New Directions: Exploring Charm

1. Null tests and more for e^+e^- and pp colliders
2. U-spin/CP puzzle and pion form factor: a light Z'?

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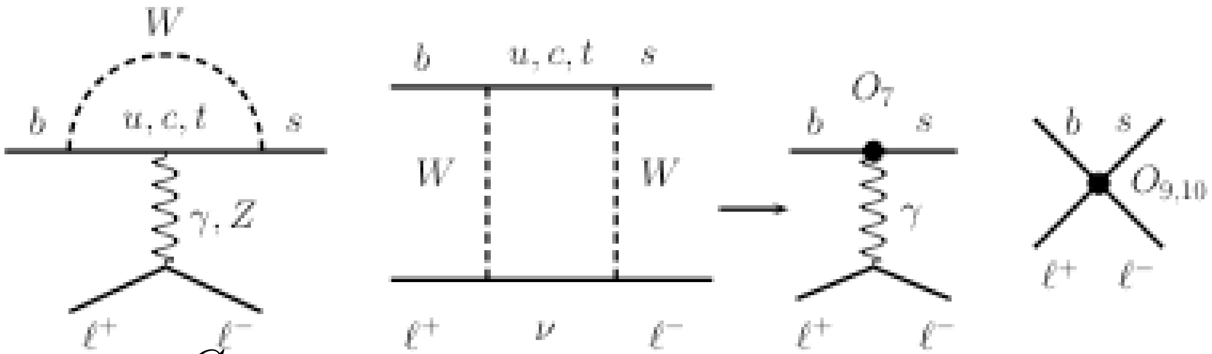
We look for New Physics in Flavor Changing Neutral Currents (FCNCs), because they are suppressed in SM by 1. loop-factor 2. CKM-mixing 3. GIM –mass degeneracies of quarks in loop; very strong in Charm FCNCs, where d, s, b are in loop



$$\mathcal{H}_{\rm eff} \quad = \quad -4\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^* \sum_i C_i(\mu)O_i(\mu), \qquad G_F/\sqrt{2} = g^2/(8m_W^2)$$

$$\mathcal{O}_9 \quad = \quad \bar{s}_L\gamma_\mu b_L\, \bar{\ell}\gamma^\mu\ell \text{ (vector)} \quad \mathcal{O}_{10} = \bar{s}_L\gamma_\mu b_L\, \bar{\ell}\gamma^\mu\gamma_5\ell \text{ (axial-vector)}$$

Ongoing precision programs in B-physics. ($b \to s\ell\ell, \gamma$ global fit, $b \to d\ell\ell, \gamma$ 2209.04457) —> Pursue charm program

Testing the Standard Model with $c \to u$ FCNCs of mesons and baryons:

- $c \to u\gamma$ Br $\sim 10^{-6} - 10^{-4}$
- $c \to u\mu\mu, uee$ Br $\sim 10^{-7} - 10^{-6}$
- $c \to u\nu\bar{\nu}, a, Z', ...$ Br $\lesssim 10^{-5}$

Probe various different types of physics (dipole couplings, 4-fermion operators, light NP, ..)

Complementary to kaon and B-physics – charm is unique probe of flavor in the up-sector

0112235, 1510.00965, 1805.08516 , 2011.09478,.... Adolph, de Boer, Bause, Bharucha, Brod, Bigi, Burdman, d'Ambrosio, Cata, Fajfer, Feldmann, Gisbert, Golowich, Golz, Hewett, Kosnic, Magorsch, Meinel, Pakvasa, Petrov, Seidel, Singer, Silva, Solomonidi, Zwicky, ...

radiative $c \to u\gamma$: $D \to V\gamma$, $V = \rho, ..,$ $D \to P_1 P_2 \gamma$,
$D \to A\gamma$, $A = K_1, ..$ $D \to P_1 P_2 P_3 \gamma$, $\Lambda_c \to p\gamma$, $\Xi_c^0 \to \Lambda(\to p\pi)\gamma$,....
$B(D^0 \to \rho^0 \gamma) = (1.77 \pm 0.31) \cdot 10^{-5}$ Belle'16, Cabibbo-favored modes:
$B(\Lambda_c \to \Sigma\gamma) < 2.6 \cdot 10^{-4}$, $B(\Xi_c^0 \to \Xi^0 \gamma) < 1.8 \cdot 10^{-4}$ Belle 2206.12517
$B(\Lambda_c \to \Sigma\gamma) < 4.4 \cdot 10^{-4}$ BESIII 2212.07214

semileptonic $c \to u\ell\ell^{(\prime)}$: $D \to \pi\mu\mu$, $D \to \mu\mu$, $D \to P_1 P_2 \ell\ell$,
$\Lambda_c \to p\ell\ell$, $\Xi_c^0 \to \Lambda(\to p\pi^-)\ell\ell$,... $B(D \to \pi\pi\mu\mu) \simeq 9.6 \cdot 10^{-7}$ LHCb'18 ,
$B(\Lambda_c \to p\mu\mu) \lesssim 7.7 \cdot 10^{-8}$ LHCb'17, $B(\Xi_c^0 \to \Xi^0 \mu^+ \mu^-) < 6.5 \cdot 10^{-5}$,
$B(\Xi_c^0 \to \Xi^0 e^+ e^-) < 9.9 \cdot 10^{-5}$ Belle 2312.02580

dineutrinos/MET/ALPs $c \to u\nu\bar{\nu}$: $D \to \pi\nu\bar{\nu}$, $D \to \nu\bar{\nu}$, $D \to P_1 P_2 \nu\bar{\nu}$,
$\Lambda_c \to p\nu\bar{\nu}$, $\Xi_c^0 \to \Lambda(\to p\pi^-)\nu\bar{\nu}$,... $B(D^0 \to nothing) < 9.4 \cdot 10^{-5}$
Belle'16, $B(D^0 \to \pi^0 \nu\bar{\nu}) < 2.1 \cdot 10^{-4}$ BESIII 2112.14236

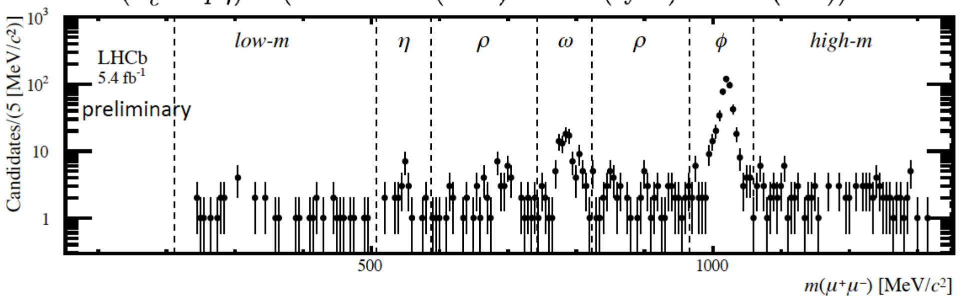
On April 10, 2024 BES III arXiv:2404.05973,

$B(D_s^+ \to K^+\pi^0 e^+ e^-) < 7.1 \cdot 10^{-5}$

April 23, 2024, Cern seminar ”from unseen to rare”, search for $\Lambda_c \to p\mu\mu$ at LHCb, LHCb-PAPER-2024-005

- Rare mode, extrapolating to full mass region from low- and high masses:
  - signal region (extrapolated): $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.3\ (8.2) \times 10^{-8}$ at 90% (95%) CL.
  - **low-mass:** $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 6.5\ (7.8) \times 10^{-8}$ at 90% (95%) CL
  - **high-mass:** $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 11.8\ (13.1) \times 10^{-8}$ at 90% (95%) CL
- Resonant mode mass regions (assuming no interference):

$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.82 \pm 1.23\ (\text{stat.}) \pm 0.72\ (\text{syst.}) \pm 2.79\ (\text{ext.})) \times 10^{-4}$$
$$\mathcal{B}(\Lambda_c^+ \to p\rho) = (1.52 \pm 0.34\ (\text{stat.}) \pm 0.14\ (\text{syst.}) \pm 0.24\ (\text{ext.})) \times 10^{-3}$$
$$\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.67 \pm 0.69\ (\text{stat.}) \pm 0.23\ (\text{syst.}) \pm 0.34\ (\text{ext.})) \times 10^{-3}$$



TH Progress: New BSM strategies for $|\Delta c| = |\Delta u| = 1$

SM tests in rare charm decays are null tests based on approximate symmetries of the SM: GIM, CP, cLFC, LFU, LNC, $SU(3)_F$

GIM-suppression very efficient: In SM, everything follows from tree-level W-exchange plus RGE, μ_b-matching 1707.00988 :

$$O_7 = \bar{u}_L \sigma_{\mu\nu} c_R F^{\mu\nu}, \quad O_9 = \bar{u}_L \gamma_\mu c_L \, \bar{\ell} \gamma^\mu \ell,$$

$$O_{10} = \bar{u}_L \gamma_\mu c_L \, \bar{\ell} \gamma^\mu \gamma_5 \ell \,, \quad O_\nu = \bar{u}_L \gamma_\mu c_L \, \bar{\nu} \gamma^\mu (1 - \gamma_5) \nu$$

$C_7^{\text{eff SM}} \lesssim 0.01$, $C_9^{\text{eff SM}} \lesssim 0.05$ 1510.00311 $\quad C_\nu^{\text{SM}} = 0, \quad C_{10}^{\text{SM}} = 0$

SM-Phenomenology completely dominated by 4-quark operators; Classify as CF $\sim V_{cs}^* V_{ud}$, SCS $\sim V_{cq}^* V_{uq}, V_{cq}^* V_{uq}, q = d, s$, DCS $\sim V_{cd}^* V_{us}$

$c \to u\nu\bar{\nu}$ transitions: all of them are excellent nulltests of the SM due to GIM, very clean

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

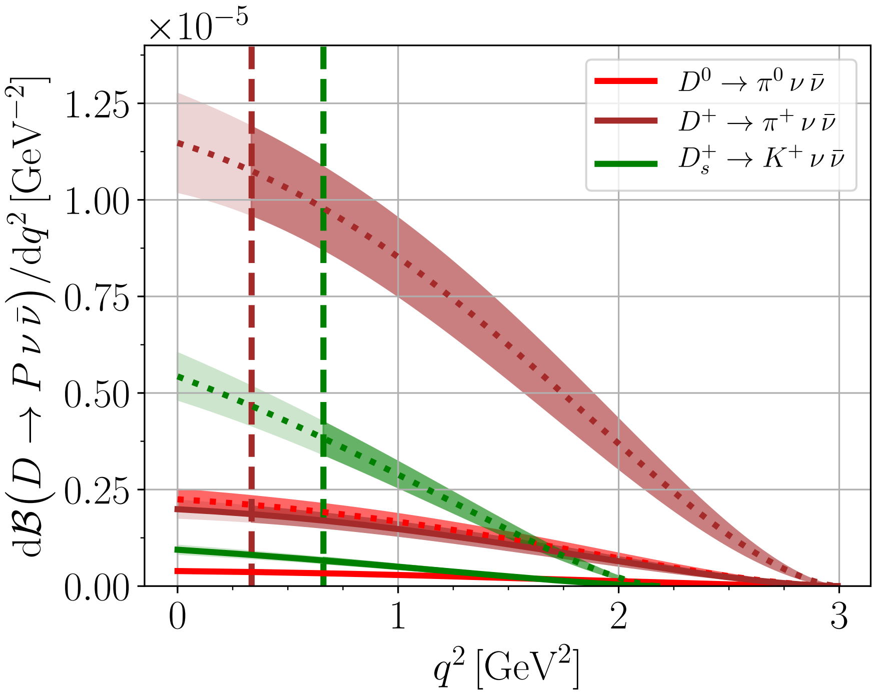


Figure 1: Differential branching ratios for $D^0 \to \pi^0\nu\bar{\nu}$, $D^+ \to \pi^+\nu\bar{\nu}$ and $D_s^+ \to K^+\nu\bar{\nu}$ in red, brown and green for the LU (cLFC) limit in solid (dotted) lines. plot shows BSM distributions The uncertainty bands are due to the form factors, here from lattice ETM'19, τ background removable by q^2-cut (vertical dashed lines) plot from 2010.02225

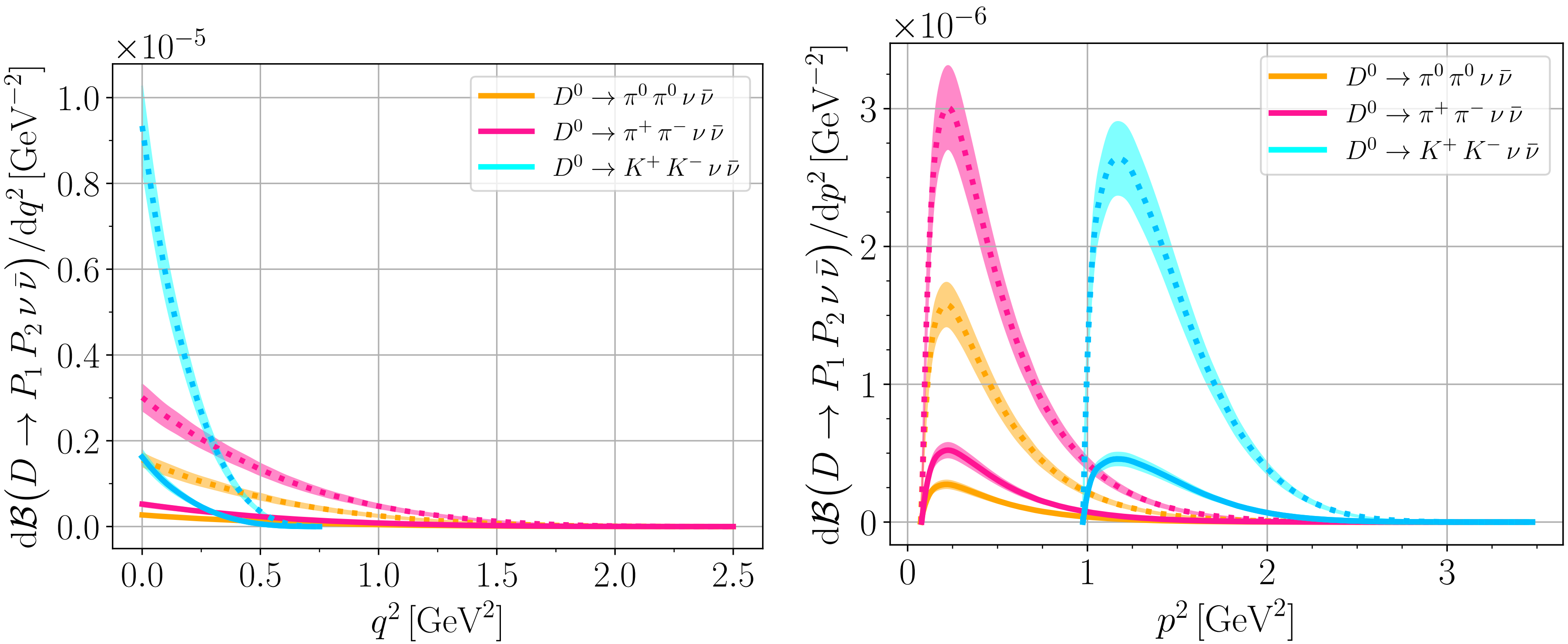


Figure 2: Differential q^2 and p^2 branching ratios for $D^0 \to \pi^0 \pi^0 \nu\bar{\nu}$, $D^0 \to \pi^+ \pi^- \nu\bar{\nu}$ and $D^0 \to K^+ K^- \nu\bar{\nu}$ decays in orange, deep pink and cyan, respectively for the LU (cLFC) limit in solid (dotted) lines. The differential branching ratio of $D^0 \to K^+ K^- \nu\bar{\nu}$ is multiplied by a factor 100 to be visible in the plots. Can we do better with $D \to \pi\pi$ form factors ? here from HHχPT Lee et al '92. with illustrative 10 % uncertainty. plots from 2010.02225

$D \to PP\nu\bar{\nu}$ predom. $C - C'$, complementary to $D \to P\nu\bar{\nu}$: $C + C'$

Leading semileptonic 4-fermion operators at scale above v (SMEFT) contributing to dineutrino modes $q \to q'\nu\bar\nu$

$$\mathcal{L}_{\text{eff}} \supset \frac{C_{\ell q}^{(1)}}{v^2}\bar{Q}\gamma_\mu Q\,\bar{L}\gamma^\mu L + \frac{C_{\ell q}^{(3)}}{v^2}\bar{Q}\gamma_\mu\tau^a Q\,\bar{L}\gamma^\mu\tau^a L + \frac{C_{\ell u}}{v^2}\bar{U}\gamma_\mu U\,\bar{L}\gamma^\mu L + \frac{C_{\ell d}}{v^2}\bar{D}\gamma_\mu D\,\bar{L}\gamma^\mu L\,. \tag{1}$$

$SU(2)_L \times U(1)_Y$ gauge invariance links up and down quarks, $Q = (u, d)$ and left-handed neutrinos and charged leptons $L = (\nu, \ell)$.

$$C_L{}^U = K_L{}^D = C_{\ell q}^{(1)} + C_{\ell q}^{(3)}\,, \quad C_R^U = K_R^U = C_{\ell u}\,, \quad C_L^D = K_L^U = C_{\ell q}^{(1)} - C_{\ell q}^{(3)}\,, \quad C_R^D = K_R^D = C_{\ell d}\,.$$

LH contribution to $c \to u\nu\bar\nu$ (C_L^U) identical to $s \to d\ell\bar\ell$ (K_L^D) etc

RH contribution to $c \to u\nu\bar\nu$ (C_R^U) identical to $c \to u\ell\bar\ell$ (K_R^U)

L,R denotes left or right handed quark currents; only SM-like light neutrinos.

Dineutrino vs lepton specific limits

left-handed $c \to u\nu\bar{\nu}$ (C_L^U)

Process	WC	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$pp \to \ell^+\ell^-$	$\mathcal{K}_{L,R}^{sd\ell\ell'}$	3.8	2.3	5.37	2.0	6.1	6.6
$K \to \ell^+\ell^- + \pi$	$\mathcal{K}_{L,R}^{sd\ell\ell'} \cdot 10^2$	5	1.6	-	0.066	-	-
$K \to \nu\bar{\nu} + \pi$	$\mathcal{K}_{R}^{sd\ell\ell'} \cdot 10^2$	[-1.9,0.7]	[-1.9,0.7]	[-1.9,0.7]	1.1	1.1	1.1
prelim. $pp \to \nu\bar{\nu} + X$	$\mathcal{K}_{L}^{sd\ell\ell'}$	4.1 (3.3)	4.1 (3.3)	4.1 (3.3)	2.9 (2.2)	2.9 (2.2)	2.9 (2.
prelim. $pp \to \nu\bar{\nu} + X$	$\mathcal{K}_{R}^{sd\ell\ell'}$	5.7 (4.6)	5.7 (4.6)	5.7 (4.6)	4.1 (3.3)	4.1 (3.3)	4.1 (3.

Table 1: Limits on $sd\ell\ell'$ WCs. The first row is based on 2304.12837, while the second and third row are taken from 2007.05001 and the NEW ones from $pp \to \nu\bar{\nu} + X$ are from 2403.17063 (recasting ATLAS 2102.10874) with projections for $3000\, fb^{-1}$ in parentheses, using $SU(2)_L$.

- synergy between high p_T flavor and rare decays
- rare kaon decays are most powerful when existing (no decays into taus)
- prelim. $pp \to MET + j$ similar level as Drell-Yan and better for taus

Dineutrino vs lepton specific limits

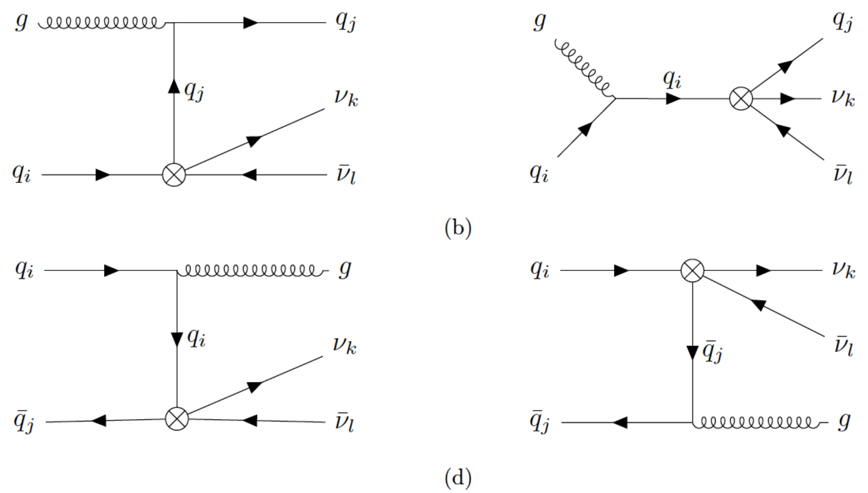
right-handed $c \to u\nu\bar{\nu}$ (C_R^U)

Process	WC	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	
$pp \to \ell^+\ell^-$	$\mathcal{K}_{L,R}^{cu\ell\ell'}$	2.9	1.6	5.6	1.6	4.7	
$D \to \ell^+\ell^- + \pi$	$\mathcal{K}_{L,R}^{cu\ell\ell'}$	4.0	0.9	-	2.2	-	
$K \to \nu\bar{\nu} + \pi$	$\mathcal{K}_{L}^{cu\ell\ell'} \cdot 10^2$	$[-1.9, 0.7]$	$[-1.9, 0.7]$	$[-1.9, 0.7]$	1.1	1.1	
prelim. $pp \to \nu\bar{\nu} + X$	$\mathcal{K}_{L}^{cu\ell\ell'}$	5.7 (4.6)	5.7 (4.6)	5.7 (4.6)	4.1 (3.3)	4.1 (3.3)	4.
prelim. $pp \to \nu\bar{\nu} + X$	$\mathcal{K}_{R}^{cu\ell\ell'}$	4.1 (3.3)	4.1 (3.3)	4.1 (3.3)	2.9 (2.2)	2.9 (2.2)	2.

Table 2: Limits on $cu\ell\ell'$ WCs. The first three rows are from 2007.05001, while the ones from $pp \to \nu\bar{\nu} + X$ are from 2403.17063

- best bound on $\mathcal{K}_R^{cu\mu\mu}$ for dimuons from LHCb

Dineutrino vs lepton specific limits



energy enhanced by $\hat{s}/\Lambda_{NP}^2$ relative to SM p_T-distribution, analytically shown in 2403.17063 , also for gluon dipole operators

Upper limits $\mathcal{B}^{\text{max}}(h_c \to F\nu\bar{\nu})$ depend on lepton flavor structure (LFV,cLFC,LFU) 2010.02225

$h_c \to F$	$\mathcal{B}^{\text{max}}_{\text{LU}}$ $[10^{-7}]$	$\mathcal{B}^{\text{max}}_{\text{cLFC}}$ $[10^{-6}]$	$\mathcal{B}^{\text{max}}$ $[10^{-6}]$	$N^{\text{max}}_{\text{LU}}/\eta_{\text{eff}}$	$N^{\text{max}}_{\text{cLFC}}/\eta_{\text{eff}}$	$N^{\text{max}}/\eta_{\text{eff}}$
$D^0 \to \pi^0$	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)

to date only a single limit exists: $B(D^0 \to \pi^0\nu\bar{\nu}) < 2.1 \cdot 10^{-4}$ BESIII 2112.14236

ULs for Belle II w $50\,\text{ab}^{-1}$ (FCC-ee@Z w $N(c\bar{c}) = 550 \cdot 10^9$) via SMEFT and dilepton data 2010.02225

Rare decays of charm baryons $\Lambda_c, \Xi_c, \Omega_c$

theory and observables: 2107.13010, 2202.02331 highlights for BSM searches: GIM $(C_{10}^{\text{SM}} = 0)$, angular distributions, CP, cLFV, LFU

Differential angular distribution for unpolarized $\Lambda_c \to p\mu\mu$, (polarized Λ_c in 2202.02331) reads:

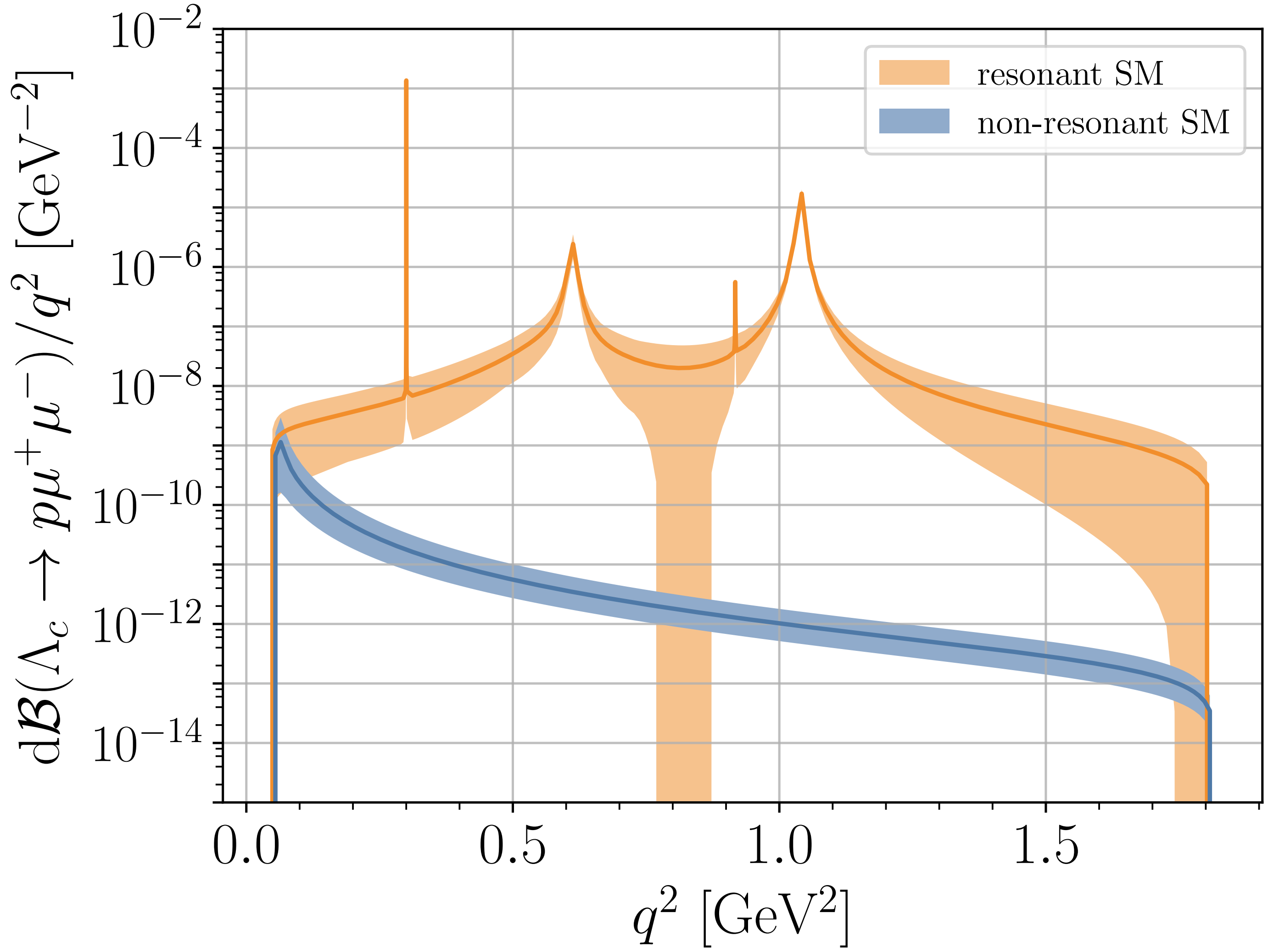
$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\vartheta_\ell} = \frac{3}{2}\left(K_{1ss}\sin^2\vartheta_\ell + K_{1cc}\cos^2\vartheta_\ell + K_{1c}\cos\vartheta_\ell\right)$$

$\to$ 3 observables: branching ratio $(-)$, longitudinal pol. fraction F_L $(+)$, Forward-Backward asymmetry $A_{\text{FB}}^\ell \propto K_{1c} \propto C_{10}$. $(++)$

$\Lambda_c \to p$ form factors from lattice 1712.05783 – $SU(3)_F$-relations to other baryonic decays 2203.14982

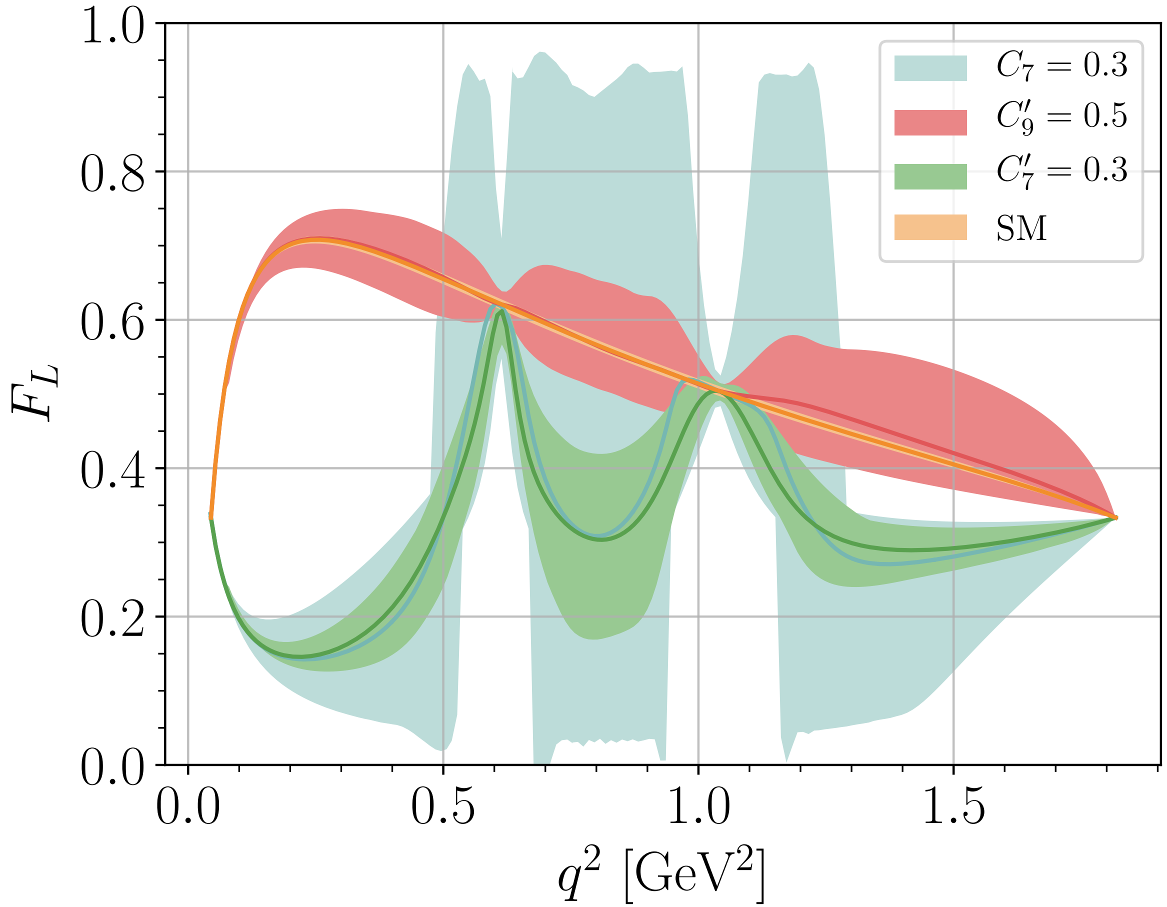
$-\sqrt{6}h_\perp^{\Xi_c^0\to\Lambda} = \sqrt{2}h_\perp^{\Xi_c^0\to\Sigma^0} = h_\perp^{\Xi_c^+\to\Sigma^+} = h_\perp^{\Lambda_c\to p}$; Endpoint relations (at q^2 =max): 2107.12993

Branching ratio: $(-)$



2107.13010

Longitudinal polarization: $(+)$



2107.13010

Sensitivity to dipole coefficients! $F_L(4m_\ell^2) = F_L(q^2_{max}) = 1/3$

GIM null tests: AFB $(++)$

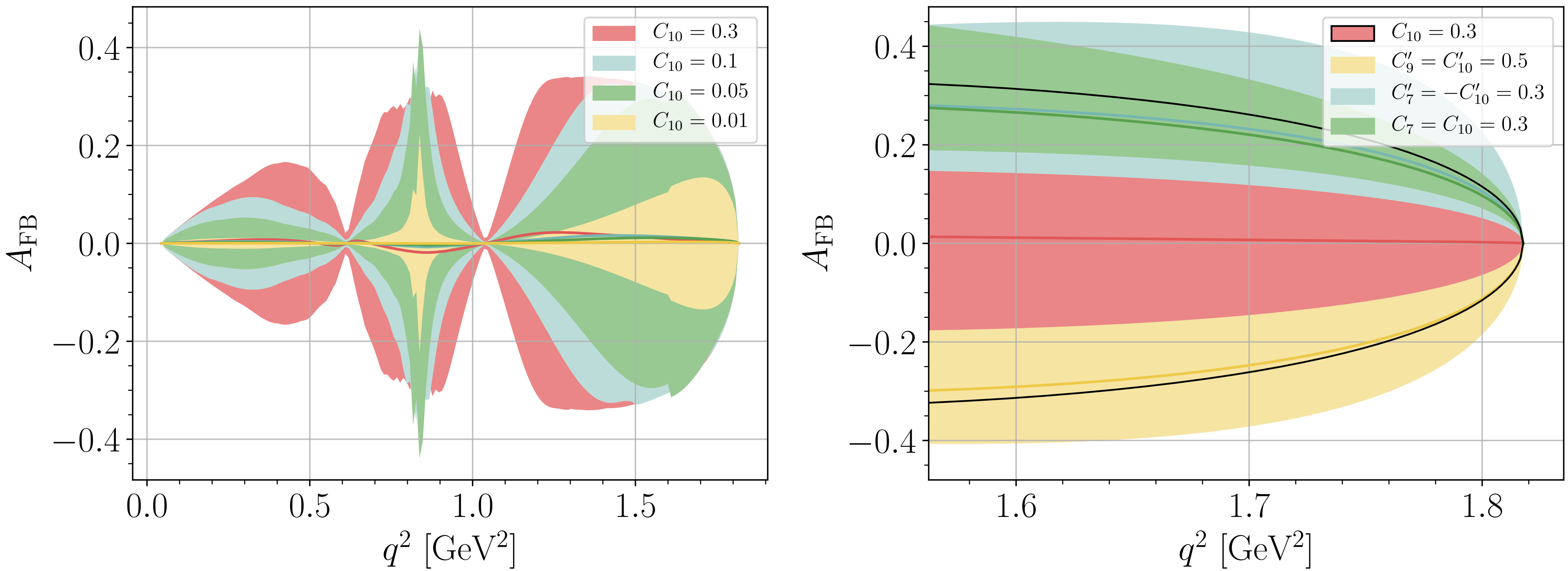


Figure 3: The forward-backward asymmetry $A_{\rm FB}$ of $\Lambda_c \to p\mu^+\mu^-$ decays for different values of C_{10} in the full q^2-region (left panel) and for various BSM contributions in the high q^2 region (right panel)

$A_{\rm FB} \propto C_{10}$ clean null test of SM (GIM); Three more GIM-based null tests in 4-body decays

$\Xi_c^+ \to \Sigma^+ (\to p\pi^0)\ell^+\ell^-$, $\Xi_c^0 \to \Lambda^0 (\to p\pi^-)\ell^+\ell^-$, $\Omega_c^0 \to \Xi^0 (\to \Lambda^0\pi^0)\ell^+\ell^-$, 2202.02331

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

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

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

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

$$I_6 = \frac{1}{2}\left[\int_0^1 d\cos\vartheta_l - \int_{-1}^0 d\cos\vartheta_l\right] \frac{d^4\Gamma}{dq^2\, dp^2\, d\cos\vartheta_{P_1}\, d\cos\vartheta_l} \,. \tag{3}$$

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

$$I_5 = \left[\int_{-\pi/2}^{\pi/2} d\varphi - \int_{\pi/2}^{3\pi/2} d\varphi\right] \frac{d^4\Gamma}{dq^2\, dp^2\, d\cos\vartheta_{P_1}\, d\varphi} \,, \tag{5}$$

$$I_8 = \frac{3\pi}{8}\left[\int_0^\pi d\varphi - \int_\pi^{2\pi} d\varphi\right]\left[\int_0^1 d\cos\vartheta_l - \int_{-1}^0 d\cos\vartheta_l\right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\cos\vartheta_{P_1}\, d\cos\vartheta_l\, d\varphi} \,, \tag{6}$$

$$I_9 = \frac{3\pi}{8}\left[\int_0^{\pi/2} d\varphi - \int_{\pi/2}^{\pi} d\varphi + \int_\pi^{3\pi/2} d\varphi - \int_{3\pi/2}^{2\pi} d\varphi\right] \frac{d^4\Gamma}{dq^2\, dp^2\, d\cos\vartheta_{P_1}\, d\varphi} \,. \tag{7}$$

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

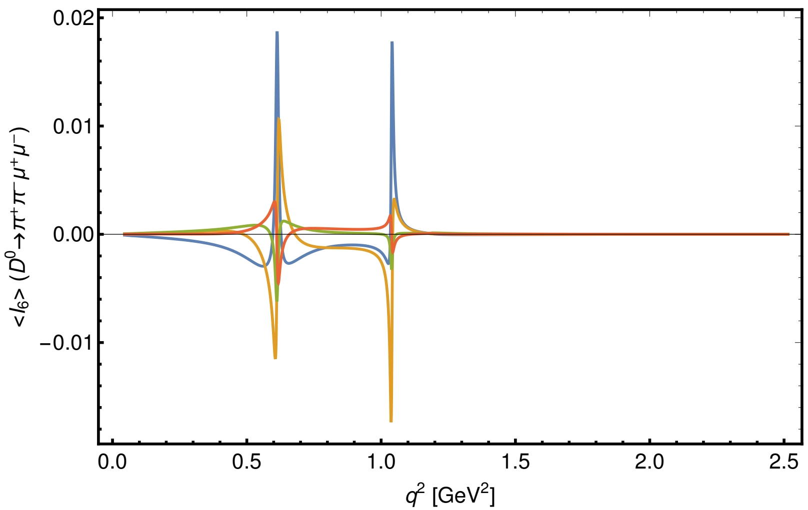
L, R: lepton current handedness, H_k: transversity amplitudes

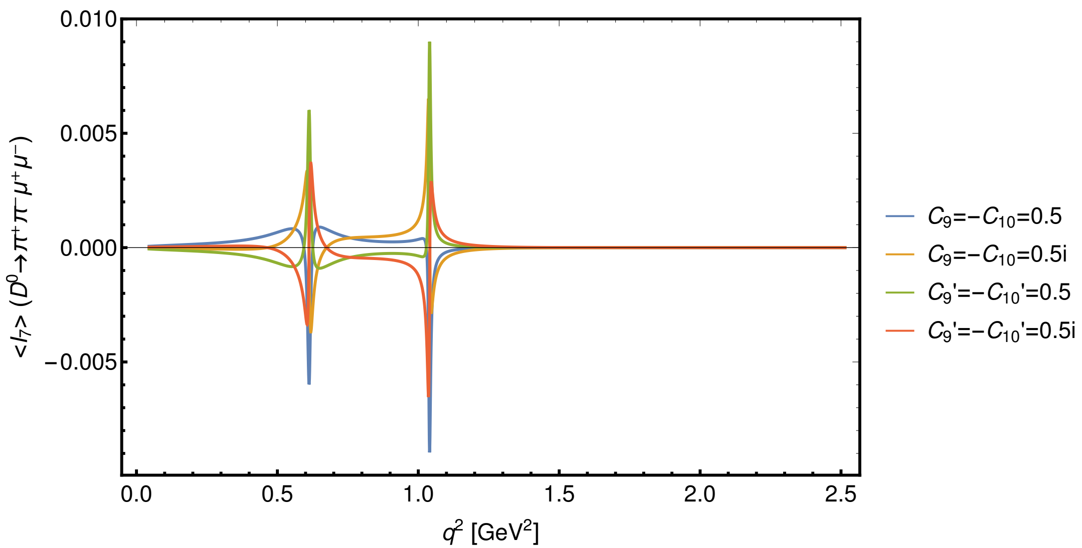
$$
\begin{aligned}
I_1 &= \frac{1}{16}\left[|H_0^L|^2 + (L \to R) + \frac{3}{2}\sin^2\vartheta_{P_1}\{|H_\perp^L|^2 + |H_\parallel^L|^2 + (L \to R)\}\right], \\
I_2 &= -\frac{1}{16}\left[|H_0^L|^2 + (L \to R) - \frac{1}{2}\sin^2\vartheta_{P_1}\{|H_\perp^L|^2 + |H_\parallel^L|^2 + (L \to R)\}\right],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

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

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





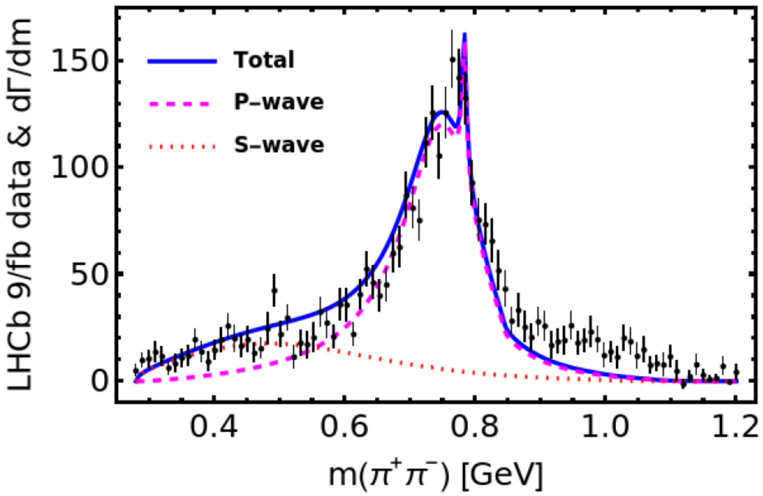
Largest BSM effects from interference with SM; peaks at ρ/ω and Φ.

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

Angular asymmetries already measured by LHCb 2111.03327, Null tests close to BSM sensitivity

Fit to spectra from 2312.07501, S-wave resonance contribution

$\sigma \to \pi\pi$



A Puzzle in hadronic charm CPX/UX

$\Delta A_{CP} = A_{CP}(D \to K^+K^-) - A_{CP}(D \to \pi^+\pi^-)$ from $A_{CP}(\pi^+\pi^-)$?

CP & U-Spin puzzle 2207.08539, 2210.16330 two approx symmetries challenged

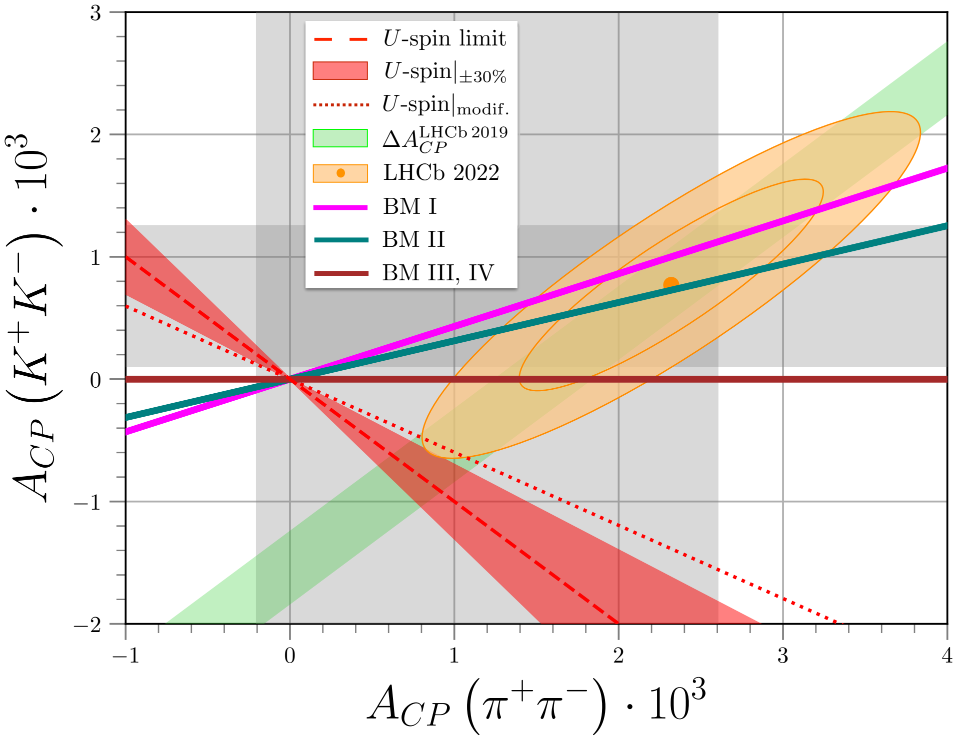


Fig from 2210.16330, LHCb result (orange ellipse) from 2209.03179 SM theory recently 2305.11951, 2312.13245

A Puzzle in hadronic charm CPX/UX

CP violation suppressed in charm
t predominantly tree, h: higher order: loops, FSI, rescattering

$$A = A(D^0 \to \pi^+\pi^-)^{\text{SM}} = \Sigma\, t + V_{cb}^* V_{ub} h e^{i\delta} \,,$$
$$\bar{A} = A(\bar{D}^0 \to \pi^+\pi^-)^{\text{SM}} = \Sigma^* t + V_{cb} V_{ub}^* h e^{i\delta} \,,$$

where $\Sigma = (V_{cd}^* V_{ud} - V_{cs}^* V_{us})/2$ and $V_{cs}^* V_{us} \simeq -V_{cd}^* V_{ud} \gg V_{cb}^* V_{ub}$.

$$A_{\text{CP SM}}^{\pi^-\pi^+} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \simeq 2 \cdot \text{Im}\Big(\frac{V_{cb}^* V_{ub}}{V_{cd}^* V_{ud}}\Big) \frac{h}{t} \sin\delta \simeq 1.2 \cdot 10^{-3} \frac{h}{t} \sin\delta$$

Data $A_{\text{CP}}^{\pi^-\pi^+} = (23.2 \pm 6.1) \cdot 10^{-4}$ implies $h/t \sin\delta \sim 2$

SM: FSI-interactions (Pich, Solomonidi, Silva) 2305.11951: $h/t \sin\delta \lesssim 0.2$, however 2203.04056 (Bediaga et al) , 1706.07780

(Khodjamirian, Petrov) $h/t \sin\delta \lesssim 0.1$. LCSR (Lenz, Piscopo et al) 2312.13245 $h/t \sin\delta \lesssim 0.1$.

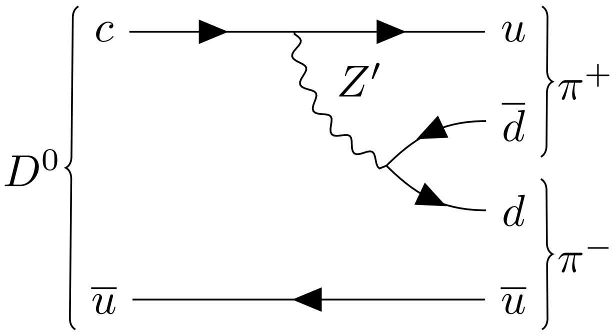
We need the U-spin breaking on top.

A light Z' in hadronic charm CPX/UX

Is large $A_{\rm CP}^{\pi^-\pi^+} = (23.2 \pm 6.1) \cdot 10^{-4}$ and $A_{\rm CP}^{K^-K^+}$ SM-like even explainable?

Single solution known 2210.16330 break U-spin explicitly, couple to charm, only $SU(2)_L$-singlets to avoid Kaons, anomaly-free $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$

Model	F_{Q_i}			F_{u_i}			F_{d_i}			F_{L_i}			F_{e_i}			F_{ν_i}		
BM I	0	0	0	9	-16	7	20	-11	-9	15	-6	-9	-16	0	16	6	12	-18
BM II	0	0	0	-19	9	10	20	-8	-12	4	1	-5	15	2	-17	8	2	-10
BM III	0	0	0	G	-F	0	F	-G	0	0	0	0	0	-G	F	0	G	-F
BM IV	0	0	0	-F_u	F_u	0	F_d	0	-F_d	0	0	0	F_e	0	-F_e	F_ν	-F_ν	0



A light Z' in hadronic charm CPX/UX

To avoid the constraints from $D-\bar{D}$-mixing, the $\bar{u}_R\gamma_\mu c_R$ coupling has to be small. To still get the effect in 4-quark operators $\sim \bar{u}_R\gamma_\mu c_R \bar{d}_R \gamma^\mu d_R$ the Z' has be light.

Sub 20 GeV Z' (CMS ISR constraints), leptophob (LHCb $A \to \mu\mu$ search), BM I,II dead, BM III $F \gg G$, BM IV $F_e \ll F_d$

Model	F_{Q_i}			F_{u_i}			F_{d_i}			F_{L_i}			F_{e_i}			F_{ν_i}		
BM III	0	0	0	G	-F	0	F	-G	0	0	0	0	0	-G	F	0	G	-F
BM IV	0	0	0	-F_u	F_u	0	F_d	0	-F_d	0	0	0	F_e	0	-F_e	F_ν	-F_ν	0

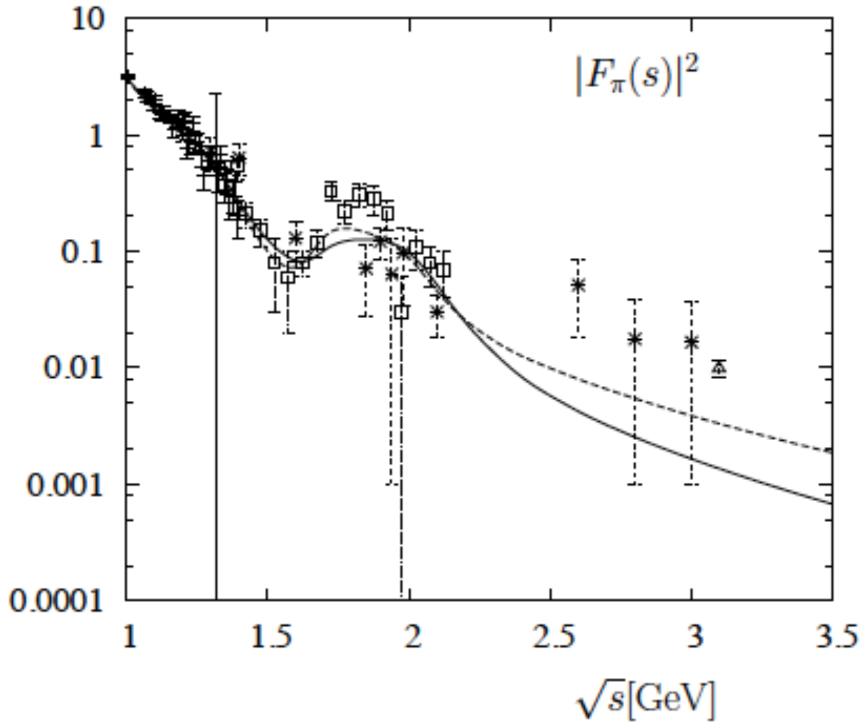
Signatures in low mass dijets, $J/\Psi/\Psi'$, Υ decays, $A_{CP}(D\to\pi^0\pi^0), A_{CP}(D\to\pi^+\pi^0) \sim A_{CP}(D\to\pi^+\pi^-)$.

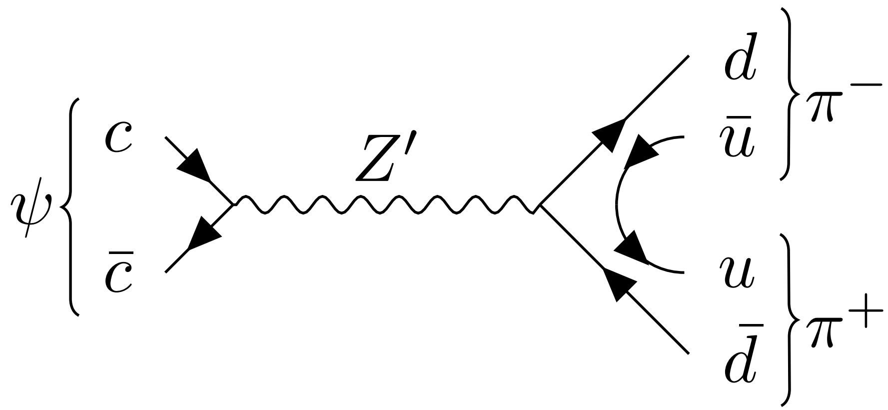
A light Z' in hadronic charm CPX/UX

Model	light quarks	b	c	e	μ	τ	ν_R
BM III$\|_{M_{Z'}=2.5\,\mathrm{GeV}}$	75	0	0	0	0	0	25
BM III$\|_{M_{Z'}=15\,\mathrm{GeV}}$	38	0	37	0	0	12	13
BM III-s$\|_{M_{Z'}=2.5\,\mathrm{GeV}}$	86	0	0	0	0	0	14
BM III-s$\|_{M_{Z'}=15\,\mathrm{GeV}}$	75	0	0	0	0	12	13
BM IV$\|_{M_{Z'}=5\,\mathrm{GeV}}$	79	0	21	0	0	0	0
BM IV$\|_{M_{Z'}=15\,\mathrm{GeV}}$	54	28	18	0	0	0	0

Table 3: Tree-level branching fractions in % for the different Z' decay modes to fermion-antifermion pairs. Results for BM III and BM III-s are given in the limit $G \ll F$. In BM IV, branching ratios depend on the different charge assignments $F_{u,d,e,\nu}$, see main text for details. The branching ratios shown in this table are obtained from $F_u = 985$, $F_d = 1393$, $F_e = 1$ and $F_\nu = 0$. Branching ratios in all BMs differ perceptibly between the low and high $M_{Z'}$ windows, as the decays $Z' \to b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$ are kinematically forbidden or suppressed in the few GeV range. Corrections to branching ratios from kinetic mixing are generically $\lesssim 10^{-7}$.

What else can the hadrophilic light Z' do for you?





plot from hep-ph/0409080, discrepancy of pion form factor (from $ee \to \pi\pi$-scattering plus theory) with $Br(J/\psi \to \pi^+\pi^-)$ (triangle).

Simultaneous explanation with charm CP data in BM III for $M_{Z'} \sim 3$ GeV, BM IV for $M_{Z'} \sim (5-6)$ GeV 2210.16330

Summary

- Rare charm decays can test the SM and signal new physics using null tests of the SM
- Very little experimentally explored in rare charm decays – lots of blanks in PDG, but plenty of recent progress.
- BSM effects in $|\Delta c| = |\Delta u| = 1$ can be large.
- U-spin/CP puzzle hints at combined breaking of SM symmetries. Possible connection with other low energy puzzles.
- Complementary search to K,B-decays.
- Plenty of Terra Incognita in flavor phenomenology — explore synergies

”charm is the new beauty”

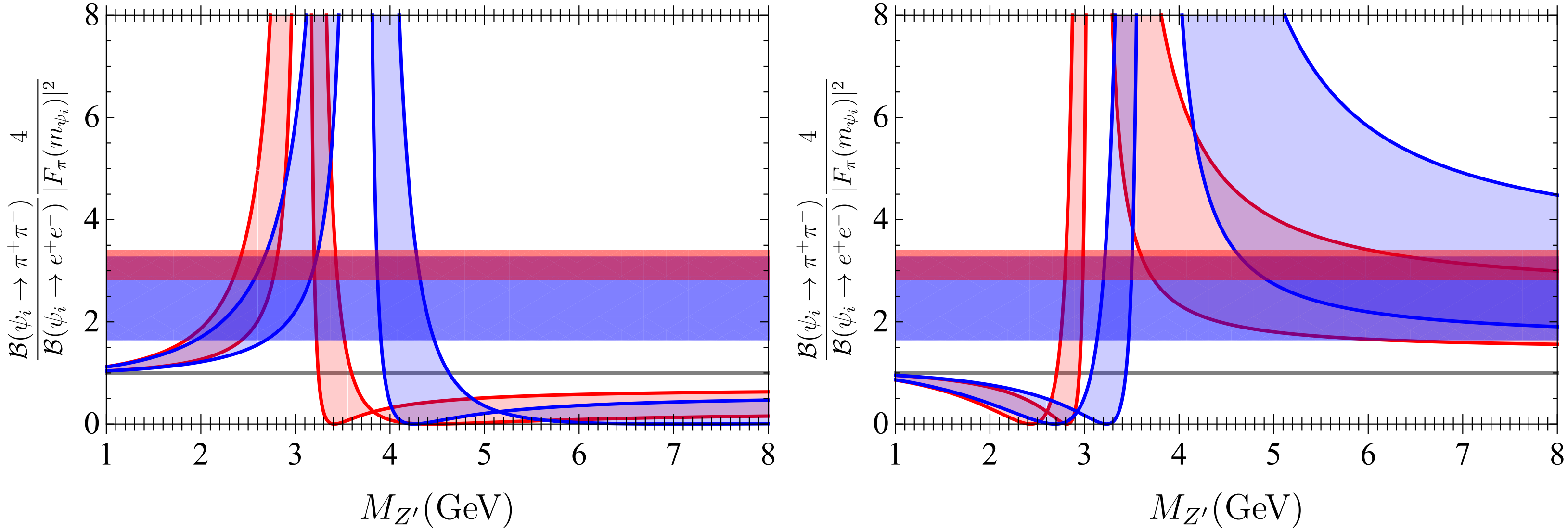


Figure 4: Constraints from charmonium decays. Horizontal red (blue) bands denote the left-hand side of (**??**) from 1 sigma ranges of J/ψ-data with $|F_\pi(m_{J/\psi})| = 0.056$ (ψ' decays with $|F_\pi(m_{\psi'})| = 0.04$.). Curves correspond to the predictions of BM III with $F \gg G$ (left) and BM IV (right). The SM prediction via photon-exchange is shown by the grey line.