Vector-like quarks and New Physics in the flavour sector

Francisco J Botella, Miguel Nebot (speaker)
Departament de Física Teórica and IFIC, Universitat de València - CSIC, E-46100, Burjassot, Spain
E-mail: Francisco.J.Botella@uv.es, Miguel.Nebot@uv.es

Gustavo C Branco
Departamento de Física and Centro de Física Teórica de Partículas, Instituto Superior Técnico, Universidade Técnica de Lisboa, Av. Rovisco Pais, P-1049-001 Lisboa, Portugal
E-mail: gbranco@ist.utl.it

Abstract. We present a detailed analysis of recent flavour data in the framework of a simple extension of the Standard Model, where a $Q = 2/3$ vector-like isosinglet quark is added to the spectrum. Constraints from all the relevant quark flavour sectors are used. Important deviations from Standard Model expectations in different observables such as the semileptonic asymmetry in $B_d$ decays, $A_{dSL}$, the time-dependent CP asymmetry in $B_s \rightarrow J/\Psi \Phi$, and rare decays such as $K^+ \rightarrow \pi^+ \bar{\nu} \nu$, can be obtained.

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 \cite{1,2,3}. After diagonalization of the up and down mass matrices, the $3 \times 3$ mixing matrix connecting standard 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

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \bar{u}_L \gamma^\mu V d_L W_\mu + \text{h.c.},$$

(1)

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

(2)

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

$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & U_{u4} \\ V_{cd} & V_{cs} & V_{cb} & U_{c4} \\ V_{td} & V_{ts} & V_{tb} & U_{t4} \\ V_{Td} & V_{Ts} & V_{Tb} & U_{T4} \end{pmatrix}.$$

(3)

The submatrix $V_{(3\times3)}$, i.e. the upper left $3 \times 3$ block within $U$, is not a unitary matrix, since $V_{(3\times3)}^\dagger V_{(3\times3)} \neq 1_{(3\times3)}$. These deviations of unitarity of the “would-be standard” mixing matrix

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Published under licence by IOP Publishing Ltd
lead to flavour changing neutral currents (FCNC) which are present just in the up sector and controlled by
\[
(VV^\dagger)_{ij} = \delta_{ij} - U_{i4}U_{j4}^*. \tag{4}
\]

Summarizing, the addition of one isosinglet vector-like up quark provides:
- A new mass eigenstate in the up sector. It can give new contributions to amplitudes involving virtual up quarks, as for example, in kaon or $B$ meson mixings.
- 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 and reduced flavour conserving couplings.

With these ingredients we can expect
- modifications in the $bd$ sector that can alleviate the existing tensions,
- new contributions to the $B_s^0 - \bar{B}_s^0$ (dispersive) mixing amplitude $M_{12}^{(3)}$ that can significantly modify its phase, and thus the $B_s \to J/\Psi \Phi$ time dependent CP asymmetry,
- that the deviations from $3 \times 3$ unitarity can change the $B_d$ and $B_s$ (absorptive) mixing amplitudes $\Gamma_{12}^{(q)}$, and produce larger-than-standard values for the semileptonic asymmetries $A_{SL}^q$,
- modifications in the rates of several rare decays.

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 is the one of the ratio of branching fractions $R = \text{Br}(t \to Wb)/\text{Br}(t \to Wq)$, $R = |V_{tb}|^2/(|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2)$. The physical phase $\gamma$, is also a tree level observable. The actual values are collected in table 1.

Finally, the decay $B^+ \to \tau^+ \nu_\tau$ is also a tree level process which participates in the so called tensions in the $bd$ sector.

| Table 1. Tree level observables $^{[4,6]}$. |
|-----------------|-----------------|
| $|V_{ud}|$       | $0.97425 \pm 0.00022$ |
| $|V_{cd}|$       | $0.230 \pm 0.011$    |
| $|V_{tb}|$       | $0.00389 \pm 0.00044$ |
| $|V_{cb}|$       | $0.0406 \pm 0.0013$  |
| $\gamma$        | $(77 \pm 14)^\circ$|
| $\text{Br}(B^+ \to \tau^+ \nu_\tau)$ | $(1.13 \pm 0.23) \times 10^{-4}$ |

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.

Notice however that, as it is helicity suppressed and proportional to $|V_{ub}|^2$, sizeable NP contributions may appear in different beyond SM scenarios, but not in our case.
• Observables related to $B^0_d\bar{B}^0_d$ and $B^0_s\bar{B}^0_s$ 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, $\sin (2\tilde{\alpha})$, $\sin (2\tilde{\beta} + \gamma)$ (and $\cos (2\tilde{\beta})$ which removes a discrete ambiguity in fixing $2\tilde{\beta} = \sin^{-1} (A_{J/\psi K_S})$), and, finally, semileptonic asymmetries $A_{S_L}^d$, $A_{S_L}^s$ and $A_{S_L}^b$. The actual values are collected in table 2.

| $A_{J/\psi K_S}$ | $0.68 \pm 0.02$ |
|------------------|------------------|
| $A_{J/\psi \Phi}$ | $0.002 \pm 0.0873$ |
| $\sin (2\tilde{\alpha})$ | $0.0 \pm 0.15$ |
| $\cos (2\tilde{\beta})$ | $1.35 \pm 0.34$ |
| $A_{S_L}^d$ | $-0.003 \pm 0.0078$ |
| $A_{S_L}^s$ | $-0.0017 \pm 0.0091$ |
| $A_{S_L}^b$ | $-0.00787 \pm 0.00196$ |

• Representative rare decays of $B$ mesons (table 3).

| $\text{Br}(B \rightarrow X_s \gamma)$ | $(3.56 \pm 0.25) \times 10^{-4}$ |
|-------------------------------|----------------------------------|
| $\text{Br}(B \rightarrow X_s \mu^+ \mu^-)$ | $(1.60 \pm 0.51) \times 10^{-6}$ |
| $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ | $(0.32 \pm 0.15) \times 10^{-9}$ |
| $\text{Br}(B_d \rightarrow \mu^+ \mu^-)$ | $(0 \pm 0.15) \times 10^{-10}$ |

• Observables from the kaon sector (table 4).

| $\epsilon_K$ | $(2.228 \pm 0.011) \times 10^{-3}$ |
|--------------|----------------------------------|
| $\epsilon'/\epsilon_K$ | $(1.67 \pm 0.16) \times 10^{-4}$ |
| $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ | $(1.73 \pm 1.05) \times 10^{-10}$ |
| $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ | $< \mathcal{O}(10^{-8})$ |
| $\text{Br}(K_L \rightarrow \mu^+ \mu^-)$ | $(6.84 \pm 0.11) \times 10^{-9}$ |

• Electroweak precision observables, in particular the oblique parameters $S$ and $T$ ($U$ too, but its role is negligible):

$$\Delta S = 0.02 \pm 0.11, \quad \Delta T = 0.05 \pm 0.12,$$

with a correlation coefficient 0.879.

• $D^0-\bar{D}^0$ mixing: we require that the $Z$-mediated, short distance, contribution to the $D^0-\bar{D}^0$ mixing amplitude does not give a larger than observed mixing parameter $x_D$. Notice that, as long distance contributions to $D^0-\bar{D}^0$ are also present, we are not requiring that the short distance ones fully account for the observed $x_D = (0.8 \pm 0.2) \cdot 10^{-2}$. 


3. Results
We summarize the results of a complete numeric analysis of the model \[3\] in tables 5 to 8, where experimental results (where available), SM expectations and the predictions of the model are displayed together as colored bars corresponding to 1, 2 and 3\(\sigma\) ranges.

Table 5 illustrates how the mixing matrix can depart from the SM tight 3\(\times\)3 unitary structure: invariant phases such as \(\beta\) and \(\beta_s\) and mixing elements such as \(|V_{tb}|\) and \(|V_{ub}|\), span much wider ranges than in the SM.

| Quantity | Experimental | Exp. | SM | Model |
|----------|--------------|------|----|-------|
| \(\gamma\) | 1.34 ± 0.24 | | | |
| \(\beta\) | – | | | |
| \(\beta_s\) | – | | | |
| \(|V_{ub}|\) | (4.15 ± 0.49) \times 10^{-3} | | | |
| \(\text{Br}(B^+ \rightarrow \tau^+\nu)\) | (1.13 ± 0.23) \times 10^{-4} | | | |
| \(|V_{tb}|\) | 0.88 ± 0.07 | | | |

Table 6 illustrates how the model adequately reproduces constraints related to \(B_d\) and \(B_s\) mixings, together with \(\epsilon_K\) and \(\epsilon'/\epsilon_K\). Notice in addition that the CP asymmetry in \(B_s \rightarrow J/\Psi\Phi\), less constraining from the experimental point of view, can sizeable depart from SM expectations (and it does so at a level that LHCb will be sensitive to).

| Quantity | Experimental | Exp. | SM | Model |
|----------|--------------|------|----|-------|
| \(A_{J/\Psi K_S}\) | 0.68 ± 0.02 | | | |
| \(\Delta M_{B_d}\) | (0.508 ± 0.004)ps\(^{-1}\) | | | |
| \(A_{J/\Psi}\) | 0.002 ± 0.087 | | | |
| \(\Delta M_{B_s}\) | (17.725 ± 0.049)ps\(^{-1}\) | | | |
| \(\epsilon_K\) | (2.228 ± 0.011) \times 10^{-3} | | | |
| \(\epsilon'/\epsilon_K\) | (1.67 ± 0.16) \times 10^{-3} | | | |

Table 7 addresses rare decays of kaons, \(B_d\) and \(B_s\) mesons. The model is in agreement with the most constraining ones while departures from SM expectations can be produced, particularly sizeable in the case of kaons.
Table 7. N.B. Black vertical lines stand for $\text{Br}(\ ) = 0$.

| Quantity                                      | Experimental                     | Exp. SM Model |
|-----------------------------------------------|----------------------------------|---------------|
| $\text{Br}(K^+ \rightarrow \pi^+\nu\bar{\nu})$ | $(1.73 \pm 1.05) \times 10^{-10}$ |               |
| $\text{Br}(K_L \rightarrow \mu^+\mu^-)$       | $6.84 \pm 0.11 \times 10^{-9}$   |               |
| $\text{Br}(B \rightarrow X_s\gamma)$          | $3.56 \pm 0.24 \times 10^{-4}$   |               |
| $\text{Br}(B \rightarrow X_s\mu^+\mu^-)$      | $1.60 \pm 0.51 \times 10^{-6}$   |               |
| $\text{Br}(Bs \rightarrow \mu^+\mu^-)$        | $3.2 \pm 1.4 \times 10^{-9}$     |               |
| $\text{Br}(Bd \rightarrow \mu^+\mu^-)$        | < $0.95 \times 10^{-9}$ (95% CL) |               |

Finally, table 8 displays the semileptonic asymmetries in $B_d$ and $B_s$ mesons. Current experimental uncertainty on $A_{SL}^d$ and $A_{SL}^s$ is too large to be displayed. Departure from SM expectations is clear possible within this model. Nevertheless, the value of $A_{SL}^b$ measured at D0 cannot be reproduced, even though the “tension” that this measurement brings into the flavour picture is softened. For completeness, the combination $A_{SL}^s - A_{SL}^d$, measurable at LHCb, is also displayed.

Table 8.

| Quantity                                      | Experimental                     | Exp. SM Model |
|-----------------------------------------------|----------------------------------|---------------|
| $A_{sl}^d$                                     | $-0.003 \pm 0.0078$              |               |
| $A_{sl}^s$                                     | $-0.0024 \pm 0.0063$             |               |
| $A_{sl}^b$                                     | $-0.00787 \pm 0.00196$           |               |
| $A_{sl}^s - A_{sl}^d$                         |                                  |               |

Besides the information summarized in the previous tables, correlations among observables provide a huge playground to put the model to the test.

- Figure 1(a) illustrates how deviations from SM expectations are correlated for $A_{SL}^d$ and $\text{Br}(B \rightarrow \tau\nu)$ (controlled by $|V_{ub}|$); red ellipses correspond to SM 68%, 95% and 99% CL regions.
- Figure 1(b) shows the strong correlation among $A_{SL}^s$ and $A_{1/\Phi}$ when non standard values for both are present. The red cross indicates the SM prediction. Notice that within the SM the allowed range of variation is too small to be resolved with the scales of the figure.
- Figure 1(c) shows how significant deviations from $|V_{tb}|$ can only be achieved for relatively light values of $m_T$. 


Figure 1(d) shows how both $\text{Br}(K_L \to \pi^0\nu\bar{\nu})$ and $\text{Br}(K^+ \to \pi^+\nu\bar{\nu})$ can deviate from SM expectations (the red cross indicates the central value, the red bars over the axes stand for the 68%, 95% and 99% CL ranges), and do following a well defined pattern.

![Figure 1](image_url)

Figure 1. $\Delta\chi^2$ profiles of different correlations; 68%, 95% and 99% CL regions are shown.

4. Conclusions
We have presented 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. Experimental constraints from all the relevant quark flavour sectors are imposed and yet important deviations from Standard Model expectations can be present. This has been illustrated with different individual observables and important correlations.
Acknowledgments

This work was partially supported by Fundação para a Ciência e a Tecnologia (FCT, Portugal) through the projects CERN/FP/109305/2009, CERN/FP/116328/2010 and CERN/FP/123580/2011, PTDC/FIS/098188/2008 and CFTP/FCT Unit 777 which are partially funded through POCTI (FEDER), by Marie Curie Initial Training Network UNILHC PITNGA-2009-237920, by Accion Complementaria Luso-Espanhola AIC-D-2011-0809, by European FEDER, Spanish MINECO under grant FPA2011-23596 and GVPROMETEO 2010-056. The authors are very grateful for the hospitality and magnificient organization of Discrete 2012.

References

[1] Langacker P and London D 1988 Phys. Rev. D38 886; del Aguila F and Bowick M 1983 Nucl. Phys. B224 107; del Aguila F, Laeremann E and Zerwas P 1988 Nucl. Phys. B297 1; Cheng T and Li L F 1992 Phys. Rev. D45 1708–1710.

[2] del Aguila F and Cortes J 1985 Phys. Lett. B156 243; del Aguila F, Chase M and Cortes J 1986 Nucl. Phys. B271 61; Branco G and Lavoura L 1986 Nucl. Phys. B278 738; Buchmuller W and Gronau M 1989 Phys. Lett. B220 641; Nir Y and Silverman D J 1990 Phys. Rev. D42 1477–1484; Nardi E, Roulet E and Tommasini D 1992 Nucl. Phys. B386 239–266; Silverman D 1992 Phys. Rev. D45 1800–1803; Branco G, Parada P, Morozumi T and Rebelo M 1993 Phys. Lett. B306 398–402; Branco G, Morozumi T, Parada P and Rebelo M 1993 Phys. Rev. D48 1167–1175; Branco G, Parada P and Rebelo M 1995 Phys. Rev. D52 4217–4222 (Preprint hep-ph/9503477).

[3] del Aguila F, Aguilar-Saavedra J and Branco G 1998 Nucl. Phys. B510 39–60 (Preprint hep-ph/9703410); Barenboim G and Botella F 1998 Phys. Lett. B433 385–395 (Preprint hep-ph/9708209); Barenboim G, Botella F, Branco G and Vives O 1998 Phys. Lett. B422 277–286 (Preprint hep-ph/9709369). Kakebe I and Yamamoto K 1998 Phys. Lett. B416 184–191 (Preprint hep-ph/9705203); Barenboim G, Botella F and Vives O 2001 Phys. Rev. D64 015007 (Preprint hep-ph/0012197); Higuchi K and Yamamoto K 2000 Phys. Rev. D62 073005 (Preprint hep-ph/0004065); Barenboim G, Botella F and Vives O 2001 Nucl. Phys. B613 285–305 (Preprint hep-ph/0105306); Aguilar-Saavedra J 2003 Phys. Rev. D67 035003 (Preprint hep-ph/0210112); Aguilar-Saavedra J, Botella F, Branco G and Nebot M 2005 Nucl. Phys. B700 204–220 (Preprint hep-ph/0406151); Botella F J, Branco G C and Nebot M 2009 Phys. Rev. D79 096009 (Preprint 0805.3995); Higuchi K and Yamamoto K 2010 Phys. Rev. D81 015009 (Preprint 0911.1175); Frampton P H, Hung P and Sher M 2000 Phys. Rept. 330 263 (Preprint hep-ph/9903387).

[4] Botella F, Branco G and Nebot M 2012 JHEP 1212 040 (Preprint 1207.4440).

[5] Beringer J and others (Particle Data Group) (Particle Data Group) 2012 Phys. Rev. D86 010001.

[6] Amhis Y and others (Heavy Flavor Averaging Group) (Heavy Flavor Averaging Group) 2012 (Preprint 1207.1158).

[7] Aubert B and others (BABAR Collaboration) (BaBar Collaboration) 2007 Phys. Rev. Lett. 99 251801 (Preprint hep-ex/0703057); Poluektov A and others (Belle Collaboration) (Belle Collaboration) 2010 Phys. Rev. D81 112002 (Preprint 1002.3360); Ikado K and others (Belle Collaboration) (Belle Collaboration) 2006 Phys. Rev. Lett. 97 251802 (Preprint hep-ex/0604018); Hara K and others (Belle Collaboration) (Belle Collaboration) 2010 Phys. Rev. D82 071101 (Preprint 1006.4201); Aubert B and others (BABAR Collaboration) (BABAR Collaboration) 2008 Phys. Rev. D77 011107 (Preprint 0708.2260); Lees J and others (BABAR Collaboration) (BABAR Collaboration) 2012 (Preprint 1207.0698).

[8] Aaij R and others (LHCb Collaboration) (LHCb Collaboration) 2012 Phys. Rev. Lett. 108 101803 (Preprint 1112.3183); Aaij R and others (LHCb Collaboration) (LHCb Collaboration) 2012 Phys. Lett. B707 497–505 (Preprint 1112.3056); Aubert B and others (BABAR Collaboration) (BABAR Collaboration) 2009 Phys. Rev. D79 072009 (Preprint 0902.1708); Adachi I, Aihara H, Asner D, Aulchenko V, Aushev T and others (Belle Collaboration) (Belle Collaboration) 2012 Phys. Rev. Lett. 108 171802 (Preprint 1201.4643); Aaij R and others (ATLAS Collaboration) (ATLAS Collaboration) 2012 Phys. Lett. B713 387 (Preprint 1204.0735).

[9] Chatrchyan S and others (CMS Collaboration) (CMS Collaboration) 2011 Phys. Rev. Lett. 107 191802 (Preprint 1107.5834); Chatrchyan S and others (CMS Collaboration) (CMS Collaboration) 2012 JHEP 1204 033 (Preprint 1203.3976); Aaij R and others (LHCb Collaboration) (LHCb Collaboration) 2012 Phys. Rev. Lett. 108 231801 (Preprint 1203.4493); Aaij R and others (LHCb Collaboration) (LHCb Collaboration) 2012 Phys. Lett. B708 55–67 (Preprint 1112.1600).

[10] Alavi-Harati A and others (KTeV Collaboration) (KTeV Collaboration) 1999 Phys. Rev. Lett. 83 22–
27 (Preprint hep-ex/9905060); Ambrose D and others (E871 Collaboration) (E871 Collaboration)
2000 Phys.Rev.Lett. 84 1389–1392; Ahn J and others (E391a Collaboration) (E391a Collaboration)
2008 Phys.Rev.Lett. 100 201802 (Preprint 0712.4164); Artamonov A and others (E949 Collaboration)
(E949 Collaboration) 2008 Phys.Rev.Lett. 101 191802 (Preprint 0808.2459); Abouzaid E and others
(KTeV Collaboration) (KTeV Collaboration) 2011 Phys.Rev. D83 092001 (Preprint 1011.0127).

[10] Cirigliano V, Ecker G, Neufeld H, Pich A and Portoles J 2012 Rev.Mod.Phys. 84 399 (Preprint 1107.6001)