IL NUOVO CIMENTO **41 C** (2018) 145
DOI 10.1393/ncc/i2018-18145-1

COLLOQUIA: LaThuile 2018

Models for B-physics anomalies

D. BUTTAZZO

INFN, Sezione di Pisa - Largo B. Pontecorvo 3, 56127 Pisa, Italy

received 6 September 2018

Summary. — Several different experiments show evidences of Lepton Flavour Universality violation in semi-leptonic B meson decays, both in charged and neutral currents. These anomalies can be interpreted in terms of new short-distance interactions that involve mainly the third generation of fermions. I will first discuss the present status of the anomalies, and their connection to other low- and high-energy observables, in a model-independent way, adopting an Effective Field Theory approach based on a CKM-like flavour structure. I will then extend the analysis to a few simple UV completions with different types of mediator, discussing the main issues that have to be faced in each case. A few models emerge, which look capable of accommodating both charged- and neutral-current anomalies consistently with all the experimental bounds, with associated flavour and high-p_T signatures within the reach of present and future experiments.

1. – Lepton Flavour Universality violations

The gauge sector of the Standard Model (SM) exhibits an accidental invariance under a large flavour group $U(3)^5$. This flavour symmetry is broken by the Yukawa interactions —and hence by the fermion masses and mixings. However, due to the smallness of the lepton Yukawa couplings, all SM processes are approximately universal for the three lepton families, with the exception of phase-space effects related to the different fermion masses. This property goes under the name of Lepton Flavour Universality (LFU).

Various recent experiments [1-4] have observed deviations from LFU in different semi-leptonic B-meson decays. The anomalies can be classified in two broad categories:

- Deviation from τ *vs.* light lepton universality in charged-current $b \to c\ell\bar{\nu}$ decays. These processes are mediated by a tree-level W exchange in the SM. Three different experiments have observed a $\sim 20\%$ deviation from the rather clean SM expectations in the LFU ratios $R_{D^{(*)}} = \mathrm{BR}(B \to D^{(*)}\tau\bar{\nu})/\mathrm{BR}(B \to D^{(*)}\ell\bar{\nu})$ [3].

- Deviation from μ *vs.* e universality in neutral-current $b \to s\ell^+\ell^-$ decays. These processes are generated at loop-level in the SM. The LHCb experiment has measured the LFU ratios $R_{K^{(*)}} = \mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)/\mathrm{BR}(B \to K^{(*)}e^+e^-)$ in different energy intervals, always finding a $\sim 20\%$ suppression with respect to the very clean SM prediction [1, 2]. In addition, measurements of the angular distribution of $B \to K^*\mu^+\mu^-$ [4], and of several $b \to s\mu^+\mu^-$ branching ratios with different hadronic final states, also deviate from the SM expectations, although being affected by larger theoretical uncertainties.

While none of these observations alone possesses the significance to claim a discovery, the various anomalies taken together seem to coherently point to the presence of new phenomena beyond the SM in the flavour sector. The combined significance of the anomalies in each of the two categories above is around the 4σ level or more [3, 5].

1) The anomalies are observed only in semi-leptonic processes; no deviation from the SM is seen in either pure-quark or pure-lepton transitions.

2) The anomalies are consistent with new physics in left-handed operators; right-handed or scalar contributions are not excluded, but, if present, have to be a subleading effect.

3) In order to explain both charge-current and neutral-current anomalies with the same physics, the coupling to third-generation fermions (taus) has to be the dominant one, with a subdominant coupling to the second generation (muons).

4) The flavour structure of the new interactions has to be CKM-like, in order to be consistent with the many constraints from flavour-changing processes (this is true for any SM extension close to the electroweak scale).

2. – Effective Field Theory

We will now construct a general Effective Field Theory (EFT) framework in order to describe the B-physics anomalies in a combined fashion. Given points 1 and 2 above, we will consider only left-handed semi-leptonic operators, which leaves us with the following effective Lagrangian [6, 7]:

$$\mathcal{L} = \frac{1}{v^2}\left[\Lambda_S^{ij\alpha\beta}(\bar{q}_L^i\gamma_\mu q_L^j)(\bar{\ell}_L^\alpha\gamma^\mu\ell_L^\beta) + \Lambda_T^{ij\alpha\beta}(\bar{q}_L^i\gamma_\mu\sigma^a q_L^j)(\bar{\ell}_L^\alpha\gamma^\mu\sigma^a\ell_L^\beta)\right], \tag{1}$$

where i, j are quark flavour indices, α, β are lepton flavour indices, $v = 246\,\mathrm{GeV}$, and $\Lambda_{S,T}$ are the Wilson coefficients.

In accordance with the observations in point 3 and 4 above, we will assume the flavour structure to be consistent with a minimally broken $U(2)$ symmetry [8] both in the quark and in the lepton sector. This constrains the flavour matrices $\Lambda_{S,T}$ to have the following approximate form:

$$\Lambda_{S,T} = C_{S,T}\begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \lambda_{bs} \\ \cdot & \lambda_{bs}^* & 1 \end{pmatrix} \otimes \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \lambda_{\mu\mu} & \lambda_{\tau\mu} \\ \cdot & \lambda_{\tau\mu}^* & 1 \end{pmatrix}, \tag{2}$$

where $\lambda_{bs} \approx \mathcal{O}(V_{ts})$, and the dots indicate small numbers. The relevant parameters that determine the phenomenology of semi-leptonic processes turn out to be the four $\{C_S, C_T, \lambda_{bs}, \lambda_{\mu\mu}\}$.

We now briefly discuss the main constraints on these coefficients.

- The $R_{D^{(*)}}$ anomaly fixes a combination of C_T and λ_{bs},

$$\frac{R_{D^{(*)}}}{R^{\rm SM}_{D^{(*)}}} \approx 1 + 2\,C_T\left(1 - \frac{\lambda_{bs}}{V^*_{ts}}\right) = 1.237 \pm 0.053. \tag{3}$$

  μ *vs.* e universality in charged-currents sets an upper limit on the size of $\lambda_{\mu\mu}$.

- $b \to s\nu\bar{\nu}$ decays receive a contribution from both the $SU(2)_L$ triplet and singlet. The Wilson coefficient of the effective operator reads

$$\Delta C_{b\to s\nu\bar{\nu}} \propto (C_T - C_S)\lambda_{bs}. \tag{4}$$

  For $\lambda_{bs} \gtrsim \mathcal{O}(V_{cb})$, in order to satisfy the upper bound $\mathrm{BR}(B \to K^*\nu\bar{\nu})/\mathrm{SM} < 5.4$, a cancellation $C_T \sim C_S$ is required. The other transition with third-generation leptons in the final state, $b \to s\tau\tau$, is proportional to the orthogonal combination $C_T + C_S$, and therefore cannot be simultaneously suppressed; the experimental constraints are however very weak.

- The neutral-current anomalies $R_{K^{(*)}}$ are an independent quantity in this setup, whose size determines $\lambda_{\mu\mu}$,

$$\Delta C_9 = -\Delta C_{10} \propto (C_T + C_S)\lambda_{bs}\lambda_{\mu\mu}. \tag{5}$$

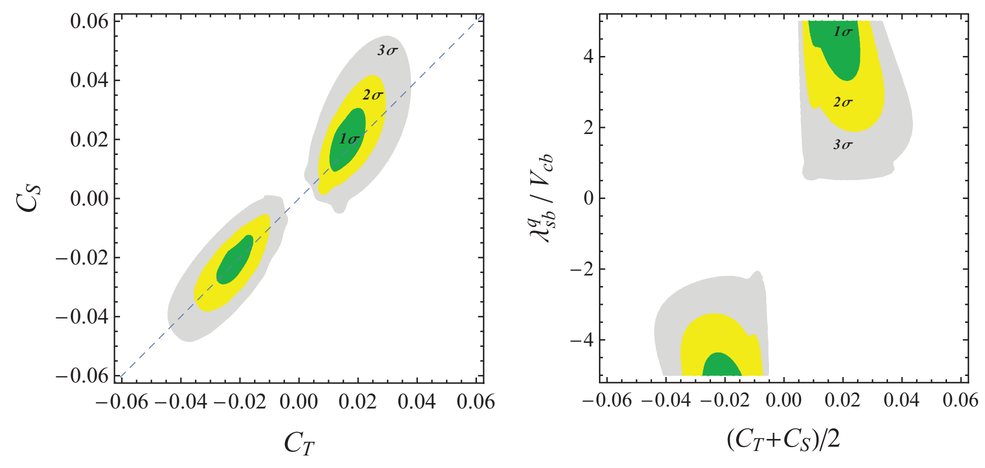

Fig. 1. – Fit results for C_S, C_T, and λ_{bs}. The green, yellow, and grey regions are preferred at 1σ, 2σ, and 3σ. Figures from ref. [7].

- Modified W and Z couplings, which are constrained by electroweak precision tests and τ decays, are induced by renormalisation group running via top quark loops. These effects do not depend on the flavour breaking coefficients, and set a constraint on the overall scale of new physics, C_S and C_T [9].

- The parameter $\lambda_{\tau\mu}$ controls lepton flavour violating τ decays, but for $\lambda_{\tau\mu} \approx 10^{-1}$ —which is consistent with the values of $\lambda_{\mu\mu}$— the experimental constraints are not relevant. All the flavour parameters involving the light generations are small because of the flavour symmetry.

Performing a full fit to all the semi-leptonic observables described above [7], it is possible to determine all the parameters in eq. (2). At this stage we do not include constraints from non-semi-leptonic processes, or direct searches, which are model-dependent. Details about the fitting procedure and all the observables considered can be found in ref. [7]. The results of the fit are shown in fig. 1. It can be seen that a mild cancellation between the triplet and singlet operator is required, and that relatively large values of λ_{bs} —although consistent with the $U(2)$ prediction $\lambda_{bs} \approx V_{ts}$— are preferred. The left panel of fig. 2 shows that the two anomalies are fitted very well by the model.

3. – Simplified models

There are three classes of mediators that can generate the effective operators of eq. (1):

1) Colorless vector resonances, coupled both to left-handed lepton and quark currents.

2) Vector leptoquarks, coupled to the $\bar{q}_L \gamma_\mu \ell_L$ current.

3) Scalar leptoquarks, coupled to the scalar current $q_L^c \sigma_2 \ell_L$.

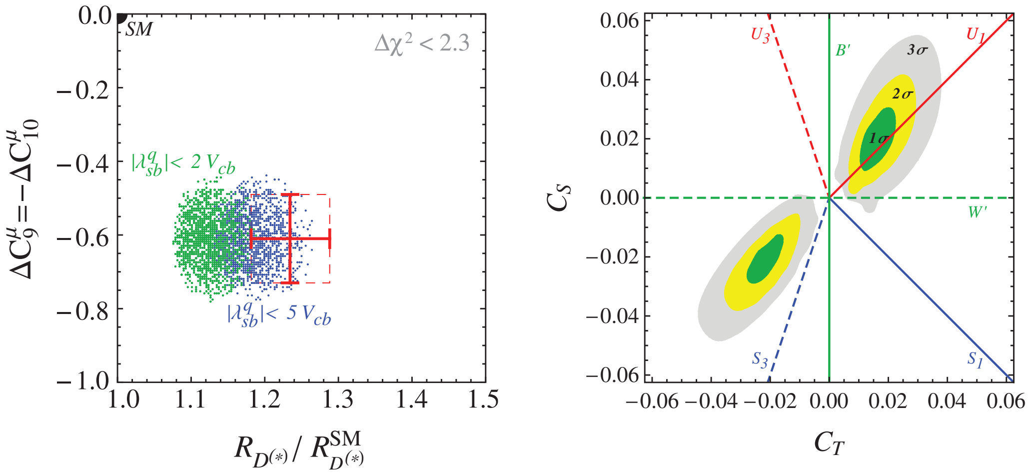

Fig. 2. – Left: fit results for the charged- and neutral-current anomalies. The red bars show the experimental results, the coloured points are within the 1σ preferred region, allowing for $\lambda_{bs} < 2V_{ts}$ (green) or $\lambda_{bs} < 5V_{ts}$ (blue). Right: correlation between C_T and C_S in various single-mediator models. Figures from ref. [7].

In all three cases the new states can be either $SU(2)_L$ triplets or singlets. The predictions for the two Wilson coefficients of eq. (1) for each of the six mediators are shown in the right panel of fig. 2, together with the results of the fit. It can be seen that the only single mediator that is able to reproduce the anomalies alone is a vector leptoquark, singlet of $SU(2)_L$.

3˙1. *Vector resonances.* – In the presence of a concrete model, a connection between the semi-leptonic observables described above, and other observables such as pure-quark operators or high-p_T searches can be made. Among the three classes of mediators, colorless vector resonances [6] are expected to generate large tree-level four-quark and four-lepton operators. In particular, a contribution to the B_s meson mixing amplitude proportional to $|\lambda_{bs}|^2$ is generated, which is more than two orders of magnitude larger than the experimental bound, and therefore needs to be cancelled in a concrete model by another contribution with a fine-tuning of a few permille. In addition, for $C_{S,T}$ of a few 10^{-2} as required by the fit, resonances of a few TeV are expected, with large couplings to fermions. Direct searches for vector resonances decaying to τ pairs at the LHC exclude these states, unless their decay width is extremely large. These considerations strongly disfavour the vector resonance interpretation [7].

3˙2. *Leptoquarks.* – Both these major problems are avoided in the case of leptoquarks. Pure quark or lepton operators are absent at tree-level, given that the leptoquarks couple only to mixed quark-lepton currents. Contributions to meson mixing and tau decays are however generated at one-loop, and can still pose a significant constraint, especially for strong coupling [7]. The reach of LHC searches for leptoquarks is also lower. Pair production in gluon-fusion proceeds through a strong interaction, and is independent of the leptoquark coupling to fermions. These searches presently exclude masses up to roughly a TeV, and will only mildly improve with the full LHC luminosity. Single leptoquark production in association with a τ lepton, on the other hand, is proportional to the coupling to fermions, and becomes an important channel for larger masses and couplings. Figure 3 left shows the production cross-sections for pair-production and single

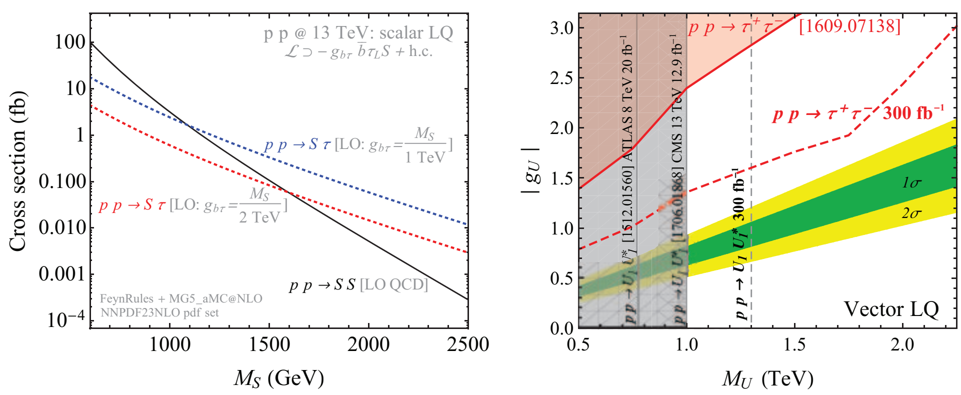

Fig. 3. – Left: single and double production cross-sections for a scalar leptoquark at the 13 TeV LHC. Right: present and future exclusions for a vector leptoquark in the plane (M_U, g_U). Figures from ref. [7].

production of a scalar leptoquark at the 13 TeV LHC. Finally, a leptoquark exchange in the t-channel gives a contribution to the process $bb \to \tau\tau$, that can be seen in the tails of the $\tau\tau$ distribution at large p_T. This non-resonant effect is a general prediction of any model addressing the B-physics anomalies with large third-generation couplings, although a precise prediction cannot be made in the EFT due to the large exchanged momentum. In fig. 3 right we show the present and future LHC limits on a vector leptoquark, as a function of its mass and coupling to b and τ. It can be seen that the LHC will not be able to probe the complete parameter space that is able to explain the flavour anomalies [7].

4. – UV completions

The models described in the previous section are only simplified toy models that catch the main phenomenological features of the mediators responsible for the flavour anomalies. All these models need to be completed in the ultraviolet, if one aims at a fully consistent theory. Here we sketch two different examples of UV completion.

4·1. *Vector leptoquark in Pati-Salam unification.* – In Pati-Salam unification models [10] the gauge group of the Standard Model is embedded in $SU(4) \times SU(2)_L \times SU(2)_R$, where lepton number is unified with colour inside $SU(4) \supset SU(3)_c \times U(1)_{B-L}$. The SM fermions, including the right-handed neutrino, fit precisely in two matter multiplets $\psi_L \sim (\mathbf{4}, \mathbf{2}, \mathbf{1})$, $\psi_R \sim (\mathbf{4}, \mathbf{1}, \mathbf{2})$. The gauge bosons of $SU(4)$ are in the adjoint representation, which decomposes as $\mathbf{15} = \mathbf{8}_0 \oplus \mathbf{3}_{4/3} \oplus \bar{\mathbf{3}}_{-4/3} \oplus \mathbf{1}_0$ under $SU(4) \to SU(3) \times U(1)_{B-L}$. Hypercharge is defined, after the breaking of the Pati-Salam group, as $Y = T_{3L} + T_{3R} + (B - L)/2$. One can see that the gauge bosons contain a state with exactly the quantum numbers of the vector leptoquark $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$ that is able to explain the flavour anomalies. In this simple version of the model, however, the couplings of a gauge vector to fermions are fixed, and the flavour structure is constrained to be a unitary matrix. This would imply the presence of large couplings to the first and second generations, which are ruled out: the non-observation of the decay $K_L \to \mu e$, *e.g.*, sets a lower bound on the mass of the Pati-Salam leptoquark of about 1000 TeV. Non-universal couplings can be obtained in different ways:

- The vector states could be resonances of a strongly coupled sector with an invariance under a global Pati-Salam group [11]. In this case the couplings to SM fermions can be obtained for instance though partial compositeness, and can have arbitrary flavour structure;

- In weakly coupled models, a larger gauge group $SU(4) \times SU(3) \to SU(3)_c$ can be considered. In this setup, SM colour is the diagonal subgroup, while different generations can have different quantum numbers under the full group. Various models based on this general paradigm, with either additional vector-like fermions or scalars, have been proposed in the literature [12, 13].

A generic feature of all these models is the presence, together with the vector leptoquark, of a color octet and a color singlet state with similar masses and couplings, that complete the $SU(4)$ multiplet. The search for these states at the LHC poses strong bounds on the models.

4˙2. *Scalar leptoquarks as Goldstone bosons.* – Scalar leptoquarks can be naturally lighter than other particles if they are pseudo-Goldstone bosons of some spontaneously broken symmetry. One can construct a theory with new fermions Ψ that are charged under a strongly coupled gauge group that confines at a scale of a few TeV. If a condensate is generated which breaks the chiral symmetry of the new fermions —in complete analogy with QCD— light composite Goldstone bosons will be present. This class of models goes under the name of *vector-like confinement*. It is easy to see that if there are fermions with the SM quantum numbers of the left-handed quark and lepton doublets, $\Psi_Q \sim (\mathbf{3}, \mathbf{2}, 1/6)$, $\Psi_L \sim (\mathbf{1}, \mathbf{2}, -1/2)$, $SU(2)_L$-triplet and -singlet scalar leptoquarks with the correct quantum numbers to generate the anomalies will be present [7,14]. If, in addition, also the additional states $\Psi_E \sim (\mathbf{1}, \mathbf{1}, -1)$, $\Psi_N \sim (\mathbf{1}, \mathbf{1}, 0)$ are present, a composite Higgs will also be present in the Goldstone spectrum. The scale of spontaneous symmetry breaking f has to be above roughly a TeV in order to be in agreement with the bounds from Higgs and electroweak physics. The origin of the Yukawa couplings of the Higgs and the leptoquarks to fermions is not addressed: this is a well-known problem of all composite Higgs models. However, whatever their origin is, it is interesting that in these models the flavour structure of the leptoquark couplings is linked to the SM Yukawa couplings, as required in order to fit the anomalies.

5. – Conclusions

Various experimental anomalies have shown up in different B-physics observables, and in different experiments. While it is too early to establish whether these effects are the sign of new unknown phenomena, their coherent indication for a nontrivial flavour pattern is surely interesting. We have shown that the complete set of anomalies can be described in an EFT framework with new left-handed semi-leptonic interactions, and a weakly broken $U(2)_q \times U(2)_\ell$ flavour symmetry. The phenomenology is described by a small number of parameters, that fit the anomalies with an overall scale of new physics of a few TeV, and CKM-like flavour violation. Three classes of mediators can generate these effective interactions: vector or scalar leptoquarks, and colorless vector resonances. A vector leptoquark is the only candidate that can explain all the anomalies alone as a single mediator. Various bounds from meson mixing, tau physics, and direct LHC searches have to be taken into account in each case. Many UV completions for the mentioned models have been proposed in the literature, with very interesting connections with gauge unification and Higgs compositeness. The experimental progress of the next few years, both in flavour physics and in high-p_T collisions, will shed light on the nature of these anomalies, maybe opening the road for a deeper understanding of flavour and particle physics beyond the Standard Model.

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The results presented here are based on ref. [7] written in collaboration with A. Greljo, G. Isidori, and D. Marzocca. This work is supported by the INFN grant “ FLAVOR”.

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