Higgs Decay $h \to \mu\tau$ in Minimal Flavor Violation Framework

Jusak Tandean

National Taiwan University

Based on

XG He, JT, YJ ZHeng, JHEP 09 (2015) 093 [arXiv:1507.02673]

Annual Theory Meeting on Particles, Cosmology and String

National Center for Theoretical Sciences, Hsinchu, Taiwan

9 December 2015

Outline

- Introduction
- Minimal flavor violation framework
- Lepton-flavor-violating decays of the Higgs boson
- Conclusions

Higgs dilepton decays

- ATLAS & CMS data on the flavor-conserving channels
  - $h \to \mu^+\mu^-$ $\quad \mathcal{B}(h \to \mu^-\mu^+) < 1.5 \times 10^{-3}$ and 1.6×10^{-3} 1406.7663 1410.6679
  - $h \to \tau^+\tau^-$ $\quad \sigma/\sigma_{\rm SM} = 1.44^{+0.42}_{-0.37}$ and 0.91 ± 0.28 ATLAS-CONF-2015-007 1412.8662

- CMS results on the flavor-violating channels
  - $\mathcal{B}(h \to \mu\tau) = \mathcal{B}(h \to \mu^-\tau^+) + \mathcal{B}(h \to \mu^+\tau^-) = (0.84^{+0.39}_{-0.37})\%$

    $\mathcal{B}(h \to \mu\tau) < 1.51\%$ at 95% CL 1502.07400
  - $\mathcal{B}(h \to e\tau) < 0.7\%$ at 95% CL CMS PAS HIG-14-040
  - $\mathcal{B}(h \to e\mu) < 0.036\%$ at 95% CL

- ATLAS results $\quad \mathcal{B}(h \to \mu\tau) = (0.77 \pm 0.62)\%$

  $\mathcal{B}(h \to \mu\tau) < 1.85\%$ at 95% CL 1508.03372

Higgs dilepton decays

- ATLAS & CMS data on the flavor-conserving channels
  - $h \to \mu^+\mu^-$ $\quad \mathcal{B}(h \to \mu^-\mu^+) < 1.5 \times 10^{-3}$ and 1.6×10^{-3} 1406.7663 1410.6679
  - $h \to \tau^+\tau^-$ $\quad \sigma/\sigma_{\rm SM} = 1.44^{+0.42}_{-0.37}$ and 0.91 ± 0.28 ATLAS-CONF-2015-007 1412.8662

- CMS results on the flavor-violating channels
  - $\mathcal{B}(h \to \mu\tau) = \mathcal{B}(h \to \mu^-\tau^+) + \mathcal{B}(h \to \mu^+\tau^-) = (0.84^{+0.39}_{-0.37})\%$

    $\mathcal{B}(h \to \mu\tau) < 1.51\%$ at 95% CL 1502.07400
  - $\mathcal{B}(h \to e\tau) < 0.7\%$ at 95% CL CMS PAS HIG-14-040
  - $\mathcal{B}(h \to e\mu) < 0.036\%$ at 95% CL

- ATLAS results $\quad \mathcal{B}(h \to \mu\tau) = (0.77 \pm 0.62)\%$

  $\mathcal{B}(h \to \mu\tau) < 1.85\%$ at 95% CL 1508.03372

- The tentative hint of $h \to \mu\,\tau$ would be a clear new physics signal if confirmed in future measurements.

Minimal flavor violation

- The standard model has been successful in describing the current data on flavor-changing neutral currents & *CP* violation in the quark sector.
- This motivates the hypothesis of minimal flavor violation for quarks: Yukawa couplings are the only sources for the breaking of flavor & *CP* symmetries.

  Chivukula & Georgi
  Hall & Randall

  - Effective field theory approach with MFV.

  Buras *et al.*
  D'Ambrosio *et al.*

- The standard model has been successful in describing the current data on flavor-changing neutral currents & *CP* violation in the quark sector.

- This motivates the hypothesis of minimal flavor violation for quarks: Yukawa couplings are the only sources for the breaking of flavor & *CP* symmetries.

  Chivukula & Georgi
  Hall & Randall

  - Effective field theory approach with MFV.

  Buras *et al.*
  D'Ambrosio *et al.*

- It's interesting to extend the MFV notion to the lepton sector

  Cirigliano *et al.*

  - which may offer insights into the origin of neutrino mass
  - but there are ambiguities in implementing leptonic MFV.

  Davidson & Palorini
  Gavela *et al.*, 2009
  He, Lee, JT, Zheng
  . . . .

- We consider an effective MFV scenario involving the seesaw mechanism of type I.

- The kinetic part of the Lagrangian for SM leptons plus 3 right-handed neutrinos

$$\mathcal{L} \supset i\bar{L}_{kL}\partial\!\!\!/ L_{kL} + i\bar{\nu}_{kR}\partial\!\!\!/ \nu_{kR} + i\bar{E}_{kR}\partial\!\!\!/ E_{kR}\,, \qquad k=1,2,3 \text{ summed over}$$

$$L_{jL} = \begin{pmatrix} \nu_{jL} \\ \ell_{jL} \end{pmatrix}, \quad j=1,2,3\,, \qquad (E_1,E_2,E_3)=(\ell_1,\ell_2,\ell_3)=(e,\mu,\tau)$$

- It's invariant under the global flavor rotations

$$L_{jL} \to (V_L)_{jk} L_{kL}\,, \qquad \nu_{jR} \to (V_\nu)_{jk}\nu_{kR}\,, \qquad E_{jR} \to (V_E)_{jk} E_{kR}\,, \qquad V_X \in \mathrm{SU}(3)_X$$

- The flavor symmetry is explicitly broken by the lepton mass terms

$$\mathcal{L} \supset -(Y_e)_{jk}\bar{L}_{jL}E_{kR}H - (Y_\nu)_{jk}\bar{L}_{jL}\nu_{kR}\tilde{H} - \tfrac{1}{2}(M_\nu)_{jk}\overline{\nu^{c}_{jR}}\nu_{kR} + \text{H.c.}$$

$Y_{e,\nu}$ are Yukawa coupling matrices, the Higgs doublet $H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(h+v) \end{pmatrix}, \quad \tilde{H} = i\sigma_2 H^*$

$M_\nu = \mathcal{M}\,\mathrm{diag}(1,1,1)$ is the Majorana mass matrix of the degenerate ν_{kR}

- $\mathcal{L}$ is formally flavor-symmetric if the Yukawa couplings are spurions transforming as

$$Y_e \to V_L Y_e V_E^\dagger\,, \qquad Y_\nu \to V_L Y_\nu \mathcal{O}^{\mathrm{T}}$$

- ⋆ We work in the basis where Y_e are diagonal, $Y_e = \mathrm{diag}(y_e, y_\mu, y_\tau)$, $y_f \equiv \sqrt{2}\,\frac{m_f}{v}$

  and E_k and ν_k refer to the mass eigenstates. Thus

$$L_{j,L} = \begin{pmatrix} (U_{\rm PMNS})_{jk}\,\nu_{k,L} \\ E_{j,L} \end{pmatrix} , \qquad Y_\nu = \frac{i\sqrt{2}}{v}\,U_{\rm PMNS}\,\hat{m}_\nu^{1/2} O M_\nu^{1/2}$$

Casas & Ibarra

$\hat{m}_\nu = \mathrm{diag}(m_1, m_2, m_3)$ is the light ν mass matrix, $U_{\rm PMNS}\hat{m}_\nu U_{\rm PMNS}^{\rm T} = -\frac{v^2}{2} Y_\nu M_\nu^{-1} Y_\nu^{\rm T}$

O is a complex matrix satisfying $O O^{\rm T} = 1\!\!1$

- ⋆ The Yukawa combinations of interest are

$$\mathsf{A} = Y_\nu Y_\nu^\dagger = \frac{2\mathcal{M}}{v^2}\,U_{\rm PMNS}\,\hat{m}_\nu^{1/2} O O^\dagger \hat{m}_\nu^{1/2} U_{\rm PMNS}^\dagger , \qquad \mathsf{B} = Y_e Y_e^\dagger = \mathrm{diag}(y_e^2, y_\mu^2, y_\tau^2)$$

⋆ We work in the basis where Y_e are diagonal, $Y_e = \mathrm{diag}(y_e, y_\mu, y_\tau)$, $y_f \equiv \sqrt{2}\,\frac{m_f}{v}$

and E_k and ν_k refer to the mass eigenstates. Thus

$$L_{j,L} = \begin{pmatrix} (U_{\rm PMNS})_{jk}\,\nu_{k,L} \\ E_{j,L} \end{pmatrix}, \qquad Y_\nu = \frac{i\sqrt{2}}{v}\,U_{\rm PMNS}\,\hat{m}_\nu^{1/2} O M_\nu^{1/2}$$

Casas & Ibarra

$\hat{m}_\nu = \mathrm{diag}(m_1, m_2, m_3)$ is the light ν mass matrix, $U_{\rm PMNS}\hat{m}_\nu U_{\rm PMNS}^{\rm T} = -\frac{v^2}{2} Y_\nu M_\nu^{-1} Y_\nu^{\rm T}$

O is a complex matrix satisfying $OO^{\rm T} = \mathbb{1}$

⋆ The Yukawa combinations of interest are

$$\mathsf{A} = Y_\nu Y_\nu^\dagger = \frac{2\mathcal{M}}{v^2}\,U_{\rm PMNS}\,\hat{m}_\nu^{1/2} O O^\dagger \hat{m}_\nu^{1/2} U_{\rm PMNS}^\dagger\,, \qquad \mathsf{B} = Y_e Y_e^\dagger = \mathrm{diag}(y_e^2, y_\mu^2, y_\tau^2)$$

⋆ Model-independently, one can construct Δ comprising an infinite number of terms

$$\Delta = \sum_{j,k,l,\cdots} \xi_{jkl\cdots}\,\mathsf{A}^j \mathsf{B}^k \mathsf{A}^l \cdots \qquad \text{with coefficients} \quad |\xi_{jkl\cdots}| \le \mathcal{O}(1)$$

The MFV hypothesis requires $\xi_{jkl\cdots}$ to be real so as not to introduce new sources of CP violation beyond those in the Yukawa couplings.

- Using the Cayley-Hamilton identity for an invertible 3×3 matrix X

$$X^3 = X^2\,\mathrm{Tr}X + \tfrac{1}{2}X\left[\mathrm{Tr}X^2 - (\mathrm{Tr}X)^2\right] + \mathbb{1}\,\mathrm{Det}X$$

one can resum the infinite series into a finite number of terms

$$\begin{aligned}\Delta = {} & \xi_1 \mathbb{1} + \xi_2 \mathsf{A} + \xi_3 \mathsf{B} + \xi_4 \mathsf{A}^2 + \xi_5 \mathsf{B}^2 + \xi_6 \mathsf{AB} + \xi_7 \mathsf{BA} + \xi_8 \mathsf{ABA} + \xi_9 \mathsf{BA}^2 \\ & + \xi_{10} \mathsf{BAB} + \xi_{11} \mathsf{AB}^2 + \xi_{12} \mathsf{ABA}^2 + \xi_{13} \mathsf{A}^2\mathsf{B}^2 + \xi_{14} \mathsf{B}^2\mathsf{A}^2 + \xi_{15} \mathsf{B}^2\mathsf{AB} \\ & + \xi_{16} \mathsf{AB}^2\mathsf{A}^2 + \xi_{17} \mathsf{B}^2\mathsf{A}^2\mathsf{B}\end{aligned}$$

Colangelo, Mercolli, Smith

Due to the resummation, the coefficients $\xi_{1,2,\ldots,17}$ develop tiny imaginary parts.

- Using the Cayley-Hamilton identity for an invertible 3×3 matrix X

$$X^3 = X^2\,\mathrm{Tr}X + \tfrac{1}{2}X\left[\mathrm{Tr}X^2 - (\mathrm{Tr}X)^2\right] + \mathbb{1}\,\mathrm{Det}X$$

one can resum the infinite series into a finite number of terms

$$\Delta = \xi_1\mathbb{1} + \xi_2\mathsf{A} + \xi_3\mathsf{B} + \xi_4\mathsf{A}^2 + \xi_5\mathsf{B}^2 + \xi_6\mathsf{AB} + \xi_7\mathsf{BA} + \xi_8\mathsf{ABA} + \xi_9\mathsf{BA}^2$$
$$+ \xi_{10}\mathsf{BAB} + \xi_{11}\mathsf{AB}^2 + \xi_{12}\mathsf{ABA}^2 + \xi_{13}\mathsf{A}^2\mathsf{B}^2 + \xi_{14}\mathsf{B}^2\mathsf{A}^2 + \xi_{15}\mathsf{B}^2\mathsf{AB}$$
$$+ \xi_{16}\mathsf{AB}^2\mathsf{A}^2 + \xi_{17}\mathsf{B}^2\mathsf{A}^2\mathsf{B}$$

Colangelo, Mercolli, Smith

Due to the resummation, the coefficients $\xi_{1,2,\dots,17}$ develop tiny imaginary parts.

$$\mathsf{A} = \frac{2\mathcal{M}}{v^2}U_{\rm PMNS}\,\hat{m}_\nu^{1/2}OO^\dagger\hat{m}_\nu^{1/2}U_{\rm PMNS}^\dagger\,, \qquad \mathsf{B} = \mathrm{diag}(y_e^2, y_\mu^2, y_\tau^2)$$

- We entertain the possibility that the largest eigenvalue of A is $\mathcal{O}(1)$.

Thus all B terms in Δ can be neglected: $\Delta \simeq \xi_0\mathbb{1} + \xi_1\mathsf{A} + \xi_2\mathsf{A}^2 \simeq \Delta^\dagger$

- Effective dimension-6 MFV operators involving H

$$\mathcal{L}_{\rm MFV} \supset \frac{1}{\Lambda^2}\Big(O_{RL}^{(e1)} + O_{RL}^{(e2)} + O_{RL}^{(e3)} + O_{RL}^{(e4)} + O_{LL}^{(1)} + O_{LL}^{(2)} + {\rm H.c.}\Big) + \cdots$$

Λ is the scale of MFV,

$$O_{RL}^{(e1)} = g'\bar{E}_R Y_e^\dagger \Delta_{RL}^{(1)} \sigma_{\rho\omega} H^\dagger L_L B^{\rho\omega}$$

$$O_{RL}^{(e2)} = g\,\bar{E}_R Y_e^\dagger \Delta_{RL}^{(2)} \sigma_{\rho\omega} H^\dagger \tau_a L_L W_a^{\rho\omega}$$

$$O_{RL}^{(e3)} = (\mathcal{D}^\rho H)^\dagger\, \overline{E}_R Y_e^\dagger \Delta_{RL}^{(3)} \mathcal{D}_\rho L_L$$

$$O_{LL}^{(1)} = \tfrac{i}{4}[H^\dagger(\mathcal{D}_\rho H) - (\mathcal{D}_\rho H)^\dagger H]\,\bar{L}_L \gamma^\rho \Delta_{LL}^{(1)} L_L\,,$$

$$O_{LL}^{(2)} = \tfrac{i}{4}[H^\dagger\tau_a(\mathcal{D}_\rho H) - (\mathcal{D}_\rho H)^\dagger \tau_a H]\,\bar{L}_L \gamma^\rho \tau_a \Delta_{LL}^{(2)} L_L$$

generalized from
D'Ambrosio *et al.*
Cirigliano *et al.*

- $\Delta_{RL}^{(1,2,3)}$ and $\Delta_{LL}^{(1,2)}$ are the same in form as Δ, but have their own coefficients ξ_r

MFV contribution to dilepton Higgs decay

★ $\mathcal{L}_{\rm MFV} \supset \dfrac{O_{RL}^{(e3)}}{\Lambda^2} + {\rm H.c.}\,,$ $\quad O_{RL}^{(e3)} = (\mathcal{D}^\rho H)^\dagger\, \overline{E}_R Y_e^\dagger \Delta\, \mathcal{D}_\rho L_L$

- $\mathcal{L}_{\rm MFV} \supset \dfrac{O_{RL}^{(e3)}}{\Lambda^2} + {\rm H.c.}\,, \qquad O_{RL}^{(e3)} = (\mathcal{D}^\rho H)^\dagger \overline{E}_R Y_e^\dagger \Delta\, \mathcal{D}_\rho L_L$
- Alternative $h \to \ell\bar{\ell}'$ operator: $H^\dagger H\, \overline{E}_{jR} H^\dagger L_{kL}$
- They are related

$$\begin{aligned}
O_{RL}^{(e3)} + {\rm H.c.} = {} & \tfrac{i}{8}\Big[H^\dagger \mathcal{D}_\rho H - (\mathcal{D}_\rho H)^\dagger H\Big]\Big(\overline{L}_L \gamma^\rho \big\{\Delta, Y_e Y_e^\dagger\big\} L_L + 4\overline{E}_R \gamma^\rho Y_e^\dagger \Delta Y_e E_R\Big) \\
& + \tfrac{i}{8}\Big[H^\dagger \tau_a \mathcal{D}_\rho H - (\mathcal{D}_\rho H)^\dagger \tau_a H\Big]\, \overline{L}_L \gamma^\rho \big\{\Delta, Y_e Y_e^\dagger\big\} \tau_a L_L \\
& + \tfrac{i}{8}\Big[H^\dagger \mathcal{D}_\rho H + (\mathcal{D}_\rho H)^\dagger H\Big]\, \overline{L}_L \gamma^\rho \big[\Delta, Y_e Y_e^\dagger\big] L_L \\
& + \tfrac{i}{8}\Big[H^\dagger \tau_a \mathcal{D}_\rho H + (\mathcal{D}_\rho H)^\dagger \tau_a H\Big]\, \overline{L}_L \gamma^\rho \big[\Delta, Y_e Y_e^\dagger\big] \tau_a L_L \\
& + \tfrac{1}{8}\bigg[\bigg(\frac{4H^\dagger H}{v^2} - 2\bigg) m_h^2\, \overline{E}_R Y_e^\dagger \Delta H^\dagger L_L + 4\overline{L}_L Y_e E_R\, \overline{E}_R Y_e^\dagger \Delta L_L \\
& \qquad + \overline{E}_R Y_e^\dagger \Delta\, \sigma_{\rho\omega} H^\dagger (g' B^{\rho\omega} + g\, \tau_a W_a^{\rho\omega}) L_L + {\rm H.c.}\bigg] \\
& + (\text{quark terms})
\end{aligned}$$

- The effective Lagrangian describing $h \to \ell^- \ell'^+, \ell'^- \ell^+$ for $\ell \neq \ell'$

$$\mathcal{L}_{h\ell\ell'} = -\mathcal{Y}_{\ell\ell'} \overline{\ell} P_R \ell' - \mathcal{Y}_{\ell'\ell} \overline{\ell'} P_R \ell + \text{H.c.}$$

implies the combined rate

$$\Gamma_{h\to\ell\ell'} = \Gamma_{h\to\ell\bar{\ell}'} + \Gamma_{h\to\bar{\ell}\ell'} = \frac{m_h}{8\pi}\left(|\mathcal{Y}_{\ell\ell'}|^2 + |\mathcal{Y}_{\ell'\ell}|^2\right)$$

For the flavor-conserving mode $h \to \ell^- \ell^+$

$$\Gamma_{h\to\ell\bar{\ell}} = \frac{m_h}{8\pi}|\mathcal{Y}_{\ell\ell}|^2$$

- The SM and $\mathcal{L}_{\text{MFV}}$ contributions to $h \to E_k^- E_l^+$

$$\mathcal{Y}_{E_k E_l} = \delta_{kl}\,\mathcal{Y}^{\text{SM}}_{E_k E_k} - \frac{m_{E_l} m_h^2}{2\Lambda^2 v}\Delta_{kl}\,, \qquad \mathcal{Y}^{\text{SM}}_{E_k E_k} = \frac{m_{E_k}}{v}$$

Constraints on Yukawa couplings

- $\mu \to e\gamma$ $\qquad \mathcal{B}(\mu \to e\gamma)_{\rm exp} < 5.7 \times 10^{-13}$

$$\sqrt{\left|(\mathcal{Y}_{\mu\mu}+r_\mu)\mathcal{Y}_{\mu e}+9.19\,\mathcal{Y}_{\mu\tau}\mathcal{Y}_{\tau e}\right|^2+\left|(\mathcal{Y}_{\mu\mu}+r_\mu)\mathcal{Y}_{e\mu}+9.19\,\mathcal{Y}_{e\tau}\mathcal{Y}_{\tau\mu}\right|^2} < 5.1 \times 10^{-7}$$

$$r_\mu = 0.29$$

Goudelis, Lebedev, Park
Blankenburg, Ellis, Isidori
Harnik, Kopp, Zupan
Dery *et al.*

- $\tau \to e\gamma$ $\qquad \mathcal{B}(\tau \to e\gamma)_{\rm exp} < 3.3 \times 10^{-8}$

$$|\mathcal{Y}_{\tau\tau}+r_\tau|\sqrt{|\mathcal{Y}_{\tau e}|^2+|\mathcal{Y}_{e\tau}|^2} < 5.2 \times 10^{-4}\,, \qquad r_\tau = 0.03$$

- LHC data on $h \to \mu^+\mu^-$, $\tau^+\tau^-$

$$|\mathcal{Y}_{\mu\mu}/\mathcal{Y}_{\mu\mu}^{\rm SM}|^2 < 6.5\,, \qquad 0.7 < |\mathcal{Y}_{\tau\tau}/\mathcal{Y}_{\tau\tau}^{\rm SM}|^2 < 1.8$$

- CMS data on $h \to \mu\tau$

$$2.0 \times 10^{-3} < \sqrt{|\mathcal{Y}_{\tau\mu}|^2+|\mathcal{Y}_{\mu\tau}|^2} < 3.3 \times 10^{-3}$$

$$\sqrt{|\mathcal{Y}_{\tau\mu}|^2+|\mathcal{Y}_{\mu\tau}|^2} < 3.6 \times 10^{-3}$$

⋆ Consider the MFV scenario with the type-I seesaw mechanism involving 3 heavy right-handed neutrinos, $M_\nu = \mathcal{M}\,\mathrm{diag}(1,1,1)$, so that

$$\Delta = \xi_0 \mathbb{1} + \xi_1 \mathsf{A} + \xi_2 \mathsf{A}^2, \qquad \mathsf{A} = Y_\nu Y_\nu^\dagger = \frac{2\mathcal{M}}{v^2} U_{\rm PMNS}\, \hat{m}_\nu^{1/2} O O^\dagger \hat{m}_\nu^{1/2} U_{\rm PMNS}^\dagger$$

- ⋆ Consider the MFV scenario with the type-I seesaw mechanism involving 3 heavy right-handed neutrinos, $M_\nu = \mathcal{M}\,\mathrm{diag}(1,1,1)$, so that

$$\Delta = \xi_0 \mathbb{1} + \xi_1 \mathsf{A} + \xi_2 \mathsf{A}^2, \qquad \mathsf{A} = Y_\nu Y_\nu^\dagger = \frac{2\mathcal{M}}{v^2} U_{\rm PMNS}\, \hat{m}_\nu^{1/2} O O^\dagger \hat{m}_\nu^{1/2} U_{\rm PMNS}^\dagger$$

- ⋆ If O in Y_ν is real, $|\mathcal{Y}_{\mu\tau}|$ can only reach $\sim 2\times 10^{-4} \ll |\mathcal{Y}_{\mu\tau}^{\rm CMS}| \sim 3\times 10^{-3}$

- ⋆ Consider the MFV scenario with the type-I seesaw mechanism involving 3 heavy right-handed neutrinos, $M_\nu = \mathcal{M}\,\mathrm{diag}(1,1,1)$, so that

$$\Delta = \xi_0 \mathbb{1} + \xi_1 \mathsf{A} + \xi_2 \mathsf{A}^2, \qquad \mathsf{A} = Y_\nu Y_\nu^\dagger = \frac{2\mathcal{M}}{v^2} U_{\mathrm{PMNS}} \hat{m}_\nu^{1/2} O O^\dagger \hat{m}_\nu^{1/2} U_{\mathrm{PMNS}}^\dagger$$

- ⋆ If O in Y_ν is real, $|\mathcal{Y}_{\mu\tau}|$ can only reach $\sim 2\times 10^{-4} \ll |\mathcal{Y}_{\mu\tau}^{\mathrm{CMS}}| \sim 3\times 10^{-3}$
- ⋆ To attain $|\mathcal{Y}_{\mu\tau}^{\mathrm{CMS}}|$, a less simple structure of Y_ν is needed, particularly with a complex O, so that $OO^\dagger = e^{2i\mathsf{R}}$, with $\mathsf{R} = \begin{pmatrix} 0 & r_1 & r_2 \\ -r_1 & 0 & r_3 \\ -r_2 & -r_3 & 0 \end{pmatrix}$ and $r_{1,2,3}$ real

Dery *et al.*
He, JT, Zheng

Numerical results

	$\frac{\alpha_1}{\pi}$	$\frac{\alpha_2}{\pi}$	r_1	r_2	r_3	$10^5\,\xi_1/\Lambda^2$ (GeV^{-2})	$10^5\,\xi_2/\Lambda^2$ (GeV^{-2})	$10^5\,\xi_4/\Lambda^2$ (GeV^{-2})	$\frac{\mathcal{Y}_{ee}}{\mathcal{Y}_{ee}^{\mathrm{SM}}}$	$\frac{\mathcal{Y}_{\mu\mu}}{\mathcal{Y}_{\mu\mu}^{\mathrm{SM}}}$	$\frac{\mathcal{Y}_{\tau\tau}}{\mathcal{Y}_{\tau\tau}^{\mathrm{SM}}}$	$\frac{\lvert\mathcal{Y}_{e\mu}\rvert}{10^{-6}}$	$\frac{\lvert\mathcal{Y}_{e\tau}\rvert}{10^{-4}}$	$\frac{\lvert\mathcal{Y}_{\mu\tau}\rvert}{10^{-3}}$
NH	0	0	0.81	−1.7	−0.89	−6.3	6.2	5.4	1.5	1.2	0.89	1.7	0.3	3.1
	0	0	−0.86	1.8	−0.92	−7.1	8.7	4.5	1.6	1.2	0.87	2.0	0.4	3.5
	0	0.23	0.74	−0.80	−0.20	4.9	−6.7	−5.9	0.63	0.93	1.3	1.7	2.2	3.2
IH	0	0	0.04	0.63	−0.93	−7.9	8.8	2.6	1.5	1.2	1.1	2.1	2.8	3.2
	0	0	0.02	−0.75	1.1	−5.7	3.8	8.1	1.4	1.1	0.90	2.4	1.3	3.3
	0.79	1.3	−0.61	−0.79	1.4	−5.3	5.0	7.6	1.4	1.0	0.84	1.2	0.4	3.5

Higgs-lepton Yukawa couplings corresponding to sample values of the Majorana phases $\alpha_{1,2}$, the parameters $r_{1,2,3}$ of the complex O matrix, and the coefficients $\xi_{1,2,4}$ in the MFV building block Δ which can yield $|\mathcal{Y}_{\mu\tau}| \gtrsim 3\times 10^{-3}$. The calculation of the NH (IH) results also relies on the measured neutrino mixing parameters in the case of normal (inverted) hierarchy of neutrino masses.

- $|\mathcal{Y}_{\mu\tau}|/|\mathcal{Y}_{e\tau}| \sim 10$ or more, consistent with CMS results
- The $\mathcal{Y}_{\mu\mu}$ and $\mathcal{Y}_{\tau\tau}$ predictions are testable with future collider data

- If future searches yield $\mathcal{B}(\mu \to e\gamma) < 5 \times 10^{-14}$

$$0.5 < \Gamma_{h\to\mu\bar{\mu}}/\Gamma^{\rm SM}_{h\to\mu\bar{\mu}} < 1.5$$

$$0.8 < \Gamma_{h\to\tau\bar{\tau}}/\Gamma^{\rm SM}_{h\to\tau\bar{\tau}} < 1.2$$

	$\frac{\alpha_1}{\pi}$	$\frac{\alpha_2}{\pi}$	r_1	r_2	r_3	$10^5\,\xi_1/\Lambda^2$ (GeV^{-2})	$10^5\,\xi_2/\Lambda^2$ (GeV^{-2})	$10^5\,\xi_4/\Lambda^2$ (GeV^{-2})	$\frac{\mathcal{Y}_{ee}}{\mathcal{Y}_{ee}^{\rm SM}}$	$\frac{\mathcal{Y}_{\mu\mu}}{\mathcal{Y}_{\mu\mu}^{\rm SM}}$	$\frac{\mathcal{Y}_{\tau\tau}}{\mathcal{Y}_{\tau\tau}^{\rm SM}}$	$\frac{\lvert\mathcal{Y}_{e\mu}\rvert}{10^{-6}}$	$\frac{\lvert\mathcal{Y}_{e\tau}\rvert}{10^{-4}}$	$\frac{\lvert\mathcal{Y}_{\mu\tau}\rvert}{10^{-3}}$
NH	0	0	−0.53	0.73	−0.40	6.0	−0.7	−9.5	0.53	0.79	1.1	0.6	0.2	2.7
	0	0.4	0.68	−0.80	−0.15	−5.4	−2.3	12	1.4	1.2	0.93	0.3	0.5	2.6
IH	0	0	0.0	−0.73	1.1	−4.7	−1.9	11	1.4	1.1	0.96	0.5	0.1	2.5
	0.8	1.3	−0.60	−0.81	1.4	−6.5	9.4	1.1	1.5	1.2	1.0	0.1	0.5	2.9

The same as Table I, except the $\mu \to e\gamma$ and $h \to \mu\bar{\mu}, \tau\bar{\tau}$ constraints are replaced with their projected future experimental limits, as described in the text.

$$\mathcal{B}(\mu \to e\gamma) = (1.2\text{-}4.4) \times 10^{-14}$$

- $$O_{RL}^{(e3)} = \frac{\Delta_{kl}\, m_{E_k}}{v}\, \bar{E}_k P_L \left(\partial_\eta E_l - ieA_\eta E_l + ig_L Z_\eta E_l + \frac{ig}{\sqrt{2}} W_\eta^- \nu_l\right)\partial^\eta h$$
$$+ \frac{\Delta_{kl}\, g\, m_{E_k}}{v}\, \bar{E}_k P_L \left[\frac{iZ^\eta\, \partial_\eta E_l}{2c_{\rm w}} - \frac{iW_\eta^-\, \partial^\eta \nu_l}{\sqrt{2}} + \left(\frac{eA\cdot Z}{2c_{\rm w}} - \frac{g_L Z^2}{2c_{\rm w}} + \frac{g}{2} W^+\!\cdot W^-\right) E_l\right](h+v)$$
$$g_L = g\left(s_{\rm w}^2 - 1/2\right)/c_{\rm w}, \qquad c_{\rm w} = \left(1 - s_{\rm w}^2\right)^{1/2} = gv/\left(2m_Z\right)$$

- This leads to the decay rates

$$\Gamma_{Z\to\mu\bar{e}} = \Gamma_{Z\to\bar{\mu}e} \simeq \frac{\left|\Delta_{12}\, m_\mu\right|^2 m_Z^5}{192\,\Lambda^4\,\pi\, v^2} = \frac{\left|\mathcal{Y}_{e\mu}\right|^2 m_Z^5}{48\pi\, m_h^4}$$

and similarly for $Z \to e\tau, \mu\tau$. Thus, for, say, $\left|\mathcal{Y}_{e\mu}\right| = 2.1\times 10^{-6}$, $\left|\mathcal{Y}_{e\tau}\right| = 2.8\times 10^{-4}$, and $\left|\mathcal{Y}_{\mu\tau}\right| = 0.0032$ from the $\mathcal{Y}_{\ell\ell'}$ results, we get

$$\mathcal{B}\left(Z\to e^\pm\mu^\mp\right) = 6.0\times 10^{-13}, \quad \mathcal{B}\left(Z\to e^\pm\tau^\mp\right) = 1.1\times 10^{-8}, \quad \mathcal{B}\left(Z\to \mu^\pm\tau^\mp\right) = 1.4\times 10^{-6}$$

For comparison, the 95% CL experimental limits from the PDG are

$$\mathcal{B}\left(Z\to e^\pm\mu^\mp\right)_{\rm exp} < 1.7\times 10^{-6}, \quad \mathcal{B}\left(Z\to e^\pm\tau^\mp\right)_{\rm exp} < 9.8\times 10^{-6}, \quad \mathcal{B}\left(Z\to \mu^\pm\tau^\mp\right)_{\rm exp} < 1.2\times 10^{-5}$$

The predicted $\mathcal{B}(Z\to\mu\tau)$ is below its experimental bound by only less than a factor of 10. Thus, in this scenario $Z\to\mu\tau$ is potentially more testable than $Z\to e\mu, e\tau$, and the quest for it can provide a complementary check on $\mathcal{L}_{\rm MFV}$.

Conclusions

- We have explored the MFV hypothesis in the lepton sector and applied it to flavor-violating Higgs-boson processes
- The leptonic MFV framework involving the type-I seesaw mechanism can accommodate the recent tentative hint of $h \to \mu\tau$ from the LHC if the right-handed neutrinos have nontrivial couplings to the Higgs boson.