BSM reach of rare charm decays, including the rising star $\Lambda_c \to p\mu^+\mu^-$

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in collaboration with H. Gisbert, G. Hiller
based on arXiv:2410.00115

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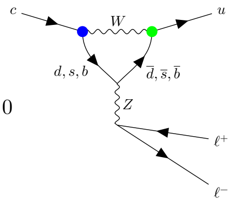


$$V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0$$

Why rare charm decays?

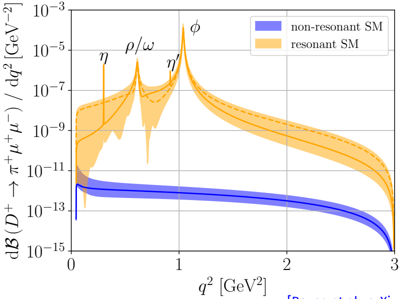
- Flavour-Changing-Neutral-Currents (FCNCs) like $c \to u\ell^+\ell^-$ only allowed on loop-level in SM
- Unique opportunity to probe FCNCs for up-type quarks inside hadrons
- SM+NP description with EFT ansatz

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\sum_i \mathcal{C}_i(\mu)\ \mathcal{O}_i(\mu)$$

e.g. $\mathcal{O}_{10}^{(\prime)} = (\bar{u}_{L(R)}\,\gamma_\mu\,c_{L(R)})\,(\bar{\ell}\,\gamma^\mu\,\gamma_5\,\ell)$

- Special features of charm: Stronger GIM suppression than K and B-physics
- Resonance contributions dominate over short-distance contributions
- **Null tests!** $\mathcal{C}_{10}^{(\prime)\,\text{SM}} = 0$

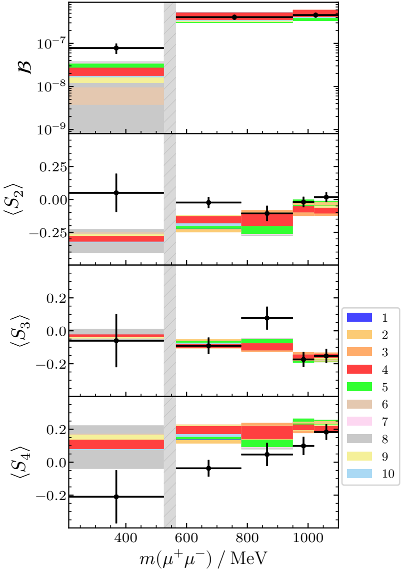
$$\mathcal{A}(c \to u) \propto \frac{1}{16\pi^2} V_{cs}^* V_{us}\left(f\left(\frac{m_s^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right) + \frac{1}{16\pi^2}\underbrace{V_{cb}^* V_{ub}}_{\mathcal{O}(\lambda^5)}\left(f\left(\frac{m_b^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right)$$



[Bause et al., arXiv:1909.11108]

4-body decay $D^0 \to \pi^+\pi^-\mu^+\mu^-$

- $D^0 \to \pi^+\pi^-\mu^+\mu^-$ ($D^0 \to K^+K^-\mu^+\mu^-$) angular analysis available
  [LHCb,arXiv:2111.03327]
- rich 5-differential distribution $\frac{d^5\Gamma}{dq^2 dp^2 d\cos\theta_{P_1} d\cos\theta_\ell d\phi}$
  [de Boer, Hiller, arXiv:1805.08516]
- including 3 CP-symmetries + 9 CP-asymmetries as **clean null tests**
- sensitivity to QCD models [Fajfer, Solomonidi, Vale Silva, arXiv:2312.07501]
  - difficult to model SM-dominated observables



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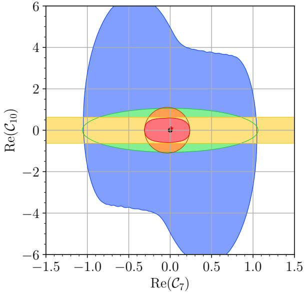
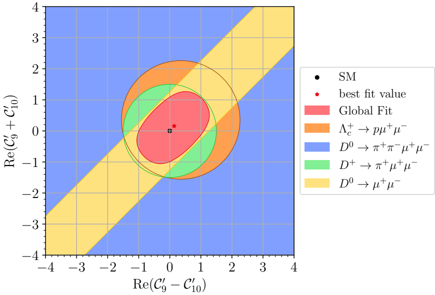


First global fit of $\Delta c = \Delta u = 1$

- complementarity between modes essential
- NP limits from null tests weaker than from upper limits of BRs
- caused by experimental precision and uncertainty in strong phases

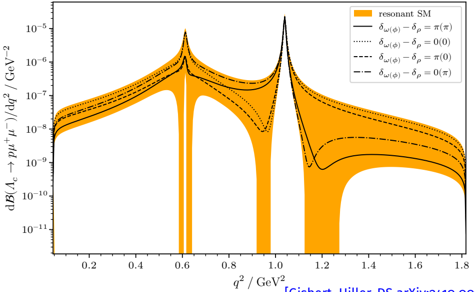


[Gisbert, Hiller, DS arXiv:2410.00115]

Rising star $\Lambda_c \to p\mu^+\mu^-$

- Theoretically simpler and sufficient hadronic structure
  - Lattice form factors [Meinel, arXiv:1712.05783] + less strong phases
- measured by LHCb [LHCb,arXiv:2407.11474, 2502.04013]
- relative strong phases cannot be constrained without $\mathrm{d}\Gamma/\mathrm{d}q^2$ data

⇒ **Please publish background subtracted spectra!**



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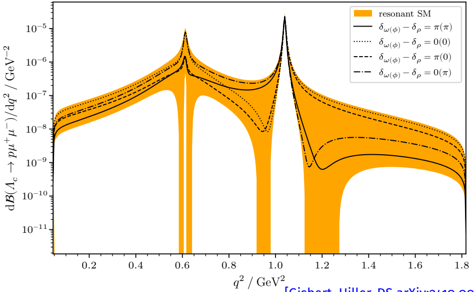

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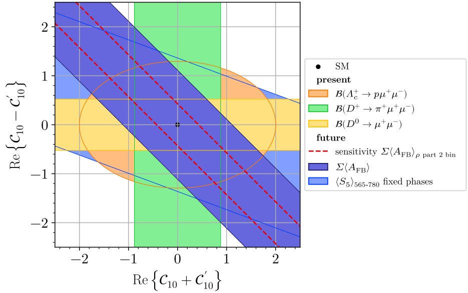


[Gisbert, Hiller, DS arXiv:2410.00115]

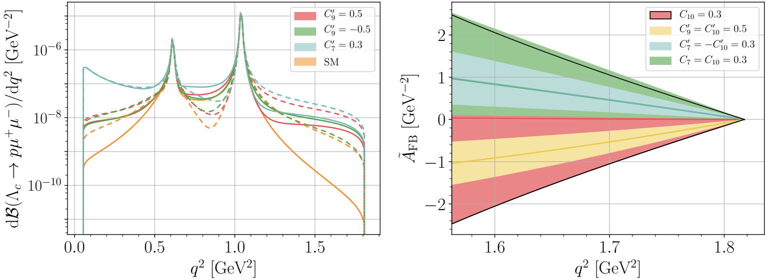
Angular observables include A_{FB} as a **null test**

[Golz, Hiller, Magorsch, arXiv:2107.13010]

- complementary to BRs limits and competitive
- strong phases have still large effects on NP limits
- "sensitivity" = optimal strong phases without uncertainty
- optimized binning is essential to get good NP bounds

Summary & Outlook

- Null tests available to cleanly signal NP in rare charm decays
- Strong phases remain large source uncertainty in extracting limits
  - dimuon spectra & optimized binning are useful
- $\Lambda_c \to p\mu^+\mu^-$ is the rising star for rare charm
  - simple 3-body decay
  - sensitivity to $\mathcal{C}^{(\prime)}_{7,9,10}$
  - A_{FB} is a null test
  - BR & A_{FB} already probed by LHCb



[Golz, Hiller, Magorsch, arXiv:2107.13010]

Backup

Angular observables of $\Lambda_c^+ \to p\mu^+\mu^-$

- Double differential distribution

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

- Longitudinal polarization fraction

$$\langle F_L\rangle = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}}(2K_{1ss}(q^2)-K_{1cc}(q^2))\,\mathrm{d}q^2}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}}(2K_{1ss}(q^2)+K_{1cc}(q^2))\,\mathrm{d}q^2}$$

$$0 \leq \langle F_L\rangle \leq 1$$

bin	$\mathcal{B}_{\text{exp,bin}}$	$\mathcal{B}_{\text{SM,bin}}$	$\langle F_L\rangle_{\text{SM,bin}}$
low-q^2	$< 0.93\times10^{-8}$	$[0.26, 0.83]\times10^{-8}$	$[0.62, 0.71]$
high-q^2	$< 3.0\times10^{-8}$	$[0.02, 2.3]\times10^{-8}$	$[0.00, 0.91]$
low & high-q^2	$< 2.9\times10^{-8}$	$[0.3, 3.1]\times10^{-8}$	$[0.48, 0.71]$
ω	$(7.3\pm2.9)\times10^{-8}$ †	$[5.1, 9.6]\times10^{-8}$	$[0.57, 0.67]$
ρ	$(6.9\pm2.0)\times10^{-8}$ †	$[4.3, 11.9]\times10^{-8}$	$[0.59, 0.66]$
ϕ	$(3.02\pm0.45)\times10^{-7}$ †	$[2.3, 3.7]\times10^{-7}$	$[0.48, 0.53]$
full-q^2	-	$[3.6, 6.0]\times10^{-7}$	$[0.51, 0.57]$

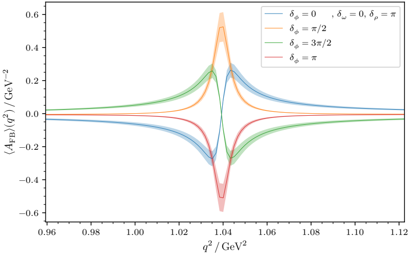
[Gisbert, Hiller, DS arXiv:2410.00115]

- Forward-backward asymmetry of the lepton pair

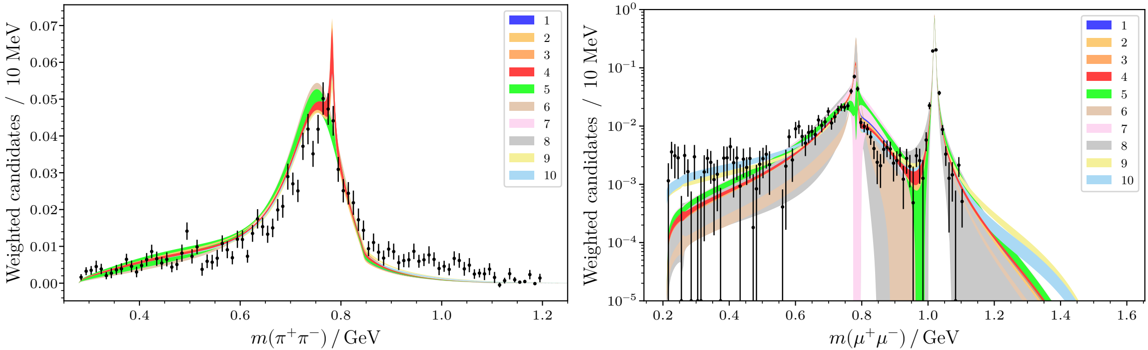
$$\langle A_{\text{FB}}\rangle(q^2) = \frac{1}{\langle\Gamma\rangle}\left[\int_0^1 - \int_{-1}^0\right]\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\cos\theta_l}\,\mathrm{d}\cos\theta_l$$

bin	$q^2\,/\,\text{GeV}^2$ region	$\mathcal{B}_{\text{SM,bin}}$	$\langle A_{\text{FB}}\rangle_{\text{bin}}$, $\mathcal{C}_{10} = 0.30$
ϕ [LHCb, arXiv:2407.11474]	$[0.959, 1.122]$	$[2.3, 3.7]\times10^{-7}$	$[-0.011, 0.011]$
ϕ right	$[1.039, 1.122]$	$[1.1, 2.0]\times10^{-7}$	$[-0.018, 0.018]$
ϕ right optimized	$[1.052, 1.818]$	$[0.15, 0.70]\times10^{-7}$	$[-0.10, 0.10]$

[Gisbert, Hiller, DS arXiv:2410.00115]



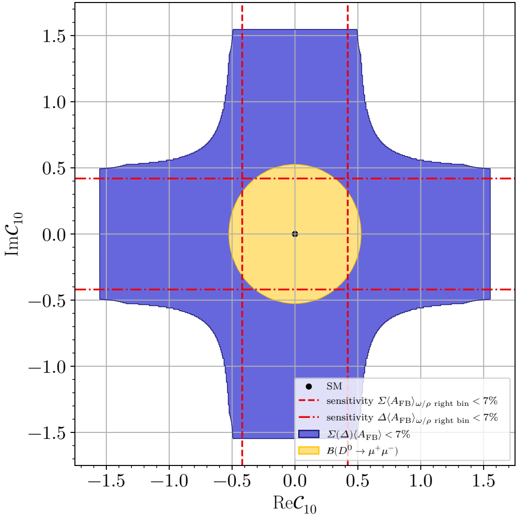
Differential branching fraction of $D^0 \to \pi^+\pi^-\mu^+\mu^-$



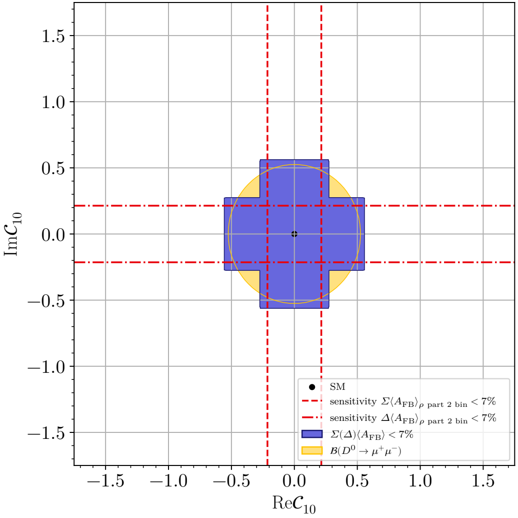
$\langle A_{FB} \rangle$ prediction for different bins

bin	q^2 / GeV^2 region	$\mathcal{B}_{\text{SM,bin}}$	$\langle A_{FB} \rangle_{\text{bin}}$, $\mathcal{C}_{10} = 0.30$	$\langle A_{FB} \rangle_{\text{bin}}$, $\mathcal{C}_{10} = 0.05$
ω/ρ left optimized	$[0.045, 0.478]$	$[0.15, 0.41] \times 10^{-7}$	$[-0.06, 0.06]$	$[-0.010, 0.010]$
ω/ρ left	$[0.346, 0.613]$	$[0.58, 1.07] \times 10^{-7}$	$[-0.029, 0.029]$	$[-0.005, 0.005]$
ω/ρ right	$[0.613, 0.932]$	$[0.41, 1.05] \times 10^{-7}$	$[-0.05, 0.05]$	$[-0.009, 0.009]$
ρ part 2 [LHCb, arXiv:2407.11474]	$[0.677, 0.932]$	$[0.15, 0.67] \times 10^{-7}$	$[-0.10, 0.10]$	$[-0.017, 0.017]$
ϕ [LHCb, arXiv:2407.11474]	$[0.959, 1.122]$	$[2.3, 3.7] \times 10^{-7}$	$[-0.011, 0.011]$	$[-0.0018, 0.0018]$
ϕ left	$[0.959, 1.039]$	$[1.0, 2.0] \times 10^{-7}$	$[-0.018, 0.018]$	$[-0.0030, 0.0030]$
ϕ right	$[1.039, 1.122]$	$[1.1, 2.0] \times 10^{-7}$	$[-0.018, 0.018]$	$[-0.0031, 0.0031]$
ϕ right optimized	$[1.052, 1.818]$	$[0.15, 0.70] \times 10^{-7}$	$[-0.10, 0.10]$	$[-0.017, 0.017]$
$\sqrt{q^2} > 1.25\,\mathrm{GeV}$ [Golz, Hiller, Magorsch, arXiv:2107.13010]	$[1.562, 1.818]$	$[0.11, 1.84] \times 10^{-9}$	$[-0.29, 0.29]$	$[-0.14, 0.14]$

$\langle A_{\text{FB}} \rangle$ bounds for different bins



(a) Bins ω/ρ left, ω/ρ right, ϕ left and ϕ right



(b) Bins ω/ρ left optimized, ρ part 2 and ϕ right optimized