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Theory Status - Puzzles in B Meson Decays and LFU?

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Abstract

Currently B meson puzzles motivate many studies of New Physics due to the observed deviations from the Standard Model predictions. There are two B meson puzzles, $R_{D^{(*)}}$ and $R_{K^{(*)}}$. The first one denotes the deviations in the decays driven by the charged current in the ratio of the decay widths for $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}\mu\nu$, while the second one is related to the ratio of the decay widths for $B \to K^{(*)}\mu^+\mu^-$ and $B \to K^{(*)}e^+e^-$ transition. Also, the measured muon anomalous magnetic moment differs from the SM predictions. Usually, the effective Lagrangian approach containing New Physics effects is used to analyse $R_{D^{(*)}}$ and $R_{K^{(*)}}$. Among many models of New Physics, various leptoquark models are suggested to resolve both B meson anomalies. If New Physics is confirmed in B decays a number of processes at low and high energies should confirm its presence.

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1 Introduction

The Standard Model (SM) as a gauge theory of strong and electroweak interactions is being intensively tested in last decades. Experimental results agree very well with results of theoretical calculations. However, it does not include mechanisms for generating neutrino masses, dark matter explanation or understanding hierarchy. The Large Hadron Collider (LHC) in CERN enabled the SM testing at energies in TeV regime, not finding any disagreement with its predictions. However, nowadays at low-energies there are a few discrepancies at $\sim 4\sigma$ level. One of them is the muon anomalous magnetic moment [1], whose experimental value differs from the SM prediction for 3 to 4 σ. According to the literature [1] the main reason for the disagreement comes from the hadronic contributions. Lattice QCD was very successful in determining the vacuum polarization and light-by-light contributions [2,3]. Next year, new experiments at Fermilab (USA) and J-PARC (Japan) are expected to achieve four times better precision.

In B meson decays there are three anomalies: $R_{D^{(*)}}$, $R_{K^{(*)}}$ and P_5'. The $R_{D^{(*)}}$ observables is related to the $b \to c l \bar{\nu}_l$ process for which this ratio is defined as

$$R_D = \left.\frac{\Gamma(B \to D\tau\bar{\nu}_\tau)}{\Gamma(B \to D l \bar{\nu}_l)}\right|_{l\in\{e,\mu\}} = 0.41 \pm 0.05. \tag{1}$$

Namely, ratios give a possibility not to be dependent on the CKM matrix element and due to the expectation that hadronic properties should mainly cancel in the ratios, it was found that it is 3.9σ higher than the SM prediction, $R_D^{\rm SM} = 0.286 \pm 0.012$, based on the lattice QCD data for the vector and scalar form factors, obtained by MILC collaboration [6]. In the case of the vector D^*, it was found that $R_{D^*} = 0.317 \pm 0.017$, also confirmed by LHCb [5]. This appears to be 3.3σ larger than predicted, $R_{D^*}^{\rm SM} = 0.252 \pm 0.003$ [7–9]. However, the lattice calculations for the $B \to D^*$ form factors are still lacking. In the ratio $R_{J/\Psi} = (\Gamma(B_c \to J/\Psi\tau\nu)/(\Gamma(B_c \to J/\Psi\tau\nu)$, a similar deviation was measured with the experimental value being larger than the theoretical prediction at the 2σ level [10]. Currently, the first differential decay distribution $B \to D^{(*)}\tau^-\bar{\nu}_\tau$ was performed in [11], further angular analyses in these processes would help in differentiating between various New Physics scenarios [12,13].

For the SM calculations of R_{D^*}, the form factors were extracted from the angular distribution of $d\Gamma(B \to D^*\mu\nu_\mu)/dq^2$, up to a normalization, and the leading order heavy quark effective theory has been used in evaluating the pseudoscalar form factor [8,9].

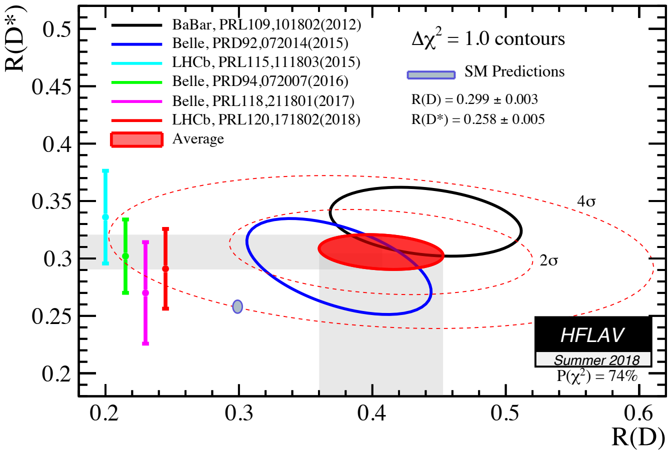

Figure 1: R_{D^*} and R_D experimental results and the SM predictions by HFLAV (summer 2018).

For the neutral current transition the LHCb collaboration found

$$R_K = \frac{\Gamma(B \to K\mu^+\mu^-)}{\Gamma(B \to Ke^+e^-)} = 0.745 \pm^{0.090}_{0.074} \pm 0.036\,, \tag{2}$$

2.6σ below the SM prediction, $R_K^{\mathrm{SM}} = 1.00(1)$ [29]. In the case of the flavour changing neutral current transition (FCNC) $b \to s\mu^+\mu^-$, the LHCb experiment has measured ratios $R_{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \to K^{(*)}e^+e^-)$ at the low di-lepton invariant mass. Interestingly, these ratios were found to be systematically lower than expected in the SM. In the case of a K meson in the final state, the ratio R_K was measured in the kinematical region $q^2 \in [1.1, 6]$ GeV^2 [25], while R_{K^*} was measured also in the region $q^2 \in [0.045, 1.1]$ GeV^2 [28]. The three measured $R_{K^{(*)}}$ ratios deviate from the SM predictions at $\sim 2.5\,\sigma$ level [29, 30]. In the SM, Lepton Flavour Universality (LFU) results from the basic property of the $SU(2)_L \times U(1)_Y$ gauge group. The part of SM local gauge invariant Lagrangian for the left-handed fermions is

$$\mathcal{L} \in \bar{\Psi}_L i\gamma^\mu D_\mu \Psi_L = \bar{\Psi}_L i\gamma^\mu(\partial_\mu - ig\frac{1}{2}\tau_i W^i_\mu - ig' Y_L B_\mu)\Psi_L\,, \tag{3}$$

with $\Psi_L = q_L, \ell_L$ and q_L, $(\Psi_L = 1/2(1-\gamma^5)\Psi)$, denoting a weak doublet of quark and lepton generations

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \ \ell_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}. \tag{4}$$

The coupling g is the same for all left-handed quarks and leptons and this is a reason why we have universality of the weak coupling constant. In the case of leptons, therefore we talk about LFU. As stated in high-energy textbooks for beginners, the Fermi weak coupling constant at low-energies is

$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J^\dagger_\mu J^\mu, \quad \frac{G_F}{\sqrt{2}} = \frac{g^2}{m_W^2}. \tag{5}$$

For example, the LFU gives $\Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = \Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$ up to tiny mass effects.

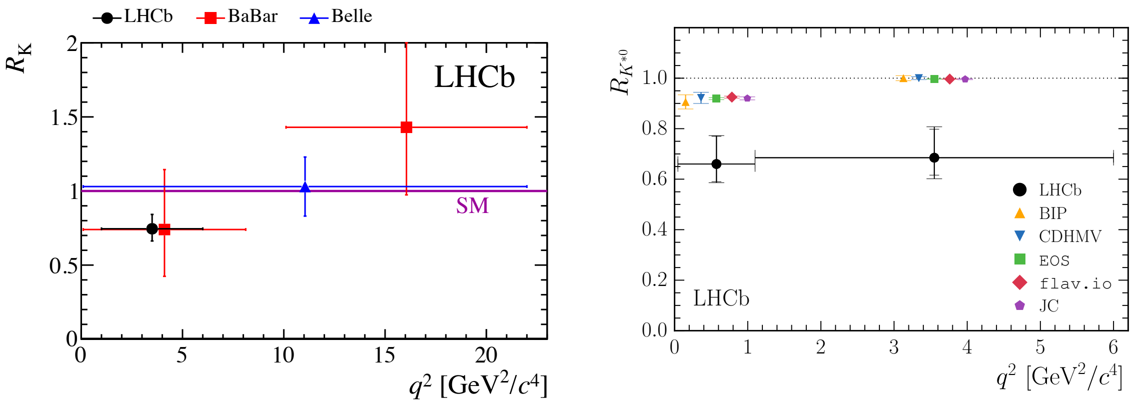

Figure 2: Left: LHCb results for R_K [25]. Right: R_{K^*} from LHCb measurements [28].

2 Effective Lagrangian approach in B anomalies

At low-energies the most general approach is given by the effective Lagrangians. The construction of the effective Lagrangian at the 1 TeV scale is based on the symmetries of the SM.

After establishing the form of the local operators of the appropriate dimension, which might explain the observed anomalies, one searches for an appropriate NP model. In order to constrain the parameter space, all possible observables at low and high energies should be taken into account. This leads towards constructing a full ultra-violat complete theory (such a theory theory must be well-defined at arbitrarily high energies, should be renormalizable and without Landau poles or at least has a nontrivial fixed point).

2.1 Effective Lagrangian approach in $R_{D^{(*)}}$

The effective Lagrangian for the $b \to c l \bar{\nu}_l$ transition, assuming the SM neutrino is

$$\begin{aligned}\mathcal{L}_{\text{eff}} &= -\frac{4\,G_F}{\sqrt{2}} V_{cb}\Big[(1+g_V)(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu \nu_L) \\ &+ \quad g_S(\mu)\,(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T(\mu)\,(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big]. \qquad (6)\end{aligned}$$

According to various studies (see e.g., [8, 14, 15]), the favourable solution is just a product of the two left-handed currents with $0.09 \le g_V \le 0.13$. There are approaches, which include the right-handed neutrino, as presented in [17, 18]. If one writes the coefficient

$$\frac{4G_F}{\sqrt{2}} V_{cb} g_V \to \frac{2}{\Lambda_{NP}^2}, \qquad (7)$$

then the scale of NP is $\Lambda_{NP} \simeq 3$ TeV. For scales $\Lambda_{NP} > 3$ TeV, the theory becomes nonperturbative. However, the $V-A$ form of the NP is not the only solution, as suggested in recent publications [19, 20]. These approaches use possibility of using scalar and tensor couplings. In the case of the pseudoscalar couplings, the strongest constraint comes from $\Gamma(B_c \to \tau\nu)$ [21]. In Ref. [19], it was noticed that the muon anomalous magnetic moment can be explained by the hierarchical tensor couplings $|C_T^\tau| \gg C_T^\mu > C_T^e$. In Fig. 3, constraints on tensor and scalar couplings from the $R_{D^{(*)}}$ ratios are presented[1].

2.2 Effective Lagrangian approach in $R_{K^{(*)}}$

The SM processes with the flavour structure $(\bar{s}b)(\bar{\mu}\mu)$ at the scale $\mu = \mu_b = 4.8$ GeV are governed by the dimension-6 effective Hamiltonian [22–24]

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_{i=7,\ldots,10} \left(C_i(\mu)\mathcal{O}_i(\mu)\right), \qquad (8)$$

$$\mathcal{O}_7 = \frac{e}{g^2} m_b(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad \mathcal{O}_9 = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell), \qquad \mathcal{O}_{10} = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell).$$

Here $P_{L/R} = (1 \mp \gamma_5)/2$, while e is the electromagnetic and g the color gauge coupling, $F^{\mu\nu}$ and $G^{\mu\nu}$ are the electromagnetic and color field strength tensors, respectively. At the scale $\mu_b = 4.8$ GeV, the effective SM Wilson coefficients are $C_7^{SM} = 0.29$; $C_9^{SM} = 4.1$ $C_{10}^{SM} = -4.3$ [22–24]. The measurements of $R_{K^{(*)}}$ by the LHCb collaboration [25, 28] at the low di-lepton invariant mass distribution q^2 pointed out that the values of C_9^{SM} and C_{10}^{SM} cannot be described by experimental results. According to Refs. [26, 27], NP might contribute to the Wilson coefficients $C_i = C_i^{SM} + C_i^{NP}$; the best fit point is $C_9^{NP} = -C_{10}^{NP} = -0.64$, assuming that NP comes from the muonic sector, as presented in Fig. 4. Such fits indicate that NP has the following structure:

$$\mathcal{L}_{NP}^{K^{(*)}} = \frac{1}{\Lambda_{NP}^2}(\bar{s}_L\gamma^\alpha b_L)(\bar{\mu}_L\gamma_\alpha\mu_L). \qquad (9)$$

The scale of NP calculated from this Lagrangian is $\Lambda_{NP} \simeq 30$ TeV.

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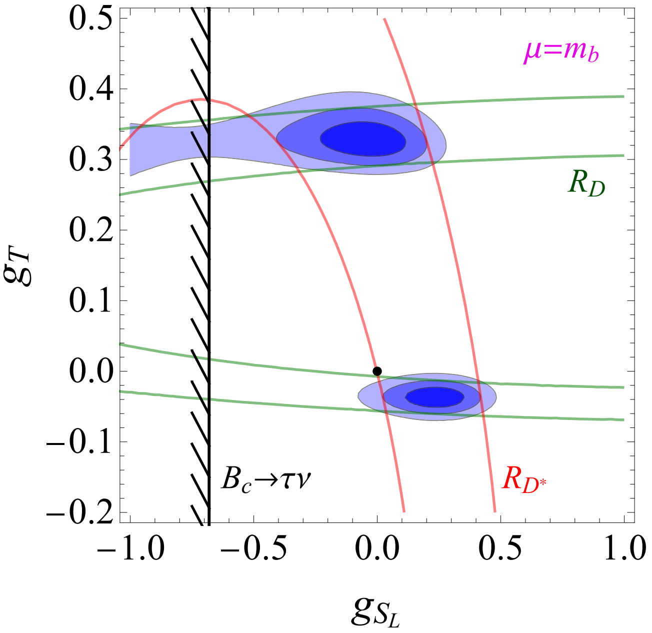

Figure 3: Constrains on the scalar and tensor couplings coming from R_D, R_{D^*} and $B_c \to \tau\nu$.

2.3 NP explaining both anomalies

The experimental results point towards

$$R^{exp}_{D^{(*)}} > R^{SM}_{D^{(*)}} \text{ and } R^{exp}_{K^{(*)}} < R^{SM}_{K^{(*)}}\,, \tag{10}$$

which indicates that the NP scales are $\Lambda^D_{NP} \simeq 3$ TeV and $\Lambda^K_{NP} \simeq 30$ TeV. If one assumes that the same NP explains both anomalies, then the effective Lagrangian

$$\mathcal{L}_{NP} = \frac{2}{\Lambda^2}(\bar{c}_L\gamma_\alpha b_L)(\bar{\ell}_L\gamma^\alpha\nu_L) + \frac{C_K}{\Lambda^2}(\bar{s}_L\gamma^\alpha b_L)(\bar{\mu}_L\gamma_\alpha\mu_L)\,. \tag{11}$$

Previous reasoning leads to the suppression factor $C_K \simeq 0.1$. Therefore, if NP is expected at the scale $\Lambda \simeq 3$ TeV, then its contribution to $R_{K^{(*)}}$ should be suppressed by a factor 1/100 in comparison with $R_{D^{(*)}}$. This can be realised as in the scenario of Ref. [31], in which the NP couples dominantly to the third generation of quarks and leptons. The coupling to the second generation is just a small correction in comparison with the NP coupling of the third generation. The NP Lagarangian as in (11) was considered in many studies (see e.g., [15, 32, 33]). The suppression factor ~ 0.01 can come from the contribution of NP at the loop level [34, 35] . The constraints coming from the observables in the processes presented in Table 1 determine the allowed parameter space.

In constructing a NP model at the TeV scale, one can have one NP mediator with the spin 0 or spin 1. Scalar leptoquarks are typical examples of these models (see e.g., [20, 33, 36–39]). Spin 1 resonances are considered as a remnant of some techni-fermion models [40, 41] or as gauge bosons [43–47].

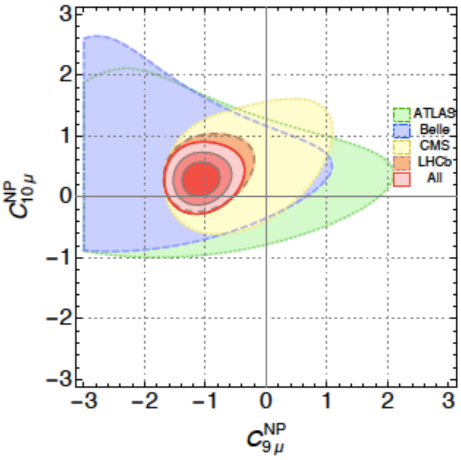

Figure 4: C_9^{NP}, C_{10}^{NP} fit using the available experimental data, taken from ([27]).

Table 1: Constraints from flavour observables and lepton flavour violating processes.

Flavour observables	**LFV**
$(g-2)_\mu$	$\tau \to \mu\gamma$
$B(B_c) \to \tau\nu$	$\mu \to e\gamma$
$B \to K^{(*)}\bar{\nu}\nu$	$\tau \to K(\pi)\mu(e)$
$B_s - \bar{B}_s$, $D^0 - \bar{D}^0$	$K \to \mu e$
$B \to D\bar{\nu}\mu$	$B \to K\mu e$
$K \to \mu\nu$	$\tau \to \mu\mu\mu$
$D_{(s)} \to \mu(\tau)\nu$	$\tau \to \mu ee$
$\tau \to K\nu$, $K \to \pi\mu\nu$	$\tau \to \Phi\mu$
$W \to \tau\nu$, $\tau \to l\nu\bar{\nu}$	$t \to cl^+l'^-$
$Z \to b\bar{b}(l^+l^-)$	$Z \to \mu\tau$

3 Leptoquarks explaining B anomalies

Leptoquarks interact with quarks and leptons. The leptoquark (LQ) states can be classified according to their quantum numbers of $SU(3)_c$, $SU(2)_w$ and $U(1)_Y$ representations of the SM [48]. In Table 2, leptoquark states which can explain either $R_{D(*)}$ or $R_{K(*)}$ or both anomalies are listed. In the case of $(g-2)_\mu$, only R_2 and S_1 might explain the observed deviations due to the m_t/m_μ enhancement at the one-loop level [49].

3.1 Pati-Salam unifying model

The U_1 vector leptoquark is the only single LQ which can explain both B meson anomalies, but cannot explain the muon anomalous magnetic moments. The light vector leptoquark is most trivial to accommodate in the Pati-Salam-like model with a gauge group $SU(4) \times SU(3) \times SU(2) \times U(1)$ which is then spontaneously broken [45–47]. One of the approaches is based on the tri-site Pati-Salam model $[PS]^3$ [43, 44] which can offer an explanation of the "flavour puzzle". This model, however, contains new Z', new colorons with masses between $1.3-1.9$ TeV. The unification scale in this model is quite low, at the order 10^6

Table 2: Single scalar and vector LQs explaining either one of the B anomalies or both at tree level.

$(SU(3)_c, SU(2)_w, U(1)_Y)$	Spin	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ and $R_{K^{(*)}}$
$S_3 \equiv (\overline{3}, 3, 1/3)$	0	no	yes	no
$R_2 \equiv (3, 2, 7/6)$	0	yes	no	no
$\tilde{R}_2 \equiv (3, 2, 1/6)$	0	yes	no	no
$S_1 \equiv (\overline{3}, 1, 1/3)$	0	yes	no	no
$U_3 \equiv (3, 3, 2/3)$	1	no	yes	no
$U_1 \equiv (3, 1, 2/3)$	1	yes	yes	yes

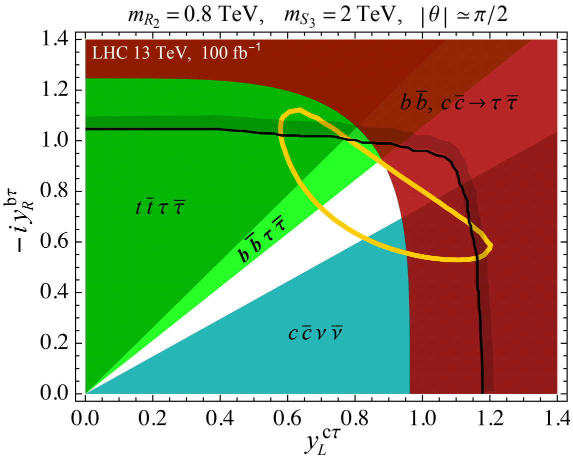

Figure 5: Summary of the LHC limits for each LQ process at a projected luminosity of 100 fb^{-1} for $m_{R_2} = 800$ GeV, $m_{S_3} = 2$ TeV. The region above the solid black contour represents values of the couplings that become non-perturbative at the GUT scale. The region inside the yellow contour corresponds to the 1σ fit to the low-energy observables, according to [20].

GeV and the proton does not decay.

3.2 Two scalar LQs solution of $R_{D^{(*)}}$ and $R_{K^{(*)}}$

There is a couple of reasons to consider a two scalar leptoquark solution of the B meson anomalies. The unification of the three fundamental interactions within $SU(5)$ grand unifying group is possible with two light leptoquarks as we showed in [48]. Also, two light scalar leptoquark might generate neutrino masses at the loop level [51].

In [20] a two scalar LQ extension of the SM was constructed that can accommodate all measured LFU ratios in B-meson decays and the related flavour observables, while being compatible with direct search constraints at the LHC. A nice feature of this model is that within $SU(5)$ Yukawa couplings of the two LQs can be related through a mixing angle and all Yukawas remain perturbative up to the unification scale. An immediate consequence is that there is a correletaion between $\mathcal{B}(B \to K\mu\tau)$ and $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$. A lower bound for $\mathcal{B}(\tau \to \mu\gamma)$ is also predicted just below the current experimental limit.

4 Conclusion

To find a model of NP which can explain the B physics anomalies and possibly $(g-2)_\mu$ motivates many studies of NP. Such kind of NP has direct consequences for the LHC searches as well as ongoing and future B physics experiments. NP seen in B decays should also be present in $B \to K^{(*)}\nu\bar{\nu}$ and lepton flavour violating processes, such as $\tau \to \mu\gamma$, $\tau \to 3\pi$, $B \to K^{(*)}\tau\mu$ and $B_s \to \tau\mu$.

The correlations of B anomalies and $K \to \pi\nu\bar{\nu}$ were already pointed out ($R_{D^{(*)}}$ [53] and $R_{K^{(*)}}$ [54]). Effects were found to be of the order $\sim 20\%$.

An additional aspect of NP explanations of the B puzzles is understanding the origin of the hierarchical structure of the SM quark and lepton masses, known as the "Flavour puzzle".

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