Null test searches for BSM physics with rare charm decays

Marcel Golz

Eur.Phys.J. C80 (2020) no.1 65; [arxiv:1909.11108] R. Bause, MG, G. Hiller, A. Tayduganov
Phys.Rev.D 101 (2020) 11, 115006; [arxiv:2004.01206] R. Bause, H. Gisbert, MG, G. Hiller
[arxiv:2007.05001] R. Bause, H. Gisbert, MG, G. Hiller
PhysR.Rev.D 103 (2021) 1, 015033; [arxiv:2010.02225] R. Bause, H. Gisbert, MG, G. Hiller
DO-TH 21/13 (in preparation) MG, G. Hiller, T. Magorsch

10$^{\text{th}}$ **International Workshop on Charm Physics**

June, **2021**

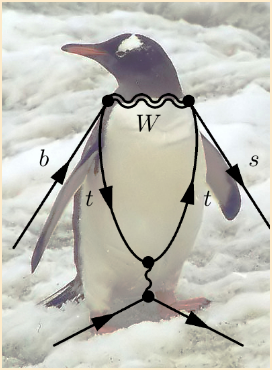
technische universität
dortmund

Outline

- Introduction rare charm decays
- Overview null test strategies
- Part I - $\Lambda_c \to p\ell^+\ell^-$
  - Angular observables
  - CP-violation
  - Lepton universality tests
- Part II - Dineutrino modes
- Outlook

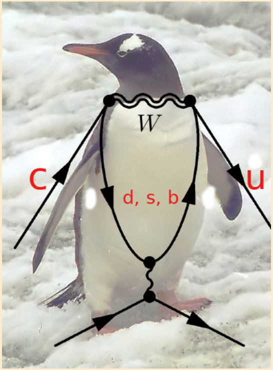
EFT at the charm scale de Boer, (2017), PhD thesis, TU Dortmund

What is the difference between $b \to s$ and $c \to u$ penguins?



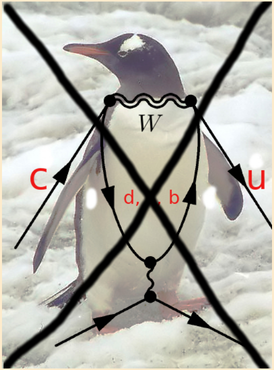
EFT at the charm scale de Boer, (2017), PhD thesis, TU Dortmund

What is the difference between $b \to s$ and $c \to u$ penguins?



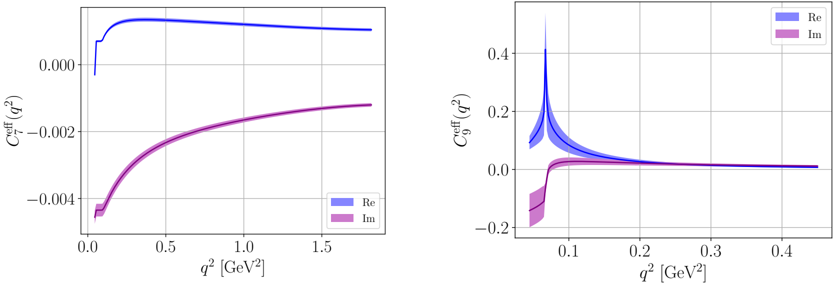
EFT at the charm scale de Boer, (2017), PhD thesis, TU Dortmund

What is the difference between $b \to s$ and $c \to u$ penguins?



- Light quark masses need to be set to zero at μ_W
- Effective GIM-mechanism kills $C_{7,9,10}$ at μ_W
- $C_{7,9}^{\text{eff}}$ are induced by RG running to μ_c
- $C_{10}(\mu_c) = 0$

Introduction



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

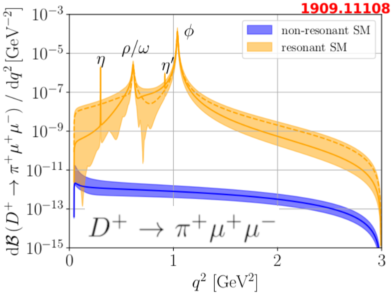
$$O_7 = \frac{m_c}{e}(\bar{u}_L \sigma_{\mu\nu} c_R) F^{\mu\nu},$$

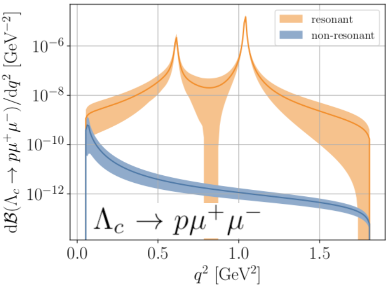
$$O_9 = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \ell), \quad O_{10} = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

$$O_S = (\bar{u}_L c_R)(\bar{\ell}\ell), \quad O_P = (\bar{u}_L c_R)(\bar{\ell}\gamma_5 \ell),$$

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

- Primed operators obtained with $L \leftrightarrow R$
- $C_{7,9}^{\text{eff}}$ remain tiny in the SM
- All other Wilson coefficients are zero in the SM





- SM contributions dominated by long range dynamics
  $\mathcal{B}^{\mathrm{SM}}(h_c \to h_u \ell^+\ell^-) \approx \mathcal{B}(h_c \to h_u M(\to \ell^+\ell^-))$
- $M = \rho(770), \omega(782), \phi(1020), \ldots$
- Parametrized by a sum of Breit-Wigner contributions (fit from data)
  $$C_9^R(q^2) = a_\omega e^{\mathrm{i}\delta_\omega}\left(\frac{1}{q^2 - m_\omega^2 + \mathrm{i}m_\omega\Gamma_\omega} - \frac{3}{q^2 - m_\rho^2 + \mathrm{i}m_\rho\Gamma_\rho}\right) + \frac{a_\phi e^{\mathrm{i}\delta_\phi}}{q^2 - m_\phi^2 + \mathrm{i}m_\phi\Gamma_\phi}.$$

Overview null test strategies

- 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)
  - $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$
  - $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 6.7 \times 10^{-8}$
  - $\mathcal{B}(D_s^+ \to K^+\mu^+\mu^-) < 1.4 \times 10^{-7}$
  - $\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7}$
  - $\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) < 3.3 \times 10^{-5}$
  - $\mathcal{B}(\Lambda_c \to p\mu^+\mu^-) < 7.7 \times 10^{-8}$

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

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

Overview null test strategies

NP searches in branching ratios are difficult. Instead define null test observables where **signal $\leftrightarrow$ NP**

- Angular observables, CP–asymmetries, LU ratios, LFV and dineutrino modes

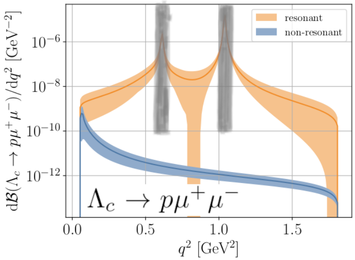
NP searches in branching ratios are difficult. Instead define null test observables where signal $\leftrightarrow$ NP

- Angular observables, CP–asymmetries, LU ratios, LFV and dineutrino modes

Why study different modes? Why baryons?

- Complementarity:
  - $D \to P\ell^+\ell^-$ sensitive to $|C_i + C_i'|^2$
  - $\Lambda_c \to p\ell^+\ell^-$ sensitive to both $|C_i \pm C_i'|^2$
- Possibilities:
  - # of angular observables increases with spin structure and # of hadrons in the final state
  - (Future) global fits help to disentangle QCD and NP

Part I - $\Lambda_c \to p\ell^+\ell^-$



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

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

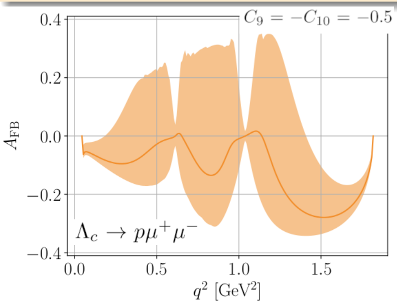
- Including form factor and resonance uncertainties and integrating the LHCb search region

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

From twofold $\Lambda_c \to p\mu^+\mu^-$ decay distribution: $\frac{d\Gamma}{dq^2 d\cos\theta_\ell} = \frac{3}{2}\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right)$, we define the lepton forward-backward asymmetry

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

K_{1c} contains $C_9 C_{10}$, $C_9' C_{10}'$ and $C_7^{(\prime)} C_{10}^{(\prime)}$ interference terms $\Rightarrow$ no SM.
Complementary results in $D \to P\mu^+\mu^-$

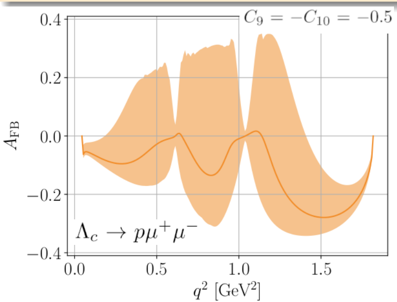


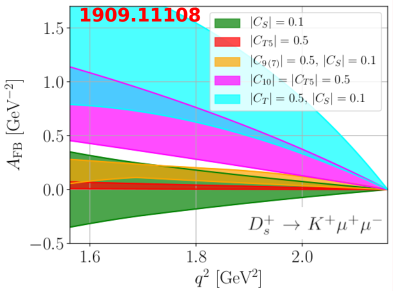
Angular observables

From twofold $\Lambda_c \to p\mu^+\mu^-$ decay distribution: $\frac{d\Gamma}{dq^2 d\cos\theta_\ell} = \frac{3}{2}\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right)$, we define the lepton forward-backward asymmetry

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

K_{1c} contains $C_9 C_{10}$, $C_9' C_{10}'$ and $C_7^{(\prime)} C_{10}^{(\prime)}$ interference terms $\Rightarrow$ no SM.
Complementary results in $D \to P\mu^+\mu^-$ (Normalized to integrated rate)

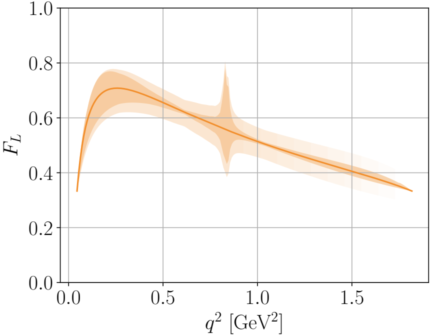


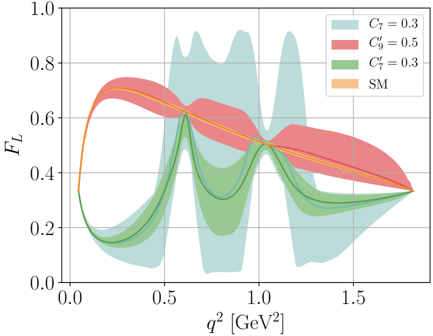


Fraction of longitudinally polarized dimuons

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

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

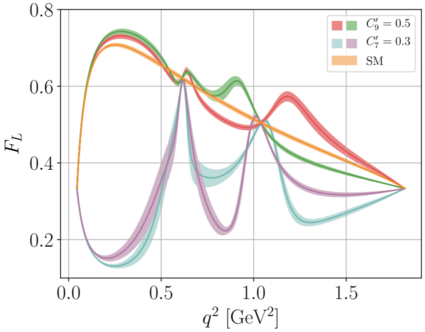


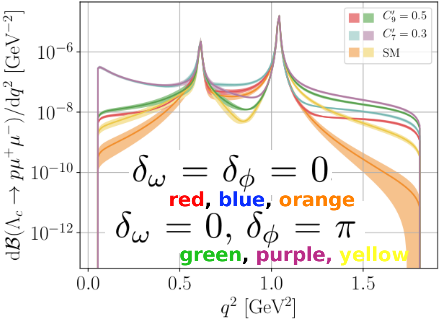


Fraction of longitudinally polarized dimuons

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

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

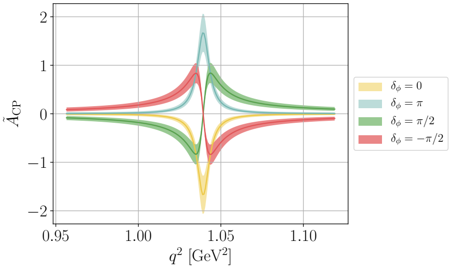


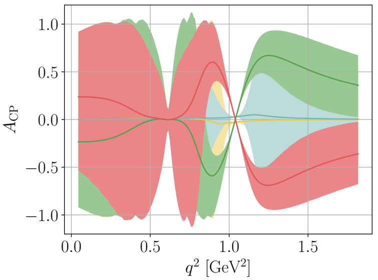


CP–asymmetries

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

- Strong phase from resonances needed $\longrightarrow$ measurement around the ϕ resonance. S. Fajfer et al. PRD 87 (2013), 5, 054026
- NP weak phase needed. $\longrightarrow$ benchmark $C_9 = 0.5 \exp(i\pi/4)$.
- Binning necessary.





- Increasing hints for LUV in rare b-decays motivate further LU tests
- Similar R ratios can be defined in rare charm decays
- Huge effects $\mathcal{O}(100)$ are still possible at high q^2

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

$R_p^{\Lambda_c}$	SM	$\lvert C_9\rvert = 0.5$	$\lvert C_{10}\rvert = 0.5$	$\lvert C_9\rvert = \lvert C_{10}\rvert = 0.5$
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	$1.00 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$

- Increasing hints for LUV in rare b-decays motivate further LU tests
- Similar R ratios can be defined in rare charm decays
- Huge effects $\mathcal{O}(100)$ are still possible at high q^2

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

$R_p^{\Lambda_c}$	SM	$\lvert C_9\rvert = 0.5$	$\lvert C_{10}\rvert = 0.5$	$\lvert C_9\rvert = \lvert C_{10}\rvert = 0.5$
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	$1.00 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$

- Similar results are obtained in R_π^D, $R_K^{D_s}$, $R_{\pi\pi}^D$, R_{KK}^D

Part II - Dineutrino modes

Link dineutrino to charged dilepton modes via $SU(2)_L$ in SMEFT 2007.05001, 2010.02225

$$\mathcal{B} \propto \sum_{\nu=i,j} \left(|\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2 \right) = \mathrm{Tr}\left[\mathcal{C}_L^U \, \mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U \, \mathcal{C}_R^{U\dagger} \right]$$

$$= \mathrm{Tr}\left[\mathcal{K}_L^D \mathcal{K}_L^{D\dagger} + \mathcal{K}_R^U \mathcal{K}_R^{U\dagger} \right] + \mathcal{O}(\lambda) = \sum_{\ell=i,j} \left(|\mathcal{K}_L^{Dij}|^2 + |\mathcal{K}_R^{Uij}|^2 \right) + \mathcal{O}(\lambda)$$

- **SU(2) relates up, down, neutrinos and charged leptons.**

$c \to u\,\ell^+\ell^-$ ⟶ $c \to u\,\nu\bar{\nu}$ ⟵ $s \to d\,\ell^+\ell^-$

⋆ **Independent of PMNS matrix and subleading $\mathcal{O}(\lambda)$ corrections!**

⋆ **Prediction of dineutrino rates for different leptonic flavor structures $\mathcal{K}_{L,R}^{ij}$ can be probed with lepton-specific measurements!**

Possible leptonic flavor structures for $\mathcal{K}_{L,R}^{ij}$

i) **Lepton-universality (LU).**

$$\begin{pmatrix} k & 0 & 0 \\ 0 & k & 0 \\ 0 & 0 & k \end{pmatrix}$$

ii) **Charged lepton flavor conservation (cLFC).**

$$\begin{pmatrix} k_{11} & 0 & 0 \\ 0 & k_{22} & 0 \\ 0 & 0 & k_{33} \end{pmatrix}$$

iii) $\mathcal{K}_{L,R}^{ij}$ **arbitrary.**

$$\begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix}$$

Upper limits on dineutrino modes can probe lepton unversality!

- **Bounds on lepton specific WCs for $\ell, \ell' = e, \mu, \tau$.** 2003.12421, 2002.05684

	$\lvert\mathcal{K}_A^{P\ell\ell'}\rvert$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$s \to d$	$\lvert\mathcal{K}_L^{D\ell\ell'}\rvert$	3.5	1.9	6.7	2.0	6.1	6.6
$c \to u$	$\lvert\mathcal{K}_R^{U\ell\ell'}\rvert$	2.9	1.6	5.6	1.6	4.7	5.1

- $\mathcal{B} \propto x = \sum_{\ell,\ell'} \left(\lvert\mathcal{K}_L^{D\ell\ell'}\rvert^2 + \lvert\mathcal{K}_R^{U\ell\ell'}\rvert^2\right) + \mathcal{O}(\lambda) = \sum_{\ell,\ell'} R^{\ell\ell'} + \mathcal{O}(\lambda)$

  $x = 3\,R^{\mu\mu} \lesssim 34\,,$ **(Lepton Universality)**

  $x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} \lesssim 196\,,$ **(charged Lepton Flavor Conservation)**

  $x = R^{ee} + R^{\mu\mu} + R^{\tau\tau} + 2\left(R^{e\mu} + R^{e\tau} + R^{\mu\tau}\right) \lesssim 716.$

LU is fixed by the most stringent bound (muons) and the $\mathcal{O}(\lambda)$ corrections are included

Dineutrino modes

$$\mathcal{B}(h_c \to F\,\nu\bar{\nu}) = A_+^{h_c F}\, x_+ + A_-^{h_c F}\, x_- , \quad x_\pm = \sum_{i,j} |\mathcal{C}_L^{Uij} \pm \mathcal{C}_R^{Uij}|^2 < 2\,x\,.$$

$N_i = \eta_{\text{eff}}\, \mathcal{B}_i\, N(h_c)$, $N(c\bar{c})_{\text{Belle II}} = 65 \cdot 10^9$ for 50 ab^{-1}, $N(c\bar{c})_{\text{FCC-ee}} = 550 \cdot 10^9$.

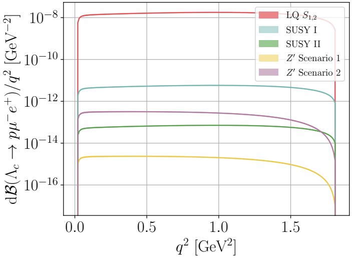
$h_c \to F$	$\mathcal{B}^{\text{max}}_{\text{LU}}$ $[10^{-7}]$	$\mathcal{B}^{\text{max}}_{\text{cLFC}}$ $[10^{-6}]$	$\mathcal{B}^{\text{max}}$ $[10^{-6}]$	$N^{\text{max}}_{\text{LU}}/\eta_{\text{eff}}$	$N^{\text{max}}_{\text{cLFC}}/\eta_{\text{eff}}$	$N^{\text{max}}/\eta_{\text{eff}}$
$D^0 \to \pi^0$	6.1	3.5	13	47 k (395 k)	270 k (2.3 M)	980 k (8.3 M)
$D^+ \to \pi^+$	25	14	52	77 k (650 k)	440 k (3.7 M)	1.6 M (14 M)
$D_s^+ \to K^+$	4.6	2.6	9.6	6 k (50 k)	34 k (290 k)	120 k (1.1 M)
$D^0 \to \pi^0\pi^0$	1.5	0.8	3.1	11 k (95 k)	64 k (540 k)	230 k (2.0 M)
$D^0 \to \pi^+\pi^-$	2.8	1.6	5.9	22 k (180 k)	120 k (1.0 M)	450 k (3.8 M)
$D^0 \to K^+K^-$	0.03	0.02	0.06	0.2 k (1.9 k)	1.3 k (11 k)	4.8 k (40 k)
$\Lambda_c^+ \to p^+$	18	11	39	14 k (120 k)	82 k (700 k)	300 k (2.6 M)
$\Xi_c^+ \to \Sigma^+$	36	21	76	28 k (240 k)	160 k (1.4 M)	590 k (5.0 M)
$D^0 \to X$	12	6.8	25	91 k (770 k)	520 k (4.4 M)	1.9 M (16 M)
$D^+ \to X$	30	17	63	94 k (800 k)	540 k (4.6 M)	2.0 M (17 M)
$D_s^+ \to X$	13	7.3	27	17 k (140 k)	95 k (810 k)	350 k (2.9 M)

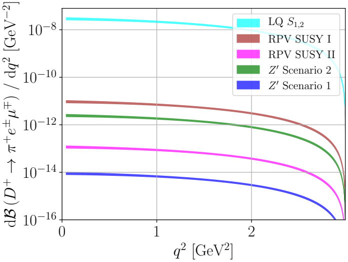
(EFT breakdown) $> \mathcal{B}^{\max}$ (LFV)$> \mathcal{B}^{\max}_{\text{cLFC}}$ (LU violation)$> \mathcal{B}^{\max}_{\text{LU}}$

Outlook

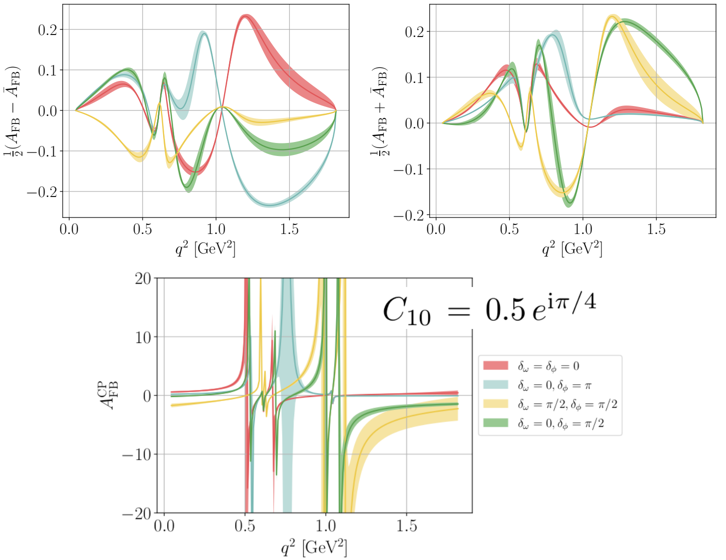
- Sizable hadronic uncertainties in rare charm decays overcome in null test observables
- Plenty of opportunities → we are only at the very beginning
- More null tests with charm baryons not covered in this talk
  - $A_{\mathrm{FB}}^{\mathrm{CP}}$ sensitive to $\mathrm{Im}\, C_{10}$
  - Lepton flavor violating decays
- More possibilities
  - Radiative decays → Nico Adolph's talk in parallel
  - Four-body baryon decays
  - Decays of polarized Baryons

BACKUP

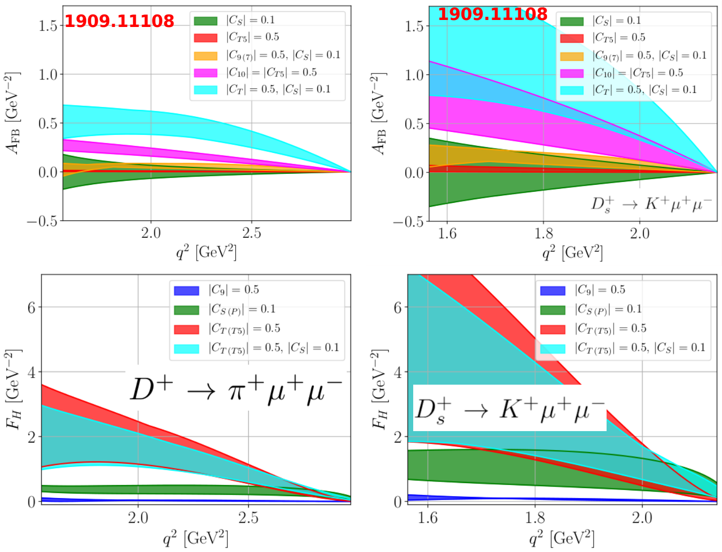




LQ's ($K_9' = K_{10}' = 0.5$),
SUSY + R-parity violation ($K_9 = -K_{10} = 0.009$),
SUSY no R-parity violation ($K_9 = -K_{10} = 0.001$),
Z' 1 ($K_9 = K_9' = -K_{10} = -K_{10}' = 1.4 \cdot 10^{-4}$),
Z' 2 ($K_9 = K_9' = -K_{10} = -K_{10}' = 2.3 \cdot 10^{-4}$).



$$C_{10} = 0.5\, e^{\mathrm{i}\pi/4}$$


1909.11108
$|C_S| = 0.1$
$|C_{T5}| = 0.5$
$|C_{9(7)}| = 0.5,\ |C_S| = 0.1$
$|C_{10}| = |C_{T5}| = 0.5$
$|C_T| = 0.5,\ |C_S| = 0.1$
$A_{\rm FB}$ [GeV^{-2}]
q^2 [GeV^2]
1909.11108
$D_s^+ \to K^+\mu^+\mu^-$
$|C_9| = 0.5$
$|C_{S(P)}| = 0.1$
$|C_{T(T5)}| = 0.5$
$|C_{T(T5)}| = 0.5,\ |C_S| = 0.1$
$D^+ \to \pi^+\mu^+\mu^-$
F_H [GeV^{-2}]
$D_s^+ \to K^+\mu^+\mu^-$

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

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	$1.00 \pm \mathcal{O}(\%)$	$0.2\ldots11$	$3\ldots7$	$2\ldots17$

SU(2)–link relating dineutrino and dilepton modes

- $SU(2)_L \times U(1)_Y$-invariant effective theory (1008.4884)

$$\mathcal{L}^{\rm LO}_{\rm SMEFT} \supset \frac{C^{(1)}_{\ell q}}{v^2} \bar{Q}\gamma_\mu Q\, \bar{L}\gamma^\mu L + \frac{C^{(3)}_{\ell q}}{v^2} \bar{Q}\gamma_\mu \tau^a Q\, \bar{L}\gamma^\mu \tau^a L + \frac{C_{\ell u}}{v^2} \bar{U}\gamma_\mu U\, \bar{L}\gamma^\mu L + \frac{C_{\ell d}}{v^2} \bar{D}\gamma_\mu D\, \bar{L}\gamma^\mu L$$

- C^P_A and K^P_A matched via $SU(2)_L$-components in gauge basis

$$C^U_L = K^D_L = C^{(1)}_{\ell q} + C^{(3)}_{\ell q} \quad C^U_R = K^U_R = C_{\ell u}$$
$$C^D_L = K^U_L = C^{(1)}_{\ell q} - C^{(3)}_{\ell q} \quad C^D_R = K^D_R = C_{\ell d}$$

- going to *mass basis*: $Q_\alpha = (u_{L\,\alpha},\, V_{\alpha\beta} d_{L\,\beta}), \quad L_i = (\nu_{L\,i},\, W^*_{ki} \ell_{L\,k})$
  (V: CKM, W: PMNS)

$$\boxed{\mathcal{C}^U_L = W^\dagger\, \mathcal{K}^D_L\, W + \mathcal{O}(\lambda), \quad \mathcal{C}^U_R = W^\dagger\, \mathcal{K}^U_R\, W}$$

Upper limits on x from high-p_T

$$\mathcal{C}_L^{U_{12}} = W^\dagger \mathcal{K}_L^{D_{12}} W + \lambda\, W^\dagger (\mathcal{K}_L^{D_{22}} - \mathcal{K}_L^{D_{11}}) W + \mathcal{O}(\lambda^2)\,, \qquad \mathcal{C}_R^{U_{12}} = W^\dagger \mathcal{K}_R^{U_{12}} W$$

	$\lvert\bar{\mathcal{K}}_A^{P\ell\ell'}\rvert$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$d \to d$	$\lvert\mathcal{K}_{L,R}^{D_{11}\ell\ell'}\rvert$	2.8	1.5	5.5	1.1	3.3	3.6
$s \to s$	$\lvert\mathcal{K}_{L,R}^{D_{22}\ell\ell'}\rvert$	9.0	4.9	17	5.2	17	18
$s \to d$	$\lvert\bar{\mathcal{K}}_{L,R}^{D_{12}\ell\ell'}\rvert$	3.5	1.9	6.7	2.0	6.1	6.6
$c \to u$	$\lvert\bar{\mathcal{K}}_{L,R}^{U_{12}\ell\ell'}\rvert$	2.9	1.6	5.6	1.6	4.7	5.1

(2003.12421), (2002.05684)

	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$R^{\ell\ell'}$	21	6.0	77	6.6	59	70
$\delta R^{\ell\ell'}$	19	5.4	69	5.7	55	63
$r^{\ell\ell'}$	39	11	145	12	115	133

with $r^{\ell\ell'} = R^{\ell\ell'} + \delta R^{\ell\ell'}$

$$\begin{aligned} R^{\ell\ell'} &= \left|\mathcal{K}_L^{D_{12}\ell\ell'}\right|^2 + \left|\mathcal{K}_R^{U_{12}\ell\ell'}\right|^2, \\ R_\pm^{\ell\ell'} &= \left|\mathcal{K}_L^{D_{12}\ell\ell'} \pm \mathcal{K}_R^{U_{12}\ell\ell'}\right|^2, \\ \delta R^{\ell\ell'} &= 2\,\lambda\,\Re\mathcal{K}_L^{D_{12}\ell\ell'}\,\mathcal{K}_L^{D_{22}\ell\ell'\,*} - \mathcal{K}_L^{D_{12}\ell\ell'}\,\mathcal{K}_L^{D_{11}\ell\ell'\,*} \end{aligned}$$

$$x = \sum_{\ell,\,\ell'} \left(R^{\ell\ell'} + \delta R^{\ell\ell'}\right)\,, \qquad x_\pm = \sum_{\ell,\,\ell'} R_\pm^{\ell\ell'}$$

construct bounds on $x = \frac{x_+ + x_-}{2}$, with $x^\pm \leq 2\,x$,

$$\begin{aligned} x &= 3\,r^{\mu\mu} \lesssim 34\,, \quad \text{(LU)} \\ x &= r^{ee} + r^{\mu\mu} + r^{\tau\tau} \lesssim 196\,, \quad \text{(cLFC)} \\ x &= r^{ee} + r^{\mu\mu} + r^{\tau\tau} + 2\,(r^{e\mu} + r^{e\tau} + r^{\mu\tau}) \lesssim 716\,. \end{aligned}$$