Controlled flavour changing in multi Higgs models with residual family symmetries

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Based on

Family symmetries and alignment in multi-Higgs doublet models
Ivo de Medeiros Varzielas (Dortmund U.). Apr 2011. 4 pp.
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FCNC-free MHDM from broken family symmetries
Ivo de Medeiros Varzielas, Jim Talbert. Aug 28, 2019. 8 pp.
DESY 19-147
e-Print: **arXiv:1908.10979 [hep-ph]** | **PDF**

[Re]constructing Finite Flavour Groups: Horizontal Symmetry Scans from the Bottom-Up
Jim Talbert (Oxford U., Theor. Phys.). Sep 25, 2014. 18 pp.
Published in **JHEP 1412 (2014) 058**
DOI: 10.1007/JHEP12(2014)058
e-Print: **arXiv:1409.7310 [hep-ph] | PDF**

Bottom-Up Discrete Symmetries for Cabibbo Mixing
Ivo de Medeiros Varzielas (Southampton U.), Rasmus W. Rasmussen (DESY, Zeuthen), Jim Talbert (Oxford U., Theor. Phys. & Oxford U., Theor. Phys.). May 11, 2016. 21 pp.
Published in **Int.J.Mod.Phys. A32 (2017) no.06n07, 1750047**
DESY-16-125
DOI: 10.1142/S0217751X17500476
e-Print: **arXiv:1605.03581 [hep-ph] | PDF**

Simplified Models of Flavourful Leptoquarks

Ivo de Medeiros Varzielas (Lisbon U. & Lisbon, CFTP), Jim Talbert (DESY). Jan 29, 2019. 29 pp.

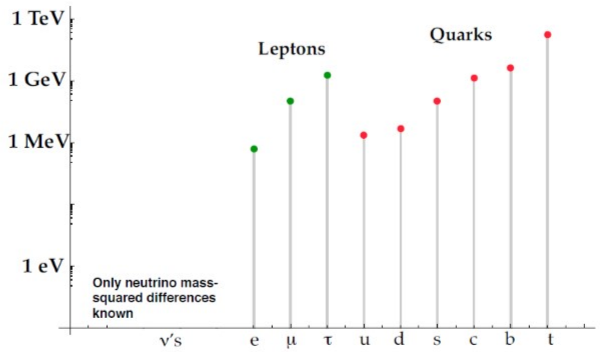
Published in **Eur.Phys.J. C79 (2019) no.6, 536**
DESY-18-210, DESY 18-210
DOI: 10.1140/epjc/s10052-019-7047-2
e-Print: **arXiv:1901.10484 [hep-ph] | PDF**

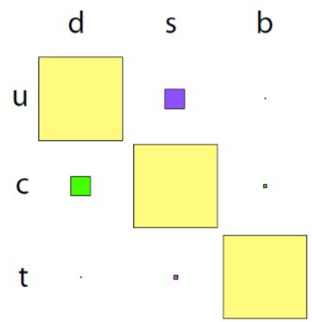
Finite Family Groups for Fermionic and Leptoquark Mixing Patterns

Jordan Bernigaud (Annecy, LAPTH), Ivo de Medeiros Varzielas (Lisbon, CFTP), Jim Talbert (DESY). Jun 26, 2019. 39 pp.

LAPTH-033/19, DESY-19-091
e-Print: **arXiv:1906.11270 [hep-ph] | PDF**

Flavour problem

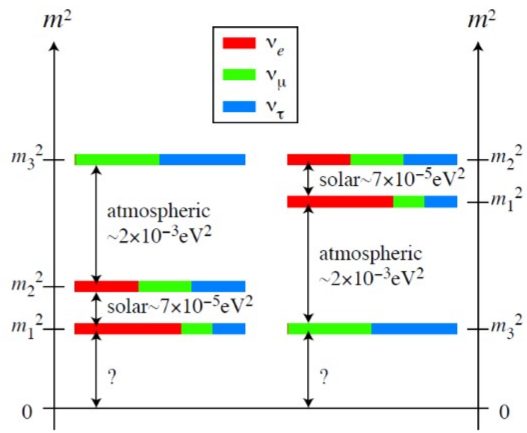


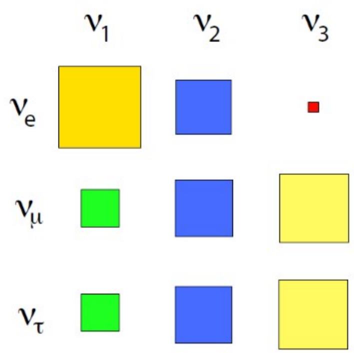


Quarks

CKM (PDG)

$$\begin{pmatrix} \binom{0.97456}{0.97436} & \binom{0.22496}{0.22408} & \binom{0.00377}{0.00353} \\ \binom{0.22482}{0.22394} & \binom{0.97369}{0.97348} & \binom{0.04290}{0.04138} \\ \binom{0.00920}{0.00873} & \binom{0.04207}{0.04059} & \binom{0.999137}{0.999073} \end{pmatrix}$$





Leptons

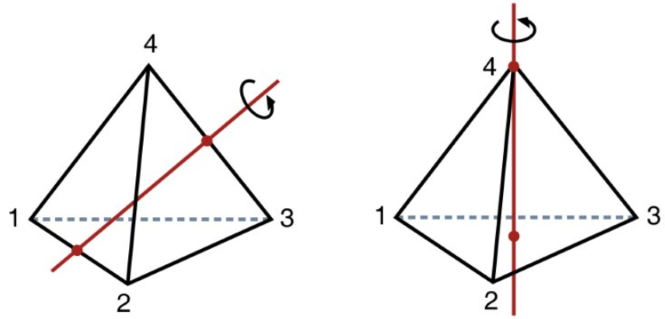
PMNS (Nufit)

$$\begin{pmatrix} \binom{0.844}{0.799} & \binom{0.582}{0.516} & \binom{0.156}{0.141} \\ \binom{0.494}{0.242} & \binom{0.678}{0.467} & \binom{0.774}{0.639} \\ \binom{0.521}{0.284} & \binom{0.695}{0.490} & \binom{0.754}{0.615} \end{pmatrix}$$

Non-Abelian Discrete Symmetries (NADS)

A_4 example

Group that leaves the tetrahedron invariant



$$T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix}, \quad \omega = e^{i\frac{2\pi}{3}}, \quad \omega^3 = 1$$

$$S = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix}; \quad T^3 = S^2 = \mathbb{1}$$

Field	L	e^c	μ^c	τ^c	ν^c	ϕ_T	ϕ_S
A_4	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}''$	$\mathbf{1}'$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$

Yukawas from flavons ϕ_i charged under A_4 and other "driving symmetries".

$$\begin{cases} \phi_T \to (v_T, 0, 0) \\ \phi_S \to (v_S, v_S, v_S) \end{cases}$$

$T\langle\phi_T\rangle = \langle\phi_T\rangle \qquad S\langle\phi_S\rangle = \langle\phi_S\rangle$

$\underbrace{m_\ell \text{ invariant under T}}_{m_\ell \text{ diagonal in this fermion basis}}$, m_ν invariant under S.

$(L\phi_T)[e^c + \mu^c + \tau^c] \ldots$

$$\Longrightarrow U_{PMNS} = U_{TB}$$

Residual Family Symmetries (RFS)

$$SM \sim q_L^i\,(3,2)_{+1/3}\,,\quad \overline{u}_L^i\,(\overline{3},1)_{-4/3}\,,\quad \overline{d}_L^i\,(\overline{3},1)_{+2/3}\,,\quad l_L^i\,(1,2)_{-1}\,,\quad \overline{e}_L^i\,(1,1)_{+2}$$

$$\mathbf{U(3)^5 \sim U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e}$$

Yukawa / Mass terms have innate symmetries

$$\mathcal{L}_{SM}^{Y} = -\left(\bar{l}_L\, m_e\, e_R + \bar{u}_L\, m_u\, u_R + \bar{d}_L\, m_d\, d_R\right)\,,$$

$$A \to T_A A, \quad \text{with} \quad A \in \{u_L, u_R, d_L, d_R, l_L, e_R\},$$
$$T_A = \mathrm{diag}\left(e^{i\alpha_A}, e^{i\beta_A}, e^{i\gamma_A}\right).$$

trivial in the mass basis, functions of mixing in flavour basis

$$T_A \to T_{AU} = U_A\, T_A\, U_A^\dagger\,, \qquad m_{AU} = T_{AU}^\dagger\, m_{AU}\, T_{AU}.$$

We consider scenarios where these innate symmetries are RFS, remnants of a parent Flavour Symmetry, e.g. broken by flavon fields

$$T_A \langle\phi\rangle_A = \langle\phi\rangle_A$$

(This is the case for the A_4 example)

$$G_F \longrightarrow \begin{cases} G_L \longrightarrow \begin{cases} G_\nu \\ G_l \end{cases} \\ G_d \longrightarrow \begin{cases} G_u \\ G_d \end{cases} \end{cases}$$

Multi Higgs Doublet Models (MHDM)

MHDM are well motivated BSM theories
But in general suffer from uncontrolled FCNC
(a flavour problem worse than in the SM)
Easy to see in Higgs basis:

$$\begin{pmatrix} H_1 \\ H_2 \\ \vdots \\ H_N \end{pmatrix}' \longrightarrow \begin{pmatrix} H_1 \\ H_2 \\ \vdots \\ H_N \end{pmatrix} = U_{H.B.} \begin{pmatrix} H_1 \\ H_2 \\ \vdots \\ H_N \end{pmatrix}' \quad \text{where} \quad \left\langle \begin{pmatrix} H_1 \\ H_2 \\ \vdots \\ H_N \end{pmatrix} \right\rangle = \begin{pmatrix} v \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

$$H'_k = \frac{e^{i\theta_k}}{\sqrt{2}} \begin{pmatrix} H_k^+ \\ v_k + \rho_k + i\eta_k \end{pmatrix}, \quad \text{after EWSB}$$

$$\Big\downarrow \text{Scalar basis change} \quad U_{H.B.} \text{ (not unique)}$$

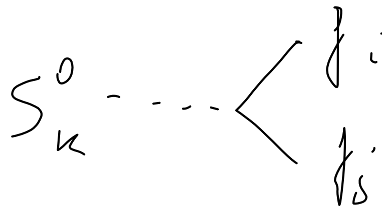
$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, G^+ \\ v + S_1^0 + iG^0 \end{pmatrix}, \quad H_{k>1} = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, S_k^+ \\ S_k^0 + iP_k^0 \end{pmatrix},$$

$$\mathcal{L}^Y = -\sum_{k=1}^{N} \Big\{ \bar{Q}'_L \left(Y_k^{d,\prime} H'_k d'_R + Y_k^{u,\prime} \tilde{H}'_k u'_R \right) + \bar{L}'_L Y_k^{e,\prime} H'_k e'_R + h.c. \Big\} .$$

Scalar basis change
Fermion basis change

$\Downarrow$ Diagonal m, Y_1

$$\begin{aligned}
\text{Mass terms} \quad \mathcal{L}^Y = & -\left(1 + \frac{S_1^0}{v}\right) \left(\bar{d}_L m_d d_R + \bar{u}_L m_u u_R + \bar{l}_L m_e e_R\right) \\
\text{Neutral currents} \quad & -\frac{1}{v} \sum_{k=2}^{N} \left(S_k^0 + i P_k^0\right) \left(\bar{d}_L Y_k^d d_R + \bar{u}_L Y_k^u u_R + \bar{l}_L Y_k^e e_R\right) \\
\text{Charged currents} \quad & -\frac{\sqrt{2}}{v} \sum_{k=2}^{N} S_k^+ \left(\bar{u}_L V Y_k^d d_R - \bar{u}_R Y_k^{u,\dagger} V d_L + \bar{\nu}_L Y_k^e e_R\right) \\
& + h.c. \,,
\end{aligned} \tag{10}$$



$(i \neq j)$

FCNC from $Y_{k \neq 1}$

Family Symmetries can address the MHDM flavour problem

e.g. $SU(3)_F$ contractions

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$$\mathcal{L}_u = \sum_{A=1}^{N} c^u_A \underbrace{H^\dagger_A}_{\text{F.S. singlet}} [\phi^i_Q Q_i](\phi^j_u u^c_j) + h.c.$$

Unique Family Symmetry Invariant Contraction (FSIC), Higgs are FS singlets
All up quark Yukawa matrices are rank 1 and diagonal in same basis as they share the same flavons
Generalisation to all sectors is simple: each sector has a unique FSIC

$$\mathcal{L} = \sum_{A=1}^{N} \Big(c^d_A H_A [\phi^i_Q Q_i](\phi^j_d d^c_j) + c^u_A H^\dagger_A [\phi^i_Q Q_i](\phi^j_u u^c_j) + c^e_A H_A [\phi^i_L L_i](\phi^j_e e^c_j) + c^\nu_A H^\dagger_A [\phi^i_L L_i](\phi^j_\nu \nu^c_j) \Big) + h.c. \longrightarrow Y^{ij}_{fA} = c^f_A \langle \phi^i_F \rangle \langle \phi^j_f \rangle$$

Yukawa Alignment
Pich, Tuzón 0908.1554

More realistic models would deviate from strict Yukawa alignment as each sector has more than one FSIC

E.g. $$Y_{fA} = c^f_{23A} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + c^f_{3A} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

RFS for MHDM

Our hypothesis is the Yukawa terms inherit RFS from some parent FS (e.g. sourced by a specific flavon)

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$$A \to T_A A, \quad \text{with} \quad A \in \{u_L, u_R, d_L, d_R, l_L, e_R\},$$
$$T_A = \text{diag}\left(e^{i\alpha_A}, e^{i\beta_A}, e^{i\gamma_A}\right).$$

$$Y_k^A \stackrel{!}{=} T_A Y_k^A T_A^\dagger,$$

$$\begin{pmatrix} Y_{11} & e^{i(\alpha_l-\beta_l)}\,Y_{12} & e^{i(\alpha_l-\gamma_l)}\,Y_{13} \\ e^{i(\beta_l-\alpha_l)}\,Y_{21} & Y_{22} & e^{i(\beta_l-\gamma_l)}\,Y_{23} \\ e^{i(\gamma_l-\alpha_l)}\,Y_{31} & e^{i(\gamma_l-\beta_l)}\,Y_{32} & Y_{33} \end{pmatrix} \stackrel{!}{=} \begin{pmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{pmatrix}$$

If no phase degeneracy, tree-level FCNC avoided → All Y_k are diagonal in fermion mass basis (strict RFS)
If two phase degeneracy, off-diagonal elements in the sector are allowed;
Also lose prediction of the mixing in that sector (weak RFS)

Residual symmetry with degenerate phases: can't reproduce entirely the associated mixing

$$T_{AU} = U_A\, T_A^{ii=jj}\, U_A^\dagger = U_A\, R_A^{ij}\, T_A^{ii=jj}\, R_A^{ji\star}\, U_A^\dagger.$$

$$R^{ij} \equiv \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij}\, e^{-i\delta_{ij}} \\ -\sin\theta_{ij}\, e^{i\delta_{ij}} & \cos\theta_{ij} \end{pmatrix}.$$

E.g. RFS predicts only Cabibbo angle -> forbids the most dangerous FCNC involving light quark generations

General Yukawa Alignment

$$Y_k^d = \varsigma_k^d \, Y_1^d , \quad Y_k^u = \varsigma_k^u \, Y_1^u , \quad Y_k^e = \varsigma_k^e \, Y_1^e ,$$

$$\varsigma_k^A = \mathrm{diag}\left(\varsigma_k^{A_1}, \varsigma_k^{A_2}, \varsigma_k^{A_3}\right) , \quad \varsigma_1^A \equiv \mathbb{1} ,$$

C.f.

Yukawa Alignment in the 2HDM; Pich,Tuzón; 0908.1554

Flavour alignment in multi-Higgs-doublet models; Peñuelas, Pich; 1710.02040

Talks this Saturday

Mass Matrix Ansatz and Flavor Nonconservation in Models with Multiple Higgs Doublets; Cheng, Sher; 1987

MHDM and Singular Alignment; Rodejohann, Saldaña-Salazar; 1903.00983

Renormalisation Group stability

Studied by Peñuelas, Pich. Leading order FCNC operators are proportional to
(in the Higgs and fermion mass basis):

$$\tilde{\Theta}_k^d = -V^\dagger \sum_{l=1}^{N} \zeta_l^{u,\dagger}\, m_u m_u^\dagger\, \zeta_k^u\, V\, \zeta_l^d$$
$$+ \zeta_k^d\, V^\dagger \sum_{l=1}^{N} \zeta_l^{u,\dagger}\, m_u m_u^\dagger\, V\, \zeta_l^d$$
$$+ \frac{1}{4}\left[V^\dagger \left(\sum_{l=1}^{N} \zeta_l^{u,\dagger} m_u m_u^\dagger \zeta_l^u \right) V,\ \ \zeta_k^d \right],$$

similar for up quarks and absent for charged leptons

Dimension seven, suppressed by two CKM factors, three alignment factors and three mass insertions.

Constraints on the alignment factors can be obtained $\bar{B}^0_s \to \mu^+\mu^-$; $\bar{B}_{0s} - B_{0s}$ mixing

General Yukawa Alignment at very high scales satisfies all experimental bounds
(consistent with RFS arising from the breaking of a Family Symmetry)

Realistic toy model

A_4 , $\langle \phi_l \rangle = (u, 0, 0)$

Similar idea in IdMV 1104.2601

$$\frac{H_1'}{\Lambda}\left(y_e^1[\bar{L}\phi_l]e_R + y_\mu^1[\bar{L}\phi_l]'\mu_R + y_\tau^1[\bar{L}\phi_l]''e_R\right) + \frac{H_2'}{\Lambda}\left(y_e^2[\bar{L}\phi_l]e_R + y_\mu^2[\bar{L}\phi_l]'\mu_R + y_\tau^2[\bar{L}\phi_l]''e_R\right) ,$$

$$\left\{\begin{aligned} [\bar{L}\phi_l] &= \bar{L}_1\phi_{l1} + \bar{L}_2\phi_{l3} + \bar{L}_3\phi_{l2}, \\ [\bar{L}\phi_l]' &= \bar{L}_1\phi_{l2} + \bar{L}_2\phi_{l1} + \bar{L}_3\phi_{l3}, \\ [\bar{L}\phi_l]'' &= \bar{L}_1\phi_{l3} + \bar{L}_2\phi_{l2} + \bar{L}_3\phi_{l1} , \end{aligned}\right.$$

$$Y_1^{e,\prime} = \frac{u}{\Lambda}\begin{pmatrix} y_e^1 & 0 & 0 \\ 0 & y_\mu^1 & 0 \\ 0 & 0 & y_\tau^1 \end{pmatrix} , \quad Y_2^{e,\prime} = \frac{u}{\Lambda}\begin{pmatrix} y_e^2 & 0 & 0 \\ 0 & y_\mu^2 & 0 \\ 0 & 0 & y_\tau^2 \end{pmatrix} .$$

Can then go to Higgs basis (redefines the entries but keeps both diagonal)

This toy model implements the (strict) RFS scenario for charged leptons: General Yukawa Alignment

Adding the neutrino terms makes the model realistic

$$H_1' \, y_\nu^1 \, [\bar{L}\nu_R] + H_2' \, y_\nu^2 \, [\bar{L}\nu_R] \; ,$$

$$(x_A \xi + x_A' \xi') \, [\nu_R \nu_R] + x_B \, [\phi_\nu \nu_R \nu_R] \; .$$

Just

$\mathbb{Z}_2$

$\langle \phi_\nu \rangle = (w, w, w)$

$\mathbb{Z}_2 \times \mathbb{Z}_2'$ RFS

$$|\sin\theta_{13}^l| = \frac{2}{\sqrt{6}} |\sin\theta| \, ,$$ viable PMNS mixing!

Conclusion

Flavour symmetries and RFS can control MHDM FCNC

Examples based on unique FSIC

Strict RFS lead to General Yukawa Alignment, absence of tree-level FCNC

Weak RFS can control the most problematic tree-level FCNC

Simple toy model demonstrates Strict RFS scenario and predicts viable PMNS mixing