Flavor-Changing mediated by scalar at loop-level

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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

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

Scalar Sector

We recall the Scalar Sector is composed for kinetic and interaction parts. Φ is the doublet. Sometimes the doublet is labeled as: H or ϕ, and it could be confusing.

The doublet (Φ) is given by:

$$\Phi = \begin{pmatrix} \phi^{\pm} \\ \phi \end{pmatrix} = \begin{pmatrix} \eta_1 + i\eta_2 \\ \phi^0 + i\eta^0 \end{pmatrix} \tag{1}$$

and we define:

- $\phi^{\pm}$ complex scalar charged field. Operator for the charged sector
- ϕ complex scalar neutral field. Operator for the neutral sector

Goldstone Theorem

The spontaneous symmetry breaking of a continuous symmetry of the Lagrangian generates massless scalars.

We introduce the spontaneous symmetry breaking (SSB) concept. Now the theory gets [16, pag. 347, 388]:

1. Ultraviolet divergences.
2. Renormalization to constrain the divergences.
3. The matrix of second derivates of the potential has a corresponding zero eigenvalue.
4. The theory has massless scalar particles.

Scalar sector and LHC

Data for the higgs and before 4th July 2012 (one more).

Today at LHC

Today we know h mass and it is a scalar boson and the Higgs mechanism work (potential as a mexican hat).

At LHC the researchers can study the structure of matter at $10^{-18} - 10^{-17}$ cm (~ 1 TeV). For the higgs boson (scalar sector) we know:

Mass: $= 125.7 \pm 0.4$ GeV

Decay width: 4×10^{-3} GeV.

Mean lifetime: $= 1.56 \times 10^{-22}$ GeV

Charge: is neutral boson.

Parity: +1 (a measure of how its mirror image behaves).

Golden channel: it is the best channel to the Higgs decay $h \to ZZ$.

Scalar: It is a scalar with 0 spin.

Tests of the Higgs particle properties:

Decay modes of the Higgs boson

- $\gamma\gamma$ decay mode ✔
- ZZ decay mode ✔
- W^+W^- decay mode ✔
- $\tau^+\tau^-$ decay mode ✔

m_h (GeV)	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$c\bar{c}$	$s\bar{s}$
125.0	57.7 %	6.32 %	0.0219 %	2.91 %	0.0246 %
125.3	57.2 %	6.27 %	0.0218 %	2.89 %	0.0244 %
125.6	56.7 %	6.22 %	0.0216 %	2.86 %	0.0242 %
125.9	56.3 %	6.17 %	0.0214 %	2.84 %	0.0240 %
126.2	55.8 %	6.12 %	0.0212 %	2.81 %	0.0238 %
126.5	55.3 %	6.07 %	0.0211 %	2.79 %	0.0236 %

m_h (GeV)	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ	Γ_H (MeV)
125.0	8.57 %	0.228 %	0.154 %	21.5 %	2.64 %	4.07
125.3	8.54 %	0.228 %	0.156 %	21.9 %	2.72 %	4.11
125.6	8.52 %	0.228 %	0.158 %	22.4 %	2.79 %	4.15
125.9	8.49 %	0.228 %	0.162 %	22.9 %	2.87 %	4.20
126.2	8.46 %	0.228 %	0.164 %	23.5 %	2.94 %	4.24
126.5	8.42 %	0.228 %	0.167 %	24.0 %	3.02 %	4.29

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).

Motivation

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

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

Second column constrains the processes with Higgs boson [2, 14].

Vertex bounds for the flavor-changing in the SM. (Experimental reports are given in [1]).

Standard Model			
	$f_i f_j\ Z$	$f_i f_j\ \gamma$	$f\ f\ h$
$e\ \mu$	1.7×10^{-6} [4]	5.7×10^{-13} [4]	
$\mu\ \tau$	1.2×10^{-5} [4]	4.4×10^{-8} [4]	8.4×10^{-8} [4]
$e\ \tau$	9.8×10^{-6} [4]	3.3×10^{-8} [4]	3.1×10^{-8} [4]
$t\ u$	8×10^{-17} [8]	3.7×10^{-16} [8]	2×10^{-17} [8]
$t\ c$	1×10^{-14} [8]	4.6×10^{-14} [8]	3×10^{-15} [8]

Constraints for the flavor-changing in the THDM.

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}[8]
$t\ c$	$\sim 10^{-6,-7}$ [3, 8]	$\sim 10^{-6,-7}$ [8, 3]	$\sim \times 10^{-10}$ [11]	$1.5 \times 10^{-3,-7(-13)}$ [8, 11]

Some schemes for the NP

There are different schemes for the NP; i.e.:

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

F. Quevedo's talk

2HDM and some other types (doublet)

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

- 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.

M. Carena's talk
L. Serkin's talk

2HDM-III: Interesting properties

2HDM: Interesting properties

A rich Higgs boson spectrum: three neutral (H, h, A^0) degrees of freedom and one charged Higgs boson $(H^{\pm})$.

New Physics

A^0 would be a clear sign of new Physics. And more phenomenology available to explore (For our analysis, we consider the potential is CP conserving and then A^0 could be eigenstates of mass.)

Contributions at loop-level

A^0 does not coupling to vector bosons at tree level. However, such couplings could be induced at loop-level.

2HDM-III Lagrangian

The general potential is the most general for the 2HDM, and we do not consider CP violation. The Yukawa sector for the 2HDM-III is given by,

$$\mathcal{L}_{YS}^{THDM-III} \quad = \quad Y_1^u \overline{Q}_L^0 \tilde{\Phi}_1 u_R^0 + Y_2^u \overline{Q}_L^0 \tilde{\Phi}_2 u_R^0 + Y_1^d \overline{Q}_L^0 \Phi_1 d_R^0 + Y_2^d \overline{Q}_L^0 \Phi_2 d_R^0 + h.c.$$

where,

$$Q_L^0 = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \qquad \overline{Q}_L^0 = \left(\overline{u}_L, \overline{d}_L\right), \qquad \Phi_1 = \begin{pmatrix} \phi_1^{\pm} \\ \phi_1 \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^{\pm} \\ \phi_2 \end{pmatrix},$$

$$\tilde{\Phi}_j = i\sigma_2 \Phi_j^* = \begin{pmatrix} {\phi_j}^* \\ -\phi_i^{\mp} \end{pmatrix}.$$

and Y_i are the Yukawa couplings.

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

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

Then que mass matrix is given by $\widetilde{m}_f = \frac{1}{\sqrt{2}}\left(v_1 \widetilde{Y}_1^f + v_2 \widetilde{Y}_2^f\right)$ where, $\widetilde{Y}_i^f = U_L^\dagger Y_i^f U_R$. The Yukawa couplings are defined in terms of $\widetilde{\chi}_{ij}$ parameters [10]; namely,

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

where m_i and m_j are the fermion masses, and $\widetilde{\chi}_{ij}^f$ are free parameters. This specific pattern is known as cheng & Sher ansatz [6]. Through this mechanism is possible to flavor-changing neutral currents (FCNC) at tree-level.

Part III: Phenomenology THDM-III

Considering $\bar{u}uA^0$ vertex

We are considering next lagrangian: pseudoscalar and couple of fermions.

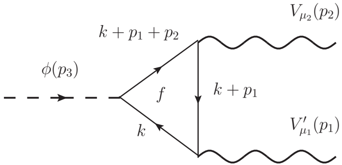
$$\mathcal{L} \quad = \quad \bar{u}\Big(S^u_{ij\ A} + i\gamma^5 P^u_{ij\ A}\Big)u_j A^0 + h.c.$$

It is similar for the type-d quarks and leptons. with $S^u_{ijA} = i\frac{\sqrt{m_i m_j}}{2\sqrt{2}v\cos\beta}\left(\chi_{ij} - \chi^\dagger_{ij}\right)$ *and* $P^u_{ijA} = \frac{1}{2v}M^U_{ij}\tan\beta - \frac{\sqrt{m_i m_j}}{2\sqrt{2}v\cos\beta}\left(\chi_{ij} + \chi^\dagger_{ij}\right)$ where χ_{ij} are dimensionless coefficients those are a parameterization for the Flavor changing neutral scalar interactions.

Considering the diagonal couplings, we will get $\mathcal{L}^f_{A^0} = \frac{gm^f_i}{2m_W}\overline{f}_i\left(g^f_{S_i} + i\gamma^5 g^f_{P_i}\right)f_i A^0$ and thinking Yukawa matrices are hermitian, $g^f_{S_i} = 0$; then we found $g^u_{P_i} = \cot\beta - \frac{1}{\sin\beta}\left(\chi_{ii}\right)$.

$A \to \gamma\gamma$ decay

$A^0\gamma\gamma$ term does not exist at loop-level but it does at tree-level.



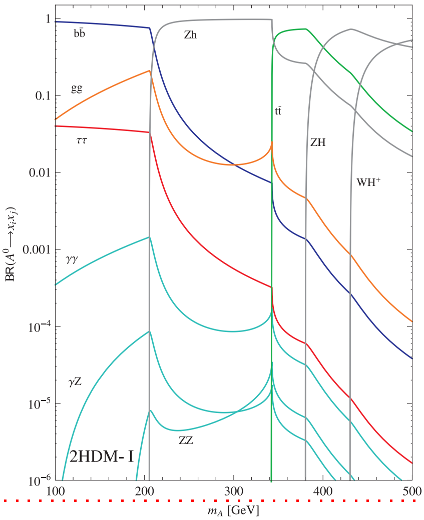
	Type I	Type II	Type III
g_P^u	$\cot\beta$	$\cot\beta$	$\cot\beta - \frac{1}{\sin\beta}(\chi_{ii}^u)$
g_P^d	$-\cot\beta$	$\tan\beta$	$\tan\beta - \frac{1}{\cos\beta}(\chi_{ii}^d)$
g_P^l	$-\cot\beta$	$\tan\beta$	$\tan\beta - \frac{1}{\cos\beta}(\chi_{ii}^l)$

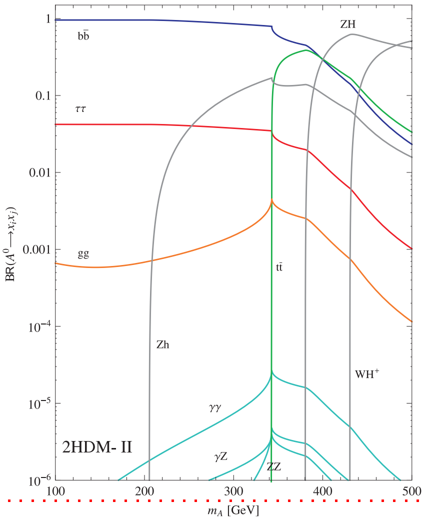
$\mathcal{M} = \frac{ig\, r_f N_C\, k_{V_1ff}\, k_{V_2ff}\, \mathcal{A}^{\mu_1\mu_2}_{VV'}\, \epsilon^*{}_{\mu_1}\epsilon^*{}_{\mu_2}}{16 m_W \pi^2 \left(1-2\left(r_1+r_2\right)+\left(r_1-r_2\right)^2\right)^2}$, where $r_i = \frac{M^2_{V_i}}{m_A^2}$, $\mathcal{A}^{\mu_1\mu_2}_{VV'} = g_S^f \left(\mathcal{A}_1 \; g^{\mu_1\mu_2} + \mathcal{A}_2 \; p_2^{\mu_1}p_1^{\mu_2}\right) + g_P^f\; \mathcal{A}_3 \; \epsilon^{\alpha\beta\mu_1\mu_2}p_{1_\alpha}p_{2_\beta}$. We found the decay width[10]:

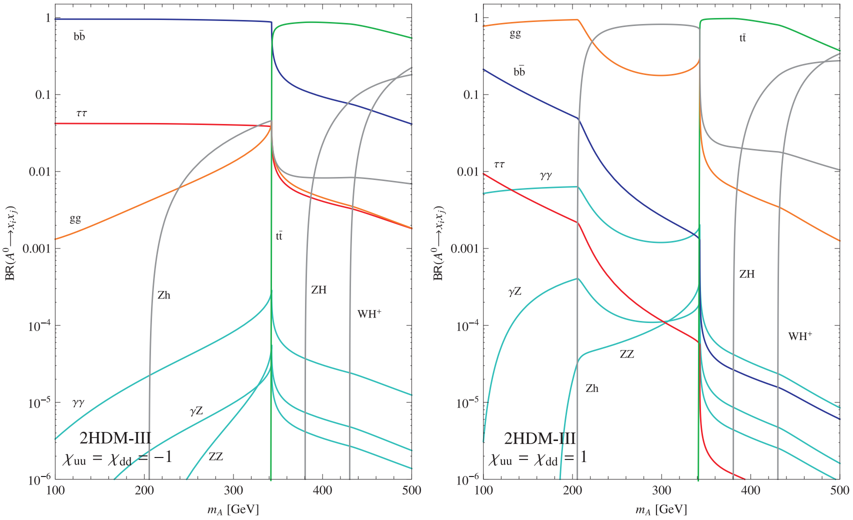
$$\Gamma(A^0 \to \gamma\gamma) = m_A r_f \kappa_{\gamma\gamma}\left(I_f^2 {g_P^f}^2 + 2{g_S^f}^2\left(I_f(4r_f-1)+2\right)^2\right),$$

where $I_f = C_0(0,0)m_A^2$ y $\kappa_{\gamma\gamma} = \frac{(N_C^f)^2}{128\pi^5}\left(\frac{gm_f}{2m_W}\right)^2\left(e|Q_f|\right)^4$

Results: $\tan\beta = 5$, $m_H = 300$ GeV and $m_{H^\pm} = 350$ GeV .

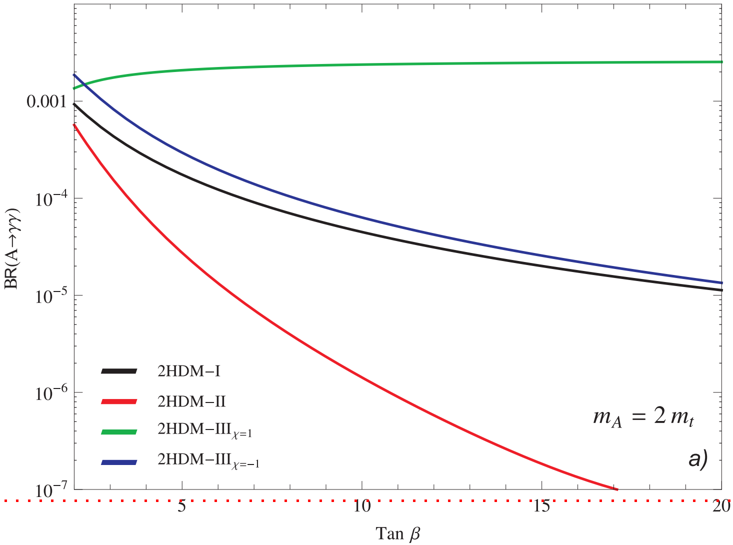






1
0.1
0.01
0.001
10^{-4}
10^{-5}
10^{-6}
$BR(A^0 \longrightarrow x_i x_j)$
$b\bar{b}$
$\tau\tau$
gg
$t\bar{t}$
Zh
ZH
WH^+
$\gamma\gamma$
γZ
ZZ
2HDM-III
$\chi_{uu} = \chi_{dd} = -1$
100
200
300
400
500
m_A [GeV]
1
0.1
0.01
0.001
10^{-4}
10^{-5}
10^{-6}
$BR(A^0 \longrightarrow x_i x_j)$
gg
$b\bar{b}$
$t\bar{t}$
$\tau\tau$
$\gamma\gamma$
γZ
ZH
WH^+
ZZ
Zh
2HDM-III
$\chi_{uu} = \chi_{dd} = 1$
100
200
300
400
500
m_A [GeV]

Comparison among type-I, II and III



FC results: Phenomenology for FC mediated by scalar boson

Considering the experimental for Br and using the lowest limit for the $\tan\beta$ given for extended models [4], we obtain the allowed regions for the parameter space (fig. 1). We can define the Yukawa elements in terms of the $\widetilde{\chi}_{ij}$ parameters [6]; namely,

$$\widetilde{Y}^f_{ij} = \sqrt{2}\frac{\sqrt{m_i m_j}}{v}\widetilde{\chi}^f_{ij}$$

where m_i and m_j are the fermion masses, and $\widetilde{\chi}^f_{ij}$ are free parameters.

Considering the bounds given by fig. 1, we explore the decay width for the Higgs. Fig. 4 shows the total width decay for the Higgs boson with different values for the $\chi_{uu'}-$ versus the $\chi_{dd'}-$parameter and allowing for $\tan\beta = 0.4, 1$.

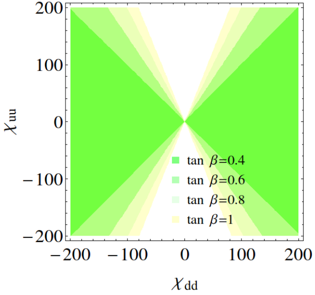


Figure 1: Constraints for the FC parameters, we consider $m_h = 125.7$ GeV, Br$(h \to \gamma\gamma) = 2.27 \times 10^{-3}$, $m_H = 300$ GeV and $m_{H^\pm} = 350$ GeV .

Constraints from the recent experimental results

We consider the recent experimental results coming from [15] for processes: $t \to c\,V$ those processes are emphasized because they could give evidence for the new physics (see fig. 2).

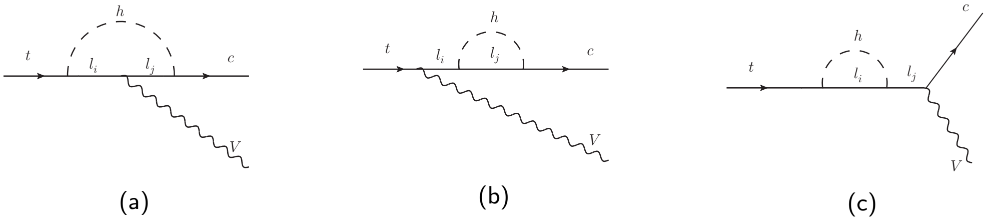


Figure 2: Feynman diagrams for the processes $t \to c\ V$, where $V = \gamma, Z, g$. We considered the contributions to the FC mediated by scalar bosons.

Naive exploration

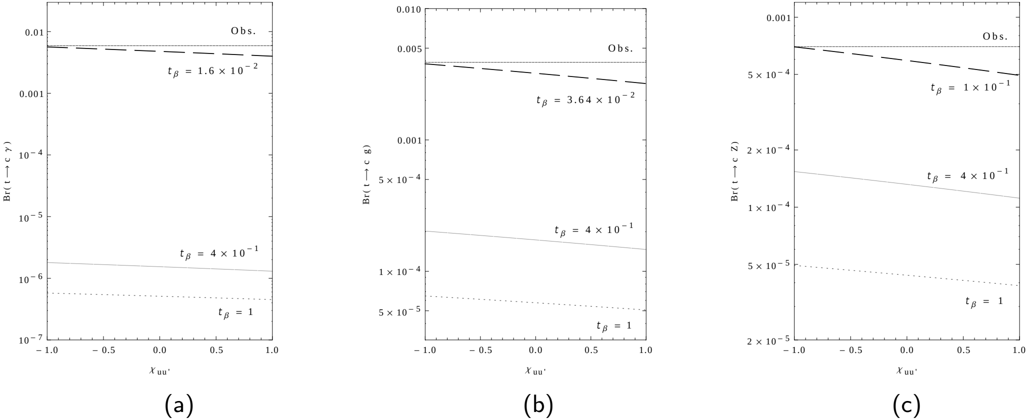


Figure 3: This plot shows the Br's for the a) $t \to c\,\gamma$, b) $t \to c\,g$ and c) $t \to c\,Z$. In all cases we have considered $\delta = 5 \times 10^{-2}$

Constraints over Total Width (naive)

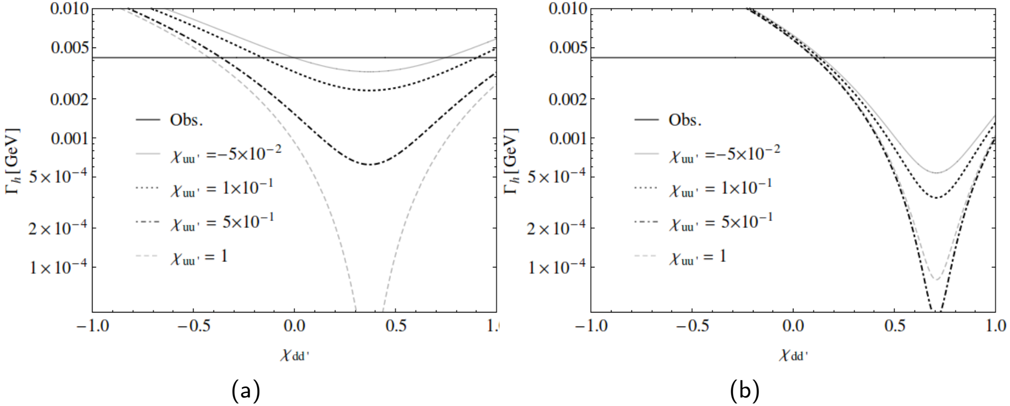
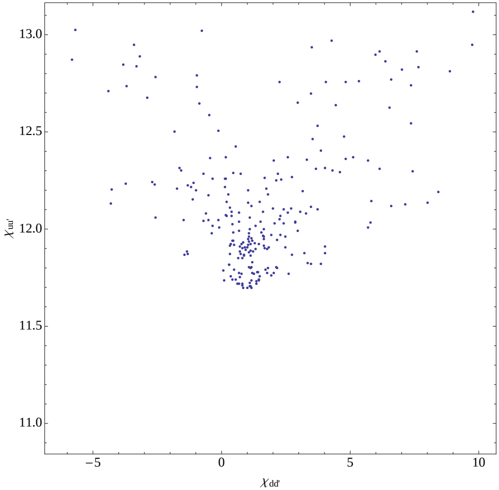
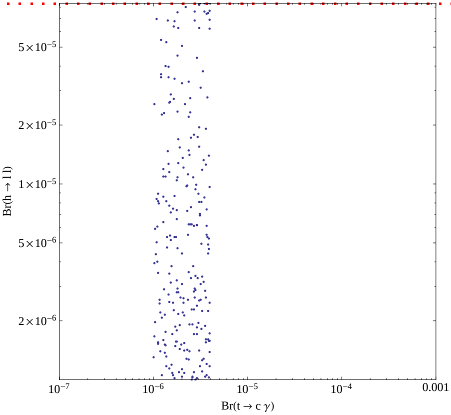


Figure 4: Total Higgs width decay for different parameter values. We consider several cases for the $\chi_{uu'}$ parameter. We consider following cases: a) $\tan\beta = 0.4$, b) $\tan\beta = 1$. Plot contains decay width of Higgs boson given by ATLAS, CMS [9, 7].

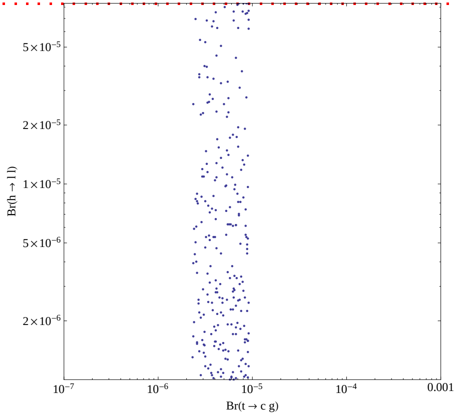
Deeper exploration



We consider the different constraints for the processes with FC as $t \to cV$ and $t \to ch$ for constraining the parameter space. We generate random values for the parameters: $\chi_{uu'}, \chi_{dd'}, \tan\beta, m_{H^\pm}$ and Br′s $t \to cZ, t \to c\gamma, t \to cZ, t \to cg, t \to ch, h \to l\bar{l}, h \to gZ$.

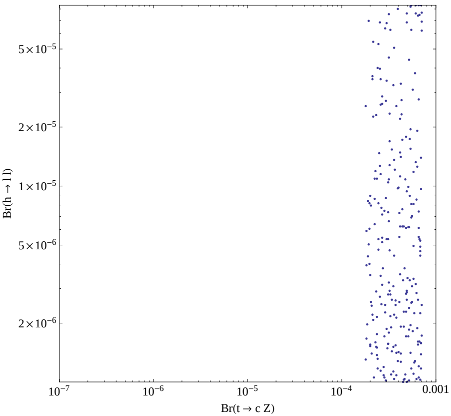


(a)

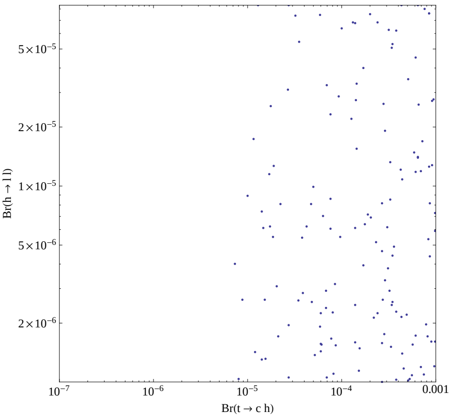


(b)

Figure 5: Scattering plot for the parameters $\tan\beta, \chi_{uu'}, \chi_{dd'}, m_{H^\pm}$. The figure shows: a) Br$(h \to l\bar{l})$ vs. Br$(t \to c\gamma)$ and b) Br$(h \to l\bar{l})$ vs. Br$(t \to cg)$

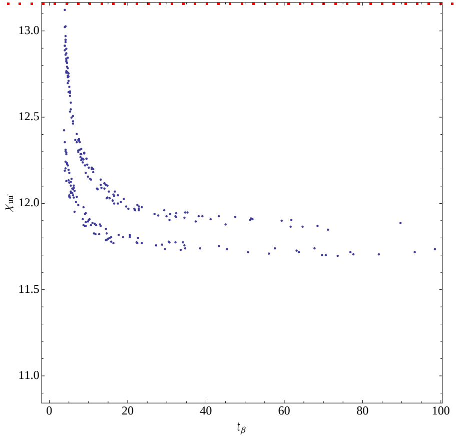


(a)

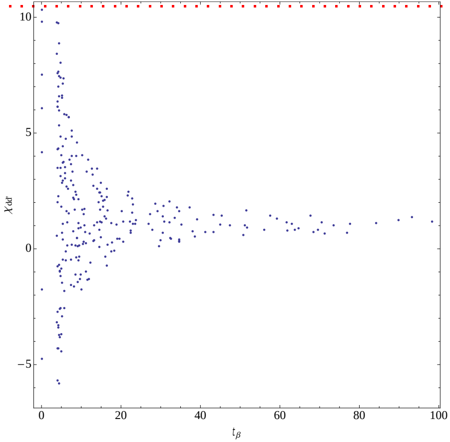


(b)

Figure 6: Scattering plot for the parameters $\tan\beta, \chi_{uu'}, \chi_{dd'}, m_{H^\pm}$. The figure shows: a) Br$(h \to l\bar{l})$ vs. Br$(t \to cZ)$ and b) Br$(h \to l\bar{l})$ vs. Br$(t \to ch)$.



(a)



(b)

Figure 7: Scattering plot for the parameters $\tan\beta, \chi_{uu'}, \chi_{dd'}, m_{H^\pm}$. The figure shows: a) $\chi_{uu'}$ vs. t_β and b) $\chi_{dd'}$ vs. t_β

Br vs. $\chi_{dd'}$

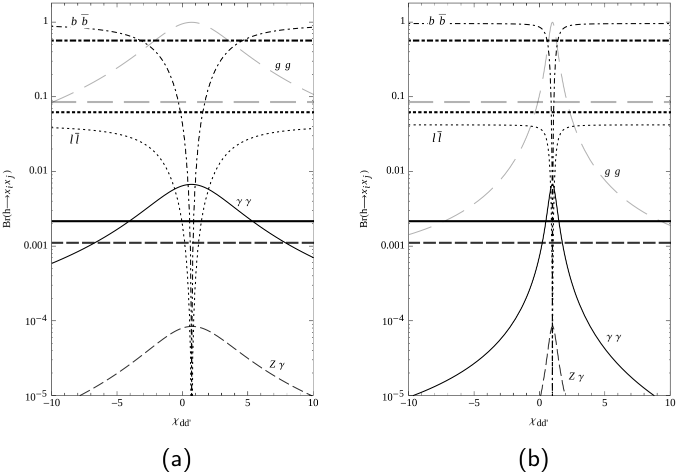
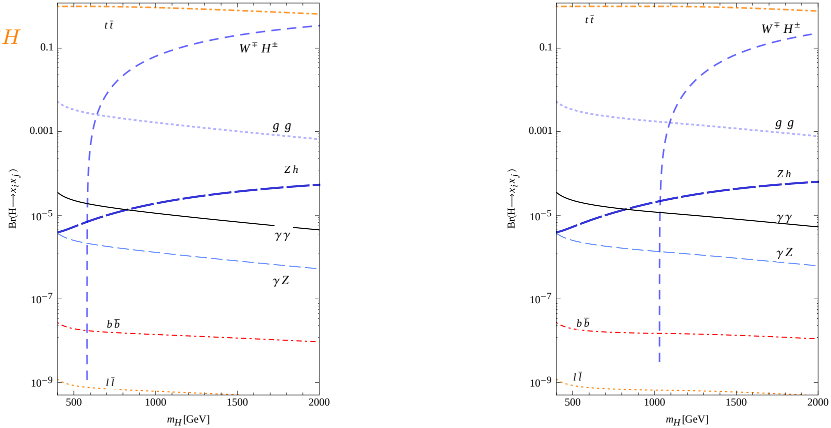


Figure 8: Br's for different channels versus the FC parameter for the d-type quark. We consider: a) $\tan\beta = 1$ and b) $\tan\beta = 10$, and for both cases $\chi_{uu'} = 12$.

Br vs. m_H

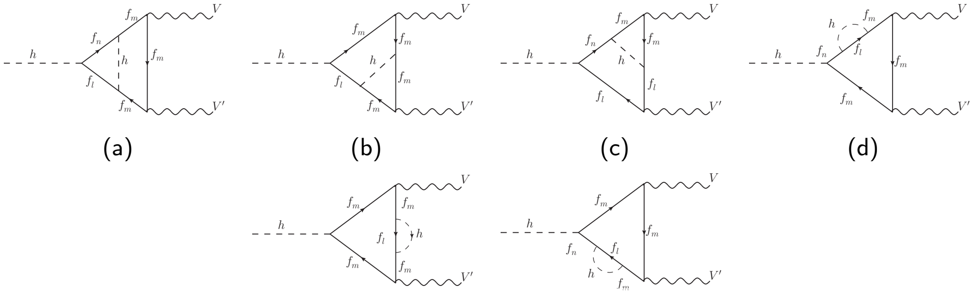


(a) (b)

Figure 9: a) $m_{H^{\pm}} = 500$ and b) $m_{H^{\pm}} = 950$ in both cases we fix on $\chi_{uu'} = 12, \chi_{dd'} = 1$ and $t_\beta = 1 \times 10$.

FC at two-loop level

We explore the FC at two-loop level (we know about the low contribution)



(a) (b) (c) (d)

(e) (f)

For the THDM-III is

$$\mathcal{M}_2(\phi \to V'V) = -\frac{i\mathrm{Tr}\left(M_2^{\mu_1\mu_2}\right)}{256\pi^8 m_h^{12}\prod_{l=1}^{6} P_l}\epsilon^*_{\mu_1}(p_2)\epsilon^*_{\mu_2}(p_3)$$

where the product of the propagators is

$$\prod_{\lambda=1}^{6} P_\lambda = (r_{q_1} - r_l)(r_{q_2} - r_m)(r_{p_3\bar{q}_2} - r_m) \times (r_{q_1q_2} - 1)(r_{p_2p_3q_1} - r_n)(r_{p_2p_3\bar{q}_2} - r_m)$$

with $r_i = \frac{m_i^2}{m_h^2}$, $r_{p_i\bar{p}_j} = \frac{(p_i-p_j)^2}{m_h^2}$, $r_{q_iq_j} = \frac{(q_i+q_j)^2}{m_h^2}$, $r_{p_ip_jq_k} = \frac{(p_i+p_j+q_k)^2}{m_h^2}$, $r_{p_ip_j\bar{q}_k} = \frac{(p_i+p_j-q_k)^2}{m_h^2}$. p_1 is the momentum for the scalar boson, $p_{2,3}$ are the momentum of the particles in the final state and $q_{1,2}$ are the momentum for the loops. The tensorial amplitud for the THDM-III is (for the SM see ref. [12])

$$
\begin{aligned}
M_2^{\mu_1\mu_2} \quad = \quad & \kappa(m_m+\gamma^{\nu_1}P^{\nu_1}_{q_2\bar{p}_2\bar{p}_3})\gamma^{\mu 1}(P_L+P_R)(m_m+\gamma^{\nu_2}P^{\nu_2}_{q_2\bar{p}_3})\gamma^{\mu 2}(P_L+P_R) \\
& \big(m_m+\gamma^{\nu_3}q_2^{\nu_3}\big)(i\mathcal{G}_{L_m}P_L+i\mathcal{G}_{R_m}P_R)\big(m_l-\gamma^{\nu_4}q_1^{\nu_4}\big)(i\mathcal{G}_{L_l}P_L+i\mathcal{G}_{R_l}P_R) \\
& \big(m_n+\gamma^{\nu_5}P^{\nu_5}_{\bar{p}_2\bar{p}_3\bar{q}_1}\big)(i\mathcal{G}_{L_n}P_L+i\mathcal{G}_{R_n}P_R)
\end{aligned}
$$

where $\kappa=(-ie)(-ie)$ and $\mathcal{G}_{L,R_{m,n,l}}$ are model-dependent complex functions given by (fig. 10a)

$$
\mathcal{G}_{L_m}=-\frac{c_\alpha}{t_\beta v_1}\widetilde{M}^{lm}+\frac{c_\alpha}{\sqrt{2}t_\beta}\widetilde{Y}^{*lm}+\frac{s_\alpha}{\sqrt{2}}\widetilde{Y}^{*lm} \qquad \mathcal{G}_{R_m}=-\frac{c_\alpha}{t_\beta v_1}\widetilde{M}^{ml}+\frac{c_\alpha}{\sqrt{2}t_\beta}\widetilde{Y}^{ml}-\frac{s_\alpha}{\sqrt{2}}\widetilde{Y}^{ml}
$$

$$
\mathcal{G}_{L_l}=-\frac{c_\alpha}{t_\beta v_1}\widetilde{M}^{nl}+\frac{c_\alpha}{\sqrt{2}t_\beta}\widetilde{Y}^{*nl}-\frac{s_\alpha}{\sqrt{2}}\widetilde{Y}^{*nl} \qquad \mathcal{G}_{R_l}=-\frac{c_\alpha}{t_\beta v_1}\widetilde{M}^{ln}+\frac{c_\alpha}{\sqrt{2}t_\beta}\widetilde{Y}^{ln}-\frac{s_\alpha}{\sqrt{2}}\widetilde{Y}^{ln}
$$

$$
\mathcal{G}_{L_n}=-\frac{c_\alpha}{t_\beta v_1}\widetilde{M}^{nm}+\frac{c_\alpha}{\sqrt{2}t_\beta}\widetilde{Y}^{*nm}-\frac{s_\alpha}{\sqrt{2}}\widetilde{Y}^{*nm} \qquad \mathcal{G}_{R_n}=-\frac{c_\alpha}{t_\beta v_1}\widetilde{M}^{mn}+\frac{c_\alpha}{\sqrt{2}t_\beta}\widetilde{Y}^{mn}-\frac{s_\alpha}{\sqrt{2}}\widetilde{Y}^{mn}.
$$

F. Febres' talk

Conclusions

1. 2HDM contains a rich spectrum of neutral and charged Higgs bosons, whose detection at current and future colliders would be a clear signal of new physics.

2. We have evaluated the generic fermionic contribution to the decays $A^0 \rightarrow ZZ, Z\gamma, \gamma\gamma$, including its scalar and pseudoscalar vertices.

3. Considering gauge bosons in the final state and FC inside the loop then we obtain 324 diagrams. The analysis for those diagrams could be awkward so we write down the amplitudes at two-loop level.

4. We found some restrictions over for the 2HDM parameters and the behavior for the Br$(h \rightarrow x_i x_j)$ versus m_H.

5. 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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