Lepton universality tests with dineutrino modes

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Invisibles21 PhD Forum

based on works with H. Gisbert, M. Golz, G. Hiller:

arXiv:2007.05001 ,
PRD 103, 015033 (arXiv:2010.02225) ,
and ongoing works (DO-TH 21/17, to appear soon on arXiv)

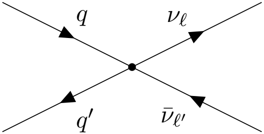
EFT framework of $q \to q' \nu \bar{\nu}$ decays

$c \to u\, \nu\bar{\nu}$ (up-sector) or $b \to s\, \nu\bar{\nu}$ (down-sector)

hierarchies of rare dineutrino decays

- charm: no resonance pollution, strong GIM-suppression in SM
  $\longrightarrow$ any signal = New Physics !
- beauty: close to sensitivity of SM, but $\to$ deviations from
  Lepton Universality (LU) possible
  (expected from B-anomalies, R_K in $b \to s\ell\ell$)

charm: **Excellent null tests of the SM**



$$\mathcal{H}_{\text{eff}}^{\nu_\ell \bar{\nu}_{\ell'}} \sim \left(\mathcal{C}_L^{\ell\ell'}\, Q_L^{\ell\ell'} + \mathcal{C}_R^{\ell\ell'}\, Q_R^{\ell\ell'} \right) + \text{H.c.}$$

with only *two* operators

$$Q_{L(R)}^{\ell\ell'} = (\bar{q}'_{L(R)} \gamma_\mu q_{L(R)})\, (\bar{\nu}_{\ell' L} \gamma^\mu \nu_{\ell L})$$

$$\mathcal{H}_{\text{eff}}^{\ell\ell'} \supset \left(\mathcal{K}_L^{\ell\ell'}\, O_L^{\ell\ell'} + \mathcal{K}_R^{\ell\ell'}\, O_R^{\ell\ell'} \right) + \text{H.c.}$$

with dileptonic operators

$$O_{L(R)}^{\ell\ell'} = (\bar{q}'_{L(R)} \gamma_\mu q_{L(R)})\, (\bar{\ell}'_L \gamma^\mu \ell_L)$$

important: neutrino flavour indices *not* experimentally tagged!

$$\mathcal{B}(q \to q'\, \nu\bar{\nu}) = \sum_{\ell,\, \ell'} \mathcal{B}(q \to q'\, \nu_{\ell'} \bar{\nu}_\ell)$$

$$\sim \sum_{\ell,\, \ell'} |\mathcal{C}_L^{\ell\ell'} \pm \mathcal{C}_R^{\ell\ell'}|^2$$

$\longrightarrow$ Can we find a *correlation* or *connection* between $\mathcal{C}$ and $\mathcal{K}$?!

SU(2)–link between charged leptons and neutrinos

- SU(2) relates neutrino and lepton couplings (same doublet)
- use SMEFT framework to relate neutrino $C_{L,R}$ and dileptons $K_{L,R}$ in gauge basis
- going to mass basis: $\mathcal{C}_L^{U,D} = W^\dagger \mathcal{K}_L^{D,U} W + \mathcal{O}(\lambda)$, $\mathcal{C}_R^{U,D} = W^\dagger \mathcal{K}_R^{U,D} W$

e.g. charm $(c \to u)$

$c_R \to u_R \ell\ell'$ $\longrightarrow$ $c \to u \nu_\ell \bar{\nu}_{\ell'}$ $\longleftarrow$ $s_L \to d_L \ell\ell'$

$K_R^U = C_R^U$ and $C_L^U = K_L^D$

$$\mathcal{B}(h \to F\nu\bar{\nu}) = A_+^{hF} x_+ + A_-^{hF} x_- \,, \quad x_\pm = \sum_{\ell,\ell'} |\mathcal{C}_L^{\ell\ell'} \pm \mathcal{C}_R^{\ell\ell'}|^2$$

- long-distance dynamics: $A_\pm^{h\,F}$ (form factors)
- short-distance dynamics: $x_\pm$ (Wilson coefficients)

- use bounds on specific $\mathcal{K}$ to calculate **constraints on dineutrino $\mathcal{B}$**
- benchmark scenarios for lepton flavour structures $\mathcal{K}_{L,R}^{\ell\ell'}$
  1. lepton universality (LU)
  2. charged lepton flavour conservation (cLFC)
  3. arbitrary couplings $\mathcal{K}_{L,R}^{\ell\ell'}$

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$K_R^U = C_R^U$ and $C_L^U = K_L^D$

① Lepton Universality (LU) benchmark:

strongest constraints from muons (high–p_T, global fits, ...)

$$\mathcal{K} = \begin{pmatrix} k_{ee} & k_{e\mu} & k_{e\tau} \\ k_{\mu e} & k_{\mu\mu} & k_{\mu\tau} \\ k_{\tau e} & k_{\tau\mu} & k_{\tau\tau} \end{pmatrix} \longrightarrow \mathcal{K} = \begin{pmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{pmatrix}$$

- use bounds on specific $\mathcal{K}$ to calculate

  constraints on dineutrino $\mathcal{B}$

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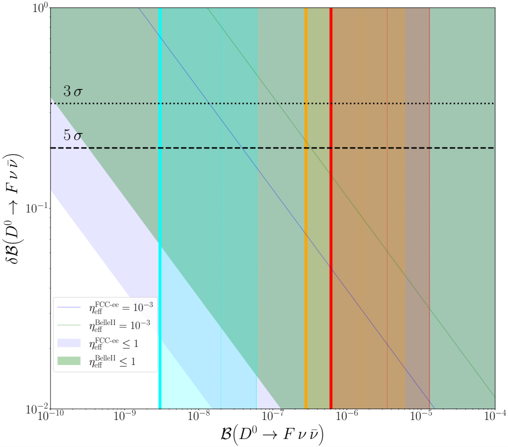
LU tests in $c \to u\,\nu\bar{\nu}$

$h_c \to F$	$\mathcal{B}^{\max}_{\text{LU}}$ $[10^{-7}]$	$\mathcal{B}^{\max}_{\text{cLFC}}$ $[10^{-6}]$	$\mathcal{B}^{\max}$ $[10^{-6}]$
$D^0 \to \pi^0$	6.1	3.5	13
$D^0 \to \pi^+\pi^-$	2.8	1.6	5.9
$D^0 \to K^+K^-$	0.03	0.02	0.06

$h_c \to F$	$N^{\max}_{\text{LU}}/\eta_{\text{eff}}$	$N^{\max}_{\text{cLFC}}/\eta_{\text{eff}}$	$N^{\max}/\eta_{\text{eff}}$
$D^0 \to \pi^0$	47 k (395 k)	270 k (2.3 M)	980 k (8.3 M)
$D^0 \to \pi^+\pi^-$	22 k (180 k)	120 k (1.0 M)	450 k (3.8 M)
$D^0 \to K^+K^-$	0.2 k (1.9 k)	1.3 k (11 k)	4.8 k (40 k)

relative uncertainty:

$$\delta\mathcal{B} = \frac{1}{\sqrt{N(h_c)\cdot\eta_{\text{eff}}\cdot\mathcal{B}}}$$



- $N^{\max}$: projected # of events for Belle II (FCCee) with reconstruction efficiency η_{eff}

  $\left(N_F^{\text{exp}} = \eta_{\text{eff}}\, N(h_c)\, \mathcal{B}(h_c \to F\,\nu\,\bar{\nu}),\quad N(h_c)\ :\ \#\text{ of charmed hadrons}\right)$ (1808.10567) , (EPJC 79 (2019) 6, 474)

- measurement in excess of LU → *breakdown* of corresponding symmetry !

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

NEW ongoing works in b–physics

- global fit *without* $R_{K^{(*)}}$ using *flavio* (1810.08132)

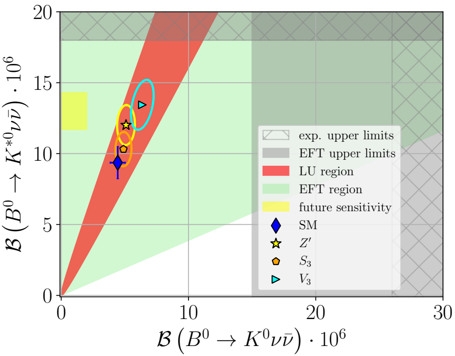
  $\kappa_R = C_9^{\mu\mu\prime} - C_{10}^{\mu\mu\prime} = \quad 0.47 \pm 0.27$
- translate into LU region allowed from fit with $\kappa_R = \kappa_{R,\text{NP}}^{D_{23}\mu\mu}$

use relation: $\mathcal{B}(B^0 \to K^{*0}\,\nu\bar{\nu})_{\text{LU}}$

$$= \frac{A_+^{B^0 K^{*0}}}{A_+^{B^0 K^0}} \mathcal{B}(B^0 \to K^0\,\nu\bar{\nu})_{\text{LU}}$$

$$+ \, 3\, A_-^{B^0 K^{*0}} \; |V_{tb} V_{ts}^*|^2$$

$$\left(\sqrt{\frac{\mathcal{B}(B^0 \to K^0\,\nu\bar{\nu})_{\text{LU}}}{3\,|V_{tb} V_{ts}^*|^2\, A_+^{B^0 K^0}}} \mp 2\, \kappa_{R,\text{NP}}^{D_{23}\mu\mu} \right)^2$$



$SU(2)$–link

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

Lepton Universality tests in dineutrino modes:

- use $SU(2)$–link in SMEFT to correlate $q \to q'\ell\ell$ and $q \to q'\nu\bar{\nu}$ transitions at low energies
- applicable in charm (up-sector) and also in B–physics (down-sector)

charm

- upper limits $\mathcal{B}\,(h_c \to F\,\nu\bar{\nu}) \sim 10^{-7} - 10^{-5}$
  $\longrightarrow$ *accessible* with current (Belle II) and future (FCC-ee) e^+e^-–colliders

beauty

- test LU with correlation in $B \to K^{(*)}\,\nu\bar{\nu}$ using global fit on $C_{9,10}^{\mu\mu(\prime)}$ in $b \to s\mu\mu$
- also possible in $b \to d\,\nu\bar{\nu}$ transitions

!

next round of dineutrino measurements in $c \to u$, and $b \to d, s$
will have *huge* impact on our understanding of flavour structure of the SM
in the charged lepton sector

complementary tests of *LU Violation* are possible!

Backup

SU(2)–link relating dineutrino and dilepton modes

- $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$-invariant effective theory (1008.4884)

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

- obtain couplings to dineutrinos C_A^P and charged leptons K_A^P via $\mathrm{SU}(2)_L$-components

$$C_L^U = K_L^D = C_{\ell q}^{(1)} + C_{\ell q}^{(3)} \qquad C_R^U = K_R^U = C_{\ell u}$$
$$C_L^D = K_L^U = C_{\ell q}^{(1)} - C_{\ell q}^{(3)} \qquad C_R^D = K_R^D = C_{\ell d}$$

- relating neutrino C and dileptons K in gauge basis:

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

- going to *mass basis*:

define mass eigenstates: $Q_\alpha = (u_{L\,\alpha},\; V_{\alpha\beta}\, d_{L\,\beta}),\quad L_i = (\nu_{L\,i},\; W_{ki}^* \ell_{L\,k})$ (V: CKM, W: PMNS)

it follows $\boxed{\mathcal{C}_L^U = W^\dagger\, \mathcal{K}_L^D\, W + \mathcal{O}(\lambda), \quad \mathcal{C}_R^U = W^\dagger\, \mathcal{K}_R^U\, W}$

Probe $\mathcal{K}^{\ell\ell'}_{L,R}$ with lepton-specific measurements

$$\mathcal{B}\,(h \to F\nu\bar{\nu}) = A_+^{hF} x_+ + A_-^{hF} x_- \,, \quad x_\pm = \sum_{\ell,\,\ell'} |\mathcal{C}_L^{\ell\ell'} \pm \mathcal{C}_R^{\ell\ell'}|^2$$

- long-distance dynamics: $A_\pm^{h\,F}$ (form factors)
- short-distance dynamics: $x_\pm$ (Wilson coefficients)

charm

- use bounds from high-p_T on lepton couplings

$$x_\pm = \sum_{\ell,\ell'} |\mathcal{K}_L^{D_{12}\,\ell\ell'} \pm \mathcal{K}_R^{U_{12}\,\ell\ell'}|^2$$

beauty

- strongest limits from global fits on semileptonic Wilson coefficients: $C_{9,\mu}^{\text{NP}}, C_{10,\mu}^{\text{NP}}, \ldots$

$$x_\pm = \sum_{\ell,\ell'} |\mathcal{C}_{L,\text{SM}}^{D_{23}\,\ell\ell'} + \mathcal{K}_{L,\text{NP}}^{U_{23}\,\ell\ell'} \pm \mathcal{K}_{R,\text{NP}}^{D_{23}\,\ell\ell'}|^2$$

- **Lepton Universality (LU) benchmark**: strongest constraints from muons

$$\mathcal{K} = \begin{pmatrix} k_{ee} & k_{e\mu} & k_{e\tau} \\ k_{\mu e} & k_{\mu\mu} & k_{\mu\tau} \\ k_{\tau e} & k_{\tau\mu} & k_{\tau\tau} \end{pmatrix} \longrightarrow \mathcal{K} = \begin{pmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{pmatrix}$$

Upper limits on x from high-p_T

$$\mathcal{C}_L^{U12} = W^\dagger \mathcal{K}_L^{D12}\, W + \lambda\, W^\dagger (\mathcal{K}_L^{D22} - \mathcal{K}_L^{D11})\, W + \mathcal{O}(\lambda^2)\,, \qquad \mathcal{C}_R^{U12} = W^\dagger \mathcal{K}_R^{U12}\, W$$

	$\lvert\bar{\mathcal{K}}_A^{P\ell\ell'}\rvert$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$d\to d$	$\lvert\mathcal{K}_{L,R}^{D_{11}\ell\ell'}\rvert$	2.8	1.5	5.5	1.1	3.3	3.6
$s\to s$	$\lvert\mathcal{K}_{L,R}^{D_{22}\ell\ell'}\rvert$	9.0	4.9	17	5.2	17	18
$s\to d$	$\lvert\bar{\mathcal{K}}_{L,R}^{D_{12}\ell\ell'}\rvert$	3.5	1.9	6.7	2.0	6.1	6.6
$c\to u$	$\lvert\bar{\mathcal{K}}_{L,R}^{U_{12}\ell\ell'}\rvert$	2.9	1.6	5.6	1.6	4.7	5.1

(2003.12421), (2002.05684)

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

with $r^{\ell\ell'} = R^{\ell\ell'} + \delta R^{\ell\ell'}$

- define combinations of WCs that can be bounded model-independently by high-p_T data

$$\begin{aligned} R^{\ell\ell'} &= \lvert\mathcal{K}_L^{D12\,\ell\ell'}\rvert^2 + \lvert\mathcal{K}_R^{U12\,\ell\ell'}\rvert^2\,,\\ R_\pm^{\ell\ell'} &= \lvert\mathcal{K}_L^{D12\,\ell\ell'} \pm \mathcal{K}_R^{U12\,\ell\ell'}\rvert^2\,,\\ \delta R^{\ell\ell'} &= 2\,\lambda\,\mathrm{Re}\{\mathcal{K}_L^{D12\,\ell\ell'}\,\mathcal{K}_L^{D22\,\ell\ell'\,*} - \mathcal{K}_L^{D12\,\ell\ell'}\mathcal{K}_L^{D11\,\ell\ell'\,*}\}\end{aligned}$$

$$x = \sum_{\ell,\,\ell'}\left(R^{\ell\ell'} + \delta R^{\ell\ell'}\right)\,, \quad x_\pm = \sum_{\ell,\,\ell'} R_\pm^{\ell\ell'}$$

- construct bounds on $x = \frac{x_+ + x_-}{2}$, with $x^\pm \leq 2\,x$,

$$\begin{aligned} x &= 3\,r^{\mu\mu} \lesssim 34\,, \quad \text{(LU)}\\ x &= r^{ee} + r^{\mu\mu} + r^{\tau\tau} \lesssim 196\,, \quad \text{(cLFC)}\\ x &= r^{ee} + r^{\mu\mu} + r^{\tau\tau} + 2\,(r^{e\mu} + r^{e\tau} + r^{\mu\tau}) \lesssim 716\,,\end{aligned}$$