Flavour in the Higgs Era

talk given at Planck 2013
Bonn, Germany

Gustavo C. Branco
CFTP/IST, Lisboa, Portugal

based on work done with F. Botella, M. N. Nebot, M. N. Rebelo
and earlier work with L. Lavoura, W. Grimus.

Some of the Open Questions in Flavour Physics.

- Why is there "Flavour"?
  i.e. What is the Origin of Family replication
- How to understand the observed spectrum of Fermion Masses and Mixing?
  Why is Leptonic Mixing Large, in contrast to Small Quark Mixing?
- Why is there Flavour Alignment in the Quark Sector?

The Question of Alignment

Within the SM, consider a set of Yukawa couplings Y_u, Y_d leading to hierarchical quark masses and small mixing. By small mixing we mean that there is a Weak Basis (WB) where:

$$M_u = \text{diag.}(m_u, m_c, m_t)\,; \quad M_d \simeq \text{diagonal}$$

The absolute ordering of quark mass eigenstates has no physical meaning. But the relative ordering, does have physical meaning. Since in the SM, Y_u, Y_d are <u>entirely independent</u> it is as likely that, in the basis where $M_u = \text{diag.}(m_u, m_c, m_t)$, one has $M_d \approx \text{diag}(m_d, m_s, m_b)$ corresponding to Alignment as to have $M_d \approx (m_b, m_d, m_s)$ implying Misalignment. Obviously, even assuming "small mixing" the probability of Aligment is only $1/6$.

CP Violation is closely related to the Question of Flavour

An open question :

- Is CP broken explicitly through complex Yukawa couplings like in the SM

or (T. D. Lee)

- Spontaneously : Lagrangian is invariant under CP but the vacuum violates CP?

At present, there is solid experimental evidence for a complex V^{CKM}.

Does this imply complex Yukawa couplings?

NO!!

There are realistic models of spontaneous CP violation where the vacuum phase generates a complex V^{CKM}.

Can one have geometrical CP violation?

For definiteness, let us consider an extension of the SM where n $SU(2) \times U(1)$ scalar doublets are introduced. In order to include the possible existence of "family" symmetries of the Lagrangian under which the scalar doublets transform non-trivially, one has to consider the most general CP transformation which leaves invariant the kinetic energy terms of the scalar doublets:

$$\boxed{CP\, \phi_i (CP)^\dagger = \sum_{j=1}^{n} U_{ij}\, \phi_j^*}$$

Let us assume that the vacuum is CP invariant, meaning that:

$$CP|0\rangle = |0\rangle$$

One can then derive, the following relation:

$$\boxed{\sum_{j=1}^{n} U_{ij} \langle 0|\Phi_j|0\rangle^* = \langle 0|\phi_i|0\rangle}$$

If the vacuum is such that none of the symmetries allowed by the Lagrangian satisfy the above equation, then this means that the vacuum is not CP invariant and we say that CP is <u>spontaneously broken</u>.

There are various examples of multi-Higgs models with "family" symmetries, where in a certain region of parameter space, the minimum of the scalar potential corresponds to fixed values of the vacuum phases, which do not depend on the specific values of the parameters of the potential.

Z_2 symmetry $\longrightarrow \langle \phi_1^0 \rangle = v_1 \; ; \; \langle \phi_2^0 \rangle = v_2 e^{i\pi/2}$

S_3 symmetry $\longrightarrow \langle \phi_1^0 \rangle = v \; ; \; \langle \phi_2^0 \rangle = v e^{i2\pi/3} \; ; \; \phi_3 = v e^{i4\pi/3}$

It has been shown by G.B, Gérard, J.M., Grimus, W that, contrary to naïve expectation all these vaccua are CP conserving.

However, an example was found, based on the group $\Delta(27)$ leading to genuine CP and T geometrical valuation.

Recently, interesting other examples have been found:

I. M. Varzielas, D. E. Costa, P. Leser Phys. Lett (2012)

I. P. Ivanov, L. Lavoura, Eur. Phys. (2013)

Realistic model?

Generation of the Baryon Asymmetry of the Universe (BAU)

The ingredients to dynamically generate BAU from an initial state with zero B. A. , were formulated by Sakharov (1967)

(i) Baryon number violation

(ii) C and CP Violation

(iii) Departure from thermal equilibrium

131

50

All these ingredients exist in the SM, but it has been established that in the SM, one cannot generate the observed BAU:

$$\boxed{\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm .15) \times 10^{-10}}$$

n_B, $n_{\bar{B}}$, n_γ number densities of baryons, antibaryons and photons at present time.

Reasons why the SM cannot generate sufficient BAU :

(i) CP violation in the SM is too small

$$\boxed{\frac{\mathrm{tr}\left[H_u, H_d\right]^3}{T_{ew}^{12}} \approx 10^{-20}}$$

(ii) Successful baryogenesis requires a strongly first order phase transition which would require a light Higgs mass

$$m_H \leq 70\,\mathrm{GeV}$$

The various manifestations of **CP violation**:

- CP violation in the quark sector
- CP violation in the lepton sector
- CP violation needed to generate **BAU**

A Common Origin?

- What about the Strong CP problem?

The need to suppress Flavour-Changing-neutral-currents (FCNC) led to the following two Dogmas:

- No Z-mediated FCNC at tree level
- No Scalar-mediated FCNC at tree level

{ Glashow, Weinberg
Paschos

Can one violate these two dogmas in reasonable extensions of the SM? Yes!

"Reasonable" means that FCNC should be naturally suppressed, without fine-tuning.

- In the gauge sector, the Dogma can be violated through the introduction of a $Q = 1/3$ and/or $Q = 2/3$ vector-like quark.

$\Downarrow$

Naturally small violations of 3×3 unitarity of V^{CKM}

$\Downarrow$

Z-mediated, Naturally suppressed FCNC at tree level

Yukawa interactions in the General two Higgs doublet Model

$$-\mathcal{L}_Y = \overline{Q}^0_L \Gamma_1 \phi_1 d^0_R + \overline{Q}^0_L \Gamma_2 \phi_2 d^0_R + \overline{Q}^0 \Delta_1 \tilde{\phi}_1 u^0_R + \overline{Q}_L \Delta_2 \tilde{\phi}_2 u^0_R + h.c.$$

Quark mass matrices:

$$M_d = \frac{1}{\sqrt{2}}\left(v_1 \Gamma_1 + v_2 e^{i\alpha} \Gamma_2\right) \; ; \; M_u = \frac{1}{\sqrt{2}}\left(v_1 \Delta_1 + v_2 e^{-i\alpha} \Delta_2\right)$$

Diagonalized by:

$$(U_d)_L^{\dagger} M_d (U_d)_R = D_d = \mathrm{diag}\,(m_d, m_s, m_b)$$

$$(U_u)_L^{\dagger} M_u U_{uR} = D_d = \mathrm{diag}\,(m_u, m_c, m_t)$$

Expanding around the vacuum:

$$\langle \Phi_j^0 \rangle = e^{i\alpha_j} \frac{1}{\sqrt{2}} \left(v_j + \rho_j + i\eta_j \right) \qquad j = 1,2$$

It is useful to introduce new fields:

$$\begin{pmatrix} H^0 \\ R \end{pmatrix} = O \begin{bmatrix} \rho_1 \\ \rho_2 \end{bmatrix} ; \quad \begin{bmatrix} G^0 \\ I \end{bmatrix} = O \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} ; \quad \begin{bmatrix} G^+ \\ H^+ \end{bmatrix} = O \begin{bmatrix} \phi_1^+ \\ \phi_2^0 \end{bmatrix}$$

$$O = \frac{1}{v} \begin{bmatrix} v_1 & v_2 \\ v_2 & -v_1 \end{bmatrix} ; \quad v = \sqrt{v_1^2 + v_2^2} \cong 246\ \text{GeV}$$

$H^0 \rightarrow$ has couplings to quarks proportional to mass matrices

$G^0 \rightarrow$ neutral pseudo Goldstone boson

$H^\pm \rightarrow$ charged pseudo-Goldstone bosons

Neutral and charged Higgs interactions in the quark sector

$$-\mathcal{L}_Y = \overline{d}_L^0 \frac{1}{v}\left(M_d H^0 + N_d^0 R + i N_d^0 I\right) d_R^0 +$$
$$+ \overline{u}_L^0 \frac{1}{v}\left(M_u H^0 + N_u^0 R + i N_u^0 I\right) u_R^0 +$$
$$+ \frac{\sqrt{2}}{v} H^+ \left(\overline{u}_L^0 N_d^0 d_R^0 - \overline{u}_R^0 N_u^{0\dagger} d_L^0\right) + h.c.$$

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

In the quark mass eigenstate basis N_d, N_u are not flavour diagonal.

Physical neutral Higgs are combinations of H^0, R, I

Yukawa Couplings in terms of quark mass eigenstates:

$$\mathcal{L}_Y = \frac{\sqrt{2}\,H^+}{v}\,\bar{u}\left[-V N_d \gamma_R + N_u^\dagger V \gamma_L\right] d + \text{h.c.} -$$

$$-\frac{H^0}{v}\left[\bar{u}\, D_u\, u + \bar{d}\, D_d\, d\right] -$$

$$-\frac{R}{v}\left[\bar{u}\left(N_u \gamma_R + N_u^\dagger \gamma_L\right) u + \bar{d}\left(N_d \gamma_R + N_d^\dagger \gamma_L\right) d\right]$$

$$+\frac{I}{v}\left[\bar{u}\left(N_u \gamma_R - N_u^\dagger \gamma_L\right) u - \bar{d}\left(N_d \gamma_R - N_d^\dagger \gamma_L\right) d\right]$$

$\gamma_L = \frac{1}{2}(1-\gamma_5)$; $\gamma_R = \frac{1}{2}(1+\gamma_5)$; V is the CKM matrix

Flavour changing neutral currents are controlled by :

$$N_d = \frac{1}{\sqrt{2}}\, U_{d_L}^{\dagger} \left(v_2 \Gamma_1 - v_1 e^{i\alpha} \Gamma_2 \right) U_{d_R}$$

$$N_u = \frac{1}{\sqrt{2}}\, U_{uL}^{\dagger} \left(v_2 \Delta_1 - v_1 e^{-i\alpha} \Delta_2 \right) U_{uR}$$

For generic two Higgs doublet models N_u, N_d are non-diagonal, arbitrary matrices.

$\Downarrow$

too large Higgs mediated Flavour changing neutral currents, unless a suppression mechanism is introduced

G.C.B, Grimus, W and Lavoura, L (BGL) have shown that it is possible to find a symmetry which when imposed on a 2-Higgs doublet extension of the SM, leads to a structure of the Yukawa couplings such that there are FCNC at tree level, with strength completely controlled by V_{CKM}, i.e., N_d, N_u only depend on V_{CKM} and on $\frac{v_1}{v_2}$.

Possible choice of the symmetry S:

$$Q^0_{L3} \to \exp(i\alpha)\, Q^0_{L3} \quad ; \quad u^0_{R3} \to \exp(i2\alpha)\, u^0_{R3}$$

$$\phi_2 \to \exp(i\alpha)\, \phi_2 \,,$$ where $\alpha \neq 0, \pi$

all other fields transform trivially under S.
This leads to the Yukawa couplings:

$$\Gamma_1 = \begin{bmatrix} \times & \times & \times \\ \times & \times & \times \\ 0 & 0 & 0 \end{bmatrix} \quad ; \quad \Gamma_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \times & \times & \times \end{bmatrix}$$

$$\Delta_1 = \begin{bmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad ; \quad \Delta_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \times \end{bmatrix}$$

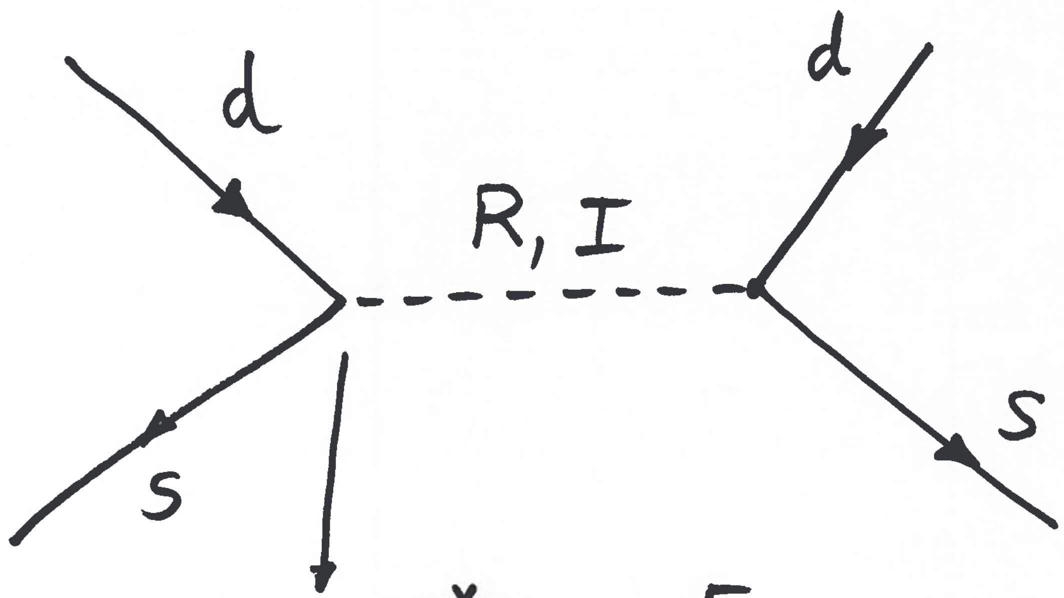
These Yukawa structures lead to:

$$\left(N_d\right)_{ij} = \frac{v_2}{v_1}\left(D_d\right)_{ij} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right)\left[V_{CKM}\right]_{3j}\left(D_d\right)_{jj}$$

$$\left(N_u\right) = -\frac{v_1}{v_2}\,\text{diag.}\left(0, 0, m_t\right) + \frac{v_2}{v_1}\,\text{diag.}\left(m_u, m_c, 0\right)$$

In this particular BGL model there are FCNC only in the down sector, but there is a strong, natural suppression of the most "dangerous" processes

$K^0 - \overline{K^0}$ mixing



$V_{td} V_{ts}^* \sim \lambda^5$

λ^{10} suppression!!

There are 6 different BGL models in the quark sector

An important Question:

Are there any other models, based on abelian symmetries, which lead to FCNC at tree level, completely controlled by V^{CKM}, without further parameters?

Intuitive Answer: Yes

Correct Answer: No!

P. Ferreira and J. Silva (Phys. Rev. D83 (2011)) have classified all possible implementations of an abelian symmetry in 2-Higgs doublet models, imposing the request of having non-vanishing quark masses and not block diagonal V^{CKM}!

Their conclusion : BGL models are unique

Open question : Non-abelian symmetries?

Other Approaches to Multi-Higgs Models

- **Minimal Flavour Violation**

  G. D'Ambrosio, G.F. Giudici, G. Isidori, A. Strumia (2002

  A. Buras, P. Gambino, M. Gorbahn, S. Jager, L. Silvestrini (2001)

  A. Dery, A. Efrati, G. Hiller, Y. Hochberg, Y. Nir (2013)

- **Alignment**

  A. Pich, P. Tuzon (2009)

In the quark mass eigenstate basis flavour mixing can be parametrized by various unitary matrices which arise from the misalignment in flavour space between pairs of various Hermitian flavour matrices.

This is entirely analogous to what one encounters in the SM

$V_{CKM} \rightarrow$ arises from the misalignment between $H_u \equiv M_u M_u^\dagger$ and $H_d \equiv M_d M_d^\dagger$

Weak-basis invariants are a useful to study Flavour.

Example :

J. Bernabeu, G.C.B., M. Gronau

$$\mathrm{tr}\left[H_u, H_d\right]^3 = 6i\,(m_c^2 - m_u^2)(m_t^2 - m_c^2)(m_t^2 - m_u^2) \times (m_s^2 - m_d^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2) \times \mathrm{Im}\, Q$$

$\propto \det\left[H_u, H_d\right]$ for 3 generations (C. Jarlskog)

$Q \rightarrow$ invariant quartet of V_{CKM}

One may also study invariants under Higgs basis transformations

G.C.B., M.N. Rebelo, Silva-Marcos ; H. Haber, F. Gunion
S. Davidson, H. Haber

We have seen that under a WB transformation:

$$d^0_L = W_L\, d^{0\prime}_L \quad ; \quad d^0_R = W^d_R\, d^{0\prime}_R$$

$$u^0_L = W_L\, u^{0\prime}_L \quad ; \quad u^0_R = W^u_R\, u^{0\prime}_R$$

Under a WB transformation the flavour matrices transform as:

$$M_d \longrightarrow M'_d = W_L^\dagger M_d W^d_R \quad ; \quad M_u \to M'_u = W_L^\dagger M_u W^u_R$$

$$N^0_d \longrightarrow N^{0\prime}_d = W_L^\dagger N^0_d W^d_R \quad ; \quad N^0_u \to N^{0\prime}_u = W_L^\dagger N^0_u W^u_R$$

In view of the freedom of choice of WB, it is useful to express the physical content of M_d, M_u, N^0_d, N^0_u in terms of WB invariants.

Examples of Invariants:

$$I_1 \equiv \mathrm{tr}\left(M_d N_d^{0\dagger}\right) = m_d (N_d^*)_{11} + m_s (N_d^*)_{22} + m_b (N_b^*)_{33}$$

where N_d is N_d^0 in the basis where the down quark mass matrix is diagonal. This invariant is not sensitive to Higgs mediated FCNC but $\mathrm{Im}\, I_1$ is specially important, since it probes the phases of $(N_d)_{jj}$ which contribute to the electric dipole moment of down quarks.

Analogous comments apply to $\mathrm{tr}\left(M_u N_u^{0\dagger}\right)$

Consider now a WB invariant which is sensitive to the off-diagonal elements of N_d:

$$I_2 \equiv \mathrm{tr}\left[M_d N_d^{0\dagger}, M_d M_d^\dagger\right]^2 = -2 m_d m_s (m_s^2 - m_d^2)^2 (N_d)_{12} N^*_{d\,21} - 2 m_d m_b (m_b^2 - m_d^2)(N_d^*)_{13}(N_d^*)_{31} - 2 m_s m_b (m_b^2 - m_s^2)^2 \times (N_d)_{23}(N_d^*)_{32}$$

CP-odd WB invariant:

$(m_u^2 - m_c^2)\ldots.$

analogous

$$I_2^{CP} \equiv \mathrm{tr}\left[H_u, H_{N_d^0}\right]^3 = 6 i \Delta_u \, \Delta_{N_d} \, \mathrm{Im}\, Q_2$$

$Q_2 \rightarrow$ is a rephasing invariant quartet of V_2

$$V_2 \equiv U_u^\dagger (U_{N_d^0})_L$$

These invariants can be very useful to study the CP properties (as well as FCNC) in specific models. For example in BGL models:

$$\mathrm{Im}\,\mathrm{tr}\left(M_d N_d^{0\dagger}\right) = 0$$

In BGL models the lowest order invariant sensitive to CP violation is:

$$I_g^{CP} \equiv \mathrm{tr}\left[M_d N_d^{0\dagger} M_d M_d^\dagger M_u M_u^\dagger M_d M_d^\dagger\right]$$

This may be relevant for Baryogenesis.

See M. N. Rebelo talk

Conclusions

- We are entering the **Higgs Era** in Particle Physics.
- A crucial question is : Will Higgs particle(s) play an important rôle in Flavour?
- My guess : Yes, it will not be just **Vanilla Higgs**.
- It may take some time until Higgs Flavour be tasted experimentally. We have to be patient and remember **Neutrinos**
- We can safely violate the two Flavour Dogmas.

A Minimal Model

Consider an extension of the SM, where the following new fields are introduced:

- A vectorial quark D^0, with both D^0_L and D^0_R are $SU(2)_L$ singlets with charge $Q = -1/3$ (or $Q = 2/3$)
- 3 right-handed neutrinos ν^0_{Rj}
- A neutral complex singlet S

- Since we want to have Spontaneous CP violation, we impose CP invariance at the Lagrangian level: All couplings real.
- Introduce a Z_4 symmetry on the Lagrangian, under which:

$$\psi_\ell^0 \to i\,\psi_\ell^0 \;;\quad e_{R_j}^0 \to i\, e_{R_j}^0 \;;\; \nu_{R_j}^0 \to i\,\nu_{R_j}^0$$

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

The Z_4 symmetry is crucial to obtain a solution of the Strong CP problem and Leptogenesis

Scalar Potential

The Scalar potential contains various terms which do not have phase dependence, but there are terms with phase dependence.

$$V_{phase} = \left[\mu^2 + \lambda_1 S^* S + \lambda_2 \phi^\dagger \phi\right](S^2 + S^{*2}) + \lambda_3 (S^4 + S^{*4})$$

There is a range of the parameters of the Higgs potential, where the minimum is at:

$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \; ; \; \langle S \rangle = \frac{V}{\sqrt{2}} e^{i\theta}$$

Most general $SU(2)_L \times U(1) \times SU(3)_c \times Z_4$ invariant Yukawa couplings in the quark sector :

$$\mathcal{L}_Y = -(\bar{u}^0 \ \bar{d}^0)_{L_i} \left[g_{ij}\, d^0_{R_j} + h_{ij}\, \tilde{\phi}\, u^0_{R_j} \right] - \bar{M}(\bar{D}^0_L D^0_R)$$

$$- (f_i S + f' S^*)\, \bar{D}^0 d^0_{R_i} + h.c.$$

Quark mass matrix for down-type quarks :

$$\begin{pmatrix} \bar{d}^0_{1L} & \bar{d}^0_{2L} & \bar{d}^0_{3L} & \bar{D}^0_L \end{pmatrix} \begin{bmatrix} \underset{\uparrow}{\overset{3\times 3,\ \text{real}}{}} \ m_d & 0 \\ M_1 \ M_2 \ M_3 & \bar{M} \end{bmatrix} \begin{bmatrix} d^0_{1R} \\ d^0_{2R} \\ d^0_{3R} \\ D^0_R \end{bmatrix}$$

"zero" due to Z_4 symmetry

$$M_j = f_j V e^{i\theta} + f'_j V e^{-i\theta}$$

$$\mathcal{M} \equiv \left[\begin{array}{c:c} m_d & 0 \\ \hdashline M_1, M_2, M_3, & \bar{M} \end{array}\right];$$

$$U_L^\dagger \left(\mathcal{M}\mathcal{M}^\dagger\right) U_L = \text{diag.}\left(d^2, D^2\right)$$

$\mathcal{U} = \begin{bmatrix} K & R \\ S & T \end{bmatrix}$; One can easily derive :

$$K^{-1}\left[m_d m_d^\dagger - \frac{m_d \overbrace{M^\dagger M}^{\text{complex}} m_d^\dagger}{\left(MM^\dagger + \bar{M}^2\right)}\right] K = d^2$$

A remarkable feature of the Model :

The phase θ arising from $\langle S \rangle$, generates a non-trivial CKM phase, provided $|M_j|$ and $\bar{M}$ are of the same order of magnitude (This is "natural")

$$K^{-1} \; m_{eff} \, m_{eff}^{\dagger} \; K = \text{diag.}\left(m_d^2, m_s^2, m_b^2\right)$$

$$m_{eff} \, m_{eff}^{\dagger} = m_d m_d^{\dagger} - \frac{m_d M^{\dagger} M m_d^{\dagger}}{M M^{\dagger} + \bar{M}^2}$$

$$M_j = \left(f_j V e^{i\theta} + f_j' V e^{-i\theta}\right)$$

Naturally small deviations of 3x3 unitarity

Naturally Small Flavour-Changing Neutral Currents

For definiteness, consider the case of one isosinglet $Q = -1/3$ quark

3x3 VCKM

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} (\bar{u}\ \bar{c}\ \bar{t})_L \gamma^\mu \begin{bmatrix} K & R \end{bmatrix} \begin{bmatrix} d \\ s \\ b \\ D \end{bmatrix} W_\mu^+$$

$$\mathcal{L}_Z = -\frac{g}{2\cos\theta_W} \left\{ (\bar{u}\ \bar{c}\ \bar{t})_L \gamma^\mu \begin{bmatrix} u \\ c \\ t \end{bmatrix}_L - \begin{bmatrix} \bar{d} & \bar{s} & \bar{b} & \bar{D} \end{bmatrix} \begin{bmatrix} K^\dagger K & K^\dagger R \\ R^\dagger K & R^\dagger R \end{bmatrix} \gamma^\mu \begin{bmatrix} d \\ s \\ b \\ D \end{bmatrix} \right.$$

$$\left. - \sin^2\theta_W J_{em}^\mu \right\} Z_\mu$$

Why deviations of 3×3 unitarity are naturally small:

$$\mathcal{U}_L^\dagger \mathcal{M}\mathcal{M}^\dagger \mathcal{U}_L = \mathrm{diag.}(m_d^2, m_s^2, m_b^2, M_D^2)$$

$$\mathcal{U}_L = \begin{bmatrix} K & R \\ S & T \end{bmatrix} \quad ; \quad K^\dagger K + S^\dagger S = 1$$

but $\quad S \simeq -\dfrac{M\, m_d^\dagger K}{\overline{M}^2} \to O(m/M)$;

$K^\dagger K = 1 - O(m^2/M^2)$. Note that there is nothing strange about violations of 3×3 unitarity. The PMNS matrix is not unitary in the framework of seesaw mechanism, type I.

Some comments :

- Nothing "strange" in having deviations of 3×3 unitarity of V_{CKM}. The PMNS matrix in the leptonic sector, in the context of type-one seesaw, is not 3×3 unitary.
- Vector-like quarks provide the simplest model with Spontaneous CP violation, with a complex V_{CKM}, in agreement with experiment
- Provide a framework to have a Common Origin of all CP violations.
- Potential Solution of Strong CP problem without Axions