_j^\dagger; \quad c_L \frac{4\pi f_{TC}^4}{8\pi^2} = Q_\xi (\Delta M^\xi)^{\tau\mu} \frac{2m_\xi^2}{m_\tau^2}, \quad (17)$$

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

The chiral Lagrangian yields $R_Y \gtrsim \cos \alpha/\sin \beta$ to all orders in the chiral expansion [27], where $\alpha$ is the $\phi - \sigma_{TC}$ mixing angle. Given that $\cos \alpha \approx 1$ (due to the relatively large $\sigma_{TC}$ 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 $\sigma_{TC}$.

Numerical examples consistent with the $\tau \to \mu \gamma$ bound are easily found. For instance, $h' = h^e$, the CMS result (less $1\sigma$) is obtained for $h' \approx 2.1(1.5)$ and $h' \approx 0.6(0.6)$ at the matching scale $\mu \sim m_\xi$. Alternatively, for $h' = h^0$, the signal (less $1\sigma$) is obtained if $h_2 h_2^* \approx 0.6(0.4)$ and $h_3 h_3^* \approx 2.5(1.5)$. In these examples $R_Y = 1.3$, $f_{TC} = 80$ GeV, $\eta \approx 3$ based on two loop estimates in $\alpha_{TC}$, and $m_\tau \approx 88 (7.6)$ TeV, yielding $Br(\tau \to \mu \gamma)$ at the bound.

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

We extend (8) to the quark sector via the colored techniscalar $\omega$ with couplings to the quark doublets ($h^u, d$) and quark singlets ($h^{u, d}$) analogous to $h^t$ and $h^\tau$, respectively [27]. Rank 1 $\Delta M^{u,d}$ follow in analogy with (16), (17). Consistency with (12) and with the bound on $Br(b \to s\tau\nu)$ requires a scale $m_\omega \gtrsim 5$ TeV, similar to the $\tau \to \mu \gamma$ bounds on $m_\xi$. In turn, the quark masses and mixings can be obtained with all $h_i^{u,d} \lesssim 1$. The flavor diagonal Yukawa couplings satisfy $\tilde{y}_{q,i} \approx 1 - R_Y$ and $\tilde{y}_{t,b} \approx 1$, 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 $(\Delta M^{q})_{1i,11} = O(m_e)$. The couplings $Y_{e_x,e_x} (x = \mu, \tau)$ then yield Higgs mediated $\mu \to e\gamma$ rates below the current bound. In the quark sector, with $(\Delta M^{u,d})_{1i,11} = O(m_{u,d})$, consistency of the Higgs mediated FCNC’s, e.g., $\epsilon_K$ [26], with $\epsilon_{\mu}$ requires $(\Delta M^{d})_{ji} \lesssim (\Delta M^{u})_{ji}/10 (|ji| = 13, 23)$. These relations could result from horizontal symmetries which address the fermion mass and mixing hierarchies. It is noteworthy that $s \to d\gamma$ dipole operators, with scaling analogous to (11), could play a role in $\epsilon'/\epsilon$, bridging the gap between experiment [46–48] and the SM prediction [49, 50].

A novel Yukawa coupling sum rule holds if $\Delta M^\xi$, like $M^u_{ii}$, 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

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

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

Generation of the CMS $h \to \tau \mu$ result and $V_{ub}$ (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 $Br(B_s \to \mu \mu)$ grows as $(\tan \beta)^2$ and tends to interfere destructively with the SM. Thus, large values of the ratio $R_{\tau\mu} \equiv Br(B_s \to \tau \mu)/Br(B_s \to \mu \mu)_{SM}$ are possible, without tuned cancelations in $Br(B_s \to \mu \mu)$. 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 $Br(B_s \to \mu \mu)$. However, for $\tan \beta \approx 6 - 10$, 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 $\approx 200 (\sim 50)$ accompanied by $\sim 20\%$ suppression ($\sim 20\%$ enhancement) of $Br(B_s \to \mu \mu)$. We estimate that $Br(B \to K^{(*)} \mu \mu$) can be as large as $O(10^{-7})$ in such cases. The above framework could lead
to potentially observable \( t \to hc \) decays \cite{27} if, e.g., \( V_{cb} \) receives a sizable contribution via \( \Delta M^a \) \cite{21} = \( O(V_{cb} m_t) \).

In summary, an observable \( h \to \tau \mu \) signal is naturally realized in models where the 1st and 2nd generation masses and CKM mixing are due to a second source of EWSB. We have focused on the 2nd and 3rd 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 \( \text{Br}(B_s \to \tau \mu) \lesssim 10^{-7} \) and significant shifts in \( \text{Br}(B_s \to \mu \mu) \), both potentially detectable at the LHC.

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