Rare charm decays: theory and BSM reach

based on a series of papers with Stefan de Boer, Nico Adolph, Rigo Bause, Marcel Golz, Andrey Tayduganov and Hector Gisbert

Gudrun Hiller, TU Dortmund Supported in part by the Federal Ministry for Education and Research (BMBF)

BSM Charm physics

... because, we can:

– sizable branching ratios within $10^{-7} - 10^{-6}$ (semileptonic $c \to ull$) and $10^{-6} - 10^{-4}$ (radiative $c \to u\gamma$)

– plenty of BSM opportunities (see below)

– in fact, its already happening LHCb'17,18 $D \to \pi\pi\mu\mu$, Belle'16$D \to \rho\gamma$, BES III '18 $D \to \pi\pi ee$...

LHCb'20: 25 $D \to Pll'$ branching ratios – see talk by Dominik Mitzel

AND its a unique probe of the up-sector:

1) leaving no stone unturned (BSM searches)

2) complementarity (w.r.t. K,B) (flavor origins)

pursue general flavor physics $, t, b, c, s, ...,$ exploit correlations

BSM opportunities with $|\Delta c| = |\Delta u| = 1$ studies

In view of the hadronic backgrounds in rare charm decays, the name of the game in flavor/BSM probes is ”null tests”, based on (approximate) symmetries of the SM, or optimized observables with reduced SM uncertainties:

lepton-universality, lepton flavor conservation, CP, polarization studies, data-driven SM estimations, angular distributions

Procedure very well-known in state-of-the -art b-physics studies. Actually, it is essential in pursuit of beauty-anomalies, e.g., R_K, P_5'.

There is one more thing, genuinely available to charm, the GIM-suppression in charm FCNCs:
$c \to u \nu \bar{\nu}$ and contributions to $c \to u \ell^+ \ell^-$ with axial-vector lepton-currents ”$C_{10}^{(\prime)}$” vanish in SM the latter up to higher order QED-corrections

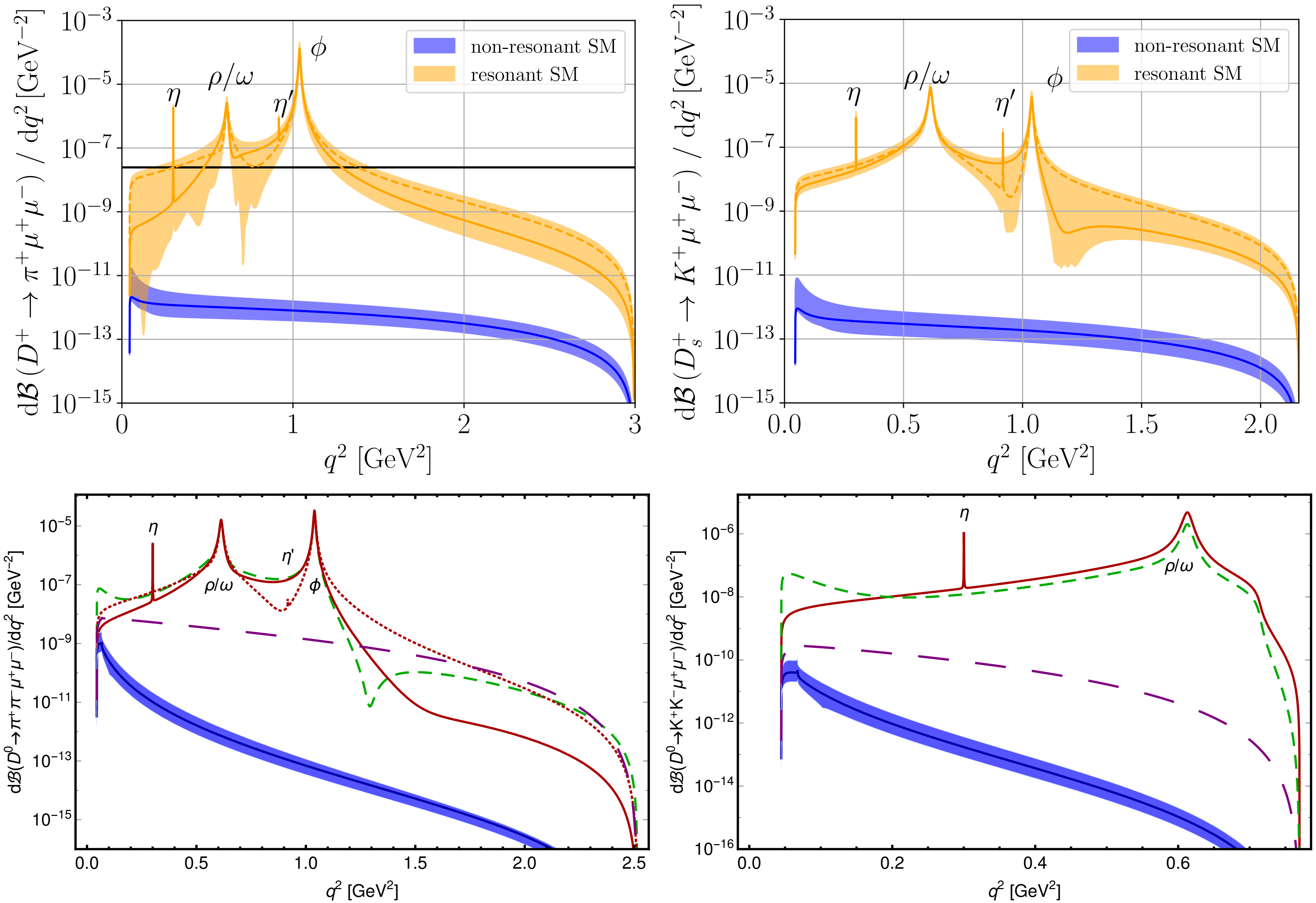
BSM opportunities with $|\Delta c| = |\Delta u| = 1$ studies

consider rare charm decays $c \to u\ell\ell^{(\prime)}, c \to u\gamma$

Adolph, Bause, Bigi, Burdman, d'Ambrosio, Cata, Fajfer, Feldmann, Gisbert, Golowich, Golz, Hewett, Kosnic, Meinel, Pakvasa, Petrov, Seidel, Singer, Tayduganov, Zwicky, de Boer, GH 1510.00311 $D \to \pi ll$, 1701.06392 Br and A_{CP} radiative D-decays, 1802.02769 photon polarization from TDA or up-down asymmetry; 1805.08516 on $D \to P_1 P_2 ll$, $P_{1,2} = \pi, K$, 1812.04679 $D \to K_1(\to K\pi\pi)\gamma$, Z'-effects and ΔA_{CP} 2004.01206

plus recent new comers from high p_T!

Resonance contributions vs BSM



Resonance contributions vs BSM

BSM windows in branching ratios only in $D \to \pi\mu^+\mu^-$ (upper left) at high q^2 1510.00311, to appear; $D \to \pi^+\pi^-\mu\mu$ (mid), $D \to K^+K^-\mu\mu$ (right), 1805.08516, 1705.05891

$c \to u$ amplitudes are strongly GIM-suppressed:
$\mathcal{A}_{c\to u} \simeq \sin\Theta_C[f(m_s^2/m_W^2) - f(m_d^2/m_W^2)] + O(\sin^5\Theta_C)$

To observe BSM in rare charm either
i) BSM is an obvious excess in rates,
ii) SM BDG can be measured, e.g. $D \to V\gamma$ using U-spin, or
iii) contributes to SM null tests related to (approx.) SM symmetries.

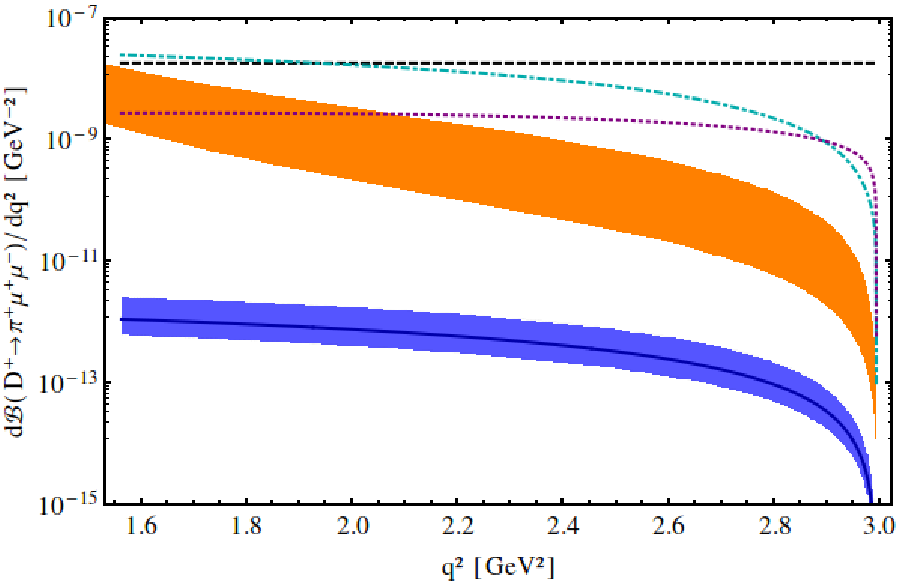
Model-independent constraints on $|\Delta c| = |\Delta u| = 1$

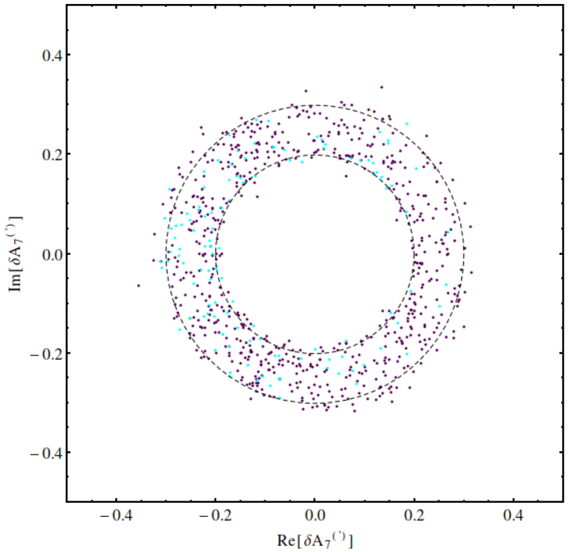
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left[\sum_{i=7,9,10,S,P}(C_iO_i + C_i'O_i') + \sum_{i=T,T5} C_iO_i + \sum_{q=d,s} V_{cq}^* V_{uq} \sum_{i=1}^{2} C_i O_i^q\right], \quad (1)$$

$$\begin{aligned} O_7 &= \frac{m_c}{e}(\overline{u}_L \sigma_{\mu\nu} c_R)F^{\mu\nu}\,, O_9 = (\overline{u}_L\gamma_\mu c_L)(\bar{\ell}\gamma^\mu \ell)\,, && (2)\\ O_{10} &= (\overline{u}_L\gamma_\mu c_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,, O_S = (\overline{u}_L c_R)(\bar{\ell}\ell)\,, && (3)\\ O_P &= (\overline{u}_L c_R)(\bar{\ell}\gamma_5\ell)\,, O_T = \frac{1}{2}(\overline{u}\sigma_{\mu\nu}c)(\bar{\ell}\sigma^{\mu\nu}\ell)\,, && (4)\\ O_{T5} &= \frac{1}{2}(\overline{u}\sigma_{\mu\nu}c)(\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell)\,. && (5) \end{aligned}$$

Non-resonant anatomy of $c \to ull, \gamma$ known to higher order 1510.00311, 1606.05521, 1707.00988

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





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

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

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.

Predictions for charm decays– links with K, B

	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$	$\mathcal{B}(D^0 \to \mu^+\mu^-)$	$\mathcal{B}(D^+ \to \pi^+ e^\pm \mu^\mp)$	$\mathcal{B}(D^0 \to \mu^\pm e^\mp)$	$\mathcal{B}(D^+ \to \pi^+ \nu\bar{\nu})$
i)	SM-like	SM-like	$\lesssim 2 \cdot 10^{-13}$	$\lesssim 7 \cdot 10^{-15}$	$\lesssim 3 \cdot 10^{-13}$
ii.1)	$\lesssim 7 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$\lesssim 3 \cdot 10^{-9}$	0	0	$\lesssim 8 \cdot 10^{-8}$
ii.2)	SM-like	$\lesssim 4 \cdot 10^{-13}$	0	0	$\lesssim 4 \cdot 10^{-12}$
iii.1)	SM-like	SM-like	$\lesssim 2 \cdot 10^{-6}$	$\lesssim 4 \cdot 10^{-8}$	$\lesssim 2 \cdot 10^{-6}$
iii.2)	SM-like	SM-like	$\lesssim 8 \cdot 10^{-15}$	$\lesssim 2 \cdot 10^{-16}$	$\lesssim 9 \cdot 10^{-15}$

Table 1: Branching fractions for the full q^2-region (high q^2-region) for different classes of leptoquark couplings. Summation of neutrino flavors is understood. "SM-like" denotes a branching ratio which is dominated by resonances or is of similar size as the resonance-induced one. All $c \to u e^+ e^-$ branching ratios are "SM-like" in the models considered. Note that in the SM $\mathcal{B}(D^0 \to \mu\mu) \sim 10^{-13}$.

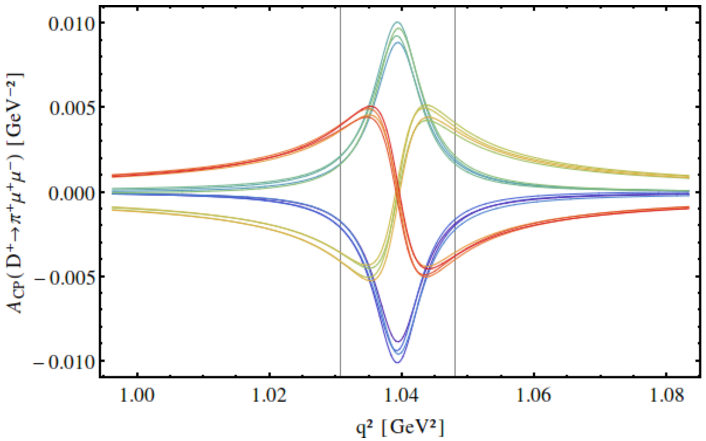
LHCb: arXiv:1512.00322 [hep-ex] $\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 1.3 \cdot 10^{-8}$ at 90 % CL

i): hierarchy, ii) muons only iii) skewed, 1) no kaon bounds 2) kaon bounds apply for $SU(2)_L$-doublets $Q = (c, s)$ 1510.00311

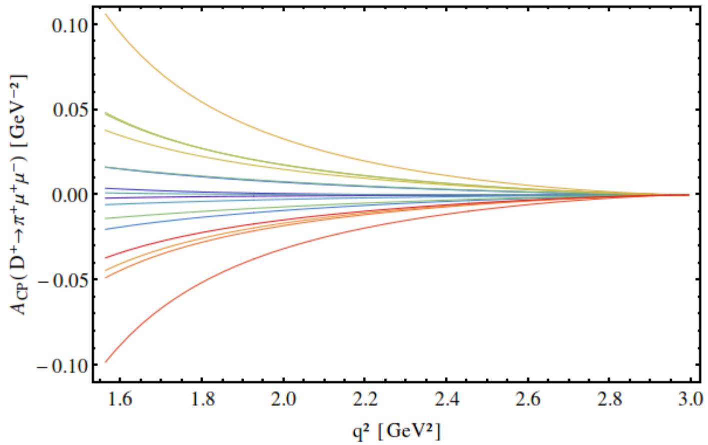
Complementarity with down-sector; Leptoquark models already probed by LHCb.

Probing even small couplings: $A_{CP}(D \to \pi ll)$

GIM-suppression can be eased by the resonances, which are less $SU(3)_F$-symmetric than the nr- contributions. also "resonance-catalyzed CP", Fajfer et al '13



ii 2)



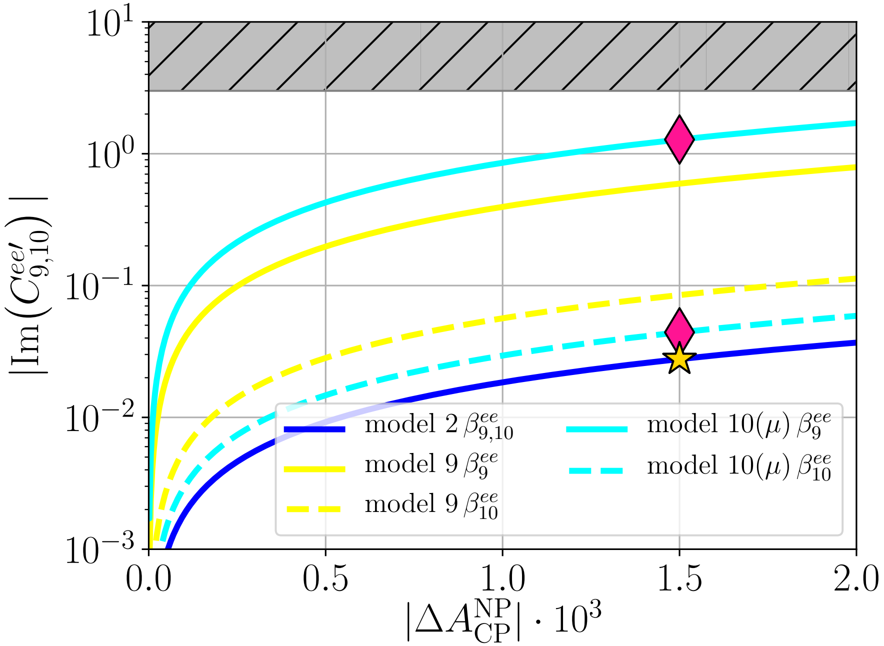
ii 2)

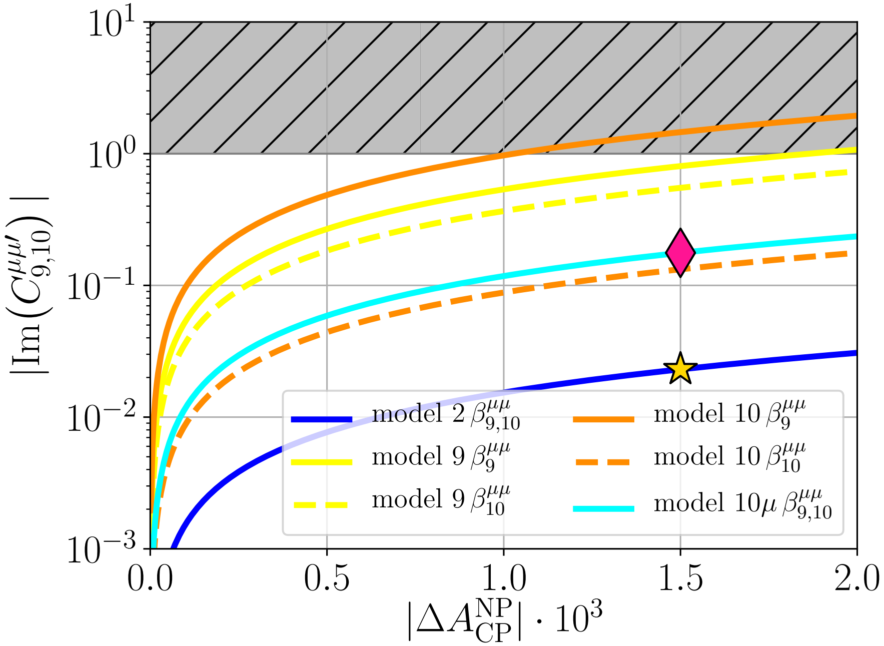
Large uncertainties, however, large BSM signals possible ($|A_{CP}^{\mathrm{SM}}| \lesssim few 10^{-3}$) even independent of strong phases around Φ.

Opportunity to probe SM-like lorentz-structure $C_{V,A}$ even in presence of $SU(2)$-link to K-physics – links between charm and b-physics

$A_{CP}(D \to \pi ll)$ vs ΔA_{CP}

2004.01206





Flavorful Z'-models (generation dependent charges, anomaly-free); induce tree-level FCNCs

Sensitivity if $ImC_{9,10} \gtrsim 10^{-2} - 10^{-1}$. Golden star: $\varphi_R \sim \pi/2$, $g_4/M_{Z'} \sim 0.4/TeV$, $\vartheta_u \sim 10^{-4}$, diamond: $\varphi_R \sim \pi/2$, $g_4/M_{Z'} \sim 2/TeV$, $\vartheta_u \sim 10^{-5}$,

Observation of enhanced CP-violation in rare semileptonic charm decays would support NP interpretation of ΔA_{CP}, and vice versa.

Null tests for rare charm decays

Besides statistics, BSM reach is limited by theoretical uncertainties, mostly dominated by hadronic physics.

Use approximate symmetries of SM to bypass precision barrier: (useful in beauty $\Lambda/m_b \simeq O(0.1)$, key in charm $\Lambda/m_c \sim 0.6$).

We briefly discuss next:

– GIM, angular distributions, helicity $D \to \pi\pi\mu^+\mu^-$, a la $B \to K^*(\to K\pi)\ell^+\ell^-$, F_H

– lepton universality a la R_K, R_{K^*}

– U-spin $D \to V\gamma$

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

$$\frac{d^3\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1}} = 2\left(I_1 - \frac{I_2}{3}\right)\,. \tag{6}$$

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

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

$$I_6 = \frac{1}{2}\left[\int_0^1 d\cos\vartheta_l - \int_{-1}^0 d\cos\vartheta_l\right] \frac{d^4\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\cos\vartheta_l}\,. \tag{7}$$

$$I_7 = \left[\int_0^\pi d\varphi - \int_\pi^{2\pi} d\varphi\right] \frac{d^4\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\varphi}\,, \tag{8}$$

$$I_5 = \left[\int_{-\pi/2}^{\pi/2} d\varphi - \int_{\pi/2}^{3\pi/2} d\varphi\right] \frac{d^4\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\varphi}\,, \tag{9}$$

$$I_8 = \frac{3\pi}{8}\left[\int_0^\pi d\varphi - \int_\pi^{2\pi} d\varphi\right]\left[\int_0^1 d\cos\vartheta_l - \int_{-1}^0 d\cos\vartheta_l\right] \frac{d^5\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\cos\vartheta_l d\varphi}\,, \tag{10}$$

$$I_9 = \frac{3\pi}{8}\left[\int_0^{\pi/2} d\varphi - \int_{\pi/2}^{\pi} d\varphi + \int_\pi^{3\pi/2} d\varphi - \int_{3\pi/2}^{2\pi} d\varphi\right] \frac{d^4\Gamma}{dq^2 dp^2 d\cos\vartheta_{P_1} d\varphi}\,. \tag{11}$$

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

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

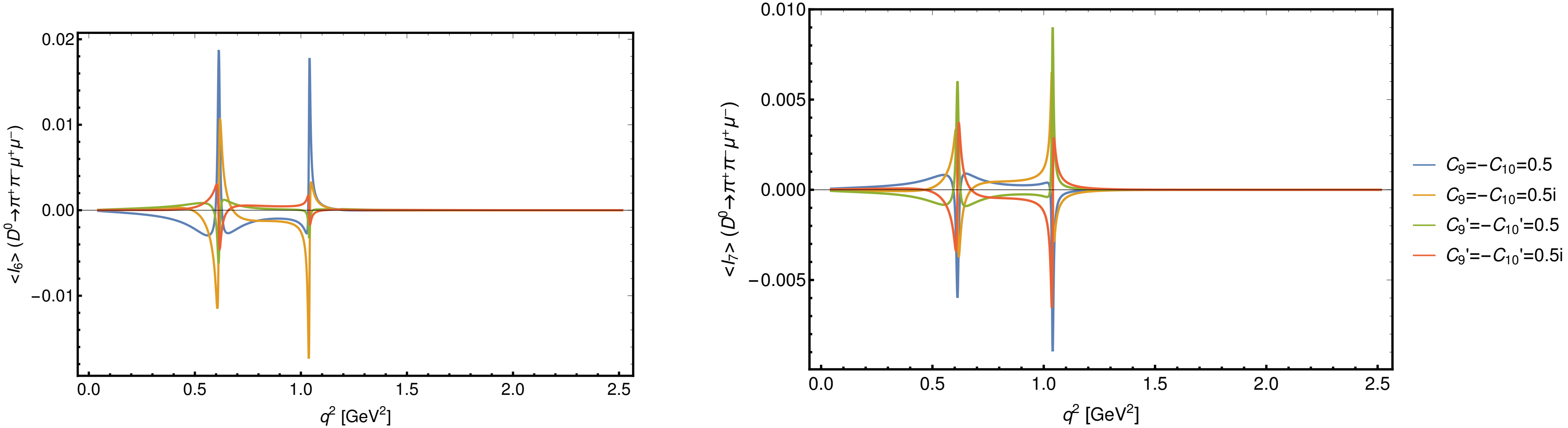
$$
\begin{aligned}
I_1 &= \frac{1}{16}\left[|H_0^L|^2 + (L \to R) + \frac{3}{2}\sin^2\vartheta_{P_1}\{|H_\perp^L|^2 + |H_\parallel^L|^2 + (L \to R)\}\right], \\
I_2 &= -\frac{1}{16}\left[|H_0^L|^2 + (L \to R) - \frac{1}{2}\sin^2\vartheta_{P_1}\{|H_\perp^L|^2 + |H_\parallel^L|^2 + (L \to R)\}\right], \\
I_3 &= \frac{1}{16}\left[|H_\perp^L|^2 - |H_\parallel^L|^2 + (L \to R)\right]\sin^2\vartheta_{P_1}, \\
I_4 &= -\frac{1}{8}\left[\mathrm{Re}(H_0^L H_\parallel^{L*}) + (L \to R)\right]\sin\vartheta_{P_1}, \\
I_5 &= -\frac{1}{4}\left[\mathrm{Re}(H_0^L H_\perp^{L*}) - (L \to R)\right]\sin\vartheta_{P_1}, \\
I_6 &= \frac{1}{4}\left[\mathrm{Re}(H_\parallel^L H_\perp^{L*}) - (L \to R)\right]\sin^2\vartheta_{P_1}, \\
I_7 &= -\frac{1}{4}\left[\mathrm{Im}(H_0^L H_\parallel^{L*}) - (L \to R)\right]\sin\vartheta_{P_1}, \\
I_8 &= -\frac{1}{8}\left[\mathrm{Im}(H_0^L H_\perp^{L*}) + (L \to R)\right]\sin\vartheta_{P_1}, \\
I_9 &= \frac{1}{8}\left[\mathrm{Im}(H_\parallel^{L*} H_\perp^L) + (L \to R)\right]\sin^2\vartheta_{P_1}.
\end{aligned}
\tag{12}
$$

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

Very different from 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 $I_{5,6,8,9}$

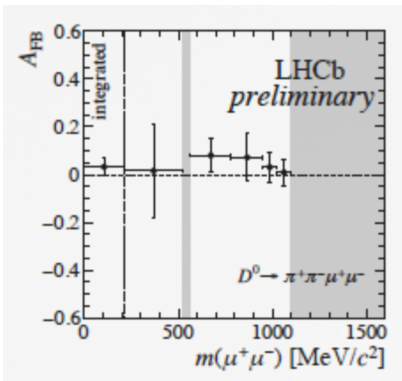
$$A_k = 2\frac{I_k - \bar{I}_k}{\Gamma + \bar{\Gamma}} = \frac{I_k - \bar{I}_k}{\Gamma_{ave}} \,, \qquad (13)$$

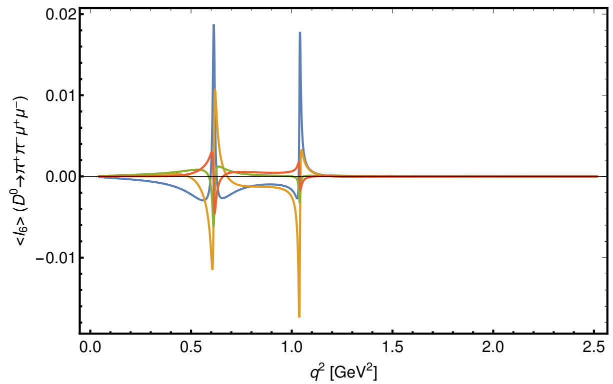
	$C_9 = -C_{10} = \pm 0.5i$	$C_9' = -C_{10}' = \pm 0.5i$
$\langle A_5 \rangle$	$[-0.04, 0.04]$	$[-0.03, 0.03]$
$\langle A_6 \rangle$	$[-0.06, 0.05]$	$[-0.06, 0.06]$
$\langle A_8 \rangle$	$[-0.02, 0.02]$	$[-0.02, 0.02]$
$\langle A_9 \rangle$	$[-0.03, 0.03]$	$[-0.03, 0.03]$

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.

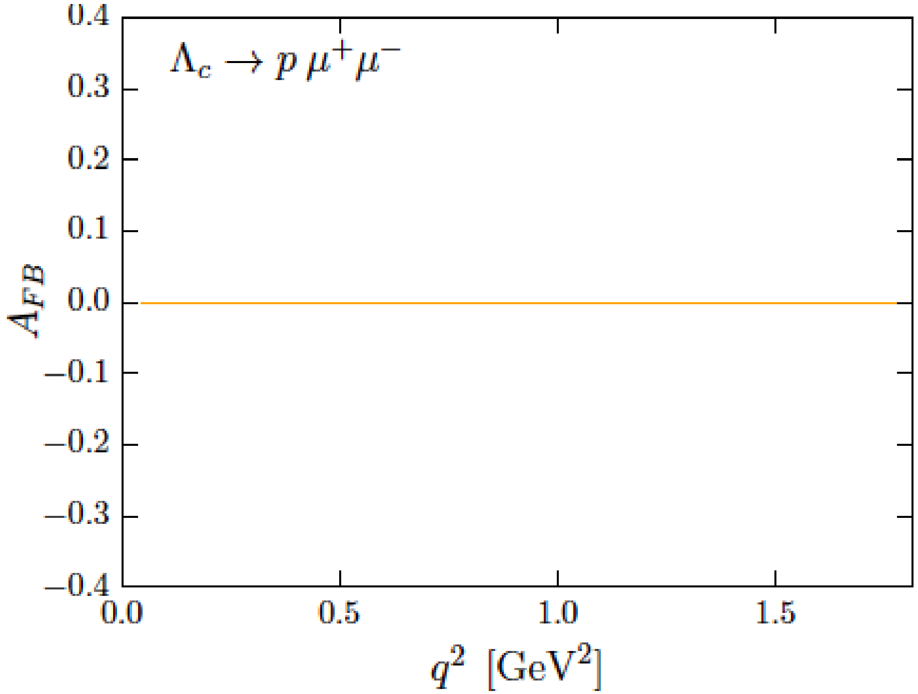
$$
\begin{aligned}
A_{\rm FB}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &= (3.3 \pm 3.7 \pm 0.6)\%,\\
A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &= (-0.6 \pm 3.7 \pm 0.6)\%,\\
A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) &= (4.9 \pm 3.8 \pm 0.7)\%,\\
A_{\rm FB}(D^0 \to K^+K^-\mu^+\mu^-) &= (0 \pm 11 \pm 2)\%,\\
A_{2\phi}(D^0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

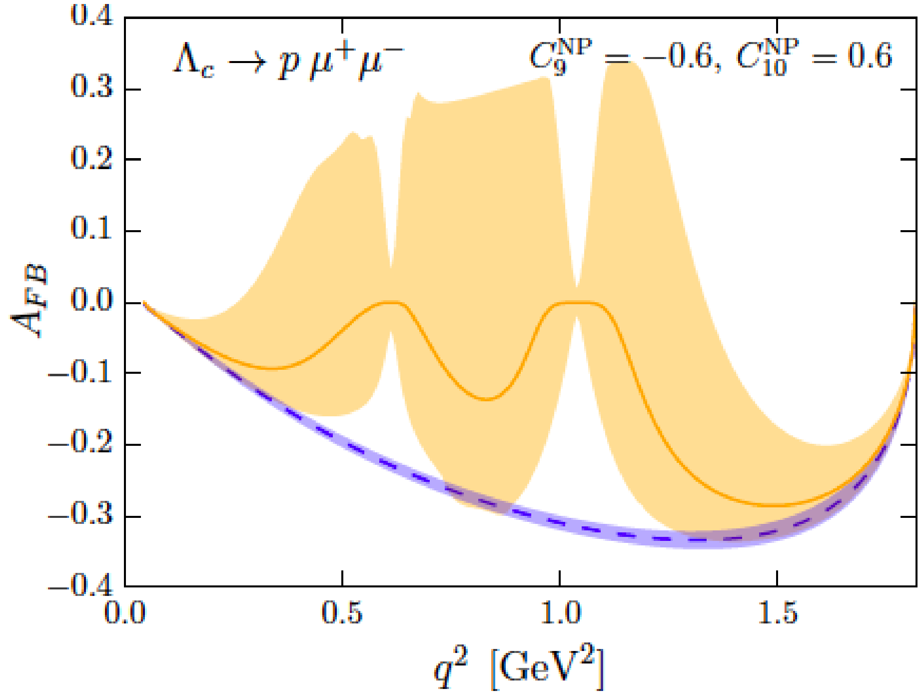




LHCb Phys.Rev.Lett. 121 (2018) no.9, 091801

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





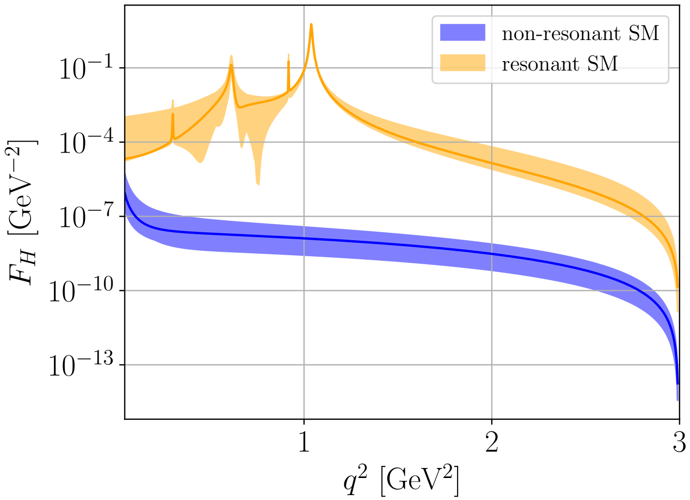
Plots from 1712.05783

SM null tests $D \to \pi l^+ l^-$ and $D_s \to K l^+ l^-$

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

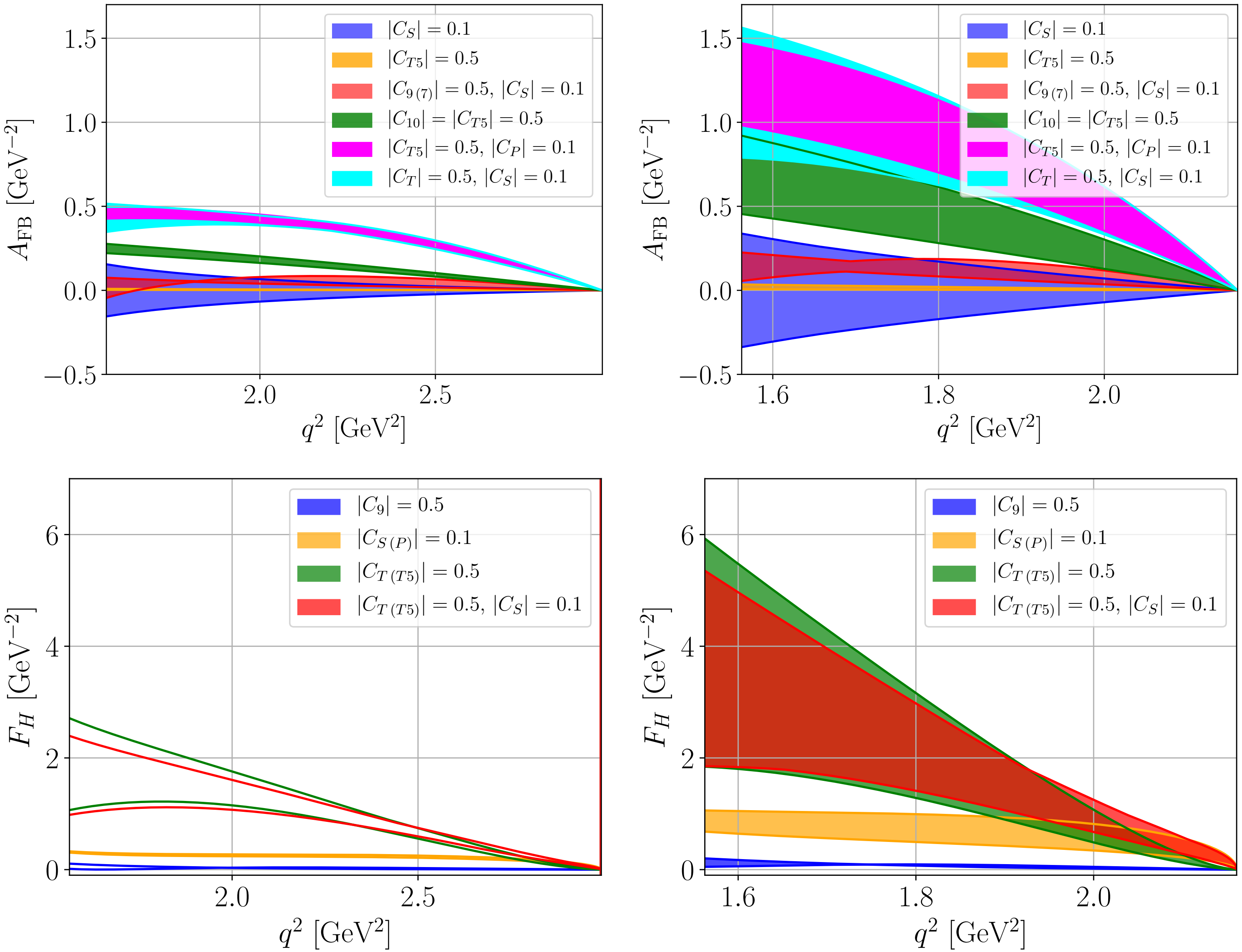
SM: $A_{FB}, F_H \simeq 0$ by lorentz-structure and small lepton masses. Both require S,P- and or tensor operators.



$D \to \pi\mu\mu$

from 1909.11108

SM null tests $D \to \pi l^+ l^-$ and $D_s \to K l^+ l^-$



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	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$	$10^{-10} - 10^{-9}$	$\mathcal{O}(10^{-10})$

$$R^D_{P_1 P_2} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D \to P_1 P_2 \mu^+\mu^-)}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} d\mathcal{B}/dq^2(D \to P_1 P_2 e^+e^-)}$$ with same cuts $q^2_{\text{min}} \geq 4m^2_\mu$

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.

Photon polarization in $c \to u\gamma$

Right-handed currents exist in many BSM scenarios and induce wrong-chirality $c \to u\gamma$ contribution "A_7'".

2 recent proposals to probe these with radiative D-decays; unlike in corresponding B-decays, in charm partner decays exist which are SM-dominated, and a theory computation of the SM-prediction can be avoided by measuring the respective observable in the SM-dominated and the BSM-sensitive mode.

They should be equal in SM up to U-spin breaking ($\lesssim O(25\%)$), i.e. we probe SM-correlations.

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

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

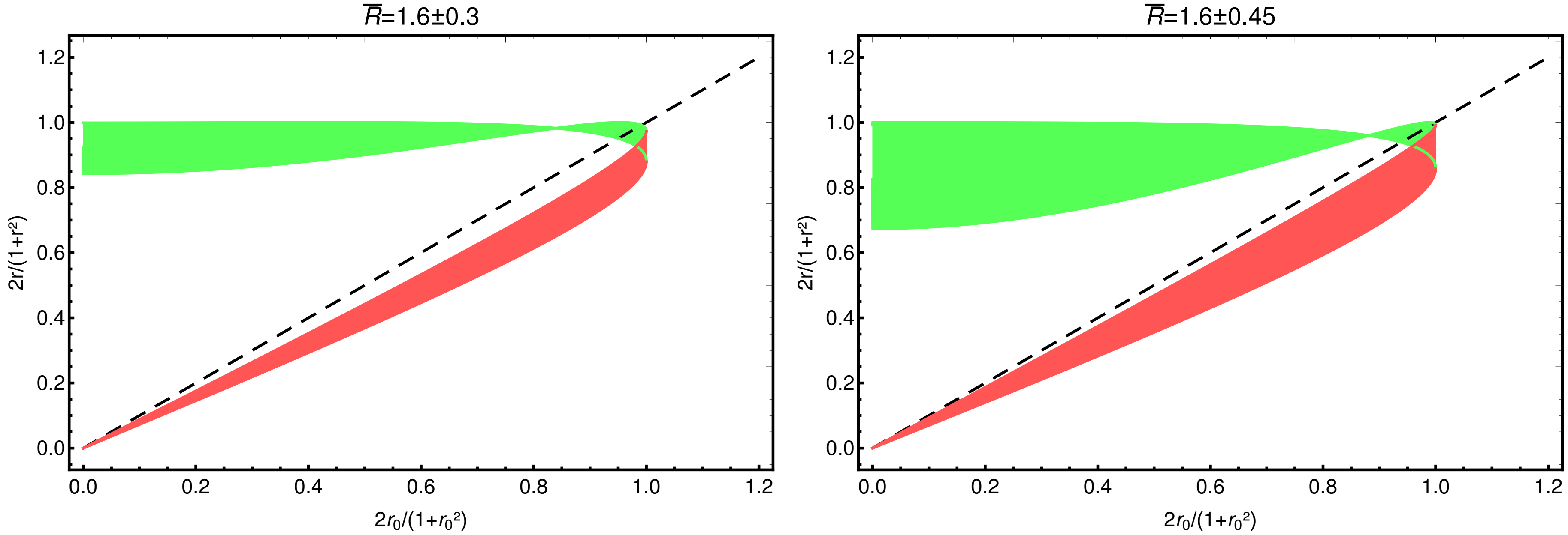
$$\Gamma(t) = \mathcal{N} e^{-\Gamma t} \left(\cosh[\Delta\Gamma t/2] + A^{\Delta} \sinh[\Delta\Gamma t/2] + \zeta C \cos[\Delta m t] - \zeta S \sin[\Delta m t]\right)$$

$A^{\Delta}(D^0 \to \bar{K}^{*0}\gamma) \simeq \frac{4\,\xi_{\bar{K}^{*0}} \left|\frac{q}{p}\right| \cos\varphi}{\left(1+\left|\frac{q}{p}\right|^2\right)} \frac{r_0}{1+r_0^2}$ 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: $r(D^0 \to \Phi\gamma) = r_0$, $r(D^0 \to \rho\gamma) = r_0$; perturbative $r = C_7'/C_7$, in SUSY, r unconstrained.

Br's	$D^0 \to \rho^0\gamma$	$D^0 \to \omega\gamma$	$D^0 \to \Phi\gamma$	$D^0 \to \bar{K}^{*0}\gamma$ (SM-domin.)
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 $2r_0/(1+r_0^2)$, 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).

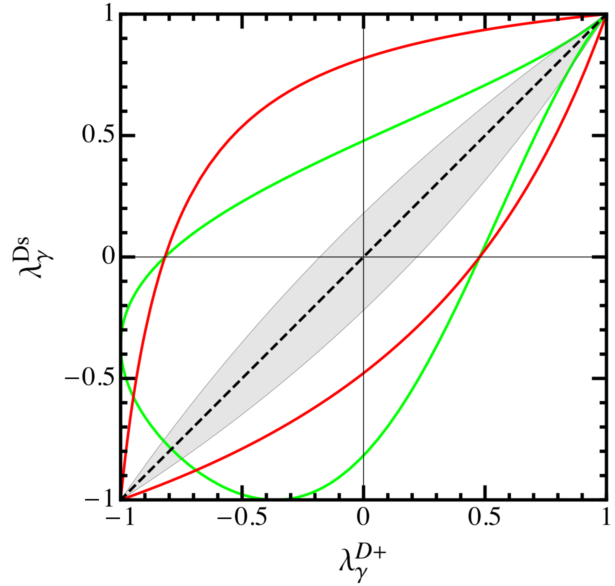
$\bar{R} = 1/f^2 \frac{|V_{cs}|^2}{|V_{cd}|^2} \frac{\mathcal{B}(D^0 \to \rho\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)}$ with leading U-spin breaking removed $f = m_\rho f_\rho/(m_{K^{*0}} f_{K^{*0}})$

Photon polarization from up-down asymmetry

Method 2: probe the photon polarization with an up-down asymmetry in $D^+ \to K_1^+(\to K\pi\pi)\gamma$ (a la $B \to K_1\gamma$ 1812.04679 , and (Gronau, Pirjol, Grossman, Kou) $\frac{d\Gamma}{ds_{13}\,ds_{23}\,d\cos\vartheta} \propto |\boldsymbol{J}|^2(1+\cos^2\vartheta) + \lambda_\gamma 2\,\mathrm{Im}[\boldsymbol{n}\cdot(\boldsymbol{J}\times\boldsymbol{J}^*)]\cos\vartheta\,,\ \lambda_\gamma = -\frac{1-r_0^2(\bar{K}_1)}{1+r_0^2(\bar{K}_1)}$

The corresponding BSM-sensitive mode is $D_s \to K_1^+(\to K\pi\pi)\gamma$.

Method 2 requires D-tagging but unlike TDA, does not depend on strong phases between the left- and right-handed amplitude.



grey: SM, red, green: BSM scenarios

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 $|C_7^{\text{effSM}}| = \mathcal{O}(0.001)\,, |C_9^{\text{effSM}}| \lesssim 0.01\,,\quad C_{10}^{\text{SM}} = 0\,,$ (GIM !) $\quad C'^{\text{SM}}, C_{S,P,T,T5}^{\text{SM}} = 0$

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. SM BGD in $c \to u$ photon polarization can be measured using U-spin.

clean $=$ clean enough

Great prospects to test the SM and look for BSM physics in semileptonic and radiative rare D decays, that is, obtain unique information on flavor complementary to K, B-decays. Plenty of opportunities for BaBar, BESIII, Belle (II), LHCb and FCC-ee at the Z.

Back up

New Physics models for $c \to u\gamma, \ell\ell$

BSM: SUSY, leptoquarks and Z' models. Hewett, Golowich, Fajfer, Kosnic, 1909.11108, 2004.01206

SUSY: chirality enhanced gluino-squark loops with flavor violation induce $C_7^{(\prime)}$. study in $A_{\rm CP}(D \to \pi\ell^+\ell^-)$
SUSY can also induce $C_9 = -C_{10}$ in RPV, however, this is constrained by kaon decays. yet, LFV!

leptoquarks: $S_{1,2}, \tilde{V}_{1,2}$ induce $C'_{9,10}$, no kaon constraints. Probe in LFV, universality tests, $A_{\rm CP}$

Z' models: consider anomaly-free ones with generation-dependent charges Allanach, Ellis, Fajfer, Kosnic, GH to appear

$$\mathcal{H}_{Z'} \supset \left(g_L^{uc}\,\overline{u}_L\gamma_\mu c_L + g_R^{uc}\,\overline{u}_R\gamma_\mu c_R + g_L^{\ell\ell'}\,\overline{\ell}_L\gamma_\mu\ell'_L + g_R^{\ell\ell'}\,\overline{\ell}_R\gamma_\mu\ell'_R\right) Z'^{\mu} + \mathrm{h.c.}$$

$$g_L^{uc} = g_4 \, \Delta F_L \cos\Phi_u \sin\Phi_u \, , \quad g_R^{uc} = g_4 \, \Delta F_R \cos\vartheta_u \sin\vartheta_u \, ,$$

Φ_u: from V_u, and $V_{CKM} = V_u^\dagger V_d$

ϑ_u: from RH rotations

ΔF difference of $U(1)'$ charges.

deeply linked to flavor; makes V_u and V_d physical:

synergy between up and down sector