New Physics opportunities in rare charm

Dominik Suelmann

in collaboration with H. Gisbert, G. Hiller

Supported by the Federal Ministry for Education and Research (BMBF)

TU Dortmund

Department of Physics

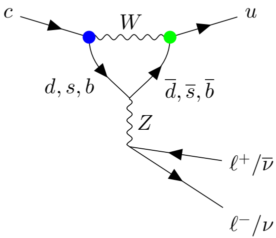
1. October 2024

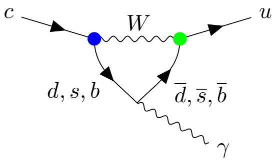
Belle II Germany Meeting

technische universität dortmund

Bundesministerium für Bildung und Forschung

Rare charm decays





Why rare charm decays?

- Unique probe of Flavor-Changing-Neutral-Currents for up-quarks in $c \to u$
- Complementary to down-type decays ($s \to d$, $b \to d$, $b \to s$)
- Strong GIM and CKM suppression

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

New Physics (NP) constraints from
$c \to u\nu\bar{\nu}$, $c \to u\ell^+\ell^-$, $c \to u\gamma$

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

Flavor-changing neutral currents (FCNCs)

$c \to u +$ invisible

- SM strongly suppressed
- $\mathcal{B}(D^+ \to \pi^+ \nu\bar{\nu}) \sim 10^{-16}$
  $\to$ **null test**
- Few upper limits available

[Belle, arXiv:1611.09455]

$\mathcal{B}(D^0 \to \text{invisible}) < 9.4 \cdot 10^{-5}$

[BESIII, arXiv:2112.14236]

$\mathcal{B}(D^0 \to \pi^0 \nu\bar{\nu}) < 2.1 \cdot 10^{-4}$

[BESIII, arXiv:2208.04496]

$\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8 \cdot 10^{-5}$

[BESIII, arXiv:2409.02578]

$\mathcal{B}(D^0 \to \omega\gamma') < 1.1 \cdot 10^{-5}$

- **perfect opportunity for Belle II!**

Flavor-changing neutral currents (FCNCs)

$c \to u +$ invisible

- SM strongly suppressed
- $\mathcal{B}(D^+ \to \pi^+ \nu\overline{\nu}) \sim 10^{-16}$ $\to$ **null test**
- Few upper limits available

[Belle, arXiv:1611.09455]

$\mathcal{B}(D^0 \to \text{invisible}) < 9.4 \cdot 10^{-5}$

[BESIII, arXiv:2112.14236]

$\mathcal{B}(D^0 \to \pi^0 \nu\overline{\nu}) < 2.1 \cdot 10^{-4}$

[BESIII, arXiv:2208.04496]

$\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8 \cdot 10^{-5}$

[BESIII, arXiv:2409.02578]

$\mathcal{B}(D^0 \to \omega\gamma') < 1.1 \cdot 10^{-5}$

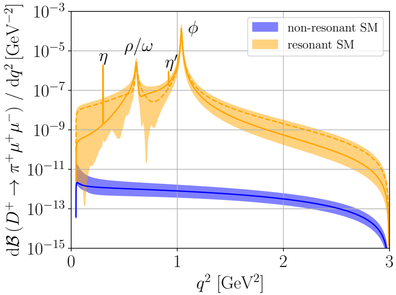
- **perfect opportunity for Belle II!**

$c \to u\ell^+\ell^-$

- NP constraints in low-q^2, high-q^2
- Dominated by resonances whose theoretical prediction is challenging
  But null tests remain!

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

[Bause, Golz, et al. 2020]



Flavor-changing neutral currents (FCNCs)

$c \to u +$ invisible

- SM strongly suppressed
- $\mathcal{B}(D^+ \to \pi^+ \nu\bar{\nu}) \sim 10^{-16}$ $\to$ **null test**
- Few upper limits available

[Belle, arXiv:1611.09455]

$$\mathcal{B}(D^0 \to \text{invisible}) < 9.4 \cdot 10^{-5}$$

[BESIII, arXiv:2112.14236]

$$\mathcal{B}(D^0 \to \pi^0 \nu\bar{\nu}) < 2.1 \cdot 10^{-4}$$

[BESIII, arXiv:2208.04496]

$$\mathcal{B}(\Lambda_c^+ \to p\gamma') < 8 \cdot 10^{-5}$$

[BESIII, arXiv:2409.02578]

$$\mathcal{B}(D^0 \to \omega\gamma') < 1.1 \cdot 10^{-5}$$

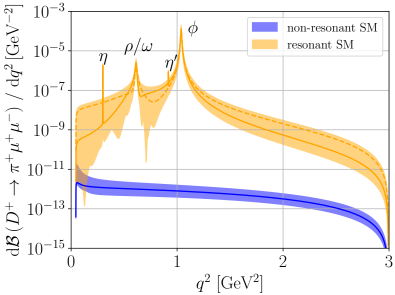
- **perfect opportunity for Belle II!**

$c \to u\ell^+\ell^-$

- NP constraints in low-q^2, high-q^2
- Dominated by resonances whose theoretical prediction is challenging
But null tests remain!

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

[Bause, Golz, et al. 2020]



$(c \to u\gamma)$

- BR & A_{CP} measured for vector mesons
[Belle, arXiv:1603.03257]

$$\mathcal{B}(D^0 \to \rho^0\gamma) = (1.77 \pm 0.31) \cdot 10^{-5}$$

- agreement with SM (large uncertainties)
- highly sensitive to dipole operators

$$\mathcal{O}_7 \propto (\bar{u}_L\, \sigma_{\mu\nu}\, c_R)\, F^{\mu\nu}$$

- many left to explore

$$c \to u + \text{invisible}$$

Study $\Lambda_c \to p +$ invisible

- Differential branching fraction

$$\frac{d\mathcal{B}}{dq^2} = \frac{1}{2m_{\Lambda_c}} \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}E_{\text{miss}}}, \qquad q^2 = (p_{\Lambda_c} - p_p)^2$$

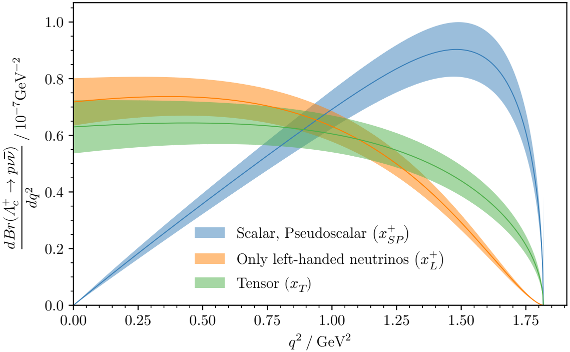
- EFT with ν_L & ν_R

$$\mathcal{H}_{\text{eff}}^{\nu_i \bar{\nu}_j} = -\frac{4G_F}{\sqrt{2}} \sum_k \mathcal{C}_k^{ij} \cdot Q_k^{ij} + \text{h.c.}$$

- additional operators allowed

$\mathcal{C}_{\text{SM}} \approx 0$

$$Q_{L(R)\,L}^{ij} = (\bar{u}_{L(R)} \gamma_\mu c_{L(R)})(\bar{\nu}_{jL} \gamma^\mu \nu_{iL})$$
$$Q_{L(R)\,R}^{ij} = (\bar{u}_{L(R)} \gamma_\mu c_{L(R)})(\bar{\nu}_{jR} \gamma^\mu \nu_{iR})$$
$$Q_S^{(\prime)ij} = (\bar{u}_{L(R)} c_{R(L)})(\bar{\nu}_j \nu_i)$$
$$Q_P^{(\prime)ij} = (\bar{u}_{L(R)} c_{R(L)})(\bar{\nu}_j \gamma_5 \nu_i)$$
$$Q_{T_{(5)}}^{ij} = (\bar{u} \sigma_{\mu\nu} c)(\bar{\nu}_j \sigma^{\mu\nu} (\gamma_5) \nu_i)$$



[Hiller, Suelmann In preparation]

- sum over neutrino flavors for observables

$$x_{SP}^{\pm} = \sum_{\substack{\text{flavor} \\ ij}} \left|\mathcal{C}_S^{ij} \pm \mathcal{C}_S^{\prime ij}\right|^2 + \left|\mathcal{C}_P^{ij} \pm \mathcal{C}_P^{\prime ij}\right|^2$$

$c \to u +$ invisible

- Multiple constraints for vector/axial-vector available

$$x_{L\pm} = \sum_{ij} \left| \mathcal{C}^{ij}_{LL} \pm \mathcal{C}^{ij}_{RL} \right|^2$$
$$x_L = \frac{x_{L+} + x_{L-}}{2}$$

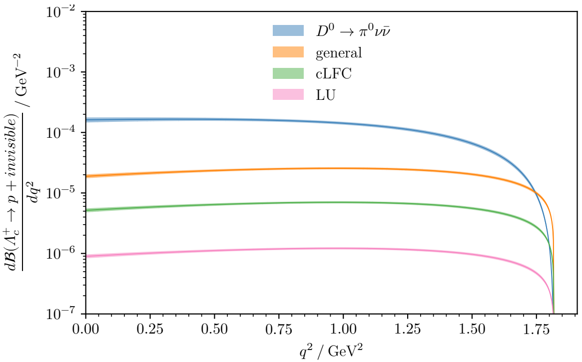
- Upper limits through $SU(2)_L$ link

[Bause, Gisbert, et al. 2021]

$x_L \lesssim 34,$ Lepton Universal (LU)
$x_L \lesssim 196,$ charged lepton flavor conservation (cLFC)
$x_L \lesssim 716,$ general

- Direct upper limit from $D^0 \to \pi^0 \nu\bar{\nu}$

$$x_{L+} \lesssim 24 \cdot 10^3$$



[Hiller, Suelmann In preparation]

- Direct limit weaker than $SU(2)_L$ limits
- Much potential for the future!
- Other light NP plausible, like light Z'/γ' or axion-like particles

$$c \to u\ell^+\ell^-$$

$c \to u\ell^+\ell^-$

What can already be measured?

- rare charm decays $D^+ \to \pi^+\mu^+\mu^-$, $\Lambda_c \to p\mu^+\mu^-$, $D^0 \to \pi^+\pi^-\mu^+\mu^-$ in reach of LHCb for $\mu^+\mu^-$
- $D^0 \to \pi^+\pi^- e^+ e^-$ close to discovery for e^+e^-, upper limits set at 90% C.L. $[2\text{-}8] \cdot 10^{-7}$

  [Belle, Moriond 2024]

$\Rightarrow$ work out $c \to u\mu^+\mu^-$ NP constraints

- Operators for $c \to u\ell^+\ell^-$ transition (weak effective field theory)

$$\begin{aligned}
\mathcal{O}_7 &= \frac{m_c}{e}\,(\bar{u}_L\,\sigma_{\mu\nu}\,c_R)\,F^{\mu\nu}\,,\\
\mathcal{O}_9 &= (\bar{u}_L\,\gamma_\mu\,c_L)\,(\bar{\ell}\,\gamma^\mu\,\ell)\,,\\
\mathcal{O}_{10} &= (\bar{u}_L\,\gamma_\mu\,c_L)\,(\bar{\ell}\,\gamma^\mu\,\gamma_5\,\ell)\,, \qquad \mathcal{O}_i' = \mathcal{O}_i|_{R(L)\to L(R)}\\
\mathcal{O}_{S(P)} &= (\bar{u}_L\,c_R)\,(\bar{\ell}\,(\gamma_5)\,\ell)\,,\\
\mathcal{O}_{T(T_5)} &= \tfrac{1}{2}\,(\bar{u}\,\sigma_{\mu\nu}\,c)\,(\bar{\ell}\,\sigma^{\mu\nu}\,(\gamma_5)\,\ell)\,.
\end{aligned}$$

- 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

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

Experimental status of $c \to u\mu^+\mu^-$

	[CMS-PAS-BPH-23-008] $D^0 \to \mu^+\mu^-$	[LHCb, arXiv:2011.00217] $D^+ \to \pi^+\mu^+\mu^-$	[LHCb, arXiv:2407.11474] $\Lambda_c^+ \to p\mu^+\mu^-$	[LHCb, arXiv:1707.08377, arXiv:2111.03327] $D^0 \to \pi^+\pi^-\mu^+\mu^-$
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

Experimental status of $c \to u\mu^+\mu^-$

	[CMS-PAS-BPH-23-008] $D^0 \to \mu^+\mu^-$	[LHCb, arXiv:2011.00217] $D^+ \to \pi^+\mu^+\mu^-$	[LHCb, arXiv:2407.11474] $\Lambda_c^+ \to p\mu^+\mu^-$	[LHCb, arXiv:1707.08377, arXiv:2111.03327] $D^0 \to \pi^+\pi^-\mu^+\mu^-$
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. $\langle S_{2-9}\rangle$,$\langle A_{2-9}\rangle$

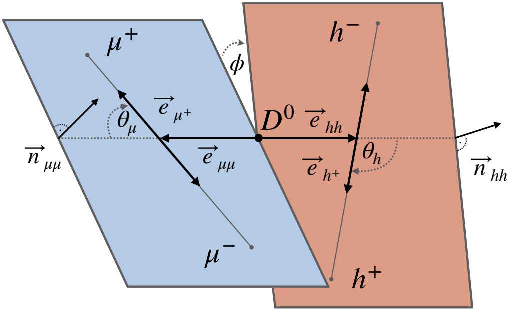
Constrain NP model independently in low-q^2 & high-q^2

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

- 5-differential distribution:

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

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



[LHCb, arXiv:2111.03327]

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

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

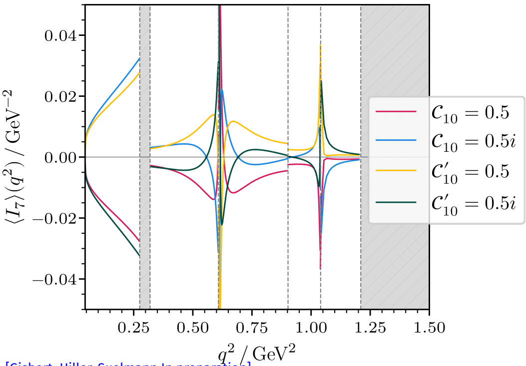
$$\langle I_{4,5,7,8}\rangle_{[q^2_{\text{min}},q^2_{\text{max}}]} = \frac{1}{\Gamma_{[q^2_{\text{min}},q^2_{\text{max}}]}}\int \mathrm{d}q^2\mathrm{d}p^2 \left[\int_{0}^{1}\mathrm{d}\cos\theta_{P_1} - \int_{-1}^{0}\mathrm{d}\cos\theta_{P_1}\right] I_{4,5,7,8},$$

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

- 5-differential distribution:

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

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



[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

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

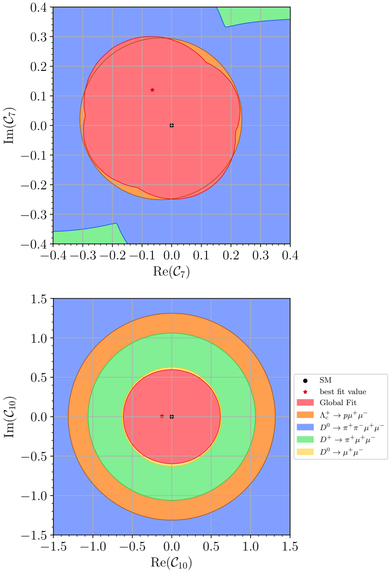
$$\langle I_{4,5,7,8}\rangle_{[q^2_{\mathrm{min}},q^2_{\mathrm{max}}]} = \frac{1}{\Gamma_{[q^2_{\mathrm{min}},q^2_{\mathrm{max}}]}}\int \mathrm{d}q^2\mathrm{d}p^2 \left[\int_{0}^{1}\mathrm{d}\cos\theta_{P_1} - \int_{-1}^{0}\mathrm{d}\cos\theta_{P_1}\right] I_{4,5,7,8},$$

Fits of $c \to u\mu^+\mu^-$ 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
  - some problems with SM prediction
- 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, Aaij et al. 2024]

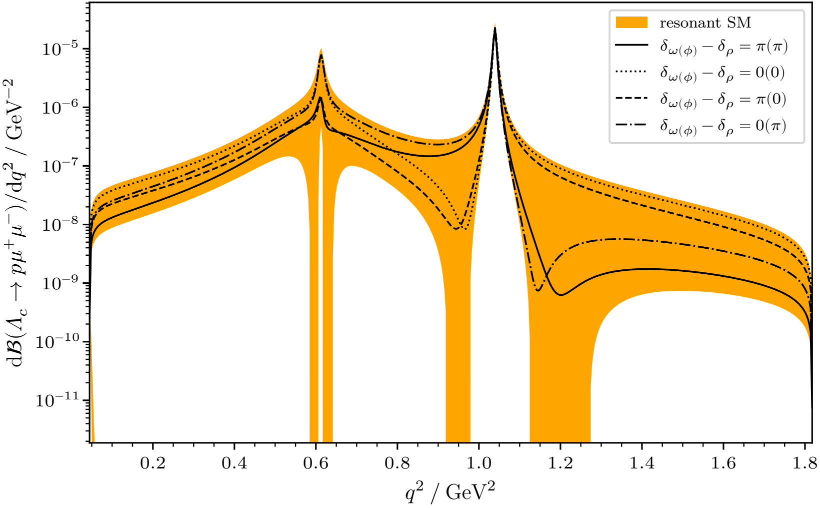
$$\left\langle p(k,s_p)\middle|\bar{u}\gamma^\mu c\middle|\Lambda_c(p,s_{\Lambda_c})\right\rangle = \bar{u}_p(k,s_p)\left[f_0(q^2)(m_{\Lambda_c} - m_p)\frac{q^\mu}{q^2} + \ldots\right]u_{\Lambda_c}(p,s_{\Lambda_c})$$

- Fit parameters a_R, but relative phases unconstrained!

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

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

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



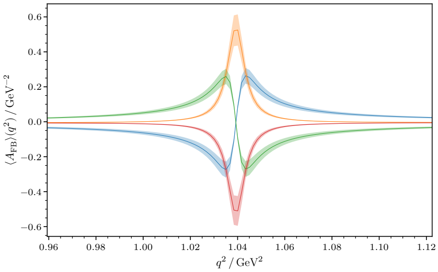
[Gisbert, Hiller, Suelmann In preparation]

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

- Forward-backward asymmetry of the lepton pair

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

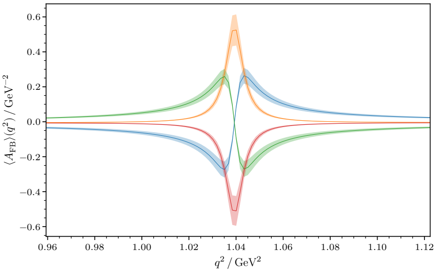
- Strongly depends on an overall strong phase of $\mathcal{C}_9^{\mathcal{R}}$
- Binning is important around resonances



- Forward-backward asymmetry of the lepton pair

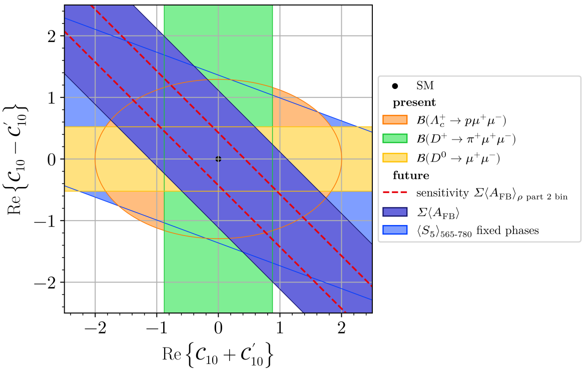
$$\langle A_{\mathrm{FB}}\rangle(q^2) = \frac{1}{\langle\Gamma\rangle}\left[\int_0^1 - \int_{-1}^0\right]\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l}\,\mathrm{d}\cos\theta_l \propto \mathrm{Re}\left\{\mathcal{C}_9^{\mathcal{R}}\mathcal{C}_{10}^*\right\}$$

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



- 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
- few limits for $c \to u +$ invisible, various missing energy scenarios distinguishable by $d\mathcal{B}/dq^2$
- $D^0 \to \pi^+\pi^-e^+e^-$ close to discovery
- present $D^0 \to \pi^+\pi^-\mu^+\mu^-$ null tests less sensitive than BRs
  - theory prediction more challenging
  - interpreting NP limits more difficult due to strong phases
  - presently a QCD laboratory
- Low-q^2 and high-q^2 BR give stronger $c \to u\mu^+\mu^-$ bounds, but will reach resonant SM contribution eventually
- Focus on $\langle A_{\text{FB}} \rangle$ null test in $\Lambda_c \to p\mu^+\mu^-$

Conclusion

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

- Progress in charm is starting, more modes / observables are getting measured
- few limits for $c \to u +$ invisible, various missing energy scenarios distinguishable by $d\mathcal{B}/dq^2$
- $D^0 \to \pi^+\pi^-e^+e^-$ close to discovery
- present $D^0 \to \pi^+\pi^-\mu^+\mu^-$ null tests less sensitive than BRs
  - theory prediction more challenging
  - interpreting NP limits more difficult due to strong phases
  - presently a QCD laboratory
- Low-q^2 and high-q^2 BR give stronger $c \to u\mu^+\mu^-$ bounds, but will reach resonant SM contribution eventually
- Focus on $\langle A_{\mathrm{FB}} \rangle$ null test in $\Lambda_c \to p\mu^+\mu^-$

Paper about $c \to u\mu^+\mu^-$ will be on arXiv tomorrow! Stay tuned!

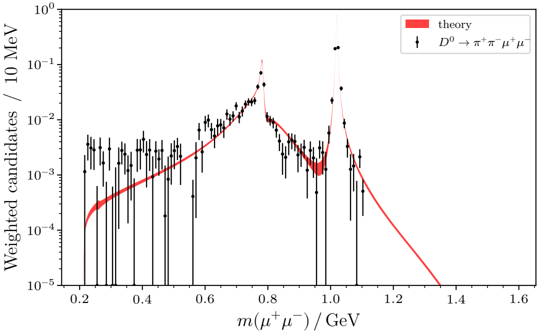
Backup

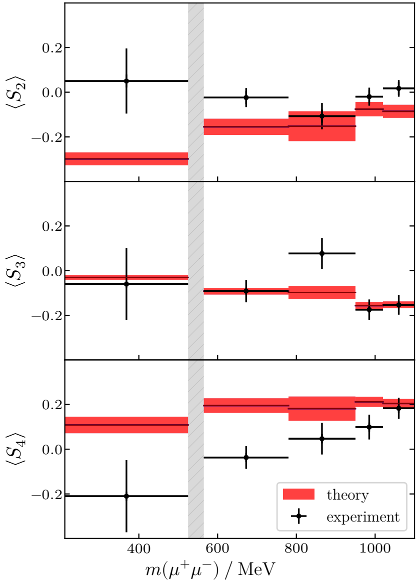
$D^0 \to \pi^+\pi^-\mu^+\mu^-$

Some problems with SM fit

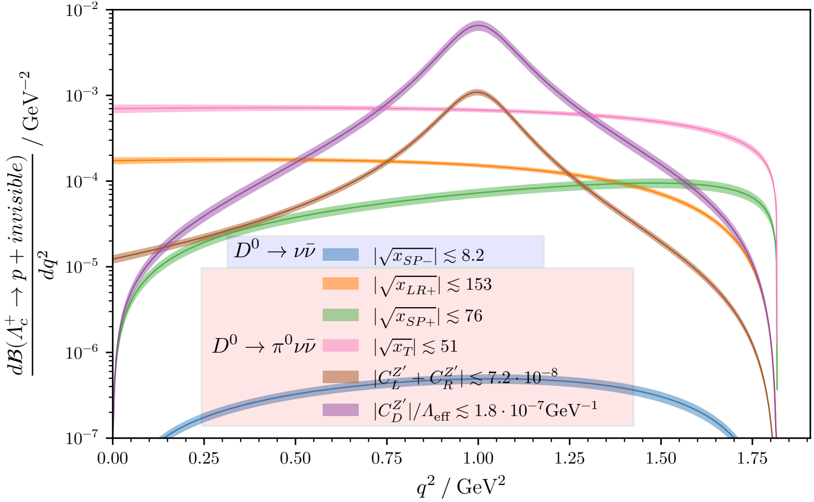
[Gisbert, Hiller, Suelmann In preparation]

- discrepency in $\langle S_{2,4}\rangle$ 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
- How will be the situtation for $D^0 \to \pi^+\pi^-e^+e^-$?
- presently a QCD laboratory





Experimental upper limits $\Lambda_c \to p + invisible$



Experimental upper limits $D^0 \to \pi^0 + invisible$