Decays of charmed and strange hadrons shining light on dark photons

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NCTS

Based on

Jhih-Ying Su & JT, arXiv:1911.13301 & ongoing work

NCTS Dark Physics Workshop

National Center for Theoretical Sciences, Hsinchu, Taiwan

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- Introduction
- Flavor-changing neutral current (FCNC) decays of hadrons induced by $q \to q'\bar{\gamma}$ with a massless dark photon ($\bar{\gamma}$) emitted invisibly.
  - Strange hadron decays
  - Charmed hadron decays.
- Conclusions

- Flavor-changing neutral current (FCNC) transitions, $q \to q' \not{E}$, with missing energy ($\not{E}$) have suppressed rates in the standard model (SM)
- New physics (NP) beyond the SM could modify the SM contribution and/or induce new channels with one or more invisible particles, possibly enhancing the rates significantly relative to the SM expectations.
- If large enough, the potential NP effects would likely be testable by near-future or even ongoing experiments searching for FCNC hadron decays with missing energy.

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- If large enough, the potential NP effects would likely be testable by near-future or even ongoing experiments searching for FCNC hadron decays with missing energy.
- Of interest here are the decays of hadrons induced by $s \to d\not{E}$ & $c \to u\not{E}$.
  - The missing energy may be carried away by one or more invisible particles.

- If the SM is extended with the addition of a dark sector having an unbroken U(1) gauge group, its associated gauge field and that of the SM U(1) can be defined such that Holdom, 1986
  - one of their gauge bosons, the dark photon ($\bar{\gamma}$), only sees the dark sector
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- Of interest here are the FCNC quark transitions $s \to d\bar{\gamma}$ and $c \to u\bar{\gamma}$ with the massless dark photon appearing as missing energy.
- If their couplings are sufficiently large, they may give rise to FCNC decays of hadrons with missing energy which are potentially discoverable at ongoing or near-future experiments.

- Massive dark photon couplings to SM fermions $\epsilon e A'_\mu J^\mu_{\rm EM}$

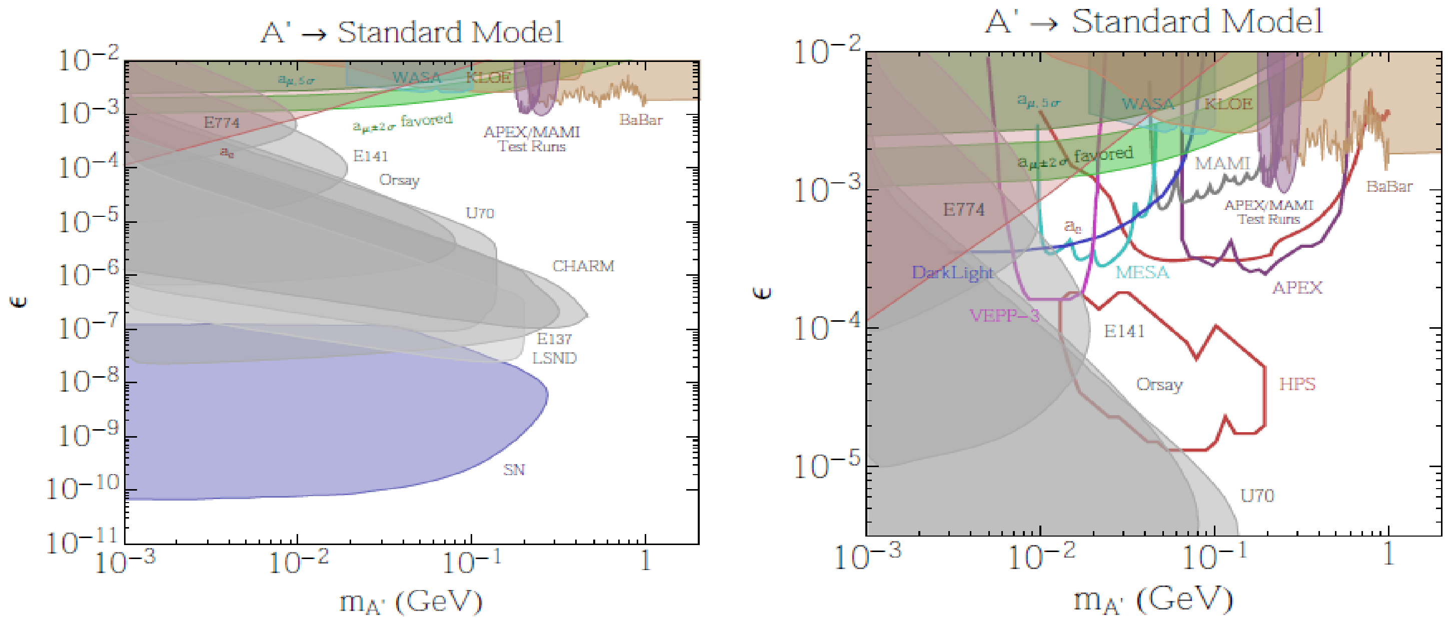


FIG. 6. Parameter space for dark photons (A') with mass $m_{A'} > 1$ MeV (see Fig. 7 for $m_{A'} < 1$ MeV). Shown are existing 90% confidence level limits from the SLAC and Fermilab beam dump experiments E137, E141, and E774 [116–119] the electron and muon anomalous magnetic moment a_μ [120–122], KLOE [123] (see also [124]), WASA-at-COSY [125], the test run results reported by APEX [126] and MAMI [127], an estimate using a BaBar result [116, 128, 129], and a constraint from supernova cooling [116, 130, 131]. In the green band, the A' can explain the observed discrepancy between the calculated and measured muon anomalous magnetic moment [120] at 90% confidence level. On the right, we show in more detail the parameter space for larger values of ϵ. This parameter space can be probed by several proposed experiments, including APEX [132], HPS [133], DarkLight [134], VEPP-3 [135, 136], MAMI, and MESA [137]. Existing and future e^+e^- colliders such as *BABAR*, BELLE, KLOE, Super*B*, BELLE-2, and KLOE-2 can also probe large parts of the parameter space for $\epsilon > 10^{-4} - 10^{-3}$; their reach is not explicitly shown.

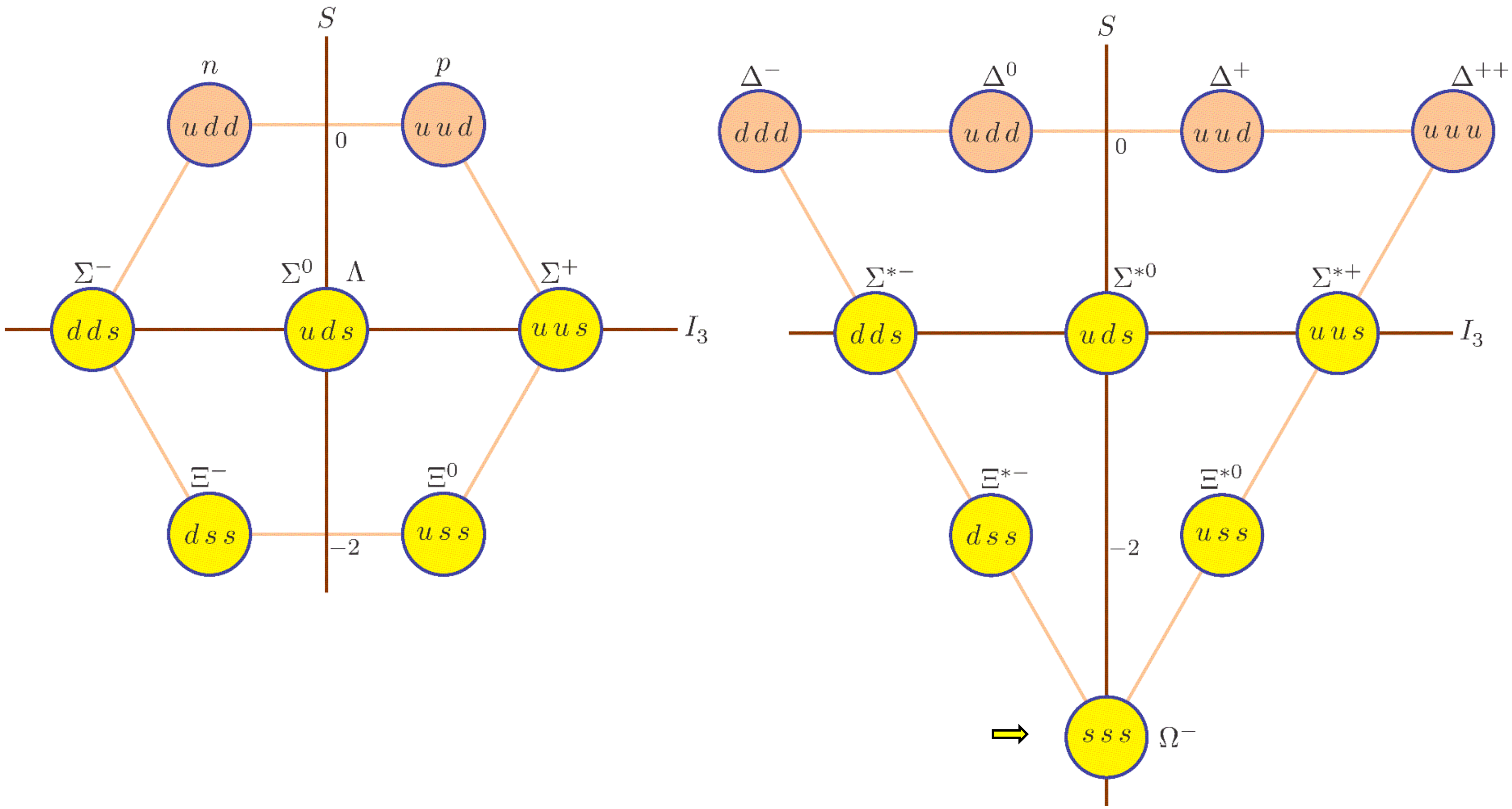
- Massive dark photon couplings to SM fermions $\epsilon e A'_\mu J^\mu_{\rm EM}$

- Constraints from kaon decays
  - $K \to \pi A'$
  - $K \to \mu\nu A'$

- Massless dark photons evade the above constraints because of no direct couplings to SM fermions
  - $K \to \pi\bar{\gamma}$ forbidden by angular momentum conservation

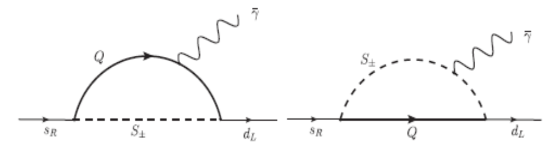
Flavor-SU(3) octet of spin-1/2 baryons & decuplet of spin-3/2 baryons

- **Hyperons**



* Interactions of on-shell massless dark photon with d and s quarks

$$\mathcal{L}_{ds\bar{\gamma}} = -\overline{d}\sigma^{\mu\nu}(\mathbb{C} + \gamma_5\mathbb{C}_5)s\bar{B}_{\mu\nu} + \mathrm{H.c.}$$



$\mathbb{C}$ & $\mathbb{C}_5$ are constants which depend on the NP model details,

$\bar{B}_{\mu\nu} = \partial_\mu\bar{A}_\nu - \partial_\nu\bar{A}_\mu$ is the dark photon's field strength tensor,

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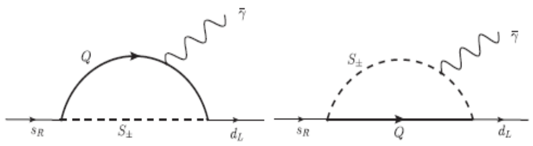

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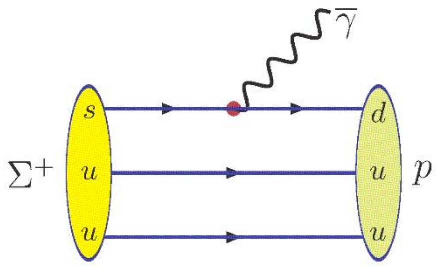

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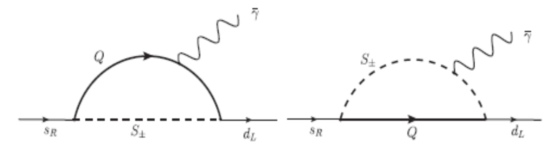

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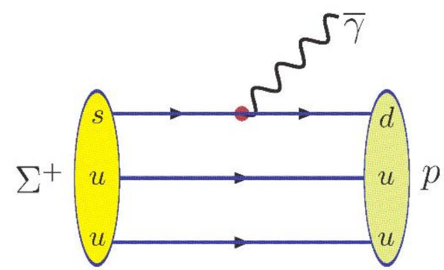

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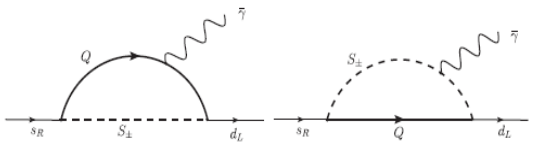

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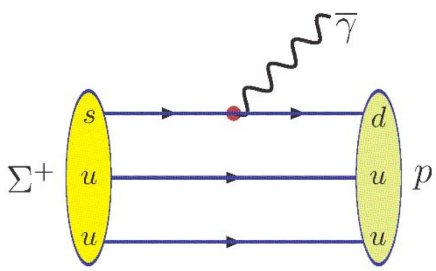

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∗ They were already estimated by Gilman & Wise (1978) for $\mathfrak{B} \to \mathfrak{B}'\gamma$ using quark-model SU(6) wave functions.

Decay rates

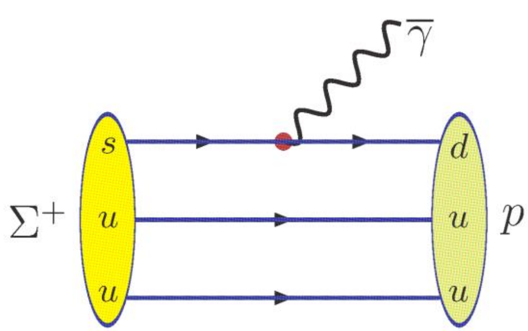
* Decay rate $\Gamma(\mathfrak{B} \to \mathfrak{B}'\overline{\gamma}) = \frac{\mathcal{C}^2_{\mathfrak{B}'\mathfrak{B}}\left(m^2_{\mathfrak{B}} - m^2_{\mathfrak{B}'}\right)^3 m_{\mathfrak{B}'}}{2\pi\, m^4_{\mathfrak{B}}}\left(|\mathbb{C}|^2 + |\mathbb{C}_5|^2\right)$

$\mathfrak{B}'\mathfrak{B}$	$n\Lambda$	$p\Sigma^+$	$\Lambda\Xi^0$	$\Sigma^0\Xi^0$	$\Sigma^-\Xi^-$	$\Xi^-\Omega^-$
$\mathcal{C}^2_{\mathfrak{B}'\mathfrak{B}}$	$\frac{3}{2}$	$\frac{1}{9}$	$\frac{1}{6}$	$\frac{25}{18}$	$\frac{25}{9}$	$\frac{4}{3}$

Gilman & Wise, 1978

Decay mode	$\Lambda \to n\overline{\gamma}$	$\Sigma^+ \to p\overline{\gamma}$	$\Xi^0 \to \Lambda\overline{\gamma}$	$\Xi^0 \to \Sigma^0\overline{\gamma}$	$\Xi^- \to \Sigma^-\overline{\gamma}$	$\Omega^- \to \Xi^-\overline{\gamma}$
$\frac{\mathcal{B}}{\lvert\mathbb{C}\rvert^2}$ (GeV^2)	2.75×10^{12}	1.54×10^{11}	4.95×10^{11}	1.12×10^{12}	1.32×10^{12}	5.18×10^{12}

The branching fractions $\mathcal{B}$ of $\mathfrak{B} \to \mathfrak{B}'\overline{\gamma}$ divided by $|\mathbb{C}|^2$.



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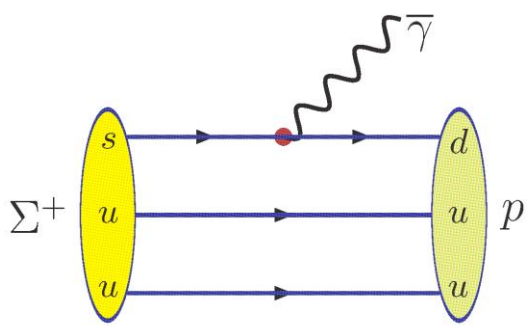
- How large $\mathbb{C}$ and $\mathbb{C}_5$ may be depends on the NP model.



* In Scenario I the $ds\bar{\gamma}$ coupling constant $\mathbb{C} = \dfrac{e_D\,\xi}{64\pi^2\tilde{\Lambda}}$

e_D is the dark photon's coupling, $\tilde{\Lambda}$ the NP effective heavy mass scale,
ξ contains Yukawa couplings of the new particles and SM quarks.

Fabbrichesi, Gabrielli, Mele, PRL 2017

These Yukawa couplings are most constrained by kaon-mixing data

$$\Delta m_K^{\rm NP} = 8.47 \times 10^{-13}\,{\rm TeV}^3\,\xi^2/\tilde{\Lambda}^2 < 0.3\Delta m_K^{\rm exp}$$

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* Prediction: $\mathcal{B}(K^+ \to \pi^+\pi^0\bar{\gamma}) \lesssim 1.0 \times 10^{-5}$, potentially testable by NA62.

Predictions of 2 different NP scenarios

Decay mode	$\Lambda \to n\overline{\gamma}$	$\Sigma^+ \to p\overline{\gamma}$	$\Xi^0 \to \Lambda\overline{\gamma}$	$\Xi^0 \to \Sigma^0\overline{\gamma}$	$\Xi^- \to \Sigma^-\overline{\gamma}$	$\Omega^- \to \Xi^-\overline{\gamma}$
$\mathcal{B}_{\rm max}$ [I]	1.1×10^{-5}	6.0×10^{-7}	1.9×10^{-6}	4.3×10^{-6}	5.1×10^{-6}	2.0×10^{-5}
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Su & JT, 1911.13301

- Some of these numbers may be probed by BESIII

Estimated BESIII sensitivity for branching fractions

HB Li, 1612.01775

$\Lambda \to n\nu\bar{\nu}$	$\Sigma^+ \to p\nu\bar{\nu}$	$\Xi^0 \to \Lambda\nu\bar{\nu}$	$\Xi^0 \to \Sigma^0\nu\bar{\nu}$	$\Xi^- \to \Sigma^-\nu\bar{\nu}$	$\Omega^- \to \Xi^-\nu\bar{\nu}$
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3×10^{-7}	4×10^{-7}	8×10^{-7}	9×10^{-7}	—	2.6×10^{-5}

- But already the current hyperon data (PDG 2019) have started to constrain Scenario II
  - Indirect (2σ) upper limits on the branching fractions of yet-unobserved decay modes of Λ, Σ^+, Ξ^0, Ξ^-, and Ω^-, are 1.4%, 8.0×10^{-3}, 3.4×10^{-4}, 8.3×10^{-4}, and 1.6%, respectively.

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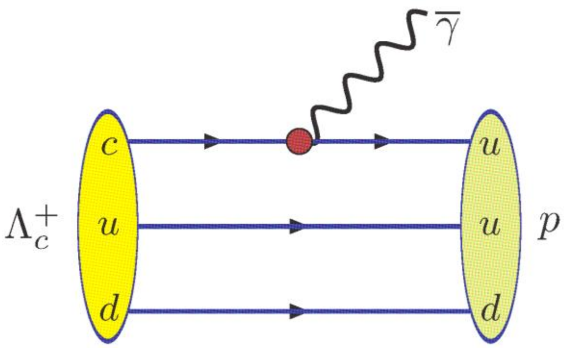

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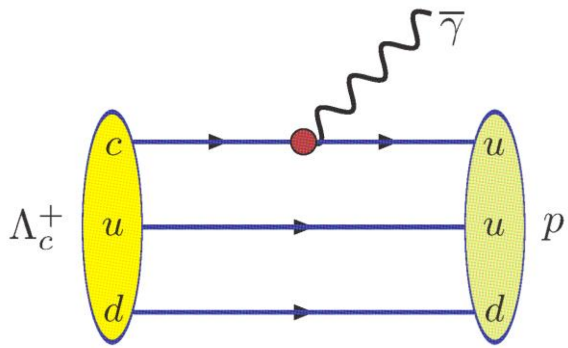

$$\langle p|\overline{u}\sigma^{\mu\nu}(1,\gamma_5)c|\Lambda_c^+\rangle\,\bar{\varepsilon}^*_\mu\bar{q}_\nu = f_T\,\bar{u}_p\sigma^{\mu\nu}(1,\gamma_5)u_{\Lambda_c}\,\bar{\varepsilon}^*_\mu\bar{q}_\nu$$

$f_T = 0.38(1\pm0.1)$ & $0.50(1\pm0.07)$

1805.02516 & 1712.05783

$$\Gamma_{\Lambda_c^+\to p\bar{\gamma}} = \frac{f_T^2\left(m_{\Lambda_c}^2-m_p^2\right)^3}{8\pi m_{\Lambda_c}^3}\left(|\mathcal{C}|^2+|\mathcal{C}_5|^2\right)$$

$$\mathcal{B}(\Lambda_c^+\to p\overline{\gamma}) \lesssim 1.7\times10^{-4}$$

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- In an example of NP model $|\mathcal{C}| \lesssim 6.3\times10^{-8}\ \mathrm{GeV}^{-1}$ Gabrielli *et al.*, 2016

- The corresponding predicted branching fractions can be significant

$$\mathcal{B}(\Lambda_c^+\to p\overline{\gamma}) \lesssim 1.7\times10^{-4}$$

$$\mathcal{B}(D^+\to \rho^+\overline{\gamma}) \lesssim 8.1\times10^{-4}$$

$$\mathcal{B}(D^0\to \omega\overline{\gamma}) \lesssim 2.7\times10^{-4}$$

$$\mathcal{B}(D_s^+\to K^{*+}\overline{\gamma}) \lesssim 3.8\times10^{-4}$$

$\Lambda_c^+ = u\,d\,c$

$D^+ = c\overline{d},\ D^0 = c\overline{u}$

$D_s^+ = c\overline{s}$

- Some of these may be detectable by Belle 2 or BESIII.

- If massless dark photons exist, they do not couple at tree level to SM fermions but can still interact with them via higher-dimensional operators.
- In NP models, massless dark photons can have nonnegligible flavor-changing dipole-type interactions with the lightest down-type or up-type quarks.
- Such interactions can induce FCNC decays of charmed and strange hadrons with missing energy carried away by the dark photon.
- Their rates may be sufficiently significant to be discoverable in ongoing & near-future experiments at Belle II and BESIII.