Rare Charm Decays as Flavor Probes

Gudrun Hiller, CERN/TU Dortmund

the bigger picture – Flavor Puzzle

The unexplained peculiarities of the SM flavor sector $u, d, s, c, b, t, e, \mu, \tau, \nu_\ell$

–3 generations – just enough to have CP violated, but not enough for BAU

–spectrum hierachical $m_u/m_t \sim 10^{-5}$, $m_d/m_b \sim m_e/m_\tau \sim 10^{-3}$, but otherwise universal couplings to $SU(3)_C \times SU(2)_L \times U(1)_Y$

–flavor mixing, but just a bit, with hierarchy (CKM, quarks), and $O(1)$ (PMNS, leptons)

It is quite puzzling that in view of this ”quasi-structured conglomerate” BSM physics has not been observed yet. 1812.10913

$\Lambda_{sd} \gtrsim 2 \cdot 10^5$TeV, $\Lambda_{cu} \gtrsim 1 \cdot 10^5$TeV, $\Lambda_{bd} \gtrsim 2 \cdot 10^3$TeV, $\Lambda_{bs} \gtrsim 3 \cdot 10^2$TeV

On the other hand, these very specificities with its suppressions and systematics (GIM, CKM, approx symmetries) give New physics sensitivity and broad set of targets for dedicated study and tests.

Flavor Big Questions

1. **origin of matter** (matter-antimatter asymmetry, needs CP violation, only seen in flavor violation, needs New Physics)

2. **origin of flavor** (SM flavor patterns & hierarchies, needs New Physics)

3. **origin of mass** (is Higgs responsible for quark and lepton masses, Yukawa proportional to mass? Absence of FCNC such as $h \to \tau\mu$?

origin of mass largely open for 1st generation and strange

$y/y_{\rm SM} < 560(u), 260(d), 13(s), 260(e)$ 1905.03764, 2107.02686

$1.1 < y/y_{\rm SM} < 5.5$ charm CMS '23

4. **Where does the SM fail and is New Physics flavorful?** Systematic survey of rare processes, searches in SMEFT, and models, null tests FCNCs in $s \to d$, $b \to s, d$ and the up-sector: CHARM $c \to u$

5. **nature of dark matter** (searching heavy& light invisibles in rare decays)

SM tests with $c \to u$ FCNCs of mesons and baryons and high p_T

- $c \to u\gamma$ 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 $\lesssim 10^{-5}$
- $c \to ug$ in $pp \to$ MET+j 2502.12250
- $c \to u\tau\tau, \tau\mu$ in $pp \to \ell\ell$ 2207.10714

Sensitivity to large range of physics (dipole couplings, 4-fermion operators, heavy and light NP, CPX, LFV, ..)

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

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, $SU(3)_F$

SM-Phenomenology completely dominated by 4-quark operators, induced by tree-level W-exchange, plus RGE, μ_b-matching 1707.00988 :

$$O_7 = \frac{m_c}{e}(\bar{u}_L \sigma_{\mu\nu} c_R) F^{\mu\nu} \, , O_9 = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \ell) \, , O_{10} = (\bar{u}_L \gamma_\mu c_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \, ,$$

$$O_S = (\bar{u}_L c_R)(\bar{\ell}\ell) \, , O_P = (\bar{u}_L c_R)(\bar{\ell}\gamma_5 \ell) \, , O_T = \frac{1}{2}(\bar{u}\sigma_{\mu\nu} c)(\bar{\ell}\sigma^{\mu\nu}\ell) \, , O_{T5} = \frac{1}{2}(\bar{u}\sigma_{\mu\nu} c)(\bar{\ell}\sigma^{\mu\nu}\gamma_5 \ell) \, ,$$

$O_\nu = \bar{u}_L \gamma_\mu c_L \, \bar{\nu}_L \gamma^\mu \nu_L$ operator names as in $b \to s\mu\mu$ $\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \frac{\alpha_e}{4\pi} \sum C_i O_i$

GIM-suppression very efficient: SM coefficients

$$|\mathcal{C}_9^{\text{eff}}(q^2)| \lesssim \mathcal{O}(0.1)(\lesssim 0.01) \, , |\mathcal{C}_7^{\text{eff}}(q^2)| \lesssim 0.01(\simeq \mathcal{O}(0.001))$$

values in parentheses for high $q^2 > 1$ GeV^2. 1510.00311

vanish by GIM: $C_{10}^{\rm SM} = 0 \, , C_\nu^{\rm SM} = 0, \; C'^{\rm SM}, C_{S,P,T,T5}^{\rm SM} = 0$

Where are we today?

$B(D \to \pi\nu\bar{\nu}) < 2.1 \cdot 10^{-4}$ (BESIII21): $|C_\nu + C'_\nu| \lesssim 150$!!!

$B(D \to \mu\mu) < 2.2 \cdot 10^{-9}$ (CMS24): $|C_{10} - C'_{10}| \lesssim 0.52$

$B(D^+ \to \pi^+\mu\mu)$ (LHCb21) : $|C_{10} + C'_{10}| \lesssim 0.85 \to |C_{10}|, |C'_{10}| \lesssim 0.7$

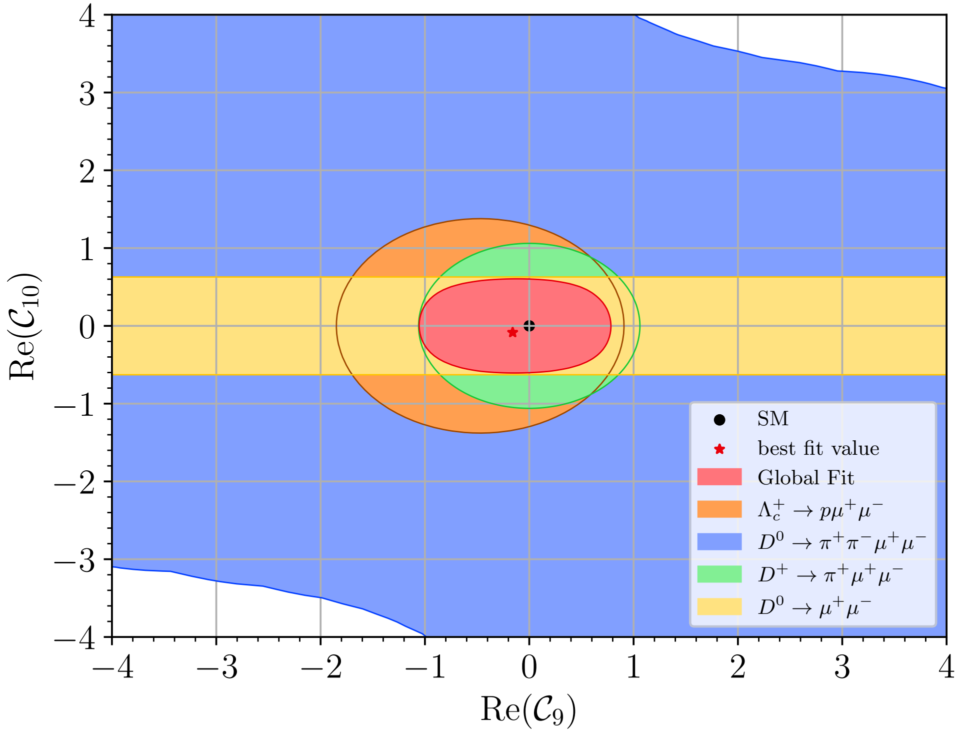
$B(D \to \mu\mu)$: $(|C_S - C'_S|^2 + C_P - C'_P|^2)^{1/2} \lesssim 0.04$

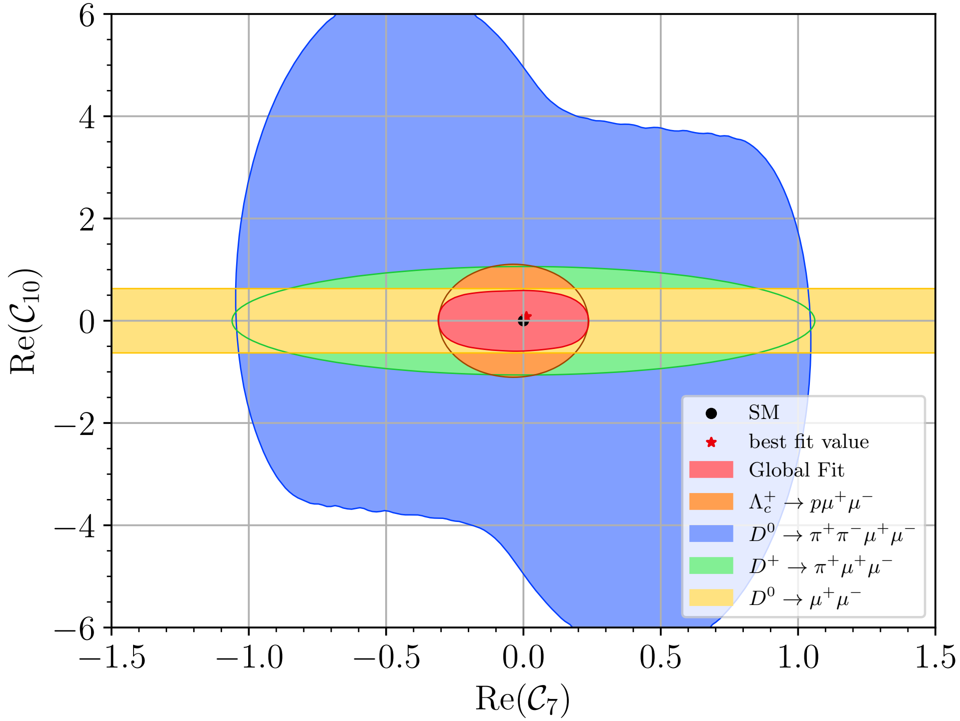
$B(\Lambda_c \to p\mu\mu)_{loq^2}$ (LHCb24) : $|C_7|, |C'_7| \lesssim 0.2$ (a bit stronger than $D \to \rho\gamma$)

limits much larger than non-resonant SM coefficients

... of course, combine more systematically. in global fit

Global analysis, using $D \to \mu\mu$, $D \to \pi\mu\mu$, $\Lambda_c \to p\mu\mu$, and $D \to \pi\pi\mu\mu$





2410.00115 Sensitivity in $B(D \to \mu\mu) \propto f_D^2$ limited to $C_{10} - C'_{10} \simeq 0.01$ by $D \to \gamma\gamma$. All other modes can also cleanly signal NP in nulltest angular obsbles, but require QCD progress to improve sensitivity.

points of interest: dineutrino charm decays

The $c \to u\nu\bar{\nu}$ modes are ALL BSM, due to GIM.

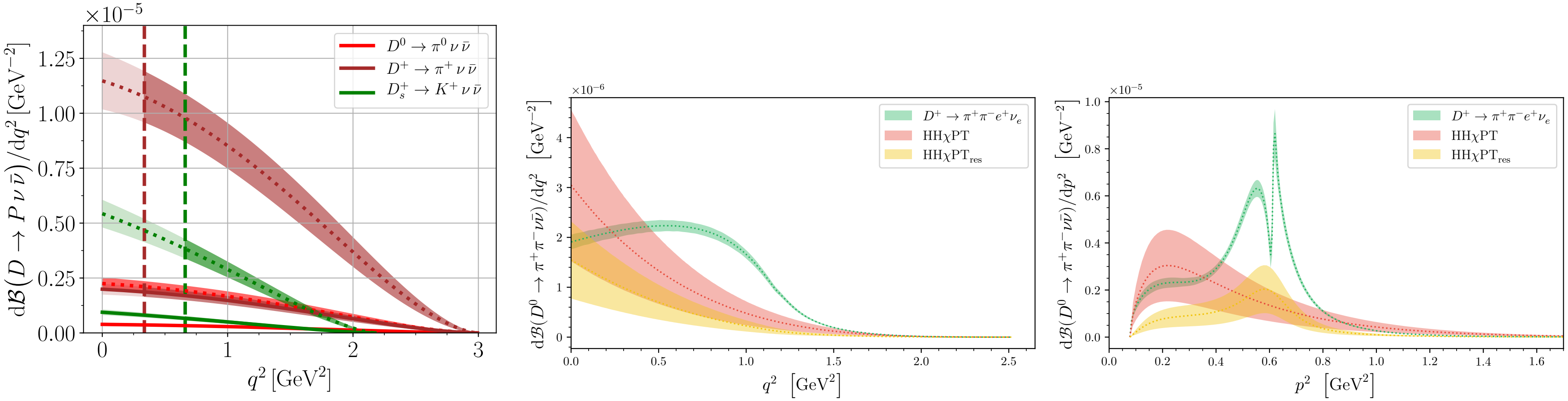


Figure 1: Differential branching ratios for $D \to P\nu\bar{\nu}$ (left) $D^0 \to PP\nu\bar{\nu}$ (mid, right) this plot shows BSM distributions uncertainty bands from form factors, τ background removable by q^2-cut (vertical dashed lines) from 2010.02225, 2509.10447

$\langle\pi\pi|\bar{u}\Gamma c|D\rangle$ form factors poorly known (HHχPT) Lee, Lu, Wise '92, also $\langle\rho|\bar{u}\Gamma c|D\rangle$; Suitable for e^+e^--machines (Tera-Z, Belle II, BESIII,..)

$D \to \pi\pi\nu\bar{\nu}$ sens. at Tera-Z about $2 - 3 \cdot 10^{-7}$ for 3 σ 2509.10447 (with TUDo)

$B(Z \to c\bar{c}) = 0.12$

$N(c\bar{c}) = 550 \cdot 10^9$ (FCC-ee) and $N(c\bar{c}) = 65 \cdot 10^9$ (Belle II with $50\,\text{ab}^{-1}$)

h_c	$f(c \to h_c)$	$N(h_c)$ FCC-ee	$N(h_c)$ Belle II	$N(h_c)$ $10\,\text{ab}^{-1}$
D^0	0.59	$6 \cdot 10^{11}$	$8 \cdot 10^{10}$	$2 \cdot 10^{10}$
D^+	0.24	$3 \cdot 10^{11}$	$3 \cdot 10^{10}$	$6 \cdot 10^{9}$
D_s^+	0.10	$1 \cdot 10^{11}$	$1 \cdot 10^{10}$	$3 \cdot 10^{9}$
Λ_c^+	0.06	$7 \cdot 10^{10}$	$8 \cdot 10^{9}$	$2 \cdot 10^{9}$

Table 1: Number of charmed hadrons h_c, $N(h_c)$, from 2010.02225.

Charm Dineutrino null tests

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

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

$B(c \to u\nu\bar{\nu})^{\text{SM}} \simeq 0$; only 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

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

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

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

4. hadronic: $D \to hh'$ ....

decays of mesons and baryons, 2,3, and multibody decays

points of interest: radiative charm decays

radiative $c \to u\gamma$:

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

$D \to P_1P_2\gamma$, 2009.14212, 2104.08287 A_{FB}, A_{CP}

$D \to A\gamma$, $A = K_1, ..,$ $D \to P_1P_2P_3\gamma$, 1812.04679 Up-Down-Asymmetry

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

Very few SM tests 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 $B(D^+ \to \rho^+\gamma) < 1.3 \cdot 10^{-5}$

BESIII 2410.06500 Cabibbo-favored modes (red):

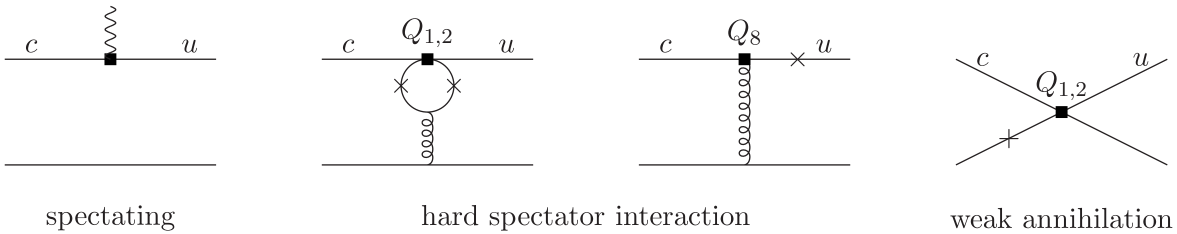
$A_{CP}(D^0 \to \bar{K}^{*0}\gamma) = -0.003 \pm 0.020$, Belle'16

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

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

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: $C_7^{\rm eff}, C_7' \lesssim 0.3$

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	$(0.04 - 1.17) \cdot 10^{-5}$	$(0.042 - 1.12) \cdot 10^{-5}$	$(0.24 - 2.8) \cdot 10^{-5}$	$(0.26 - 4.6) \cdot 10^{-4}$



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

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

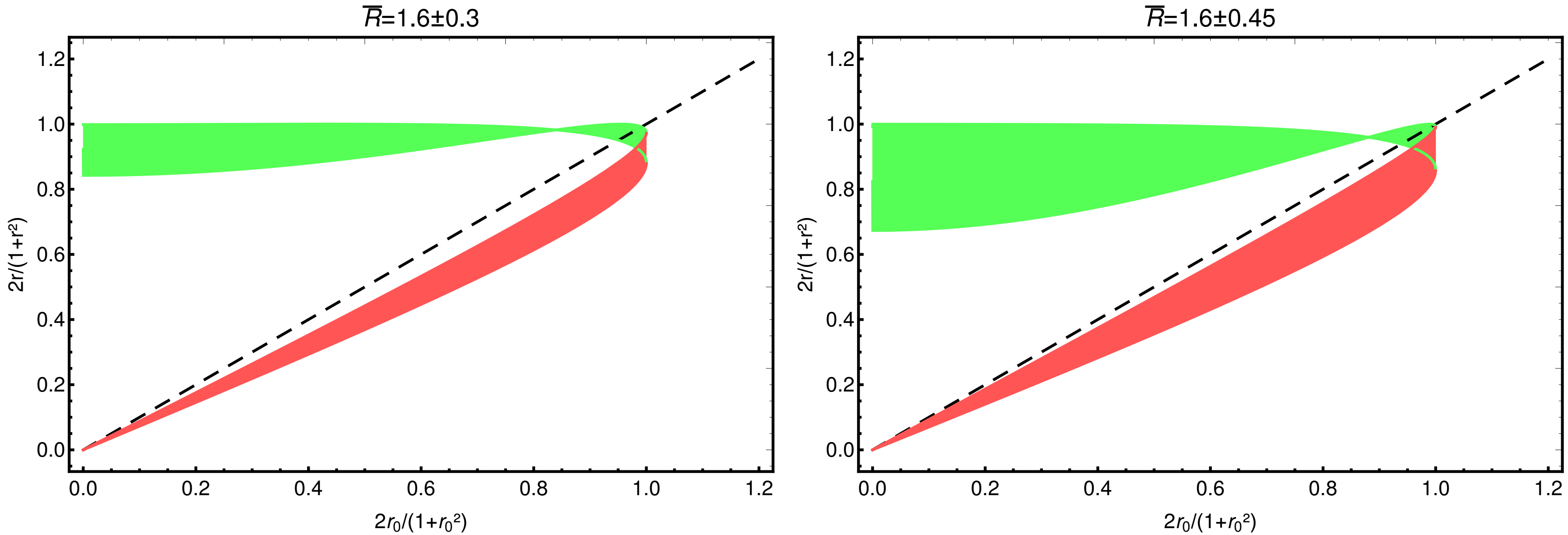
$A^{\Delta}(D^0 \to \bar{K}^{*0}\gamma) \simeq \frac{4\,\xi_{\bar{K}^{*0}} \left|\frac{q}{p}\right| \cos\varphi}{\left(1+\left|\frac{q}{p}\right|^2\right)} \frac{r_0}{1+r_0^2}$ Here, r_0 is ratio of wrong-chirality (RH) to LH-photons in SM-like process $D^0 \to \bar{K}^{*0}\gamma$.

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 essentially 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).

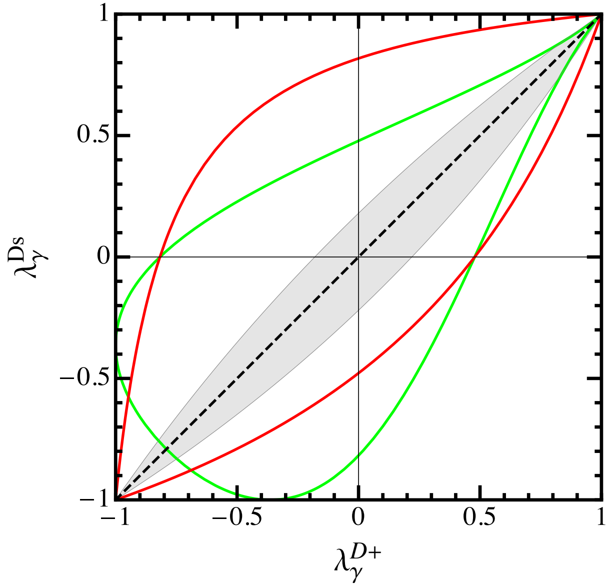
$\bar{R} = 1/f^2 \frac{|V_{cs}|^2}{|V_{cd}|^2} \frac{\mathcal{B}(D^0 \to \rho\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)}$ with leading U-spin breaking removed $f = m_\rho f_\rho/(m_{K^{*0}} f_{K^{*0}})$

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

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

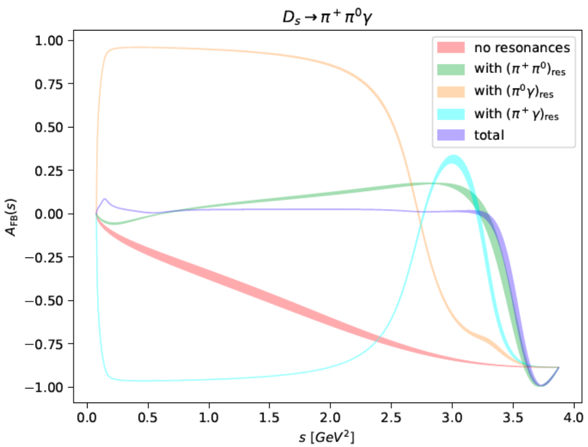
$D^+ \to K^+\overline{K}^0\gamma\,, D^0 \to \pi^+\pi^-\gamma\,,\ D^0 \to K^+K^-\gamma$

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

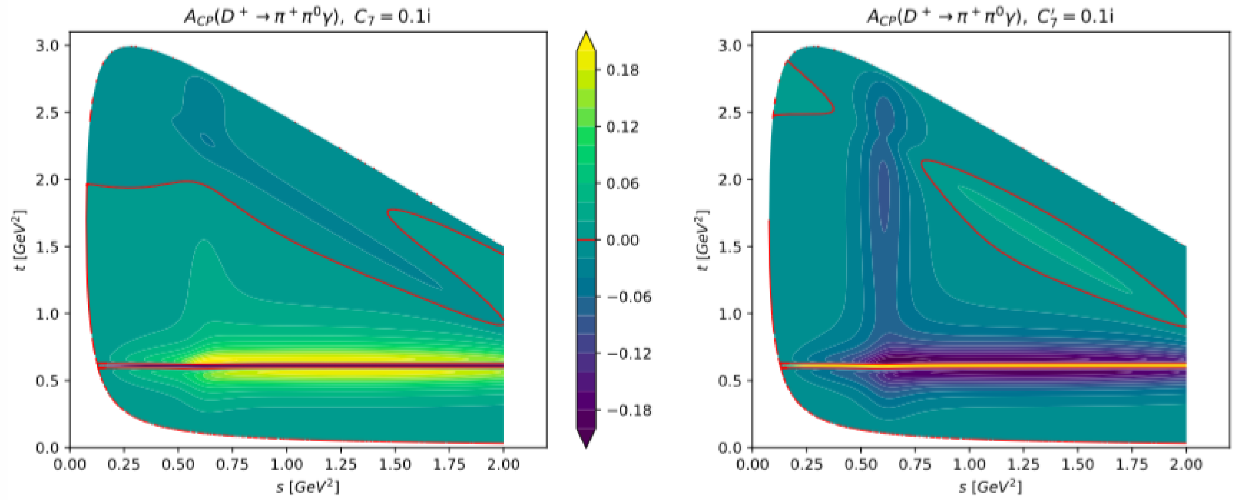
Test QCD methods (QCDF/weak annihilation, HHχPT) with CF,DCS and then SM with SCS

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

CP-asymmetries in Dalitz region



SM



BSM

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

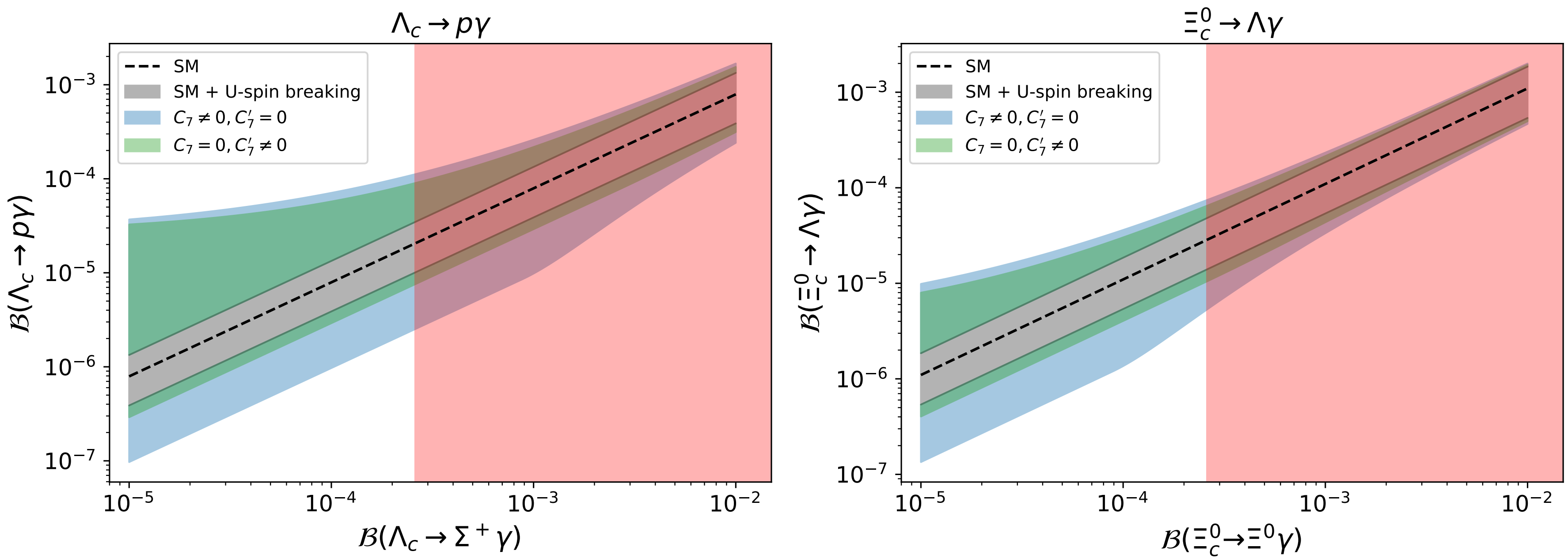
theory and observables: 2203.14982 $SU(3)_F$ techniques

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 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. $A_7^{(\prime)} = A_{\text{NP}}^{(\prime)} + A_{\text{LD}}^{(\prime)}$ 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.

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

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



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 $B(\Xi_c^0 \to \Lambda\gamma) \lesssim 7 \cdot 10^{-5}$

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:

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

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

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

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

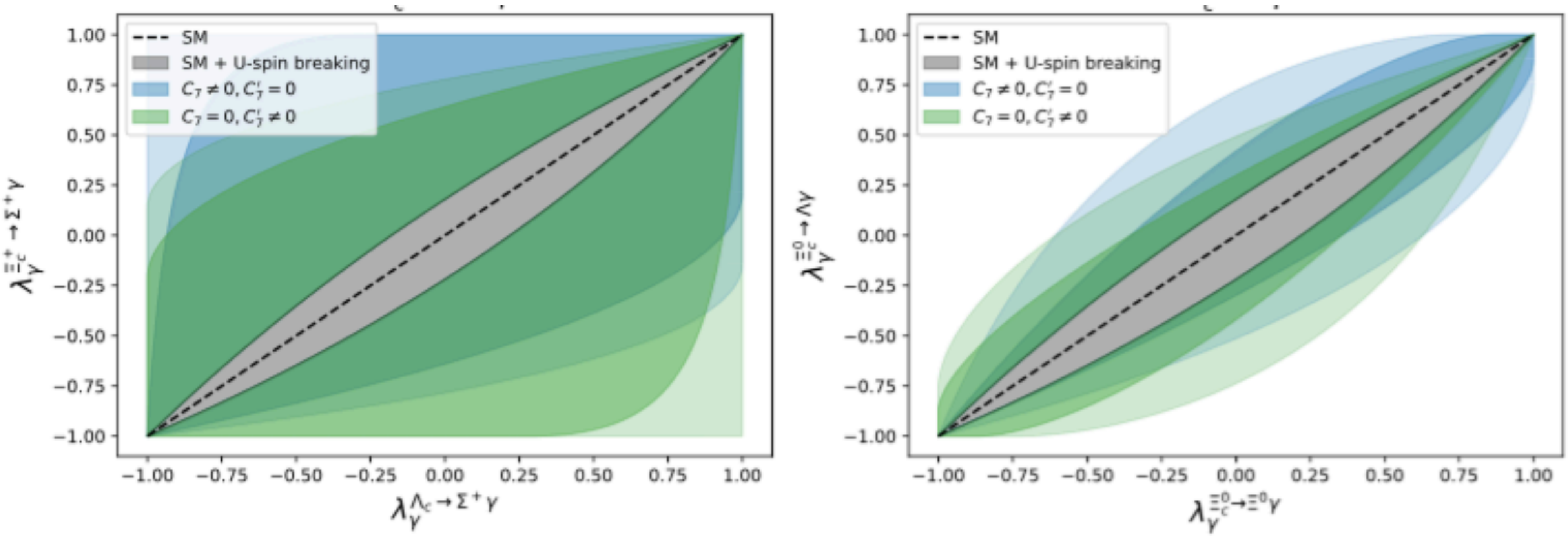


Figure 2: BSM reach of λ_γ of the BSM sensitive decay modes $\Xi_c^+ \to \Sigma^+\gamma$ (left plot) and $\Xi_c^0 \to \Lambda\gamma$ (right plot) as a function of the photon polarization of the corresponding SM-like decay modes, $\Lambda_c \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$, respectively, 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

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

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

points of interest: dileptonic charm decays

$B(D \to \pi\pi\mu\mu) \simeq 9.6 \cdot 10^{-7}$ LHCb'18

$B(\Lambda_c \to p\mu\mu) \lesssim 7.7 \cdot 10^{-8}$ LHCb'17,

angular distributions $D \to \pi\pi\mu\mu$ LHCb, $A_{FB}(\Lambda_c \to p\mu\mu)$ and CP at few $\%$ level, LHCb2025

$D \to \pi\mu\mu, D \to \mu\mu$ upper limits by LHCb and CMS

see talk by Dominik Mitzel

$B(\Xi_c^0 \to \Xi^0\mu^+\mu^-) < 6.5 \cdot 10^{-5}$, $B(\Xi_c^0 \to \Xi^0 e^+e^-) < 9.9 \cdot 10^{-5}$ Belle 2312.02580 $B(D_s^+ \to K^+\pi^0 e^+e^-) < 7.1 \cdot 10^{-5}$ BES III 2404.05973

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:

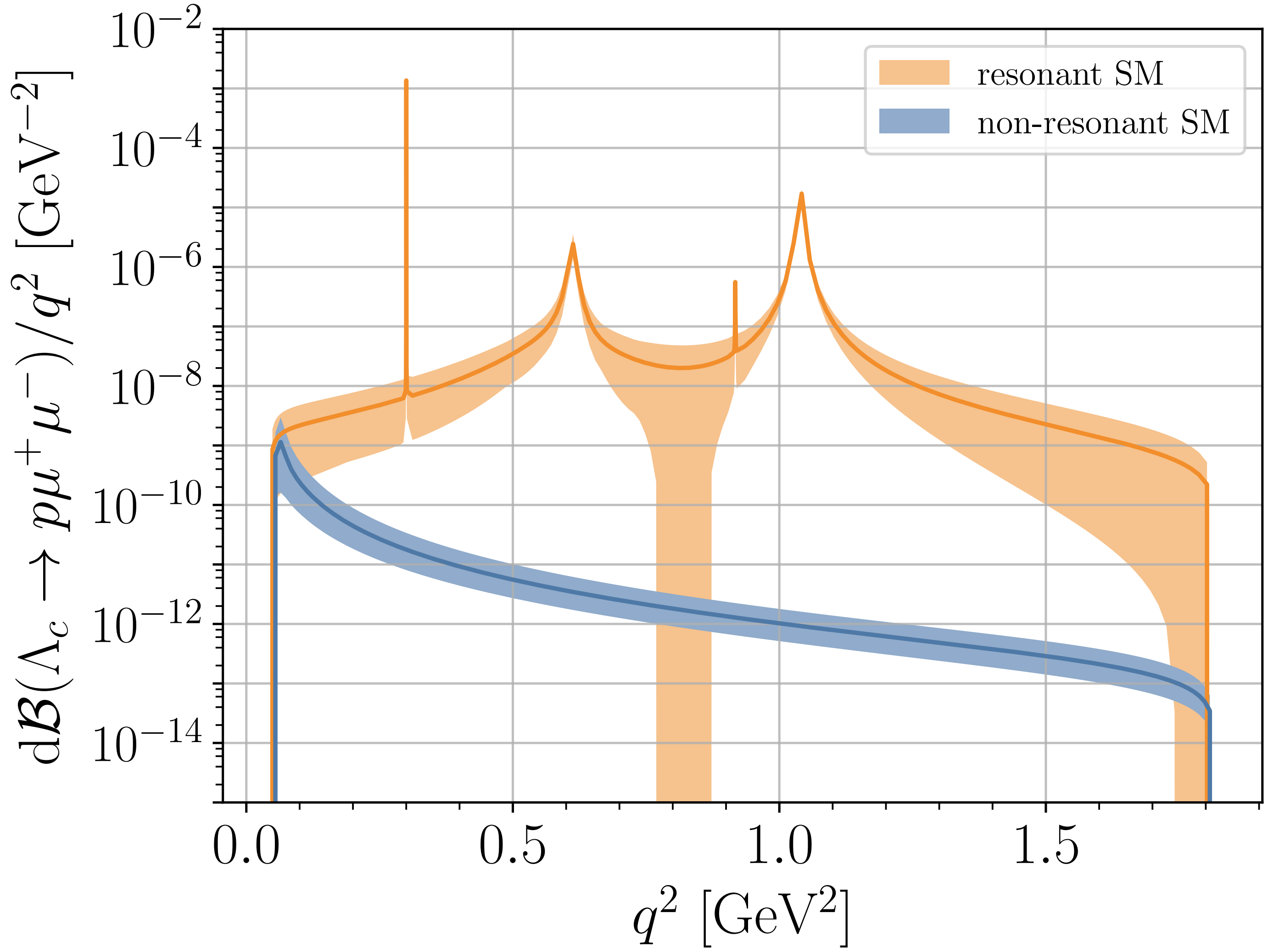
$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2 \mathrm{d}\cos\vartheta_\ell} = \frac{3}{2}\left(K_{1ss}\sin^2\vartheta_\ell + K_{1cc}\cos^2\vartheta_\ell + K_{1c}\cos\vartheta_\ell\right)$$

$\rightarrow$ 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 others 2203.14982

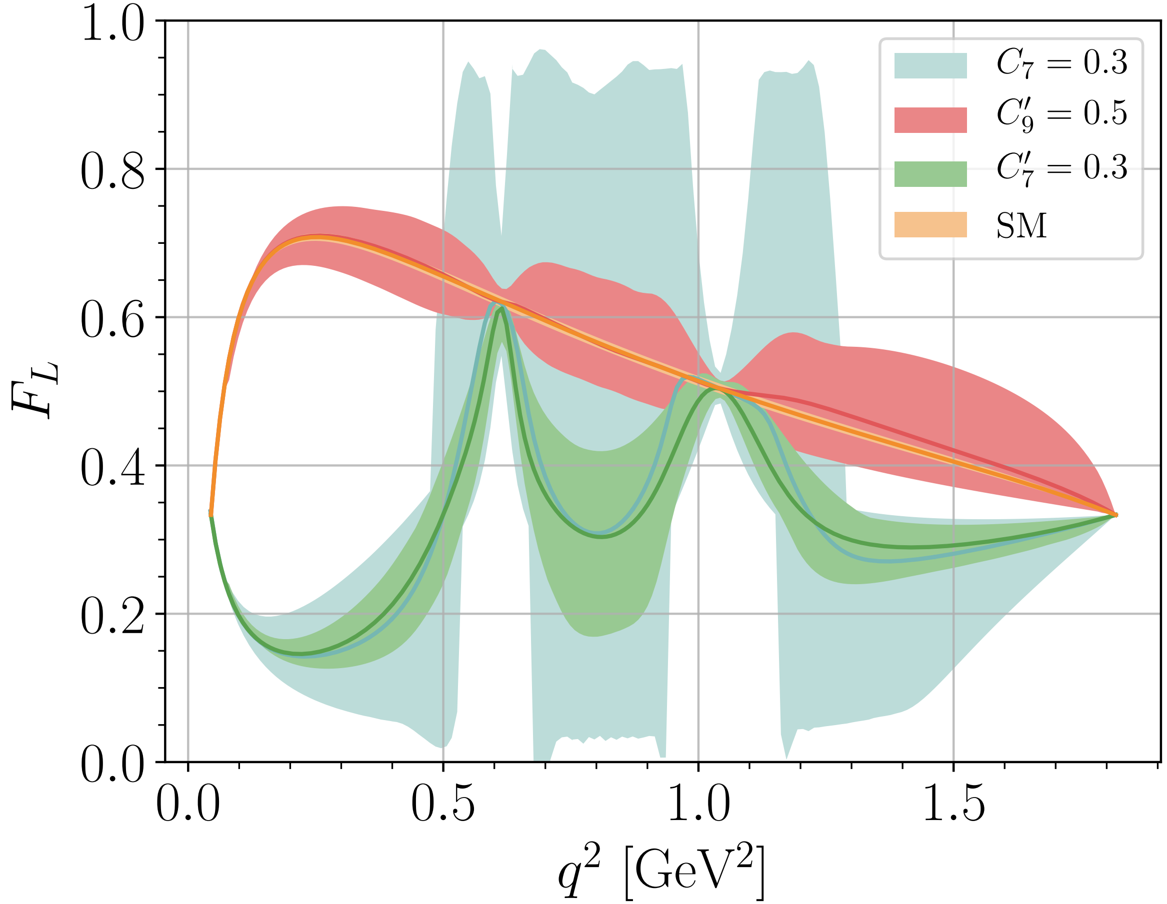
$-\sqrt{6}h_\perp^{\Xi_c^0\to\Lambda} = \sqrt{2}h_\perp^{\Xi_c^0\to\Sigma^0} = h_\perp^{\Xi_c^+\to\Sigma^+} = h_\perp^{\Lambda_c\to p}$; Endpoint relations (at q^2 =max): 2107.12993

Branching ratio: $(-)$



2107.13010

Longitudinal polarization: $(+)$



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Sensitivity to dipole coefficients!

GIM null tests: AFB $(++)$

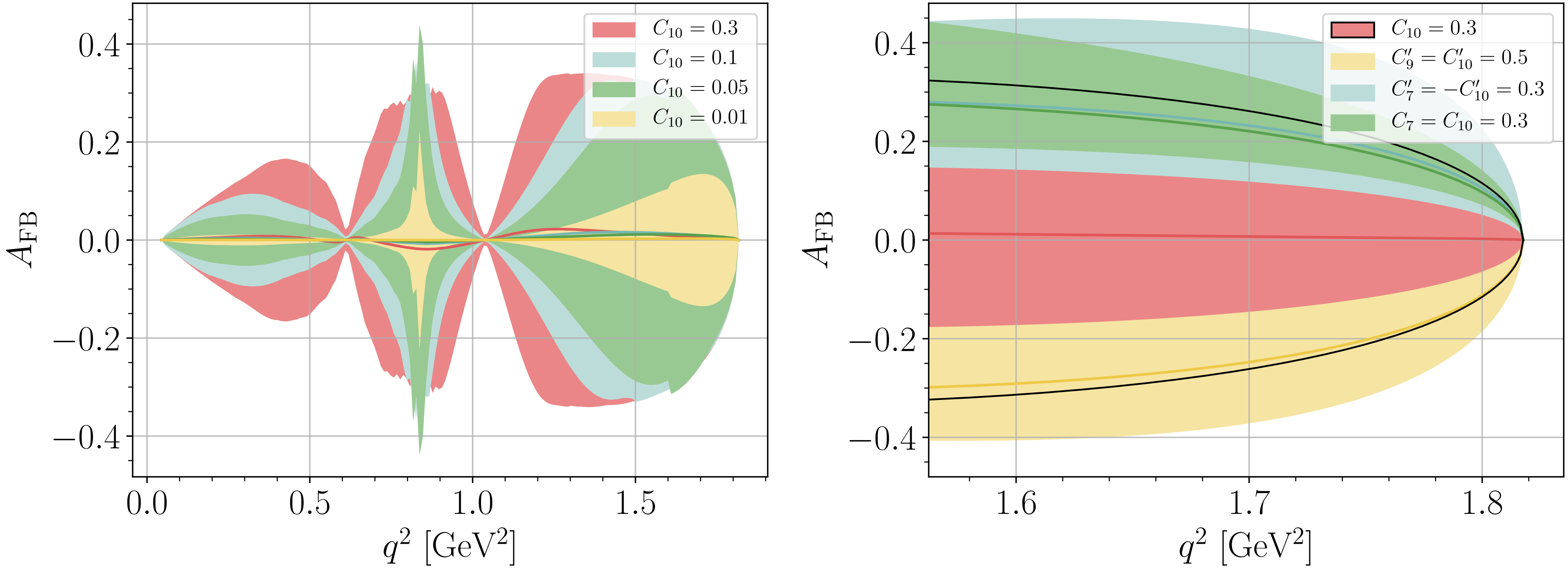


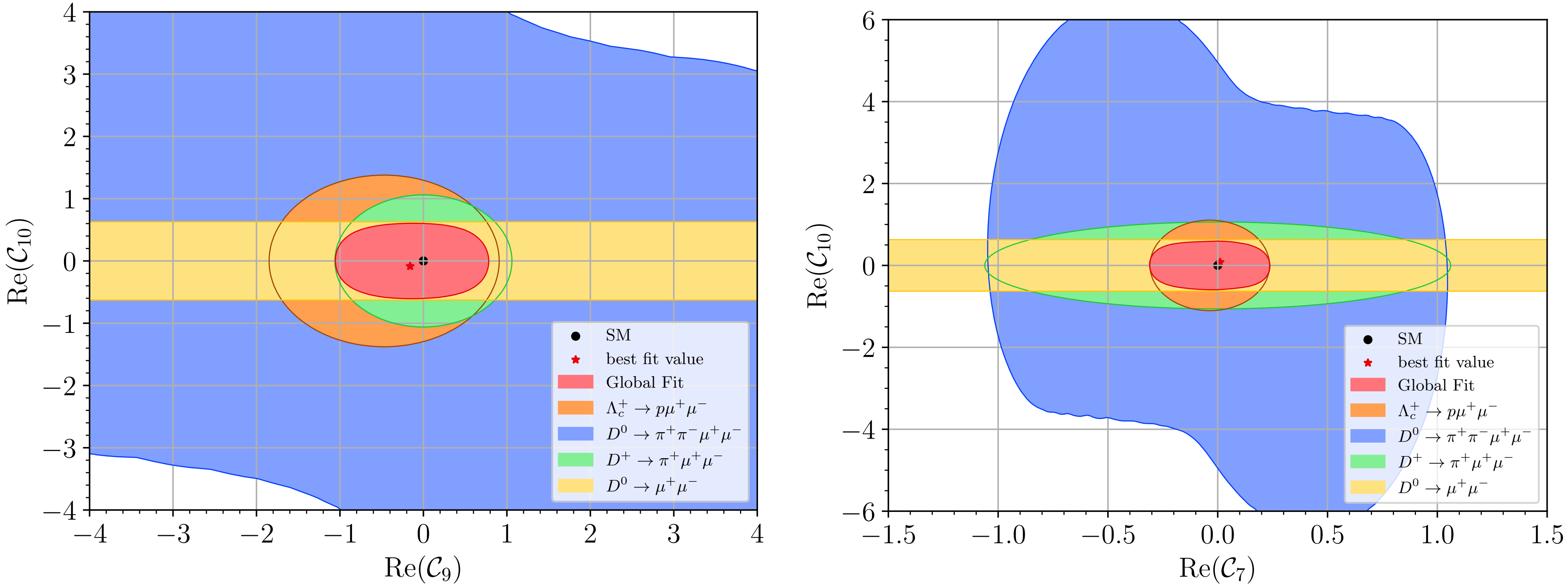
Figure 3: The forward-backward asymmetry $A_{\rm FB}$ of $\Lambda_c \to p\mu^+\mu^-$ decays for different values of C_{10} in the full q^2-region (left panel) and for various BSM contributions in the high q^2 region (right panel)

$A_{\rm FB} \propto C_{10}$ 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

First global $|\Delta c| = |\Delta u| = 1$ fit

Global analysis, using $D \to \mu\mu$, $D \to \pi\mu\mu$, $\Lambda_c \to p\mu\mu$, and $D \to \pi\pi\mu\mu$



2410.00115 $\Lambda_c \to p\mu\mu$ rising star: null test available, also polarization obsevables, 3-body decay

$A_{FB}(\Lambda_c \to p\mu\mu)$, and $S_{5,6,7}, A_{5,6,7}$ of $D \to \pi\pi\mu\mu$ clean null tests due to GIM-protection ($\propto C_{10}$).

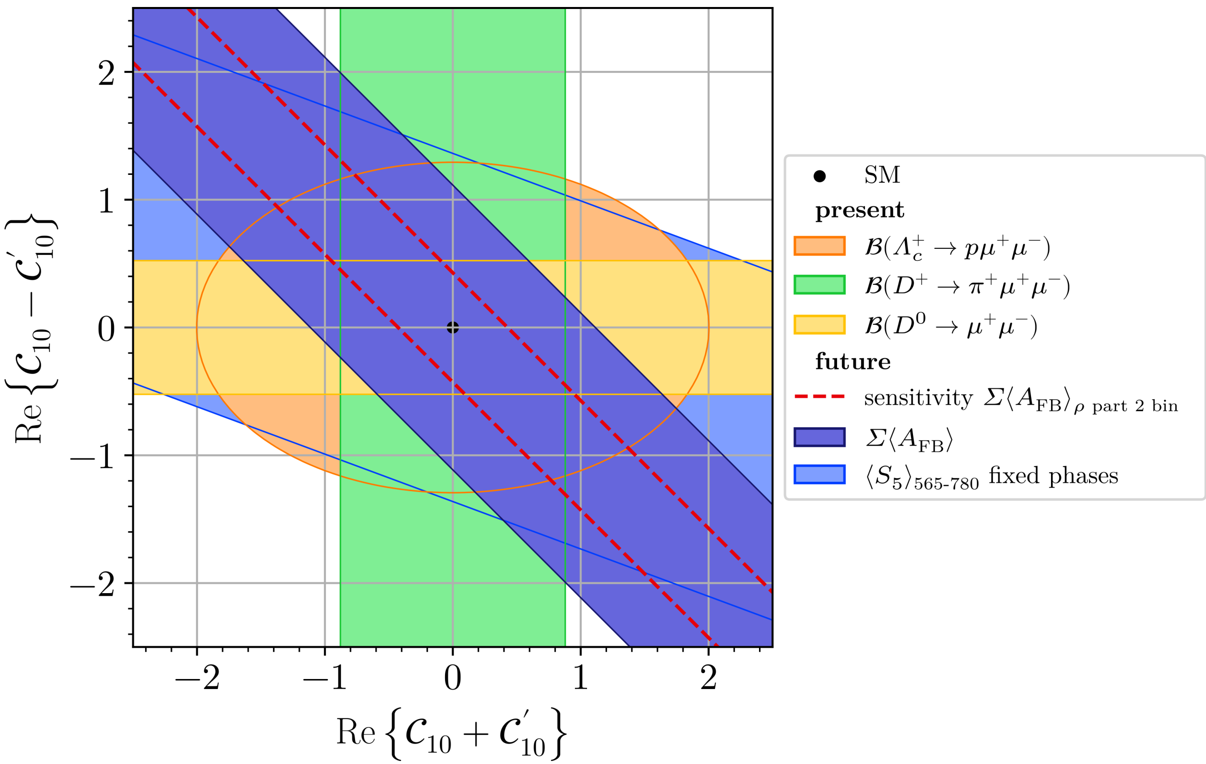


Figure 4: Complementarity of constraints in $\mathrm{Re}\,\{\mathcal{C}_{10} \pm \mathcal{C}_{10}'\}$ from current branching ratio data on $D \to \mu^+\mu^-$ (yellow), $D^+ \to \pi^+\mu^+\mu^-$ (green) and $\Lambda_c \to p\mu^+\mu^-$ (orange), together with hypothetical future measurements of $\Sigma\langle A_{\rm FB}\rangle$ at 7% level (dark blue) and $\langle S_5\rangle$ at 0.7% (light blue), see 2410.00115

Sensitivity limited by strong phases, also for null tests; binning matters 2410.00115

Summary

- Rare charm decays test the SM and can cleanly signal new physics with null tests of the SM
- BSM effects in $|\Delta c| = |\Delta u| = 1$ can be huge; complement searches in B, K-sectors
- Lots of blanks in PDG, but experiments are ramping up (LHCb, BESIII, Belle (II) ,..)
- Nature has given us a gift with strong GIM that defines powerful null tests in charm FCNCs C_{10}, and with dineutrinos
  $SU(3)_F$,, U-spin etc helpful but limited once data are near SM
- If NP is seen, the hadronic ME's strike back: more TH effort in taking more control of non-perturbative effects, esp. strong phases to improve interpretability of possible NP signals
- U-spin/CP puzzle hints at combined breaking of SM symmetries. Possible connection with other low energy puzzles

TH suggestions

–improve transition form factors: CKM for $c \to (d,s)\ell\nu$
clean interpretation of $c \to u\nu\bar{\nu}$ and cLFV $c \to ue\mu$
specifically $D \to \pi\pi\nu\bar{\nu}$, $D \to \rho\nu\bar{\nu}$ have room for improvement
input for $c \to u\ell\ell$
–radiative decays: impact of resonances, understand $D \to V\gamma$;
$D \to \pi\pi\gamma$ and angular distribution diagnostic or QCD
– dileptonic decays: computation of 3-body decay amplitudes
$D \to \pi R$, or $\Lambda_c \to pR$, $R \to \mu\mu$, with resonances $R = \rho, \omega, \varphi, ...$
– experimentally promising $D \to \pi\pi\mu\mu$ with even more complicated resonance structure but also further null tests.
– $SU(3)_F$ system in $D \to PP$ observables can indicate BSM CPX in U-spin and/or Isopsin violation, presently exciting due to large $A_{CP}(\pi^+\pi^-)$; $\pi^+\pi^0, K_s K_s, \pi^0\pi^0$

Back up

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

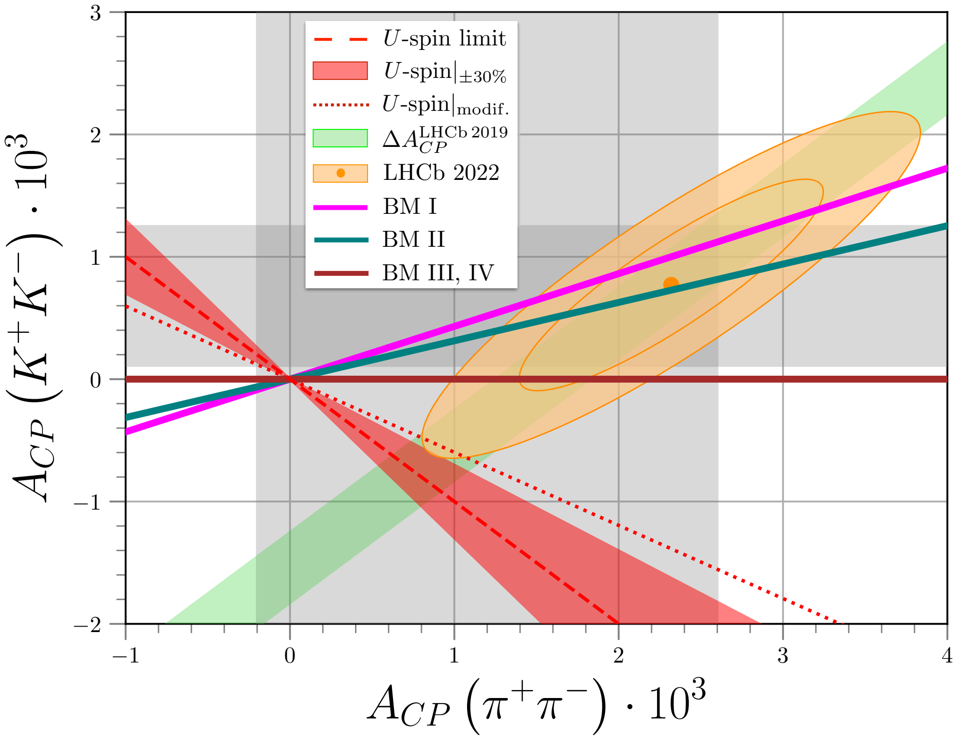


Fig from 2210.16330, LHCb result (orange ellipse) from 2209.03179 SM theory recently 2305.11951, 2312.13245

A Puzzle in hadronic charm CPX/UX

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

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

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

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

Data $A_{\mathrm{CP}}^{\pi^-\pi^+} = (23.2 \pm 6.1) \cdot 10^{-4}$ 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 $h/t \sin\delta \lesssim 0.1$.

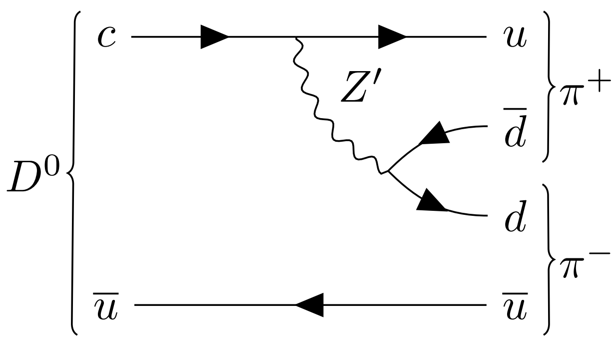
We need the U-spin breaking on top.

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

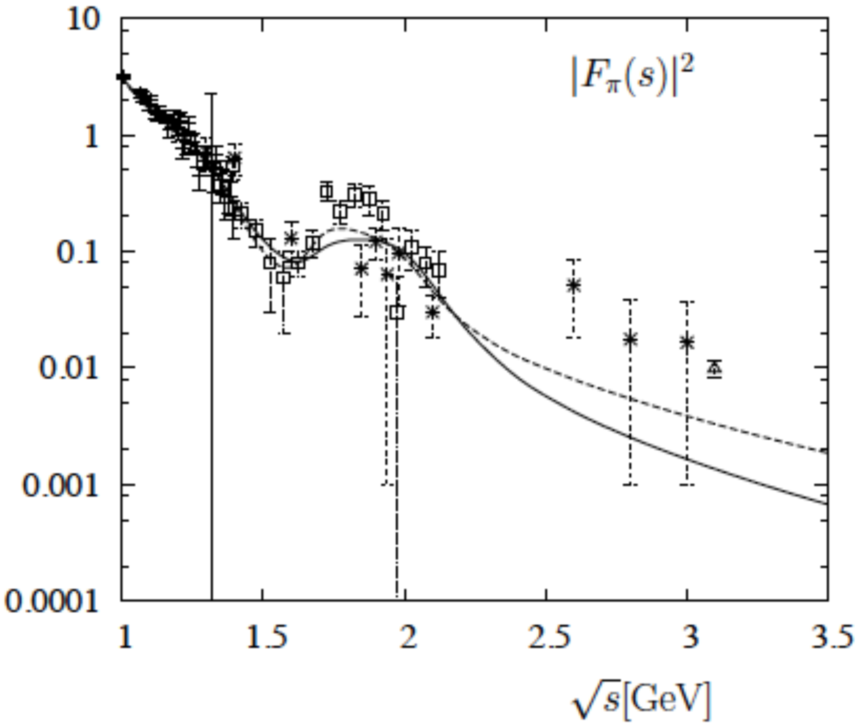
Signatures in low mass dijets, $J/\Psi/\Psi'$, Υ decays, $A_{CP}(D\to\pi^0\pi^0), A_{CP}(D\to\pi^+\pi^0) \sim A_{CP}(D\to\pi^+\pi^-)$.

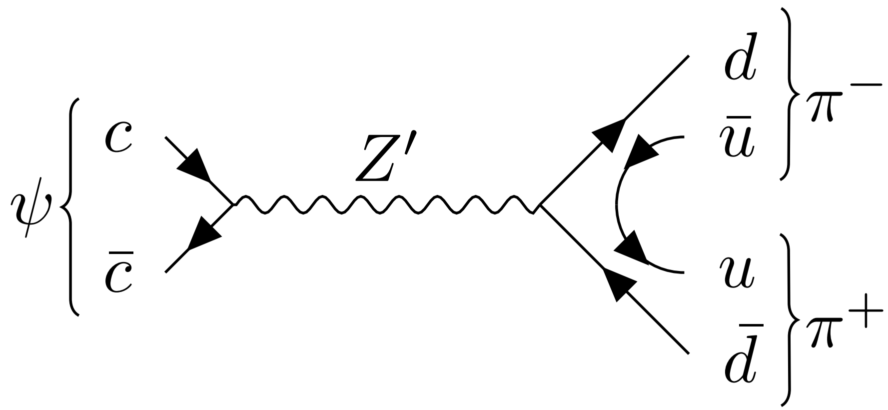
A light Z' in hadronic charm CPX/UX

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

Table 4: 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

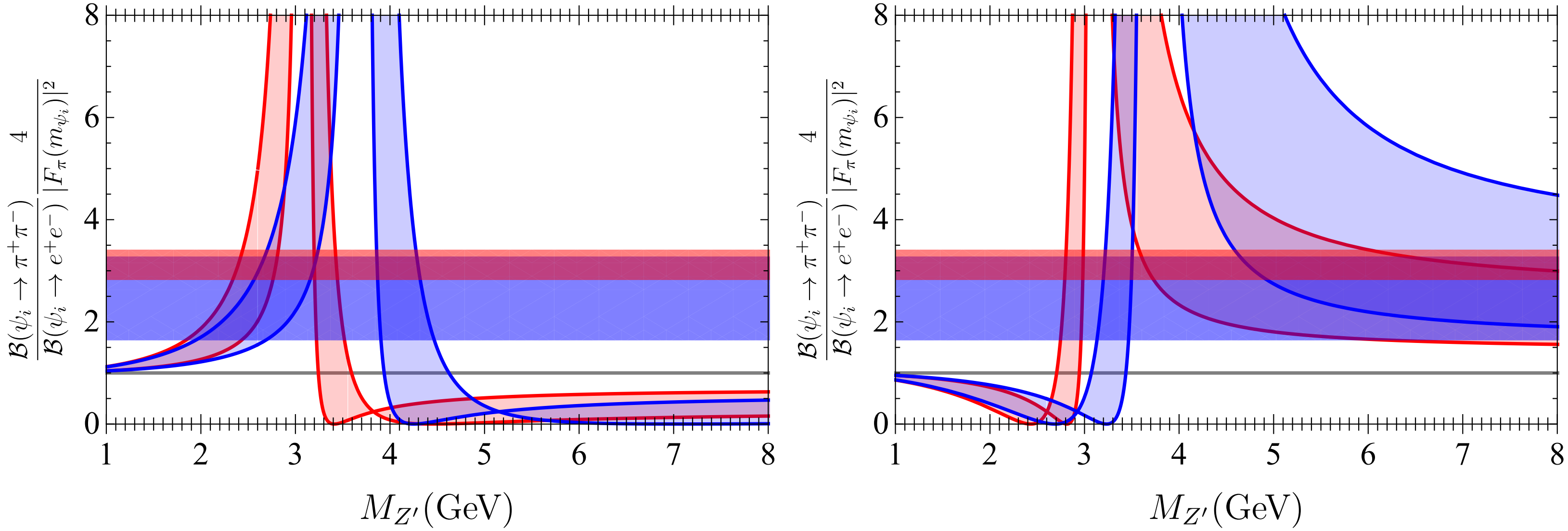


Figure 5: Constraints from charmonium decays. Horizontal red (blue) bands denote the left-hand side of (**??**) from 1 sigma ranges of J/ψ-data with $|F_\pi(m_{J/\psi})| = 0.056$ (ψ' decays with $|F_\pi(m_{\psi'})| = 0.04$.). Curves correspond to the predictions of BM III with $F \gg G$ (left) and BM IV (right). The SM prediction via photon-exchange is shown by the grey line.