Probing invisibles with rare charm decays

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Why are we interested in invisible rare charm decays?

$c \to u\nu\bar{\nu}$

$D^+ \to \pi^+\nu\bar{\nu}$	$D^0 \to \pi^0\nu\bar{\nu}$ BESIII 2021
$D^0 \to \nu\bar{\nu}\gamma$	$D^0 \to \pi^0 a$
$D_s^+ \to K^+\nu\bar{\nu}$	$D^0 \to K^+K^-\nu\bar{\nu}$
$D^0 \to invisible$ Belle 2016	
$D^0 \to \pi^0\pi^0\nu\bar{\nu}$	$D^0 \to \pi^+\pi^-\nu\bar{\nu}$
$\Lambda_c^+ \to p^+\nu\bar{\nu}$	$\Lambda_c^+ \to p\gamma'$ BESIII 2022

- Strong GIM and CKM suppression in $c \to u\nu\bar{\nu}$
- Branching ratio limits are for $b \to s\nu\bar{\nu}$ a factor of few away from SM prediction and for $c \to u\nu\bar{\nu}$ null tests of SM Bause et al. 2021
- Light NP might be hiding in missing energy modes $\to$ light $\nu_L + \nu_R$, light Z', ALPs a
- Complementary to kaon and B-physics, but very few measurements in charm

1. Light $\nu_L + \nu_R$ EFT

- Effective Hamiltonian Bause et al. 2021 :

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

- Operators with left-handed neutrinos:

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

- GIM and CKM suppression
  - $C_{LL,\text{SM}}^{ij} \approx 0,\ C_{RL,\text{SM}}^{ij} \approx 0$

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- GIM and CKM suppression
  - $C_{LL,\text{SM}}^{ij} \approx 0,\ C_{RL,\text{SM}}^{ij} \approx 0$

- Operators including light right-handed neutrinos:

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

2. Light Z' EFT

- Light Z' as a vector-boson of an additional $U(1)'$ gauge-symmtery and a dark BSM fermion χ coupling only to Z'
- Consider smaller masses $m_{Z'} \ll m_W$ and dominant decay channel to invisible final states $\Gamma_{Z'} \equiv \Gamma(Z' \to \chi\bar{\chi})$
- EFT vector coupling to χ and up-type quarks

$$\mathcal{L}_{Z'}^{\text{eff}} \supset C_L^{Z'} \bar{u}_L \gamma^\mu c_L Z'_\mu + C_R^{Z'} \bar{u}_R \gamma^\mu c_R Z'_\mu + C_\chi^{Z'} \bar{\chi} \gamma^\mu \chi Z'_\mu + \text{h.c.}\,.$$

- Dipole coupling to Z'

$$\mathcal{L}_{Z'}^{\text{eff}} \supset \frac{1}{\Lambda_{\text{eff}}} \bar{u} \left(C_D^{Z'} + \gamma_5 C_{D5}^{Z'} \right) \sigma^{\mu\nu} \, c \, Z'_{\mu\nu} + \text{h.c.}$$

3. Axion-like particles (ALPs) EFT

- Axion-like particles (ALPs) EFT Bauer et al. 2021 with ALPs a as pseudo Nambu-Goldstone bosons from spontaneous breaking of a global symmetry
- ALPs have mass m_a and include the QCD axion for certain parameters
- We consider lifetimes of ALPs for which they decay dominantly outside the detector
- Allows an interpretation of $h_c \to F + invisible$ as two-body decays

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

Observables

Differential Branching Fractions

$$\frac{d\mathcal{B}\left(D^0 \to \pi^0 + invisible\right)}{dq^2}$$

$$\frac{d\mathcal{B}\left(\Lambda_c^+ \to p^+ + invisible\right)}{dq^2}, \quad q^2 = (p_1 - p_2)^2$$

$$\frac{d\mathcal{B}}{dq^2} = \frac{1}{2m_{h_c}} \frac{\mathrm{d}\mathcal{B}r}{\mathrm{d}E_{\text{miss}}}, \quad E_{\text{miss}} = \frac{m_{h_c}^2 - m_F^2 + q^2}{2m_{h_c}}$$

Branching Fractions

$$\mathcal{B}\left(D^0 \to invisible\right)$$

$$\mathcal{B}\left(D^0 \to \pi^0 + invisible\right)$$

$$\mathcal{B}\left(\Lambda_c^+ \to p^+ + invisible\right)$$

- Calculate differential branching fraction using LatticeQCD form factors $\Lambda_c \to p$, $D \to \pi$
- Differential branching fraction allows separation of various NP models
- Extend to $SU(3)_F$-related decays $\Xi_c \to \Sigma^+$, $D^+ \to \pi^+$, $D_s^+ \to K^+$

Experimental Limits for $\nu_L + \nu_R$ EFT

$D^0 \to inv.$ Belle 2016

$$\mathcal{B}(D^0 \to inv.) < 9.4 \cdot 10^{-5} \,@\, 90\% C.L.$$

- Only Scalar- and Pseudoscalar WCs contribute

$$\mathcal{B}(D^0 \to \nu\bar{\nu}) \approx \frac{G_F^2 \alpha_e^2 f_D^2 m_{D^0}^5 \tau_{D^0}}{64\pi^3 m_c^2} x_{SP-}$$

$$x_{SP\pm} = \sum_{\substack{\text{flavor} \\ ij}} \left| C_S^{ij} \pm C_S^{\prime ij} \right|^2 + \left| C_P^{ij} \pm C_P^{\prime ij} \right|^2$$

- Limit on x_{SP-}

$$|\sqrt{x_{SP-}}| \lesssim 8.2$$

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$$\left|\sqrt{x_{SP-}}\right| \lesssim 8.2$$

$D^0 \to \pi^0 + inv.$ BESIII 2021

$$\mathcal{B}(D^0 \to \pi^0 \nu\bar{\nu}) < 2.1 \cdot 10^{-4} \text{ @ } 90\% C.L.$$

- Only 3 kinds of WC combinations contribute

$$\mathcal{B}(D^0 \to \pi^0 \nu\bar{\nu}) = A_{SP+}^{D\to\pi} x_{SP+} + A_T^{D\to\pi} x_T + A_{LR+}^{D\to\pi} x_{LR+}$$

$$x_{LR+} = \sum_{ij} \left|C_{LL}^{ij} + C_{RL}^{ij}\right|^2 + \left|C_{RR}^{ij} + C_{LR}^{ij}\right|^2$$

$$x_T = \sum_{ij} \left|C_T^{ij}\right|^2 + \left|C_{T_5}^{ij}\right|^2$$

- Give upper limits on the coefficients

$$\left|\sqrt{x_{SP+}}\right| \lesssim 76, \quad \left|\sqrt{x_{LR+}}\right| \lesssim 154, \quad \left|\sqrt{x_T}\right| \lesssim 51$$

- For $C_{S,P}^{(\prime)} = 0$ the relation $x_{SP+} = x_{SP-}$ holds
  - Stronger limits on scalar operators from $D^0 \to inv.$

Only light left-handed neutrinos

- Vector- and axial-vector

$$x_{L\pm} = \sum_{ij} \left| C_{LL}^{ij} \pm C_{RL}^{ij} \right|^2$$

- Upper limits Bause et al. 2021 on $x_L = \frac{x_{L+} + x_{L-}}{2}$ through $SU(2)_L$ link

$x_L \lesssim 34,$ Lepton Universal (LU)

$x_L \lesssim 196,$ charged lepton flavor conservation (cLFC)

$x_L \lesssim 716,$ general

- Predict upper bounds:

$$\frac{\mathrm{d}\mathcal{B}r\left(\Lambda_c \to p\nu\bar{\nu}\right)}{\mathrm{d}q^2} = a_+^{\Lambda_c \to p}(q^2)\, x_{L+} + a_-^{\Lambda_c \to p}(q^2)\, x_{L-}$$

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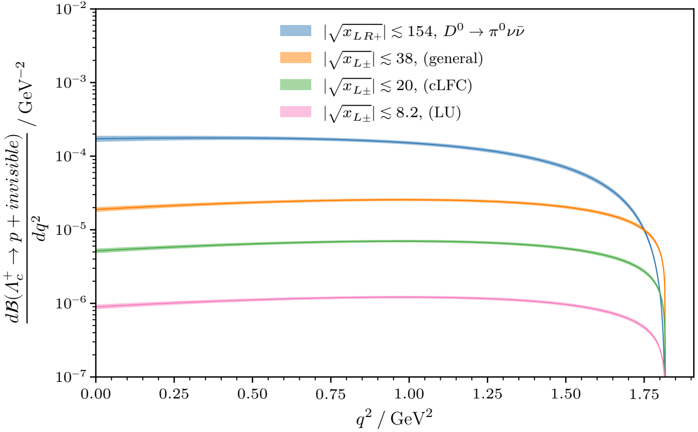

- direct $\nu_L + \nu_R$ EFT bound weaker than $SU(2)_L$ bound for most of q^2

Experimental Limits for light Z' EFT

$D^0 \to \pi^0 + inv.$ BESIII 2021

$$\mathcal{B}(D^0 \to \pi^0 \nu\bar{\nu}) < 2.1 \cdot 10^{-4} \ @ \ 90\% C.L.$$

- Approximation via two consecutive two-body decays and Breit-Wigner distribution

$$\mathcal{B}(D^0 \to \pi^0 Z'(\to \chi\bar{\chi})) \simeq \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 \Gamma_{Z'}(q^2) BW(q^2) \mathcal{B}(D^0 \to \pi^0 Z')(q^2) \, .$$

- Two-body branching ratio depends only on vector and dipole WCs

$$\mathcal{B}(D^0 \to \pi^0 Z')(q^2) = a_V^{Z'}(q^2) |C_L^{Z'} + C_R^{Z'}|^2 + a_D^{Z'}(q^2) \frac{|C_D^{Z'}|^2}{\Lambda^2_{\text{eff}}} + a_I^{Z'}(q^2) Re\left\{ (C_L^{Z'} + C_R^{Z'}) C_D^{Z',*} \right\}$$

- Limits on coefficients for BM $m_{Z'} = 1$ GeV, $\Gamma_{Z'} = 10\% m_{Z'}$ and $m_\chi = 0$ GeV

$$|C_L^{Z'} + C_R^{Z'}| \lesssim 7.2 \cdot 10^{-8} \, , \qquad \frac{|C_D^{Z'}|}{\Lambda_{\text{eff}}} \lesssim 1.8 \cdot 10^{-7} \text{GeV}^{-1}$$

Predictions for differential branching fraction of $\Lambda_c \to p + inv.$

- Differential branching fraction for $\nu_L + \nu_R$ EFT

$D^0 \to \pi^0 + inv.$ BESIII 2021

$$\frac{\mathrm{d}\mathcal{B}\left(\Lambda_c \to p\nu\bar{\nu}\right)}{\mathrm{d}q^2} = a_{SP+}^{\Lambda_c\to p}(q^2)\, x_{SP+} + a_{SP-}^{\Lambda_c\to p}(q^2)\, x_{SP-} + a_{T}^{\Lambda_c\to p}(q^2)\, x_{T} + a_{LR+}^{\Lambda_c\to p}(q^2)\, x_{LR+} + a_{LR-}^{\Lambda_c\to p}(q^2)\, x_{LR-}$$

$D^0 \to inv.$ Belle 2016

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$D^0 \to inv.$ Belle 2016

- Differential branching fraction for Z' EFT

$$\mathcal{B}(\Lambda_c \to pZ')(q^2) = a_V^{Z'}(q^2)|C_L^{Z'} + C_R^{Z'}|^2 + a_A^{Z'}(q^2)|C_L^{Z'} - C_R^{Z'}|^2 + a_D^{Z'}(q^2)\frac{|C_D^{Z'}|^2}{\Lambda_{\text{eff}}^2} + a_{D5}^{Z'}(q^2)\frac{|C_{D5}^{Z'}|^2}{\Lambda_{\text{eff}}^2} + a_{I_1}^{Z'}(q^2) Re\left\{(C_L^{Z'} + C_R^{Z'})C_D^{Z',*}\right\} + a_{I_2}^{Z'}(q^2) Re\left\{(C_L^{Z'} - C_R^{Z'})C_{D5}^{Z',*}\right\}$$

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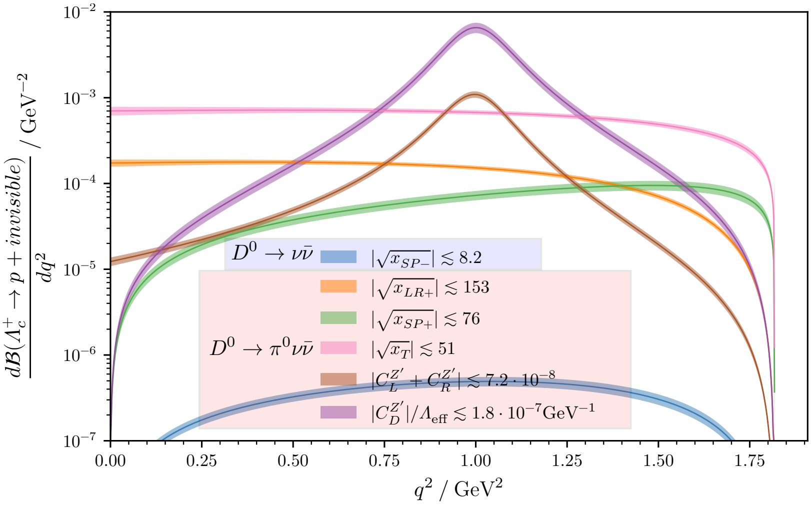
- Allows to restrict otherwise unrestricted WCs

$$x_{LR-} = \sum_{\substack{\text{flavor}\\ ij}} \left|C_{LL}^{ij} - C_{RL}^{ij}\right|^2 + \left|C_{RR}^{ij} - C_{LR}^{ij}\right|^2, \qquad \frac{|C_{D5}^{Z'}|^2}{\Lambda_{\text{eff}}^2}, \qquad |C_L^{Z'} - C_R^{Z'}|^2$$

Differential branching fraction $\Lambda_c \to p + inv.$

- Strongest limit for Scalar- Pseudoscalar WCs from $D^0 \to inv.$
- Other limits are weaker and distinguishable by q^2 behavior
- Non zero contributions at low q^2 for Tensor and Vector WCs
- Slope for Scalar-Pseudoscalar WCs at low q^2
- Resonance structure for Z' EFT



Branching fraction bounds

- Obtain branching fractions $\mathcal{B}(h_c \to F + inv.) = \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \mathrm{d}\mathcal{B}/\mathrm{d}q^2$
- $q^2_{\text{min}} = 0.34\,\text{GeV}^2 (0.66\,\text{GeV}^2)$ for $D^+ \to \pi^+$ ($D_s^+ \to K^+$) to remove tree-level τ-background

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	$\nu_{i,L}$ and $\nu_{i,R}$				
$h_c \to F$	$\mathcal{B}_{SP-}$ $[10^{-4}]$	$\mathcal{B}_{SP+}$ $[10^{-4}]$	$\mathcal{B}_{SP\pm}$ $[10^{-4}]$	$\mathcal{B}_{LR+}$ $[10^{-4}]$	$\mathcal{B}_{T}$ $[10^{-4}]$
$\Lambda_c \to p$	0.0056	1.1	0.018	2.4	11.2
$\Xi_c \to \Sigma^+$	0.0098	1.9	0.032	4.4	22.5
$D^0 \to \pi^0$	-	[2.1]	0.024	[2.1]	[2.1]
$D^+ \to \pi^+$	-	10.5	0.123	8.5	10.2
$D_s^+ \to K^+$	-	2.0	0.023	1.6	1.3

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- Scalar- and pseudoscalar contributions are constrained the strongest

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	$\nu_{i,L}$ and $\nu_{i,R}$					Light Z' and χ	
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$\Lambda_c \to p$	0.0056	1.1	0.018	2.4	11.2	3.1	17.8
$\Xi_c \to \Sigma^+$	0.0098	1.9	0.032	4.4	22.5	5.4	32.2
$D^0 \to \pi^0$	-	$[2.1]$	0.024	$[2.1]$	$[2.1]$	$[2.1]$	$[2.1]$
$D^+ \to \pi^+$	-	10.5	0.123	8.5	10.2	10.5	10.7
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$h_c \to F$	$\mathcal{B}_{SP-}$ $[10^{-4}]$	$\mathcal{B}_{SP+}$ $[10^{-4}]$	$\mathcal{B}_{SP\pm}$ $[10^{-4}]$	$\mathcal{B}_{LR+}$ $[10^{-4}]$	$\mathcal{B}_{T}$ $[10^{-4}]$	$\mathcal{B}_V^{Z'}$ $[10^{-4}]$	$\mathcal{B}_D^{Z'}$ $[10^{-4}]$	$\mathcal{B}_{\text{LU}}$ $[10^{-4}]$	$\mathcal{B}_{\text{cLFC}}$ $[10^{-4}]$	$\mathcal{B}_{\text{general}}$ $[10^{-4}]$
$\Lambda_c \to p$	0.0056	1.1	0.018	2.4	11.2	3.1	17.8	0.018	0.11	0.39
$\Xi_c \to \Sigma^+$	0.0098	1.9	0.032	4.4	22.5	5.4	32.2	0.036	0.21	0.76
$D^0 \to \pi^0$	-	[2.1]	0.024	[2.1]	[2.1]	[2.1]	[2.1]	0.0061	0.035	0.13
$D^+ \to \pi^+$	-	10.5	0.123	8.5	10.2	10.5	10.7	0.025	0.14	0.52
$D_s^+ \to K^+$	-	2.0	0.023	1.6	1.3	3.9	2.7	0.0046	0.26	0.096

- Tensor contributions are the least constrained ones
- Scalar- and pseudoscalar contributions are constrained the strongest
- Upper limit $\mathcal{B}_{LR+}$ is weaker than limits from $SU(2)_L$

Experimental bounds on ALP couplings

$\Longrightarrow$ Now model with two-body decay missing energy signature

- Fraction of ALPs, which escape detector of transverse radius $R_{\text{max}} = 2.8\,\text{m}$

$$F_T(\Gamma, m_a) = \int_0^{\frac{\pi}{2}} \sin\theta \mathrm{d}\theta \exp\left(-\frac{m_a \Gamma R_{\text{max}}}{|p^T_{LAB}|}\right)$$

- Meson decays constrain only vector couplings

$$\mathcal{B}(D^0 \to \pi^0 a) = F_T(\Gamma, m_a)\, a_V^{D^0\to\pi^0}(m_a)\, \frac{|k^V_{12}|^2}{f^2}$$

- For $\Gamma = 0$ the bound is nearly mass independent

$$\left|k^V_{12}\right| / f < 2.4 \cdot 10^{-7}\,\text{GeV}^{-1}$$

$D^0 \to \pi^0 + inv.$ BESIII 2021

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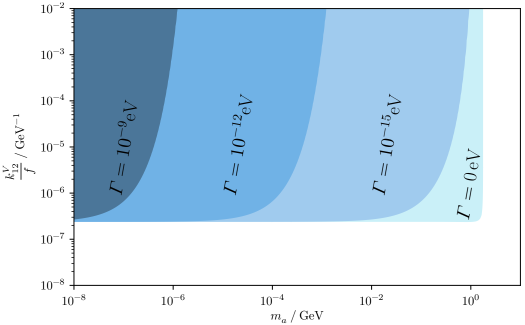
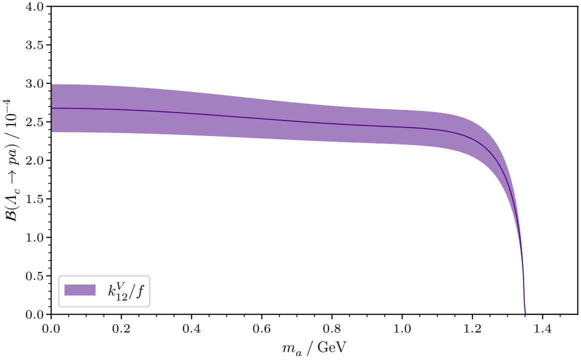


Bounds ALPs

- Baryon decays constrain vector and axial couplings at the same time

$$\mathcal{B}(\Lambda_c \to pa) = \frac{\left|k_{12}^V\right|^2}{f^2} a_V^{\Lambda_c \to p}(m_a) + \frac{\left|k_{12}^A\right|^2}{f^2} a_A^{\Lambda_c \to p}(m_a)$$

- Axial coupling of ALPs in $c \to u$ is unconstrained by experiment
- Upper bound on $\mathcal{B}(\Lambda_c \to p + inv.)$ is predicted by bound on vector coupling
- Small dependence on the ALP mass m_a for k_{12}^V



Conclusion

- Invisible rare charm decays are null tests and probe NP uniquely in up-type sector
- Baryon decays allow to probe certain operators for the first time and are advantageous for others
- The differential branching ratio can distinguish different scenarios of NPs
  - Scalar- and Pseudoscalar contributions that require additional RH neutrinos have steep slope near $q^2 = 0$
  - Z' contributions have resonance shape
  - Bounds on certain operators types can already profit from a few q^2 bins
  - Relevant for two-body decay interpretation of invisible decays for models like ALPs
- There are exiting times ahead for charm and invisible decays!

In preparation

Stay tuned!

Appendix

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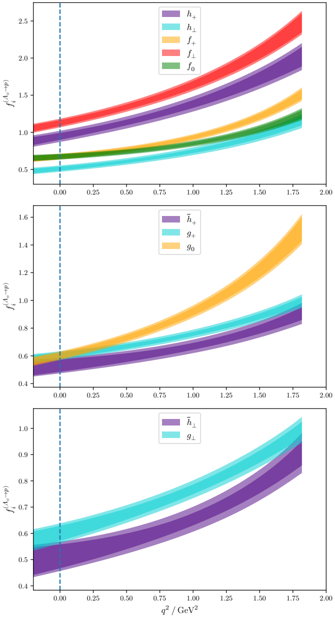
Numerical evaluation of form factors

- The numerical results of the $\Lambda_c \to p$ form factors are given in Lattice QCD Meinel 2018
- z-Expansion to interpolate for the whole kinematic q^2 range

$$f(q^2) = \frac{1}{1 - q^2/(m^f_{\text{pole}})^2} \sum_{n=0}^{k} a_n$$

- Form factors for other decays are related via flavor symmetries Golz, Hiller, and Magorsch 2021

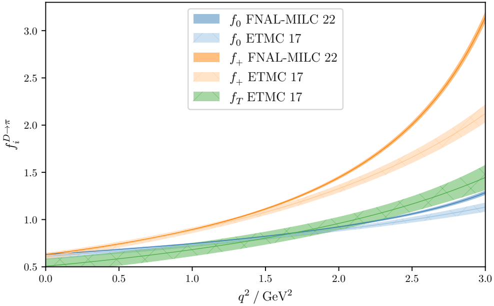
$$f_{\Lambda_c \to p} = f_{\Xi_c^+ \to \Sigma^+} = \sqrt{2} f_{\Xi_c^0 \to \Sigma^0} = \sqrt{6} f_{\Xi_c^0 \to \Lambda^0}$$



Numerical evaluation of form factors

- The numerical results of the $D^0 \to \pi^0$ form factors are given in Lattice QCD Lubicz et al. 2017, Lubicz et al. 2018, Bazavov et al. 2023
- z-Expansion to interpolate for the whole kinematic q^2 range

$$f(q^2) = \frac{1}{1 - q^2/(m^f_{\text{pole}})^2} \sum_{n=0}^{k} a_n$$



Differential branching fraction $D^0 \to \pi^0 + inv.$