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[Light Mediators and Flavor Anomalies]

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Abstract: Flavor physics offers many opportunities to search for new physics that lies beyond the standard model. This new physics may also resolve the longstanding flavor puzzles of the origins of quark and lepton masses and mixing. Several anomalies in the flavor sector could be hinting at new physics and this new physics could be light. We discuss light new physics solutions to the flavor puzzles and suggest some future research directions.

1 Introduction

The standard model (SM) of particle physics is not a complete theory, and the goal of the particle physics community is to find the new physics (NP) that lies beyond the SM. However, with no evidence of new physics from energy frontier experiments that were widely anticipated to discover new states, one should also look in other places to find NP. In the intensity frontier, flavor physics offers many avenues to search for new physics. Interestingly, there are several hints of NP in the flavor sector, and we will focus on a few of them.

Starting from the charged leptons, there is the longstanding anomaly in the anomalous magnetic moment of the muon, $(g-2)_\mu$. The SM prediction [1, 2] is 3.7σ smaller than the experimental measurement [3]:

$$(g-2)_\mu^{\text{exp}} - (g-2)_\mu^{\text{SM}} = 27.4\,(2.7)\,(2.6)\,(6.3) \times 10^{-10}\,. \tag{1}$$

The first two uncertainties are theoretical and the last, and largest, is experimental. The experimental uncertainty is expected to be reduced by a factor of four by the Muon $g-2$ Experiment [12] at Fermilab, which is currently collecting data. It is known that this anomaly can be explained by new light mediators with mass ~ 10 MeV to 1 GeV [4, 5, 6].

Recently, a 2.4 σ discrepancy is also observed between the experimental [7, 8] and theoretical [9] values of the anomalous magnetic moment of the electron due to a recent precise measurement of the fine structure constant [10]. It is interesting to note that the deviations from the SM in these two anomalies are in opposite directions, and $\Delta a_e/\Delta a_\mu$ does not follow the lepton mass scaling $m_e^2/m_\mu^2 \sim 2.25 \times 10^{-5}$. A model with new flavor structure in the leptonic sector may be needed to explain these discrepancies. Both $(g-2)_{\mu,e}$ discrepancies can be resolved in the context of light scalar [11].

In the neutrino sector there are several anomalies; one of the most intriguing in the MiniBooNE anomaly. The MiniBooNE data show a 4.8σ excess in the low energy part of electron spectra in both the neutrino and antineutrino channels [13]. The excess can be explained by a light neutrino upscattering into a sterile neutrino, which subsequently decays into an e^+e^- or photon pair via the emission of a light particle. As was shown recently [14, 11, 15], this light particle has be a scalar to satisfy other constraints emerging from CHARM II [16] and MINERvA [17].

If this light state couples to quarks or leptons, such as through portal interactions, FCNC processes at measurable rates can be generated in the quark sector. A singlet scalar that mixes with the Higgs doublet of a 2HDM model is an interesting possibility [18, 19, 11, 20]. This now opens up the possibility to address some of the anomalies that have been persisting in the quark sector. In K meson decays the rare kaon decays $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ are expected to be very sensitive to NP effects. These decays are being probed by the KOTO experiment at J-PARC and the NA62 experiment at CERN. Recent reports from KOTO [21, 22] indicate that $K_L \to \pi^0 \nu\bar{\nu}$ decays occur at a rate much larger than predicted by the SM [23]. As shown in Refs. [14, 11], the same scalar that can resolve the MiniBooNE anomaly can also explain the $K_L \to \pi^0 \nu\bar{\nu}$ measurement of the KOTO experiment.

In B decays there has been a lot of excitement over results in semileptonic B decays. These anomalies are found in the charged current $b \to c\tau^-\bar{\nu}_\tau$ and neutral current $b \to s\ell^+\ell^-$ transitions. Here we focus on the neutral current anomalies, although the anomalies might be related [24].

Several measurements in $b \to s\mu^+\mu^-$ decays, including rates and angular observables, have been difficult to understand in the SM. However, such measurements are not free from hadronic effects that cannot be calculated from first principle but only estimated. An observable which has received a lot of attention is $R_K \equiv \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ as this is a clean test of lepton universality with tiny hadronic correction. Combining the Run 1 and Run 2 results, the LHCb measurement of R_K is [25, 26]

$$R_K = 0.846^{+0.060}_{-0.054}\ (\text{stat})^{+0.016}_{-0.014}\ (\text{syst})\ . \tag{2}$$

This differs from the SM prediction of $R_K^{\text{SM}} = 1 \pm 0.01$ [27] by $\sim 2.5\sigma$. Note that the observable R_K is a measure of lepton flavor universality, as gauge interactions are universal for all lepton generations in the SM. Hence to explain the R_K measurement one requires different new physics for the muons versus the electrons, while it is possible to explain the anomalies in the angular observables in $b \to s\mu^+\mu^-$ in terms of lepton flavor universal new physics [28].

The LHCb Collaboration also reported the measurement of the ratio

$$R_{K^*} \equiv \mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathcal{B}(B^0 \to K^{*0}e^+e^-)$$

in two different ranges of the dilepton invariant mass-squared q^2 [29]:

$$R_{K^*}^{\text{expt}} = \begin{cases} 0.660^{+0.110}_{-0.070}\ (\text{stat}) \pm 0.024\ (\text{syst})\ , & 0.045 \le q^2 \le 1.1\ \text{GeV}^2\ , \quad (\text{low q}^2) \\ 0.685^{+0.113}_{-0.069}\ (\text{stat}) \pm 0.047\ (\text{syst})\ , & 1.1 \le q^2 \le 6.0\ \text{GeV}^2\ , \quad (\text{central q}^2)\ . \end{cases} \tag{3}$$

These differ from the SM predictions by 2.2-2.4σ (low q^2) and 2.4-2.5σ (central q^2), which further strengthens the hint of lepton non-universality observed in R_K. Lepton universality violating new physics may occur in $b \to s\mu^+\mu^-$ and/or $b \to se^+e^-$ transitions. While earlier analysis pointed to NP only in $b \to s\mu^+\mu^-$, the new data seem to indicate NP also in $b \to se^+e^-$ [30]. A possible source of the NP in $b \to se^+e^-$ could be a light state that can kinematically decay only to electron pairs. Light states that can kinematically decay to muon pairs is much more constrained from experiments [31].

The general conclusion one draws from the $b \to s\mu^+\mu^-$ and $b \to se^+e^-$ data is that there is a significant disagreement with the SM, possibly as large as $\sim 6\sigma$, and that theoretical hadronic uncertainties are insufficient to understand the data. However, with heavy new physics it is difficult to understand the R_{K^*} measurement in the very low q^2 bin $0.045 \le q^2 \le 1.1$ GeV^2, although the predictions are consistent with measurements within 1.5σ. A resolution to this problem may again point to new physics that is light with a mass scale $\le$ 200 MeV [32, 33]. In fact, even measurements in the central q^2 bin can be understood in terms of light new physics [34, 35] if the FCNC $b \to s$ vertex is loop-induced through possible hidden sector states [36]. Once can also look for the signatures of the light states in other processes like coherent neutrino scattering [37, 38, 36].

Although most of the light physics models have been discussed at an effective theory level, it is necessary to consider UV-complete models [18]. Well-studied models, like the dark photon case, cannot produce enough FCNC effect to address the B or K anomalies with the present constraint on the mixing parameter. Hence there is the need for UV-complete models, where such light states will arise with the right couplings and masses to resolve the flavor puzzles. It is will also be interesting to find any possible role these light mediators may play in dark matter physics.

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