

Nonlocal portal to the dark sector

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(Received 30 March 2026; accepted 29 May 2026; published 10 July 2026)

We propose a nonlocal realization of the Stueckelberg portal between the Standard Model and dark sector, which decouple in the local limit. This implies that the mediator, $U(1)_D$ dark photon A' with a Stueckelberg mass, interacts nonlocally with the Standard Model quarks and leptons. We study phenomenological implications of this scenario for the meson decays into semi-invisible and invisible channels. We discuss the experimental limitations on the model parameters, including the nonlocality scale.

DOI: [10.1103/xqyc-6vgs](https://doi.org/10.1103/xqyc-6vgs)

I. INTRODUCTION

Light, feebly coupled vector bosons appear ubiquitously in extensions of the Standard Model (SM), motivated by dark sectors (DSs), anomaly-free $U(1)$ gauge symmetries, and mediators connecting visible and hidden degrees of freedom. A particularly well-studied benchmark is the “dark photon” scenario, in which a new Abelian gauge boson interacts with the SM through kinetic mixing with hypercharge or electromagnetism [1–4]. In this work, we focus on a complementary and phenomenologically distinct setup: a massive dark photon A'_μ as a $U(1)'$ gauge boson acquiring its mass via the Stueckelberg mechanism. The latter also leads to flavor-nondiagonal A' -SM fermion couplings—Stueckelberg portal (StP) introduced in Ref. [5]. The kinetic mixing, if introduced, can be absorbed by the flavor-diagonal vector couplings by an appropriate field redefinition. Moreover, we assume that these A' -SM interactions are nonlocal with a characteristic nonlocality scale Λ_{NL} related to some UV, possibly super-Planckian, physics. As revealed in Ref. [6], the nonlocality allows, in the case of the kinetic mixing, reconciling the tension between the observable dark-matter (DM) relic density and nonobservations DM signal in direct-detection experiments.

Depending on the spectrum of possible hidden-sector states, A' can decay visibly into lepton flavor-conserving as well as flavor-violating channels $A' \rightarrow \ell_1^\pm \ell_2^\mp$ with $\ell = e, \mu, \tau$ and into hadrons or dominantly invisibly $A' \rightarrow \chi\bar{\chi}$ into the DS particles. The hadronic phenomenology is controlled by the embedding of the quark currents in low-energy QCD degrees of freedom. This makes rare meson processes one of the primary probes of the model for $m_{A'}$ ranging from the sub-MeV up to the multi-GeV scale and yields a set of constraints and signatures that can be different from the usual kinetically mixed dark photon scenario.

Our goal is twofold. First, we match the quark-level A' nonlocal interactions onto an effective theory of pseudo-scalar and vector mesons including the anomalous Wess-Zumino-Witten (WZW) terms. Second, using this effective framework, we compute a set of benchmark amplitudes and decay widths relevant to laboratory searches, including radiative semi-invisible pseudoscalar meson decays and invisible vector-meson decays with missing energy lost in A' decays into the DS particles. These observables allow for a consistent recasting of existing limits and provide a map between fermion-level couplings and accessible meson phenomenology. We analyze the impact of the nonlocality of A' -SM interactions and estimate the corresponding scale of nonlocality.

The paper is organized as follows. In Sec. II, we formulate the quark-level nonlocal A' model with the assumptions and conventions we adopt. In Sec. III, we match the quark currents onto the chiral and resonance (vector-meson)

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effective theory, including the WZW-induced interactions relevant for anomalous transitions. In Sec. IV, we derive decay widths and branching ratios for the key mesonic channels and discuss characteristic kinematic regimes (on-shell versus off-shell A' production). Also, we assemble and interpret the corresponding constraints, distinguishing visible and invisible A' decay scenarios, and summarize our analysis. In Sec. V, we briefly discuss existing constraints on dark photons from the perspective of our nonlocal model. Finally, in Sec. VI, we present the summary of our results and findings.

II. THEORETICAL SETUP

We consider a setup involving two isolated sectors—the SM sector and the DS mutually singlet or sterile with respect to gauge symmetries of each other. For the DS, we assume a simplified structure based on the $U(1)_D$ gauge group with the scalars S and vectorlike fermions χ charged under $U(1)_D$ and sterile with respect to the SM gauge groups. In this scenario, all the SM fields have $U(1)_D$ charges zero. The model gauge group is

$$\mathcal{G} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_D. \quad (1)$$

The relevant part of the model Lagrangian is

$$\begin{aligned} \mathcal{L} \supset & -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} - \frac{1}{2}B_{\mu\nu}\epsilon_Y X^{\mu\nu} - \frac{1}{2}M_X^2 X^\mu X_\mu \\ & + \bar{\psi}(i\not{D} - m_\psi)\psi + \bar{\chi}(i\not{D} - m_\chi)\chi + e'X^\mu\bar{\chi}\gamma_\mu\chi, \end{aligned} \quad (2)$$

where

$$X_{\mu\nu} \equiv \partial_\mu X_\nu - \partial_\nu X_\mu, \quad B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu, \quad (3)$$

where B_μ and X_μ are the gauge fields of the Abelian groups $U(1)_Y$ and $U(1)_D$, respectively. Note that, without introduction of the SM-DS portal, the SM and DS are completely decoupled from each other even at the quantum level. Neither SM nor DS interactions can generate the cross terms. The gauge kinetic terms in Eq. (2) can be diagonalized by rotating the gauge fields (for recent review, see, e.g., Ref. [3]). At the limit $\epsilon_Y \ll 1$, we have

$$B_\mu = A_\mu + \epsilon A'_\mu, \quad X_\mu = A'_\mu - \epsilon \tan \theta_W Z_\mu \quad (4)$$

with $\epsilon = \epsilon_Y \cos \theta_W$. Here, A_μ and Z_μ are the usual neutral electroweak gauge bosons—photon and Z^0 boson, respectively. Then, in the A' sector, we have

$$\begin{aligned} \mathcal{L} \supset & -e\hat{e}A'_\mu \sum_i Q_{\psi_i} \bar{\psi}_i \gamma^\mu \psi_i - g_D A'_\mu \bar{\chi} \gamma^\mu \chi + \frac{1}{2}M_{A'}^2 A'_\mu A'^\mu \\ & + A'_\mu \sum_{ij} \bar{\psi}_i \gamma^\mu (g_{ij}^v + g_{ij}^a \gamma_5) \psi_j, \end{aligned} \quad (5)$$

where $\psi_i = q, \ell$ are the SM quarks and leptons with electric charges Q_{ψ_i} and $M_{A'} = M_X$. Here, the last dimension-4 operator, with $g_{ij}^{v,a}$ flavor-nondiagonal couplings, originates from a dimension-5 operator arising in the Stueckelberg realization of $U(1)_D$ symmetry group. These flavor-nondiagonal SM-DS portal was recently found in Ref. [5]. Once this StP portal is included the first term, originating from the kinetic $A - A'$ mixing, can be eliminated by the redefinition of the flavor-diagonal vector coupling $g_{ii}^v \rightarrow g_{ii}^v + e\epsilon$.

Here, we will focus on the StP as a unique communication between the SM and DS. Note that the $A - A'$ kinetic mixing is regenerated by StP interactions in (5) via fermion loop corrections. This mixing can be eliminated through appropriate A and A' field redefinition and absorption into couplings $g^{v,a}$. This results their renormalization scale μ dependence controlled by the well-known renormalization-group equation running. We choose the scale $\mu = \mu_0$ at which the kinetic mixing is vanishing. In the phenomenological treatment, we can always restore the conventional case of the pure kinetic mixing identifying $e\epsilon = g^{(v)}$ and imposing $g_{ii}^{(v)} = g^{(v)}$, $g_{i \neq j}^{(v)} = 0$, $g_{ij}^{(a)} = 0 \forall i, j$.

In this setup, we will explore a scenario assuming that this communication is *nonlocal* while the SM and the DS separately are described by local theories. This is an extension of the idea about nonlocality of the kinetic mixing, recently proposed in Ref. [7]. The nonlocality is implemented by promoting the couplings $g^{v,a}$ in Eq. (5) to differential operators. We assume the universal nonlocality, replacing

$$g_{ij}^{v,a} \rightarrow \hat{e}(\partial^2)g_{ij}^{v,a}, \quad (6)$$

which, in the matrix elements of physical processes, gives rise to a *vertex form factor* $\hat{e}(k^2)$ depending on the squared momentum transfer k^2 .

For a nonlocal theory to be physically tractable, this form factor must satisfy certain conditions [8,9]; in particular, it must be an entire function (for more recent publications, see Refs. [7,10,11]). We choose it in the following simplified form:

$$\hat{e}(k^2) = \left(\frac{k^2}{\Lambda_{\text{NL}}^2} \right)^2 \exp\left(\frac{k^2}{\Lambda_{\text{NL}}^2} \right). \quad (7)$$

Here, Λ_{NL} is a scale referring to a fundamental physics behind nonlocality of the SM-DS communication. Also, in the limit $\Lambda_{\text{NL}} \rightarrow \infty$, the nonlocal portal specified by Eqs. (6) and (7) is turning off. In Euclidean momentum space, this form factor provides ultraviolet and infrared convergence of the loop diagrams. Here, the ultraviolet and infrared convergences imply the matrix elements to be finite at large loop momentum and vanishing masses of the SM fermion, respectively. In Fig. 1, we show the k^2 behavior of the

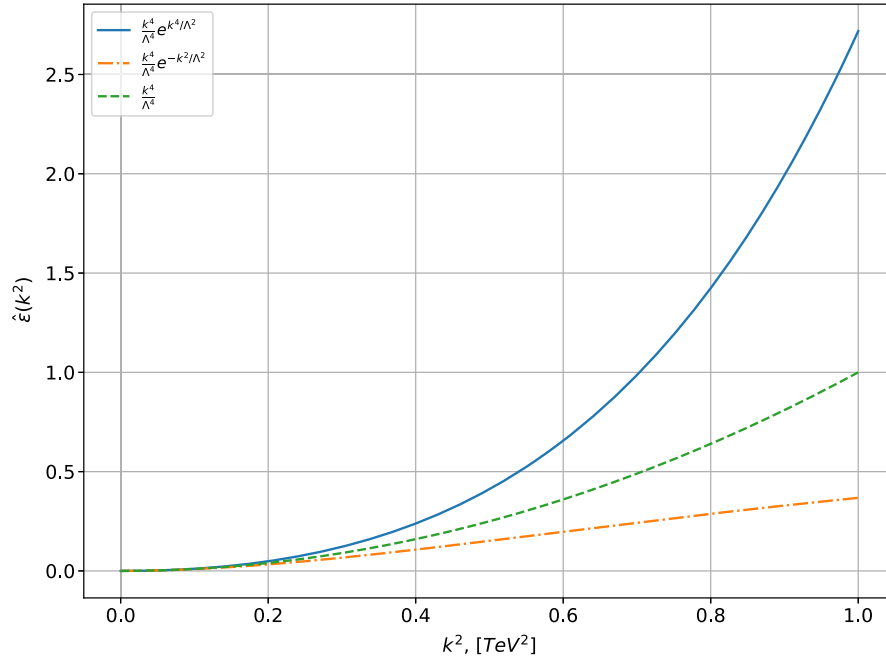


FIG. 1. Three examples of the nonlocal form factor $\hat{\epsilon}(k^2)$ at the nonlocality scale $\Lambda_{\text{NL}} = 1$ TeV.

nonlocal form factor for the three different analytic forms and at the nonlocality scale $\Lambda_{\text{NL}} = 1$ TeV.

Note that this type of nonlocality cannot be generated by local renormalizable interactions mediated by particle exchange. Note, nonlocality via an infinite number of local fields was proposed in Ref. [6]. Its fundamental origins should reside among nonlocal objects like strings, topological defects, or compact manifolds in extra-dimensional theories. In this case, one expects that Λ_{NL} is of the order of the Planck scale Λ_{Pl} . Importantly, some of these frameworks do not exclude sub-Planckian values for the nonlocality scale Λ_{NL} , which, in certain scenarios such as large extra dimensions, may lie in the TeV ballpark.

III. DARK PHOTON INTERACTIONS WITH MESONS

In order to study vector meson $V = \rho, \omega, \phi$ and the light pseudoscalar $P = \pi^0, \eta, \eta'$ meson decays as well as their contribution to the processes with dark photon, we use the meson effective field theory framework. To this end, we integrate out the light quark fields u, d , and s in the Lagrangian (5), embedding it to the low-energy effective Lagrangian based on ideas of chiral perturbation theory [12]. The terms relevant for the A' -light meson phenomenology include the $A' - V$ kinetic mixing (or, equivalently, mass mixing), the WZW plus vector-meson dominance. Explicitly, we have

$$\mathcal{L} \supset \frac{1}{2} g_{VA'} V_{\mu\nu} \hat{\epsilon} F'^{\mu\nu} + \frac{e^2}{4} g_{P\gamma A'} \epsilon_{\mu\nu\alpha\beta} P F'^{\mu\nu} \hat{\epsilon} F'^{\alpha\beta} + \frac{e}{4} g_{VPA'} \epsilon_{\mu\nu\alpha\beta} P V^{\mu\nu} \hat{\epsilon} F'^{\alpha\beta} + \text{H.c.}, \quad (8)$$

where $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ is the stress tensor of vector-meson field V_μ . In what follows, we are studying a simplified case of the $A'qq$ vector couplings $g_V = g_{A'} Q_q$, where Q_q is the quark electric charge and $g_{A'}$ is a universal parameter for the light quarks. For this benchmark case, we have

$$g_{VA'} = g_{V\gamma} g_{A'}, \quad g_{P\gamma A'} = g_{P\gamma\gamma} g_{A'}, \quad g_{VPA'} = g_{VP\gamma} g_{A'}. \quad (9)$$

The effective couplings $g_{V\gamma}$, $g_{P\gamma\gamma}$, and $g_{VP\gamma}$ can be extracted from data on the corresponding meson decays and the decay rate formulas

$$\Gamma(V \rightarrow e^+ e^-) = \frac{4\pi}{3} \alpha^2 g_{V\gamma}^2 M_V, \quad (10)$$

$$\Gamma(P \rightarrow \gamma\gamma) = \frac{\pi\alpha^2}{4} g_{P\gamma\gamma}^2 m_P^3, \quad (11)$$

$$\Gamma(V \rightarrow P\gamma) = \frac{\alpha}{24} g_{VP\gamma}^2 m_V^3 (1 - x_{PV})^3, \quad (12)$$

$$\Gamma(P \rightarrow V\gamma) = \frac{\alpha}{8} g_{VP\gamma}^2 m_P^3 (1 - x_{VP})^3, \quad (13)$$

where M_V and M_P are the masses of the vector $V = \rho^0, \omega, \phi$ and pseudoscalar $P = \pi^0, \eta, \eta'$ mesons, respectively. Here and in the following, we denote by $x_{ij} = m_i^2/m_j^2$ the ratio of squares of masses m_i and m_j .

The values of the couplings $g_{V\gamma}$, $g_{P\gamma\gamma}$, and $g_{VP\gamma}$ can be found in Ref. [13]. In our analysis, we use their central

values:

$$\begin{aligned}
 g_{\rho^0\gamma} &= 0.202, & g_{\omega\gamma} &= 0.059, & g_{\phi\gamma} &= 0.075, \\
 g_{\pi^0\gamma\gamma} &= g_{\eta\gamma\gamma} = 0.274 \text{ GeV}^{-1}, & g_{\eta'\gamma\gamma} &= 0.341 \text{ GeV}^{-1}, \\
 g_{\rho^0\pi^0\gamma} &= 0.699 \text{ GeV}^{-1}, & g_{\rho^0\eta\gamma} &= 1.55 \text{ GeV}^{-1}, & g_{\rho^0\eta'\gamma} &= 2.73 \text{ GeV}^{-1}, \\
 g_{\omega\pi^0\gamma} &= 2.33 \text{ GeV}^{-1}, & g_{\omega\eta\gamma} &= 0.45 \text{ GeV}^{-1}, & g_{\omega\eta'\gamma} &= 0.45 \text{ GeV}^{-1}, \\
 g_{\phi\pi^0\gamma} &= 0.136 \text{ GeV}^{-1}, & g_{\phi\eta\gamma} &= 0.67 \text{ GeV}^{-1}, & g_{\phi\eta'\gamma} &= 0.706 \text{ GeV}^{-1}.
 \end{aligned} \tag{14}$$

IV. MESON PHENOMENOLOGY OF DARK PHOTON

Here, we analyze some phenomenological aspects of dark photon in the sector of light mesons and compute amplitudes and decay widths of benchmark processes on the basis of the effective hadronic Lagrangian (8).

A. A' decay to lepton-antilepton pair

We start with the A' decay to lepton-antilepton pair. There are two diagrams contributing to this decay: direct (left panel) and resonant via the dark photon–vector meson mixing (right panel) diagrams, shown in Fig. 2.

The corresponding matrix element $\mathcal{M}(A' \rightarrow \ell^+ \ell^-)$ is given by the sum of direct (D) and resonance (R) contributions:

$$\mathcal{M}(A' \rightarrow \ell^+ \ell^-) = \mathcal{M}_D(A' \rightarrow \ell^+ \ell^-) + \mathcal{M}_R(A' \rightarrow \ell^+ \ell^-), \tag{15}$$

which we calculate from the Lagrangian (8). For the direct contribution, we have

$$\mathcal{M}_D(A' \rightarrow \ell^+ \ell^-) = \varepsilon_\mu(p) \bar{u}(q_1) \gamma^\mu (G_{\ell\bar{\ell}}^v + G_{\ell\bar{\ell}}^a \gamma^5) v(q_2), \tag{16}$$

where $\bar{u}(q_1)$ and $v(q_2)$ are spinors of lepton with momentum q_1 and antilepton with momentum q_2 , respectively; $\varepsilon_\mu(p)$ is polarization vector of the dark photon. Here, we denoted the nonlocal vector and axial couplings of A' with leptons as $G_{\ell\bar{\ell}}^{v,a} = \varepsilon(m_{A'}^2) g_{\ell\bar{\ell}}^{v,a}$.

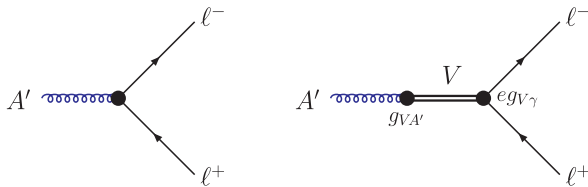


FIG. 2. Feynman diagrams contributing to A' decay to lepton-antilepton pair: direct and resonance diagram.

The contribution of the resonance diagram is

$$\begin{aligned}
 \mathcal{M}_R(A' \rightarrow \ell^+ \ell^-) &= e^2 \varepsilon_\mu(p) g_{A'\ell\bar{\ell}}^R \bar{u}(q_1) \gamma^\mu v(q_2), \\
 g_{A'\ell\bar{\ell}}^R &= \sum_{V=\rho^0, \omega, \phi} g_{V\gamma} \frac{m_{A'}^2 g_{VA'}(m_{A'}^2)}{m_V^2 - m_{A'}^2 - i\Gamma_V m_V}.
 \end{aligned} \tag{17}$$

In order to avoid the $m_V^2 \simeq m_{A'}^2$ singularity, we retain the finite width Γ_V in the Breit-Wigner propagator. For convenience, we define $g_{VA'} \equiv g_{V\gamma} g^v$ as in Eq. (9). Summing up the direct and the resonant contributions of the $V = \rho^0, \omega, \phi$, we get the $A' \rightarrow \ell^+ \ell^-$ decay width

$$\begin{aligned}
 \Gamma(A' \rightarrow \ell^+ \ell^-) &= \frac{am_{A'}}{3} \sqrt{1 - 4x_{\ell A'}} (1 + 2x_{\ell A'}) \\
 &\times [(G_{\ell\bar{\ell}}^v)^2 + (G_{\ell\bar{\ell}}^a)^2 + 2G_{\ell\bar{\ell}}^v \text{Re}(g_{A'\ell\bar{\ell}}^R) + |g_{A'\ell\bar{\ell}}^R|^2].
 \end{aligned} \tag{18}$$

The similar analysis can be straightforwardly extended to the e^+e^- collisions and the bremsstrahlung processes with dark photon production. These processes are important to search for dark-matter signals by the missing energy technique [14,15].

B. A' production in rare decays of π^0 , η , and η' mesons

Next, we consider the A' production in rare decays of light pseudoscalar mesons $P = \pi^0, \eta, \eta'$. In our approach, there are two diagrams in Fig. 3 which contribute to this process at leading order. The left diagram describes the direct A' production, while the right one the resonant, induced by the $V - A'$ transition.

The total matrix element of the $P \rightarrow \gamma A'$ decay is given by

$$\mathcal{M}(P \rightarrow \gamma A') = \mathcal{M}_D(P \rightarrow \gamma A') + \mathcal{M}_R(P \rightarrow \gamma A'), \tag{19}$$

where $\mathcal{M}_D$ and $\mathcal{M}_R$ correspond to direct (D) and V -resonance (R) diagrams in Fig. 3, respectively. Matrix element is induced by the $PF\bar{F}'$ anomaly term in the effective Lagrangian (8). For the local FF' -portal scenario, $\hat{\varepsilon} \equiv \varepsilon$ is a constant to be determined from the data analysis. In the nonlocal case for the on-shell A' , we have $\hat{\varepsilon} = \varepsilon(m_{A'}^2)$. For the direct matrix element $\mathcal{M}_D$ of A' production, we have

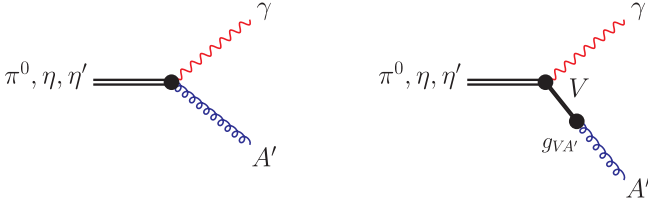


FIG. 3. Feynman diagrams contributing to semi-invisible modes of light neutral pseudoscalars $P = \pi^0, \eta, \eta'$.

$$\mathcal{M}_D = e^2 \epsilon_{\mu\nu\alpha\beta} \epsilon_\gamma^\mu(q_1) \epsilon_{A'}^\nu(q_2) q_1^\alpha q_2^\beta g_{P\gamma A'}, \quad (20)$$

where we denoted $g_{P\gamma A'} = \epsilon(m_{A'}^2) g_{P\gamma A}$. To calculate resonance matrix element $\mathcal{M}_R$, we need to specify interaction Lagrangians describing the couplings $g_{VP\gamma}$ of $P = \pi^0, \eta$, and η' mesons with photon and vector mesons $V = \rho^0, \omega$, and ϕ . These couplings occur in the effective Lagrangians given by

$$\mathcal{L}_{VP\gamma} = \frac{e}{4} g_{VP\gamma} \epsilon_{\mu\nu\alpha\beta} P V^{\mu\nu} F^{\alpha\beta}. \quad (21)$$

The V -resonance contribution $\mathcal{M}_R$ to the matrix element of the A' production is given by

$$\mathcal{M}_R = e^2 \epsilon_{\mu\nu\alpha\beta} \epsilon_\gamma^\mu(q_1) \epsilon_{A'}^\nu(q_2) q_1^\alpha q_2^\beta g_{P\gamma A'}^R, \quad (22)$$

$$g_{P\gamma A'}^R = \sum_{V=\rho^0, \omega, \phi} g_{VP\gamma} \frac{m_{A'}^2}{m_V^2} \frac{m_{A'}^2 g_{A'V}^2(m_V^2)}{m_V^2 - m_{A'}^2 - i\Gamma_V m_V}.$$

The width of the $P \rightarrow \gamma A'$ decay is calculated using the formula

$$\Gamma(P \rightarrow \gamma A') = \frac{\pi \alpha^2}{4} m_P^3 [g_{P\gamma A'}^2 + 2g_{P\gamma A'} \text{Re}(g_{P\gamma A'}^R) + |g_{P\gamma A'}^R|^2]. \quad (23)$$

Note that decays of neutral light pseudoscalar mesons (π^0, η , and η') to $\gamma A'$ are under study in the NA64, NA62, and COHERENT experiments [16–19].

C. Invisible decays of vector mesons

The vector mesons can decay invisibly $V \rightarrow \chi \bar{\chi}$ to the dark fermions $\chi \bar{\chi}$ due to the $V - A'$ mixing induced by the first term in (8). The Feynman diagram contributing to this invisible decay mode of neutral vector mesons is shown in Fig. 4. The second vertex is described by the $g_{DA'} \chi \bar{\chi}$ term in (5).

Then, the vector-meson decay rates to this invisible mode is given by

$$\Gamma(V \rightarrow \chi \bar{\chi}) = \frac{\alpha_D}{6} g_{A'V}^2(m_V^2) m_V \frac{(1 + 2x_{\chi V}) \sqrt{1 - 4x_{\chi V}}}{(1 - x_{A'V})^2 + z^2}, \quad (24)$$

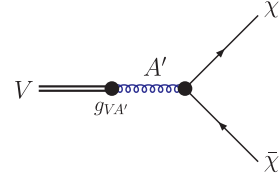


FIG. 4. Feynman diagram contributing to invisible modes of neutral vector mesons.

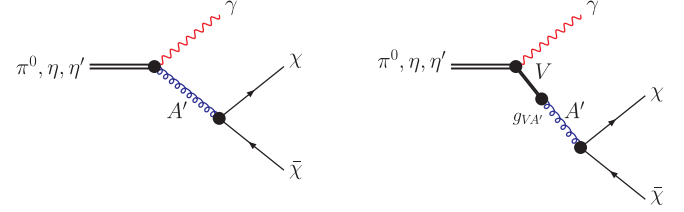


FIG. 5. Feynman diagrams contributing to semi-invisible decays of light pseudoscalar mesons.

where $z = \Gamma_{A' \rightarrow \chi \bar{\chi}} / m_V, m_V, m_{A'}$, and m_χ are the masses of the vector meson, intermediate dark photon, and DM fermion, respectively. Here, we use the Breit-Wigner propagator for A' to avoid $m_{A'}^2 \simeq m_V^2$ singularity by assuming that A' its total width is dominated by the $A' \rightarrow \chi \bar{\chi}$ invisible mode.

D. Semi-invisible decays of light pseudoscalar mesons

In this section, we discuss results for the semi-invisible decays of light pseudoscalar mesons $P = \pi^0, \eta, \eta'$. Diagrams contributing to these processes are shown in Fig. 5. Here, as before, we consider two mechanisms: (i) direct A' production (left diagram) and (ii) resonant via $V - A'$ transition (right diagram).

Summing up both contributions, we obtain

$$d\Gamma(P \rightarrow \chi \bar{\chi} \gamma) = \frac{\alpha \alpha_D}{24\pi m_P^3} \frac{(q^2 - m_{\eta'}^2)^3 (q^2 + 2m_\chi^2) (q^2 - 4m_\chi^2)^{\frac{1}{2}}}{(m_{A'}^2 - q^2)^2 + \Gamma_{A' \rightarrow \chi \bar{\chi}}^2 m_{A'}^2} \frac{dq^2}{\sqrt{q^2}} \times [g_{P\gamma A'}^2 + 2g_{P\gamma A'} \text{Re}(g_{P\gamma A'}^R(q^2)) + |g_{P\gamma A'}^R(q^2)|^2], \quad (25)$$

where

$$g_{P\gamma A'}^R(q^2) = \sum_{V=\rho^0, \omega, \phi} \frac{q^2 g_{VP\gamma} g_{VA'}(q^2)}{q^2 - m_V^2 + i\Gamma_V m_V}. \quad (26)$$

This is the nonlocal generalization of the result derived in Ref. [20].

V. DISCUSSION

Here, we briefly discuss the impact of existing experimental bounds in the case of the nonlocal realization of the Stueckelberg portal between the SM and DS. The main constraints on the dark photon parameters are obtained from

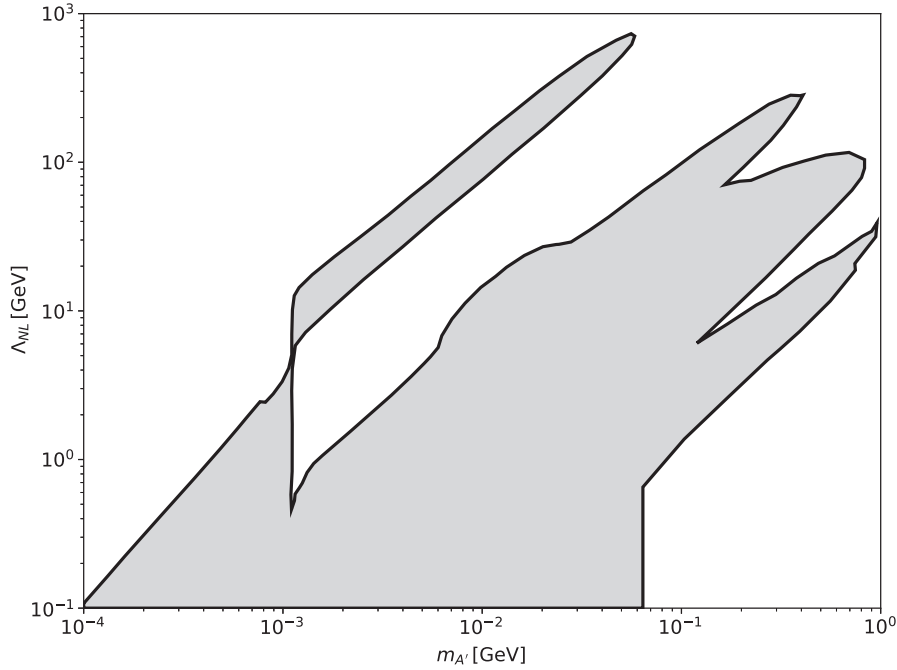


FIG. 6. Exclusion plot in the $(m_{A'}, \Lambda_{NL})$ plane for $\epsilon = 1$ derived from Ref. [21]. Shaded region is excluded by the observations and calculation from cosmology.

s -channel processes, where a massive dark photon is produced on shell, corresponding to timelike momentum transfer $k^2 = m_{A'}^2$. In the nonlocal portal models, the constant kinetic mixing parameter ϵ_Y in (2) or, as in the present case, the Stueckelberg couplings $g_{ij}^{v,a}$ in (5) are replaced by momentum-dependent quantities according to Eq. (6). Therefore, the bounds existing in the literature on local dark photon models, typically presented in the form $\epsilon < \epsilon_{\text{exp}}(m_{A'})$, can be recast into the constraint $\hat{\epsilon}(m_{A'}^2; \Lambda_{NL})g/e < \epsilon_{\text{exp}}(m_{A'})$ for processes involving s -channel photon exchange $k^2 = m_{A'}^2$, resulting in a lower bound curve in the $(m_{A'}, \Lambda_{NL})$ plane. We show the corresponding exclusion plot in Fig. 6, derived by applying this approach to the collider and cosmological bounds on the local dark photon collected in Ref. [21].

As seen from Fig. 6, the scale Λ_{NL} of nonlocal interaction between dark photons of mass $m_{A'}$ and SM fermions weakens in the small $m_{A'}$ limit, although the couplings may remain significant. This behavior originates from the infrared suppression of the nonlocal form factor $\hat{\epsilon}(k^2) \propto (k^2/\Lambda_{NL}^2)^2$ in (7), significantly reducing the on-shell production rate in the regime $m_{A'} \ll \Lambda_{NL}$. Consequently, searches relying on resonant dark photon production lose sensitivity in the presence of nonlocal interactions.

As observed in Ref. [7] for the case of nonlocal photon- A' kinetic mixing, this kind of behavior also allows one to reconcile the stringent limits from direct dark-matter searches with the observed relic abundance. The same occurs in our nonlocal Stueckelberg portal scenario. Indeed, direct detection of the dark fermion χ proceeds through elastic scattering $\chi + \text{SM} \rightarrow \chi + \text{SM}$ mediated by t -channel A' exchange.

Since the typical momentum transfer q^2 in direct-detection experiments is very small, the corresponding scattering amplitude is strongly suppressed by the nonlocal form factor $\epsilon(q^2)$ in Eq. (7), which vanishes in the low-momentum-transfer limit. By contrast, thermal annihilation $\chi\chi \rightarrow \text{SM}$ in the early Universe is dominated by the s -channel near-resonant or on-shell A' contribution and is controlled by momentum scales of the order of $m_{A'}^2$. Therefore, the annihilation cross section can remain sufficiently large to reproduce the observed dark-matter relic density while the direct-detection rate is naturally suppressed.

Invisible and semi-invisible meson decays considered in the previous sections are tightly constrained by fixed-target experiments employing missing-energy and missing-momentum techniques. For fully invisible final states, the strongest bounds come from the *BABAR* search [15] and from the NA64 program at the CERN Super Proton Synchrotron using electron and positron beams [22]. In addition, projected sensitivities based on the expected π^0 , η , and η' yields in NA64 with a negative-pion beam were estimated in Ref. [20]. For the invisible decay $\rho^0 \rightarrow \chi\bar{\chi}$, constraints derived from the ρ -meson yields—computed within a Glauber-model treatment for NA64—were presented in Ref. [23]. We used these experimental constraints to analyze the numerical impact of the nonlocality form factor (6) on the meson decay rates derived in the previous sections and estimated the corresponding limits on the scale Λ_{NL} .

We found that the decay rates of both vector $V = \rho, \omega, \phi, J/\psi, \Upsilon$ and pseudoscalar $P = \pi^0, \eta, \eta'$ mesons

probe the effective nonlocal couplings at timelike momentum transfer, $\hat{e}(k^2 = m_{A'}^2)$, implying that the corresponding bounds become suppressed in the nonlocal scenario when $\Lambda_{\text{NL}} \gg m_M$. Consequently, limits derived from invisible meson decay searches rapidly weaken due to the momentum-dependent suppression $\hat{e}(k^2) \propto (k^2/\Lambda_{\text{NL}}^2)^2$. As a result, for $\Lambda_{\text{NL}} > 1$ TeV the dark photon mass $m_{A'}$ becomes unconstrained both from meson decays and from cosmological and collider data in Fig. 6. We already noted in Sec. II that values of the nonlocality scale Λ_{NL} below the TeV range are challenging from the viewpoint of theoretical consistency and the construction of a sensible UV completion.

VI. CONCLUSIONS

We have developed a meson-level effective description for a light vector boson A'_μ that couples directly to SM quark and lepton currents through generic vector and axial-vector interactions. In this class of models, the dominant hadronic production and decay channels of A' at sub- to few-GeV energies are governed by how the underlying quark currents are embedded into low-energy QCD, so rare meson processes provide an essential—and often leading—set of probes.

Starting from the quark-level interactions in Eq. (5), we constructed an effective theory for pseudoscalar mesons supplemented by vector-meson resonances, Eq. (8). The matching is realized through resonance saturation: Vector quark currents generate A' couplings mediated by vector mesons and their mixing, providing a practical description in the GeV regime. We also incorporated the anomalous WZW terms that govern radiative and anomalous transitions such as $P \rightarrow \gamma A'$, $V \rightarrow PA'$, and related channels and expressed the corresponding effective couplings in terms of the underlying quark-level parameters. Within this unified framework, we derived the decay widths and branching ratios relevant for both visible and invisible scenarios. For visible A' decays, narrow-resonance searches in dilepton spectra map directly onto meson transition rates, while for invisible A' decays the same meson transitions lead to missing-energy or missing-mass signatures, enabling stringent constraints on A' models.

We also explored the phenomenological viability of the nonlocal setup, assuming that the SM–dark-sector portal is nonlocal and characterized by a nonlocality scale Λ_{NL} controlling the effective A' –SM-fermion interaction. In particular, for values of the nonlocality scale in the UV-controlled regime, $\Lambda_{\text{NL}} \gtrsim 1$ TeV, the portal suppression renders existing meson-decay, cosmological, and collider limits insensitive to the dark photon mass $m_{A'}$, leaving it unconstrained, at least for the benchmark assumptions adopted in our analysis.

Let us finally comment on the possible observability of nonlocal effects in the present scenario. The scale Λ_{NL} entering our framework parametrizes specifically the

nonlocality of the portal interaction between the Standard Model and the dark sector rather than a universal nonlocal modification of all Standard Model interactions. Therefore, the existing ATLAS and CMS bounds [13] on generic nonlocal scales at the level of several TeV should be viewed as an important reference scale but not necessarily as a direct exclusion of the scenario considered here.

Note that if the effective portal nonlocality scale is extremely high, for example, close to the Planck scale, the resulting effects become negligibly small and the model effectively reduces to the local limit. On the other hand, if Λ_{NL} lies in the multi-TeV range, observable effects of nonlocality may still be accessible in rare meson decays and missing-energy experiments.

The characteristic signature of nonlocality is the momentum dependence of the effective A' interactions encoded in the form factor $\epsilon(q^2)$. This can lead to correlated distortions of production rates and spectra in processes probing different momentum transfers. Our analysis demonstrates that present and future meson-decay searches can probe a substantial part of the corresponding parameter space.

At the same time, we note that momentum-dependent effective interactions may also emerge in certain local UV-complete scenarios after integrating out additional heavy degrees of freedom. Therefore, establishing experimentally the genuinely nonlocal origin of such effects may represent a nontrivial challenge.

In conclusion, the effective description presented here provides a systematic and flexible framework for embedding nonlocality in quark- A' interactions into meson-level observables and can be straightforwardly extended to refined hadronic inputs and dedicated experimental sensitivity studies.

ACKNOWLEDGMENTS

This work was funded by Fondo Nacional de Desarrollo Científico y Tecnológico (FONDECYT) (Chile) under Grants No. 1230160 and No. 1240066 and by Agencia Nacional de Investigación y Desarrollo de (ANID)-Millennium Program—ICN2019_044 (Chile). The work of A. S. Z. is supported by the Foundation for the Advancement of Theoretical Physics and Mathematics “BASIS” and by President’s International Fellowship Initiative Chinese Academy of Sciences (PIFI CAS) Grant No. 2024PVB0070. A. S. Z. also is grateful Xurong Chen [Institute of Modern Physics, Chinese Academy of Sciences (IMP CAS), China] and Pengming Zhang (Sun Yat-Sen University, China) for the warm hospitality, where part of work was done.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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