Rare charm dineutrino modes $c \to u\,\nu\bar{\nu}$

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Charm physics is exceptional

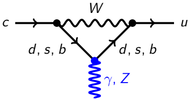
1. **Unique window to explore FCNCs in the up-sector!**

2. **Non-perturbative dynamics** $\rightarrow$ **"Null tests" observables $\mathcal{O} \pm \delta\,\mathcal{O}$**

   Bird's-eye view of the playground:[1]

   - SM symmetries: $\mathcal{O}_{\mathrm{SM}} = \mathbf{0}$.
   - Small uncertainties: $\mathcal{O}_{\mathrm{SM}} \gg \delta\,\mathcal{O}_{\mathrm{SM}}$.
   - Large hadronic effects to enhance small NP contributions.
   - Sensitive to specific NP.

3. **Very efficient GIM mechanism:** $\sum_i \lambda_i = 0$ with $\lambda_i \equiv V_{ci}^* V_{ui}$.



$$= \sum_{i=d,s,b} \lambda_i\, f_i \;=\; \lambda_s \left[(f_s - f_d) + \frac{\lambda_b}{\lambda_s}\,(f_b - f_d) \right]$$

$f_i \sim \frac{m_i^2}{(4\pi)^2\, M_W^2}$, $\mathrm{Im}(\lambda_b/\lambda_s) \sim 10^{-3}$

BRs (A_{CP}) are loop-(CKM-) suppressed!

Formidable place to search for BSM physics!

[1] 1510.00311, 1701.06392, 1802.02769, 1805.08516, 1812.04679, 1909.11108, 2004.01206, 2007.05001,...

Rare charm dineutrino modes $c \to u\,\nu\bar{\nu}$

- $c \to u\,\nu\bar{\nu}$ **are GIM-suppressed in the SM:**[2]

Any observation would cleanly signal NP!

- **Well-suited for e^+e^-–colliders** such as **Belle II**.

- **What is the new physics reach?**

⋆ fragmentation fractions $f(c \to h_c)$, 1509.01061

⋆ Luminosity $50\,\mathrm{ab}^{-1}$,

⋆ $N(c\bar{c})_{\text{Belle II}} = 65 \cdot 10^9$, Abada:2019lih

⋆ $N(h_c) = 2\,f(c \to h_c)\,N(c\bar{c})$.

h_c	$f(c \to h_c)$	$N(h_c)_{\text{Belle II}}$
D^0	0.59	$8 \cdot 10^{10}$
D^+	0.24	$3 \cdot 10^{10}$
D_s^+	0.10	$1 \cdot 10^{10}$
Λ_c^+	0.06	$8 \cdot 10^9$

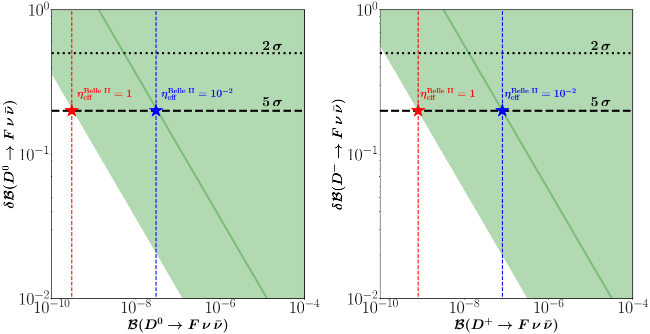
[2] hep-ph/0112235, 0908.1174

Experimental projections: $\delta\mathcal{B}$ versus $\mathcal{B}$

SM contribution can't be seen in plot, it is well below 10^{-10}

Any signal is NP: model independently LQs, Z',...

$$\delta\mathcal{B}(h_c \to F\,\nu\,\bar\nu) = 1/\sqrt{N_F^{\text{exp}}} \text{ with } N_F^{\text{exp}} = \eta_{\text{eff}}\,N(h_c)\,\mathcal{B}(h_c \to F\,\nu\,\bar\nu).$$



If no loss of information, Belle II can reach BRs $\sim 10^{-10}$!

- $\mathcal{B}^{5\,\sigma}_{\text{Belle II}}(D^0 \to F\nu\bar\nu) \approx 3\cdot 10^{-10}$ and $3\cdot 10^{-8}$!
- $\mathcal{B}^{5\,\sigma}_{\text{Belle II}}(D^+ \to F\nu\bar\nu) \approx 8\cdot 10^{-10}$ and $8\cdot 10^{-8}$!

Are there any model-independent upper limits?

$\boxed{c \to u\,\ell\ell} \xrightarrow{?} \boxed{c \to u\,\nu\bar{\nu}}$

- Low energy $\mathcal{H}_{\text{eff}}$ for $|\Delta c| = |\Delta u| = 1$ dineutrino transitions:

$$\mathcal{H}_{\text{eff}}^{c\to u\,\nu_i\bar{\nu}_j} = -\frac{4\,G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\left(\mathcal{C}_L^{Uij}\,Q_L^{ij} + \mathcal{C}_R^{Uij}\,Q_R^{ij}\right) + \text{h.c.}\,,$$

$Q^{ij}_{\mathrm{L\,(R)}} = \left(\bar{u}_{L\,(R)}\gamma_\mu c_{L\,(R)}\right)\left(\bar{\nu}_{j\,L}\gamma^\mu \nu_{i\,L}\right)$, Only two operators (no RH neutrinos like SM)

- Low energy $\mathcal{H}_{\text{eff}}$ for $|\Delta c| = |\Delta u| = 1$ dileptonic transitions:

$$\mathcal{H}_{\text{eff}}^{c\to u\,\ell\ell'} = -\frac{4\,G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\left(\mathcal{K}_L^{U\ell\ell'}\,O_L^{\ell\ell'} + \mathcal{K}_R^{U\ell\ell'}\,O_R^{\ell\ell'} + \ldots\right) + \text{h.c.}\,,$$

$O^{\ell\ell'}_{\mathrm{L\,(R)}} = \left(\bar{u}_{L\,(R)}\gamma_\mu c_{L\,(R)}\right)\left(\bar{\ell}'_L\gamma^\mu \ell_L\right)$, Further operators non-connected

- Dineutrino BR is obtained via an incoherent neutrino flavor sum:

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) = \sum_{i,j}\mathcal{B}\,(c \to u\,\nu_i\bar{\nu}_j) \to x = \sum_{i,j}\left(|\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2\right)$$

Is it possible to translate x in terms of $\mathcal{K}$? ($\mathcal{C}$ and $\mathcal{K}$ in the mass basis)

Correlate neutrinos and charged leptons with SU(2)

1. **$SU(2)_L \times U(1)_Y$–invariant effective theory:**[3]

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

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

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

3. **$C_R^{U,D} = K_R^{U,D}$ holds model independently! But, $C_L^{U,D} = K_L^{D,U}$!**
4. In terms of mass eigenstates, $Q_\alpha = (u_{L\alpha}, V_{\alpha\beta}\, d_{L\beta})$, $L_i = (\nu_{Li}, W^*_{ki}\,\ell_{Lk})$

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

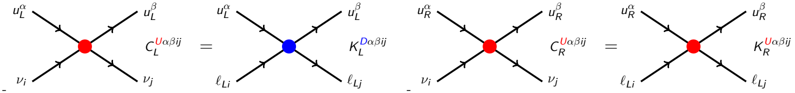
[3] 1008.4884

Connection via "trace identities" in the mass basis

$$\mathcal{B} \propto \sum_{\nu=i,j} \left(|\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2 \right) = \mathrm{Tr}\left[\mathcal{C}_L^U \, \mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U \, \mathcal{C}_R^{U\dagger} \right]$$

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

1. **SU(2) relates up, down, neutrinos and charged leptons.**



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

3. **Unitarity $WW^\dagger = W^\dagger W = I$**

$c \to u \ell\ell$ ⟶ $c \to u \nu\bar{\nu}$ ⟵ $d \to s \ell\ell$

Independent of PMNS matrix and subleading $\mathcal{O}(\lambda)$ corrections!
We can predict dineutrino rates for different leptonic flavor structures $\mathcal{K}_{L,R}^{ij}$, that can be probed with lepton-specific measurements!

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

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

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

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

$$\begin{pmatrix} k_{11} & 0 & 0 \\ 0 & k_{22} & 0 \\ 0 & 0 & k_{33} \end{pmatrix}$$

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

$$\begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix}$$

Upper limits on dineutrino modes can probe lepton unversality!

- **Bounds on lepton specific WCs for $\ell, \ell' = e, \mu, \tau$.**[4]

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

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

$$x = 3\, R^{\mu\mu} \lesssim 18\,, \quad \textbf{(Lepton Universality)}$$

$$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} \lesssim 103\,, \quad \textbf{(charged Lepton Flavor Conservation)}$$

$$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} + 2\left(R^{e\mu} + R^{e\tau} + R^{\mu\tau}\right) \lesssim 375.$$

LU is fixed by the most stringent bound (muons).

[4] 2003.12421, 2002.05684

Dineutrino branching ratios upper limits

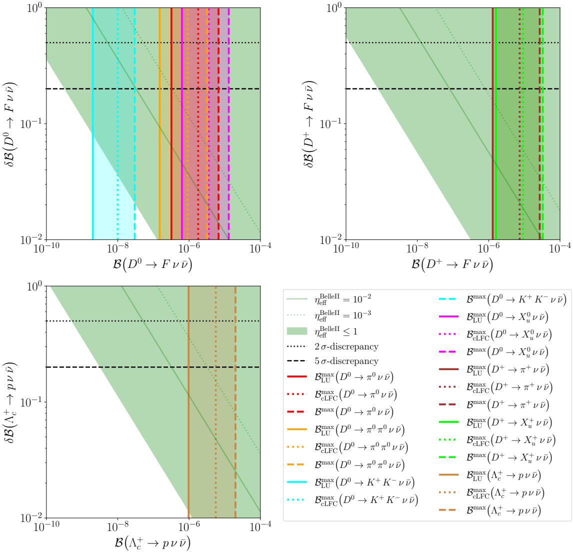
$$\mathcal{B}(h_c \to F\,\nu\bar{\nu}) = A_+^{h_c F}\, x_+ + A_-^{h_c F}\, x_-\,, \quad x_\pm = \sum_{i,j} |\mathcal{C}_L^{Uij} \pm \mathcal{C}_R^{Uij}|^2 < 2\,x\,.$$

$N_i = \eta_{\text{eff}}\,\mathcal{B}_i\,N(h_c)$, $N(c\bar{c})_{\text{Belle II}} = 65 \cdot 10^9$, luminosity $50\,\text{ab}^{-1}$

$h_c \to F$	$\mathcal{B}_{\text{LU}}^{\text{max}}$ $[10^{-7}]$	$\mathcal{B}_{\text{cLFC}}^{\text{max}}$ $[10^{-7}]$	$\mathcal{B}^{\text{max}}$ $[10^{-7}]$	$N_{\text{LU}}^{\text{Belle II}}/\eta_{\text{eff}}$ $[10^5]$	$N_{\text{cLFC}}^{\text{Belle II}}/\eta_{\text{eff}}$ $[10^5]$	$N_{\text{max}}^{\text{Belle II}}/\eta_{\text{eff}}$ $[10^5]$
$D^0 \to \pi^0$	3.2	18	67	0.3	1.4	5.4
$D^+ \to \pi^+$	13	74	270	0.4	2.2	8.1
$D_s^+ \to K^+$	2.4	14	50	0.02	0.1	0.5
$D^0 \to \pi^0\pi^0$	1.5	9	32	0.1	0.7	2.6
$D^0 \to \pi^+\pi^-$	1.5	9	31	0.1	0.7	2.5
$D^0 \to K^+K^-$	0.02	0.1	0.3	0.002	0.008	0.024
$\Lambda_c^+ \to p^+$	9.7	56	200	0.08	0.4	1.6
$\Xi_c^+ \to \Sigma^+$	19	110	400	0.2	0.9	3.2
$D^0 \to X_u$	6.3	36	130	0.5	2.9	10.4
$D^+ \to X_u$	16	92	330	0.5	2.8	9.9
$D_s^+ \to X_u$	7.7	44	160	0.08	0.4	1.6

$\delta\mathcal{B}$ vs $\mathcal{B}$: exp. projections and theo. predictions

Preliminary



Final remarks

- $c \to u\,\nu\bar{\nu}$ modes are well-suited for e^+e^-–colliders.
- Based on the current experimental sensitivities:

  Any signal would be a clear sign of NP!

- Novel idea: $\boxed{c \to u\,\ell\ell} \longrightarrow \boxed{c \to u\,\nu\bar{\nu}} \longleftarrow \boxed{d \to s\,\ell\ell}$

  $SU(2)_L$–links between charged leptons and neutrinos!

  Allow to probe lepton flavor in two benchmarks: cLFC and LU!

  Upper limits for different modes!

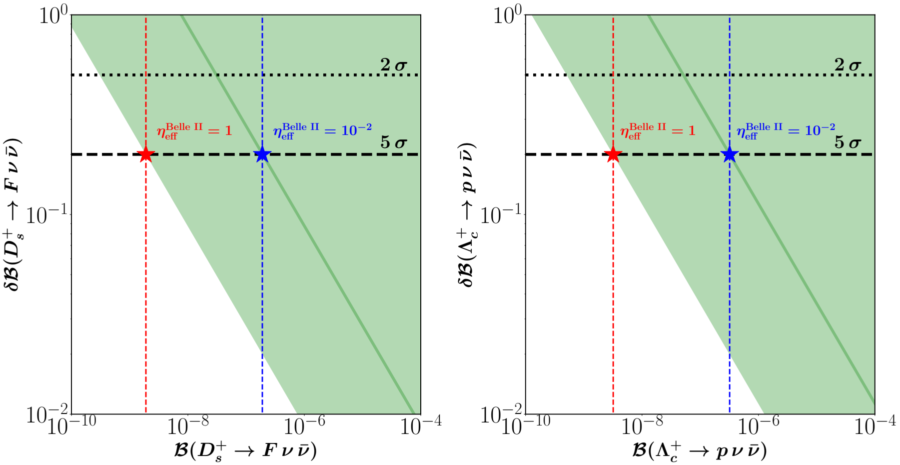
- The experimental study of these modes could shed some light on the leptonic flavor structure (persistent in B-decays)!

  $\boxed{c \to u\,\ell\ell} \longleftarrow \boxed{c \to u\,\nu\bar{\nu}} \longrightarrow \boxed{d \to s\,\ell\ell}$

Thank you for your attention!

BACKUP

Experimental projections for D_s^+ and Λ_c^+



- $\mathcal{B}^{5\,\sigma}_{\text{Belle II}}(D_s^+ \to F\nu\bar\nu) \approx 1.9 \cdot 10^{-9}$ and $1.9 \cdot 10^{-7}$!
- $\mathcal{B}^{5\,\sigma}_{\text{Belle II}}(\Lambda_c^+ \to p\nu\bar\nu) \approx 3.2 \cdot 10^{-9}$ and $3.2 \cdot 10^{-7}$!

Correlations between different dineutrino modes

- The **excellent complementarity between different dineutrino modes** provides a **formidable environment for NP searches!**

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

- **Correlations test the completeness of EFT:**

$$\boxed{\mathcal{B}(h_c \to F\,\nu\,\bar{\nu}) \;=\; r_+^{h_c F}\,\mathcal{B}(D \to P\nu\bar{\nu}) + r_-^{h_c F}\,\mathcal{B}(D' \to P_1\,P_2\,\nu\,\bar{\nu})}$$

where $r_+^{h_c F} = A_+^{h_c F}/A_+^{DP}$ and $r_-^{h_c F} = A_-^{h_c F}/A_-^{DP_1P_2}$.

- **$x^{\pm}$–independent! Model independent correlations!**
- **All dineutrino BRs from two experimental measurements.**
- **Measurements of *a priori* disconnected modes could provide hints on missing information in the EFT,** *i.e.* light fields.