Flavor-changing charm decays illuminating dark photons at CEPC

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Based on

Jhih-Ying Su & JT, arXiv:2005.05297

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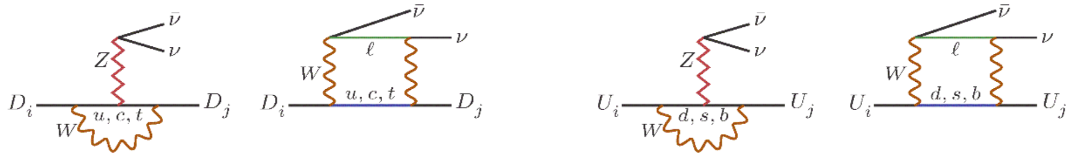
- Introduction
  - FCNC transitions with missing energy
  - Massive vs massless dark photons
- FCNC decays of charmed hadrons with a massless dark photon emitted invisibly
- Conclusions

- Flavor-changing neutral current (FCNC) quark transitions $q \to q'\not{E}$ with missing energy ($\not{E}$) are suppressed in the standard model (SM)
  - due to the GIM mechanism and loop factors.



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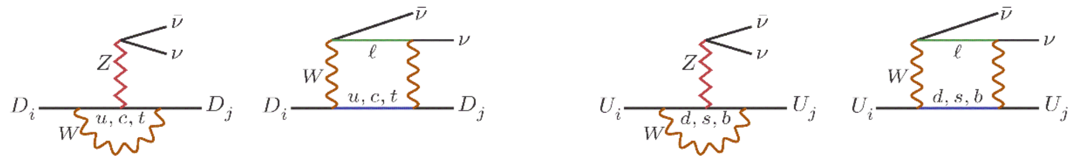

- New physics (NP) beyond the SM could modify the SM contribution and/or induce channels with one or more invisible new particles.
  - If large enough, the potential NP impact may be testable by ongoing or near-future experiments seeking the FCNC decays of hadrons with missing energy.

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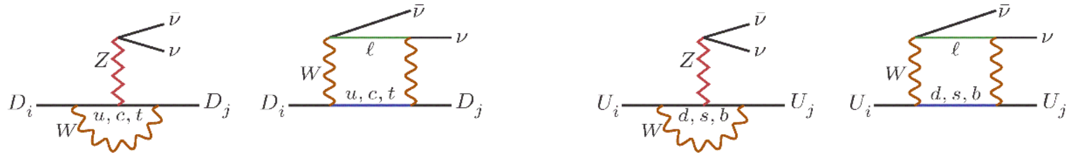

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  - If large enough, the potential NP impact may be testable by ongoing or near-future experiments seeking the FCNC decays of hadrons with missing energy.

- Of interest here are the decays of charmed hadrons induced by $c \to u\not{E}$.
  - The SM contribution is extremely small due to highly effective GIM suppression.
- Our focus is on the possibility in which the missing energy is carried away by a massless dark photon.

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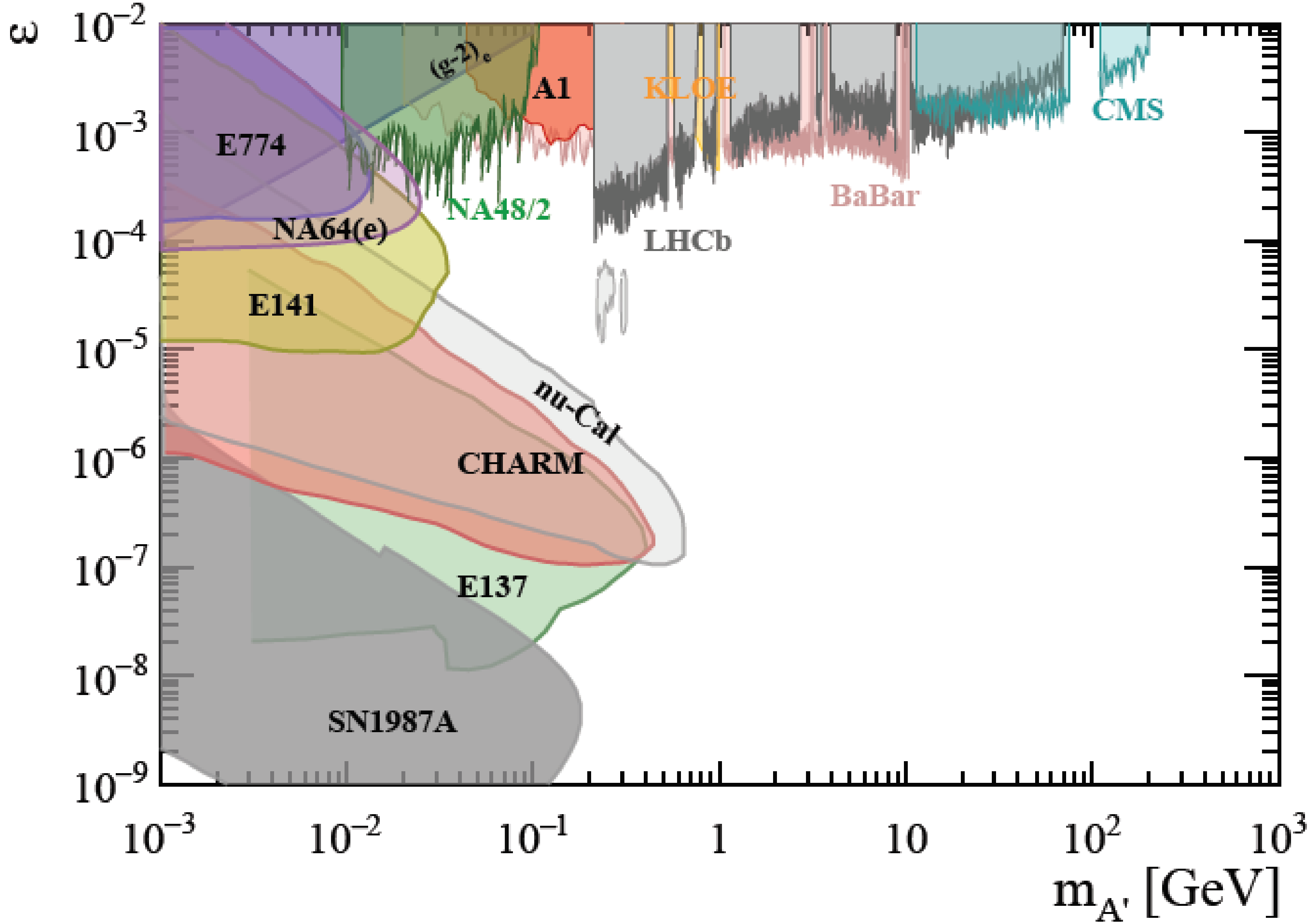
- If $\mathrm{U}(1)_D$ is spontaneously broken, its associated gauge boson, the dark photon, becomes massive.
- If the dark and SM U(1) gauge fields kinetically mix, the massive dark photon, A', gains direct couplings to SM fermions given by $\varepsilon e A' \cdot J_{\rm EM}$ involving mixing parameter ε and the electromagnetic current $eJ_{\rm EM}$.
- This possibility has motivated many searches for A', but with negative results so far.

Some limits on massive dark photon from negative results of its searches



Fabbrichesi *et al.*, 2005.01515

- If $U(1)_D$ stays unbroken, it is always possible for the associated gauge field and its SM counterpart to form linear combinations such that Holdom, 1986
  - one of them, the massless dark photon ($\bar{\gamma}$), only sees the dark sector
  - the other one, identified with the ordinary photon, couples to both the SM and dark sectors, the latter with reduced strength.

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- This implies the need for different strategies to hunt the dark photon if it is massless.

- We focus on such operators inducing the transition $c \to u\bar{\gamma}$.
  - The massless dark photon is emitted invisibly.
- They contribute to the FCNC decays of charmed hadrons with missing energy, potentially testable in running or upcoming experiments.

* Massless dark photon's flavor-changing couplings to u & c quarks

$$\mathcal{L}_{uc\bar{\gamma}} = \overline{u}\sigma^{\mu\nu}(\mathbb{C} + \gamma_5\mathbb{C}_5)c\bar{F}_{\mu\nu} + \text{H.c.}$$

$\mathbb{C}$ & $\mathbb{C}_5$ are constants depending on the NP model details, $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$

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

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* $\mathcal{L}_{uc\bar{\gamma}}$ could originate from dim-6 effective operators invariant under the SM gauge groups and the unbroken $\mathrm{U}(1)_D$

$$\mathcal{L}_{\rm NP} = \frac{1}{\Lambda_{\rm NP}^2}\left(\mathtt{C}_{12}\overline{\mathcal{Q}_1}\sigma^{\mu\nu}u_2 + \mathtt{C}_{21}\overline{\mathcal{Q}_2}\sigma^{\mu\nu}u_1\right)\tilde{H}\bar{F}_{\mu\nu} + \text{H.c.}$$

Dobrescu, 2005

$\Lambda_{\rm NP}$ is an effective heavy mass scale, $\mathtt{C}_{12,21}$ are generally complex, dimensionless coefficients $\mathcal{Q}_{1,2}$ ($u_{1,2}$) are left-handed quark doublets (right-handed up-type quark singlets) from the first two families, $\tilde{H} = i\tau_2 H^*$, and H is the SM Higgs.

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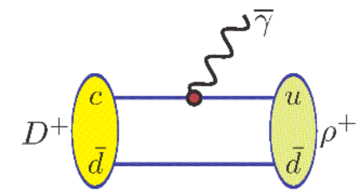
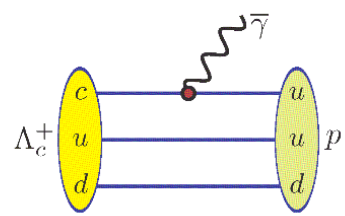
- The decays of interest here include
  - $D \to \rho\overline{\gamma}, \quad D^0 \to \omega\overline{\gamma}, \gamma\overline{\gamma}, \quad D_s^+ \to K^{+*}\overline{\gamma}$
  - $\Lambda_c^+ \to p\overline{\gamma}, \quad \Xi_c^{+(0)} \to \Sigma^{+(0)}\overline{\gamma}$





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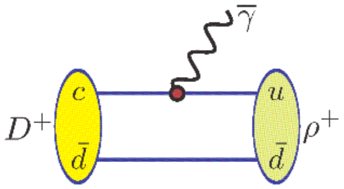
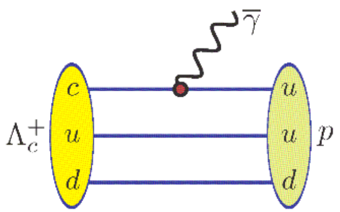




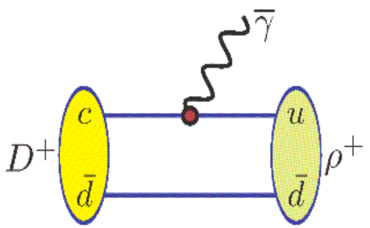
- Two-fold motivation to study them
  - Since $\overline{\gamma}$ evades the constraints on its massive counterpart, new ways are needed to probe it, which include using FCNC processes.
  - These FCNC decays may have large enough rates to be detectable by ongoing experiments, BESIII & BELLE II, or future ones such as super charm-tau factories and CEPC operated as a Z factory.

⋆ Mesonic matrix elements

$$\langle \rho^+(k)|\overline{u}\sigma^{\mu\nu}c|D^+(k+\bar{q})\rangle \bar{\varepsilon}^*_\mu \bar{q}_\nu = 2i f_{D^+\rho^+}\, \epsilon^{\eta\tau\mu\nu}\varepsilon^*_\eta k_\tau \bar{\varepsilon}^*_\mu \bar{q}_\nu$$

$$\langle \rho^+(k)|\overline{u}\sigma^{\mu\nu}\gamma_5 c|D^+(k+\bar{q})\rangle \bar{\varepsilon}^*_\mu \bar{q}_\nu = 2 f_{D^+\rho^+}\left(\varepsilon^*\!\cdot\bar{q}\,\bar{\varepsilon}^*\!\cdot k - \varepsilon^*\!\cdot\bar{\varepsilon}^* k\cdot\bar{q}\right)$$

k (ε) is the ρ^+ momentum (polarization vector), $k+\bar{q}$ is the D^+ momentum
$f_{D^+\rho^+}$ parametrizes form-factor effects at $\bar{q}^2 = 0$.



⋆ Decay amplitude

$$\mathcal{M}_{D^+\to\rho^+\bar{\gamma}} = 4 f_{D^+\rho^+}\left[\epsilon^{\eta\kappa\nu\tau}\varepsilon^*_\eta \bar{\varepsilon}^*_\kappa k_\nu \bar{q}_\tau \mathbb{C} + i\left(\varepsilon^*\!\cdot\bar{q}\,\bar{\varepsilon}^*\!\cdot k - \varepsilon^*\!\cdot\bar{\varepsilon}^* k\cdot\bar{q}\right)\mathbb{C}_5\right]$$

⋆ Branching fraction

$$\mathcal{B}(D^+ \to \rho^+\bar{\gamma}) = \frac{\tau_{D^+} f^2_{D^+\rho^+}\left(m^2_{D^+} - m^2_{\rho^+}\right)^3}{2\pi m^3_{D^+}}\left(|\mathbb{C}|^2 + |\mathbb{C}_5|^2\right)$$

⋆ $D^0\to\rho^0\bar{\gamma}, \omega\bar{\gamma}$ & $D_s^+\to K^{*+}\bar{\gamma}$ have analogous branching fractions.

- Mesonic matrix elements

$$\langle\gamma(k)|\overline{u}\sigma^{\mu\nu}c|D^0(k+\bar{q})\rangle\bar{\varepsilon}^*_\mu\bar{q}_\nu = ief_{D^0\gamma}\,\epsilon^{\eta\tau\mu\nu}\breve{\varepsilon}^*_\eta k_\tau\bar{\varepsilon}^*_\mu\bar{q}_\nu\,,$$
$$\langle\gamma(k)|\overline{u}\sigma^{\mu\nu}\gamma_5 c|D^0(k+\bar{q})\rangle\bar{\varepsilon}^*_\mu\bar{q}_\nu = ef_{D^0\gamma}\left(\breve{\varepsilon}^*\cdot\bar{q}\;\bar{\varepsilon}^*\cdot k - \breve{\varepsilon}^*\cdot\bar{\varepsilon}^*\;k\cdot\bar{q}\right)$$

which involve the electric charge e, the photon's polarization vector $\breve{\varepsilon}$, and the form-factor parameter $f_{D^0\gamma}$.

- Branching fraction

$$\mathcal{B}(D^0\to\gamma\bar{\gamma}) = \frac{\alpha_e}{2}\,\tau_{D^0}f^2_{D^0\gamma}m^3_{D^0}\left(|\mathbb{C}|^2+|\mathbb{C}_5|^2\right)$$

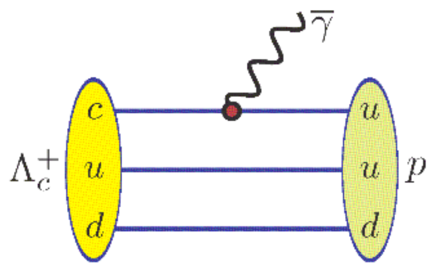
* Baryonic matrix elements

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

$U_{\Lambda_c,p}$ are the baryons' Dirac spinors, $f_{\Lambda_c^+p}$ encodes form-factor effects at $\bar{q}^2=0$.

* Decay amplitude

$$\mathcal{M}_{\Lambda_c^+\to p\bar{\gamma}} = 2f_{\Lambda_c^+p}\,\overline{U_p}(\mathbb{C}+\gamma_5\mathbb{C}_5)i\sigma^{\mu\nu}U_{\Lambda_c}\bar{\varepsilon}_\mu^*\bar{q}_\nu$$



* Branching fraction

$$\mathcal{B}(\Lambda_c^+\to p\bar{\gamma}) = \frac{\tau_{\Lambda_c^+}f_{\Lambda_c^+p}^2\left(m_{\Lambda_c^+}^2-m_p^2\right)^3}{2\pi m_{\Lambda_c^+}^3}\left(|\mathbb{C}|^2+|\mathbb{C}_5|^2\right)$$

* $\Xi_c^{+,0}\to\Sigma^{+,0}\bar{\gamma}$ have analogous branching fractions.

- How big the branching fractions might be depends on the largest values of the coefficients allowed by the relevant constraints.
  - ⋆ There are still no direct experimental constraints on $\mathbb{C}$ and $\mathbb{C}_5$.
  - ⋆ An indirect weak bound on $|\mathbb{C}|^2 + |\mathbb{C}_5|^2$ can be inferred from the existing data on charmed-hadron decays.
  - ⋆ There are simplified models giving ranges of $\mathbb{C}$ and $\mathbb{C}_5$. Gabrielli *et al.*, 1607.05928

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- All this suggests adopting the benchmark limit

$$|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < \frac{1.9 \times 10^{-16}}{\mathrm{GeV}^2}$$

- Resulting predictions for branching fractions

$$\mathcal{B}(D^+ \to \rho^+ \bar{\gamma}) < 7.7 \times 10^{-5}$$
$$\mathcal{B}(D^0 \to \rho^0 \bar{\gamma}) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(D^0 \to \omega \bar{\gamma}) < 2.5 \times 10^{-5}$$
$$\mathcal{B}(D_s^+ \to K^{*+} \bar{\gamma}) < 3.6 \times 10^{-5}$$

$$\mathcal{B}(D^0 \to \gamma \bar{\gamma}) < 3.1 \times 10^{-7}$$

$$\mathcal{B}(\Lambda_c^+ \to p \bar{\gamma}) < 1.6 \times 10^{-5}$$
$$\mathcal{B}(\Xi_c^+ \to \Sigma^+ \bar{\gamma}) < 2.9 \times 10^{-5}$$
$$\mathcal{B}(\Xi_c^0 \to \Sigma^0 \bar{\gamma}) < 7.4 \times 10^{-6}$$

- One or more of them may be within the reach of BESIII, Belle II, or future facilities such as super charm-tau factories & the CEPC.

CEPC CDR, 1811.10545

Particle	**Tera-Z**	**Belle II**	**LHCb**
b hadrons			
B^+	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} ($5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
c hadrons			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	

Table 2.4: Collection of expected number of particles produced at a tera-Z factory from 10^{12} Z-boson decays. We have used the hadronization fractions (neglecting p_T dependencies) from Refs. [431, 432] (see also Ref. [433]). For the decays relevant to this study we also show the corresponding number of particles produced by the full $50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$ and $5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S)$ runs at Belle II [430], as well as the numbers of b hadrons at LHCb with $50\,\mathrm{fb}^{-1}$ (using the number of $b\bar{b}$ pairs within the LHCb detector acceptance from [435] and the hadronization fractions from [431]).

- The FCNC charmed-hadron decays with missing energy are of great importance because they can serve as potentially promising searching grounds for light new particles from beyond the SM.
- If the missing energy is carried away by a massless dark photon, these charmed-hadron modes may have rates which are potentially discoverable by running or future heavy-flavor factories.