Angular distributions of semi-leptonic D decays (arXiv:1805.08516, in PRD)

Uncharted territory: $|\Delta c| = |\Delta u| = 1$

based on a series of papers with Stefan de Boer

Gudrun Hiller, TU Dortmund Supported in part by the DFG research Unit FOR 1873 and the Federal Ministry for Education and Research (BMBF)

With or without b anomalies

LNU anomalies in B-decays will be sorted out.

Irrespective of this, it is a truly flavor-type question whether BSM in $b \to s$-FCNC decays has implications for $c \to u$ decays.

$|\Delta c| = |\Delta u| = 1$ is genuine probe of flavor in the up-quark sector, analyzable at LHCb, BaBar, Belle, Belle II, BESIII.

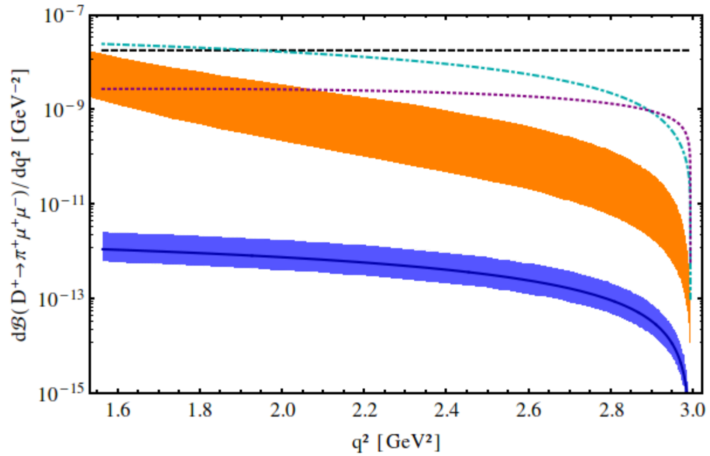
charm is the new beauty

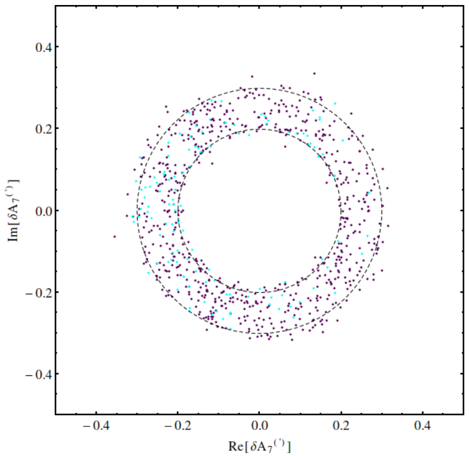
Bigi, Burdman, d'Ambrosio, Cata, Fajfer, Feldmann, Golowich, Hewett, Kosnic, Meinel, Pakvasa, Petrov, Seidel, Singer, Zwicky, de Boer, GH

1510.00311 on $D \to \pi ll$, 1701.06392 on Br and A_{CP} in radiative D-decays, 1802.02769 on photon polarization from TDA or up-down asymmetry; 1805.08516 on $D \to P_1 P_2 ll$, $P_{1,2} = \pi, K$

Model-independent constraints on $|\Delta c| = |\Delta u| = 1$

What do we know about $|\Delta c| = |\Delta u| = 1$ couplings anyway?





$(\bar{u}\Gamma c)(\bar{\mu}\Gamma\mu)$: $|C_{9,10}^{(\prime)}| \lesssim 1, \;|C_{T,T5}| \lesssim 1, \;|C_{S,P}^{(\prime)}| \lesssim 0.1, \;|C_7^{(\prime)}| \lesssim 0.3.$

vs $|C_9^{\mathrm{effSM}}| \lesssim 0.01\,, \;C_{10}^{\mathrm{SM}} = 0\,, \;C^{\prime\mathrm{SM}}, C_{S,P,T,T5}^{\mathrm{SM}} = 0, \;|C_7^{\mathrm{effSM}}| = \mathcal{O}(0.001)$.

BSM weak loop $\Lambda_{NP} \gtrsim O(5)$ TeV, BSM tree level $\Lambda_{NP} \gtrsim$ weak scale.

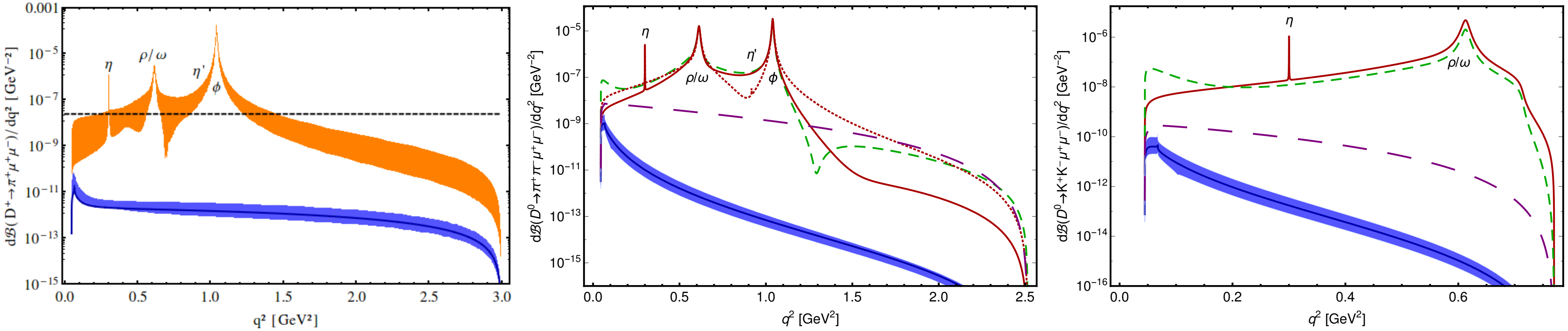
$(\bar{u}\Gamma c)(\bar{e}\Gamma e)$: constraints (2-4) $\times$ weaker (data) than muon constraints.

$(\bar{u}\Gamma c)(\bar{\mu}\Gamma e)$, $(\bar{e}\Gamma\mu)$: (6-7) $\times$ weaker than muon constraints.

Lessons from beauty

Study of angular distribution in $B \to K^*(\to K\pi)\mu^+\mu^-$ was a game changer in $b \to s$ FCNC to progress in global fit.

Even more so in charm: $\delta\mathcal{B}(D)_{\rm SM} \sim \mathcal{O}(1)$.



BSM windows in branching ratios only in $D \to \pi\mu^+\mu^-$ (left) at high q^2 1510.00311; $D \to \pi^+\pi^-\mu\mu$ (mid), $D \to K^+K^-\mu\mu$ (right),1805.08516, 1705.05891 To observe BSM in rare charm either i) BSM is an obvious excess in rates, ii) SM BDG can be measured, e.g. $D \to V\gamma$, or iii) contributes to SM null tests related to (approx.) symmetries.

Null tests of the SM based on

1. CP & GIM
2. angular distributions
3. LNU
4. LFV
5. ....

Full $D \to P_1 P_2 l^+ l^-$ angular distribution

Learn, e.g., from B-physics literature 1406.6681, earlier works in charm 1209.4235

$$\frac{d^5\Gamma(D\to P_1 P_2 l^+ l^-)}{dq^2 dp^2 d\cos\vartheta_{P_1} d\cos\vartheta_l d\varphi} = \frac{1}{2\pi}\left[\sum_i \underbrace{c_i(\vartheta_l,\varphi)}_{known}\underbrace{I_i(q^2,p^2,\cos\vartheta_{P_1})}_{SM,BSM}\right]$$

$c_1 = 1\,,\quad c_2 = \cos 2\vartheta_l\,,\quad c_3 = \sin^2\vartheta_l \cos 2\varphi\,,\quad c_4 = \sin 2\vartheta_l \cos\varphi\,,\quad c_5 = \sin\vartheta_l\cos\varphi\,, c_6 = \cos\vartheta_l\,,\quad c_7 = \sin\vartheta_l \sin\varphi\,,\quad c_8 = \sin 2\vartheta_l \sin\varphi\,,\quad c_9 = \sin^2\vartheta_l \sin 2\varphi\,.$

I_i: angular observables; contain SM and possibly BSM contributions.

branching ratio

$$\frac{d^3\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1}} = 2\left(I_1 - \frac{I_2}{3}\right)\,. \qquad (1)$$

Full $D \to P_1 P_2 l^+ l^-$ angular distribution

Angular distributions, such as forward-backward asymmetry in the leptons, $A_{\rm FB} \propto I_6$

$$I_6 = \frac{1}{2}\left[\int_0^1 d\cos\vartheta_l - \int_{-1}^0 d\cos\vartheta_l\right] \frac{d^4\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\cos\vartheta_l} \,. \qquad (2)$$

$$I_7 = \left[\int_0^\pi d\varphi - \int_\pi^{2\pi} d\varphi\right] \frac{d^4\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\varphi} \,, \qquad (3)$$

$$I_5 = \left[\int_{-\pi/2}^{\pi/2} d\varphi - \int_{\pi/2}^{3\pi/2} d\varphi\right] \frac{d^4\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\varphi} \,, \qquad (4)$$

$$I_8 = \frac{3\pi}{8}\left[\int_0^\pi d\varphi - \int_\pi^{2\pi} d\varphi\right]\left[\int_0^1 d\cos\vartheta_l - \int_{-1}^0 d\cos\vartheta_l\right] \frac{d^5\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\cos\vartheta_l d\varphi} \,, \qquad (5)$$

$$I_9 = \frac{3\pi}{8}\left[\int_0^{\pi/2} d\varphi - \int_{\pi/2}^{\pi} d\varphi + \int_\pi^{3\pi/2} d\varphi - \int_{3\pi/2}^{2\pi} d\varphi\right] \frac{d^4\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\varphi} \,. \qquad (6)$$

Full $D \to P_1 P_2 l^+ l^-$ angular distribution

L, R: lepton current handedness, H_k: transversity amplitudes

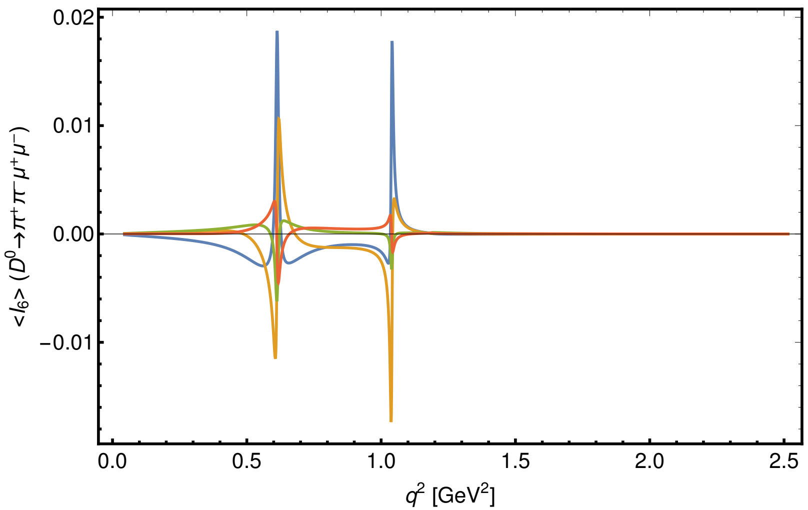
$$
\begin{aligned}
I_1 &= \frac{1}{16}\left[|H_0^L|^2 + (L \to R) + \frac{3}{2}\sin^2\vartheta_{P_1}\{|H_\perp^L|^2 + |H_\parallel^L|^2 + (L \to R)\}\right], \\
I_2 &= -\frac{1}{16}\left[|H_0^L|^2 + (L \to R) - \frac{1}{2}\sin^2\vartheta_{P_1}\{|H_\perp^L|^2 + |H_\parallel^L|^2 + (L \to R)\}\right], \\
I_3 &= \frac{1}{16}\left[|H_\perp^L|^2 - |H_\parallel^L|^2 + (L \to R)\right]\sin^2\vartheta_{P_1}, \\
I_4 &= -\frac{1}{8}\left[\mathrm{Re}(H_0^L H_\parallel^{L*}) + (L \to R)\right]\sin\vartheta_{P_1}, \\
I_5 &= -\frac{1}{4}\left[\mathrm{Re}(H_0^L H_\perp^{L*}) - (L \to R)\right]\sin\vartheta_{P_1}, \\
I_6 &= \frac{1}{4}\left[\mathrm{Re}(H_\parallel^L H_\perp^{L*}) - (L \to R)\right]\sin^2\vartheta_{P_1}, \\
I_7 &= -\frac{1}{4}\left[\mathrm{Im}(H_0^L H_\parallel^{L*}) - (L \to R)\right]\sin\vartheta_{P_1}, \\
I_8 &= -\frac{1}{8}\left[\mathrm{Im}(H_0^L H_\perp^{L*}) + (L \to R)\right]\sin\vartheta_{P_1}, \\
I_9 &= \frac{1}{8}\left[\mathrm{Im}(H_\parallel^{L*} H_\perp^L) + (L \to R)\right]\sin^2\vartheta_{P_1}.
\end{aligned}
\tag{7}
$$

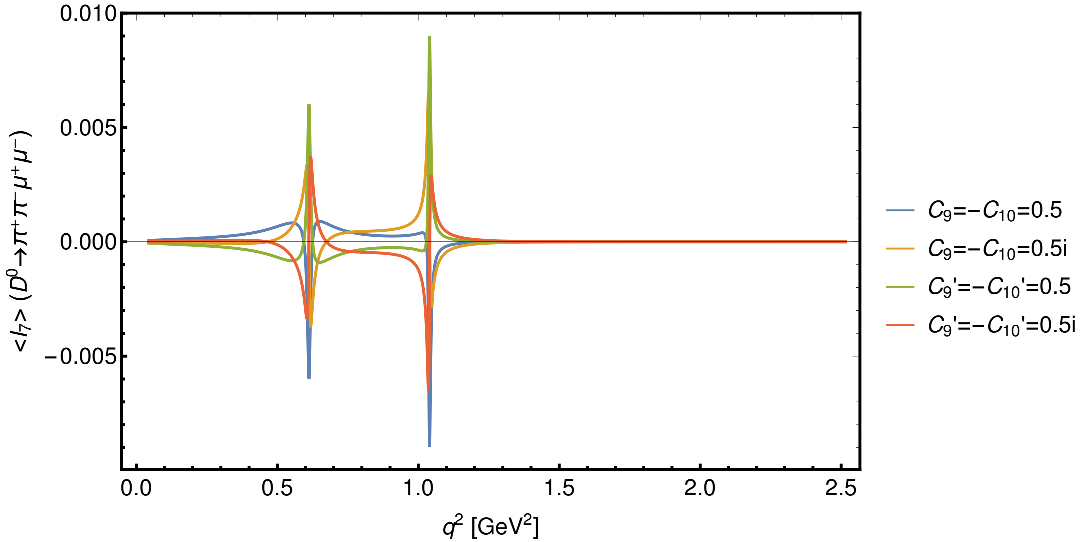
$I_{5,6,7}$ vanish due to minus signs (red) in absence of axial vector couplings.

Not useful in B-decays, $I_{5\,\mathrm{SM}} \propto P'_{5\,\mathrm{SM}}(B \to K^* ll) \neq 0$.

Full $D \to P_1 P_2 l^+ l^-$ angular distribution

In charm, due to GIM, dynamics dominated by $SU(3)_C \times U(1)_{em}$: all vector-like: $I^{\rm SM}_{5,6,7} = 0$ (proportional to $C^{(\prime)}_{10\,\rm SM} \lesssim 10^{-3} - 10^{-4}$) 1805.08516
Things are simpler than in B-decays because of the resonances.





Largest BSM effects from interference with SM; peaks at ρ/ω and Φ.

Model-independent BSM effects up to few $\%$.

Untagged CP asymmetries from CP-odd observables $I_{5,6,8,9}$

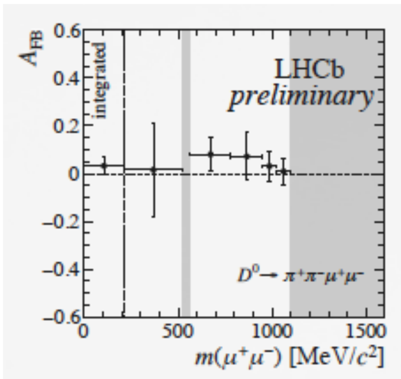
$$A_k = 2\frac{I_k - \bar{I}_k}{\Gamma + \bar{\Gamma}} = \frac{I_k - \bar{I}_k}{\Gamma_{ave}}\,, \qquad (8)$$

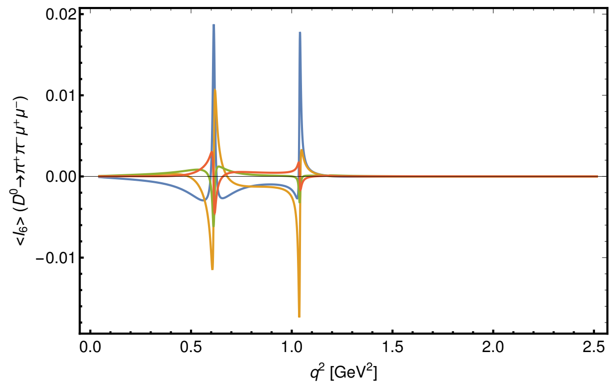
	$C_9 = -C_{10} = \pm 0.5i$	$C_9' = -C_{10}' = \pm 0.5i$
$\langle A_5 \rangle$	$[-0.04, 0.04]$	$[-0.03, 0.03]$
$\langle A_6 \rangle$	$[-0.06, 0.05]$	$[-0.06, 0.06]$
$\langle A_8 \rangle$	$[-0.02, 0.02]$	$[-0.02, 0.02]$
$\langle A_9 \rangle$	$[-0.03, 0.03]$	$[-0.03, 0.03]$

Ranges for the high q^2, $q^2_{\text{min}} = (1.1\ \text{GeV})^2$, integrated CP asymmetries $\langle A_i \rangle$ for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ decays for different BSM benchmarks, varying strong phases. $\langle A_{5,6} \rangle_{\text{SM}} = 0$ (GIM), $\langle A_{8,9} \rangle_{\text{SM}} \lesssim 10^{-3}$.

Some angular asymmetries already measured by LHCb; talk by D.Mitzel at CHARM 2018 (grey: NS), $A_{\rm FB}^{\rm CCD} = -2 < I_6 >$; model-independent BSM effects up to few $\%$ – experimental sensitivity close.

$$A_{\rm FB}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 3.3 \pm 3.7 \pm 0.6)\%,$$
$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%,$$
$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 4.9 \pm 3.8 \pm 0.7)\%,$$
$$A_{\rm FB}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$
$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) = (9 \pm 11 \pm 1)\%,$$
$$A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$





LHCb Phys.Rev.Lett. 121 (2018) no.9, 091801

branching ratio	$D^0 \to \pi^+\pi^-\mu^+\mu^-$	$D^0 \to K^+K^-\mu^+\mu^-$	$D^0 \to \pi^+\pi^-e^+e^-$	$D^0 \to K^+K^-e^+e^-$
LHCb 17	$(9.64 \pm 1.20) \times 10^{-7}$	$(1.54 \pm 0.33) \times 10^{-7}$	–	–
BESIII 18	–	–	$< 0.7 \times 10^{-5}$	$< 1.1 \times 10^{-5}$
resonant	$\sim 1 \times 10^{-6}$	$\sim 1 \times 10^{-7}$	$\sim 10^{-6}$	$\sim 10^{-7}$
non-resonant	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$

$$R^D_{P_1P_2} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D\to P_1P_2\mu^+\mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D\to P_1P_2e^+e^-)}$$ with same cuts $q^2_{\rm min} \geq 4m^2_\mu$

full q^2	SM	BSM	LQ	hi q^2 SM	LQs	lo q^2 SM	BSM
$R^D_{\pi\pi}$	$1.00 \pm \mathcal{O}(\%)$	0.85 ...0.99	SM-like	$1.00 \pm \mathcal{O}(\%)$	0.7 ...4.4		
R^D_{KK}	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	NA	NA	$0.83 \pm \mathcal{O}(\%)$	0.60..0.87

O(1)BSM effects in $R^D_{\pi\pi}$ above Φ; small BSM effects in R^D_{KK} below η.

Naive ratios $\bar{R}^{D\,exp}_{\pi^+\pi^-} \gtrsim 0.1\,,\, \bar{R}^{D\,exp}_{K^+K^-} \gtrsim 0.01$ based on different cuts and about one order of magnitude away from SM, are model-dependent.

Θ: angle between negatively charged lepton and D in dilepton cms

$$\frac{d\Gamma(D \to \pi l^+ l^-)}{d\cos\Theta} = \frac{3}{4}(1 - F_H)(1 - \cos^2\Theta) + A_{FB}\cos\Theta + F_H/2$$ Bobeth et al '07

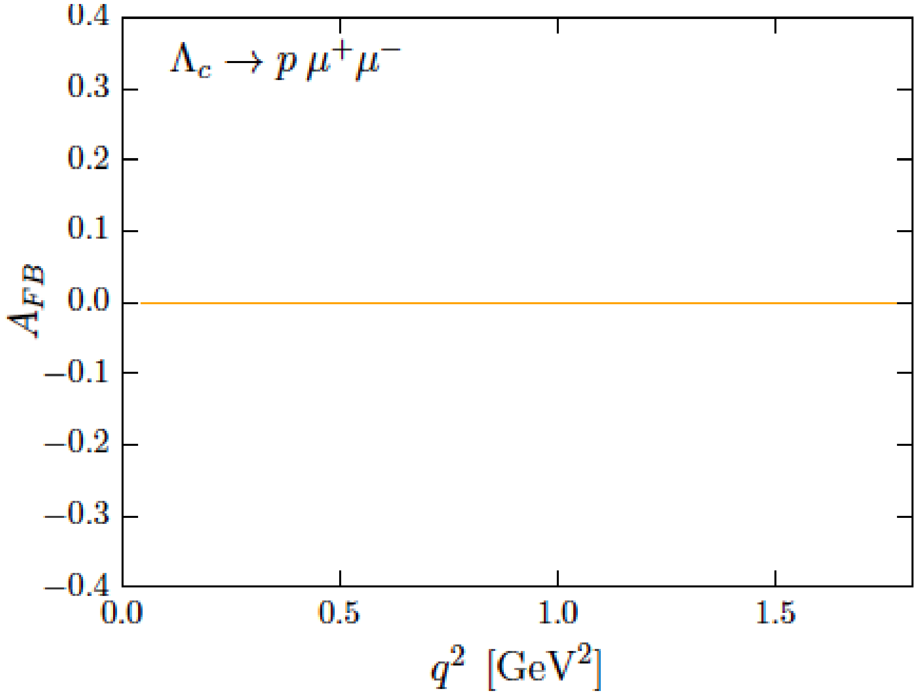
SM: $A_{FB}, F_H \simeq 0$ by lorentz-structure and small lepton masses. Both require S,P- and or tensor operators.

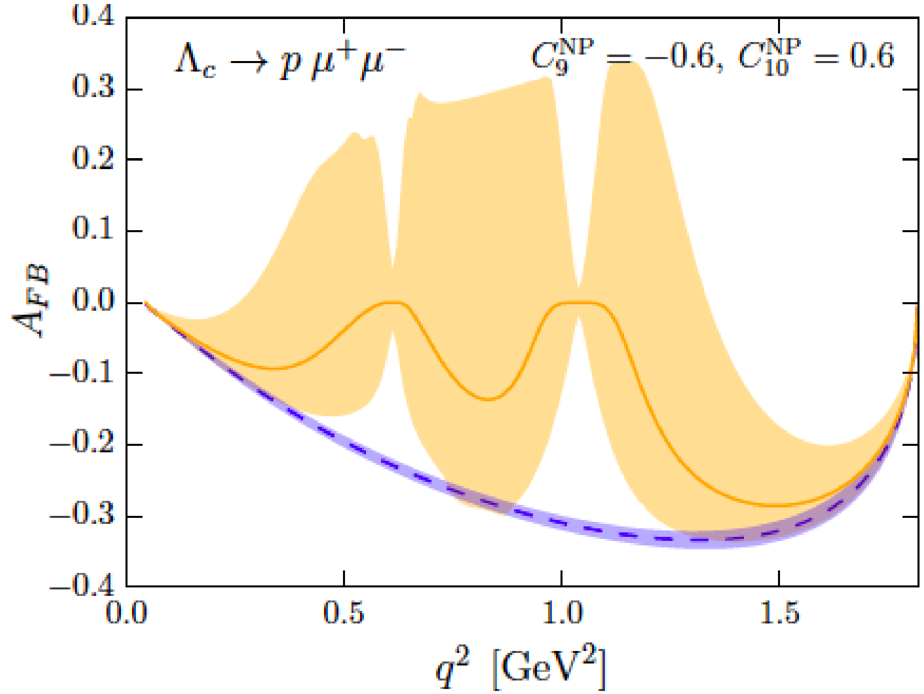
Model-independently, striking BSM signals possible (high q^2):

$|A_{\rm FB}(D^+ \to \pi^+ \mu^+ \mu^-)| \lesssim 0.6$, $|A_{\rm FB}(D^+ \to \pi^+ e^+ e^-)| \lesssim 0.8$ and $F_H(D^+ \to \pi^+ l^+ l^-) \lesssim 2$ for $l = e, \mu$. arXiv:1510.00311

LFV-rates and dineutrino modes which vanish in SM can be just around the corner (model-independently).

$A_{\text{FB}} \propto C_{10}$ null test of SM (GIM)





Plots from 1712.05783

Summary

Constraints on up-sector FCNCs are at the level of b-physics in the last millenium. $c \to u\mu\mu, \gamma$: $|C_{9,10}^{(\prime)}| \lesssim 1$, $|C_7^{(\prime)}| \lesssim 0.3$, $|C_{T,T5}| \lesssim 1$, $|C_{S,P}^{(\prime)}| \lesssim 0.1$.

versus $|C_7^{\rm effSM}| = \mathcal{O}(0.001)\,, |C_9^{\rm effSM}| \lesssim 0.01\,, \quad C_{10}^{\rm SM} = 0\,,$ (GIM !) $\quad C^{\prime \rm SM}, C_{S,P,T,T5}^{\rm SM} = 0$

Charm decays into leptons are plagued by resonance contributions, and $1/m_c$ not ideal 1705.05891. BSM physics can be seen in rates only if very large (still possible!), or in null tests. – Great prospects to test the SM and look for BSM physics in semileptonic and radiative rare D decays, complementary to K, B-decays.

clean $=$ clean enough

Plenty of opportunities for BaBar, BESIII, Belle, Belle II and LHCb.

Unique information on flavor in the up-sector.

It's already happening LHCb'17,18 $D \to \pi\pi\mu\mu$, Belle'16$D \to \rho\gamma$, BES III '18 $D \to \pi\pi ee$...

BACK-UP

Photon polarization in $c \to u\gamma$ from untagged TDA

Time-dependent analysis $D^0, \bar{D}^0 \to V\gamma$, $V = \rho^0, \Phi, \bar{K}^{*0}$ (decays to CP eigenstate with CP eigenvalue ξ) 1210.6546 ,1802.02769

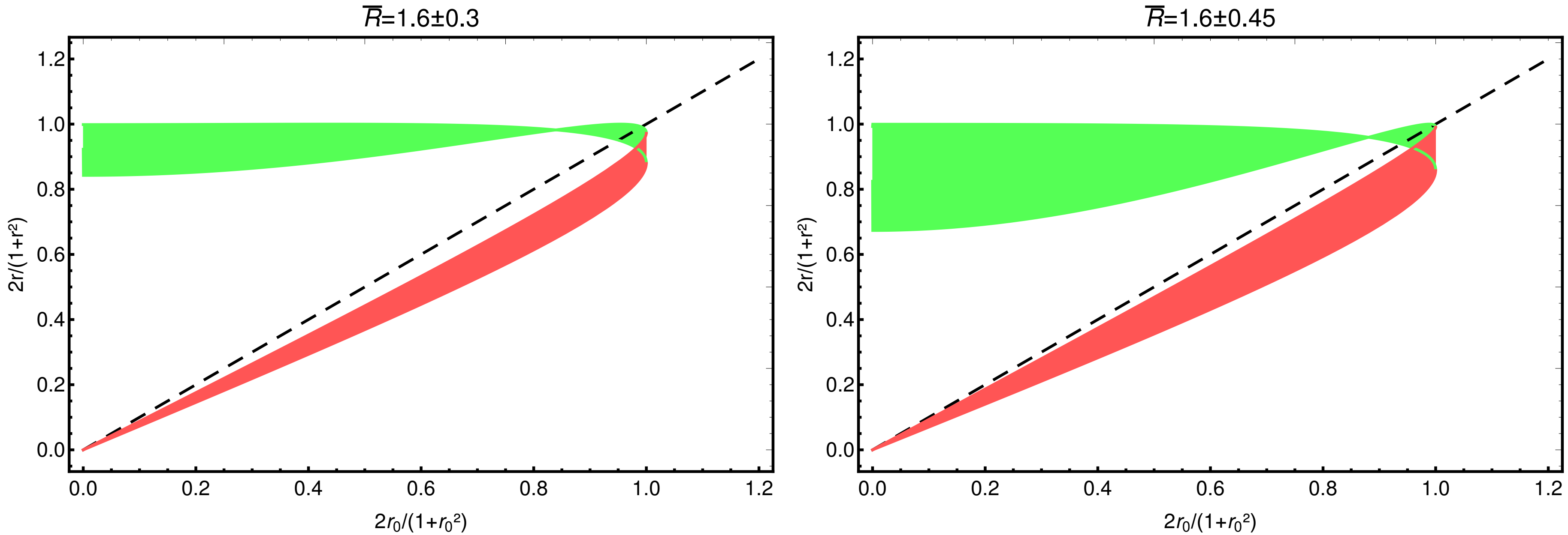
$$\Gamma(t) = \mathcal{N} e^{-\Gamma t} \left(\cosh[\Delta\Gamma t/2] + A^\Delta \sinh[\Delta\Gamma t/2] + \zeta C \cos[\Delta m t] - \zeta S \sin[\Delta m t]\right)$$

$A^\Delta(D^0 \to \bar{K}^{*0}\gamma) \simeq \frac{4\,\xi_{\bar{K}^{*0}} \left|\frac{q}{p}\right| \cos\varphi}{\left(1+\left|\frac{q}{p}\right|^2\right)} \frac{r_0}{1+r_0^2}$ Here, r_0 is ratio of wrong-chirality (RH) to LH-photons in SM-like process $D^0 \to \bar{K}^{*0}\gamma$.

Up to $SU(3)$-breaking: $r(D^0 \to \Phi\gamma) = r_0$, $\quad r(D^0 \to \rho\gamma) = r_0$; perturbative $r = C_7'/C_7$, in SUSY, r unconstrained.

Br's	$D^0 \to \rho^0\gamma$	$D^0 \to \omega\gamma$	$D^0 \to \Phi\gamma$	$D^0 \to \bar{K}^{*0}\gamma$
Belle 2016	$(1.77 \pm 0.31) \times 10^{-5}$	–	$(2.76 \pm 0.21) \times 10^{-5}$	$(4.66 \pm 0.30) \times 10^{-4}$
BaBar 2008	–	–	$(2.81 \pm 0.41) \times 10^{-5}$	$(3.31 \pm 0.34) \times 10^{-4}$
CLEO 1998	–	$< 2.4 \times 10^{-4}$	–	–

Photon polarization in $c \to u\gamma$ from untagged TDA



$2r/(1+r^2)$ as a function of $2r_0/(1+r_0^2)$ (plots to the right), in the cases a) (SM case) $C_7, C_7' \simeq 0$ (black, dashed curve), c) $C_7 \simeq 0$ (green, upper band) and d) $C_7' \simeq 0$ (red, lower band). The upper (lower) plots correspond to $\bar{R}_{ave} = 1.6 \pm 0.3$ ($\bar{R} = 1.6 \pm 0.45$ from 50% inflated uncertainty).

$\bar{R} = 1/f^2 \frac{|V_{cs}|^2}{|V_{cd}|^2} \frac{\mathcal{B}(D^0 \to \rho\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)}$ with leading U-spin breaking removed $f = m_\rho f_\rho/(m_{K^{*0}} f_{K^{*0}})$

Photon polarization from up-down asymmetry

Method 2: probe the photon polarization with an up-down asymmetry in $D^0 \to \bar{K}_1(\to \bar{K}\pi\pi)\gamma$ (a la $B \to K_1\gamma$ (Gronau, Pirjol, Grossman, Kou)

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{d}\cos\vartheta} \propto |\boldsymbol{J}|^2(1+\cos^2\vartheta) + \lambda_\gamma 2\,\mathrm{Im}[\boldsymbol{n}\cdot(\boldsymbol{J}\times\boldsymbol{J}^*)]\cos\vartheta\,,\; \lambda_\gamma = -\frac{1-r_0^2(\bar{K}_1)}{1+r_0^2(\bar{K}_1)}$$

The corresponding BSM-sensitive mode is $D_s \to \bar{K}_1(\to \bar{K}\pi\pi)\gamma$.

Method requires D-tagging but unlike TDA, does not depend on strong phases between LH and RH amplitude.

$K_1(1270)$ dominant in charm as $K(1400)$ family phase space suppressed by about factor of 2.