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2HDM with MFV

(another point of view)

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Introduction

SM
MFV
2HDM

Standard Model flavor structure

The Standard Model, in the absence of Yukawa interactions gains

$G = \mathrm{SU}(3)_Q \times \mathrm{SU}(3)_U \times \mathrm{SU}(3)_D \times \mathrm{SU}(3)_L \times \mathrm{SU}(3)_E$,

broken by a single spurion in each sector

$$Y^u \sim (3, \bar{3}, 1,1,1)$$
$$Y^d \sim (3,1, \bar{3}, 1,1)$$
$$Y^e \sim (1,1,1,3, \bar{3})$$

Minimal Flavor Violation

Light New Physics, coupled to the SM fermions, should have very non generic flavor structure

An extreme solution: Minimal Flavor Violation

- All Lagrangian terms (SM&NP) should be formally invariant under $G = SU(3)^5$
- G broken by a single spurion in each sector

- Straightforward to implement in models with Natural Flavor Conservation, in which there is a single Yukawa in each sector

$$Y^u = \frac{\sqrt{2}M^u}{v_u} \qquad Y^d = \frac{\sqrt{2}M^d}{v_d} \qquad Y^e = \frac{\sqrt{2}M^e}{v_e}$$

2HDM with MFV

Generic 2HDM – Two Yukawa matrices for each sector

$$L_{\mathrm{Y}} = -\sum_i \bar{Q}\tilde{\phi}_i Y_i^u U + \bar{Q}\phi_i Y_i^d D + \bar{L}\phi_i Y_i^e E$$

How to implement the idea of MFV?

- Are there basic spurions? Y_1? Y_2? Y_M?
- What are the predictions of 2HDM with MFV?
- Can it be tested in the near future?

Previous works:

- Assume approximate NFC or alignment (see talk by Varzielas)
- Use different definition for MFV (see talk by Rebelo)

Insights on the generic 2HDM

Physical scalars $S = h, H, A, H^{\pm}$ with

$$Y_M^f = +c_\beta Y_1^f + s_\beta Y_2^f = \sqrt{2}M^f/v$$
$$Y_h^f = -s_\alpha Y_1^f + c_\alpha Y_2^f$$

$$Y_H^f = Y_h^f \tan(\alpha - \beta) + Y_M^f/\cos(\alpha - \beta)$$
$$Y_A^f = Y_h^f/\cos(\alpha - \beta) + Y_M^f \tan(\alpha - \beta)$$

$(\alpha - \beta)$ known from hWW and hZZ coupling

Insights on the generic 2HDM

1. Measuring Y_h^f is sufficient to predict $Y_{H,A}^f$
   (see talks by Ginzburg & Krawczyk)
2. There is no preferred basis for defining $\phi_{1,2}$, therefore,
   neither α nor β can be observed, only $(\alpha - \beta)$ (see talk by Haber)
3. $\frac{W_{\tau\mu}^H}{W_{\tau\mu}^h} = \tan(\alpha - \beta)$ with $W_{\tau\mu}^S = \frac{(Y_S)_\tau}{m_\tau} - \frac{(Y_S)_\mu}{m_\mu}$

MFV in the Lepton sector

Minimal Lepton Flavor Violation

$G^{\ell} = SU(3)_L \times SU(3)_E$ with one basic spurion $\hat{Y} \sim (3, \overline{3})$ which breaks this symmetry

Claim: the best spurion choice is Y_M^e

- No loss of generality since neither $Y_{1,2}^e$ nor $\hat{Y}$ are known
- Measured

$$Y_S^e = \left[A_S + B_S \lambda_M^e \lambda_M^{e\dagger} + C_S \left(\lambda_M^e \lambda_M^{e\dagger}\right)^2 + \cdots\right] \lambda_M^e$$

with $\lambda = \mathrm{diag}(y_1, y_2, y_3)$

MLFV predictions

1. No flavor changing couplings in the minimal MLFV
   (see talk by Dery)
2. 9 observables, only 3 independent
3. Universality relations may have large corrections

$$\frac{(Y_S)_\mu}{(Y_S)_\tau} = \frac{m_\mu}{m_\tau}\left(1 + \mathcal{O}(\hat{Y}_\tau^2)\right)$$

4. Three generation relation

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

MFV in the Quark sector

Minimal quark flavor violation

Two spurions breaking $G^q = SU(3)_Q \times SU(3)_U \times SU(3)_D$

Claim: the best spurion choices are Y_M^u and Y_M^d

- No loss of generality
- Measured

$$U \text{ mass basis}: \; Y_S^U = (A_S^U + B_S^U \lambda_u^2 + C_S^U V \lambda_d^2 V^\dagger)\lambda_u,$$
$$D \text{ mass basis}: \; Y_S^D = (A_S^D + B_S^D \lambda_d^2 + C_S^D V^\dagger \lambda_u^2 V)\lambda_d,$$

With V=CKM & $\lambda = \mathrm{diag}(y_1, y_2, y_3)$

MQFV predictions

Various relations arise between different generations

$$\frac{(Y_S^U)_{uc}}{(Y_S^U)_{ct}} = \frac{V_{ub}V_{cb}^*}{V_{cb}V_{tb}^*}\left(1+\frac{m_s^2}{m_b^2}\frac{V_{us}V_{cs}^*}{V_{ub}V_{cb}^*}\right)\frac{m_c}{m_t}.$$

$$\frac{(Y_S^U)_{cu}}{(Y_S^U)_{uc}} = \frac{V_{ub}^*V_{cb}}{V_{ub}V_{cb}^*}\frac{\left(1+\frac{m_s^2}{m_b^2}\frac{V_{cs}V_{us}^*}{V_{cb}V_{ub}^*}\right)}{\left(1+\frac{m_s^2}{m_b^2}\frac{V_{us}V_{cs}^*}{V_{ub}V_{cb}^*}\right)}\frac{m_u}{m_c}$$

$$\frac{(Y_S^U)_u}{(Y_S^U)_c} = \frac{m_u}{m_c}\left(1+\mathcal{O}(y_t^2)\right)$$

$$\frac{(Y_S^U)_c}{(Y_S^U)_t} = \frac{m_c}{m_t}\left(1+\mathcal{O}(|V_{cb}|^2)\right)$$

$$\frac{(Y_S^U)_{ut}}{(Y_S^U)_{ct}} = \frac{V_{ub}}{V_{cb}},$$

$$\frac{(Y_S^U)_{tu}}{(Y_S^U)_{tc}} = \frac{V_{ub}^*}{V_{cb}^*}\frac{m_u}{m_c}$$

$$\frac{(Y_S^D)_d}{(Y_S^U)_s} = \frac{m_d}{m_s}\left(1+\mathcal{O}(y_t^2|V_{ts}|^2)\right)$$

$$\frac{(Y_S^D)_s}{(Y_S^U)_b} = \frac{m_s}{m_b}\left(1+\mathcal{O}(y_t^2|V_{tb}|^2)\right)$$

$$\frac{(Y_S^D)_{ds}}{(Y_S^D)_{sb}} = \frac{V_{td}^*V_{ts}}{V_{ts}^*V_{tb}}\frac{m_s}{m_b} \qquad \frac{(Y_S^D)_{bs}}{(Y_S^D)_{sb}} = \frac{V_{tb}^*V_{ts}}{V_{ts}^*V_{tb}}\frac{m_s}{m_b};$$

$$\frac{(Y_S^D)_{db}}{(Y_S^D)_{sb}} = \frac{V_{td}^*}{V_{ts}^*},$$

$$\frac{(Y_S^D)_{bd}}{(Y_S^D)_{bs}} = \frac{V_{td}}{V_{ts}}\frac{m_d}{m_s},$$

$$\frac{(Y_S^D)_{sd}}{(Y_S^D)_{ds}} = \frac{V_{td}V_{ts}^*}{V_{td}^*V_{ts}}\frac{m_d}{m_s}.$$

$$\frac{(Y_S^U)_{tc}}{(Y_S^U)_{ct}} = \frac{V_{tb}V_{cb}^*}{V_{cb}V_{tb}^*}\frac{m_c}{m_t},$$

$$\frac{(Y_S^U)_u/(Y_S^U)_t - m_u/m_t}{(Y_S^U)_c/(Y_S^U)_t - m_c/m_t} = \frac{m_u}{m_c}\left(1+\frac{m_c^2-m_u^2}{m_t^2}\right)$$

$$\frac{(Y_S^D)_d/(Y_S^D)_b - m_d/m_b}{(Y_S^D)_s/(Y_S^D)_b - m_s/m_b} = \frac{m_d}{m_s}\left(1+\frac{|V_{ts}|^2-|V_{td}|^2}{|V_{tb}|^2}\right)$$

MQFV predictions (highlights)

1. Y_{ct} is the largest off diagonal coupling, obeying

$$\frac{(Y_S^U)_{ct}}{(Y_S^U)_{tt}} \leq V_{cb}$$

2. Off-diagonal couplings

$$\frac{(Y_S^U)_{ut}}{(Y_S^U)_{ct}} = \frac{V_{ub}}{V_{cb}} \qquad \frac{(Y_S^D)_{db}}{(Y_S^D)_{sb}} = \frac{V_{td}^*}{V_{ts}^*}$$

3. Diagonal couplings may exhibit large deviations from universality

$$\frac{(Y_S^U)_c}{(Y_S^U)_t} = \frac{m_c}{m_t}\left(1 + \mathcal{O}(y_t^2)\right) \qquad \frac{(Y_S^U)_s}{(Y_S^U)_b} = \frac{m_s}{m_b}\left(1 + \mathcal{O}(y_t^2)\right)$$

Conclusions

2HDM with MFV – conceptual points

1. MFV is not straightforwardly implemented in models without NFC
2. One can choose as the “basic” spurions any matrices that transform correctly
3. A convenient choice is then the mass matrices

2HDM with MFV - predictions

1. Once $H\&A$ will be discovered, their couplings are predicted (2HDM)
2. The ratios between flavor changing couplings in the quark sector depends on the quark masses and CKM angles (some may exhibit large corrections)
3. Diagonal couplings may largely deviate from universality

2HDM with MFV – future test

1. Search for $h \to \tau\mu$
   - If observed, the simplest MLFV will be excluded
   - CMS favors $BR[h \to \tau\mu] \neq 0$ at 2.5σ (see talk by Pieri)
2. Searches for $h \to \tau\tau$ and $h \to \mu\mu$
   - If $\frac{BR[h\to\tau\tau]}{BR[h\to\mu\mu]} = \frac{m_\tau^2}{m_\mu^2}$ is violated, can be explained within MLFV
   - Naïve LHC combination already gives $\frac{y_\tau}{y_\mu} \geq \frac{1}{5}\frac{m_\tau}{m_\mu}$
3. Search for $t \to ch$
   - If $\frac{y_{ct}}{y_t} \geq V_{cb}$ is observed, MQFV will be excluded
   - CMS current bound $y_{ct} \leq 0.14$

Thank you

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