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A common origin of CKM and PMNS phases within 2HDM

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A framework where the CKM and PMNS complex phases are vacuum induced is presented. It consist in a Two Higgs Doublet Model with a $\mathbb{Z}_2$ symmetry which is softly broken, where the only source of CP-violation is the irremovable vacuum phase. This scenario requires non-vanishing but controlled Flavor Changing Neutral Couplings. Using the experimental data we are able to give a prediction to the lepton mixing matrix phase as well as to some flavor changing transitions ($c \rightleftarrows t$ and $d \rightleftarrows b$).

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1. Introduction

In this proceedings, we review a framework where the CKM and PMNS complex phases are related [1]. It is well-established that the CKM mixing matrix is complex [2] no matter that one allows New Physics to generate additional sources of CP violation [3]. Regarding the leptonic sector, the situation is not so clear, and in fact, there are several neutrino experiments trying to detect CP-violating transitions.

It was shown in Ref. [4] that in a Two Higgs Doublet Model (2HDM) with a softly broken flavor $\mathbb{Z}_2$ symmetry it is possible to generate the measured CKM complex phase through the complex phase of the vacuum. That is, in this framework, to have complex Yukawa matrices is not a necessary condition to get a realistic quark mixing matrix. Conversely, if the SM is extended with RH-neutrinos and the source of CP violation is in the Yukawa matrices, the CKM and PMNS matrices are completely independent. In order to achieve the goal of relating the δ_{CKM} and δ_{PMNS} we will assume that CP is spontaneously broken in the scalar potential and the complex phases of the mixing matrices will be vacuum induced.

2. The framework

The scalar potential with two Higgs doublets Φ_i and a softly broken $\mathbb{Z}_2$ symmetry reads

$$\begin{aligned} V(\Phi_1,\Phi_2) = {}& \mu_{11}^2\Phi_1^\dagger\Phi_1 + \mu_{22}^2\Phi_2^\dagger\Phi_2 + \left(\mu_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ & + 2\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + 2\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left(\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right), \end{aligned} \tag{1}$$

where $\mu_{ij},\ \lambda_k \in \mathbb{R}$ and the bilinear term $\mu_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right)$ is introduced to softly break the $\mathbb{Z}_2$ symmetry, which allows to have spontaneous CP violation [5]. The desired relation between the CKM and PMNS complex phases is achieved in a 2HDM generated by the $\mathbb{Z}_2$ flavor symmetry

$$\begin{aligned} & Q_{L_3} \mapsto -Q_{L_3}, \quad && L_{L_3} \mapsto -L_{L_3}, && \\ & d_R \mapsto d_R, && \ell_R \mapsto \ell_R, && \Phi_1 \mapsto \Phi_1, \\ & u_R \mapsto u_R, && \nu_R \mapsto \nu_R, && \Phi_2 \mapsto -\Phi_2, \end{aligned} \tag{2}$$

that once it is applied to the Yukawa Lagrangian

$$\begin{aligned} \mathscr{L}_{\text{Y}} = & -\bar{Q}_L^0\left(\Phi_1 Y_{d,1} + \Phi_2 Y_{d,2}\right)d_R^0 - \bar{Q}_L^0\left(\tilde{\Phi}_1 Y_{u,1} + \tilde{\Phi}_2 Y_{u,2}\right)u_R^0 \\ & - \bar{L}_L^0\left(\Phi_1 Y_{\ell,1} + \Phi_2 Y_{\ell,2}\right)\ell_R^0 - \bar{L}_L^0\left(\tilde{\Phi}_1 Y_{\nu,1} + \tilde{\Phi}_2 Y_{\nu,2}\right)\nu_R^0 + \text{h.c.}, \end{aligned} \tag{3}$$

enforce the Yukawa matrices to be of the form

$$Y_{d,1} \sim Y_{u,1} \sim Y_{\ell,1} \sim Y_{\nu,1} \sim \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{pmatrix}, \quad Y_{d,2} \sim Y_{u,2} \sim Y_{\ell,2} \sim Y_{\nu,2} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{pmatrix}, \tag{4}$$

where $\times$ is an arbitrary real entry. This zero texture was introduced and studied in Refs. [6, 7] and belong to the so-called gBGL model, wich is a generalization of the well-known BGL models [8].

To spontaneously break the symmetry, the doublets must acquire a vacuum expectation value (vev). In general, both doublets can do so

$$\left\langle 0\middle|\Phi_1\middle|0\right\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 e^{i\theta_1}\end{pmatrix}, \quad \left\langle 0\middle|\Phi_2\middle|0\right\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 e^{i\theta_2}\end{pmatrix}, \tag{5}$$

but one can always rotate the fields into a basis where just one of the doublets acquires a non-zero vev. It is known as the Higgs basis and it is defined by the rotation

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \mathcal{R}_\beta \begin{pmatrix} e^{-i\theta_1}\Phi_1 \\ e^{-i\theta_2}\Phi_2 \end{pmatrix}, \quad \text{with} \quad \mathcal{R}_\beta = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix}, \tag{6}$$

where in this case, the vevs are $\langle H_1\rangle = \frac{v}{\sqrt{2}}\binom{0}{1}$, $\langle H_2\rangle = \binom{0}{0}$. As usual we have defined $v^2 \equiv v_1^2 + v_2^2$ and we have used the shortage $c_\beta \equiv \cos\beta = v_1/v$ and $s_\beta \equiv \sin\beta = v_2/v$. In the Higgs basis the Yukawa Lagrangian takes the form

$$\begin{aligned} \mathscr{L}_\text{Y} = &-\frac{\sqrt{2}}{v}\bar{Q}_L^0\left(H_1\mathrm{M}_d^0 + H_2\mathrm{N}_d^0\right)d_R^0 - \frac{\sqrt{2}}{v}\bar{Q}_L^0\left(\tilde{H}_1\mathrm{M}_u^0 + \tilde{H}_2\mathrm{N}_u^0\right)u_R^0 \\ &-\frac{\sqrt{2}}{v}\bar{L}_L^0\left(H_1\mathrm{M}_\ell^0 + H_2\mathrm{N}_\ell^0\right)\ell_R^0 - \frac{\sqrt{2}}{v}\bar{L}_L^0\left(\tilde{H}_1\mathrm{M}_\nu^0 + \tilde{H}_2\mathrm{N}_\nu^0\right)\nu_R^0 + \text{h.c.}\,. \end{aligned} \tag{7}$$

and we can already identify the mass matrices

$$\mathrm{M}_{d(\ell)}^0 = \frac{v\,e^{i\theta_1}}{\sqrt{2}}\left[c_\beta Y_{d(\ell),1} + e^{i\theta}s_\beta Y_{d(\ell),2}\right], \quad \mathrm{M}_{u(\nu)}^0 = \frac{v\,e^{-i\theta_1}}{\sqrt{2}}\left[c_\beta Y_{u(\nu),1} + e^{-i\theta}s_\beta Y_{u(\nu),2}\right], \tag{8}$$

with $\theta = \theta_2 - \theta_1$, and the new flavor structures N_f^0 that can be parametrized as

$$\mathrm{N}_f^0 = \left[-t_\beta\mathbf{1} + \left(t_\beta + t_\beta^{-1}\right)\mathrm{P}_3\right]\mathrm{M}_f^0\,. \tag{9}$$

Here, P_3 is the projector $\mathrm{P}_3 = \mathrm{diag}\,(0,0,1)$ so the proportionality between N_f^0 and M_f^0 involves a diagonal matrix but not the identity, this, in general, leads to the appearance of flavor Changing Neutral Couplings (FCNC). Thanks to the fact that the Yukawa matrices are real and to the position of the irremovable phase in eq. (8) together with the textures in eq. (4), the mass matrices can be diagonalized by an orthogonal matrix on the right, O_{f_R}, and an unitary matrix on the left, $\mathcal{U}_{f_L}^\dagger$. The last is the the product of a diagonal of phases, $\varphi_3(\sigma_f) = \mathbf{1} + (e^{i\sigma_f} - 1)\mathrm{P}_3$, times an orthogonal matrix, O_{f_L}. The diagonal mass matrices read

$$\mathrm{M}_f = \mathcal{U}_{f_L}^\dagger\mathrm{M}_f^0 O_{f_R} = \begin{pmatrix} m_{f_1} & 0 & 0 \\ 0 & m_{f_2} & 0 \\ 0 & 0 & m_{f_3}\end{pmatrix}, \quad \mathcal{U}_{f_L} = \varphi_3(\sigma_f)O_{f_L}, \tag{10}$$

with $\sigma_u = \sigma_\nu = -\theta$ and $\sigma_d = \sigma_\ell = \theta$. The new non-diagonal flavor structures

$$\mathrm{N}_f = \mathcal{U}_{f_L}^\dagger\,\mathrm{N}_f^0\,O_{f_R} = \left[-t_\beta\mathbf{1} + \left(t_\beta + t_\beta^{-1}\right)P_3^{[f]}\right]\mathrm{M}_f\,, \tag{11}$$

where we have introduced the projection operators

$$P_3^{[f]} \equiv \mathcal{U}_{f_L}^\dagger\,\mathrm{P}_3\,\mathcal{U}_{f_L} = O_{f_L}^T\,\mathrm{P}_3\,O_{f_L} = \left|\hat{r}_{[\mathrm{f}]}\right\rangle\left\langle\hat{r}_{[\mathrm{f}]}\right|. \tag{12}$$

Here $\hat{r}_{[\mathrm{f}]}$ are real unit vectors with three dimensions. As usual, the CKM and PMNS matrices are built in terms of the diagonalization matrices, and in our case they read

$$V = O_{u_L}^T\, \varphi_3(2\theta)\, O_{d_L}, \quad U = O_{\ell_L}^T\, \varphi_3(-2\theta)\, O_{\nu_L}\,. \tag{13}$$

We can see here that the only complex phase in the mixing matrices is the one coming from the vacuum expectation value of the Higgs doublet. At this point, it is important to notice that there is a deep connection between the mixing matrices and the FCNC enclosed in N_f. In fact, it was shown in Ref. [4] that in this framework if the FCNC are absent one ends up having a real CKM matrix, which is contrary to evidence. This is completely analogous in the lepton sector[1]. The absence of FCNC in a given sector happens when one entry of the unit vector of that sector, $\hat{r}_{[\mathrm{f}]i}$, equals one. In that scenario, it is straightforward to see that the matrix N_f in eq. (11) is diagonal.

3. Results

The model is fully defined once the four unit vectors $\hat{r}_{[\mathrm{f}]}$ are fixed. We have mentioned that no entry can equal one, otherwise the model will not have FCNC which produces real mixing matrices. We have studied the next simplest scenario where just one of the entries equals zero and none of them equals one (see Table 1). This means that in each sector there is just one allowed neutral transition that changes flavor. Looking at the vectors in Table 1 it is straightforward to see that there are 81 different ways of combining the four of them (one per each sector), leading to 81 different models. As we have mentioned $\hat{r}_{[\mathrm{f}]}$ are the third row of the matrices O_{f_L}. An orthogonal matrix

$\hat{r}_{[\mathrm{f}]}$	$(0,\times,\times)$	$(\times,0,\times)$	$(\times,\times,0)$

Table 1: Studied possibilities for the four $\hat{r}_{[\mathrm{f}]}$ where $\times$ denote an arbitrary real entry.

can be decomposed in a product of three elemental rotations around the Cartesian axes as

$$O_{f_L} = \mathcal{R}_{12}(p_1^f)\mathcal{R}_{23}(p_2^f)\mathcal{R}_{13}(p_3^f), \tag{14}$$

so the vectors are also parametrized in terms of the same angles p_i^f. It might seem that six angles plus the vacuum phase are needed to build the mixing matrix of each sector but, in fact, one of the angles is redundant since

$$V = O_{u_L}^T \varphi_3(2\theta) O_{d_L} = V(p_1^u - p_1^d)\,, \quad U = O_{\ell_L}^T\, \varphi_3(-2\theta)\, O_{\nu_L} = U(p_1^\nu - p_1^\ell)\,. \tag{15}$$

One can always choose $p_1^d = p_1^\ell = 0$ leaving just 5 angles plus the vacuum phase to be fitted. The experimental inputs to fit the model parameters will be the three moduli and one complex phase of the mixing matrices together with two flavor changing neutral processes as $t \to hq$, $h \to qq'$ and $\mathrm{h} \to \ell\ell'$. Given that CP violation is well established in the quark sector but not in the lepton one, we will use the experimental information to predict the PMNS phase. We proceeded as follow:

1. We chose a model by fixing the texture of $\hat{r}_{[u]}$, $\hat{r}_{[d]}$, $\hat{r}_{[\nu]}$ and $\hat{r}_{[\ell]}$ among the 81 possibilities.

[1] This is not a problem since the PMNS matrix has not been proven to be complex.

2. Using the experimental information of the CKM matrix together with flavor changing observables as $t \longrightarrow hq$ and $h \longrightarrow qq'$ we fixed θ.

3. With that θ fixed, we fitted PMNS and got a prediction for δ_ℓ.

The only model that surpassed all the FCNC constraints[2] and produced realistic mixing matrices was the one defined by the vectors

$$\begin{aligned} \hat{r}_{[u]} &= (0, -\sin p_2^u, \cos p_2^u)\,, \quad \hat{r}_{[d]} = (-\sin p_2^d, 0, \cos p_2^d)\,, \\ \hat{r}_{[\nu]} &= (-\sin p_2^\nu, \cos p_2^\nu, 0)\,, \quad \hat{r}_{[\ell]} = (-\sin p_2^\ell, 0, \cos p_2^\ell)\,. \end{aligned} \tag{16}$$

The fit in the quark sector fixed the parameters to the following values:

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

what produced the vectors

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

With the value for θ obtained in the quark sector we performed the fit in the lepton sector and we obtained two different solutions:

	p_1^ℓ	p_2^ℓ	p_2^ν	δ_ℓ	J_{PMNS}
Solution 1	0.7496	1.3541	0.8974	293°	-0.0316
Solution 2	2.3889	1.3541	1.0542	126°	0.0282

4. Discussion

We have shown that in this framework, a 2HDM with a softly broken $\mathbb{Z}_2$ symmetry, it is possible to generate both the CKM and PMNS complex phases and to relate them. Using the fact that CP violation is well established in the quark sector we have been able to get a prediction for the δ_ℓ phase. We get two different solutions, $\delta_\ell = 293$ and $\delta_\ell = 126$. The first one is in great agreement with PMNS fits. We have mentioned as well that FCNC are a necessary condition in this framework to get realistic mixing matrices. This may be seen as a problem but it is not, since our study also provides some predictions to flavor changing transitions which may prove or falsify the model in the near future. In the quark sector, the allowed transitions are the ones that involve $c \rightleftarrows t$ and $d \rightleftarrows b$. In this scenario, the top decay into a Higgs and a charm quark must be in the range

$$1.8 \times 10^{-4} \leq \mathrm{Br}(t \longrightarrow c\mathrm{h}) \leq 4.3 \times 10^{-4}\,. \tag{17}$$

which is not far from current LHC bounds [9, 10]. On the other hand, the $d \rightleftarrows b$ does not offer any relevant constraint since its effect to $B_d^0 - \bar{B}_d^0$ is negligible and the prediction to $\mathrm{h} \longrightarrow b\bar{d}$, $\bar{b}d$ is far below the LHC bounds. Regarding the leptons, the $e \rightleftarrows \tau$ transition provide the constraint

$$2.0 \times 10^{-3} \leq \mathrm{Br}(\mathrm{h} \longrightarrow e\bar{\tau} + \bar{e}\tau)\frac{\Gamma(\mathrm{h})}{\Gamma(\mathrm{h_{SM}})} \leq 5.0 \times 10^{-3}. \tag{18}$$

Even taking into account that there is some freedom in $\frac{\Gamma(\mathrm{h})}{\Gamma(\mathrm{h_{SM}})}$ this should be observed or disproved in the near future since the current bound by LHC is $\mathrm{Br}(\mathrm{h} \longrightarrow e\bar{\tau} + \bar{e}\tau)_{\mathrm{Exp}} \leq 2 \times 10^{-3}$[11].

[2]The detailed constraints can be found in Ref. [1]

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