Higgs LFV in the general Two-Higgs-Doublet model

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Motivation

- CMS reported the BR for $h \to \tau\mu$ to be $BR(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$ a 2.4 $\sigma$ deviation, PLB749(15)

- ATLAS did not see the significant excess, $BR(h \to \tau\mu) < 1.85\%$

- We study the implications on rare tau decays, muon g-2, $Z \to \mu\tau$, etc

<table>
<thead>
<tr>
<th></th>
<th>SR1</th>
<th>SR2</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected limit on $Br(H \to \mu\tau)$ [%]</td>
<td>$1.60^{+0.64}_{-0.45}$</td>
<td>$1.75^{+0.71}_{-0.49}$</td>
<td>$1.24^{+0.50}_{-0.35}$</td>
</tr>
<tr>
<td>Observed limit on $Br(H \to \mu\tau)$ [%]</td>
<td>1.55</td>
<td>3.51</td>
<td>1.85</td>
</tr>
<tr>
<td>Best fit $Br(H \to \mu\tau)$ [%]</td>
<td>$-0.07^{+0.81}_{-0.86}$</td>
<td>$1.94^{+0.92}_{-0.89}$</td>
<td>$0.77\pm0.62$</td>
</tr>
</tbody>
</table>

JHEP1511(15)
What has been done?

- $S_4$ flavor symmetry, Campos et al arXiv:1408.1652
- 2HDM type-III, Sierra et al, arXiv:1409.7690
- DM with minimal FV, Lee & Tandeant arXiv:1410.6803
- Gauged $L_\mu - L_\tau$ in a 2HDM, Crivellin et al arXiv:1501.00993
- Horizontal gauge symmetries, Crivellin et al arXiv:1503.03477
- Hidden scalars, Das & Kundun, arXiv:1504.01125
- MFV, He et al arXiv:1507.02673
- Axion model, Chiang et al arXiv:1507.04354
- Leptoquark, Cheung et al arXiv:1508.01897
- SUSY inverse seesaw, Arganda et al arXiv:1508.04623
- Leptoquark, Baek et al arXiv:1509.07410
- R-parity, Huang & Tang arXiv:1509.08599
- SUSY, Arganda arXiv:1510.04685
- MSSM, Aloni arXiv:1511.00979
- More ....
Why is LFV interesting?

- Flavor changing neutral currents (FCNCs) appear in the SM via the charged weak interactions, $D \bar{D}, K \bar{K}, B_q \bar{B}_q, b \rightarrow s \gamma$, etc

- Most of these processes involve nonperturbative QCD effects; It is difficult to distinguish the new physics from the SM effects due to the QCD uncertainty

- LFV can be induced in the SM and is irrelevant to QCD; but they are tiny, e.g. $\tau \rightarrow \mu \gamma \sim O(10^{-40})$

- Unlike the hadronic cases, if any LFV signal is observed, it is certainly strong evidence for new physics
Higgs LFV in the 2HDM

- Simple extension to the SM by adding a second Higgs doublet; originally proposed for spontaneous CP Violation T.D. Lee PRD8(73); resolution of the strong CP problem Peccei-Quinn PRL38(77)

- Studied well in the literature and classified by several types without FCNCs at tree:

<table>
<thead>
<tr>
<th>Model</th>
<th>$u_R^i$</th>
<th>$d_R^i$</th>
<th>$e_R^i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
</tr>
<tr>
<td>Type II</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
<td>$\Phi_1$</td>
</tr>
<tr>
<td>Lepton-specific</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
</tr>
<tr>
<td>Flipped</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
<td>$\Phi_2$</td>
</tr>
</tbody>
</table>

\[ \mathcal{L}_Y = y_{ij}^1 \bar{\psi}_i \psi_j \Phi_1 + y_{ij}^2 \bar{\psi}_i \psi_j \Phi_2, \]

Branco et al. Phys. Rept 516(12)
Higgs LFV in the general 2HDM (Type-III)

- Higgs doublet of SU(2)

\[ H_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i + i\eta_i)/\sqrt{2} \end{pmatrix} \]

- Scalars:

\[ h = -s_\alpha \phi_1 + c_\alpha \phi_2, \]
\[ H = c_\alpha \phi_1 + s_\alpha \phi_2, \]
\[ H^{\pm}(A) = -s_\beta \phi_1^{\pm}(\eta_1) + c_\beta \phi_2^{\pm}(\eta_2) \]

2 CP-even; 1 CP-odd; 2 charged Higgs \( H^{\pm} \)

\[ \nu = \sqrt{\nu_1^2 + \nu_2^2} \]
\[ s_\alpha = \sin\alpha, c_\alpha = \cos\alpha \]
\[ s_\beta = \sin\beta = \frac{v_1}{\nu}, \]
\[ c_\beta = \cos\beta = \frac{v_2}{\nu} \]
Type-III

- Yukawa sector

\[ -\mathcal{L}_Y = \bar{Q}_L Y_1^u U_R \tilde{H}_1 + \bar{Q}_L Y_2^u U_R \tilde{H}_2 + \bar{Q}_L Y_1^d D_R H_1 + \bar{Q}_L Y_2^d D_R H_2 + \bar{L} Y_1^\ell \ell_R H_1 + \bar{L} Y_2^\ell \ell_R H_2 + h.c., \]

- Fermion mass matrix

\[ M_f = \frac{v}{\sqrt{2}} \left( \cos \beta Y_1^f + \sin \beta Y_2^f \right) \]

- \( Y_1^f \) & \( Y_2^f \) cannot be diagonalized simultaneously; Unless \( Y_1^f \) and \( Y_2^f \) are correlated

\[ Y_1^f \propto Y_2^f : \text{Aligned case, Pich \& Tuzon PRD80(09)} \]

\[ \tilde{Y}_{2(1)}^F = \tilde{I}_F \tilde{Y}_{1(2)}^F \tilde{I}_R \]

- Ahn\&Chen, PLB690(10)

- Chen\&Nomura, PLB749(15)

- Type-III: \( Y_1^\ell, Y_2^\ell \) are independent in the lepton sector; \( Y_1^q, Y_2^q \) are just like type-II

LFV IN 2HDM
Higgs LFV

\[-\mathcal{L}_{Y\phi} = \bar{\ell}_L \epsilon_\phi y^\ell_L \ell_R \phi + \bar{\nu}_L y^{H\pm}_L \ell_R H^+ + h.c.,\]

\[
(y^\ell_h)_{ij} = -\frac{s_\alpha m_i}{c_\beta v} \delta_{ij} + \frac{c_\beta \alpha}{c_\beta} X^\ell_{ij}, \]

\[
(y^\ell_H)_{ij} = \frac{c_\alpha m_i}{c_\beta v} \delta_{ij} - \frac{s_\beta \alpha}{c_\beta} X^\ell_{ij}, \]

\[
(y^\ell_A)_{ij} = -\tan \beta \frac{m_i}{v} \delta_{ij} + \frac{X^\ell_{ij}}{c_\beta}, \]

\[
X^\ell = V^\ell_L \frac{Y^\ell_2}{\sqrt{2}} V^\ell_R \]

Cheng&Sher PRD35 (87)

\[Y^\ell_2 = \text{diag}(y^\ell_1, y^\ell_2, y^\ell_3)\]

\[c_\beta \alpha = \cos(\beta - \alpha)\]

\[s_\beta \alpha = \sin(\beta - \alpha)\]

- Flavor conserving parts \(\propto m_\ell/v\), H and A couplings have \(\tan \beta\) enhancement
- Decoupling limit \(c_\beta \alpha \to 0\), FCNCs at tree still exist in H and A couplings
- Besides the flavor changing, \(X^\ell_{ii}\) also affect the flavor conserving couplings
Scalar potential for 2HD

- If we assume the Yukawa matrix to be hermitian, $V_L^\ell = V_R^\ell$

$$X^\ell = V_L^\ell \frac{Y_2^\ell}{\sqrt{2}} V_R^{\ell\dagger} \quad \rightarrow \quad X_{ij}^\ell = X_{ji}^\ell$$

$$V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c}) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2$$

$$+ \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$

$$+ \left[ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \left( \lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2 \right) \Phi_1^\dagger \Phi_2 + \text{h.c.} \right].$$
Constraints:

Perturbativity: \( \lambda_i < 8\pi \)
\[
\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0, \quad \sqrt{\lambda_1 \lambda_2} + \lambda_3 + \lambda_4 - |\lambda_5| > 0,
\]

Vacuum stability:
\[
2|\lambda_6 + \lambda_7| \leq \frac{1}{2}(\lambda_1 + \lambda_2) + \lambda_3 + \lambda_4 + \lambda_5.
\]

Unitarity: \( \phi_i \phi_j \rightarrow \phi_i \phi_j \)
\[
\delta \rho = (4.0 \pm 2.4) \times 10^{-4}
\]

Oblique parameters: \( S = 0.05 \pm 0.11, T = 0.09 \pm 0.13, U = 0.01 \pm 0.01 \)

\( b \rightarrow s\gamma \rightarrow m_{H^\pm} \geq 480 \text{ GeV} \)

Parameters used for analysis are
\[
\{m_h, m_H, m_A, m_{H^\pm}, v, \tan \beta, \alpha, \lambda_6, \lambda_7\}
\]
and 2 respectively stand for ggF+tth and VBF+Vh, and \( \mu_1, \mu_2 \) are the results in the THDM.

The global \( \chi^2 \)-square is defined by

\[
\chi^2 = \sum f \chi^2_f + \chi^2_{ST},
\]

where \( \chi^2_{ST} \) is the \( \chi^2 \) for S and T parameters; its definition can be obtained from Eq.(24) by using the replacements \( \mu_f \to S_{THDM} \) and \( \mu_f \to T_{THDM} \), and the corresponding values can be determined from Eq. (22).

Besides the bounds from theoretical considerations, Higgs data, and upper limit \( BR(\mu \to 3e) < 1.0 \times 10^{-12} \), the schemes for the setting of parameters in this study are as follows: the masses of SM Higgs and charged Higgs are fixed to be \( m_h = 125 \) GeV and \( m_{H^\pm} = 500 \) GeV, respectively, and the regions of other involved parameters are chosen as:

\[
m_{H,A} \supset [126, 1000] \text{ GeV}, \quad m^2_{12} \supset [-1.0, 1.5] \times 10^5 \text{ GeV}^2,
\]

\[
\tan \beta \supset [0.5, 50], \quad \alpha = [-\pi/2, \pi/2].
\]

Since our purpose is to show the impacts of THDM on LFV, to lower the influence of the quark sector, we set \( X_q \sim 0 \) in the current analysis; i.e., the Yukawa couplings of quarks behave like the type II THDM. The influence of \( X_q \neq 0 \) can be found elsewhere [43]. To understand the small lepton FCNCs, we use the ansatz

\[
X_{\ell ij} = \sqrt{m_i m_j / v} \chi_{\ell ij};
\]

thus, \( \chi_{\ell ij} \) can be on the order of one. Although \( h^{-\ell} + h^{-\ell} \) couplings also contribute to the \( h \to 2\gamma \) process, unless one makes an extreme tuning on \( \chi_{\ell ii} \), their contributions to \( h \to 2\gamma \) are small in the THDM.

We now present the numerical analysis. Combining the theoretical requirements and \( \delta \rho = (4.0 \pm 2.4) \times 10^{-4} \), the allowed ranges of \( \tan \beta \) and \( c_\beta \alpha \) are shown by the yellow dots in Fig. 2, where the scanned regions of Eq. (26) were used. When the measurement of oblique parameters are included, the allowed parameter space is changed slightly, as shown by blue dots in Fig. 2. In both cases, data with 2\( \sigma \) errors are adopted. From the results, we see that the constraint on \( c_\beta \alpha \) is loose and the favorable range for \( \tan \beta \) is \( \tan \beta < 20 \).

To perform the constraints from Higgs data listed in Table I, we use the minimum \( \chi^2 \)-square approach. The best fit is taken at 68\%, 95\% and 99.7\% CLs; that is, the corresponding errors of \( \chi^2 \) are \( \Delta \chi^2 \leq 2, 5, 11.8 \), respectively. With the definitions in Eqs. (24) and (25), we present the allowed values of parameters in Fig. 3(a), where the theoretical requirements, \( \delta \rho \), oblique parameters, and Higgs data are all included. In the plots, blue, green: theoretical requirements + \( \delta \rho \)

Red: Green + oblique parameters

Basically, the constraint on \( \cos(\beta - \alpha) \) is not strong
Constraints: from Higgs measurements

TABLE I: Combined best-fit signal strengths $\hat{\mu}_{ggF+tth}$ and $\hat{\mu}_{VBF+Vh}$ and the associated correlation coefficient $\rho$ for corresponding Higgs decay mode [61, 62].

<table>
<thead>
<tr>
<th>$f$</th>
<th>$\hat{\mu}_{ggF+tth}^f$</th>
<th>$\hat{\mu}_{VBF+Vh}^f$</th>
<th>$\pm 1\hat{\sigma}_{ggF+tth}$</th>
<th>$\pm 1\hat{\sigma}_{VBF+Vh}$</th>
<th>$\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>1.32</td>
<td>0.8</td>
<td>0.38</td>
<td>0.7</td>
<td>-0.30</td>
</tr>
<tr>
<td>$ZZ^*$</td>
<td>1.70</td>
<td>0.3</td>
<td>0.4</td>
<td>1.20</td>
<td>-0.59</td>
</tr>
<tr>
<td>$WW^*$</td>
<td>0.98</td>
<td>1.28</td>
<td>0.28</td>
<td>0.55</td>
<td>-0.20</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>2</td>
<td>1.24</td>
<td>1.50</td>
<td>0.59</td>
<td>-0.42</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>1.11</td>
<td>0.92</td>
<td>0.65</td>
<td>0.38</td>
<td>0</td>
</tr>
</tbody>
</table>

$$
\chi_f^2 = \frac{1}{\hat{\sigma}^2_1(1-\rho^2)}(\mu_1^f - \hat{\mu}_1^f)^2 + \frac{1}{\hat{\sigma}^2_1(1-\rho^2)}(\mu_2^f - \hat{\mu}_2^f)^2 - \frac{2\rho}{\hat{\sigma}_1\hat{\sigma}_2(1-\rho^2)}(\mu_1^f - \hat{\mu}_1^f)(\mu_2^f - \hat{\mu}_2^f),
$$

$$
\chi^2 = \sum_f \chi_f^2 + \chi_{ST}^2,
$$
Blue: $\Delta \chi^2 = 2.3$; Green: $\Delta \chi^2 = 5.99$; Red: $\Delta \chi^2 = 11.8$

Higgs data give a strict constraint on $\cos(\beta - \alpha)$, approaching to decoupling limit
Flavor conserving & violating processes

\[ h \rightarrow \tau \mu: \]

\[ BR(h \rightarrow \mu\tau) = \frac{c_{\beta\alpha}^2 (|X_{23}^\ell|^2 + |X_{32}^\ell|^2)}{16\pi c_{\beta}^2 \Gamma_h} m_h. \]

With \( m_h = 125 \) GeV, \( \Gamma_h \approx 4.21 \) MeV, and \( X_{32}^\ell = X_{23}^\ell \), we can express \( X_{23}^\ell \) as

\[ X_{23}^\ell = 3.77 \times 10^{-3} \left( \frac{c_{\beta}}{0.02} \right) \left( \frac{0.01}{c_{\beta\alpha}} \right) \sqrt{\frac{BR(h \rightarrow \mu\tau)}{0.84 \times 10^{-2}}}, \]

ansatz \( X_{\mu\tau}^\ell = \sqrt{\frac{m_\mu m_\tau}{v^2}} \chi_{\mu\tau}^\ell \) \( \chi_{\mu\tau}^\ell \sim 2 \) can satisfy the central value of CMS

- In the decoupling limit, \( c_{\beta\alpha} = 0 \rightarrow BR(h \rightarrow \tau\mu) = 0 \)
$\chi^2_{23} = 4$

$\chi^2_{23} = 6$

$\text{BR}(h \to \mu \tau) = 0.84\%$

(a)

$\tan \beta$

$\cos(\beta - \alpha)$

(b)

$\text{BR}(h \to \mu \tau)$

$\cos(\beta - \alpha)$
Tree level $\tau \to 3\mu$:

$$BR(\tau \to 3\mu) = \frac{\tau_{\tau} m_{\tau}^5}{3 \cdot 2^9 \pi^3} \frac{|X_{23}|^2}{c_\beta^2}\left[\left|\frac{c_\beta \alpha y_{h22}}{m_h^2} - \frac{s_\beta \alpha y_{H22}}{m_H^2}\right|^2 + \frac{y_{A22}^2}{m_A^2}\right]^2 + \frac{y_{\chi}^2}{v^2}\right]$$

$$X_{ij}^\ell = \sqrt{\frac{m_\mu m_\tau}{v}} \chi_{ij}^\ell$$

$$BR(\tau \to 3\mu)_{\exp} < 1.2 \times 10^{-8} \text{ HFAG}$$
$\tau \rightarrow \mu \gamma$: one + two loops

$BR(\tau \rightarrow \mu \gamma)^{\text{exp}} < 4.4 \times 10^{-8}$
Muon g-2 vs $\mu \rightarrow e\gamma$:

$$\Delta a_\mu \simeq \frac{m_\mu m_\tau X_{23}^\ell X_{32}^\ell}{8\pi^2 c_\beta^2} Z_\phi,$$

$$Z_\phi = \frac{c_{32}\alpha}{m_h^2} \left( \ln \left( \frac{m_h^2}{m_\tau^2} \right) - \frac{3}{2} \right) + \frac{s_{32\alpha}^2}{m_H^2} \left( \ln \left( \frac{m_H^2}{m_\tau^2} \right) - \frac{3}{2} \right)$$

$$- \ln \left( \frac{m_A^2}{m_\tau^2} \right) - \frac{3}{2} \frac{m_A^2}{m_\tau^2},$$

$$\mathcal{L}_{\mu \rightarrow e\gamma} = \frac{e m_\mu}{16\pi^2} \bar{e} \gamma \sigma_{\mu\nu} (C_L P_L + C_R P_R) \mu F^{\mu\nu},$$

$$C_{L(R)} = C_{L(R)}^\phi + C_{L(R)}^{H^\pm},$$

$$C_L^\phi = \frac{X_{32}^\ell X_{13}^\ell m_\tau}{2 c_\beta} m_\mu Z_\phi,$$

$$C_L^{H^\pm} = -\frac{1}{12 m_H^2} \left( \frac{2 X_{23}^\ell X_{13}^\ell}{c_\beta^2} \right),$$

$$C_{L(R)}^\phi = \frac{X_{13}^\ell}{X_{23}^\ell} \frac{4\pi^2}{m_\mu^2} \Delta a_\mu.$$

Strongly correlated between $\Delta a_\mu$ and $BR(\mu \rightarrow e\gamma)$

Much smaller than the neutral bosons
Muons vs $\mu \to e\gamma$:

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.8 \pm 8.0) \times 10^{-10}$$

$$\cos(\beta - \alpha) = -0.05$$

$\chi_{23}^\ell = 5$

$m_A = 300$ GeV

$BR(\mu \to e\gamma)^{\text{exp}} < 5.7 \times 10^{-13}$

$BR(h \to e\tau) < 2 \times 10^{-4} \left(\frac{\chi_{13}^\ell / \chi_{23}^\ell}{10^{-3}}\right)^2 BR(h \to \mu\tau)$. 

$\chi_{13}^\ell \ll \chi_{23}^\ell$
$Z \rightarrow \mu \tau$:  

\[\cos(\beta - \alpha) = -0.05\]

\[\chi_{23}^{\ell} = 0\]

\[m_H = 200 \text{ GeV}\]

\[m_A = 300 \text{ GeV}\]

\[BR(Z \rightarrow \mu \tau)^{\text{exp}} < 2.1 \times 10^{-5}\]
Conclusions:

- We revisit the constraints on the 2HDM by using the theoretical requirements + $\delta \rho$ + oblique parameters + Higgs measurements

- Higgs data give strict constraints on $\cos(\beta - \alpha)$ and $\tan\beta$

- With the values of parameters that satisfy CMS $BR(h \rightarrow \tau\mu) \sim 0.84\%$
  
  - $\tau \rightarrow 3\mu, \tau \rightarrow \mu\gamma$ can fit the upper limits of current data
  - $\Delta a_\mu$ can be explained
  - $\Delta a_\mu$ has a strong correlation with $\mu \rightarrow e\gamma$
  - $\frac{BR(h \rightarrow e\tau)}{BR(h \rightarrow \mu\tau)} \sim 10^{-4}$
  - $BR(Z \rightarrow \mu\tau) < 10^{-6}$