Vector-like quarks and New Physics in the flavour sector

Francisco J Botella, Miguel Nebot (speaker)
Departament de Física Teòrica 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^d_{SL}, the time-dependent CP asymmetry in $B_s \to J/\Psi\Phi$, and rare decays such as $K^+ \to \pi^+\bar{\nu}\nu$, 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 [1,2,3]. After diagonalization of the up and down mass matrices, the 3×3 mixing matrix connecting standard quarks is no longer unitary, but a submatrix of a larger 4×4 unitary matrix U. The charged and neutral current interactions have the form

$$\mathscr{L}_W = -\frac{g}{\sqrt{2}}\bar{\mathbf{u}}_L\,\gamma^\mu\,V\,\mathbf{d}_L\,W_\mu + \text{h.c.}\,, \tag{1}$$

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

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

$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & U_{u4} \\ V_{cd} & V_{cs} & V_{cb} & U_{c4} \\ V_{td} & V_{ts} & V_{tb} & U_{t4} \\ V_{Td} & V_{Ts} & V_{Tb} & U_{T4} \end{pmatrix}\,. \tag{3}$$

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

Journal of Physics: Conference Series **447** (2013) 012061 doi:10.1088/1742-6596/447/1/012061

lead to flavour changing neutral currents (FCNC) which are present just in the up sector and controlled by[1]

$$\left(VV^\dagger\right)_{ij} = \delta_{ij} - U_{i4}U^*_{j4}\ . \tag{4}$$

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 3×3 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^0_s–$\bar{B}^0_s$ (dispersive) mixing amplitude $M^{(s)}_{12}$ that can significantly modify its phase, and thus the $B_s \to J/\Psi\Phi$ time dependent CP asymmetry,
- that the deviations from 3×3 unitarity can change the B_d and B_s (absorptive) mixing amplitudes $\Gamma^{(q)}_{12}$, and produce larger-than-standard values for the semileptonic asymmetries A^q_{SL},
- 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 $R = \mathrm{Br}(t \to Wb)/\mathrm{Br}(t \to Wq)$, $R = |V_{tb}|^2/(|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2)$. The physical phase γ, 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[2].

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

$\lvert V_{ud}\rvert$	0.97425 ± 0.00022	$\lvert V_{us}\rvert$	0.2252 ± 0.0009
$\lvert V_{cd}\rvert$	0.230 ± 0.011	$\lvert V_{cs}\rvert$	1.023 ± 0.036
$\lvert V_{ub}\rvert$	0.00389 ± 0.00044	$\lvert V_{cb}\rvert$	0.0406 ± 0.0013
γ	$(77 \pm 14)^\circ$	R	0.88 ± 0.07
$\mathrm{Br}(B^+ \to \tau^+\nu_\tau)$	$(1.13 \pm 0.23) \times 10^{-4}$		

[1] 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.

[2] 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_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 ΔM_{B_d}, $\Delta\Gamma_d$, and ΔM_{B_s}, $\Delta\Gamma_s$, additional CP asymmetries involving *different* combinations of invariant phases, $\sin(2\bar{\alpha})$, $\sin(2\bar{\beta}+\gamma)$ (and $\cos(2\bar{\beta})$ which removes a discrete ambigity in fixing $2\bar{\beta}=\sin^{-1}(A_{J/\Psi K_S})$), and, finally, semileptonic asymmetries A^d_{SL}, A^s_{SL} and A^b_{SL}. The actual values are collected in table 2.

Table 2. B_d and B_s mixing-related observables [4, 5, 7].

$A_{J/\Psi K_S}$	0.68 ± 0.02	ΔM_{B_d}	$(0.508 \pm 0.004)\,\text{ps}^{-1}$
$A_{J/\Psi\Phi}$	0.002 ± 0.0873	ΔM_{B_s}	$(17.725 \pm 0.049)\,\text{ps}^{-1}$
$\sin(2\bar{\alpha})$	0.00 ± 0.15	$\sin(2\bar{\beta}+\gamma)$	1.0 ± 0.16
$\cos(2\bar{\beta})$	1.35 ± 0.34		
A^d_{SL}	-0.003 ± 0.0078	$\Delta\Gamma_d/\Gamma_d$	-0.017 ± 0.021
A^s_{SL}	-0.0017 ± 0.0091	$\Delta\Gamma_s$	$(0.116 \pm 0.019)\,\text{ps}^{-1}$
A^b_{SL}	-0.00787 ± 0.00196		

- Representative rare decays of B mesons (table 3).

Table 3. B_d and B_s rare decays [4, 5, 8].

$\text{Br}(B \to X_s\gamma)$	$(3.56 \pm 0.25) \times 10^{-4}$
$\text{Br}(B \to X_s\mu^+\mu^-)$	$(1.60 \pm 0.51) \times 10^{-6}$
$\text{Br}(B_s \to \mu^+\mu^-)$	$(0\,^{+2.25}_{--}) \times 10^{-9}$
$\text{Br}(B_d \to \mu^+\mu^-)$	$(0\,^{+5.15}_{--}) \times 10^{-10}$

- Observables from the kaon sector (table 4).

Table 4. Kaon mixing and rare decays [9, 10].

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

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

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

  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 3σ ranges.
Table 5 illustrates how the mixing matrix can depart from the SM tight 3×3 unitary structure: invariant phases such as β and β_s and mixing elements such as $|V_{tb}|$ and $|V_{ub}|$, span much wider ranges than in the SM.

Table 5.

Quantity	Experimental	Exp. SM Model
γ	1.34 ± 0.24	
β	–	
β_s	–	
$\lvert V_{ub}\rvert$	$(4.15 \pm 0.49) \times 10^{-3}$	
$\mathrm{Br}(B^+ \to \tau^+\nu)$	$(1.13 \pm 0.23) \times 10^{-4}$	
$\lvert V_{tb}\rvert$	0.88 ± 0.07	

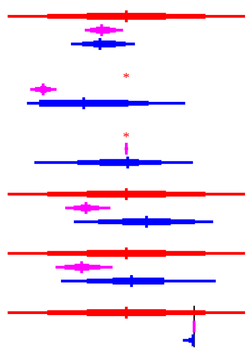


Table 6 illustrates how the model adequately reproduces constraints related to B_d and B_s mixings, together with ϵ_K and ε'/ϵ_K. Notice in addition that the CP asymmetry in $B_s \to J/\Psi\Phi$, less constraining from the experimental point of view, can sizeable depart from SM expectations (and it does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

Table 6.

Quantity	Experimental	Exp. SM Model
$A_{J/\Psi K_S}$	0.68 ± 0.02	
ΔM_{B_d}	$(0.508 \pm 0.004)\mathrm{ps}^{-1}$	
$A_{J/\Psi\Phi}$	0.002 ± 0.087	
ΔM_{B_s}	$(17.725 \pm 0.049)\mathrm{ps}^{-1}$	
ϵ_K	$(2.228 \pm 0.011) \times 10^{-3}$	
ε'/ϵ_K	$(1.67 \pm 0.16) \times 10^{-3}$	

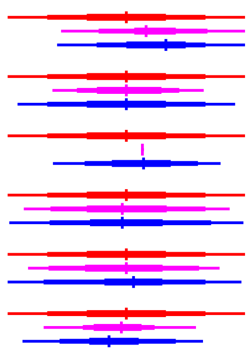
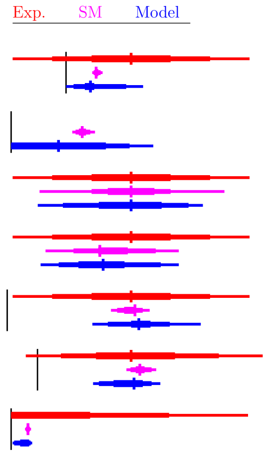


Table 7 addresses rare decays of kaons, B_d and B_s mesons. The model is in agreement with the most constraining ones while departures from SM expectations can be produced, particularly sizeable in the case of kaons.

Table 7. N.B. Black vertical lines stand for Br( ) = 0.

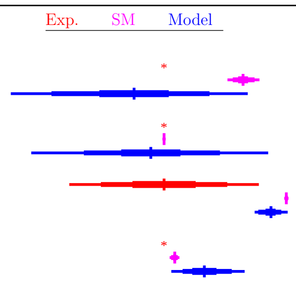
Quantity	Experimental
$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$	$(1.73 \pm 1.05) \times 10^{-10}$
$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu})$	–
$\mathrm{Br}(K_L \to \mu^+\mu^-)$	$(6.84 \pm 0.11) \times 10^{-9}$
$\mathrm{Br}(B \to X_s\gamma)$	$(3.56 \pm 0.24) \times 10^{-4}$
$\mathrm{Br}(B \to X_s\mu^+\mu^-)$	$(1.60 \pm 0.51) \times 10^{-6}$
$\mathrm{Br}(B_s \to \mu^+\mu^-)$	$(3.2 \pm 1.4) \times 10^{-9}$
$\mathrm{Br}(B_d \to \mu^+\mu^-)$	$< 0.95 \times 10^{-9}(95\%\ \mathrm{CL})$



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

Table 8.

Quantity	Experimental
A^d_{sl}	-0.003 ± 0.0078
A^s_{sl}	-0.0024 ± 0.0063
A^b_{sl}	-0.00787 ± 0.00196
$A^s_{sl} - A^d_{sl}$	

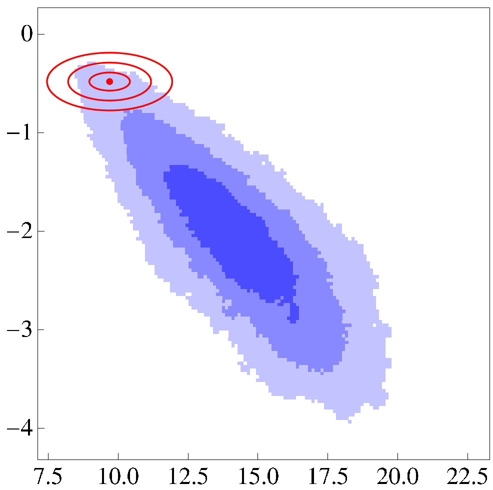


Besides the information summarized in the previous tables, correlations among observables provide a huge playground to put the model to the test.

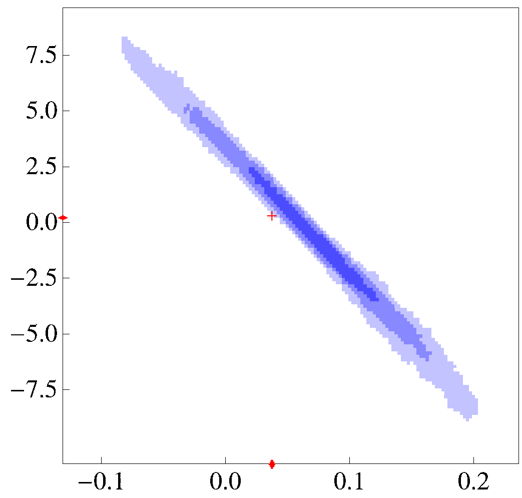
- Figure 1(a) illustrates how deviations from SM expectations are correlated for A^d_{SL} and $\mathrm{Br}(B \to \tau\nu)$ (controlled by $|V_{ub}|$); red ellipses correspond to SM 68%, 95% and 99% CL regions.
- Figure 1(b) shows the strong correlation among A^s_{SL} and $A_{J/\Psi\Phi}$ when non standard 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.

Journal of Physics: Conference Series **447** (2013) 012061 doi:10.1088/1742-6596/447/1/012061

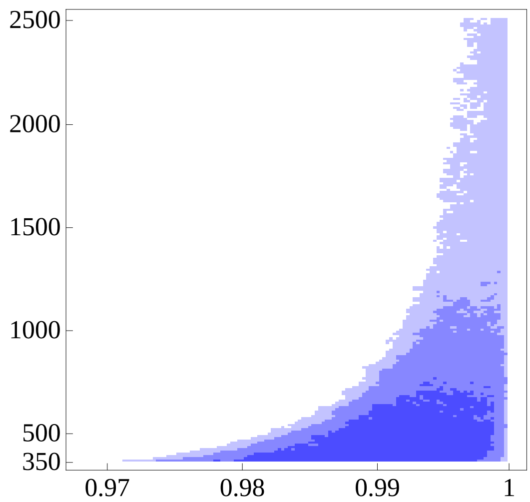
- Figure 1(d) shows how both $Br(K_L \to \pi^0 \nu\bar{\nu})$ and $Br(K^+ \to \pi^+ \nu\bar{\nu})$ can deviate from SM expectations (the red cross indicates the central value, the red bars over the axes stand for the 68%, 95% and 99% CL ranges), and do following a well defined pattern.



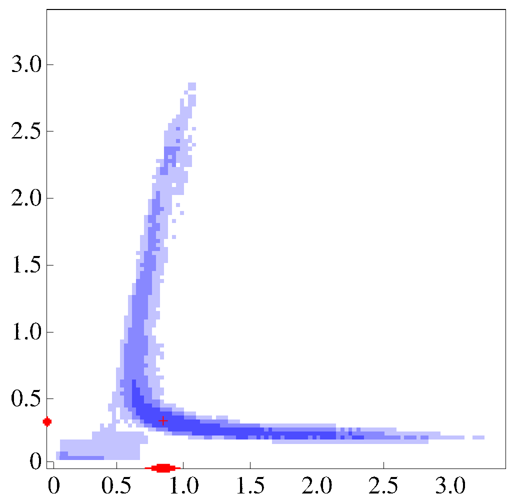
(a) $A^d_{SL} \times 10^3$ vs. $\text{Br}(B \to \tau\nu) \times 10^4$.



(b) $A^s_{SL} \times 10^4$ vs. $A_{J/\Psi\Phi}$.



(c) $m_T(\text{GeV})$ vs. $|V_{tb}|$.



(d) $Br(K_L \to \pi^0 \nu\bar{\nu}) \times 10^{10}$ vs. $Br(K^+ \to \pi^+ \nu\bar{\nu}) \times 10^{10}$.

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 CFTPFCT Unit 777 which are partially funded through POCTI (FEDER), by Marie Curie Initial Training Network UNILHC PITN-GA-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, Laermann 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/9501347`); Barger V, Berger M and Phillips R 1995 *Phys.Rev.* **D52** 1663–1683 (*Preprint* `hep-ph/9503204`); 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.* **B706** 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`).

[3] Botella F, Branco G and Nebot M 2012 *JHEP* **1212** 040 (*Preprint* `1207.4440`)

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

[5] Amhis Y and others (Heavy Flavor Averaging Group) (Heavy Flavor Averaging Group) 2012 (*Preprint* `1207.1158`)

[6] Aubert B and others (BABAR Collaboration) (BaBar Collaboration) 2007 *Phys.Rev.Lett.* **99** 251801 (*Preprint* `hep-ex/0703037`); Poluektov A and others (Belle Collaboration) (Belle Collaboration) 2010 *Phys.Rev.* **D81** 112002 (*Preprint* `1003.3360`); 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`).

[7] 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`); Aad G and others (ATLAS Collaboration) (ATLAS Collaboration) 2012 *Phys. Lett.* **B713** 387 (*Preprint* `1204.0735`).

[8] 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`).

[9] 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)