Flavor changing neutral scalar interactions (FCNSI)

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

FLASY 2015
Manzanillo, Colima, 29-jun-2015.

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

Two Higgs Doublet Models

The SM quantum number for the doublets

$$\Phi_{1,2} \sim (1,\, 2,\, 1)$$

Yukawa couplings ⇒ Different types (type-I,-II,-III).

Scalar potential ⇒ CPC or CPV

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.

General VEVs

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

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_1 \end{array} \right),$$

$$\langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \left(\begin{array}{c} 0 \\ v_2 e^{i\xi} \end{array} \right),$$

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

We set $\xi = 0$

Mass and Mixing Matrix

After some steps, the mass matrix for neutral scalar fields is

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

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

Mass-eigenstates

The fields have been written as

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

All three neutral states will then mix, with the physical Higgs particles h_i related to the weak fields η_j by

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

where $\eta_3 = -\chi_1 \sin\beta + \chi_2 \cos\beta$, $c_i = \cos\alpha_i$, $s_i = \sin\alpha_i$ for $-\frac{\pi}{2} \leq \alpha_{1,2} \leq \frac{\pi}{2}$, ,$0 \leq \alpha_3 \leq \frac{\pi}{2}$ and $m_{h_1} \leq m_{h_2} \leq m_{h_3}$.

Yukawa couplings

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

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

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

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

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 $t \to c\gamma$

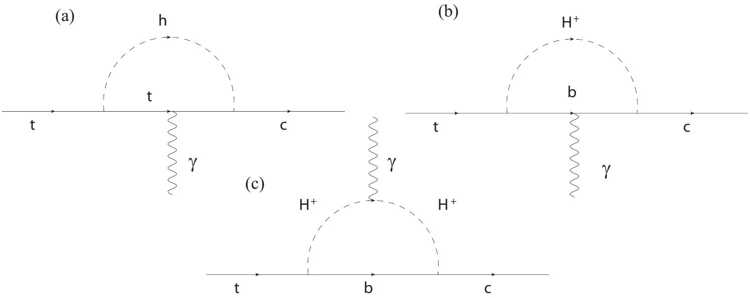


Figure: One loop Feynman diagrams with Higgs boson in internal line, (a) flavor changing neutral scalar contribution, (b) and (c) charged contributions.

Rare top decay cont...

If only the dominant contribution of the FCNSI is taken, partial width is

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

We have used the Cheng-Sher Ansatz $Y_{ij} \sim \frac{\sqrt{m_i m_j}}{M_W}$.

The functions $f_{1,2}$ are defined as

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

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

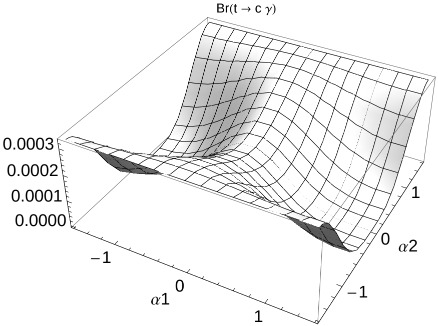
with $\widehat{m}_i = m_{h_i}/m_t$.

Branching ratio

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

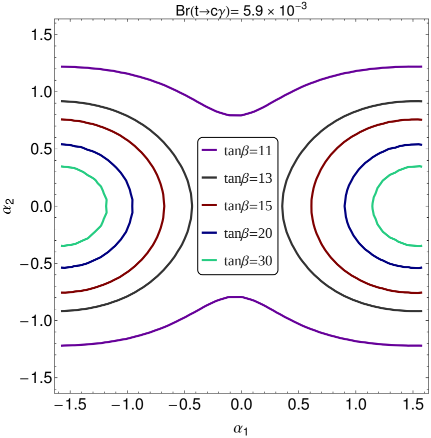
$$\mathrm{Br}\left(t \rightarrow c\gamma\right) \approx \frac{\Gamma\left(t \rightarrow c\gamma\right)}{\Gamma_{\rm top}},$$

- Case $\tan\beta = 5$, $M_{h_1} \approx 125$ GeV, $M_{h_2,h_3} > 600$ GeV (α_3 independent),



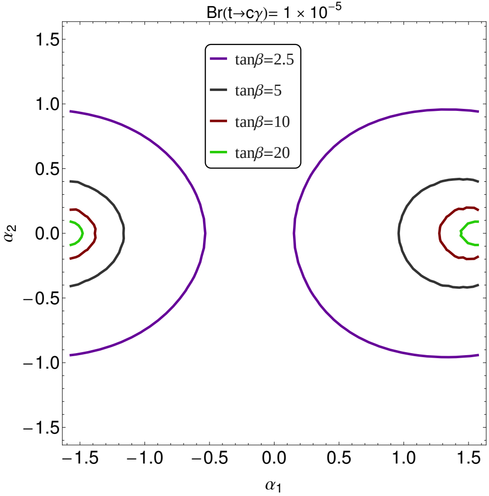
Current LHC Limit

The limit is reported as $\mathrm{Br}(t \to c\gamma) < 5.9 \times 10^{-3}$ *



* PDG, *Chin. Phys. C*, **38**, 090001 (2014)

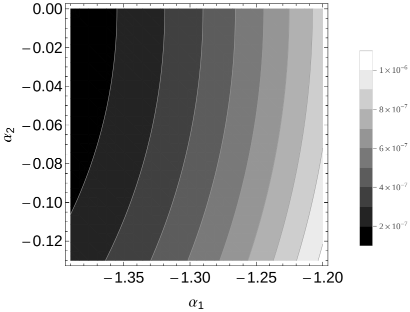
Expected LHC Limit



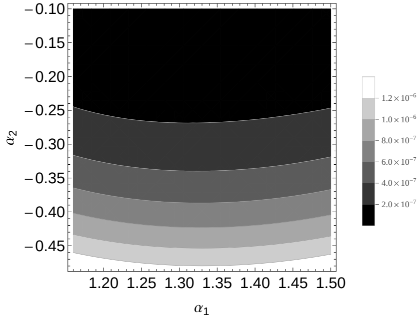
In a good approximation

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.
- More precision (work in progress).
- Experimental constrains and to including other processes (work in progress).
- 2HDM could be a source for FCNC and CPV.

Thank you