Flavor changing neutral scalar interactions (FCNSI)

Jose Halim Montes de Oca
Facultad de Estudios Superiores Cuautitlan
UNAM
josehalim@gmail.com

Reunion anual de la DPyC 2015

In collaboration with:
R. Gaitan (FESC-UNAM)
E. A. Garces (FESC-UNAM)
R. Martinez (UNC)

General THDM

Φ_1 and Φ_2 are two complex $SU(2)_L$ doublet scalar fields with hypercharge-one. The most general $U(1)_{EM}$-conserving vacuum expectation values are

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix},$$

$$\langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 e^{i\xi} \end{pmatrix},$$

where v_1 and v_2 are real and non-negative, $0 \leq |\xi| \leq \pi$, and $v^2 \equiv v_1^2 + v_2^2 = \frac{4M_W^2}{g^2} = (246\ \mathrm{GeV})^2$.

General 2HDM potential

Given Φ_1 and Φ_2 two complex $SU(2)_L$ doublet scalar fields with hypercharge-one, the most general gauge invariant and renormalizable Higgs scalar potential is

$$\begin{aligned} V &= m_{11}^2\Phi_1^+\Phi_1 + m_{22}^2\Phi_2^+\Phi_2 - \left[m_{12}^2\Phi_1^+\Phi_2 + h.c.\right] + \frac{1}{2}\lambda_1\left(\Phi_1^+\Phi_1\right)^2 \\ &+\frac{1}{2}\lambda_2\left(\Phi_2^+\Phi_2\right)^2 + \lambda_3\left(\Phi_1^+\Phi_1\right)\left(\Phi_2^+\Phi_2\right) + \lambda_4\left(\Phi_1^+\Phi_2\right)\left(\Phi_2^+\Phi_1\right) \\ &+\left[\frac{1}{2}\lambda_5\left(\Phi_1^+\Phi_2\right)^2 + \lambda_6\left(\Phi_1^+\Phi_1\right)\left(\Phi_1^+\Phi_2\right) + \lambda_7\left(\Phi_2^+\Phi_2\right)\left(\Phi_1^+\Phi_2\right)\right. \\ &\left.+\, h.c.\right], \end{aligned}$$

where m_{11}^2, m_{22}^2 and λ_1, λ_2, λ_3, λ_4 are real parameters and in general m_{12}^2, λ_5, λ_6, λ_7 are complex parameters.

Mass and Mixing Matrix

$$
\begin{aligned}
\mathcal{M}_{11}^2 &= v^2[c_\beta^2\,\lambda_1 + s_\beta^2\,\nu + \frac{s_\beta}{2c_\beta}\mathrm{Re}\,(3c_\beta^2\,\lambda_6 - s_\beta^2\,\lambda_7)], \\
\mathcal{M}_{22}^2 &= v^2[s_\beta^2\,\lambda_2 + c_\beta^2\,\nu + \frac{c_\beta}{2s_\beta}\mathrm{Re}\,(-c_\beta^2\,\lambda_6 + 3s_\beta^2\,\lambda_7)], \\
\mathcal{M}_{33}^2 &= v^2\mathrm{Re}\,[-\lambda_5 + \nu - \frac{1}{2c_\beta s_\beta}(c_\beta^2\,\lambda_6 + s_\beta^2\,\lambda_7)], \\
\mathcal{M}_{12}^2 &= v^2[c_\beta s_\beta(\mathrm{Re}\,\lambda_{345} - \nu) + \tfrac{3}{2}\mathrm{Re}\,(c_\beta^2\,\lambda_6 + s_\beta^2\,\lambda_7)], \\
\mathcal{M}_{13}^2 &= -\tfrac{1}{2}v^2\mathrm{Im}\,[s_\beta\,\lambda_5 + 2c_\beta\,\lambda_6], \\
\mathcal{M}_{23}^2 &= -\tfrac{1}{2}v^2\mathrm{Im}\,[c_\beta\,\lambda_5 + 2s_\beta\,\lambda_7],
\end{aligned}
$$

with $\mathcal{M}_{ji}^2 = \mathcal{M}_{ij}^2$ and $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$.

Mass-eigenstates

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \eta_1 + i\chi_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \eta_2 + i\chi_2) \end{pmatrix},$$

$\Rightarrow$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 c_3 & -(c_1 s_1 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix}$$

where $\eta_3 = -\chi_1 \sin\beta + \chi_2 \cos\beta$, $c_i = \cos\alpha_i$, $s_i = \sin\alpha_i$ for $-\frac{\pi}{2} \leq \alpha_{1,2} \leq \frac{\pi}{2}$ and $0 \leq \alpha_3 \leq \frac{\pi}{2}$.

The neutral Higgs bosons h_i satisfy the mass relation

$m_{h_1} \leq m_{h_2} \leq m_{h_3}$

Yukawa couplings

For the Yukawa interactions between fermions and scalar fields, the most general structure is

$$\mathcal{L}_{Yukawa} = \sum_{i,j=1}^{3} \sum_{a=1}^{2} \left(\overline{q}_{Li}^{0} Y_{aij}^{0u} \widetilde{\Phi}_a u_{Rj}^{0} + \overline{q}_{Li}^{0} Y_{aij}^{0d} \Phi_a d_{Rj}^{0} + \overline{l}_{Li}^{0} Y_{aij}^{0l} \Phi_a e_{Rj}^{0} + h.c. \right),$$

where $Y_a^{u,d,l}$ are the 3×3 Yukawa matrices.
After getting a correct spontaneous symmetry breaking the mass matrices become

$$M^{u,d,l} = \frac{1}{\sqrt{2}} v_1 Y_1^{u,d,l} + \frac{1}{\sqrt{2}} v_2 Y_2^{u,d,l},$$

where $Y_a^f = V_L^f Y_a^{0f} \left(V_R^f\right)^\dagger$ for $f = u, d, l$.

Flavor Changing Neutral Scalar Interactions

The Yukawa interactions between neutral Higgs bosons and quarks are

$$\begin{aligned}\mathcal{L}_{\text{Neutral}} &= \frac{1}{v\cos\beta}\sum_{ijk}\bar{u}_i M^u_{ij}\left(A_k P_L + A^*_k P_R\right) u_j h_k \\ &+ \frac{1}{v\cos\beta}\sum_{ijk}\bar{d}_j M^d_{ij}\left(A^*_k P_L + A_k P_R\right) d_j h_k \\ &+ \frac{1}{\cos\beta}\sum_{ijk}\bar{u}_i Y^u_{ij}\left(B_k P_L + B^*_k P_R\right) u_j h_k \\ &+ \frac{1}{\cos\beta}\sum_{ijk}\bar{d}_i Y^d_{ij}\left(B^*_k P_L + B_k P_R\right) d_j h_k,\end{aligned}$$

where

$$\begin{aligned}A_k &= R_{k1} - iR_{k3}\sin\beta, \\ B_k &= R_{k2}\cos\beta - R_{k1}\sin\beta + iR_{k3},\end{aligned}$$

Rare top decay

The relevant contributions for $t \to c\gamma$

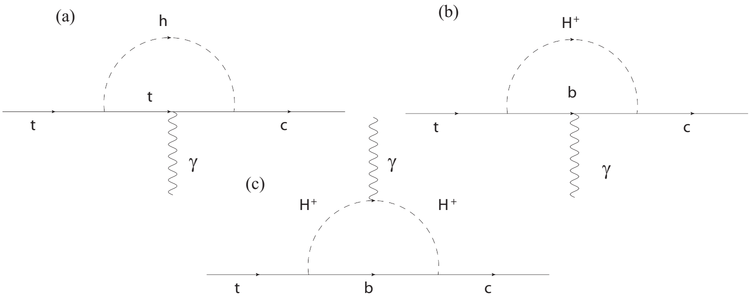


Figure: One loop Feynman diagrams with Higgs boson in internal line, (a) flavor changing neutral scalar contribution, (b) and (c) charged contributions.

Rare top decay cont...

The partial width is

$$\Gamma\left(t \to c\gamma\right) = \frac{G_F^2 m_t^4 m_c}{192\pi^5 \cos^4\beta \sin^2\theta_W} \sum_k \left[\left| f_1\left(\widehat{m}_k\right) A_k^* B_k + f_2\left(\widehat{m}_k\right) A_k B_k \right|^2 + \left| f_1\left(\widehat{m}_k\right) A_k B_k^* + f_2\left(\widehat{m}_k\right) A_k^* B_k^* \right|^2 \right],$$

where $G_F^{-1} = \sqrt{2} v^2$ and the functions $f_{1,2}$ are defined as

$$f_1\left(\widehat{m}_k\right) = \int_0^1 dx \int_0^{1-x} dy \frac{x\left(x+y-1\right)}{x^2 + xy - \left(2 - \widehat{m}_k^2\right) x + 1},$$

$$f_2\left(\widehat{m}_k\right) = \int_0^1 dx \int_0^{1-x} dy \frac{\left(x-1\right)}{x^2 + xy - \left(2 - \widehat{m}_k^2\right) x + 1},$$

with $\widehat{m}_i = m_{h_i}/m_t$. We use the Cheng- Sher Ansatz $Y_{ij} \sim \frac{\sqrt{m_i m_j}}{M_W}$

Branching ratio

The branching ratio can be written ($\Gamma_{\rm top} \approx 1.6$ GeV) as

$$\mathrm{Br}\left(t \to c\gamma\right) \approx \frac{\Gamma\left(t \to c\gamma\right)}{\Gamma_{\rm top}},$$

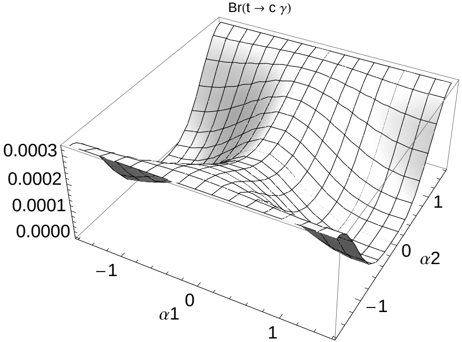
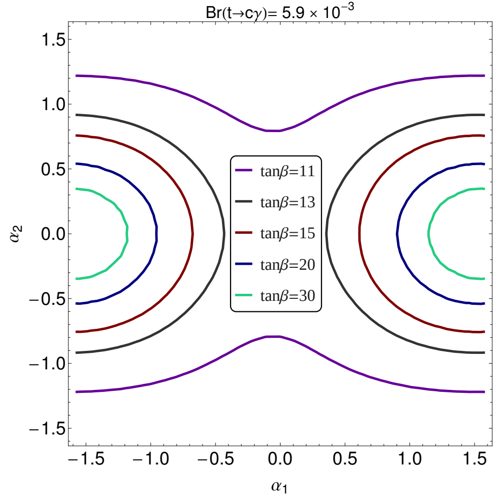
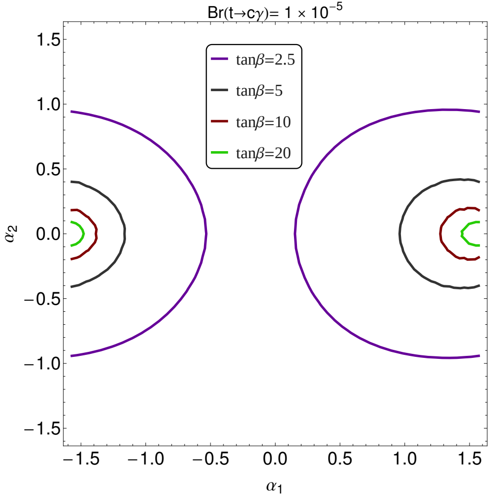


Figure: Branching ratio for $\tan\beta = 5$.

Current LHC Limit



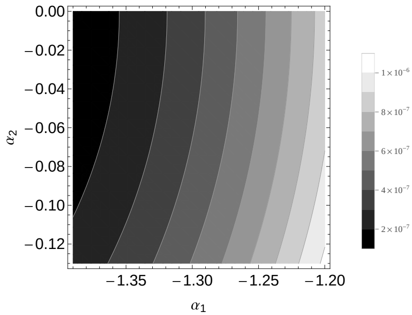
Expected LHC Limit



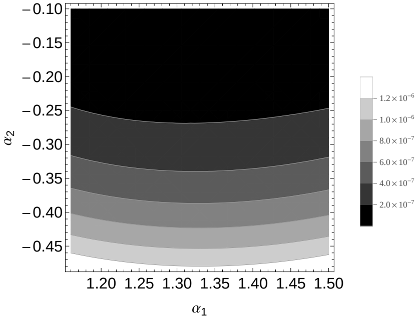
In a good approximation

Regions for α_1 and α_2 from $0.5 \leq R_{\gamma\gamma} \leq 2$ with $m_{H^\pm} = 300$ GeV and $\tan\beta = 2.5$ [L. Basso, et. al., *JHEP* **1211**, 011 (2012)]:

$$R_1 = \{-1.39 \leq \alpha_1 \leq -1.2 \quad \text{and} \quad -0.13 \leq \alpha_2 \leq 0\}\,,$$



$$R_2 = \{1.16 \leq \alpha_1 \leq 1.5 \text{ and } -0.48 \leq \alpha_2 \leq -0.1\}\,.$$



Final remarks

- $\mathrm{Br}(t \to c\gamma) \sim O(10^{-10})$ in Standard Model.
- Experimental constrains and precision (work in progress).
- 2HDM could be a source for FCNC and CPV.

Thank you