Breviary on Flavor-Changing Neutral Scalar Interactions

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Part I: Standard Model

The Standard Model (SM) is a good description for interactions at $\sim 10^{-16}$ cm .

Gauge sector

Neutral Currents Sector

Scalar Sector

Yukawa Sector

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{GS} + \mathcal{L}_{SM}^{NC} + \mathcal{L}_{SM}^{SS} + \mathcal{L}_{SM}^{YS}$$

Part II: Beyond Standard Model (BSM)

We can extend the SM, it means a phenomenological rich models. New particles imply new interactions; namely, New Physics (NP).

Some schemes for the NP

There are differents for the NP; i.e.:

- Extended Gauge Groups.
- Extra Dimensions
- Model with extended scalar sector: scalar sector and Yukawa Sector
- GUT
- String

Motivation: 2HDM

Introducing a new doublet, we can:

- Explain the matter-antimatter asymmetry
- Explain the CP violation
- Even, imposing a Z_2 symmetry on the Lagrangian; this is either: $\Phi_1 \longleftrightarrow \Phi_1, \Phi_2 \longleftrightarrow -\Phi_2$ or $\Phi_1 \longleftrightarrow -\Phi_1, \Phi_2 \longleftrightarrow \Phi_2,$ or new constraints, we could neglect FCNC and/or CP-violation

2HDM and some other types

- 2HDM-I. All quarks couple to just one of the Higgs doublets (normally, Φ_2).

where h is the light neutral Higgs (I used the label SM for the standard model), H is the heavy neutral Higgs and $V = W, Z$

- 2HDM-II. u_R quarks couple to Φ_2 and d_R quarks couple to Φ_1.

- En 2HDM-III. Each doublet couples to u and d type. Besides one can consider parameters, as χ_{ij} which may induce FCNC through scalar bosons.

2HDM Lagrangian

The general potential is given by, The Yukawa sector for the 2HDM-III is given by,

$$\begin{aligned}\mathcal{L}_{YS}^{THDM-III} &= Y_1^u \overline{u}_L \phi_1^{0*} u_R + Y_2^u \overline{u}_L \phi_2^{0*} u_R + Y_1^d \overline{d}_L \phi_1^0 d_R + Y_2^d \overline{d}_L \phi_2^0 d_R \\ &+ Y_1^u \overline{d}_L (-\phi_2^-) u_R + Y_2^u \overline{d}_L (-\phi_1^-) u_R + Y_1^d \overline{u}_L \phi_1^+ d_R + Y_2^d \overline{u}_L \phi_2^+ d_R \\ &+ h.c.\end{aligned}$$

Part III: Flavor Change (FC)

FCNC and BSM

There are two ways to obtain flavor changing in some BSM eschemes:

1. the mixing of the SM fermions with the new fermions introduced to avoid anomalies [16, 15],
2. the fermion charges related to the extra group can be NUF [6, 7, 8, 18].

FC by scalar boson

Flavor-Changing Scalar Current (FCSC)

the diagonalization of the mass matrices fermions does not ensure the diagonalization of the yukawa couplings.

In this sector the interaction between fermions and scalar is given by the yukawa couplings (Y_f), in general, this is: $g_{hff} \sim Y^f \sim m_f$ where g_{hff} represents the vertex higgs and pair of fermions. In the SM the coupling is given by,

$$g_{hff}^{SM} = Y_{SM}^{f} = \sqrt{2}\frac{m_f}{v} \tag{1}$$

where m_f is fermion mass and v is the vaccum expectation value (VEV). For the THDM, after the spontaneous symmetry breaking the mass matrix is given by (L_{YS}^{THDM}):

$$m_f = \frac{1}{\sqrt{2}}\left(v_1 Y_1^f + v_2 Y_2^f\right) \tag{2}$$

where we have two VEV's v_1 and v_2, which are relationated by: $\frac{v_2}{v_1} = \tan\beta$. In a general form, the eq. (2) is non-diagonal, and it can be made by: $\left(U_L^f\right)^* m_f \left(U_R^f\right)^\dagger = \widetilde{m}_f$

Then que mass matrix is given by:

$$\widetilde{m}_f = \frac{1}{\sqrt{2}}\left(v_1 \widetilde{Y}_1^f + v_2 \widetilde{Y}_2^f\right) \tag{3}$$

where, $\widetilde{Y}_i^f = U_L^\dagger Y_i^f U_R$.

In order to reduce the free parameters,

$$\begin{aligned} \widetilde{Y}_1^f &= \sqrt{2}\frac{m_f}{v_1} - \frac{v_2}{v_1}\widetilde{Y}_2^f \\ \widetilde{Y}_1^f &= \sqrt{2}\frac{m_f}{v_1} - \widetilde{Y}_2^f \ \tan\beta \\ \widetilde{Y}_1^f &= \sqrt{2}\frac{m_f}{v\cos\beta} - \widetilde{Y}_2^f \ \tan\beta \end{aligned} \tag{4}$$

Sometimes Yukawas are defined in terms on $\widetilde{\chi}_{ij}$ parameters [10]; namely,

$$\widetilde{Y}_{ij}^f = \sqrt{2}\frac{\sqrt{m_i m_j}}{v}\widetilde{\chi}_{ij}^f \tag{5}$$

Experimental data for FC

Nowadays we have strong motivations to study some rare decays, e.g.: $t \to c\gamma, t \to c\ Z$, and $t \to c\ g$. These proccesses allow to perform precision studies on the top decay [2]. Next we show the experimental results for flavor violation in tree and loop-level [3]. Br$(\tau^- \to \mu^-\mu^+\mu^-) = 2.1 \times 10^{-8}$ [5].

	Belle	BaBar	CLEO	Belle II
Br$(\tau \to \mu^-\pi^+\pi^-)$	10^{-7}	10^{-6}	10^{-5}	$\sim 2022?$

Experimental data			
	$f_i f_j\ \gamma$		$h\ f\ f$
$\mu(\to)e$	X		$< 10^{-8}$
$\tau(\to)e$	X		$< 10^{-1}$
$\tau(\to)\mu$	X$(g-2)$	$\sim 7 \times 10^{-7}$,	8×10^{-7}

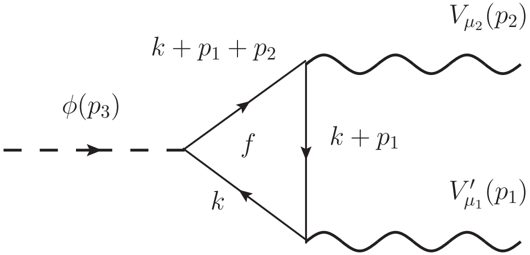
Experimental data at tree and loop-level

	Standard Model				
	$f_i f_j\ Z$	$f_i f_j\ \gamma$	$f_i f_j\ g$	$f\ f\ h$	$V'Vh$
$e\ \mu$	1.7×10^{-6} [5]	5.7×10^{-13} [5]			
$\mu\ \tau$	1.2×10^{-5} [5]	4.4×10^{-8} [5]		8.4×10^{-8} [5]	
$e\ \tau$	9.8×10^{-6} [5]	3.3×10^{-8} [5]		3.1×10^{-8} [5]	
$t\ u$	8×10^{-17} [9]	3.7×10^{-16} [9]		2×10^{-17} [9]	
$t\ c$	1×10^{-14} [9]	4.6×10^{-14} [9]		3×10^{-15} [9]	
ZZ					?
$\gamma\gamma$					?

Table 1: Here it was considered $m_h = 125.7\,\text{GeV}$. Experimental reports are given in [1].

Flavor Change at loop-level

The flavor-changing in the loop-level has some restrictions. The effects at this level will be much smaller compared to effects at tree level, however we did not find studies inside this phenomenological scenarios.



The table 1 shows the bounds for the Standard model (SM) including two fermions, and Z, γ and h.

BSM and GIM mechanism

In BSM, GIM mechanism can be relaxed, is possible have effective $t\ q\ h$ couplings much larger SM couplings yielding FCNC.

Different phenomenology and theoretical reports can be found in [12, 13]. We show some results in table 4 for the Two-Higgs-doublet model.

THDM				
	$f_i f_j\ Z$	$f_i f_j\ \gamma$	$f_i f_j\ g$	$f\ f\ h$
$t\ u$				5.5×10^{-6}[9]
$t\ c$	$\sim 10^{-6,-7}$ [4, 9]	$\sim 10^{-6,-7}$ [9, 4]	$\sim \times 10^{-10}$ [11]	$1.5 \times 10^{-3,-7(-13)}$ [9, 11]

Table 2: Branching ratio constraints for the flavor change in the THDM-III.

On the other hand, papers analize the lepton sector and the Higgs the results for the 331 model are shown in table 3:

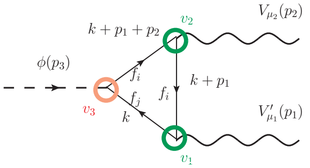
331 Model			
	$f_i f_j\ Z$	$f_i f_j\ \gamma$	$f\ f\ h$
$e\ \mu$		$\sim 10^{-33}$	1.44×10^{-14}
$e\ \tau$		$\sim 10^{-29}$	1.92×10^{-13}
$\mu\ \tau$		$\sim 10^{-31}$	1.42×10^{-14}

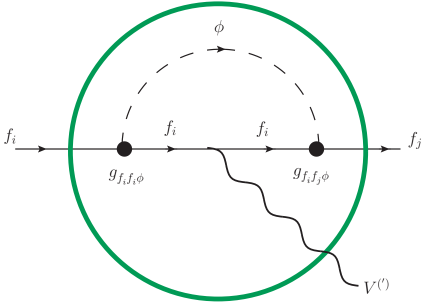
Table 3: Vertex bounds for the flavor change in 331 models. Besides ref. [17] obtained: Br$(l_i \to l_j l_k l_k) \sim 10^{-15}$ with $l_i = \tau$

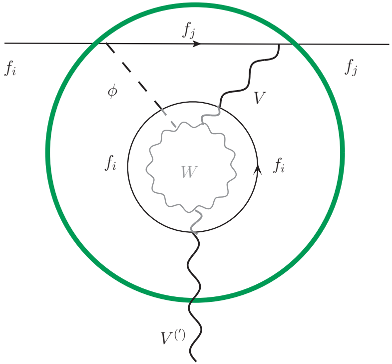
Next we show some results for SUSY models.

Supersymmetric Models			
	$f_i f_j\ Z$	$f_i f_j\ \gamma$	$f\ f\ h$
$t\ c$	$\sim \times 10^{-6}$ [2]	$\sim \times 10^{-6}$ [2]	

Table 4: Branching ratio constraints for the flavor change in SUSY models.


$V_{\mu_2}(p_2)$
v_2
$k + p_1 + p_2$
$\phi(p_3)$
f_i
$k + p_1$
f_i
f_j
v_3
k
$V'_{\mu_1}(p_1)$
v_1


ϕ
f_i
f_i
f_i
f_j
$g_{f_i f_i \phi}$
$g_{f_i f_j \phi}$
$V^{(\prime)}$


f_j
f_i
f_j
ϕ
V
f_i
W
f_i
$V^{(\prime)}$

Consider leptons the $f_i f_j h$ where

$$g_{\tau\tau h} = Y^*_{\tau\tau} P_L + Y_{\tau\tau} P_R \tag{6a}$$

$$g_{\tau\mu h} = Y^*_{\tau\mu} P_L + Y_{\mu\tau} P_R \tag{6b}$$

where the $P_{R,L}$ are projectors (see [13]).

In general, this is in a model with FCNC, but not at tree-level, we obtain:

$$\mathcal{M}_0(\phi \to V'V) \propto g_{V'V\phi} \tag{7a}$$

$$\begin{aligned}\mathcal{M}_3(\phi \to V'V) &\propto g_{l_i l_i \phi}\left(g_{l_i l_i V'}\ g_{l_i l_i \phi}\ g_{l_i l_j \phi}\right)\left(g_{l_i l_i V}\ g_{l_i l_i \phi}\ g_{l_i l_j \phi}\right) \\ &\propto g_{l_i l_i \phi}\left(g_{l_i l_i \phi}\ g_{l_i l_j \phi}\right)^2 g_{l_i l_i V'}\ g_{l_i l_i V}\end{aligned} \tag{7b}$$

$$\begin{aligned}\mathcal{M}_5(\phi \to V'V) &\propto g_{l_i l_i \phi}\ \left(g_{l_i l_j \phi}\ g_{l_j l_j V}\ g_{q_i q_i \phi}\ g_{q_i q_i V}\ g_{q_i q_i V'}\right)\times \\ &\qquad \left(g_{l_i l_j \phi}\ g_{l_j l_j V}\ g_{q_i q_i \phi}\ g_{q_i q_i V}\ g_{q_i q_i V}\right) \\ &\propto g_{l_i l_i \phi}\ \left(g_{l_i l_j \phi}\ g_{l_j l_j V}\ g_{q_i q_i \phi}\ g_{q_i q_i V}\ \right)^2 g_{q_i q_i V'} g_{q_i q_i V}\end{aligned} \tag{7c}$$

where l, q are leptons and quarks, respectively; in both cases, we consider $i > j > k$. The factor inside parenthesis is relationed to the loop-level.

Example

Using the eqs. (7a), (7b) and (7c); we will obtain for the amplitud:

$$\mathcal{M}_0(h \to \gamma\gamma) \propto g_{\gamma\gamma h} \tag{8a}$$

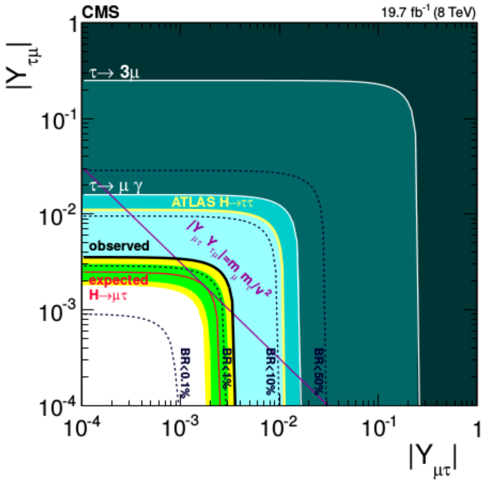
$$\mathcal{M}_3(h \to \gamma\gamma) \propto g_{\tau\tau h}\big(g_{\tau\tau h}\ g_{\tau\mu h}\big)^2 g_{\tau\tau\gamma}\ g_{\tau\tau\gamma} \tag{8b}$$

$$\mathcal{M}_5(h \to \gamma\gamma) \propto g_{\tau\tau h}\big(g_{\tau\mu h}\ g_{\mu\mu V}\ g_{tth}\ g_{ttV}\ \big)^2 g_{tt\gamma}\ g_{tt\gamma} \tag{8c}$$

where $V = \gamma, Z$. The couplings are proportional to the Yukawas as was shown in eqs. (6a) and (6b). But $g_{\tau\mu h} \propto Y_{\tau\mu}$ (I assumed $Y^\star_{ji} = Y^\star_{ij} = Y_{ij} = Y_{ji}$) [14]...

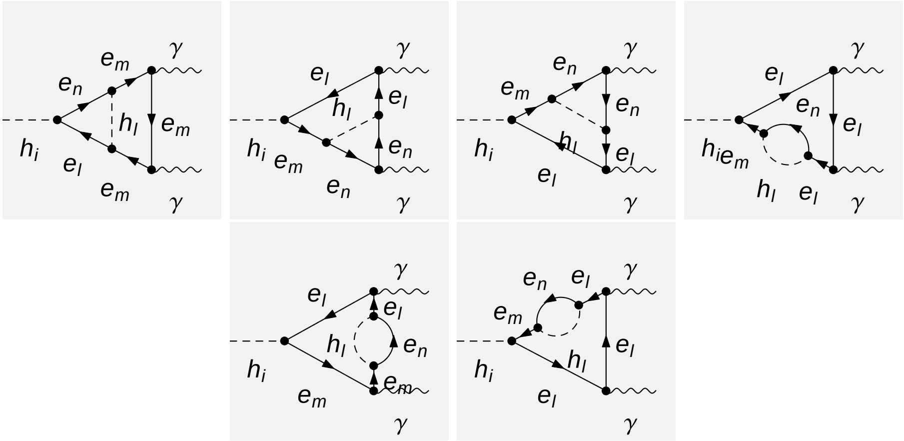
$$\sqrt{Y_{\tau\mu} + Y_{\tau\mu}} < 3.6 \times 10^{-3} \tag{9}$$

Besides [14] (CMS):



Part IV: Two loop diagrams

However We can explore . . .



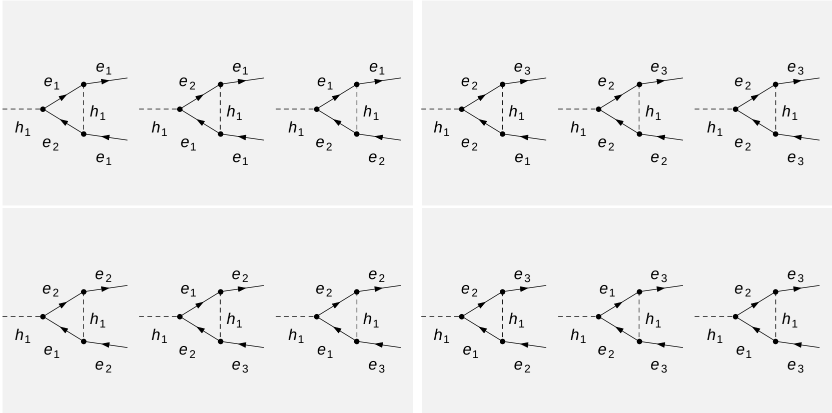
The Cutkosky theorem (optical theorem)

Abstract for the RADyPC-2016

Cutkosky method [19]

1. Cut through the diagram in al possible ways such that the cut propagators can simultaneously be put on shell.
2. For each cut, replace $\frac{1}{p^2-m^2+i\epsilon} \to -2\pi i\delta(p^2-m^2)$ in each cut propagator, then perform the loop integrals.
3. Sum the contributions of all possible cuts.

Generating the model in SARAH for FeynArts



Conclusions

We showed an overview on Flavor-changing neutral currents. We told about some models for the new physics (NP). I showed some experimental and theoretical results for several NP models, and finally we showed some interesting processes with FC at loop level.

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