The Flavor of Higgs

Probing the Standard Model and New Physics
at Low and High Energies

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Plan of Talk

1. The flavor puzzles
2. The flavor of Higgs   Dery, Efrati, Hochberg, YN, 1302.3229
3. MFV 2HDM   Dery, Efrati, Hiller, Hochberg, YN, in preparation

The Flavor Puzzles

The SM flavor puzzle

$$Y_t \sim 1, \quad Y_c \sim 10^{-2}, \quad Y_u \sim 10^{-5}$$
$$Y_b \sim 10^{-2}, \quad Y_s \sim 10^{-3}, \quad Y_d \sim 10^{-4}$$
$$Y_\tau \sim 10^{-2}, \quad Y_\mu \sim 10^{-3}, \quad Y_e \sim 10^{-6}$$
$$|V_{us}| \sim 0.2, \quad |V_{cb}| \sim 0.04, \quad |V_{ub}| \sim 0.004, \quad \delta_{\rm KM} \sim 1$$

- For comparison: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 1$
- SM flavor parameters have structure: smallness + hierarchy
- Why? = The SM flavor puzzle
  - Approximate symmetry? Strong dynamics? Location in extra dimension?
- ν flavor surprise: Neither smallness nor (strong) hierarchy
  - Anarchy? Tribimaximal?

The NP flavor puzzle

- $\frac{z_{ij}}{(1\ \text{TeV})^2}\ \bar{q}_i q_j \bar{q}_i q_j$

	$z_{ij} \lesssim$		$\mathcal{I}m(z_{ij}) \lesssim$
$\frac{\Delta m_K}{m_K} = 7.0 \times 10^{-15}$	9×10^{-7}	$\epsilon_K = 2.3 \times 10^{-3}$	4×10^{-9}
$\frac{\Delta m_D}{m_D} = 8.7 \times 10^{-15}$	6×10^{-7}	$A_\Gamma \leq 0.004$	1×10^{-7}
$\frac{\Delta m_B}{m_B} = 6.3 \times 10^{-14}$	5×10^{-6}	$S_{\psi K_S} = 0.67 \pm 0.02$	1×10^{-6}
$\frac{\Delta m_{B_s}}{m_{B_s}} = 2.1 \times 10^{-12}$	2×10^{-4}	$S_{\psi\phi} \leq 0.2$	1×10^{-4}

- The flavor structure of NP@TeV must be highly non-generic:
  Degeneracies/Alignment
- How? Why? = The NP flavor puzzle
- MFV?
  Approximate U(1)? Approximate U(2)?

Can we make progress?

- NP that couples to quarks/leptons $\Longrightarrow$ New flavor parameters (spectrum, flavor decomposition) that can be measured
- The NP flavor structure could be:
  - MFV
  - Related but not identical to SM
  - Unrelated to SM or even anarchical
- The NP flavor puzzle:
  With ATLAS/CMS we will surely understand how it is solved
- The SM flavor puzzle:
  Progress possible if structure not MFV but related to SM

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- $\boxed{h}$ $\Longrightarrow$ The "NP" is already here!
  $Y_{\bar{f}_i f_j}$ are new flavor parameters that can be measured

The Flavor of Higgs

Avital Dery, Aielet Efrati, Yonit Hochberg, YN, arXiv:1302.3229

Present

Observable	Experiment
$R_{\gamma\gamma}$	1.1 ± 0.2
R_{ZZ^*}	1.1 ± 0.2

- $R_f = \frac{\sigma_{\rm prod}{\rm BR}(h\to f)}{[\sigma_{\rm prod}{\rm BR}(h\to f)]^{\rm SM}}$
- Indication that $Y_t = \mathcal{O}(1)$
- The beginning of Higgs flavor physics

Future

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

- What can we learn from $R_{\tau\tau},\ X_{\mu\mu},\ X_{\tau\mu}$?
- Interplay of flavor with electroweak symmetry breaking

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- What can we learn from $R_{\tau\tau},\ X_{\mu\mu},\ X_{\tau\mu}$?
- Interplay of flavor with electroweak symmetry breaking
- ATLAS/CMS: $R_{\tau\tau} \sim 1.0 \pm 0.4, \quad R_{\mu\mu} < 9.8$

MHDM with NFC

- Only one Higgs doublet couples to the charged lepton sector ϕ_ℓ
- $\phi_h = V_{h\ell}\phi_\ell + \cdots$

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$$\Downarrow$$

- $Y_\tau = \frac{V_{h\ell} v}{\langle\phi_l\rangle} \; \frac{\sqrt{2} m_\tau}{v}$

  2HDM type II: $Y_\tau = -\frac{\sin\alpha}{\cos\beta} \; \frac{\sqrt{2} m_\tau}{v}$
- $\frac{Y_\mu}{Y_\tau} = \frac{m_\mu}{m_\tau}$
- $Y_{\mu\tau} = Y_{\tau\mu} = 0$

1HDM with MFV

- $\lambda_{ij}\bar{L}_i\phi E_j + \frac{\lambda'_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{L}_i\phi E_j + \cdots$
- MFV: $\lambda' = a\lambda + b\lambda\lambda^\dagger\lambda + \cdots$

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$$\Downarrow$$

- $Y_\tau = \left(1 + \frac{av^2}{\Lambda^2}\right)\ \frac{\sqrt{2}m_\tau}{v}$
- $\frac{Y_\mu}{Y_\tau} = \left[1 - \frac{2b(m_\tau^2 - m_\mu^2)}{\Lambda^2}\right]\ \frac{m_\mu}{m_\tau}$
- $Y_{\mu\tau} = Y_{\tau\mu} = 0$

1HDM with FN

- $\lambda_{ij}\bar{L}_i\phi E_j + \frac{\lambda'_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{L}_i\phi E_j + \cdots$
- FN: $\lambda'_{ij} = \mathcal{O}(1) \times \lambda_{ij}$

1HDM with FN

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$$\Downarrow$$

- $Y_\tau = \left[1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right] \; \frac{\sqrt{2}m_\tau}{v}$
- $\frac{Y_\mu}{Y_\tau} = \left[1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right] \; \frac{m_\mu}{m_\tau}$
- $Y_{\mu\tau} = \mathcal{O}\left(\frac{|U_{23}| v m_\tau}{\Lambda^2}\right), \quad Y_{\tau\mu} = \mathcal{O}\left(\frac{v m_\tau}{|U_{23}|\Lambda^2}\right)$

Summary: The flavorful h

Model	$R_{\tau^+\tau^-}$	$X_{\mu^+\mu^-}/(m_\mu^2/m_\tau^2)$	$X_{\tau\mu}$
SM	1	1	0
NFC	$(V_{h\ell}v/v_\ell)^2$	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\lvert U_{23}\rvert m_\tau v/\Lambda^2)$

MFV 2HDM

Avital Dery, Aielet Efrati, Gudrun Hiller, Yonit Hochberg, YN, in preparation

MFV in 2HDM's

- Definition: A single $(3,\bar{3})$ spurion breaks $SU(3)_L \times SU(3)_E$
- Ambiguity: $\hat{Y}^E$? Y_1^E? Y_2^E? $\frac{\sqrt{2}}{v}M^E$?
- Answer: No loss of generality as long as $Y_X^E = a_X \hat{Y}^E + \cdots$
- Caution: It may be that $a_X \ll 1$ ($\hat{Y}_\tau = \mathcal{O}(1) \;\Leftrightarrow\; \frac{\sqrt{2}m_\tau}{v} \ll 1$)

MLFV predictions

- For any $S = h, H, A$:
  - $(Y_s)_{\ell\ell'} = 0$ for $\ell \neq \ell'$
  - $\frac{(Y_S)_e}{(Y_S)_\mu} \simeq \frac{m_e}{m_\mu}$
  - $\frac{[(Y_S)_e/(Y_S)_\tau]^2 - (m_e/m_\tau)^2}{[(Y_S)_\mu/(Y_S)_\tau]^2 - (m_\mu/m_\tau)^2} \simeq \frac{m_e^2}{m_\mu^2}\left(1 + \frac{m_\mu^2 - m_e^2}{m_\tau^2}\right)$

  - If $\hat{Y}_\tau = \mathcal{O}(1)$:
    $\mathcal{O}(1)$ deviations from $R_{\tau\tau} = 1$ and from
    $\mathrm{BR}(h \to \mu\mu)/\mathrm{BR}(h \to \tau\tau) = m_\mu^2/m_\tau^2$

MQFV predictions: The up sector

- $\frac{(Y_S^U)_{ut}}{(Y_S^U)_{ct}} \simeq \frac{V_{ub}}{V_{cb}}$
- $\frac{(Y_S^U)_{tu}}{(Y_S^U)_{tc}} \simeq \frac{V_{ub}^*}{V_{cb}^*}\frac{m_u}{m_c}$
- $\frac{(Y_S^U)_u}{(Y_S^U)_c} \simeq \frac{m_u}{m_c}$
- $\frac{(Y_S^U)_u/(Y_S^U)_t - m_u/m_t}{(Y_S^U)_c/(Y_S^U)_t - m_c/m_t} \simeq \frac{m_u}{m_c}$
- If $\hat{Y}_b \ll 1$: $\frac{(Y_S^U)_{cu}}{(Y_S^U)_{uc}} \simeq \frac{V_{ub}^* V_{cb}}{V_{ub} V_{cb}^*} \frac{\left(1+\frac{m_s^2}{m_b^2}\frac{V_{cs}V_{us}^*}{V_{cb}V_{ub}^*}\right)}{\left(1+\frac{m_s^2}{m_b^2}\frac{V_{us}V_{cs}^*}{V_{ub}V_{cb}^*}\right)} \frac{m_u}{m_c}$

MQFV predictions: The down sector

- $\frac{(Y_S^D)_{db}}{(Y_S^D)_{sb}} \simeq \frac{V_{td}^*}{V_{ts}^*}$
- $\frac{(Y_S^D)_{bd}}{(Y_S^D)_{bs}} \simeq \frac{V_{td}}{V_{ts}} \frac{m_d}{m_s}$
- $\frac{(Y_S^D)_{sd}}{(Y_S^D)_{ds}} \simeq \frac{V_{td} V_{ts}^*}{V_{td}^* V_{ts}} \frac{m_d}{m_s}$
- $\frac{(Y_S^D)_{d}}{(Y_S^U)_{s}} \simeq \frac{m_d}{m_s}$
- $\frac{(Y_S^D)_d/(Y_S^D)_b - m_d/m_b}{(Y_S^D)_s/(Y_S^D)_b - m_s/m_b} \simeq \frac{m_d}{m_s}$
- If $\hat{Y}_b \ll 1$:
  - $\frac{(Y_S^D)_{bs}}{(Y_S^D)_{sb}} \simeq \frac{V_{tb}^* V_{ts}}{V_{ts}^* V_{tb}} \frac{m_s}{m_b}$
  - $\frac{(Y_S^D)_{ds}}{(Y_S^D)_{sb}} \simeq \frac{V_{td}^* V_{ts}}{V_{ts}^* V_{tb}} \frac{m_s}{m_b}$

h Physics = New Flavor Arena

Measure:

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

Test:

- MFV
- FN
- NFC
- ...