

BSM probes with charm



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Testing the Standard Model with $|\Delta c| = |\Delta u| = 1$ FCNCs of mesons and baryons:

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

Probe different 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, ...

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, $SU(3)_F$**

Advantages charm (vs beauty):

i) GIM-suppression very efficient: $C_\nu^{\text{SM}} = C_{10}^{\text{SM}} = 0$

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

ii) $SU(3)_F$ partner modes - related SM-like and NP-sensitive 4-fermion operators exist.

charm: $ucqq$ (FCNC) vs $uscd$ (SM); not in beauty: second light up-type quark missing.

More pheno-tricks from state-of-the-art b -physics studies come in handy: angular distributions.

resonant and multi-bodies, mesons and baryons,.. $P_{1,2,3} = \pi, K$

radiative $c \rightarrow u\gamma$: $D \rightarrow V\gamma, V = \rho, \dots, D \rightarrow P_1 P_2 \gamma,$
 $D \rightarrow A\gamma, A = K_1, \dots, D \rightarrow P_1 P_2 P_3 \gamma,$
 $\Lambda_c \rightarrow p\gamma, \Xi_c^0 \rightarrow \Lambda(\rightarrow p\pi)\gamma, \dots$

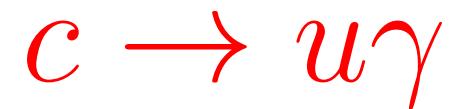
semileptonic $c \rightarrow u\ell\ell^{(\prime)}$: $D \rightarrow \pi\mu\mu, D \rightarrow \mu\mu, D \rightarrow P_1 P_2 \ell\ell,$
 $\Lambda_c \rightarrow p\ell\ell, \Xi_c^0 \rightarrow \Lambda(\rightarrow p\pi^-)\ell\ell, \dots$

dineutrinos/MET/ALPs $c \rightarrow u\nu\bar{\nu}$: $D \rightarrow \pi\nu\bar{\nu}, D \rightarrow \nu\bar{\nu}, D \rightarrow P_1 P_2 \nu\bar{\nu},$
 $\Lambda_c \rightarrow p\nu\bar{\nu}, \Xi_c^0 \rightarrow \Lambda(\rightarrow p\pi^-)\nu\bar{\nu}, \dots$

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

semileptonic $c \rightarrow u\ell\ell^{(\prime)}$: $D \rightarrow \pi\mu\mu, D \rightarrow \mu\mu, D \rightarrow P_1 P_2 \ell\ell,$
 $\Lambda_c \rightarrow p\ell\ell, \Xi_c^0 \rightarrow \Lambda(\rightarrow p\pi^-)\ell\ell, \dots B(D \rightarrow \pi\pi\mu\mu) \simeq 9.6 \cdot 10^{-7}$ **LHCb'18**,
 $B(\Lambda_c \rightarrow p\mu\mu) \lesssim 7.7 \cdot 10^{-8}$ **LHCb'17**, [$D \rightarrow \pi\mu\mu, D \rightarrow \mu\mu$ upper limits]

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



NP in $\Delta c = \Delta u = 1$ dipole operators $O_7 = \bar{u}_L \sigma_{\mu\nu} c_R F^{\mu\nu}, O'_7 = \bar{u}_R \sigma_{\mu\nu} c_L F^{\mu\nu}$

Tree-level W -exchange, RG and μ_b -matching [1707.00988](#): $C_7^{\text{eff SM}} \lesssim 0.01$

Need ways to control SM resonance BGD.

Recent data-driven proposals:

A) use charm as test lab for QCD frameworks

e.g. A_{FB} in $D \rightarrow PP\gamma$ modes [2009.14212](#), [2104.08287](#)

B) use plethora of modes available to charm and extract A_{SM} from SM-like modes; **nulltest = correlation**

Observables: branching ratios, CPA's and those sensitive to the photon polarization λ_γ :

Time-dependent CP asymmetries (TDCPAs), up-down asymmetries

Rare radiative decays of Λ_c , Ξ_c , Ω_c

theory and observables: 2203.14982 SU(3)-F techniques

Decay	U-Spin	$SU(3)_F$	$SU(3)_F$ IRA
$\Lambda_c \rightarrow \Sigma^+ \gamma$	$V_{cs}^* V_{ud} A_\Sigma$	$V_{cs}^* V_{ud} \textcolor{red}{B}_\Sigma$	$V_{cs}^* V_{ud} D$
$\Xi_c^0 \rightarrow \Xi^0 \gamma$	$V_{cs}^* V_{ud} A'_\Sigma$	$V_{cs}^* V_{ud} B'_\Sigma$	$V_{cs}^* V_{ud} D'$
$\Lambda_c \rightarrow p \gamma$	$-\Sigma A_\Sigma + \Delta A_\Delta + A_7$	$\Sigma \textcolor{red}{B}_\Sigma - \Delta B_\Delta + \textcolor{blue}{B}_7$	$\Sigma D - \Delta \tilde{b}_4 + D_7$
$\Xi_c^+ \rightarrow \Sigma^+ \gamma$	$\Sigma A_\Sigma + \Delta A_\Delta + A_7$	$-\Sigma \textcolor{red}{B}_\Sigma - \Delta B_\Delta + \textcolor{blue}{B}_7$	$\Sigma D + \Delta \tilde{b}_4 - D_7$
$\Xi_c^0 \rightarrow \Lambda \gamma$	$-\sqrt{\frac{3}{2}} \Sigma A'_\Sigma - \frac{1}{2} (\Delta A'_\Delta + A'_7)$	$\sqrt{\frac{3}{2}} \Sigma B'_\Sigma + \sqrt{\frac{3}{2}} \Delta B_\Delta + \frac{1}{\sqrt{6}} B_7$	$-\sqrt{\frac{3}{2}} \Sigma D' + \sqrt{\frac{3}{2}} \Delta \tilde{b}_4 + \frac{1}{\sqrt{6}} D_7$
$\Xi_c^0 \rightarrow \Sigma^0 \gamma$	$-\frac{1}{\sqrt{2}} \Sigma A'_\Sigma + \frac{\sqrt{3}}{2} (\Delta A'_\Delta + A'_7)$	$-\frac{1}{\sqrt{2}} \Sigma B'_\Sigma + \frac{3}{\sqrt{2}} \Delta B_\Delta + \sqrt{\frac{1}{2}} B_7$	$\frac{1}{\sqrt{2}} \Sigma D' + \frac{3}{\sqrt{2}} \Delta \tilde{b}_4 + \frac{1}{\sqrt{2}} D_7$
$\Xi_c^+ \rightarrow p \gamma$	$V_{cd}^* V_{us} A_\Sigma$	$V_{cd}^* V_{us} B_\Sigma$	$V_{cd}^* V_{us} D$
$\Xi_c^0 \rightarrow n \gamma$	$-V_{cd}^* V_{us} A'_\Sigma$	$V_{cd}^* V_{us} B'_\Sigma$	$-V_{cd}^* V_{us} D'$

Table 1: Flavor symmetry relations of charmed anti-triplet baryons. $A_\Sigma^{(')}$ and $A_\Delta^{(')}$ refer to the U-spin triplet and singlet SM contributions of the W-exchange diagrams. $A_7^{(')} = A_{\text{NP}}^{(')} + A_{\text{LD}}^{(')}$ denote the $c \rightarrow u \gamma$ short distance and long distance contributions with intermediate vector resonances. $\Sigma = \frac{V_{cs}^* V_{us} - V_{cd}^* V_{ud}}{2}$, $\Delta = \frac{V_{cs}^* V_{us} + V_{cd}^* V_{ud}}{2} = -\frac{V_{cb}^* V_{ub}}{2}$. Top: CF, SM-like decays, Middle: SCS, NP-sensitive, Bottom: DCS, SM-like decays Relations for charm sextett-decays ($\Omega_c \rightarrow \Lambda, \Sigma^0, \Xi^0$) also in 2203.14982.

Extract B_Σ from SM-decay $\Lambda_c \rightarrow \Sigma^+ \gamma$ and use to predict SM value of SCS-decay ($\Lambda_c \rightarrow p \gamma, \Xi_c^+ \rightarrow \Sigma^+ \gamma$); probe NP in B_7 amplitude

Rare radiative decays of Λ_c , Ξ_c , Ω_c

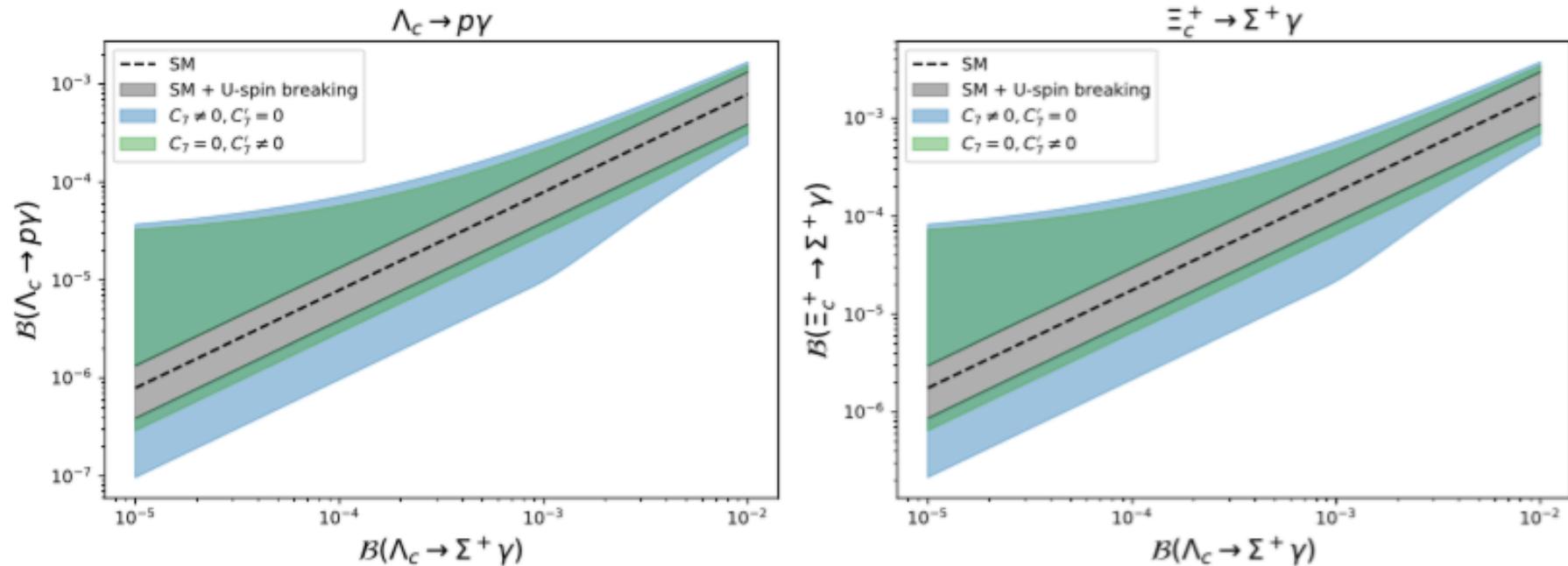
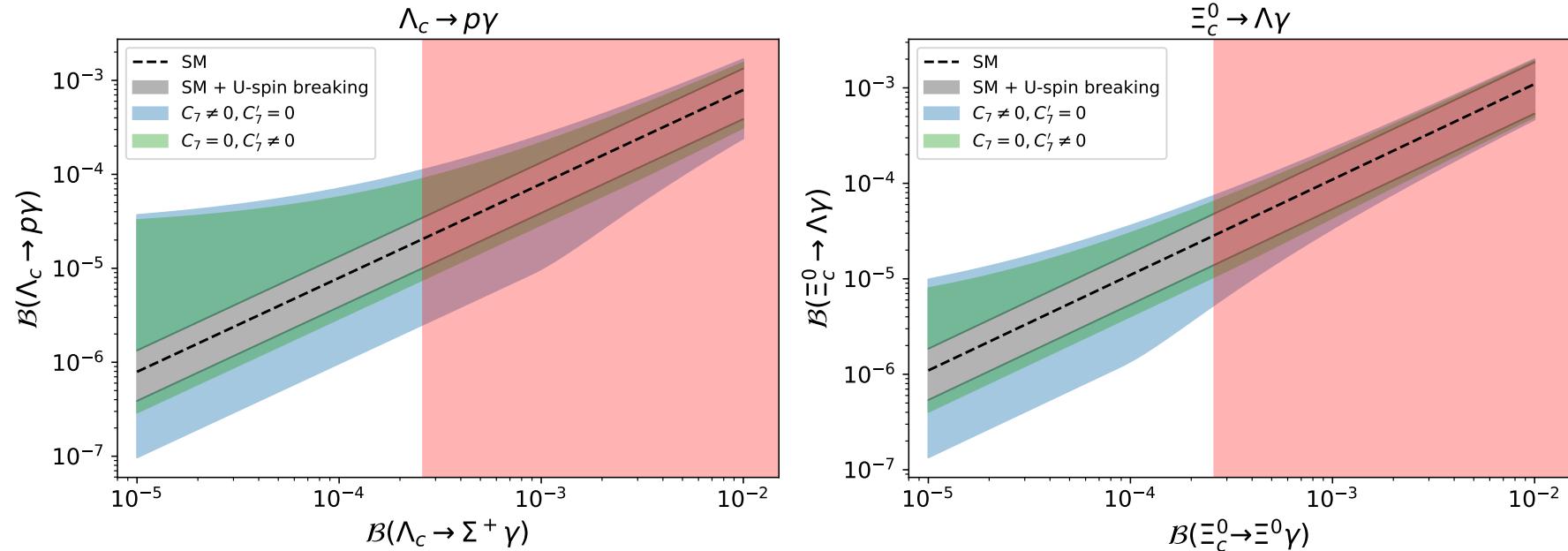


Figure 1: NP effects in the branching ratios of the BSM sensitive decay modes as a function of the branching ratios of the SM-like decay modes, for $\lambda_\gamma^{\text{CF}} = -0.5$. The black dashed line denotes the SM in the U-spin limit. The gray shaded area shows $\pm 30\%$ U-spin breaking in $A_{L/R}^{\text{SM}}$. The blue (green) region illustrates the BSM reach in C_7 (C'_7). We set $C'_7 = 0$ ($C_7 = 0$) and varied the other coefficient within $-0.3 \leq C_7^{(')} \leq 0.3$. The BSM regions also include the $\pm 30\%$ U-spin breaking of the SM amplitudes. **Cabibbo-favored modes:** $B(\Lambda_c \rightarrow \Sigma\gamma) < 2.6 \cdot 10^{-4}$, Belle 2206.12517, that is $B(\Lambda_c \rightarrow p\gamma) \lesssim 10^{-4}$,

Rare radiative decays of $\Lambda_c, \Xi_c, \Omega_c$



Theory 2203.14982 plus Belle exclusion (red areas) 2206.12517:

$B(\Lambda_c \rightarrow \Sigma\gamma) < 2.6 \cdot 10^{-4}$ predicts $B(\Lambda_c \rightarrow p\gamma) \lesssim 10^{-4}$

$B(\Xi_c^0 \rightarrow \Xi^0\gamma) < 1.8 \cdot 10^{-4}$ predicts $B(\Xi_c^0 \rightarrow \Lambda\gamma) \lesssim 7 \cdot 10^{-5}$

Beyond branching ratios: Rare rad. Λ_c , Ξ_c , Ω_c decays

Probing photon polarization 2203.14982

P_{B_c} : polarization of charm baryon, α_B : weak decay parameter of secondary decays ($\alpha_B = 0$ for strong decays)

The full angular distribution $B_c \rightarrow B_1(\rightarrow B_2\pi)\gamma$:

$$\frac{d^2\mathcal{B}}{d\cos(\vartheta_\gamma)d\cos(\vartheta_B)} \propto [1 + P_{B_c}\alpha_B \cos(\vartheta_\gamma) \cos(\vartheta_B) + \alpha_B \lambda_\gamma \cos(\vartheta_B) + P_{B_c} \lambda_\gamma \cos(\vartheta_\gamma)] . \quad (1)$$

The polarization asymmetries:

$$A_{FB}^\gamma = \frac{1}{\mathcal{B}} \left(\int_0^1 d\cos(\vartheta_\gamma) \frac{d\mathcal{B}}{d\cos(\vartheta_\gamma)} - \int_{-1}^0 d\cos(\vartheta_\gamma) \frac{d\mathcal{B}}{d\cos(\vartheta_\gamma)} \right) = \frac{P_{B_c} \lambda_\gamma}{2} . \quad (2)$$

$$A_{FB}^B = \frac{1}{\mathcal{B}} \left(\int_0^1 d\cos(\vartheta_B) \frac{d\mathcal{B}}{d\cos(\vartheta_B)} - \int_{-1}^0 d\cos(\vartheta_B) \frac{d\mathcal{B}}{d\cos(\vartheta_B)} \right) = \frac{\alpha_B \lambda_\gamma}{2} . \quad (3)$$

extract λ_γ^{SM} from Cabibbo-favored partner mode

Beyond branching ratios: Rare rad. Λ_c , Ξ_c , Ω_c decays

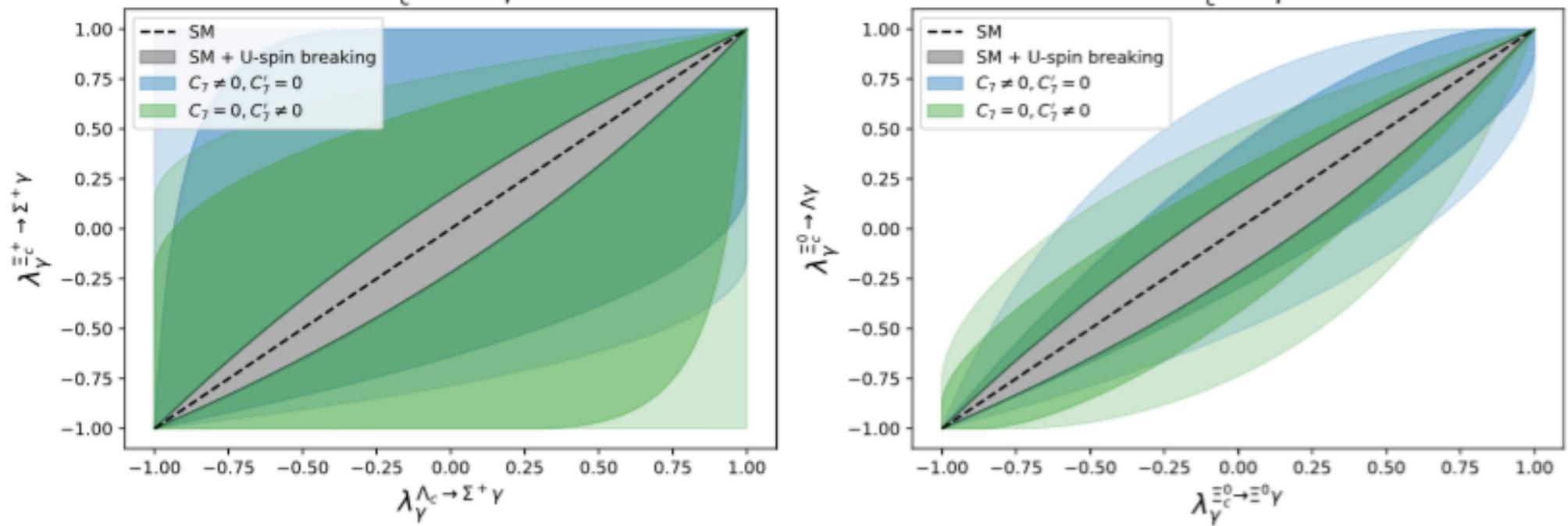


Figure 2: BSM reach of λ_γ of BSM modes $\Xi_c^+ \rightarrow \Sigma^+ \gamma$ (left) and $\Xi_c^0 \rightarrow \Lambda \gamma$ (right) versus photon polarization of SM-like modes, $\Lambda_c \rightarrow \Sigma^+ \gamma$ and $\Xi_c^0 \rightarrow \Xi^0 \gamma$, respectively, for $B^{\text{CF}} = 5 \cdot 10^{-4}$. The black dashed line denotes the SM in the U-spin limit. The gray shaded area shows $\pm 20\%$ U-spin breaking between $r_{\text{SM}}^{\text{CF}}$ and $r_{\text{SM}}^{\text{SCS}}$. The blue (green) region illustrates the BSM reach in C_7 (C'_7). We set $C'_7 = 0$ ($C_7 = 0$) and varied the other coefficient within $-0.3 \leq C_7^{(')} \leq 0.3$. For the darker shaded area we used the SM amplitudes in the exact U-spin limit. For the lighter shaded area we additionally considered $\pm 30\%$ U-spin breaking in $F_{L/R}^{\text{SM}}$, while keeping the U-spin breaking of the ratio $r_{\text{SM}}^{\text{SCS}}$ limited to $\pm 20\%$.

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

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

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

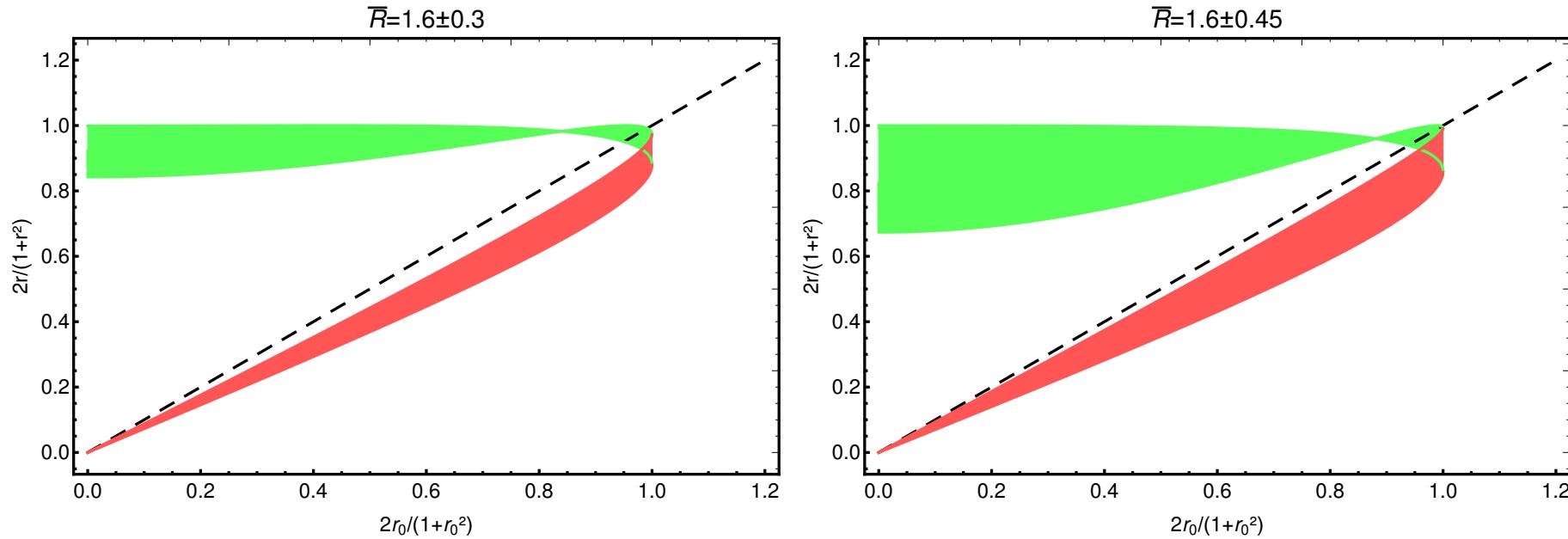
$$A^\Delta(D^0 \rightarrow \bar{K}^{*0}\gamma) \simeq \frac{4\xi_{\bar{K}^{*0}} \left| \frac{q}{p} \right| \cos \varphi}{\left(1 + \left| \frac{q}{p} \right|^2 \right)} \frac{r_0}{1+r_0^2} \text{ Here, } r_0 \text{ is ratio of wrong-chirality}$$

(RH) to LH-photons in SM-like process $D^0 \rightarrow \bar{K}^{*0}\gamma$.

Up to $SU(3)$ -breaking: $r(D^0 \rightarrow \Phi\gamma) = r_0, \quad r(D^0 \rightarrow \rho\gamma) = r_0$;
perturbative $r = C'_7/C_7$, in SUSY, r unconstrained.

Br's	$D^0 \rightarrow \rho^0\gamma$	$D^0 \rightarrow \omega\gamma$	$D^0 \rightarrow \Phi\gamma$	$D^0 \rightarrow \bar{K}^{*0}\gamma$ (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 $c \rightarrow u\gamma$ 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).

$$\bar{R} = 1/f^2 \frac{|V_{cs}|^2}{|V_{cd}|^2} \frac{\mathcal{B}(D^0 \rightarrow \rho\gamma)}{\mathcal{B}(D^0 \rightarrow \bar{K}^{*0}\gamma)}$$

with leading U-spin breaking removed $f = m_\rho f_\rho / (m_{K^{*0}} f_{K^{*0}})$

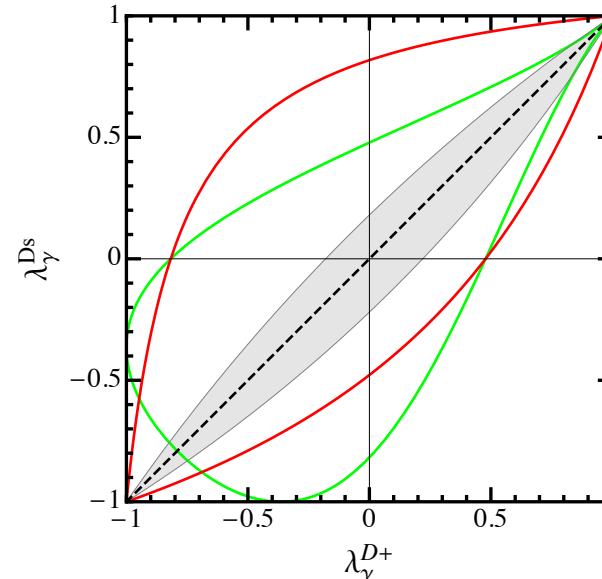
Photon polarization from up-down asymmetry

Method 2: probe the photon polarization with an up-down asymmetry in $D^+ \rightarrow K_1^+(\rightarrow K\pi\pi)\gamma$ (a la $B \rightarrow K_1\gamma$ 1812.04679 , and (Gronau, Pirjol,

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

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

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

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

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

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

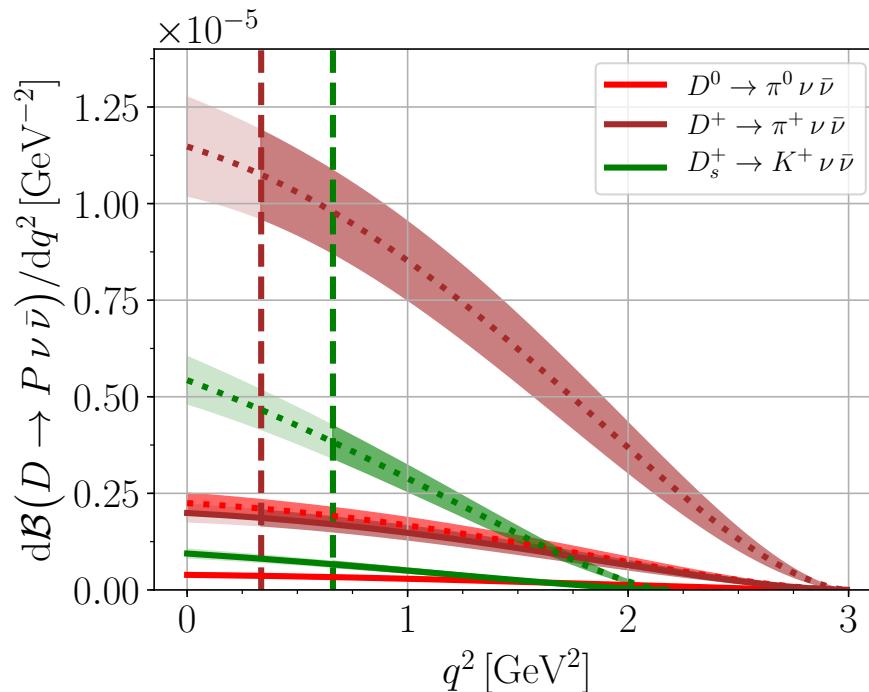


Figure 3: Differential branching ratios for $D^0 \rightarrow \pi^0 \nu\bar{\nu}$, $D^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $D_s^+ \rightarrow K^+ \nu\bar{\nu}$ in red, brown and green, respectively for the LU (cLFC) limit in solid (dotted) lines. **this plot shows BSM distributions** The uncertainty bands are due to the form factors, τ background removable by q^2 -cut (vertical dashed lines)

from 2010.02225

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

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

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

ULs via SMEFT from charged lepton data 2010.02225

Cross checking: $D \rightarrow \text{nothing}$

$\mathcal{B}(D^0 \rightarrow \text{inv.}) < 9.4 \cdot 10^{-5}$, at 90 % CL. (Belle '16). Consistency check; constrains operators with light right-handed neutrinos

$$Q_{LR}^{ij} = (\bar{u}_L \gamma_\mu c_L) (\bar{\nu}_{jR} \gamma^\mu \nu_{iR}), \quad Q_{RR}^{ij} = (\bar{u}_R \gamma_\mu c_R) (\bar{\nu}_{jR} \gamma^\mu \nu_{iR}),$$
$$Q_{S(P)}^{ij} = (\bar{u}_L c_R) (\bar{\nu}_j (\gamma_5) \nu_i), \quad Q_{T(T5)}^{ij} = \frac{1}{2} (\bar{u} \sigma_{\mu\nu} c) (\bar{\nu}_j \sigma^{\mu\nu} (\gamma_5) \nu_i),$$

$Q_{S(P)}^{ij}$ would have effect less than $\sim 10\%$ of LU upper limits iff improved limit exists [2010.02225](#)

$$\mathcal{B}(D^0 \rightarrow \text{inv.})^{\text{hypothetical}} \lesssim 2 \cdot 10^{-6}. \quad (4)$$

would reinforce EFT framework "NP is heavy".

$D \rightarrow \text{nothing}$ constrains LNV $\Delta L = 2$ interactions $\mathcal{O}_{4a}^{(7)} = L_i^\alpha L_j^\beta \bar{Q}_\alpha^b \bar{U}_a^c H^\rho \epsilon_{\beta\rho}$, [de Gouvea](#)

Existing Belle limit on $D \rightarrow \text{nothing}$ probes LNV effects $\Lambda_{\text{LNV}}^{ij} \gtrsim 1.5 \text{ TeV}$. [2010.02225](#)

$c \rightarrow ull$

Rare electroweak decays of Λ_c , Ξ_c , Ω_c

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

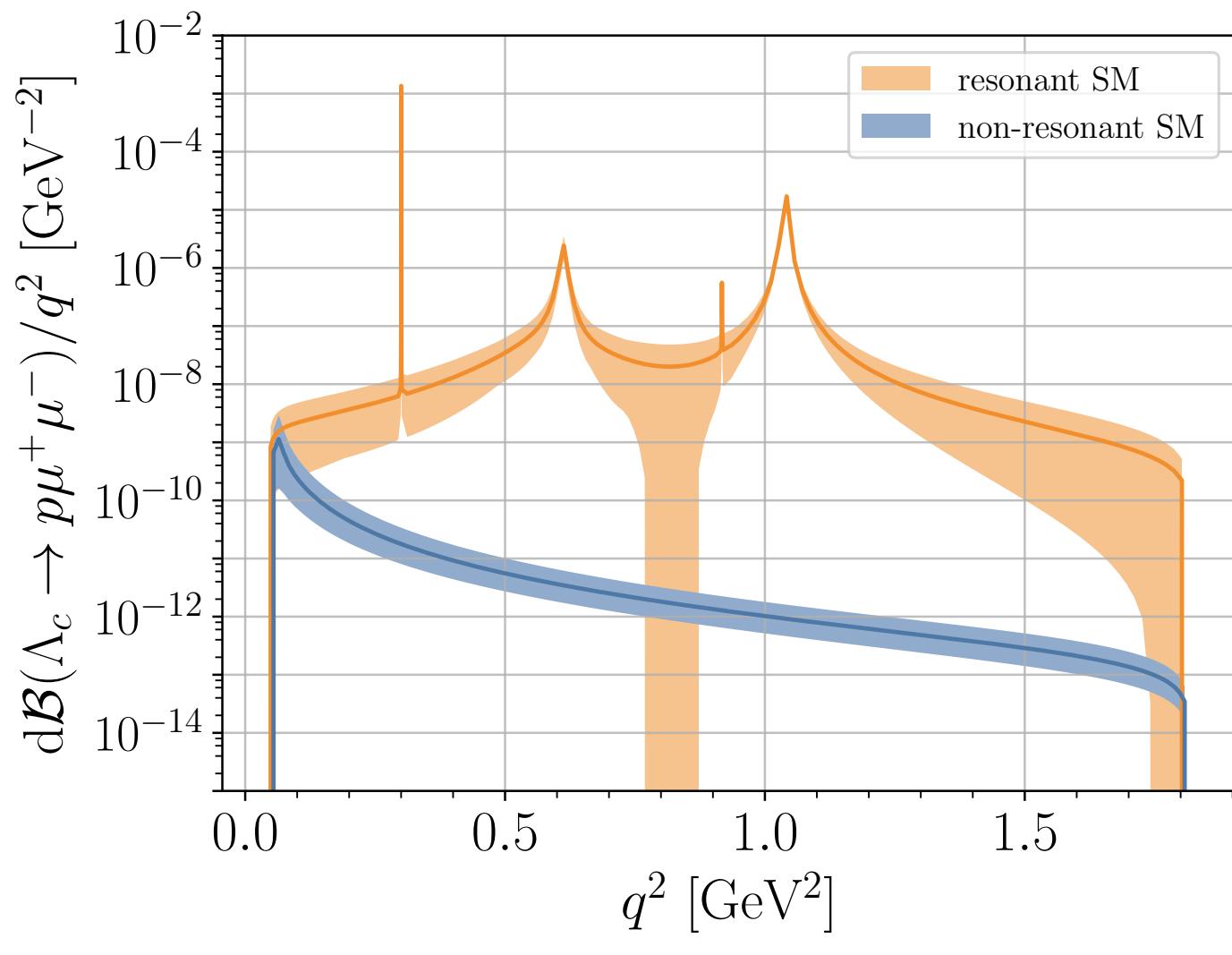
The differential angular distribution for unpolarized Λ_c , (polarized Λ_c worked out in 2202.02331) reads:

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

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

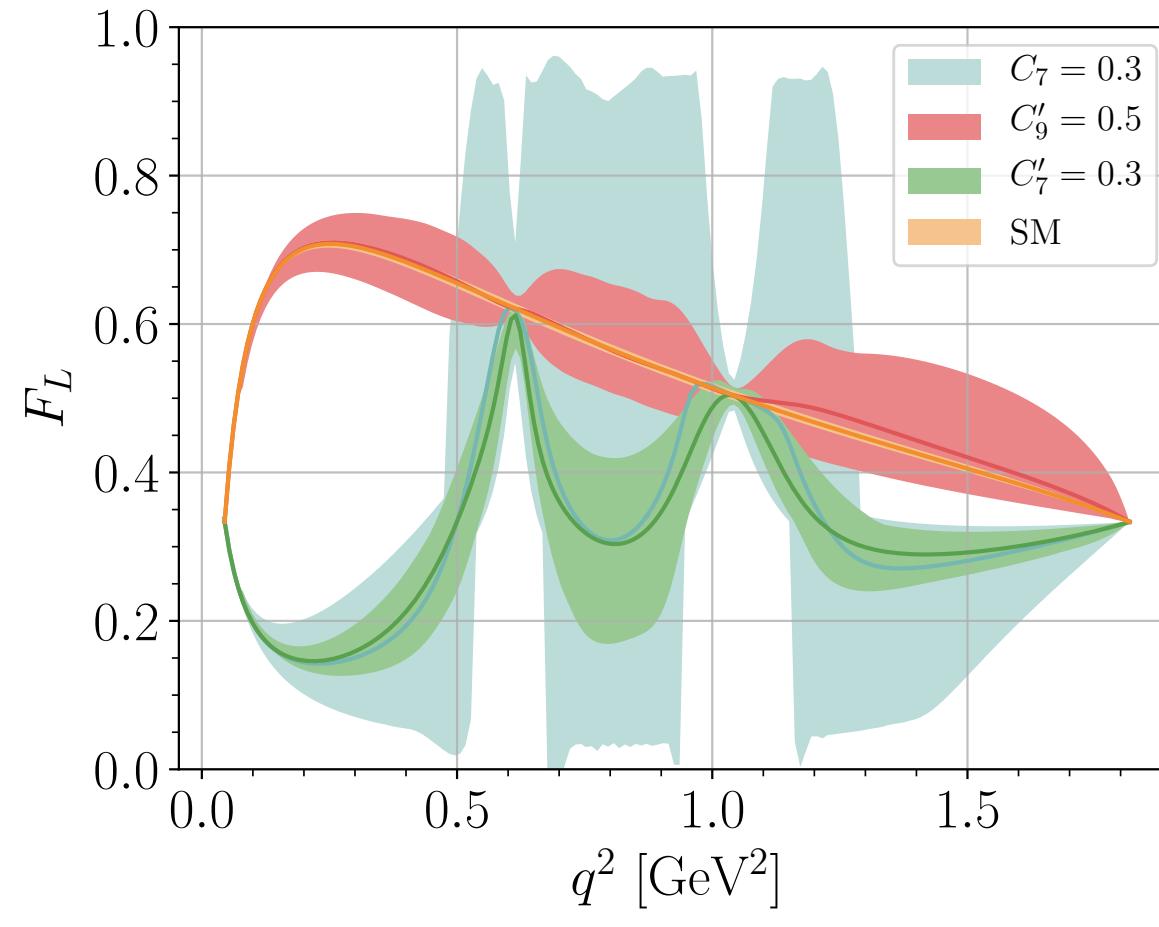
$\Lambda_c \rightarrow p$ form factors from lattice 1712.05783 – $SU(3)_F$ -relations to others 2203.14982

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



2107.13010

Longitudinal polarization: (+)



2107.13010

Sensitivity to dipole coefficients!

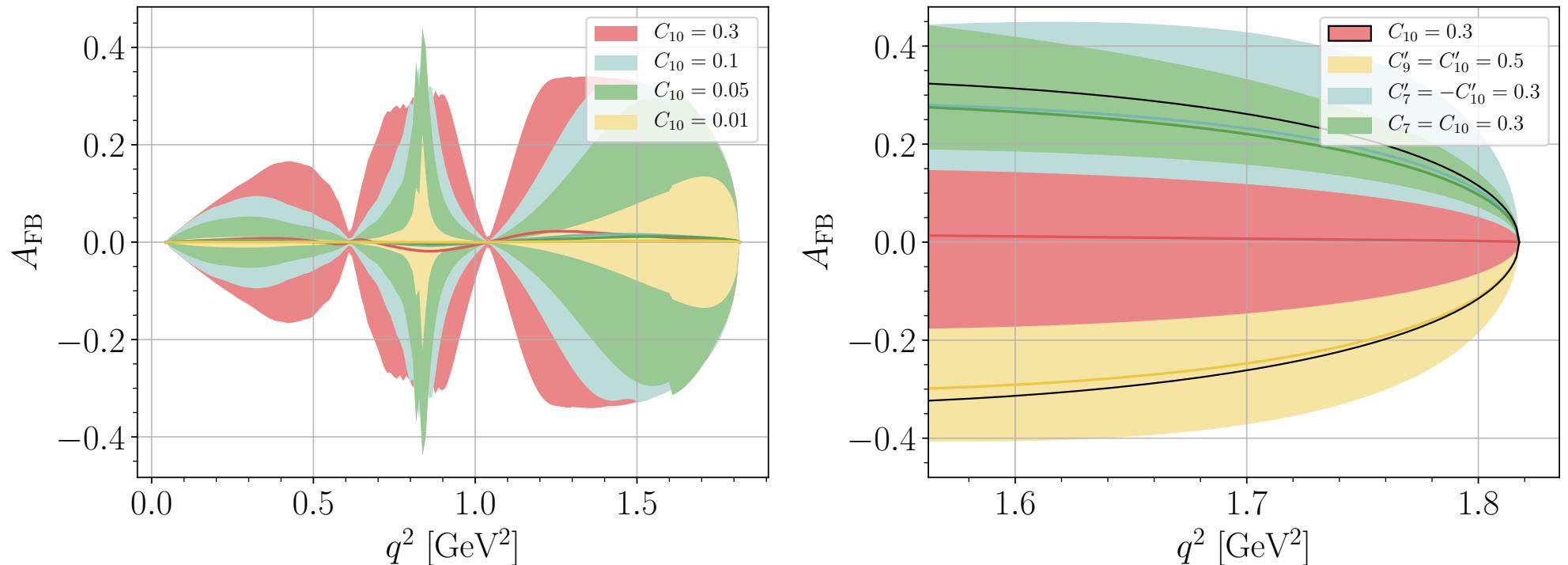


Figure 4: The forward-backward asymmetry A_{FB} of $\Lambda_c \rightarrow p \mu^+ \mu^-$ decays for different values of C_{10} in the full q^2 -region (left panel) and for various BSM contributions in the high q^2 region (right panel)

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

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

A Puzzle in hadronic charm CPX

Can ΔA_{CP} come mainly from $A_{CP}(D \rightarrow \pi^+\pi^-)$?

CP and U-Spin puzzle [2207.08539](#), [2210.16330](#) - two approx symmetries

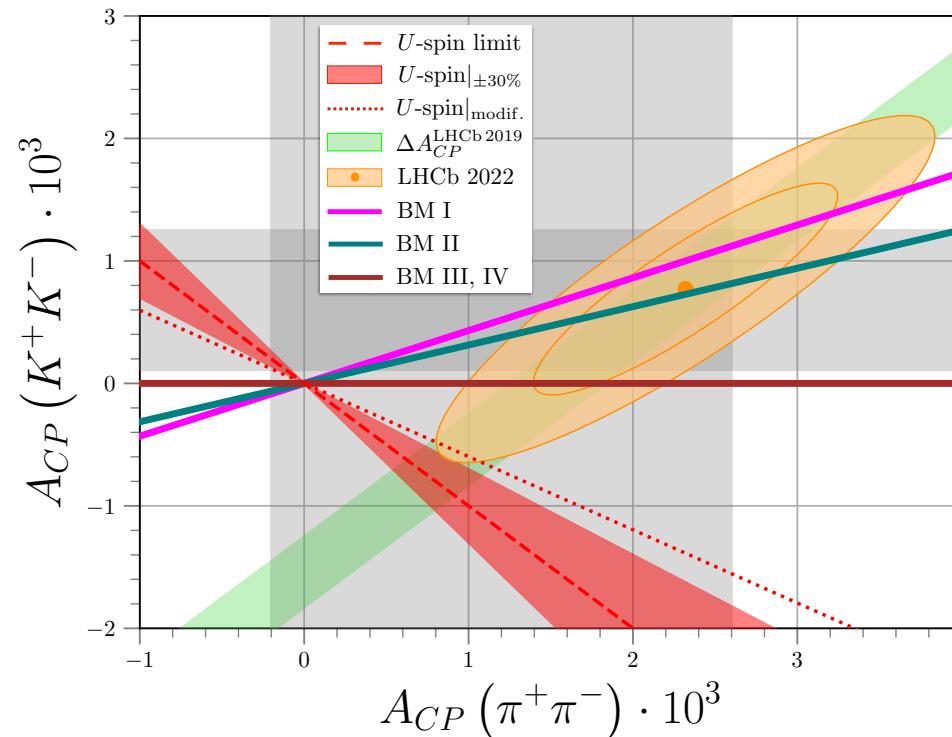


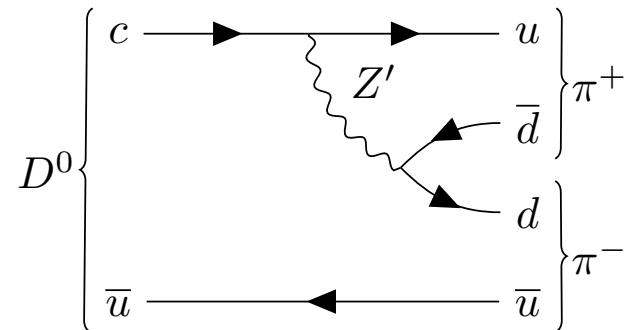
Fig from [2210.16330](#), LHCb result (orange ellipse) from [2209.03179](#)

A Puzzle in hadronic charm CPX

Is this even explainable?

Single solution known [2210.16330](#)

BSM effects in semileptonic 4-fermion operators $\sim \bar{u}_R \gamma_\mu c_R \bar{d}_R \gamma^\mu d_R$.
Very light Z' , sub 20 GeV (CMS ISR constraints), leptophob (LHCb
 $A \rightarrow \mu\mu$ search)



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

- Very little experimentally explored in rare charm decays – lots of blanks in PDG and opportunities
- Theory control by null tests
- Charm is advantageous because $SU(3)$ -related partners exist: measure the SM-like CF-decay and use symmetry to obtain the SM prediction of the SCS, BSM-sensitive mode. Then measure the SCS decay and test the SM. Many tests in radiative charm baryons and mesons.
- NP sensitivity from null tests in branching ratios $c \rightarrow u\nu\bar{\nu}$ (GIM).
Upper limits on $B(\Lambda_c \rightarrow p\nu\bar{\nu})$ depends lepton flavor.
- Angular distributions $C_{10}^{SM} = 0$ kills couplings to axial-vector lepton currents $\bar{\ell}\gamma_\mu\gamma_5\ell$, hence $I_{5,6,7}^{SM} = 0$, as well as $A_{FB}^{\ell SM}(\Lambda_c \rightarrow p\mu\mu) = 0$. More observables in full distributions.
- BSM effects in $|\Delta c| = |\Delta u| = 1$ can be huge.
- Complementary search to K - and b -decays.

Back up

An anomaly-free Z' -model for the charm puzzle

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	$-F_\nu$	0

Table 2: Benchmarks for several anomaly-free $U(1)'$ –extensions of the SM+3 ν_R . Note, $|G/F| \ll 1$ in BM III. BM IV may or may not contain right-handed neutrinos, in which case $F_\nu = 0$. It also can feature integer charges with hierarchy $|F_e| \ll |F_u|, |F_d|$ in which case it becomes leptophob.

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

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CF: $D_s \rightarrow \pi^+ \pi^0 \gamma, D_s \rightarrow K^+ \bar{K}^0 \gamma, D^+ \rightarrow \pi^+ \bar{K}^0 \gamma, (D^0 \rightarrow \pi^0 \bar{K}^0 \gamma, D^0$

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

$D^+ \rightarrow K^+ \bar{K}^0 \gamma, (D^0 \rightarrow \pi^+ \pi^- \gamma, D^0 \rightarrow K^+ K^- \gamma)$

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

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

leading order QCDF: $A_{FB}^{SM} = 0$ (only s -channel resonances) ideal:
forward-backward and CP-asymmetries in Dalitz region

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

