Flavour alignment in multi-Higgs-doublets models

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Introduction

- **Standard Model:** Great success but still
  - Strong CP problem
  - CP-violation
  - Dark Matter
  - (...)
- Doublets under the $SU(2)_L$ group $\longrightarrow \rho = \frac{M_W^2}{M_Z^2 \cos\theta_W^2} = \sum_i \frac{v_i^2\left[T_i(T_i+1)-Y_i^2\right]}{2v_i^2 Y_i^2} = 1$
- Adding N Higgs doublets $\longrightarrow$

3 Goldstone bosons
$+$
N - 1 charged scalars $\phi_a^{\pm}\,(H_a^{\pm})$
$+$
2N - 1 neutral scalars $\rho_a, \eta_a\,(S_i^0, P_i^0)$

Introduction

$$\phi_a \equiv \mathrm{e}^{i\theta_a} \begin{bmatrix} \phi_a^+ \\ \frac{1}{\sqrt{2}}(v_a + \rho_a + i\eta_a) \end{bmatrix} , \qquad v = \left(\sum_a v_a^2 \right)^{1/2} > 0 \, .$$

$$\mathcal{L}_Y = - \sum_{a=1}^{N} \left\{ \bar{Q}'_L \left(\mathbf{\Gamma_a} \phi_a \, d'_R + \mathbf{\Delta_a} \tilde{\phi}_a \, u'_R \right) + \bar{L}'_L \, \mathbf{\Pi_a} \phi_a \, \ell'_R + \mathrm{h.c.} \right\} ,$$

$\downarrow$ $SU(N)$ transformation

Higgs basis

$$\Phi_a = \sum_{b=1}^{N} \Omega_{ab} \, \mathrm{e}^{-i\tilde{\theta}_b} \, \phi_b \, , \qquad \Omega^T \cdot \Omega = 1 \, , \qquad \sum_{a=1}^{N} \Omega_{1a} = v_a / v \, .$$

Introduction

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + S_1^0 + i\, G^0\right) \end{bmatrix}, \qquad \Phi_{a>1} = \begin{bmatrix} H_a^+ \\ \frac{1}{\sqrt{2}}\left(S_a^0 + i\, P_a^0\right) \end{bmatrix}.$$

FCNC at tree level (very constrained phenomenologically)

Yukawa Lagrangian

$$\begin{aligned}\mathcal{L}_Y = & -\frac{1}{v}\left\{\bar{d}_L M_d d_R + \bar{u}_L M_u u_R + \bar{\ell}_L M_l \ell_R\right\} \\ & - \sum_{a=2}^{N} \frac{1}{v}\Bigg\{\sum_i^{2N-1} \mathcal{R}_{ia}\varphi_a^0 \left(\bar{d}_L Y_d^{(a)} d_R + \bar{u}_R Y_u^{(a)\dagger} u_L + \bar{\ell}_L Y_\ell^{(a)} \ell_R\right) \\ & + \frac{\sqrt{2}}{v} H_a^+ \left(\bar{u}_L V_{\mathrm{CKM}} Y_d^{(a)} d_R - \bar{u}_R Y_u^{(a)\dagger} V_{\mathrm{CKM}} d_L + \bar{\nu}_L Y_\ell^{(a)} \ell_R\right)\Bigg\} + \mathrm{h.c.}\,,\end{aligned}$$

$\downarrow$ **Natural flavour conservation**

$\downarrow$ **Flavour alignment**

Natural flavour conservation

- Discrete $\mathcal{Z}_2^d \otimes \mathcal{Z}_2^u \otimes \mathcal{Z}_2^\ell$ symmetry

$$\boxed{\mathcal{Z}_2^f : f_R' \rightarrow -f_R' \,, \quad \phi_{a_f} \rightarrow -\phi_{a_f} \,,}$$

$$\downarrow$$

- Family universality
- Absence of CP-violation
- **Stable** under quantum corrections

$N = 2$: 2HDM ($\mathcal{Z}_2$ symmetry)

$$\begin{array}{lll}
\text{Type :} & \{a_u, a_d, a_l\} & \\
\text{Type I :} & \{2,2,2\}, & \varsigma_d = \varsigma_u = \varsigma_\ell = \cot\beta \,, \\
\text{Type II :} & \{1,2,1\}, & \varsigma_d = \varsigma_\ell = -\tan\beta \,, \varsigma_u = \cot\beta \,, \\
\text{Type X :} & \{2,2,1\}, & \varsigma_d = \varsigma_u = \cot\beta \,, \varsigma_\ell = -\tan\beta \,, \\
\text{Type Y :} & \{1,2,2\}, & \varsigma_d = -\tan\beta \,, \varsigma_u = \varsigma_\ell = \cot\beta \,.
\end{array}$$

Flavour alignment

- Alignment in flavour space

$$Y_{d,\ell}^{(a)} = \varsigma_{d,\ell}^{(a)} \, M_{d,\ell} \, , \qquad\qquad Y_{u}^{(a)} = \varsigma_{u}^{(a)*} \, M_{u} \, ,$$

$\downarrow$

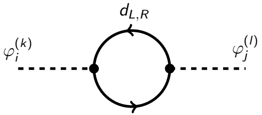
- Family universality
- Sources of CP-violation
- No FCNC **at tree level**

Most general structure (~~Family universality~~)

$$\varsigma_{d,\ell}^{(a)} \equiv Y_{d,\ell}^{(a)} \, M_{d,\ell}^{-1} \, , \qquad\qquad \varsigma_{u}^{(a)\dagger} \equiv Y_{u}^{(a)} \, M_{u}^{-1} \, .$$

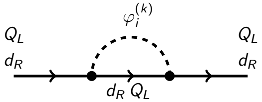
$$\varsigma_d^{(a)} = \mathrm{diag}(\varsigma_d^{(a)}, \varsigma_s^{(a)}, \varsigma_b^{(a)}), \quad \varsigma_u^{(a)} = \mathrm{diag}(\varsigma_u^{(a)}, \varsigma_c^{(a)}, \varsigma_t^{(a)}), \quad \varsigma_\ell^{(a)} = \mathrm{diag}(\varsigma_e^{(a)}, \varsigma_\mu^{(a)}, \varsigma_\tau^{(a)}).$$

Renormalization group equations



Scalar self-energy

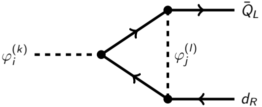
$$\mathrm{Tr}\left(Y_d^{(a)} Y_d^{(b)\dagger} + Y_u^{(a)} Y_u^{(b)\dagger}\right) Y_d^{(b)}$$



Q_L and d_R self energies

$$\mathbf{Q_L} : \left(Y_d^{(b)} Y_d^{(b)\dagger} + Y_u^{(b)} Y_u^{(b)\dagger}\right) Y_d^{(a)}$$

$$\mathbf{d_L} : \quad Y_d^{(a)} Y_d^{(a)\dagger} Y_d^{(b)}$$



Vertex correction

$$V_{\mathrm{CKM}}^\dagger Y_u^{(b)} Y_u^{(a)\dagger} V_{\mathrm{CKM}} Y_d^{(b)} \to \mathrm{FCNC}$$

FCNC Lagrangian, $N = 2$

$$\mathcal{L}_{\mathrm{FCNC}} = \frac{1}{4\pi^2 v^3} \left(1 + \varsigma_u^* \varsigma_d\right) \sum_{k=1}^{3} \varphi_k^0 \left\{ \mathcal{C}_d(\mu) \left(\mathcal{R}_{k2} + i\,\mathcal{R}_{k3}\right) \left(\varsigma_d - \varsigma_u\right) \bar{d}_L V_{\mathrm{CKM}}^\dagger M_u M_u^\dagger V_{\mathrm{CKM}} M_d d_R \right.$$
$$\left. - \mathcal{C}_u(\mu) \left(\mathcal{R}_{k2} - i\,\mathcal{R}_{k3}\right) \left(\varsigma_d^* - \varsigma_u^*\right) \bar{u}_L V_{\mathrm{CKM}} M_d M_d^\dagger V_{\mathrm{CKM}}^\dagger M_u u_R \right\} + \mathrm{h.c}$$

$$\mathcal{C}_f(\mu) = \mathcal{C}_f(\mu_0) - \log\frac{\mu}{\mu_0}, \qquad \mu_0 = \Lambda_A \leq M_{\mathrm{Planck}} = 10^{19}\,\mathrm{GeV} \to \mathcal{C}_f(M_W) \leq 40$$

Flavour symmetries

Symmetries under flavour-phase transformations

$$f_X^i \to e^{i\alpha_i^{f,X}}\, f_X^i\,, \qquad Y_f^{(a),ij} \to e^{i\alpha_i^{f,L}}\, Y_f^{(a),ij}\, e^{-i\alpha_j^{f,R}}\,,$$

$$M_f^{ij} \to e^{i\alpha_i^{f,L}}\, M_f^{ij}\, e^{-i\alpha_j^{f,R}}\,, \qquad V_{\text{CKM}}^{ij} \to e^{i\alpha_i^{u,L}}\, V_{\text{CKM}}^{ij}\, e^{-i\alpha_j^{d,L}}\,.$$

$f = u, d, \ell\,,\quad X = L, R\,,\quad i, j \to$ fermion families

FCNC operators

$$\mathcal{O}_d^{n,m} = \bar{d}_L (\varsigma_d)^{p_1} V_{\text{CKM}}^\dagger (\varsigma_u^\dagger)^{p_n} (M_u M_u^\dagger)^n (\varsigma_u)^{p'_n} V_{\text{CKM}} (\varsigma_d)^{p_m} (M_d M_d^\dagger)^m (\varsigma_d^\dagger)^{p'_m} (\varsigma_d)^{p'_1} M_d d_R\,,$$

$$\mathcal{O}_u^{n,m} = \bar{u}_L (\varsigma_u)^{p_1} V_{\text{CKM}} (\varsigma_d)^{p_n} (M_d M_d^\dagger)^n (\varsigma_d^\dagger)^{p'_n} V_{\text{CKM}}^\dagger (\varsigma_u^\dagger)^{p_m} (M_u M_u^\dagger)^m (\varsigma_u)^{p'_m} (\varsigma_u^\dagger)^{p'_1} M_u u_R\,,$$

$p_k, p'_k \leq k$

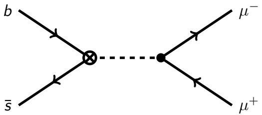
Phenomenology of the A2HDM

Aligned Two-Higgs Doublet Model (A2HDM)

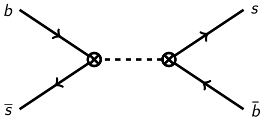
Two doublets aligned in flavour space, in the CP-conserving limit,

$$Y_{d,\ell} = \underbrace{\varsigma_{d,\ell}}_{\text{real}} M_{d,\ell}\,, \qquad\qquad Y_u = \underbrace{\varsigma_u}_{\text{real}} M_u\,.$$

$$\mathcal{R}_{11} = \mathcal{R}_{22} = \cos\tilde{\alpha}, \quad \mathcal{R}_{21} = -\mathcal{R}_{21} = \sin\tilde{\alpha}, \quad \mathcal{R}_{33} = 1, \quad \mathcal{R}_{i3} = \mathcal{R}_{3i} = 0 \ (i \neq 3)$$



$B_s^0 \to \mu^+\mu^-$



$B_s^0 - \bar{B}_s^0$ mixing

- FCNC vertices at **one loop**
- Also scalar penguins and boxes ($H^\pm$)(needed to cancel divergences)

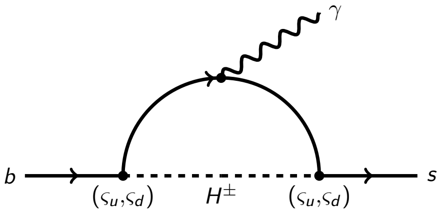
- FCNC vertices at **two loops**
- Box contributions ($H^\pm$) finite by themselves (GIM mechanism)

Phenomenology of the A2HDM

Mass configurations

Red :	$M_{H^\pm} = 100$ GeV ,	$M_H = 50$ GeV ,	$M_A = 50$ GeV ,
Green :	$M_{H^\pm} = 100$ GeV ,	$M_H = 200$ GeV ,	$M_A = 200$ GeV ,
Blue :	$M_{H^\pm} = 500$ GeV ,	$M_H = 500$ GeV ,	$M_A = 200$ GeV ,
Orange :	$M_{H^\pm} = 500$ GeV ,	$M_H = 200$ GeV ,	$M_A = 500$ GeV .

$+$ constraints from $\bar{B} \to X_s \gamma$



Observable

$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{A2HDM}}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{SM}}} = \left\{ |P|^2 + \left(1 - \frac{\Delta\Gamma_s}{\Gamma_L^s}\right) |S|^2 \right\} ,$$

$$P \subset C_{10}^{\text{A2HDM}},\ C_P^{\varphi_i^0,\text{A2HDM}}$$

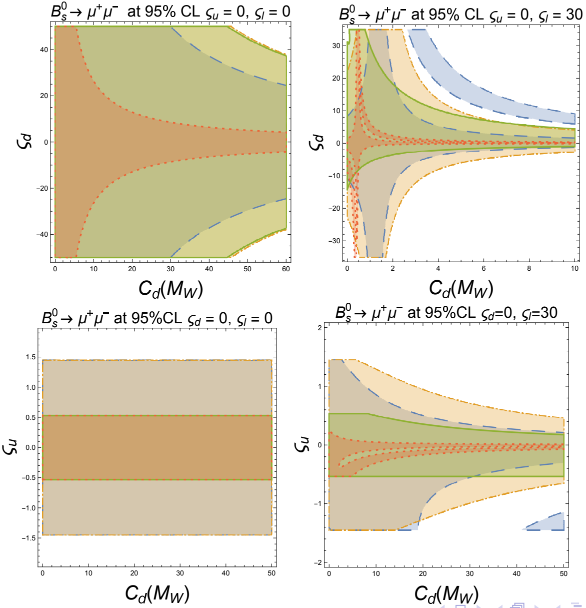
$$S \subset C_S^{\varphi_i^0,A2HDM}$$

$$\Delta C_{10}^{\text{A2HDM}} = |\varsigma_u|^2 \frac{x_t^2}{8} \left[\frac{1}{x_{H^+} - x_t} + \frac{x_{H^+}}{(x_{H^+} - x_t)^2} \left(\ln x_t - \ln x_{H^+}\right) \right] .$$

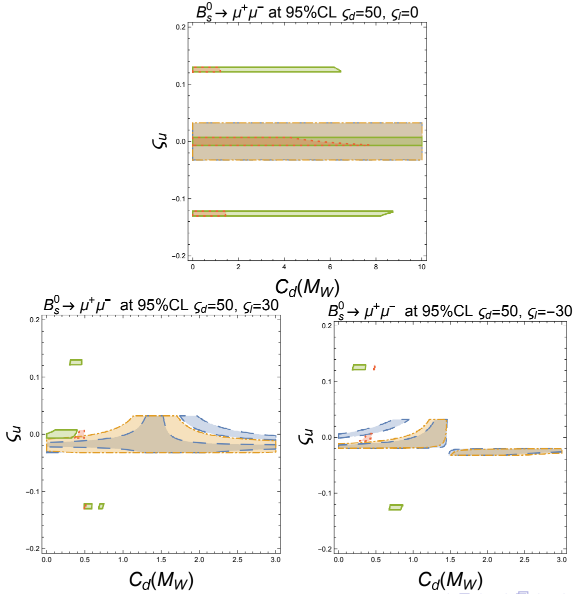
$$\Delta C_S^{\varphi_i^0,\,\text{A2HDM}} = \frac{x_t}{2x_h} \left(c_{\tilde{\alpha}} + s_{\tilde{\alpha}}\, \varsigma_\ell\right) \left\{ s_{\tilde{\alpha}} \left(\varsigma_u - \varsigma_d\right) \left(1 + \varsigma_u \varsigma_d\right) \mathcal{C}_d(M_W) + \ldots \right\},$$

$$\Delta C_P^{\varphi_i^0,\,\text{A2HDM}} = -\varsigma_\ell \frac{x_t}{2x_A} \left[\left(\varsigma_u - \varsigma_d\right) \left(1 + \varsigma_u \varsigma_d\right) \mathcal{C}_d(M_W) + \ldots \right] ,$$

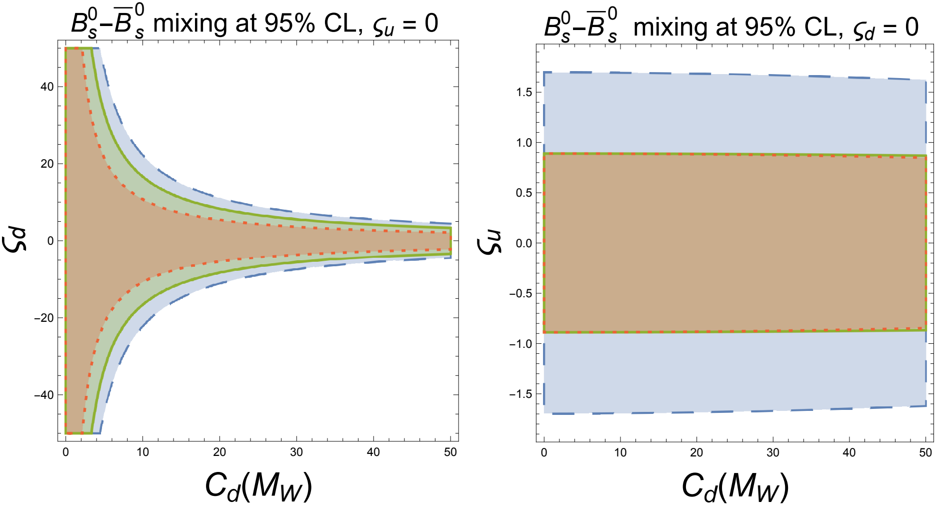
Phenomenology of the A2HDM. $B_s^0 \to \mu^+\mu^-$



Phenomenology of the A2HDM. $B_s^0 \to \mu^+\mu^-$



Phenomenology of the A2HDM. $B_s^0 - \bar{B}_s^0$ mixing



Summary

- Motivation for the study of extensions $\rightarrow$ aspects of nature not explained only by the SM + freedom to extend the scalar sector

- NHDM: N doublets with the same quantum numbers as the Higgs doublet$\rightarrow$ 2N-1 scalar neutral particles (φ_i^0) + N-1 charged particles $(H_i^{\pm})$

- In general FCNC at tree level, to avoid them:
  - Natural flavour conservation: $\mathcal{Z}_2^d \otimes \mathcal{Z}_2^u \otimes \mathcal{Z}_2^\ell$ symmetry, stable under quantum corrections
  - Flavour alignment: one loop-misalignment
    - small quantum corrections (flavour-phase symmetry)

- Phenomenological constraints for the A2HDM
  - $B_s^0 \rightarrow \mu^+\mu^-$
  - Meson mixing

- $\Lambda_A \leq M_{\text{Planck}} \sim 10^{19}$ GeV $\rightarrow \mathcal{C}_d(M_W) = \log \frac{\Lambda_A}{M_W} \leq 40$ ✓

Back up

Multi-Higgs-doublets models: Original and Higgs basis

Original basis:

$$\phi_a = e^{i\theta_a} \begin{bmatrix} \phi_a^+ \\ \frac{1}{\sqrt{2}}(v_a + \rho_a + i\,\eta_a) \end{bmatrix} .$$

$$\mathcal{L}_Y = -\sum_{a=1}^{N} \left\{ \bar{Q}'_L \left(\Gamma_a \phi_a\, d'_R + \Delta_a \tilde{\phi}_a\, u'_R \right) + \bar{L}'_L\, \Pi_a \phi_a\, \ell'_R + \mathrm{h.c.} \right\} ,$$

$SU(N)$ transformation, so that just one doublet acquiere a vev

$$\Phi_a = \sum_{b=1}^{N} \Omega_{ab}\, e^{-i\tilde{\theta}_b}\, \phi_b , \qquad \phi_b = e^{i\tilde{\theta}_b} \sum_{a=1}^{N} \Omega_{ab}\, \Phi_a , \qquad \Omega \cdot \Omega^T = \Omega^T \cdot \Omega = 1 ,$$

Multi-Higgs-doublets models: Original and Higgs basis

Higgs basis:

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + S_1^0 + i\, G^0\right) \end{bmatrix}, \qquad \Phi_{a>1} = \begin{bmatrix} H_a^+ \\ \frac{1}{\sqrt{2}}\left(S_a^0 + i\, P_a^0\right) \end{bmatrix}.$$

In the Higgs basis the Yukawa structures:

$$\sum_{a=1}^{N} \Gamma_a \phi_a = \sum_{b=1}^{N} \hat{\Gamma}_b \Phi_b\,, \qquad \sum_{a=1}^{N} \Delta_a \tilde{\phi}_a = \sum_{b=1}^{N} \hat{\Delta}_b \tilde{\Phi}_b\,, \qquad \sum_{a=1}^{N} \Pi_a \phi_a = \sum_{b=1}^{N} \hat{\Pi}_b \Phi_b\,,$$

with

$$\hat{\Gamma}_b = \sum_{a=1}^{N} \Omega_{ba}\, e^{i\tilde{\theta}_a}\, \Gamma_a\,, \qquad \hat{\Delta}_b = \sum_{a=1}^{N} \Omega_{ba}\, e^{-i\tilde{\theta}_a}\, \Delta_a\,, \qquad \hat{\Pi}_b = \sum_{a=1}^{N} \Omega_{ba}\, e^{i\tilde{\theta}_a}\, \Pi_a\,.$$

$\mathcal{Z}\in$ symmetries for N doublets

$N \geq 3$: 3N-1 inhert doublets

$$
\begin{aligned}
&\text{Type A}: && \{1,1,1\}, && \varsigma_d^{(a)} = \varsigma_u^{(a)} = \varsigma_\ell^{(a)} = \Omega_{a1}/\Omega_{11} \\
&\text{Type B}: && \{1,2,1\}, && \varsigma_d^{(a)} = \varsigma_\ell^{(a)} = \Omega_{a1}/\Omega_{11}\,, \varsigma_u^{(a)} = \Omega_{a2}/\Omega_{12}\,, \\
&\text{Type C}: && \{1,1,2\}, && \varsigma_d^{(a)} = \varsigma_u^{(a)} = \Omega_{a1}/\Omega_{11}\,, \qquad \varsigma_\ell^{(a)} = \Omega_{a2}/\Omega_{12}\,, \\
&\text{Type D}: && \{1,2,2\}, && \varsigma_d^{(a)} = \Omega_{a1}/\Omega_{11}\,, \varsigma_u^{(a)} = \varsigma_\ell^{(a)} = \Omega_{a2}/\Omega_{12}\,, \\
&\text{Type E}: && \{1,2,3\}, && \varsigma_d^{(a)} = \Omega_{a1}/\Omega_{11}\,, \varsigma_u^{(a)} = \Omega_{a2}/\Omega_{12}\,, \varsigma_\ell^{(a)} = \Omega_{a3}/\Omega_{13}\,.
\end{aligned}
$$

Renormalization Group Equations

$$\mathcal{D}\Gamma_a = a_\Gamma \, \Gamma_a + \sum_{b=1}^{N} \left[N_C \; \mathrm{Tr}\left(\Gamma_a \Gamma_b^\dagger + \Delta_a^\dagger \Delta_b\right) + \mathrm{Tr}\left(\Pi_a \Pi_b^\dagger\right)\right] \Gamma_b$$

$$+ \sum_{b=1}^{N} \left(-2\, \Delta_b \Delta_a^\dagger \Gamma_b + \Gamma_a \Gamma_b^\dagger \Gamma_b + \frac{1}{2}\, \Delta_b \Delta_b^\dagger \Gamma_a + \frac{1}{2}\, \Gamma_b \Gamma_b^\dagger \Gamma_a \right),$$

$$\mathcal{D}\Delta_a = a_\Delta \, \Delta_a + \sum_{b=1}^{N} \left[N_C \; \mathrm{Tr}\left(\Delta_a \Delta_b^\dagger + \Gamma_a^\dagger \Gamma_b\right) + \mathrm{Tr}\left(\Pi_a^\dagger \Pi_b\right)\right] \Delta_b$$

$$+ \sum_{l=1}^{N} \left(-2\, \Gamma_b \Gamma_a^\dagger \Delta_b + \Delta_a \Delta_b^\dagger \Delta_b + \frac{1}{2}\, \Gamma_b \Gamma_b^\dagger \Delta_a + \frac{1}{2}\, \Delta_b \Delta_b^\dagger \Delta_a \right),$$

$$\mathcal{D}\Pi_a = a_\Pi \, \Pi_a + \sum_{b=1}^{N} \left[N_C \; \mathrm{Tr}\left(\Gamma_a \Gamma_b^\dagger + \Delta_a^\dagger \Delta_b\right) + \mathrm{Tr}\left(\Pi_a \Pi_b^\dagger\right)\right] \Pi_b$$

$$+ \sum_{l=1}^{N} \left(\Pi_a \Pi_b^\dagger \Pi_b + \frac{1}{2}\, \Pi_b \Pi_b^\dagger \Pi_a \right),$$

where $\mathcal{D} \equiv 16\pi^2 \mu\,(d/d\mu)$, being μ the renormalization scale, and $N_C = 3$ is the number of quark colours.

Renormalization Group Equations

$$\mathcal{L}_{\rm FCNC} = \frac{1}{4\pi^2 v^3} \sum_{a=1}^{N} \sum_{k=1}^{N-1} \varphi_a^0 \left\{ C_d^{(a)} \left(\mathcal{R}_{a,2k} + \mathcal{R}_{a,2k+1}\right) \bar{d}_L \widetilde{\Theta}_d^{(a)} M_d d_R - C_u^{(a)} \left(\mathcal{R}_{a,2k} - \mathcal{R}_{a,2k+1}\right) \bar{u}_L \widetilde{\Theta}_u^{(a)} M_u u_R \right\} + \text{ h.c.}\,,$$

$$\widetilde{\Theta}_d^{(a)} = -V_{\rm CKM}^\dagger \sum_{b=1}^{N} \varsigma_u^{(b)\dagger} M_u M_u^\dagger \varsigma_u^{(a)} V_{\rm CKM} \varsigma_d^{(b)} + \varsigma_d^{(a)} V_{\rm CKM}^\dagger \sum_{b=1}^{N} \varsigma_u^{(b)\dagger} M_u M_u^\dagger V_{\rm CKM} \varsigma_d^{(b)} + \Delta\widetilde{\Theta}_d^{(a)}\,,$$

$$\widetilde{\Theta}_u^{(a)} = -V_{\rm CKM} \sum_{b=1}^{N} \varsigma_d^{(b)} M_d M_d^\dagger \varsigma_d^{(a)\dagger} V_{\rm CKM}^\dagger \varsigma_u^{(b)\dagger} + \varsigma_u^{(a)\dagger} V_{\rm CKM} \sum_{b=1}^{N} \varsigma_d^{(b)} M_d M_d^\dagger V_{\rm CKM}^\dagger \varsigma_u^{(b)\dagger} + \Delta\widetilde{\Theta}_u^{(a)}\,,$$

$$\Delta\widetilde{\Theta}_d^{(a)} = \frac{1}{4}\left[V_{\rm CKM}^\dagger \left(\sum_{b=1}^{N} \varsigma_u^{(b)\dagger} M_u M_u^\dagger \varsigma_u^{(b)} \right) V_{\rm CKM}\,,\, \varsigma_d^{(a)} \right] = \frac{N}{4}\left[V_{\rm CKM}^\dagger M_u M_u^\dagger V_{\rm CKM}\,,\, \varsigma_d^{(a)} \right]$$

$$\Delta\widetilde{\Theta}_u^{(a)} = \frac{1}{4}\left[V_{\rm CKM} \left(\sum_{b=1}^{N} \varsigma_d^{(b)} M_d M_d^\dagger \varsigma_d^{(b)\dagger} \right) V_{\rm CKM}^\dagger\,,\, \varsigma_u^{(a)\dagger} \right] = \frac{N}{4}\left[V_{\rm CKM} M_d M_d^\dagger V_{\rm CKM}\,,\, \varsigma_d^{(a)} \right]$$

Renormalization Group Equations

$$\widetilde{\Theta}_d^{(a)} = \left(\varsigma_d^{(a)} - \varsigma_u^{(a)}\right) \left(\sum_{b=1}^{N} \varsigma_u^{(b)\dagger} \varsigma_d^{(b)}\right) V_{\text{CKM}}^{\dagger} M_u M_u^{\dagger} V_{\text{CKM}} \,,$$

$$\widetilde{\Theta}_u^{(a)} = \left(\varsigma_u^{(a)\dagger} - \varsigma_d^{(a)\dagger}\right) \left(\sum_{b=1}^{N} \varsigma_u^{(b)\dagger} \varsigma_d^{(b)}\right) V_{\text{CKM}} M_d M_d^{\dagger} V_{\text{CKM}}^{\dagger} \,.$$

Flavour symmetries

- In the absence of Yukawa couplings $\rightarrow$ huge $SU(3)^5$ flavour symmetry
- $f_X \rightarrow S_{f_X} f_X, \; S_{f_X} \in SU(3)_{f_X}$

$$f_X^i \rightarrow e^{i\alpha_i^{f,X}} f_X^i \,, \qquad Y_f^{(a),ij} \rightarrow e^{i\alpha_i^{f,L}} Y_f^{(a),ij} e^{-i\alpha_j^{f,R}} \,.$$

$$M_f^{ij} \rightarrow e^{i\alpha_i^{f,L}} M_f^{ij} e^{-i\alpha_j^{f,R}} \,, \qquad V_{\text{CKM}}^{ij} \rightarrow e^{i\alpha_i^{u,L}} V_{\text{CKM}}^{ij} e^{-i\alpha_j^{d,L}} \,.$$

The generalized alignment condition implies then

$$\varsigma_f^{(a),ij} \rightarrow e^{i\alpha_i^{f,L}} \varsigma_f^{(a),ij} e^{-i\alpha_j^{f,L}} \,.$$

FCNC operators of the form

$$\mathcal{O}_d^{n,m} = \bar{d}_L (\varsigma_d)^{p_1} V_{\text{CKM}}^\dagger (\varsigma_u^\dagger)^{p_n} (M_u M_u^\dagger)^n (\varsigma_u)^{p_{n'}} V_{\text{CKM}} (\varsigma_d)^{p_m} (M_d M_d^\dagger)^m (\varsigma_d^\dagger)^{p_{m'}} (\varsigma_d)^{p_2} M_d d_R$$

$$\mathcal{O}_u^{n,m} = \bar{u}_L (\varsigma_u)^{p_1} V_{\text{CKM}} (\varsigma_d)^{p_n} (M_d M_d^\dagger)^n (\varsigma_d^\dagger)^{p_{n'}} V_{\text{CKM}}^\dagger (\varsigma_u^\dagger)^{p_m} (M_u M_u^\dagger)^m (\varsigma_u)^{p_{m'}} (\varsigma_u^\dagger)^{p_2} M_u u_R$$

or similar structures with additional factors of V_{CKM}, $V_{\text{CKM}}^\dagger$, $(M_f M_f^\dagger)$ and alignment matrices.

Example of 2HDM as a solution of DM

- A. Drozd, B.Grzadkowski1, J.F. Gunion and Y. Jiang (arXiv: 1408.2106)
- 2HDM type I or II + real gauge singlet S (2HDMS)
- S does not acquiere a vev
- Extra symmetry $\mathcal{Z}_2'$: $S \rightarrow -S$ (remaining particles unchanged)