Paper of the Month: On the flavour anomalies and connections to new physics

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The Standard Model (SM) of particle physics, in spite of its incredible success in explaining lots of experimental results and predicting accurately a number of phenomena, cannot accommodate several experimental observations of our Universe such as dark matter or neutrino masses. Therefore, the SM cannot be the fundamental theory of Nature, being instead regarded as its low-energy limit.

Persistent and corroborated measurements showing deviations from the SM predictions could be potential hints towards the nature of the unknown physics at higher energies. Particularly, several experiments around the world focused on the study of heavy flavored mesons have been observing a different behavior of leptons in the following transitions:

$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)} \quad \text{and} \quad R_{D^{(*)}} = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\bar{\nu}_\tau\right)}{\mathcal{B}\left(B \to D^{(*)}\ell\bar{\nu}_\ell\right)}\,, \tag{1}$$

which in the SM are expected to be very close to 1. These observables are written in terms of ratios to cancel large uncertainties which are, for instance, related to our inability to accurately predict the dynamics of the strong force inside the mesons. The departures from the SM in these flavour observables became known as the *B-anomalies*; the first (second) showing a combined tension of nearly 4.7σ (3σ) with respect to the SM prediction. The updated measurement of R_K alone by the LHCb collaboration [1] shows in turn a statistical significance of 3.1σ. However, other B-factories such as Belle-II did not yet gathered enough data to confirm this improved result.

The LHCb experiment detects electrons and muons in a very different way: electrons are detected in the first layers, while muons fly a larger distance, being detected in the outer layers of the experiment in dedicated sub-detectors. So, one might rise the question of whether the deficit of muons (originating these deviations) could be just an experimental error. Taking this into account we can normalize this ratio by the decay of $B \to J/\Psi\, K^{(*)}$ and $J/\Psi \to \ell^+\ell^-$. This latter process is purely electromagnetic; thus, the ratio of the branching ratio of $B \to J/\Psi\, K^{(*)}$ in the muon channel over the electron channel is expected to be 1. So, we can measure the double ratio of R_K divided by the process involving the resonance J/Ψ, canceling possible systematic uncertainties due to the different detector responses for electrons and muons.

Taking into account also less clean observables, such as angular distributions of $B \to K^*\mu^+\mu^-$, the flavour anomalies are the largest coherent set of deviations ever observed since the observation of neutrino masses. Let us remark that the different fermion flavours in the SM are indistinguishable in all interactions, up to their masses. The anomalies observed in their behaviour are therefore the first hint that their similarity in the SM could be just an accidental property of low-energy physics, with new heavy interactions differentiating the various fermion flavours, specially those of the third generation (the heaviest).

Adding to these anomalous results, there are the longstanding deviation with respect to the SM in the anomalous magnetic moment of the muon (with a combined significance of 4.2σ) and the Cabibbo-angle anomaly, referring to the tension between the value of the V_{us} entry of the CKM matrix computed from kaon decays and the one following from the unitarity of the CKM matrix.

It is possible to learn which new interactions could lead to these anomalous results using a model-independent (effective field theory) approach, that is, by studying which particles and new types of interactions could be responsible for the effects observed in the data. With that knowledge, we can further infer which new models (with new particles) could generate the four-fermion interactions that lead to the decays in equation 1, as well as contribute to the magnetic moments of leptons.

In the work presented in Ref. [2], a model completing the SM was proposed to explain the four classes of anomalies described above using a minimal particle content: a colorless charged scalar ϕ^+ and a scalar leptoquark S_1 (a hypothetical particle that couples both to leptons and quarks). Such particles are represented in the left panel of figure 1, in the internal lines of the diagrams.

Performing a global analysis, the authors found the preferred regions of the parameter space that comply with several other observations to which the new particles contribute (and which of course cannot spoil), such as $B-\bar{B}$ mixing; see the upper right panel in figure 1. Subsequently, they studied how the preferred regions translate into observables that show discrepancies with the SM; see the bottom right panel in figure 1 for an example, where it is shown that the model can address the charged flavour anomalies at the 1σ level. Similar conclusions were found for the remaining three anomalous results, for masses of the exotic particles equal to 5.5 TeV.

While such large masses are beyond the reach of direct searches at current energies, they could distort the high-energy tail of kinematic distributions, which will become increasingly significant with the expected growth of luminosity by the end of the HL-LHC. Furthermore, the model under discussion induces additional effects in low-energy data such as flavour-violating τ decays with rates close to the experimental bounds. Therefore, updated bounds from the future run of the Belle-II and the LHCb experiments could potentially probe important regions of the model parameter space. At the same time, the new data being currently collected at the Fermilab and the LHCb experiments will further reduce the uncertainties in the observables of relevance and consequently on the possible new physics solutions to the flavour anomalies which remain one of the most interesting developments in our field of research. Physicists are even betting on the date of a possible 5σ discovery (`https://sites.google.com/view/allthingseft-bets/home`).

References

[1] LHCb collaboration. R. Aaij *et al. Tests of lepton universality using* $B^0 \to K^0_S \ell^+ \ell^-$ *and* $B^+ \to K^{*+} \ell^+ \ell^-$ *decays.* 2021. arXiv: `2110.09501 [hep-ex]`.

[2] David Marzocca and Sokratis Trifinopoulos. "Minimal Explanation of Flavor Anomalies: B - Meson Decays, Muon Magnetic Moment, and the Cabibbo Angle". In: *Physical Review Letters* 127.6 (2021). DOI: `10.1103/physrevlett.127.061803`.

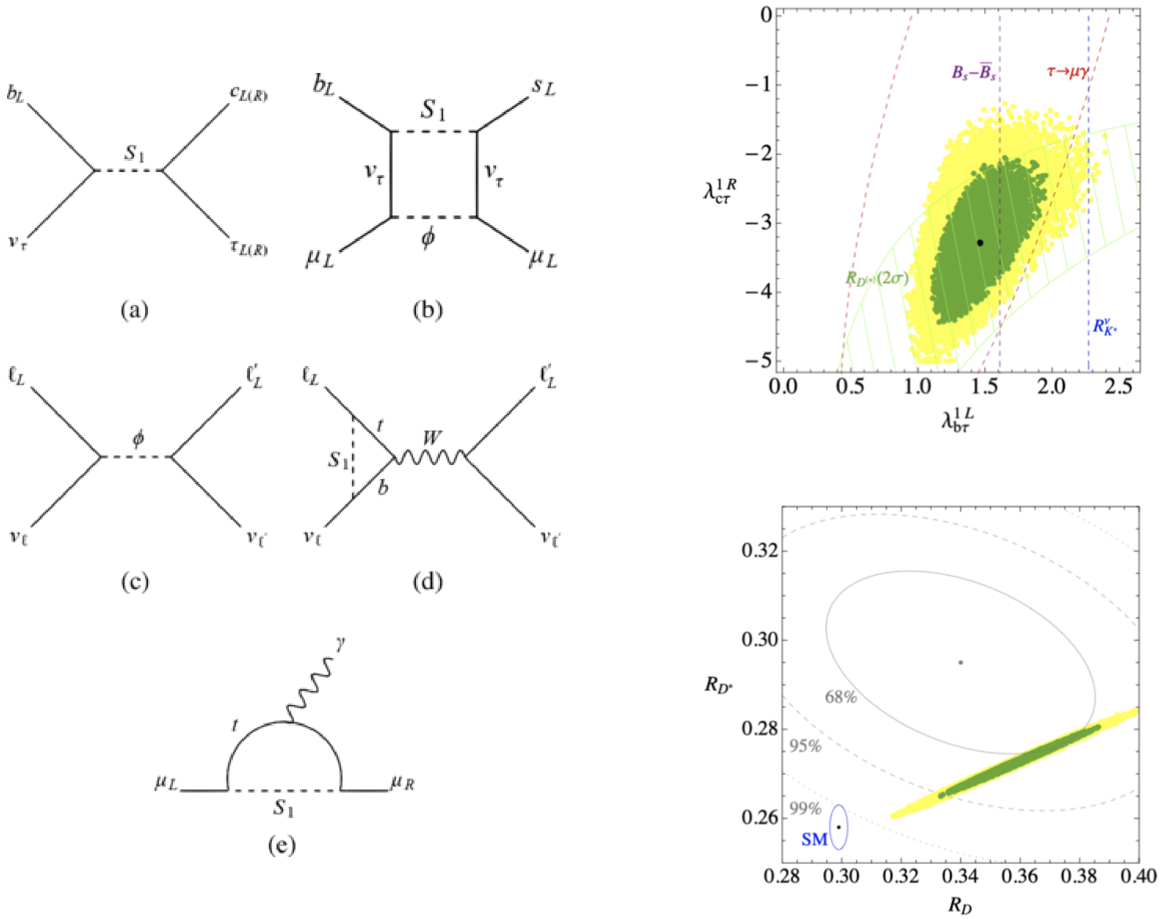

Figure 1: *(Left) Contribution of the hypothetical particles of the model proposed in [2] to the flavour observables showing large deviations with respect to the SM prediction. (Top-right) Preferred region of the model parameters for exotic masses of* 5.5 *TeV. (Bottom-right) Contributions of the model to* $R_{D^{(*)}}$*, assuming the parameter space defined in the upper panel. The green and yellow bands are within* 1σ *and* 2σ *of the best fit point, respectively.*