Constraints on on vector-like quark model from rare B decays.

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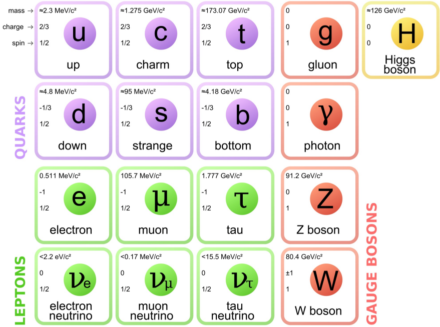
Standard Model Quarks

The SM has 6 quarks in 3 generations:

- Up-type: u, c, t (charge +2/3)
- Down-type: d, s, b (charge -1/3)
- Left-handed doublets, right-handed singlets under $SU(2)_L$.
- Dirac mass terms not allowed, Higgs mechanism via Yukawa couplings generates quark mass.



Yukawa Couplings

In SM quarks acquire their mass through invariant Yukawa couplings to an isodoublet scalar Higgs field ϕ:

$$-f_d^{ij}\bar{\psi}_L^i d_R^j \phi - f_u^{ij}\bar{\psi}_L^i u_R^j \tilde{\phi} + \mathrm{H.C.}\ ,$$

where the three generations of the regular quarks are indexed as $i, j = 1, 2, 3$ with the quark and Higgs doublets are defined as:

$$\psi_L^i = \begin{pmatrix} u^i \\ d^i \end{pmatrix}_L, \ \ \phi = \begin{pmatrix} \chi^+ \\ \frac{1}{\sqrt{2}}(v + H + i\chi^\circ) \end{pmatrix}, \ \ \tilde{\phi} = \begin{pmatrix} \frac{1}{\sqrt{2}}(v + H - i\chi^\circ) \\ -\chi^- \end{pmatrix}.$$

v, H and $\chi^{\circ\pm}$ are Higgs vacuum expectation value, physical and unphysical Higgs, respectively.

Spontaneous Electroweak Symmetry Breaking

The non-zero v leads to spontaneous electroweak symmetry breaking and creation of mass terms for quarks as follows

$$\bar{d}_L^i M_d^{ij} d_R^j + \bar{u}_L^i M_u^{ij} u_R^j + \mathrm{H.C.} ,$$

where $i,\ j = 1, 2, 3$.
To diagonalize the mass matrix, 3×3 unitary transformations $A_L^{u,d}$ and $A_R^{u,d}$ rotate the weak left- and right-handed eigenstates into the mass (physical) eigenstates, i.e.

$$A_L^{d\dagger} M_d A_R^d = \mathrm{diag}(m_d, m_s, m_b) \ , \ A_L^{u\dagger} M_u A_R^u = \mathrm{diag}(m_u, m_c, m_t) \ ,$$

The mass eigenstates $u'_{L,R}$ and $d'_{L,R}$ are related to weak eigenstates via

$$u_{L,R}^i = \sum_{j=1}^{3} (A_{L,R}^u)^{ij} u'^j_{L,R} \ , \ \ d_{L,R}^i = \sum_{k=1}^{3} (A_{L,R}^d)^{ik} d'^k_{L,R} \ .$$

Quark mixing

Rotation from weak eigenstates to mass eigenstates leads to quark mixing. For example, the charge current interaction term:

$$J_{CC} = \sum_{i=1}^{3} \frac{g}{\sqrt{2}} \bar{u}_L^i \gamma^\mu d_L^i W_\mu^+ + \mathrm{H.C.} \, ,$$

trasforms to

$$J_{CC} = \sum_{j,k=1}^{3} \frac{g}{\sqrt{2}} \bar{u}_L'^j V^{jk} \gamma^\mu d_L'^k W_\mu^+ + \mathrm{H.C.} \, ,$$

where the quark mixing matrix (CKM) V is unitary:

$$V = A_L^{u\dagger} A_L^d \;\; , \;\; V^\dagger V = A_L^{d\dagger} A_L^u A_L^{u\dagger} A_L^d = 1$$

FCNCs are absent at tree level due to GIM mechanism. Suppressed at loop level.

What are Vector-Like Quarks?

Vector-like quarks transform identically under the SM gauge group for left and right chiral components:

- No chiral asymmetry (vector-like couplings)
- Dirac mass terms allowed without Yukawa/Higgs breaking gauge symmetry
- Appear in many BSM models (composite Higgs, extra dimensions, etc.)

Recent direct searches at the LHC, at a center-of-mass energy of 13 TeV, have set lower limits on the masses of VLQs: $M_U > 1.26\ \mathrm{TeV}$ and $M_D > 1.33\ \mathrm{TeV}$ for the up-type and down-type vector quarks respectively.

Adding a Single Down-type VLQ to SM

$$\mathcal{L}_{\rm VLQ}^{\rm Dirac} = M(\bar{D}_R D_L + \bar{D}_L D_R) \ , \ \mathcal{L}_{\rm VLQ}^{\rm Yukawa} = -f_d^{i4} \bar{\psi}_L^i D_R \phi + {\rm H.C.}$$

After spontaneous symmetry breaking, quark mass matrices are now the followings:

$$\bar{d}_L^\alpha M_d^{\alpha\beta} d_R^\beta + \bar{u}_L^i M_u^{ij} u_R^j + {\rm H.C.}$$

where $\alpha, \ \beta = 1, 2, 3, 4$. M_d is now a 4×4 matrix which can be written as

$$M_d = \frac{v}{\sqrt{2}} \begin{pmatrix} f_d^{11} & f_d^{12} & f_d^{13} & f_d^{14} \\ f_d^{21} & f_d^{22} & f_d^{23} & f_d^{24} \\ f_d^{31} & f_d^{32} & f_d^{33} & f_d^{34} \\ 0 & 0 & 0 & \frac{\sqrt{2}M}{v} \end{pmatrix}$$

4×4 unitary transformations A_L^d and A_R^d rotate the weak left- and right-handed eigenstates into the mass (physical) eigenstates, i.e.

$$A_L^{d\dagger} M_d A_R^d = {\rm diag}(m_d, m_s, m_b, M_D) \ ,$$

Extended Quark Mixing Matrix

$M \gg v$, which means that the mixing between SM quarks and the VLQ is small. Indeed, assuming $f^{i4}\frac{v}{\sqrt{2}} \ll M$, one can treat the diagonalization perturbatively and therefore, the left-handed mixing can be written as:

$$(A_L^d)^{i4} \approx f^{i4}\frac{v}{\sqrt{2}M}$$

The **extended** 3×4 **CKM quark mixing matrix** , is the product of the elements of the unitary matrices A_L^u (3×3) and A_L^d (4×4):

$$V^{i\alpha} = \sum_{j=1}^{3} A_L^{u\,ij} A_L^{d\,j\alpha} \ .$$

$$(V^\dagger V)^{\alpha\beta} = \delta^{\alpha\beta} - (A_L^{d\,*})^{4\alpha} A_L^{d\,4\beta} \ .$$

Indeed, this non-unitarity leads to the possibility of having non-zero FCNC at the tree level in the VLQ NP scenario.

VLQ Model Parameters for FCNC $b \to s$ Transitions

Non-unitarity of the extended quark mixing leads to the tree level vertices bsZ, bsH and $bs\chi^\circ$ are all proportional to the model parameter U^{sb} defined as

$$U^{sb} = (V^\dagger V)^{sb} = -({A_L^{d*}})^{42} A_L^{d\,43} \approx \frac{f^{42} f^{43} v^2}{M_D^2} \equiv \frac{y_{sb} v^2}{M_D^2}$$

where $y_{sb} = f^{42} f^{43} = |y_{sb}| e^{i\theta_{sb}}$. Thus, we have 3 free parameters in this VLQ scenario: $|y_{sb}|, \theta_{sb}$ and M_D.
The experimental limit on unitarity violation

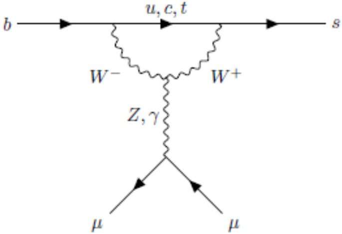
$$\left| \frac{U_{sb}}{V_{tb} V_{ts}^*} \right| = 0.04 \pm 0.04 \ ,$$

VQL Contributions to $b \to s\mu^+\mu^-$ Decay

Standard Model: Penguin diagram $\to$ Effective vertex $F(x_i), x_i = m_i^2/m_W^2, i = u, c, t$

- x_i-independent terms which are absent within the SM due to the unitarity of the CKM quark mixing need to be taken into account in the presence of VLQ.
- This new contribution has the form of

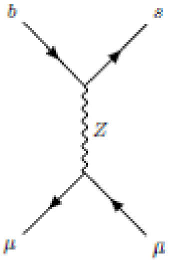
$$\text{constant} \times U^{sb}$$



VQL Contributions to $b \to s\mu^+\mu^-$ Decay

Tree-level FCNC:

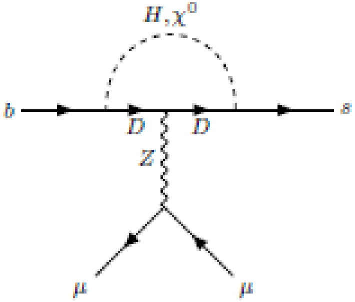
- Non-unitarity of the quark mixing leads to tree-level FCNC transitions which are absent in SM.
- This new contribution which scales with U^{sb} is taken as the most significant VLQ amplitude, leading to sever constraint on model parameters.



VQL Contributions to $b \to s\mu^+\mu^-$ Decay

One-loop Higgs exchange:

- This Higgs penguin amplitude, which is absent in SM, is boosted by the large mass of the VLQ, i.e. M_D.
- The interference between the tree-leval and one-loop Higgs amplitude can open new windows for allowed VLQ model parameters.



Results

Constraints on the VLQ model parameters from inclusive $B \to X_s \mu^+ \mu^-$ data: