# Vector-Like Quarks and Right-Handed Neutrinos

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# Standard Model (SM) and Neutrino Masses

In the SM Neutrinos are strictly massless:

No Dirac mass $\nu_R$ is not introduced

No Majorana mass neither at tree level nor at higher orders due to:

Exact B-L conservation

Therefore: The SM has been ruled out by experiment. One has $\nu_{SM} \equiv SM + \nu_R$

$$\nu SM \equiv SM + \nu_R$$

If one follows "the rules" and writes the most general neutrino mass terms, one has:

Dirac mass : $g_\nu v \, \overline{\nu}_L \nu_R + h.c.$

Majorana mass : $M_R \, \nu_R^T C \nu_R$

Since the Majorana mass term is gauge invariant, one can have $M_R \gg v$. This leads to the Seesaw mechanism with :

$$m_\nu \approx \frac{(m_\nu^D)^2}{M_R}$$

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Historically, the seesaw mechanism
was suggested in a different way

{ Rabi Mohapatra — in the context of
{ Goran Senjanovic left — right symmetry
                                    theories

Gell — Mann, Ramond and Slansky in
the context of SO(10)

So the Harvard Group dictated
that neutrinos have no mass and
the "right GUT" was SU(5)

Where neutrinos are again massless
due to accidental B-L conservation

Recall the talk by Murray Gell-Mann
at Columbia about SO(10)...

Important feature of $\nu_R$

The Majorana mass term $\nu_R^T C \nu_R$
is $SU(2)_L \times U(1)$ invariant. Therefore
$M_R$ can be significantly larger than $v$.

$$M_R > v$$

Question: Can one have an analogous
situation in the quark sector?

Answer: Yes! Vector-like quarks:
$Q_L, Q_R$ transform in the same way under $SU(2) \times U(1)$

$\overline{Q_L} Q_R$ is $SU(2) \times U(1)$ invariant

# Possible motivations to introduce isosinglet vector-like quarks

Quarks with L and R components transforming in the same way under the SM gauge group

Vector-like fermions arise for instance in grand unified models

Naturally small violation of 3x3 unitarity of the VCKM and non-vanishing but naturally suppressed flavour-changing neutral currents (FCNC)

This opens up many interesting possibilities for rare K and B decays as well as CP asymmetries in neutral B decays

Adding isosinglet quarks to the SM leads to new sources of CP violation

In particular one may achieve spontaneous CP violation in this framework with the addition of a complex scalar singlet to the Higgs sector consistent with experiment since it leads to a complex VCKM

Possibility of solving the strong CP problem a la Barr and Nelson

Bento, gcb, Parada, 1991

Possibility of having a Common Origin for all CP Violations

gcb, Parada, Rebelo, 2003

Both Frameworks i.e., Models with right-handed neutrinos and Models with Vector Like quarks (VLQs) lead to non-unitary fermionic mixing matrices.

Recall that even in the simple type I seesaw mechanism one has deviations from unitarity in the 3x3 leptonic mixing matrix (PMNS)

# Physics BSM with vector-like quarks (VLQs)

Bare mass terms in the Lagrangian are allowed (as it is the case of neutrino Majorana mass terms)

**VLQs may populate the desert between the EW and the GUT scale without worsening the hierarchy problem**

P. Ramond, 1981

**Mixing of the new quarks with the SM-like quarks gives rise to:**

Deviations from unitarity of the VCKM

Z mediated Flavour-Changing-Neutral-Currents

**Violation of some Dogmas of the Past!**

Higgs mediated Flavour-Changing-Neutral-Currents

These new phenomena are suppressed by the ratio of electroweak scale and the masses of the new heavy quarks

**Rich variety of new Physics**

# Fundamental properties of the CKM matrix

$$\mathscr{L}_{\mathrm{CC}} = \begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix}_L \gamma^\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W_\mu^+ + \mathrm{H.c.}$$

The CKM matrix is complex but not all its phases have physical meaning

$$u_\alpha = e^{i\varphi_\alpha} u'_\alpha, \qquad d_k = e^{i\varphi_k} d'_k$$

There is freedom to rephase the mass eigenstate quark fields. As a result:

$$V'_{\alpha k} = e^{i(\varphi_k - \varphi_\alpha)} V_{\alpha k}$$

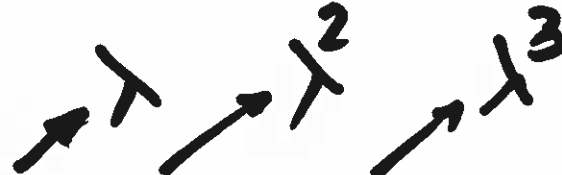Only rephasing invariant quantities have physical meaning.
The simplest rephasing invariants of the CKM matrix are moduli and "quartets"

$$|V_{\alpha k}| \qquad\qquad Q_{\alpha i \beta j} \equiv V_{\alpha i} V_{\beta j} V_{\alpha j}^* V_{\beta i}^* \qquad\qquad \text{with } \alpha \neq \beta \text{ and } i \neq j$$

Higher order Invariants can in general be written in terms of these .

Details about Rephasing invariant quantities

**Example :**

$$Q = V_{us} V_{cb} V_{cs}^* V_{ub}^*$$

with orders $\lambda$, $\lambda^2$, $\lambda^3$ indicated above the respective factors.

$$\mathrm{Im}\, Q \simeq \lambda^6 \sin(\arg Q) \qquad \arg Q \quad \text{is of order 1}$$

$\lambda$    is essentially the sine of the Cabibbo angle and it is a parameter appearing in the Wolfenstein parametrisation of the CKM matrix

|Im Q| has the same value for all quartets and measures the strength of CP violation in the SM.

# Differences between the imaginary parts of the quartets

In the SM, one can show that all imaginary parts of rephasing invariant quartets:

$$V_{us} V_{cb} V_{ub}^* V_{cs}^* \equiv Q_{uscb}$$

$$V_{cd} V_{ts} V_{td}^* V_{cs}^* \equiv Q_{cdts}$$

have the same modulus

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} ,$$

In the presence of VLQs one obtains a different result, for example:

$$\text{Im } Q\_2112 - \text{Im } Q\_1132 = \text{Im } Q\_1142$$

# Changes in the unitarity relations in the presence of VLQs

**Moduli differences:** <span style="color:teal">Albergaria, gcb, 2023</span>

In the SM, 3x3 unitarity of the CKM matrix leads to an "asymmetry" defined as:

$$\mathbf{a} \equiv |V_{31}|^2 - |V_{13}|^2 = |V_{23}|^2 - |V_{32}|^2 = |V_{12}|^2 - |V_{21}|^2$$

In an SM extension with one up-type VLQ the quark mixing matrix consists of the first three columns of a 4x4 unitary matrix:

$$V = \begin{pmatrix} V_{11} & V_{12} & V_{13} & V_{14} \\ V_{21} & V_{22} & V_{23} & V_{24} \\ V_{31} & V_{32} & V_{33} & V_{34} \\ V_{41} & V_{42} & V_{43} & V_{44} \end{pmatrix}$$

# Changes in the unitarity relations in the presence of VLQs

From unitarity of first row and first column of V, one derives:

$$a_{12,13} \equiv \left(|V_{12}|^2 - |V_{21}|^2\right) - \left(|V_{31}|^2 - |V_{13}|^2\right) = |V_{41}|^2 - |V_{14}|^2$$

Using unitarity of other rows and columns of V one obtains:

$$a_{12,32} \equiv \left(|V_{12}|^2 - |V_{21}|^2\right) - \left(|V_{23}|^2 - |V_{32}|^2\right) = |V_{24}|^2 - |V_{42}|^2,$$
$$a_{13,23} \equiv \left(|V_{13}|^2 - |V_{31}|^2\right) - \left(|V_{32}|^2 - |V_{23}|^2\right) = |V_{34}|^2 - |V_{43}|^2.$$

From $D_0 - \overline{D_0}$ mixing, we know that, in models with one up-type VLQ, we have

$$|V_{14}|^2|V_{24}|^2 < (2.1 \pm 1.2) \times 10^{-8}.$$

# In the SM it is not possible to generate the Baryon Asymmetry of the Universe (BAU)

One of the reasons is that in the SM CP violation is too small:

$$\mathcal{I}_{\rm CP} = {\rm tr}[y_u y_u^\dagger, y_d y_d^\dagger]^3 \sim \frac{{\rm tr}[h_u, h_d]^3}{v^{12}} \sim 10^{-25}$$

## In models with VLQs one may have CP odd invariants of much lower mass scale

Example:

$${\rm tr}\left([h_u, h_d^s]\, H_u^{(2)}\right)$$

$$H_u^{(r)} \equiv m_u(m_u^\dagger m_u + M_u^\dagger M_u)^{r-1} m_u^\dagger$$
$$h_d \equiv m_d m_d^\dagger$$

A surprising result: In the 3×3 up corner of a $V^{CKM}$ matrix of arbitrary size one has:

$$9 - 5 = 4 \text{ rephasing invariant phases}$$

The following phase convention may be chosen, in general

$$\chi' \equiv \beta_k$$
$$\chi \equiv \beta_s$$

$$\arg V^{3\times 3} = \begin{bmatrix} 0 & \beta_k & \gamma \\ \pi & 0 & 0 \\ -\beta & \pi+\beta_s & 0 \end{bmatrix}$$

$$V = \begin{pmatrix} \boxed{\begin{matrix} |V_{ud}| & |V_{us}|\,e^{i\chi'} & |V_{ub}|\,e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|\,e^{-i\beta} & -|V_{ts}|\,e^{i\chi} & |V_{tb}| \end{matrix}} & \begin{matrix} \cdots \\ \cdots \\ \cdots \end{matrix} \\ \begin{matrix} \vdots & \quad \vdots & \quad \vdots \end{matrix} & \ddots \end{pmatrix}$$

$V_{CKM}$

The phases $\gamma, \beta, \beta_s, \beta_K$ are arguments of rephasing invariant quartets:

$$\gamma = \arg\left(- V_{ud} V_{cb} V_{ub}^* V_{cd}^*\right)$$

$$\beta = \arg\left(- V_{cd} V_{tb} V_{cb}^* V_{td}^*\right)$$

$$\beta_s = \arg\left(- V_{cb} V_{ts} V_{cs}^* V_{tb}^*\right)$$

$$\beta_K = \arg\left(- V_{us} V_{cd} V_{ud}^* V_{cs}^*\right)$$

Sometimes one also introduces $\alpha = \arg\left(-V_{td} V_{ub} V_{ud}^* V_{tb}^*\right)$ which is unnecesary, because

$$\alpha \equiv \pi - \beta - \gamma \qquad \text{By definition !!!}$$

Within the SM, 3×3 unitarity implies some exact relations among rephasing invariant quantities:

$$\frac{|V_{ub}|}{|V_{td}|} = \frac{\sin\beta}{\sin\gamma} \frac{|V_{tb}|}{|V_{ud}|}$$

$$\sin\beta_s = \frac{|V_{td}|}{|V_{ts}|} \frac{|V_{cd}|}{|V_{cs}|} \sin\beta = O(\lambda^2)$$

$$\sin\beta_K = \frac{|V_{ub}|}{V_{us}} \frac{|V_{cb}|}{|V_{cs}|} \sin\gamma = O(\lambda^4)$$

# Identification of the Small numbers in VCKM :

$$|V_{ub}| \approx 3.6 \times 10^{-3}$$

$$|Im\, Q| \approx 3 \times 10^{-5}$$

$Q \rightarrow$ Rephasing invariant quartet of VCKM

In the SM, $|Im\, Q|$ has the same value for all quartets and gives the strength of CP violation in the SM

Conjecture : The small numbers in $V^{CKM}$ arise from **New Physics**

The conjecture implies that within the SM,

$$|V_{ub}| = 0$$

$$\text{Im } Q = 0$$

A simple realization of the Conjecture can be constructed within SM + **VLQs**

# The generation of |V_ub| and ImQ

## from New Physics

**We propose that the CKM matrix is generated from three different contributions**

$$V_{\text{CKM}}^{\text{eff}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}_{\text{up}} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{12} \end{pmatrix}_{\text{NP}} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{13} & 0 \\ 0 & 0 & 1 \end{pmatrix}_{\text{down}}$$

In order to implement the structure
we assume that there is a basis where the
down and up quark matrices take the form:

$$M_d = \begin{pmatrix} m_{11}^d & m_{12}^d & 0 \\ m_{21}^d & m_{22}^d & 0 \\ 0 & 0 & m_{33}^d \end{pmatrix} \qquad M_u = \begin{pmatrix} m_{11}^u & 0 & 0 \\ 0 & m_{22}^u & m_{23}^u \\ 0 & m_{32}^u & m_{33}^u \end{pmatrix}$$

**It can be shown that one can obtain these patterns through the introduction of a Z_4 symmetry at the Lagrangian level**

Without the introduction of New Physics, one simply obtains a simplified and reduced CKM mixing, where

$$V_{\text{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}_{\text{up}} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}_{\text{down}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}c_{23} & c_{23}c_{12} & -s_{23} \\ -s_{23}s_{12} & s_{23}c_{12} & c_{23} \end{pmatrix}$$

At this level one has: $|V_{31}| = |V_{12}| |V_{23}|$ and $V_{13} = 0$

Our conjecture offers an explanation why:

$|V\_31| > |V\_13|$ !!!

$V_{13} = 0$ also leads to vanishing CP violation

# Introduce an up-type VLQ

## and assume the 4x4 up-type quark matrix to be of the form:

$$\mathcal{M}_u = \begin{pmatrix} 0 & 0 & 0 & m_{14} \\ 0 & m_{22} & m_{23} & m_{24}e^{i\beta} \\ 0 & m_{32}e^{i\alpha} & m_{33} & 0 \\ m_{41} & 0 & -m_{43}e^{i\delta} & M \end{pmatrix}$$

## then one can generate:

$$\left( V_{4H}^{CKM} \right)_{13} \neq 0 \qquad |Im\, Q|_{4H} \neq 0$$

# Numerical example:

## Mass matrices in GeV at the m_Z scale:

$$M_d = \begin{pmatrix} 0.00292338 & -0.0134741 & 0 \\ 0.000673705 & 0.0584675 & 0 \\ 0 & 0 & 2.9 \end{pmatrix}$$

$$m_d = 0.003, \quad m_s = 0.060, \quad m_b = 2.9,$$

$$\mathcal{M}_u = \begin{pmatrix} 0 & 0 & 0 & 53.7334 \\ 0 & 0.59952 & -6.91815 & 1.250e^{-0.285i} \\ 0 & -0.0239936 & 172.862 & 0 \\ 0.046526 & 0 & 14.886e^{-1.190i} & 1250 \end{pmatrix}$$

$$m_u = 0.002, \quad m_c = 0.60, \quad m_t = 173, \quad m_T = 1251.$$

$$
\begin{bmatrix} \bar{u} & \bar{c} & \bar{t} & \bar{T} \end{bmatrix}
\begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb} \\
V_{Td} & V_{Ts} & V_{Tb}
\end{bmatrix}
\begin{bmatrix} d \\ s \\ b \end{bmatrix}
$$

The CKM matrix is the $4 \times 3$ left-sub-matrix of the following full $4 \times 4$ mixing matrix

$$
|\mathcal{V}| =
\begin{pmatrix}
0.97354 & 0.224413 & 0.00370431 & 0.0429468 \\
0.224536 & 0.973644 & 0.0399975 & 0.000996211 \\
0.00833917 & 0.0393001 & 0.999192 & 0.00151171 \\
0.0416344 & 0.0105585 & 0.001674 & 0.999076
\end{pmatrix}
$$

# These mass matrices lead to:

CP violation rephasing invariant phases are

$$\gamma \equiv \arg\left(-V_{ud}V_{cb}V_{ub}^*V_{cd}^*\right) \simeq 68.0^\circ,$$

$$\sin(2\beta) \equiv \sin\left[2\ \arg\left(-V_{cd}V_{tb}V_{cb}^*V_{td}^*\right)\right] \simeq 0.746,$$

$$\chi \equiv \arg\left(-V_{ts}V_{cb}V_{cs}^*V_{tb}^*\right) \simeq 0.020,$$

$$\chi' \equiv \arg\left(-V_{cd}V_{us}V_{cs}^*V_{ud}^*\right) \simeq 5.71 \times 10^{-4}.$$

CP-odd invariant quantity $I_{\mathrm{CP}} = |\mathrm{Im}Q| \equiv |\mathrm{Im}\left(V_{ub}V_{cd}V_{ud}^*V_{cb}^*\right)|$

$$I_{\mathrm{CP}} \simeq 3.00 \times 10^{-5}.$$

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VLQs may play an important rôle
in providing an explanation for the
$\sqrt{}^{CKM}$ unitarity problem.

$$|V_{us}|^2 + |V_{ud}|^2 + |V_{ub}|^2 < 1$$

at the level of 2,3 standard deviations.

See    J. T. Penedo, Pedro Pereira, M.N.Rebelo
                                    GCB
        published in JHEP

See also nice work by Belfatto and
                                    Berezhiani

**VLQs** Provide a simple framework where there are New Physics (NP) contributions to $B_d - \bar{B}_d$ mixing, $B_s - \bar{B}_s$ mixing and/or $\bar{D}^0 - D^0$ mixing; Also new contributions to

$$t \longrightarrow c \, Z_\mu$$

may receive Tree-level contributions in models with up-type VLQs.

VLQs may populate the desert between $v$ and some higher scale ($M_{GUT}$?) without worsening the hierarchy problem

To my knowledge, this was first emphasized in a paper by Pierre Ramond.

"Fermions in the Desert"

(talk given at Erice)

Appears in Spires

# A Common Origin for all CP Violations

## The Lagrangian is CP invariant. CP is spontaneously violated

Field content, Higgs and quark sector:

$$\left( \begin{array}{c} u^0 \\ d^0 \end{array} \right)_{iL}, \; u^0_{iR}, \; d^0_{\alpha R}, \; D^0_L, \; i = 1, 2, 3, \; \alpha = 1, ..., 4, \; \phi, \; S$$

D is a down-type vector-like quark, S is a scalar singlet

A $Z_2$ symmetry is imposed in order to naturally suppress    strong CP a la Barr and Nelson

$$D^0 \to -D^0, \quad S \to -S$$

$SU(2) \times U(1) \times Z_2$ invariant  scalar potential

$$V = V_0 \left( \phi, S \right) + (\mu^2 + \lambda_1 \; S^* S + \lambda_2 \; \phi^\dagger \phi)(S^2 + S^{*2}) + \lambda_3 \; (S^4 + S^{*4})$$

$V_0$ contains all terms that are phase independent and includes the SM Higgs

Real coefficients spontaneous CP violation    $\langle \phi^0 \rangle = \dfrac{v}{\sqrt{2}}, \quad \langle S \rangle = \dfrac{V \exp(i\beta)}{\sqrt{2}}$

# A Common Origin for all CP Violations

The Yukawa interactions of the quarks are given by:   (all coefficients are real)

$$\mathcal{L}_Y = -\sqrt{2}(\overline{u^0}\ \overline{d^0})^i_L (g_{ij}\phi\, d^0_{jR} + h_{ij}\tilde{\phi}\, u^0_{jR}) - M_d \overline{D^0_L}\, D^0_R - \sqrt{2}(f_i\, S + f'_i\, S^*)\overline{D^0_L} d^0_{iR} + \text{h.c.}$$

with (i,j = 1, 2, 3) and the down quark mass matrix is now of the form:

$$\mathcal{M}_d = \begin{pmatrix} m_d & 0 \\ \overline{M_d} & M_d \end{pmatrix}$$

**Diagonalisation of this mass matrix:**                    Bento, gcb, Parada, 1991

$$\mathcal{M}_d \mathcal{M}_d^\dagger\, U_L = U_L \begin{pmatrix} d_d^2 & \\ & D_d^2 \end{pmatrix} \qquad \text{with} \qquad U_L = \begin{pmatrix} K & R \\ S & T \end{pmatrix}$$

**Working in the weak basis where the up quark mass matrix is diagonal)**

$$S \simeq -\frac{1}{D_d^2}(\overline{M_d}\, m_d^\dagger)\, K \qquad\qquad \text{where here } \overline{M_{dj}} = f_j\, V e^{i\beta} + f'_j V e^{-i\beta}$$

$$D_d^2 \simeq (\overline{M_d}\ \overline{M_d}^\dagger + M_d^2) \qquad\qquad \mathcal{H}_{eff} = m_d\, m_d^\dagger - \frac{1}{D_d^2}(m_d\ \overline{M_d}^\dagger)(\overline{M_d}\, m_d^\dagger)$$

– Non decoupling provided the scale of the bare mass term of D does not dominate over the scale of the vev of the scalar singlet, concerning the generation of a complex VCKM

- Suppression of deviations from unitarity irrespective of which scale dominates

# A Common Origin for all CP Violations

From the previous page we see that in the Bento, gcb, Parada framework a complex CKM matrix can be generated from spontaneous CP violation at a high energy scale

## Concerning strong CP violation:

$$\mathscr{L} \supset \theta_{\text{QCD}} \frac{g_s^2}{64\pi^2} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$

The QCD Lagrangian contains a CP violating term originating from the QCD vacuum

However, CP violation has not been observed in the strong interactions

Furthermore, $\theta_{\text{QCD}}$ is a free parameter

Experimentally what is measurable is the combination: $\qquad \bar{\theta} = \theta_{\text{QCD}} - \theta_{\text{weak}}$

$\theta_{\text{weak}} = \arg(\det \mathcal{M}_u \times \det \mathcal{M}_d)$

Within the SM the electric dipole moment of the neutron which is CP, P and T violating is proportional to $\bar{\theta}$.

It is the fact that $\bar{\theta}$. is tiny that constitutes the strong CP problem: $\qquad \bar{\theta} \lesssim 10^{-10}$

No additional symmetry is restored at Lagrangian level is restored when $\qquad \bar{\theta} = 0$

So $\bar{\theta} = 0$ is unnatural

# A Common Origin for all CP Violations

## Strong CP

## Nelson-Barr proposal

1. VEVs that break the SM gauge group cannot break CP and they only connect the usual quark fields.

2. VEVs that break CP spontaneously cannot break the SM gauge group and they can only connect SM quark fields with the additional VLQs.

## Bento, gcb, Parada model

$$\mathcal{L}_Y = -\sqrt{2}(\overline{u^0}\ \overline{d^0})^i_L(g_{ij}\phi\, d^0_{jR}+h_{ij}\tilde{\phi}\, u^0_{jR})-M_d\overline{D^0_L}\, D^0_R-\sqrt{2}(f_i\, S+f'_i\, S^*)\, \overline{D^0_L}d^0_{iR}+\text{h.c.}$$

Since CP is a symmetry imposed in the Lagrangian $\qquad \theta_{QCD}=0$

$$\theta_{\text{weak}} = \arg(\det \mathcal{M}_d \times \det m_u)$$

$$\theta_{\text{weak}} = 0 \qquad\qquad \mathcal{M}_d = \begin{pmatrix} m_d & 0 \\ M_d & M_d \end{pmatrix}$$

# A Common Origin for all CP Violations

## Extension to the Leptonic sector: three right handed neutrinos are included

$$\mathcal{L}_l = \overline{\psi_l^0} G_l \phi \, e_R^0 + \overline{\psi_l^0} G_\nu \tilde{\phi} \, \nu_R^0 + \frac{1}{2} \nu_R^{0T} C (f_\nu S + + f_\nu' S^*) \nu_R^0 + h.c. \qquad \text{all coefficients are real}$$

Imposed symmetry:
$$\psi_l^0 \to i\psi_l^0, \quad e_R^0 \to ie_R^0, \quad \nu_R^0 \to i\nu_R^0$$

The initial $Z_2$ symmetry is thus promoted to a $Z_4$ symmetry

$$\mathcal{L}_l = \overline{\psi_l^0} G_l \phi \, e_R^0 + \overline{\psi_l^0} G_\nu \tilde{\phi} \, \nu_R^0 + \frac{1}{2} \nu_R^{0T} C (f_\nu S + + f_\nu' S^*) \nu_R^0 + h.c.$$

the symmetry prevents the existence of bare Majorana terms, however these are generated by the couplings to the field S

there are standard model particles transforming non-trivially under the symmetry

# A Common Origin for all CP Violations

$$\mathcal{L}_l = \overline{\psi_l^0} G_l \phi \; e_R^0 + \overline{\psi_l^0} G_\nu \tilde{\phi} \; \nu_R^0 + \frac{1}{2} \nu_R^{0T} C (f_\nu S + + f_\nu' S^*) \nu_R^0 + h.c.$$

$$\mathcal{M} = \begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix}, \quad m_l = \frac{v}{\sqrt{2}} G_l, \quad m = \frac{v}{\sqrt{2}} G_\nu$$

$$M = \frac{V}{\sqrt{2}} (f_\nu^+ \cos(\alpha) + i f_\nu^- \sin(\alpha)) \qquad\qquad f_\pm^\nu \equiv f_\nu \pm f_\nu'$$

In the weak basis where $m_l$ is to chosen to be real and diagonal

light neutrino masses and low energy leptonic mixing are obtained to an excellent approximation by:

$$- K^\dagger m \frac{1}{M} m^T K^* = d_\nu \qquad\qquad \text{where } U_{\text{PMNS}} \text{ can be identified to } K.$$

m is a real matrix, while M is a generic complex matrix, therefore K will also be complex

Leptonic CP violation is generated at low energies. CP violation at high energies can also be generated. Possibility of having Leptogenesis

Lepton number asymmetry is sensitive to the CP violating phases appearing in $m^\dagger m$

in the weak basis where m_l and M are chosen to be real and diagonal

# CONCLUSIONS

**Vector-like quarks are very interesting candidates for physics BSM**

**Very simple extension of the SM, providing striking new experimental effects**

**Vector-like quarks are "cousins" of right-handed neutrinos which provide through seesaw the most plausible explanation of the smallness of neutrino masses**

- Weak point : No firm prediction for the scale of VLQs.

  This is a <u>universal weak point</u> in <u>all</u> (so far) proposed New Physics proposals... !!

  The SM was an notable exception. Before gauge interactions the sugestion was IVB with $\approx 2 \, GeV$ !

  ↑ intermediate vector boson...