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# Searching for the massless dark photon in $c \to u\gamma'$

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In the effective field theory, the massless dark photon $\gamma'$ can only couple with the Standard Model particle through operators of dimension higher than four, thereby offering a high sensitivity to the new physics energy scale. Using 7.9 $\text{fb}^{-1}$ of $e^+e^-$ collision data collected at $\sqrt{s} = 3.773$ GeV with the BESIII detector at the BEPCII collider, we measure the effective flavor-changing neutral current coupling of $cu\gamma'$ in $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$ processes to search for the massless dark photon. No significant signals are observed, and the upper limits at the 90% confidence level on the massless dark photon branching fraction are set to be $1.1 \times 10^{-5}$ and $2.0 \times 10^{-6}$ for $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$, respectively. These results provide the most stringent constraint on the new physics energy scale associated with $cu\gamma'$ coupling in the world, with the new physics energy scale related parameter $|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < 8.2 \times 10^{-17}$ GeV$^{-2}$ at the 90% confidence level, playing a unique role in the dark sector search with the charm sector.

Although the standard model (SM) has achieved great success in high-energy physics, some questions like, e.g., dark matter, matter and anti-matter asymmetry, fermion mass hierarchy remain unresolved. So-called "dark" sectors have been theorized, named as such due to their assumed extremely faint interactions with the visible sector. Searching for these dark sectors offers a unique opportunity to uncover new physics (NP) beyond the SM, which would require extension to accommodate for these new particles and their interaction with SM matter. In the SM, the Abelian gauge group $U(1)_Y$ (with hypercharge $Y$) describes the electromagnetic interaction and produces the associated gauge boson, the SM photon $\gamma$. A minimum extension of the SM with an extra Abelian gauge group, $U(1)_D$ ($D$ denoting dark) produces another gauge boson, the dark photon [1–3]. These two Abelian gauge fields could have a kinetic mixing because the field strengths can be multiplied to form a dimension-four operator [4]. The dark photon may be a portal between the SM matter and the dark sector matter, and it could be massive or massless. If the symmetry of $U(1)_D$ is broken spontaneously, the dark photon will acquire mass, which will be called $A'$. If the symmetry of $U(1)_D$ remains unbroken, it will produce the massless dark photon, $\gamma'$ [5–13]. This massless dark photon could provide a natural explanation for the fermion mass hierarchy puzzle [12, 13].

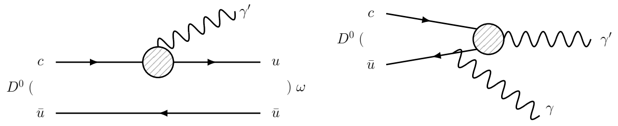
While the massive dark photon couples to SM matter via the coupling strength $e\varepsilon$ through the kinetic mixing, where $\varepsilon$ is the mixing parameter [1], the massless dark photon has no direct interaction with the SM particle in the dimension-four operator [5]. In the massless dark photons case, the SM photon can couple with the dark sector particle, which is usually called milli-charge particle [14]. The massive dark photon can be produced in many processes by replacing the SM photon, such as $e^+e^- \to \gamma A'$, a process that has not been confirmed yet despite extensive search. A stringent constraint is set on the mixing parameter $\varepsilon$ with different $m_{A'}$ [15–23], indicating that the value of $\varepsilon$ must be small. Since the massless dark photon has no interaction with SM particles within the dimension-four operator, the restrictions obtained from the massive dark photon do not apply to the massless dark photon.

A dimension-six operator has been proposed to provide a connection between SM matter and the massless dark photon [5]:

$$\begin{aligned}\mathcal{L}_{\rm NP} =& \frac{1}{\Lambda^2_{\rm NP}}(C^U_{jk}\bar{q}_j\sigma^{\mu\nu}u_k\tilde{H} + C^D_{jk}\bar{q}_j\sigma^{\mu\nu}d_kH \\ &+ C^L_{jk}\bar{l}_j\sigma^{\mu\nu}e_kH + h.c.)F'_{\mu\nu},\end{aligned} \tag{1}$$

where $\Lambda_{\rm NP}$ is the effective mass, indicating the NP energy scale, $C^U_{jk}$, $C^D_{jk}$, and $C^L_{jk}$ are the up-type, down-type, and charged-lepton-type dimensionless coefficients, respectively, depending on the NP and not necessarily related to one another, $j(k) = 1, 2, 3$ is the generation tag of the SM particle. More details can be found in Ref. [5]. The first three terms in this equations are the couplings between the massless dark photon and the up-type quarks, down-type quarks, and charged leptons, where the flavors of the two quarks or leptons could be identical or different, differing to flavor diagonal of the tree-level couplings of the massive dark photon. This effective operator may cover some new dark-sector particles with very heavy mass in the NP energy scale $\Lambda_{\rm NP}$ [12, 13]. Up to now, no new particles have been found up to the mass of $\sim 1$ TeV, but some anomalies require an energy scale above the electroweak energy scale $\Lambda_{\rm EW}$ ($\sim 100$ GeV). Similar to the $\beta$ decay observed in low energy experiments [24], where a missing neutrino within the four-fermion effective coupling [25] can predict the electroweak energy scale at about 100 GeV [26], the massless dark photon could provide a portal for exploring the NP energy scale $\Lambda_{\rm NP}$ beyond the TeV magnitude.

In this Letter, we focus on the first item of the dimension-six operator in Eq. (1), which causes the $cu\gamma'$ coupling in the flavor-changing neutral current (FCNC) process of a charm quark with $j = 1, k = 2$. In the SM, the FCNC processes are strongly suppressed by the Glashow-Iliopoulos-Maiani mechanism [27], stating that these processes are forbidden at the tree level and can only happen through a loop diagram. In the SM, the branching fraction (BF) of the FCNC charm process is expected to be smaller than $10^{-9}$ [28–31]. But for the $cu\gamma'$ coupling, its FCNC process originates from the NP coupling in the NP energy scale, which is different from the SM. In the charm sector, the massless dark photon can be searched for in $D$ meson or $\Lambda_c^+$ baryon decays, such as $D \to V\gamma'$, $D \to \gamma\gamma'$, or $\Lambda_c^+ \to p\gamma'$, where $V$ is a vector particle like $\rho$ or $\omega$. The BFs of these processes are directly related to $|\mathbb{C}|^2 + |\mathbb{C}_5|^2$ [11]. Here $\mathbb{C} = \Lambda_{\rm NP}^{-2}(C^U_{12} + C^{U*}_{12})\nu/\sqrt{8}$ and $\mathbb{C}_5 = \Lambda_{\rm NP}^{-2}(C^U_{12} - C^{U*}_{12})\nu/\sqrt{8}$ with the Higgs vacuum expectation value $\nu = 246.2$ GeV [32], which are determined by the NP energy scale $\Lambda_{\rm NP}$ and the up-type dimensionless coefficient $C^U_{12}$. From the constraint of the dark matter (DM) and the vacuum stability (VS) in the universe [11, 12], the allowed BF of the massless dark photon in charm FCNC processes can be enhanced to $10^{-7} \sim 10^{-5}$ [11]. Previously, BESIII searched for $\Lambda_c^+ \to p\gamma'$ and set the upper limit (UL) of its decay BF to be $8 \times 10^{-5}$ at the 90% confidence level (CL) [33]. This, however, is still above the allowed region obtained from DM and VS [10–12]. In this Letter, we search for the massless dark photon and probe the NP energy scale through the FCNC processes $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$ for the first time, which can be mediated via Feynman diagrams shown in FIG 1, by analyzing $e^+e^-$ collision data of 7.9 fb$^{-1}$ at a center-of-mass energy of $\sqrt{s} = 3.773$ GeV with the BESIII detector.



(a) (b)

FIG. 1. The Feynman diagrams of $D^0 \to \omega\gamma'$ (a) and $D^0 \to \gamma\gamma'$ (b) through $cu\gamma'$ effective coupling in dimension-six operator.

Details about the BESIII detector design and performance are provided elsewhere [34]. The simulated Monte Carlo (MC) samples, also described in Ref. [34], are used to determine detection efficiencies and to estimate backgrounds. The generator of the signal MC samples is parameterized by the helicity amplitudes same as the radiative decay of the $D$ meson [35, 36]. At $\sqrt{s} = 3.773$ GeV, the $D^0\bar{D}^0$ meson pairs are produced from $\psi(3770)$ decays without accompanying hadrons, which provide an ideal opportunity to study invisible massless dark photon decays of $D$ mesons using the double tag (DT) method [37]. The $\bar{D}^0$ mesons are first tagged with the main hadronic-decay modes $\bar{D}^0 \to K^+\pi^-$, $\bar{D}^0 \to K^+\pi^-\pi^0$ and $\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$, and the selected candidates are referred to as the single tag (ST) sample. Here and throughout this letter, charge conjugations are always implied. Then, the signal processes $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$ are searched for in the system recoiling against the ST $\bar{D}^0$ meson, and the selected candidates are denoted as the DT sample. Here, $\omega$ is reconstructed through its decay $\omega \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$, and $\gamma'$ is missing in the detector. The BFs of $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$ are calculated by

$$\mathcal{B}(D^0 \to \omega(\gamma)\ \gamma') = \frac{N_{\rm sig}/\hat{\epsilon}}{\mathcal{B}_{\rm int} \sum\limits_i N_i^{\rm ST}}, \tag{2}$$

with $\sum\limits_i N_i^{\rm ST} = (6306.7 \pm 2.8) \times 10^3$ [34] and the effective efficiency

$$\hat{\epsilon} = \sum_i \frac{\epsilon_i^{\rm DT}}{\epsilon_i^{\rm ST}} \times \frac{N_i^{\rm ST}}{\sum\limits_i N_i^{\rm ST}}, \tag{3}$$

where $i$ indicates each mode of $\bar{D}^0 \to$ hadrons, $N_{\rm sig}$ is the signal yield of the massless dark photon in data, $N_i^{\rm ST}$ is the ST yield of $\bar{D}^0$ meson samples in data, $\epsilon_i^{\rm ST}$ is the ST efficiency of $\bar{D}^0 \to$ hadrons, $\epsilon_i^{\rm DT}$ is the DT efficiency of $\bar{D}^0 \to$ hadrons, $D^0 \to \omega(\gamma)\gamma'$, $\mathcal{B}_{\rm int} = \mathcal{B}(\omega \to \pi^+\pi^-\pi^0) \times \mathcal{B}(\pi^0 \to \gamma\gamma)$ is obtained from Particle Data Group [38] for $D^0 \to \omega\gamma'$ and $\mathcal{B}_{\rm int} = 1$ for $D^0 \to \gamma\gamma'$.

The selection criteria of ST samples, the ST yield $N_i^{\rm ST}$, and the ST efficiency $\epsilon_i^{\rm ST}$ can be found in Ref. [34]. The selection criteria of $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$, based on the tagged $\bar{D}^0$ meson samples, are described below. To select $D^0 \to \gamma\gamma'$, no additional charged track is allowed. The good charged track, particle identification (PID), and photon candidates are selected with the same strategy as outlined in Ref. [34]. To select $D^0 \to \omega\gamma'$, only events with exactly two selected charged tracks, both identified as pions with zero net charge, are retained for further analysis. There should be at least one photon with energy larger than 0.5 GeV for $D^0 \to \gamma\gamma'$ and at least two photons for $D^0 \to \omega\gamma'$, where the two photons with minimum $\chi^2$ value of the kinematic fit [39] constraining $M_{\gamma\gamma}$ to the nominal $\pi^0$ mass are regarded as the correct photons from the $\pi^0$ meson. To select the $\omega$ meson in the data samples, the invariant mass of the two photons $M_{\gamma\gamma}$ before the kinematic fit must be in the region of [0.115, 0.150] GeV/$c^2$, and the invariant mass $M_{\pi^+\pi^-\pi^0}$ of the $\omega$ candidate is required to be in the region of [0.700, 0.850] GeV/$c^2$. To further reduce the non-$\omega$ background, a kinematic fit [39] constraining $M_{\gamma\gamma}$ to the nominal $\pi^0$ mass and $M_{\pi^+\pi^-\pi^0}$ to the nominal $\omega$ mass is performed to obtain the $\chi^2_{\rm 2C}$ value which is required to be less than 44, optimized with the Punzi-optimization method [40]. To suppress the background with additional photons or $\pi^0$, the total energy of photon candidates other than those from the $\pi^0$ ($\gamma$) and the $\bar{D}^0$ meson ($E^{\rm tot}_{{\rm oth.}\gamma}$) is required to be less than 0.1 GeV for $D^0 \to \omega\gamma'$ ($D^0 \to \gamma\gamma'$). After these selections, there may still be some background particles flying to the endcap of the detector that cannot be effectively detected [41], so the recoiling angle of $\bar{D}^0\omega$ ($\bar{D}^0\gamma$) is applied to veto these associated background events. The cosine of the recoiling angle is defined as $\cos\theta^{\rm reccoil}_{\bar{D}\omega(\gamma)} = \frac{|\vec{\mathbf{p}}_{\rm cms} - \vec{\mathbf{p}}_{\bar{D}^0} - \vec{\mathbf{p}}_{\omega(\gamma)}|_z}{|\vec{\mathbf{p}}_{\rm cms} - \vec{\mathbf{p}}_{\bar{D}^0} - \vec{\mathbf{p}}_{\omega(\gamma)}|}$, where $\vec{\mathbf{p}}_{\rm cms}$ is the momentum of the center-of-mass in $e^+e^-$ collision, $\vec{\mathbf{p}}_{\bar{D}^0}$ is the reconstructed momentum of the $\bar{D}^0$ meson, $\vec{\mathbf{p}}_{\omega(\gamma)}$ is the reconstructed momentum of $\omega$ ($\gamma$), and the subscript $z$ refers to the $z$-component. To suppress these background events, a requirement of $|\cos\theta^{\rm recoil}_{\bar{D}\omega(\gamma)}| < 0.7$ is applied. With the above selection criteria, the effective efficiency is estimated from the MC samples, which is $\hat{\epsilon} = (15.98 \pm 0.02)\%$ for $D^0 \to \omega\gamma'$ and $\hat{\epsilon} = (52.18 \pm 0.05)\%$ for $D^0 \to \gamma\gamma'$. The main background after the selections comes from the $K_L^0$ associated background events, such as $D^0 \to \omega K_L^0$ for $D^0 \to \omega\gamma'$ and $D^0 \to \pi^0 K_L^0$ for $D^0 \to \gamma\gamma'$.

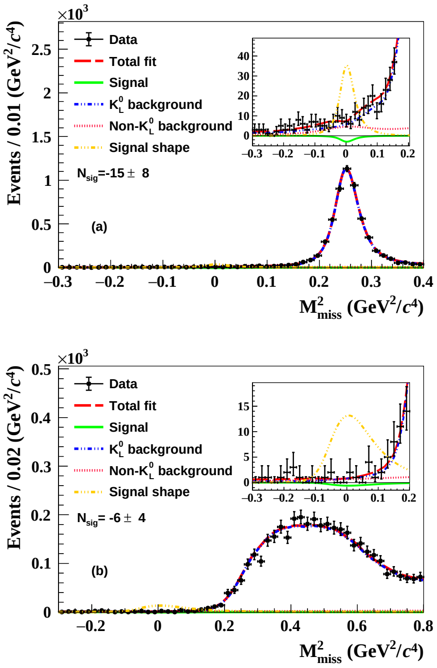


FIG. 2. The $M^2_{\rm miss}$ distributions of the accepted candidates of $D^0 \to \omega\gamma'$ (a) and $D^0 \to \gamma\gamma'$ (b). In the plot, the magnitude of the signal shape corresponds to $\mathcal{B}(D^0 \to \omega\gamma') = 2 \times 10^{-4}$ (a) and $\mathcal{B}(D^0 \to \gamma\gamma') = 4 \times 10^{-5}$ (b) respectively.

The signals of the massless dark photon are extracted from an unbinned extended maximum likelihood fit on the distribution of the square of the missing mass, $M^2_{\rm miss}$, defined as

$$M^2_{\rm miss} = |p_{\rm cms} - p_{\bar{D}^0} - p_{\omega(\gamma)}|^2/c^4, \tag{4}$$

where $p_{\rm cms}$ is the four-momentum of the $e^+e^-$ center-of-mass system in the laboratory frame, $p_{\omega(\gamma)}$ is the kinematic fitted (reconstructed) four-momentum of $\omega(\gamma)$, $p_{\bar{D}^0}$ is the four-momentum of the $\bar{D}^0$ meson, achieved by the kinematic fit [39] constraining $M_{\gamma\gamma}$ to the nominal $\pi^0$ mass and $M_{K^+\pi^-}$, $M_{K^+\pi^-\pi^0}$, $M_{K^+\pi^-\pi^+\pi^-}$ to the nominal $\bar{D}^0$ meson mass. In the fit, the background is separated into the $K^0_L$-related and non-$K^0_L$ backgrounds [42]. The background shape is derived from the inclusive MC sample [43], with the number of non-$K^0_L$ background events assumed to follow a Gaussian distribution and constrained by the MC simulation (referred to as the Gaussian constraint), while the number of $K^0_L$-related background events is left as a floating parameter. The signal is derived by the simulated shape convolved with a Gaussian function $G(\mu, \sigma)$, where $\mu$ and $\sigma$ are restrained to the values obtained from the control samples $D^0 \to \omega K^0_S$ ($D^0 \to \pi^0 K^0_S$) for $D^0 \to \omega\gamma'$ ($D^0 \to \gamma\gamma'$). The fit results are shown in FIG 2, with the massless dark photon signal yield $N_{\mathrm{sig}} = -15 \pm 8$ for $D^0 \to \omega\gamma'$ and $N_{\mathrm{sig}} = -6 \pm 4$ for $D^0 \to \gamma\gamma'$.

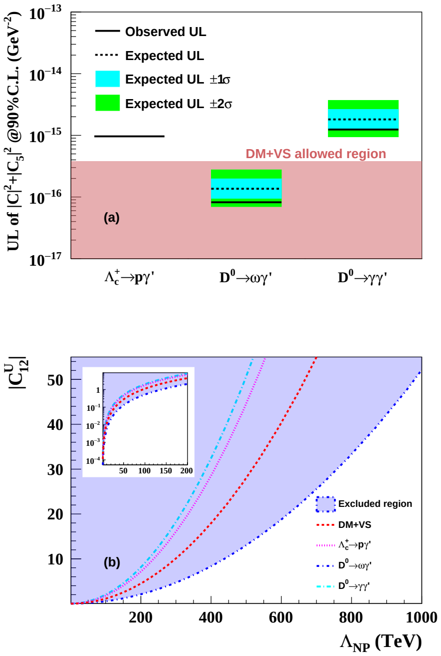


FIG. 3. (a) The ULs of $|\mathbb{C}|^2 + |\mathbb{C}_5|^2$ for $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$ obtained in this work and $\Lambda_c^+ \to p\gamma'$ in Ref. [33]. (b) The two-dimensional constraints on the NP energy scale $\Lambda_{\mathrm{NP}}$ and the dimensionless coefficient $|C^U_{12}|$.

The systematic uncertainty sources for the BF measurement include ST yield, intermediate BF, signal generator, DT signal efficiency, and signal extraction. With the DT method, several systematic uncertainties associated with the ST selection can be canceled without impacting the BF measurement. The uncertainty of ST yield is assigned as 0.1% [34]. The uncertainty of the generator is estimated from the efficiency difference compared with a flat angular generation of $\gamma'$ (phase space model), which is 1.3% (0.6%) for $D^0 \to \omega\gamma'$ ($D^0 \to \gamma\gamma'$). The uncertainty of the BF of $\omega \to \pi^+\pi^-\pi^0$ is 0.8% and that of $\pi^0 \to \gamma\gamma$ is negligible [38]. The uncertainty of photon detection is assigned as 1.0% per photon [44]. The uncertainties of pion tracking and PID are studied from the control sample $J/\psi \to \pi^+\pi^-\pi^0$, which is assigned as 0.9% for tracking and 1.1% for PID of the two pions. The uncertainties of other selections are estimated from the control sample $D^0 \to \omega K^0_S$ ($D^0 \to \pi^0 K^0_S$) for $D^0 \to \omega\gamma'$ ($D^0 \to \gamma\gamma'$), where the $K^0_S$ meson is regarded as a missing particle. For $D^0 \to \omega\gamma'$, the uncertainty is 0.2% for the $M_{\gamma\gamma}$ selection, negligible for the $M_{\pi^+\pi^-\pi^0}$ selection, 3.1% for the $\chi^2_{2\mathrm{C}}$ selection, 5.9% for the $E^{\mathrm{tot}}_{\mathrm{oth}.\gamma}$ selection and 1.1% for the $\cos\theta^{\mathrm{recoil}}_{\bar{D}\omega}$ selection, respectively. For $D^0 \to \gamma\gamma'$, the uncertainty is 2.4% for the $E^{\mathrm{tot}}_{\mathrm{oth}.\gamma}$ selection and is 0.6% for the $\cos\theta^{\mathrm{recoil}}_{\bar{D}\gamma}$ selection, respectively. The total systematic uncertainty is calculated by summing up all sources in quadrature, yielding 7.4% for $D^0 \to \omega\gamma'$ and 2.7% for $D^0 \to \gamma\gamma'$. For the uncertainty from the signal extraction, the signal shape is convolved with a Gaussian function to describe the difference where the parameter of the Gaussian function is in a Gaussian constraint within its uncertainty, the $K^0_L$ background yield is floating in the fit, and the non-$K^0_L$ background yield is also floating in a Gaussian constraint within its uncertainty. The uncertainty of signal extraction is negligible.

Since no significant excess of signal above the background is observed, a UL on the BF is set using a Bayesian approach following Ref. [45], where the BF is calculated by Eq. (2) and the systematic uncertainty is estimated with the method in Refs. [46, 47]. The UL on the BF at the 90% CL is calculated by integrating the likelihood distribution with different signal assumptions to the 90% region, which is $\mathcal{B}(D^0 \to \omega\gamma') < 1.1 \times 10^{-5}$ and $\mathcal{B}(D^0 \to \gamma\gamma') < 2.0 \times 10^{-6}$. Note that in the $D^0 \to \omega\gamma'$ measurement, the non-$\omega$ contribution can not be fully removed, and the current UL of $\mathcal{B}(D^0 \to \omega\gamma')$ is a conservative estimation. Since the BF of massless dark photon production is related to $|\mathbb{C}|^2 + |\mathbb{C}_5|^2$ and directly includes the NP energy scale [11], the constraint on $|\mathbb{C}|^2 + |\mathbb{C}_5|^2$ can be performed as well. The UL of $|\mathbb{C}|^2 + |\mathbb{C}_5|^2$ is shown in FIG 3. For $D^0 \to \omega\gamma'$, one sees that $|\mathbb{C}|^2 + |\mathbb{C}_5|^2 < 8.2 \times 10^{-17}$ GeV$^{-2}$, reaching the DM and VS allowed region [11, 12] for the first time. The channel $D^0 \to \gamma\gamma'$ has a better UL of the BF but a worse constraint on $cu\gamma'$ coupling due to an additional electromagnetic vertex in FIG 1(b). The two-dimensional constraint on the NP energy scale $\Lambda_{\mathrm{NP}}$ and the up-type dimensionless coefficient $C^U_{12}$ is given in FIG 3 (b). Our result currently resemble the best constraint on the NP parameter space. Assuming $|C^U_{12}| = 1$, our results can exclude NP energy scales below 138 TeV in the dark sector, which is approximately ten times the energy reached at the Large Hadron Collider [48], suggesting a challenge of directly detecting superheavy particles at the NP energy scale associated with the $cu\gamma'$ coupling in the present collider settings. Note that the value of $|C^U_{12}|$ is model-dependent.

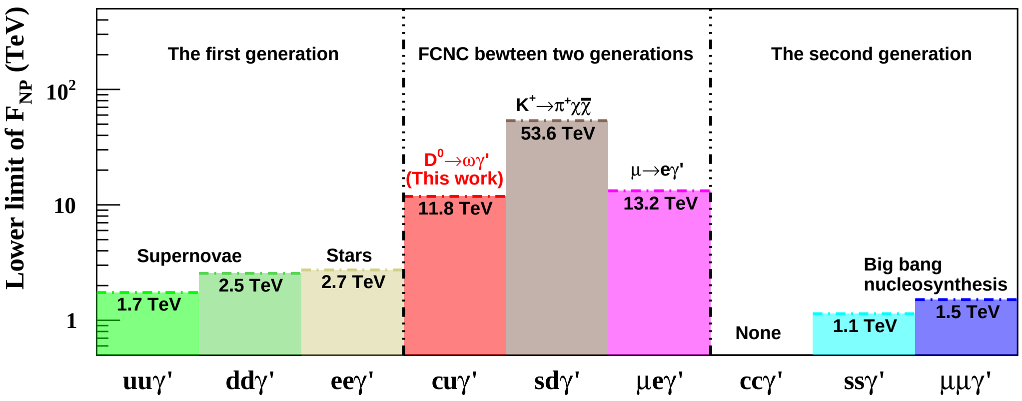


FIG. 4. The current constraint of the $F_{\rm NP}$ between the massless dark photon and the SM particle, where the fill-regions are the excluded region. In the plot, $\chi\bar{\chi}$ are the dark-sector fermions coupled with a virtual dark photon [4]. This work provides the best constraint on $cu\gamma'$ coupling.

In the dimension-six operator of the massless dark photon (Eq. (1)), there are three terms with the same NP energy scale but different types of dimensionless coefficients $C^U_{jk}$, $C^D_{jk}$, $C^L_{jk}$. For each type, the massless dark photon can couple with a pair of SM particles involving identical or different flavors. In principle, these dimensionless coefficients are not necessarily related to one another. To compare the difference between different couplings, we follow the method from Ref. [5], constructing a uniform variable $F_{\rm NP} = \Lambda_{\rm NP}/\sqrt{|C^i_{jk}|\nu/\sqrt{2m^2}}$ to perform the comparison on the first two generations, where $i = U, D, L$, $|C^i_{jk}|\nu/\sqrt{2m^2}$ indicates the strength of the massless dark photon coupled with the SM particle. Here, $m$ is the mass of the heavier SM particle in the coupling, and $F_{\rm NP}$ represents the NP energy scale when $|C^i_{jk}|$ equals to the Higgs-fermions coupling $\frac{\sqrt{2}m}{v}$ [5]. The summary of the constraints in different couplings is shown in FIG 4, depicting only the best constraint on the coupling. The constraints on the massless dark photon coupled with the same-flavor SM particles are mainly from astrophysics and cosmology [4, 49–54], while the constraints on the different flavors are mainly from laboratory physics [4, 55, 56]. This Letter provides the best constraint for the $cu\gamma'$ coupling, which plays a unique role in the dark sector of the charm sector.

In summary, we search for the massless dark photon and constraint the NP scale through the $cu\gamma'$ coupling in $D^0 \to \omega\gamma'$ and $D^0 \to \gamma\gamma'$ for the first time. Based on 7.9 fb$^{-1}$ of $e^+e^-$ collision data at $\sqrt{s} = 3.773$ GeV, no significant signals are observed. The constraints on the BF and the NP energy scale of the massless dark photon production are given. The result of $D^0 \to \omega\gamma'$ gives the most stringent constraint on $cu\gamma'$ coupling to date, exploring the DM and VS allowed space for the first time. The result of $D^0 \to \gamma\gamma'$ has a 5.5 times better UL of the BF than $D^0 \to \omega\gamma'$ but a worse constraint on $cu\gamma'$ coupling.

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