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# Where we are on B-physics discrepancies

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We discuss the theory interpretation of the discrepancies in semi-leptonic $B$ decays as of Moriond 2019. By critically including loop-induced effects that have not been discussed before in the context of global fits, we show that a fully coherent picture is possible all the way from the weak-effective-theory to the SMEFT to the simplified-model level.

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## 1. Introduction

Recent years witnessed the build-up of several deviations from Standard-Model (SM) expectations in semi-leptonic $B$ decays. These deviations fall in four groups of datasets, each of which characterized by different measurements, and different theory and experimental challenges:

*(a)* $b \to s\mu\mu$ differential branching-ratio data lower than the corresponding SM predictions [1, 2]. Here the main challenge is the control over $B$ to light meson hadronic form factors [3, 4, 5];

*(b)* Deviations with respect to SM predictions in $B \to K^*\mu^+\mu^-$ angular observables in certain kinematic regions for the di-lepton $q^2$ [6, 7, 8, 9]. Although form factor uncertainties are under better control than for branching ratios, hadronic uncertainties are nevertheless significant [10, 11] (see however [12]);

*(c)* Deviations from lepton universality in $b \to s\ell\ell$ transitions in the processes $B \to K\ell\ell$ and $B \to K^*\ell\ell$ (via the $\mu/e$ ratios $R_K$ [13] and $R_{K^*}$ [14]). Here the challenge is mostly statistics, due in particular to the $ee$ channel, that requires harder $p_T$ thresholds and has larger bremsstrahlung systematics;

*(d)* Deviations from $\tau$-$\mu$ and $\tau$-$e$ universality in $b \to c\ell\nu$ transitions [15, 16, 17, 18, 19, 20, 21]. Here uncertainties, besides statistics, include a non-negligible experimental systematics, whereas theory uncertainties are small [22, 23, 24, 25].

It is quite impressive that items *(a)* to *(c)* can be *simultaneously* explained with one and the same shift to two four-fermion semi-leptonic operators and as a result, the picture be substantially improved with respect to the SM. It is likewise quite enticing that *all* items *(a)* to *(d)* can be explained, not only qualitatively but even quantitatively, all the way from the level of the Weak Effective Theory (WET), to the so-called SM Effective Field Theory (SMEFT), to the level of simplified models, as shown in Ref. [26].

Ref. [26]'s conclusions rely on a number of data updates, among the others:

*(1)* The new measurement of $R_K$ by the LHCb collaboration combining Run-1 data with 2 fb$^{-1}$ of Run-2 data (corresponding to about one third of the full Run-2 data set) [27].

The SM predicts lepton flavour universality, i.e. $R_K^{\rm SM}$ is unity with uncertainties [28] that are well below the current experimental sensitivities. While the updated experimental value is closer to the SM prediction than the Run-1 result [13], the reduced experimental uncertainties imply a tension between theory and experiment at the level of $2.5\sigma$, which is comparable to the situation before the update.

*(2)* The new, preliminary measurement of $R_{K^*}$ by Belle [29].

Averaged over $B^\pm$ and $B^0$ decays, the measured $R_{K^*}$ values at low and high $q^2$ are

$$R_{K^*} = \frac{{\rm BR}(B \to K^*\mu\mu)}{{\rm BR}(B \to K^*ee)} = \begin{cases} 0.90^{+0.27}_{-0.21} \pm 0.10\,, & \text{for } 0.1\,{\rm GeV}^2 < q^2 < 8\,{\rm GeV}^2\,, \\ 1.18^{+0.52}_{-0.32} \pm 0.10\,, & \text{for } 15\,{\rm GeV}^2 < q^2 < 19\,{\rm GeV}^2\,. \end{cases} \quad (1.1)$$

Given their sizable uncertainties, these values are compatible with both the SM predictions and previous results on $R_{K^*}$ from LHCb [14]

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^* \mu\mu)}{\mathrm{BR}(B \to K^* ee)} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03\,, & \text{for } 0.045\,\mathrm{GeV}^2 < q^2 < 1.1\,\mathrm{GeV}^2\,, \\ 0.69^{+0.11}_{-0.07} \pm 0.05\,, & \text{for } 1.1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2\,, \end{cases} \tag{1.2}$$

that are in tension with the SM predictions by $\sim 2.5\sigma$ in both $q^2$ bins.

*(3)* One further, important piece of information included in our study is the 2018 measurement of $B_s \to \mu\mu$ by the ATLAS collaboration [30], that we combine with the existing measurements by CMS and LHCb [31, 32, 33]. (Later experimental updates are not included as of this writing.)

We refer the reader to Ref. [26] for full details.

## 2. Weak Effective Theory

The first step is to address the question whether these datasets can be described within the most general effective theory constructed at the electroweak scale. As well known, this is not only possible, but even rather simple to accomplish. Data obey a pattern, which quite clearly suggests that new effects may involve two dominant structures: a left-handed $\bar{b}s$ current times a vector ($\mathcal{O}_9$) or an axial-vector muon current ($\mathcal{O}_{10}$). The best performing new-physics scenarios to explain the data involve precisely these two operators, and in particular either $\mathcal{O}_9$ alone, or the combination $\mathcal{O}_9 - \mathcal{O}_{10}$, yielding a $(V-A) \times (V-A)$ structure, well suited to UV interpretations.

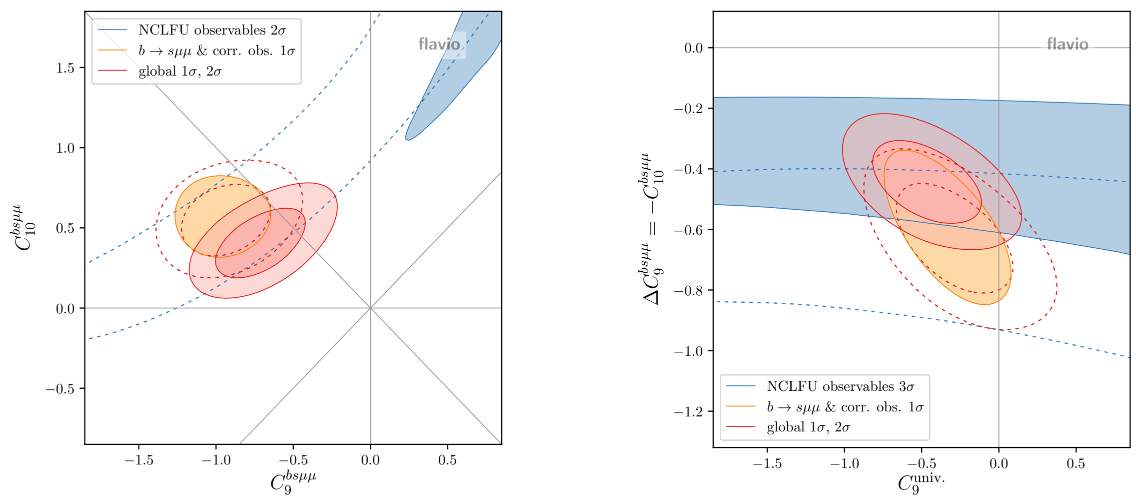


**Figure 1:** Neutral-current lepton flavour universality (NCLFU) observables (blue), $b \to s\mu\mu$ and correlated observables (yellow) and global fit (red). Dashed contours exclude the Moriond-2019 results.

At the quantitative level, one may first try with a single d.o.f. left floating, and fit it to data. In this case, two scenarios stand out, either $C_9^{(\mu)}$ alone or $C_9^{(\mu)} = -C_{10}^{(\mu)}$. This was the case also before Moriond 2019. However, at least within the approach of [26], the second scenario has an appreciably better performance with respect to the former. This is due to a concurrence of causes, notably the fact that $\mathscr{B}(B_s \to \mu\mu)$ prefers more and more a non-zero shift to $C_{10}^{(\mu)}$, as shown in the $C_9^{(\mu)}$ vs. $C_{10}^{(\mu)}$ plane in Fig. 1. We see that $R_{K^{(*)}}$ and $b \to s\mu\mu$ data perfectly overlapped before the Moriond-2019 update. Thereafter, these two regions are in much lesser agreement, especially in the $C_9$ direction. There is likewise a slight tension between $R_K$ and $R_{K^*}$, which may be addressed with right-handed quark currents. Thus one would be tempted to advocate e.g. $O_9^{(\mu)\prime}$. However, such operator would not accommodate $B_s \to \mu\mu$.

One important point is that, as mentioned, in the $C_9^{(\mu)}$ vs. $C_{10}^{(\mu)}$ plane there is a degree of tension between $R_{K^{(*)}}$ and $b \to s\mu\mu$ data, and a lepton-universal shift to $C_9$ would shift $b \to s\mu\mu$ but not ratio data.

It is thus interesting to consider the case of $\Delta C_9^{(\mu)} = -C_{10}^{(\mu)}$ vs. $C_9^{\text{univ.}}$, displayed in the right panel of Fig. 1. Before Moriond 2019, the $R_K$ band was lower, and overlapped with $b \to s\mu\mu$ in a region with zero $C_9^{\text{univ.}}$. After Moriond, accord between the two datasets prefers a non-zero $C_9^{\text{univ.}}$. As we will see, such occurrence admits a well-defined UV interpretation.

## 3. SMEFT

We next discuss the performance of an EFT description at a scale of a few TeV, and without new d.o.f. beyond those in the SM. Effects beneath such new scale are described by the SMEFT. In our case, contributions to the two directions identified before, namely $\Delta C_9^{(\mu)} = -C_{10}^{(\mu)}$ and $C_9^{\text{univ.}}$, can come from: *(i)* these very semi-leptonic operators, constructed out of left-handed SM multiplets, $L$ and $Q$, and either singlets or triplets under $SU(2)_L$, i.e. $\bar{L}^{(3)}\gamma^\alpha L^{(3)}\bar{Q}^{(2)}\gamma_\alpha Q^{(3)}$ and $\bar{L}^{(3)}\gamma^\alpha \tau^a L^{(3)}\bar{Q}^{(2)}\gamma_\alpha \tau^a Q^{(3)}$; *(ii)* $C_9^{\text{univ.}}$ can be generated by 4-fermion operators where one of the two bilinears is closed in a loop to which a virtual gauge boson emitting a lepton pair is attached [34, 35]. Hence the amplitude is lepton-universal by gauge universality.

Interestingly, if the closed loop involves two $\tau$'s, the corresponding 4-fermion operator can also explain $R_{D^{(*)}}$ [35]. We find that the induced $C_9^{\text{univ.}}$ contribution has the correct size *and* sign to quantitatively accommodate $b \to s\mu\mu$. Then the very same operators, but with muonic indices, can explain $R_{K^{(*)}}$. The only caveat is that singlet and triplet couplings in the semi-tauonic case must be approximately equal in size in order to avoid $B \to K^{(*)}\nu\bar{\nu}$ constraints [36].

This scenario can be visualized in the first panel of fig. 2, in the plane of tauonic vs. muonic singlet-equal-to-triplet couplings. Again, before Moriond 2019, $R_K$ (blue) and $b \to s\mu\mu$ (yellow) were in perfect agreement in a region that however did not overlap with the $R_{D^{(*)}}$ region (green). After Moriond 2019, the blue, yellow and green regions all overlap.

## 4. Simplified models

The previous EFT picture finds a UV interpretation within the $U_1$ vector-leptoquark model, with $U_1 \sim (\mathbf{3},\mathbf{1})_{2/3}$ under the SM gauge group [37, 38, 39, 40, 41, 42, 43, 44, 45, 46]. This is the only single mediator that can yield non-zero values for $[C_{lq}^{(1)}]_{3323} = [C_{lq}^{(3)}]_{3323}$ and $[C_{lq}^{(1)}]_{2223} = [C_{lq}^{(3)}]_{2223}$.

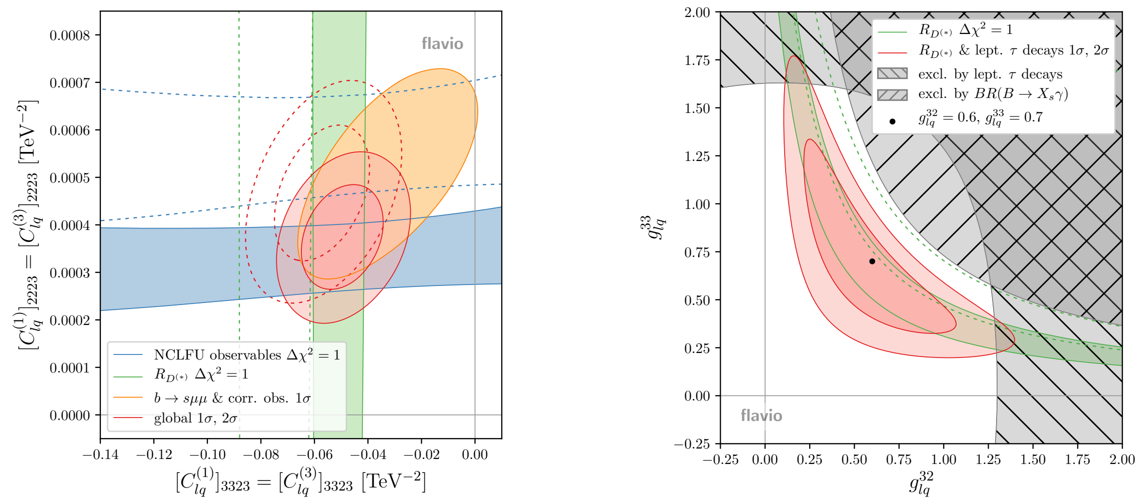


**Figure 2:** First panel: Neutral-current lepton flavour universality (NCLFU) observables (blue), $b \to s\mu\mu$ and correlated observables (yellow), $R_{D^{(*)}}$ (green) and global fit (red). Dashed contours exclude the Moriond-2019 results. Second panel: plane of tauonic couplings within the $U_1$ simplified model.

One can then define the simplified-model coupling $\mathscr{L}_{U_1} \supset g_{lq}^{ji} \left(\bar{q}^i \gamma^\mu l^j\right) U_\mu + \text{h.c.}$. A shift to $R_{K^{(*)}}$ will depend on $g_{lq}^{22,23}$, whereas a shift to $R_{D^{(*)}}$ depends on $g_{lq}^{33,32}$. Tauonic couplings are known to be constrained by $\tau \to \ell\nu\nu$, hence it is far from obvious that the whole picture can work quantitatively. The plane of tauonic couplings is displayed in Fig. 2 (second panel) and it shows that $R_{D^{(*)}}$ can indeed be comfortably accommodated in compliance with all constraints. We note that radiative decays provide a further constraint, which is however very model-dependent, because additional fermions would also contribute to dipole structures and shift $B \to X_s\gamma$ along the diagonal [47]. Choosing a benchmark point in the tauonic-couplings plane, e.g. $(g_{lq}^{32}, g_{lq}^{33}) = (0.6, 0.7)$ also displayed in the figure, one can see that all constraints are fulfilled in the plane $g_{lq}^{22,23}$ of the muonic couplings [26]. In particular, the above benchmark point performs way better than the case of null tauonic couplings. Finally, this model also allows to address the question whether such tauonic couplings may be constrained by direct searches, discussed in [48, 49, 50, 51, 52, 53]. We find that the indirect constraint from leptonic $\tau$ decays [54, 55] is stronger than the direct constraints in nearly all of the parameter space.

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