Opportunities in rare charm decays @ Belle II

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Anomalies and Precision in the Belle II Era

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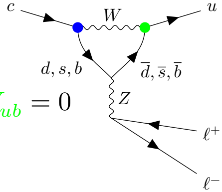
Motivation

Why rare charm decays?

- Flavour-Changing-Neutral-Currents (FCNCs) only allowed at loop-level in SM
  - NP contributions possibly sizable
- Unique opportunity to probe FCNCs for up-type quarks inside hadrons
- Special features of charm: Stronger GIM suppression than K and B-physics
- Much less done than in experiment and theory
- Resonance contributions dominate over short-distance contributions
  - Focus on null test observables

$$V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0$$



$$\mathcal{A}(c \to u) \propto \frac{1}{16\pi^2} V_{cs}^* V_{us} \left(f\left(\frac{m_s^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right) + \frac{1}{16\pi^2} \underbrace{V_{cb}^* V_{ub}}_{\mathcal{O}(\lambda^5)} \left(f\left(\frac{m_b^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right)$$

Progress in $c \to u\mu^+\mu^-$

- SM+NP description with EFT ansatz

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\sum_i \mathcal{C}_i(\mu)\;\mathcal{O}_i(\mu) \qquad \text{e.g.} \quad \mathcal{O}_{10}^{(\prime)} = (\bar{u}_{L(R)}\,\gamma_\mu\,c_{L(R)})\,(\bar{\ell}\,\gamma^\mu\,\gamma_5\,\ell)$$

- Bounds on GIM-protected Wilson coefficients

$$\mathcal{B}(D^0 \to \mu\mu) < 2.2\cdot 10^{-9} \quad \text{[CMS, 2024]} \quad \to \quad |\mathcal{C}_{10} - \mathcal{C}'_{10}| \lesssim 0.52$$

$$\mathcal{B}(D^+ \to \pi^+\mu\mu) < 6.7\cdot 10^{-8} \quad \text{[LHCb, arXiv:2011.00217]} \quad \to \quad |\mathcal{C}_{10} + \mathcal{C}'_{10}| \lesssim 0.85$$

$$\Rightarrow \quad |\mathcal{C}_{10}|\,,|\mathcal{C}'_{10}| \lesssim 0.7$$

- Bounds on scalar- & pseudoscalar Wilson coefficients

$$\mathcal{B}(D^0 \to \mu\mu) \quad \to \quad \left(|\mathcal{C}_S - \mathcal{C}'_S|^2 + |\mathcal{C}_P - \mathcal{C}'_P|^2\right)^{1/2} \lesssim 0.04$$

$$\mathcal{B}(D^+ \to \pi^+\mu\mu) \quad \to \quad \left(|\mathcal{C}_S + \mathcal{C}'_S|^2 + |\mathcal{C}_P + \mathcal{C}'_P|^2\right)^{1/2} \lesssim 0.60$$

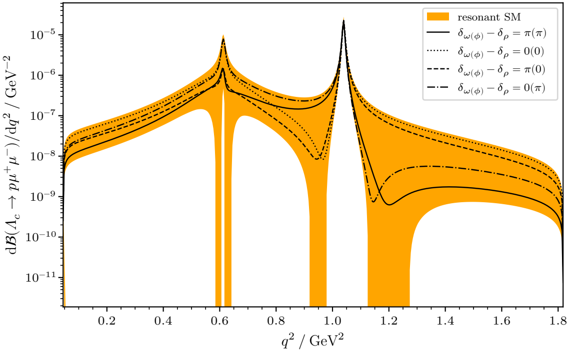
$$\Rightarrow \quad |\mathcal{C}_S|\,,|\mathcal{C}'_S|\,,|\mathcal{C}_P|\,,|\mathcal{C}'_P| \lesssim 0.4$$

- Competitive bounds on dipole coefficients (slightly stronger than from $D \to \rho\gamma$)

$$\mathcal{B}(\Lambda_c \to p\mu^+\mu^-)_{\text{low-}q^2} < 0.93\cdot 10^{-8} \quad \text{[LHCb, arXiv:2407.11474]} \quad \to \quad |\mathcal{C}_7|\,,|\mathcal{C}'_7| \lesssim 0.2$$

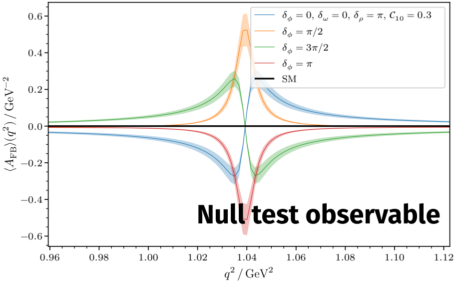
Beyond branching ratios – angular observables

- Uncertainty (orange band) dominated by strong phases
- Constrain NP above resonances in low- & high-q^2 region



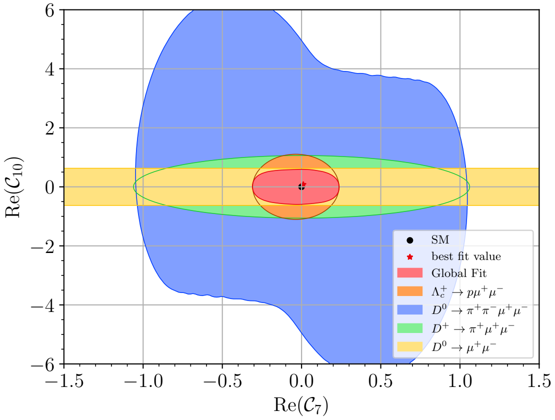
[H. Gisbert, G. Hiller, DS, arXiv:2410.00115]

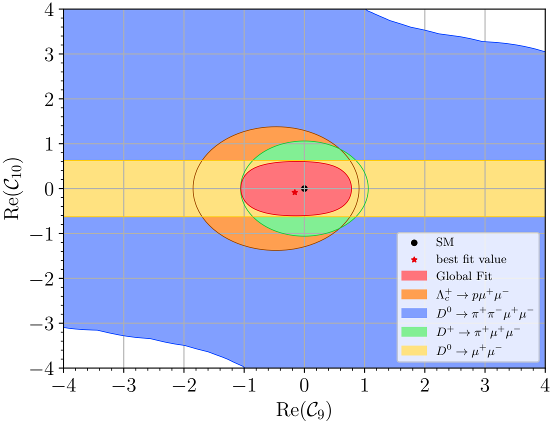
- Use angular observables with null tests
- NP signal via resonance enhanced contributions
  - Strong dependence on strong phases
  - Interpretation in terms of Wilson coefficients limits difficult (even more for $D^0 \to \pi^+\pi^-\mu^+\mu^-$)



First global $|\Delta c| = |\Delta u| = 1$ fit

Using $\mathcal{B}$ of $D^0 \to \mu^+\mu^-$, $D^+ \to \pi^+\mu^+\mu^-$, $\Lambda_c \to p\mu^+\mu^-$ and angular analysis of $D^0 \to \pi^+\pi^-\mu^+\mu^-$



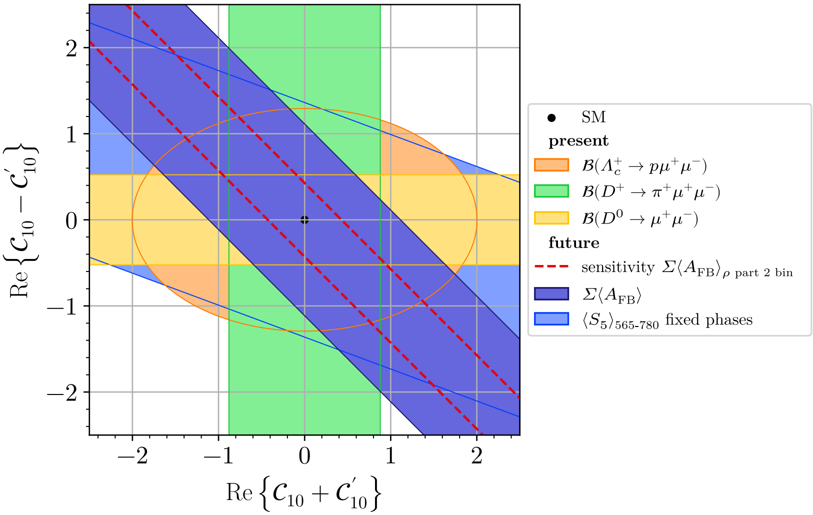


[H. Gisbert, G. Hiller, DS, arXiv:2410.00115]

- clean null tests $\langle S_{5,6,7}\rangle$ & $\langle A_{5,6,7}\rangle$ of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ due to GIM-protection ($\propto \mathcal{C}_{10}$)
- NEW First measurement of clean null test $\langle A_{\rm FB}\rangle$ in $\Lambda_c \to p\mu^+\mu^-$ [LHCb, arXiv:2502.04013]

Complementarity & Rising star $\Lambda_c \to p\mu^+\mu^-$

- all channels needed
- projection for $\langle A_{\rm FB}\rangle$ in optimized q^2-bins looks promising



[H. Gisbert, G. Hiller, DS, arXiv:2410.00115]

Status and advantages of $c \to u\nu\bar{\nu}$

- Branching ratio is clean null test because of GIM suppression $\left(\mathcal{C}^{ij}_{LL,\text{SM}} = \mathcal{C}^{ij}_{RL,\text{SM}} = 0\right)$
  - No relevant resonance pollution
  - Various NP models motivating enhanced signals in invisible modes
- Few measurements available $\to$ lots of opportunities for Belle II

$\mathcal{B}(D^0 \to invisible) < 9.4 \cdot 10^{-5}$ [Belle, arXiv:1611.09455] $\mathcal{B}(D^0 \to \pi^0\nu\bar{\nu}) < 2.1 \cdot 10^{-4}$ [BESIII, arXiv:2112.14236]

- Dedicated searches for specific NP models (massless Z' / dark photon)

$\mathcal{B}(\Lambda_c \to p\gamma') < 8.0 \cdot 10^{-5}$ [BESIII, arXiv:2208.04496]

$\mathcal{B}(D^0 \to \omega\gamma') < 1.1 \cdot 10^{-5}$ [BESIII, arXiv:2409.02578]

$\mathcal{B}(D^0 \to \gamma\gamma') < 2.0 \cdot 10^{-6}$ [BESIII, arXiv:2409.02578]

- Wishlist for the future:

$$\Lambda_c^+ \to p\nu\bar{\nu},\ D^0 \to \pi^+\pi^-\nu\bar{\nu},\ D^+ \to \pi^+\nu\bar{\nu}\ldots$$

& improvements on existing modes!

Rare charm + invisible signatures

1.) Light right-handed neutrino

2.) Light Z' decaying to dark sector

3.) Axion-like particles (ALPs)

1.) Light neutrino EFT

- Effective Hamiltonian [Bause et al., arXiv:2010.02225]

$$\mathcal{H}_{\text{eff}}^{\nu_i\bar{\nu}_j} = -\frac{4G_F}{\sqrt{2}} \sum_k C_k^{ij} \cdot Q_k^{ij} + \text{h.c.}$$

- Operators with left-handed neutrinos:

only ν_L
$$\begin{cases} Q_{LL}^{ij} & = (\bar{u}_L \gamma_\mu c_L)(\bar{\nu}_{jL} \gamma^\mu \nu_{iL}) \\ Q_{RL}^{ij} & = (\bar{u}_R \gamma_\mu c_R)(\bar{\nu}_{jL} \gamma^\mu \nu_{iL}) \end{cases}$$

- GIM & CKM suppression with no resonance pollution
  - $\mathcal{C}_{LL,\text{SM}}^{ij} = \mathcal{C}_{RL,\text{SM}}^{ij} = 0$

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- GIM & CKM suppression with no resonance pollution
  - $\mathcal{C}_{LL,\text{SM}}^{ij} = \mathcal{C}_{RL,\text{SM}}^{ij} = 0$

- Extend by light right-handed neutrinos:

$\nu_L + \nu_R$
$$\begin{cases} Q_{LR}^{ij} &= (\bar{u}_L \gamma_\mu c_L)(\bar{\nu}_{jR}\gamma^\mu \nu_{iR}) \\ Q_{RR}^{ij} &= (\bar{u}_R \gamma_\mu c_R)(\bar{\nu}_{jR}\gamma^\mu \nu_{iR}) \\ Q_{S}^{ij} &= (\bar{u}_L c_R)(\bar{\nu}_j \nu_i) \\ Q_{P}^{ij} &= (\bar{u}_L c_R)(\bar{\nu}_j \gamma_5 \nu_i) \\ Q_{S}^{\prime ij} &= (\bar{u}_R c_L)(\bar{\nu}_j \nu_i) \\ Q_{P}^{\prime ij} &= (\bar{u}_R c_L)(\bar{\nu}_j \gamma_5 \nu_i) \\ Q_{T}^{ij} &= (\bar{u}\sigma_{\mu\nu} c)(\bar{\nu}_j \sigma^{\mu\nu} \nu_i) \\ Q_{T_5}^{ij} &= (\bar{u}\sigma_{\mu\nu} c)(\bar{\nu}_j \sigma^{\mu\nu}\gamma_5 \nu_i) \end{cases}$$

- Contribution to $D^0 \to$ nothing now possible
- 3-body decay for $D^0 \to \pi^0 \nu\bar{\nu}$

Light neutrinos, light Z' & ALPs

2.) Light Z'

- Light neutral Z' vector boson from $U(1)'$ gauge group
  [Dobrescu,arXiv:hep-ph/0411004, J. Eguren et. al., arXiv:2405.00108]
- Decay dominantly to dark sector particles with mass m_χ

$$\mathcal{L}_{Z'}^{\text{eff}} \subset \frac{1}{\Lambda_{\text{eff}}} \bar{u} \left(C_D^{Z'} + \gamma_5 C_{D5}^{Z'} \right) \sigma^{\mu\nu} c \, Z'_{\mu\nu}$$
$$+ C_L^{Z'} \bar{u}_L \gamma^\mu c_L Z'_\mu + C_R^{Z'} \bar{u}_R \gamma^\mu c_R Z'_\mu + \text{h.c.}$$
$$+ C_V^{Z'\chi} \bar{\chi} \gamma^\mu \chi Z'_\mu + C_A^{Z'\chi} \bar{\chi} \gamma^\mu \gamma_5 \chi Z'_\mu$$

- 3-body decay for $D^0 \to \pi^0 Z' (\to \chi\bar{\chi})$

3.) Axion-like particles (ALPs)

- ALPs are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries
- derived from several well motivated theories
- EFT approach [Bauer et. al., arXiv:2012.12272]
- Long lifetimes give $h_c \to F +$ invisible signature

$$\mathcal{L}_{\text{ALP}}^{c\to u} = \frac{\partial^\mu a}{2f} \left(k_{12}^V \, \bar{u} \, \gamma_\mu \, c + k_{12}^A \, \bar{u} \, \gamma_\mu \gamma_5 \, c \right) + \text{h.c.}$$

- 2-body decay for $D^0 \to \pi^0 a$

$SU(2)_L$ link for left-handed neutrinos

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_d^{\infty} \sum_i \frac{\mathcal{C}_i^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_i^{(d)}$$

- Using SMEFT framework ν_ℓ and $\ell^\pm$ share $SU(2)_L$ doublet

$$L = \begin{pmatrix} \ell_L \\ \nu_{\ell\,L} \end{pmatrix}$$

- Consider new physics in

$$\mathcal{Q}_{\ell q}^{(1)} = \overline{Q}\gamma_\mu Q \overline{L}\gamma^\mu L \qquad \mathcal{Q}_{\ell q}^{(3)} = \overline{Q}\gamma_\mu \tau^a Q \overline{L}\tau^a \gamma^\mu L$$

$$\mathcal{Q}_{\ell u} = \overline{U}\gamma_\mu U \overline{L}\gamma^\mu L \qquad \mathcal{Q}_{\ell d} = \overline{D}\gamma_\mu D \overline{L}\gamma^\mu L$$

- [Bause et al., arXiv:2010.02225] Upper limits through $SU(2)_L$ link for flavour scenarios:
  - Lepton Universal (LU)
  - charged lepton flavor conserving (cLFC)
  - democratic
  - general

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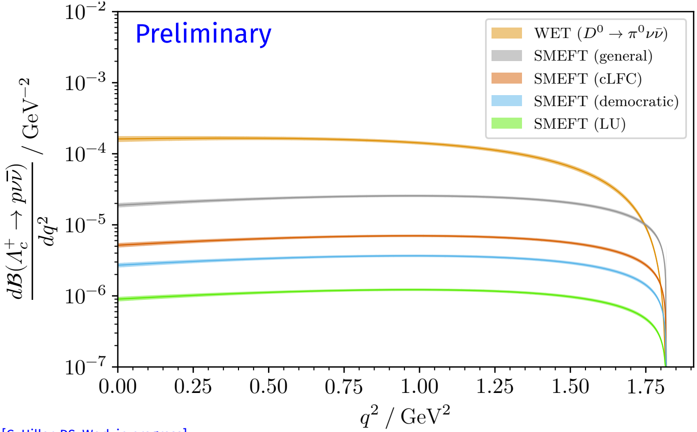
  - Lepton Universal (LU)
  - democratic
  - charged lepton flavor conserving (cLFC)
  - general
- WET EFT bound $D^0 \to \pi^0 \nu\bar{\nu}$ (some vector & axial-vector operators unconstrained)

	$\mathcal{B}_{LR+}$ $[10^{-4}]$	$\mathcal{B}_{\text{LU}}$ $[10^{-6}]$	$\mathcal{B}_{\text{democratic}}$ $[10^{-6}]$	$\mathcal{B}_{\text{cLFC}}$ $[10^{-5}]$	$\mathcal{B}_{\text{general}}$ $[10^{-5}]$
$\Lambda_c \to p\nu\bar{\nu}$	2.4	1.9	5.7	1.1	3.9

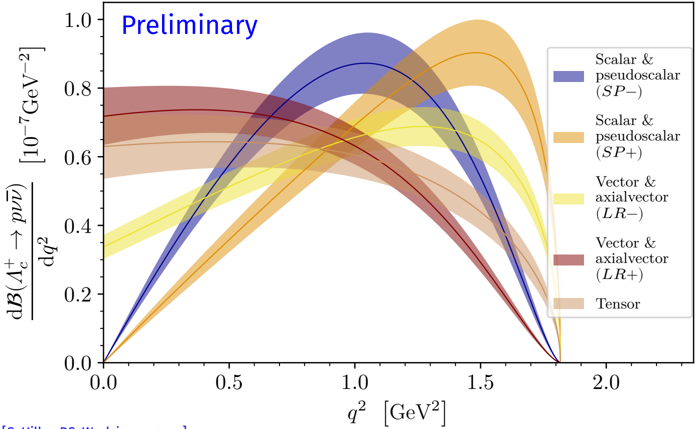


[G. Hiller, DS, Work in progress]

- direct $\nu_L + \nu_R$ EFT bound weaker than $SU(2)_L$ bounds

Shape matters – Extended neutrino EFT with ν_L and ν_R

- Different shapes for different operators (arbitrarily normalized)
- Scalar & pseudoscalar contributions with steep slope $q^2 \to 0$



[G. Hiller, DS, Work in progress]

Extended neutrino EFT with ν_L and ν_R

[G. Hiller, DS, Work in progress]

	$\mathcal{B}_{SP-}$ $[10^{-7}]$	$\mathcal{B}_{SP+}$ $[10^{-4}]$	$\mathcal{B}_{LR+}$ $[10^{-4}]$	$\mathcal{B}_{T}$ $[10^{-3}]$
$\Lambda_c \to p\nu\bar{\nu}$	5.6	1.1	2.4	1.1

- Upper bounds on $\Lambda_c \to p\nu\bar{\nu}$ from

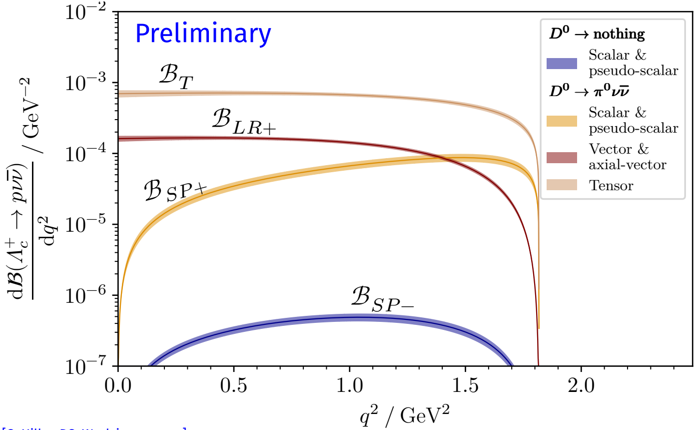
[Belle, arXiv:1611.09455]

$$\mathcal{B}(D^0 \to invisible) < 9.4 \cdot 10^{-5}$$

[BESIII, arXiv:2112.14236]

$$\mathcal{B}(D^0 \to \pi^0\nu\bar{\nu}) < 2.1 \cdot 10^{-4}$$

- Note: Some operators unconstrained



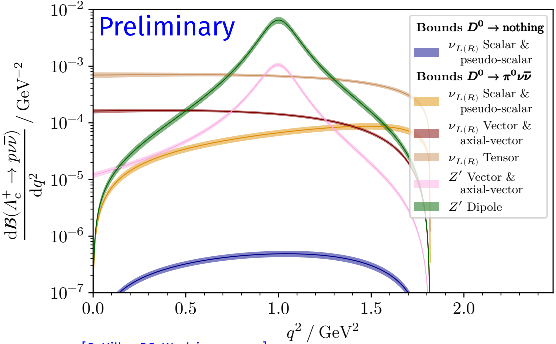
[G. Hiller, DS, Work in progress]

Upper limits on branching ratios

[G. Hiller, DS, Work in progress]

$h_c \to F\nu\bar{\nu}$	$\nu_{i,L}$ and $\nu_{i,R}$				Light Z' and χ $(m_{Z'}, m_\chi, \Gamma_{Z'}) = (1, 0, 0.1)\mathrm{GeV}$		$SU(2)_L$ link [Bause et al., arXiv:2010.02225], [G. Hiller, DS, Work in progress]			
	$\mathcal{B}_{SP-}$ $[10^{-7}]$	$\mathcal{B}_{SP+}$ $[10^{-4}]$	$\mathcal{B}_{LR+}$ $[10^{-4}]$	$\mathcal{B}_T$ $[10^{-4}]$	$\mathcal{B}_V^{Z'}$ $[10^{-4}]$	$\mathcal{B}_D^{Z'}$ $[10^{-4}]$	$\mathcal{B}_{\text{LU}}$ $[10^{-6}]$	$\mathcal{B}_{\text{democratic}}$ $[10^{-6}]$	$\mathcal{B}_{\text{cLFC}}$ $[10^{-5}]$	$\mathcal{B}_{\text{general}}$ $[10^{-5}]$
$\Lambda_c \to p\nu\bar{\nu}$	5.6	1.1	2.4	11.2	3.1	17.8	1.9	5.7	1.1	3.9
$D^0 \to \pi^0\nu\bar{\nu}$	-	[2.1]	[2.1]	[2.1]	[2.1]	[2.1]	0.61	2.0	0.35	1.3
$D^+ \to \pi^+\nu\bar{\nu}$	-	10.5	8.5	10.2	10.5	10.7	2.5	7.9	1.4	5.2

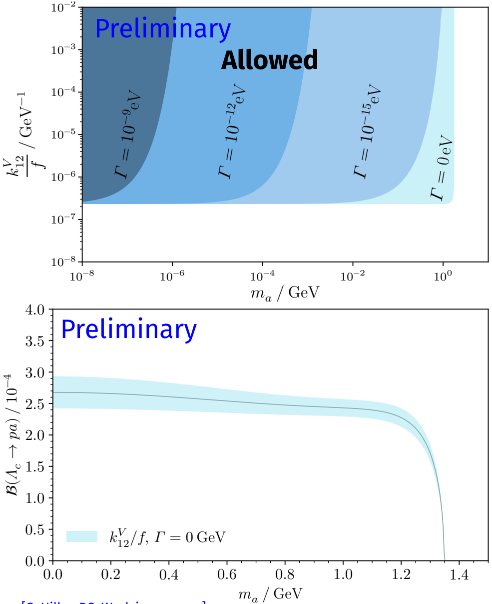
- $D^+ \to \pi^+\nu\bar{\nu}$ with cuts on q^2 to remove tree-level τ-background
- Similar constraints for benchmark of light Z' model



[G. Hiller, DS, Work in progress]

Upper limits for ALPs

- Use $D^0 \to \pi^0 \nu\bar{\nu}$ as constraints on ALP couplings
- Dependence on ALP mass m_a and decay width
- $\mathcal{B}(\Lambda_c \to pa) \sim \mathcal{O}(10^{-4})$
- Note: Some operators unconstrained



[G. Hiller, DS, Work in progress]

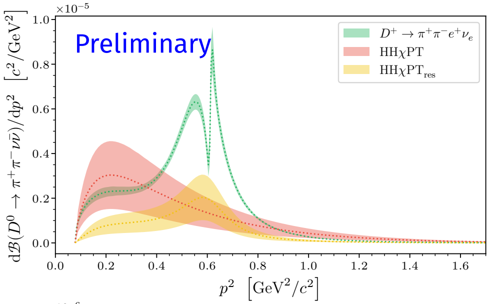
$D^0 \to \pi^+\pi^-\nu\bar{\nu}$

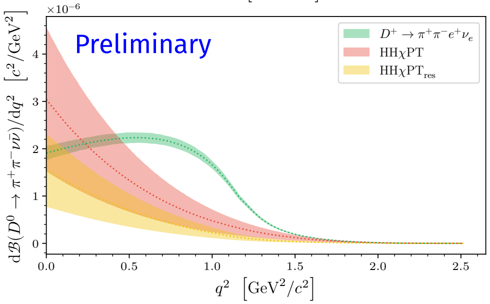
- Complicated 4-body decay
- Sensitivity studies @ FCC-ee

  [T. Hacheney, et. al., https://doi.org/10.17181/e3nw3-fx653]

- Update NP predictions by different form factor models
  - HHχPT [Bause et. al., arXiv:2010.02225]
  - HHχPT$_{\text{res}}$ with added resonances
  - data driven via measurements of $D^+ \to \pi^+\pi^- e^+\nu_e$ [BESIII, 1809.06496]

Form factors $D^0 \to \pi^+\pi^-\nu\bar{\nu}$	$\mathcal{B}_{\text{LU}}$ $[10^{-7}]$	$\mathcal{B}_{\text{democratic}}$ $[10^{-6}]$	$\mathcal{B}_{\text{cLFC}}$ $[10^{-6}]$	$\mathcal{B}_{\text{general}}$ $[10^{-6}]$
data driven	4.4	1.3	2.5	9.2
HHχPT	2.9	0.86	1.6	6.0
HHχPT$_{\text{res}}$	1.4	0.43	0.83	3.0





[A. Canto, T. Hacheney, G. Hiller, D. Mitzel, S. Monteil, L. Röhrig, DS, work in progress]

Radiative charm decays

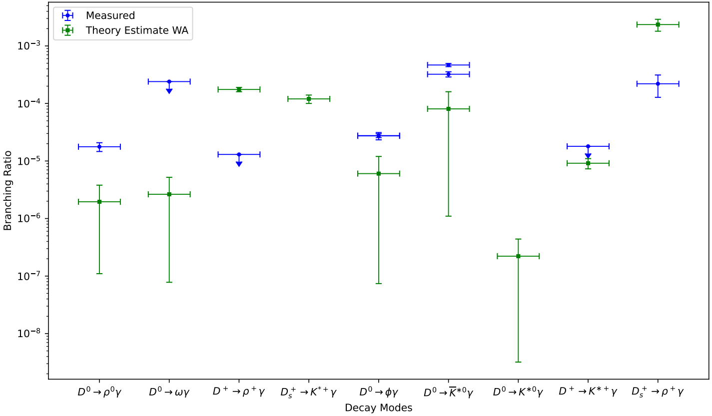
Adapted from [S. De Boer, G. Hiller, arXiv:1701.06392] **NEW**

branching ratio	$D^0 \to \rho^0\gamma$	$D^0 \to \omega\gamma$	$D^+ \to \rho^+\gamma$	$D_s \to K^{*+}\gamma$
HSI+WA	$(0.11 - 3.8) \cdot 10^{-6}$	$(0.078 - 5.2) \cdot 10^{-6}$	$(1.6 - 1.9) \cdot 10^{-4}$	$(1.0 - 1.4) \cdot 10^{-4}$
data	$(1.77 \pm 0.31) \cdot 10^{-5}$	$< 2.4 \cdot 10^{-4}$	$< 1.3 \cdot 10^{-5}$ [BESIII, arXiv:2410.06500]	

branching ratio	$D^0 \to \phi\gamma$	$D^0 \to \bar{K}^{*0}\gamma$	$D^0 \to K^{*0}\gamma$	$D^+ \to K^{*+}\gamma$	$D_s \to \rho^+\gamma$
WA	$(0.0074 - 1.2) \cdot 10^{-5}$	$(0.011 - 1.6) \cdot 10^{-4}$	$(0.032 - 4.4) \cdot 10^{-7}$	$(0.73 - 1.1) \cdot 10^{-5}$	$(1.8 - 2.9) \cdot 10^{-3}$
data	$(2.76 \pm 0.21) \cdot 10^{-5}$ $(2.81 \pm 0.41) \cdot 10^{-5}$	$(4.66 \pm 0.30) \cdot 10^{-4}$ $(3.31 \pm 0.34) \cdot 10^{-4}$		$< 1.8 \cdot 10^{-5}$ [BESIII, arXiv:2410.06500]	$(2.2 \pm 0.9) \cdot 10^{-4}$ [BESIII, arXiv:2408.03980]

- Open problem with estimates from weak annihilation (WA)
- Incompatible $D^0 \to \bar{K}^{*0}\gamma$ measurements by Belle & BaBar
- $D_s^+ \to K^{*+}\gamma$, $D^0 \to K^{*0}\gamma$ unconstrained
- Measure baryons? $\mathcal{B}(\Lambda_c \to p\gamma) \sim \mathcal{O}(10^{-5})$

[S. De Boer, G. Hiller, arXiv:1701.06392]



Summary

- Many recent advancements in rare charm decays
  - Promising future for charm
- Angular null test become accessible in $c \to u\mu^+\mu^-$
- Dineutrino branching ratios as **clean nulltests** in charm
- Various well motivated models induce decays with missing energy
- Lots of channels not or weakly constrained
  - $\Lambda_c^+ \to p\nu\overline{\nu},\ D^0 \to \pi^+\pi^-\nu\overline{\nu},\ D^+ \to \pi^+\nu\overline{\nu}\ldots$
- Radiative decays are/become reachable by experiments
- Advancements will help to increase understanding of QCD effects for charm

Thank you for your attention!