Higgs Flavor Physics

Yonit Hochberg

[1] Dery, Efrati, YH and Nir JHEP 1305, 039 (2013)
[2] Dery, Efrati, Hiller, YH and Nir JHEP 1308, 006 (2013)
[3] YH, Spira and Nir, work in progress

Outline

- Why is higgs + flavor interesting?
- Demonstrate how it is interesting:
  - Observables
  - SM predictions
  - Examples

Why is it interesting?

- “The God particle was discovered in the black hole machine”
- Golden channels $h \to \gamma\gamma, ZZ^*$ with measured rates

$$R_{\gamma\gamma} = 1.1 \pm 0.2$$
$$R_{ZZ^*} = 1.1 \pm 0.2$$
$$R_f \equiv \frac{\sigma(pp \to h)\mathrm{BR}(h \to f)}{[\sigma(pp \to h)\mathrm{BR}(h \to f)]^{\mathrm{SM}}}$$

- First indication that $Y_t = \mathcal{O}(1)$
- A new arena for the exploration of flavor physics

Flavor goals

- **The Standard Model flavor puzzle:**

  Why are the flavor parameters small and hierarchical?

Flavor goals

Mass pattern and mixing angles:

$$Y_t \sim 1,\ Y_c \sim 10^{-2},\ Y_u \sim 10^{-5}$$

$$Y_b \sim 10^{-2},\ Y_s \sim 10^{-3},\ Y_d \sim 10^{-5}$$

$$Y_\tau \sim 10^{-2},\ Y_\mu \sim 10^{-3},\ Y_e \sim 10^{-6}$$

$$|V_{us}| \sim 0.2,\ |V_{cb}| \sim 0.04,\ |V_{ub}| \sim 0.004,\ \delta_{\rm KM} \sim 1$$

(Compare to gauge sector:

$$g_s \sim 1,\ g \sim 0.6,\ g' \sim 0.3$$)

Smallness and hierarchy

Why? = The SM flavor puzzle

Approximate symmetry? Strong dynamics? Location in extra dimension?...

Flavor goals

- **The Standard Model flavor puzzle:**

  Why are the flavor parameters small and hierarchical?

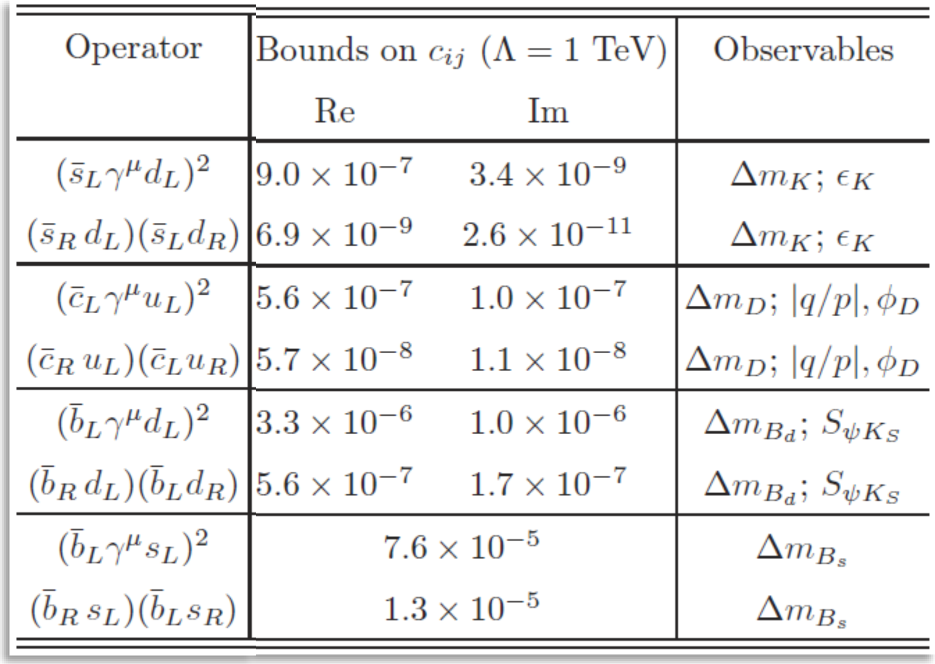
- **The New Physics flavor puzzle:**

  If there is new physics at the TeV scale, why are flavor changing neutral currents so small?

Flavor goals

Flavor structure of NP @ the TeV scale must be highly non-generic

$$\frac{c_{ij}}{\Lambda^2}\bar{q}_i q_j \bar{q}_i q_j$$



Operator	Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	1.3×10^{-5}		Δm_{B_s}

Image from Isidori, Nir, Perez, Ann. Rev. Nucl. Part. Sci. 60, 355 (2010)

Why/How? = The NP flavor puzzle

Minimal flavor violation? Approximate U(1)? Approximate U(2)? ...

Flavor goals

- **The Standard Model flavor puzzle:**

  Why are the flavor parameters small and hierarchical?

- **The New Physics flavor puzzle:**

  If there is new physics at the TeV scale, why are flavor changing neutral currents so small?

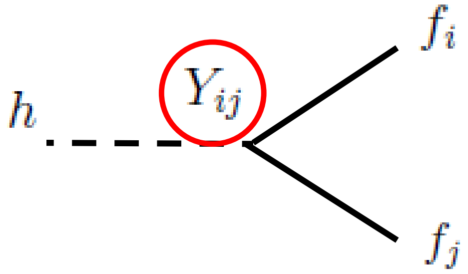
- **Are the two puzzles related?**

Why is it interesting?

Opportunity to probe flavor parameters of h =

better our understanding of flavor puzzles

(+ don't assume, measure!)



Higgs flavor physics

Sector in which we have best experimental chance:
charged leptons

How is it interesting?

- Focus on $h \to \tau\tau, \mu\mu, \tau\mu$
- Current status @ ATLAS: $R_{\tau\tau} = 1.4 \pm 0.5,\ \ R_{\mu\mu} < 9.8$

  @ CMS: $R_{\tau\tau} = 0.9 \pm 0.3,\ \ R_{\mu\mu} < 7.4$

- In the future:

Observable	SM	
$R_{\tau^+\tau^-}$	1	
$X_{\mu\mu} \equiv \frac{\mathrm{BR}(h\to\mu^+\mu^-)}{\mathrm{BR}(h\to\tau^+\tau^-)}$	$(m_\mu/m_\tau)^2$	$\longleftarrow \quad (Y_\mu/Y_\tau)^2$
$X_{\mu\tau} \equiv \frac{\mathrm{BR}(h\to\mu^\pm\tau^\mp)}{\mathrm{BR}(h\to\tau^+\tau^-)}$	0	$\longleftarrow \quad (Y_{\mu\tau}/Y_\tau)^2$

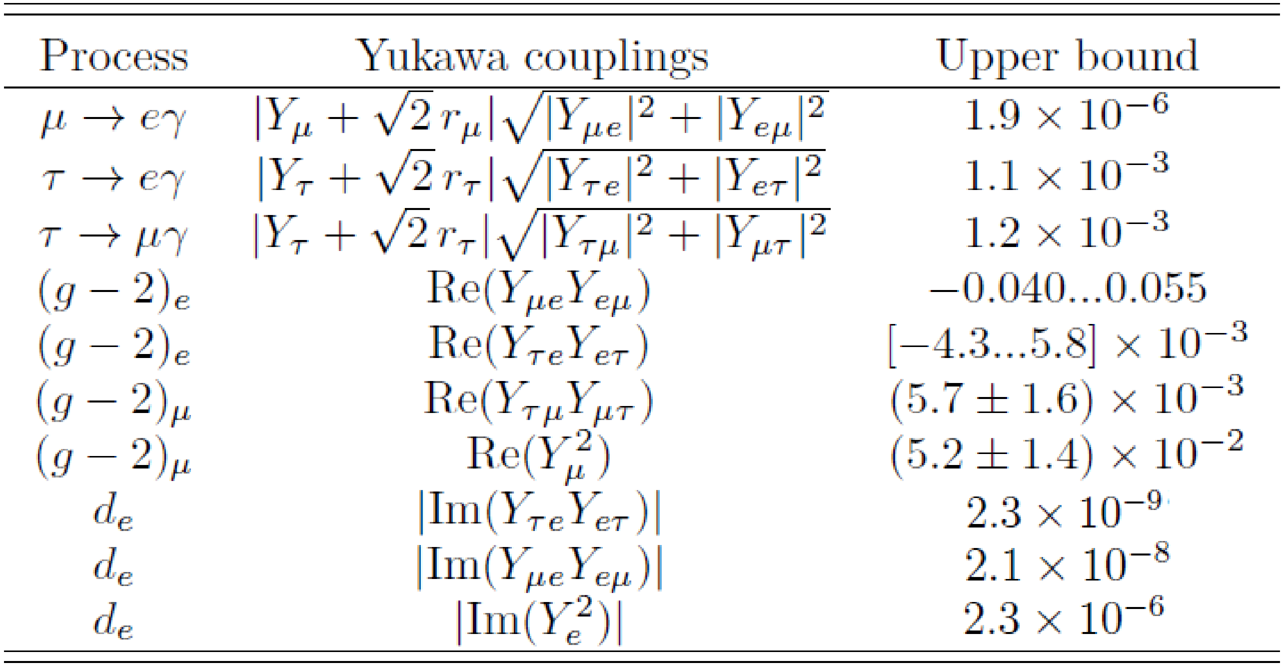
- What can we learn from $R_{\tau\tau}, X_{\mu\mu}, X_{\tau\mu}$?

Theoretical predictions

$X_{\mu\mu} \equiv \frac{\mathrm{BR}(h\to\mu^+\mu^-)}{\mathrm{BR}(h\to\tau^+\tau^-)}$ theoretically very clean!

- Total width effects cancel
- LO: $\Gamma^{\mathrm{LO}}(h \to \ell^+\ell^-) = \frac{G_F m_h}{4\sqrt{2}\pi} m_\ell^2 \beta_\ell^3, \qquad \beta_\ell = (1 - 4m_\ell^2/m_h^2)^{1/2}$
- + EW corrections: $X_{\mu^+\mu^-} = \left[\frac{m_\mu(m_h)}{m_\tau(m_h)}\right]^2 \left[1 + \underbrace{\frac{6(m_\tau^2 - m_\mu^2)}{m_h^2}}_{\text{permil}}\right]$

Indirect constraints



Process	Yukawa couplings	Upper bound
$\mu \to e\gamma$	$\lvert Y_\mu + \sqrt{2}\, r_\mu\rvert \sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	1.9×10^{-6}
$\tau \to e\gamma$	$\lvert Y_\tau + \sqrt{2}\, r_\tau\rvert \sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	1.1×10^{-3}
$\tau \to \mu\gamma$	$\lvert Y_\tau + \sqrt{2}\, r_\tau\rvert \sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	1.2×10^{-3}
$(g-2)_e$	$\mathrm{Re}(Y_{\mu e} Y_{e\mu})$	$-0.040...0.055$
$(g-2)_e$	$\mathrm{Re}(Y_{\tau e} Y_{e\tau})$	$[-4.3...5.8] \times 10^{-3}$
$(g-2)_\mu$	$\mathrm{Re}(Y_{\tau\mu} Y_{\mu\tau})$	$(5.7 \pm 1.6) \times 10^{-3}$
$(g-2)_\mu$	$\mathrm{Re}(Y_\mu^2)$	$(5.2 \pm 1.4) \times 10^{-2}$
d_e	$\lvert\mathrm{Im}(Y_{\tau e} Y_{e\tau})\rvert$	2.3×10^{-9}
d_e	$\lvert\mathrm{Im}(Y_{\mu e} Y_{e\mu})\rvert$	2.1×10^{-8}
d_e	$\lvert\mathrm{Im}(Y_e^2)\rvert$	2.3×10^{-6}

Sector where these are tight: $\lvert Y_{\mu e}\rvert \lesssim 10^{-5}$

In $\mu\mu$ LHC is doing better than this

(and in $\tau\mu$ it can be doing better than this)

Harnik, Kopp, Zupan JHEP 1303, 026 (2013)

(See also Davidson, Verdier PRD 86, 111701 (2012))

Proof of principle

$$\mathcal{L}_Y = -m_i \bar{\ell}^i_L \ell^i_R - \frac{Y_{ij}}{\sqrt{2}} \bar{\ell}^i_L \ell^j_R h + \text{h.c.}\,, \qquad i,j = e,\mu,\tau$$

(In SM: $Y_{ij} = \delta_{ij}\sqrt{2}m_i/v$)

General procedure:

- Write down favorite model
- Expand around vacuum, rotate to Higgs mass basis and to charged lepton mass basis, and read off the couplings
- Insert into observables

Ex. I: MHDM with NFC

- Multi Higgs doublet model (MHDM), where only one doublet ϕ_ℓ couples to the charged lepton sector
- $h = V_{h\ell}\phi_\ell^0 + \ldots$, and $-\mathcal{L}_Y \supset \frac{Y_{ij}}{\sqrt{2}}\bar{\ell}_L^i \ell_R^j h + \mathrm{h.c.}$

Ex. I: MHDM with NFC

- Multi Higgs doublet model (MHDM), where only one doublet ϕ_ℓ couples to the charged lepton sector
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⇒

1) $Y_\tau = \underbrace{\frac{V_{h\ell}^* v}{\langle \phi_\ell \rangle}}_{\text{flavor universal}} \underbrace{\frac{\sqrt{2}m_\tau}{v}}_{\text{SM Yukawa coupling}}$

2) $\frac{Y_\mu}{Y_\tau} = \frac{m_\mu}{m_\tau}$

3) $Y_{\mu\tau} = Y_{\tau\mu} = 0$

(In 2HDM type II (& MSSM): $Y_\tau = -\frac{\sin\alpha}{\cos\beta}\frac{\sqrt{2}m_\tau}{v}$)

Ex. II: 1HDM with MFV

- SM + non-renormalizable operators:

$$-\mathcal{L}_Y = \lambda_{ij}\overline{L}_i E_j \phi + \frac{\lambda'_{ij}}{\Lambda^2}\overline{L}_i E_j \phi(\phi^\dagger\phi) + \mathrm{h.c.}, \quad \phi = \frac{1}{\sqrt{2}}(v+h)$$

Ex. II: 1HDM with MFV

- SM + non-renormalizable operators:

$$-\mathcal{L}_Y = \lambda_{ij}\overline{L}_i E_j \phi + \frac{\lambda'_{ij}}{\Lambda^2}\overline{L}_i E_j \phi(\phi^\dagger \phi) + \text{h.c.}, \quad \phi = \frac{1}{\sqrt{2}}(v+h)$$

- **Minimal flavor violation (MFV) cheat sheet:**
  - In absence of lepton Yukawas, SM has global flavor symmetry

    $SU(3)_L \times SU(3)_E$, with $L \sim (3,1)$

    $E \sim (1,\bar{3})$
  - Promote Yukawa to spurion: $Y \sim (3,\bar{3})$
  - MFV requires all terms in the Lagrangian be formally invariant → insert appropriate powers of Yukawas into new terms.

Ex. II: 1HDM with MFV

- SM + non-renormalizable operators:

$$-\mathcal{L}_Y = \lambda_{ij}\overline{L}_i E_j \phi + \frac{\lambda'_{ij}}{\Lambda^2}\overline{L}_i E_j \phi(\phi^\dagger \phi) + \text{h.c.}, \quad \phi = \frac{1}{\sqrt{2}}(v+h)$$

- **MFV:** $\lambda' = a\lambda + b\lambda\lambda^\dagger\lambda + \mathcal{O}(\lambda^5)$

1) $Y_\tau = \left(1 + \frac{av^2}{\Lambda^2}\right)\frac{\sqrt{2}m_\tau}{v}$

2) $\frac{Y_\mu}{Y_\tau} = \frac{m_\mu}{m_\tau}\left(1 - \frac{2b(m_\tau^2 - m_\mu^2)}{\Lambda^2}\right)$

3) $Y_{\mu\tau} = Y_{\tau\mu} = 0$

Ex. III: 1HDM with FN

- SM + non-renormalizable operators:

$$-\mathcal{L}_Y = \lambda_{ij}\overline{L}_i E_j \phi + \frac{\lambda'_{ij}}{\Lambda^2}\overline{L}_i E_j \phi(\phi^\dagger\phi) + \mathrm{h.c.}, \quad \phi = \frac{1}{\sqrt{2}}(v+h)$$

- **Froggatt-Nielsen (FN) cheat sheet:**
  - Horizontal $U(1)_H$ symmetry = different charges for different generations
  - Broken by small parameter ϵ_H
  - Generates parametric pattern:

$$\lambda_{ij} \propto \epsilon_H^{H(E_j)-H(L_i)}$$

couplings, masses and mixing angles

$$m_{\ell_i}/v \sim \epsilon_H^{H(E_i)-H(L_i)}$$

$$|U_{ij}| \sim \epsilon_H^{H(L_j)-H(L_i)}$$

Ex. III: 1HDM with FN

- SM + non-renormalizable operators:

$$-\mathcal{L}_Y = \lambda_{ij}\overline{L_i}E_j\phi + \frac{\lambda'_{ij}}{\Lambda^2}\overline{L_i}E_j\phi(\phi^\dagger\phi) + \mathrm{h.c.}, \quad \phi = \frac{1}{\sqrt{2}}(v+h)$$

- **FN:** Parametric pattern $\lambda'_{ij} = \mathcal{O}(1) \times \lambda_{ij}$

⇨

1) $Y_\tau = \frac{\sqrt{2}m_\tau}{v}\left[1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right]$

2) $\frac{Y_\mu}{Y_\tau} = \frac{m_\mu}{m_\tau}\left[1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right]$

3) $Y_{\mu\tau} = \mathcal{O}\left(\frac{|U_{23}|vm_\tau}{\Lambda^2}\right), \quad Y_{\tau\mu} = \mathcal{O}\left(\frac{vm_\mu}{|U_{23}|\Lambda^2}\right)$

Ex. IV: 2HDM with MFV

- 2HDM → 2 Yukawa matrices: $-\mathcal{L}_Y = \bar{L}\Phi_1 Y_1 E + \bar{L}\Phi_2 Y_2 E$
- Leptonic MFV =

  single spurion $(3,\bar{3})$ breaks the symmetry $SU(3)_L \times SU(3)_E$

- **Find:** 1) No flavor-violating decays

  2) If resummation is important ($\longrightarrow$ $(Y_A)_\tau \sim 1$):
  $\mathcal{O}(1)$ deviations in $R_{\tau\tau} = 1$ and $X_{\mu\mu} = \frac{\text{BR}(h\to\mu\mu)}{\text{BR}(h\to\tau\tau)} = \frac{m_\mu^2}{m_\tau^2}$

Predictions

Model	$(Y_\tau/Y_{\tau,\mathrm{SM}})^2$	$X_{\mu\mu}/(m_\mu^2/m_\tau^2)$	$X_{\mu\tau}$
`SM`	1	1	0
`MHDM + NFC`	$(V_{h\ell}^* v/v_\ell)^2$	1	0
`MSSM`	$(\sin\alpha/\cos\beta)^2$	1	0
`1HDM + MFV`	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
`1HDM + FN`	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\lvert U_{23}\rvert^2 v^4/\Lambda^4)$
`2HDM + MFV` $(Y_A)_\tau \sim 1$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	0

$$X_{\mu\mu} \equiv \frac{\mathrm{BR}(h\to\mu^+\mu^-)}{\mathrm{BR}(h\to\tau^+\tau^-)}$$

$$X_{\mu\tau} \equiv \frac{\mathrm{BR}(h\to\mu^\pm\tau^\mp)}{\mathrm{BR}(h\to\tau^+\tau^-)}$$

Dery, Efrati, YH, Nir, JHEP 1305, 039 (2013)

Dery, Efrati, Hiller, YH, Nir, JHEP 1308, 006 (2013)

Summary

- Higgs = opportunity for flavor
- (Progress in the up sector, probe Y_c, Y_{tc} , $\mathrm{BR}(t \to hc)$)

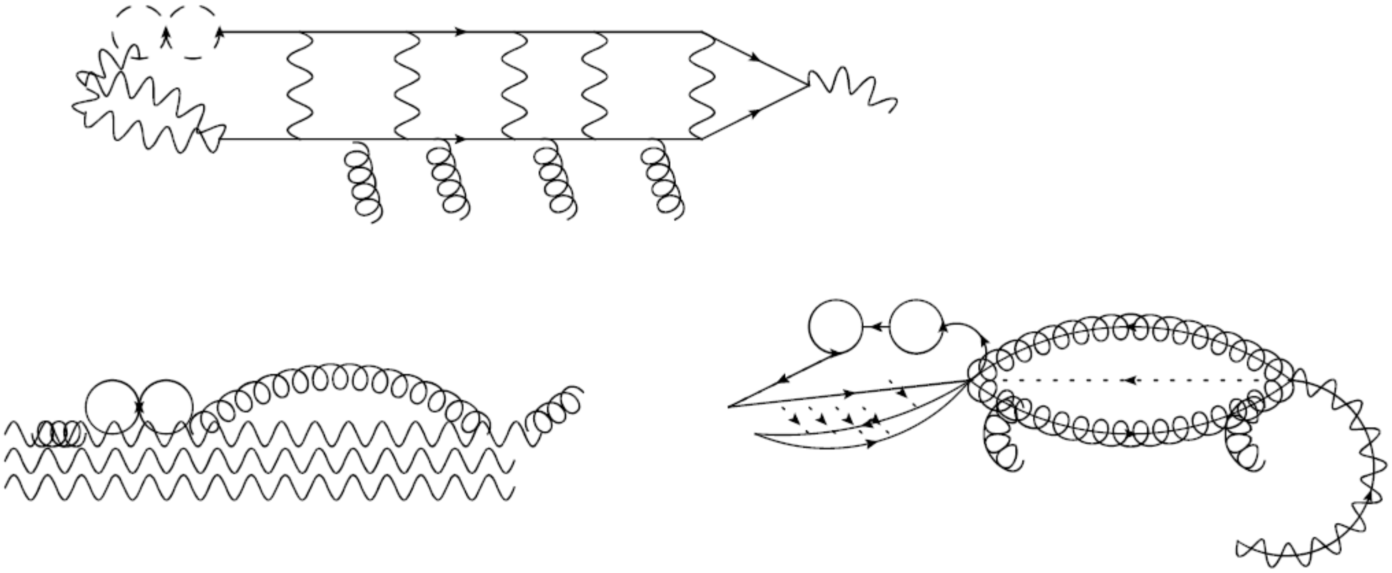
<u>Measure:</u>

- Y_t, Y_b, Y_τ
- $\mathrm{BR}(h \to \mu\mu)/\mathrm{BR}(h \to \tau\tau)$
- $\mathrm{BR}(h \to \mu\tau)/\mathrm{BR}(h \to \tau\tau)$

<u>Test:</u>

- MFV
- NFC
- FN
- .....

Thanks!



Backup

Theoretical predictions

$$\Gamma(h \to \ell^+\ell^-) = \Gamma^{\rm LO}\left(1+\delta^\ell_{\rm QED}\right)\left(1+\delta^\ell_{\rm weak}\right)$$

$$\begin{aligned}
\delta^\ell_{\rm QED} &= \frac{3\alpha}{2\pi}\left(\frac{3}{2} - \log\frac{m_h^2}{m_\ell^2}\right), \\
\delta^\ell_{\rm weak} &= \frac{G_F}{8\pi^2\sqrt{2}}\left[7m_t^2 + m_W^2\left(-5 + \frac{3\log c_W^2}{s_W^2}\right) - m_Z^2\,\frac{6(1-8s_W^2+16s_W^4)-1}{2}\right]
\end{aligned}$$

2HDM with MFV

- 2HDM → Two Yukawa matrices: $-\mathcal{L}_Y = \bar{L}\Phi_1 Y_1^E E + \bar{L}\Phi_2 Y_2^E E$
- Define leptonic MFV =

  single spurion $(3,\bar{3})$ breaks the symmetry $SU(3)_L \times SU(3)_E$
- Spurion options: $\hat{Y}^E,\ Y_1^E,\ Y_2^E,\ Y_M^E \equiv \sqrt{2}M^E/v$
- No loss of generality for $Y_Z^E = a_Z \hat{Y}^E + \ldots$

Dery, Efrati, Hiller, YH, Nir, JHEP 1308, 006 (2013)

2HDM with MFV

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- No loss of generality for $Y_Z^E = a_Z \hat{Y}^E + \ldots$

- Only one of neutral scalars h, H, A couplings to fermions is independent:

$$\begin{aligned} Y_M^E &= -s_{\alpha-\beta} Y_h^E + c_{\alpha-\beta} Y_H^E \\ Y_A^E &= \underline{+c_{\alpha-\beta}} Y_h^E + s_{\alpha-\beta} Y_H^E \end{aligned}$$

(α-β) known from
hZZ coupling

Dery, Efrati, Hiller, YH, Nir, JHEP 1308, 006 (2013)

2HDM with MFV

- For any $S = h, H, A$:

1) $(Y_S)_{\ell\ell'} = 0 \text{ for flavors } \ell \neq \ell'$

2) $\frac{(Y_S)_e}{(Y_S)_\mu} \simeq \frac{m_e}{m_\mu}$

3) $\frac{[(Y_S)_e/(Y_S)_\tau]^2 - (m_e/m_\tau)^2}{[(Y_S)_\mu/(Y_S)_\tau]^2 - (m_\mu/m_\tau)^2} = \frac{m_e^2}{m_\mu^2}\left(1 + \frac{m_\mu^2 - m_e^2}{m_\tau^2}\right)$

- If $\hat{Y}_\tau \sim 1$ ($\longrightarrow (Y_A)_\tau \sim 1$):

$\mathcal{O}(1)$ deviations from $R_{\tau\tau} = 1$ and $\frac{\text{BR}(h\to\mu\mu)}{\text{BR}(h\to\tau\tau)} = \frac{m_\mu^2}{m_\tau^2}$

Dery, Efrati, Hiller, YH, Nir, JHEP 1308, 006 (2013)

2HDM with MFV

$$\begin{aligned}
Y_M^F &= +c_\beta Y_1^F + s_\beta Y_2^F \\
Y_A^F &= -s_\beta Y_1^F + c_\beta Y_2^F \\
Y_h^F &= -s_\alpha Y_1^F + c_\alpha Y_2^F \\
Y_H^F &= +c_\alpha Y_1^F + s_\alpha Y_2^F
\end{aligned}$$

$$\begin{aligned}
Y_M^F &= -s_{\alpha-\beta} Y_h^F + c_{\alpha-\beta} Y_H^F\,, \\
Y_A^F &= +c_{\alpha-\beta} Y_h^F + s_{\alpha-\beta} Y_H^F\,.
\end{aligned}$$

$$(Y_M)_\tau^2 + (Y_A)_\tau^2 = (Y_h)_\tau^2 + (Y_H)_\tau^2$$

$$W_{\tau\mu}^S \equiv \frac{(Y_S^E)_\tau}{y_\tau} - \frac{(Y_S^E)_\mu}{y_\mu}\,, \qquad S = h, H, A$$

$$\frac{W_{\tau\mu}^H}{W_{\tau\mu}^h} = \tan(\alpha - \beta) = \frac{c_V^h}{c_V^H}$$

In 2HDM MFV:

$$(Y_h^U)_{ct}/(Y_h^U)_{tt} \lesssim \hat{Y}_b^2 V_{cb}$$

and so

$$\mathrm{BR}(t \to ch)/\mathrm{BR}(t \to sW) \lesssim 1$$

Current status:

$$\mathrm{BR}(t \to hc) < 0.83\%$$

ATLAS-CONF-2013-081

Ex. V: Higgs-dependent Yukawas

- Only Y_t renormalizable, all other Yukawas from non-renormalizable terms:

$$\mathcal{L} \supset -\frac{\lambda'_{33}}{\Lambda^2}\overline{L_3}E_3\phi(\phi^\dagger\phi) - \frac{\lambda'_{23}}{\Lambda^2}\overline{L_2}E_3\phi(\phi^\dagger\phi) - \frac{\lambda''_{22}}{\Lambda^4}\overline{L_2}E_2\phi(\phi^\dagger\phi)^2 - \frac{\lambda''_{32}}{\Lambda^4}\overline{L_3}E_2\phi(\phi^\dagger\phi)^2 + \text{h.c.}$$

⇒

1) $Y_\tau \simeq 3\,\frac{\sqrt{2}m_\tau}{v}\,, \quad Y_\mu \simeq 5\,\frac{\sqrt{2}m_\mu}{v}$

2) $\frac{Y_\mu}{Y_\tau} \simeq \frac{5}{3}\,\frac{m_\mu}{m_\tau}$

3) $Y_{\tau\mu} = \mathcal{O}(Y_\mu)\,, \qquad \frac{Y_{\mu\tau}}{Y_{\tau\mu}} = \frac{m_\mu}{m_\tau}$