Lepton universality tests with dineutrino modes

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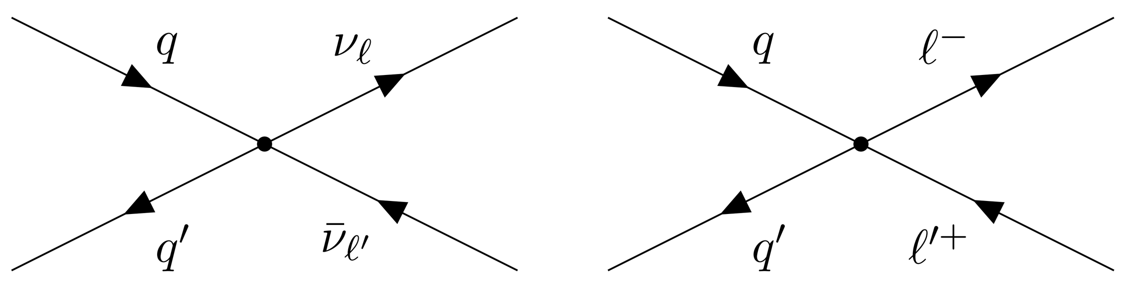
1. Introduction

Rare $|\Delta c| = |\Delta u| = 1$ transitions into dineutrinos, which suffer from a severe GIM-suppression, constitute excellent null tests, since SM branching ratios are tiny, such that any observation with current experimental sensitivities would cleanly signal new physics (NP). On the other hand for the beauty counterpart, $b \to s\nu\bar{\nu}$ in the down-sector, sensitivities down to SM rates are expected in the next round of measurements, while both sectors still provide room for NP contributions.



On this poster we give a brief overview on the EFT framework as well as the $SU(2)$–link connecting dineutrino $q \to q'\nu\bar{\nu}$ and charged dilepton $q \to q'\ell\ell'$ decays depicted above.
Based on recent works [1–3] we show promising lepton universality (LU) tests in rare charm and beauty decays, while also more general flavor structures of charged leptons, e.g. charged lepton flavor conservation (cLFC), can be probed.

2. EFT framework

In the absence of light RH neutrinos, as in the SM, rare $q \to q'$ dineutrino transitions can be described by two operators amended by flavor indices in the weak effective hamiltonian

$$\mathcal{H}_{\text{eff}}^{\nu_i\bar{\nu}_j} = -\frac{4\,G_{\text{F}}}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left(\mathcal{C}_L^{Sij} Q_L^{ij} + \mathcal{C}_R^{Sij} Q_R^{ij}\right) + \text{H.c.}\,, \quad (1)$$

with the four-fermion operators

$$Q_{L(R)}^{ij} = (\bar{q}_{L(R)}\gamma_\mu q'_{L(R)})\,(\bar{\nu}_{jL}\gamma^\mu \nu_{iL})\,, \quad (2)$$

where $S = U, D$ for up- and down-sector, respectively, and i, j denote the neutrino flavors.
Since the neutrino flavor indices are not experimentally tagged, dineutrino branching ratios are obtained by adding all dineutrino flavors incoherently

$$\mathcal{B}(q \to q'\,\nu\bar{\nu}) = \sum_{i,j} \mathcal{B}(q \to q'\,\nu_j\bar{\nu}_i)\,, \quad (3)$$

which depend on at most two combinations of Wilson coefficients

$$x_S^{\pm} = \sum_{i,j} |\mathcal{C}_L^{Sij} \pm \mathcal{C}_R^{Sij}|^2\,. \quad (4)$$

The weak effective hamiltonian for charged leptons can be written analogously to Eq. (1), where the Wilson coefficients and the associated operators are denoted by $\mathcal{K}_{L(R)}^{Sij}$ and $O_{L(R)}^{ij} = (\bar{q}_{L(R)}\gamma_\mu q'_{L(R)})\,(\bar{\ell}_{jL}\gamma^\mu \ell_{iL})$, respectively.

6. References

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[2] R. Bause, H. Gisbert, M. Golz, G. Hiller, *Phys. Rev. D* **2021**, *103*, 015033, arXiv: `2010.02225 [hep-ph]`.

[3] R. Bause, H. Gisbert, M. Golz, G. Hiller, **2021**, *in preparation* (DO-TH 21/17).

[4] W. Altmannshofer et al., *PTEP* **2019**, *2019*, (Eds.: E. Kou, P. Urquijo), [Erratum: PTEP 2020, 029201 (2020)], 123C01, arXiv: `1808.10567 [hep-ex]`.

[5] A. Abada et al., *Eur. Phys. J. C* **2019**, *79*, 474.

3. SU(2)–link and dineutrino branching ratios

Interestingly, a connection between $\mathcal{C}$ and $\mathcal{K}$ can be established using a SM effective field theory (SMEFT) framework and matching onto the weak effective operators [1, 2]. In the gauge basis, this SU(2)$_L$–link is materialized as

$$\boxed{c_R \to u_R\,\ell\ell'} \longleftrightarrow \boxed{c \to u\,\nu_\ell\bar{\nu}_{\ell'}} \longleftrightarrow \boxed{s_L \to d_L\,\ell\ell'} \qquad \boxed{b_R \to s_R\,\ell\ell'} \longleftrightarrow \boxed{b \to s\,\nu_\ell\bar{\nu}_{\ell'}} \longleftrightarrow \boxed{\cancel{t_L \to c_L\,\ell\ell'}}$$

$$\boxed{K_R^U = C_R^U} \text{ and } \boxed{C_L^U = K_L^D} \qquad \boxed{K_R^D = C_R^D} \text{ and } \boxed{C_L^D = K_L^U}$$

These links are broken by the required rotations for going from gauge to mass basis, $\mathcal{C}_L^{U,D} = W^\dagger\,\mathcal{K}_L^{D,U}\,W + \mathcal{O}(\lambda)$, $\mathcal{C}_R^{U,D} = W^\dagger\,\mathcal{K}_R^{U,D}\,W$, where W denotes the unitary PMNS matrix and $\lambda \sim 0.2$ the Wolfenstein parameter. However, the physical quantities $x_S^{\pm}$ required to describe $q \to q'\,\nu\bar{\nu}$ remain unbroken

$$\begin{aligned} x_{U,D}^{\pm} &= \sum_{i,j} |\mathcal{C}_L^{U,Dij} \pm \mathcal{C}_R^{U,Dij}|^2 = \text{Tr}\left((\mathcal{C}_L^{U,D} \pm \mathcal{C}_R^{U,D})^\dagger(\mathcal{C}_L^{U,D} \pm \mathcal{C}_R^{U,D})\right) \\ &= \text{Tr}\left(W^\dagger\,(\mathcal{K}_L^{D,U} \pm \mathcal{K}_R^{U,D})^\dagger W\,W^\dagger\,(\mathcal{K}_L^{D,U} \pm \mathcal{K}_R^{U,D})\,W\right) = \sum_{i,j} |\mathcal{K}_L^{D,Uij} \pm \mathcal{K}_R^{U,Dij}|^2\,, \end{aligned} \quad (5)$$

up to small $\mathcal{O}(\lambda)$ corrections. Eq. (5) allows us to perform tests of the lepton flavor structures in the charged lepton Wilson coefficients with dineutrino branching ratios:

$$\textbf{LU}: \mathcal{K}_{L,R}^S = \begin{pmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{pmatrix}; \quad \textbf{cLFC}: \mathcal{K}_{L,R}^S = \begin{pmatrix} k_{ee} & 0 & 0 \\ 0 & k_{\mu\mu} & 0 \\ 0 & 0 & k_{\tau\tau} \end{pmatrix}; \quad \textbf{general}: \mathcal{K}_{L,R}^S = \begin{pmatrix} k_{ee} & k_{e\mu} & k_{e\tau} \\ k_{\mu e} & k_{\mu\mu} & k_{\mu\tau} \\ k_{\tau e} & k_{\tau\mu} & k_{\tau\tau} \end{pmatrix}$$

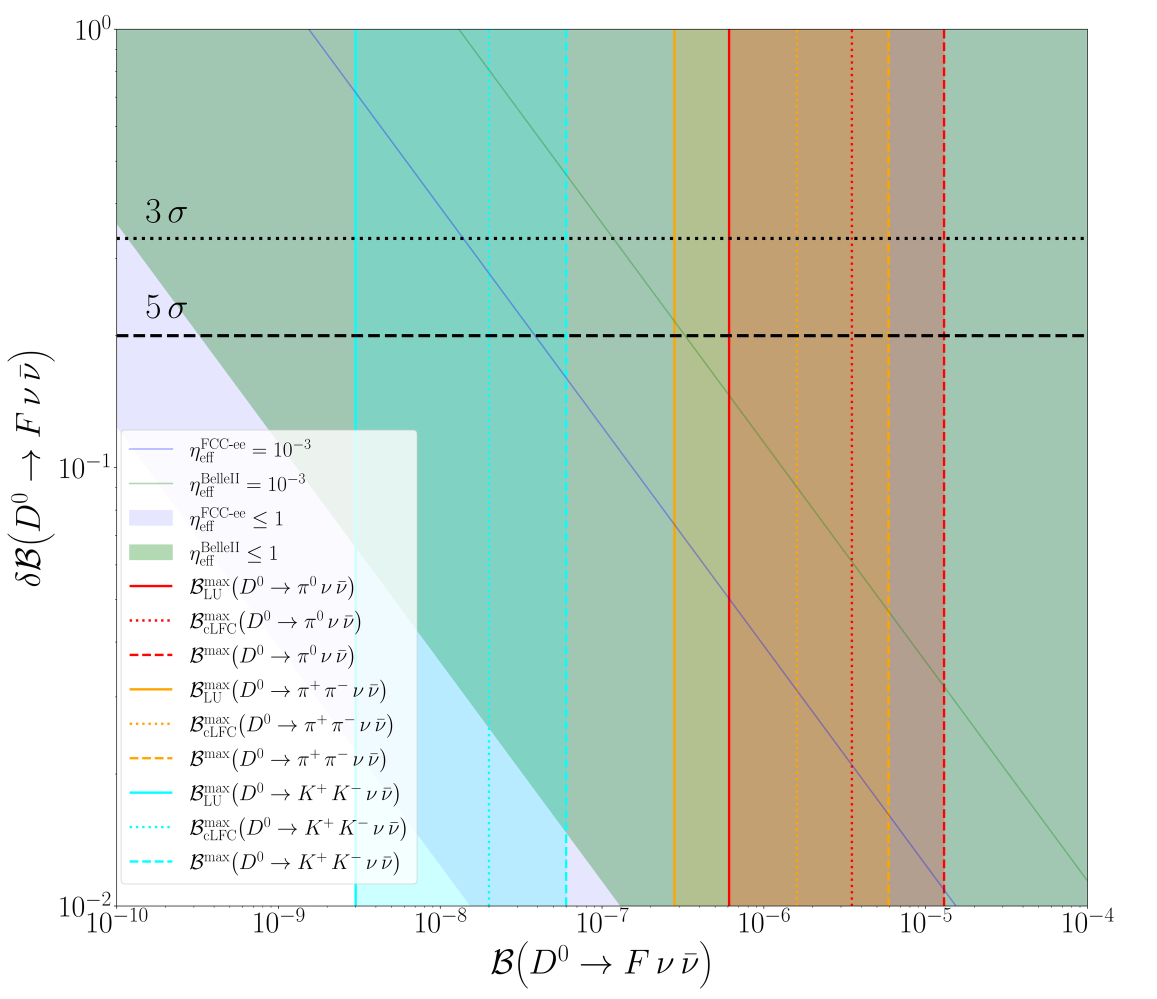
The integrated branching ratios of the dineutrino modes can be written as [1, 2]

$$\mathcal{B}(h \to F\,\nu\bar{\nu}) = A_+^{hF}\,x_S^+ + A_-^{hF}\,x_S^-\,, \quad (6)$$

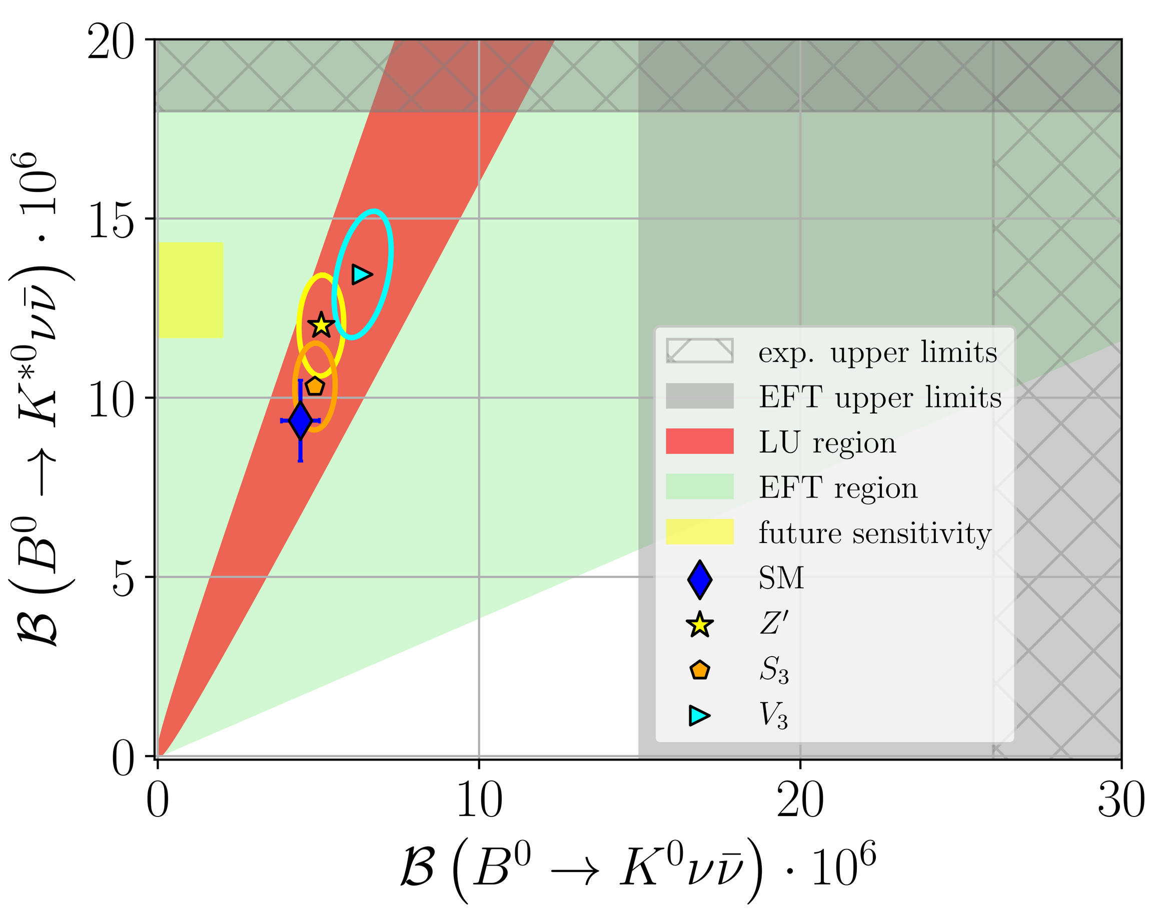
where h refers to a D or B–meson in charm or beauty decays, respectively, and F denotes the final hadronic state. $A_\pm^{hF}$ encodes the long distance dynamics (form factors), numerical values can be found in Ref. [2, 3].
Interestingly, we observe that using charged dilepton data (high–p_T, global fits, etc.) together with specific assumptions on the Wilson coefficients $\mathcal{K}_{L,R}$, allows us to set upper limits on branching ratios with Eq. (6).

4. Lepton universality tests in charm

Dineutrino modes in charm are well-suited for a clean e^+e^-–collider environment, such as Belle II [4] or future colliders like the FCC-ee [5] with charged hadron numbers of $\sim 10^{10}$. In the figure we show on the x–axis branching ratio bounds for $D^0 \to F\,\nu\bar{\nu}$ modes in LU, cLFC, and general scenarios. The relative statistical uncertainty $\delta\mathcal{B} = \frac{1}{\sqrt{N(h_c)\cdot\eta_{\text{eff}}\cdot\mathcal{B}}}$ is depicted on the y–axis, with the number of charmed hadrons $N(h_c)$ produced at a collider and the reconstruction efficiency η_{eff}. For instance, looking at $\mathcal{B}_{\text{LU}}^{\text{max}}\left(D^0 \to \pi^+\pi^-\right)$ (solid orange line) we can infer that a measurement $\sim 10^{-6}$ would imply a breakdown of LU, which could be observed (5σ) for $\eta_{\text{eff}} = 10^{-3}$ by both e^+e^-–colliders considered [2].



5. Lepton universality tests in beauty



In rare beauty decays, the strongest limits on $\mathcal{K}_{L,R}^{D_{23}\ell\ell}$ are provided by global fits from pure $b \to s\,\mu + \mu^-$ data. Performing a global fit, we find values [3]

$$\kappa_{R,\text{NP}}^{D_{23}\mu\mu} = C_9^{\mu\mu\prime} - C_{10}^{\mu\mu\prime} = \quad 0.47 \pm 0.27\,, \quad (7)$$

where in particular $\mathcal{K}_{L,R}^{D_{23}\mu\mu} = V_{tb}\,V_{ts}^*\,\kappa_{L,R}^{D_{23}\mu\mu}$. Assuming LU, the following correlation can be established

$$\begin{aligned} \mathcal{B}(B \to V\,\nu\bar{\nu})_{\text{LU}} &= \frac{A_+^{BV}}{A_+^{BP}}\,\mathcal{B}(B \to P\,\nu\bar{\nu})_{\text{LU}} \\ &+ 3\,A_-^{BV}\,\left|V_{tb}V_{tq}^*\right|^2\left(\sqrt{\frac{\mathcal{B}(B \to P\,\nu\bar{\nu})_{\text{LU}}}{3\,\left|V_{tb}V_{tq}^*\right|^2 A_+^{BP}}} \mp 2\,\kappa_{R,\text{NP}}^{D_{q3}\mu\mu}\right)^2. \end{aligned} \quad (8)$$

The correlation between $B^0 \to K^0\,\nu\bar{\nu}$ and $B^0 \to K^{*0}\,\nu\bar{\nu}$ in the LU limit (red cone) is generated by varying the best fit value of $\kappa_{R,\text{NP}}^{D_{23}\mu\mu}$ within 1σ in Eq. (8). Similar to the discussion in charm, measured branching ratios outside this region would imply a violation of LU. Current experimental upper limits as well as limits that test the validity of our EFT framework are shown in the figure. The yellow block illustrates the projected experimental sensitivity (10%) of Belle II with $50\,\text{ab}^{-1}$. The SM prediction (blue diamond) is accompanied by LU benchmarks of tree-level mediators, such as Z' boson or leptoquarks, for details see [3].