New physics in rare semileptonic charm baryon decays (theory)

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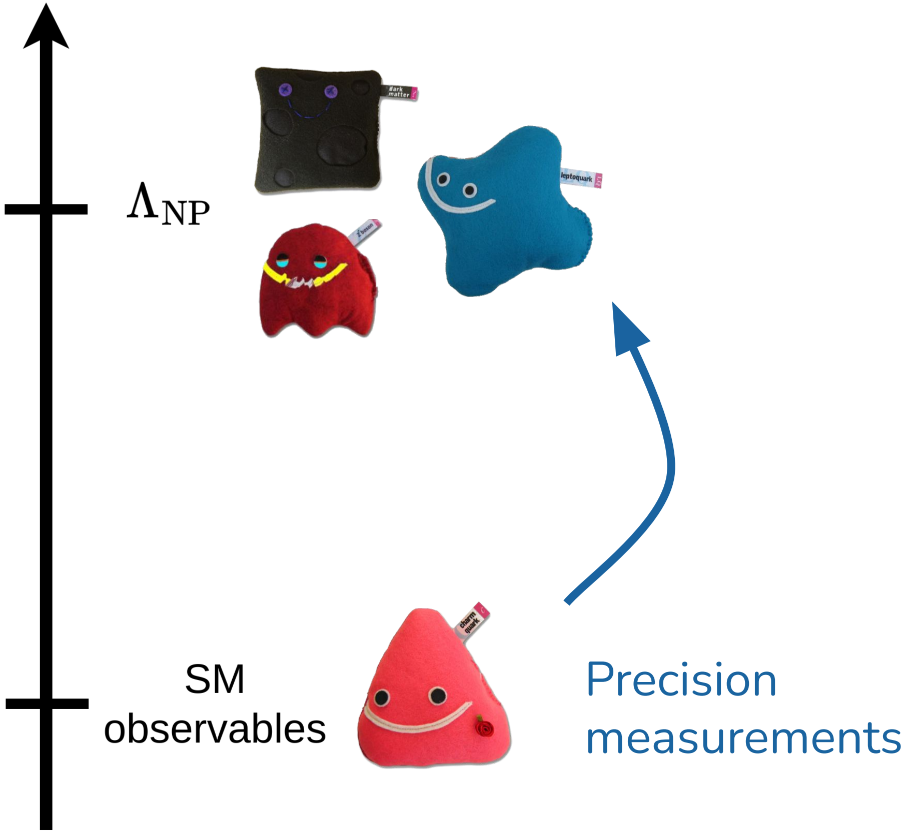
23.04.2024

based on:

2107.13010
2202.02331

with Marcel Golz
and Gudrun Hiller

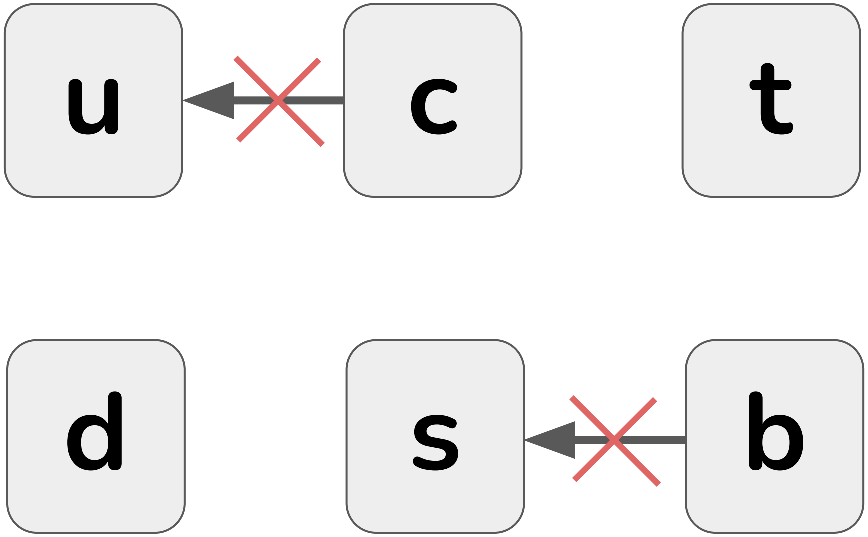
Indirect NP searches



FCNCs as rare processes for NP sensitivity

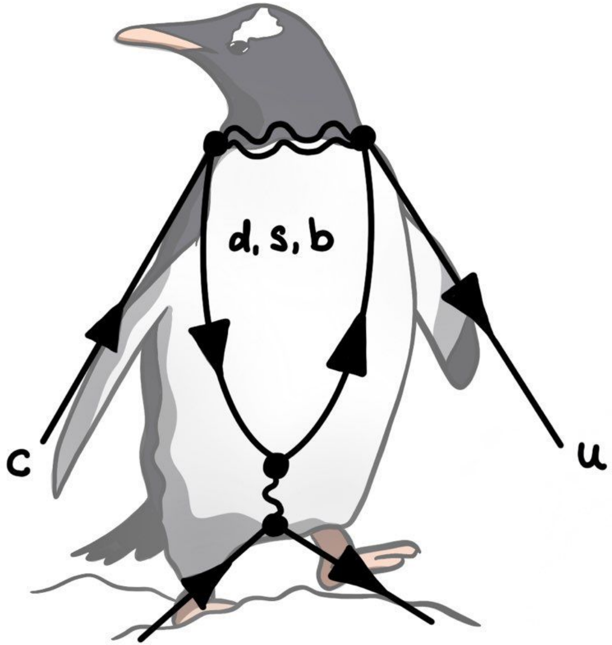
- In the SM: No FCNCs at tree level
- Rare semileptonic processes:

$$b \to s\ell\ell$$
$$c \to u\ell\ell$$



FCNCs as rare processes for NP sensitivity

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

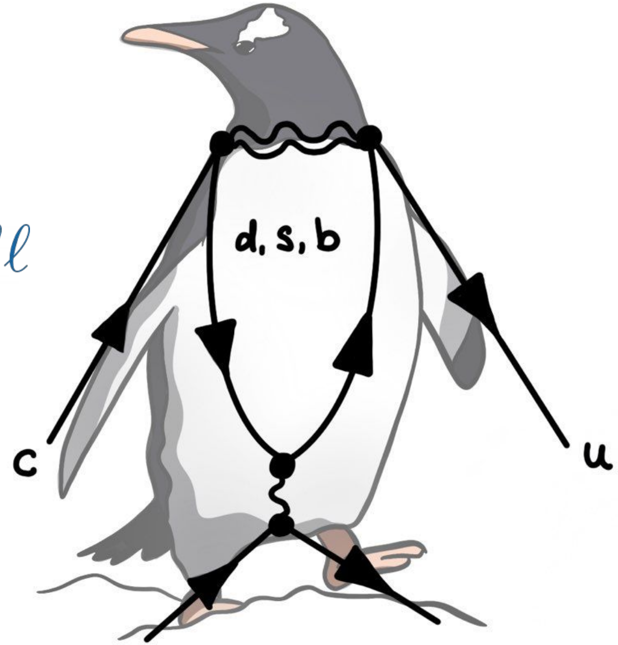


FCNCs as rare processes for NP sensitivity

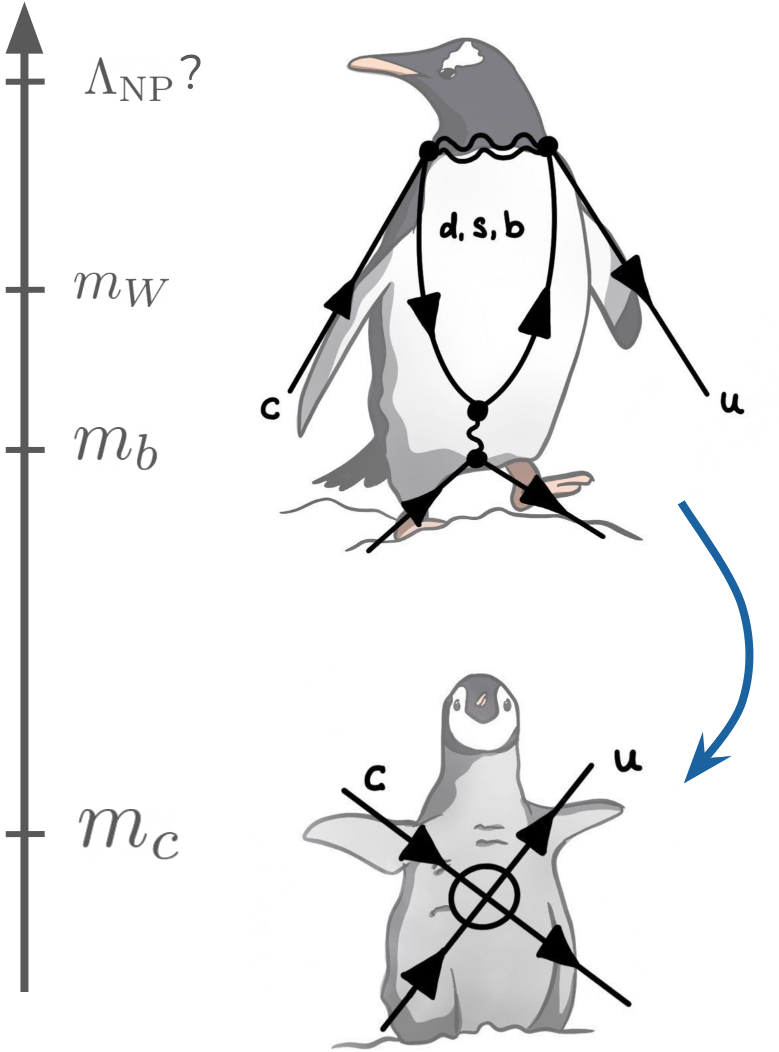
$$b \to s\ell\ell$$

$$c \to u\ell\ell$$

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



EFT:



Weak effective theory $c \to u\ell\ell$

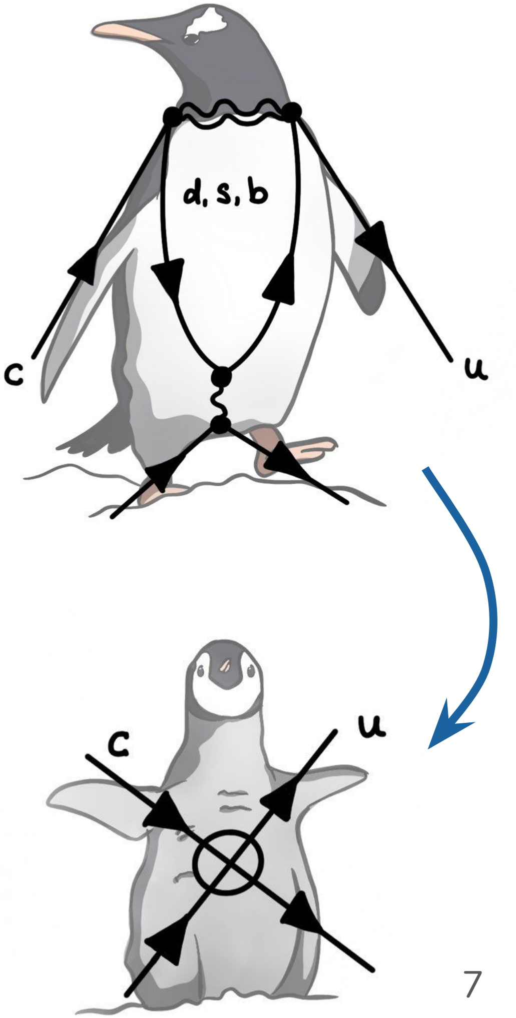
$$\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left[\sum_{i=7,9,10}(C_i O_i + C_i' O_i') + C_P O_P\right]$$

$$O_7 = \frac{m_c}{e}(\bar{u}_L \sigma_{\mu\nu} c_R) F^{\mu\nu}$$

$$O_9 = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \ell)$$

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

$$O_P = (\bar{u}_L c_R)(\bar{l}\gamma_5 \ell)$$



SM contributions $c \to u\ell\ell$

$$\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left[\sum_{i=7,9,10}(C_i O_i + C_i' O_i') + C_P O_P\right]$$

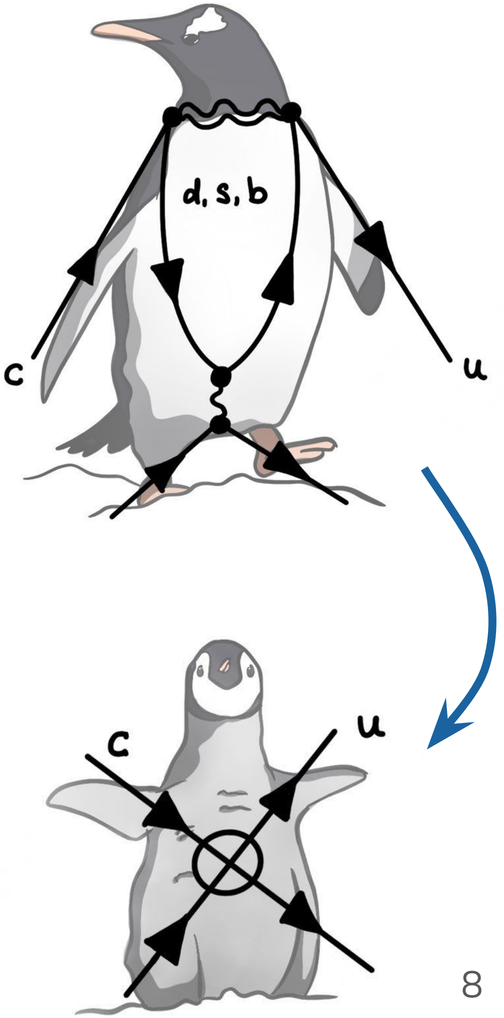
$$O_7 = \frac{m_c}{e}(\bar{u}_L \sigma_{\mu\nu} c_R) F^{\mu\nu} \qquad |C_7| \sim \mathcal{O}(10^{-3})$$

$$O_9 = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \ell) \qquad |C_9| \sim \mathcal{O}(10^{-1})$$

$$O_{10} = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \qquad C_{10} = 0$$

$$O_P = (\bar{u}_L c_R)(\bar{l}\gamma_5 \ell)$$

de Boer, S., & Hiller, G. (2016). Flavor and new physics opportunities with rare charm decays into leptons. *Physical Review D*, *93*(7), 074001.



"short-distance contributions"

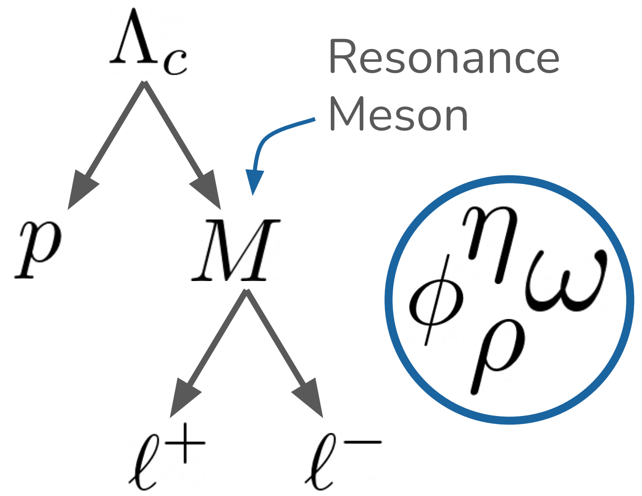
Long distance resonance contributions

- Non factorizable SM contributions
- Phenomenological model:

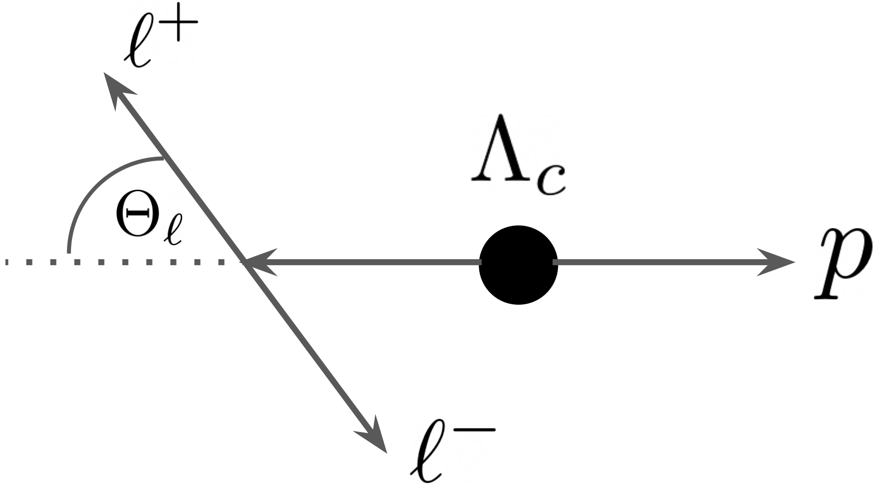
$$C_i^R = \frac{a_M e^{i\delta_M}}{q^2 - m_M^2 + i m_M \Gamma_M}$$

- a_M, δ_M are parameters
- Determine a_M from data by

$$\mathcal{B}(\Lambda_c \to p\mu^+\mu^-) = \mathcal{B}_{\exp}(\Lambda_c \to pM)\mathcal{B}_{\exp}(M \to \mu^+\mu^-)$$



Kinematics



- Dilepton invariant mass q^2

Helicity formalism

$$A \rightarrow \left.\begin{matrix} b \\ a \end{matrix}\right\} \; |p, \Theta, \phi, \lambda_a, \lambda_b\rangle$$

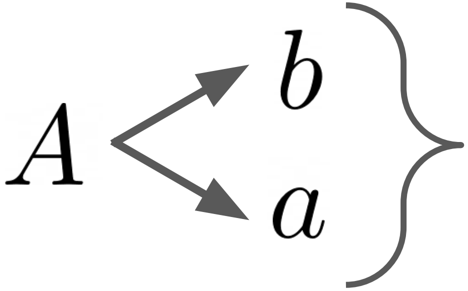
Write in terms of

$$|p, J, M, \lambda_a, \lambda_b\rangle$$

rotate states

$$R(\alpha,\beta,\gamma)\,|j,m\rangle = \sum_{m'=-j}^{j} D^{j}_{m',m}(\alpha,\beta,\gamma)\,|j,m'\rangle$$

Helicity formalism



$$|p, \Theta, \phi, \lambda_a, \lambda_b\rangle$$

$$\mathcal{A}(A \to ab) \propto \underbrace{D^{*J}_{M,\lambda_a - \lambda_b}(\Omega_f)}_{\text{Angular part}} \underbrace{A_{\lambda_a,\lambda_b}}_{\text{Helicity Amplitude}}$$

Helicity amplitudes

$$\mathcal{H}_{\lambda_p,\lambda_\gamma} \qquad \mathcal{L}_{\lambda_\gamma,\lambda_+,\lambda_-}$$

Hadronic

$$\langle p|\bar{u}\gamma^\mu c|\Lambda_c\rangle$$

Formfactors - Lattice QCD

Leptonic

Evaluate in CM frame

Meinel, S. (2018). Λ c→ N form factors from lattice QCD and phenomenology of Λ c→ n ℓ+ ν ℓ and Λ c→ p μ+ μ− decays. *Physical Review D*, *97*(3), 034511.

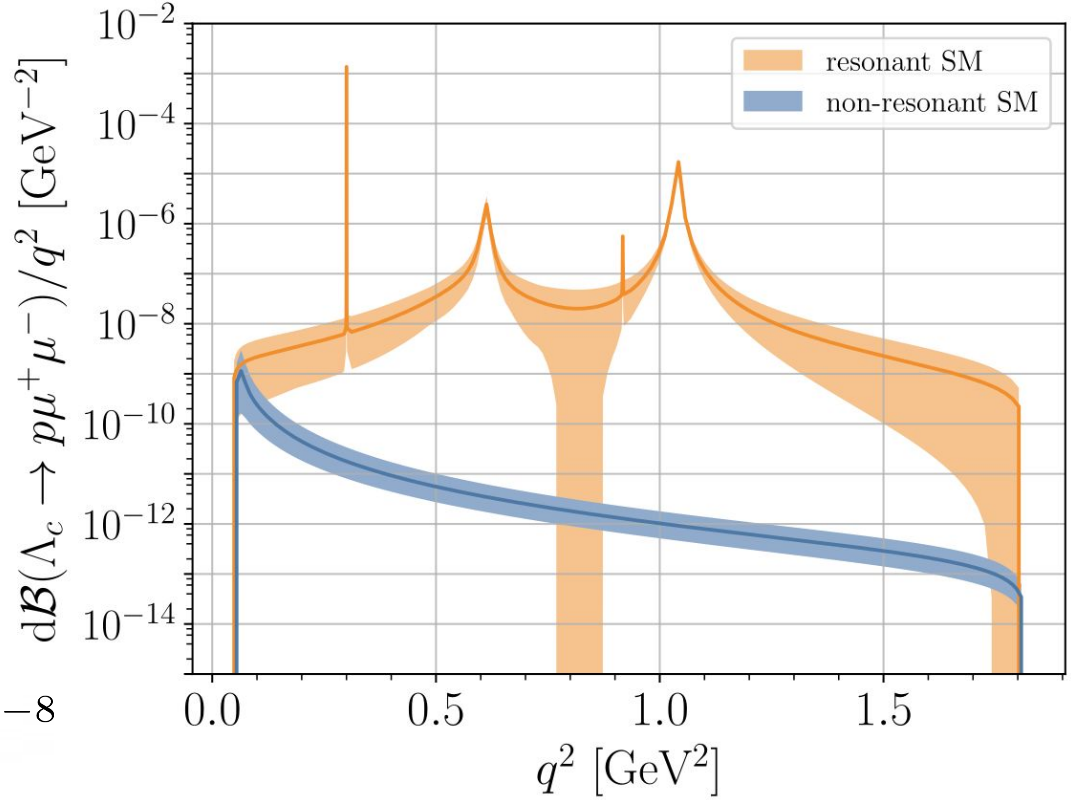
Angular distribution

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

Angular observables
depend on Wilson coefficients

Branching Ratio

$$\frac{d\Gamma}{dq^2} = \int_{-1}^{1} \frac{d^2\Gamma}{dq^2 d\cos\Theta_\ell} d\cos\Theta_\ell$$
$$= 2K_{1ss} + K_{1cc}$$

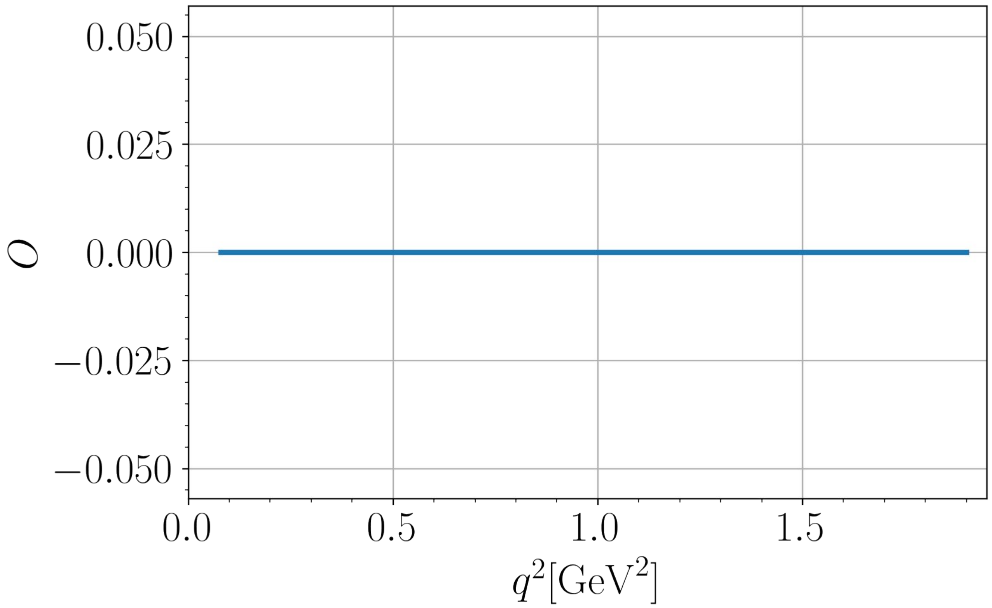


$$\mathcal{B}(\Lambda_c \to p\mu^+\mu^-) = (1.9^{+1.8}_{-1.5}) \times 10^{-8}$$

excluding $\pm 40\mathrm{MeV}$
around Resonances

Large uncertainties, no precision test possible

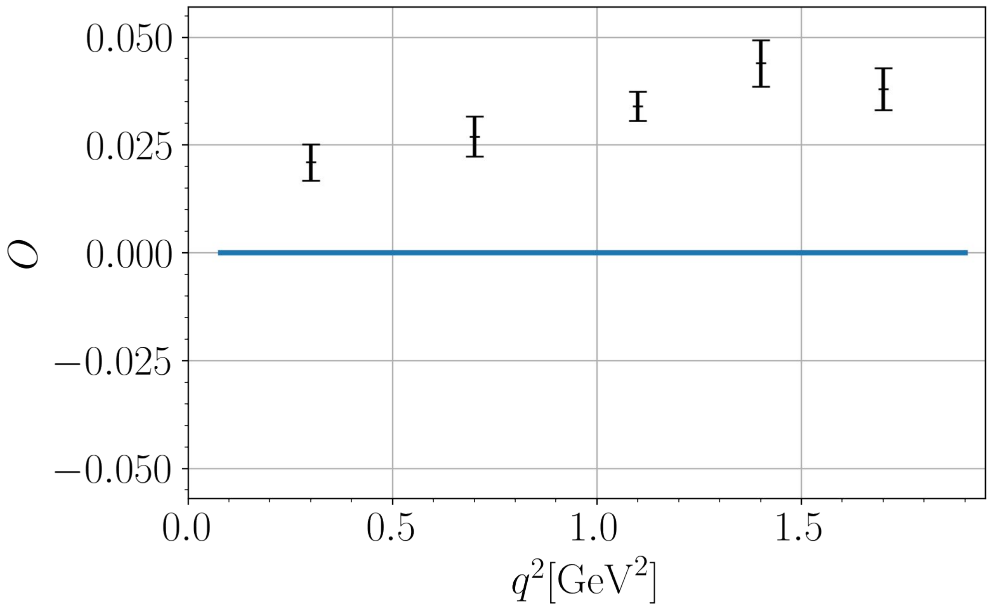
Null tests



No SM uncertainty

Observable which is zero in the SM

Null tests



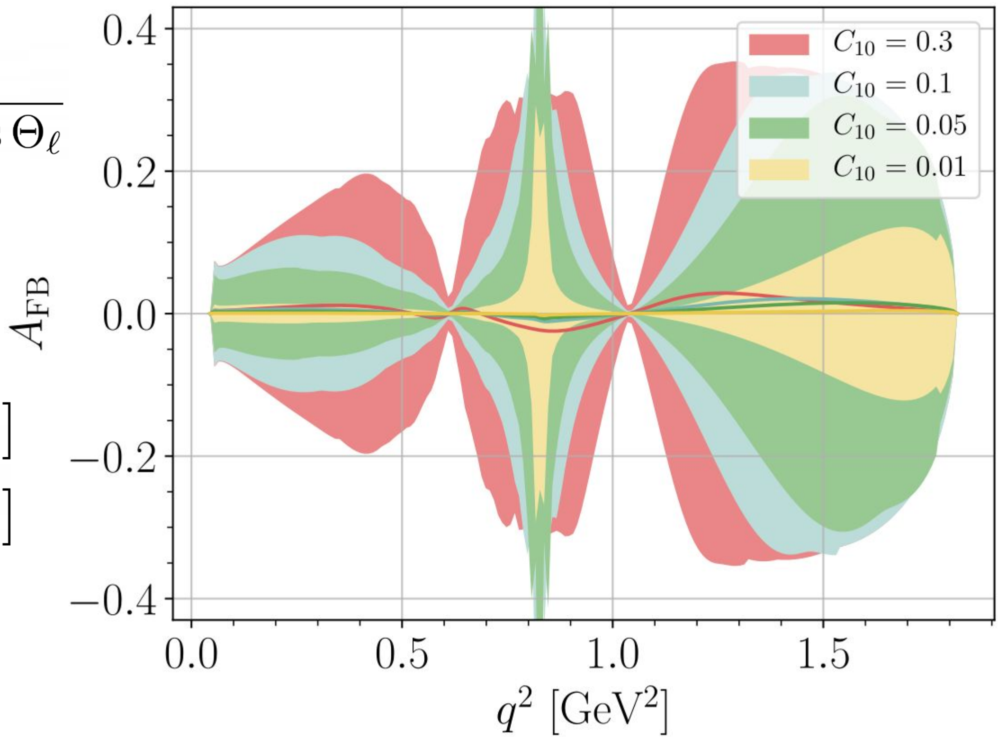
No SM uncertainty

Any signal hints at NP

Forward-backward asymmetry

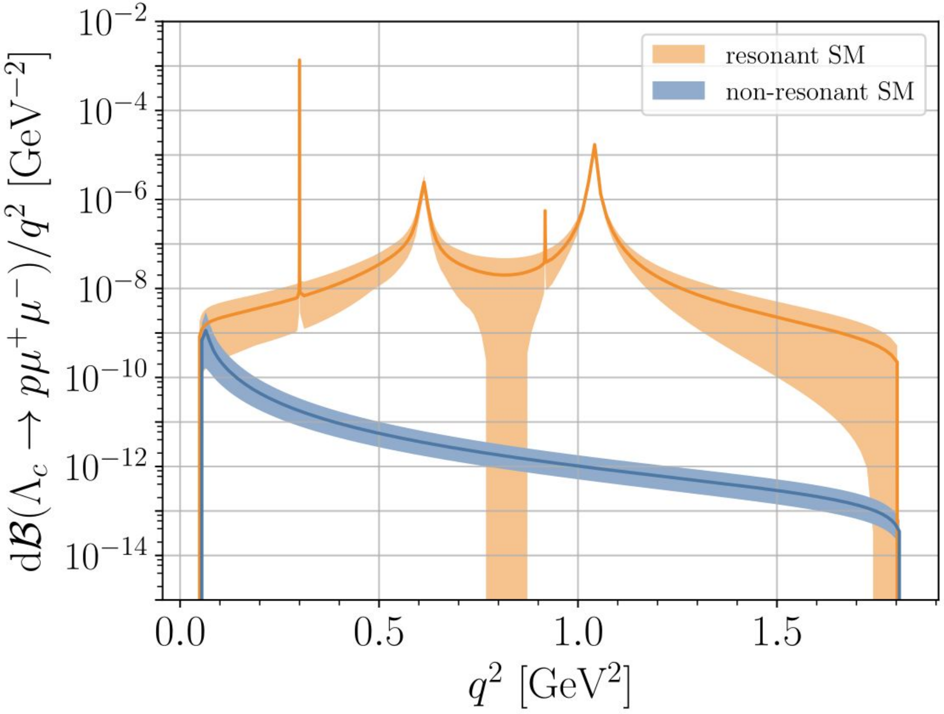
$$A_{\rm FB} = \frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\left[\int_0^1 - \int_{-1}^0\right]\mathrm{d}\cos\Theta_\ell \frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\Theta_\ell}$$
$$= \frac{3}{2}\frac{K_{1c}}{K_{1ss}+K_{1cc}}$$

$$K_{1c} \propto F_1 \mathrm{Re}\left[(C_7 - C_7')(C_{10}^* + C_{10}'^*)\right] + F_2 \mathrm{Re}\left[(C_7 + C_7')(C_{10}^* - C_{10}'^*)\right] + F_3 \mathrm{Re}\left[C_9 C_{10}^* - C_9' C_{10}'^*\right]$$



Lepton flavor universality

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



	SM	$\lvert C_9^\mu\rvert = 0.5$	$\lvert C_{10}^\mu\rvert = 0.5$	$\lvert C_9^\mu\rvert = \lvert C_{10}^\mu\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like

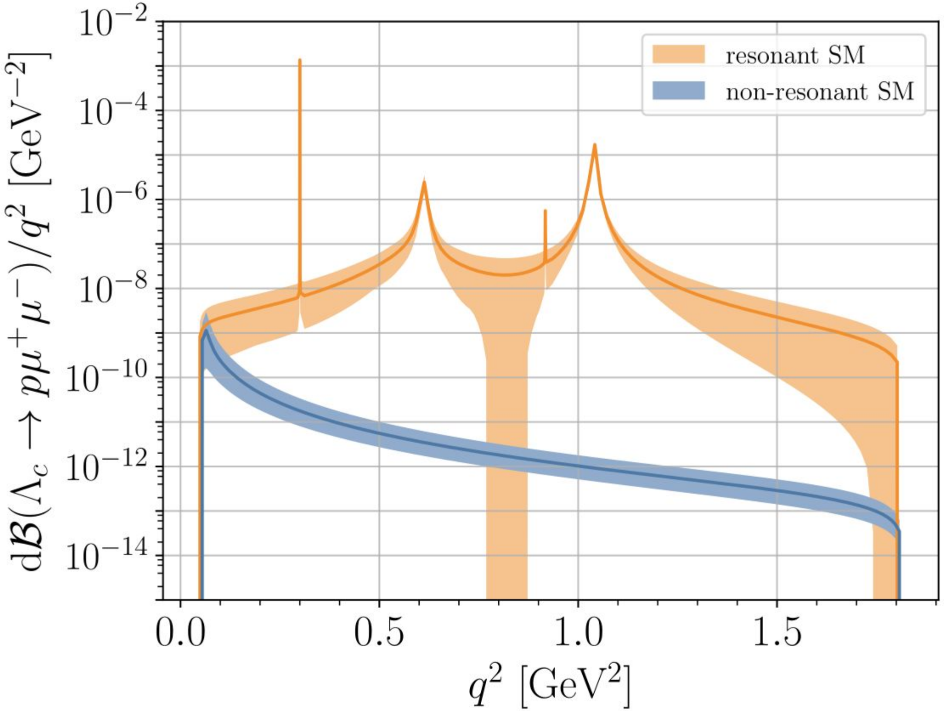
Lepton flavor universality

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

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

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

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



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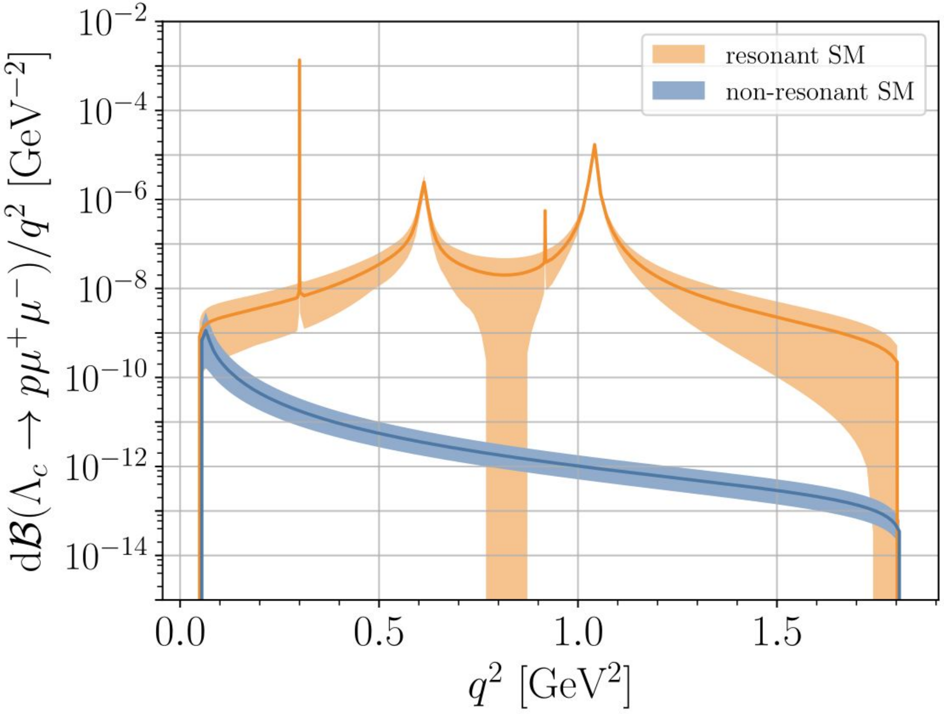


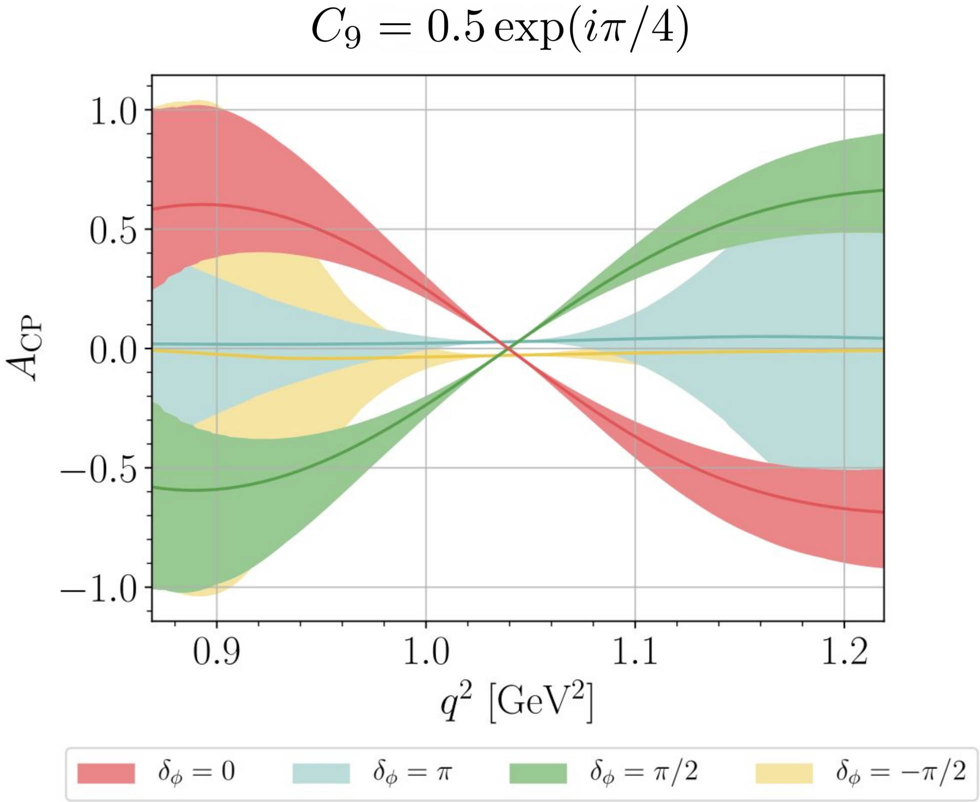
	SM	$\lvert C_9^\mu\rvert = 0.5$	$\lvert C_{10}^\mu\rvert = 0.5$	$\lvert C_9^\mu\rvert = \lvert C_{10}^\mu\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like
low q^2	$0.94 \pm \mathcal{O}(\%)$	$7.5 \ldots 20$	$4.4 \ldots 13$	$11 \ldots 32$
high q^2	$1.00 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$

CP-asymmetry

- SM source of CP violation: CKM - negligible

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

- Correct binning required



Lepton flavor violation

- Same calculation with $\ell \neq \ell'$

$$\mathcal{H}_{\text{eff}}^{\text{LFV}} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\sum_{i=9,10}\left(K_i^{(\ell\ell')}O_i^{(\ell\ell')} + K_i'^{(\ell\ell')}O_i'^{(\ell\ell')}\right)$$

Bounds from $D \to \pi\mu e:\ \left|K_9^{(\prime)(\mu e)}\right| \lesssim 1.6, \quad \left|K_{10}^{(\prime)(\mu e)}\right| \lesssim 1.6$

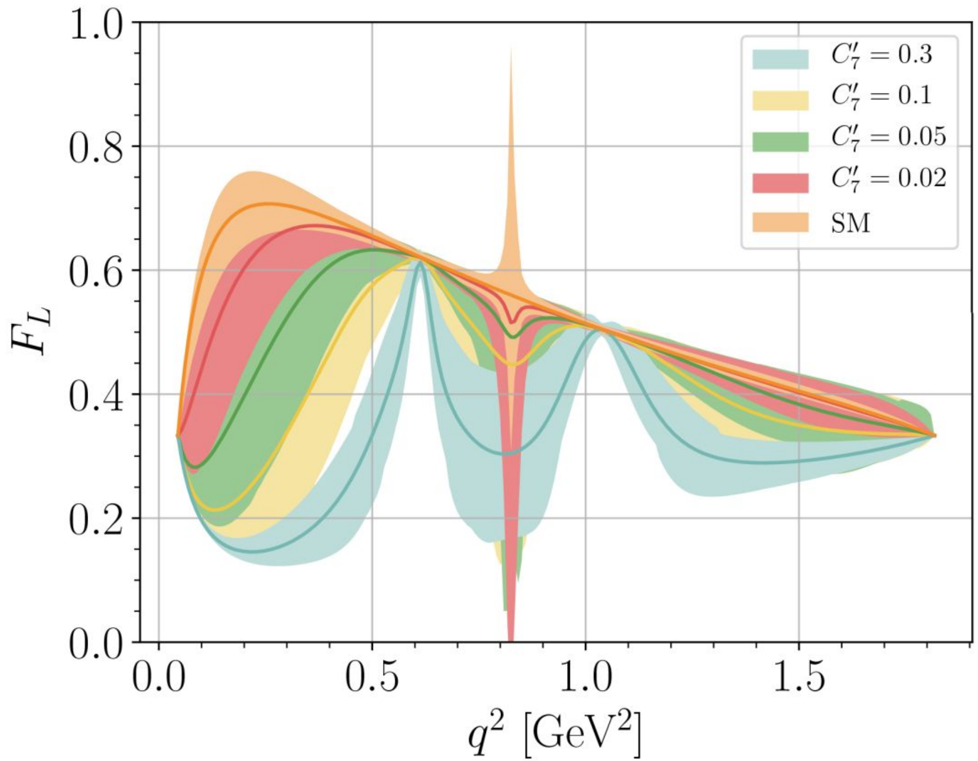
$$\mathcal{B}(\Lambda_c \to p\mu^{\pm}e^{\mp}) \lesssim 8.2 \cdot 10^{-7}$$

Fraction of longitudinally polarized dimuons

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

- Not a Null test!
- Maybe sufficient sensitivity to disentangle NP in C_7 or C_7'

$$\left|C_7^{(\prime)}\right| \lesssim 0.3$$



Summary

1. Angular distribution from Helicity formalism

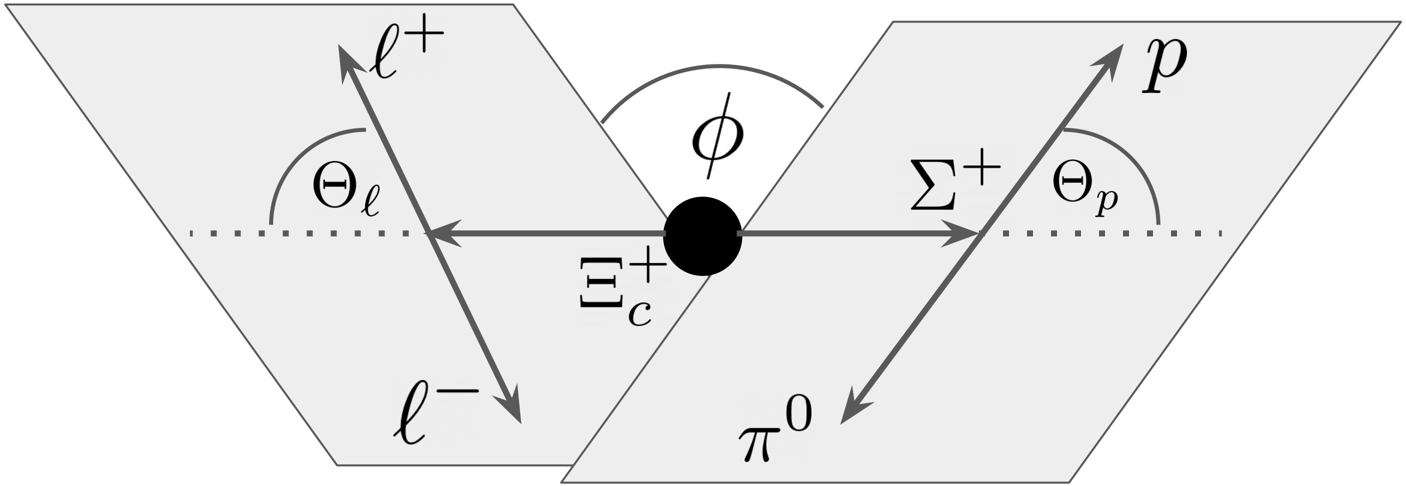
$$\frac{d^2\Gamma}{dq^2 d\cos\Theta_\ell} = \frac{3}{2}\left(K_{1ss}\sin^2\Theta_\ell + K_{1cc}\cos^2\Theta_\ell + K_{1c}\cos\Theta_\ell\right)$$

2. Branching fraction large uncertainties from long distance SM contributions

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

3. Null tests for NP: $A_{\mathrm{FB}} \propto C_{10}$ and C'_{10}
4. $R^{\Lambda_c}(p)$ to test LVU violation
5. Potentially test Lepton flavor violation in $\Lambda_c \to p\mu^\pm e^\mp$
6. Fraction of longitudinally polarized dimuons F_L to test C_7 and C'_7

Outlook four body decays $\Xi_c^+ \to \Sigma^+(\to p\pi^0)\ell^+\ell^-$



- Dilepton invariant mass q^2

Outlook four body decays $\Xi_c^+ \to \Sigma^+(\to p\pi^0)\ell^+\ell^-$

- Additional helicity amplitude for $\Sigma^+ \to p\pi^0$: $\quad h^{\Sigma}_{\lambda_p}$
- Self analyzing decays:

$$\alpha = \frac{|h^{\Sigma}_{1/2}|^2 - |h^{\Sigma}_{-1/2}|^2}{|h^{\Sigma}_{1/2}|^2 + |h^{\Sigma}_{-1/2}|^2]}$$

Decay	$\mathcal{B}(B_1 \to B_2\pi)$	α^{PDG}
$\Sigma^+ \to p\pi^0$	$51.6 \pm 0.3\%$	-0.98 ± 0.01
$\Xi^0 \to \Lambda^0\pi^0$	$99.5 \pm 0.0\%$	-0.36 ± 0.01
$\Lambda^0 \to p\pi^-$	$63.9 \pm 0.5\%$	0.73 ± 0.01

Angular distribution $\Xi_c^+ \to \Sigma^+(\to p\pi^0)\ell^+\ell^-$

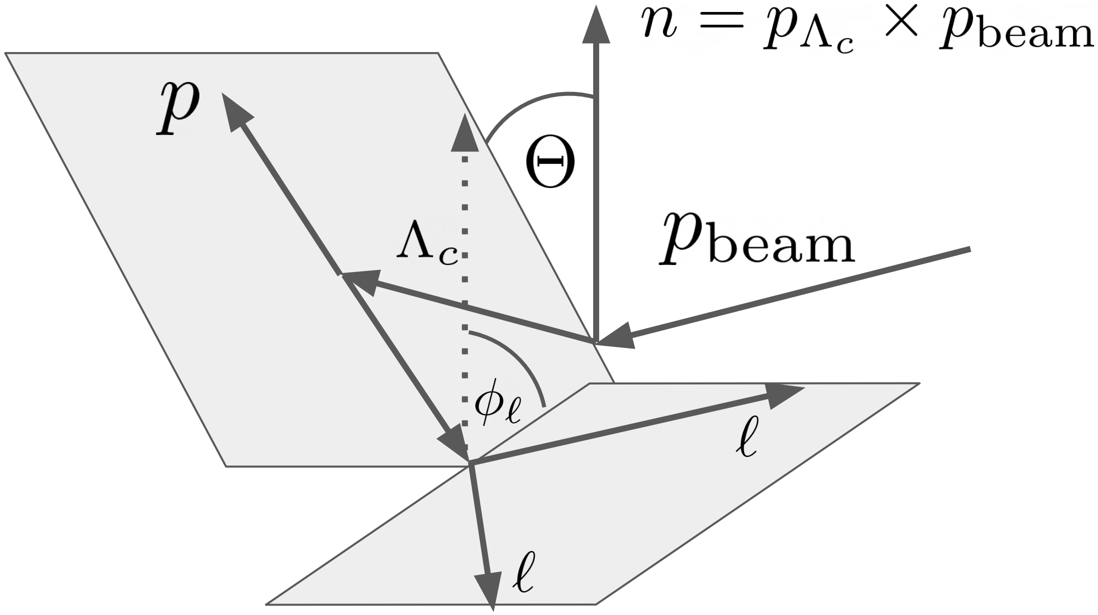
Three-body

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\Theta_\ell\mathrm{d}\cos\Theta_p\mathrm{d}\phi} \propto \boxed{\left(K_{1ss}\sin^2\Theta_\ell + K_{1cc}\cos^2\Theta_\ell + K_{1c}\cos\Theta_\ell\right)}$$
$$+\left(K_{2ss}\sin^2\Theta_\ell + K_{2cc}\cos^2\Theta_\ell + K_{2c}\cos\Theta_\ell\right)\cos\Theta_p$$
$$+\left(K_{3sc}\sin\Theta_\ell\cos\Theta_\ell + K_{3s}\sin\Theta_\ell\right)\sin\Theta_p\cos\phi$$
$$+\left(K_{4sc}\sin\Theta_\ell\cos\Theta_\ell + K_{4s}\sin\Theta_\ell\right)\sin\Theta_p\sin\phi,$$

K_{2c} Null test $A_{\mathrm{FB}}^{\mathrm{Comb}}$

Pin down Wilson coefficients $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

Polarized Λ_c



Polarized Λ_c angular distribution

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\Theta\mathrm{d}\cos\Theta_\ell\mathrm{d}\phi_\ell} \propto K_{1ss}\sin^2\Theta_\ell + K_{1cc}\cos^2\Theta_\ell + K_{1c}\cos\Theta_\ell$$
$$+\left(K_{11}\sin^2\Theta_\ell + K_{12}\cos^2\Theta_\ell + K_{13}\cos\Theta_\ell\right)\cos\Theta$$
$$+\left(K_{21}\cos\Theta_\ell\sin\Theta_\ell + K_{22}\sin\Theta_\ell\right)\sin\phi_\ell\sin\Theta$$
$$+\left(K_{23}\cos\Theta_\ell\sin\Theta_\ell + K_{24}\sin\Theta_\ell\right)\cos\phi_\ell\sin\Theta$$

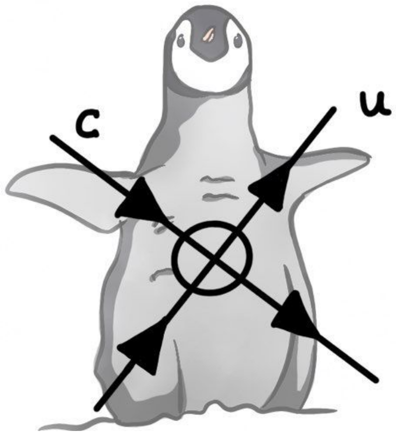
Polarized Λ_c angular distribution

$$
\begin{aligned}
\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\Theta\mathrm{d}\cos\Theta_\ell\mathrm{d}\phi_\ell} \propto\ & K_{1ss}\sin^2\Theta_\ell + K_{1cc}\cos^2\Theta_\ell + K_{1c}\cos\Theta_\ell \\
&+ \left(\boxed{K_{11}}\sin^2\Theta_\ell + \boxed{K_{12}}\cos^2\Theta_\ell + \boxed{K_{13}}\cos\Theta_\ell\right)\cos\Theta \\
&+ \left(\boxed{K_{21}}\cos\Theta_\ell\sin\Theta_\ell + \boxed{K_{22}}\sin\Theta_\ell\right)\sin\phi_\ell\sin\Theta \\
&+ \left(\boxed{K_{23}}\cos\Theta_\ell\sin\Theta_\ell + \boxed{K_{24}}\sin\Theta_\ell\right)\cos\phi_\ell\sin\Theta
\end{aligned}
$$

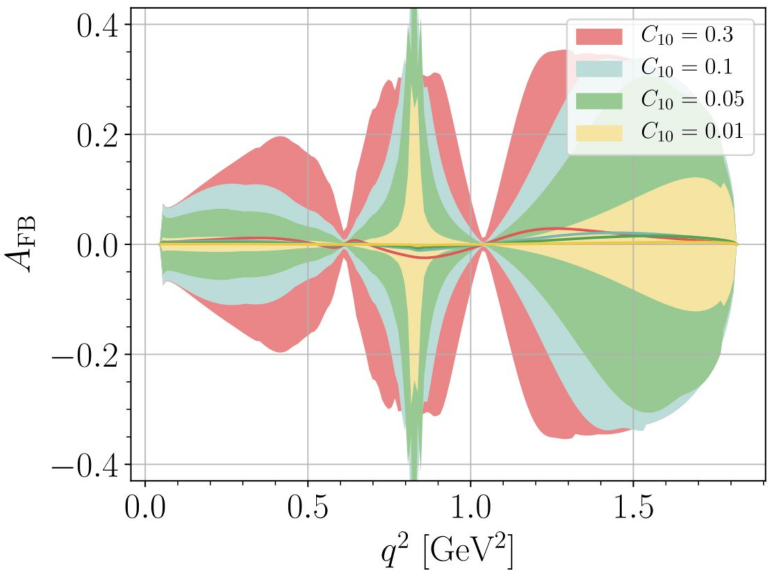
$$\propto P_{\Lambda_c}$$

K_{13}, K_{22}, K_{24} **Null tests!**

Summary



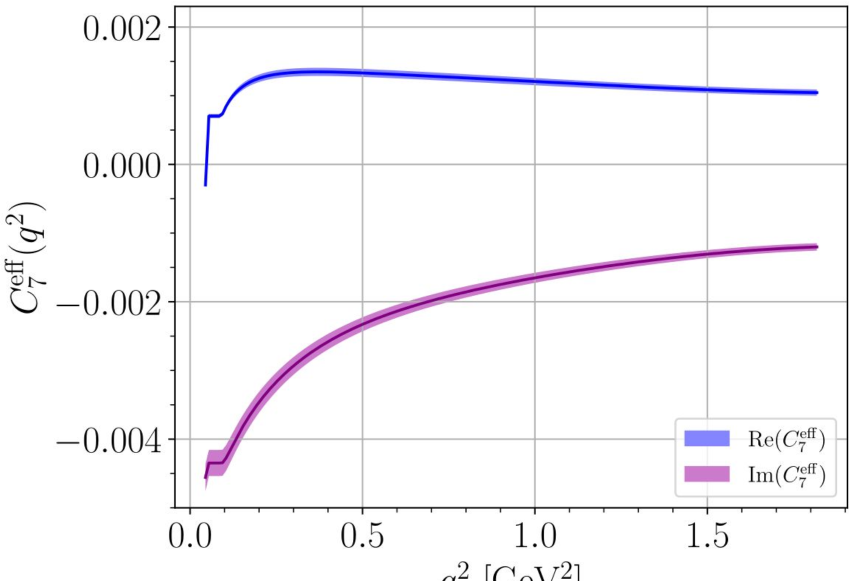
- Potential to test for NP with null tests
- Observables with Wilson coefficient sensitivity
- Future global fit of Wilson coefficients

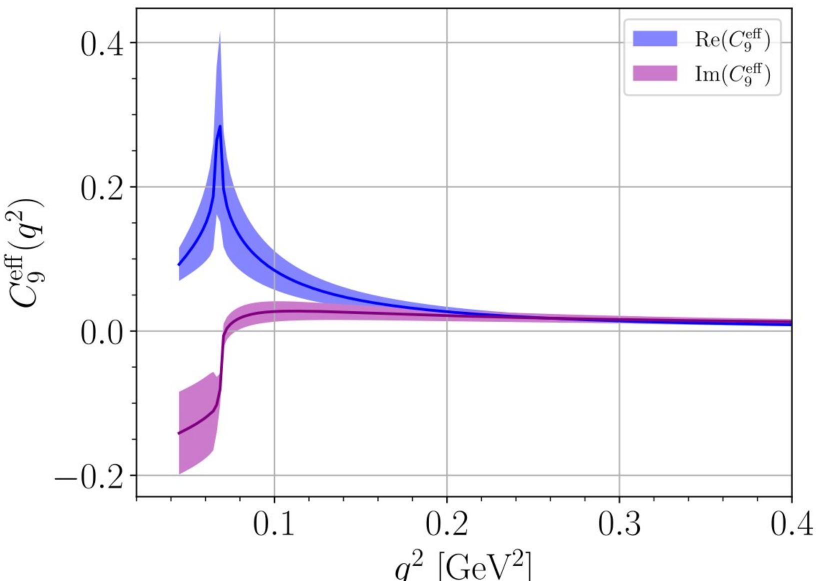


Backup slides

SM contributions $c \to u\ell\ell$

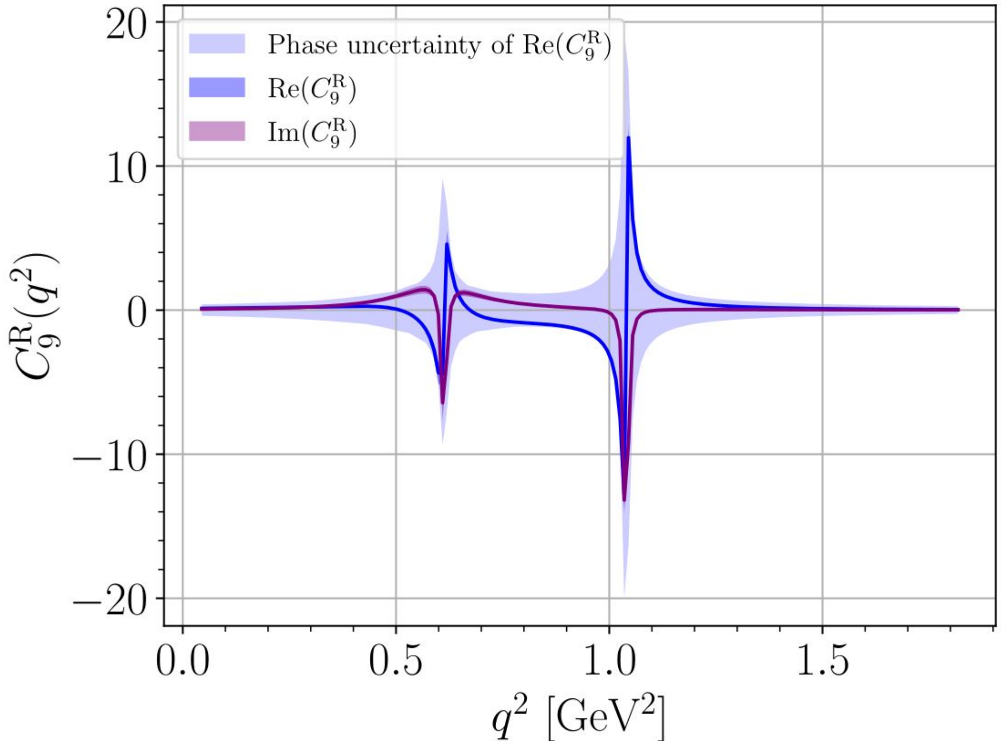
$$\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left[\sum_{i=7,9,10}(C_iO_i + C_i'O_i') + C_PO_P\right]$$





SM contributions $c \to u\ell\ell$

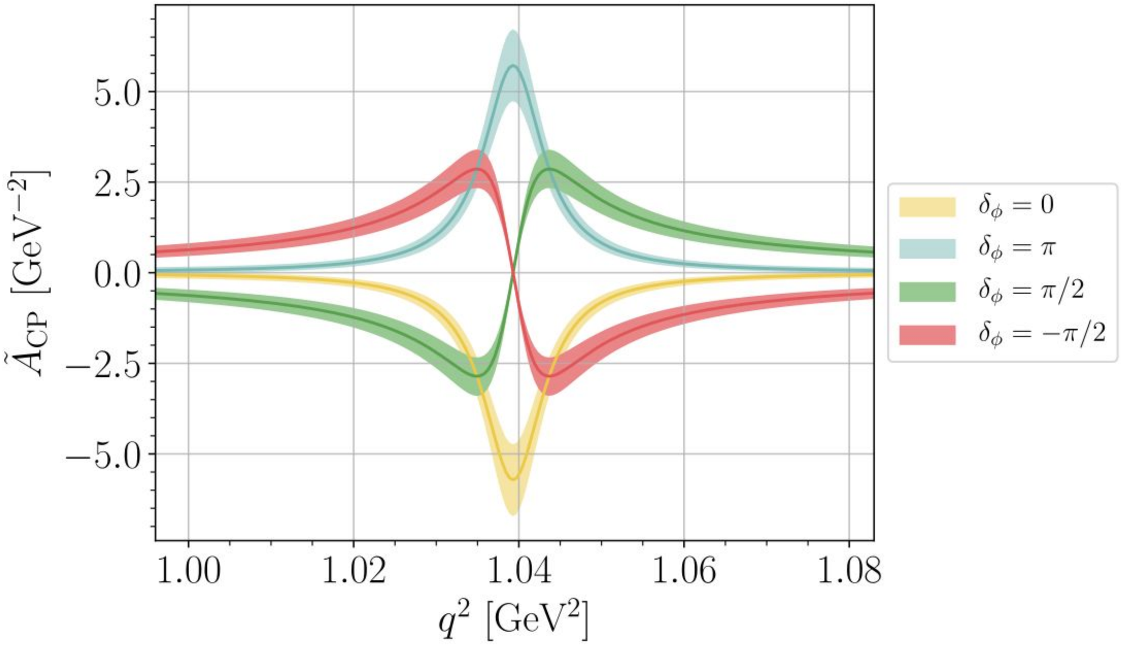
M	m	Γ	J^P
η	(547.8 ± 0.0) MeV	(1.3 ± 0.0) keV	0^-
ρ	(775.3 ± 0.2) MeV	(147.4 ± 0.8) MeV	1^-
ω	(782.7 ± 0.1) MeV	(8.6 ± 0.1) MeV	1^-
η'	(957.8 ± 0.0) MeV	(0.2 ± 0.0) MeV	0^-
ϕ	(1019.5 ± 0.0) MeV	(4.2 ± 0.0) MeV	1^-



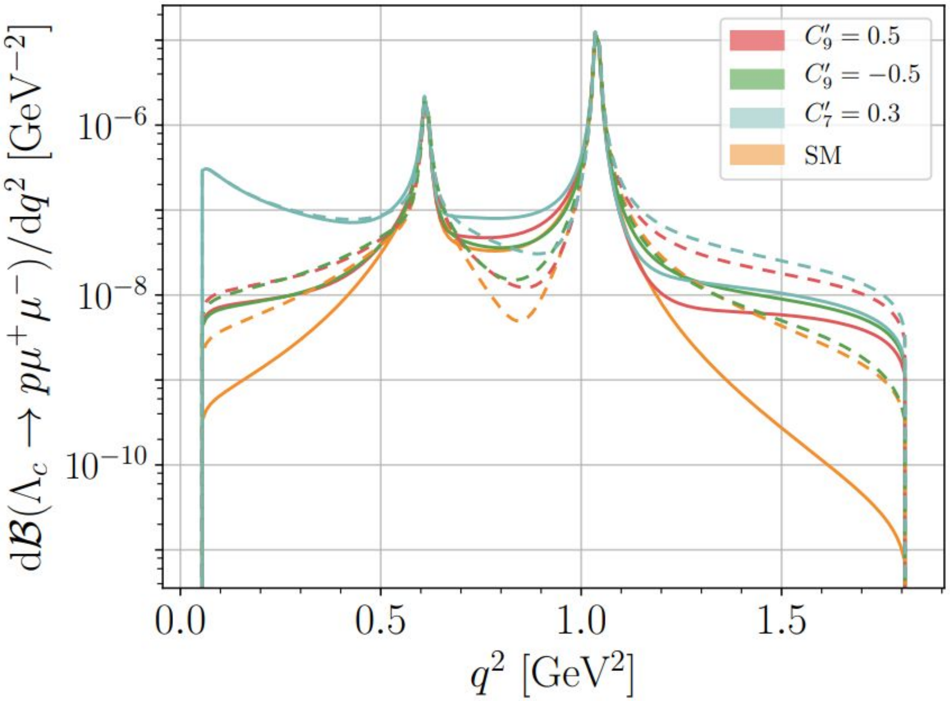
CP-asymmetry

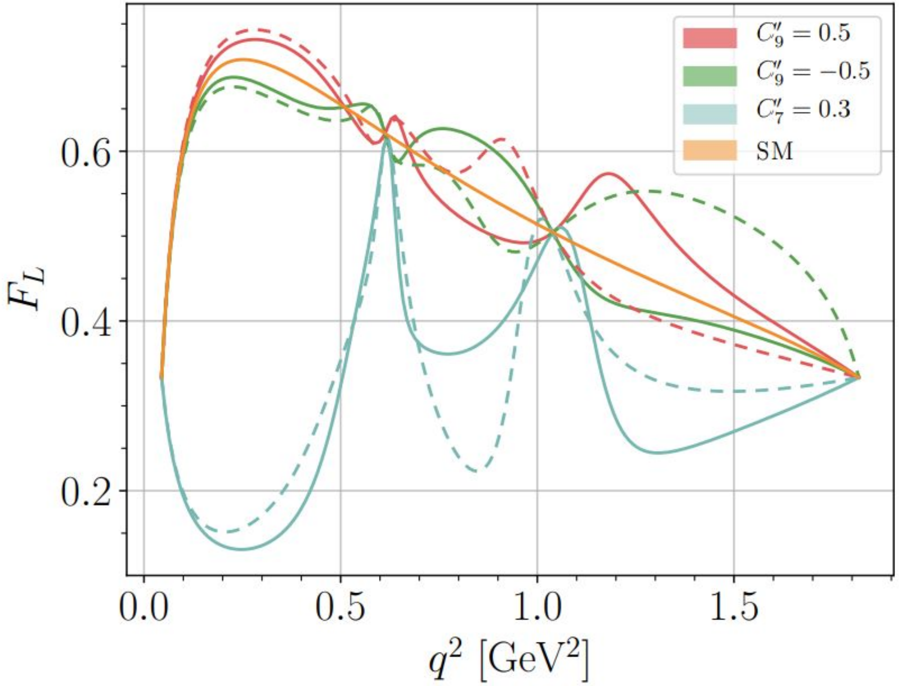
$$C_9 = 0.5\,\exp(i\pi/4)$$

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



Baryon	Quark content	Isospin representation	U-spin represantation
Λ_c	udc	$\vert 0,0\rangle_I$	$\vert \frac{1}{2},\frac{1}{2}\rangle_U$
Ξ_c^0	dsc	$\vert \frac{1}{2},-\frac{1}{2}\rangle_I$	$\vert 0,0\rangle_U$
Ξ_c^+	usc	$\vert \frac{1}{2},\frac{1}{2}\rangle_I$	$\vert \frac{1}{2},-\frac{1}{2}\rangle_U$
Ω_c^0	ssc	$\vert 0,0\rangle_I$	$\vert 1,-1\rangle_U$
p	uud	$\vert \frac{1}{2},\frac{1}{2}\rangle_I$	$\vert \frac{1}{2},\frac{1}{2}\rangle_U$
Σ^0	uds	$\vert 1,0\rangle_I$	$\frac{1}{2}\vert 1,0\rangle_U+\frac{\sqrt{3}}{2}\vert 0,0\rangle_U$
Λ^0	uds	$\vert 0,0\rangle_I$	$\frac{\sqrt{3}}{2}\vert 1,0\rangle_U-\frac{1}{2}\vert 0,0\rangle_U$
Σ^+	uus	$\vert 1,1\rangle_I$	$\vert \frac{1}{2},-\frac{1}{2}\rangle_U$
Ξ^0	uss	$\vert \frac{1}{2},\frac{1}{2}\rangle_I$	$\vert 1,-1\rangle_U$


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