Flavour changing neutral interactions in models with vector-like quarks

Dinesh Kumar

University of Rajasthan, Jaipur

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Plan of talk

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2. Models with vector-singlet quark
3. Parametrization of quark mixing matrix
4. Results of the fit
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6. Conclusions

Motivation

There is no *a-priori* reason for there to be only three down-type and three up-type quarks. Many models of physics beyond the SM include new, exotic quarks. The simplest of these are:

- fourth generation of quarks (SM4)
- an isosinglet down-type quark d' (VdQ; both d'_L and d'_R have weak isospin $I = 0$)
- an isosinglet up-type quark u' (VuQ)

SM4 is highly disfavored by the LHC data on Higgs searches.

As vector like fermions do not receive their masses from a Higgs doublet, they are still allowed by the existing experimental data and hence keep us interested.

We investigate VuQ and VdQ models.

Motivation

In VuQ and VdQ models, the full mixing matrix is larger than 3×3:

- *"A signal of the new physics can be the non-unitarity of the 3×3 CKM matrix"*
- V_{tq} $(q = d, s, b)$ are determined from decays involving loops and by using the unitarity of the 3×3 CKM matrix. Hence one expects deviations from SM predictions in these models.

These models provide a self-consistent framework to study deviations from the unitarity of the CKM matrix as well as FCNC at tree level. Also, the addition of vector quarks modify the couplings of SM quarks with W, Z and Higgs boson.

We explore possibility of such deviations by performing a fit to all relevant flavor physics data available till date.

Models with vector-singlet quark

- In the VdQ model, the quark mixing matrix is 3×4 submatrix of the 4×4 SM4 quark mixing matrix, denoted CKM4 whereas in the VuQ model the quark mixing matrix is 4×3.
- There are many parametrizations of CKM4. For the VuQ 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.
- 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, we use the full or exact parametrization of CKM4.
- We use the flavor-physics data to perform a combined fit to these parameters. This yields the best-fit values, along with errors of all the quark mixing elements.

Parametrization for VuQ model: Hou-Soni-Steger (HSS) parametrization

$$V_{us} \equiv \lambda \ , \qquad V_{cb} \equiv A\lambda^2 \ , \qquad V_{ub} \equiv A\lambda^3 C e^{-i\delta_{ub}} \ ,$$
$$V_{t'd} \equiv -p\lambda^3 e^{i\delta_{t'd}} \ , \qquad V_{t's} \equiv -q\lambda^2 e^{i\delta_{t's}} \ , \qquad V_{t'b} \equiv -r\lambda \ .$$

4 SM parameters (λ, A, C, δ_{ub}) and 5 NP parameters (p, q, r, $\delta_{t'd}$, $\delta_{t's}$).

$$\begin{aligned}
V_{td} &= A\lambda^3\left(1 - Ce^{i\delta_{ub}}\right) - pr\lambda^4 e^{i\delta_{t'd}} + \frac{1}{2}AC\lambda^5 e^{i\delta_{ub}} \ , \\
V_{ts} &= -A\lambda^2 - qr\lambda^3 e^{i\delta_{t's}} + A\lambda^4\left(\frac{1}{2} - Ce^{i\delta_{ub}}\right) \ . \\
V_{tb} &= 1 - \frac{1}{2}r^2\lambda^2 \ .
\end{aligned}$$

Parametrization for VdQ model: Full parametrization

$$
\begin{aligned}
V_{us} &= c_{13} c_{14} s_{12}, & V_{cb} &= c_{13} c_{24} s_{23} - s_{13} s_{14} s_{24} e^{-i(\delta_{13}+\delta_{24}-\delta_{14})}, \\
V_{ub} &= c_{14} s_{13} e^{-i\delta_{13}}, & V_{ub'} &= c_{14} s_{24} e^{-i\delta_{24}}, \\
V_{cb'} &= c_{14} s_{24} e^{-i\delta_{24}}, & V_{tb'} &= c_{14} c_{24} s_{34}.
\end{aligned}
$$

- The SM 3×3 CKM matrix can be parameterized with three angles $\theta_{12}, \theta_{13}, \theta_{23}$ and one CP violating phase δ_{13}. The parameterization of 4×4 matrix requires three additional angles $\theta_{14}, \theta_{24}, \theta_{34}$ and two phases δ_{14}, δ_{24}.
- All the elements of the measurable 3×4 sub-matrix of CKM4 can now be expressed in terms of the above nine parameters.

Flavor observables used in fit

- The six directly measured magnitudes of the CKM matrix elements
- the measurement of the angle γ of the unitarity triangle from *tree-level decays*
- ϵ_K and ϵ'/ϵ from $K_L \to \pi\pi$, $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$ and $\mathcal{B}(K_L \to \mu^+ \mu^-)$
- R_b ,R_c, A_b and A_{FB}^b from Z decay

$$R_{b/c} = \frac{\Gamma(Z \to b\bar{b}/c\bar{c})}{\Gamma(Z \to hadrons)}$$

- B_s^0-$\bar{B}_s^0$ and B_d^0-$\bar{B}_d^0$ mixing
- the time-dependent indirect CP asymmetries in $B_d^0 \to J/\psi\, K_S$ and $B_s^0 \to J/\psi\, \phi$

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)}$$

Flavor observables used in fit

- the branching ratio of the inclusive decay $B \to X_s \mu^+ \mu^-$ in the high-q^2 and low-q^2 regions
- the branching ratio of $B \to K \mu^+ \mu^-$ in the high-q^2 and low-q^2 regions
- many observables in $B \to K^* \mu^+ \mu^-$ including branching ratio
- the branching ratios of $B_s^0 \to \mu^+ \mu^-$, $B_d^0 \to \mu^+ \mu^-$ and $B^+ \to \tau^+ \nu_\tau$
- the like-sign dimuon charge asymmetry A_{SL}^b

$$A_{SL}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

  where $N_b^{\pm\pm}$ is the number of events of $b\bar{b} \to \mu^\pm \mu^\pm X$.
- the oblique parameters S, T and U.

Method of fit

- For the fit, we define the total χ^2 function as

$$\begin{aligned}\chi^2_{\rm total} \quad = \quad & \chi^2_{\rm CKM} + \chi^2_{|\epsilon_K|} + \chi^2_{\epsilon'/\epsilon} + \chi^2_{K\to\pi^+\nu\bar{\nu}} + \chi^2_{K_L\to\mu^+\mu^-} + \chi^2_{Z\to b\bar{b}} \\ & + \chi^2_{M_R} + \chi^2_{B^0_d} + \chi^2_{\sin 2\beta_s} + \chi^2_{\sin 2\beta} + \chi^2_{\gamma} + \chi^2_{B\to X_s\, l^+\, l^-} \\ & + \chi^2_{B\to X_s\,\gamma} + \chi^2_{B_q\to\mu^+\mu^-} + \chi^2_{B\to K\,\mu^+\,\mu^-} + \chi^2_{B\to K^*\,\mu^+\,\mu^-} + \\ & + \chi^2_{B\to\tau\,\nu} + \chi^2_{A^b_{SL}} + \chi^2_{\rm Oblique}\,.\end{aligned}$$

- In our analysis χ^2 of an observable A is defined as

$$\chi^2_A = \left(\frac{A - A^c_{exp}}{A^{err}_{exp}}\right)^2 ,$$

- The measured value of A is $(A^c_{exp} \pm A^{err}_{exp})$.
- The individual components of the function $\chi^2_{\rm total}$, i.e the χ^2 of different observables.

Result of fit to CKM parameters in SM and VuQ Model

Parameter	SM	$m_{t'}$= 800 GeV	$m_{t'}$= 1200 GeV
λ	0.226 ± 0.001	0.226 ± 0.001	0.226 ± 0.001
A	0.780 ± 0.015	0.770 ± 0.019	0.769 ± 0.019
C	0.39 ± 0.01	0.44 ± 0.02	0.43 ± 0.02
δ_{ub}	1.21 ± 0.08	1.13 ± 0.11	1.15 ± 0.09
p	–	0.40 ± 0.26	0.30 ± 0.21
q	–	0.04 ± 0.06	0.03 ± 0.05
r	–	0.45 ± 0.25	0.36 ± 0.22
$\delta_{t'd}$	–	0.55 ± 0.45	0.76 ± 0.42
$\delta_{t's}$	–	0.52 ± 3.26	0.96 ± 1.21
$\chi^2/d.o.f.$	$71.15/60$	$63.35/59$	$63.60/59$

Table: Results of the fits to the parameters of the CKM matrix in the SM and in the VuQ model.

All three new real parameters of the CKM4 matrix are consistent with zero.

Predictions for CKM elements in VuQ Model

Quantity	SM	$m_{t'} = 800$ GeV	$m_{t'} = 1200$ GeV
$\lvert V_{ud}\rvert$	0.9745 ± 0.0002	0.9745 ± 0.0002	0.9745 ± 0.0002
$\lvert V_{us}\rvert$	0.226 ± 0.001	0.226 ± 0.001	0.226 ± 0.001
$\lvert V_{ub}\rvert$	$(3.52 \pm 0.13) \times 10^{-3}$	$(3.92 \pm 0.24) \times 10^{-3}$	$(3.85 \pm 0.21) \times 10^{-3}$
$\lvert V_{cd}\rvert$	0.226 ± 0.001	0.226 ± 0.001	0.226 ± 0.001
$\lvert V_{cs}\rvert$	0.9745 ± 0.0002	0.9745 ± 0.0002	0.9745 ± 0.0002
$\lvert V_{cb}\rvert$	0.040 ± 0.001	0.039 ± 0.001	0.039 ± 0.001
$\lvert V_{td}\rvert$	0.0084 ± 0.0003	0.0078 ± 0.0005	0.0080 ± 0.0004
$\lvert V_{ts}\rvert$	0.039 ± 0.001	0.039 ± 0.001	0.039 ± 0.001
$\lvert V_{tb}\rvert$	1	0.995 ± 0.006	0.997 ± 0.004
$\lvert V_{t'd}\rvert$	–	0.005 ± 0.003	0.003 ± 0.002
$\lvert V_{t's}\rvert$	–	0.002 ± 0.003	0.001 ± 0.002
$\lvert V_{t'b}\rvert$	–	0.101 ± 0.056	0.082 ± 0.049

Table: Predictions for CKM elements

- $|V_{tb}| = 0.87 \pm 0.07$ (CDF and D0) and 1.14 ± 0.22(CMS) .
- We find at 3σ, $|V_{tb}| \geq 0.98$. No large deviation of $|V_{tb}|$ from unity in this model.
- The mixing of the t' quark with the other three is constrained to be $|V_{t'd}| < 0.01$, $|V_{t's}| < 0.01$, and $|V_{t'b}| < 0.27$ at 3σ.

Predictions for observables in the VuQ model

- The SM prediction for the branching ratio of $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$ is $(2.48 \pm 0.29) \times 10^{-11}$. As far as experiments are concerned, at present we only have an upper bound,is (2.6×10^{-8}) at 90% C.L.
- In this model we find that $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) \leq 4.72 \times 10^{-11}$, indicating that a large enhancement in the branching ratio is not allowed.
- Large enhancement in the branching fraction of $B \to X_s \nu \bar{\nu}$ is also not allowed in this model.
- The present measurement of the $D^0 - \bar{D}^0$ mixing parameter x_D is $(0.8 \pm 0.1)\%$.
  A. K. Alok, S. Banerjee, Dinesh Kumar, S. Uma Sankar , David London (Phys. Rev. D 92, 013002 (2015))

Predictions for observables in the VuQ model

- The SM prediction for the branching ratio of $D \to \mu^+\mu^-$ is $\approx 3 \times 10^{-13}$, hence highly supressed. As far as experiments are concerned, at present we only have an upper bound, $\mathcal{B}(D \to \mu^+\mu^-) \le 1.4 \times 10^{-7}$ at 90% C.L.
- In VuQ model, we observe that the branching ratio of $D \to \mu^+\mu^-$ can be enhanced by one order above its SM value, which is still below the present detection level.
- Within the SM, the branching ratios of top decay $t \to cZ$ is $\sim 10^{-14}$. The discovery potential of $t \to cZ$ is $\sim 10^{-4} - 10^{-5}$ at the ATLAS and the CMS.
- This decay can only be observed if new physics enhances its branching ratio by several orders of magnitude.
- We find that $\mathcal{B}(t \to cZ) \sim 10^{-7}$. Hence can be enhanced by several orders of magnitude above SM value but still two orders of magnitude below the present detection level.

Result of fit to CKM parameters in SM and VdQ Model

Parameter	SM	$m_{b'}$=800 GeV	$m_{b'}$=1200 GeV
θ_{12}	0.2273 ± 0.0007	0.2271 ± 0.0008	0.2270 ± 0.0008
θ_{13}	0.0035 ± 0.0001	0.0038 ± 0.0001	0.0038 ± 0.0001
θ_{23}	0.0397 ± 0.0007	0.0391 ± 0.0007	0.0391 ± 0.0007
δ_{13}	1.10 ± 0.10	1.04 ± 0.08	1.04 ± 0.08
θ_{14}	–	0.0151 ± 0.0154	0.0147 ± 0.0149
θ_{24}	–	0.0031 ± 0.0039	0.0029 ± 0.0036
θ_{34}	–	0.0133 ± 0.0130	0.0123 ± 0.0122
δ_{14}	–	0.11 ± 0.22	0.11 ± 0.23
δ_{24}	–	3.23 ± 0.24	3.23 ± 0.27
$\chi^2/d.o.f.$	$82.42/60$	$70.99/63$	$70.96/63$

Table: The results of the fit to the parameters of CKM and VdQ.

- All three new real parameters of the CKM4 matrix are consistent with zero.

Predictions for CKM elements in VdQ Model

Qunatity	SM	$m_{b'} = 800$ GeV	$m_{b'} = 1200$ GeV
$\lvert V_{ud}\rvert$	0.9743 ± 0.0002	0.9742 ± 0.0003	0.9742 ± 0.0003
$\lvert V_{us}\rvert$	0.225 ± 0.001	0.225 ± 0.001	0.225 ± 0.001
$\lvert V_{ub}\rvert$	$(3.50 \pm 0.10) \times 10^{-3}$	$(3.80 \pm 0.10) \times 10^{-3}$	$(3.80 \pm 0.10) \times 10^{-3}$
$\lvert V_{ub'}\rvert$	–	0.0151 ± 0.0154	0.0147 ± 0.0149
$\lvert V_{cd}\rvert$	0.225 ± 0.001	0.225 ± 0.001	0.2249 ± 0.0008
$\lvert V_{cs}\rvert$	0.9735 ± 0.0002	0.9736 ± 0.0002	0.9736 ± 0.0002
$\lvert V_{cb}\rvert$	0.040 ± 0.001	0.0391 ± 0.0007	0.0391 ± 0.0007
$\lvert V_{cb'}\rvert$	–	0.0031 ± 0.0039	0.0029 ± 0.0036
$\lvert V_{td}\rvert$	0.0080 ± 0.0004	0.0074 ± 0.0004	0.0075 ± 0.0004
$\lvert V_{ts}\rvert$	0.039 ± 0.001	0.0385 ± 0.0007	0.0385 ± 0.0007
$\lvert V_{tb}\rvert$	1	0.9991 ± 0.0002	0.9991 ± 0.0002
$\lvert V_{tb'}\rvert$	–	0.0133 ± 0.0130	0.0123 ± 0.0122

Table: Magnitudes of the 3×4 CKM elements obtained from the fit.

- We find at 3σ, $|V_{tb}| \geq 0.99$. No large deviation of $|V_{tb}|$ from unity in this model.
- The mixing of the b' quark with the other three is constrained to be $|V_{ub'}| < 0.07$, $|V_{cb'}| < 0.02$, and $|V_{tb'}| < 0.06$ at 3σ.

ZFCNC couplings and predictions in the VdQ model

- The tree level ZFCNC couplings are constrained to be small. At 3σ, $U_{sd} < 1.8 \times 10^{-4}$, $U_{sb} < 1.6 \times 10^{-4}$ and $U_{db} < 1.1 \times 10^{-3}$.
- In this model we find that $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \leq 8.61 \times 10^{-11}$ at 2σ, indicating that enhancement is possible in the branching ratio.
- Large enhancement in the branching fraction of $B \to X_s \nu\bar{\nu}$ is also not allowed in this model.
- Deviation of the bottom coupling to Higgs boson is $< 1\%$ at 2σ.

  A. K. Alok, S. Banerjee , Dinesh Kumar, S. Uma Sankar (Nucl.Phys. B906 (2016) 321-341)

Conclusions

- A vector isosinglet up-type quark t' or down-type quark b' is added to the Standard model. The full CKM matrix includes NP parameters, three magnitudes and two(CP-violating) phases.
- No evidence of NP is found : the values of the three NP magnitudes are consistent with zero, in which case the two NP phase have no significance.
- Current flavor data puts extremely stringent constraints on the VuQ and VdQ model.
- No hints of NP in the CKM matrix.The tree level ZFCNC couplings are constrained to be small.
- Any VuQ contributions to loop-level flavor-changing $b \to s, b \to d$ 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 detection levels.

Thank you