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New Physics in the Flavour Sector in the presence of Flavour Changing Neutral Currents

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In the Standard Model (SM) flavour changing neutral currents (FCNC) are forbidden at three level. In the first part we discuss the extension of the SM with extra vectorial isosinglet fermions in the up sector giving rise to naturally suppressed Z mediated FCNC and deviations from unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Special emphasis is given to the implications of such an extension for correlations among various measurable quantities. The inclusion of constraints from all the relevant quark flavour sectors allows to give precise predictions for selected rare processes. In the second part we discuss extensions of the SM with two Higgs doublets, without the assumption of natural flavour conservation, giving rise to Higgs mediated FCNC. The existence of strict experimental limits on processes sensitive to Higgs FCNC requires the strong suppression of these currents. We present scenarios resulting from discrete symmetries where all new flavour structures in the quark sector are parametrized by elements of the CKM matrix, together with the ratio of vacuum expectation values of the Higgs doublets in the Higgs basis defined by the symmetry. We extend these scenarios to the leptonic sector with the Pontecorvo-Maki-Nakagawa-Sakata matrix playing a rôle similar to the CKM matrix in the quark sector.

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1. Introduction

The Standard Model (SM) is very successful in accounting for the experimental observations of the hadronic sector except for a few anomalies and tensions, still to be confirmed. In the leptonic sector we are confronted with a different situation. Extending the SM in order to account for the observed leptonic mixing and neutrino masses involves novel features not present in the quark sector. Even the most straightforward extension consisting of simply introducing righthanded neutrinos opens up the possibility of very rich new phenomena such as baryogenesis through leptogenesis, this results from the fact that neutrinos are neutral fermions. Therefore, there is physics beyond the SM in the leptonic sector. Furthermore, on one hand the SM leaves many unanswered questions, on the other hand it cannot accommodate the observed baryon asymmetry of the universe, requiring new sources of CP violation. Most extensions of the SM have new sources of CP violation. Moreover, extensions of the SM with vectorial quarks allow to establish a parallel with models including additional righthanded neutrinos. Extending the SM with vectorial isosinglet quarks leads to Z mediated flavour changing neutral currents (FCNC) as well as deviations from unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix in such a way that the strength of both effects are inter-related. Furthermore, such extensions allow for a natural suppression of these effects, as required by experiment. Section 2 is dedicated to the description of extensions of the SM with vector-like quarks and naturally suppressed flavour changing neutral currents . In Section 3 we discuss a two Higgs doublet model, without natural flavour conservation, where all new flavour structures in the quark sector are parametrized by elements of the CKM matrix, together with the ratio of vacuum expectation values of the Higgs doublets, whereas in the leptonic sector the same rôle is played by the Pontecorvo-Maki-Nagawa-Sakata (PMNS) matrix. In general two Higgs doublet models have Higgs mediated FCNC as well as processes mediated by a charged Higgs field which, of course, is not present in the SM.

2. New Physics in the Flavour Sector in the Presence of Heavy Fermions

One of the dogmas in the construction of unified gauge models is the absence of Z-mediated tree-level flavour changing neutral currents. The origin of this dogma [1], [2] stems from the fact that Z-mediated FCNC, if not suppressed, lead to too large contributions to various processes like $K_L^0 \to \mu^+\mu^-$, $K_L - K_S$ mass difference, $K^+ \to \pi^+\nu\overline{\nu}$, etc. One may ask the question whether this dogma can be violated in realistic and plausible extensions of the SM. In this section we emphasize that this is indeed the case. This talk is based on work done in the framework of models with vector-like quarks [3], [4]. Models with vector-like quarks (see also [5]) provide a framework where there are FCNC at tree level, which are naturally suppressed by factors of m^2/M^2, where m and M stand for the masses of the SM quarks and the vector-like quarks. For definitness, let us consider an extension of the SM where one up-type isosinglet quark T is added to the SM spectrum [4]. Both T_L and T_R are isosinglets, so mass terms of the type $\overline{T_L}T_R$, $\overline{T_L}u_{Rj}$ ($j = 1$ to 3) are $SU(2) \times U(1)$ gauge invariant and can be large. Without loss of generality one can choose a weak basis where the down quark mass matrix is diagonal real. In this basis, U is just the 4×4 unitary matrix which enters the diagonalization of the up quark mass matrix. With no loss of generality, one can also use the freedom to rephase quark fields, to choose the phases of U in the following way:

$$\arg(U) = \begin{pmatrix} 0 & \chi' & -\gamma & \ldots \\ \pi & 0 & 0 & \ldots \\ -\beta & \pi+\chi & 0 & \ldots \\ \ldots & \ldots & \ldots & \ldots \end{pmatrix} \tag{2.1}$$

where the four rephasing invariant phases are [6] ,[7]:

$$\begin{aligned} \beta &\equiv \arg(-V_{cd}V_{cb}^*V_{td}^*V_{tb}) \ ; \quad \gamma \equiv \arg(-V_{ud}V_{ub}^*V_{cd}^*V_{cb}); \\ \chi &\equiv \arg(-V_{ts}V_{tb}^*V_{cs}^*V_{cb}) \ ; \quad \chi' \equiv \arg(-V_{cd}V_{cs}^*V_{ud}^*V_{us}). \end{aligned} \tag{2.2}$$

some authors use $\beta_s \equiv \chi$, $\phi_1 \equiv \beta$ and $\phi_3 \equiv \gamma$; χ' is usually neglected. It should be emphasized that independently of the dimensions of U, only the four rephasing invariant phases in 2.2 enter its 3×3 sector connecting standard quarks. In the three generations SM, these four rephasing invariant phases and the nine moduli of V_{CKM} are related by various exact relations [8] which provide a test of the SM. It can be readily verified that in the context of the SM, the phases χ and χ' are small, of order λ^2 and λ^4, respectively, with $\lambda \simeq 0.2$. It has been pointed out that in the framework of models with up-type isosinglet quarks [9], one can obtain larger values of χ The recent measurements of χ are in agreement with the SM, but the errors are large and it is clear that there is room for New Physics contributions, which can be discovered once a better precision is obtained in the measurement of χ.

As mentioned above, we assume that there is only one up-type isosinglet quark, which we denote T. In the mass eigenstate basis the charged and neutral current interactions can be written:

$$\begin{aligned} \mathscr{L}_{\mathscr{W}} &= -\frac{g}{\sqrt{2}}\bar{\mathbf{u}}_L\gamma^\mu V\mathbf{d}_L W_\mu^\dagger + \text{H.c.} \ , \\ \mathscr{L}_{\mathscr{Z}} &= -\frac{g}{2\cos\theta_W}\left[\bar{\mathbf{u}}_L\gamma^\mu(VV^\dagger)\mathbf{u}_L - \bar{\mathbf{d}}_L\gamma^\mu\mathbf{d}_L - 2\sin^2\theta_W J^\mu_{em}\right]Z_\mu \ , \end{aligned} \tag{2.3}$$

where $\mathbf{u} = (u,c,t,T)$, $\mathbf{d} = (d,s,b)$, while V is a 4×3 submatrix of the 4×4 unitary matrix U which enters the diagonalization of the up-type quark mass matrix:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \\ V_{Td} & V_{Ts} & V_{Tb} \end{pmatrix}. \tag{2.4}$$

It is clear from Eqs. (2.3), (2.4), that $VV^\dagger \neq 1$, which leads to FCNC in the up-quark sector. The salient feature of this class of models with isosinglet quarks is that there are naturally small violations of unitarity. It is clear from Eq. 2.4 that the columns of V are orthogonal, while its rows are not. At this point it should be emphasized that there is nothing “strange" in having small violations of 3×3 unitarity. The leptonic mixing matrix also has small deviations of unitarity in the seesaw framework. It can be readily verified [10] that deviations of unitarity are suppressed by m^2/M^2.

Physical Implications of small Violation of 3×3 unitarity

Next we briefly mention some of the consequences of having small deviations of unitarity. Although our analysis is done within the framework of one isosinglet quark T, a good part of our results hold in a much larger class of extensions of the SM. The crucial ingredient is the presence of small violations of unitarity, independently of their origin.

From orthogonality of the second and third column of V, one obtains [9]:

$$\sin\chi = \frac{|V_{ub}||V_{us}|}{|V_{cb}||V_{cs}|}\sin(\gamma-\chi+\chi') + \frac{|V_{Tb}||V_{Ts}|}{|V_{cb}||V_{cs}|}\sin(\sigma-\chi)\ , \tag{2.5}$$

where σ is a rephasing invariant phase, $\sigma \equiv \arg(V_{Ts}V_{cb}V^*_{Tb}V^*_{cs})$. It is clear that χ can be of order λ if one has, for example, $V_{Tb} \approx \mathscr{O}(\lambda)$, $V_{Ts} \approx \mathscr{O}(\lambda^2)$, $\sigma \approx \mathscr{O}(1)$. In the SM one has, of course, $\sin\chi = \mathscr{O}(\lambda^2)$, since only the first term in Eq. (2.5) is present. It is clear that in this extension of the SM one may obtain an enhancement of χ provided the mixing factor $|V_{Tb}||V_{Ts}|$ is not too small.

This model has FCNC in the up sector and in particular one has couplings of the type $\bar{c_L}\gamma^\mu t_L Z_\mu$ which are proportional to $|u_{24}u_{34}|$, which measures deviations of orthogonality of the second and third rows of V. Provided $|u_{24}u_{34}|$ is not too small, one may have rare top decays $t \to cZ$ at rates which can be observed at the LHC. In this model one also has Z couplings to $\bar{c_L}\gamma^\mu u_L$ at tree level [11] . In order for these couplings to be able to account for the observed size of $D^0 - \bar{D}^0$ mixing, the size of $|u_{14}u_{24}|$ has to be of order λ^5 [12] .

It has also been pointed out that [4] that in the framework of this model one has the potential for solving the tension between experimental values of $A_{J/\Psi K_S}$ and Br($B^+ \to \tau^+\nu_\tau$) with respect to SM expectations. One may also have important deviations from the SM in observables in the bd sector like the semi-leptonic asymmetry A^d_{SL}, $B^0_d \to \mu^+\mu^-$ and $A^s_{SL} - A^d_{SL}$. Other potential places where NP can show up include $A_{J/\Psi\phi}$, γ, $K^0_L \to \pi^0\nu\bar{\nu}$, $D^0 \to \mu^+\mu^-$.

3. Minimal Flavour Violation with Two Higgs Doublets

The flavour structure of Yukawa couplings is not constrained by gauge invariance. In the SM all flavour changing transitions are mediated by charged weak currents with flavour mixing controlled by V_{CKM}, the Cabibbo-Kobayashi-Maskawa matrix. Models with two Higgs doublets [13], [14] have potentially large Higgs FCNC. The existence of strict limits on FCNC processes requires a mechanism of suppression. The elimination of tree level FCNC is accomplished, for instance, in the context of natural flavour conservation [1] through a discrete symmetry such that only one Higgs doublet couples and gives mass to each fermionic sector. An alternative proposal is the Aligned two Higgs doublet model [15]. An alternative idea, put forward in the early nineties, is to have tree level Higgs mediated FCNC suppressed by small factors given in terms of small entries of the V_{CKM} matrix [16], [17]. The first models of this type with no ad-hoc assumptions. obtained from a symmetry, were proposed by Branco, Grimus and Lavoura [18] (BGL). Later on, we have generalized BGL models [19], and extended the idea to the leptonic sector [20] as reported in this talk. In the early year two thousands the designation Minimal Flavour Violation (MFV) was coined [21], [22], referring to extensions of the SM model where the breaking of the large $U(3)^5$ flavour symmetry of the gauge sector is completely determined by Yukawa couplings, as it is the case in the SM. The definition requires, in addition, that the top quark Yukawa couplings should play a special rôle. Due to this requirement, not all BGL implementations, which are presented below, fall into the category of models considered as being of MFV type, only a specific example out of the six possible BGL models is recognized as such by authors of the definition [23]. An interesting alternative definition of MFV in the context of two Higgs doublet models was given and discussed in a recent work [24]. A feature common to all these models is the fact that the flavour structure of the quark sector is expressed in terms of entries of the V_{CKM} matrix. A distinctive feature of BGL models is that they are obtained from a global Abelian symmetry.

In order to fix our notation, we specify the Yukawa interactions, starting with the quark sector:

$$L_Y = -\overline{Q_L^0}\,\Gamma_1\Phi_1 d_R^0 - \overline{Q_L^0}\,\Gamma_2\Phi_2 d_R^0 - \overline{Q_L^0}\,\Delta_1\tilde{\Phi}_1 u_R^0 - \overline{Q_L^0}\,\Delta_2\tilde{\Phi}_2 u_R^0 \;+\text{h. c.} \tag{3.1}$$

where Γ_i and Δ_i denote the Yukawa couplings of the lefthanded quark doublets Q_L^0 to the righthanded quarks d_R^0, u_R^0 and the Higgs doublets Φ_j. The quark mass matrices generated after spontaneous gauge symmetry breaking are given by:

$$M_d = \frac{1}{\sqrt{2}}(v_1\Gamma_1 + v_2 e^{i\alpha}\Gamma_2), \quad M_u = \frac{1}{\sqrt{2}}(v_1\Delta_1 + v_2 e^{-i\alpha}\Delta_2), \tag{3.2}$$

where $v_i \equiv |<0|\phi_i^0|0>|$ and α denotes the relative phase of the vacuum expectation values (vevs) of the neutral components of Φ_i. The matrices M_d, M_u are diagonalized by the usual bi-unitary transformations:

$$U_{dL}^\dagger M_d U_{dR} = D_d \equiv \mathrm{d}iag\;(m_d, m_s, m_b) \tag{3.3}$$

$$U_{uL}^\dagger M_u U_{uR} = D_u \equiv \mathrm{d}iag\;(m_u, m_c, m_t) \tag{3.4}$$

The neutral and the charged Higgs interactions obtained from the quark sector of Eq. (3.1) are of the form

$$\begin{aligned} \mathscr{L}_Y(\text{quark, Higgs}) \;=\; & -\overline{d_L^0}\frac{1}{v}\,[M_d H^0 + N_d^0 R + iN_d^0 I]\,d_R^0 - \\ & -\;\overline{u_L^0}\frac{1}{v}\,[M_u H^0 + N_u^0 R + iN_u^0 I]\,u_R^0 - \\ & -\;\frac{\sqrt{2}H^+}{v}(\overline{u_L^0}N_d^0\,d_R^0 - \overline{u_R^0}N_u^{0\dagger}\,d_L^0) + \text{h.c.} \end{aligned} \tag{3.5}$$

where $v \equiv \sqrt{v_1^2+v_2^2} \approx 246$ GeV, and H^0, R are orthogonal combinations of the fields ρ_j, arising when one expands [25] the neutral scalar fields around their vacuum expectation values, $\phi_j^0 = \frac{e^{i\alpha_j}}{\sqrt{2}}(v_j + \rho_j + i\eta_j)$, choosing H^0 in such a way that it has couplings to the quarks which are proportional to the mass matrices, as can be seen from Eq. (3.5). Similarly, I denotes the linear combination of η_j orthogonal to the neutral Goldstone boson. The matrices N_d^0, N_u^0 are given by:

$$N_d^0 = \frac{1}{\sqrt{2}}(v_2\Gamma_1 - v_1 e^{i\alpha}\Gamma_2), \quad N_u^0 = \frac{1}{\sqrt{2}}(v_2\Delta_1 - v_1 e^{-i\alpha}\Delta_2) \tag{3.6}$$

The flavour structure of the quark sector of two Higgs doublet models is thus fully specified in terms of the four matrices M_d, M_u, N_d^0, N_u^0. In terms of the quark mass eigenstates u, d, the Yukawa couplings are:

$$L_Y \;=\; -\frac{\sqrt{2}H^+}{v}\bar{u}\left(VN_d\gamma_R - N_u^\dagger\,V\gamma_L\right)d + \text{h.c.} - \frac{H^0}{v}\left(\bar{u}D_u u + \bar{d}D_d\,d\right) -$$

$$
\begin{aligned}
& - \frac{R}{v} \left[\bar{u}(N_u \gamma_R + N_u^\dagger \gamma_L) u + \bar{d}(N_d \gamma_R + N_d^\dagger \gamma_L)\, d \right] + \\
& + i \frac{I}{v} \left[\bar{u}(N_u \gamma_R - N_u^\dagger \gamma_L) u - \bar{d}(N_d \gamma_R - N_d^\dagger \gamma_L)\, d \right]
\end{aligned} \tag{3.7}
$$

with $\gamma_L = (1-\gamma_5)/2$, $\gamma_R = (1+\gamma_5)/2$ and where V stands for the V_{CKM} matrix. The matrices N_d and N_u are:

$$
N_d = U_{dL}^\dagger N_d^0 U_{dR}, \qquad N_u = U_{uL}^\dagger N_u^0 U_{uR} \tag{3.8}
$$

Comparison with Eqs. (3.3), (3.4) shows that the matrices N_d^0, N_u^0 transform in the same way as the matrices M_d, M_u under unitary transformations of the quark fields. The physical neutral Higgs fields are combinations of H^0, R and I. Flavour changing neutral currents are controlled by N_d and N_u. For generic two Higgs doublet models N_d, N_u are non-diagonal arbitrary.

In order to obtain a structure for the matrices Γ_i and Δ_i such that the the strength of the tree level FCNC is completely controlled by V_{CKM}, Branco, Grimus and Lavoura (BGL) imposed the following symmetry on the quark and scalar sector of the Lagrangian [18]:

$$
Q_{Lj}^0 \to \exp(i\tau)\, Q_{Lj}^0 \,, \qquad u_{Rj}^0 \to \exp(i2\tau) u_{Rj}^0 \,, \qquad \Phi_2 \to \exp(i\tau)\Phi_2 \,, \tag{3.9}
$$

where $\tau \neq 0, \pi$, with all other quark fields transforming trivially under the symmetry. The index j can be fixed as either 1, 2 or 3. Alternatively the symmetry may be chosen as:

$$
Q_{Lj}^0 \to \exp(i\tau)\, Q_{Lj}^0 \,, \qquad d_{Rj}^0 \to \exp(i2\tau) d_{Rj}^0 \,, \quad \Phi_2 \to \exp(-i\tau)\Phi_2 \,. \tag{3.10}
$$

The symmetry given by Eq. (3.9) leads to Higgs FCNC in the down sector, whereas the symmetry specified by Eq. (3.10) leads to Higgs FCNC in the up sector. In the case of the symmetry given by Eq. (3.9), for $j = 3$ there are FCNC in the down sector controlled by the matrix N_d given by [18]

$$
(N_d)_{ij} \equiv \frac{v_2}{v_1}(D_d)_{ij} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2} \right) (V_{CKM}^\dagger)_{i3} (V_{CKM})_{3j} (D_d)_{jj} \,. \tag{3.11}
$$

whereas, there are no FCNC in the up sector and the coupling matrix of the up quarks to the R and I fields is of the form:

$$
N_u = -\frac{v_1}{v_2} \mathrm{diag}\ (0, 0, m_t) + \frac{v_2}{v_1} \mathrm{diag}\ (m_u, m_c, 0) \,. \tag{3.12}
$$

It is clear that BGL models are very constrained. Only one new parameter, not present in the SM, appears in the flavour sector, that is the ratio $\tan\beta = v_2/v_1$. As a result of the imposed symmetry the Higgs potential, together with a soft symmetry breaking term, required in order to avoid an ungauged accidental continuos symmetry, has seven parameters which can be chosen to be real, without loss of generality. The Higgs sector does not violate CP neither explicitly nor spontaneously. The seven independent parameters of the potential determine the masses of the four Higgs fields, $\tan\beta$, the quantity $v \equiv \sqrt{v_1^2 + v_2^2}$ and the mixing among H^0 and R, which is supposed to be small due to the fact that the Higgs field discovered at the LHC [26], [27], behaves very much like a SM Higgs field. The study of the phenomenological implications of this class of models is underway. This requires the specification of the leptonic sector. For Dirac neutrinos the extension

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is straightforward in analogy to the quark sector. The case of Majorana type neutrinos is more involved.

In terms of the low energy effective theory for Majorana neutrino masses, a priori, it looks more difficult to implement MFV. However, this can be done by imposing a Z_4 symmetry to the effective Lagrangian as presented in Ref. [20] . In the seesaw case, with the introduction of three righthanded neutrinos the leptonic part of Yukawa couplings and invariant mass terms can then be written:

$$\begin{aligned}\mathscr{L}_{Y+\text{mass}} &= -\overline{L^0_L}\,\Pi_1\Phi_1 l^0_R - \overline{L^0_L}\,\Pi_2\Phi_2 l^0_R - \overline{L^0_L}\,\Sigma_1\tilde{\Phi}_1\nu^0_R - \overline{L^0_L}\,\Sigma_2\tilde{\Phi}_2\nu^0_R \; + \\ &+ \frac{1}{2}\nu^{0T}_R C^{-1} M_R \nu^0_R + \text{h.c.}\;. \end{aligned} \tag{3.13}$$

The matrix M_R stands for the righthanded neutrino Majorana mass matrix. The leptonic mass matrices generated after spontaneous gauge symmetry breaking are given by:

$$m_l = \frac{1}{\sqrt{2}}(v_1\Pi_1 + v_2 e^{i\theta}\Pi_2)\;, \quad m_D = \frac{1}{\sqrt{2}}(v_1\Sigma_1 + v_2 e^{-i\theta}\Sigma_2)\;. \tag{3.14}$$

The neutral Higgs interactions with the fermions, obtained from Eq. (3.13) can be written:

$$\begin{aligned}\mathscr{L}_Y(\text{neutral, lepton}) &= -\overline{l^0_L}\frac{1}{v}\,[m_l H^0 + N^0_l R + iN^0_l I]\; l^0_R + \\ &- \overline{\nu^0_L}\frac{1}{v}\,[m_D H^0 + N^0_\nu R + iN^0_\nu I]\; \nu^0_R + \text{h.c.}\;, \end{aligned} \tag{3.15}$$

with

$$N^0_l = \frac{v_2}{\sqrt{2}}\Pi_1 - \frac{v_1}{\sqrt{2}}e^{i\theta}\Pi_2\;, \tag{3.16}$$

$$N^0_\nu = \frac{v_2}{\sqrt{2}}\Sigma_1 - \frac{v_1}{\sqrt{2}}e^{-i\theta}\Sigma_2\;. \tag{3.17}$$

There is a new feature in the seesaw framework due to the fact that in the neutrino sector the light neutrino masses are not obtained from the diagonalization of m_D. In general the couplings of Eq. (3.15) lead to arbitrary scalar FCNC at tree level. In order for these couplings to be completely controlled by the PMNS matrix we introduce the following Z_4 symmetry on the Lagrangian:

$$L^0_{L3} \to \exp(i\alpha)\; L^0_{L3}\;, \qquad \nu^0_{R3} \to \exp(i2\alpha)\,\nu^0_{R3}\;, \qquad \Phi_2 \to \exp(i\alpha)\Phi_2\;, \tag{3.18}$$

with $\alpha = \pi/2$ and all other fields transforming trivially under Z_4. The most general matrices Π_i, Σ_i and M_R consistent with this Z_4 symmetry have the following structure:

$$\Pi_1 = \begin{bmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{bmatrix}\;, \qquad \Pi_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{bmatrix}\;, \tag{3.19}$$

$$\Sigma_1 = \begin{bmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{bmatrix}\;, \qquad \Sigma_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{bmatrix}\;, \qquad M_R = \begin{bmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{bmatrix}\;, \tag{3.20}$$

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where $\times$ denotes an arbitrary entry while the zeros are imposed by the symmetry Z_4. Note that the choice of Z_4 is crucial in order to guarantee $M_{33} \neq 0$ and thus a non-vanishing $\det M_R$. In this case there are flavour changing neutral currents in the charged leptonic sector given by:

$$(N_l)_{ij} \equiv (U_{lL}^{\dagger}\, N_l^0\, U_{lR})_{ij} = \frac{v_2}{v_1}(D_l)_{ij} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right)(U_\nu^\dagger)_{i3}(U_\nu)_{3j}(D_l)_{jj}\,. \tag{3.21}$$

U_ν is the PMNS matrix. In the neutrino sector we have three light and three heavy neutrinos. The light-light Higgs mediated neutral currents are flavour diagonal. On the other hand Higgs mediated light-heavy and heavy-heavy neutrino couplings can be parametrized [20] in terms of neutrino masses and the orthogonal complex matrix of the Casas and Ibarra parametrization [28]. This matrix plays an important rôle for leptogenesis [29]. In the context of seesaw the masses of heavy neutrinos are many orders of magnitude above the TeV scale, therefore processes involving heavy neutrinos are not relevant for low energy physics.

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