Probing NP with rare charm baryon decays

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Rare charm baryon decays

$b \to s\ell\ell$		$c \to u\ell\ell$	
Mesons	Baryons	Mesons	Baryons
$B \to K\ell\ell$	$\Lambda_b \to \Lambda\ell\ell$	$D \to \pi\ell\ell$	$\Lambda_c \to p\ell\ell$
$B_s \to \phi\ell\ell$	$\Lambda_b \to N\pi\ell\ell$	$D_s \to K\ell\ell$	$\Xi_c \to \Sigma\ell\ell$
$B \to K\pi\ell\ell$			$\Omega_c \to \Xi\ell\ell$
			$\Xi_c \to p\pi\ell\ell$

- Study rare semileptonic charm decays
- Probe BSM physics of up-type FCNCs
- Complement charm meson studies (1805.08516, 1909.11108, 2010.02225)

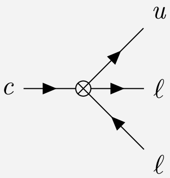
Charm EFT-approach

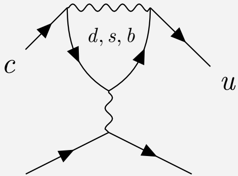
- Short distance contributions:
  - GIM-mechanism: $C_{7,9,10}(m_W) = 0$
  - Mixing by RG running: $C_{7,9}(m_c) \neq 0$, $C_{10}(m_c) = 0$ (1510.00311)
- Operators:

$$\mathcal{O}_7 = \frac{m_c}{e}(\bar{u}_L \sigma_{\mu\nu} c_R) F^{\mu\nu} \qquad \mathcal{O}_P = (\bar{u}_L c_R)(\bar{\ell}\gamma_5 \ell)$$

$$\mathcal{O}_9 = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$





$$\mathcal{A} = V_{cs}^* V_{us}\left(f(m_s^2/m_W^2) - f(m_d^2/m_W^2)\right) + V_{cb}^* V_{ub}\left(f(m_b^2/m_W^2) - f(m_d^2/m_W^2)\right)$$

Charm EFT-approach

- Short distance contributions:
  - GIM-mechanism: $C_{7,9,10}(m_W) = 0$
  - Mixing by RG running: $C_{7,9}(m_c) \neq 0$, $C_{10}(m_c) = 0$ (1510.00311)
- Long distance contributions (resonant): $\Lambda_c \to pM(\to \ell\ell)$

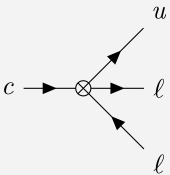
$$C_9 = C_9^{\text{eff}} + C_9^{\text{R}}$$
$$C_7 = C_7^{\text{eff}}$$
$$C_P = C_P^{\text{R}}$$

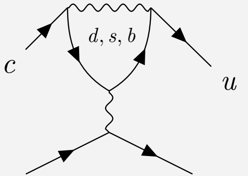
- Model resonances as sum of Breit–Wigners:

$$C_9^{\text{R}}(q^2) = \sum_M \frac{a_M e^{i\delta_M}}{q^2 - m_M^2 + i m_M \Gamma_M}$$

- Strong phases δ_M unknown: Main source of uncertainty
- Parameters a_M estimated from data

$$\mathcal{B}(\Lambda_c \to pM(\to \ell\ell)) = \mathcal{B}_{\text{exp}}(\Lambda_c \to pM)\mathcal{B}_{\text{exp}}(M \to \ell\ell)$$





$$\mathcal{A} = V_{cs}^* V_{us} \left(f(m_s^2/m_W^2) - f(m_d^2/m_W^2)\right) + V_{cb}^* V_{ub} \left(f(m_b^2/m_W^2) - f(m_d^2/m_W^2)\right)$$

SM decay

- Angular distribution:

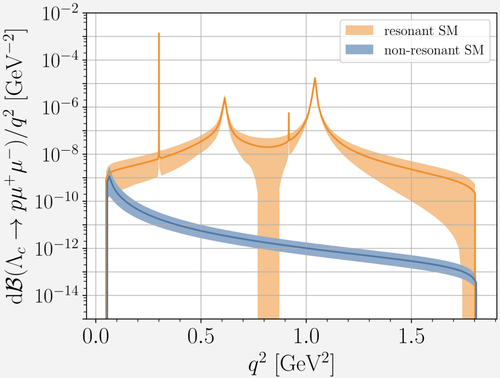
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\Theta_\ell} = \frac{3}{2}(K_{1ss}\sin^2\Theta_\ell + K_{1cc}\cos^2\Theta_\ell + K_{1c}\cos\Theta_\ell)$$

- Form factors for $\Lambda_c \to p$ in Lattice QCD (1712.05783)
- non resonant contributions negligible
- Upper Limit by LHCb (1712.07938)

$$\mathcal{B}_{\mathrm{LHCb}}(\Lambda_c \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$$

- Prediction excluding ± 40 MeV around the resonances

$$\mathcal{B}_{\mathrm{SM}}(\Lambda_c \to p\mu^+\mu^-) = (1.9^{+1.8}_{-1.5}) \times 10^{-8}$$



- Estimations for other baryonic modes

$$\Xi_c^+ \to \Sigma^+\mu^+\mu^- \sim \text{factor } 1.8$$
$$\Omega_c^0 \to \Xi^0\mu^+\mu^- \sim \text{factor } 1.3$$
$$\Xi_c^0 \to \Sigma^0\mu^+\mu^- \sim \text{factor } 0.4$$
$$\Xi_c^0 \to \Lambda^0\mu^+\mu^- \sim \text{factor } 0.2$$

Forward-backward asymmetry

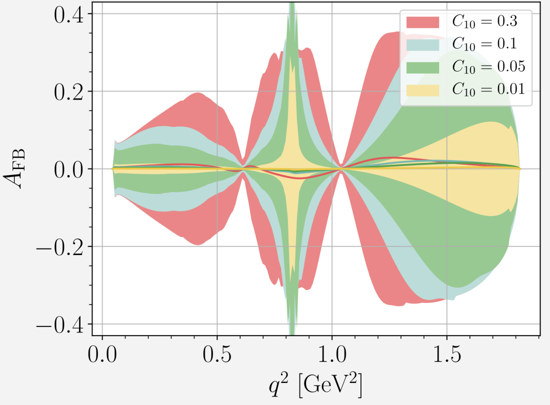
- Forward backward asymmetry of leptons

$$A_{\rm FB} = \frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\left[\int_0^1 - \int_{-1}^0\right]\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell}\,\mathrm{d}\cos\theta_\ell$$
$$\propto K_{1c}$$

- If $C_7^{(\prime)} = 0$ then

$$A_{\rm FB} \propto \mathrm{Re}\big(C_9\,C_{10}^* - C_9'\,C_{10}'^*\big)$$

- Large uncertainties due to strong phases
- SM null test!



Current bounds (2011.09478):
$$\left|C_{10}^{(\prime)\mu}\right| \lesssim 0.8$$

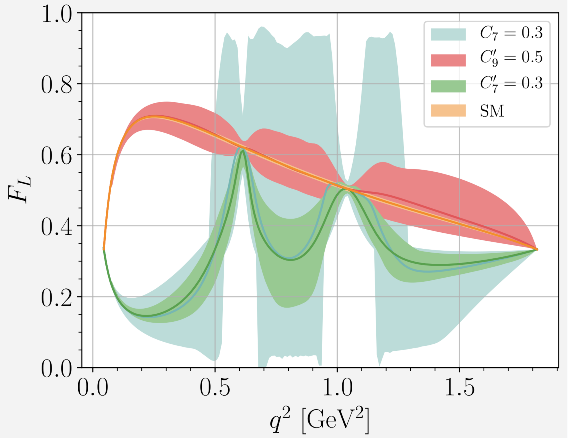
Fraction of longitudinal polarized dimuons

- In terms of angular observables:

$$F_L = \frac{2K_{1ss} - K_{1cc}}{2K_{1ss} + K_{1cc}}$$

- Not a SM null test
- Only resonances: C_9^R cancels out - small uncertainties
- Sensitive to $C_7^{(\prime)}$ contributions down to $\mathcal{O}(\%)$
- Endpoint relations

$$F_L(q^2_{\text{max}}) = F_L(q^2_{\text{min}}) = \frac{1}{3}$$



Current bounds (2011.09478):

$$\left|C_7^{(\prime)\mu}\right| \lesssim 0.3 \qquad \left|C_9^{(\prime)\mu}\right| \lesssim 0.9$$

Lepton flavor universality

- Similar to charm meson decays (1805.08516, 1909.11108)
- Ratio of integrated branching fractions for μ and e

$$R_p^{\Lambda_c} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\mathcal{B}(\Lambda_c \to p \mu^+ \mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\mathcal{B}(\Lambda_c \to p e^+ e^-)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

- $R_p^{\Lambda_c} - 1$ is a SM null test
- Full q^2 would not unveil NP because resonances dominate
- Low and high q^2 show clear deviations from 1 in the presence of NP

NP only couples to muons

	full q^2	low q^2	high q^2
SM	$1.00 \pm \mathcal{O}(\%)$	$0.94 \pm \mathcal{O}(\%)$	$1.00 \pm \mathcal{O}(\%)$
$\lvert C_9^\mu \rvert = 0.5$	SM-like	$7.5 \ldots 20$	$\mathcal{O}(100)$
$\lvert C_{10}^\mu \rvert = 0.5$	SM-like	$4.4 \ldots 13$	$\mathcal{O}(100)$
$\lvert C_9^{\prime\mu} \rvert = 0.5$	SM-like	$4.6 \ldots 14$	$\mathcal{O}(100)$
$\lvert C_{10}^{\prime\mu} \rvert = 0.5$	SM-like	$4.4 \ldots 13$	$\mathcal{O}(100)$

$$\text{full}: \quad 4m_\mu^2 \le q^2 \le (m_{\Lambda_c} - m_p)^2$$

$$\text{high}: \quad 1.25^2\mathrm{GeV}^2 \le q^2 \le (m_{\Lambda_c} - m_p)^2$$

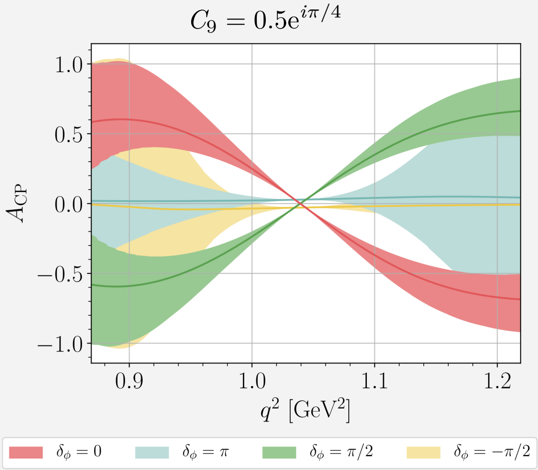
$$\text{low}: \quad 4m_\mu^2 \le q^2 \le 0.525^2\mathrm{GeV}^2$$

CP–asymmetry

- CP–violation in the SM is negligible
- CP–asymmetry constitutes a null test

$$A_{\text{CP}} = \frac{\mathrm{d}\Gamma/\mathrm{d}q^2 - \mathrm{d}\bar{\Gamma}/\mathrm{d}q^2}{\mathrm{d}\Gamma/\mathrm{d}q^2 + \mathrm{d}\bar{\Gamma}/\mathrm{d}q^2}$$

- Non vanishing CP–asymmetry would be a result of CP–violating NP in $C_9^{(\prime)}$ or $C_7^{(\prime)}$
- Right binning necessary to observe a signal



CP–asymmetry of A_{FB}

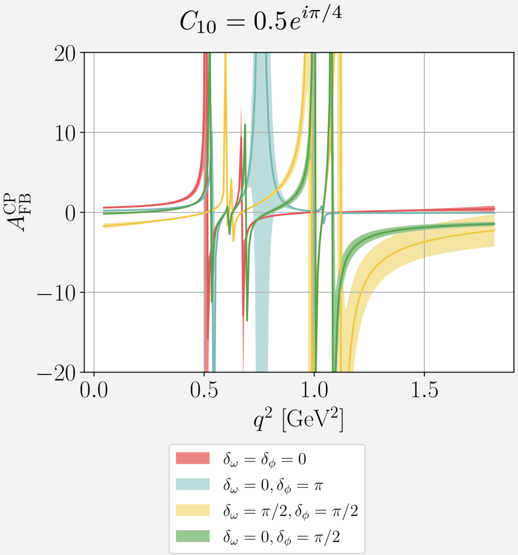
- CP asymmetry for angular observable

$$A_{\mathsf{FB}}^{\mathsf{CP}} = \frac{A_{\mathsf{FB}} + \bar{A}_{\mathsf{FB}}}{A_{\mathsf{FB}} - \bar{A}_{\mathsf{FB}}}$$

$$A_{\mathsf{FB}}^{\mathsf{CP}} = \frac{\mathrm{Im}\ C_9^R}{\mathrm{Re}\ C_9^R} \frac{\mathrm{Im}\ C_{10}}{\mathrm{Re}\ C_{10}}$$

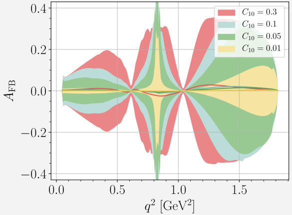
$$= \frac{(q^2 - m_\phi^2)\ \tan\delta_\phi - m_\phi\Gamma_\phi}{q^2 - m_\phi^2 + m_\phi\Gamma_\phi\ \tan\delta_\phi} \cdot \frac{\mathrm{Im}\ C_{10}}{\mathrm{Re}\ C_{10}}$$

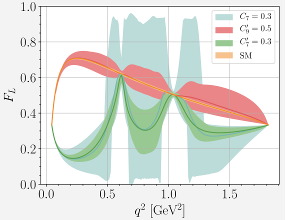
- Position of divergence depends on strong phases
- SM null test sensitive to $\mathrm{Im}\, C_{10}$



Summary

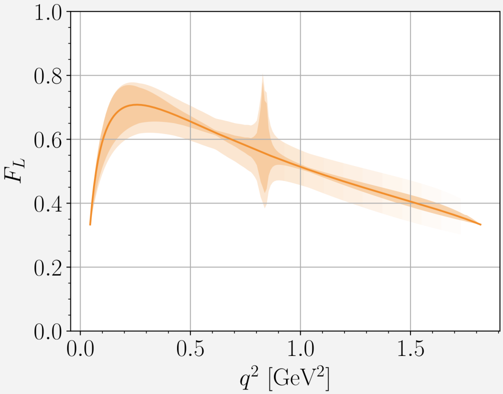
1. Rare charm baryon decays $\Lambda_c \to p\ell\ell$, $\Xi_c \to \Sigma(\Lambda)\ell\ell$ and $\Omega_c^0 \to \Xi^0\ell\ell$ can probe NP in up-type sector
2. Null tests and other suitable observables circumvent hadronic uncertainties
3. Complementary sensitivity to meson decays for potential future global fit

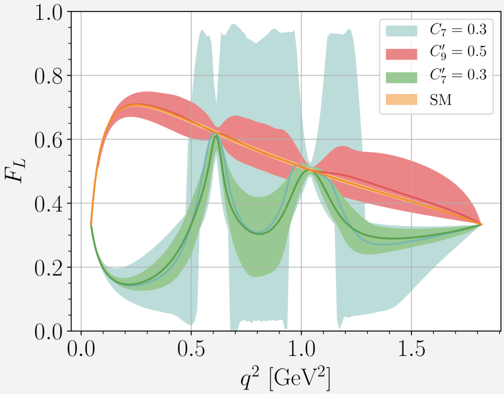




Backup

F_L

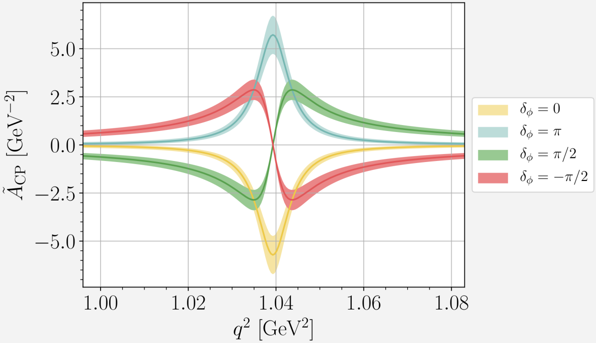

1.0
0.8
0.6
0.4
0.2
0.0
F_L
0.0
0.5
1.0
1.5
q^2 [GeV^2]


$C_7 = 0.3$
$C_9' = 0.5$
$C_7' = 0.3$
SM
1.0
0.8
0.6
0.4
0.2
0.0
F_L
0.0
0.5
1.0
1.5
q^2 [GeV^2]

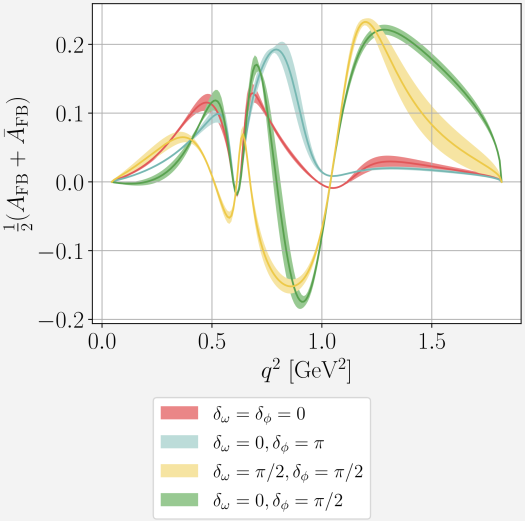
CP–asymmetry normalization

- Alternative normalization to the integrated decay rate

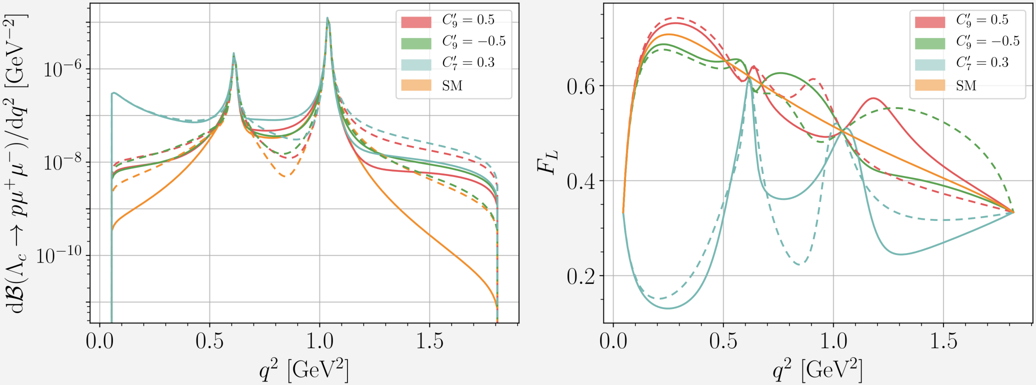
$$\tilde{A}_{\mathsf{CP}} = \frac{\mathrm{d}\Gamma/\mathrm{d}q^2 \; - \; \mathrm{d}\bar{\Gamma}/\mathrm{d}q^2}{\Gamma \; + \; \bar{\Gamma}}$$



$A_{\mathrm{FB}}^{\mathrm{CP}}$

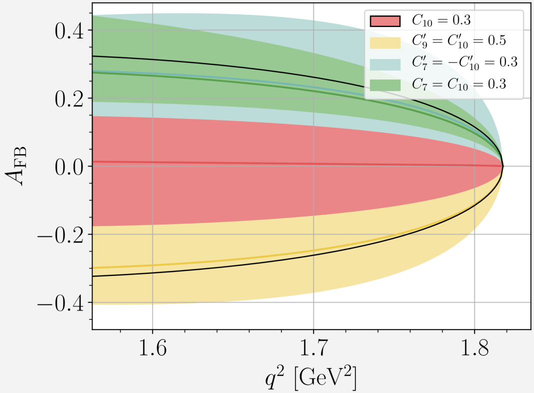


F_L



$C_9' = 0.5$
$C_9' = -0.5$
$C_7' = 0.3$
SM
$\mathrm{d}\mathcal{B}(\Lambda_c \to p\mu^+\mu^-)/\mathrm{d}q^2$ [GeV^{-2}]
10^{-6}
10^{-8}
10^{-10}
0.0
0.5
1.0
1.5
q^2 [GeV^2]
$C_9' = 0.5$
$C_9' = -0.5$
$C_7' = 0.3$
SM
F_L
0.6
0.4
0.2
0.0
0.5
1.0
1.5
q^2 [GeV^2]

A_{FB}



$C_{10} = 0.3$
$C'_9 = C'_{10} = 0.5$
$C'_7 = -C'_{10} = 0.3$
$C_7 = C_{10} = 0.3$
0.4
0.2
0.0
−0.2
−0.4
A_{FB}
1.6
1.7
1.8
q^2 [GeV^2]