Do the Small numbers in VCKM arise from New Physics?

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work done in recent collaboration with J. Bastos and J.I. Silva Marcos and older collaboration with F. Botella, M.N. Rebelo et al

Organization of the talk

- Identification of the small numbers in V_{CKM}
- Conjecture: The small numbers in V^{CKM} arise from New Physics
- Motivation for vector-like quarks (VLQs) and simple realization of the Conjecture with VLQs
- Phenomenological consequences
- Conclusions

Identification of the Small numbers in V_{CKM} :

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

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

$Q \to$ Rephasing invariant quartet of V_{CKM}

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

Details about Rephasing invariant quantities

Example:

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

$$\mathrm{Im}\, Q \cong \lambda^6 \sin(\arg Q)$$

$|\mathrm{Im}\, Q|$ has the same value for all quartets and measures the strength of CP violation in the SM. One can have rephasing invariants of higher order in V_{ij}, but they can be written in terms of Qs and moduli

A surprising result: In the 3x3 up corner of a V^{CKM} matrix of arbitrary size one has:

9-5 = 4 rephasing invariant phases

The following phase convention may be chosen, in general

$$\arg V^{3\times3} = \begin{pmatrix} 0 & \beta_K & \gamma \\ \pi & 0 & 0 \\ -\beta & \pi+\beta_s & 0 \end{pmatrix}$$

The phases γ, β, β_s, β_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 unnecessary, because

$$\alpha \equiv \pi - \beta - \gamma$$

By definition !!!

Within the SM, 3x3 unitarity implies some exact relations among rephasing invariant quantities:

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

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

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

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

The conjecture implies that within the SM,

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

$$\mathrm{Im}\, Q = 0$$

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

A crucial question:

What can VLQs do for you?

(i) They provide a simple alternative solution to the Strong CP problem without axions. Barr and Nelson
Bento, G.C.B and Parada

(ii) They provide the simplest extension of the SM with Spontaneous CP Violation in a model consistent with experiment.

Requirements to have a viable model of Spontaneous CP Violation:

- Lagrangian should be CP invariant but CP invariance should be broken by the vacuum.

One has to be careful. Often a "geometrical" vacuum phase does not violate CP

- The vacuum phase should be able to generate a complex CKM matrix

Experimentally $\gamma \neq 0, \pi$

(iii) 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 $t \to c Z_\mu$

may receive tree-level contributions in models with up-type VLQs

IV 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

V VLQs may play an important rôle in providing an explanation for the ...

V^{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

Question : Should we take this "deviation of unitarity" seriously?

My approach was : "When you are not sure, ask a friend who is a specialist.

In this case we asked Bill Marciano

His answer : Yes, it should be taken seriously !!

The generation of $|V_{ub}|$ and $\operatorname{Im} Q$ from New Physics

We propose that V^{CKM}_{eff} is generated from three different contributions:

$$V^{CKM}_{eff} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}_{up} \begin{bmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & e^{i\delta'} & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix}_{NP} \times$$

$$\times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}_{down}$$

In order to obtain the proposed V^{CKM} structure, we assume that there is a weak-basis where M_d, M_u have the following structure:

$$M_d = \begin{bmatrix} m^d_{11} & m^d_{12} & 0 \\ m^d_{21} & m^d_{22} & 0 \\ 0 & 0 & m_b \end{bmatrix} ; \quad M_u = \begin{bmatrix} m^u & 0 & 0 \\ 0 & m^u_{22} & m^u_{23} \\ 0 & m^u_{32} & m^u_{33} \end{bmatrix}$$

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

Without New Physics one has:

$$V^{CKM} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} =$$

$$\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12}c_{23} & c_{23}c_{12} & +s_{23} \\ -s_{23}s_{12} & -s_{23}c_{12} & c_{23} \end{bmatrix}$$

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

Our conjecture offers an explanation why $|V_{31}| > |V_{13}|$!!!

Introduce an up-type VLQ and assume the 4×4 up-type quark mass matrix:

$$M_u = \begin{bmatrix} 0 & 0 & 0 & m_{14} \\ 0 & m_{22} & m_{23} & 0 \\ 0 & m_{32}e^{i\alpha} & m_{33} & 0 \\ m_{41} & 0 & m_{43} & M \end{bmatrix}$$

Then one can generate

$$|V^{CKM}_{eff}|_{13} \neq 0 \qquad |\mathrm{Im}\, Q_{eff}| \neq 0$$

Numerical Example

Mass matrices in GeV at M_Z scale

$$M_d = \begin{bmatrix} 0.0029 & -1.35\times 10^{-2} & 0 \\ 6.73\times 10^{-4} & 0.058 & 0 \\ 0 & 0 & 2.9 \end{bmatrix}$$

$m_d = 0.003$; $m_s = 0.06$; $m_b = 2.9$

$$M_u = \begin{bmatrix} 0 & 0 & 0 & 53.73 \\ 0 & 0.59 & -6.91 & 1.25\,e^{-0.285i} \\ 0 & -0.024 & 172.8 & 0 \\ 0.046 & 0 & 14.88\,e^{-1.99i} & 1250 \end{bmatrix}$$

$m_u = 0.02$ $m_c = 0.60$ $m_t = 173$ $m_T = 1251$

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

The CKM matrix is the 4x3 left submatrix of the following 4x4 unitary matrix

$$V = \begin{pmatrix} 0.9735 & 0.2244 & 0.0037 & 0.0423 \\ 0.224 & 0.9736 & 0.0399 & 0.00099 \\ 0.00834 & 0.0393 & 0.999 & 0.00151 \\ 0.04163 & 0.0105 & 0.001674 & 0.999 \end{pmatrix}.$$

These mass matrices lead to:

$$\gamma \approx 68^\circ$$

$$\sin 2\beta \approx .746$$

$$\beta_s \cong 0.02$$

$$I^{CP} \equiv |\mathrm{Im}\, Q| \approx 3 \times 10^{-5}$$

Conclusions

- VLQs are one of the simplest extension of the SM, with a large number of phenomenological implication
- VLQs are "cousins" of ν_R which provide through seesaw the most plausible explanation of the smallness of neutrino masses.
- The effects of VLQs may have been seen already in deviations of unitarity in the first line of V_{CKM}.

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

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

The SM was an notable exception.

Before gauge interactions the suggestion was IVB with ≈ 2 GeV!

intermediate vector boson...