Dineutrino modes probing lepton flavor violation

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\textit{SU}(2)_{L}-\textit{invariance links charged dilepton }\bar{q} q' \ell^+ \ell^- \textit{ and dineutrino }\bar{q} q' \nu \nu \textit{ couplings. This connection can be established using the Standard Model Effective Field Theory framework, and allows to perform complementary experimental tests of lepton universality and charged lepton flavor conservation with flavor-summed dineutrino observables. We present its phenomenological implications for the branching ratios of rare charm decays }c \rightarrow u \nu \bar{\nu} \textit{ and rare }B \textit{ decays }b \rightarrow s \nu \bar{\nu} \textit{ decays.}

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1. Introduction

Flavor-changing neutral currents (FCNCs) of $q^\alpha$ and $q^\beta$ quarks induced by $|\Delta q^\alpha| = |\Delta q^\beta| = 1$ processes represent excellent probes of New Physics (NP) beyond the Standard Model (SM). Their weak loop suppression triggered by the Glashow-Iliopoulos-Maiani (GIM) mechanism and Cabibbo-Kobayashi-Maskawa (CKM) hierarchies, not necessarily present in SM extensions, can result in large experimental deviations from the SM predictions alluding to a breakdown of SM symmetries. In addition, its environment is enriched with further tests if leptons are involved, that is $q_\alpha q_\beta \ell_i^\dagger \ell_j$. We exploit the $SU(2)_L$-link between left-handed charged lepton and neutrino couplings, which may be used to assess charged lepton flavor conservation (cLFC) and lepton universality (LU) quantitatively using flavor-summed dnuino observables [1]. This link (3) is presented for $|\Delta q^\alpha| = |\Delta q^\beta| = 1$ processes, but we stress that it holds analogously for other conserved quark transitions, both in the up- and down-sector.

These proceedings are organized as follows: In Section 2, we present the effective theory framework where the $SU(2)_L$-link between neutrino and charged lepton couplings is derived. In Sections 3 and 4, we work out its phenomenological implications for charm and beauty, respectively. The conclusions are drawn in Section 5. The results are based on Refs. [1–3], we refer there for further details.

2. $SU(2)_L$–link between dnuino and charled dilepton couplings

At lowest order in the SM effective field theory (SMEFT), the Lagrangian accounting for semileptonic (axial-)vector four-fermion operators is given by [4],

$$L_{\text{eff}} \supset \frac{C_{\ell q}^{(1)}}{v^2} \overline{Q} \gamma_\mu Q \overline{L} \gamma^\mu \nu L + \frac{C_{\ell q}^{(3)}}{v^2} \overline{Q} \gamma_\mu \gamma^\mu Q \overline{L} \gamma^\mu \nu L + \frac{C_{\ell u}^{}}{v^2} \overline{U} \gamma_\mu U \overline{L} \gamma^\mu \nu L + \frac{C_{\ell d}^{}}{v^2} \overline{D} \gamma_\mu D \overline{L} \gamma^\mu \nu L.$$ (1)

Reading off couplings to dnuinos ($C_N^A$) and charged dileptons ($K_N^A$) by writing the operators (1) into $SU(2)_L$-components, one obtains

$$C^U_L = K^D_L = \frac{2\pi}{\alpha} \left( C_{\ell q}^{(1)} + C_{\ell q}^{(3)} \right) , \quad C^U_R = K^D_R = \frac{2\pi}{\alpha} C_{\ell u}^{} ,$$

$$C^D_L = K^U_L = \frac{2\pi}{\alpha} \left( C_{\ell q}^{(1)} - C_{\ell q}^{(3)} \right) , \quad C^D_R = K^U_R = \frac{2\pi}{\alpha} C_{\ell d}^{} ,$$

where $N = U (N = D)$ represents the up-quark sector (down-quark sector), and $A = L(R)$ denotes left- (right-) handed quark currents. Interestingly, $C_N^A = K_N^A$ holds model-independently, while $C_L^N$ is not fixed by $K_L^N$ in general due to the different relative signs of $C_{\ell q}^{(1)}$ and $C_{\ell q}^{(3)}$. Expressing Eqs. (2) in the mass basis, that is $C_N^A = W^\dagger K_N^A W + O(\lambda)$, $K_N^A = W^\dagger K_N^A W$ where $W$ is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix and $\lambda \sim 0.2$ the Wolfenstein parameter, and summing lepton flavors $i, j$ incoherently, one obtains the following identity [1]

$$\sum_{\nu = \text{e, } \mu} \left( |C_L^{N(i)}|^2 + |C_R^{N(i)}|^2 \right) = \sum_{\ell = \text{e, } \mu} \left( |K_L^{M(i)}|^2 + |K_R^{M(i)}|^2 \right) + O(\lambda) ,$$

between charged lepton couplings $K_{L,R}$ and neutrino ones $C_{L,R}$.

Here, we use $N, M = U, D$ when the link is exploited for neutrino couplings in the up-quark sector, while $N, M = D, U$ for

\footnote{Wilson coefficients in calligraphic style denote those for mass eigenstates.}
the down-quark sector. Eq. (3) allows the prediction of dineutrino rates for different leptonic flavor structures $\mathcal{K}_{N_{ij}}^{L,R}$,

i) $\mathcal{K}_{N_{ij}}^{L,R} \propto \delta_{ij}$, i.e. lepton-universality (LU),

ii) $\mathcal{K}_{N_{ij}}^{L,R}$ diagonal, i.e. charged lepton flavor conservation (cLFC),

iii) $\mathcal{K}_{N_{ij}}^{L,R}$ arbitrary,

which can be probed with lepton-specific measurements. In the following sections, we use the following notation i.e. $\mathcal{K}_{N_{ij}}^{L,R} = \mathcal{K}_{L,R}^{D_{ij}}, \mathcal{C}_{N_{ij}}^{L,R} = \mathcal{C}_{L,R}^{D_{ij}}$, etc., to improve the readability.

| $R^{\ell\ell}$ | $\delta R^{\ell\ell}$ | $r^{\ell\ell}$ |
|--------------|----------------|---------|
| $ee$ | $\mu\mu$ | $\tau\tau$ | $e\mu$ | $e\tau$ | $\mu\tau$ |
| 21 | 6.0 | 77 | 6.6 | 59 | 70 |
| 19 | 5.4 | 69 | 5.7 | 55 | 63 |
| 39 | 11 | 145 | 12 | 115 | 133 |

Table 1: Bounds on $|\Delta c| = |\Delta u| = 1$ parameters $R^{\ell\ell}$ and $\delta R^{\ell\ell}$ from Eqs. (4), as well as their sum, $r^{\ell\ell} = R^{\ell\ell} + \delta R^{\ell\ell}$. Table taken from Ref. [2].

3. Predictions for charm

In this section, we study the implications of (3) for $c \to u \nu \bar{\nu}$ dineutrino transitions, where the situation is exceptional as the SM amplitude is fully negligible due to an efficient GIM-suppression [5] and the current lack of experimental constraints. We use upper limits on $\mathcal{K}_{N_{ij}}^{L,R}$ from high-$p_T$ [6, 7], which allow to set constraints on

$$R^{\ell\ell} = |\mathcal{K}_{L}^{d_{ij}\ell\ell}|^2 + |\mathcal{K}_{R}^{d_{ij\ell\ell}}|^2, \quad R_{\pm}^{\ell\ell} = |\mathcal{K}_{L}^{d_{ij\ell\ell}} \pm \mathcal{K}_{R}^{d_{ij\ell\ell}}|^2, \quad \delta R^{\ell\ell} = 2 \lambda \text{Re} \left\{ \mathcal{K}_{L}^{d_{ij\ell\ell}} \mathcal{K}_{L}^{d_{ij\ell\ell}}^* - \mathcal{K}_{L}^{d_{ij\ell\ell}} \mathcal{K}_{L}^{d_{ij\ell\ell}}^* \right\},$$

(4)

which directly enter in $c \to u \nu \bar{\nu}$ branching ratios. Upper limits on $R^{\ell\ell}$, $\delta R^{\ell\ell}$ and their sum $r^{\ell\ell} = R^{\ell\ell} + \delta R^{\ell\ell}$ are provided in Table 1. Since the neutrino flavors are not tagged, the branching ratio is obtained by an incoherent sum

$$\mathcal{B} \left( c \to u \nu \bar{\nu} \right) = \sum_{i,j} \mathcal{B} \left( c \to u \nu_i \bar{\nu}_j \right) \propto x_{uc},$$

(5)

where $x_{uc} = \sum_{i,j} \left( |C_{L}^{U_{ij}}|^2 + |C_{R}^{U_{ij}}|^2 \right)$. Using (3) with $N,M = U,D$ and Table 1, we obtain upper limits for the different benchmarks $i$-iii):

$$x_{uc} = 3 r^{\mu\mu} \lesssim 34, \quad \text{(LU)}$$

$$x_{uc} = r^{ee} + r^{\mu\mu} + r^{\tau\tau} \lesssim 196, \quad \text{(cLFC)}$$

$$x_{uc} = r^{ee} + r^{\mu\mu} + r^{\tau\tau} + 2 (r^{e\mu} + r^{e\tau} + r^{\mu\tau}) \lesssim 716.$$
Since dimuon bounds are the most stringent ones, see Table 1, they set the LU-limit (6). Experimental measurements above the upper limit in (6) would indicate a breakdown of LU, while values above the limit in (7) would imply a violation of cLFC. Corresponding upper limits on branching ratios of dineutrino modes of a charmed hadron $h_c$ into a final hadronic state $F$,

$$\mathcal{B}(h_c \to F \nu \bar{\nu}) = A_{h_c}^{h_c F} x_{cu}^+ + A_{h_c}^{h_c F} x_{cu}^-,$$

are provided in Table 2 for several decays modes. The $A_{h_c}^{h_c F}$ coefficients in Eq. (9) are given in the second column of Table 2. Using the limits (6), (7), (8), together with Eq. (9) and the values of $A_{h_c}^{h_c F}$, we obtain upper limits on branching ratios for the three flavor scenarios $\mathcal{B}_{\text{LU}}^{\text{max}}$, $\mathcal{B}_{\text{cLFC}}^{\text{max}}$, and $\mathcal{B}_{\text{max}}$. A branching ratio measurement $\mathcal{B}_{\text{exp}}$ within $\mathcal{B}_{\text{LU}}^{\text{max}} < \mathcal{B}_{\text{exp}} < \mathcal{B}_{\text{cLFC}}^{\text{max}}$ would be a clear signal of LU violation. In contrast, a branching ratio above $\mathcal{B}_{\text{cLFC}}^{\text{max}}$ would imply a breakdown of cLFC.

### Table 2: Coefficients $A_{h_c}^{h_c F}$, as defined in (9), and model-independent upper limits on $\mathcal{B}_{\text{LU}}^{\text{max}}$, $\mathcal{B}_{\text{cLFC}}^{\text{max}}$, $\mathcal{B}_{\text{max}}$ from (6), (7) and (8), respectively, corresponding to the lepton flavor symmetry benchmarks i-iii). Table taken from Ref. [2].

| $h_c \to F$     | $A_{h_c}^{h_c F}$ | $A_{h_c}^{h_c F}$ | $\mathcal{B}_{\text{LU}}^{\text{max}}$ | $\mathcal{B}_{\text{cLFC}}^{\text{max}}$ | $\mathcal{B}_{\text{max}}$ |
|-----------------|-------------------|-------------------|-----------------|-----------------|-----------------|
| $D^0 \to e^0$   | 0.9               | –                 | 6.1             | 3.5             | 13              |
| $D^+ \to \pi^+$ | 3.6               | –                 | 25              | 14              | 52              |
| $D^+ \to K^+$   | 0.7               | –                 | 4.6             | 2.6             | 9.6             |
| $D^0 \to \pi^0\pi^0$ | $O(10^{-1})$   | 0.21              | 1.5             | 0.8             | 3.1             |
| $D^0 \to \pi^0\pi^-$ | $O(10^{-1})$ | 0.41              | 2.8             | 1.6             | 5.9             |
| $D^0 \to K^+K^-$ | $O(10^{-4})$     | 0.004             | 0.03            | 0.02            | 0.06            |
| $\Lambda^0 \to \rho^+$ | 1.0              | 1.7               | 18              | 11              | 39              |
| $\Xi^- \to \Sigma^+$ | 1.8              | 3.5               | 21              | 15              | 76              |
| $B^0 \to X$     | 2.2               | 2.2               | 15              | 8.7             | 32              |
| $D^+ \to X$     | 5.6               | 5.6               | 38              | 22              | 80              |
| $D^+ \to X$     | 2.7               | 2.7               | 18              | 10              | 38              |

4. Testing lepton universality with $b \to s \nu \bar{\nu}$

In this section we study $b \to s \nu \bar{\nu}$ transitions and their interplay with $b \to s \ell^+\ell^-$ transitions routed by (3). The branching ratios for $B \to V \nu \bar{\nu}$ and $B \to P \nu \bar{\nu}$ decays in the LU limit are given by

$$\mathcal{B}(B \to V \nu \bar{\nu})_{\text{LU}} = A_{B}^{BV} x_{bs,LU}^+ + A_{B}^{BV} x_{bs,LU}^-,$$

$$\mathcal{B}(B \to P \nu \bar{\nu})_{\text{LU}} = A_{B}^{BP} x_{bs,LU}^+,$$

where $x_{bs,LU}^\pm = 3 \left| C_{\text{SM}}^{bs,\ell\ell} + K_{L}^{\ell\ell} \pm K_{R}^{\ell\ell} \right|^2$, and the values of $A_{B}^{BV}$ and $A_{B}^{BP}$ for different modes can be found in Ref. [3]. We obtain two solutions for the coupling $K_{L}^{\ell\ell}$ when we solve $\mathcal{B}(B \to P \nu \bar{\nu})_{\text{LU}}$ in Eq. (10). Plugging them into Eq. (10) results in a correlation between both LU branching ratios $[3]$

$$\mathcal{B}(B \to V \nu \bar{\nu})_{\text{LU}} = \frac{A_{B}^{BV}}{A_{B}^{BP}} \mathcal{B}(B \to P \nu \bar{\nu})_{\text{LU}} + 3 A_{B}^{BV} \left| \sqrt{\frac{\mathcal{B}(B \to P \nu \bar{\nu})_{\text{LU}}}{3 A_{B}^{BP}}} \pm 2 K_{R}^{\ell\ell} \right|^2. \quad (11)$$
The most stringent limits on $\mathcal{K}_{R}^{\text{best} \ell}$ are given for $\ell \ell = \mu \mu$. Performing a 6D global fit of the semileptonic Wilson coefficients $C^{(\epsilon)}_{(7,9,10),\mu}$ to the current experimental data on $b \to s \mu^+ \mu^-$ data (excluding $R_{K^{(*)}}$ which can be polluted by NP effects in electron couplings), we obtain the following $1\sigma$ fit value [3]

$$\mathcal{K}_{R}^{\text{best} \ell} = V_{tb} V_{ts}^{*} (0.46 \pm 0.26). \quad (12)$$

Fig. 1 displays the correlation between $\mathcal{B}(B^{0} \to K^{*0} \nu \bar{\nu})$ and $\mathcal{B}(B^{0} \to K^{0} \nu \bar{\nu})$, cf. Eq. (11). The SM predictions $\mathbb{B}(B^{0} \to K^{*0} \nu \bar{\nu})_{\text{SM}} = (8.2 \pm 1.0) \cdot 10^{-6}$, $\mathbb{B}(B^{0} \to K^{0} \nu \bar{\nu})_{\text{SM}} = (3.9 \pm 0.5) \cdot 10^{-6}$ [3] are depicted as a blue diamond with their $1 \sigma$ uncertainties (blue bars). We have scanned $\mathcal{K}_{R}^{\text{best} \mu}$, $A^{B^{0}K^{*0}}_{\pm}$, and $A^{B^{0}K^{0}}_{\pm}$ within their $1 \sigma$ ($2 \sigma$) regions in Eq. (10), resulting in the dark red region (dashed red lines) which represents the LU region, numerically [3]

$$\frac{\mathbb{B}(B^{0} \to K^{*0} \nu \bar{\nu})}{\mathbb{B}(B^{0} \to K^{0} \nu \bar{\nu})} = 1.7 \ldots 2.6 \quad (1.3 \ldots 2.9). \quad (13)$$

Interestingly, a branching ratio measurement outside the red region would clearly signal evidence for LU violation, but if a future measurement is instead inside this region, this may not necessarily imply LU conservation. Outside the light green region the validity of our effective field theory (EFT) framework gets broken [3]. More stringent limits for specific LU SM extensions are depicted as benchmarks, resulting in best fit values (markers) and $1 \sigma$ regions (ellipses) for $Z'$ (red star), LQ representations $S_{3}$ (pink pentagon) and $V_{3}$ (celeste triangle) from $b \to s \mu^+ \mu^-$ global fits, see Ref. [3] for details. The current experimental 90% CL upper limits, $\mathbb{B}(B^{0} \to K^{*0} \nu \bar{\nu})_{\text{exp}} < 1.8 \cdot 10^{-5}$ [8] and $\mathbb{B}(B^{0} \to K^{0} \nu \bar{\nu})_{\text{exp}} < 2.6 \cdot 10^{-5}$ [8], are displayed by hatched bands. The gray bands represent the derived EFT limits, $\mathbb{B}(B^{0} \to K^{0} \nu \bar{\nu})_{\text{derived}} < 1.5 \cdot 10^{-5}$, from Ref. [3]. A measurement between gray and hatched area would infer a clear hint of NP not covered by our EFT framework, i.e. light particles. The projected experimental sensitivity (10% at the chosen point) of Belle II with 50 ab$^{-1}$ is illustrated by the yellow boxes [9]. Similar conclusions can be drawn in $b \to d \nu \bar{\nu}$ decay [3].

![Figure 1: Correlation between $\mathbb{B}(B^{0} \to K^{*0} \nu \bar{\nu})$ and $\mathbb{B}(B^{0} \to K^{0} \nu \bar{\nu})$. Details are given in the main text. Figure taken from Ref. [3].](image)
5. Conclusions

$SU(2)_L$-invariance relates dineutrinos $\bar{q} q' \tilde{\nu} \nu$ and charged dilepton couplings $\bar{q} q' \ell^+ \ell^-$ in a model-independent way. This link (3) allows probing lepton flavor structure in dineutrino observables in three benchmarks: lepton universality, charged lepton flavor conservation and lepton flavor violation. The link has been exploited for the rare charm and $B$ decays, resulting in novel tests of the aforementioned symmetries, see Table 2 and Eq. (13), respectively. Our predictions are well-suited for the experiments Belle II [9], BES III [10], and future $e^+e^-$-colliders, such as an FCC-ee running at the $Z$ [11], and could offer some insight on the persistent anomalies in $B$ decays.

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