A Selection of Models with Modified (Quark) Yukawa Couplings

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Based on analysis in: F.B., J. Brod, P. Uttayarat, and J. Zupan [arXiv:1504.04022]

Overview

Will consider the following 'selection' of models

- Dim. 6 operators with MFV
- Multi-Higgs-doublet models with natural flavor conservation
- Type II two Higgs doublet model
- Giudice-Lebedev model (+ modification)
- Models with a pNGB Higgs

Motivation

A fit to the data where all Higgs couplings are fixed to their SM values except for one light-quark Yukawa at a time gives (Kagan, Perez, Petriello, Soreq, Stoynev, and Zupan [arXiv:1406.1722])

$$|\kappa_u| < 0.98 m_b/m_u$$
$$|\kappa_d| < 0.93 m_b/m_d$$
$$|\kappa_s| < 0.70 m_b/m_d$$

However, such large values are not likely to be obtained in a complete model.

This motivates a survey of models of new physics with viable flavor structures

Mod. Yukawas are interesting because, e.g.: DM, dipole moms., etc.

Setup

Flavor diagonal — Flavor violating

$$\mathcal{L}_{\rm eff,q} = -\kappa_q \frac{m_q}{v_W}\bar{q}qh - i\tilde{\kappa}_q \frac{m_q}{v_W}\bar{q}\gamma_5 qh - \left[\left(\kappa_{qq'} + i\tilde{\kappa}_{qq'}\right)\bar{q}_L q'_R h + \text{h.c.}\right]$$

CP conserving — CP violating

$\Re\left(\kappa_{qq'} + i\tilde{\kappa}_{qq'}\right)$: CPC

$\Im\left(\kappa_{qq'} + i\tilde{\kappa}_{qq'}\right)$: CPV

In the SM, $\kappa_q = 1$ while $\tilde{\kappa}_q = \kappa_{qq'} = \tilde{\kappa}_{qq'} = 0$

For lepton Yukawas, see, e.g.:

Dery, Efrati, Nir, Soreq, & Susic [arXiv:1408.1371]; Dery, Efrati, Hiller, Hochberg, & Nir [arXiv:1304.6727]; Dery, Efrati, Hochberg, & Nir [arXiv:1302.3229]

Minimal Flavor Violation

- $\mathcal{L}_{\mathrm{SM}}$ enjoys an enhanced symmetry G_F in the limit $m_q \to 0$
- $G_F = SU(3)_Q \times SU(3)_U \times SU(3)_D$
- Symmetry is retained if Yukawa matrices are promoted to spurions that transform under G_F as

$$Y_U \sim (\mathbf{3}, \overline{\mathbf{3}}, \mathbf{1}), \qquad Y_D \sim (\mathbf{3}, \mathbf{1}, \overline{\mathbf{3}})$$

- The Yukawa interactions $u^c Y_U^\dagger q H$, $d^c Y_D^\dagger q H^c$ are then formally invariant under G_F

The SM Yukawas are the only source of flavor breaking.

[1] Chivukula & Georgi (1987); Hall & Randall (1990); Buras, Gambino, Gorbahn, Jager & Silvestrini (2001); D'Ambrosio, Giudice, Isidori & Strumia (2002);

Dim. 6 operators with MFV

$$\mathcal{L}_{\rm EFT} = Y_u \bar{Q}_L H^c u_R + Y_d \bar{Q}_L H d_R + \frac{Y'_u}{\Lambda^2} \bar{Q}_L H^c u_R (H^\dagger H) + \frac{Y'_d}{\Lambda^2} \bar{Q}_L H d_R (H^\dagger H) + \text{h.c.}$$

$$M_{u,d} = \frac{v_W}{\sqrt{2}} \left(Y_{u,d} + Y'_{u,d} \frac{v_W^2}{2\Lambda^2} \right), \qquad y_{u,d} = Y_{u,d} + 3 Y'_{u,d} \frac{v_W^2}{2\Lambda^2}$$

Coefficients are different,

→ $M_{u,d}$ & $y_{u,d}$ are not simult. diagonalizable

Coefficients of the D6 operators

Flavor basis

$$Y'_u = a_u Y_u + b_u Y_u Y_u^\dagger Y_u + c_u Y_d Y_d^\dagger Y_u + \cdots$$
$$Y'_d = a_d Y_d + b_d Y_d Y_d^\dagger Y_d + c_d Y_u Y_u^\dagger Y_d + \cdots$$

Mass basis

$$Y'_u = \left[a_u + b_u Y_u Y_u^\dagger + c_u V Y_d Y_d^\dagger V^\dagger\right] Y_u + \cdots$$
$$Y'_d = \left[a_d + b_d Y_d Y_d^\dagger + c_d V Y_u Y_u^\dagger V^\dagger\right] Y_d + \cdots$$

The Yukawas are then given by

Flavor violating

$$y_u = \left[1 + \frac{v_W^2}{\Lambda^2}\left(a_u + b_u (y_{\rm SM}^u)^2 + c_u V (y_{\rm SM}^d)^2 V^\dagger + \cdots\right)\right] y_{\rm SM}^u$$
$$y_d = \left[1 + \frac{v_W^2}{\Lambda^2}\left(a_d + b_d (y_{\rm SM}^d)^2 + c_d V (y_{\rm SM}^u)^2 V^\dagger + \cdots\right)\right] y_{\rm SM}^d$$

MHDM with NFC [§]

For *N* Higgs doublets with the Natural Flavor Conservation (NFC) assumption, only one Higgs doublet is allowed to couple to up-type and one to down-type fermions.

All the vevs must satisfy the sum rule

$$v_W^2 = \sum_i v_i^2$$

and the neutral scalar component of the i[th] doublet is

$$\left(v_i + h_i\right) / \sqrt{2}$$

The fields h_i are linear combinations of the mass eigenstates

$$h_i = V_{hi}\, h + \ldots$$

Finally, the Yukawas are modified by

$$\kappa_u = \kappa_c = \kappa_t = V_{hu} \frac{v_W}{v_u}\,, \qquad \kappa_d = \kappa_s = \kappa_b = V_{hd} \frac{v_W}{v_d}$$

[§] Glashow and Weinberg [Phys.Rev. D15, 1958 (1977)]; Paschos [Phys.Rev. D15, 1966 (1977)]

Type II 2HDM §

This is a special case of MHDM with NFC with

$$v_u = \sin\beta\, v_W\,, \qquad v_d = \cos\beta\, v_W$$

The mixing of h_u and h_d into the mass eigenstates *h* and *H* is given by

$$\begin{pmatrix} h_u \\ h_d \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

The up- and down-type quark Yukawas are then modified as follows

$$\kappa_u = \kappa_c = \kappa_t = \frac{\cos\alpha}{\sin\beta}\,,$$

$$\kappa_d = \kappa_s = \kappa_b = -\frac{\sin\alpha}{\cos\beta}\,,$$

§ See, e.g., H. Haber and G. Kane [Phys.Rept. 117 (1985) 75-263]; J. Gunion, H. Haber, G. Kane, S. Dawson [Front.Phys. 80 (2000) 1-448]

Higgs-dependent Yukawa couplings [§]

$$Y_{ij}(H) = \sum_{n=0}^{\infty} c_{ij}^{(n)} \left(\frac{H^\dagger H}{M^2}\right)^n \quad \text{where} \quad c_{ij}^{u,d} \sim \mathcal{O}(1),\ n_{ij}^{u,d} \in \mathbb{Z}^*$$

$$\mathcal{L}_q = c_{ij}^u \left(\frac{H^\dagger H}{M^2}\right)^{n_{ij}^u} \bar{Q}_{L,i} u_{R,j} H^c + c_{ij}^d \left(\frac{H^\dagger H}{M^2}\right)^{n_{ij}^d} \bar{Q}_{L,i} d_{R,j} H + \text{h.c.}$$

Ansatz: $n_{ij}^{u,d} = a_i + b_j^{u,d}$ with $a = (1,1,0),\ b^d = (2,1,1),\ b^u = (2,0,0)$

This fixes the expansion parameter $\epsilon \equiv \frac{v_W^2}{M^2} = \frac{m_b}{m_t} \approx \frac{1}{60}$

The Yukawas take the form

$$y_{ij}^{u,d} = (2n_{ij}^{u,d} + 1)(y_{ij}^{u,d})_{\text{SM}}$$

Note that $y_{ij}^{u,d}$ are not diagonal in the mass basis

[§] G. Giudice and O. Lebedev [arXiv:0804.1753]

GL2: a modified GL model

Why? Because in simplest GL, $\kappa_b \sim 3$ and is excluded at 6.8σ (CMS)

Solution: extend Higgs sector → H_u, H_d (i.e. like a Type II 2HDM)

Gives acceptable Higgs phenomenology provided that

$$\kappa_b = -\sin\alpha / \cos\beta \simeq 1$$
$$\kappa_t = \cos\alpha / \sin\beta \simeq 1$$

Ansatz: $n_{ij}^{u,d} = a_i + b_j^{u,d}$ with $a = (1,1,0)$, $b^d = (1,0,0)$, $b^u = (2,0,0)$

pNGB Higgs §

Assuming that the fermions couple linearly to composite operators (D. B. Kaplan [Nucl.Phys. B365 (1991) 259-278])

$$\lambda^q_{L,i}\bar{Q}_{L,i}O^i_R + \lambda^u_{R,j}\bar{u}_{R,j}O^j_L + h.c.$$

In the case where each SM fermion is coupled to only one composite operator (K. Agashe and R. Contino [arXiv:0906.1542])

$$Y_u\bar{Q}_L H u_R + Y'_u\bar{Q}_L H u_R\frac{(H^\dagger H)}{\Lambda^2} + \ldots \quad \rightarrow \quad c^u_{ij}\, P(h/f)\,\bar{Q}^i_L H u^j_R$$

With $P(h/f) = a_0 + a_2(h/f)^2 + \ldots$ and $f \sim \mathcal{O}(v_W)$

And so the corrections to the Yukawa couplings from these operators are flavor diagonal

$$\kappa_q \sim 1 + \mathcal{O}\left(\frac{v_W^2}{f^2}\right)$$

§ Dugan, Georgi, and Kaplan [Nucl.Phys. B254, 299 (1985)]; Georgi, Kaplan, and Galison [Phys.Lett. B143, 152 (1984)]; Kaplan, Georgi, and Dimopoulos [Phys.Lett. B136, 187 (1984)]

pNGB Higgs – flavor violation

Flavor violation originates from the kinetic terms

$$\bar{q}_L i\not{D} q_L \frac{H^\dagger H}{\Lambda^2},\ \bar{u}_R i\not{D} u_R \frac{H^\dagger H}{\Lambda^2}, \ldots$$

These operators arise after integrating out vector resonances with mass

$$M_* \sim \Lambda$$

The NDA estimates for these contributions is

$$\kappa^u_{ij} \sim 2y_*^2 \frac{v_W^2}{M_*^2}\left(\lambda^q_{L,i}\lambda^q_{L,j}\frac{m_{u_j}}{v_W} + \lambda^u_{R,i}\lambda^u_{R,j}\frac{m_{u_i}}{v_W}\right)$$

There is also a contribution the to the flavor diagonal Yukawas

$$\Delta\kappa_{q_i} \sim 2y_*^2 \frac{v_W^2}{M_*^2}\left[\left(\lambda^q_{L,i}\right)^2 + \left(\lambda^u_{R,i}\right)^2\right]$$

Predictions for the diag. up-type yukawas

Model	κ_b	$\kappa_{s(d)}/\kappa_b$	$\tilde{\kappa}_b/\kappa_b$	$\tilde{\kappa}_{s(d)}/\kappa_b$
SM	1	1	0	0
NFC	$V_{hd}\, v_W/v_d$	1	0	0
MSSM	$-\sin\alpha/\cos\beta$	1	0	0
GL	$\simeq 3$	$\simeq 5/3(7/3)$	$\mathcal{O}(1)$	$\mathcal{O}(\kappa_{s(d)}/\kappa_b)$
GL2	$-\sin\alpha/\cos\beta$	$\simeq 3(5)$	$\mathcal{O}(\epsilon^2)$	$\mathcal{O}(\kappa_{s(d)}/\kappa_b)$
MFV	$1+\frac{\mathrm{Re}(a_d v_W^2+2c_d m_t^2)}{\Lambda^2}$	$1-\frac{2\mathrm{Re}(c_d)m_t^2}{\Lambda^2}$	$\frac{\Im(a_d v_W^2+2c_d m_t^2)}{\Lambda^2}$	$\frac{\Im(a_d v_W^2+2c_d \lvert V_{ts(td)}\rvert^2 m_t^2)}{\Lambda^2}$
RS	$1-\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$
pNGB	$1+\mathcal{O}\left(\frac{v_W^2}{f^2}\right)+\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$	$1+\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$

Predictions for the diag. down-type yukawas

Model	κ_b	$\kappa_{s(d)}/\kappa_b$	$\tilde{\kappa}_b/\kappa_b$	$\tilde{\kappa}_{s(d)}/\kappa_b$
SM	1	1	0	0
NFC	$V_{hd}\, v_W/v_d$	1	0	0
MSSM	$-\sin\alpha/\cos\beta$	1	0	0
GL	$\simeq 3$	$\simeq 5/3(7/3)$	$\mathcal{O}(1)$	$\mathcal{O}(\kappa_{s(d)}/\kappa_b)$
GL2	$-\sin\alpha/\cos\beta$	$\simeq 3(5)$	$\mathcal{O}(\epsilon^2)$	$\mathcal{O}(\kappa_{s(d)}/\kappa_b)$
MFV	$1+\frac{\mathrm{Re}(a_d v_W^2+2c_d m_t^2)}{\Lambda^2}$	$1-\frac{2\mathrm{Re}(c_d)m_t^2}{\Lambda^2}$	$\frac{\Im(a_d v_W^2+2c_d m_t^2)}{\Lambda^2}$	$\frac{\Im(a_d v_W^2+2c_d \lvert V_{ts(td)}\rvert^2 m_t^2)}{\Lambda^2}$
RS	$1-\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$
pNGB	$1+\mathcal{O}\left(\frac{v_W^2}{f^2}\right)+\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$	$1+\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$

Predictions for the off-diagonal couplings

Up-type quarks

Model	$\kappa_{ct(tc)}/\kappa_t$	$\kappa_{ut(tu)}/\kappa_t$	$\kappa_{uc(cu)}/\kappa_t$
GL & GL2	$\epsilon(\epsilon^2)$	$\epsilon(\epsilon^2)$	ϵ^3
MFV	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{cb}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(c)}}{v_W}$	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(u)}}{v_W}$	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub(cb)} V_{cb(ub)}^*\right)}{\Lambda^2}\frac{\sqrt{2}m_{c(u)}}{v_W}$
RS	$\sim \lambda^{(-)2}\frac{m_{t(c)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$	$\sim \lambda^{(-)3}\frac{m_{t(u)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$	$\sim \lambda^{(-)1}\frac{m_{c(u)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$
pNGB	$\mathcal{O}(y_*^2\frac{m_t}{v_W}\frac{\lambda_{L(R),2}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_t}{v_W}\frac{\lambda_{L(R),1}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_c}{v_W}\frac{\lambda_{L(R),1}\lambda_{L(R),2}m_W^2}{M_*^2})$

Down-type quarks

Model	$\kappa_{bs(sb)}/\kappa_b$	$\kappa_{bd(db)}/\kappa_b$	$\kappa_{sd(ds)}/\kappa_b$
GL & GL2	$\epsilon^3(\epsilon^2)$	ϵ^2	$\epsilon^3(\epsilon^4)$
MFV	$\frac{\mathrm{Re}\left(c_d m_t^2 V_{ts}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{s(b)}}{v_W}$	$\frac{\mathrm{Re}\left(c_d m_t^2 V_{td}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{d(b)}}{v_W}$	$\frac{\mathrm{Re}\left(c_d m_t^2 V_{ts(td)}^* V_{td(ts)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{s(d)}}{v_W}$
RS	$\sim \lambda^{(-)2}\frac{m_{b(s)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$	$\sim \lambda^{(-)3}\frac{m_{b(d)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$	$\sim \lambda^{(-)1}\frac{m_{s(d)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$
pNGB	$\mathcal{O}(y_*^2\frac{m_b}{v_W}\frac{\lambda_{L(R),2}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_b}{v_W}\frac{\lambda_{L(R),1}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_s}{v_W}\frac{\lambda_{L(R),1}\lambda_{L(R),2}m_W^2}{M_*^2})$

Conclusions

- Modified light-quark Yukawa couplings in a selection of NP models do not saturate the bounds obtained from global fits

- In the models considered in this talk, flavor violating couplings are subleading to the flavor conserving ones

Backup