Yukawa Alignment in a Multi Higgs Doublet Model: An effective approach

H. Serôdio
Centro de Física Teórica de Partículas (CFTP)

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Natural Flavour Conservation

with extended scalar sector

For the 2HDM:

- Z_2 **symmetry**: Only one $\mathbf{Y}_h^q$ is not zero for every q. Way to implement:

  Higgs: $\phi_1 \to \phi_1$ and $\phi_2 \to -\phi_2$.

  Fermions: ψ_R with the appropriate charge.

- **Alignment**: More general statement, all Yukawa couplings proportional.

  $\mathbf{Y}_1^q = \varsigma_f \mathbf{Y}_2^q$. **No symmetry**

  ς_f complex parameters

  [A.Pich and P.Tuzon 2009]

NFC requirement

$$\mathbf{U}_L^{q\dagger} \mathbf{Y}_h^q \mathbf{U}_R^q = \text{diag} \ \forall \, h$$

No spontaneous CP Violation

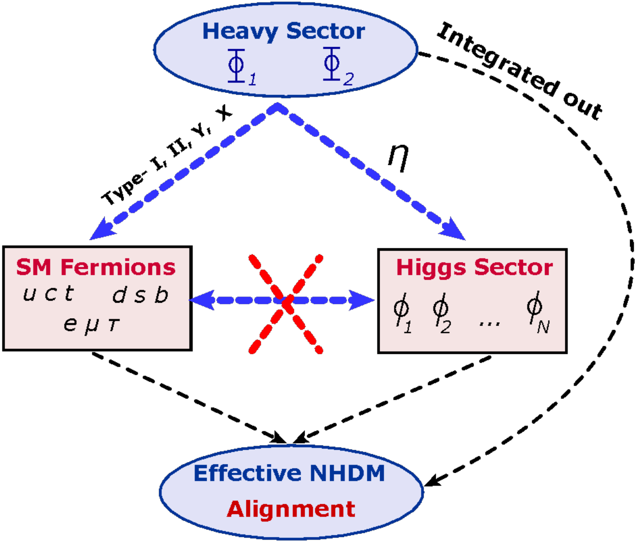
Spontaneous CPV. Not stable under RGE unless is Z_2.

[P.Ferreira, L.Lavoura and J.P.Silva 2010]

If Alignment is true we need additional particles

The renormalizable model

$N + 2$ **Higgs doublet Model + 2 real singlets with NFC**



The renormalizable model

$N+2$ **Higgs doublet Model + 2 real singlets with NFC**

	Φ_1	Φ_2	$\phi_{a=1,\ldots,N}$	η_1	η_2
$SU(2)_L$	2	2	2	1	1
$U(1)_Y$	1/2	1/2	1/2	0	0
$Z_2 \times Z_2$	$(1,1)$	$(1,-1)$	$(-1,1)$	$(-1,1)$	$(-1,-1)$

$$-\mathcal{L}_{\text{Yuk}} = \overline{Q_L^0}\,\mathbf{Y}_d\,\Phi_i\,d_R^0 + \overline{Q_L^0}\,\mathbf{Y}_u\,\tilde{\Phi}_j\,u_R^0 + \overline{\ell_L^0}\,\mathbf{Y}_\ell\,\Phi_k\,e_R^0 + \text{h.c.}$$

Implementation of NFC with Z_2

	u_R	d_R	e_R
Type-I	$(1,1)$	$(1,1)$	$(1,-1)$
Type-II	$(1,-1)$	$(1,1)$	$(1,1)$
Type-X	$(1,-1)$	$(1,-1)$	$(1,1)$
Type-Y	$(1,-1)$	$(1,1)$	$(1,-1)$
Inert	$(1,1)$	$(1,1)$	$(1,1)$

Enlarged scalar sector

$$V(\Phi,\phi,\eta) = M_i^2\Phi_i^\dagger\Phi_i + \ldots + \lambda_a M_1 \Phi_1^\dagger \phi_a \eta_1 + \lambda'_a M_2 \Phi_2^\dagger \phi_a \eta_2$$

The low energy limit

Very heavy states:
$M^2 \gg p^2, m_\phi^2, m_\eta^2$

Integrate Φ_i using EOM

$$\Phi_i^c \simeq -\frac{1}{M_i^2} X_i - \frac{1}{M_i} \lambda'_a \eta_i \phi_a$$

Effective potential

$$V_{\text{eff}}(\phi, \eta) \simeq V(0, \phi, \eta) - - \lambda_a^* \lambda_b \phi_a^\dagger \phi_b \eta_1^2 - \lambda_a'^* \lambda'_b \phi_a^\dagger \phi_b \eta_2^2$$

fermion-scalar interactions

$$-\mathcal{L}_{int}^{eff} \simeq \frac{\eta_1}{M_1} X_1^\dagger \sum_{a=1}^{N} \lambda_a \phi_a + \frac{\eta_2}{M_2} \sum_{a=1}^{N} \lambda_a'^* \phi_a^\dagger X_2 + \text{h.c.}$$

[(FS) I. de Medeiros Varzielas 2011]

Type-I:
$$\begin{cases} X_1 = \overline{d_R^0}\, \mathbf{Y}_d^\dagger\, Q_L^0 + \left(\overline{Q_L^0}\, \mathbf{Y}_u \epsilon\, u_R^0\right)^T \\ X_2 = \overline{e_R^0}\, \mathbf{Y}_\ell^\dagger\, \ell_L^0 \end{cases}$$

Type-II:
$$\begin{cases} X_1 = \overline{d_R^0}\, \mathbf{Y}_d^\dagger\, Q_L^0 + \overline{e_R^0}\, \mathbf{Y}_\ell^\dagger\, \ell_L^0 \\ X_2 = \left(\overline{Q_L^0}\, \mathbf{Y}_u \epsilon\, u_R^0\right)^T \end{cases}$$

Type-X:
$$\begin{cases} X_1 = \overline{e_R^0}\, \mathbf{Y}_\ell^\dagger\, \ell_L^0 \\ X_2 = \overline{d_R^0}\, \mathbf{Y}_d^\dagger\, Q_L^0 + \left(\overline{Q_L^0}\, \mathbf{Y}_u \epsilon\, u_R^0\right)^T \end{cases}$$

Type-Y:
$$\begin{cases} X_1 = \overline{d_R^0}\, \mathbf{Y}_d^\dagger\, Q_L^0 \\ X_2 = \left(\overline{Q_L^0}\, \mathbf{Y}_u \epsilon\, u_R^0\right)^T + \overline{e_R^0}\, \mathbf{Y}_\ell^\dagger\, \ell_L^0 \end{cases}$$

Inert:
$$\begin{cases} X_1 = \overline{d_R^0}\, \mathbf{Y}_d^\dagger\, Q_L^0 + \left(\overline{Q_L^0}\, \mathbf{Y}_u \epsilon\, u_R^0\right)^T + \overline{e_R^0}\, \mathbf{Y}_\ell^\dagger\, \ell_L^0 \\ X_2 = 0 \end{cases}$$

Effective Alignment in 2HDM

Type-II: $\Gamma_a = \frac{\langle \eta_1 \rangle}{M_1} \lambda_a \mathbf{Y}_d$, $\quad \Delta_a = \frac{\langle \eta_2 \rangle}{M_2} \lambda_a'^* \mathbf{Y}_u$, $\quad \Pi_a = \frac{\langle \eta_1 \rangle}{M_1} \lambda_a \mathbf{Y}_\ell$

$$-\mathcal{L}_{\text{Yuk}}^{2HDM} = \overline{Q_L^0} \left(\Gamma_1 \phi_1 + \Gamma_2 \phi_2\right) d_R^0 + \overline{Q_L^0} \left(\Delta_1 \tilde{\phi}_1 + \Delta_2 \tilde{\phi}_2\right) u_R^0 + \overline{\ell_L^0} \left(\Pi_1 \phi_1 + \Pi_2 \phi_2\right) e_R^0 + \text{h.c.} ,$$

$$\Gamma_2 = \xi_d \Gamma_1 \, , \; \Delta_2 = \xi_u^* \Delta_1 \, , \; \Pi_2 = \xi_\ell \Pi_1$$

with

$$\xi_{d,\ell} = \frac{\lambda_2}{\lambda_1} \, , \; \xi_u = \frac{\lambda_2'}{\lambda_1'}$$

Only 2 out of 3 are independent

Relation between mass and flavour-changing matrices

$$\mathbf{N}_u = \varsigma_u^* \mathbf{M}_u \, , \; \mathbf{N}_d = \varsigma_d \mathbf{M}_d \, , \; \mathbf{N}_\ell = \varsigma_\ell \mathbf{M}_\ell$$

with the proportionality factors given by

$$\varsigma_f = \frac{\tan\beta - e^{i\alpha}\xi_f}{1 + e^{i\alpha}\xi_f \tan\beta} \, , \quad \tan\beta = \frac{v_2}{v_1}$$

New sources of CPV
Possibility of spontaneous CPV

Conclusions

- FCNC are problematic in multiple Higgs scenarios
- A simple model where the Yukawa couplings are naturally aligned
- Alignment is a consequence of NFC at the UV scale:
  - Imposition of a discrete symmetry
  - Decoupling of heavy states that couple to fermions

More details see: H. Serôdio, **Phys. Lett. B700** (2011) 133-138.