CP violating rare charm decays

Marcel Golz

Eur.Phys.J. C80 (2020) no.1 65; [arxiv:1909.11108] R. Bause, MG, G. Hiller, A. Tayduganov
JHEP 09 (2021) 208; [arxiv:2107.13010] MG, G. Hiller, T. Magorsch

Workshop on future Super c-tau factories 2021

15$^{\text{th}}$ November 2021

technische universität dortmund

Outline

- Introduction to rare charm decays - Repetition
- Main part - Null test observables
  - Angular observables
  - LU tests
  - CP–violation
- Summary

Introduction

$$\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left[\sum_{i=7,9,10,S,P}\left(C_i O_i + C_i' O_i'\right) + \sum_{i=T,T5} C_i O_i\right],$$

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

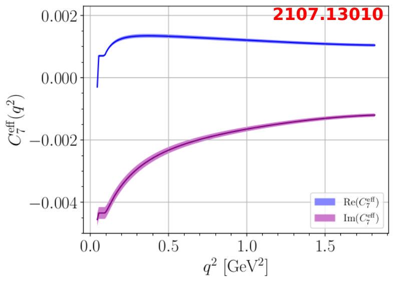
$$O_9 = (\overline{u}_L \gamma_\mu c_L)(\overline{\ell}\gamma^\mu \ell)\,, \quad O_{10} = (\overline{u}_L \gamma_\mu c_L)(\overline{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

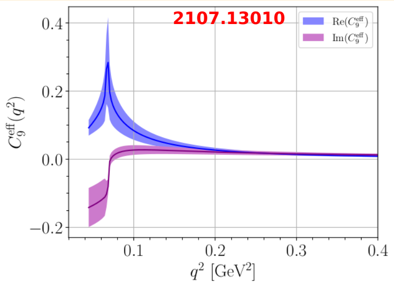
$$O_S = (\overline{u}_L c_R)(\overline{\ell}\ell)\,, \qquad O_P = (\overline{u}_L c_R)(\overline{\ell}\gamma_5 \ell)\,,$$

$$O_T = \frac{1}{2}(\overline{u}\sigma_{\mu\nu} c)(\overline{\ell}\sigma^{\mu\nu}\ell)\,, O_{T5} = \frac{1}{2}(\overline{u}\sigma_{\mu\nu} c)(\overline{\ell}\sigma^{\mu\nu}\gamma_5 \ell)\,.$$

- Primed operators obtained with $L \leftrightarrow R$

Similar to b-physics, BUT...



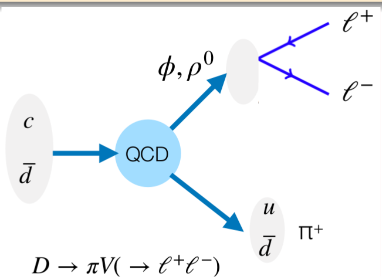


- $C_7^{\text{eff}} = \mathcal{O}(10^{-3})$, $C_9^{\text{eff}} = \mathcal{O}(10^{-2})$.
- $C_{10}^{(\prime)} = C_S^{(\prime)} = C_P^{(\prime)} = 0$ and $C_T = C_{T5} = 0$

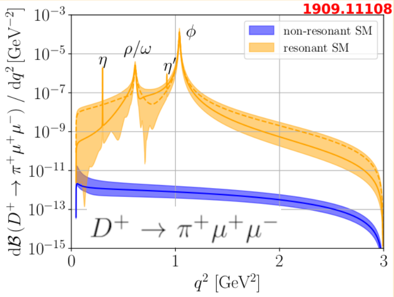
- SM contributions dominated by long range dynamics
  $\mathcal{B}^{\mathrm{SM}}(D \to \pi \ell^+ \ell^-) \approx \mathcal{B}(D \to \pi V(\to \ell^+ \ell^-))$
  $\to$Not in dineutrino modes (Gudruns talk)
- Parametrized by a sum of Breit-Wigner contributions (fit from data)

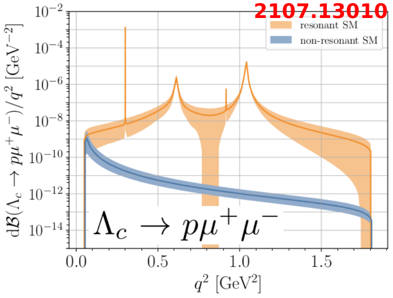
$$C_9^R(q^2) = a_\omega e^{i\delta_\omega} \left(\frac{1}{q^2 - m_\omega^2 + i m_\omega \Gamma_\omega} - \frac{3}{q^2 - m_\rho^2 + i m_\rho \Gamma_\rho} \right) + \frac{a_\phi e^{i\delta_\phi}}{q^2 - m_\phi^2 + i m_\phi \Gamma_\phi}.$$

$$C_P^R(q^2) = \frac{a_\eta e^{i\delta_\eta}}{q^2 - m_\eta^2 + i m_\eta \Gamma_\eta} + \frac{a_{\eta'}}{q^2 - m_{\eta'}^2 + i m_{\eta'} \Gamma_{\eta'}}$$



Resulting differential branching ratios





- Rare charm decays observed only at the resonances, for the rest of the signal region U.L. are available at 90 % C.L. (see 2011.09478)
  - $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$
  - $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 6.7 \times 10^{-8}$
  - $\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7}$
  - $\mathcal{B}(\Lambda_c \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$
  - **New results already presented at implications workshop**

Direct bounds on WC's from $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$, $\mathcal{B}(D^0 \to \mu^+\mu^-)$ imply

- $C_{S,\,P} \lesssim \mathcal{O}(0.1)$ $\quad C_{7,\,9,\,10,\,T,\,T5} \lesssim \mathcal{O}(1)$

Introduction

NP searches in branching ratios are challenging.

Instead define null test observables where

Signal $\leftrightarrow$ NP

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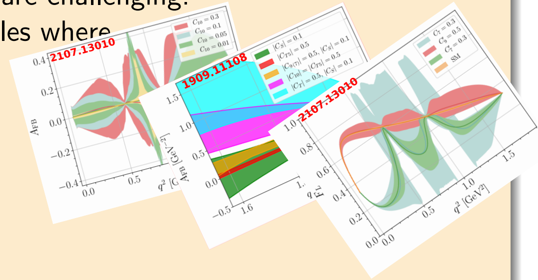
- Angular observables

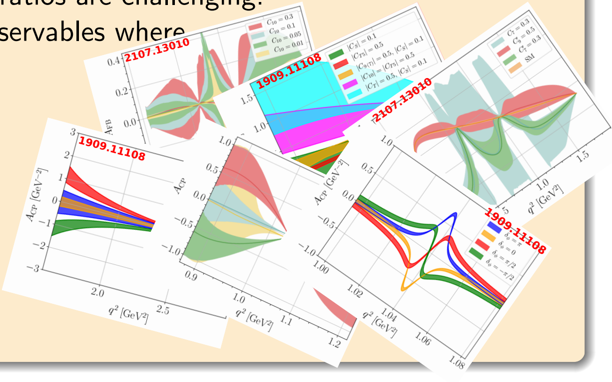


NP searches in branching ratios are challenging.

Instead define null test observables where

Signal $\leftrightarrow$ NP

- Angular observables
- CP–asymmetries



NP searches in branching ratios are challenging.

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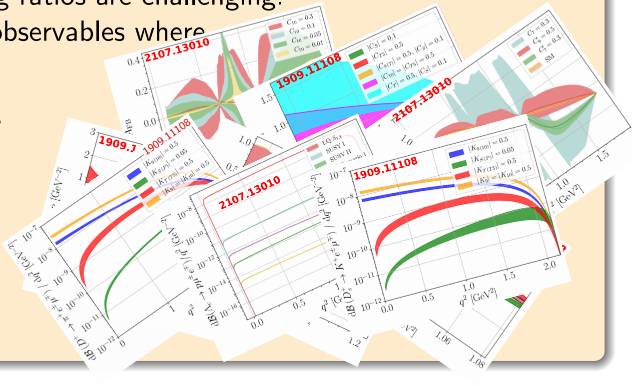
Signal $\leftrightarrow$ NP

- Angular observables
- CP–asymmetries
- LFV

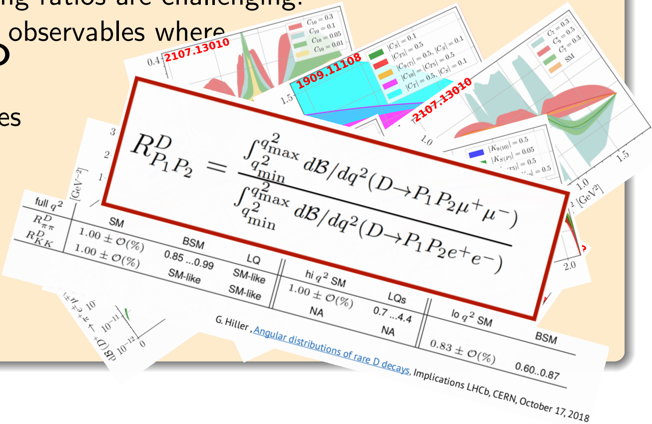


NP searches in branching ratios are challenging.

Instead define null test observables where

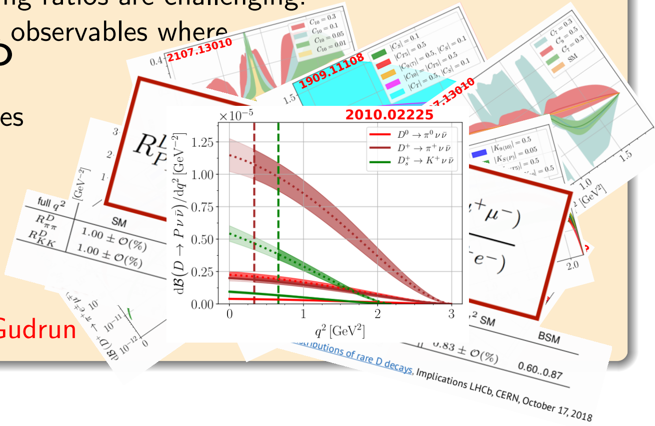
Signal $\leftrightarrow$ NP

- Angular observables
- CP–asymmetries
- LFV
- LU ratios



NP searches in branching ratios are challenging.
Instead define null test observables where
Signal $\leftrightarrow$ NP

- Angular observables
- CP–asymmetries
- LFV
- LU ratios
- Dineutrino modes
  Previous talk by Gudrun



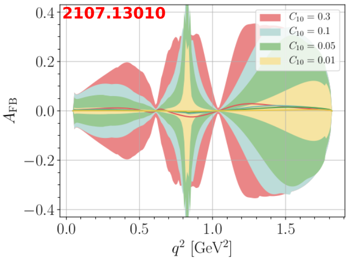
Main part-
Null test observables

$\Lambda_c \to p\mu^+\mu^-$ decay distribution:

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

$$A_{FB} = \frac{1}{d\Gamma/dq^2}\left[\int_0^1 - \int_{-1}^0\right]\frac{d\Gamma}{dq^2 d\cos\theta_\ell}\, d\cos\theta_\ell = \frac{3}{2}\frac{K_{1c}}{2K_{1ss}+K_{1cc}}.$$

$K_{1c} \sim C_9 C_{10}$, $C_9' C_{10}'$ and $C_7^{(\prime)} C_{10}^{(\prime)}$ interference terms $\Rightarrow$ **no SM**.



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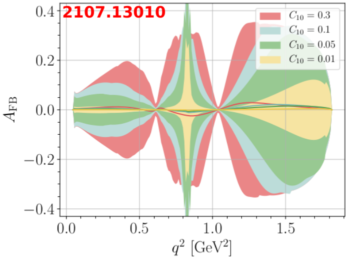
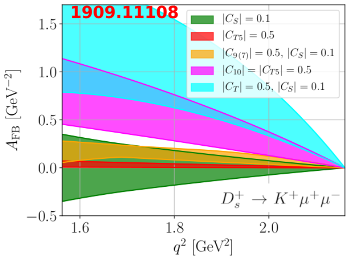
$K_{1c} \sim C_9 C_{10}$, $C_9' C_{10}'$ and $C_7^{(\prime)} C_{10}^{(\prime)}$ interference terms $\Rightarrow$ **no SM**.

Complementary results in $D \to P\mu^+\mu^-$ (Normalized to integrated rate)

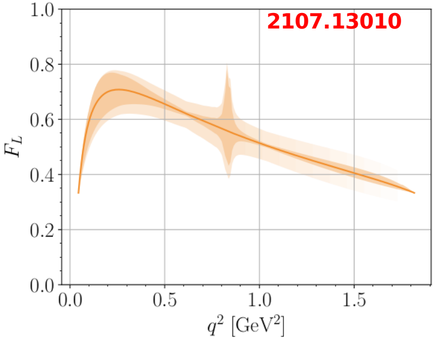


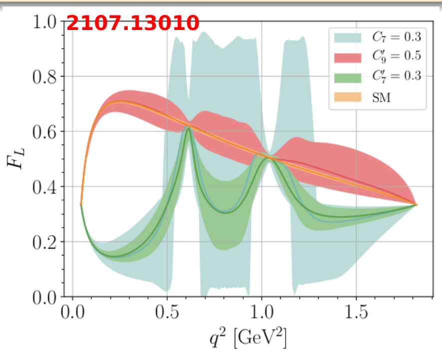


Fraction of longitudinally polarized dimuons

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

No null test, but cancellation of hadronic uncertainties in the SM and highly sensitive to $C_7^{(\prime)}$.





LU ratios

$$R_\pi^D = \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{\mathrm{d}\mathcal{B}(D \to \pi \mu^+ \mu^-)}{\mathrm{d}q^2} \mathrm{d}q^2 \Big/ \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{\mathrm{d}\mathcal{B}(D \to \pi e^+ e^-)}{\mathrm{d}q^2} \mathrm{d}q^2$$

R_π^D	SM	$\lvert C_9 \rvert = 0.5$	$\lvert C_{10} \rvert = 0.5$	$\lvert C_9 \rvert = \pm \lvert C_{10} \rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like
low q^2	$0.95 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$
high q^2	$1.00 \pm \mathcal{O}(\%)$	$0.2 \ldots 11$	$3 \ldots 7$	$2 \ldots 17$

1909.11108

LU ratios

$$R_\pi^D = \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\mathcal{B}(D \to \pi\mu^+\mu^-)}{dq^2} dq^2 \Big/ \int^{q^2} \ldots dq^2$$

$$R_p^{\Lambda_c} = \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\mathcal{B}(\Lambda_c \to p\mu^+\mu^-)}{dq^2} dq^2 \Big/ \int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{d\mathcal{B}(\Lambda_c \to pe^+e^-)}{dq^2} dq^2$$

	SM	$\lvert C_9^\mu\rvert = 0.5$	$\lvert C_{10}^\mu\rvert = 0.5$	$\lvert C_9^\mu\rvert = \lvert C_{10}^\mu\rvert = 0.5$	$\lvert C_9'^\mu\rvert = 0.5$	$\lvert C_{10}'^\mu\rvert = 0.5$	$\lvert C_9'^\mu\rvert = \lvert C_{10}'^\mu\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like	SM-like	SM-like	SM-like
low q^2	$0.94 \pm \mathcal{O}(\%)$	$7.5 \ldots 20$	$4.4 \ldots 13$	$11 \ldots 32$	$4.6 \ldots 14$	$4.4 \ldots 13$	$8.2 \ldots 26$
high q^2	$1.00 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$

2107.13010

LU ratios

$$R_\pi^D = \int_{q^2_{\rm min}}^{q^2_{\rm max}} \ldots$$

$$R^D_{P_1P_2} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D\to P_1P_2\mu^+\mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D\to P_1P_2e^+e^-)}$$

$$\ldots d\mathcal{B}(\Lambda_c \to p e^+e^-) \over dq^2 \quad dq^2$$

full q^2	SM	BSM	LQ
$R^D_{\pi\pi}$	$1.00 \pm \mathcal{O}(\%)$	0.85 ...0.99	SM-like
R^D_{KK}	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like

hi q^2 SM	LQs
$1.00 \pm \mathcal{O}(\%)$	0.7 ...4.4
NA	NA

lo q^2 SM	BSM
$0.83 \pm \mathcal{O}(\%)$	0.60..0.87

	$\lvert C_9'^{\mu}\rvert = \lvert C_{10}'^{\mu}\rvert = 0.5$
	SM-like
	$8.2\ldots26$
	$\mathcal{O}(100)$

	SM		
full q^2	$1.00 \pm \mathcal{O}(\%)$	$7.5\ldots20$	$\mathcal{O}(1$
low q^2	$0.94 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	
high q^2	$1.00 \pm \mathcal{O}(\%)$		

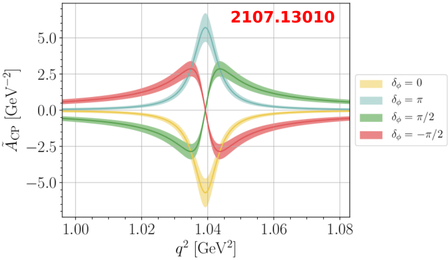
G. Hiller, Angular distributions of rare D decays, Implications LHCb, CERN, October 17, 2018

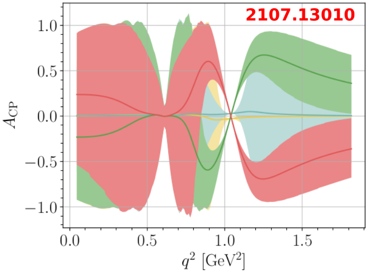
1805.08516

CP–asymmetries

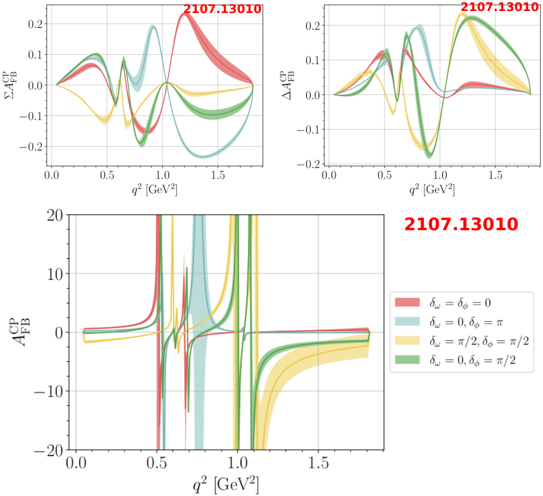
$$\tilde{A}_{\mathrm{CP}}(q^2) = \frac{1}{\Gamma + \bar{\Gamma}}\left(\frac{d\Gamma}{dq^2} - \frac{d\bar{\Gamma}}{dq^2}\right) \quad \text{with} \quad \Gamma = \int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{d\Gamma}{dq^2} dq^2 \quad \text{or} \quad A_{\mathrm{CP}}(q^2) = \frac{\frac{d\Gamma}{dq^2} - \frac{d\bar{\Gamma}}{dq^2}}{\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}}$$

- Strong phase from resonances needed $\longrightarrow$ measurement around the ϕ resonance. S. Fajfer and N. Kosnik 1208.0759
- NP weak phase needed. $\longrightarrow$ benchmark $C_9 = 0.5\exp(i\pi/4)$.
- Binning necessary.
- Plots for $\Lambda_c \to p\mu^+\mu^-$





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

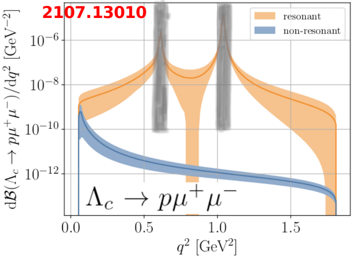


$C_{10} = 0.5 \exp(i\pi/4) \rightarrow$ pin down strong phases

Summary

- Rare charm decays ($c \to u\ell\ell$) are dominated by long-distance resonance contributions
- NP can be probed in **clean** null test observables
- Null test observables make use of resonance enhancement
- Many modes: $D \to \pi$, $D \to \pi\pi$, $\Lambda_c \to p$, $\Xi_c \to \Sigma$, ... plenty of opportunities

BACKUP



- LHCb upper limit at 90 % C.L. with ± 40 MeV cuts around known resonance masses, then extrapolated to full q^2 region

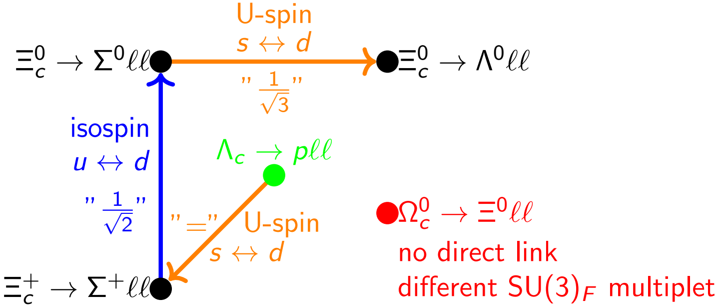
$$\mathcal{B}_{\mathrm{LHCb}}(\Lambda_c \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$$

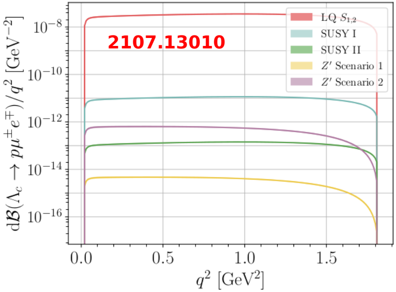
- Including form factor and resonance uncertainties and integrating the LHCb search region

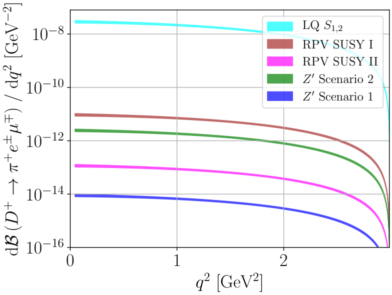
$$\mathcal{B}^{\mathrm{SM}}(\Lambda_c \to p\mu^+\mu^-) = (1.9^{+1.8}_{-1.5}) \times 10^{-8}$$
$$\mathcal{B}^{\mathrm{SM}}(\Xi_c^+ \to \Sigma^+\mu^+\mu^-) \sim 1.8 \times \mathcal{B}^{\mathrm{SM}}(\Lambda_c \to p\mu^+\mu^-)$$
$$\mathcal{B}^{\mathrm{SM}}(\Xi_c^0 \to \Sigma^0\mu^+\mu^-) \sim 0.4 \times \mathcal{B}^{\mathrm{SM}}(\Lambda_c \to p\mu^+\mu^-)$$
$$\mathcal{B}^{\mathrm{SM}}(\Omega_c^0 \to \Xi^0\mu^+\mu^-) \sim 1.3 \times \mathcal{B}^{\mathrm{SM}}(\Lambda_c \to p\mu^+\mu^-)$$

A note on form factors

- Form factors are availbale for $\Lambda_c \to p\mu^+\mu^-$ from Lattice QCD (see 1712.05783)
- No results for other decay modes (from the lattice) available yet.
- Use $SU(3)_F$ flavor symmetries to relate modes



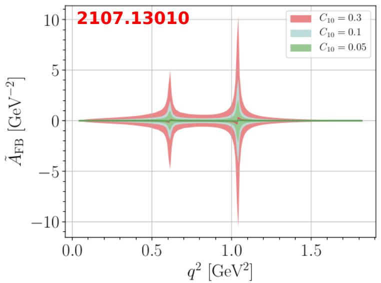


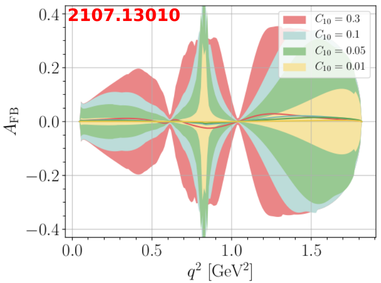


LQ's ($K_9' = K_{10}' = 0.5$),
SUSY + R-parity violation ($K_9 = -K_{10} = 0.009$),
SUSY no R-parity violation ($K_9 = -K_{10} = 0.001$),
Z' 1 ($K_9 = K_9' = -K_{10} = -K_{10}' = 1.4 \cdot 10^{-4}$),
Z' 2 ($K_9 = K_9' = -K_{10} = -K_{10}' = 2.3 \cdot 10^{-4}$).

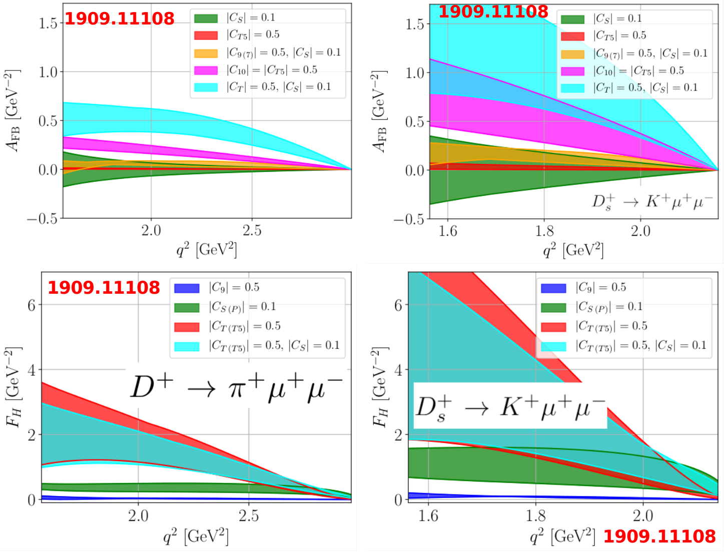
Normalization matters

- $\tilde{A}_{\mathrm{FB}} = \frac{3}{2} \frac{K_{1c}}{\Gamma}$ with $\Gamma = \int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} (2\, K_{1ss} + K_{1cc})$
- $A_{\mathrm{FB}} = \frac{3}{2} \frac{K_{1c}}{\mathrm{d}\Gamma/\mathrm{d}q^2}$ with $\mathrm{d}\Gamma/\mathrm{d}q^2 = 2\, K_{1ss} + K_{1cc}$
- Resonance enhancement





Angular observables in $D \to P\ell\ell$



Resonance parameters

- Parameters in C_9^R, C_P^R are main source of uncertainties
- Process dependent 1909.11108, 1805.08516

	a_ρ / GeV^2	a_ϕ / GeV^2	a_η / GeV^2	$a_{\eta'}$ / GeV^2
$D^+ \to \pi^+$	~ 0.2	~ 0.2	$\sim 6 \times 10^{-4}$	$\sim 8 \times 10^{-4}$
$D^0 \to \pi^0$	~ 0.9	~ 0.3	$\sim 5 \times 10^{-4}$	$\sim 8 \times 10^{-4}$
$D_s^+ \to K^+$	~ 0.5	~ 0.1	$\sim 6 \times 10^{-4}$	$\sim 7 \times 10^{-4}$
$D^0 \to \pi^+\pi^-$	~ 0.7	~ 0.3	$\sim 1 \times 10^{-3}$	$\sim 1 \times 10^{-3}$
$D^0 \to K^+K^-$	~ 0.7	–	$\sim 3 \times 10^{-4}$	–

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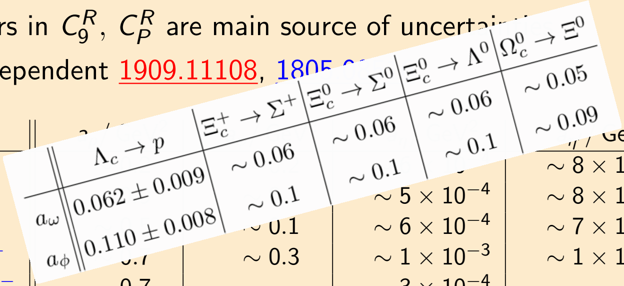
- Process dependent 1909.11108, 1805.0

	[illegible]	[illegible]	[illegible]	[illegible] / GeV^2
$D^+ \to \pi^+$	[illegible]	[illegible]	[illegible]	$\sim 8 \times 10^{-4}$
$D^0 \to \pi^0$	[illegible]	[illegible]	$\sim 5 \times 10^{-4}$	$\sim 8 \times 10^{-4}$
$D_s^+ \to K^+$	[illegible]	~ 0.1	$\sim 6 \times 10^{-4}$	$\sim 7 \times 10^{-4}$
$D^0 \to \pi^+\pi^-$	0.7	~ 0.3	$\sim 1 \times 10^{-3}$	$\sim 1 \times 10^{-3}$
$D^0 \to K^+K^-$	~ 0.7	—	$\sim 3 \times 10^{-4}$	—



	$\Lambda_c \to p$	$\Xi_c^+ \to \Sigma^+$	$\Xi_c^0 \to \Sigma^0$	$\Xi_c^0 \to \Lambda^0$	$\Omega_c^0 \to \Xi^0$
a_ω	0.062 ± 0.009	~ 0.06	~ 0.06	~ 0.06	~ 0.05
a_ϕ	0.110 ± 0.008	~ 0.1	~ 0.1	~ 0.1	~ 0.09

2107.13010

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- Process dependent 1909.11108, 1805.0[illegible]

	[illegible]	[illegible]	[illegible]	[illegible] GeV^2
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$D^0 \to \pi^+\pi^-$	[illegible]	~ 0.3	$\sim 1 \times 10^{-3}$	$\sim 1 \times 10^{-3}$
$D^0 \to K^+K^-$	~ 0.7	—	$\sim 3 \times 10^{-4}$	—

	$\Lambda_c \to p$	$\Xi_c^+ \to \Sigma^+$	$\Xi_c^0 \to \Sigma^0$	$\Xi_c^0 \to \Lambda^0$	$\Omega_c^0 \to \Xi^0$
a_ω	0.062 ± 0.009	~ 0.06	~ 0.06	~ 0.06	~ 0.05
a_ϕ	0.110 ± 0.008	~ 0.1	~ 0.1	~ 0.1	~ 0.09

2107.13010

- With more data model parameters (a_i, δ_i) can be constrained and the model can be improved.