# Towards New Physics in Semileptonic Charm Decays

## $\Lambda_c \to p\nu\bar{\nu}$, $D \to hh\mu\mu$ plans

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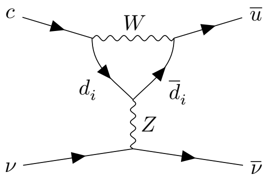
# Why are we interested in Semileptonic Charm Decays?

- Unique probe of up-type FCNCs
- Complementary to etablished studies in down-type decays
- GIM and CKM suppression in $c \to u \ell^+ \ell^-$, $c \to u \nu \bar{\nu}$




$$\mathcal{A}(c \to u) \propto V_{cs}^* V_{us} \left( f\left(\frac{m_s^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right) + V_{cb}^* V_{ub} \left( f\left(\frac{m_b^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right)$$

# Rare decays with missing energy

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

| | |
|---|---|
| $D^+ \to \pi^+\nu\bar{\nu}$ | $D^0 \to \pi^0\nu\bar{\nu}$ BESIII 2021 |
| $D^0 \to \nu\bar{\nu}\gamma$ | $D^0 \to \pi^0 a$ |
| $D_s^+ \to K^+\nu\bar{\nu}$ | $D^0 \to K^+K^-\nu\bar{\nu}$ |
| $D^0 \to \nu\bar{\nu}, \nu\bar{\nu}\nu\bar{\nu}$ 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 |

- Branching ratios 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 (2010.0225)
- Resonances are not a problem for baryon decays
- Study $\Lambda_c \to p + invisible$

# Introduction of the Helicity Formalism

- We use the Helicity Formalism to calculate differential branching fraction in terms of Helicity amplitudes
- Already used in $\Lambda_c \to p\ell^+\ell^-$, $\Xi_c^+ \to \Sigma^+(\to p\pi^0)\ell^+\ell^-$ angular distributions
- Possible to construct more sophisticated observables for null tests
- For $\Lambda_c \to p\nu\bar{\nu}$ the differential branching ratio is a null test

# Charm EFT approach

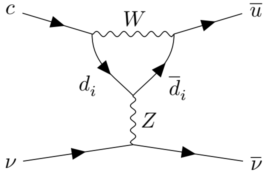
- Effective Hamiltonian (2010.02225) :

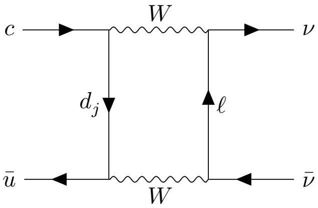
$$\mathcal{H}_{\text{eff}}^{\nu_i\bar{\nu}_j} = -\frac{4G_F}{\sqrt{2}} \sum_k C_k^{ij} \cdot Q_k^{ij} + \text{h.c.}$$

- Operators in the SM with left-handed neutrinos:

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

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




$$\mathcal{A}(c \to u) \propto V_{cs}^* V_{us} \left( f\left(\frac{m_s^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right) + V_{cb}^* V_{ub} \left( f\left(\frac{m_b^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right)$$

# Charm EFT approach

- Operators with light right-handed neutrinos:

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

# Charm EFT approach

- How are these new operators generated?
- Neutrinos are invisible therefore $c \to u\nu\nu$ contributes & $\Delta L = 2$ can be probed
- Using Standard-Model-Effective-Field-Theory (SMEFT) with SM d.o.f + higher dim. operators

# Charm EFT approach

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- Neutrinos are invisible therefore $c \to u\nu\nu$ contributes & $\Delta L = 2$ can be probed
- Using Standard-Model-Effective-Field-Theory (SMEFT) with SM d.o.f + higher dim. operators
- SMEFT Lagrangian with LNV operators up to dimension 7

$$\mathcal{L}_{\text{SMEFT}}^{\text{LNV}} = \mathcal{L}_{\text{SM}} + \sum_{n=\{5,7\}} \sum_{\mathcal{O} \in \text{dim}n} \frac{C_{\mathcal{O}}}{\Lambda_{\text{LNV}}^{n-4}} \mathcal{O} + \text{h.c.} \, ,$$

- Relevant operators for $c \to u\nu\nu$ dineutrino modes:

$$\mathcal{O}_{\ell^2 quH}^{prst} = \epsilon^{\alpha\beta} \left(l_{p\alpha}^T \, C \, l_{r\sigma}\right) \left(\bar{q}_s^\sigma \, u_t\right) H_\beta$$

- Matching contributions to Scalar- and Pseudoscalar operators

$$\mathcal{C}_{S(P)}^{ij} = \pm\sqrt{2} \frac{2\pi}{\alpha_e} \left(\frac{v}{\Lambda_{\text{LNV}}}\right)^3 C_{\ell^2 quH}^{ij12}$$

# Differential Branching Fraction

- Calculate differential branching fraction

$$\frac{d\mathcal{B}\left(\Lambda_c^+ \to p^+\nu\bar{\nu}\right)}{dq^2} = \frac{1}{2m_{\Lambda_c}}\frac{\mathrm{d}\mathcal{B}r}{\mathrm{d}E_{\text{miss}}} = \sum_{\substack{\text{flavour}\\ ij}} \sum_{\lambda_p,\lambda_{\Lambda_c},\lambda_1,\lambda_2} N^2 \times \int \left|\mathcal{M}^{\lambda_1,\lambda_2,i,j}_{\lambda_p,\lambda_{\Lambda_c}}\right|^2 d\cos\theta_\nu$$

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with

$$N^2 = \frac{\tau_{\Lambda_c}\lambda^{\frac{1}{2}}(m^2_{\Lambda_c}, q^2, m^2_p)}{2^{10}\pi^3 m^3_{\Lambda_c}} \cdot \left(\frac{4G_F}{\sqrt{2}} \cdot \frac{\alpha_e}{4\pi}\right)^2 \quad \text{and} \quad E_{\text{miss}} = \frac{m^2_{\Lambda_c} - m^2_p + q^2}{2m_{\Lambda_c}}$$

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- Helicity approach and factorization

$$\begin{aligned}\mathcal{M}^{\lambda_1,\lambda_2,i,j}_{\lambda_p,\lambda_{\Lambda_c}} &\equiv \left\langle \bar{\nu}_j(\mathbf{q}_2,\lambda_2)\,\nu_i(\mathbf{q}_1,\lambda_1)\,p(\mathbf{p}_p,\lambda_p)\middle|\mathcal{H}_{\text{eff}}\middle|\Lambda_c(\mathbf{p}_{\Lambda_c},\lambda_{\Lambda_c})\right\rangle \\ &= \left\langle \bar{\nu}_j(\mathbf{q}_2,\lambda_2)\,\nu_i(\mathbf{q}_1,\lambda_1)\middle|\mathcal{H}^{\text{Lepton},\alpha_1,\ldots,\alpha_n}_{\text{eff}}\middle|0\right\rangle \times \left\langle p(\mathbf{p}_p,\lambda_p)\middle|\mathcal{H}^{\text{Hadron}}_{\text{eff},\alpha_1,\ldots,\alpha_n}\middle|\Lambda_c(\mathbf{p}_{\Lambda_c},\lambda_{\Lambda_c})\right\rangle\end{aligned}$$

# Helicity approach and factorization

- How do we factorize into helicity amplitudes?
- Introduce polarization vectors to exchange Lorentz indices with helicity indices

$$\sum_{\lambda,\lambda'} \epsilon^{\mu}(\lambda,\mathbf{q})\epsilon^{\nu *}(\lambda',\mathbf{q})G_{\lambda,\lambda'} = \mathbf{g}^{\mu\nu}$$

- Helicities $\lambda, \lambda'$ are summed over $t, 0, \pm 1$ and $G_{\lambda\lambda'} = \mathrm{diag}(-1,1,1,1)$

$$\begin{aligned}
&\left\langle \bar{\nu}_j(\mathbf{q}_2,\lambda_2)\,\nu_i(\mathbf{q}_1,\lambda_1)\middle|\bar{\nu}_{jL(R)}\gamma_\mu\nu_{iL(R)}\middle|0\right\rangle \times \left\langle p(\mathbf{p}_p,\lambda_p)\middle|\bar{u}\gamma^\mu c\middle|\Lambda_c(\mathbf{p}_{\Lambda_c},\lambda_{\Lambda_c})\right\rangle \\
&= \sum_{\lambda} G_{\lambda\lambda} \underbrace{\epsilon^{\mu}(\lambda,\mathbf{q})\left\langle \bar{\nu}_j(\mathbf{q}_2,\lambda_2)\,\nu_i(\mathbf{q}_1,\lambda_1)\middle|\bar{\nu}_{jL(R)}\gamma_\mu\nu_{iL(R)}\middle|0\right\rangle}_{L^{ij,\lambda_1,\lambda_2}_{L(R),\lambda}} \\
&\quad\times \underbrace{\epsilon^{\nu *}(\lambda,\mathbf{q})\left\langle p(\mathbf{p}_p,\lambda_p)\middle|\bar{u}\gamma_\nu c\middle|\Lambda_c(\mathbf{p}_{\Lambda_c},\lambda_{\Lambda_c})\right\rangle}_{H^{\lambda_p,\lambda_{\Lambda_c}}_{V,\lambda}}
\end{aligned}$$

- Repeat same procedure for other operators

# Lepton Amplitude

- Lepton helicity amplitudes

$$\langle \bar{\nu}_j(\mathbf{q}_2, \lambda_2)\, \nu_i(\mathbf{q}_1, \lambda_1) \big| \mathcal{H}_{\text{eff}}^{\text{Lepton}\,,\alpha_1,\ldots,\alpha_n} \big| 0 \rangle$$

- Calculate in the restframe of the dineutrino system

$$\begin{aligned} L^{ij,\lambda_1\lambda_2}_{L(R),\lambda} &= \epsilon^{\nu}(\lambda, \mathbf{q}) \, \langle \bar{\nu}_j(\mathbf{q}_2, \lambda_2)\, \nu_i(\mathbf{q}_1, \lambda_1) \big| \, \overline{\nu}_{jL(R)} \gamma_\nu \nu_{iL(R)} \, \big| 0 \rangle \\ &= \epsilon^{\nu}(\lambda, \mathbf{q}) \bar{u}(\vec{\mathbf{k}}, \lambda_1) \gamma_\nu P_{L(R)} v(-\vec{\mathbf{k}}, \lambda_2) \end{aligned}$$

- Get Helicity amplitudes depending on the angle $\theta_\nu$ between proton and neutrino momenta

$$\begin{aligned} L^{ij+\frac{1}{2}-\frac{1}{2}}_{R,0} &= L^{ij-\frac{1}{2}+\frac{1}{2}}_{L,0} = \sqrt{q^2} \sin\theta_\nu \, , \\ L^{ij+\frac{1}{2}-\frac{1}{2}}_{R,+} &= -L^{ij-\frac{1}{2}+\frac{1}{2}}_{L,-} = \sqrt{\frac{q^2}{2}} (\cos\theta_\nu - 1) \, , \\ L^{ij-\frac{1}{2}+\frac{1}{2}}_{L,+} &= -L^{ij+\frac{1}{2}-\frac{1}{2}}_{R,-} = \sqrt{2q^2} \cos^2\left(\frac{\theta_\nu}{2}\right) \end{aligned}$$

# Hadron Amplitude

- Hadron helicity amplitudes

$$\left\langle p(\mathbf{p}_p, \lambda_p) \middle| \mathcal{H}^{\text{Hadron}}_{\text{eff},\alpha_1,\ldots,\alpha_n} \middle| \Lambda_c(\mathbf{p}_{\Lambda_c}, \lambda_{\Lambda_c}) \right\rangle$$

  - Non-perturbative techniques for QCD-effects
  - QCD effects are described by form factors
  - Otherwise same procedure

$$\begin{aligned}\left\langle p(p_p, \lambda_p) \middle| \bar{u}\gamma^\mu c \middle| \Lambda_c(p_{\Lambda_c}, \lambda_{\Lambda_c}) \right\rangle = \bar{u}_p(p_p, \lambda_p) \Bigg[ & f_0(q^2)(m_{\Lambda_c} - m_p)\frac{q^\mu}{q^2} \\ & + f_+(q^2)\frac{m_{\Lambda_c} + m_p}{s_+}\left(p^\mu_{\Lambda_c} + p^\mu_p - (m^2_{\Lambda_c} - m^2_p)\frac{q^\mu}{q^2}\right) \\ & + f_\perp(q^2)\left(\gamma^\mu - \frac{2m_p}{s_+}p^\mu_{\Lambda_c} - \frac{2m_{\Lambda_c}}{s_+}p^\mu_p\right)\Bigg] u_{\Lambda_c}(p_{\Lambda_c}, \lambda_{\Lambda_c})\end{aligned}$$

# Hadron helicity amplitude

- Hadron helicity amplitudes

$$\left\langle p(\mathbf{p}_p, \lambda_p) \middle| \mathcal{H}^{\text{Hadron}}_{\text{eff},\alpha_1,\ldots,\alpha_n} \middle| \Lambda_c(\mathbf{p}_{\Lambda_c}, \lambda_{\Lambda_c}) \right\rangle$$

- Calculate helicity amplitude in restframe of $\Lambda_c$ baryon

$$H^{\lambda_p \lambda_{\Lambda_c}}_{V,\lambda} = \epsilon^{\mu *}(\lambda, \mathbf{q}) \left\langle p^+(\mathbf{p}_p, \lambda_p) \right| \overline{u} \gamma_\mu c \left| \Lambda_c(\mathbf{p}_{\Lambda_c}, \lambda_{\Lambda_c}) \right\rangle$$

- Get helicity amplitude depending on the form factors

$$H^{+\frac{1}{2}+\frac{1}{2}}_{V,0} = H^{-\frac{1}{2}-\frac{1}{2}}_{V,0} = +f_+(q^2)\left(m_{\Lambda_c} + m_p\right)\sqrt{\frac{s_-}{q^2}}\,,$$

$$H^{+\frac{1}{2}+\frac{1}{2}}_{V,t} = H^{-\frac{1}{2}-\frac{1}{2}}_{V,t} = +f_0(q^2)\left(m_{\Lambda_c} - m_p\right)\sqrt{\frac{s_+}{q^2}}\,,$$

$$H^{-\frac{1}{2}+\frac{1}{2}}_{V,+} = H^{+\frac{1}{2}-\frac{1}{2}}_{V,-} = -f_\perp(q^2)\sqrt{2s_-}\,,$$

with $\quad s_\pm = \left(m_{\Lambda_c} \pm m_p\right)^2 - q^2$

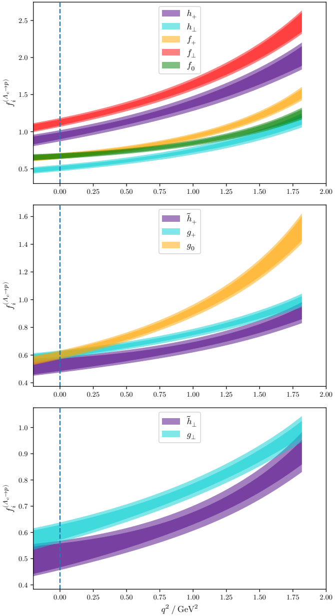
# Numerical evaluation of form factors

- The numerical results of the $\Lambda_c \to p$ form factors are given in Lattice QCD (1712.05783)
- Expansion of the form factors in z-Expansion

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

- Main source of uncertainty
- Form factors for other decays are related via flavor symmetries (2107.13010)

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



# Only light left-handed neutrinos

- Integrate over $\theta_\nu$, sum over flavours and helicities
- Differential branching fraction:

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

- Vector- and axial-vector

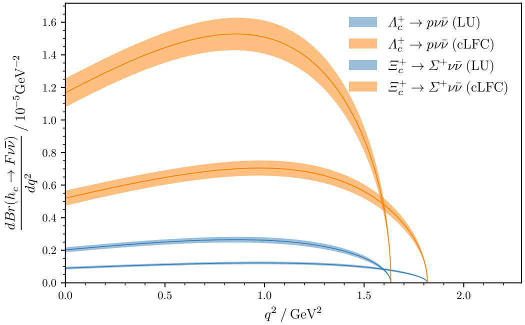
$$x_L^\pm = \sum_{ij}\left|C_{LL}^{ij} \pm C_{RL}^{ij}\right|^2$$

- Upper limits (2010.02225) 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



# Differential Branching Fraction

- Differential branching fraction:

$$\frac{\mathrm{d}\mathcal{B}r}{\mathrm{d}q^2} = \sum_{k=\{SP\pm,LR\pm,T\}} a_k(q^2)\, x_k \,,$$

- Scalar and pseudoscalar

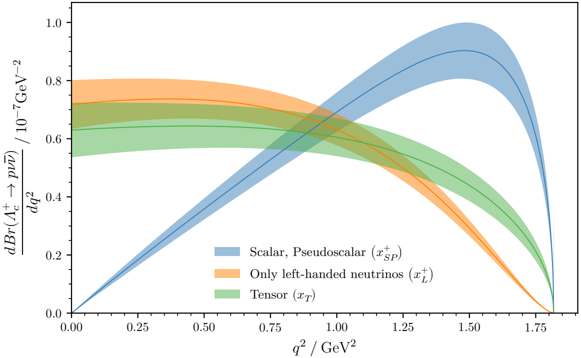
$$x^{\pm}_{SP} = \sum_{\substack{\text{flavor}\\ ij}} \left|C_S^{ij} \pm C_S^{\prime ij}\right|^2 + \left|C_P^{ij} \pm C_P^{\prime ij}\right|^2$$

- Vector and axialvector

$$x^{\pm}_{LR} = \sum_{\substack{\text{flavor}\\ ij}} \left|C_{LL}^{ij} \pm C_{RL}^{ij}\right|^2 + \left|C_{RR}^{ij} \pm C_{LR}^{ij}\right|^2$$

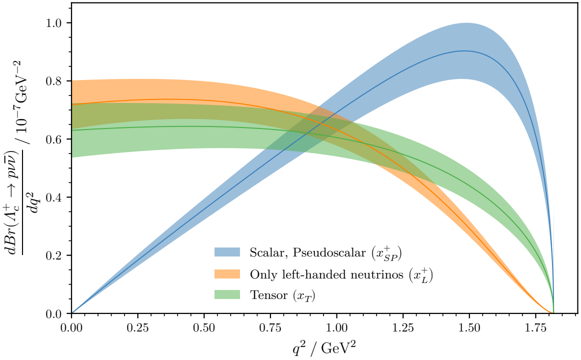
- Tensor

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



# Differential branching fraction

- Distinguish NP via differential branching fraction
- Slope for $x_{SP}^{\pm}$ near $q^2 = 0$
- $x_{LR}^{\pm}$ and $x_T$ finite at endpoint
- $x_{LR}^{\pm}$ and $x_T$ enhanced compared to $x_{SP}^{\pm}$ when only considering region e.g. $q^2 \in \{0, 0.25\}$GeV$^2$



# Conclusion

- Rare dineutrino modes in charm decays are null tests and probe NP in up-type sector
- Charm baryon decays do not have resonance contributions
- Scalar and pseudoscalar operators suppressed for low $q^2$
- The differential branching ratio can distinguish NP with light right-handed neutrinos

# Whats next?

- Continue work in Semileptonic Charm Decays
- Look at previous works on $D \to P_1 P_2 \ell^+ \ell^-$ (1805.08516)
- Proposed null test from coefficients $I_i$ of angular distribution

$$d^5\Gamma = \frac{1}{2\pi}\left[\sum c_i(\theta_l, \phi) I_i(q^2, p^2, \cos\theta_{P_1})\right] \times dq^2 dp^2 d\cos\theta_{P_1} d\cos\theta_l d\phi$$

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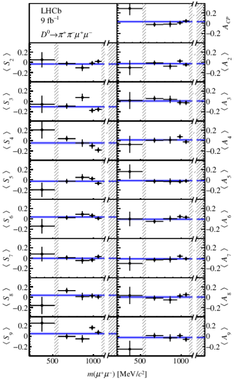
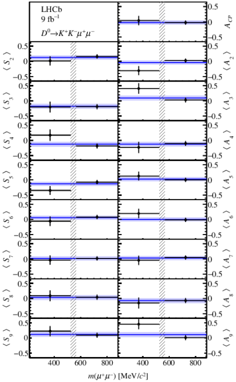
- CP averages and asymmetries of these coefficients $I_i$ measured by LHCb (2111.03327)
- How much NP is left?

(2111.03327)



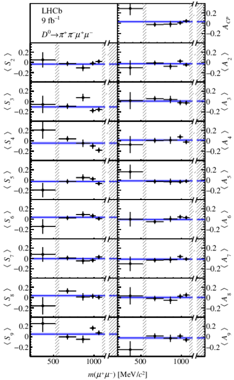
# Whats next?

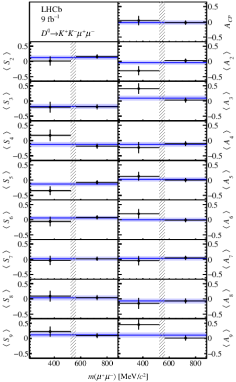
(2111.03327)

- Perform similar analysis as in $b \to s\mu\mu$
- Restrict semileptonic Wilson coefficient $c \to u\ell^+\ell^-$

$$\mathcal{O}_7^{(\prime)} = \frac{m_c}{e}(\bar{u}_{L(R)}\sigma_{\mu\nu}c_{R(L)})F^{\mu\nu} ,$$
$$\mathcal{O}_9^{(\prime)} = (\bar{u}_{L(R)}\gamma_\mu c_{L(R)})(\bar{\ell}\gamma^\mu\ell) ,$$
$$\mathcal{O}_{10}^{(\prime)} = (\bar{u}_{L(R)}\gamma_\mu c_{L(R)})(\bar{\ell}\gamma^\mu\gamma_5\ell) ,$$

- Towards global fit of $c \to u\ell^+\ell^-$
- Connect with $D \to \pi\ell^+\ell^-$, $\Lambda_c \to p\ell^+\ell^-$



*Thank you for your attention!*

# Appendix

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# Branching Ratio

$$\frac{d\mathcal{B}\,(\Lambda_c \to p\,\nu\bar{\nu})}{dq^2} = \frac{G_F^2\,\alpha_e^2\,\tau_{\Lambda_c}\,\sqrt{\lambda(m_{\Lambda_c}^2, q^2, m_p^2)}}{2^{11}\pi^5 m_{\Lambda_c}^3} \times \sum_{k=\{SP\pm,LR\pm,T\}} a_k(q^2)\,x_k\;,$$

$$a_{SP+}(q^2) = 2q^2 f_0^2 s_+ \left(\frac{m_{\Lambda_c} - m_p}{m_c - m_u}\right)^2$$

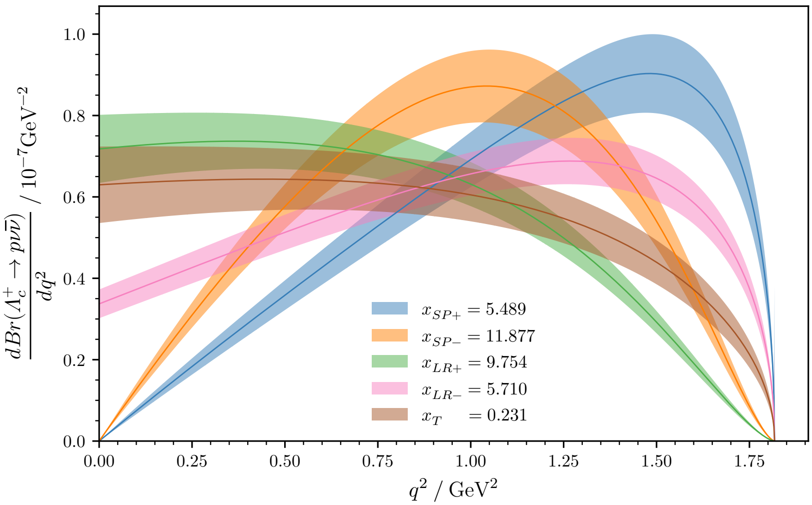
$$a_{SP-}(q^2) = 2q^2 g_0^2 s_- \left(\frac{m_{\Lambda_c} + m_p}{m_c + m_u}\right)^2$$

$$a_{LR+}(q^2) = \frac{2}{3} s_- \left(f_+^2 \left(m_{\Lambda_c} + m_p\right)^2 + 2q^2 f_\perp^2\right)$$

$$a_{LR-}(q^2) = \frac{2}{3} s_+ \left(g_+^2 \left(m_{\Lambda_c} - m_p\right)^2 + 2q^2 g_\perp^2\right)$$

$$a_T = \frac{32}{3} \left(h_\perp^2 s_- 2 \left(m_{\Lambda_c} + m_p\right)^2 + h_+^2 s_+ q^2 + \tilde{h}_\perp^2 s_+ 2 \left(m_{\Lambda_c} - m_p\right)^2 + \tilde{h}_+^2 s_- q^2\right)\;.$$

# Branching Ratio



# Only light left-handed neutrinos

- Differential branching fraction:

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

- Vector- and axial-vector

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

- Null test of the SM with upper limits (2010.02225) 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