Radiatively induced flavour violation in a general 2HDM with Yukawa alignment

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Two Higgs doublet Models (2HDM)

particles that have already been discovered

$$+ \quad \phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \qquad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

CP even neutral scalars

CP odd neutral scalar

Charged scalars

$$\mathcal{L}_{\text{Yukawa}} = \bar{q}'_L Y_u^{(1)} u'_R \tilde{\phi}_1 + \bar{q}'_L Y_d^{(1)} d'_R \phi_1 + \bar{l}'_L Y_e^{(1)} e'_R \phi_1$$
$$+ \bar{q}'_L Y_u^{(2)} u'_R \tilde{\phi}_2 + \bar{q}'_L Y_d^{(2)} d'_R \phi_2 + \bar{l}'_L Y_e^{(2)} e'_R \phi_2 + \text{h.c.}$$
$$\left(\tilde{\phi}_a = i\tau_2 \phi_a^* \right)$$

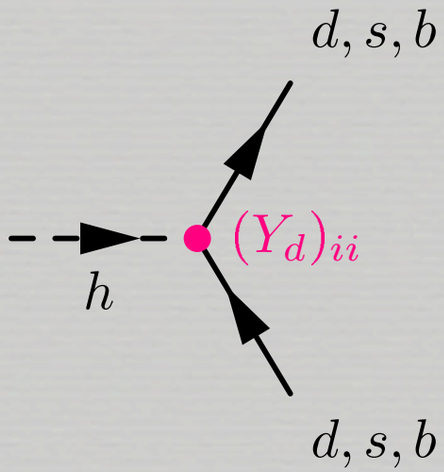
FCNC in the Higgs sector

$$\mathcal{L}_{Yukawa} \supseteq \underbrace{\bar{u}'_L Y_d^{(1)} d'_R \phi_1^+ + \bar{d}'_L Y_d^{(1)} d'_R \phi_1^0}_{\text{SM}} + \bar{u}'_L Y_d^{(2)} d'_R \phi_2^+ + \bar{d}'_L Y_d^{(2)} d'_R \phi_2^0 + \text{h.c.}$$

$$d'_L = V_d^L d_L \qquad d'_R = V_d^R d_R \qquad V_d^{L\dagger} Y_d^{(1)} V_d^R = \text{diag.}(y_d, y_s, y_b)$$

Standard Model

$$V_d^{L\dagger} Y_d V_d^R = \text{diag.}(y_d, y_s, y_b)$$

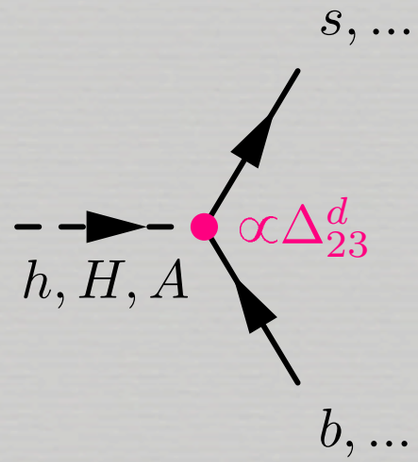


NO flavour changing couplings

2HDM

$$V_d^{L\dagger} Y_d^{(1)} V_d^R = \text{diag.}(y_d^1, y_s^1, y_b^1)$$

$$V_d^{L\dagger} Y_d^{(2)} V_d^R \neq \text{diag.}(y_d^2, y_s^2, y_b^2)$$



Flavour changing couplings

How to "tame" FCNCs in 2HDMs

- Discrete symmetry: type I & II 2HDMs

- Yukawa alignment (A.Pich & P. Tuzón: arXiv:0908.1554)

$$Y_u^{(1)} = \cos\psi_u Y_u \qquad Y_u^{(2)} = \sin\psi_u Y_u$$

$$Y_d^{(1)} = \cos\psi_d Y_d \qquad Y_d^{(2)} = \sin\psi_d Y_d$$

Justified by Minimal Flavour violation (G. D'Ambrosio, G.F. Giudice, G. Isidori, A. Strumia: arXiv:hep-ph/0207036)

- Type I & II are special cases
- CP-violation in Higgs sector

Renormalization introduces FCNC

Radiative corrections ⇒ misalignment of Yukawa couplings at the electroweak scale.

$$Y_d^{(1)} \not\propto Y_d^{(2)} \qquad Y_u^{(1)} \not\propto Y_u^{(2)}$$

Numerical solution as well as analytical formula using **leading log** approximation.

Off-diagonal couplings at the electroweak scale:

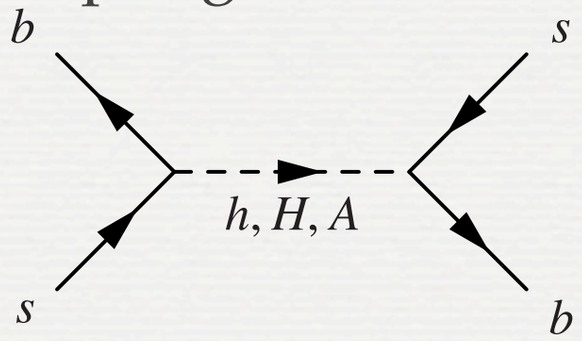
$$\Delta_d^{\mathrm{off-diag.}} = E_d Q_d$$

$$Q_d = \frac{1}{v^3}\left(V_{\mathrm{CKM}}^{\dagger}\left(M_u^{\mathrm{diag.}}\right)^2 V_{\mathrm{CKM}} M_d^{\mathrm{diag.}}\right)^{\mathrm{off-diag.}}$$

$$E_d = -\frac{1}{8\pi^2}\frac{\sin\left(2\left(\psi_u-\psi_d\right)\right)}{\cos^2(\beta-\psi_u)\cos^2(\beta-\psi_d)}\log\left(\frac{M_Z}{\Lambda}\right)$$

Meson-antimeson mixing

- SM: only at loop level
- 2HDM with flavour violating couplings: tree level



- Strongest constraints: $B_s - \bar{B}_s$
- Effective Hamiltonian: $H_{\text{eff.}}^{\Delta B=2} = \sum_{i,a} C_i^a(m_Z) Q_i^a(m_Z),$

$$Q_1^{SLL} = (\bar{b}_R s_L)(\bar{b}_R s_L), \quad Q_1^{SRR} = (\bar{b}_L s_R)(\bar{b}_L s_R), \quad Q_2^{LR} = (\bar{b}_R s_L)(\bar{b}_L s_R)$$

- Bound on alignment parameters:

$$\left| \frac{s_{\alpha-\beta}^2}{m_H^2} + \frac{c_{\alpha-\beta}^2}{m_h^2} - \frac{1}{m_A^2} \right| |E_d|^2 \lesssim \frac{1}{(80\ \text{Gev})^2}$$

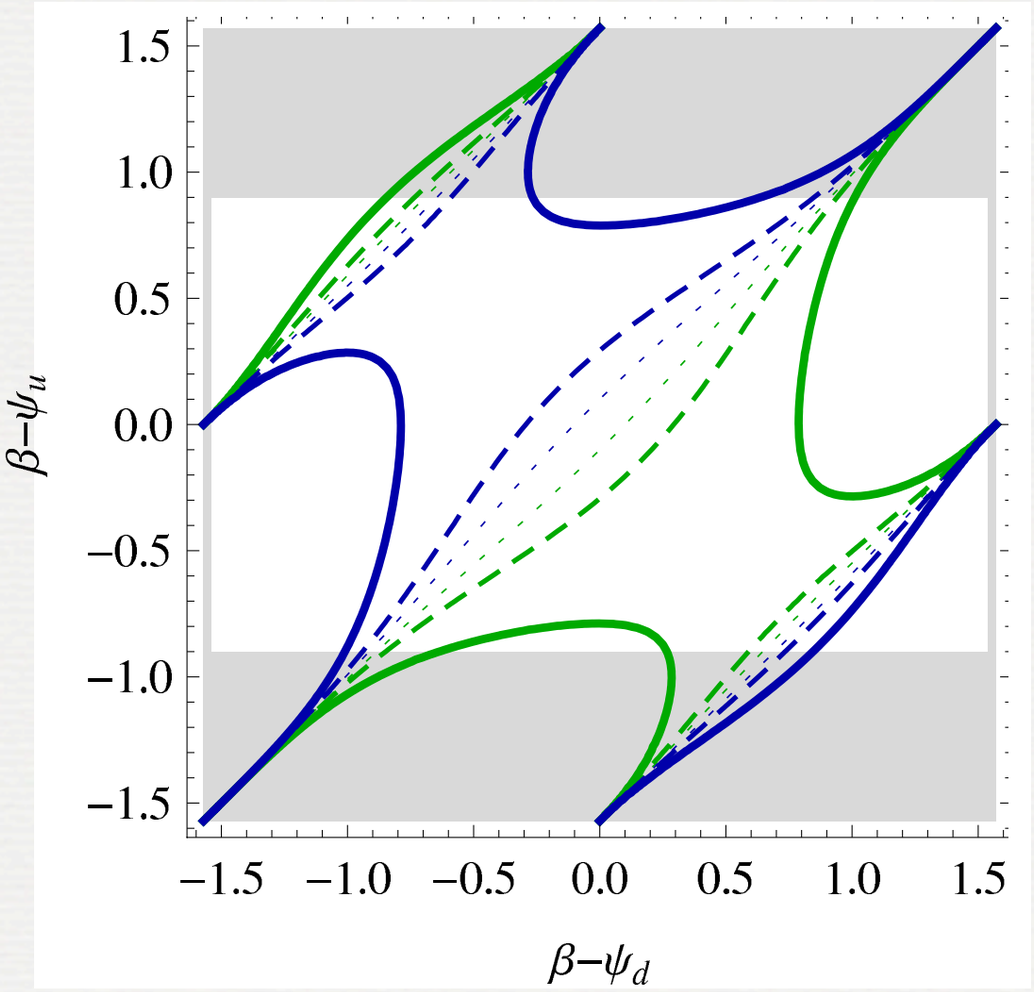
How big is the the factor E_d?

$$Y_d^{(1)} = \cos\psi_d Y_d$$
$$Y_d^{(2)} = \sin\psi_d Y_d$$
$$Y_u^{(1)} = \cos\psi_u Y_u$$
$$Y_u^{(2)} = \cos\psi_u Y_u$$

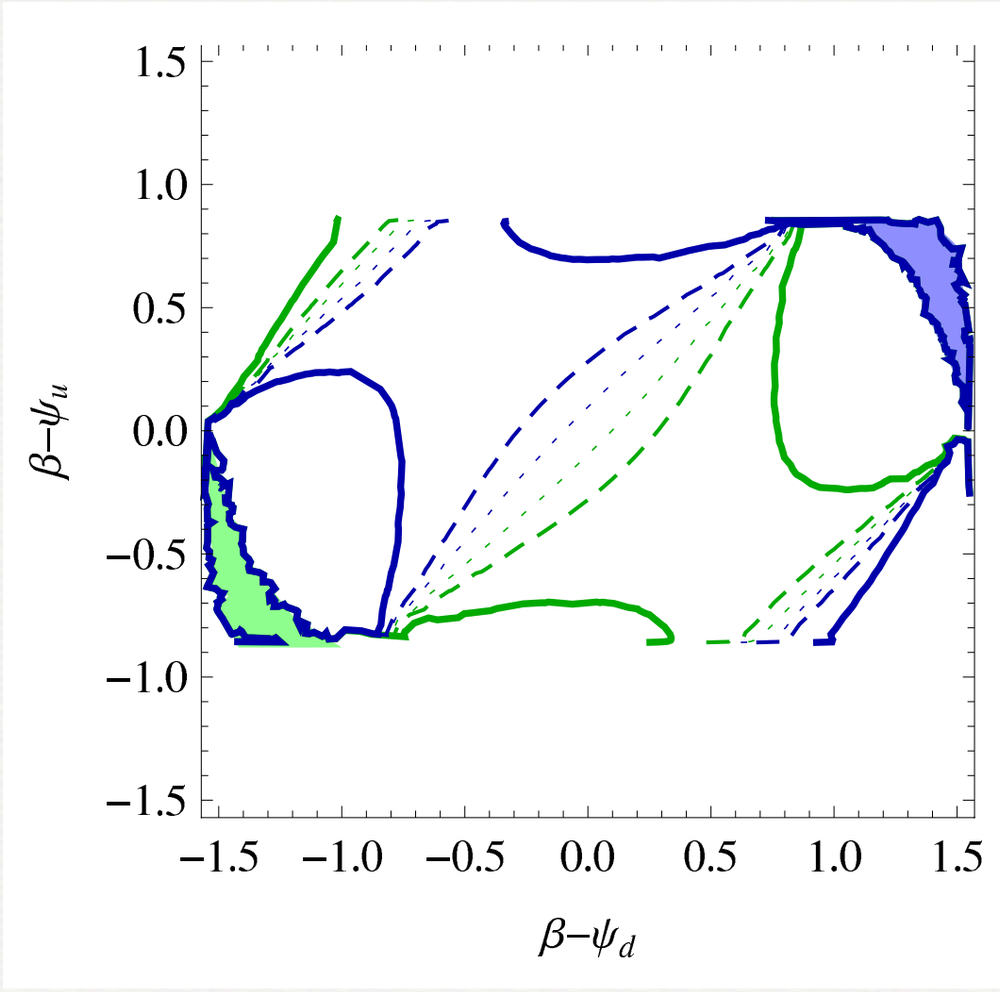
$$\Delta_d^{\text{off}-\text{diag.}} = E_d Q_d$$

Depends on $\beta - \psi_u,\ \beta - \psi_d, \Lambda$

Depends on mass matrices and CKM matrix



Analytical approximation of E_d



Numerical results for 2.5 E_d

Conclusions

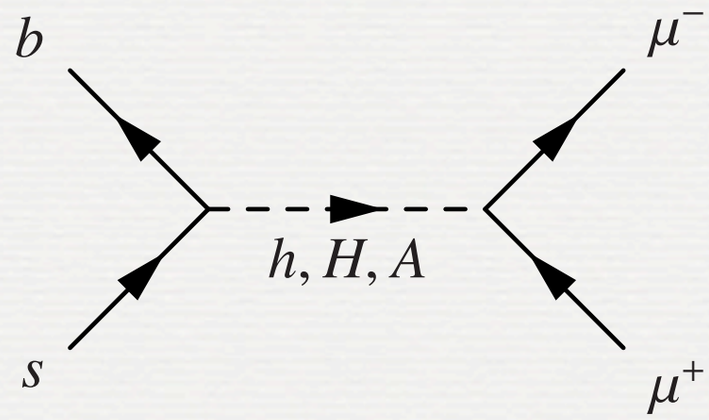
- LHC finally running and searching for the Higgs(es) ⇒ important to investigate different scenarios for the Higgs sector
- Yukawa couplings of each fermion type aligned at high scale ⇒ no new sources of flavour violation at tree level
- Quantum corrections ⇒ misalignment at low energies ⇒ flavour violating Higgs couplings
- Minimal size of the exotic contributions to FCNCs in any 2HDM in the absence of tuning and discrete symmetries
- Exotic contribution well below experimental bounds for wide parameter range

Experimental bounds II:

Leptonic B decays

- Strongest constraints: $\bar{B}_s \to \mu^+\mu^-$

- SM: only at loop level
- General 2HDM: tree level



- Bound on alignment parameters for $\Delta_{e\,22} \gg \dfrac{m_\mu}{v}$:

$$\sqrt{\frac{1}{m_A^4} + \left|\frac{s^2_{\alpha-\beta}}{m_H^2} + \frac{c^2_{\alpha-\beta}}{m_h^2}\right|^2}\,\Delta_{e\,22}|E_d| \lesssim \frac{1}{(600\ \text{Gev})^2}.$$