Discussion: $c \to u(ll, \gamma, \nu\bar{\nu})$ as null tests of the SM

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... because, we can:
– sizable branching ratios within $10^{-7}-10^{-6}$ (semileptonic $c\to ull$) up to few 10^{-5} (dineutrino $c\to u\nu\bar{\nu}$) and $10^{-6}-10^{-4}$ ($c\to u\gamma$)

– plenty of BSM opportunities (nulltests!)

– in fact, its already happening LHCb'17, 18 $D\to\pi\pi\mu\mu$, Belle'16 $D\to\rho\gamma$, BES III '18 $D\to\pi\pi ee$, 25 $D\to Pll$ channels LHCb 2011.00217

...and its a unique probe of flavor in the up-sector:

1) leaving no stone unturned (BSM searches)

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

pursue flavor physics globally $, t, b, c, s, ...,$ exploit correlations and connect to anomalies

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

$$c \to u\nu\bar{\nu}$$

$c \to u\nu\bar{\nu}$ excellent nulltest of SM due to GIM – not a single entry in PDG for semileptonic decays!

$D^+, D_s \to M\nu\bar{\nu}$ has BGD from $D^+, D_s \to \tau(\to M\nu)\bar{\nu}$; reducible via cuts

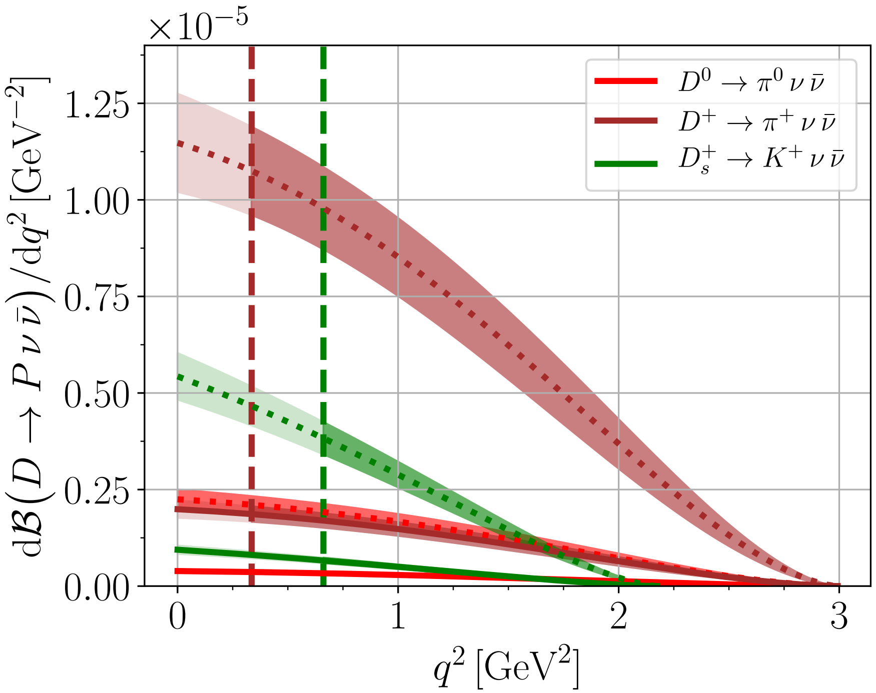


Figure 1: Differential branching ratios for $D^0 \to \pi^0\nu\bar{\nu}$, $D^+ \to \pi^+\nu\bar{\nu}$ and $D_s^+ \to K^+\nu\bar{\nu}$ in red, brown and green, respectively for the LU (cLFC) limit in solid (dotted) lines. this plot shows BSM distributions The uncertainty bands are due to the form factors, the vertical dashed lines illustrate the cuts needed to avoid the τ background. from 2010.02225

Upper limits $\mathcal{B}^{\text{max}}(h_c \to F \nu \bar{\nu})$ depend on lepton flavor (LFV,cLFC,LFU) – probe universality!

$h_c \to F$	$\mathcal{B}^{\text{max}}_{\text{LU}}$ $[10^{-7}]$	$\mathcal{B}^{\text{max}}_{\text{cLFC}}$ $[10^{-6}]$	$\mathcal{B}^{\text{max}}$ $[10^{-6}]$	$N^{\text{max}}_{\text{LU}}/\eta_{\text{eff}}$	$N^{\text{max}}_{\text{cLFC}}/\eta_{\text{eff}}$	$N^{\text{max}}/\eta_{\text{eff}}$
$D^0 \to \pi^0$	6.1	3.5	13	47 k (395 k)	270 k (2.3 M)	980 k (8.3 M)
$D^+ \to \pi^+$	25	14	52	77 k (650 k)	440 k (3.7 M)	1.6 M (14 M)
$D_s^+ \to K^+$	4.6	2.6	9.6	6 k (50 k)	34 k (290 k)	120 k (1.1 M)
$D^0 \to \pi^0\pi^0$	1.5	0.8	3.1	11 k (95 k)	64 k (540 k)	230 k (2.0 M)
$D^0 \to \pi^+\pi^-$	2.8	1.6	5.9	22 k (180 k)	120 k (1.0 M)	450 k (3.8 M)
$D^0 \to K^+K^-$	0.03	0.02	0.06	0.2 k (1.9 k)	1.3 k (11 k)	4.8 k (40 k)
$\Lambda_c^+ \to p^+$	18	11	39	14 k (120 k)	82 k (700 k)	300 k (2.6 M)
$\Xi_c^+ \to \Sigma^+$	36	21	76	28 k (240 k)	160 k (1.4 M)	590 k (5.0 M)
$D^0 \to X$	15	8.7	32	120 k (980 k)	660 k (5.6 M)	2.4 M (21 M)
$D^+ \to X$	38	22	80	120 k (1.0 M)	680 k (5.8 M)	2.5 M (21 M)
$D_s^+ \to X$	18	10	38	24 k (200 k)	140 k (1.1 M)	500 k (4.2 M)

$B(D \to \nu \bar{\nu}) < 9.4 \cdot 10^{-5}$(Belle): sensitive to RH-neutrinos, lepton number violation $\Lambda > 1.5$TeV

2010.02225; TH: Anyone looking into modes into ”nothing”?

$$c \to u\gamma$$

$c \to u\gamma$ probe NP in dipole operators O_7, O_7', incl. CPX

Unlike dineutrino modes, need ways to control SM BGD.

Recent data-driven proposals; charm test lab for QCD frameworks.

– Photon polarization: TDCPAs, up-down asymmetries; use plethora of modes and extract $\mathcal{A}_{\rm SM}$ from SM-like modes; nulltest $=$ correlation

– $D \to PP\gamma$: Use dB/dq^2 and forward-backward asymmetry to understand QCD dynamics in CF,DCS modes and test SM with A_{FB} in SCS modes and CP-asymmetries 2009.14212, 2104.08287

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

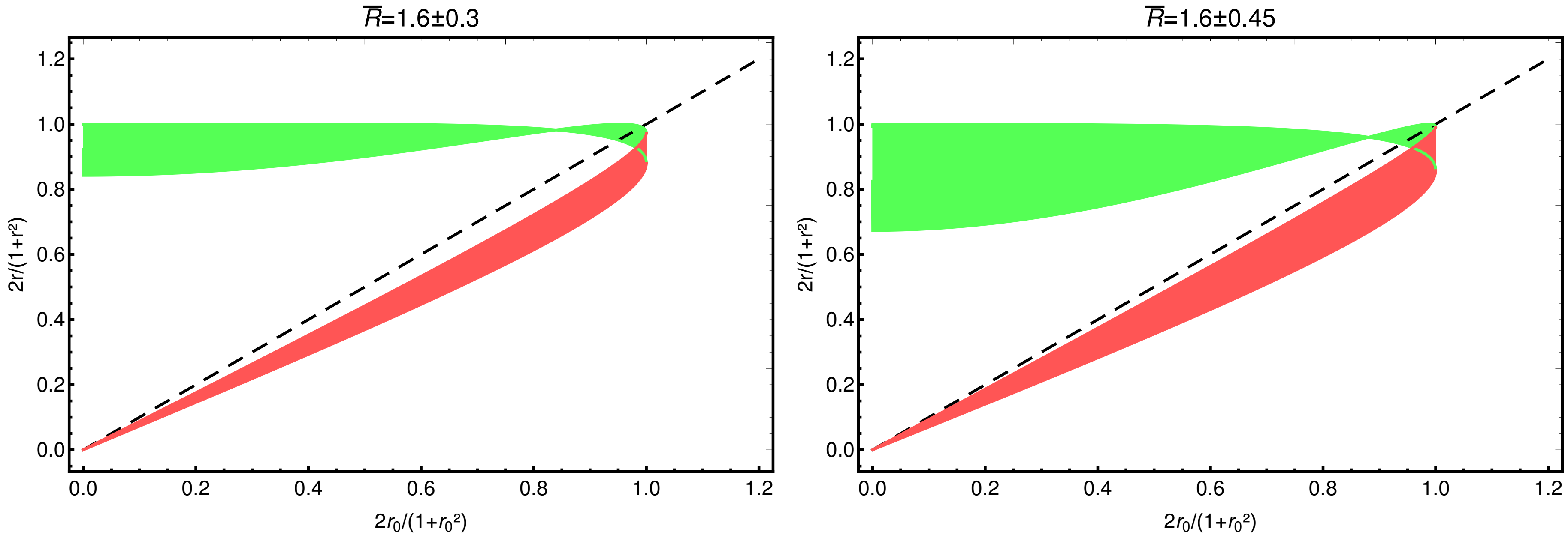
$$\Gamma(t) = \mathcal{N} e^{-\Gamma t} \left(\cosh[\Delta\Gamma t/2] + A^{\Delta} \sinh[\Delta\Gamma t/2] + \zeta C \cos[\Delta m t] - \zeta S \sin[\Delta m t]\right)$$

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

Br's	$D^0 \to \rho^0\gamma$	$D^0 \to \omega\gamma$	$D^0 \to \Phi\gamma$	$D^0 \to \bar{K}^{*0}\gamma$ (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	–	$< 2.4 \times 10^{-4}$	–	–
LHCb			wip	

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



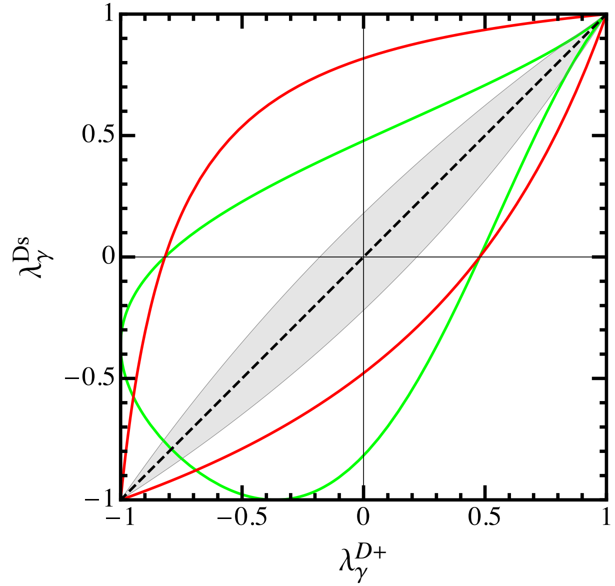
$2r/(1+r^2)$ as a function of $2r_0/(1+r_0^2)$, in the cases a) (SM case) $C_7, C_7' \simeq 0$ (black, dashed curve), c) $C_7 \simeq 0$ (green, upper band) and d) $C_7' \simeq 0$ (red, lower band). The upper (lower) plots correspond to $\bar{R}_{ave} = 1.6 \pm 0.3$ ($\bar{R} = 1.6 \pm 0.45$ from 50%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

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

Probing the SM and QCD with $D \to PP\gamma$

CF: $D_s \to \pi^+\pi^0\gamma\,,\ D_s \to K^+\overline{K}^0\gamma\,,\ D^+ \to \pi^+\overline{K}^0\gamma\,,\ (D^0 \to \pi^0\overline{K}^0\gamma\,,\ D^0 \to \pi^+K^-\gamma)$

SCS: $D^+ \to \pi^+\pi^0\gamma\,,\ D_s \to \pi^+K^0\gamma\,,\ D_s \to K^+\pi^0\gamma\,,$

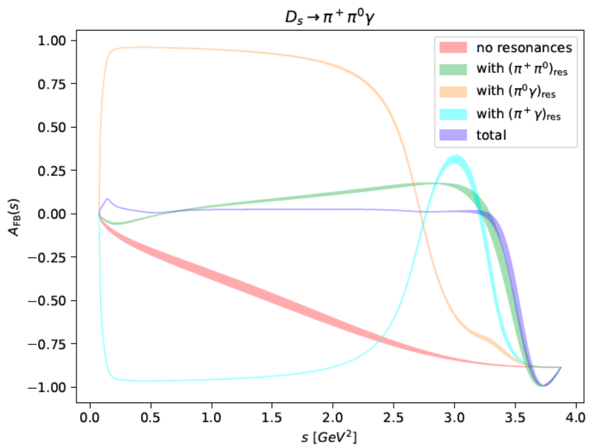
$D^+ \to K^+\overline{K}^0\gamma\,, (D^0 \to \pi^+\pi^-\gamma\,,\ D^0 \to K^+K^-\gamma)$

DCS: $D^+ \to \pi^+K^0\gamma\,, D^+ \to K^+\pi^0\gamma\,,\ D_s \to K^+K^0\gamma$

Test QCD methods (QCDF/weak annihilation, HHχPT) with CF,DCS and then SM with SCS

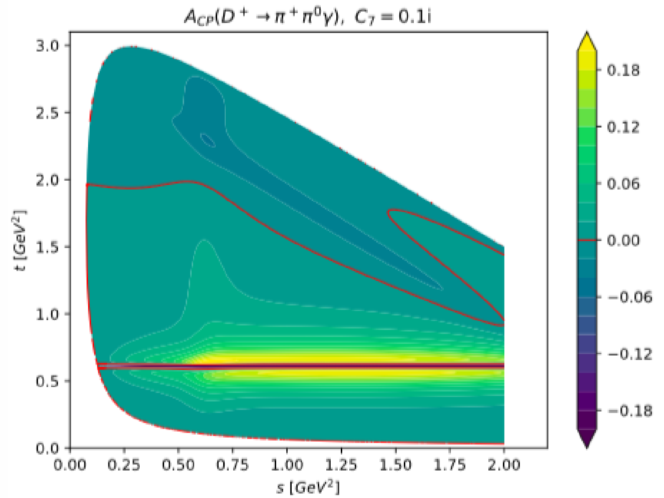
leading order QCDF: $A_{\rm FB}^{\rm SM} = 0$ (only s-channel resonances) ideal: forward-backward and

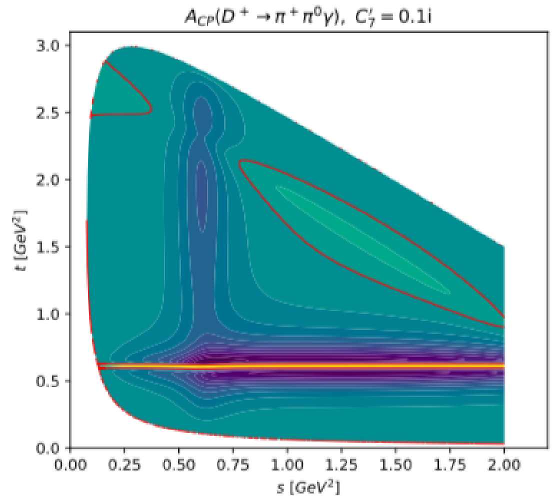
CP-asymmetries in Dalitz region



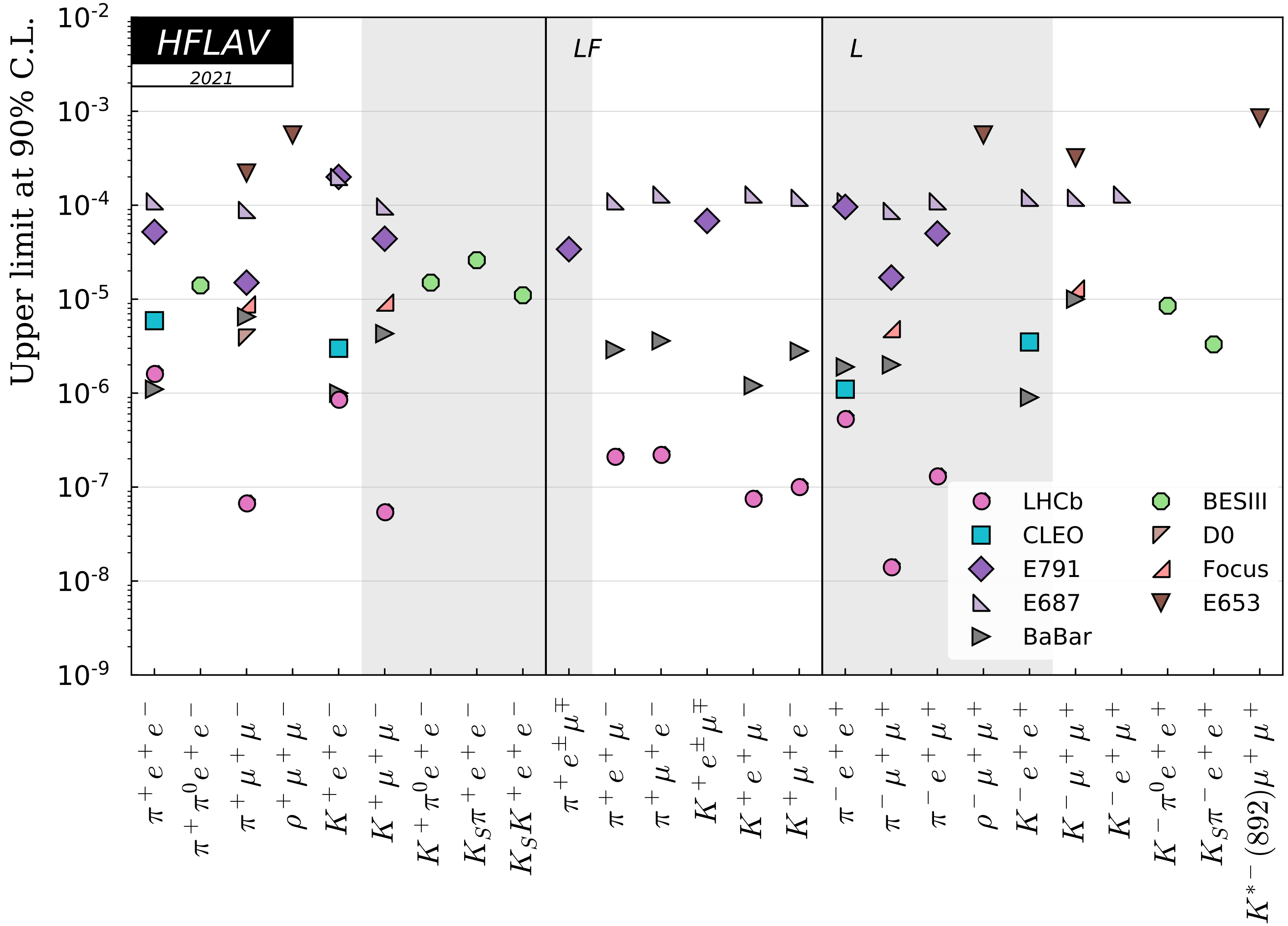
SM

BSM





$$c \to ull$$


HFLAV
2021
LF
L
Upper limit at 90% C.L.
10-2
10-3
10-4
10-5
10-6
10-7
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10-9
LHCb
CLEO
E791
E687
BaBar
BESIII
D0
Focus
E653
$\pi^+ e^+ e^-$
$\pi^+ \pi^0 e^+ e^-$
$\pi^+ \mu^+ \mu^-$
$\rho^+ \mu^+ \mu^-$
$K^+ e^+ e^-$
$K^+ \mu^+ \mu^-$
$K^+ \pi^0 e^+ e^-$
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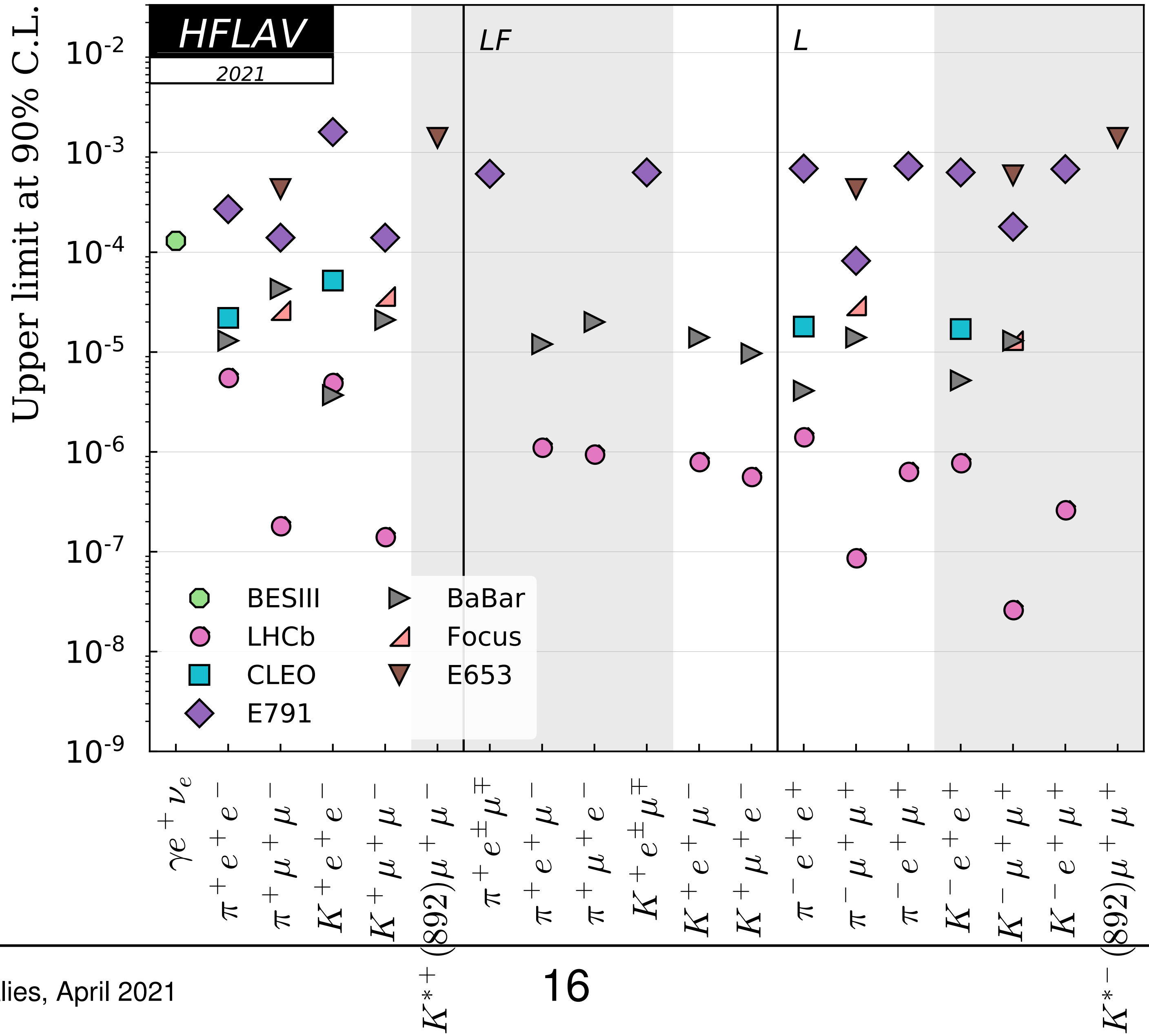
$K_S \pi^- e^+ e^+$
$K^{*-}(892) \mu^+ \mu^+$


HFLAV
2021
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Upper limit at 90% C.L.
10^{-2}
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BESIII
LHCb
CLEO
E791
BaBar
Focus
E653
$\gamma e^+ \nu_e$
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$K^+ e^+ e^-$
$K^+ \mu^+ \mu^-$
$K^{*+}(892) \mu^+ \mu^-$
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$K^+ e^\pm \mu^\mp$
$K^+ e^+ \mu^-$
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$\pi^- e^+ \mu^+$
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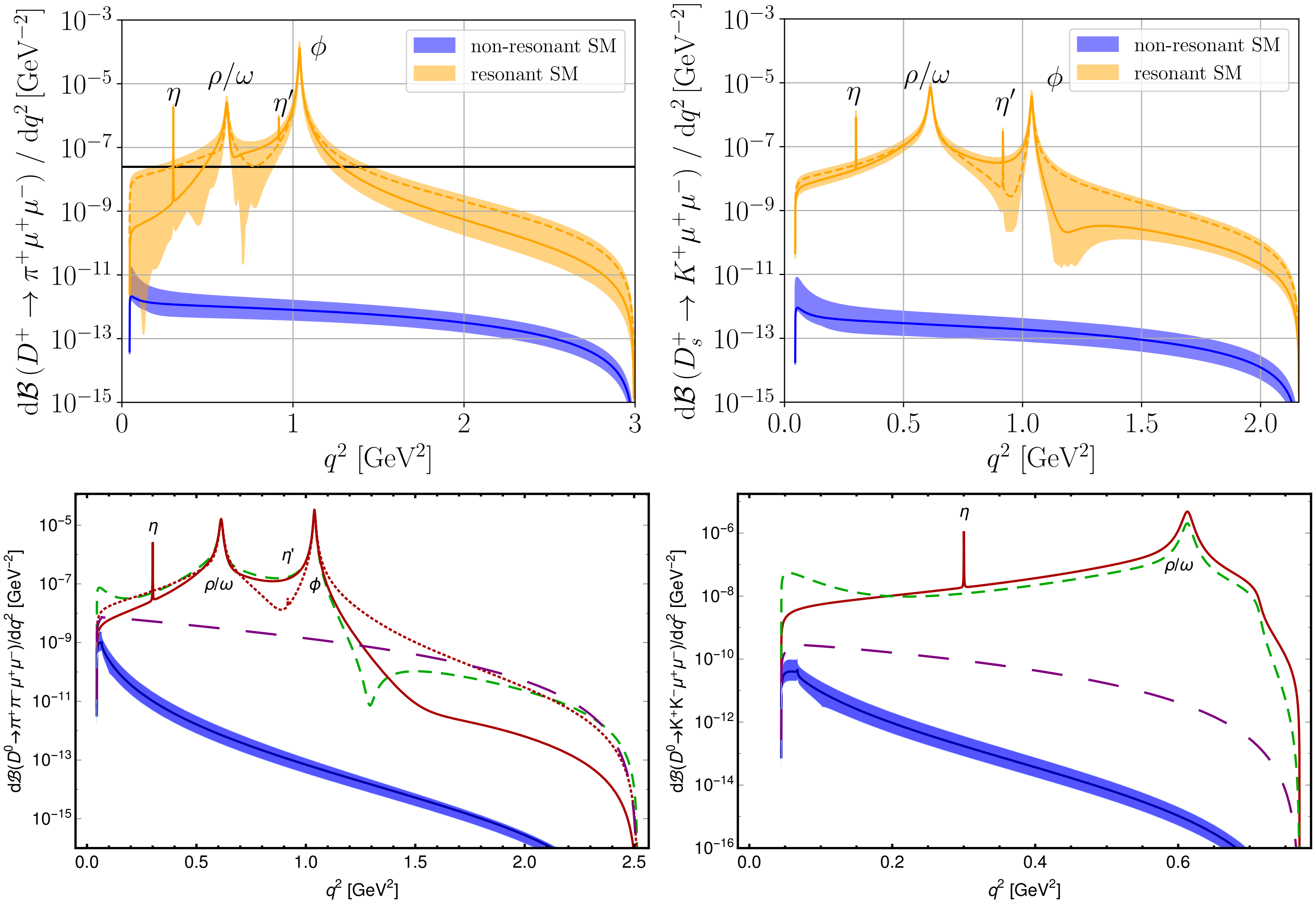
$K^- e^+ \mu^+$
$K^{*-}(892) \mu^+ \mu^+$

Resonance contributions vs BSM



Resonance contributions vs BSM

TH: please provide cuts and measurements corresponding to these cuts — ”inter/extrapolations” between resonances are model-dependent and diminish the sensitivity to flavor [a]

EXP: query - for the resonant modes - is there anything we can usefully measure on the resonance shapes to help constrain the predictions for the resonance tails ? See figure 1 for the resonant modes used for calibration.

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.

[a] they can also cause confusion to the reader

$D \to Pll$, $P = \pi, K$ nulltests:

- LFV $D \to Pe^{\pm}\mu^{\mp}$
- LNV $D^+_{(s)} \to P^-\ell^+\ell^+$
- universality ratios "a la R_K" $R_P^D = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(D \to P\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(D \to Pe^+e^-)}{dq^2} dq^2}$. Fajfer, Kosnic, 1909.11108
- angular distributions $A_{\rm FB}$, F_H $\frac{d^2\Gamma}{dq^2\, d\cos\vartheta} = a(q^2) + b(q^2)\cos\vartheta + c(q^2)\cos^2\vartheta$
- CP-asy

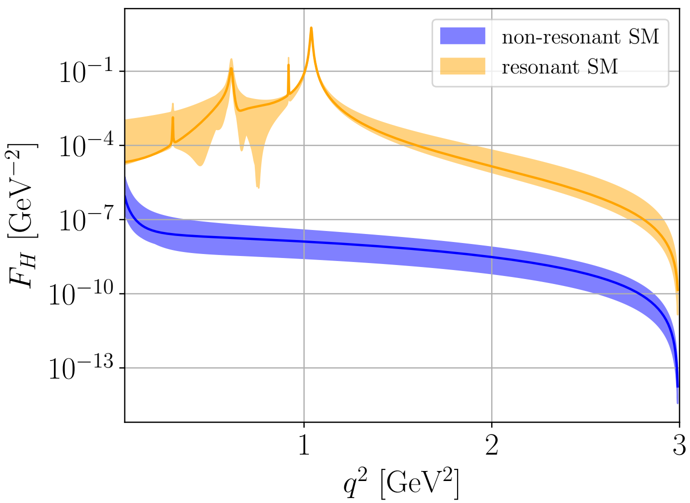
SM null tests $D \to \pi l^+ l^-$ and $D_s \to K l^+ l^-$

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

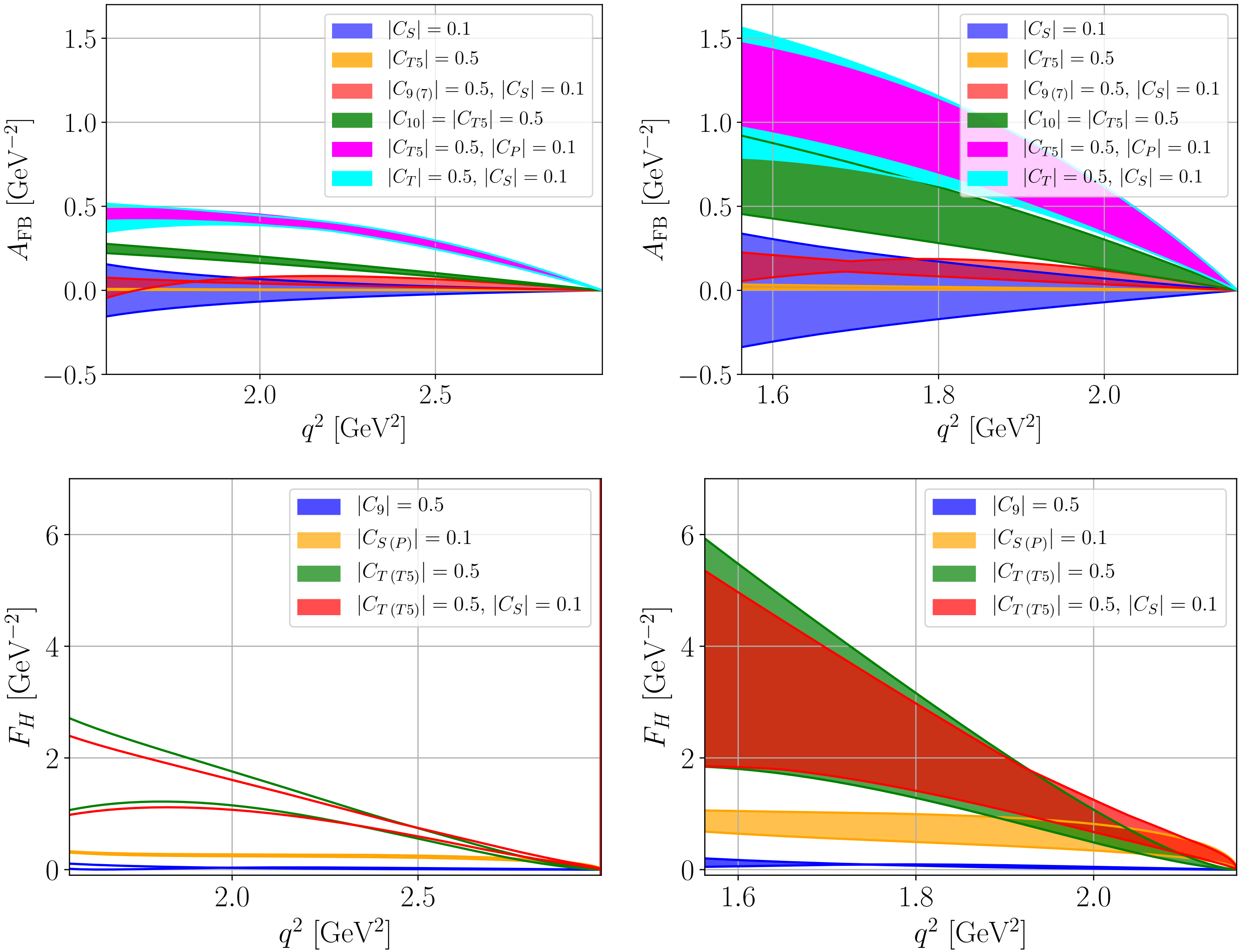
$A_{\rm FB}^{\rm SM} \simeq 0$, $F_H^{\rm SM} \propto m_\ell^2 |C_9|^2$, suppressed for muons, negligible for electrons

Both $A_{\rm FB}$ and F_H very sensitive to S,P- and or tensor operators. Fig from 1909.11108



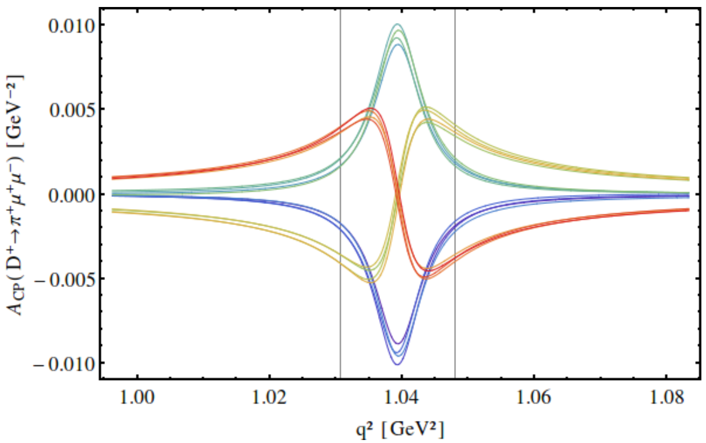
$D \to \pi\mu\mu$

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

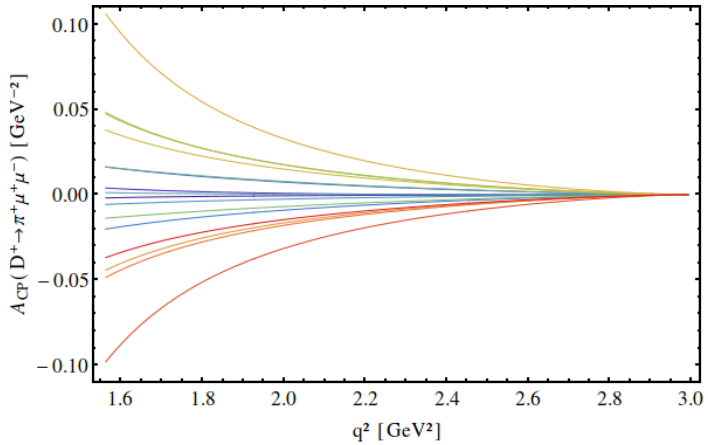


Probing even small couplings: $A_{CP}(D \to \pi ll)$

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)

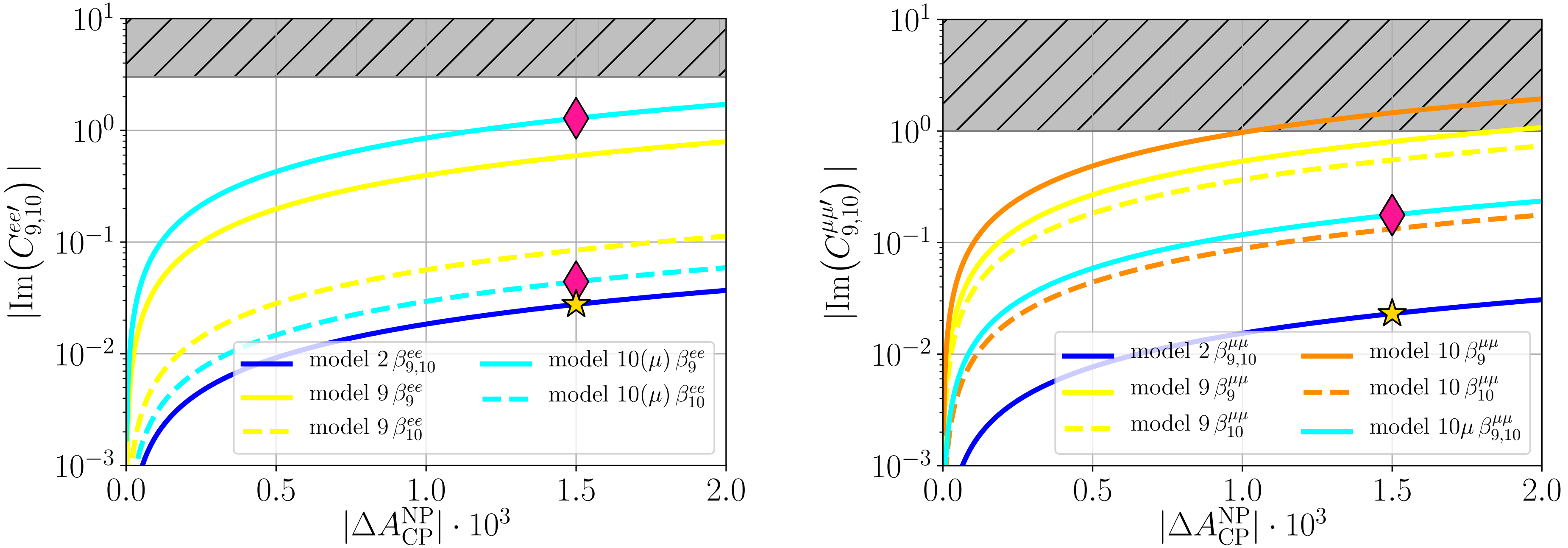


ii 2)

Large uncertainties, however, large BSM signals possible ($|A_{CP}^{\rm SM}| \lesssim few10^{-3}$) 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

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.

$D \to PPll$, $P = \pi, K$ nulltests:

- LFV $D \to PPe^\pm\mu^\mp$
- LNV $D^+_{(s)} \to P^0 P^- \ell^+ \ell^+$, $D^0 \to P^- P^- \ell^+ \ell^+$
- universality ratios ”a la R_K” First probes available from combining LHCb with BESIII
- angular distributions $I_{5,6,7} \propto C_{10}^{(\prime)} = 0$ (GIM)
- CP-asy

universality tests in $c \to u$

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

$$R^D_{P_1 P_2} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2 (D \to P_1 P_2 \mu^+\mu^-)}{\int_{q^2_{\min}}^{q^2_{\max}} d\mathcal{B}/dq^2 (D \to P_1 P_2 e^+e^-)}$$ 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. EXP: expect LHCb and Belle II should make significant improvements on universality ratios, require both measurements made by same detector with same techniques for systematics to be controlled for ratio.

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

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

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

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

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

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

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

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

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

Angular dist. LHCb 1806.10793 update with full Run1+2 data is being worked on.

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

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

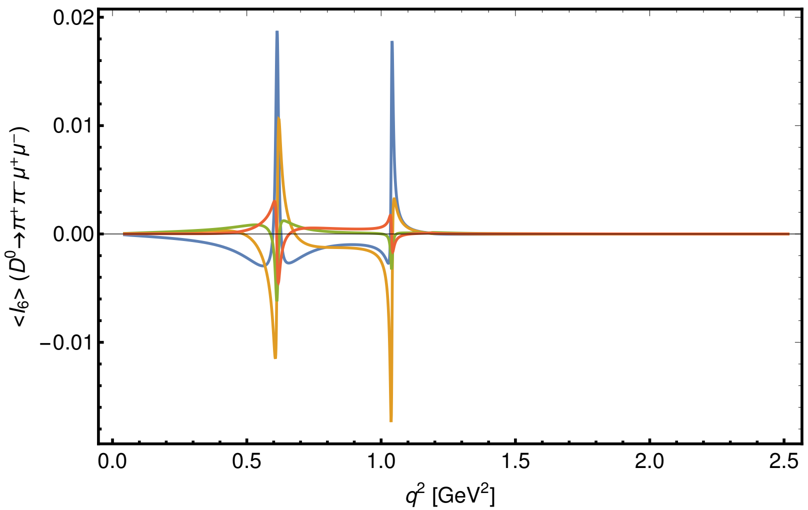
$$\begin{aligned}
I_1 &= \frac{1}{16}\left[|H_0^L|^2 + (L \to R) + \frac{3}{2}\sin^2\vartheta_{P_1}\{|H_\perp^L|^2 + |H_\parallel^L|^2 + (L \to R)\}\right], \\
I_2 &= -\frac{1}{16}\left[|H_0^L|^2 + (L \to R) - \frac{1}{2}\sin^2\vartheta_{P_1}\{|H_\perp^L|^2 + |H_\parallel^L|^2 + (L \to R)\}\right], \\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

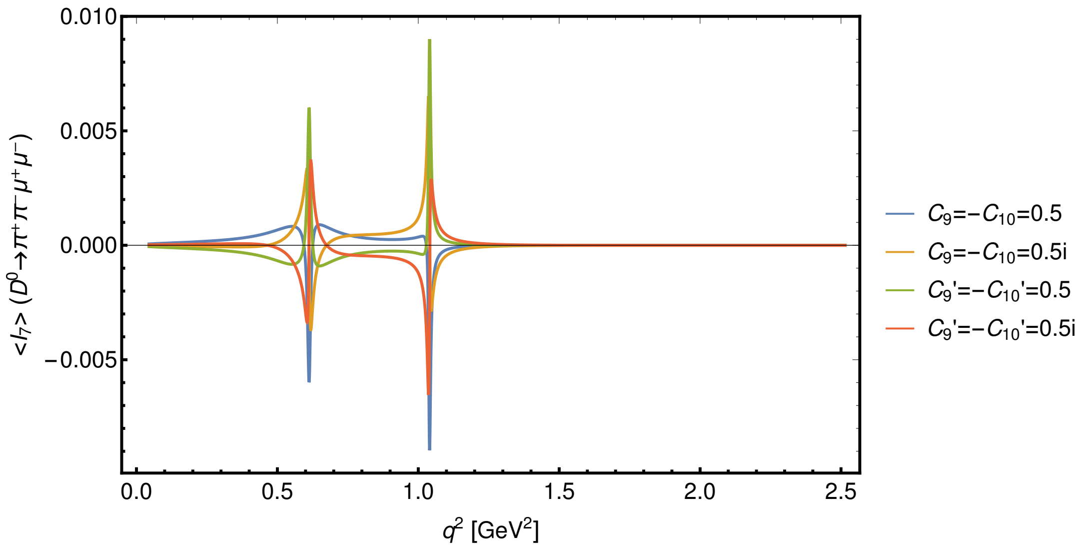
$I_{5,6,7}$ vanish due to minus signs (red) in absence of axial vector couplings.

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 $I_{5,6,8,9}$

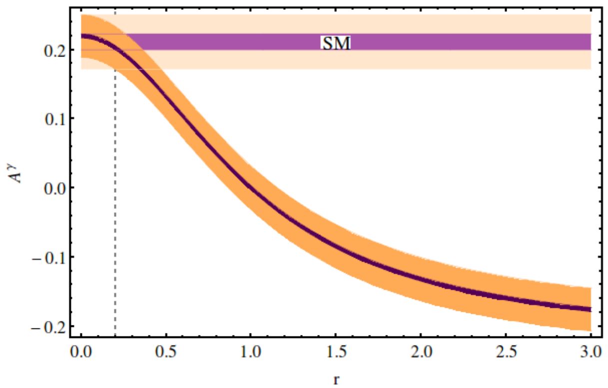
$$A_k = 2\frac{I_k - \bar{I}_k}{\Gamma + \bar{\Gamma}} = \frac{I_k - \bar{I}_k}{\Gamma_{ave}}\,, \tag{8}$$

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

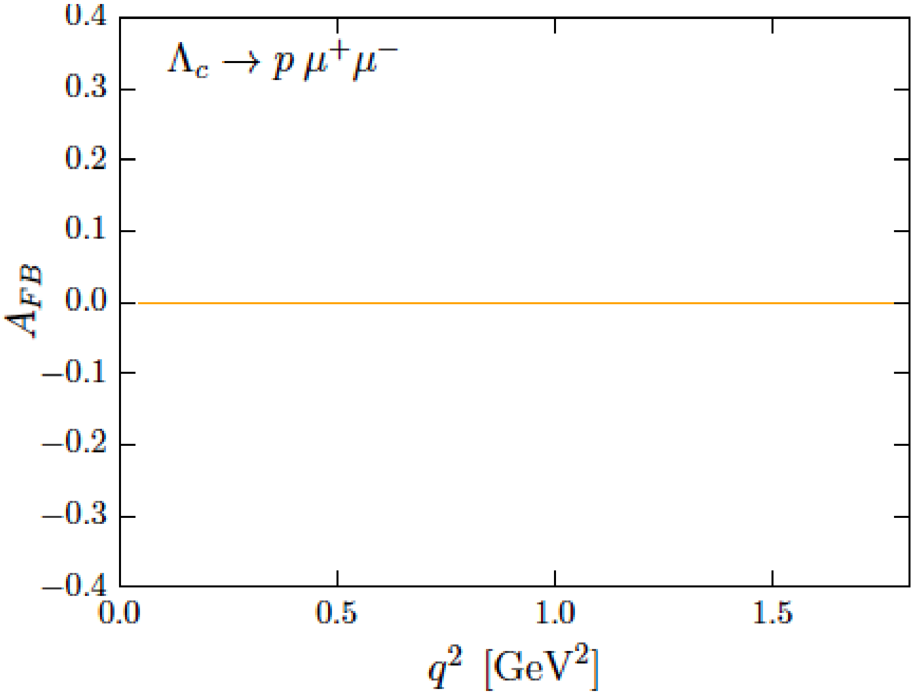
Ranges for the high q^2, $q^2_{\text{min}} = (1.1\,\text{GeV})^2$, integrated CP asymmetries $\langle A_i \rangle$ for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ decays for different BSM benchmarks, varying strong phases. $\langle A_{5,6} \rangle_{\text{SM}} = 0$ (GIM), $\langle A_{8,9} \rangle_{\text{SM}} \lesssim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

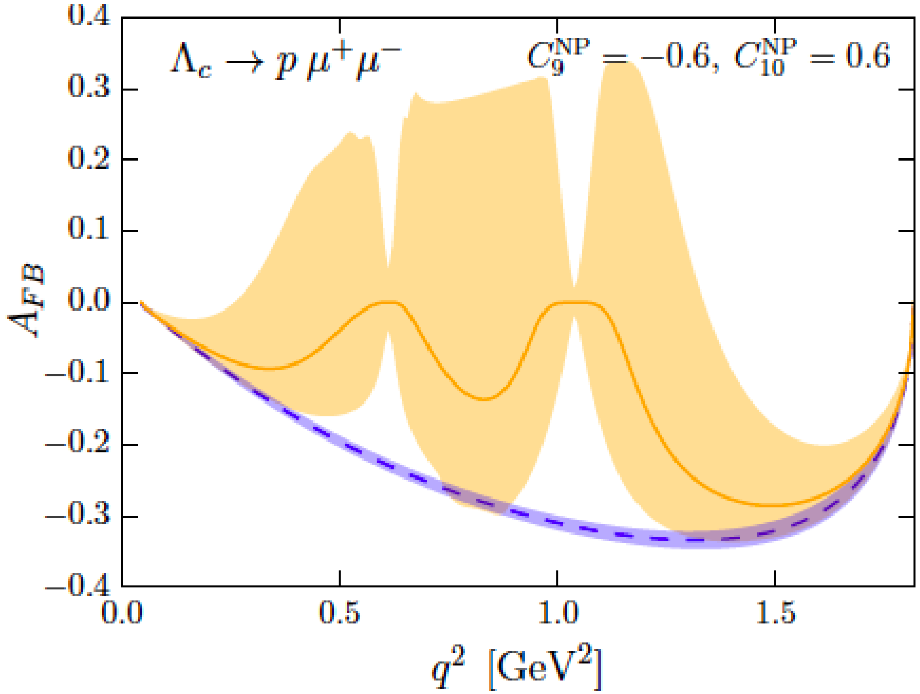
$\Lambda_c \to pll$ nulltests:

- LFV $\Lambda_c \to pe^{\pm}\mu^{\mp}$
- universality ratios "a la R_K"
- angular distributions $A_{\rm FB} \propto C_{10}^{(\prime)} = 0$ (GIM)
- CP-asy
- polarization studies (Λ_c polarized initially) $A^{\gamma} = -\frac{P_{\Lambda_c}}{2}\frac{1-|r|^2}{1+|r|^2}$, 1701.06392



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





Plots from 1712.05783

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

Charm decays into leptons are plagued by resonance contributions, and $1/m_c$ not ideal 1705.05891. HOWEVER, BSM physics can be signaled in null tests, or in observables where SM BGD can be extracted from data plus U-spin etc

clean $=$ clean enough

Great prospects to test the SM and look for BSM physics in semileptonic, dineutrino 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

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

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

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

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