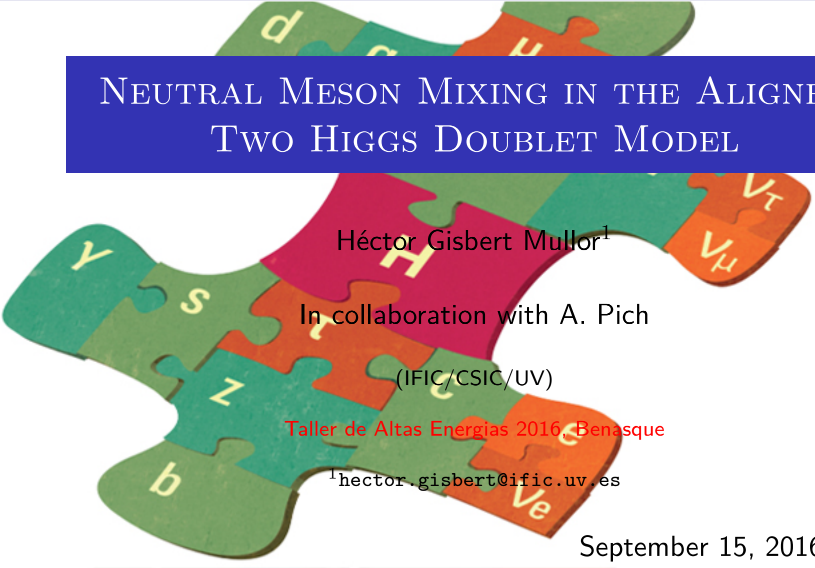

Neutral Meson Mixing in the Aligned Two Higgs Doublet Model

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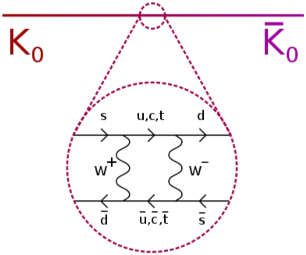
Outline

Importance of the Neutral Meson Mixing

- Is a Flavour-Changing Neutral Currents (FCNC) process.
- FCNC processes only appear at loop level in the SM.
- Good way to check the quantum structure of the SM in the search of physics beyond the SM.



Mixing Diagrams in the SM

- The responsible Feynman diagrams for this process are *box diagrams*.
- We denote the flavour of the internal quark lines as i and j.
- Limit of external momentum equal to zero ($p_{\text{ext}} = 0$).
- 't Hooft-Feynman gauge ($\xi_W = 1$).

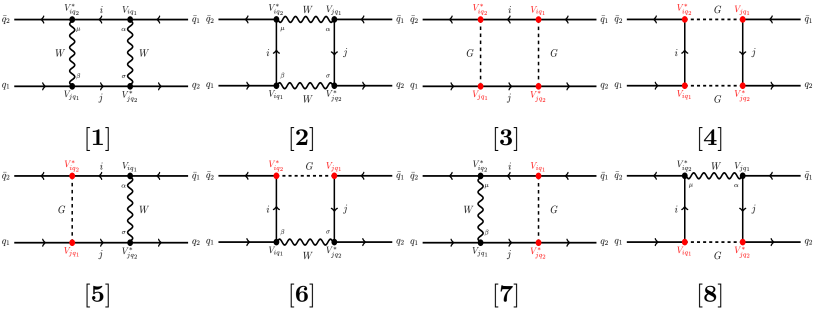
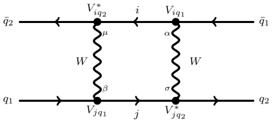


Diagram [1]

$$\mathcal{M}_{[1]} = \left(-\frac{i}{\sqrt{2}}\,g\right)^4 \left(\sum_{ij} V^*_{iq_2}\, V_{iq_1}\, V_{jq_1}\, V^*_{jq_2}\right) \cdot [\bar{u}_{q_2}(0)\,\gamma^\alpha\,\gamma_{\mathfrak{x}}\,\gamma^\mu\, P_L\, u_{q_1}(0)]$$
$$\cdot\, [\bar{v}_{q_2}(0)\,\gamma_\mu\,\gamma_{\mathfrak{x}'}\,\gamma_\alpha\, P_L\, v_{q_1}(0)] \cdot \int \frac{d^4k}{(2\pi)^4}\, \frac{k^{\mathfrak{x}}\, k^{\mathfrak{x}'}}{(k^2 - M_W^2)^2 (k^2 - m_j^2)(k^2 - m_i^2)}.$$



- Fierz identity: $(\bar{u}_1\, A\, P_L\, u_2)(\bar{u}_3\, P_R\, B\, u_4) = \frac{1}{2}\,(\bar{u}_3\,\gamma^\mu\, P_L\, u_2)(\bar{u}_1\, A\,\gamma_\mu\, P_R\, B\, u_4).$
- Lorentz invariance: $\int_k f(k^2) k_\mu\, k_\nu = \int_k f(k^2) \frac{k^2}{d}\, g_{\mu\nu}.$

$$\mathcal{M}_{[1]} = -\,i\,\frac{g^4}{4(4\pi)^2}\,[\bar{q}_{2L}\,\gamma_\mu\, q_{1L}]\left[\bar{q}'_{2L}\,\gamma^\mu\, q'_{1L}\right] \sum_{ij} V^*_{iq_2}\, V_{iq_1}\, V_{jq_1}\, V^*_{jq_2}\, D_2(m_i^2, m_j^2, M_W^2)$$

where $u_i(0) \equiv i$, $\bar{u}_i(0) \equiv \bar{i}$, $v_i(0) \equiv i'$ and $\bar{v}_i(0) \equiv \bar{i}'$.

Summing all amplitudes and taking into account relative signs between diagrams (Wick theorem):

$$\mathcal{M}_{M^0-\bar{M}^0} = -i\,\frac{G_F^2 M_W^2}{\pi^2} \sum_{ij} \lambda_i \lambda_j \tilde{S}(m_i^2, m_j^2, M_W^2)\ [\bar{q}_{2L}\,\gamma_\mu\, q_{1L}] \left[\bar{q}'_{2L}\,\gamma^\mu\, q'_{1L}\right]$$

$$\tilde{S}(m_i^2, m_j^2, M_W^2) = \left(1 + \frac{1}{4}\beta_i\beta_j\right) M_W^2\, D_2(m_i^2, m_j^2, M_W^2) - 2\,\beta_i\,\beta_j\, M_W^4\, D_0(m_i^2, m_j^2, M_W^2)$$

$$D_0(a,b,c,d) = \frac{b \ln\left(\frac{b}{a}\right)}{(b-a)(b-c)(b-d)} + \frac{c \ln\left(\frac{c}{a}\right)}{(c-a)(c-b)(c-d)} + \frac{d \ln\left(\frac{d}{a}\right)}{(d-a)(d-b)(c-d)}$$

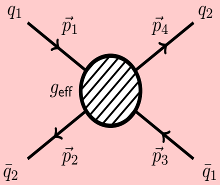
$$D_2(a,b,c,d) = \frac{b^2 \ln\left(\frac{b}{a}\right)}{(b-a)(b-c)(b-d)} + \frac{c^2 \ln\left(\frac{c}{a}\right)}{(c-a)(c-b)(c-d)} + \frac{d^2 \ln\left(\frac{d}{a}\right)}{(d-a)(d-b)(c-d)}$$

where $\beta_i \equiv \frac{m_i^2}{M_W^2}$, $\lambda_i \equiv V_{iq_2}^* V_{iq_1}$ and $\frac{g^2}{M_W^2} \equiv 4\sqrt{2}\,G_F$.

Effective Lagrangian

- The Effective Lagrangian must have this structure:

$$\mathcal{L}_{\text{eff}} = C\,[\bar{q}_{2L}(x)\gamma^{\mu}q_{1L}(x)][\bar{q}_{2L}(x)\gamma_{\mu}q_{1L}(x)]$$



✓ *Matching condition:* $\mathcal{M}_{\text{fun}} = \mathcal{M}_{\text{eff}}$.

$$C = -\frac{G_F^2 M_W^2}{4\,\pi^2}\sum_{ij}\lambda_i\lambda_j\tilde{S}(m_i^2, m_j^2, M_W^2)$$

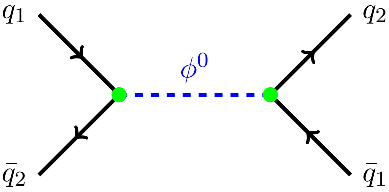
FCNC at Tree Level ($\Delta F = 2$)

- Let's consider some extension of the SM containing a zero charge scalar particle, ϕ^0, that allows FCNC by two units at tree level with the following phenomenological Lagrangian:

$$\mathcal{L}_{\phi^0 \bar{q}_i q_j} = \phi^0 \, \bar{q}_i \, (g_{ij} \, P_R + \tilde{g}_{ij} \, P_L) \, q_j ,$$

where $\tilde{g}_{ij} = g^*_{ji}$.

- We calculate this new contribution to the meson mixing, assuming zero external momenta.



Constraints to the $\Delta F = 2$ operators

- It is possible to put constrains on the coupling constants (g_{21} and $\tilde{g}_{21}$) by assuming the contributions of new physics to be smaller than the experimental values, $\Delta\, m_M^{\text{exp}} \geq \Delta\, m_M^{NP}$, where $\Delta\, m_M^{NP} = |\langle \bar{M}^0 | \mathcal{H}_{\text{eff}}^{NP} | M^0 \rangle|$.

Meson	$\lvert\mathcal{C}_{LL(RR)}^{NP}\rvert$ (TeV^{-2})	$\lvert\mathcal{C}_{LR}^{NP}\rvert$ (TeV^{-2})
K	7.1×10^{-8}	1.7×10^{-8}
D	1.8×10^{-7}	5.4×10^{-8}
B_d^0	4.9×10^{-6}	1.5×10^{-6}
B_s^0	1.2×10^{-4}	3.6×10^{-5}

$$\mathcal{C}_{RR}^{NP} \equiv \frac{g_{21} g_{21}}{2m_\phi^2}, \quad \mathcal{C}_{LL}^{NP} \equiv \frac{\tilde{g}_{21}\tilde{g}_{21}}{2m_\phi^2} \quad \text{and} \quad \mathcal{C}_{LR}^{NP} \equiv \frac{\tilde{g}_{21} g_{21}}{m_\phi^2}.$$

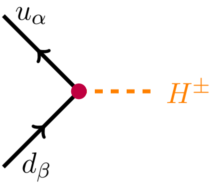
- FCNC at tree level are very constrained at TeV energy scale ($m_\phi \approx 1$ TeV).
- We could conclude that everything is consistent with the SM, $|g_{12}|, |\tilde{g}_{12}| \leq 10^{-4}$.
- But the motivations for new physics at TeV energy scale suggest that new couplings in the electroweak sector could exist and suffer also the strong suppression, similar to the SM.

(Gino Isidori, Yosef Nir, Gilad Perez) [arXiv:1002.0900]

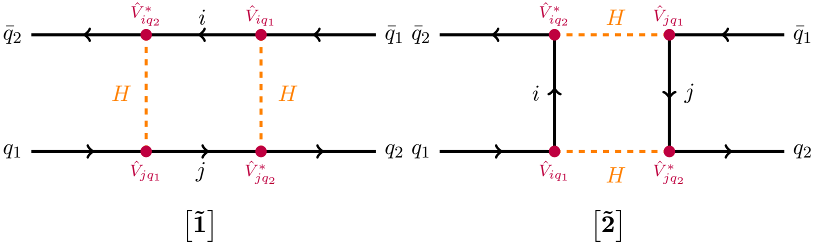
Model with Charged Higgs

- The presence of a charged scalar particle is one common characteristic of some extensions of the SM scalar sector.
- Let's consider, for instance, the following interaction

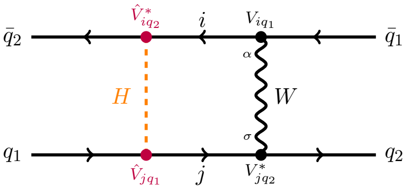
$$\mathcal{L}_{Hud} = -\frac{g}{\sqrt{2}} H^+ \bar{u}^i (a_{ij} P_L + b_{ij} P_R) d^j + \text{h.c},$$



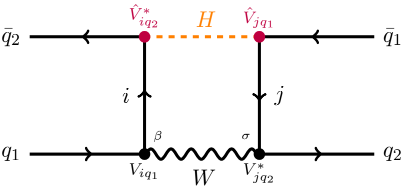
Diagrams with exchange of H



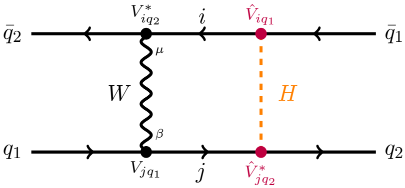
Diagrams with exchange of H and W



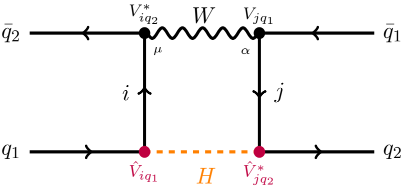
$[\tilde{\mathbf{3}}]$



$[\tilde{\mathbf{4}}]$

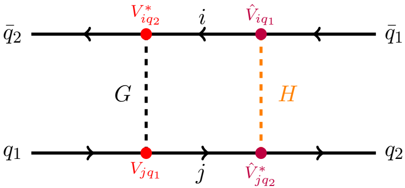


$[\tilde{\mathbf{5}}]$

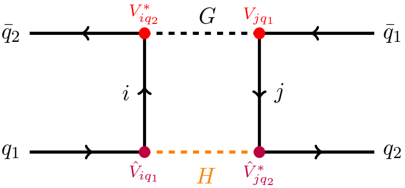


$[\tilde{\mathbf{6}}]$

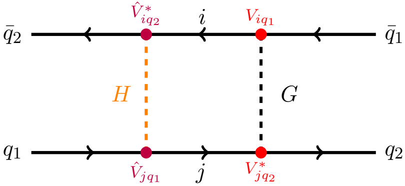
Diagrams with exchange of H and G



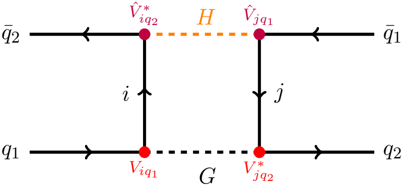
$[\tilde{\mathbf{7}}]$



$[\tilde{\mathbf{8}}]$



$[\tilde{\mathbf{9}}]$



$[\tilde{\mathbf{10}}]$

$$\mathcal{M}^{H^\pm}_{M^0-\bar{M}^0} = \sum_{i=1}^{20} X_i\, \mathcal{O}_i^X ,$$

where

$$\begin{aligned}
\mathcal{O}_1^X &= \left[\bar{q}_{2L}\,\gamma^\mu\, q'_{1L}\right]\left[\bar{q}'_{2L}\,\gamma_\mu\, q_{1L}\right], \\
\mathcal{O}_2^X &= \left[\bar{q}_{2L}\,\gamma^\mu\, q_{1L}\right]\left[\bar{q}'_{2L}\,\gamma_\mu\, q'_{1L}\right], \\
\mathcal{O}_3^X &= \left[\bar{q}_{2L}\,\gamma^\mu\, q'_{1L}\right]\left[\bar{q}'_{2R}\,\gamma_\mu\, q_{1R}\right], \\
\mathcal{O}_4^X &= \left[\bar{q}'_{2L}\,\gamma^\mu\, q'_{1L}\right]\left[\bar{q}_{2R}\,\gamma_\mu\, q_{1R}\right], \\
\mathcal{O}_5^X &= \left[\bar{q}_{2L}\,\gamma^\mu\, q_{1L}\right]\left[\bar{q}'_{2R}\,\gamma_\mu\, q'_{1R}\right], \\
\mathcal{O}_6^X &= \left[\bar{q}'_{2L}\,\gamma^\mu\, q_{1L}\right]\left[\bar{q}_{2R}\,\gamma_\mu\, q'_{1R}\right], \\
\mathcal{O}_7^X &= \left[\bar{q}_{2R}\,\gamma^\mu\, q'_{1R}\right]\left[\bar{q}'_{2R}\,\gamma_\mu\, q_{1R}\right], \\
\mathcal{O}_8^X &= \left[\bar{q}'_{2R}\,\gamma^\mu\, q'_{1R}\right]\left[\bar{q}_{2R}\,\gamma_\mu\, q_{1R}\right], \\
\mathcal{O}_9^X &= \left[\bar{q}_{2R}\, q'_{1L}\right]\left[\bar{q}'_{2R}\, q_{1L}\right], \\
\mathcal{O}_{10}^X &= \left[\bar{q}_{2R}\, q_{1L}\right]\left[\bar{q}'_{2R}\, q'_{1L}\right],
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}_{11}^X &= \left[\bar{q}_{2R}\, q'_{1L}\right]\left[\bar{q}'_{2L}\, q_{1R}\right], \\
\mathcal{O}_{12}^X &= \left[\bar{q}'_{2R}\, q'_{1L}\right]\left[\bar{q}_{2L}\, q_{1R}\right], \\
\mathcal{O}_{13}^X &= \left[\bar{q}_{2R}\, q_{1L}\right]\left[\bar{q}'_{2L}\, q'_{1R}\right], \\
\mathcal{O}_{14}^X &= \left[\bar{q}'_{2R}\, q_{1L}\right]\left[\bar{q}_{2L}\, q'_{1R}\right], \\
\mathcal{O}_{15}^X &= \left[\bar{q}_{2L}\, q'_{1R}\right]\left[\bar{q}'_{2L}\, q_{1R}\right], \\
\mathcal{O}_{16}^X &= \left[\bar{q}_{2L}\, q'_{1R}\right]\left[\bar{q}'_{2L}\, q'_{1R}\right], \\
\mathcal{O}_{17}^X &= \left[\bar{q}_{2R}\,\sigma_{\mu\nu}\, q'_{1L}\right]\left[\bar{q}'_{2R}\,\sigma^{\mu\nu}\, q_{1L}\right], \\
\mathcal{O}_{18}^X &= \left[\bar{q}_{2R}\,\sigma_{\mu\nu}\, q_{1L}\right]\left[\bar{q}'_{2R}\,\sigma^{\mu\nu}\, q'_{1L}\right], \\
\mathcal{O}_{19}^X &= \left[\bar{q}_{2L}\,\sigma_{\mu\nu}\, q'_{1R}\right]\left[\bar{q}'_{2L}\,\sigma^{\mu\nu}\, q_{1R}\right], \\
\mathcal{O}_{20}^X &= \left[\bar{q}_{2L}\,\sigma_{\mu\nu}\, q_{1R}\right]\left[\bar{q}'_{2L}\,\sigma^{\mu\nu}\, q'_{1R}\right].
\end{aligned}$$

Coefficients

$$X_1 = -X_2 = i\,\frac{g^4}{4(4\pi)^2}\left\{\sum_{ij}\frac{1}{4}\left[a^*_{jq_2}a_{jq_1}a^*_{iq_2}a_{iq_1}\right]\,D_2(m_i^2,m_j^2,M_H^2)\right.$$
$$\left.-\sum_{ij}V_{iq_1}V^*_{jq_2}a_{jq_1}a^*_{iq_2}m_im_j\left[2D_0(m_i^2,m_j^2,M_W^2,M_H^2)\,-\,\frac{1}{2M_W^2}\,D_2(m_i^2,m_j^2,M_W^2,M_H^2)\right]\right\},$$

$$X_3 = -X_4 = -X_5 = X_6 = i\,\frac{g^4}{4(4\pi)^2}\left\{\sum_{ij}\frac{1}{4}\left[a^*_{jq_2}a_{jq_1}b^*_{iq_2}b_{iq_1}\right]\,D_2(m_i^2,m_j^2,M_H^2)\right.$$
$$\left.-\sum_{ij}\frac{1}{4}V^*_{iq_2}V_{jq_1}\left[\frac{m_jm_{q_2}}{M_W^2}a^*_{jq_2}b_{iq_1}\,+\,\frac{m_{q_1}m_i}{M_W^2}b^*_{jq_2}a_{iq_1}\right]\,D_2(m_i^2,m_j^2,M_W^2,M_H^2)\right\},$$

$$X_7 = -X_8 = i\,\frac{g^4}{4(4\pi)^2}\left\{\sum_{ij}\frac{1}{4}\left[b^*_{jq_2}b_{jq_1}b^*_{iq_2}b_{iq_1}\right]\,D_2(m_i^2,m_j^2,M_H^2)\right.$$
$$\left.+\sum_{ij}V^*_{iq_2}V_{jq_1}\left[\frac{1}{2}\frac{m_{q_1}m_{q_2}}{M_W^2}b^*_{jq_2}b_{iq_1}\right]\,D_2(m_i^2,m_j^2,M_W^2,M_H^2)\right\},$$

Building the Effective Lagrangian

The Effective Lagrangian that reproduces the previous results must have the following structure

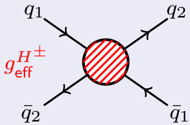
$$\mathcal{L}_{\text{eff}}^{H^\pm} = \sum_i A_i\, \mathcal{O}_i,$$

where we have introduced an eight operators basis,

$$\begin{aligned}
\mathcal{O}_1 &= [\bar{q}_2\, \gamma^\mu\, P_L\, q_1]\, [\bar{q}_2\, \gamma_\mu\, P_L\, q_1]\,, & \mathcal{O}_5 &= [\bar{q}_2\, P_L\, q_1]\, [\bar{q}_2\, P_R\, q_1]\,,\\
\mathcal{O}_2 &= [\bar{q}_2\, \gamma^\mu\, P_L\, q_1]\, [\bar{q}_2\, \gamma_\mu\, P_R\, q_1]\,, & \mathcal{O}_6 &= [\bar{q}_2\, P_R\, q_1]\, [\bar{q}_2\, P_R\, q_1]\,,\\
\mathcal{O}_3 &= [\bar{q}_2\, \gamma^\mu\, P_R\, q_1]\, [\bar{q}_2\, \gamma_\mu\, P_R\, q_1]\,, & \mathcal{O}_7 &= [\bar{q}_2\, \sigma_{\mu\nu}\, P_L\, q_1]\, [\bar{q}_2\, \sigma^{\mu\nu}\, P_L\, q_1]\,,\\
\mathcal{O}_4 &= [\bar{q}_2\, P_L\, q_1]\, [\bar{q}_2\, P_L\, q_1]\,, & \mathcal{O}_8 &= [\bar{q}_2\, \sigma_{\mu\nu}\, P_R\, q_1]\, [\bar{q}_2\, \sigma^{\mu\nu}\, P_R\, q_1]\,.
\end{aligned}$$

The Effective Lagrangian for the Charged Higgs model

$$\mathcal{L}_{\text{eff}}^{H^\pm} = -\frac{G_F^2 M_W^2}{16\pi^2} \sum_{ij} \lambda_i \, \lambda_j \, C_i(\mu) \, \mathcal{O}_i$$



and specifying to the ATHDM (No FCNC at tree level!!!):

$$a_{ij} \equiv -\frac{1}{M_W} \varsigma_u \, m_{u_i} \, V_{ij} , \quad b_{ij} \equiv \frac{1}{M_W} \varsigma_d \, m_{d_j} \, V_{ij} .$$

(A. Pich and P. Tuzón) [Phys. Rev. D 80, 091702(R)]

$$C_1 \;=\; 2\,|\varsigma_u|^2\,\beta_i\,\beta_j\,\Big[M_W^2\,D_2(m_i^2,m_j^2,M_W^2,M_H^2)\;-\;4\,M_W^4\,D_0(m_i^2,m_j^2,M_W^2,M_H^2)\Big] + |\varsigma_u|^4\,\beta_i\,\beta_j\,M_W^2\,D_2(m_j^2,m_i^2,M_H^2),$$

$$C_2 \;=\; 2\,\frac{m_{q_1}m_{q_2}}{M_W^2}\,\Big\{|\varsigma_u|^2|\varsigma_d|^2\beta_j M_W^2\,D_2(m_i^2,m_j^2,M_H^2) + [\beta_j\,\varsigma_u^*\,\varsigma_d\,+\beta_i\,\varsigma_d^*\,\varsigma_u]\,M_W^2\,D_2(m_i^2,m_j^2,M_W^2,M_H^2)\Big\},$$

$$C_3 \;=\; \frac{m_{q_1}^2 m_{q_2}^2}{M_W^4}\,\Big[|\varsigma_d|^4 M_W^2\,D_2(m_j^2,m_i^2,M_H^2)\;+\;2\,|\varsigma_d|^2\,M_W^2\,D_2(m_i^2,m_j^2,M_W^2,M_H^2)\Big],$$

$$C_4 \;=\; 4\,\frac{m_{q_2}^2}{M_W^2}\,\beta_i\beta_j\,\Big[(\varsigma_u\varsigma_d^*)^2 M_W^4\,D_0(m_j^2,m_i^2,M_H^2)\;+\;2\,\varsigma_u\varsigma_d^*\,M_W^4\,D_0(m_i^2,m_j^2,M_W^2,M_H^2)\Big],$$

$$C_5 \;=\; 2\,\frac{m_{q_1}m_{q_2}}{M_W^2}\,\Big[4|\varsigma_d|^2|\varsigma_u|^2\beta_i\beta_j M_W^4\,D_0(m_j^2,m_i^2,M_H^2)\;-\;4\,|\varsigma_d|^2\,M_W^2\,D_2(m_i^2,m_j^2,M_W^2,M_H^2) + 4(|\varsigma_d|^2+|\varsigma_u|^2)\beta_i\beta_j M_W^4 D_0(m_i^2,m_j^2,M_W^2,M_H^2)\Big],$$

$$C_6 \;=\; 4\,\frac{m_{q_1}^2}{M_W^2}\,\beta_i\beta_j\,\Big[(\varsigma_u^*\varsigma_d)^2 M_W^4\,D_0(m_j^2,m_i^2,M_H^2)\;+\;2\,\varsigma_u^*\varsigma_d\,M_W^4\,D_0(m_i^2,m_j^2,M_W^2,M_H^2)\Big],$$

$$C_7 \;=\; C_8 \;=\; 0,$$

B Meson Mixing

- We can take the limit $m_{u,c} \to 0$ because the B meson mixing is completely dominated by the top quark contributions

$$\mathcal{H}_{\text{eff}}^{\Delta B=2} = \frac{G_F^2 M_W^2}{16\pi^2} (V_{td}^\star V_{tb})^2 \sum_i C_i(\mu)\, \mathcal{O}_i .$$

$\mathcal{O}_i$	$C_i(\mu_{tW})$
$\mathcal{O}_1$	$(4x_W + x_W^2) M_W^2 D_2(m_t, M_W) - 8x_W^2 M_W^4 D_0(m_t, M_W) +$ $+2\lvert\varsigma_u\rvert^2 x_W^2 \left[M_W^2 D_2(m_t, M_W, M_{H\pm}) - 4M_W^4 D_0(m_t, M_W, M_{H\pm})\right] +$ $+\lvert\varsigma_u\rvert^4 x_W^2 M_W^2 D_2(m_t, M_{H\pm})$
$\mathcal{O}_2$	$2\frac{m_d m_b}{M_W^2} x_W \left[\lvert\varsigma_d\rvert^2 \lvert\varsigma_u\rvert^2 M_W^2 \widetilde{D}_2(m_t, M_{H\pm}) + 2\text{Re}(\varsigma_d^\star \varsigma_u) M_W^2 \widetilde{D}_2(m_t, M_W, M_{H\pm})\right]$
$\mathcal{O}_3$	$\frac{m_d^2 m_b^2}{M_W^4} \left[\lvert\varsigma_d\rvert^4 x_H M_W^2 D_2(m_t, M_{H\pm}) + 2\lvert\varsigma_d\rvert^2 M_W^2 \overline{D}_2(m_t, M_W, M_{H\pm})\right]$
$\mathcal{O}_4$	$4\frac{m_d^2}{M_W^2} x_W^2 \left[(\varsigma_u \varsigma_d^\star)^2 M_W^4 D_0(m_t, M_{H\pm}) + 2\varsigma_u \varsigma_d^\star M_W^4 D_0(m_t, M_W, M_{H\pm})\right]$
$\mathcal{O}_5$	$2\frac{m_d m_b}{M_W^2} \left[4\lvert\varsigma_d\rvert^2 \lvert\varsigma_u\rvert^2 x_W^2 M_W^4 D_0(m_t, M_{H\pm}) - 4\lvert\varsigma_d\rvert^2 M_W^2 \overline{D}_2(m_t, M_W, M_{H\pm})\right.$ $\left.+4(\lvert\varsigma_d\rvert^2 + \lvert\varsigma_u\rvert^2) x_W^2 M_W^4 D_0(m_t, M_W, M_{H\pm})\right]$
$\mathcal{O}_6$	$4\frac{m_b^2}{M_W^2} x_W^2 \left[(\varsigma_d \varsigma_u^\star)^2 M_W^4 D_0(m_t, M_{H\pm}) + 2\varsigma_d \varsigma_u^\star M_W^4 D_0(m_t, M_W, M_{H\pm})\right]$
$\mathcal{O}_7$	0
$\mathcal{O}_6$	0

Constraints to $|\varsigma_u|$

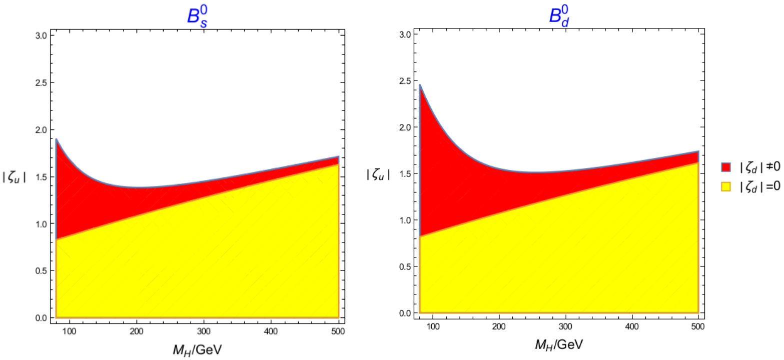


Figure 1 : The 95% CL constraint coming from $\Delta m_{B_i^0}$ $(i = s, d.)$ in the $M_{H^\pm} - |\varsigma_u|$ plane for $|\varsigma_d| \in [0,\ 50]$, varying in addition the relative phase φ in $[0,\ 2\pi]$. The excluded area lies above the dark (red) region anly. In yellow the allowed area $|\varsigma_d| = 0$ is shown.

Conclusions

- FCNC don't exist at tree level in the SM (good way of testing its quantum structure).
- FCNC at tree level have strong constraints.
- Study of the NMM in the ATHDM at LO.
- The new physics contributions ($|\varsigma_u|^2$ y $|\varsigma_u|^4$) can have sensible repercussions to the SM contributions ($|\varsigma_u| \sim 1$).
- Still working on the NMM in the ATHDM at NLO $\left(\mathcal{O}(\frac{m_{\text{ext}}^2}{M_W^2})\right)$ and the results will be available soon.

THANKS