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A Theoretical Prespective on Flavor Physics

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Flavor physics offers many opportunities to probe the fundamental nature of matter and their interactions. The standard model (SM) of particle physics has a very unique flavor structure which is being tested by precision measurements at flavor experiments. Deviations from the SM predictions can point to new flavor structures and new states which can offer clues to the various flavor puzzles in the standard model. Motivated by recent results and flavor anomalies, we will focus on various processes that can reveal possible extension of the SM with new states such as leptoquarks, diquarks, sterile neutrino and dark sectors.

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1. Introduction

In spite of the spectacular success of the standard model (SM), its flavor structure remains the least understood. There is no explanation of the quark and lepton masses and mixing, including CP violation. There is no understanding of the representations that the quarks and leptons come in or the assumptions that are put in by hand such as the universality in the couplings of the quark and lepton generations to the gauge interactions. Results from the various flavor physics experiments can gives clues to the underlying flavor structure of new physics. Of particular interest are the flavor anomalies that could be pointing to beyond the SM physics.

One of the outstanding puzzles of the flavor structure of the SM is the existence of three families of quarks and leptons. In this context the discovery of the charm quark 50 years ago holds a special significance. Following the discovery of the charm quark, the bottom and the top quarks were discovered. In due time the three families in the lepton sector were also established. A crucial theoretical motivation for the existence of the charm quark was the proposal of the GIM mechanism by Glashow, Iliopoulos and Maiani (GIM) [1] to explain the suppressed rate for $K_L \to \mu^+\mu^-$. The GIM mechanism is also applicable to rare Flavor Changing Neutral Current (FCNC) bottom and strange quark decays. Crucial inputs in the GIM mechanism are the unitarity of the mixing matrices in the quark and lepton sectors and the assumption of universal coupling of the gauge bosons to the different families of quarks and leptons. Both these assumptions need to be tested and there are already hints that there may be deviation from this expectation. The assumption of universal gauge interactions of the leptons is under tension from results in semileptonic B decays known as the B anomalies. We are going to start with a discussion on the present status of these anomalies.

1.1 B anomalies: $R(D) - R(D^*)$ puzzle

The processes $\bar{B} \to D^+\ell^-\bar{\nu}_\ell$ and $\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell$ with the leptons $\ell = e, \mu, \tau$ are simple tree level processes in the SM. For the τ lepton the matrix element for the process is

$$A_{SM} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\langle D^{(*)}(p') | \bar{c}\gamma^\mu (1-\gamma_5) b | \bar{B}(p) \rangle \right] \bar{\tau}\gamma_\mu (1-\gamma_5)\nu_\tau .$$

There can be new physics contribution in these decays through the exchange of new mediators like the charged Higgs, extra gauge bosons and leptoquarks. In Figure 1 are shown the contributions

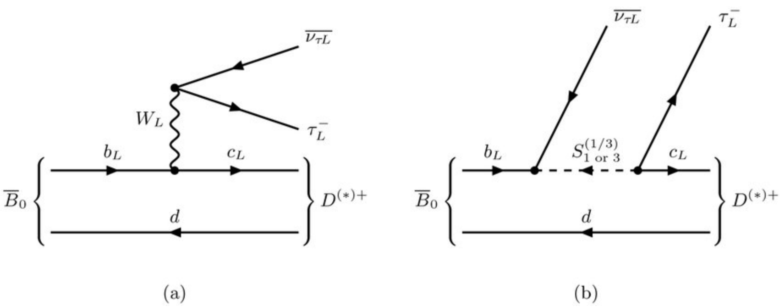

Figure 1

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from the SM and a new physic model with scalar leptoquark exchange to these decays. Test of lepton universality of the gauge interactions is measured through the following ratios

$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+\ell^-\bar{\nu}_\ell)} \qquad R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}.$$

Over the years these ratios have shown deviation from the SM expectations[2] as shown Figure 2. Including correlations, one finds that the deviation is at the level of 3.31σ from the SM predictions.

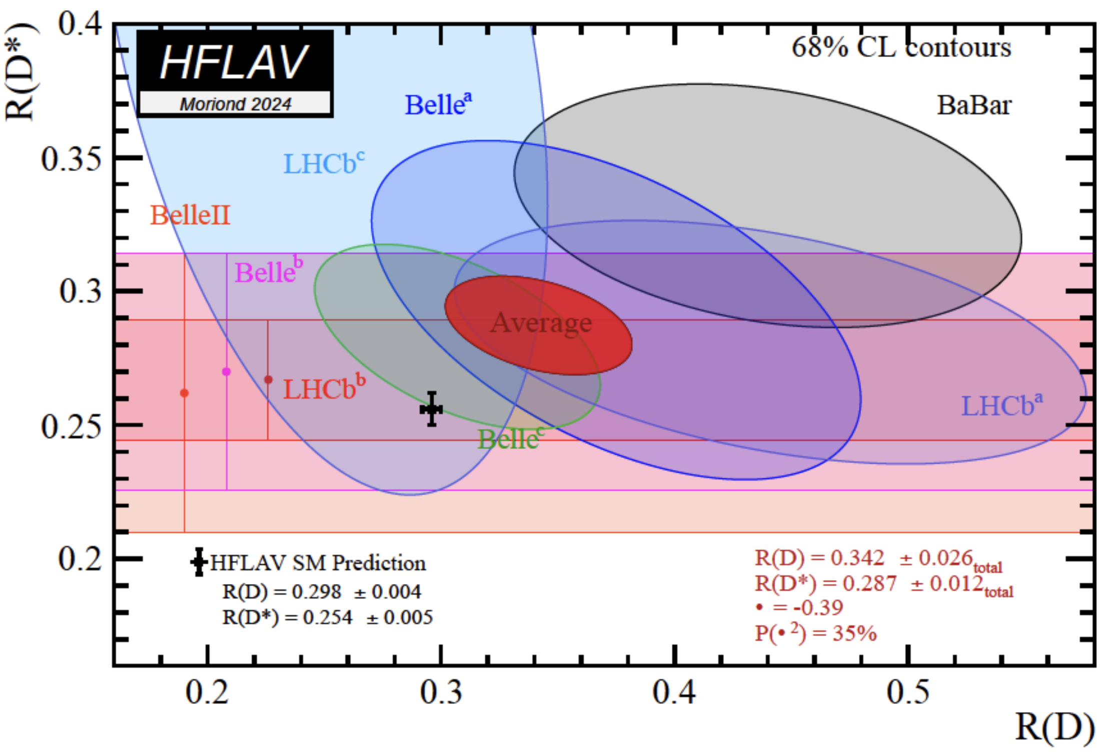

Figure 2

This is known as the $R(D) - R(D^*)$ puzzle.

1.2 NC FCNC: $b \to s\ell^+\ell^-$

The FCNC rare decays $b \to s\ell^+\ell^-$, as shown in Figure 3, are particularly sensitive to new physics as they are loop induced. Precise measurements of the branching ratios and angular distributions can be used to test the SM at loop level and find evidence for new physics. The basic electroweak penguin processes are $b \to s\ell^+\ell^-$, $b \to s\nu\bar{\nu}$ and $b \to s\gamma$ and the interactions are

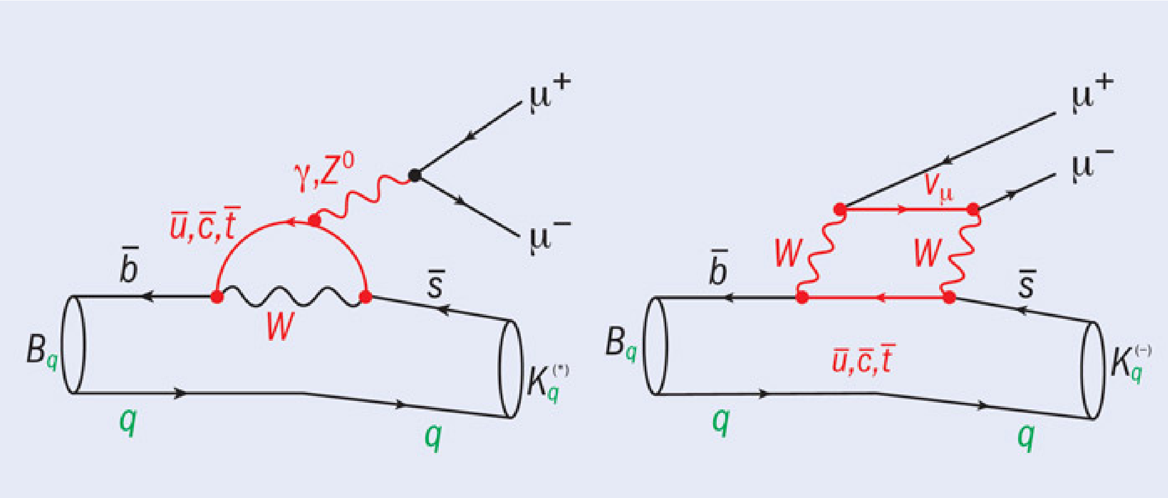

Figure 3

represented in terms of operators with the appropriate Wilson's co-efficients

$$
\begin{aligned}
H_{\rm eff}(b \to s\ell\bar{\ell}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^{*} \left[C_9 \, (\bar{s}_L \gamma^{\mu} b_L) \, (\bar{\ell}\gamma_{\mu}\ell) \right. \\
&\qquad \left. + C_{10} \, (\bar{s}_L \gamma^{\mu} b_L) \left(\bar{\ell}\gamma_{\mu}\gamma^{5}\ell\right) \right] , \\
H_{\rm eff}(b \to s\nu\bar{\nu}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^{*} C_L \, (\bar{s}_L \gamma^{\mu} b_L) \left(\bar{\nu}\gamma_{\mu}(1-\gamma^{5})\nu\right) , \\
H_{\rm eff}(b \to s\gamma^{*}) &= C_7 \, \frac{e}{16\pi^2} \left[\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R) b\right] F^{\mu\nu} .
\end{aligned}
$$

Over the last decade there has been a number of measurements of branching ratios and angular observables involving the semileptonic decay $b \to s\ell^+\ell^-$ ($\ell = \mu, e$) that are in disagreement with the predictions of the SM. Initially it appeared that only the $b \to s\mu^+\mu^-$ decays were affected by new physics and this was a clear evidence of lepton universality violating new physics. . However, in late 2022, LHCb announced that it had remeasured the ratios R_K and R_{K^*}, that test for lepton-flavour universality, and found that they agree with the SM [3, 4]. At this point, though the branching ratios and angular observables for $b \to s\mu^+\mu^-$ processes are still discrepant from the SM the LUV ratios seem to consistent with the SM indicating that new physics, if present, is lepton universal at least in the muon and the electron sectors. Note that the branching ratios and angular observables for $b \to s\mu^+\mu^-$ processes can be explained by charm loop contribution though this framework also has its theoretical challenges and can be tested with more data. Now the most promising new physics explanation is that the NP contributes equally to $b \to s\mu^+\mu^-$ and $b \to se^+e^-$ [5–7]. (A model to generate equal contribution to $b \to s\mu^+\mu^-$ and $b \to se^+e^-$ via four quark operators was proposed much earlier [8].) The current status in the $b \to s\ell^+\ell^-$ anomalies can be neatly expressed by the following plots in Figure 4 [9]. In a model independent manner one can look for Standard Model Effective Field Theory (SMEFT) operators that can generate the correct new

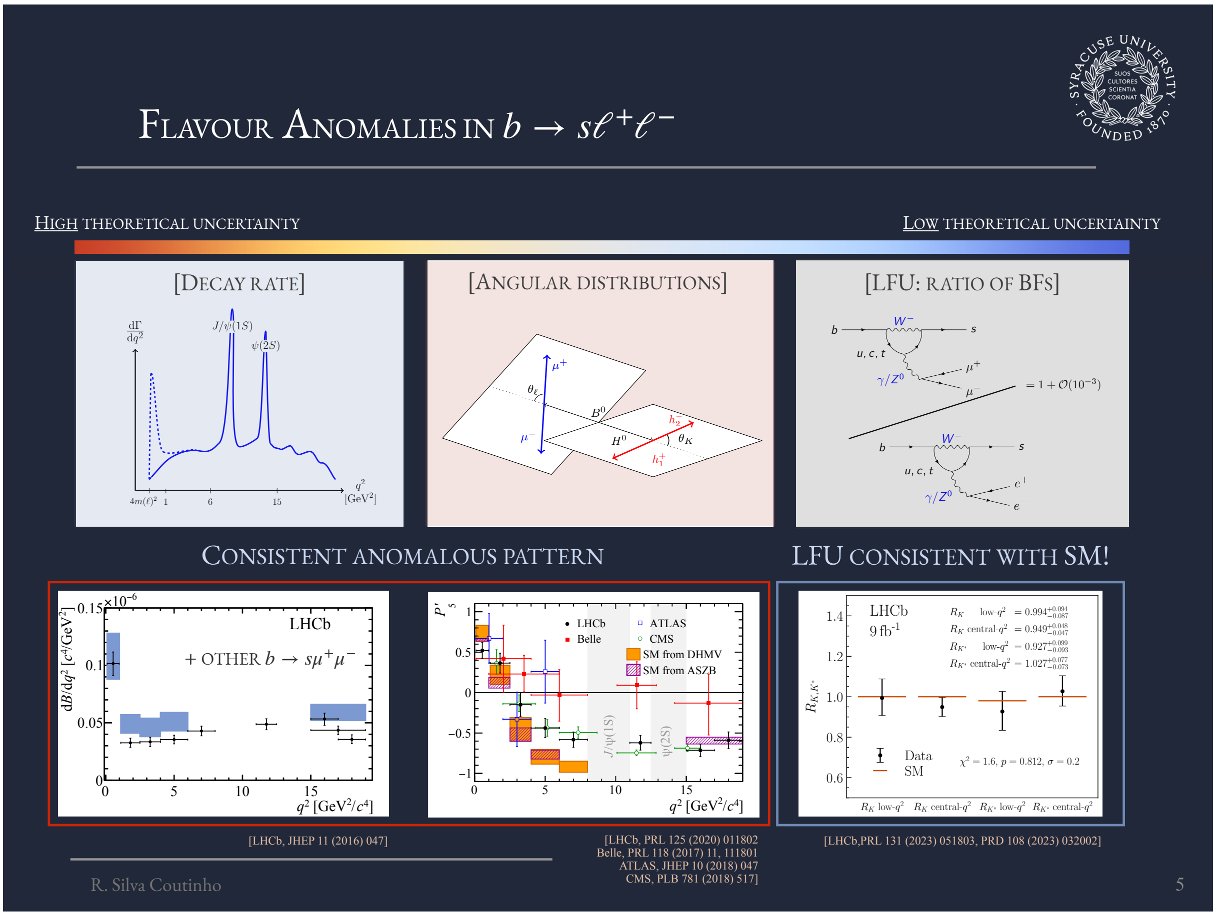

Figure 4

operator	definition	chirality	flavor structure
$Q_{\ell q}^{(1)}$	$(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_\ell)$	$(\bar{L}L)(\bar{L}L)$	3323
$Q_{\ell q}^{(3)}$	$(\bar{\ell}_i \gamma_\mu \tau^I \ell_j)(\bar{q}_k \gamma^\mu \tau^I q_\ell)$		3323
$Q_{\ell d}$	$(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{d}_k \gamma^\mu d_\ell)$	$(\bar{L}L)(\bar{R}R)$	3323
Q_{qe}	$(\bar{q}_i \gamma_\mu q_j)\,(\bar{e}_k \gamma^\mu e_\ell)$		2333
Q_{ed}	$(\bar{e}_i \gamma_\mu e_j)(\bar{d}_k \gamma^\mu d_\ell)$	$(\bar{R}R)(\bar{R}R)$	3323

Table 1: The list of semileptonic SMEFT operators that can potentially generate an LFU $O_{9\ell}$ at scale m_b.

physics contribution ensuring lepton universality in the muon and electron sector. One kind of structure involves operators with two quark and two lepton fields of the third generation. These kind of operators can be generated by leptoquark or additional $U(1)$ gauge boson exchange (Z' models). Another possibility, pointed out recently [10] are four quark operators that can arise in models with diquarks or Z' models. In the tables below the two group of structures that can solve the $b \longrightarrow s\ell^+\ell^-$ anomalies are shown.

$C_{\rm SMEFT}$ (TeV^{-2})		$C_9^{\rm U}$	$C_{10}^{\rm U}$	$C_9'^{\rm U}$	$C_{10}'^{\rm U}$
$[C_{lq}^{(1)}]_{3323}$	-0.23 ± 0.04	$-1.20 - i0.022$	-0.004	0	0
$[C_{lq}^{(3)}]_{3323}$	-0.23 ± 0.04	$-1.17 - i0.022$	-0.021	0	0
$[C_{qe}]_{2333}$	-0.22 ± 0.03	$-1.16 - i0.022$	-0.005	0	0

Table 2: Fit prefers $C_9^{\rm U} = -1.18 \pm 0.19$

$C_{\rm SMEFT}$	ΔM_s ($\times 10^{11}$)	κ_ε	ε'/ε ($\times 10^4$)	$S_{\psi\phi}$
$[C_{qq}^{(1)}]_{1123}$	(1.15 ± 0.06) (√)	-0.012 (√)	38.4 (?)	0.0369 ± 0.0019
$[C_{qq}^{(1)}]_{2223}$	(2.72 ± 0.10) (×)	0.11 (√)	15.8 (√)	0.0265 ± 0.0008
$[C_{qq}^{(3)}]_{1123}$	(1.16 ± 0.06) (√)	-0.005 (√)	23.1 (√)	0.0369 ± 0.0019
$[C_{qq}^{(3)}]_{2223}$	(0.59 ± 0.05) (×)	-0.04 (√)	17.8 (√)	0.0544 ± 0.0043
$[C_{qd}^{(1)}]_{2311}$	(1.16 ± 0.07) (√)	-0.75 (×)	13.9 (√)	0.0369 ± 0.0019
$[C_{qd}^{(1)}]_{2322}$	(1.55 ± 0.07) (×)	0.75 (×)	13.9 (√)	0.0321 ± 0.0014
$[C_{qd}^{(1)}]_{2333}$	(0.76 ± 0.06) (×)	0.0 (√)	13.9 (√)	0.0471 ± 0.0033
$[C_{qd}^{(8)}]_{2311}$	(1.16 ± 0.06) (√)	-15.0 (×)	12.8 (√)	0.0368 ± 0.0018
$[C_{qd}^{(8)}]_{2322}$	(1.18 ± 0.05) (√)	14.3 (×)	12.8 (√)	0.0128 ± 0.0002
$[C_{qd}^{(8)}]_{2333}$	(10.6 ± 0.5) (×)	-0.001 (√)	12.8 (√)	-0.0061 ± 0.0003
$[C_{qu}^{(1)}]_{2311}$	(1.15 ± 0.06) (√)	0.0 (√)	13.9 (√)	0.0369 ± 0.0018
$[C_{qu}^{(1)}]_{2322}$	(1.16 ± 0.06) (√)	0.0 (√)	13.9 (√)	0.0369 ± 0.0019
$[C_{qu}^{(8)}]_{2311}$	(1.15 ± 0.06) (√)	0.0002 (√)	13.9 (√)	0.0369 ± 0.0019
$[C_{qu}^{(8)}]_{2322}$	(1.15 ± 0.06) (√)	-0.0003 (√)	13.9 (√)	0.0369 ± 0.0020

Table 3: Four-quark SMEFT WCs that generate the desired WET WCs: predictions for ΔM_s, κ_ε and ε'/ε,along with an indicator of whether the constraint is satisfied (√) or violated (×), or if there is a tension (?).

1.3 Effective Interactions of the sterile neutrino

The existence of neutrino masses and mixing is a clear indication that the flavor structure of the SM has to be extended. One popular extension proposes the existence of new sterile neutrino states. The phenomenology of sterile neutrinos have been widely studied in neutrino experiments. Models with sterile neutrinos can lead to charged lepton flavor violation and one can study these decays in a model independent manner [11]. A recent interest is to study the phenomenology of the sterile neutrino in a model independent manner. The basic idea is that sterile neutrinos might have new interactions via the exchange of light or heavy mediators(Higgs, Vector Bosons, Leptoquarks). Heavy mediators can be integrated out to get an effective theory: SMNEFT (νSMEFT).

To lowest order in SMNEFT, the dimension-six B and L conserving SMNEFT Lagrangian is

$$L_{\rm SMNEFT} \supset L_{\rm SM} + \bar{n}\partial\!\!\!/ n + \sum_i C_i O_i \,,$$

where C_i are the WCs with the scale of new physics absorbed in them, The 16 baryon and lepton

$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{nd}	$(\bar{n}_p\gamma_\mu n_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{qn}	$(\bar{q}_p\gamma_\mu q_r)(\bar{n}_s\gamma^\mu n_t)$	$Q_{\ell n\ell e}$	$(\bar{\ell}^j_p n_r)\epsilon_{jk}(\bar{\ell}^k_s e_t)$
Q_{nu}	$(\bar{n}_p\gamma_\mu n_r)(\bar{u}_s\gamma^\mu u_t)$	$Q_{\ell n}$	$(\bar{\ell}_p\gamma_\mu \ell_r)(\bar{n}_s\gamma^\mu n_t)$	$Q^{(1)}_{\ell nqd}$	$(\bar{\ell}^j_p n_r)\epsilon_{jk}(\bar{q}^k_s d_t)$
Q_{ne}	$(\bar{n}_p\gamma_\mu n_r)(\bar{e}_s\gamma^\mu e_t)$			$Q^{(3)}_{\ell nqd}$	$(\bar{\ell}^j_p\sigma_{\mu\nu} n_r)\epsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu} d_t)$
Q_{nn}	$(\bar{n}_p\gamma_\mu n_r)(\bar{n}_s\gamma^\mu n_t)$			$Q_{\ell nuq}$	$(\bar{\ell}^j_p n_r)(\bar{u}_s q^j_t)$
Q_{nedu}	$(\bar{n}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu u_t)$				
$\psi^2\phi^3$		$\psi^2\phi^2 D$		$\psi^2 X\phi$	
$Q_{n\phi}$	$(\phi^\dagger\phi)(\bar{l}_p n_r\tilde{\phi})$	$Q_{\phi n}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu\phi)(\bar{n}_p\gamma^\mu n_r)$	Q_{nW}	$(\bar{\ell}_p\sigma^{\mu\nu}n_r)\tau^I\tilde{\phi}W^I_{\mu\nu}$
		$Q_{\phi ne}$	$i(\tilde{\phi}^\dagger D_\mu\phi)(\bar{n}_p\gamma^\mu e_r)$	Q_{nB}	$(\bar{\ell}_p\sigma^{\mu\nu}n_r)\tilde{\phi}B_{\mu\nu}$

Table 4: The 16 SMNEFT operators involving RH neutrinos n in the Warsaw basis convention which conserve baryon and lepton number ($\Delta B = \Delta L = 0$). The flavor indices '$prst$' on the operators are suppressed for simplicity. The fundamental $SU(2)$ indices are denoted by i, j, and I is the adjoint index.

number conserving ($\Delta B = \Delta L$ =0) operators involving the field n in SMNEFT are shown below in Table. 4. Based on the effective interaction the phenomenology of the sterile neutrino can be discussed in many processes[12]. In particular a sterile neutrino can solve the $R(D) - R(D^*)$ puzzle as the new physica adds incoherently with the SM and enhances the rate. Many interesting signals are also possible in the angular distribution (see Figure 5) of semileptonic B decays with a massive sterile neutrino[13].

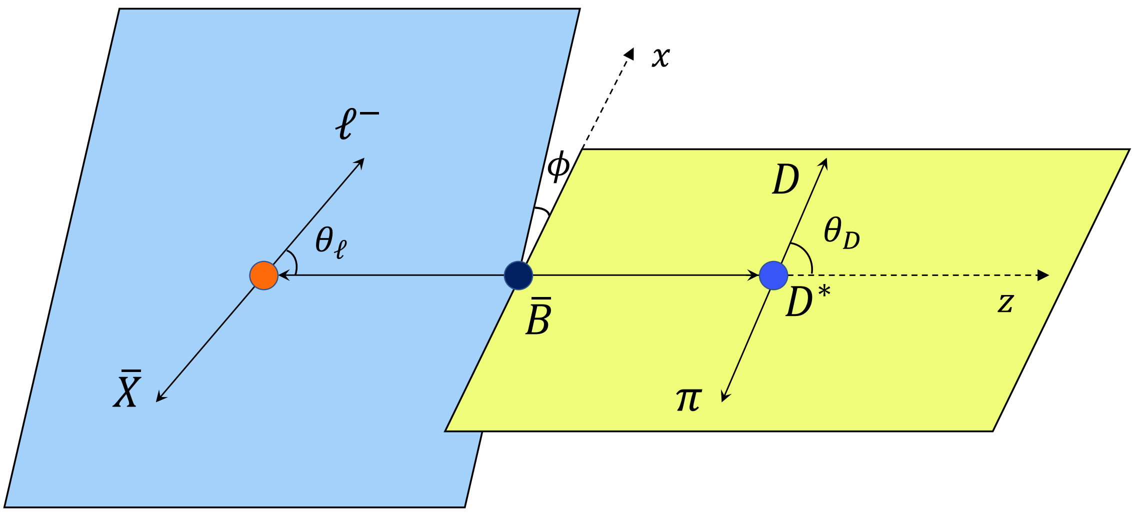

Figure 5

1.4 Dark sector in Flavor physics.

Decays with invisible final states such as $B^+ \to K^+ + \text{inv}$, $K \to \pi + \text{inv}$ offer interesting opportunities to probe dark sectors and its possible flavor structure. The decay $B^+ \to K^+ + \text{inv}$ was recently measured by Belle II with a branching ratio about 2.7 σ from SM prediction [14] as shown in Figure 6. These decays are sensitive to dark sectors and as a specific example we consider

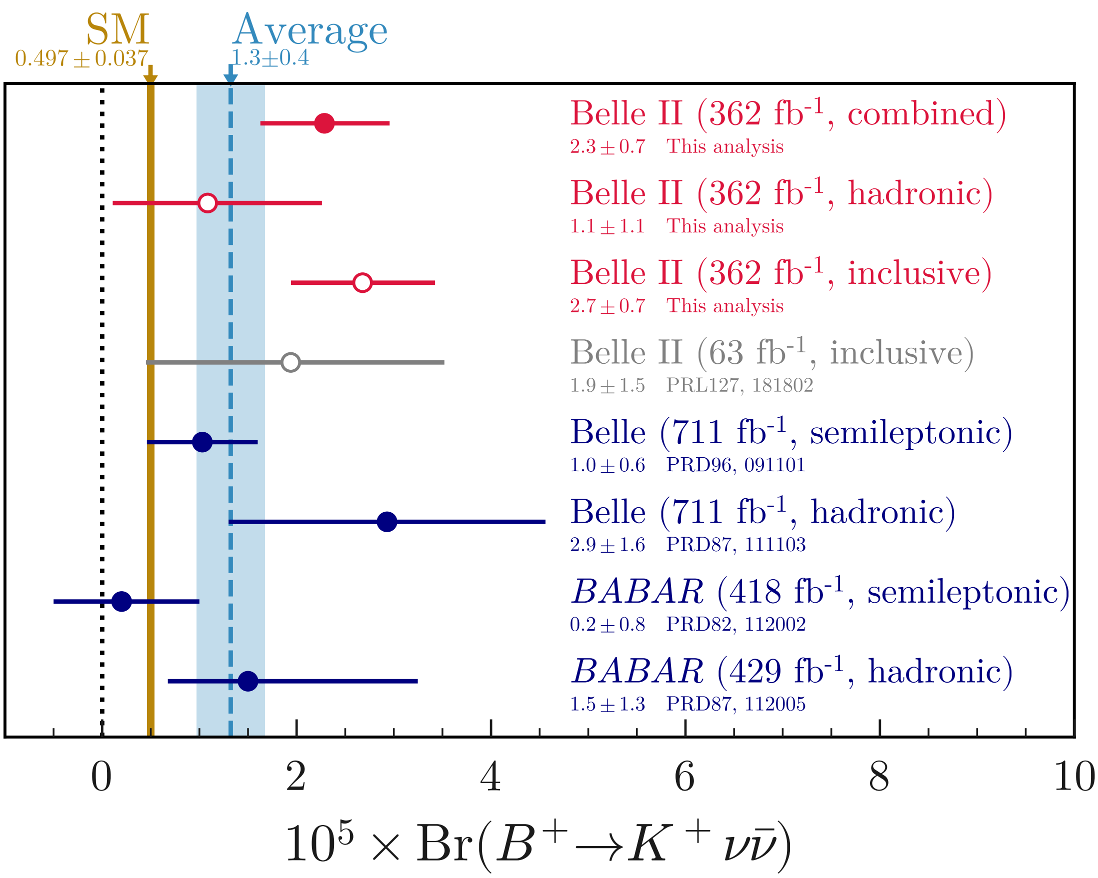

Figure 6

a model with a dark Higgs and a sterile neutrino [15]. We assume a dark Higgs, S , mixes with a general extended unspecified Higgs sector and couples to a sterile neutrino state

$$\mathcal{L}_S \supset \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \eta_d \sum_{f=d,\ell} \frac{m_f}{v}\bar{f} f S - \sum_{f=u,c,t} \eta_f \frac{m_f}{v}\bar{f} f S - g_D S \bar{\nu}_D \nu_D - \frac{1}{4}\kappa S F_{\mu\nu}F^{\mu\nu}. \tag{1}$$

The sterile neutrino ν_D and the light neutrino mix and are taken to be Dirac fermions.

$$\nu_{\alpha(L,R)} = \sum_{i=1}^{4} U_{\alpha i}^{(L,R)} \nu_{i(L,R)}\,, \quad (\alpha = e, \mu, \tau, D)\,, \tag{2}$$

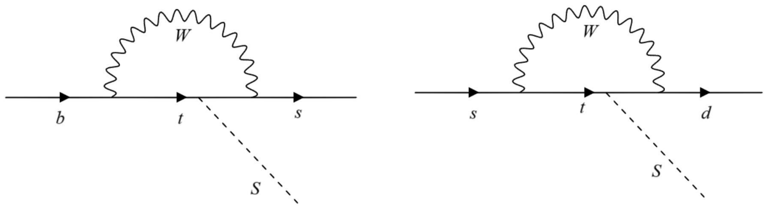

Figure 7

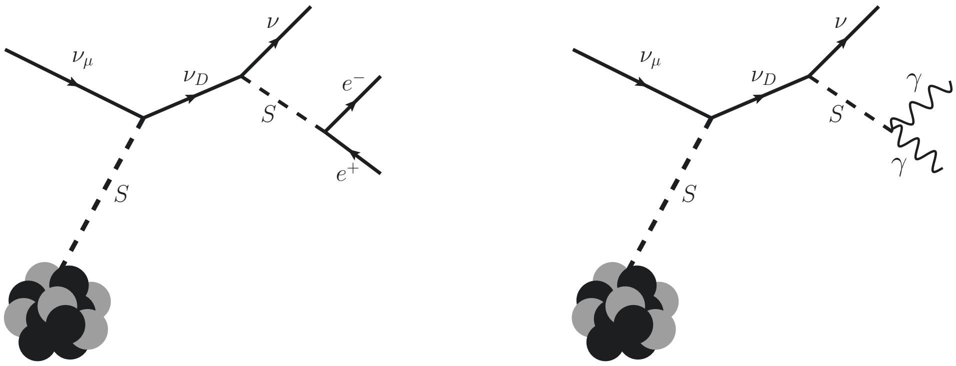

Figure 8

$(U^L = U^R \equiv U)$. Here, we assume $U_{e4} \approx U_{\tau 4} \approx 0$. The model generates $B \to KS$ and $K \to \pi S$ at loop level as shown in Figure 7. The relevant interactions are

$$\mathcal{L}_{FCNC} = g_{bs}\bar{s}P_R bS + g_{sd}\bar{d}P_R sS,$$

$$g_{bs} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_b}{v}\eta_t V_{tb}V_{ts}^*$$

and

$$g_{sd} \approx \frac{3\sqrt{2}G_F}{16\pi^2}\frac{m_t^2 m_s}{v}V_{ts}V_{td}^*\left(\eta_t + \eta_c\frac{m_c^2}{m_t^2}\frac{V_{cs}V_{cd}^*}{V_{ts}V_{td}^*}\right).$$

The model also generates neutrino nonstandard interaction and can potentially explain the MiniBooNE electron like events [16] as the model predicts new effect in neutrino scattering $\nu_\mu + Z \to \nu_4 + Z$ and ν_4 decay, $\nu_4 \to \nu_\mu S \to \nu_\mu + (e^+e^-, \gamma\gamma, \bar{\nu_\mu}\nu_\mu)$ as shown in Fig 8.

2. Conclusion

Flavor physics offers many avenues to look for beyond the standard model physics. Many experiments are testing the flavor structure of the SM and some anomalies have appeared that hint at new physics. This work discussed some of the anomalies and possible new physics models to account for them. We discussed decays to invisible final states that could probe dark sectors and sterile neutrinos.

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