Rare charm decays to invisibles

based on works with Rigo Bause, Marcel Golz and Hector Gisbert, 2007.05001 [hep-ph], 2010.02225 [hep-ph]

Gudrun Hiller, TU Dortmund Supported in part by the Federal Ministry for Education and Research (BMBF)

... because, we can:

– sizable SM branching ratios within $10^{-7} - 10^{-6}$ (semileptonic $c \to ull$), and $10^{-6} - 10^{-4}$ (radiative $c \to u\gamma$)

– plenty of BSM opportunities (this talk and talk by Marcel Golz)

– in fact, its already happening LHCb'17,18,21 $D \to \pi\pi\mu\mu$, Belle'16$D \to \rho\gamma$, BES III '18 $D \to \pi\pi ee$

AND its a unique probe of up-sector physics:

1) leaving no stone unturned (BSM searches)

2) complementarity (w.r.t. K,B) (flavor origins)

pursue general flavor physics $, t, b, c, s, ...,$ exploit correlations

BSM opportunities with $|\Delta c| = |\Delta u| = 1$ studies

In view of the hadronic backgrounds in rare charm decays, the name of the game in flavor/BSM probes is ”null tests”, based on (approximate) symmetries of the SM, or optimized observables with reduced SM uncertainties:

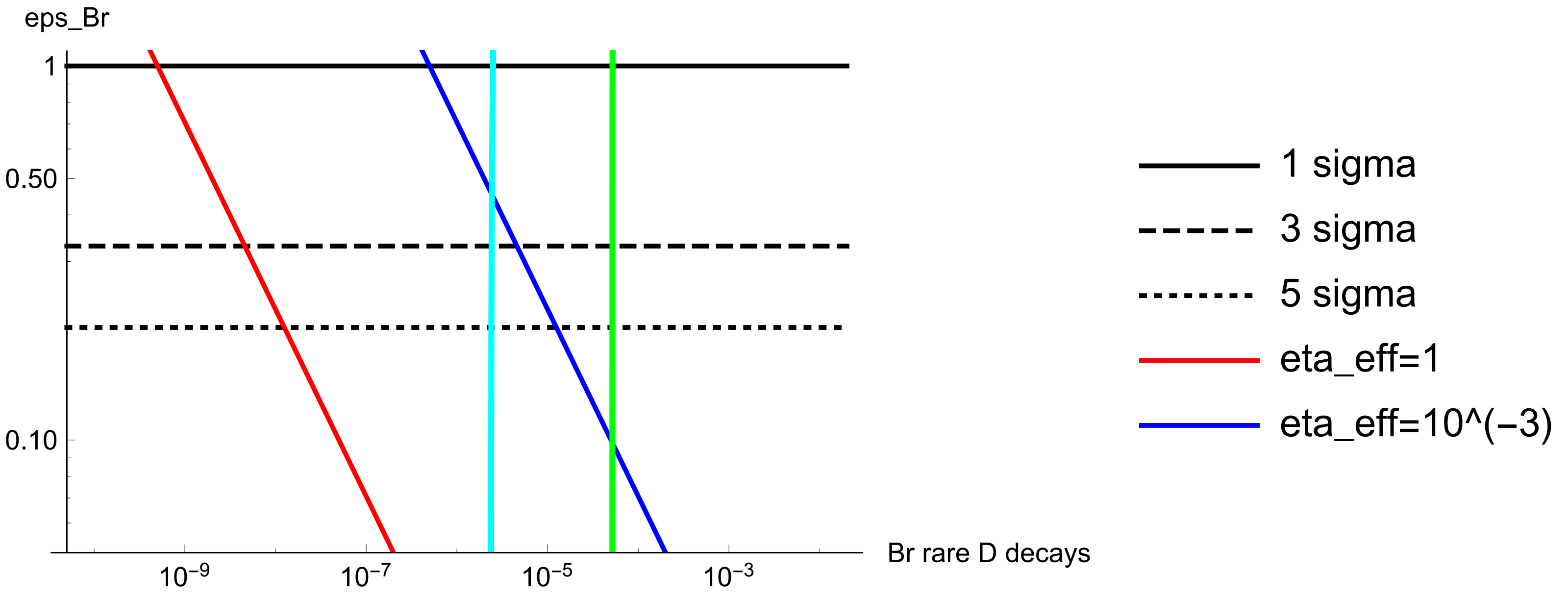
lepton-universality, lepton flavor conservation, CP, polarization studies, data-driven SM estimations, angular distributions

Procedure very well-known in state-of-the -art b-physics studies; essential in pursuit of beauty-anomalies, e.g., R_K, P_5'.

Charm FCNCs are in addition subject to a superb GIM-suppression, implying that $c \to u\nu\bar{\nu}$ modes this talk and contributions to $c \to u\ell^+\ell^-$ with axial-vector lepton-currents ”$C_{10}^{(\prime)}$” see talk by Marcel Golz vanish in SM.

Testing the SM AND lepton universality with $c \to u\nu\bar{\nu}$

What can you do with $2 \cdot 10^9$ D-mesons:



Sensitivity $\epsilon(Br) \simeq 1/\sqrt{N(h_c)Br(h_c \to F\nu\bar{\nu})\eta_{eff}}$ for reconstruction efficiency η_{eff}

limits from data + theory/SMEFT 2010.02225; $Br(D^+ \to \pi^+\nu\bar{\nu})^{\rm SM} \simeq 0$

Green: $Br(D^+ \to \pi^+\nu\bar{\nu})^{\rm EFTmax} \simeq 5.2 \cdot 10^{-5}$

Cyan: $Br(D^+ \to \pi^+\nu\bar{\nu})^{\rm LUmax} \simeq 2.5 \cdot 10^{-6}$assuming lepton universality

sample existing $|\Delta c| = |\Delta u| = 1$ studies

radiative decays, example $D^0 \to \rho^0\gamma$, $Br = (1.77 \pm 0.31) \cdot 10^{-5}$. Belle '16: $943 fb^{-1}$: 500 ± 85 events measures the direct CP-asymmetry with $\delta A_{CP} = 16\,\%$;

semileptonic decays, example $D^0 \to \pi^+\pi^-\mu^+\mu^-$, $Br \sim 9.6 \cdot 10^{-7}$. LHCb '18: $5 fb^{-1}$: 1083 ± 41 events measures angular observables with $\delta A_{CP} = 3.7\,\%$;

missing energy – only single search in PDG: $D^0 \to$ nothing, $Br < 9.4 \cdot 10^{-5}$ @ 90% CL UL. Belle'16: $924 fb^{-1}$:

LHCb excellent at $c \to u\mu^+\mu^-$ precision studies.

missing energy, π^0, photon, τ and e(?) final states advantageous w.r.t hadronic collider territory

Upper limits on $c \to u\nu\bar{\nu}$ from data+theory

$h_c \to F\nu\bar{\nu}$	$\mathcal{B}^{\text{max}}_{\text{LU}}$ $[10^{-7}]$	$\mathcal{B}^{\text{max}}_{\text{cLFC}}$ $[10^{-6}]$	$\mathcal{B}^{\text{max}}$ $[10^{-6}]$	$N^{\text{max}}_{\text{LU}}/\eta_{\text{eff}}$	$N^{\text{max}}_{\text{cLFC}}/\eta_{\text{eff}}$	$N^{\text{max}}/\eta_{\text{eff}}$
$D^0 \to \pi^0$	6.1	3.5	13	47 k (395 k)	270 k (2.3 M)	980 k (8.3 M)
$D^+ \to \pi^+$	25	14	52	77 k (650 k)	440 k (3.7 M)	1.6 M (14 M)
$D_s^+ \to K^+$	4.6	2.6	9.6	6 k (50 k)	34 k (290 k)	120 k (1.1 M)
$D^0 \to \pi^0\pi^0$	1.5	0.8	3.1	11 k (95 k)	64 k (540 k)	230 k (2.0 M)
$D^0 \to \pi^+\pi^-$	2.8	1.6	5.9	22 k (180 k)	120 k (1.0 M)	450 k (3.8 M)
$D^0 \to K^+K^-$	0.03	0.02	0.06	0.2 k (1.9 k)	1.3 k (11 k)	4.8 k (40 k)
$\Lambda_c^+ \to p^+$	18	11	39	14 k (120 k)	82 k (700 k)	300 k (2.6 M)
$\Xi_c^+ \to \Sigma^+$	36	21	76	28 k (240 k)	160 k (1.4 M)	590 k (5.0 M)
$D^0 \to X$	15	8.7	32	120 k (980 k)	660 k (5.6 M)	2.4 M (21 M)
$D^+ \to X$	38	22	80	120 k (1.0 M)	680 k (5.8 M)	2.5 M (21 M)
$D_s^+ \to X$	18	10	38	24 k (200 k)	140 k (1.1 M)	500 k (4.2 M)

Table 1: Upper limits on branching ratios and expected number of events $N_F^{\text{exp}} = \eta_{\text{eff}}\, N(h_c)\, \mathcal{B}(h_c \to F\,\nu\,\bar{\nu})$ per reconstruction efficiency η_{eff} for Belle II with $50\,\text{ab}^{-1}$ (FCC-ee in parentheses) corresponding to LU, cLFC, and general. from 2010.02225

Testing lepton universality and charged lepton flavor conservation with dineutrino* modes

method complementary to lepton-flavor specific tests a la R_K

concrete model-independent proposal 2007.05001 [hep-ph]
application to beauty 2109.01675 [hep-ph]
application to charm 2010.02225 [hep-ph]

Idea: Use $SU(2)_L$-link for left-handed SM leptons $L = (\nu, \ell)$; assume only SM-like light neutrinos (crosscheck possible)

*neutrino flavors untagged!

moving ahead model-independently

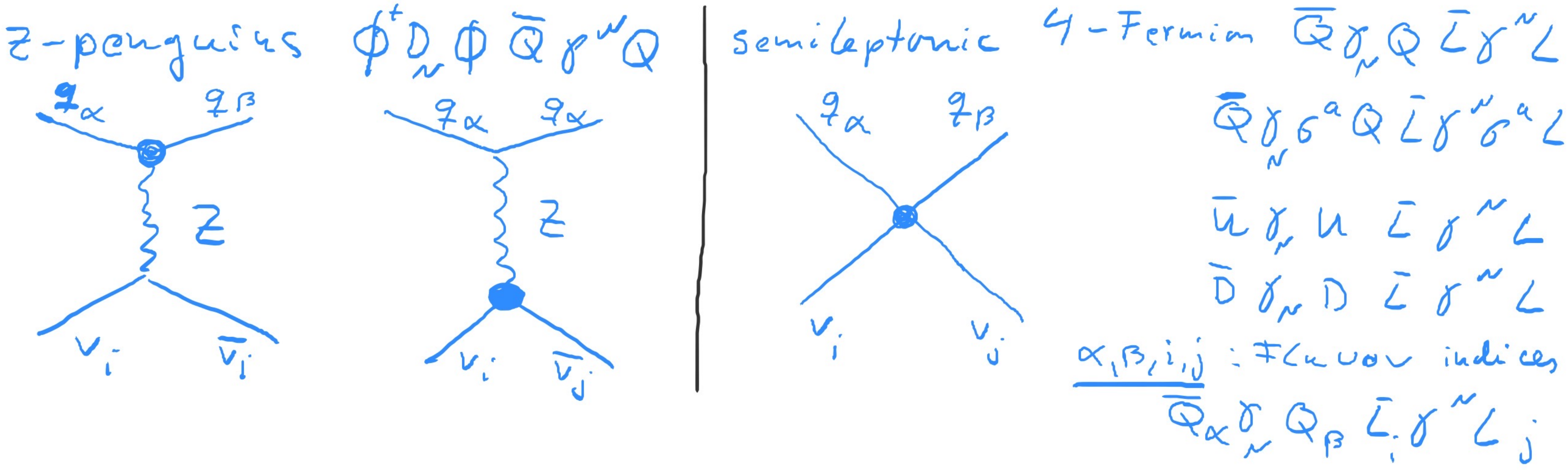
SMEFT: SM plus higher dimensional operators at scale $\Lambda \gg \Lambda_{EWK}$, consistent with Lorentz and SM-gauge symmetries $SU(3)_C \times SU(2)_L \times U(1)_Y$ made out of SM fields.

Leading terms: dim 6, Warsaw basis Misiak et al

For dineutrino modes $q \to q' \nu \bar{\nu}$ two types of contributions at tree-level:

leptonic and quark Z-penguins $\quad \Phi^\dagger D_\mu \Phi \bar{F} \gamma^\mu F, \quad F = L, Q, U, D$

semileptonic 4-fermion operators of type $\quad \bar{Q} \gamma_\mu Q \bar{L} \gamma^\mu L$



For $SU(2)_L$-doublet fermions, singlet and triplet $\sim \tau^3$ contributions

4-fermion operators: 2 lepton flavor indices i, j and 2 quark flavor indices α, β

Z-penguins strongly constrained Falkowski et al

universality tests with $q \to q'\nu\bar\nu$

Leading semileptonic 4-fermion operators at scale above m_W (SMEFT) contributing to dineutrino modes $q \to q'\nu\bar\nu$

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

$SU(2)_L \times U(1)_Y$ gauge invariance links up and down quarks, $Q = (u, d)$ and left-handed neutrinos and charged leptons $L = (\nu, \ell)$.

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

contribution to $c \to u\nu\bar\nu$ (C_L^U) identical to $s \to d\ell\bar\ell$ (K_L^D) etc

L,R denotes left or right handed quark currents; only SM-like light neutrinos.

Since the neutrino flavors are not tagged, the branching ratio, say for charm, is obtained by an incoherent sum

$$\mathcal{B}\left(c \to u\, \nu\bar{\nu}\right) = \sum_{i,j} \mathcal{B}\left(c \to u\, \nu_i \bar{\nu}_j\right)$$

in terms of Wilson coefficients

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

which can be written as a trace

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto \sum_{i,j} |\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2 = tr\Big[\mathcal{C}_L^U\,\mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U\,\mathcal{C}_R^{U\dagger}\Big]$$

and apparently PMNS rotations W between gauge and mass eigenstates (calligraphic) drop out due to unitarity.

Using SMEFT $SU(2)_L \times U(1)_Y$ gauge invariance follows

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

universality tests with $q \to q' \nu \bar{\nu}$

$$\underbrace{\mathcal{B}\,(c \to u\,\nu\bar{\nu})}_{\text{dineutrino process}} \propto \sum_{\nu=i,j} \left(|\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2 \right) = tr\left[\mathcal{C}_L^U\,\mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U\,\mathcal{C}_R^{U\dagger} \right]$$

$$= tr\left[\mathcal{K}_L^D \mathcal{K}_L^{D\dagger} + \mathcal{K}_R^U \mathcal{K}_R^{U\dagger} \right] + \mathcal{O}(\lambda) = \underbrace{\sum_{\ell=i,j} \left(|\mathcal{K}_L^{Dij}|^2 + |\mathcal{K}_R^{Uij}|^2 \right)}_{\text{charged dilepton couplings}} + \mathcal{O}(\lambda)\,,$$

$\mathcal{K}_L^{Dij}$: coeffs for mass eigenstate charged leptons in $s \to d\ell^{i+}\ell^{j-}$
$\mathcal{K}_R^{Uij}$: coeffs mass eigenstates charged leptons in $c \to u\ell^{i+}\ell^{j-}$

lhs: observable dineutrino branching ratio

rhs: couplings to charged leptons/Wilson coefficients

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto \sum_{\ell=i,j} \left(\left|\mathcal{K}_L^{Dij}\right|^2 + \left|\mathcal{K}_R^{Uij}\right|^2 \right) + \mathcal{O}(\lambda)\;,$$

We obtain upper limits on dineutrino branching ratios from upper limits of charged dilepton modes 2007.05001 depending on scenarios

i) $\mathcal{K}^{ij}_{L,R} \propto \delta_{ij}$, that is, *lepton-universality* (LU).

ii) $\mathcal{K}^{ij}_{L,R}$ are diagonal, that is, *charged lepton flavor conservation* (cLFC).

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

universality tests with $q \to q'\nu\bar{\nu}$, quantitatively

		ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
sd	$\lvert\bar{\mathcal{K}}_{L,R}^{D\ell\ell'}\rvert$	3.5	1.9	6.7	2.0	6.1	6.6
cu	$\lvert\bar{\mathcal{K}}_{L,R}^{U\ell\ell'}\rvert$	2.9	1.6	5.6	1.6	4.7	5.1
bd	$\lvert\bar{\mathcal{K}}_{L,R}^{D_{13}\ell\ell'}\rvert$	4.9	2.7	9.5	3.1	9.7	10
bs	$\lvert\bar{\mathcal{K}}_{L,R}^{D_{23}\ell\ell'}\rvert$	13	7.0	25	8.0	27	30

Upper limits on leptonic couplings $\bar{\mathcal{K}}_{L,R}$ from high–p_T Fuentes-Martin et al 2020 ,Angelescu et al 2020. The last two rows show limits on down sector couplings involving b-quarks. LFV-bounds are quoted as charge-averaged, $\sqrt{|\bar{\mathcal{K}}^{\ell^+\ell'^-}|^2 + |\bar{\mathcal{K}}^{\ell^-\ell'^+}|^2}$.

universality tests with $c \to u\nu\bar{\nu}$, quantitatively

including CKM-corrections $\mathcal{C}_L^U = W^\dagger\, \mathcal{K}_L^D\, W + \mathcal{O}(\lambda), \;\; \lambda \simeq V_{us} \sim 0.2$

$$R^{\ell\ell'} = \left|\mathcal{K}_L^{D_{12}\ell\ell'}\right|^2 + \left|\mathcal{K}_R^{U_{12}\ell\ell'}\right|^2, \qquad R_\pm^{\ell\ell'} = \left|\mathcal{K}_L^{D_{12}\ell\ell'} \pm \mathcal{K}_R^{U_{12}\ell\ell'}\right|^2, \qquad R_\pm^{\ell\ell'} \leq 2\, R^{\ell\ell'}$$

$$\delta R^{\ell\ell'} = 2\,\lambda\, \Re(\mathcal{K}_L^{D_{12}\ell\ell'}\, \mathcal{K}_L^{D_{22}\ell\ell'^*} - \mathcal{K}_L^{D_{12}\ell\ell'} \mathcal{K}_L^{D_{11}\ell\ell'^*}) < 2\,\lambda \left|\mathcal{K}_L^{D_{12}\ell\ell'}\right| \left(\left|\mathcal{K}_L^{D_{22}\ell\ell'}\right| + \left|\mathcal{K}_L^{D_{11}\ell\ell'}\right|\right)$$

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto 3\,R^{\mu\mu} \lesssim 34\,, \quad (\text{LU}) \tag{2}$$

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto R^{ee} + R^{\mu\mu} + R^{\tau\tau} \lesssim 196\,, \quad (\text{cLFC}) \tag{3}$$

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto R^{ee} + R^{\mu\mu} + R^{\tau\tau} + 2(R^{e\mu} + R^{e\tau} + R^{\mu\tau}) \lesssim 716. \tag{4}$$

dimuons have the most stringent bounds and provide the LU-limit.

Lepton flavor limit is violated if measured branching ratio is too large!

Upper limits data-driven, and evolve with charged lepton data.

Cross checking: $D \to$ nothing

$\mathcal{B}(D^0 \to \text{inv.}) < 9.4 \cdot 10^{-5}$, at 90 $\%$ CL. (Belle '16). Consistency check; constrains operators with light right-handed neutrinos

$$Q^{ij}_{LR} = (\bar{u}_L \gamma_\mu c_L)\,(\bar{\nu}_{jR} \gamma^\mu \nu_{iR})\,, \quad Q^{ij}_{RR} = (\bar{u}_R \gamma_\mu c_R)\,(\bar{\nu}_{jR} \gamma^\mu \nu_{iR})\,,$$
$$Q^{ij}_{S(P)} = (\bar{u}_L c_R)\,(\bar{\nu}_j\,(\gamma_5)\,\nu_i)\,, \quad Q^{ij}_{T(T5)} = \frac{1}{2}(\bar{u}\,\sigma_{\mu\nu}\,c)\,(\bar{\nu}_j\,\sigma^{\mu\nu}\,(\gamma_5)\,\nu_i)\,,$$

$Q^{ij}_{S(P)}$ would have effect less than $\sim 10\%$ of LU upper limits iff improved limit exists

$$\mathcal{B}(D^0 \to \text{inv.}) \lesssim 2 \cdot 10^{-6}\,. \qquad (5)$$

would reinforce framework.

Bounding Lepton Number Violation

The final state $D \to$ *nothing* could be two neutrinos, $D \to \nu\nu$, allowing to probe LNV in $\Delta L = 2$ transitions.

Lowest order operator $\mathcal{O}_{4a}^{(7)} = L_i^{\alpha} \, L_j^{\beta} \, \bar{Q}_{\alpha}^{b} \, \bar{U}_a^{c} \, H^{\rho} \, \epsilon_{\beta\rho}$, de Gouvea

Existing Belle limit on $D \to$nothing probes LNV effects $\Lambda_{\rm LNV}^{ij} \gtrsim 1.5$ TeV .

New ideas for LU and cLFC tests with dineutrino modes suitable for Belle II, BES III, Z-factory and STCF.

Great opportunity for rare charm decays:

- No exp search on any semileptonic $c \to u\nu\bar{\nu}$ mode to date!
- many modes: $D \to \pi$, $D \to \pi\pi$,$\Lambda_c \to p$, $\Xi_c \to \Sigma$... all SM nulltests
- model-independent upper limits sizable $10^{-6} - 10^{-5}$
  If in excess of $\sim 1/3$: charged lepton flavor is violated
  If in excess of $\sim 1/20$: lepton universality is broken
- Improved $D^0 \to$ *nothing* probes light right-handed neutrinos;
  Lepton number violation also testable, presently $\Lambda^{ij}_{\text{LNV}} \gtrsim 1.5$ TeV .

BACK UP

h_c	$f(c \to h_c)$	$N(h_c)$ (a)	$N(h_c)$ (b)
D^0	0.59	$6 \cdot 10^{11}$	$8 \cdot 10^{10}$
D^+	0.24	$3 \cdot 10^{11}$	$3 \cdot 10^{10}$
D_s^+	0.10	$1 \cdot 10^{11}$	$1 \cdot 10^{10}$
Λ_c^+	0.06	$7 \cdot 10^{10}$	$8 \cdot 10^{9}$

Table 2: Charm fragmentation fractions $f(c \to h_c)$ and the number of charmed hadrons h_c, $N(h_c)$, expected at benchmarks with $N(c\bar{c}) = 550 \cdot 10^9$ (a, FCC-ee) and $N(c\bar{c}) = 65 \cdot 10^9$ (b, Belle II with $50\,\text{ab}^{-1}$). In absence of further information for the Ξ_c^+ we use $f(c \to \Xi_c^+) \simeq f(c \to \Lambda_c^+)$.

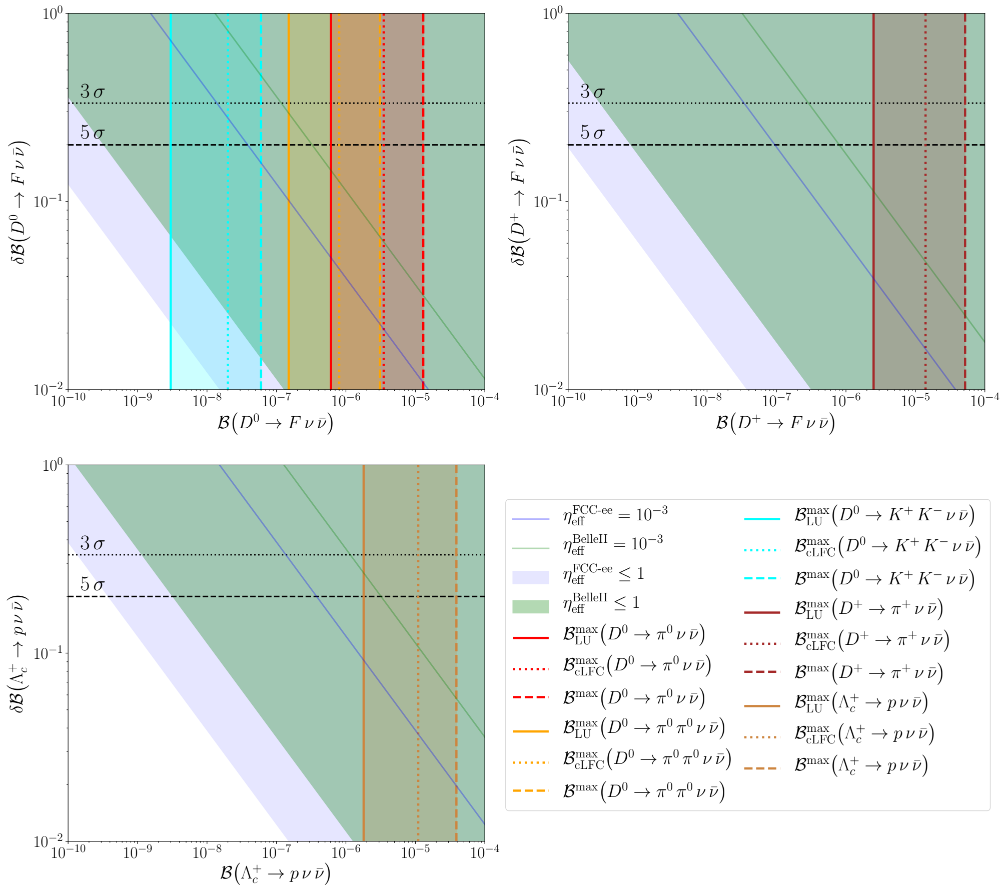


Figure 1: Relative statistical uncertainty $\delta\mathcal{B}$ versus branching ratio $\mathcal{B}$ for decays of the D^0 (upper left), the D^+ (upper right) and the Λ_c^+ (lower plot). Shaded areas correspond to $\eta_{\text{eff}} = 1$, whereas the solid tilted lines illustrate the impact of reconstruction efficiencies $\eta_{\text{eff}} = 10^{-3}$ for the FCC-ee (lilac) and Belle II (green). Horizontal lines indicate $3\,\sigma$ (dotted) and $5\,\sigma$ (dashed) black. Vertical lines represent upper limits assuming LU (solid), cLFC (dotted) and generic lepton flavor (dashed) for different decays.