Scalar FCNC and CP violating mixing matrices from the vacuum

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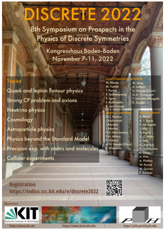

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The "goal"

Exploring the possibility of a connection between
CP violation in the quark (CKM) and lepton (PMNS) sectors

- Very solid evidence that CKM is irreducibly complex (γ)
- CP violation is "the last frontier" in PMNS
- In the SM, a CP violating CKM arises from complex Yukawa couplings
  (and the clash of up-down diagonalizations of mass matrices)
- If that ingredient is kept, together with some independent neutrino mass generation scheme $\Rightarrow$ no CKM-PMNS connection

The "road"

A common source of CP violation for both CKM and PMNS:
spontaneous CP violation (SCPV)

- T.D. Lee's original motivation for 2HDMs
- For broken symmetries, spontaneous breaking is *appealing*
- But ... generic 2HDMs (type III) have *uncontrolled* scalar flavour changing neutral couplings (SFCNC)

Outline

1. SFCNC in 2HDMs (quarks)
2. Complex CKM from the vacuum and controlled SFCNC
3. Including the lepton sector
4. Simplified models

Based on work done in collaboration with:

F.J. Botella, G.C. Branco, J. Alves & F. Cornet-Gómez

☞ arXiv:1808.00493, EPJC79 (2019)

☞ arXiv:2105.14054, EPJC81 (2021)

SFCNC in 2HDMs (quarks)

- In 2HDMs the Yukawa sector is

$$\mathscr{L}_{\mathrm{Y}} = -\bar{Q}_L^0 \left(\Phi_1 Y_{d1} + \Phi_2 Y_{d2} \right) d_R^0 - \bar{Q}_L^0 \left(\tilde{\Phi}_1 Y_{u1} + \tilde{\Phi}_2 Y_{u2} \right) u_R^0 + \mathrm{H.c.}$$

N.B. $\tilde{\Phi}_j = i\sigma_2 \Phi_j^*$

- Expansion around vacuum for appropriate electroweak symmetry breaking

$$\Phi_j = \frac{e^{i\theta_j}}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\varphi_j^+ \\ v_j + \rho_j + i\eta_j \end{pmatrix}$$

- Higgs basis, $c_\beta \equiv \cos\beta = \frac{v_1}{v}$, $s_\beta \equiv \sin\beta = \frac{v_2}{v}$, $t_\beta \equiv \tan\beta$

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \mathcal{R}_\beta \begin{pmatrix} e^{-i\theta_1}\Phi_1 \\ e^{-i\theta_2}\Phi_2 \end{pmatrix}, \quad \text{with} \quad \mathcal{R}_\beta = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix}, \; \mathcal{R}_\beta^T = \mathcal{R}_\beta^{-1}$$

SFCNC in 2HDMs (quarks)

- Higgs basis

$$\langle H_1 \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad \langle H_2 \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \qquad v^2 = v_1^2 + v_2^2 = \frac{1}{\sqrt{2} G_F}$$

$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^+ \\ v + H^0 + i G^0 \end{pmatrix}, \quad H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} \mathrm{H}^+ \\ R^0 + i I^0 \end{pmatrix}$$

  - would-be Goldstone bosons G^0, $G^\pm$
  - physical charged scalar $H^\pm$
  - neutral scalars $\{H^0, R^0, I^0\}$, not the mass eigenstates

- Yukawa couplings again

$$\mathscr{L}_{\mathrm{Y}} = -\frac{\sqrt{2}}{v} \bar{Q}_L^0 \left(H_1 \mathrm{M}_d^0 + H_2 \mathrm{N}_d^0 \right) d_R^0 - \frac{\sqrt{2}}{v} \bar{Q}_L^0 \left(\tilde{H}_1 \mathrm{M}_u^0 + \tilde{H}_2 \mathrm{N}_u^0 \right) u_R^0 + \mathrm{H.c.}$$

SFCNC in 2HDMs (quarks)

- Mass matrices

$$\mathrm{M}_d^0 = \frac{e^{i\theta_1} v}{\sqrt{2}} \left(c_\beta Y_{d1} + e^{i\theta} s_\beta Y_{d1} \right), \quad \mathrm{M}_u^0 = \frac{e^{-i\theta_1} v}{\sqrt{2}} \left(c_\beta Y_{u1} + e^{-i\theta} s_\beta Y_{d2} \right)$$

with $\theta = \theta_2 - \theta_1$

- New flavour structures

$$\mathrm{N}_d^0 = \frac{e^{i\theta_1} v}{\sqrt{2}} \left(-s_\beta Y_{d1} + e^{i\theta} c_\beta Y_{d1} \right), \quad \mathrm{N}_u^0 = \frac{e^{-i\theta_1} v}{\sqrt{2}} \left(-s_\beta Y_{u1} + e^{-i\theta} c_\beta Y_{d2} \right)$$

- Usual bi-unitary changes into the different fermion mass bases

$$\mathrm{M}_d^0 \mapsto \mathrm{M}_d = \mathrm{diag}(m_d, m_s, m_b) \qquad \mathrm{M}_u^0 \mapsto \mathrm{M}_u = \mathrm{diag}(m_u, m_c, m_t)$$

$$\mathrm{N}_d^0 \mapsto \mathrm{N}_d \qquad \mathrm{N}_u^0 \mapsto \mathrm{N}_u$$

SFCNC encoded in non-diagonal entries of N_d and N_u

Complex CKM from the vacuum and controlled SFCNC

- $\mathbb{Z}_2$ symmetry: all fields are even ($f \mapsto f$) except

$$Q^0_{L3} \mapsto -Q^0_{L3},\ \Phi_2 \mapsto -\Phi_2 \quad \text{(odd)}$$

- Yukawa matrices (generalization of BGL models)

$$Y_{d1} \sim Y_{u1} \sim \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} \qquad Y_{d2} \sim Y_{u2} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

$$\text{with } \mathrm{P}_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \begin{cases} Y_{d1} = (\mathbf{1} - \mathrm{P}_3) Y_{d1},\ Y_{d2} = \mathrm{P}_3 Y_{d2} \\ Y_{u1} = (\mathbf{1} - \mathrm{P}_3) Y_{u1},\ Y_{u2} = \mathrm{P}_3 Y_{u2} \end{cases}$$

- *Controlled* SFCNC

$$\mathrm{N}^0_d = -\left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1})\mathrm{P}_3\right] \mathrm{M}^0_d, \quad \mathrm{N}^0_u = -\left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1})\mathrm{P}_3\right] \mathrm{M}^0_u$$

Complex CKM from the vacuum and controlled SFCNC

- In order to have a spontaneous origin of CP violation

$$Y_{dj}^* = Y_{dj}\,, \quad Y_{uj}^* = Y_{uj}$$

Then, mass matrices

$$\mathrm{M}_f^0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma_f} \end{pmatrix} \widehat{\mathrm{M}_f^0} = \varphi_3(\sigma_f)\,\widehat{\mathrm{M}_f^0},\ f = u, d$$

with $\widehat{\mathrm{M}_f^0}$ real and $\sigma_d = \theta = -\sigma_u$

- CKM mixing matrix

$$V = \mathcal{O}_{u_L}^T\,\varphi_3(2\theta)\mathcal{O}_{d_L}$$

- SFCNC

$$\mathrm{N}_d = -\left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1})\mathrm{P}_3^d\right]\mathrm{M}_d, \quad \mathrm{N}_u = -\left[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1})\mathrm{P}_3^u\right]\mathrm{M}_u$$

with $\mathrm{P}_3^d = \mathcal{O}_{d_L}^T \mathrm{P}_3 \mathcal{O}_{d_L}$, $\mathrm{P}_3^u = \mathcal{O}_{u_L}^T \mathrm{P}_3 \mathcal{O}_{u_L}$ and $\mathrm{P}_3^u = V\,\mathrm{P}_3^d\,V^\dagger$

Complex CKM from the vacuum and controlled SFCNC

- SFCNC

$$[\mathrm{P}_3^f]_{ij} = \left(\mathcal{O}_{f_L}^T\,\mathrm{P}_3\,\mathcal{O}_{f_L}\right)_{ij} = [\mathcal{O}_{f_L}]_{3i}[\mathcal{O}_{f_L}]_{3j} = \hat{r}_{[f]i}\hat{r}_{[f]j}$$

with $\hat{r}_{[f]}$ a real unit vector

SFCNC in the $f = u, d$ sector between generations i and j are *controlled*, proportional to

  - bounded $\hat{r}_{[f]i}\hat{r}_{[f]j}$,
  - masses m_{f_i}, m_{f_j}.

Complex CKM from the vacuum and controlled SFCNC

- If one removes SFCNC in one sector, $\hat{r}_{[f]i} = 1$, $\hat{r}_{[f]j} = 0$, $j \neq i$,
  CKM is not CP violating

  Example:

$$\hat{r}_{[d]} = (0, 0, 1) \;\Rightarrow\; \mathcal{O}_{d_L} \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V = \mathcal{O}^T_{u_L} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i2\theta} \end{pmatrix} \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 1 \end{pmatrix} = \hat{V} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i2\theta} \end{pmatrix}$$

with $\hat{V}$ *real*

- In order to have a CP violating CKM matrix,
  one needs SFCNC in both sectors

Including the lepton sector

- Simplest extension to the lepton sector: Dirac neutrinos

$$\mathscr{L}_{\rm Y} = -\bar{L}_L^0 \left(\Phi_1 Y_{\ell 1} + \Phi_2 Y_{\ell 2}\right) \ell_R^0 - \bar{L}_L^0 \left(\tilde{\Phi}_1 Y_{\nu 1} + \tilde{\Phi}_2 Y_{\nu 2}\right) \nu_R^0 + \text{H.c.}$$

- Same kind of $\mathbb{Z}_2$ asignment, $L_{L3}^0 \mapsto -L_{L3}^0$,

$$Y_{\ell 1} \sim Y_{\nu 1} \sim \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix} \qquad Y_{\ell 2} \sim Y_{\nu 2} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}$$

- PMNS mixing matrix

$$U = \mathcal{O}_{\ell_L}^T \varphi_3(-2\theta) \mathcal{O}_{\nu_L}$$

- SFCNC

$$\mathrm{N}_\ell = -[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) \mathcal{O}_{\ell_L}^T \mathrm{P}_3 \mathcal{O}_{\ell_L}] \mathrm{diag}(m_e, m_\mu, m_\tau)$$
$$\mathrm{N}_\nu = -[t_\beta \mathbf{1} - (t_\beta + t_\beta^{-1}) \mathcal{O}_{\nu_L}^T \mathrm{P}_3 \mathcal{O}_{\nu_L}] \mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$

Including the lepton sector

- Two important aspects
  - $\theta \neq 0$ from the vacuum is the only possible source of CP violation in both CKM and PMNS
  - if SFCNC are removed in one fermion sector, CP violation in the corresponding mixing matrix disappears even for $\theta \neq 0$
- CKM parameter counting
  - 3 angles per orthogonal matrix, -1 combination, $+1$ (θ), matching
  - 4 independent quantities in the PDG parametrization $\{\theta^q_{12}, \theta^q_{13}, \theta^q_{23}, \delta_q\}$
  - 2 parameters describing quark SFCNC
  - Detailed phenomenological analysis in
    Botella, Branco & N, `arXiv:1808.00493`, EPJC79 (2019)

Including the lepton sector

- Two important aspects
  - $\theta \neq 0$ from the vacuum is the only possible source of CP violation in both CKM and PMNS
  - if SFCNC are removed in one fermion sector, CP violation in the corresponding mixing matrix disappears even for $\theta \neq 0$
- PMNS parameter counting
  - 3 angles per orthogonal matrix, -1 combination, but θ is "fixed" with CKM
  - 3 independent quantities in the PDG parametrization $\{\theta^\ell_{12}, \theta^\ell_{13}, \theta^\ell_{23}\}$, no δ_ℓ
  - 2 parameters describing lepton SFCNC
- In this sense δ_ℓ would be ideally fixed/related to δ_q
- However, from the ample freedom left in the analysis of the quark sector alone, we are far from there

Including the lepton sector

- Orthogonal matrices

$$\mathcal{O}_{u_L} = \mathrm{R}_1(p_1^u)\mathrm{R}_2(p_2^u)\mathrm{R}_3(p_3^u), \quad \mathcal{O}_{d_L} = \mathrm{R}_1(p_1^d)\mathrm{R}_2(p_2^d)\mathrm{R}_3(p_3^d)$$

  where each $\mathrm{R}_j(p_j^q)$ can be one of the following (no contiguous repetition)

$$R_{12}(x) = \begin{pmatrix} c_x & s_x & 0 \\ -s_x & c_x & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad R_{13}(x) = \begin{pmatrix} c_x & 0 & s_x \\ 0 & 1 & 0 \\ -s_x & 0 & c_x \end{pmatrix},$$

$$R_{23}(x) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_x & s_x \\ 0 & -s_x & c_x \end{pmatrix}, \qquad c_x \equiv \cos x,\ s_x \equiv \sin x$$

- Taking $\mathrm{R}_1(p_1^u) = R_{12}(p_1^u)$ and $\mathrm{R}_1(p_1^d) = R_{12}(p_1^d)$, CKM depends on $p_1^d - p_1^u$ alone
- Similarly for leptons

Simplified models

- Reduce the appearance of SFCNC to one transition per sector
  $\Leftrightarrow$ one 0 entry in the $\hat{r}_{[f]}$ vectors
- Simplified models are MFV models
- From the $3^4 = 81$ available possibilities, only one is viable!
- Quark sector

$$\mathcal{O}_{u_L} = R_{12}(p_1^u) R_{23}(p_2^u), \quad \mathcal{O}_{d_L} = R_{13}(p_3^d)$$
$$V = R_{23}(p_2^u)^T R_{12}(p_1^u)^T \varphi_3(2\theta) R_{13}(p_2^d)$$
$$\hat{r}_{[u]} = (0, -\sin p_2^u, \cos p_2^u), \qquad \hat{r}_{[d]} = (-\sin p_2^d, 0, \cos p_2^d)$$

that is $c \leftrightarrows t$ and $d \leftrightarrows b$ SFCNC

- Lepton sector

$$\mathcal{O}_{\ell_L} = R_{12}(p_1^\ell) R_{13}(p_2^\ell), \quad \mathcal{O}_{\nu_L} = P_{23} R_{12}(p_1^\nu)$$
$$U = R_{13}(p_2^\ell)^T R_{12}(p_1^\ell)^T \varphi_3(-2\theta) P_{23} R_{12}(p_1^\nu)$$
$$\hat{r}_{[\ell]} = (-\sin p_2^\ell, 0, \cos p_2^\ell), \qquad \hat{r}_{[\nu]} = (-\sin p_2^\nu, 0, \cos p_2^\nu)$$

that is $e \leftrightarrows \tau$ SFCNC

Simplified models - the viable one

- From the $3^4 = 81$ available possibilities, only one is viable!
- Quark sector, parameter values

$$2\theta = 1.077^{+0.039}_{-0.031}, \quad p_1^u = 0.22694 \pm 0.00052,$$
$$p_2^u = (4.235 \pm 0.059) \times 10^{-2}, \quad p_2^d = (3.774 \pm 0.098) \times 10^{-3}.$$

- SFCNC

$$\hat{r}_{[d]} = (-0.0038, 0, 0.9999), \qquad \hat{r}_{[u]} = (0, -0.0423, 0.9991)$$

  - For $d \leftrightarrows b$ in B_d^0–$\bar{B}_d^0$, $(\hat{r}_{[d]1}\hat{r}_{[d]2})^2 \sim 1.5 \times 10^{-5}$ is fine
  - For $c \leftrightarrows t$,

$$1.8 \times 10^{-4} \leq \text{Br}(t \to hc) \leq 4.3 \times 10^{-4}$$

. . . which is *tight*!

Simplified models - the viable one

- From the $3^4 = 81$ available possibilities, only one is viable!
- Lepton sector, two sets of parameter values

$$\text{Sol. 1: } p_1^\ell = 0.7496, \quad p_2^\ell = 1.3541, \quad p_2^\nu = 0.8974,$$
$$\text{Sol. 2: } p_1^\ell = 2.3889, \quad p_2^\ell = 1.3541, \quad p_2^\nu = 1.0542,$$

- SFCNC

$$\hat{r}_{[\ell]} = (-0.9765, 0, 0.2156)$$

which gives

$$2.0 \times 10^{-3} \leq \text{Br}(h \to e\bar{\tau} + \tau\bar{e}) \frac{\Gamma(h)}{\Gamma_{\text{SM}}(h)} \leq 5.0 \times 10^{-3}$$

…which is *tight*!

- CP violation: $J = \text{Im}\left(U_{e1}U_{\mu 2}U_{e2}^* U_{\mu 1}^*\right)$

Sol 1: $J = -0.0316, \quad \delta = 1.627\pi, \quad \Delta\chi^2_{\text{NO}}(\delta) = 5, \quad \Delta\chi^2_{\text{IO}}(\delta) = 0$

Sol 2: $J = +0.0282, \quad \delta = 0.679\pi, \quad \Delta\chi^2_{\text{NO}}(\delta) = 13, \quad \Delta\chi^2_{\text{IO}}(\delta) > 20$

Conclusions

- Real Yukawas + spontaneous CP violation in a 2HDM
  - can produce realistic CKM
  - non-vanishing SFCNC are necessary, but controlled
- Simple framework to connect CP violation in CKM and PMNS (with Dirac neutrinos)
  - Ideal case requires SFCNC input, otherwise additional freedom
  - Consider MFV simplified models, only one is viable
- The only viable model
  - can give δ_{PMNS} in good agreement with trends in PMNS fits
  - is under pressure from both $t \to hc$ and $h \to e\tau$ bounds

can be ruled out!

Thank you!

Backup

Scalar potential

$\mathbb{Z}_2$, CP symmetric potential + soft $\mathbb{Z}_2$-breaking real μ_{12}^2

$\Rightarrow$ Potential invariant under CP $\Phi_j \mapsto \Phi_j^*$

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = {} & \mu_{11}^2 \Phi_1^\dagger \Phi_1^\dagger + \mu_{22}^2 \Phi_2^\dagger \Phi_2^\dagger + \mu_{12}^2 (\Phi_1^* \Phi_2 + \Phi_2^* \Phi_1) \\
& + \lambda_1 (\Phi_1^* \Phi_1)^2 + \lambda_2 (\Phi_2^* \Phi_2)^2 + 2\lambda_3 (\Phi_1^* \Phi_1)(\Phi_2^* \Phi_2) \\
& + 2\lambda_4 (\Phi_1^* \Phi_2)(\Phi_2^* \Phi_1) + \lambda_5 ((\Phi_1^* \Phi_2)^2 + (\Phi_2^* \Phi_1)^2)
\end{aligned}
$$

P_{23} in the viable example

Permutation P_{23} can be rewritten

$$\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 1\\ 0 & 1 & 0\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & -1\\ 0 & 1 & 0\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & 0 & -1\\ 0 & 1 & 0\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & -1\end{pmatrix}$$

$$P_{23} = \text{diag}(1,-1,1)R_{23}(\pi/2) = R_{23}(\pi/2)\text{diag}(1,1-,1)$$

that is a rephasing and a fixed rotation