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Radiative neutrino mass models and the flavour anomalies

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A possible connection between the hints for lepton flavour non-universality in the B-decay observables $R_{K^{(*)}}$ and $R_{D^{(*)}}$ and radiative models for Majorana neutrino mass generation is discussed. After a brief survey of the anomalies, a systematic approach to radiative Majorana-mass model building using $\Delta L = 2$ effective operators constructed out of standard model fields is reviewed. Then two specific models are examined: a minimal model containing the $S_1 \sim (3,1,-1/3)$ scalar leptoquark, and a next-to-minimal model containing S_1 and $S_3 \sim (3,3,-1/3)$.

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1. Summary of the flavour anomalies

A number of measurements combine to give a tantalising suggestion that lepton flavour universality may be violated in B-decays. While the present anomalies require strong confirmation at higher statistical significance before they can be considered robust indications of new physics, they nevertheless provide motivation for thinking about new particles and interactions, and about connecting explanations of the anomalies with other open questions. In this talk, I briefly review a possible connection with radiative Majorana neutrino mass generation. We begin with a lightning survey of the most pertinent of the anomalies (we do not attempt an exhaustive summary). For a more detailed discussion see, for example, Refs. [1, 2] and references therein.

One class of anomalies concerns $b \to s\ell\ell$ transitions, quantified through

$$R_{K^{(*)}} \equiv \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)} \tag{1.1}$$

which are probes of μ/e universality. Systematic hadronic uncertainties largely cancel in this ratio. In the standard model (SM) the only difference between the two decays lies in the different rest masses of μ and e. Since these masses are small compared to the mass differences between B and K, and B and K^*, the SM predicts ratios close to unity. The LHCb collaboration reports the central value $R_K = 0.846$ in the $[1,6]$ GeV^2 q^2 bin, and R_{K^*} in the range $0.66-0.69$ depending on the q^2 bin [3]. The statistical and systematic errors lead these to be $2.2-2.5\sigma$ below the SM prediction. The Belle collaboration's results [4] have sufficient uncertainty to be compatible with both the SM and the anomalous LHCb results.

Another class involves the decays $b \to c\ (\tau,\mu,e)\ \nu$, through the ratios

$$R_{D^{(*)}} \equiv \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}, \quad \ell = e,\mu \tag{1.2}$$

that probe universality between τ and e/μ. In the SM, the phase space suppression for the τ mode in this ratio may be reliably computed, leading to predictions of 0.299 ± 0.003 and 0.258 ± 0.005 for R_D and R_{D^*}, respectively [5]. The HFLAV global average of the measurements from Babar, Belle and LHCb are $R_D = 0.340 \pm 0.027 \pm 0.013$ and $R_{D^*} = 0.295 \pm 0.011 \pm 0.008$ which are 3.1σ above the SM expectations (see Refs. [1, 2] for references to the original literature).

2. Systematic survey of radiative Majorana neutrino models

The puzzle of why neutrino masses are six or more orders of magnitude smaller than the smallest charged-fermion (electron) mass drives much of the research on models of neutrino mass generation. Neutrinos may be either Dirac or Majorana, and we discuss only the latter. Since Majorana masses violate lepton-number conservation by two units, a systematic approach to constructing models usefully starts with a list of gauge-invariant $\Delta L = 2$ effective operators constructed out of SM fields. An almost complete list of operators in this class that do not contain derivatives may be found in Refs. [6, 7]. The most famous of these is the dimension-5 Weinberg operator $O_1 = LLHH$, which produces the seesaw formula $m_\nu \sim v^2/M$ where $v \equiv \langle H \rangle$ and M is the scale of new physics. By "opening up" this operator – deriving it in the low-energy limit of a renormalisable new physics theory – the three famous tree-level seesaw models may be systematically derived, provided one undertakes a full analysis of all the ways $LLHH$ can be opened up.

This approach becomes almost mandatory for the construction of radiative models, i.e. models where neutrino masses are generated at loop level, simply because there are so many models of this type (the count is in the thousands). Radiative models, in turn, are motivated as one sensible answer to the question of the why neutrino masses are so small. The answer may be that these masses are a purely quantal effect due to the emission and reabsorption of very massive exotic virtual particles. The neutrino-mass suppression arises for three reasons: the $1/16\pi^2$ suppression that automatically comes with each loop, the fact that a neutrino self-energy diagram is proportional to the product of a few coupling constants which may each be somewhat less than unity, and from the high masses of the exotics. The first two features are additional suppression factors compared to tree-level seesaw models, and thus one expects the scale of new physics in radiative models to be generically smaller than that in the seesaw models. This is good from an experimental search perspective. See Ref. [8] for a review of radiative models.

There are a large number of baryon-number conserving, $\Delta L = 2$ effective operators at odd mass dimensions up to dimension-11. Dimension-13 operators are thought to be irrelevant because they would give rise to models with new physics at scales that are unacceptably low [6, 7]. Here are a few examples: The dimension-9 operator $O_9 = LLLe^cLe^c$ can be opened up at tree-level using the combination of singly-charged and doubly-charged scalars to produce the well-known Zee-Babu 2-loop neutrino mass model [9]. (The numbering convention for the operators follows Ref. [6].) The operators of relevance for the models to be considered below are $O_3 = LLQd^cH$ and $O_{11} = LLQd^cQd^c$.

The opening-up of dimension-7 operators using massive exotic scalars and vector-like fermions was performed in Refs. [6, 10]. Among the completions of O_3 are models with the leptoquark scalar $S_1 \sim (3,1,-1/3)$ and the vector-like Dirac fermion $(3,2,-5/6)$, and a second with the same fermion and S_1 replaced with $S_3 \sim (3,3,-1/3)$. (Hypercharge is normalised so that electric charge $Q = I_3 + Y$.) The leptoquark S_1 features together with a massive colour-octet Majorana fermion in a completion of O_{11} [11]. The leptoquark scalars S_1 and S_3 have also been invoked in solutions to the flavour anomalies. Can either of them, or both together, be essential for neutrino mass generation and simultaneously resolve the anomalies?

3. Brief review of the minimal Bauer-Neubert proposal

Reference [12] analysed the addition of S_1 to the SM to address the $b \to c$ anomalies at tree-level, and the $b \to s$ anomalies at 1-loop level. The phenomenological constraints on this minimal scenario were then explored in greater detail in Ref. [13], and an embedding into the neutrino mass model of Ref. [11] was studied. The conclusions are here updated post-Moriond 2019.

The outcome for accommodating $R_{D^{(*)}}$ depends on the calculation scheme employed, an issue that arose only after Ref. [13] was published. The methodology of Ref. [14] was used in the 2017 analysis to show that S_1 Yukawa interactions can improve the fit compared to the SM to within the 2σ range of the world average, and to within 1σ of the Belle result. A later analysis in Ref. [15] used the `flavio` package [16] to perform the same fit, finding that the central values of both the world average and the Belle results can be easily accommodated. The cause of this disagreement remains unclear, as far as the present author is aware. Fitting the $b \to s$ anomalies purely with S_1 is challenging, because the corrections to $R_{K^{(*)}}$ occur only at 1-loop level and the anomalies are numerically large. The result is that the two kinds of anomalies can be simultaneously accommodated at about the 2.5σ level using the world average for $R_{D^{(*)}}$ and the Ref. [14] procedure. The fit is better if only the Belle $b \to c$ results are used, and obviously much better when the `flavio` scheme is employed. Although this discussion has been framed in terms of $R_{K^{(*)}}$ for clarity and simplicity, these fits actually incorporate all $b \to s$ observables, including some such as the angular observable P_5' that also display anomalies with respect to the SM expectations.

The 2-loop neutrino mass model of Ref. [11] contains two copies of S_1 and the massive colour octet fermion mentioned above. The lighter of the two leptoquarks may in principle contribute substantially to the quark-flavour observables, and possibly resolve some of the anomalies. The result of a simultaneous fit to the neutrino mass/mixing angle and the flavour observables is that $R_{D^{(*)}}$ may be simultaneously accommodated, but the $b \to s$ anomalies cannot be. This demonstrates that the requirement of successful neutrino mass generation does impact on the quark-sector phenomenology, so simultaneous fits have the power to discriminate between different models.

4. A next-to-minimal model

The challenges to simultaneously fitting the $b \to c$, $b \to s$ and neutrino data revealed above also point the way to an obvious resolution. Recall that S_1 is adapted to fitting $R_{D^{(*)}}$ because it contributes at tree-level to an anomaly of significant magnitude. Its isospin-triplet cousin S_3 has the appropriate couplings to affect the $b \to s$ transitions at tree-level, and thus dominate over the 1-loop contributions of S_1. We are thus motivated to include both of these leptoquark species in our SM extension, and in addition include the $(3,2,-5/6)$ vector-like fermion. Recall that this fermion gives rise to radiative neutrino masses at 1-loop level when it acts in concert with either S_1 or S_3, as the dimension-7 operator analysis revealed. It will obviously continue to do so in a model that contains both S_1 and S_3. This is the next-to-minimal scenario analysed in great detail in Ref. [15].

The resulting model, even with baryon-number conservation imposed to forbid proton decay, has a large number of parameters. A practical approach to demonstrating the existence of phenomenologically-viable parameter space begins with a separation of duties between S_3 and S_1. The former will simultaneously induce the correct neutrino masses and mixing angles while also fitting the $b \to s$ observables through tree-level contributions to the anomalous processes. The S_1 leptoquark is then required to resolve the $R_{D^{(*)}}$ anomalies at tree-level, just as in the minimal model. In addition, only those family-dependent Yukawa coupling constants that are essential for fitting the three classes of observables are switched on. A large number of constraints were used to filter the parameter space, including lower bounds on the leptoquark masses from collider searches, the charged-lepton flavour violating processes $\mu \to e\gamma$, $\mu \to eee$ and $\mu \to e$ conversion on nuclei, in addition to a raft of other flavour observables involving leptons on their own, quarks own their own, and both leptons and quarks in a given process. The result of the analysis, which used `flavio` for the $b \to c$ calculations, is that everything can be simultaneously accommodated to on or very near the central values of the measurements. The analysis reveals that the $\mu \to e$ conversion experiments provide a sensitive test of the viable parameter space, and interestingly require a nonzero

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Majorana phase to produce a good fit. Within the restricted parameter region defined above to make the parameter scan tractable, the up-coming COMET [17] and Mu2e experiments [18], with their expected orders-of-magnitude improvement in sensitivity, will be able to explore most of the acceptable parameter space.

5. Final remarks

The next-to-minimal model was designed to resolve both classes of anomalies and generate radiative neutrino masses by having distinct roles for the two leptoquark multiplets. In particular, S_1 was not required to contribute to neutrino mass generation. It would be interesting to produce a model that tied the neutrino mass dynamics very closely to all the anomalies. Some candidate models have been identified: Gargalionis [19] has automated the opening-up of operators through an algorithm that spawns renormalisable theories that produce a given $\Delta L = 2$ effective operator at leading order. This program has been run on all operators up to and including dimension-11 and has revealed a number of theories where both S_1 and S_3 are essential for neutrino mass generation. Such theories promise the tight link sought with the flavour anomalies [20].

References

[1] A. Hicheur (for the LHCb collaboration) (these proceedings).

[2] Heavy Flavor Averaging Group (HFLAV), Y. Amhis *et al*, arXiv:1909.12524.

[3] LHCb collaboration, R. Aaij *et al*, Phys. Rev. Lett. **122** (2019) 191801; JHEP **08** (2017) 055.

[4] Belle collaboration, A. Abdesselam *et al*, arXiv:1904.02440; arXiv:1908.01848.

[5] D. Bigi and P. Gambino, Phys. Rev. **D94** (2016) 094008; F. U. Bernlochner *et al*, Phys. Rev. **D95** (2017) 115008 and (E) *ibid.* **D97** (2018) 059902; S. Jaiswal *et al*, JHEP **12** (2017) 060.

[6] K. S. Babu and C. N. Leung, Nucl. Phys. **B619** (2001) 667.

[7] A. de Gouvêa and J. Jenkins, Phys. Rev. **D77** (2008) 013008.

[8] Y. Cai *et al*, Front. Phys. **5** (2017) 63.

[9] A. Zee, Nucl. Phys. **B264** (1986) 99; K. S. Babu, Phys. Lett. **B203** (1988) 132.

[10] Y. Cai *et al*, JHEP **02** (2015) 161.

[11] P. W. Angel *et al*, JHEP **10** (2013) 118; (E) *ibid.* **11** (2014) 092.

[12] M. Bauer and M. Neubert, Phys. Rev. Lett. **116** (2016) 141802.

[13] Y. Cai *et al*, JHEP **10** (2017) 047.

[14] D. Bardhan, P. Byakti and D. Ghosh, JHEP **01** (2017) 125.

[15] I. Bigaran, J. Gargalionis and R. R. Volkas, JHEP **10** (2019) 106.

[16] D. M. Straub, arXiv:1810.08132.

[17] C. Wu (for the COMET collaboration), Nucl. Part. Phys. Proc. **287-288** (2017) 173.

[18] G. Pezzullo (for the Mu2e collaboration), PoS **ICHEP2018** (2019) 583.

[19] J. Gargalionis and R. R. Volkas, manuscript in preparation.

[20] J. Gargalionis, I. Popa-Mateiu and R. R. Volkas, work in progress.

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