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Exploring B-physics anomalies at colliders

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Several experimental measurements of B meson decays, in tension with Standard Model predictions, exhibit large sources of Lepton Flavour Universality violation. We perform an analysis of the effects of the global fits to the Wilson coefficients assuming a model independent effective Hamiltonian approach, by including a proposal of different scenarios to include the New Physics contributions. Both the current fits at the LHC and the ILC projections are considered. We found that for a simultaneous analysis of predictions for the $R_{D^{(*)}}$ and $R_{K^{(*)}}$ observables, the scenarios with three non-universal Wilson coefficients are favoured.

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There are several experimental hints of Lepton Flavour Universality Violation (LFUV) in $b \to c\ell\nu$ and $b \to s\ell^+\ell^-$ transitions that could be a sign for physics beyond the Standard Model (SM). In the first processes, the $R^\ell_{D^{(*)}}$ and $R^\mu_{D^{(*)}}$ ratios, defined by

$$R^\ell_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{[\mathrm{BR}(B \to D^{(*)}e\bar{\nu}_e) + \mathrm{BR}(B \to D^{(*)}\mu\bar{\nu}_\mu)]/2}\,, \qquad R^\mu_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathrm{BR}(B \to D^{(*)}\mu\bar{\nu}_\mu)}\,, \quad (1)$$

exhibit a $1.4\,\sigma$ and $2.5\,\sigma$ discrepancy with respect to the SM predictions, being $3.08\,\sigma$ when combined together. The experimental averages for these ratios are [1]: $R_D^{\mathrm{ave}} = 0.340 \pm 0.027 \pm 0.013$, $R_{D^*}^{\mathrm{ave}} = 0.295 \pm 0.011 \pm 0.008$. For $b \to s\ell^+\ell^-$ transitions, the signs of LFUV are present in the $R_{K^{(*)}}$ ratios,

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}\,. \quad (2)$$

As a consequence of Lepton Flavour Universality (LFU), $R_K = R_{K^*} = 1$ in the SM. However, the latest experimental results from LHCb, in the specified regions of q^2 di-lepton invariant mass, are [2, 3]: $R_K^{[1.1,6]} = 0.846^{+0.042+0.013}_{-0.039-0.012}$, $R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$, $R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$. Therefore, sizeable violations of LFU at the $3.1\,\sigma$ level for the R_K ratio and at the $2.3\,\sigma$ level for the R_{K^*} ratio in the low-q^2 region and $2.4\,\sigma$ in the central-q^2 region have been found.

Effective Field Theories (EFT) offer a model-independent analysis of New Physics (NP) effects. The NP contributions at an energy scale $\Lambda \sim \mathcal{O}(\mathrm{TeV})$ is described by the SMEFT Lagrangian:

$$\mathcal{L}_{\mathrm{SMEFT}} = \frac{1}{\Lambda^2}\left(C^{ijkl}_{\ell q(1)}\,O^{ijkl}_{\ell q(1)} + C^{ijkl}_{\ell q(3)}\,O^{ijkl}_{\ell q(3)}\right)\,, \quad (3)$$

where the dimension six operators are defined as $O^{ijkl}_{\ell q(1)} = (\bar{\ell}_i\gamma_\mu P_L \ell_j)(\bar{q}_k\gamma^\mu P_L q_l)$ and $O^{ijkl}_{\ell q(3)} = (\bar{\ell}_i\gamma_\mu\tau^I P_L\ell_j)(\bar{q}_k\gamma^\mu\tau^I P_L q_l)$, ℓ and q are the lepton and quark $SU(2)_L$ doublets, τ^I the Pauli matrices, and i, j, k, l denote generation indices. We will restrict our analysis to operators including only third generation quarks and same-generation leptons:

$$C^e_{\ell q} \equiv C^{1133}_{\ell q}\,, \qquad C^\mu_{\ell q} \equiv C^{2233}_{\ell q}\,, \qquad C^\tau_{\ell q} \equiv C^{3333}_{\ell q}\,. \quad (4)$$

Since the $O_{\ell q}$ operators also produce unwanted contributions to the $B \to K^{(*)}\nu\bar{\nu}$ decays, we will fix the relation $C^i_{\ell q(1)} = C^i_{\ell q(3)} \equiv C^i_{\ell q}$ in order to obey these constraints.

The above effective operators affect a large number of observables, connected between them via the Wilson coefficients. In order to have a complete analysis of the implications of the experimental measurements in flavour physics observables, a global fit to the available experimental data is required. We performed a global fit in [4, 5], where an extensive list of references to previous analyses is included. In [5] the global fits to the $C_{\ell q}$ coefficients have been performed by using the package `smelli` v1.3. This fit includes $b \to s\mu\mu$ observables; the branching ratio of $B_s \to \mu\mu$, the angular observables P_5' and $R_{K^{(*)}}$, as well as $R_{D^{(*)}}$, $b \to s\nu\bar{\nu}$ and the electroweak (EW) precision observables (W and Z decay widths and branching ratios to leptons). The goodness of each fit is evaluated with its difference of χ^2 with respect to the SM value. We have defined some specific phenomenological scenarios by choosing several combinations of the $C^i_{\ell q}$ operators [5], as shown in the first two columns of Table 1. The best fit values for the $C^i_{\ell q}$ operators and the pulls from the SM and of scenario VII are included in this table. Scenario VII corresponds with the more general one in

Scenario		$C^e_{\ell q}$	$C^\mu_{\ell q}$	$C^\tau_{\ell q}$	$\Delta\chi^2_{\rm SM}$	Pull from SM	Pull to VII
I	e	-0.14 ± 0.04			8.84	$2.97\,\sigma$	$4.37\,\sigma$
II	μ		0.10 ± 0.04		5.47	$2.34\,\sigma$	$4.73\,\sigma$
III	τ			-0.38 ± 0.19	3.85	$1.96\,\sigma$	$4.89\,\sigma$
IV	e and μ	-0.25 ± 0.07	0.24 ± 0.06		28.42	$4.97\,\sigma$	$1.75\,\sigma$
V	e and τ	-0.14 ± 0.06		-0.4 ± 0.3	12.98	$3.17\,\sigma$	$4.30\,\sigma$
VI	μ and τ		0.10 ± 0.06	-0.3 ± 0.3	8.73	$2.49\,\sigma$	$4.77\,\sigma$
VII	e, μ and τ	-0.25 ± 0.02	0.211 ± 0.016	-0.3 ± 0.4	31.50	$4.97\,\sigma$	
VIII	$e = \mu = \tau$	-0.0139 ± 0.0003	-0.0139 ± 0.0003	-0.0139 ± 0.0003	0.30	$0.55\,\sigma$	$5.23\,\sigma$
IX	$e = -\mu = \tau$	-0.232 ± 0.001	0.232 ± 0.001	-0.232 ± 0.001	30.74	$5.54\,\sigma$	$0.41\,\sigma$
X	$e = -\mu$	-0.23 ± 0.04	0.23 ± 0.04		28.13	$5.30\,\sigma$	$1.32\,\sigma$
XI	$e = -\mu, \tau$	-0.23 ± 0.02	0.23 ± 0.02	-0.3 ± 0.3	30.51	$5.17\,\sigma$	$1.00\,\sigma$

Table 1: Best fit values and pulls from the SM and of scenario VII for several combinations of the $C^i_{\ell q}$ operators; with one, two and three of the $C_{\ell q}$ operators receiving NP contributions.

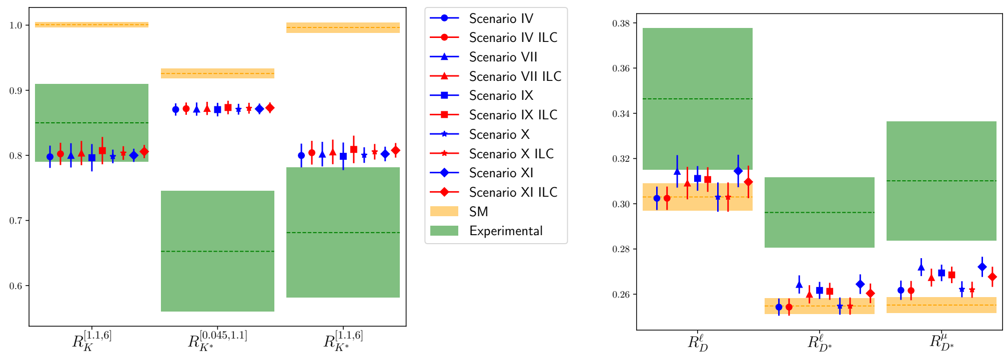

Figure 1: Central value and 1σ uncertainty of the $R_{K^{(*)}}$ observables (left), and $R_{D^{(*)}}$ observables (right) in scenarios IV, VII, IX, X and XI (blue lines for current predictions, red lines for ILC-based predictions), compared to the SM prediction (yellow) and experimental measurements (green).

which the three $C_{\ell q}$ operators - $C^e_{\ell q}$, $C^\mu_{\ell q}$ and $C^\tau_{\ell q}$ - receive independent NP contributions. We found that the prediction of the $R_{D^{(*)}}$ and $R_{K^{(*)}}$ observables in this scenario is improved. We also found that an scenario within the condition $C^e_{\ell q} = -C^\mu_{\ell q} = C^\tau_{\ell q}$ imposed, provides a similar fit goodness with a smaller set of free parameters. In general, the best results are obtained when $C^e_{\ell q} \approx -C^\mu_{\ell q}$ (scenarios IV, VII, IX, X and XI). This indicates a maximal violation of LFU, while lepton-universal NP is heavily constrained by the EW observables. The results for the $R_{K^{(*)}}$ and $R_{D^{(*)}}$ observables in the best fit points for the above scenarios are given in Figure 1. We remark that for the $R_{D^{(*)}}$ ratios, the $C^\tau_{\ell q}$ contributions are needed, making scenarios VII, IX and XI preferred over IV and X. Clearly, for a simultaneous analysis of predictions for the $R_{D^{(*)}}$ and $R_{K^{(*)}}$ observables, the scenarios with three non-universal Wilson coefficients are favoured.

Let us stress that new experimental inputs should provide valuable new information to cast light on B anomalies. In this concern, the future e^+e^- linear collider ILC will offer the opportunity to use the increased precision of the EW observables, thanks to the huge production of Z bosons, to further constrain the global fits. In order to asses the impact of the improved precision on our

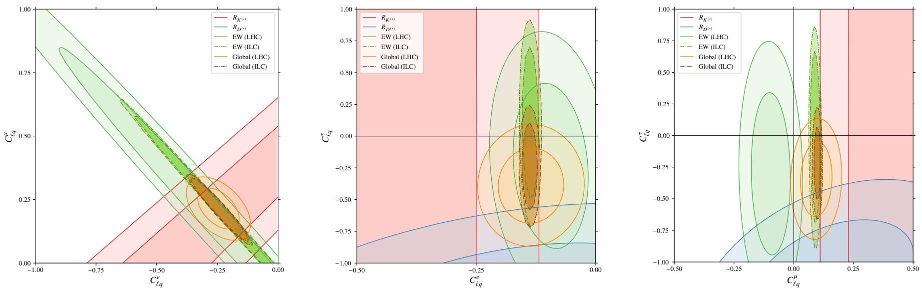

Figure 2: 1σ and 2σ contours for several scenarios: Scenario IV (left), Scenario V (center), and Scenario VI (right). Solid lines correspond to the current fits, dash-dotted lines to the fits including the ILC projections.

analysis, we have performed a new global fit in [6], by using for the central values of the EW observables their predictions as in our previous work [5] and taking the uncertainty from the ILC at $\sqrt{s} = 250$ GeV projections from [7]. For comparison, the results of the fits to scenarios IV, V and VI; in which two of the Wilson coefficients receive NP contributions simultaneously, both for the current fits at LHC and for the ILC projections, are presented in Figure 2. One can conclude that the LFU-conserving direction of the fit, corresponding to the linear combination $C^e_{\ell q} + C^\mu_{\ell q}$, is even more tightly constrained due to the better precision of the EW observables. The LFUV direction of the fit remains unchanged, since the EW observables are not sensitive to these deviations.

The results for the central value and 1σ uncertainty for the $R_{K^{(*)}}$ and $R_{D^{(*)}}$ observables in the best fit points for Scenarios IV, VII, IX, X and XI at ILC are also included in Figure 1. The error of the $R_{K^{(*)}}$ observables is improved up to factor of 3. When including the ILC projections, the error in all those observables is dominated by the theoretical uncertainty, due to that the allowed region for the Wilson coefficients in the fits is reduced.

Summarising, it is difficult to find an easy common explanation for all flavour anomalies, but the analysis of the effects of the global fit to the Wilson coefficients is mandatory. The anomalies can be described by NP displaying a maximal violation of universality between electrons and muons, but some NP in the tau sector is also needed. It is clear that new experimental inputs and updated global fits to date are needed to clarify the present situation.

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