Hunting for New Physics with Up Vector-like Quarks

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Hunting for New Physics with Up Vector-like Quarks

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Abstract. An interesting class of scenarios beyond the Standard Model extends the fermionic content of the theory through the addition of vector-like isosinglet quarks. Through a detailed analysis of available experimental constraints, potential deviations from the Standard Model expectations are addressed in observables such as the time-dependent CP asymmetry in $B_s \rightarrow J/\Psi \Phi$ decays, the $D_0$ same charge dimuon asymmetry in $B$ meson systems $A_{SL}$, rare kaon and $B$ decays and deviations from a $3 \times 3$ unitary mixing matrix.

1. Introduction
We consider an extension of the Standard Model (SM) where one isosinglet vector-like quark $T$ with charge $Q = 2/3$ is added to the spectrum [1,2,3]. In addition to the usual Yukawa terms

$$\mathcal{L}_{Y_{SM}} = -\bar{q}_0 L_i \tilde{\Phi} Y^i_{u} j u^j_0 R - \bar{q}_0 L_i \Phi Y^i_{d} j d^j_0 R + h.c.$$  \hspace{1cm} (1)

for an up vector-like quark, we have additional terms:

$$\mathcal{L}_T = -\bar{q}_0 L_i \tilde{\Phi} Y^i_{T} T^j_0 R - \bar{T}^0 L_i \mu T^j_1 u^j_0 R - M_0 T^j_0 L^j_0 R + h.c.$$ \hspace{1cm} (2)

After diagonalization of the up and down mass matrices, the $3 \times 3$ mixing matrix connecting $u, c, t$ and $d, s, b$ quarks is no longer unitary, but a submatrix of a larger $4 \times 4$ unitary matrix $U$. The charged and neutral current interactions have the form

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \bar{u}_L \gamma^\mu V d^\mu W + h.c.,$$ \hspace{1cm} (3)

$$\mathcal{L}_Z = -\frac{g}{2 \cos \theta_W} \left[ \bar{u}_L \gamma^\mu \left( V V^\dagger \right) u_L - \bar{d}_L \gamma^\mu d_L - 2 \sin^2 \theta_W J^\mu_{em} \right] Z_\mu,$$

where $d \equiv (d, s, b)$, $u \equiv (u, c, t, T)$ and $V$ is a $4 \times 3$ submatrix of the matrix $U$:

$$U = \begin{pmatrix}
V_{u_d} & V_{u_s} & V_{u_b} & U_{u_4} \\
V_{c_d} & V_{c_s} & V_{c_b} & U_{c_4} \\
V_{t_d} & V_{t_s} & V_{t_b} & U_{t_4} \\
V_{T_d} & V_{T_s} & V_{T_b} & U_{T_4}
\end{pmatrix}.$$  \hspace{1cm} (5)

1 Subindex 0 labels weak eigenstates, indices $i$ and $j$ run over the three usual generations.
The submatrix \( V_{(3 \times 3)} \), i.e. the upper left 3 \( \times \) 3 block within \( U \), is not a unitary matrix, since
\[
V_{(3 \times 3)} V_{(3 \times 3)}^\dagger \neq 1_{(3 \times 3)}.
\]
These deviations of unitarity of the “would-be standard” mixing matrix lead to flavour changing neutral currents (FCNC) which are only present in the up sector and controlled by
\[
(V V^\dagger)_{ij} = \delta_{ij} - U_{i4} U_{j4}^*.
\]
(6)

The addition of one isosinglet vector-like up quark provides:
- A new mass eigenstate in the up sector which can give new contributions to amplitudes involving virtual up quarks, as in neutral meson mixings and decays.
- A mixing matrix \( V \) which is not 3 \( \times \) 3 unitary anymore, allowing for deviations of the mixing elements \( V_{ij} \) from SM values.
- Modified couplings to the \( Z \) boson in the up sector, including tree level flavour changing couplings, and reduced flavour conserving ones.

2. Experimental constraints
To reflect the abundant experimental information that constrains modifications of the flavour sector such as the ones introduced in the present scenario, we have considered the following observables.
- Tree level observables, whose extraction from experiment is presumably unaffected by New Physics (NP) effects. These observables include moduli of the CKM elements in the first and second rows. For the third row the only relevant measurement, from single top production, concerns \( V_{tb} \). The physical phase \( \gamma \) is also obtained from tree level information. The input values for the analysis are collected in table 1.

| \( V_{ud} \) | 0.97425 ± 0.00022 |
| \( V_{cd} \) | 0.230 ± 0.011 |
| \( V_{tb} \) | 0.00375 ± 0.00046 |
| \( V_{ub} \) | 0.00375 ± 0.00027 |
| \( \gamma \) | (73.2 ± 7.0)° |

Table 1. Tree level observables [4][6].

- Concerning \( B_d^0 - \bar{B}_d^0 \) and \( B_s^0 - \bar{B}_s^0 \) mixings: we consider time-dependent CP asymmetries \( A_{J/\Psi K_S} \) and \( A_{J/\Psi \Phi} \) (the “golden” channel in each system), mass and width differences \( \Delta M_{B_d}, \Delta \Gamma_d, \) and \( \Delta M_{B_s}, \Delta \Gamma_s \), additional CP asymmetries involving different combinations of invariant phases, \( \sin(2\bar{\alpha}), \sin(2\beta + \gamma) \), the individual semileptonic asymmetries \( A_{SL}^d, A_{SL}^s \) and the same charge dimuon asymmetry \( A_{SL}^b \). Input values are collected in table 2.
- Representative rare decays of \( B \) mesons (table 3).
- Observables from the kaon sector: rare decays and CP violation in the mixing of neutral kaons (table 4).
- Electroweak precision observables: the oblique parameters \( S \) and \( T \) (the role of \( U \) is negligible):

\[
\Delta S = 0.02 \pm 0.11, \quad \Delta T = 0.05 \pm 0.12, \quad \text{with a correlation 0.879.}
\]

They are naturally suppressed by ratios \( m^2 / m_T^2 \), where \( m \) denotes generically the standard quark masses [1]. This natural suppression of FCNC is crucial in order to make the model plausible.
Deviations from the SM values can be significant in

\[ |\Delta \beta|, |\Delta \gamma| \text{ and } |\Delta \delta| \text{ are also present, we are not requiring that the short distance ones fully account for the observed } x_D = (0.8 \pm 0.2) \times 10^{-2}. \]

3. Results

In the following I present a number of selected results from a full numerical exploration of the available parameter space of the model with an up vector-like quark. In figure 1 the physical phases \( \beta \) and \( \beta_s \) of the CKM matrix are shown together with selected moduli of mixing elements. Deviations from the SM values can be significant in \( \beta_s \) and \( |V_{ub}| \). Figure 1 shows that despite the tight and abundant experimental information, there is still room for deviations from the SM picture with a 3 \times 3 unitary CKM matrix, and thus New Physics effects could be expected in some observables.

In figure 2 additional information on the deviation with respect to the 3 \times 3 unitary mixing is presented: mixing elements controlling the couplings of the new quark \( T \) are shown in subfigures 2(a), 2(b) and 2(c). Since \( |V_{Tb}| \) is typically constrained to be 10-20 times smaller than \( |V_{ub}| \), \( B \) physics flavour constraints dominated in the SM by top quark contributions can be satisfied even for values of \( |V_{Td}| \) and \( |V_{Ts}| \) as large as the ones shown, especially when compared to the values allowed for \( |V_{td}| \) and \( |V_{ts}| \). Subfigures 2(d) and 2(e) show the deviations from unitarity of the \( u \) and \( c \) rows,

\[ \Delta_u = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2, \quad \Delta_c = 1 - |V_{cd}|^2 - |V_{cs}|^2 - |V_{cb}|^2. \]
Figure 1. $\Delta \chi^2$ profiles of selected phases and moduli in the CKM matrix: solid line (blue) for the VL scenario, dashed line (red) for the SM.

Figure 2. $\Delta \chi^2$ profiles of mixings beyond $3 \times 3$ unitarity and deviations in the $u$ and $c$ rows.

While figures 1 and 2 show the possibility to accommodate deviations from the SM in the mixing matrix, figure 3 focuses then on what can be obtained for different observables.

- Figure 3(a) illustrates how a significant enhancement of the same charge dimuon asymmetry $A^{SL}_{S L}$ can be obtained in this scenario; nevertheless, values at the $-5 \times 10^{-3}$ level, as required by the D0 measurements, cannot be obtained just from the $3 \times 3$ unitarity deviations [9].
• Figure 3(b) shows that deviations from the SM expectation \( A_{J/ΨΦ} \sim 0.04 \) can be introduced at the level of uncertainty of the current LHCb measurement.

• Figures 3(c) and 3(d) illustrate how loop induced rare decays can be either enhanced or suppressed, with respect to SM expectations, at levels which could be probed in future experiments.

• Tree level flavour changing couplings of up-type quarks and the \( Z \), shown in eq. (4) and (6), allow decays highly suppressed in the SM such as \( t → cZ \) or \( t → uZ \). According to figure 3(e), the addition of an up vector-like quark allows branching ratios that could reach the \( 10^{-5} – 10^{-4} \) level, that could be explored at the LHC.

![Figure 3. \( Δχ^2 \) profiles of selected observables: solid line (blue) for the VL scenario, dashed line (red) for the SM.](image)

Figures 1, 2 and 3 display different \( Δχ^2 \) profiles of individual quantities. Beyond individual quantities, one can exploit correlations among different quantities to characterize the pattern of potential SM deviations associated to this New Physics scenario. Figures 4 to 7 show different joint \( Δχ^2 \) regions.

In terms of deviations from a \( 3 × 3 \) unitary matrix, \( |V_{ts}| \) and \( |V_{td}| \) in figure 4(a) are typically expected to be reduced with respect to SM values. Their counterparts for the new quark \( T \) couplings, \( |V_{Ts}| \) and \( |V_{Td}| \), are shown in fig. 4(b) although, as anticipated in figs. 2(a) and 2(b), they can reach sizable values, it is now clear that such values cannot be obtained for both simultaneously.

Concerning the same charge dimuon asymmetry \( A_{S_{SL}}^b \), fig. 3(a) establishes that the scenario under study cannot produce values in agreement with the D0 measurement. Figure 5 shows in addition that the partial enhancement in \( A_{S_{SL}}^b \) can only be obtained if \( |V_{ub}| \) does also deviate to larger-than-standard values.

For loop induced rare decays, figure 6 displays to contrasting cases. According to 6(a), although both \( Br(B_d → μ^+μ^-) \) and \( Br(B_d → μ^+μ^-) \) can deviate from SM expectations, it may be hard to disentangle those deviations from a SM value. For rare kaon decays, figure 6(b) shows
two connected branches: $K_L \rightarrow \pi^0 \nu \bar{\nu}$ can only be enhanced if the charged mode $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is also enhanced. There is also room for the model to keep at SM level or below the neutral mode while the charged mode can be increased up to 2-3 times the SM value.

For decays induced by the $Z$ flavour changing tree couplings, $t \rightarrow cZ$ and $t \rightarrow uZ$, figure 7 shows them in association with the mass $m_T$ of the new quark $T$. Although the branching ratios of those rare decays can reach values within reach of the LHC, it is clear that this also requires light values of the mass $m_T$. This aspect illustrates the power of detailed analyses: even though the $t \rightarrow qZ$ branching ratios do not depend on the value of $m_T$, full use of the available experimental information can establish such correlations.
4. Conclusions
An overview of a detailed analysis of flavour data in the context of a simple extension of the Standard Model, that includes an additional $Q = 2/3$ vector-like isosinglet quark is presented. Experimental constraints from all the relevant quark flavour sectors are imposed and yet deviations from Standard Model expectations can be accommodated. This is illustrated through different individual observables and the power of correlations to characterize the New Physics scenario under study.

**Figure 6.** $\Delta \chi^2$ profiles, 68%, 95% and 99% CL regions are shown: blue regions for the VL scenario, red regions for the SM.

**Figure 7.** $\Delta \chi^2$ profiles, 68%, 95% and 99% CL regions are shown: blue regions for the VL scenario, red regions for the SM.
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