Possible FCNC and LFV loop-mediated suppression in the scalar extended SM

Melina Gómez Bock
(In collaboration with **Lao-Tsé López-Lozano**)

ITESM-Puebla,
UPAEP

XIX Mexican Workshop on Particles and Fields

October 2025

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Contents

Motivation

Flavor Violation

Evidence for neutrino mixing, possibly non-universality for weak leptonic couplings.

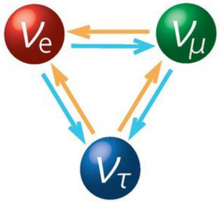
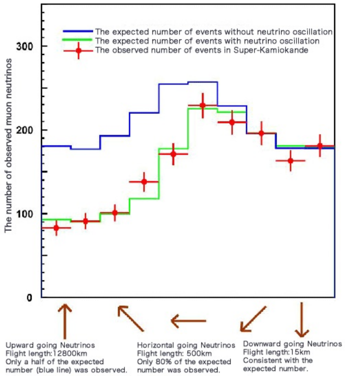


Figure: *neutrino mixing- flavor violation*



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Motivation

BSM - DM candidates

Dark Matter

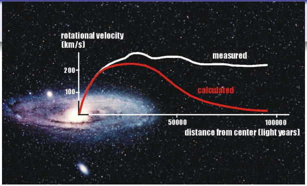

Figure: *DM evidence*

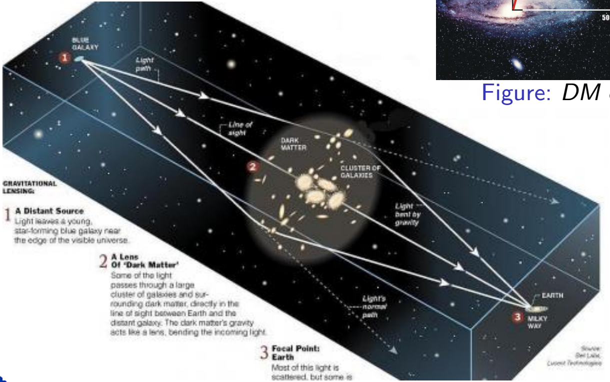

Figure: *Gravitational Lensing.*

Motivation

BSM - scalar sector

Particle spectrum, possible more scalar particles

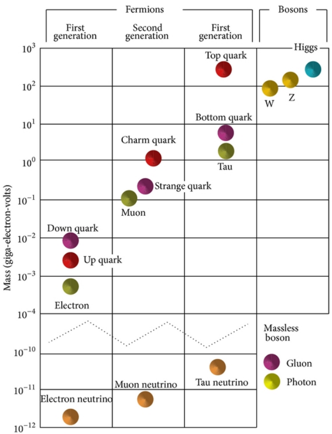

Figure: *Particle spectrum.*

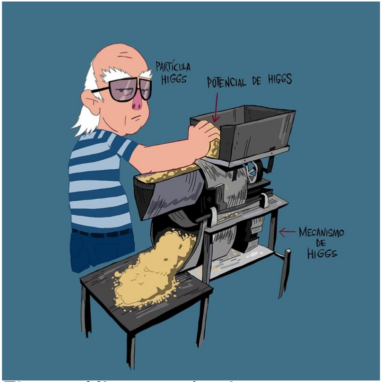

Figure: *Higgs mechanism (Mexican view)*

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The SM scalar sector

SM Higgs doublet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Higgs Lagrangian

$$\mathcal{L}_H = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \tag{1}$$

Once a vev is chosen $\langle 0|\Phi|0\rangle = v \neq 0$ the EW symmetry is broken:

- ⋆ Gauge bosons acquire mass from the kinetic term.
- ⋆ Fermions acquire mass through the Yukawa couplings.
- ⋆ The Higgs mass is obtained from the Higgs potential after EW SSB.

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The Model 2HDM-III

A minimal extension of the SM which allows for flavor changing neutral currents at the level of the Lagrangian is provided by the 2HDM-III, with Flavour Violation (FV) at Leading Order (LO). Multi-Higgs models additional scalar spectrum. Extending the scalar sector more than one Higgs leads to increasing the scalar spectrum of particles:

- SM $\rightarrow h^0$
- 2HDM $\rightarrow h^0,\ H^0,\ A^0,\ H^{\pm}$

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The Model 2HDM-III

Two complex SU(2) Higgs doublets:

$$\Phi_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

physical Higgs particle spectrum 5:

ϕ_i , $CP = 1 \rightarrow$ two scalar fields: h^0, H^0,

χ_i , $CP = -1 \rightarrow$ one pseudo scalar fields: A^0.

and

$\phi^{\pm}$, $\rightarrow$ two charged fields: $H^{\pm}$

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The Model 2HDM-III

SSB: Assuming the scalar fields to develop nonzero vacuum expectation values that break $SU(2)_L$

$$\langle \Phi_1 \rangle = v_1 \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad \langle \Phi_2 \rangle = v_2 \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{2}$$

Defining: $\tan\beta = \frac{v_2}{v_1}$ and $v = (v_1^2 + v_2^2)^{1/2} \approx 246\ GeV$.
The Lagrangian density describing the dynamics with two doubles would be:

$$\mathcal{L}_{\Phi_1,\Phi_2} = (D^\mu \Phi_1)^\dagger (D_\mu \Phi_1) + (D^\mu \Phi_2)^\dagger (D_\mu \Phi_2) - V(\Phi_1, \Phi_2) \tag{3}$$

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The Model 2HDM-III

2HDM Higgs potential

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = \mu_1^2\Phi_1^\dagger\Phi_1 + \mu_2^2\Phi_2^\dagger\Phi_2 - (\mu_{12}^2\Phi_1^\dagger\Phi_2 + h.c.) \\
+\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}[\lambda_5(\Phi_1^\dagger\Phi_2)^2 \\
+[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)](\Phi_1^\dagger\Phi_2) + h.c.]
\end{aligned}
$$

In order to preserve CP symmetry we consider $\lambda_6 = \lambda_7 = 0$

The Model 2HDM-III

The interaction with Fermions is given through the Yukawa Lagrangian:

$$L_Y^q = Y_1^u \overline{Q}'_L \tilde{\Phi}_1 u'_R + Y_2^u \overline{Q}'_L \tilde{\Phi}_2 u'_R + Y_1^d \overline{Q}'_L \Phi_1 d'_R + Y_2^d \overline{Q}'_L \Phi_2 d'_R + h.c., \tag{4}$$

where $\tilde{\Phi}_{1,2} = i\sigma_2 \Phi_{1,2}^*$ and σ_2 is the Pauli matrix. The charged leptonic sector has a similar form to the one of the $d - type$ quark, and is obtained from the latter by replacing $d_i \to l_i$, including the masses. After spontaneous symmetry breaking, each of the two doublets acquire vacuum expectation values (vevs), $v_{1,2}$ which are parametrized as $\tan\beta = \frac{v_2}{v_1}$.

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The Model 2HDM-III and the FCNC

In the fermion mass basis the neutral-scalar couplings associated with $Y_{1,2}$ are not generically diagonal and thus give tree-level FCNCs proportional to the off-diagonal entries of the combinations of $Y_{1,2}$ that couple to the physical scalars (see [Crivellin:2013] for detailed parameterizations). Popular ways to control these couplings are:

- *Alignment:* $Y_2^f = \zeta_f Y_1^f$ (A2HDM) eliminates tree-level FCNCs at the cost of introducing complex alignment parameters ζ_f [Pich:2009].
- *Textures:* impose hierarchical textures (e.g. four-zero textures) or the Cheng–Sher ansatz $(Y_{ij} \sim \lambda_{ij}\sqrt{m_i m_j}/v)$ to suppress off-diagonals by fermion-mass factors [Cheng:1987].
- *Discrete symmetries:* $\mathbb{Z}_2$ assignments that eliminate one doublet's coupling to a fermion type (Types I/II/X/Y).

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The Model 2HDM-III with *Textures*

After SSB, the second derivative of the potential yields the following form of the mass matrices:

$$M_f = \frac{1}{\sqrt{2}}(v_1 Y_1^f + v_2 . Y_2^f), \qquad f = u, d, l. \tag{5}$$

In the physical basis, M_f is diagonal but not necessary are each of the two Yukawa matrices. In order to diagonalize analytically, we reduce the possible 3×3 flavor fermion mass matrices by a proposed *ansatz* with a hierarchical structure, which is based on a textures form (zero for some flavor mixing elements guided by experimental data).

$$Y_k = \begin{pmatrix} 0 & C_k & 0 \\ C_k^* & \tilde{B}_k & B_k \\ 0 & B_k^* & A_k \end{pmatrix} \tag{6}$$

with $k = 1, 2$ then $|A_k| \gg |\tilde{B}_k|, |B_k|, |C_k|$

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The Model 2HDM-III

The femions mass matrices can be diagonalized through a similarity transformation

$$\bar{M}_u^{diag} = V_L^u M_u V_R^{u\dagger},$$
$$\bar{M}_d^{diag} = V_L^d M_d V_R^{d\dagger},$$
$$\bar{M}_l^{diag} = O_L^l M_l O_R^{l\dagger}. \tag{7}$$

Yields the CKM matrix: $V_{CKM} = V_L^u V_L^{d\dagger}$, and

$$\tilde{Y}_{1,2}^q = V_L^q Y_{1,2}^q V_R^{q\dagger} \quad \text{and} \quad \tilde{Y}_{1,2}^l = O_L^l Y_{1,2}^l O_R^{l\dagger}, \tag{8}$$

Here $q = u, b$.

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The Model 2HDM-III

We further note the following relation between the two Yukawa matrices for each fermion type:

$$\tilde{Y}_1^d = \frac{\sqrt{2}}{v\cos\beta}\bar{M}_d - \tan\beta \tilde{Y}_2^d, \tag{9}$$

$$\tilde{Y}_1^l = \frac{\sqrt{2}}{v\cos\beta}\bar{M}_l - \tan\beta \tilde{Y}_2^l, \tag{10}$$

$$\tilde{Y}_2^u = \frac{\sqrt{2}}{v\sin\beta}\bar{M}_u - \cot\beta \tilde{Y}_1^u. \tag{11}$$

Having an extra Higgs scalar doublet in the 2HDM, requires the use of α is the rotation angle for CP-even physical neutral Higgs bosons h^0 and H^0 states, and β is the angle associated with the Goldstone states basis, $\tan\beta = v_2/v_1$

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The Model 2HDM-III

In the physical basis, omitting Goldstone contributions, we have for the fermions couplings with neutral scalars:

$$
\begin{aligned}
\mathcal{L}_Y^q \;=\; & \frac{g}{2}\left\{\bar{u}_i\left[\left(\frac{m_{u_i}}{m_W}\right)\frac{\cos\alpha}{\sin\beta}\delta_{ij}-\frac{\sqrt{2}\,\cos(\alpha-\beta)}{g\,\sin\beta}(\tilde{Y}_1^u)_{ij}\right]u_j h^0\right.\\
+\; & \bar{d}_i\left[-\left(\frac{m_{d_i}}{m_W}\right)\frac{\sin\alpha}{\cos\beta}\delta_{ij}+\frac{\sqrt{2}\,\cos(\alpha-\beta)}{g\,\cos\beta}(\tilde{Y}_2^d)_{ij}\right]d_j h^0\\
& +\bar{u}_i\left[\left(\frac{m_{ui}}{m_W}\right)\frac{\sin\alpha}{\sin\beta}\delta_{ij}-\frac{\sqrt{2}\,\sin(\alpha-\beta)}{g\,\sin\beta}(\tilde{Y}_1^u)_{ij}\right]u_j H^0\\
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& +i\bar{u}_i\left[-\left(\frac{m_{u_i}}{m_W}\right)\cot\beta\delta_{ij}+\frac{\sqrt{2}}{g\,\sin\beta}(\tilde{Y}_1^u)_{ij}\right]\gamma^5 u_j A^0\\
+\; & \left. i\bar{d}_i\left[-\left(\frac{m_{d_i}}{m_W}\right)\tan\beta\delta_{ij}+\frac{\sqrt{2}}{g\,\cos\beta}(\tilde{Y}_2^d)_{ij}\right]\gamma^5 d_j A^0\right\}. \qquad (12)
\end{aligned}
$$

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The Model 2HDM-III

From this Lagrangian density we observe the following:

- The leptonic part is obtained by replacing $d_i \to l_i$.
- We apply the Cheng-Sher ansatz to reproduce the mass hierarchy of the Fermions Then, the Yukawa matrix elements would be as

$$\left(\tilde{Y}_2^{d,l}\right)_{ij} = \frac{\sqrt{m_i^{d,l} m_j^{d,l}}}{v} \tilde{\chi}_{ij}^{d,l}, \qquad \left(\tilde{Y}_1^{u,\nu_l}\right)_{ij} = \frac{\sqrt{m_i^{u,\nu_l} m_j^{u,\nu_l}}}{v} \tilde{\chi}_{ij}^{u,\nu_l}. \tag{13}$$

- The Yukawa couplings can be described in terms of dimensionless parameters $\tilde{\chi}_{ij}$ which could have a complex phase. In particular negative $\tilde{\chi}_{ij}$ are possible, as the matrices are Hermitian.
- The values for these parameters could be set experimentally.
- We see that for h^0 to be the SM-like Higgs (no flavor violation at LO), one needs to set $\alpha - \beta \sim \pi/2$ as the decoupling limit

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The decoupling limit

- The couplings of the SM-like Higgs boson h with the gauge bosons are proportional to $\sin(\beta - \alpha)$, whereas for the heavier H the couplings are proportional to $\cos(\beta - \alpha)$.
- Considering now the additional Yukawa couplings, coming from $2HDM - III$ given in the next table

Process	SM	MSSM	THDM-III
$h^0 \to u_i \bar{u}_j$	$m_{u_i}\delta_{ij}$	$\frac{m_{u_i}\cos\alpha}{\sin\beta}\delta_{ij}$	$[m_{u_i}\frac{\cos\alpha}{\sin\beta}\delta_{ij} - \frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta}\sqrt{m_{u_i}m_{u_j}}\tilde{\chi}^u_{ij}]$
$h^0 \to d_i \bar{d}_j$	$m_{d_i}\delta_{ij}$	$\frac{m_{d_i}\sin\alpha}{\cos\beta}\delta_{ij}$	$[-m_{d_i}\frac{\sin\alpha}{\cos\beta}\delta_{ij} + \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta}\sqrt{m_{d_i}m_{d_j}}\tilde{\chi}^d_{ij}]$
$H^0 \to u_i \bar{u}_j$	-	$\frac{m_{u_i}\sin\alpha}{\sin\beta}\delta_{ij}$	$[m_{u_i}\frac{\sin\alpha}{\sin\beta}\delta_{ij} - \frac{\sin(\alpha-\beta)}{\sqrt{2}\sin\beta}\sqrt{m_{u_i}m_{u_j}}\tilde{\chi}^u_{ij}]$
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$A^0 \to u_i \bar{u}_j$	-	$-m_{u_i}\cot\beta\delta_{ij}$	$[-m_{u_i}\cot\beta\delta_{ij} + \frac{\sqrt{m_{u_i}m_{u_j}}}{\sqrt{2}\sin\beta}\tilde{\chi}^u_{ij}]$
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- The latter means that the contributions from heavier Higgs boson H will be reduced in the limit of $\cos(\beta - \alpha) \to 0$.

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- The latter means that the contributions from heavier Higgs boson H will be reduced in the limit of $\cos(\beta - \alpha) \to 0$.

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The decoupling limit

It can be seen from the last column in previous table (18), that in order to reduce the $H^0 u_i u_j$ coupling, which in turn will diminish the radiative corrections, we found the following conditions:

$$\frac{\sin(\beta-\alpha)}{\sqrt{2}\sin\beta}\tilde{\chi}^u_{23} \to 0 \quad \Longrightarrow \quad \tilde{\chi}^u_{23} \sim 0$$

$$\text{or} \quad \Longrightarrow \quad \sin(\beta-\alpha) = 0$$

$$\text{and} \quad \frac{\sin\alpha}{\sin\beta} - \frac{\sin(\beta-\alpha)}{\sqrt{2}\sin\beta}\tilde{\chi}^u_{22} \to 0 \quad \Longrightarrow \quad \frac{\sqrt{2}+\cos\beta\,\tilde{\chi}^u_{22}}{\sin\beta} \simeq \cot\alpha\,\tilde{\chi}^u_{22}$$

The two last conditions are not compatible, nor with the *decoupling limit*, so we ought to consider first condition necessarily, which in fact gives the higher values for the flavour violation cross section and agrees with parameter value dictated from the experimental bounds.

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The charged scalar sector

- The charged Higgs couplings with fermions are given as

$$L^{H^\pm}_{Yuk} = \bar{u}_{Li} \left[\phi_2^+ (Y^d_{2CKM}) + \phi_1^+ (Y^d_{1CKM})\right] d_{Rj} - \bar{d}_{Li} \left[\phi_2^- (Y^u_{2CKM}) + \phi_1^- (Y^u_{1CKM})\right] u_{Rj} + h.c. \quad (14)$$

- Written in the charged Higgs basis:

$$\begin{aligned} {}^{H^\pm}_{Yuk} &= \bar{u}'_{Li}(Y^d_{1CKM})_{ij} d'_{Rj}(G^+_w \cos\beta - H^+ \sin\beta) \\ &+ \bar{u}'_{Li}(Y^d_{2CKM})_{ij} d'_{Rj}(G^+_w \sin\beta + H^+ \cos\beta) \\ &- \bar{d}'_{Li}(Y^u_{1CKM})_{ij} u'_{Rj}(G^-_w \cos\beta - H^- \sin\beta) - \\ &\bar{d}'_{Li}(Y^u_{2CKM})_{ij} u'_{Rj}(G^-_w \sin\beta + H^- \cos\beta) + H.C. \end{aligned} \quad (15)$$

- Then, rotating the quark fields to their physical basis we get the Yukawa matrices in CKM basis as

$$Y^d_{1,2CKM} = V^u_L Y^d_{1,2} V^{d\dagger}_R \quad (16)$$

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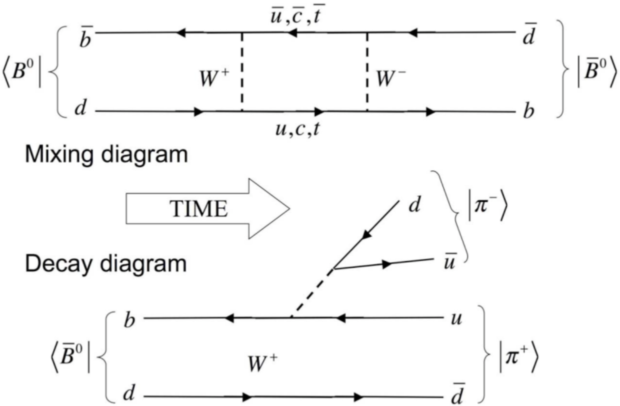
B meson and FV processes



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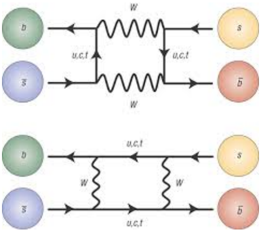
B-mixing

B-mixing

$$B_q - \bar{B}_q$$

particle-antiparticle mixing.

SM contribution



$$B_{L,H} = p|B_q^0\rangle \pm q|B_q^0\rangle \qquad (18)$$

have a mass difference $\Delta m_q = m_H - m_L > 0$, a total decay width difference $\Delta\Gamma_q = \Gamma_L - \Gamma_H$

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Preliminary Results

A preliminary bound on the FV-parameters to the well measured process $\mathcal{B}(B_s^0 \to \mu\mu)$

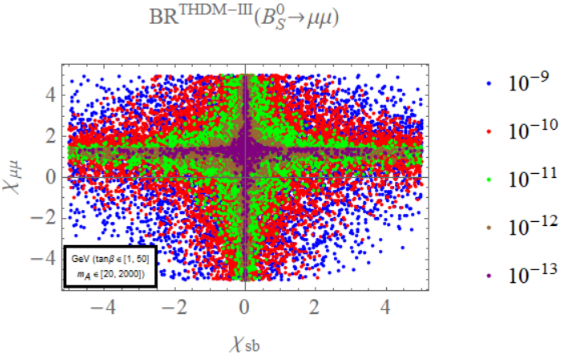

Figure: $BR(B_s \to \mu\mu)$ running aleatory and different for each parameter of the yukawa χ_{ll} and χ_{sb} between $[-5, 5]$. Running $\tan\beta$ from 1 to 50, we also consider a wide range for pseudo-scalar masses $m_A = [20, 2000]$ GeV.

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Summary for masses and interactions in the 2HDM-III

Masses

$$\mathcal{L}_{\mathsf{M}} = -\bar{f}_L^d D^d f_R^d - \bar{f}_L^u D^u f_R^u + \mathsf{H.c.}$$

with

$$\begin{aligned} D^u &= \frac{1}{\sqrt{2}} V_R^\dagger (v_1 Y_1^u + v_2 Y_2^u) V_L = \frac{1}{\sqrt{2}} (v_1 \tilde{Y}_1^u + v_2 \tilde{Y}_2^u) \\ D^d &= \frac{1}{\sqrt{2}} U_R^\dagger (v_1 Y_1^d + v_2 Y_2^d) U_L = \frac{1}{\sqrt{2}} (v_1 \tilde{Y}_1^d + v_2 \tilde{Y}_2^d) \end{aligned}$$

Charged interactions

$$\mathcal{L}_{\mathsf{C}} = -[V_{\mathsf{CKM}} \tilde{Y}_a^d R_{ab}]_{ij} \bar{f}_{Li}^u f_{Rj}^d H_b^+ + [V_{\mathsf{CKM}}^\dagger \tilde{Y}_a^u R_{ab}]_{ij} \bar{f}_{Li}^d f_{Rj}^u H_b^{+*} + \mathsf{H.c.}$$

where R_{ab} is the mixing matrix of scalar, depends on v and $\tan\beta$.

Neutral interactions

$$\begin{aligned} \mathcal{L} &= -(\tilde{Y}_{a,ij}^d \bar{f}_{Ri}^d f_{Rj}^d + \tilde{Y}_{a,ij}^u \bar{f}_{Ri}^u f_{Rj}^u) R_{ab} H_b^0 \\ &\quad -i(\tilde{Y}_{a,ij}^d \bar{f}_{Ri}^d f_{Rj}^d + \tilde{Y}_{a,ij}^u \bar{f}_{Ri}^u f_{Rj}^u) R_{ab} A_b^0 \end{aligned}$$

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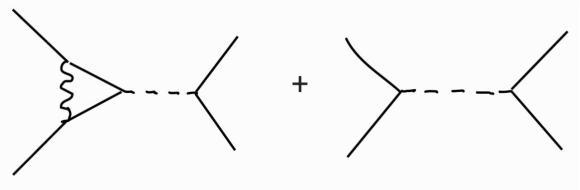
Scalar FCNC suppression in $B_s^0 - B_s^0$



- Tree level contribution of A_2^0 can be suppressed with the 1-loop contribution if

$$(\tilde{Y}_a^d R_{a2})_{32}|^2 \simeq \frac{g_2}{\sqrt{2}} M_{A_2^0} \tilde{D}_{00}(m_t^2, m_t^2, M_W^2, M_A^{0_s})(V_{\mathsf{CKM}}^*)_{33}(\tilde{Y}_a^d)_{32}(Y_a^u)_{33}$$

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Conclusion

- 2HDM-III is an excellent model to parameterized NP effects.
- Although Natural Flavor Conservation has been the usual way to suppress FCNC, there are alternative ways, as we showed here, even more natural.
- The origin of textures matrices can be a consequence of a underlying flavor symmetry that suppress FCNC at quantum correction.
- We have found that Yukawa matrices are not independent allowing to find correlations between FV processes.

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Once Again...

Really appreciate your comments

THANK YOU!