Effective field theory analysis of rare charm decays

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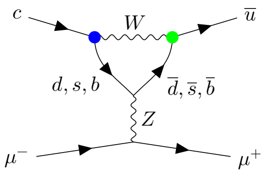
Rare charm decays

Why rare charm decays?

- Unique probe of Flavor-Changing-Neutral-Currents for up-quarks
- Complementary to down-type decays ($s \to d\mu^+\mu^-$, $b \to s\mu^+\mu^-$)
- Strong GIM and CKM suppression in $c \to u\mu^+\mu^-$
- Dominated by resonances whose theoretical prediction is challenging **BUT nulltests remain!**

Compare New Physics(NP) constraints from $D^0 \to \mu^+\mu^-$, $D^+ \to \pi^+\mu^+\mu^-$, $\Lambda_c^+ \to p\mu^+\mu^-$, $D^0 \to \pi^+\pi^-\mu^+\mu^-$

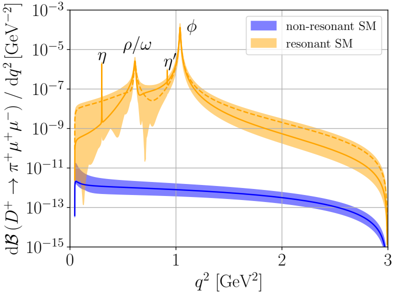


$$\mathcal{A}(c \to u) \propto \frac{1}{16\pi^2} V_{cs}^* V_{us} \left(f\left(\frac{m_s^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right) + \frac{1}{16\pi^2} \underbrace{V_{cb}^* V_{ub}}_{\mathcal{O}(\lambda^5)} \left(f\left(\frac{m_b^2}{m_W^2}\right) - f\left(\frac{m_d^2}{m_W^2}\right)\right)$$

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

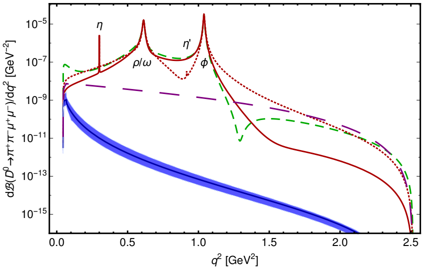
$D^+ \to \pi^+\mu^+\mu^-$

[Bause et al. 2020]



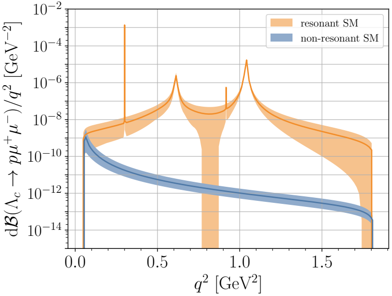
$D^0 \to \pi^+\pi^-\mu^+\mu^-$

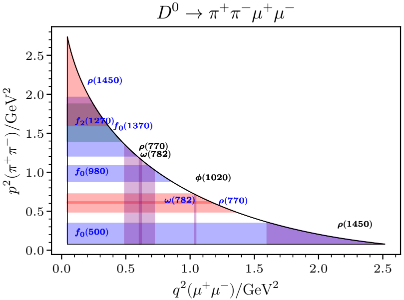
[De Boer and Hiller 2018]



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

[Golz, Hiller, and Magorsch 2021]





Weak effective field theory (WET)

- Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left[\sum_{i\neq T,T_5}\left(c_i(\mu)\;\mathcal{O}_i(\mu)\;+\;\overbrace{c_i'(\mu)\;\mathcal{O}_i'(\mu)}^{c_i'\mathcal{O}_i|_{L(R)\to R(L)}}\right)+\sum_{i=T,T_5}c_i(\mu)\,\mathcal{O}_i(\mu)\right]$$

$$\mathcal{O}_7 = \frac{m_c}{e}(\bar{u}_L\,\sigma_{\mu\nu}\,c_R)\,F^{\mu\nu}\,,\qquad \mathcal{O}_9 = (\bar{u}_L\,\gamma_\mu\,c_L)\,(\bar{\ell}\,\gamma^\mu\,\ell)\,,\qquad \mathcal{O}_{10} = (\bar{u}_L\,\gamma_\mu\,c_L)\,(\bar{\ell}\,\gamma^\mu\,\gamma_5\,\ell)\,,$$

$$\mathcal{O}_{S(P)} = (\bar{u}_L\,c_R)\,(\bar{\ell}\,(\gamma_5)\,\ell)\,,\qquad \mathcal{O}_{T(T_5)} = \tfrac{1}{2}\,(\bar{u}\,\sigma_{\mu\nu}\,c)\,(\bar{\ell}\,\sigma^{\mu\nu}\,(\gamma_5)\,\ell)\,.$$

- SM Wilson coefficients negligible

$$|\mathcal{C}_9^{\text{eff}}(q^2)| \lesssim 0.01\,,\qquad |\mathcal{C}_7^{\text{eff}}(q^2)| \simeq \mathcal{O}(0.001)$$ [De Boer and Hiller 2018]

- all others vanish and create null test opportunities

$$\mathcal{C}^{\text{SM}}_{10,S,P,T,T_5} = \mathcal{C}'^{\,\text{SM}}_{7,9,10,S,P,} = 0 \;\Rightarrow\; \boldsymbol{\mathcal{C}_i \equiv \mathcal{C}_i^{\text{NP}}}$$

Experimental status

	$D^0 \to \mu^+\mu^-$	$D^+ \to \pi^+\mu^+\mu^-$	$\Lambda_c^+ \to p\mu^+\mu^-$	$D^0 \to \pi^+\pi^-\mu^+\mu^-$
upper limits BR	✓	full-q^2, (low-q^2, high-q^2)	low-q^2, high-q^2, combined, full-q^2	high-q^2
resonant BR	$< 4 \cdot 10^{-11}$	$\mathcal{B}_\phi$, narrow-width approx. (NWA)	$\frac{\mathcal{B}_{\omega\text{-region}}}{\mathcal{B}_{\phi\text{-region}}}$, $\frac{\mathcal{B}_{\rho\text{-region}}}{\mathcal{B}_{\phi\text{-region}}}$, NWA	$\mathcal{B}_{\omega/\rho\text{-region}}, \mathcal{B}_{\phi\text{-region}}$ $\left(\frac{d\Gamma}{dm_{\mu^+\mu^-}}, \frac{d\Gamma}{dm_{\pi^+\pi^-}}\right)$
angular obs.	—	not measured	not measured	CP-sym./CP-asym. $\langle S_{2-9}\rangle$,$\langle A_{2-9}\rangle$

- Angular observables include null tests sensitive to NP
- For this we need to fix resonance parameters as best as we can from available measurements

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angular obs.	–	not measured	not measured	CP-sym./CP-asym. $\langle S_{2-9}\rangle$,$\langle A_{2-9}\rangle$

Constrain NP model independently in low-q^2 & high-q^2

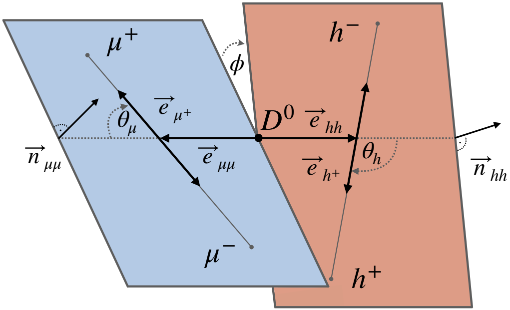
- Angular observables include null tests sensitive to NP
- For this we need to fix resonance parameters as best as we can from available measurements

$D^0 \to \pi^+\pi^-\mu^+\mu^-$

- 5-differential distribution:

[Cappiello, Cata, and D'Ambrosio 2013, De Boer and Hiller 2018]

$$\frac{d^5\Gamma}{dq^2\, dp^2\, d\cos\theta_{P_1}\, d\cos\theta_\ell\, d\phi} = \frac{1}{2\pi}\sum_{i=1}^{9} c_i(\theta_\ell,\phi)\, I_i(q^2,p^2,\cos\theta_{P_1})$$



[LHCb, arXiv: 2111.03327]

- Integrating $\cos\theta_{P_1}, p^2$ and different q^2 bins

$$\langle I_{2,3,6,9}\rangle_{[q^2_{\text{min}},q^2_{\text{max}}]} = \frac{1}{\Gamma_{[q^2_{\text{min}},q^2_{\text{max}}]}}\int dq^2 dp^2 \int_{-1}^{1} d\cos\theta_{P_1}\, I_{2,3,6,9}\,,$$

$$\langle I_{4,5,7,8}\rangle_{[q^2_{\text{min}},q^2_{\text{max}}]} = \frac{1}{\Gamma_{[q^2_{\text{min}},q^2_{\text{max}}]}}\int dq^2 dp^2 \left[\int_{0}^{1} d\cos\theta_{P_1} - \int_{-1}^{0} d\cos\theta_{P_1}\right] I_{4,5,7,8},$$

- 5-differential distribution:

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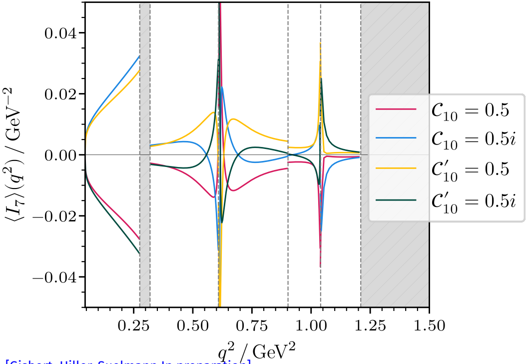

[Gisbert, Hiller, Suelmann In preparation]

- Integrating $\cos\theta_{P_1}, p^2$ and different q^2 bins

Null tests: $\langle I_{5,6,7}\rangle$ + CP-asymmetries

$$\langle I_{2,3,6,9}\rangle_{[q^2_{\text{min}},q^2_{\text{max}}]} = \frac{1}{\Gamma_{[q^2_{\text{min}},q^2_{\text{max}}]}}\int \mathrm{d}q^2\mathrm{d}p^2 \int_{-1}^{1}\mathrm{d}\cos\theta_{P_1}\, I_{2,3,6,9}\,,$$

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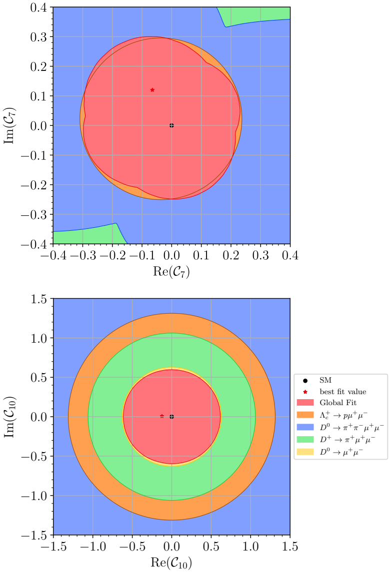
Fits of Wilson coefficients

- Compare upper limits from branching ratios and null tests
- Upper limits from $D^0 \to \pi^+\pi^-\mu^+\mu^-$ are the weakest
  - strong phases in charm (main source of uncertainty)
  - experimental sensitivity not there yet
  - Theory prediction more challenging than 3-body decays
- Best constrains for $\mathcal{C}_{10}$ from $D^0 \to \mu^+\mu^-$
- Best constrains for $\mathcal{C}_7$ from low-q^2 of $\Lambda_c^+ \to p\mu^+\mu^-$

Future directions

- Should focus on NP potential in hadronic simpler decays
- $\Lambda_c \to p\mu^+\mu^-$ with null test for $\mathcal{C}_{10}$



[Gisbert, Hiller, Suelmann In preparation] depends on: $f_i(q^2)$, $\mathcal{C}_9^{\mathcal{R}}$, $\mathcal{C}_i^{\text{NP}}$

- Double differential distribution

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

- Long-distance contribution modeled with ansatz

$$\mathcal{C}_9^R(q^2) = \frac{a_\rho\, e^{i\,\delta_\rho}}{q^2 - m_\rho^2 + i\,m_\rho\,\Gamma_\rho} + \frac{a_\omega e^{i\,\delta_\omega}}{q^2 - m_\omega^2 + i\,m_\omega\,\Gamma_\omega} + \frac{a_\phi\, e^{i\,\delta_\phi}}{q^2 - m_\phi^2 + i\,m_\phi\,\Gamma_\phi} ,$$

- Take Lattice QCD form factors [Meinel 2018] and $\mathcal{B}(\Lambda_c^+ \to p\,\mu^+\mu^-)$ data [LHCb, arXiv: 2407.11474]

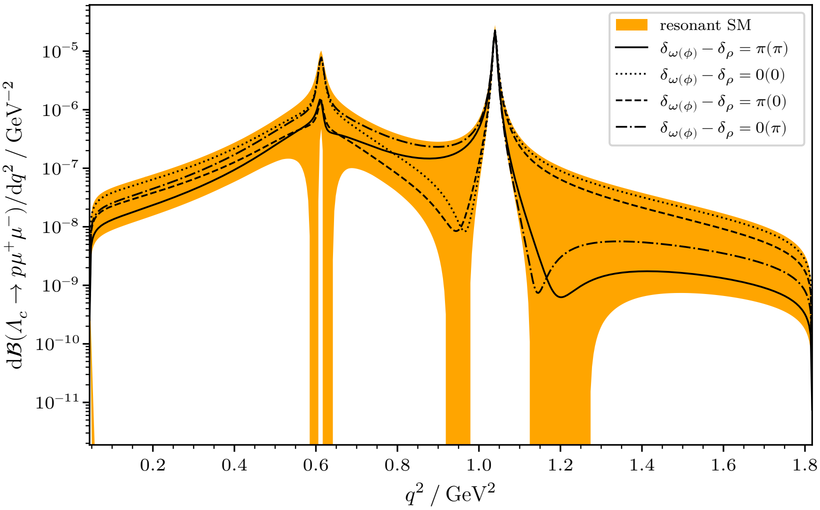
$$\left\langle p(k,s_p)\middle|\bar{u}\gamma^\mu c\middle|\Lambda_c(p,s_{\Lambda_c})\right\rangle = \bar{u}_p(k,s_p)\left[f_0(q^2)(m_{\Lambda_c} - m_p)\frac{q^\mu}{q^2} + \ldots\right]u_{\Lambda_c}(p,s_{\Lambda_c})$$

- Fit parameters a_R, but relative phases unconstrained!

measure: high-q^2 & between m_ρ^2 and m_ϕ^2

$$a_\phi = 0.108^{+0.008}_{-0.008} ,\ a_\omega = 0.074^{+0.012}_{-0.015} ,\ a_\rho = 0.50^{+0.06}_{-0.06} ,$$

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



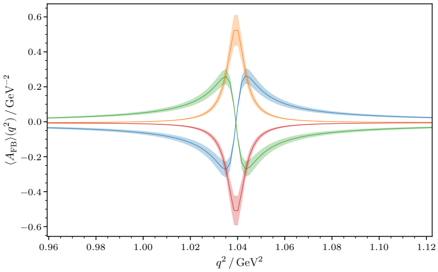
[Gisbert, Hiller, Suelmann In preparation]

Future improvements with $\Lambda_c^+ \to p\mu^+\mu^-$ null tests

- Forward-backward asymmetry of the lepton pair

$$\langle A_{\mathsf{FB}}\rangle(q^2) = \frac{1}{\langle\Gamma\rangle}\left[\int_0^1 - \int_{-1}^0\right]\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l}\,\mathrm{d}\cos\theta_l$$
$$\propto \mathrm{Re}\left\{\mathcal{C}_9^{\mathcal{R}}\boldsymbol{\mathcal{C}_{10}^*}\right\}$$

- Strongly depends on an overall strong phase of $\mathcal{C}_9^{\mathcal{R}}$
- Binning is important around resonances



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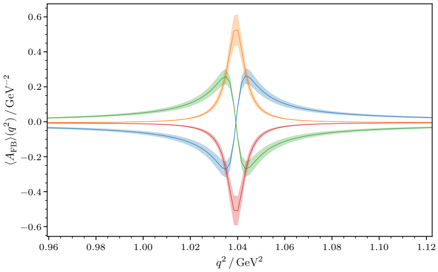
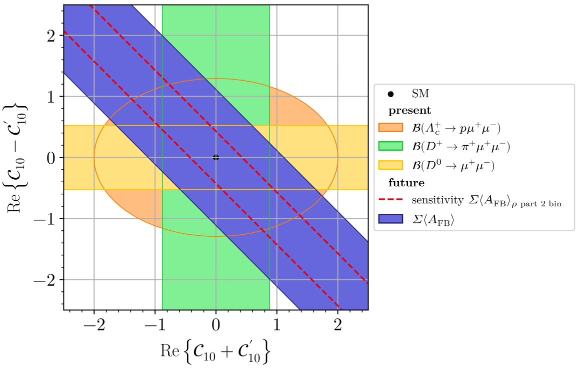


- Complementary to limits from BR

[Gisbert, Hiller, Suelmann In preparation]



Conclusion

Rare charm decays are essential to test FCNCs in the up-sector

- Progress in charm is starting, more modes / observables are getting measured

- present $D^0 \to \pi^+\pi^-\mu^+\mu^-$ null tests less sensitive than BRs
  - NP limits weaker due to strong phases
  - theory prediction more challenging

- Low-q^2 and high-q^2 BR give stronger bounds, but will reach resonant SM contribution eventually

- Focus on $\langle A_{\mathrm{FB}} \rangle$ null test in $\Lambda_c \to p\mu^+\mu^-$

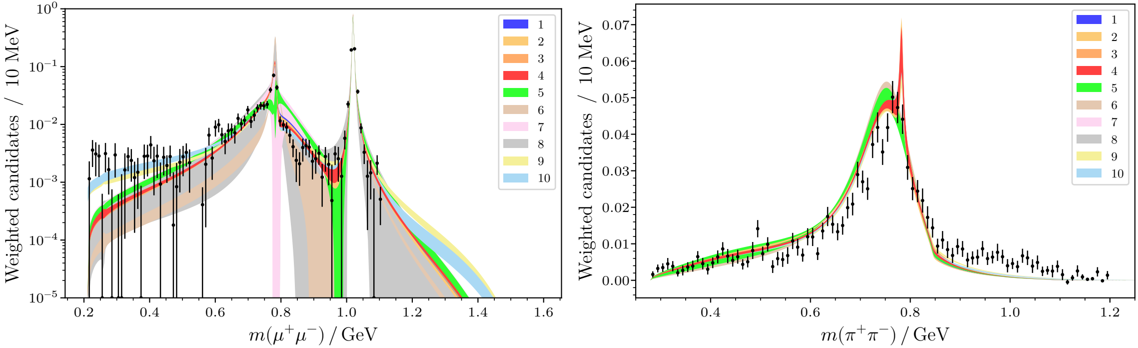
- More than one mode required for complementarity

Thank you for your attention!

Backup

Fit of resonance parameters

- $\frac{\mathrm{d}\Gamma}{\mathrm{d}\sqrt{q^2}}$, $\frac{\mathrm{d}\Gamma}{\mathrm{d}\sqrt{p^2}}$, $\langle S_{2,3,4} \rangle$ and $\mathcal{B}$ for normalization
- Different scenarios depending on which data to include / assumptions about amplitude
- Scenario 2 as in [Fajfer, Solomonidi, and Vale Silva 2023]
- Choosing scenario 4 with lowest likelihood (excluding NPs)



$D^0 \to \pi^+\pi^-\mu^+\mu^-$

[Gisbert, Hiller, Suelmann In preparation]

Some problems with SM fit

- discrepency in $\langle S_{2,3,4}\rangle$ data partially in low-q^2
- $\langle \mathcal{B}\rangle$ in first bin disagrees, no direct data on second bin
- low-q^2 for $\mathrm{d}\Gamma/\mathrm{d}q^2$ and high-p^2 for $\mathrm{d}\Gamma/\mathrm{d}p^2$ disagree
- $\langle S_9\rangle_{\mathsf{SM/NP}} = 0$, but $\langle S_9\rangle = (16.9 \pm 4.4)\%$ for $[0.950\text{-}1.02]\ \mathrm{GeV}$, a local anomaly of 3.8σ

What is the solution?

- more precise p^2, q^2 binning and double differential
- for now exclude low-q^2 region
- null tests limits more conservative & less effected