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

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We shall consider extensions of the SM with Vector-like isosinglet quarks of $Q = -1/3$ or $Q = 2/3$.

Question : Why consider these extensions?

what can vector-like quarks do for us?

Seven reasons to consider vector-like quarks

1. They provide a self-consistent framework with naturally small violations of 3×3 unitarity of V^{CKM}

$$\Downarrow$$

2. Lead to naturally small Flavour-Changing Neutral Currents (FCNC) (mediated by Z_μ)

3. Provide the simplest framework to have Spontaneous CP violation, with a Vacuum Phase generating a non-trivial CKM phase.

Important requirement:

There is experimental evidence of a Complex V^{CKM} even if one allows for the presence of New Physics.

4. Provide New Physics contributions to $B_d - \bar{B}_d$ mixing and $B_s - \bar{B}_s$ mixing.

5. Provide a simple solution to the Strong CP problem, which does not require Axions.

6. May contribute to the understanding of the observed pattern of fermion masses and mixing.

7. Provide a framework where there is a common origin of all CP Violations:

(i) CP Violation in the Quark Sector

(ii) CP Violation in the Lepton Sector detectable through neutrino oscillations $U_{e3} \neq 0$ and "relatively large": Great News!!

(iii) CP violation needed to generate the Baryon Asymmetry of the Universe (BAU) through Leptogenesis.

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:

$$\psi^0_\ell \to i\,\psi^0_\ell \; ; \quad e^0_{R_j} \to i\,e^0_{R_j} \; ; \quad \nu^0_{R_j} \to i\,\nu^0_{R_j}$$

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

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.

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

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

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

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

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

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

Quark mass matrix for down-type quarks :

$$\left(\bar{d}^0_{1L} \; \bar{d}^0_{2L} \; \bar{d}^0_{3L} \; \bar{D}^0_L \right) \left[\begin{array}{ccc:c} & \overset{3\times3,\ \text{real}}{m_d} & & 0 \\ \hdashline M_1 & M_2 & M_3 & \bar{M} \end{array} \right] \begin{bmatrix} d^0_{1R} \\ d^0_{2R} \\ d^0_{3R} \\ D^0_R \end{bmatrix}$$

"zero" due to Z_4 symmetry

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

$$\mathcal{M} \equiv \left(\begin{array}{c|c} m_d & 0 \\ \hline M_1, M_2, M_3 & \overline{M} \end{array}\right);$$

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

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

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

A remarkable feature of the Model:

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

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

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

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

Violating 3×3 Unitarity

Suppose that one drops the requirement of 3×3 unitarity. How many independent parameters are there in 3×3 V^{CKM}?

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & \cdots \\ V_{cd} & V_{cs} & V_{cb} & \cdots \\ V_{td} & V_{ts} & V_{tb} & \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

9 moduli + 4 rephasing invariant phases =

= 13 parameters

A convenient choice for the 4 independent rephasing invariant phases is:

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

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

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

$$\chi' \equiv \arg\left(-V_{us} V_{cd} V_{ud}^* V_{cs}^*\right)$$

The SM with 3 generations predicts a series of exact relations among the 13 measurable (in principle) quantities.

Violations of any of these exact relations signals the presence of New Physics which may involve deviations of 3×3 unitarity or not.

The presence of New Physics contributions to $B_d-\bar{B}_d$ and $B_s-\bar{B}_s$ mixings affects the extraction of $|V_{td}|$, $|V_{ts}|$ from the data, even in the framework of New Physics which respects 3×3 unitarity.

Example : SUSY extensions of the SM

In many of the extensions of the SM the dominant effect of New Physics arises from new contributions to $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixings, which is convenient to parametrize as:

$$M_{12}^q = (M_{12}^q)^{SM} r_q^2 e^{2i\theta_q} \qquad q = d, s$$

$$\Delta M_{B_d} = r_d^2 (\Delta M_{B_d})^{SM} \longrightarrow$$ affects the extraction of $|V_{td}|$ from ΔM_{B_d}

$$\Delta M_{B_s} = r_s^2 (\Delta M_{B_s})^{SM} \longrightarrow$$ affects the extraction of $|V_{ts}|$ from ΔM_{B_s}.

$$S_{J/\psi K_S} = \sin(2\beta + 2\theta_d) = \sin(2\bar{\beta})$$

$$S_{\rho^+\rho^-} = \sin(2\alpha - 2\theta) = \sin(2\bar{\alpha})$$

How to detect the Presence of New Physics?

Answer: One can use the exact relations predicted by the SM.

$$(db) \to \quad |V_{ub}| = \frac{V_{cd} V_{cb}}{V_{ud}} \frac{\sin\beta}{\sin(\gamma+\beta)} \to \text{extraction of } \theta_d$$

$$(sb) \to \quad \sin\chi = \frac{|V_{us}||V_{ub}|}{|V_{cs}||V_{cb}|} \sin(\gamma - \chi + \chi') \to$$

extraction of θ_s

Extraction of θ_d :

$$\tan\theta_d = \frac{R_u \sin(\gamma+\bar{\beta}) - \sin\bar{\beta}}{\cos\bar{\beta} - R_u\cos(\gamma+\bar{\beta})} \quad ; \quad R_u = \frac{|V_{ud}||V_{ub}|}{|V_{cd}||V_{cb}|}$$

Extraction of θ_s :

$$\tan\theta_s = \frac{\sin\bar{\chi} - C\sin(\gamma-\bar{\chi})}{C\cos(\gamma-\bar{\chi}) + \cos\bar{\chi}} \quad ; \quad C = \frac{|V_{us}||V_{ub}|}{|V_{cs}||V_{cb}|}$$

To an excellent approximation one has:

$$\sin\chi \approx \frac{|V_{us}|^2}{|V_{ud}|^2}\,\frac{\sin\beta\,\sin\gamma}{\sin(\gamma+\beta)} \rightarrow \text{Silva, Wolfenstein}$$

$$\sin\chi = \frac{|V_{td}|}{|V_{ts}|}\,\frac{|V_{cd}|}{|V_{cs}|}\,\sin\beta \rightarrow \text{Botella, Nebot, Rebelo, GCB}$$

$\Rightarrow$ If either (γ, χ) or $\left(\frac{\Delta M_{Bd}}{\Delta M_{Bs}}, \chi\right)$ are measured with some precision, one has novel stringent tests of the SM, where contribution of New Physics can be significant.

Naturally small deviations of 3×3 unitarity

Naturally Small Flavour-Changing Neutral Currents

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

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} (\bar{u}\ \bar{c}\ \bar{t})_L\, \gamma^\mu \left[\underset{\substack{\uparrow \\ 3\times3\ V_{CKM}}}{K}\ R \right] \begin{bmatrix} d \\ s \\ b \\ D \end{bmatrix} W_\mu^+$$

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

Why deviations of 3×3 unitarity are naturally small:

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

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

but $\quad S \approx -\dfrac{M\, m_d^\dagger K}{\bar{M}^2} \rightarrow O(m/M)$;

$K^\dagger K = 1 - O(m^2/M^2)$. 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.

Confronting experiment

Can extensions of the SM, with vector-like quarks "solve" some of the tensions between SM and experiment?

Answer: Yes! In the framework of an extension of the SM, with one $Q = 2/3$ vector-like quark, it has been shown that the tensions can be solved and various correlations are predicted.

F. Botella, M. Nebot, GCB arXiv:1207.4440 (2012)

But the important point is for experiment/theory to confirm that deviations are really there

From Cecilia Tarantino talk at ICHEP2012

From a closer look

UTfit

From the UTA (excluding its exp. constraint)

	Prediction	Measurement	Pull
$\sin 2\beta$	0.81±0.05	0.680±0.023	2.4 ←
γ	68°±3°	76°±11°	<1
α	88°±4°	91°±6°	<1
$\lvert V_{cb}\rvert \cdot 10^3$	42.3±0.9	41.0±1.0	<1
$\lvert V_{ub}\rvert \cdot 10^3$	3.62±0.14	3.82±0.56	<1
$\varepsilon_K \cdot 10^3$	1.96±0.20	2.23±0.01	1.4 ←
$BR(B \to \tau\nu) \cdot 10^4$	0.82±0.08	1.67±0.30	-2.7 ←

Leptonic Sector

Recall that the leptonic fields transform under Z_4 as: $\psi_L^0 \to i\psi_L^0$; $e_R^0 \to i e_R^0$; $\nu_R^0 \to i\nu_R^0$

Leptonic Yukawa terms:

$$\mathcal{L}_\ell = \overline{\psi}_L^0 G_\ell \phi e_R^0 + \overline{\psi}_L^0 G_\nu \tilde{\phi} e_R + \frac{1}{2} \nu_R^{0T} C (f_\nu S + f_\nu' S^*) \nu_R^0 + \text{h.c.}$$

Leptonic mass matrices:

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & m \\ m^T & M \end{bmatrix} \qquad m_\ell = \frac{v}{\sqrt{2}} G_\ell \quad ; \quad m = \frac{v}{\sqrt{2}} G_\nu$$

$$M = \frac{V}{\sqrt{2}} f_\nu^+ \cos\alpha + i f_\nu^- \sin\alpha$$

$$f^\pm \equiv f_\nu \pm f_\nu'$$

Leptonic Mixing

In the weak-basis where m_ℓ is diagonal, real, the light neutrino masses and low energy leptonic mixing are obtained from

$$K^\dagger \left[m \frac{1}{M} m^T \right] K = d_\nu$$

m is real, but since M is a generic complex matrix, m_{eff} is also a generic complex matrix.

$K \rightarrow$ 3 complex phases one Dirac-type, two Majorana-type

PMNS

Conclusions

- Vector like quarks provide a very interesting scenario for New Physics
- They are a crucial ingredient in the simplest model of spontaneous CP violation where a complex V^{CKM} is generated from a vacuum phase
- They provide a consistent framework where there are naturally small violations of 3x3 unitarity in V^{CKM}, leading to naturally small Z-FCNC.
- They provide a simple solution to the Strong CP problem, without axions