Charm opportunities for FCC-ee Tera-Z: *Rare charm dineutrino modes* $c \to u\,\nu\bar{\nu}$

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FCC-ee physics zoom meeting

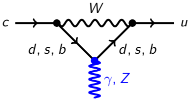
Charm physics is exceptional

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

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



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

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

BRs ($A_{\rm CP}$) 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]
- Not much experimental information available

$$\mathcal{B}(D^0 \to \nu\bar{\nu}) < 9.4 \cdot 10^{-5} \text{ at } 90\,\% \text{ C.L. (Belle, 1611.09455)}\,.$$

- Any observation would cleanly signal NP!
- Well-suited for e^+e^-–colliders: **Belle II** and future **FCC-ee**.
- Specially, FCC-ee running at the Z ($\mathcal{B}(Z \to c\bar{c}) \simeq 0.12$)[3]

Details:

- $f(c \to h_c)$, 1509.01061
- $N(c\bar{c})_{\text{FCC-ee}} = 800 \cdot 10^9$
  $N(c\bar{c})_{\text{Belle II}} = 65 \cdot 10^9$, Abada:2019lih
- $N(h_c) = 2\,f(c \to h_c)\,N(c\bar{c})$

h_c	$f(c \to h_c)$	$N(h_c)_{\text{FCC-ee}}$	$N(h_c)_{\text{Belle II}}$
D^0	0.59	$9 \cdot 10^{11}$	$8 \cdot 10^{10}$
D^+	0.24	$4 \cdot 10^{11}$	$3 \cdot 10^{10}$
D_s^+	0.10	$2 \cdot 10^{11}$	$1 \cdot 10^{10}$
Λ_c^+	0.06	$1 \cdot 10^{11}$	$8 \cdot 10^9$

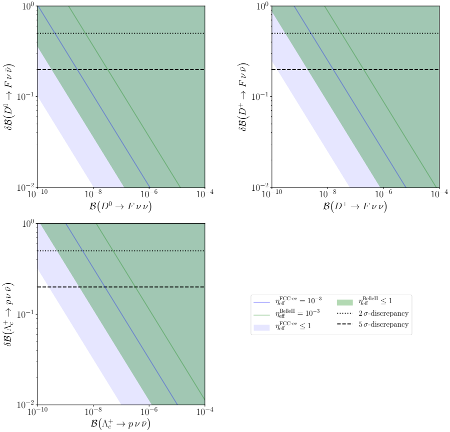
2 hep-ph/0112235, 0908.1174

3 PDG

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',...



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

Any chance to extract model independent bounds?

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

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

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

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

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

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

$O^{\ell\ell'}_{\mathrm{L\,(R)}} = (\bar{u}_{L\,(R)}\gamma_\mu c_{L\,(R)})\,(\bar{\ell}'_L\gamma^\mu\ell_L)$, 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)

From gauge basis to mass basis ...

1. **SU(2)$_L$ × U(1)$_Y$–invariant effective theory:**[4]

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

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

$$C^U_L = K^D_L = C^{(1)}_{\ell q} + C^{(3)}_{\ell q}\,, \qquad C^U_R = K^U_R = C_{\ell u}\,,$$
$$C^D_L = K^U_L = C^{(1)}_{\ell q} - C^{(3)}_{\ell q}\,, \qquad C^D_R = K^D_R = C_{\ell d}\,.$$

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

$$\mathcal{C}^U_L = W^\dagger\,\mathcal{K}^D_L\,W + \mathcal{O}(\lambda), \qquad \mathcal{C}^U_R = W^\dagger\,\mathcal{K}^U_R\,W\,,$$

[4] 1008.4884

Connection via "trace identities" in the mass basis

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

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

1. **Trace identity:** $\boxed{\mathrm{Tr}(A\,A^\dagger) = \sum_{ij} |A_{ij}|^2}$
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 $WW^\dagger = W^\dagger W = I$**

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

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.**

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

Dileptonic bounds from high-p_T data

- **High-p_T bounds** provide **a unified framework** for all lepton flavors.
- **Avoid cancellations** between WCs with **different chiralities and CP-phases**.
- **Bounds on lepton specific WCs for $\ell, \ell' = e, \mu, \tau$.**[5]

	$\lvert\mathcal{K}_A^{P\ell\ell'}\rvert$	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	1.8	5.0	5.3
$c \to u$	$\lvert\mathcal{K}_R^{U\ell\ell'}\rvert$	2.9	1.6	5.6	1.5	4.2	4.3

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

$$x = 3\, R^{\mu\mu} \lesssim 18\,, \quad \text{(LU)}$$

$$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} \lesssim 103\,, \quad \text{(cLFC)}$$

$$x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} + 2\,(R^{e\mu} + R^{e\tau} + R^{\mu\tau}) \lesssim 294.$$

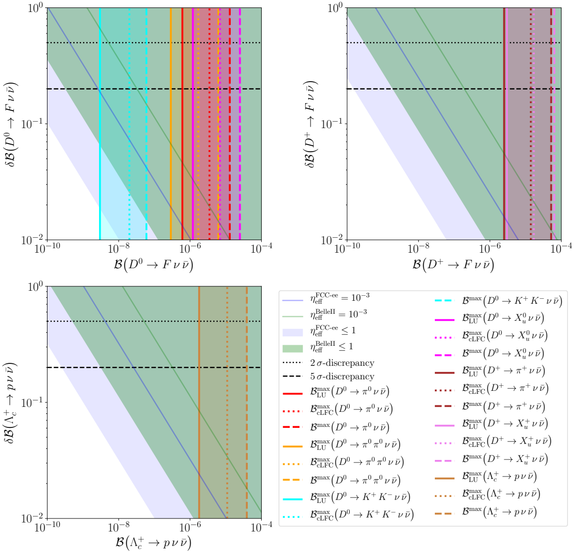
Branching ratios upper limits

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

$h_c \to F$	$\mathcal{B}^{\rm max}_{\rm LU}$ $[10^{-7}]$	$\mathcal{B}^{\rm max}_{\rm cLFC}$ $[10^{-7}]$	$\mathcal{B}^{\rm max}$ $[10^{-7}]$	$\mathcal{B}^{5\,\sigma}_{\text{Belle II}}\,[10^{-7}]$ $\eta_{\rm eff} = 10^{-3}$	$\mathcal{B}^{5\,\sigma}_{\text{FCC-ee}}\,[10^{-7}]$ $\eta_{\rm eff} = 10^{-3}$
$D^0 \to \pi^0$	3.2	18	52	3.3	0.3
$D^+ \to \pi^+$	13	74	210	8.0	0.7
$D_s^+ \to K^+$	2.4	14	39	19	1.6
$D^0 \to \pi^0\pi^0$	1.5	9	25	3.3	0.3
$D^0 \to \pi^+\pi^-$	1.5	9	24	3.3	0.3
$D^0 \to K^+K^-$	0.02	0.1	0.3	3.3	0.3
$\Lambda_c^+ \to p^+$	9.7	56	160	32	2.6
$\Xi_c^+ \to \Sigma^+$	19	110	310	32	2.6
$D^0 \to X_u$	6.3	36	100	3.3	0.3
$D^+ \to X_u$	16	92	260	8.0	0.7
$D_s^+ \to X_u$	7.7	44	130	19	1.6

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

Preliminary



Final remarks

- Charm physics is the only way to explore FCNCs in up-sector!
- Efficient GIM mechanism leads to very suppressed BRs in SM!
- $c \to u\,\nu\bar{\nu}$ 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: $c \to u\,\ell\ell$ $\longrightarrow$ $c \to u\,\nu\bar{\nu}$ $\longleftarrow$ $d \to s\,\ell\ell$

  $SU(2)_L$–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)!

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

Thank you for your attention!

BACKUP

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.