LFV in τ decays for a 2HDM-SU(3)

L. Lopez-Lozano

XV Mexican Workshop on Particles and Fields

2-6 November 2015

Outline

- Fermion mixing
- 2HDM versions
- Flavour Transformations
- 2HDM-SU(3)in τ decays

SM Parameters distribution

$$\mathcal{L}_{\mathsf{SM}} = \underbrace{-\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{(g_s, g)}$$

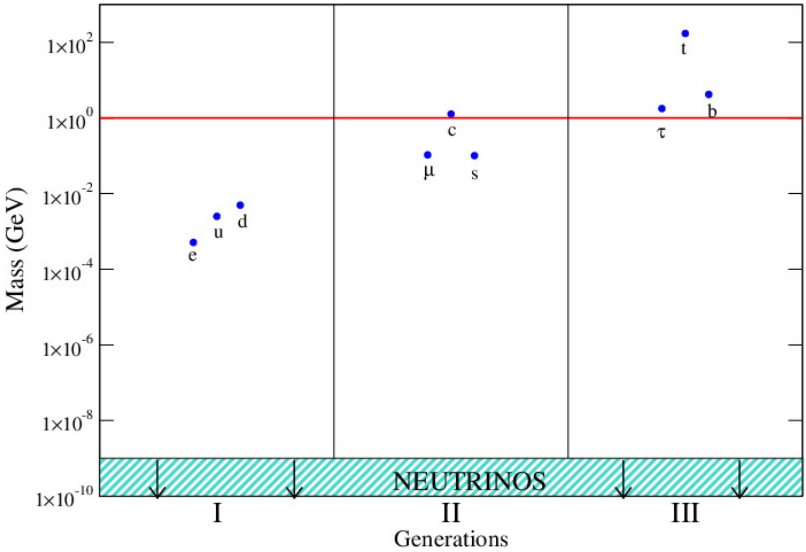
$$+ \underbrace{(D_\mu\varphi)^\dagger(D^\mu\varphi) + m_H^2\varphi^\dagger\varphi - \frac{1}{2}\lambda(\varphi^\dagger\varphi)^2}_{(g, g', m_H, m_W, m_Z)}$$

$$+ \underbrace{i\bar{\ell}_L\gamma_\mu D^\mu \ell_L + i\bar{e}_R\gamma_\mu D^\mu e_R + i\bar{\psi}_L\gamma_\mu D^\mu \psi_L + i\bar{u}_R\gamma_\mu D^\mu u_R + i\bar{d}_R\gamma_\mu D^\mu d_R}_{(g, g_s, g')}$$

$$+ \underbrace{Y^\ell \bar{\ell}_L \varphi e_R + Y^u \bar{\psi}_L \tilde{\varphi} u_R + Y^d \bar{\psi}_L \varphi d_R + \text{H.c.}}_{(m_H, m_e, m_\mu, m_\tau, m_u, m_d, m_c, m_s, m_t, m_b, \theta_1, \theta_2, \theta_3, \phi_{CP})}$$

$$+ \underbrace{\text{Neutrino Sector}}_{\text{more parameters}\cdots}$$

Mass spectrum



We can not make arbitrary extensions of the scalar sector

- $\rho = \frac{m_W^2}{m_z^2 \cos^2\theta_W} \simeq 1$
- FCNC must be small

[Gunion *et. al.*,1990]

Why study the 2HDM?

Because 2HDM is a framework

Yukawa sector of 2HDM($N = 2$)

$$\mathcal{L}_{HF}^{2HDM} = -\overline{Q}_L \sum_{a=1}^{N} (Y_a^d \Phi_a d_R + Y_a^u \tilde{\Phi}_a u_R) - \overline{L}_L \sum_{a=1}^{N} Y_a^l \Phi_a l_R + h.c.$$

$$\Phi_a = \begin{pmatrix} \varphi_a^+ \\ \varphi_a^0 e^{i\theta_a} \end{pmatrix}, \quad \varphi_a^0 = v_a + \frac{\rho_a + i\eta_a}{\sqrt{2}} \quad ; \quad a = 1, ..., N$$

Mass Matrix

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

- The same fermions than SM
- The same SM symmetries and possibly a discrete symmetry (NFC)
- $4(N-1) - 3$ new physical scalars (DM candidates)
- New sources of CP violation (θ_a and phases in $Y_a^{u,d,l}$)
- Presence of Flavour Changing Neutral Currents at tree level (version III)

Higgs mixing

$$
\begin{aligned}
H^{\pm} &= -\sin\beta\varphi_1^{\pm} + \cos\beta\varphi_2^{\pm} \\
A^0 &= \sqrt{2}\,(-\sin\beta\eta_1 + \cos\beta\eta_2) \\
H^0 &= \sqrt{2}\,[(\rho_1 - v_1)\cos\alpha + (\rho_2 - v_2)\sin\beta] \\
h^0 &= \sqrt{2}\,[-(\rho_1 - v_1)\sin\alpha + (\rho_2 - v_2)\cos\alpha]
\end{aligned}
$$

With $\beta = \tan\frac{v_2}{v_2}$ and $v^2 = v_1^2 + v_2^2$

Higgs basis (with CP conserving)

$$
\langle H_1\rangle_0 = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad ; \quad \langle H_2\rangle_0 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}
$$

Why a Version III?

- Discrete symmetries imposed on the Higgs doublets are too restrictive that it is not possible to describe deviations from the SM symmetries (if exist)
- 2HDM-II can not explain $B \to \tau\nu$, $B \to D\tau\nu$ and $B \to D * \tau\nu$ simultaneously [A. Crivellin, et al. (2013)]
- Relaxed restrictions on the Higgs doublets introduce FCNC at tree level, relative easy to restrict with phenomenology
- The FCNC need a mechanism to control them that can be inspired in a supersymmetry breaking (to be explore)

At the Higgs basis

$$
\begin{aligned}
\mathcal{L}_Y &= \eta^u \bar{Q}_L \tilde{H}_1 u_R + \eta^d \bar{Q}_L H_1 d_R + \eta^\ell \bar{L}_L H_1 \ell_R \\
&+ \hat{\xi}^u \bar{Q}_L \tilde{H}_2 u_R + \hat{\xi}^d \bar{Q}_L H_2 d_R + \hat{\xi}^\ell \bar{L}_L H_2 \ell_R + \text{H.c.}
\end{aligned}
$$

Mass matrix diagonalization

- Diagonal mass matrix

$$\tilde{M}_f \equiv \text{diag}(m_1^f, \ldots, m_n^f) = U_L^\dagger M_f U_R \quad \text{for} \quad f = u, d, \ell, \nu$$

- The hermitian squared mass matrix

$$\begin{aligned} H_f &\equiv M_f M_f^\dagger = U_L^f \tilde{M}_f^2 U_L^{f\dagger} \quad \text{(Unitary transformation)} \\ I_f &\equiv M_f^\dagger M_f = U_R^f \tilde{M}_f^2 U_R^{f\dagger} \quad (U_R^f \text{ can not be observed}) \end{aligned}$$

- Diagonalize the H_f matrix gives a mixing matrix of the form $P_f^\dagger \mathcal{O}_f$
- *Free* parameters of mass matrices $(n = 3 \Rightarrow N = 26 - X)$

$$N = 4n^2 - \underbrace{\frac{n(n-1)}{2}}_{\text{mixing}} - \underbrace{\frac{(n-1)(n-2)}{2}}_{\text{phases}} - \underbrace{2n}_{\text{masses}} - \underbrace{X}_{\text{texture assumptions}}$$

Cheng and Sher *Ansatz*

- The first attempt to control FCNSI was $m_H \sim \mathcal{O}(\text{TeV})$
- A Fritzsch form mass matrix can reproduce V_{CKM} at the quark sector

$$M_f = \begin{pmatrix} 0 & C_f & 0 \\ C_f^* & D_f & B_f \\ 0 & B_f^* & A_f \end{pmatrix}$$

- FCNSI inherits the hierarchy of mass matrix

$$\xi_{ij}^f = \frac{\sqrt{2}}{v} \underbrace{\sqrt{m_i^f m_j^f}}_{\sim M_{ij}^f} \tilde{\chi}_{ij}^f$$

- In order to preserve the hierarchy $|\tilde{\chi}_{ij}^f| \sim 1$ (can be relaxed)
- Works fine for quark and lepton sector [J. Barranco, et. al.]

Is there another way to introduce the hierarchy of masses and reduce the number of free parameters?

- Aligned 2HDM (No FCNC)

$$Y_2 = aY_1$$

- Partially Aligned 2HDM (FCNC suppressed)

$$Y_2^f = \begin{pmatrix} 0 & c_2 C_f & 0 \\ c_2^* C_f^* & d_2 D_f & b_2 B_f \\ 0 & b_2^* B_f^* & A_f \end{pmatrix}$$

$$\tilde{\chi}_{ij}^f = \tilde{\chi}_{ij}^f(b_2, c_2, d_2, a_2, \phi_C, \phi_B)$$

Flavour Transformation

$$T^f = \zeta' \cdot A_L M_{f'} A_R$$

Orthogonal transformation $A_L = \mathcal{O}^T$; $A_R = \mathcal{O}$

$$\xi_f = \zeta' \cdot R^T(\theta_1, \theta_2, \theta_3) M_f R(\theta_1, \theta_2, \theta_3)$$

- Same physical content than mass matrix
  $\text{Tr}(\xi^f) = \zeta' \text{Tr}(M_f)$, $\text{Det}(\xi^f) = \zeta' \cdot \text{Det}(M_f)$
- Establish relations between χ_{ij} reducing the number of free parameters.
- Suitable parameters of rotations can reproduce the version I, II and the A-2HDM

The infinitesimal rotation preserves approximately the hierarchy of the mass matrix ($\zeta' = 1$)

$$\xi^f = \begin{pmatrix} -2(\theta_1+\theta_3)|C_f| & |C_f|\left(1-(\theta_1+\theta_3)\frac{D_f}{|C_f|}\right) & \theta_2|C_f| - (\theta_1+\theta_3)|B_f| \\ |C_f|\left(1-(\theta_1+\theta_3)\frac{D_f}{|C_f|}\right) & |D_f| + 2(\theta_1+\theta_3)|C_f| - 2\theta_2|B_f| & |B_f| + \theta_2(D_f - A_f) \\ \theta_2|C_f| - (\theta_1+\theta_3)|B_f| & |B_f| + \theta_2(D_f - A_f) & A_f + 2\theta_2|B_f| \end{pmatrix}$$

Unitary Transformation $A_L = U^\dagger$;$A_R = U$; $U \in SU(3)$

$$\xi_f = \zeta' U^\dagger M_f U$$

$$U = \sum_a C_a \lambda_a \qquad ; \qquad C_{ab} \equiv C_a^* \cdot C_b$$

- Again the mass matrix inherits its physical content on ξ.
- In the hermitian case: $C_{ab} = C_{ba}^*$.
- There is a connection between the experimental measurements and the group parameters.

$$\mathrm{Tr}(\lambda_a \xi^f \lambda_b) = \sum_{c,d} C_{cd} \mathrm{Tr}(\lambda_a \lambda_c M_f \lambda_d \lambda_b)$$

- The texture of the mass matrix is preserved if U have only contribution of λ_3, λ_8 (Type III).

Unitary Transformation $A_L = U^\dagger \; ; A_R = U$

$$M_f = \sum_a \tilde{m}_a \lambda_a$$

The system can be solved if we define

$$\mathcal{V} = \begin{pmatrix} C_{11} \\ C_{12} \\ \vdots \\ C_{88} \end{pmatrix} ; \quad \mathcal{W} = \begin{pmatrix} \mathrm{Tr}(\lambda_1 \xi^f \lambda_1) \\ \mathrm{Tr}(\lambda_1 \xi^f \lambda_2) \\ \vdots \\ \mathrm{Tr}(\lambda_8 \xi^f \lambda_8) \end{pmatrix}$$

$$\mathcal{M} = \begin{pmatrix} \mathrm{Tr}(\lambda_1 \lambda_1 M_f \lambda_1 \lambda_1) & \dots & \mathrm{Tr}(\lambda_1 \lambda_8 M_f \lambda_8 \lambda_1) \\ \vdots & \ddots & \vdots \\ \mathrm{Tr}(\lambda_8 \lambda_1 M_f \lambda_1 \lambda_8) & \dots & \mathrm{Tr}(\lambda_8 \lambda_8 M_f \lambda_8 \lambda_8) \end{pmatrix}$$

$$\mathcal{V}_\mu = \mathcal{M}^{-1}_{\mu\nu} \mathcal{W}_\nu$$

A possible generalization with SU(3)

What if M^f comes from something more simple?

$$M^f = \sum_n a_n^f \lambda_n$$

Diagonalizability leads to

$$\sum_n a_n^f b_{nm}^f = \frac{1}{2}\mathsf{Tr}(\lambda_m \bar{M}^f) \quad \text{where} \quad U_L^{f\dagger}\lambda_n U_R^f = \sum_m b_{nm}^f \lambda_m$$

$$\sum_n a_n^f \mathsf{Tr}(\lambda_m U_L^{f\dagger}\lambda_n U_R^f) = \mathsf{Tr}(\lambda_m \bar{M}^f)$$

Mixing types of flavors

$$\begin{aligned}
\sum_n a_n^u \mathsf{Tr}(\lambda_m V_{\mathsf{CKM}} U_L^{d\dagger}\lambda_n U_R^u) &= \mathsf{Tr}(\lambda_m \bar{M}^u) \\
\sum_n a_n^d \mathsf{Tr}(\lambda_m V_{\mathsf{CKM}}^\dagger U_L^{u\dagger}\lambda_n U_R^d) &= \mathsf{Tr}(\lambda_m \bar{M}^d)
\end{aligned}$$

A simplified model with SU(3)

$$T^{f'} = \zeta A_L^{f\dagger} D^f A_R^f$$

Assumptions

- The matrices A_L^f and A_R^f are $SU(3)$ matrices
- In order to reduce the number of free parameters we impose $A_L^f = A_R^f$
- For simple the scale parameter is set by $\zeta = 1$
- A_L^f, A_R^f belongs to a invariant subgroup of $SU(3)$

S-Spin(SU(2)) U-Spin V-Spin

$$\begin{pmatrix} a_0 + B_S & A_S^* & 0 \\ A_S & a_0 - B_S & 0 \\ 0 & 0 & a_0 \end{pmatrix} \quad \begin{pmatrix} a_0 + B_U & 0 & A_U^* \\ 0 & a_0 & 0 \\ A_U & 0 & a_0 - B_U \end{pmatrix} \quad \begin{pmatrix} a_0 & 0 & 0 \\ 0 & a_0 + B_V & A_V^* \\ 0 & A_V & a_0 - B_V \end{pmatrix}$$

The model

$$\begin{aligned}\mathcal{L}_{A^0} &= (\sqrt{2}G_F)^{\frac{1}{2}}\left[\left(-m_i \tan\beta\delta_{ij} + \frac{1}{\sqrt{2}\cos\beta}(\tilde{Y'}^{\ell}_{X2})_{ij}\right)\gamma^5\ell_j\right. \\ &\quad + \left(-m_{d_i}\tan\beta\delta_{ij} + \frac{1}{\sqrt{2}\cos\beta}(\tilde{Y'}^{d}_{X2})_{ij}\right)\gamma^5 d_j \\ &\quad \left. + \left(-m_{u_i}\cot\beta\delta_{ij} + \frac{1}{\sqrt{2}\sin\beta}(\tilde{Y'}^{u}_{X2})_{ij}\right)\gamma^5 u_j\right] A^0 \\ &\quad + \text{H.c}\end{aligned}$$

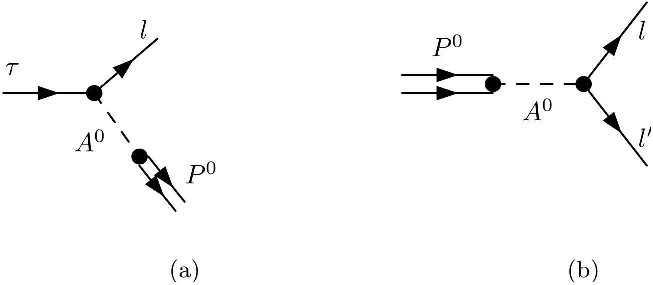
In the mass basis

$$D_f = \frac{1}{\sqrt{2}}\left(v_1 \tilde{Y}_1^f + v_2 \tilde{Y}_2^f\right)$$

$$\begin{aligned}
\tilde{Y}^d_{X2} &= (\sqrt{2}G_F)^{\frac{1}{2}} U^d_{XL} D^d U^{d\dagger}_{XL} \\
\tilde{Y}^u_{X2} &= (\sqrt{2}G_F)^{\frac{1}{2}} U^d_{XL} V^\dagger_{\mathsf{CKM}} D^u V_{\mathsf{CKM}} U^{d\dagger}_{XL} \\
\tilde{Y}^\ell_{X'2} &= (\sqrt{2}G_F)^{\frac{1}{2}} U^{\ell\dagger}_{X'L} D_\ell U^\ell_{X'L}
\end{aligned}$$

- The input parameters are masses and CKM matrix elements
- At most eight free parameters to describe all scalar interactions.

Decay and production of pseudoscalar meson



- The most important contribution are at tree level
- Excellent way to proof the model

Effective lagrangian for 2 quarks and 2 leptons interaction

$$-\mathcal{L}_{\text{eff}}^{XX'} = \sqrt{2}G_F \frac{M_W^2}{M_{A^0}^2} g^X_{A^0\ell_i\ell_j} \left(\bar{\ell}_i \gamma^5 \ell_j\right) \left[\sum_{q_n,q_m} g^{X'}_{A^0 q_m q_n} \bar{q}_n \gamma^5 q_m\right]$$

$$\begin{aligned}
g^X_{A^0\ell_i\ell_j} &= \frac{1}{M_W}\left[-m_i \tan\beta\delta_{ij} + \frac{1}{\sqrt{2}\cos\beta}\left(U^{\ell\dagger}_{XL} D^d U^\ell_{XL}\right)_{ij}\right] \\
g^X_{A^0 d_i d_j} &= \frac{1}{M_W}\left[-m_{d_i} \tan\beta\delta_{ij} + \frac{1}{\sqrt{2}\cos\beta}\left(U^{d\dagger}_{XL} D^d U^\ell_{XL}\right)_{ij}\right] \\
g^X_{A^0 u_i u_j} &= \frac{1}{M_W}\left[-m_i \cot\beta\delta_{ij} + \frac{1}{\sqrt{2}\sin\beta}\left(U^d_{XL} V^\dagger_{\text{CKM}} D^u V_{\text{CKM}} U^{d\dagger}_{XL}\right)_{ij}\right.
\end{aligned}$$

Tau decay rate

$$\Gamma_{XX'}(\tau \to \ell P^0) = \frac{G_F^2}{8\pi}\left(\frac{M_W}{M_{A^0}}\right)^4 \left[(m_\tau - m_\ell)^2 - m_P^2\right] \frac{\lambda^{1/2}(m_\tau^2, m_\ell^2, m_P^2)}{m_\tau^3}$$
$$\times |g^X_{A^0\tau\ell}|^2 \left|\langle P| \sum_{q_i,q_j} (g^{X'}_{A^0 q_i q_j})\bar{q}_i \gamma^5 q_j |0\rangle\right|^2$$

Process	Upper limit on BR	$\frac{\lvert g^X_{A^0\tau\ell}\rvert}{M_A^2}\left\lvert\langle P\rvert \sum_{q_i,q_j}(g^{X'}_{A^0 q_i q_j})\bar{q}_i\gamma^5 q_j\lvert 0\rangle\right\rvert$
$\tau \to e^- \pi^0$	$< 8.0 \times 10^{-8}$	$< 2.13 \times 10^{-8}$
$\tau \to \mu^- \pi^0$	$< 1.1 \times 10^{-7}$	$< 2.67 \times 10^{-8}$
$\tau \to e^- K_s^0$	$< 2.6 \times 10^{-8}$	$< 1.31 \times 10^{-8}$
$\tau \to \mu^- K_s^0$	$< 2.3 \times 10^{-8}$	$< 1.32 \times 10^{-8}$
$\tau \to e^- \eta$	$< 9.2 \times 10^{-8}$	$< 2.52 \times 10^{-8}$
$\tau \to \mu^- \eta$	$< 6.5 \times 10^{-8}$	$< 2.27 \times 10^{-8}$
$\tau \to e^- \eta'$	$< 1.6 \times 10^{-7}$	$< 4.24 \times 10^{-8}$
$\tau \to \mu^- \eta'$	$< 1.3 \times 10^{-8}$	$< 1.32 \times 10^{-8}$

S-Spin couplings with quarks

Leptonic Sector

$$g^S_{A^0\tau\mu} = g^S_{A^0\tau e} = 0$$

Quark sector

$$
\begin{aligned}
g^S_{A^0 uu} &= 1.87 \times 10^{-5} \left(\frac{a^d_{S0}}{\sin\beta} + \mathcal{O}\left(\frac{m_u}{m_t}\right)\right) \\
g^S_{A^0 dd} &= 8.27 \times 10^{-4} \left[\frac{|A^d_S|^2}{\cos\beta} + \mathcal{O}\left(\frac{m_c}{m_t}\right)\right] \\
g^S_{A^0 ss} &= 8.27 \times 10^{-4} \left[\frac{(a^d_{S0} - B^d_S)^2 - \sqrt{2}\sin\beta}{\cos\beta} + \mathcal{O}\left(\frac{m_d}{m_s}\right)\right] \\
g^S_{A^0 uc} &= 2.2 \times 10^{-4} \left\{ \frac{(a^d_{S0})^2}{sin\beta} + \mathcal{O}\left(\frac{m_c}{m_t}\right)\right\} \\
g^S_{A^0 sd} &= 8.27 \times 10^{-4} \left[\frac{A^d_S(a^d_{S0} - B^d_S)}{\cos\beta} + \mathcal{O}\left(\frac{m_d}{m_s}\right)\right]
\end{aligned}
$$

In this parametrization there is not LFV in tau decays

U-Spin couplings

Leptonic sector

$$g_{A^0\tau\mu} = 0 \quad ; \quad g_{A^0\tau e} = 1.56 \times 10^{-2} \left[\frac{A_U^\ell (a_{U0}^\ell - B_U^\ell)}{\cos\beta} + \mathcal{O}(\frac{m_e}{m_\tau}) \right]$$

Quark sector

$$g^U_{A^0 uu} = 1.52241 \left\{ \frac{\left[3.5 \times 10^{-3}(a^d_{U0} - B^d_U) + 0.97427 A^d_U\right]^2}{\sin\beta} + \mathcal{O}(\frac{m_c}{m_t}) \right\}$$

$$g^U_{A^0 dd} = 0.0367 \left[\frac{A_U^{d2}}{\cos\beta} + \mathcal{O}(\frac{m_s}{m_t}) \right]$$

$$g^U_{A^0 ss} = 8.26 \times 10^{-4} \left[\frac{(a^d_{U0})^2 - \sqrt{2}\sin\beta}{\cos\beta} \right]$$

$$g^U_{A^0 uc} = 1.52241 \left\{ \frac{\left[0.00351(a^d_{U0} - B^d_U) + A^d_U 0.9742\right] \left[0.0412(a^d_{U0} - B^d_U) + A^d_U 0.2252\right]}{\sin\beta} + \mathcal{O}(\frac{m_c}{m_t}) \right\}$$

$$g^U_{A^0 sd} = 8.26 \times 10^{-4} \frac{(a^d_{U0})^2}{\cos\beta}$$

V-Spin couplings

$$g^V_{A^0\tau e} = 0 \qquad ; \qquad g_{A^0\tau\mu} = 0.0156\left[A^\ell_V(a^\ell_{V0} - B^\ell_V) + \mathcal{O}\left(\frac{m_\mu}{m_\tau}\right)\right]$$

$$\begin{aligned}
g_{A^0uu} &= 2.2\times 10^{-5}\left(\frac{(a^d_{V0}) - \sqrt{2}\cos\beta}{\sin\beta}\right)\\
g_{A^0dd} &= 0.0367\left\{\frac{\left[0.00351(a^d_{V0} - B^d_V) + 0.2253A^d_V\right]^2}{\cos\beta} + \mathcal{O}(\frac{m_s}{m_b})\right\}\\
g^V_{A^0ss} &= 0.0367\left[\frac{A^{d2}_V}{\cos\beta} + \mathcal{O}(\frac{m_s}{m_b})\right]\\
g_{A^0uc} &= 1.52241\left\{\frac{\left[0.0035(a_V0^d - B^d_V) + 0.2253A^d_V\right]\left[0.0412(a^d_{V0} - B^d_V) + 0.9734A^d_V\right]}{\sin\beta}\right.\\
&\quad \left. + \mathcal{O}(\frac{m_c}{m_t})\right\}\\
g_{A^0sd} &= 0
\end{aligned}$$

Decay Rate

For a typical pseudoscalar meson

$$\Gamma \simeq (2.8 \times 10^6) \frac{|F_P|^2}{M_A^4} |g^X_{A\tau\ell}|^2 |g^X_{Aq_iq_j}|^2$$

For $M_A \simeq 300 GeV$ thus we need

$$|g^X_{A\tau\ell}|^2 |g^X_{Aq_iq_j}|^2 < 10^{-5}$$

Easy to reach...

Final comments

- 2HDM is a good model to parametrize possible new physics effects as FCNC and LFV at tree level
- The flavour parametrization allows a reduction of free parameters
- SU(3) subspaces are useful to generate suitable Yukawa matrices
- A 2HDM-SU(3) naturally suppress LFV τ decays at tree level
- It fits but is not to much predictable model if we only use LFV τ decays