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Scalar FCNC and CP violating mixing matrices from the vacuum

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A possible relation between CP violations in the lepton and quark sectors, parametrised by the PMNS and CKM phases, is analysed. We show that both mixing phases can be generated, in a class of two Higgs doublet models, by a vacuum phase. This scenario requires that scalar FCNC are present at tree level in both sectors, imposing important phenomenological constraints but also offering interesting prospects, specially in the processes $\mathrm{h} \to e^{\pm}\tau^{\mp}$ and $t \to \mathrm{h}c$.

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1. Introduction

We report on the study [1] of a possible relation between CP violation in the quark and lepton sectors, parametrized by the phases δ_{CKM} and δ_{PMNS} of the CKM and PMNS mixing matrices. At present, the CP violating nature of CKM has been robustly established, even allowing for the presence of New Physics contributing to CP violation [2], while sustained efforts to detect leptonic CP violation in neutrino experiments are in progress [3]. If one extends the Standard Model (SM) to include non-vanishing neutrino masses and assumes complex Yukawa couplings as the origin of CP violation, then δ_{CKM} and δ_{PMNS} are not related. Although CKM is complex, this does not imply that CP violation is violated at the Lagrangian level through complex Yukawa couplings. As analysed in [4], one may have vacuum induced CP violation which generates a complex CKM matrix and agrees with experiment. We consider here the simplest extension to the leptonic sector, with Dirac neutrinos, of the previous viable model. It is a generalised Branco-Grimus-Lavoura (BGL) model [5], in the context of two Higgs doublet models (2HDMs) with a flavoured $\mathbb{Z}_2$ symmetry softly broken by the scalar potential. In this scenario, generating a complex CKM matrix and tree level Scalar Flavour Changing Neutral Couplings (SFCNC) are tightly connected. The same occurs when the model is extended to the leptonic sector: $\delta_{\text{PMNS}} \neq 0$ requires SFCNC both in the charged lepton and neutrino sectors. This necessity is both an obstacle and a blessing: an obstacle because strict experimental limits on SFCNC apply, and a blessing because the models are then falsifiable in the sense that they imply SFCNC at a level within experimental reach.

2. The model

The Yukawa lagrangian of the model reads[1]

$$\mathscr{L}_Y = -\sum_{i=1}^{2}\left[\overline{Q^0_L}\,\Gamma^{(\mathrm{d})}_i\Phi_i\,d^0_R + \overline{Q^0_L}\,\Gamma^{(\mathrm{u})}_i\tilde{\Phi}_i\,u^0_R + \overline{L^0_L}\,\Gamma^{(\mathrm{e})}_i\Phi_i\,e^0_R + \overline{L^0_L}\,\Gamma^{(\nu)}_i\tilde{\Phi}_i\,\nu^0_R\right] + \text{h.c.}\,. \tag{1}$$

Concerning the $\mathbb{Z}_2$ symmetry, the fields Φ_2, $Q^0_{L_3}$ and $L^0_{L_3}$ are odd while the rest of the fields are even. This symmetry gives rise to "generalized BGL" (gBGL) textures [5] for the Yukawa coupling matrices $\Gamma^{(\mathrm{f})}_i$ (with $\times$ denoting generic entries):

$$\Gamma^{(\mathrm{d})}_1 \sim \Gamma^{(\mathrm{u})}_1 \sim \Gamma^{(\mathrm{e})}_1 \sim \Gamma^{(\nu)}_1 \sim \begin{pmatrix}\times & \times & \times\\ \times & \times & \times\\ 0 & 0 & 0\end{pmatrix},\ \Gamma^{(\mathrm{d})}_2 \sim \Gamma^{(\mathrm{u})}_2 \sim \Gamma^{(\mathrm{e})}_2 \sim \Gamma^{(\nu)}_2 \sim \begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ \times & \times & \times\end{pmatrix}, \tag{2}$$

Note that $\Gamma^{(\mathrm{f})}_2 = \mathrm{P}_3\Gamma^{(\mathrm{f})}_2$ and $\Gamma^{(\mathrm{f})}_1 = (\mathbf{1}-\mathrm{P}_3)\,\Gamma^{(\mathrm{f})}_1$ where P_3 is the projector

$$\mathrm{P}_3 = \begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 1\end{pmatrix}. \tag{3}$$

[1] We follow standard notation for fermionic left-handed doublets Q^0_L, L^0_L, right-handed singlets d^0_R, u^0_R, ℓ^0_R, ν^0_R, scalar doublets Φ_j with $\tilde{\Phi}_j = i\sigma_2\Phi^*_j$, and Yukawa matrices $\Gamma^{(\mathrm{f})}_j$.

Electroweak symmetry is spontaneously broken by the vacuum $\langle\Phi_j\rangle = \frac{v_j e^{i\theta_j}}{\sqrt{2}}\left(\begin{smallmatrix}0\\1\end{smallmatrix}\right)$, $v_j, \theta_j \in \mathbb{R}$, $v_j > 0$. As usual, $v^2 \equiv v_1^2 + v_2^2$ and β such that $v_1 = vc_\beta$, $v_2 = vs_\beta$ (here and in the following, $c_\beta = \cos\beta$, $s_\beta = \sin\beta$, $t_\beta = \tan\beta$, $t_\beta^{-1} = (t_\beta)^{-1}$) are introduced, with $v^2 = \frac{1}{\sqrt{2}G_F} \simeq (246\text{ GeV})^2$. In the "Higgs basis" $\begin{pmatrix}H_1\\H_2\end{pmatrix} = \begin{pmatrix}c_\beta & s_\beta\\ s_\beta & -c_\beta\end{pmatrix}\begin{pmatrix}e^{-i\theta_1}\Phi_1\\ e^{-i\theta_2}\Phi_2\end{pmatrix}$ one has $\langle H_1\rangle = \frac{v}{\sqrt{2}}\left(\begin{smallmatrix}0\\1\end{smallmatrix}\right)$ and $\langle H_2\rangle = \left(\begin{smallmatrix}0\\0\end{smallmatrix}\right)$. The Yukawa couplings in eq. (1) are rewritten as

$$-\mathscr{L}_Y = \overline{Q_L^0}\frac{\sqrt{2}}{v}\left[M_d^0 H_1 + N_d^0 H_2\right] d_R^0 + \overline{Q_L^0}\frac{\sqrt{2}}{v}\left[M_u^0 \widetilde{H}_1 + N_u^0 \widetilde{H}_2\right] u_R^0 + \tag{4}$$

$$\overline{L_L^0}\frac{\sqrt{2}}{v}\left[M_\ell^0 H_1 + N_\ell^0 H_2\right] e_R^0 + \overline{L_L^0}\frac{\sqrt{2}}{v}\left[M_\nu^0 \widetilde{H}_1 + N_\nu^0 \widetilde{H}_2\right] \nu_R^0 + \text{h.c.}. \tag{5}$$

$$M_d^0 = \frac{e^{i\theta_1}v}{\sqrt{2}}\left(\Gamma_1^{(\mathrm{d})}c_\beta + \Gamma_2^{(\mathrm{d})}s_\beta e^{i\theta}\right), \quad M_u^0 = \frac{e^{-i\theta_1}v}{\sqrt{2}}\left(\Gamma_1^{(\mathrm{u})}c_\beta + \Gamma_2^{(\mathrm{u})}s_\beta e^{-i\theta}\right), \tag{6}$$

are the quark mass matrices, with $\theta = \theta_2 - \theta_1$. The N_f^0 matrices are

$$N_d^0 = \frac{e^{i\theta_1}v}{\sqrt{2}}\left(\Gamma_1^{(\mathrm{d})}s_\beta - \Gamma_2^{(\mathrm{d})}c_\beta e^{i\theta}\right), \quad N_u^0 = \frac{e^{-i\theta_1}v}{\sqrt{2}}\left(\Gamma_1^{(\mathrm{u})}s_\beta - \Gamma_2^{(\mathrm{u})}c_\beta e^{-i\theta}\right). \tag{7}$$

(The global phase θ_1 in the previous expressions can be rephased away and thus from now on we set, without loss of generality, $\theta_1 = 0$.) For leptons, $u \mapsto \nu$ and $d \mapsto \ell$ in eqs. (6),(7). A very relevant property is the following:

$$N_f^0 = \left[t_\beta \mathbf{1} - \left(t_\beta + t_\beta^{-1}\right)\mathrm{P}_3\right] M_f^0. \tag{8}$$

In general, it will not be possible to bi-diagonalize simultaneously both M_f^0 and N_f^0: the matrices N_f^0 control the scalar mediated flavour changing neutral couplings.
For details concerning the scalar sector of this model, we refer to [4]. Let us just mention that in order to have CP violation arising from the vacuum one needs soft breaking of the $\mathbb{Z}_2$ symmetry, and that the lightest scalar, h, is assumed to be the SM-like Higgs with mass $m_\mathrm{h} = 125$ GeV which, in the alignment limit, has SM-like couplings. In terms of the $\mathcal{R}$ real orthogonal 3×3 matrix that controls mixing of the physical neutral scalars, the alignment limit corresponds to $\mathcal{R}_{11} \to 1$.

3. CP violating CKM and PMNS matrices and SFCNC

Invariance under CP of the entire Lagrangian implies that $\Gamma_i^{(\mathrm{f})} = \Gamma_i^{(\mathrm{f})*}$. As shown in [4], the mass matrices can be factorized as

$$M_f^0 = \begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & e^{i\sigma_f}\end{pmatrix}\widehat{M}_f^0 = \varphi_3(\sigma_f)\,\widehat{M}_f^0, \tag{9}$$

where $\widehat{M}_f^0$ are arbitrary real (mass) matrices and $\sigma_d = \sigma_e = \theta$, $\sigma_u = \sigma_\nu = -\theta$. The peculiarity of eq. (9) is that the usual bi-diagonalization involves 3×3 real orthogonal matrices in addition to $\varphi_3(\pm\theta)$, which is the unique source of irremovable complexity. It leads to the following form of the mixing matrices, $V = U^\dagger_{u_L} U_{d_L}$ (CKM) and $U = U^\dagger_{e_L} U_{\nu_L}$ (PMNS):

$$V = O^T_{u_L}\,\varphi_3(2\theta)\,O_{d_L}\,,\quad U = O^T_{e_L}\,\varphi_3(-2\theta)\,O_{\nu_L}\,. \tag{10}$$

There is enough freedom in eq. (10) to obtain arbitrary V and U, except for the fact that any CP violating observable in the quark sector and any CP violating observable in the lepton sector, must vanish with $\theta \to 0$. Notice that eq. (10) does not imply in general that $\delta_{\rm CKM} = -\delta_{\rm PMNS}$. In this class of 2HDMs with spontaneous CP violation, the complexity of the mixing matrices and the presence of SFCNC are closely connected: as discussed in [4] for the quark sector, if one imposes the absence of SFCNC to comply in a simple manner with experimental constraints, then the CKM matrix is real, contrary to evidence. Let us recall briefly how this connection works. SFCNC are encoded in the matrices N^0_f in eq. (7); in the fermion mass bases, $N^0_f \to N_f$, and eq. (8) gives

$$N_f = U^\dagger_{f_L}\,N^0_f\,O_{f_R} = \left[t_\beta \mathbf{1} - \left(t_\beta + t_\beta^{-1}\right) P^f_3\right] \mathrm{diag}(m_{f_1}, m_{f_2}, m_{f_3}), \tag{11}$$

where P^f_3 are the projection operators

$$P^f_3 \equiv U^\dagger_{f_L}\,\mathrm{P}_3\,U_{f_L} = O^T_{f_L}\,\mathrm{P}_3\,O_{f_L}. \tag{12}$$

SFCNC are thus controlled by the real projectors P^f_3, in particular the off-diagonal entries of P^f_3, given by the O_{f_L} matrices, which also enter the CKM and PMNS mixing matrices. It is also important to notice that SFCNC in the up(neutrino) and down(charged lepton) sectors are not independent since, by construction,

$$P^u_3 = V\,P^d_3\,V^\dagger,\quad P^e_3 = U\,P^\nu_3\,U^\dagger. \tag{13}$$

For example, if SFCNC in the up quark sector are fixed, SFCNC in the down quark sector are completely determined (this is relevant for the count and the election of the independent parameters). The situation in the lepton sector is analogous. The elements of P^f_3 are

$$\left(P^f_3\right)_{ij} = \left(O^T_{f_L}\,\mathrm{P}_3\,O_{f_L}\right)_{ij} = (O_{f_L})_{3i}\,(O_{f_L})_{3j} \equiv \hat{r}_{[f]i}\hat{r}_{[f]j}\,, \tag{14}$$

where $\hat{r}_{[f]i} \equiv (O_{f_L})_{3i}$ are the components of real, unit vectors in three dimensions $\hat{r}_{[f]}$, the third rows of the orthogonal matrices O_{f_L}. Following eq. (13) one has $\hat{r}_{[u]j}V_{jk} = e^{2i\theta}\hat{r}_{[d]k}$ and $\hat{r}_{[e]j}U_{jk} = e^{-2i\theta}\hat{r}_{[\nu]k}$. To avoid SFCNC in P^f_3, one needs one component $\hat{r}_{[f]k} = 1$ and the others $\hat{r}_{[f]j} = 0$, $j \neq k$. Then $\left(P^f_3\right)_{ij} = \delta_{ik}\delta_{jk} \equiv (\mathrm{P}_k)_{ij}$ for a fixed k, i.e. $P^f_3 = \mathrm{P}_k$ for that given f. This has a straightforward consequence for the mixing matrix. Consider, for example, no SFCNC in the neutrino sector: $P^\nu_3 = \mathrm{P}_k$; then

$$U = O^T_{e_L}\varphi_3(-2\theta)O_{\nu_L} = O^T_{e_L}O_{\nu_L}\left[\mathbf{1} + (e^{-2i\theta} - 1)O^T_{\nu_L}\mathrm{P}_3 O_{\nu_L}\right] = O^T_{e_L}O_{\nu_L}\left[\mathbf{1} + (e^{-2i\theta} - 1)\mathrm{P}_k\right]. \tag{15}$$

The PMNS matrix U is a real rotation times a diagonal matrix of phases with $e^{-2i\theta}$ in position k, the rest of them 1, and there is no CP violation. The same reasoning applies to all fermion sectors: if one forces the absence of SFCNC, one obtains a CP conserving mixing matrix.

4. The general relation between $\delta_{\rm CKM}$ and $\delta_{\rm PMNS}$

From the discussion in the previous sections, it is important to recall that (i) the only possible source of CP violation in the CKM and in the PMNS mixing matrices is $\theta \neq 0$ (from the vacuum), and (ii) if SFCNC are removed in one fermion sector, even if $\theta \neq 0$, CP violation disappears from the corresponding mixing matrix.
The CKM and PMNS matrices can be parametrized (up to rephasings of fields) with 4 quantities each: $\{\theta^q_{12}, \theta^q_{13}, \theta^q_{23}, \delta_q\}$ and $\{\theta^\ell_{12}, \theta^\ell_{13}, \theta^\ell_{23}, \delta_\ell\}$ in the usual PDG parametrizations [7]. For CKM, experimental information allows the extraction of θ^q_{12}, θ^q_{13}, θ^q_{23}, and of the CP violating phase δ_q, which is non-zero. In the lepton sector, experimental information allows to extract θ^ℓ_{12}, θ^ℓ_{13}, θ^ℓ_{23}, but, although some sensitivity to δ_ℓ is emerging [8], it remains "the last frontier". Although eq. (10) is different from the PDG parametrization, one can impose the experimental information encoded in $\{\theta^q_{12}, \theta^q_{13}, \theta^q_{23}, \delta_q\}$ and $\{\theta^\ell_{12}, \theta^\ell_{13}, \theta^\ell_{23}, \delta_\ell\}$ in an invariant manner. In particular, $\delta_{\rm CKM}$, the CP violating phase in V, is the model prediction for δ_q and similarly $\delta_{\rm PMNS}$, the CP violating phase in U, is the model prediction for δ_ℓ. As already mencioned, if $\theta = 0$, then $\delta_{\rm CKM} = \delta_{\rm PMNS} = 0$, but $\theta \neq 0 \nRightarrow \delta_{\rm CKM} \neq 0$, $\delta_{\rm PMNS} \neq 0$.
At this point, we need to discuss the independent parameters in the model. We start with the quark sector, and stress that an important goal is to analyse how information on CP violation in the quark sector (requiring $\delta_q = \delta_{\rm CKM}$), can translate into some prediction on $\delta_{\rm PMNS}$. The CKM matrix in eq. (10) involves 7 real parameters: 3 in O_{u_L}, 3 in O_{d_L}, and θ. This number can be reduced to 6: each rotation is written as a product of one parameter rotations $O_{f_L} = {\rm R}_1(p^f_1){\rm R}_2(p^f_2){\rm R}_3(p^f_3)$ where each ${\rm R}_j(x)$ can be one of the following

$$R_{12}(x) = \begin{pmatrix} c_x & s_x & 0 \\ -s_x & c_x & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad R_{13}(x) = \begin{pmatrix} c_x & 0 & s_x \\ 0 & 1 & 0 \\ -s_x & 0 & c_x \end{pmatrix}, \quad R_{23}(x) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_x & s_x \\ 0 & -s_x & c_x \end{pmatrix}, \tag{16}$$

with ${\rm R}_1(p) \neq {\rm R}_2(p)$, ${\rm R}_2(p) \neq {\rm R}_3(p)$, and $c_x = \cos x$, $s_c = \sin x$. If one chooses a parametrization with ${\rm R}_1(p^f_1) = R_{12}(p^f_1)$ in both O_{u_L} and O_{d_L}, then only $p^u_1 - p^d_1$ enters V and we can set $p^d_1 = 0$ without loss of generality. The remaining 6 independent parameters match 4 independent quantities in V (equivalent to $\{\theta^q_{12}, \theta^q_{13}, \theta^q_{23}, \delta_q\}$), and the 2 independent parameters which control SFCNC, e.g. $\hat{r}_{[u]1}$, $\hat{r}_{[u]2}$. That is, the experimental information constrains $\{\theta^q_{12}, \theta^q_{13}, \theta^q_{23}, \delta_q, \hat{r}_{[u]1}, \hat{r}_{[u]2}\}$, and could fix the model parameters $\{p^u_1, p^u_2, p^u_3, p^d_2, p^d_3, \theta\}$. Notice that, ideally, one can fix θ since CP violation is well established in the quark sector. Similarly, in the lepton sector one would have parameters $\{p^e_1, p^e_2, p^e_3, p^\nu_2, p^\nu_3, \theta\}$. The experimental information on PMNS strongly constrains $\{\theta^\ell_{12}, \theta^\ell_{13}, \theta^\ell_{23}\}$; additional information from SFCNC sensitive processes like ${\rm h} \to \ell_i \bar{\ell}_j$, $i \neq j$, is needed in order to constrain more parameters. The crucial point is that, a priori, θ can be fixed in the quark sector and thus, with one less experimental input in the leptonic sector, one could predict the value of the CP violating Dirac phase δ_ℓ in PMNS prior to its measurement. In this sense we can ideally relate the PMNS phase to the CKM phase in this class of models with spontaneous CP violation.

5. Simplified models incorporating MFV and their connections to SFCNC

A detailed analysis of the quark sector was presented in [4], including an extensive list of constraints related to flavour transitions, Higgs signals, etc. Surprisingly, they allowed significant freedom in the values of θ and SFCNC. If one extends the analysis to include the lepton sector straightforwardly, the connection between CP violation in CKM and PMNS would be blurred by that (current) freedom. It is thus interesting to make further simplifying assumptions, guided and compatible with experimental data.
Let us start with the quark sector. If one eliminates SFCNC either in the up or in the down sector, CP violation is removed from the CKM matrix. A weaker simplification is to impose that some SFCNC are absent: we consider models where one component vanishes, $\hat{r}_{[f]i} = 0$ for a given $i = 1, 2$ or 3, which leaves only one SFCNC transition $j \leftrightarrows k$, i, j, k all different. This can be imposed in both the up and down sectors. Together with the 4 constraints to reproduce a realistic CKM matrix, one has now 6 constraints for 6 parameters. These two SFCNC requirements translate into 4 parameters in the CKM matrix in eq. (10) and, in that case, the models incorporate the Minimal Flavor Violation ansatz. Following the same simplifying assumption in the lepton sector there are, in principle, 81 models to consider. However, since the most challenging SFCNC in the lepton sector arises from $\mu \to e + \gamma$, we directly restrict ourselves to models where $\hat{r}_{[e]1}\hat{r}_{[e]2} = 0$. From this set of models, there is only one case which appears to be viable. We briefly present this model in order to illustrate the central idea of the δ_{CKM}–δ_{PMNS} connection and refer to [1] for further details. In this model,

$$V = R_{23}(p_2^u)^T R_{12}(p_1^u)^T \varphi_3(2\theta) R_{13}(p_2^d)\,, \tag{17}$$

and $\hat{r}_{[u]} = (0, -\sin p_2^u, \cos p_2^u)$, $\hat{r}_{[d]} = (-\sin p_2^d, 0, \cos p_2^d)$. From a fit to the CKM matrix one obtains

$$\begin{aligned} 2\theta &= 1.077^{+0.039}_{-0.031}, & p_1^u &= 0.22694 \pm 0.00052, \\ p_2^u &= (4.235 \pm 0.059) \times 10^{-2}, & p_2^d &= (3.774 \pm 0.098) \times 10^{-3}\,. \end{aligned} \tag{18}$$

Concerning the lepton sector, the PMNS matrix is[2]

$$U = R_{13}(p_2^e)^T R_{12}(p_1^e)^T \varphi_3(-2\theta) P_{23} R_{12}(p_2^\nu)\,. \tag{19}$$

We can now fit the PMNS data without the information on δ_ℓ, since we are interested in its prediction, and obtain two solutions:

$$\text{Solution 1}: \quad p_1^e = 0.7496, \quad p_2^e = 1.3541, \quad p_2^\nu = 0.8974\,, \tag{20}$$

$$\text{Solution 2}: \quad p_1^e = 2.3889, \quad p_2^e = 1.3541, \quad p_2^\nu = 1.0542\,. \tag{21}$$

SFCNC are controlled (in both cases) by $\hat{r}_{[e]} = (-0.9765,\ 0,\ 0.2156)$. The solutions differ in the phase δ_{PMNS} and the (unique) CP violating imaginary part of an invariant quartet

[2] The permutation $P_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$ is just the product of a 23 rotation and a π rephasing and thus does not deviate from the general parametrization introduced in precedence.

$J_{\text{PMNS}} = \text{Im}\left(U_{e1}U_{\mu2}U^*_{e2}U^*_{\mu1}\right)$:

Case	J_{PMNS}	δ_{PMNS}	$\Delta\chi^2_{\text{NO}}(\delta_{\text{PMNS}})$	$\Delta\chi^2_{\text{IO}}(\delta_{\text{PMNS}})$
Solution 1	-0.0316	$1.629\pi\,(293^\circ)$	5	0
Solution 2	0.0282	$0.679\pi\,(126^\circ)$	13	> 20

(22)

$\Delta\chi^2_{\text{NO}}(\delta_{\text{PMNS}})$ and $\Delta\chi^2_{\text{IO}}(\delta_{\text{PMNS}})$ are the values that correspond to δ_{PMNS} attending to the $\Delta\chi^2$ profiles for δ_ℓ obtained for normal and inverted neutrino mass orderings in [8].
We have thus reached our goal: using the information on CP violation in the quark sector, we have been able to predict the phase in PMNS using the connection that SCPV provides in this model. Notice, in particular, that Solution 1 has $\delta_{\text{PMNS}} = 1.629\pi$, which is in good agreement with the most likely values in PMNS analyses [8].
As a last item in our discussion, we now comment on the SFCNC. In the down quark sector, $b \leftrightarrows d$ SFCNC have a negligible contribution to B^0_d–$\bar{B}^0_d$ oscillations, while $\text{h} \to \bar{b}d, b\bar{d}$ remain beyond the LHC capabilities. In the up quark sector, however, we have

$$1.8 \times 10^{-4} \leq \text{Br}(t \to c\text{h}) \leq 4.3 \times 10^{-4}\,, \tag{23}$$

which is quite restricted and under pressure from current LHC bounds [9]. In the lepton sector we have

$$2.0 \times 10^{-3} \leq \text{Br}(\text{h} \to e\bar{\tau} + \bar{e}\tau)\frac{\Gamma(\text{h})}{\Gamma(\text{h}_{\text{SM}})} \leq 5.0 \times 10^{-3}, \tag{24}$$

which is also under strong pressure from improving LHC bounds [10].

Conclusions

We have discussed a class of models where a connection between the CP violations in the quark and lepton mixing matrices due to a common origin, a complex vacuum phase, is present. As analysed, one has to have SFCNC in all fermion sectors in order to generate complex CKM and PMNS matrices, but these are introduced in a controlled manner. To illustrate this potential connection, we have considered a subclass of models which incorporate additional simplifications, maintaining essentially the minimal amount of SFCNC needed for a spontaneous origin of CP violation. Out of $3^4 = 81$ possible models of this type, only one model is viable and it predicts δ_{PMNS} in agreement with the trend in recent analyses. SFCNC implications of this model have been briefly addressed.

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