New Physics Signals in Vector Quark Models

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Plan of talk

Based on papers:

- **Title:** *"New-physics signals of a model with a vector-singlet up-type quark"*
  Authors: A. K. Alok, S. Banerjee (IIT Jodhpur), **Dinesh Kumar**, S. Uma Sankar (IIT Bombay), David London (University of Montreal)
  Journal: Phys. Rev. D 92, 013002 (2015) (arXiv:1504.00517 [hep-ph])
- **Title:** *"Constraining quark mixing matrix in isosinglet vector-like down quark model from a fit to flavor-physics data"*
  Authors: A. K. Alok, S. Banerjee (IIT Jodhpur),**Dinesh Kumar**, S. Uma Sankar (IIT Bombay)
  e-print: arXiv:1402.1023 [hep-ph]

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 recent 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"*

Not all elements of the CKM matrix are measured directly:

- Values of the elements 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 thus provides 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 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 Dighe-Kim (DK) parametrization of CKM4.
- We use 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

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

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

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

Parametrization for VdQ model: Dighe-Kim (DK) parametrization

$$
\begin{array}{lll}
V_{us} = \lambda, & V_{cb} = A\lambda^2, & V_{ub} = A\lambda^3 C exp(-i\delta_{ub}), \\
V_{ub'} = p\lambda^3 exp(-i\delta_{ub'}), & V_{cb'} = q\lambda^2 exp(-i\delta_{cb'}), & V_{tb'} = r\lambda.
\end{array}
$$

- The 3×3 CKM sub-block is parametrized in the standard Wolfenstein parametrization and the new parameters are introduced in the form of three magnitudes of $V_{qb'}$ and phases of two of them.
- 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 from $K_L \to \pi\pi$, $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ and $\mathcal{B}(K_L \to \mu^+\mu^-)$
- R_b and A_b from $Z \to b\bar{b}$
- 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 $B_s^0 \to J/\psi\, \phi$
- the branching ratio of the inclusive decay $B \to X_s\mu^+\mu^-$ in the high-q^2 and low-q^2 regions
- many observables in $B \to K^*\mu^+\mu^-$
- 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 and the oblique parameters S and T(only in VuQ model).

Method of fit

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

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

- 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 $(0.8 \pm 0.1)\%$.
- In VuQ model this mixing parameter at 2σ is $\leq 0.08\%$. The short distance contribution in the VuQ model falls far below the observed value of $D^0 - \bar{D}^0$ mixing.

Predictions for observables in the VuQ model

- The SM prediction for the branching ratio of $D^0 \to \mu^+\mu^-$ is $\approx 3 \times 10^{-13}$, hence highly supressed. As far as experiments are concerned, at present we only have an upper bound, $\mathcal{B}(D^0 \to \mu^+\mu^-) \leq 1.4 \times 10^{-7}$ at 90% C.L.
- In VuQ model, we observe that the branching ratio of $D^0 \to \mu^+\mu^-$ can be enhanced by an order of magnitude 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. VuQ model can be one of those potential new physics model as this decay occurs at the tree level within this model.
- We find that $\mathcal{B}(t \to cZ) \sim 10^{-7}$. Hence the branching ratio can be enhanced by several orders of magnitude above SM value but it is still two orders of magnitude below the present detection level.

Result of fit to CKM parameters in SM and VdQ Model

Parameter	SM	VdQ Model
λ	0.226 ± 0.001	0.226 ± 0.001
A	0.780 ± 0.015	0.766 ± 0.016
C	0.39 ± 0.01	0.43 ± 0.02
δ_{ub}	1.21 ± 0.08	1.06 ± 0.08
P	–	0.92 ± 1.42
Q	–	0.04 ± 0.07
r	–	0.09 ± 0.15
$\delta_{t'd}$	–	0.15 ± 0.23
$\delta_{t's}$	–	0.63 ± 1.48
$\chi^2/d.o.f.$	$71.15/60$	$70.39/58$

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

- All the new physics parameters are consistent with zero.

Predictions for CKM elements in VdQ Model

Quantity	SM	VdQ Model
$\|V_{ud}\|$	0.9745 ± 0.0002	0.9745 ± 0.0001
$\|V_{us}\|$	0.226 ± 0.001	0.226 ± 0.001
$\|V_{ub}\|$	$(3.52 \pm 0.13) \times 10^{-3}$	$(3.81 \pm 0.16) \times 10^{-3}$
$\|V_{cd}\|$	0.226 ± 0.001	0.226 ± 0.001
$\|V_{cs}\|$	0.9745 ± 0.0002	0.9745 ± 0.0001
$\|V_{cb}\|$	0.040 ± 0.001	0.039 ± 0.001
$\|V_{td}\|$	0.0084 ± 0.0003	0.0075 ± 0.0005
$\|V_{ts}\|$	0.039 ± 0.001	0.0386 ± 0.0008
$\|V_{tb}\|$	1	0.9998 ± 0.0007
$\|V_{ub'}\|$	–	0.011 ± 0.016
$\|V_{cb'}\|$	–	0.002 ± 0.003
$\|V_{tb'}\|$	–	0.021 ± 0.034

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

- We find at $3\sigma, |V_{tb}| \geq 0.99$. 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 $|V_{ub'}| < 0.06$, $|V_{cb'}| < 0.02$, and $|V_{tb'}| < 0.12$ at 3σ.

ZFCNC couplings and predictions in the VdQ model

- The tree level ZFCNC couplings are constrained to be small. At 3σ, $U_{sd} < 1.02 \times 10^{-4}$, $U_{sb} < 2.46 \times 10^{-4}$ and $U_{db} < 1.52 \times 10^{-3}$.
- In this model we find that $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \leq 8.06 \times 10^{-9}$ at 2σ, indicating that two orders of 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.

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.
- In VdQ model we find that that two orders of enhancement is possible in the branching ratio $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ over SM.
- No hints of NP in the CKM matrix.The tree level ZFCNC couplings are constrained to be small.
- Any VdQ 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