Interplay between dineutrino modes and semileptonic decays

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Based on 2007.05001, 2010.02225, and 21xx.xxxxx.

EPS-HEP, July 30, 2021.

Low-energy $|\Delta q'| = |\Delta q| = 1$ EFT description

$q' \to q\,\nu_\ell \bar{\nu}_{\ell'}$ $\overset{?}{\Longleftrightarrow}$ $q' \to q\,\ell^- \ell'^+$

$$\mathrm{H}_{\mathrm{eff}}^{\nu_\ell \bar{\nu}_{\ell'}} = -\frac{4\,G_F}{\sqrt{2}}\,\frac{\alpha}{4\pi} \sum_k \mathcal{C}_k^{D\ell\ell'}\, Q_k^{D\ell\ell'} \qquad \mathrm{H}_{\mathrm{eff}}^{\ell^- \ell'^+} = -\frac{4\,G_F}{\sqrt{2}}\,\frac{\alpha}{4\pi} \sum_k \mathcal{K}_k^{D\ell\ell'}\, O_k^{D\ell\ell'}$$

Only two operators (no RH neutrinos like SM) **Further operators non-connected**

$$Q_{\mathrm{L\,(R)}}^{D\ell\ell'} = \left(\bar{q}_{L\,(R)} \gamma_\mu q'_{\,L\,(R)}\right) \left(\bar{\nu}_{\ell'\,L} \gamma^\mu \nu_{\ell\,L}\right) \qquad O_{\mathrm{L\,(R)}}^{D\ell\ell'} = \left(\bar{q}_{L\,(R)} \gamma_\mu q'_{\,L\,(R)}\right) \left(\bar{\ell}'_L \gamma^\mu \ell_L\right)$$

...

Dineutrino BR is obtained via an incoherent neutrino flavor sum:

$$\mathcal{B}\left(q' \to q\,\nu\bar{\nu}\right) = \sum_{\ell,\ell'} \mathcal{B}\left(q' \to q\,\nu_\ell \bar{\nu}_{\ell'}\right) \sim \sum_{\ell,\ell'} \left|\mathcal{C}_L^{D\ell\ell'} \pm \mathcal{C}_R^{D\ell\ell'}\right|^2$$

$\mathcal{C}^P$ and $\mathcal{K}^P$ in the mass basis. $P = D$ $(P = U) \to$ down-quark sector (up-quark sector).

Correlate neutrinos and charged leptons with $SU(2)_L$

$SU(2)_L \times U(1)_Y$–invariant effective theory:

$$\mathcal{L}_{\text{SMEFT}}^{\text{LO}} \supset \frac{C_{\ell q}^{(1)}}{v^2}\bar{Q}\gamma_\mu Q\,\bar{L}\gamma^\mu L + \frac{C_{\ell q}^{(3)}}{v^2}\bar{Q}\gamma_\mu \tau^a Q\,\bar{L}\gamma^\mu \tau^a L + \frac{C_{\ell u}}{v^2}\bar{U}\gamma_\mu U\,\bar{L}\gamma^\mu L + \frac{C_{\ell d}}{v^2}\bar{D}\gamma_\mu D\,\bar{L}\gamma^\mu L$$

1. **Writing in $SU(2)_L$-components:** ($C \to$ dineutrinos and $K \to$ dileptons in the gauge basis)

$$C_L^D = K_L^U = C_{\ell q}^{(1)} - C_{\ell q}^{(3)}\,, \quad C_R^D = K_R^D = C_{\ell d}\,.$$

2. **Mass basis:** $\mathcal{C}_L^D = W^\dagger \mathcal{K}_L^U W + \mathcal{O}(\lambda)\,, \qquad \mathcal{C}_R^D = W^\dagger \mathcal{K}_R^D W$

3. **BR is independent of PMNS matrix!**

$$\mathcal{B}(q' \to q\,\nu\bar{\nu}) \sim \sum_{\ell,\ell'} \left|\mathcal{C}_L^{D\ell\ell'} \pm \mathcal{C}_R^{D\ell\ell'}\right|^2 = \mathrm{Tr}\left[(\mathcal{C}_L^D \pm \mathcal{C}_R^D)(\mathcal{C}_L^D \pm \mathcal{C}_R^D)^\dagger\right]$$

$$= \mathrm{Tr}\left[W^\dagger(\mathcal{K}_L^U \pm \mathcal{K}_R^D)W\,W^\dagger(\mathcal{K}_L^U \pm \mathcal{K}_R^D)^\dagger W\right] = \sum_{\ell,\ell'} \left|\mathcal{K}_L^{U\ell\ell'} \pm \mathcal{K}_R^{D\ell\ell'}\right|^2 + \mathcal{O}(\lambda)$$

Prediction of dineutrino rates for different leptonic flavor structures $\mathcal{K}_{L,R}^{\ell\ell'}$ can be probed with lepton-specific measurements!

Possible leptonic flavor structures for $\mathcal{K}_{L,R}^{\ell\ell'}$

i) ***Lepton-universality* (LU).**

$$\begin{pmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{pmatrix}$$

ii) ***Charged lepton flavor conservation* (cLFC).**

$$\begin{pmatrix} k_{ee} & 0 & 0 \\ 0 & k_{\mu\mu} & 0 \\ 0 & 0 & k_{\tau\tau} \end{pmatrix}$$

iii) $\mathcal{K}_{L,R}^{\ell\ell'}$ **arbitrary.**

$$\begin{pmatrix} k_{ee} & k_{e\mu} & k_{e\tau} \\ k_{\mu e} & k_{\mu\mu} & k_{\mu\tau} \\ k_{\tau e} & k_{\tau\mu} & k_{\tau\tau} \end{pmatrix}$$

Dineutrino branching ratios $H_{q'} \to H_q \, \nu\bar{\nu}$

$$\mathcal{B} = A_+ \, x^+ + A_- \, x^- , \qquad x^\pm = \sum_{\ell,\ell'} \left| \mathcal{C}_L^{D\ell\ell'} \pm \mathcal{C}_R^{D\ell\ell'} \right|^2$$

→ Long-distance dynamics $A_\pm$: **LCSRs (low q^2) + Lattice (high q^2)**

→ Short-distance dynamics $x^\pm$: **WCs (SM + BSM)**

→ Excellent complementarity $\mathcal{B}$:

- $A_- = 0$ in $H_{q'} \to P \nu\bar{\nu}$ decays.
- $A_- > A_+$ in $H_{q'} \to V \nu\bar{\nu}$ decays.
- $A_- = A_+$ in inclusive $H_{q'}$ decays.

$H_{q'} \to H_q$	A_+ $[10^{-8}]$	A_- $[10^{-8}]$
$B^{0,+} \to K^{0,+}$	500	0
$D^0 \to \pi^0$	0.9	0
$D^+ \to \pi^+$	3.6	0
$B^{0,+} \to K^{*\,0,+}$	200	900
$D^0 \to \pi^0\pi^0$	0	0.2
$D^0 \to \pi^+\pi^-$	0	0.4
$B^{0,+} \to X_s$	2000	2000
$D^0 \to X$	2.2	2.2
$D^+ \to X$	5.6	5.6

Upper limits on $c \to u\,\nu\bar{\nu}$ modes can probe LU!

- **Limits on $|\mathcal{K}_A^{P\ell\ell'}|$ from high-p_T:** [1]

	$\lvert\mathcal{K}_A^{P\ell\ell'}\rvert$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$s\,d$	$\lvert\mathcal{K}_L^{D\ell\ell'}\rvert$	3.5	1.9	6.7	2.0	6.1	6.6
$c\,u$	$\lvert\mathcal{K}_R^{U\ell\ell'}\rvert$	2.9	1.6	5.6	1.6	4.7	5.1

- $x^{\pm} < 2\,x\ ,\ x = \sum_{\ell,\ell'} \left(\left|\mathcal{K}_L^{D\ell\ell'}\right|^2 + \left|\mathcal{K}_R^{U\ell\ell'}\right|^2\right) + \mathcal{O}(\lambda) = \sum_{\ell,\ell'} R^{\ell\ell'} + \mathcal{O}(\lambda)$

$$x = 3\,R^{\mu\mu} \lesssim 34\,,$$ **(Lepton Universality)** **LU is fixed by muons.**

$$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} \lesssim 196\,,$$ **(charged Lepton Flavor Conservation)**

$$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} + 2\,(R^{e\mu} + R^{e\tau} + R^{\mu\tau}) \lesssim 716.$$

$h_c \to F$	$\mathcal{B}^{\max}_{\mathrm{LU}}$ $[10^{-7}]$	$\mathcal{B}^{\max}_{\mathrm{cLFC}}$ $[10^{-6}]$	$\mathcal{B}^{\max}$ $[10^{-6}]$
$D^0 \to \pi^0$	6.1	3.5	13
$D^+ \to \pi^+$	**25**	**14**	**52**
$D^0 \to \pi^0\pi^0$	1.5	0.8	3.1
$D^0 \to \pi^+\pi^-$	2.8	1.6	5.9
$\Lambda_c^+ \to p^+$	18	11	39
$\Xi_c^+ \to \Sigma^+$	36	21	76

Well-suited for e^+e^-–colliders such as Belle II and future FCC-ee!

$$N(c\bar{c}) = 6.5\,(55)\cdot 10^{10}$$

[1] 2003.12421, 2002.05684

LU bound in $b \to s\,\nu\bar{\nu}$ decays

1. **SU(2)$_L$–link:**

$$\boxed{b_R \to s_R\,\ell^-\ell'^+} \rightleftarrows \boxed{b \to s\,\nu\bar{\nu}} \leftrightarrows \boxed{t_L \to c_L\,\ell^-\ell'^+}$$

$$\mathcal{K}^{D\ell\ell'}_{R,\text{NP}} \qquad \mathcal{B}(B \to F\,\nu\bar{\nu}) \qquad \mathcal{K}^{U\ell\ell'}_{L,\text{NP}}$$

2. **LU limit ($\mathcal{K}^{P\ell\ell'}_{A,\text{NP}} = \mathcal{K}^{P\mu\mu}_{A,\text{NP}}\delta_{\ell\ell'}$):**

$$\boxed{b_R \to s_R\,\mu^-\mu^+} \rightleftarrows \boxed{b \to s\,\nu\bar{\nu}} \leftrightarrows \boxed{t_L \to c_L\,\mu^-\mu^+}$$

Global fits $\qquad \mathcal{B}(B \to F\,\nu\bar{\nu})_{\text{LU}} \qquad$ Weak bounds

3. **Complementarity between different $B \to F\,\nu\bar{\nu}$ decays:**

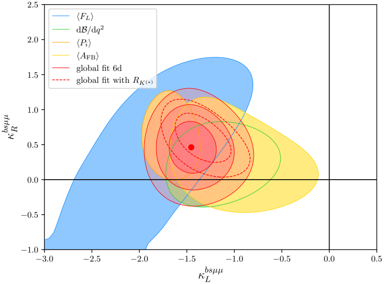
$$\boxed{B \to K^*\,\nu\bar{\nu}} \rightleftarrows \boxed{b_R \to s_R\,\mu^-\mu^+} \leftrightarrows \boxed{B \to K\,\nu\bar{\nu}}$$

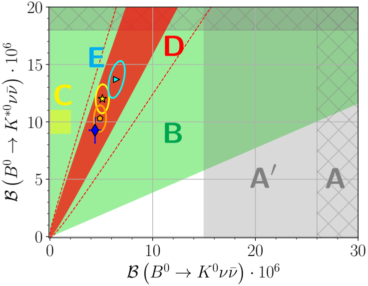
$\mathcal{B}(B \to K^*\,\nu\bar{\nu})_{\text{LU}} \qquad$ Global fits $\qquad \mathcal{B}(B \to K\,\nu\bar{\nu})_{\text{LU}}$

$$\mathcal{B}(B \to K^*\,\nu\bar{\nu})_{\text{LU}} = \frac{A_+^{BK^*}}{A_+^{BK}}\,\mathcal{B}(B \to K\,\nu\bar{\nu})_{\text{LU}} + 3\,A_-^{BK^*}\left(\sqrt{\frac{\mathcal{B}(B \to K\,\nu\bar{\nu})_{\text{LU}}}{3\,A_+^{BK}}} \mp 2\,|\mathcal{K}^{D\mu\mu}_{R,\text{NP}}|\right)^2$$

Testing LU with $b \to s\, \nu\bar{\nu}$ decays

Inputs: FFs 1503.05534, 1811.00983 + 6D global fit to $b \to s\, \mu^+\mu^-$ data: $\mathcal{K}^{D\mu\mu}_{R,\mathrm{NP}}$





A: Exp. upper limits.

A′: Derived EFT limits.

$$\mathcal{B}(B^0 \to K^0\, \nu\bar{\nu}) \lesssim 15 \cdot 10^{-6}$$

B: EFT region

$$\frac{\mathcal{B}(B \to K^*\, \nu\bar{\nu})}{\mathcal{B}(B \to K\, \nu\bar{\nu})} \gtrsim 0.4$$

C: Belle II 50 ab^{-1} $\delta_r \mathcal{B}_{\text{Belle II}} \sim 10\%$ 1808.10567

D: LU region

$$1.5 \lesssim \frac{\mathcal{B}(B \to K^*\, \nu\bar{\nu})_{\text{LU}}}{\mathcal{B}(B \to K\, \nu\bar{\nu})_{\text{LU}}} \lesssim 3$$

E: Specific LU BSMs

$$K_L^D = \gamma\, C_L^D$$

$\gamma = 1\,(Z'),\ 1/2\,(V_3),\ 2\,(S_3).$

Conclusions

⋆ $SU(2)_L$ links dineutrino and charged lepton modes.

(1) charm: $c_R \to u_R\,\ell^-\ell'^+$ ⇄ $c \to u\,\nu_\ell\bar{\nu}_{\ell'}$ ⇆ $s_L \to d_L\,\ell^-\ell'^+$

(2) beauty: $b_R \to s_R\,\ell^-\ell'^+$ ⇄ $b \to s\,\nu_\ell\bar{\nu}_{\ell'}$ ⇆ $t_L \to c_L\,\ell^-\ell'^+$

⋆ Dineutrino modes test LU and LFV!

(1) charm:

$$\mathcal{B}(D^+ \to \pi^+\,\nu\bar{\nu})_{\text{LU}} \lesssim 2.5 \cdot 10^{-6}$$

$$\mathcal{B}(D^+ \to \pi^+\,\nu\bar{\nu})_{\text{cLFC}} \lesssim 1.4 \cdot 10^{-5}$$

$$\mathcal{B}(D^+ \to \pi^+\,\nu\bar{\nu})_{\text{max}} \lesssim 5.2 \cdot 10^{-5}$$

(2) beauty:

$$1.5 \lesssim \frac{\mathcal{B}(B\to K^*\,\nu\bar{\nu})_{\text{LU}}}{\mathcal{B}(B\to K\,\nu\bar{\nu})_{\text{LU}}} \lesssim 3$$

⋆ Experimental study of $q' \to q\,\nu\bar{\nu}$ modes could shed some light on the leptonic flavor structure (persistent in B-decays)!

Thank you for your attention!