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New-physics signals of a model with an isosinglet vector-like t' quark

Ashutosh Kumar Alok
Indian Institute of Technology Jodhpur, Jodhpur 342011, India
E-mail: akalok@iitj.ac.in

Subhashish Banerjee
Indian Institute of Technology Jodhpur, Jodhpur 342011, India
E-mail: subhashish@iitj.ac.in

Dinesh Kumar
Indian Institute of Technology Bombay, Mumbai 400076, India and Department of Physics, University of Rajasthan, Jaipur 302004, India
E-mail: dinesh@phy.iitb.ac.in

S. Uma Sankar*
Indian Institute of Technology Bombay, Mumbai 400076, India
E-mail: uma@phy.iitb.ac.in

David London
Physique des Particules, Université de Montréal,
C.P. 6128, Succursale Centre-ville, Montréal, Quebec H3C 3J7, Canada
E-mail: london@lps.umontreal.ca

We consider VuQ model which involves addition of a vector isosinglet t' quark to the standard model. In this model the full CKM quark mixing matrix is 4×3. Using present flavor-physics data, we perform a fit to this full CKM matrix. We find that the current flavor data puts stringent constraints on the VuQ model. There are no hints of new physics in the CKM matrix. Furthermore, the fit to the data indicates that any new physics contributions to $b \to s$, $b \to d$ and $s \to d$ transitions are very small. There can be significant enhancements of the branching ratios of $t \to uZ$ and $t \to cZ$ decays, but these are still below present detection levels.

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*Speaker.

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1. Introduction

The standard model (SM) of particle physics can be extended by including new, exotic quarks. A minimal extension of the Standard Model (SM) can be obtained by adding a fourth generation of quarks (denoted SM4), a vector isosinglet down-type quark b' (denoted VdQ), or a vector isosinglet up-type quark t' (denoted VuQ). The perturbative SM4 is highly disfavored by the recent LHC and Tevatron data on Higgs searches [1] whereas the vector-like quarks are still allowed by the existing experimental data.

The SM4 and VdQ models were examined in Refs. [2] and [8], respectively. We now consider the VuQ model [12, 13, 14], in which the quark mixing matrix is the 4×3 submatrix of a 4×4 quark mixing matrix CKM4, which is an extension of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix in the SM. As t'_L and $\{u_L, c_L, t_L\}$ have different values of I_{3L}, Z-mediated flavor-changing neutral currents appear at the tree level. Thus VuQ model provides a self-consistent framework to study deviations of 3×3 unitarity of the CKM matrix as well as flavor changing neutral currents at the tree level. The addition of t' quark induces new sources of CP violation and can also change SM top quark couplings to W, Z and Higgs bosons.

We look for the non-unitarity of the 3×3 CKM matrix by performing a fit to full CKM matrix by using all relevant flavor physics data. We then make predictions for other quantities in the K, B, top and charm sectors that are expected to be affected by the t' quark, while still being consistent with the present flavor physics data used as constraints [15]. We also provide upper bound on the possible deviations in the SM top couplings to W, Z and Higgs bosons.

2. Methodology

We perform a χ^2 fit to the full CKM matrix using all relevant flavor physics data. There are many parametrizations of CKM4. For the VdQ model, it is best to choose one in which the new matrix elements $V_{ub'}$, $V_{cb'}$ and $V_{tb'}$ take simple forms. With this in mind, the Dighe-Kim parametrization of Refs. [16, 17] was used in Ref. [8]. For this model, it is best to choose a parametrization of CKM4 in which the new matrix elements $V_{t'd}$, $V_{t's}$ and $V_{t'b}$ take simple forms. We use the Hou-Soni-Steger (HSS) parametrization [6, 18]:

$$\begin{array}{lll} V_{us} \equiv \lambda \ , & V_{cb} \equiv A\lambda^2 \ , & V_{ub} \equiv A\lambda^3 C e^{-i\delta_{ub}} \ , \\ V_{t'd} \equiv -P\lambda^3 e^{i\delta_{t'd}} \ , & V_{t's} \equiv -Q\lambda^2 e^{i\delta_{t's}} \ , & V_{t'b} \equiv -r\lambda \ \ , \end{array} \tag{2.1}$$

where λ is the sine of the Cabibbo angle. There are four SM parameters (λ, A, C, δ_{ub}) and five new physics parameters (P, Q, r, $\delta_{t'd}$, $\delta_{t's}$).

For the fit, in addition to the six directly-measured magnitudes of CKM matrix elements, we include the following flavor-physics observables: (i) ε_K from CP violation in $K_L \to \pi\pi$, (ii) the branching fractions of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \mu^+\mu^-$, (iii) R_b and A_b from $Z \to b\bar{b}$, (iv) B_s^0-$\bar{B}_s^0$ and B_d^0-$\bar{B}_d^0$ mixing, (v) the time-dependent indirect CP asymmetries in $B_d^0 \to J/\psi K_S$ and $B_s^0 \to J/\psi \phi$, (vi) the measurement of the CP-violating angle γ of the unitarity triangle from tree-level decays, (vii) the branching ratios of the inclusive decays $B \to X_s l^+ l^-$ and $B \to X_s \gamma$, and of the exclusive decay $B \to K\mu^+\mu^-$, (viii) a number of observables in $B \to K^*\mu^+\mu^-$, (ix) the branching ratio of $B^+ \to \pi^+\mu^+\mu^-$, (x) the branching ratios of $B_s^0 \to \mu^+\mu^-$, $B_d^0 \to \mu^+\mu^-$ and $B^+ \to \tau^+\nu_\tau$, (xi) the like-sign dimuon charge asymmetry A^b_{SL}, (xii) the oblique parameters S and T. The fit is carried out for $m_{t'} = 800$ GeV and 1200 GeV.

We then make predictions for other quantities that are expected to be affected by the t' quark, while still being consistent with the above measurements.

3. Results

We find that the three-generation CKM parameters are not much affected by the addition of t' quark. The allowed parameter space for C and δ_{ub} expands a little as the constraints on $|V_{ub}|$ coming from the unitarity of the 3×3 CKM matrix are relaxed. The values of the three new physics magnitudes, P, Q and r, are consistent with zero. In addition, the vanishing of P and Q implies vanishing $V_{t'd}$ and $V_{t's}$, respectively. In this case, the phases of these two elements have no significance.

3.1 CKM elements

The magnitudes of the elements of the 4×3 CKM matrix are obtained using the fit values of the CKM parameters. We find that $|V_{tb}| \geq 0.98$ at 3σ. Although the present direct measurement of $|V_{tb}|$ is consistent with the SM, a sizeable deviation from its SM value of 1 is not ruled out due to large experimental errors. On the other hand, we see that the constraints from present flavor-physics data do not allow such a sizeable deviation. We also find that the allowed values of all of the new physics elements of the CKM matrix are consistent with zero. Furthermore, the 3σ upper limits on these are $|V_{t'd}| \leq 0.01$, $|V_{t's}| \leq 0.01$ and $|V_{t'b}| \leq 0.27$, indicating that the couplings of the t' quark to the first and the second generations are very small. But its coupling to the third generation is moderate.

3.2 *B* and *K* sector

The fit indicates that $|V_{t's}V^*_{t'b}| \ll |V_{ts}V^*_{tb}|$. Thus, new physics contribution in the $b \to s$ sector is tightly constrained. The situation is almost the same in $b \to d$ and $s \to d$ sectors: both $|V_{t'd}V^*_{t'b}|/|V_{td}V^*_{tb}|$ and $|V_{t'd}V^*_{t's}|/|V_{td}V^*_{ts}|$ are of $\mathscr{O}(10^{-1})$. Thus new physics contributions in these sectors are also expected to be small.

The SM prediction for $\mathscr{B}(B \to X_s \nu\bar{\nu})$ is $(2.16 \pm 0.23) \times 10^{-5}$. For $m_{t'} = 800\,\mathrm{GeV}$, this value changes slightly to $(1.94 \pm 0.44) \times 10^{-5}$. Hence a large enhancement of the branching fraction of $B \to X_s \nu\bar{\nu}$ is not allowed. $\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu})$ is a purely CP-violating quantity and hence sensitive to non-standard CP-violating phases. Within the SM, its branching ratio is $(2.48 \pm 0.29) \times 10^{-11}$ [19, 20] while for $m_{t'} = 800\,\mathrm{GeV}$, it can only be enhanced upto $(3.24 \pm 0.74) \times 10^{-11}$. Thus large enhancement in $\mathscr{B}(B \to X_s \nu\bar{\nu})$ and $\mathscr{B}(K_L \to \pi^0 \nu\bar{\nu})$ is not allowed.

3.3 Charm and top sector

The predictions for some of the observables in the charm and top sector are summarized in Table 1.

Observable	Predictions		
	SM	$m_{t'}$= 800 GeV	$m_{t'}$= 1200 GeV
$x_D (\equiv \Delta m_D/\Gamma_D)$	Unknown	$\leq 0.08\%$ at 2σ	$\leq 0.03\%$ at 2σ
$\mathscr{B}(D \to \mu^+\mu^-)$	$\approx 3 \times 10^{-13}$	$(4.56 \pm 10.01) \times 10^{-13}$	$(1.47 \pm 2.98) \times 10^{-13}$
$\mathscr{B}(t \to uZ)$	$\sim 10^{-17}$	$(1.34 \pm 2.19) \times 10^{-7}$	$(0.50 \pm 0.89) \times 10^{-7}$
$\mathscr{B}(t \to cZ)$	$\sim 10^{-14}$	$(1.03 \pm 2.69) \times 10^{-7}$	$(0.39 \pm 1.01) \times 10^{-7}$

Table 1: Predictions for observables in charm and top sector.

Within the SM, D^0-$\bar{D}^0$ mixing occurs at loop level and involves the lighter quarks d, s and b. This implies a strong Glashow-Iliopoulos-Maiani (GIM) cancellation, and hence a small short distance (SD) contribution. There are large long distance (LD) contributions to D^0-$\bar{D}^0$ mixing, and indeed they dominate over the SD contributions. The present measurement of the D^0-$\bar{D}^0$ mixing parameter x_D is $x_D \equiv \Delta M_D/\Gamma_D = (0.8 \pm 0.1)\%$. In the VuQ model, D^0-$\bar{D}^0$ mixing occurs at tree level. It may therefore provide a much larger contribution than that of the (short-distance) SM. We find that at 2σ, $x_D \leq 0.08\%$. We therefore see that the SD contribution in the VuQ model falls far below the observed value of D^0-$\bar{D}^0$ mixing.

Unlike D^0-$\bar{D}^0$ mixing, the SM prediction for the branching fraction of $D^0 \to \mu^+\mu^-$ can be estimated fairly accurately, even after including the LD contribution. The SM prediction for the $D^0 \to \mu^+\mu^-$ branching ratio is $\approx 3 \times 10^{-13}$, hence highly suppressed. At present, we only have an experimental upper bound on the branching ratio: $\mathscr{B}(D^0 \to \mu^+\mu^-) \leq 7.6 \times 10^{-9}$ at 95% C.L. [21], which is several orders of magnitude larger than the SM prediction. Within the VuQ model, $D^0 \to \mu^+\mu^-$ occurs at tree level due to Z-mediated FCNC's. We find that the branching ratio of $D^0 \to \mu^+\mu^-$ can be enhanced by an order of magnitude above its SM value, but this is still far below the present detection level of 10^{-9}.

Within the SM, the branching ratios of the FCNC top decays $t \to uZ$ and $t \to cZ$ are $\sim 10^{-17}$ and $\sim 10^{-14}$, respectively. The present upper bound on $\mathscr{B}(t \to qZ)$ is 0.21% at 95% C.L. [22]. The discovery potential of $\mathscr{B}(t \to qZ)$ is $\sim 10^{-4}$-10^{-5} at ATLAS and CMS. The SM value of $\mathscr{B}(t \to qZ)$ is thus far below the detection level for these decays. We find that the branching ratios of the flavor-changing decays $t \to qZ$ $(q = c, u)$ can be enhanced by many orders of magnitude. However, they are still two orders of magnitude below the present detection level.

3.4 Deviations in top couplings to W, Z and Higgs bosons

The SM top couplings to W, Z and Higgs bosons get modified due to mixing with t' quark. We find that at 2σ, deviation in top coupling to W can only be up to 2 % whereas possible deviation in Z and Higgs coupling is $< 3\%$. These deviations are too small to be observed at the LHC with present precision.

4. Conclusions

We perform a fit using flavor-physics data to constrain all CKM parameters in the VuQ model. The purpose is to determine whether there are any indications of new physics, such as nonzero values for some of the new physics parameters. And even if there is no evidence of new physics, we would like to ascertain whether sizeable new physics effects are still possible in other flavor-physics observables, while being consistent with the constraints found in the fit.

We find that the values of the three new physics magnitudes are consistent with zero. The deviations of the CKM matrix elements V_{ts} and V_{td} from their SM prediction are small. Any large deviation of $|V_{tb}|$ from unity is therefore not possible in the VuQ model. Turning to possible new physics effects in the VuQ model, we find that any new physics contributions to $b \to s$, $b \to d$ and $s \to d$ transitions are tightly constrained. The branching ratio of $D^0 \to \mu^+\mu^-$ can be enhanced by an order of magnitude above its SM value, but this is still far below the present detection level. The branching ratios of the flavor-changing decays $t \to qZ$ $(q = c, u)$ can be enhanced by many orders of magnitude. However, they are still two orders of magnitude below the present detection level.

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