Decays of rare charmed baryons

based on works with Stefan de Boer, Joachim Brod, Nico Adolph, Rigo Bause, Marcel Golz, Tom Magorsch, Andrey Tayduganov, Dominik Suelmann and Hector Gisbert-Mullor

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

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

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

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

Very little probed so far

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

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, [$D \to \pi\mu\mu$, $D \to \mu\mu$ upper limits]

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

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)

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

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

- radiative $c \to u\gamma$ 2203.14982, 1701.06392
- electroweak $c \to u\ell\ell$ 2107.13010, 2202.02331
- dineutrinos $c \to u\bar{\nu}\nu$ 2010.02225

Not a single baryonic one observed.

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

Advantages charm (vs beauty):
GIM-suppression very efficient: $C_\nu^{\mathrm{SM}} = C_{10}^{\mathrm{SM}} = 0$ (and RG effects tiny)
$SU(3)_F$ partner modes - SM-like and NP-sensitive ones related.

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

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

Table 2: Flavor symmetry relations of the decay amplitudes for the charmed anti-triplet baryons. $A_\Sigma^{(\prime)}$ and $A_\Delta^{(\prime)}$ refer to the U-spin triplet and singlet SM contributions of the W-exchange diagrams. $A_7^{(\prime)} = A_{\rm NP}^{(\prime)} + A_{\rm LD}^{(\prime)}$ denote the $c \to u\gamma$ 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 ($\Omega_c \to \Lambda, \Sigma^0, \Xi^0$) also in 2203.14982.

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

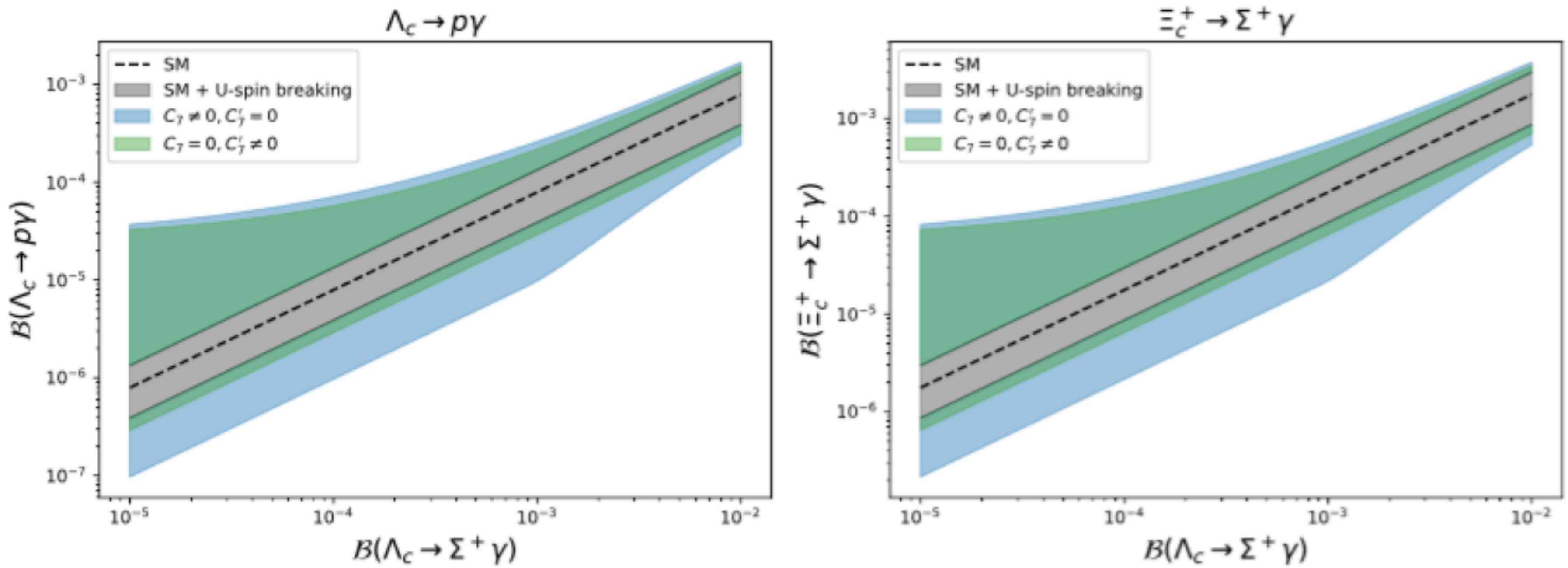


Figure 1: NP effects in the branching ratios of the BSM sensitive decay modes as a function of the branching ratios of the SM-like decay modes, for $\lambda_\gamma^{\text{CF}} = -0.5$. The black dashed line denotes the SM in the U-spin limit. The gray shaded area shows $\pm 30\%$ U-spin breaking in $A_{L/R}^{\text{SM}}$. 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 $-0.3 \leq C_7^{(\prime)} \leq 0.3$. The BSM regions also include the $\pm 30\%$ U-spin breaking of the SM amplitudes. Cabibbo-favored modes: $B(\Lambda_c \to \Sigma\gamma) < 2.6 \cdot 10^{-4}$, Belle 2206.12517, that is $B(\Lambda_c \to p\gamma) \lesssim 10^{-4}$,

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)

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

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

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

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

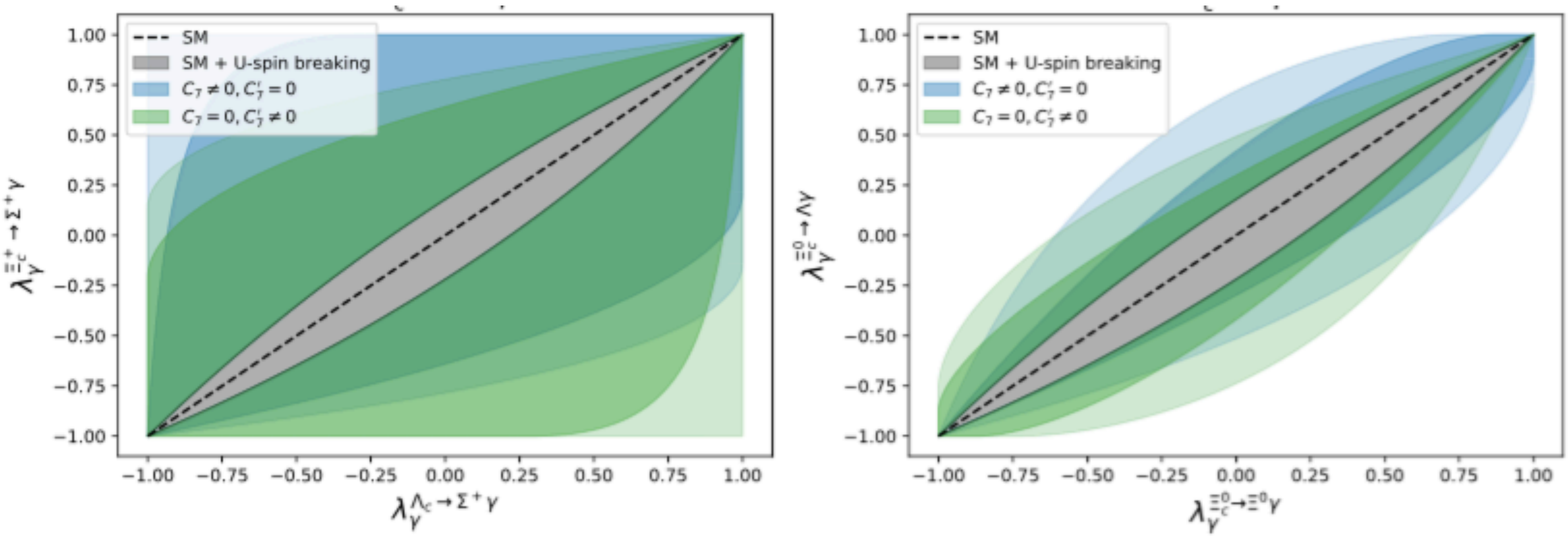


Figure 2: BSM reach of λ_γ of the BSM sensitive decay modes $\Xi_c^+ \to \Sigma^+\gamma$ (left plot) and $\Xi_c^0 \to \Lambda\gamma$ (right plot) as a function of the photon polarization of the corresponding SM-like decay modes, $\Lambda_c \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$, respectively, 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 $\pm 20\%$. The BSM reach of $\Lambda_c \to p\gamma$ and $\Xi_c^0 \to \Sigma^0\gamma$ coincides with $\Xi_c^+ \to \Sigma^+\gamma$ (left plot) and is not shown. $O(1)$ NP effects in γ-polarization; Charm quarks are produced polarized at the Z: $P_c^Z = -0.65$, depolarization in hadronization Falk, Peskin $P_{\Lambda_c}^Z \sim -0.44 \pm 0.02$. Input for BSM search, needs to be measured, e.g. from $\Lambda_c \to \Lambda(\to p\pi)\ell\nu$. 1701.06392

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

BSM sensitive (SCS) decay	CF decay ("SM-like")
$\Xi_c^+ \to \Sigma^+ \gamma$	$\Lambda_c \to \Sigma^+ \gamma$
$\Xi_c^0 \to \Lambda \gamma$	$\Xi_c^0 \to \Xi^0 \gamma$
$\Omega_c \to \Xi^0 \gamma$	$\Xi_c^{\prime 0} \to \Xi^0 \gamma$
$\Xi_c^{\prime +} \to \Sigma^+ \gamma$	$\Sigma_c^+ \to \Sigma^+ \gamma$
$\Xi_c^{\prime 0} \to \Lambda \gamma$	$\Sigma_c^0 \to \Lambda \gamma$, $\Xi_c^{\prime 0} \to \Xi^0 \gamma$

Table 3: Partner modes which enable tests of the SM by the photon polarization using the decay chains $B_c \to B(\to B' P)\gamma$ and U-spin relations. The secondary baryons $(\Lambda, \Sigma^+, \Xi^0)$ are self-analyzing.

CP-asymmetries can be enhanced: $A_{\text{CP}}^{\text{SM}} \approx \text{Im}\left(\frac{-2\Delta}{\Sigma}\right) \approx -6 \times 10^{-4}$

NP: $\left|\text{Im}\left(\frac{-2C_7^{(\prime)}}{\Sigma}\right)\right| \approx 2 \times 10^{-2}$ (with ΔA_{CP}-constraint), else if $C_7^{(\prime)} \gg C_8^{(\prime)}$ even larger 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 unpolarized Λ_c, (polarized worked out in 2202.02331)

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

$\to$ 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 others 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

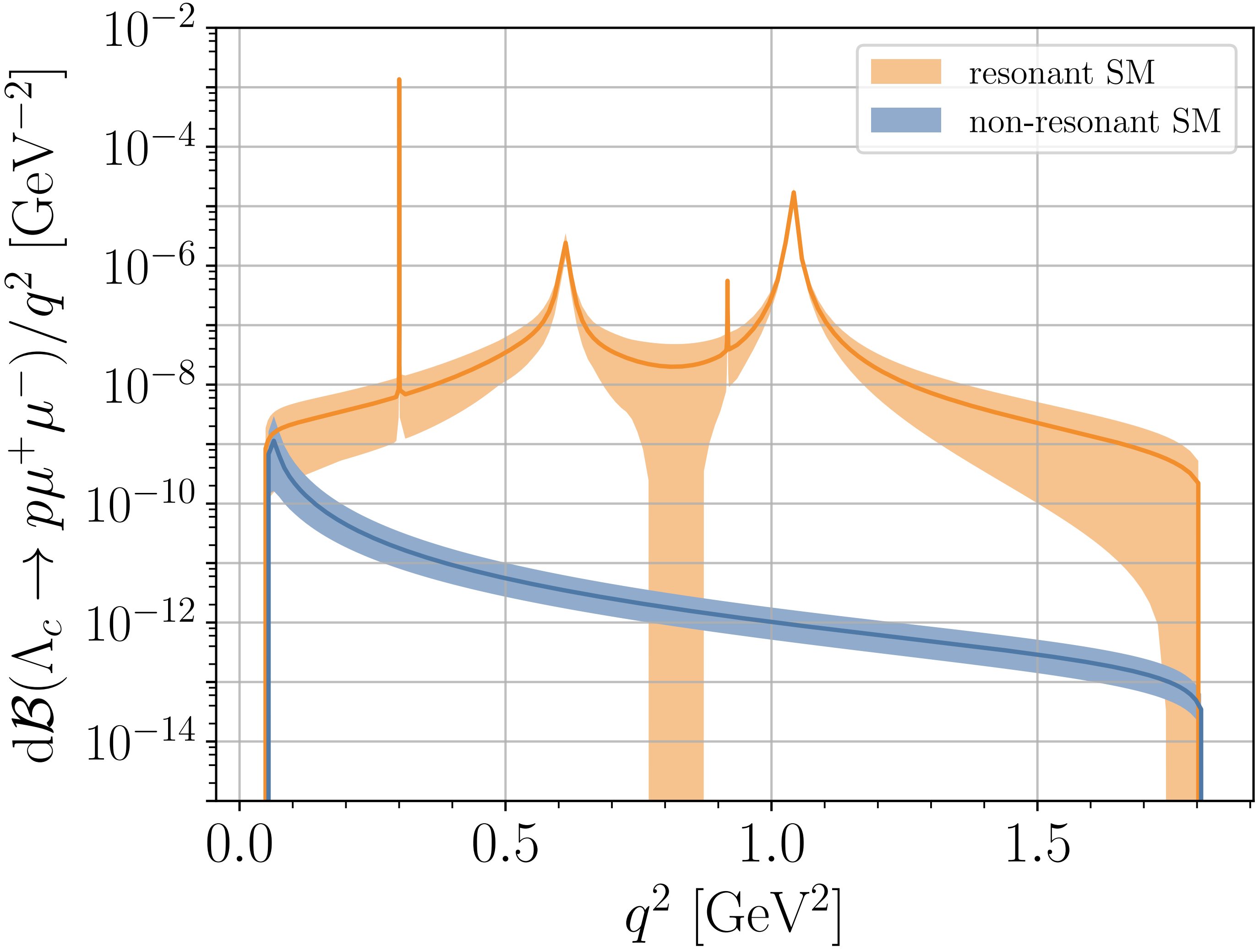


Figure 3: The differential SM branching fraction of $\Lambda_c \to p\mu^+\mu^-$. In blue (orange) the short-distance (pure resonant) contributions are shown. Their widths indicate theoretical uncertainties of hadronic form factors, resonance parameters and scale uncertainty μ_c. The central line in the resonant case is obtained by averaging after varying strong phases.

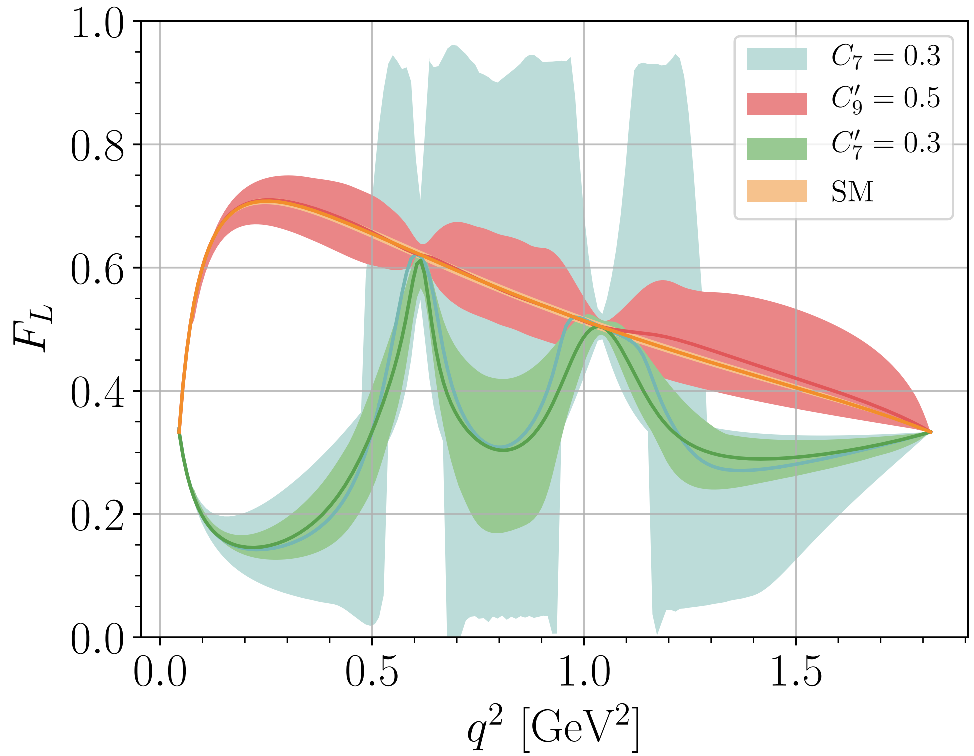


Figure 4: The fraction of longitudinally polarized dimuons F_L of $\Lambda_c \to p\mu^+\mu^-$ decays for various BSM contributions including theoretical uncertainties from form factors and resonance parameters. The orange band corresponds to the resonant SM contribution.

Sensitivity to dipole coefficients!

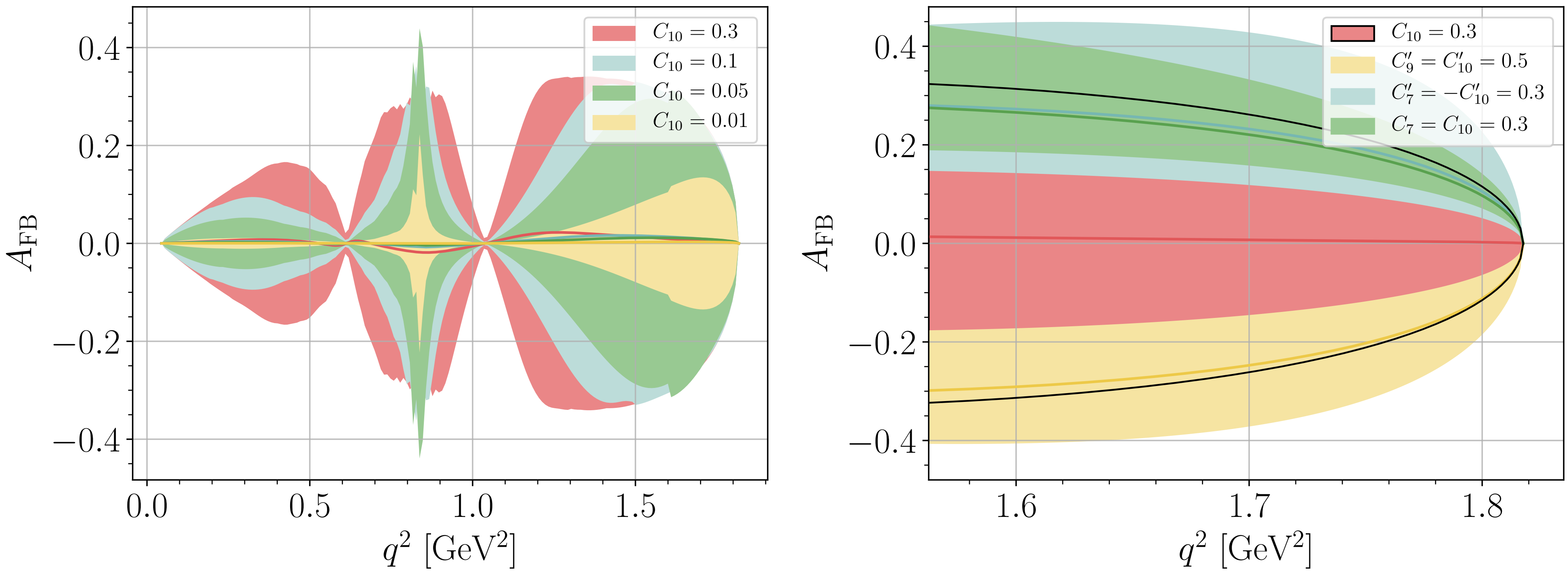
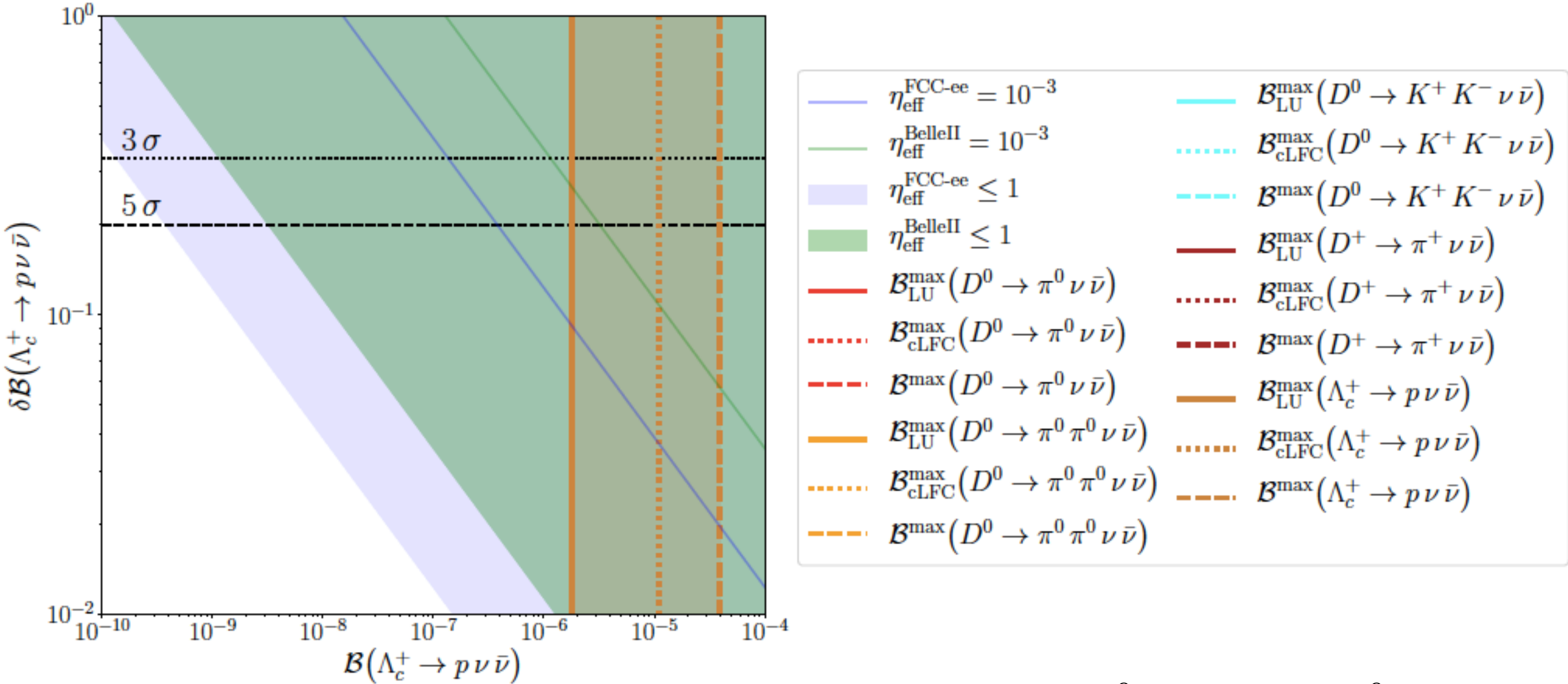


Figure 5: The forward-backward asymmetry A_{FB} of $\Lambda_c \to p\mu^+\mu^-$ decays for different values of C_{10} in the full q^2-region (left panel) and for various BSM contributions in the high q^2 region (right panel)

$A_{\text{FB}} \propto C_{10}$ 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) theory and observables: 2010.02225 all modes are null tests and can probe lepton flavor structure

highlights for BSM searches: GIM $(C_\nu^{\rm SM}=0)$, cLFV, LFU



lines are sensitivities for an assumed reconstruction efficiency of permille, $N(c\bar c) = 550 \cdot 10^9$ (FCC-ee), $65 \cdot 10^9$ (Belle II, 50 ab^{-1}).

- Very little experimentally explored in rare charm decays – lots of blanks in PDG

- 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.

  Method allows for many tests in radiative charm baryons and mesons.

- NP sensitivity from null tests in branching ratios $c \to u\nu\bar{\nu}$ (GIM) Upper limits on $B(\Lambda_c \to p\nu\bar{\nu})$ depends on whether LFC, or LFU holds !

- Angular distributions $C_{10}^{SM} = 0$ kills couplings to axial-vector lepton currents $\bar{\ell}\gamma_\mu\gamma_5\ell$, hence, unlike in b-decays $P_5'^{SM} = 0$, as well as $A_{FB}^{\ell\,SM}(\Lambda_c \to p\mu\mu) = 0$. More observable in full distribution.
- BSM effects in $|\Delta c| = |\Delta u| = 1$ can be huge.
- Complementary search to K,B-decays.
- Test cLFC, LFU in $\Lambda_c \to pe^\pm\mu^\mp$[a], $\Lambda_c \to pee$ vs $\Lambda_c \to p\mu\mu$ a la R_K.

[a] UL by Babar at $O(10^{-5})$