GAUGED FLAVOUR SYMMETRY FOR B ANOMALIES

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Signs of physics beyond our stablished theory have sprung in the field of B-meson physics. Although the evidence is not conclusive, theoretical exploratory efforts help make sense of the new data in a consistent picture and allow contrast with other experimental searches. After examining the general features that the possible new physics should have we present two models based on a U(1) flavour symmetry that account for the anomaly while within reach of direct searches.

1 Introduction

The evidence for phenomena outside the realm of the Standard Model (SM) is piling up in B-meson physics. Individually, none of these deviations from the SM is statistically significant yet, nevertheless their appearance in different measurements by different experiments is a compelling hint for some short of underlying new physics. The anomalies can be split into charged current and neutral current decays. The former involve the ratio of decays $B \to D^{(*)}\tau\nu\ /B \to D^{(*)}\ell\nu$ with D (D^*) the pseudo-scalar (spin 1) charmed meson and ℓ representing the average of μ and e; this anomaly stands at the 4σ level and has been reported by Babar [1], Belle [2] and LHCb [3]. The neutral current deviations from the SM occur, most prominently, in the theoretically clean ratio $B \to K^{(*)}\mu\mu/B \to K^{(*)}ee$ with a deficit in both the K [4] and K^* [5] channel as measured by LHCb and constituting a 4σ deviation in combination. Both sets of anomalies require lepton universality violation albeit in different channels, $\tau/(\mu, e)$ and μ/e. On the other hand flavour violation in charged decays occurs at tree level in the SM whereas the $B \to K^{(*)}$ decays are loop and GIM suppressed in the SM meaning a higher sensitivity to new interactions. Although accommodation of both anomalies is possible it is cumbersome; in this work in contrast we will focus on neutral current anomalies.

A model independent analysis allows to identify the most likely (with present data) new interaction that would account for the anomalies. The studies in the literature [6,7,8,9,10,11] find that a left-handed current of quarks and a left-handed current of leptons, when modifying the muon channel as we will assume here, fits the data best:

$$\mathcal{O}_{NP} = \bar{s}\gamma_\alpha b_L \times \bar{\mu}\gamma^\alpha\mu_L\ , \tag{1}$$

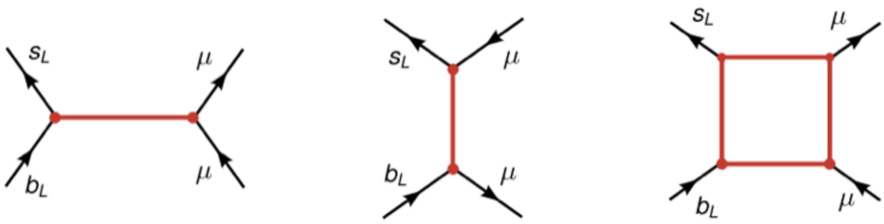

Figure 1 – UV completing the dimension 6 operator of eq. (1).

which one can naively guess as the operator one would need to interfere destructively with the SM contribution. The origin of this dimension six operator is a model dependent question, yet in the same spirit as the identification of the three types of seesaw model, one can examine what possible new particles would generate it as shown in fig. 1. If we split the operator of dimension 6 in a quark current and a lepton current then we have a spin 1 mediator that we will generically denote Z_j, whereas a pair of lepton-quark 'currents' would be connected via a lepto-quark particle. Here we will focus on a Z_j explanation of the anomaly, which is a route that has indeed been taken in the literature a number of times [12,13,14,15,16,17,18,19].

Other than a proof of principle, i.e. the anomaly can be accounted for with a Z' while being consistent with other flavour constraints and direct searches, what can the exploration of a model offer as insight? There are a number of open problems in particle physics which is believed hint at physics beyond the Standard Model, could this anomaly be connected to some of these issues? The immediate question that B anomalies is connected to is the flavour puzzle: i.e. why are there three generations? Why do they have such different masses and mixings? It is worth exploring the connection of these fundamental questions with the new phenomena in B-physics via explicit models and that is what is aimed for here.

Let us then briefly examine the flavour structure of the anomalies, they involve *i) both quark and leptons, ii) quark flavour violation yet lepton flavour conservation iii) lepton universality violation.* As shown in the literature [20], a symmetry-based justification of the absence of lepton flavour violation while allowing for universality violation can be given. This must be in contrast with the quark sector however where flavour violation is required yet restricted to the B-meson sector since no deviation is observed in Kaon or D-meson rare decays... Accounting for this flavour structure in terms of a more fundamental principle is one of the (potential) strenghts of new models. Although we do not purport to answer all the questions here we provide a first step in that direction and hopefully also inspiration for future studies.

2 Two $U(1)$ models for the anomalies

Here we present two models based on a gauged symmetry to account for the neutral current anomalies. In this quest one is however immediately faced with a choice, *what symmetry to gauge*? To answer this we first inspect what is the largest symmetry that *could be gauged* given the known fermion spectrum, i.e. what is the largest symmetry that satisfies the anomaly cancellation conditions [a] (this anomaly is not to be confused with B-meson experimental anomalies!). In the SM, this symmetry is $SU(3)_Q$ with the non-abelian group acting simultaneously on all quark fields (q_L^α, u_R^α, d_R^α). This clearly is of no help in explaining B-physics semi-leptonic decays since it does not involve leptons. In this regard a minimal extension of the SM fermion content that accounts for neutrino masses and potentially the baryon asymmetry of the universe is the type I seesaw. If we therefore add three flavours of singlet fields to the Standard Model the largest global symmetry that can be made local is $SU(3)_Q \times SU(3)_L \times U(1)_{B-L}$. Were this to be part of the fundamental symmetries of nature, flavour arises just as the 3 colours of QCD, out

[a] These conditions for the self-consistency of the gauge theory to arbitrarily high energies can alternatively be satisfied for any gauge symmetry provided one add enough extra fermions.

of a non-abelian group. At the same time, like QCD, this group contains multiple gauge bosons although none of them taken separately can account for the anomalies in B-physics, one would need a linear combination. To attain this here we follow two paths that lead to two different models:

- The sequential breaking $SU(3)_Q \times SU(3)_L \times U(1)_{B-L} \to SU(3)_H \times U(1)_{B-L} \to U(1)_h$. In the fist step the non-abelian group is broken to the diagonal, or alternatively $SU(3)_H$ can be a fundamental symmetry as imposed in a Pati-Salam model as originally proposed [18]. For the second step we consider two heavy right-handed Majorana neutrinos which suffice to account for active neutrino data and successful lepto-genesis. This necessarily breaks the symmetry down to a $U(1)_h$ subgroup. The generators in quark and lepton flavour space read:

$$T_Q^h = T_8^H + \frac{1}{3} t_\omega \mathbb{I} = \frac{1}{2\sqrt{3}} \begin{pmatrix} \frac{4}{3} & & \\ & \frac{4}{3} & \\ & & -\frac{5}{3} \end{pmatrix}, \quad T_L^h = T_8^H - t_\omega \mathbb{I} = \frac{1}{2\sqrt{3}} \begin{pmatrix} 0 & & \\ & 0 & \\ & & -3 \end{pmatrix}, \quad (2)$$

  with $t_\omega = \tan\omega = 1/2/\sqrt{3}$ as imposed by the compatibility with two massive right-handed neutrinos [18].

- The breaking $SU(3)_Q \times SU(3)_L \times U(1)_{B-L} \to U(1)_{(B-L)_3}$ where $(B-L)_3$ acts on the 'third' generation only [19] (we are still in the interaction basis however). Alternatively the $U(1)_{(B-L)_3}$ symmetry could arise from a model in which three different Pati-Salam groups act on each generation. We also note that this symmetry is compatible with two heavy right-handed neutrinos and the generators in flavour space are:

$$T_Q^{(B-L)_3} = \frac{1}{3} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad T_Q^{(B-L)_3} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}. \quad (3)$$

The action for these gauge bosons then reads:

$$\mathcal{L}_{Z_j} = \frac{1}{2} Z_j^\mu \left(\partial^2 + M^2\right) Z_{j,\mu} - g_j Z_j^\mu J_\mu^j \,, \quad (4)$$

where $j = h$ or $j = (B-L)_3$ depending on the model we are considering. The current is determined by the generators *and* rotations to the mass basis:

$$J_\mu^j = \sum_f \bar{f} U_f^\dagger T_f^j U_f \gamma_\mu f \,, \quad (5)$$

where U_f is the unitary rotation for a fermion species $f = u_{L,R}, d_{L,R}, e_{L,R}, \nu_{L,R}$; this introduces another piece of model dependence. The fermion mass and mixing pattern is in general related to the breaking of the original flavor symmetry and in turn to the mass spectrum of the flavoured gauge bosons. The way to break the symmetry with scalar flavour fields is sketched [18] for the $U(1)_h$ model whereas the extra matter content and action required for the breaking in the case of $U_{(B-L)_3}$ can be found in the literature [19]. All we are concerned here with however is the unitary rotations which we can summarize as:

$$\begin{aligned} U(1)_h \,\&\, U(1)_{(B-L)_3}: &\qquad U_{e_L} = R^{23}(\theta_l), &\qquad U_{\nu_L} = R^{23}(\theta_l) U_{PMNS}, \\ U(1)_{(B-L)_3}: &\qquad U_{d_L} = R^{23}(\theta_q), &\qquad U_{u_L} = R^{23}(\theta_q) V_{CKM}^\dagger, \\ U(1)_h: &\qquad U_{d_L} = V_{CKM}, &\qquad U_{u_L} = \mathbb{I}, \end{aligned} \quad (6)$$

where $R^{ij}(\alpha)$ is a rotation in the ij sector by an angle α whereas right-handed field rotations can be taken vanishingly small. Together with the respective gauge coupling and masses (g_h,

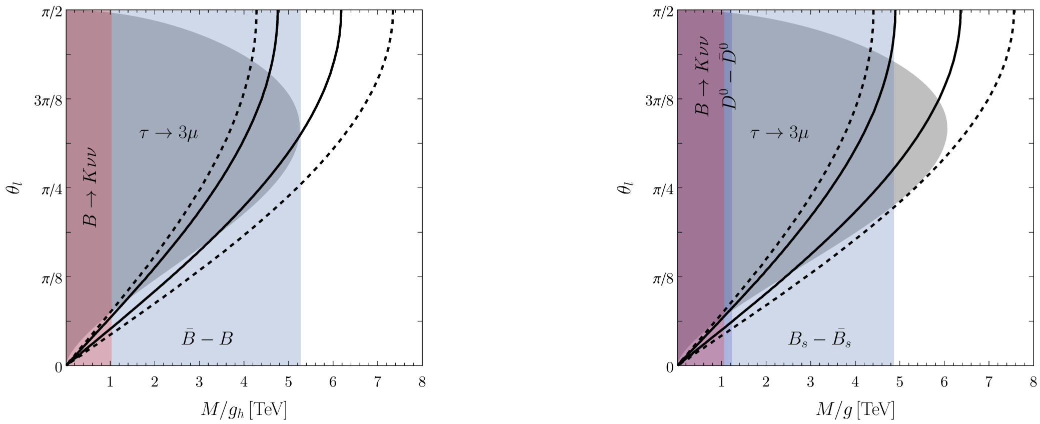

Figure 2 – LHS (RHS): Low energy constraints on the vev (M/g) vs leptonic angle θ_l plane for the $U(1)_h$ $(U(1)_{(B-L)_3})$ model. See text for details.

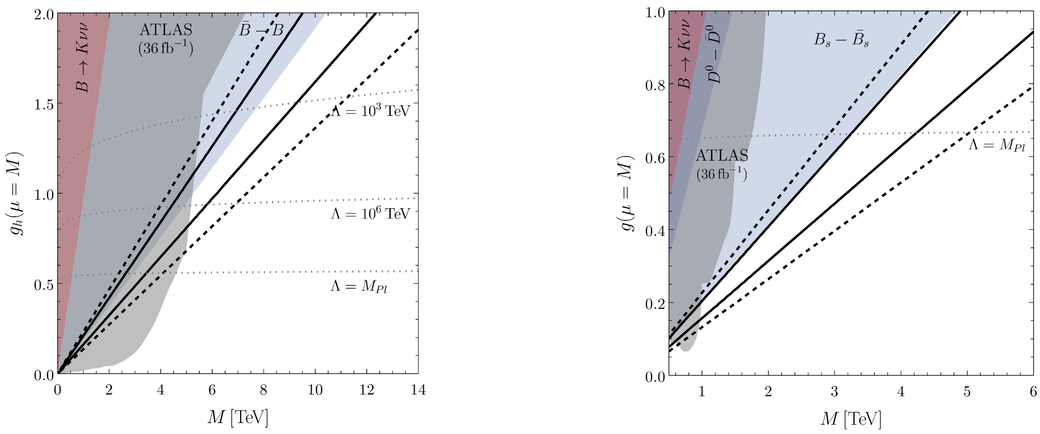

Figure 3 – LHS (RHS): Collider, flavour and theoretical constraints on the mass vs coupling plane for the $U(1)_h$ $(U(1)_{(B-L)_3})$ model. See text for details.

M_h), (g_{BL3}, M_{BL3}) this specifies the phenomenology of the gauge bosons Z_j. In particular since we take their masses to be above or around the TeV scale their effect in B anomalies can be extracted after integrating them out,

$$S = \int d^4x \left\{ \frac{1}{2} Z_j^\mu \left(\partial^2 + M^2\right) Z_{j,\mu} - g_j Z_j^\mu J_\mu^j \right\} \overset{\text{On-shell } Z_j}{=} \int d^4x \left(-\frac{1}{2} \frac{g_j^2 J_j^2}{M^2} + \mathcal{O}\left(\partial^2/M^2\right) \right), \quad (7)$$

and matching to the effective field theory. In addition to affecting semi-leptonic decays however a feature of Z' models is that the operator generated is of the form (quark current +lepton current)^2 and hence purely leptonic and hadronic physics is affected as well. Among the most relevant processes one has $B - \bar{B}$ mixing and charged lepton number violation. Both are very restrictive although whereas the former is quite unavoidable the violation of charged lepton can be restricted to the $\mu - \tau$ sector resulting in loosened constraints.

Low energy data does however only probe g/M or the vev of the breaking of the $U(1)$; the possibility to directly produce the gauge bosons in colliders opens a new direction in parameter space. Searches for extra gauge-bosons provide exclusion limits which are strongest when coming from LHC; these are stronger for $U(1)_h$ where the gauge boson couples sizably to the first generations and would be more copiously produced, whereas for $U(1)_{(B-L)_3}$ the new particle could be as light as TeV.

All of the above mentioned constraints are displayed in figs 2,3; in the latter on the mass-coupling plane and in the former on the vev-leptonic angle plane. In addition to experimental constraints, fig. 3 displays a theoretical constraint; given the large number of fermions that the gauge bosons couple to, their coupling runs quite fast, if one demands a perturbative theory below a scale Λ one should restrict to the parameter space *below* dotted lines.

3 CONCLUSIONS

Tantalizing hints for new physics in B meson decays may unveil a new phase in particle physics; while the final word will come from future experimental results on the theory side exploratory efforts reveal that new physics could be behind the signal while being compatible with direct and indirect searches. Furthermore, other than a simple addition to our list of particles, if proven true this effect may finally shed light in the flavour structure of elementary particles.

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