Radiative Charm Decays

based on works with Stefan de Boer 1701.06392, 1802.02769, and the charm team at Dortmund

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Charm mission

Testing the Standard Model with $|\Delta c| = |\Delta u| = 1$ 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 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. Largely unexplored to date.

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, $SU(3)_F$, cLFC, LFU, LNC

Tool box/opportunities BSM-charm:

i) GIM-suppression very efficient: In SM, everything follows from tree-level W-exchange plus RGE, μ_b-matching 1707.00988 : $C_7^{\mathrm{eff\,SM}} \lesssim 0.01$

$$c \to u\gamma : \quad O_7 = \bar{u}_L \sigma_{\mu\nu} c_R F^{\mu\nu}, \quad O_7' = \bar{u}_R \sigma_{\mu\nu} c_L F^{\mu\nu}$$

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 $\sim V_{cd}^* V_{us}$

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

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

iii) angular distributions/asymmetries/ratios ”optimized observables”

BSM-sensitive radiative charm decays

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

radiative $c \to u\gamma$:

$D \to V\gamma$, $V = \rho, ..,$ This Talk, 1701.06392, 1802.02769

$D \to P_1 P_2 \gamma$, 2009.14212, 2104.08287 A_{FB}, A_{CP}

$D \to A\gamma$, $A = K_1, ..,$ $D \to P_1 P_2 P_3 \gamma$, 1812.04679 Up-Down-Asymmetry

$\Lambda_c \to p\gamma$, $\Xi_c^0 \to \Lambda(\to p\pi)\gamma$,.... 2203.14982 polarization asymmetries

Very little probed so far :

$B(D^0 \to \rho^0\gamma) = (1.77 \pm 0.31) \cdot 10^{-5}$, $A_{CP} = 0.056 \pm 0.152$,

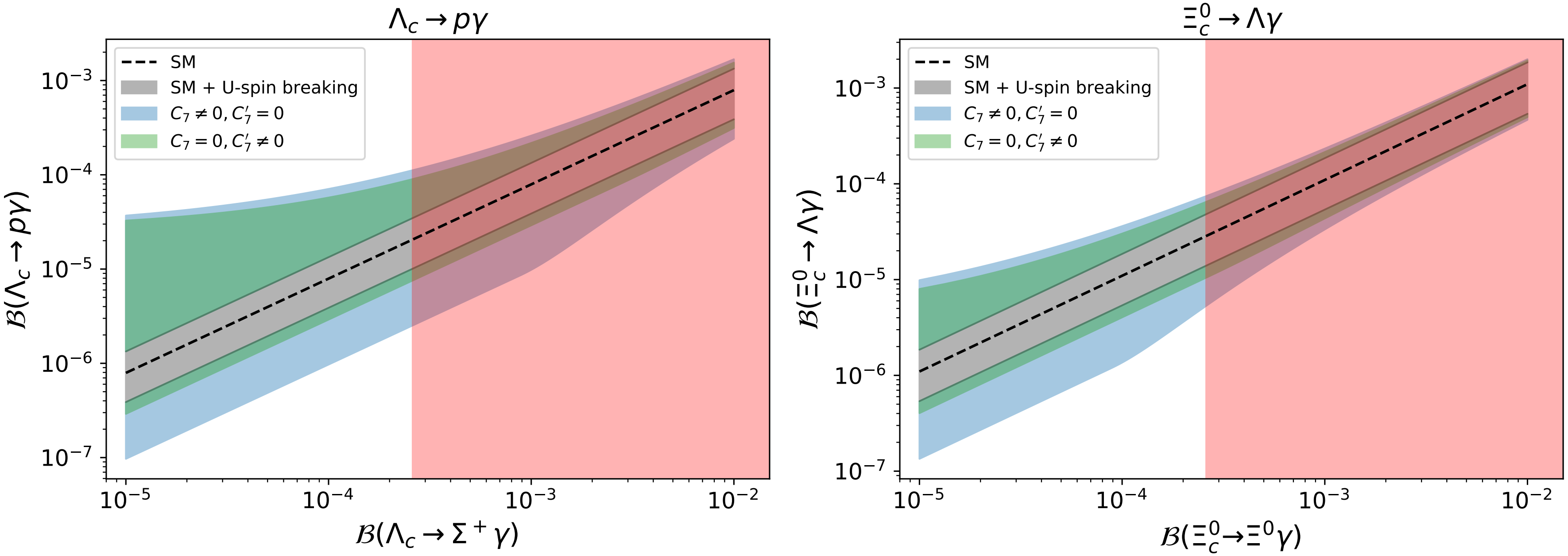
$A_{CP}(D^0 \to \Phi\gamma) = -0.094 \pm 0.066$ Belle'16 Cabibbo-favored modes:

$A_{CP}(D^0 \to \bar{K}^{*0}\gamma) = -0.003 \pm 0.020$, Belle'16

$B(\Lambda_c \to \Sigma\gamma) < 2.6 \cdot 10^{-4}$, $B(\Xi_c^0 \to \Xi^0\gamma) < 1.8 \cdot 10^{-4}$ Belle 2206.12517

$B(\Lambda_c \to \Sigma\gamma) < 4.4 \cdot 10^{-4}$ BESIII 2212.07214

BSM-sensitive radiative charm decays



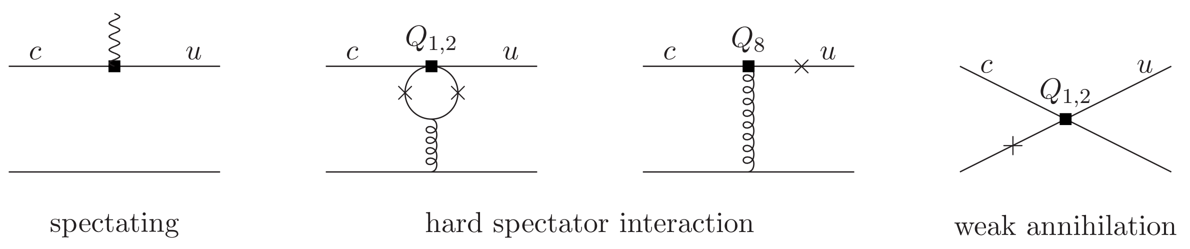
Theory 2203.14982 plus Belle exclusion (red areas) 2206.12517:

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

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

In $D \to V\gamma$, one can measure BRs, A_{CP} (direct), and time-dependent-CP-asymmetries A^{Δ}. Brs can be used to test QCD methods, and provides upper limits on NP: $C_7^{\mathrm{eff}}, C_7' \lesssim 0.3$

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	$(1.77 \pm 0.31) \times 10^{-5}$	–	$2.76 \pm 0.21 \times 10^{-5}$	$4.66 \pm 0.30 \cdot 10^{-4}$
BaBar 2008	–	–	$2.81 \pm 0.41 \times 10^{-5}$	$3.31 \pm 0.34 \cdot 10^{-4}$
CLEO 1998	–	$< 2.4 \times 10^{-4}$	–	–
LHCb			wip?	
th HS+WA	$(0.11 - 3.8) \cdot 10^{-6}$	$(0.08 - 5.2) \cdot 10^{-6}$	$(0.007 - 1.2) \cdot 10^{-5}$	$(0.01 - 1.6) \cdot 10^{-4}$
th hybrid	$(0.04 - 1.17) \cdot 10^{-5}$	$(0.042 - 1.12) \cdot 10^{-5}$	$(0.24 - 2.8) \cdot 10^{-5}$	$(0.26 - 4.6) \cdot 10^{-4}$



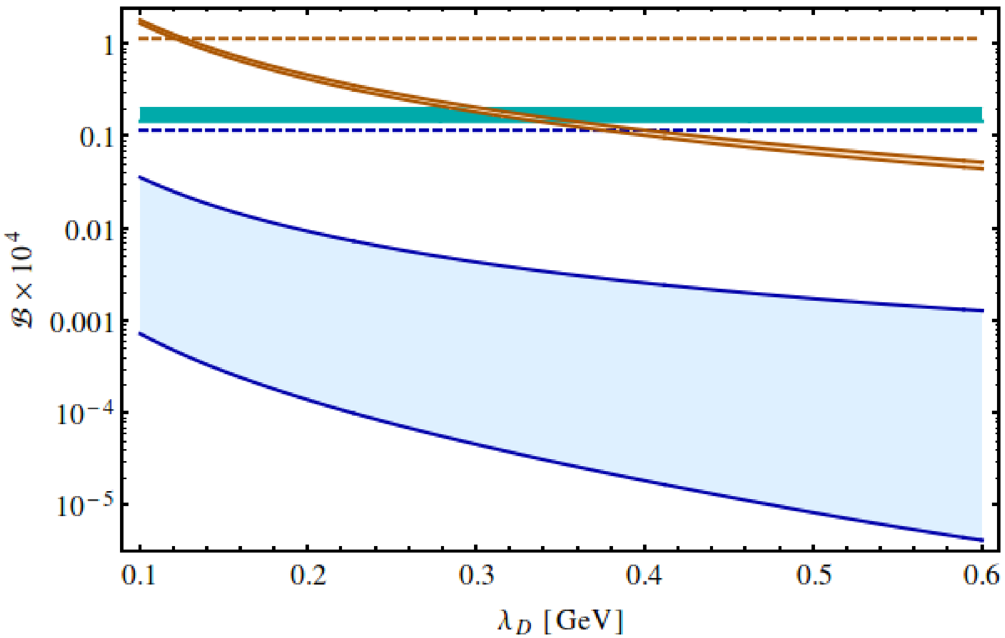


Figure 1: Branching ratios of $D \to \rho\gamma$ as a function of λ_D. The upper orange curves are for $D^+ \to \rho^+\gamma$ and the lower blue curves are for $D^0 \to \rho^0\gamma$. The solid curves represent the bands of two-loop QCD and hard spectator interaction plus weak annihilation, the dashed lines are the maximal predictions in the hybrid approach and the cyan band depicts the measured branching ratio from Belle'16. We vary the form factors, decay constants, lifetimes, Gegenbauer moments, relative strong phases and $\mu_c \in [m_c/\sqrt{2}, \sqrt{2}m_c]$.

Vector LQs" via tau-loop: $A_{CP} \lesssim 10\%$ $(\tilde{V}_1)$, for $S_{1,2}, \tilde{V}_2 :\lesssim O(0.01)$ 1701.06392,

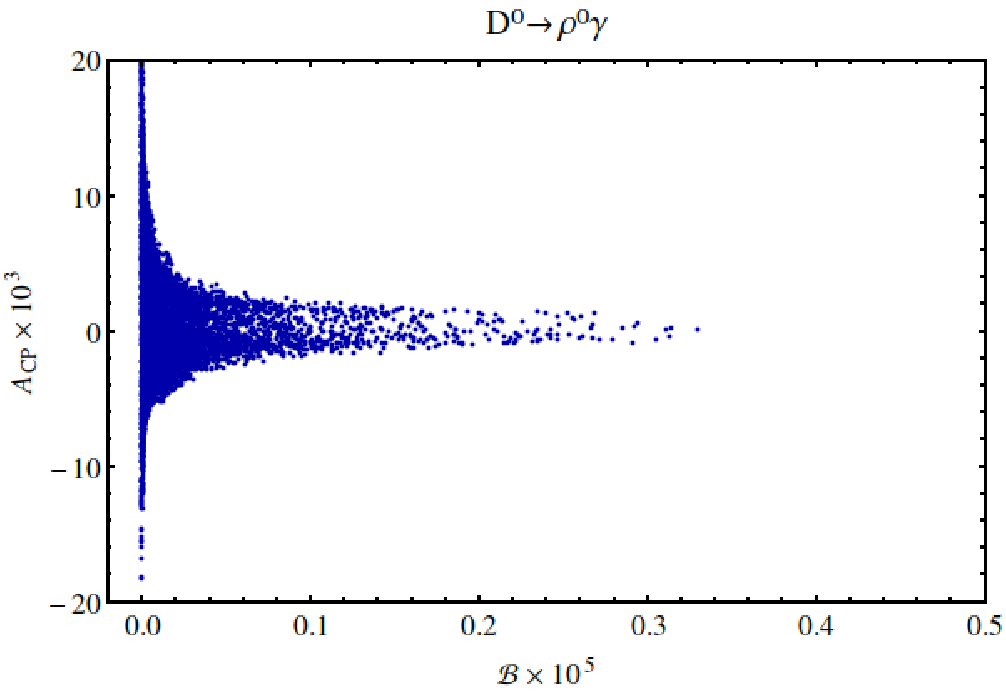


Figure 2: A_{CP} versus branching ratio for $D^0 \to \rho^0\gamma$ decays in SM. We vary the form factor, the two-loop QCD and hard spectator interaction plus weak annihilation within uncertainties, where $\lambda_D \in [0.1, 0.6]$ GeV, A'_7-contributions and relative strong phases. The measured A_{CP} covers the shown range $\pm 15\%$, whereas the measured branching ratio at one σ is above it.

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

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

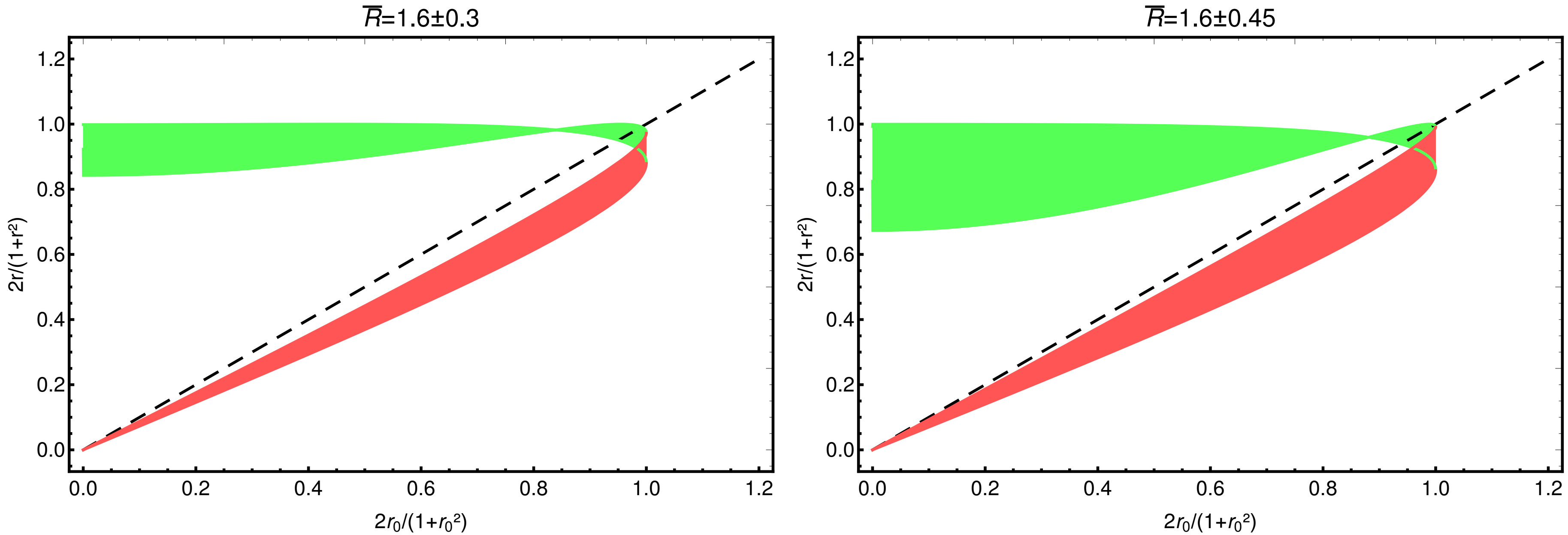
$A^{\Delta}(D^0 \to \bar{K}^{*0}\gamma) \simeq \frac{4\,\xi_{\bar{K}^{*0}} \left|\frac{q}{p}\right| \cos\varphi}{\left(1+\left|\frac{q}{p}\right|^2\right)} \frac{r_0}{1+r_0^2}$ Here, r_0 is ratio of wrong-chirality (RH) to LH-photons in SM-like process $D^0 \to \bar{K}^{*0}\gamma$.

Up to $SU(3)$-breaking: $r(D^0 \to \Phi\gamma) = r_0$, $\quad r(D^0 \to \rho\gamma) = r_0$;

$r = C_7'/C_7$, in SUSY, r ess. unconstrained.

SM, leptoquark models: $r \lesssim 0.2$

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).

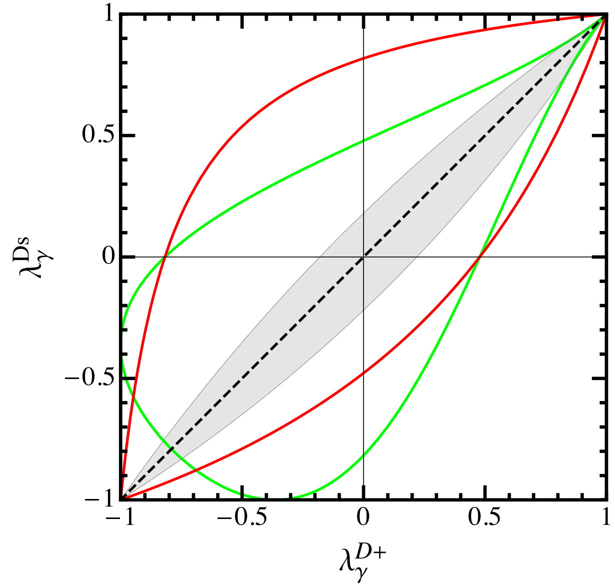
$\bar{R} = 1/f^2 \frac{|V_{cs}|^2}{|V_{cd}|^2} \frac{\mathcal{B}(D^0 \to \rho\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)}$ with leading U-spin breaking removed $f = m_\rho f_\rho / (m_{K^{*0}} f_{K^{*0}})$

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

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

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

Summary

- Very little experimentally explored in rare charm decays – lots of blanks in PDG
- 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.
- The photon polarization in $c \to u\gamma$ can be probed in several ways: TDCPA, up-down asymmetry, initial charm baryon polarization, or with decays into weakly decaying, self-analyzing hyperons.
- BSM effects in $|\Delta c| = |\Delta u| = 1$ can be huge. SM: $C_7^{eff} \lesssim 0.01$, data: $C_7^{eff} \lesssim 0.3$
- Complementary search to K,B-decays.

Back up

Beyond branching ratios: Rare rad. $\Lambda_c, \Xi_c, \Omega_c$ decays

Probing photon polarization 2203.14982

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

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

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

The polarization asymmetries:

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

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

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

Beyond branching ratios: Rare rad. $\Lambda_c, \Xi_c, \Omega_c$ decays

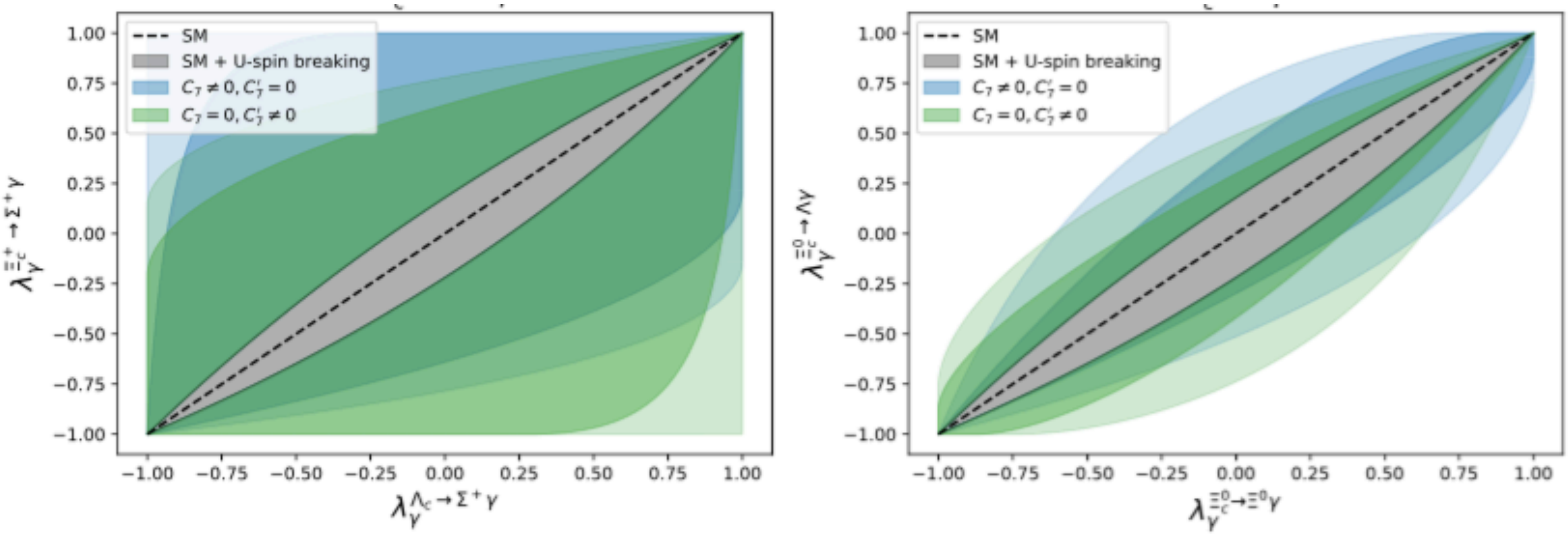


Figure 3: BSM reach of λ_γ of BSM modes $\Xi_c^+ \to \Sigma^+\gamma$ (left) and $\Xi_c^0 \to \Lambda\gamma$ (right) versus photon polarization of SM-like modes, $\Lambda_c \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$, respectively, for $B^{\text{CF}} = 5 \cdot 10^{-4}$. The black dashed line denotes 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 $-0.3 \leq C_7^{(\prime)} \leq 0.3$. For the darker shaded area we used the SM amplitudes in the exakt 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 $\pm 20\%$.

Rare decays of $\Lambda_c, \Xi_c, \Omega_c$ theory and observables

Baryons are sensitive to many couplings and can be polarized or undergo self-analyzing (weakly-induced) decays 2203.14982, 2202.02331

Decay	Br	α_B
$\Lambda(1116) \to p\pi^-$	$(63.9 \pm 0.5)\%$	0.732 ± 0.014
$\Sigma^+(1189) \to p\pi^0$	$(51.57 \pm 0.30)\%$	-0.982 ± 0.014
$\Xi^0(1315) \to \Lambda\pi^0$	$(99.52 \pm 0.012)\%$	-0.356 ± 0.011

Table 1: Branching ratio and weak decay parameter α_B of self-analyzing hyperon decays [PDG]. Note, the $\Xi^-(1322)$ decays almost entirely to $\Lambda\pi^-$ with sizable $\alpha_B = -0.4$, however, it is not produced in rare decays of charm baryons. (from 2203.14982)

this is where this works:

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