

Article

A Visible Coupling Benchmark for Massive Dark Photon Searches in $D^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$

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Abstract

Rare charm decays offer a clean arena for visible massive dark photon searches through narrow dielectron resonances. In the process $D^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$, the observable signal rate is controlled simultaneously by the flavor changing charm transition, the radiative $D^0 \rightarrow \gamma$ hadronic matrix element, the visible decay probability of A' , and the experimental response of the reconstructed mass spectrum. We introduce a visible coupling formulation that combines these ingredients into a single search parameter while keeping the form factor and the $A' \rightarrow e^+ e^-$ branching fraction as explicit external inputs. This provides a direct bridge between branching fraction sensitivity and coupling reach, without assuming a specific experimental background model. The central novelty of this approach is that it separates the particle physics information entering the signal rate from the analysis-dependent ingredients that determine the observable mass spectrum. We apply this construction to the $D^0 \rightarrow \gamma e^+ e^-$ spectrum, including effective exposure, reconstruction efficiency, mass resolution, and the treatment of the ρ/ω and ϕ regions. The ρ/ω and ϕ dominated intervals are kept outside the coupling definition and left to experiment specific resonance treatment. This formulation gives a practical and reusable basis for comparing visible massive dark photon sensitivity across current and future charm data sets.

Keywords: massive dark photon; rare charm decay; benchmark; sensitivity

1. Introduction

A massive dark photon A' provides a well-motivated low-energy window onto hidden vector interactions. If the new boson A' has a nonzero mass, it can be produced on shell and searched for as a localized structure in a visible invariant-mass spectrum. In the minimal kinetic-mixing picture, constraints are commonly displayed in the ϵ - $m_{A'}$ plane, where ϵ denotes the conventional dimensionless kinetic mixing parameter between the photon and the dark photon. Extensive fixed-target, $e^+ e^-$, and hadron-collider programs have explored both visible and invisible A' decays [1–6]. This organization is most transparent when production and decay are governed by flavor-universal kinetic mixing [7,8]. It becomes less direct when the production vertex is flavor changing, because a visible final-state limit then constrains not only a microscopic coupling but also short-distance flavor dynamics, non-perturbative hadronic input, and the visible decay probability of the massive A' [9,10].

Rare charm decays are a natural setting for such a study. Standard Model flavor changing neutral current amplitudes in the up-quark sector are strongly suppressed, while exclusive charm modes are strongly affected by long distance hadronic effects and vector-meson resonances [11–17]. Consequently, inclusive rates alone are often difficult to interpret,



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whereas narrow structures and differential null tests can provide cleaner sensitivity to short-distance contributions [18–23]. Existing measurements and searches in radiative and dileptonic charm channels, including $D^0 \rightarrow \phi\gamma$, $D^0 \rightarrow K^{*0}\gamma$, $D^0 \rightarrow \rho^0\gamma$, $D^0 \rightarrow \gamma\gamma$, and $D^0 \rightarrow h^+h^-\ell^+\ell^-$, demonstrate the feasibility of such final states while emphasizing the need for controlled continuum and ρ/ω , ϕ -region treatments [24–29]. The recent BESIII search for a massless dark photon in $c \rightarrow u\gamma'$ decays is therefore closely related, but the massive visible case considered here is experimentally and interpretively distinct because the A' is reconstructed through $A' \rightarrow e^+e^-$ [30].

The study focuses on $D^0 \rightarrow \gamma A' \rightarrow \gamma e^+e^-$ with $2m_e < m_{A'} < m_{D^0}$. The signal topology is illustrated in Figure 1. The channel combines a two-body radiative production process with a narrow dielectron resonance search, but its rate cannot be mapped to a single microscopic parameter without additional assumptions. It depends simultaneously on the short-distance $c \rightarrow uA'$ transition, the $D^0 \rightarrow \gamma$ hadronic matrix element at $q^2 = m_{A'}^2$, and the branching fraction for $A' \rightarrow e^+e^-$. The experimentally useful mass range is further shaped by photon and electron reconstruction, bremsstrahlung recovery, conversion backgrounds, endpoint phase-space suppression, and resonance vetoes or templates near the ρ/ω and ϕ bands. A direct bound on ϵ would therefore mix detector sensitivity with hadronic and model-dependent inputs.

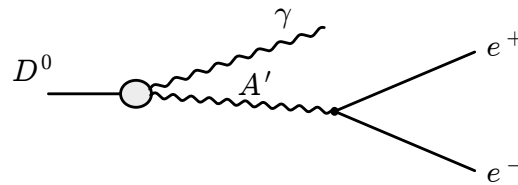


Figure 1. Schematic illustration of the signal topology $D^0 \rightarrow \gamma A'$, followed by the visible decay $A' \rightarrow e^+e^-$. The shaded vertex denotes the effective flavor-changing transition.

To keep these ingredients separate, we parameterize the flavor-changing $c \rightarrow uA'$ transition by an effective dipole operator and retain the $D^0 \rightarrow \gamma$ hadronic transition as an explicit factor $F_{D^0\gamma}(q^2)$. We then combine this factor and the visible A' branching fraction with the effective dipole strength into a visible coupling g_{vis} . In this normalization, $\mathcal{B}(D^0 \rightarrow \gamma A' \rightarrow \gamma e^+e^-)$ is proportional to g_{vis}^2 multiplied by the cubic two-body phase-space factor, so an experimental branching-fraction sensitivity can be converted into a g_{vis} reach without fixing a particular ultraviolet completion, form-factor model, or A' decay scenario. Detector-level inputs from BESIII-like, Belle II-like, LHCb-like, or future samples enter through the effective exposure, efficiency, mass resolution, background level, and resonance treatment [31–34]. The resulting framework is therefore a portable normalization for searches for a massive visible A' in $D^0 \rightarrow \gamma e^+e^-$, with later translations to the underlying effective flavor changing coupling or to ϵ left to model-specific input.

2. Effective Description and Visible Normalization

In this benchmark, the signal topology can be organized into two main ingredients that are useful to treat separately at the outset. The first is the short-distance flavour changing transition $c \rightarrow uA'$, which is described by an effective operator at the charm scale. The second is the long-distance hadronic transition in which the D^0 meson emits the photon. Keeping these two ingredients separate makes the normalization transparent and allows the hadronic input to be updated independently. Unless otherwise stated, we use natural units with $c = \hbar = 1$. For numerical evaluations in which the measured D^0 lifetime is inserted in seconds, $\hbar$ is restored explicitly in Equations (9) and (12) to convert between seconds and GeV^{-1} , while masses quoted in GeV implicitly use $c = 1$.

At the lowest non-trivial order, the short distance flavor changing $c \rightarrow uA'$ transition is represented by the dipole interaction,

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda} \bar{u} \sigma_{\mu\nu} (C + C_5 \gamma_5) c F'^{\mu\nu} + \text{h.c.} \quad (1)$$

where $F'^{\mu\nu}$ is the field strength tensor of the vector state A' , $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$, and C and C_5 are dimensionless Wilson coefficients. The scale Λ represents the heavy mass scale that suppresses the dimension-five operator.

In this benchmark, the term “dark photon” is used in a broad phenomenological sense: it denotes a massive visible vector state that can decay into e^+e^- . The flavor changing production vertex $c \rightarrow uA'$ is not assumed to arise from minimal kinetic mixing alone, but is parameterized directly by the effective dipole operator in Equation (1). Consequently, translating the effective normalization introduced below into the conventional kinetic mixing parameter ϵ requires additional theoretical input, as discussed in Section 4.

For an unpolarized benchmark rate, and under the common form factor normalization introduced below, the two dipole structures enter through the quadratic combination

$$g_{\text{eff}} = \frac{\sqrt{|C|^2 + |C_5|^2}}{\Lambda}, \quad [g_{\text{eff}}] = \text{GeV}^{-1}. \quad (2)$$

This definition should be understood as a convenient low energy coupling strength. It does not assume a specific ultraviolet model, nor does it fix possible CP phases that would require a more differential analysis.

The remaining part of the amplitude is the non-perturbative hadronic matrix element for the $D^0 \rightarrow \gamma$ transition. Rather than assigning a model-dependent numerical value to this matrix element, we absorb it into a dimensionless transition factor $F_{D^0\gamma}(q^2)$, evaluated at $q^2 = m_{A'}^2$. To make this convention explicit, we fix the normalization of $F_{D^0\gamma}$ through the polarization summed amplitude,

$$\sum_{\text{pol}} |\mathcal{M}(D^0 \rightarrow \gamma A')|^2 = 2m_{D^0}^4 |F_{D^0\gamma}(m_{A'}^2)|^2 g_{\text{eff}}^2 \left(1 - \frac{m_{A'}^2}{m_{D^0}^2}\right)^2. \quad (3)$$

With this definition, Equation (3) should be regarded as a normalization convention rather than as an independent dynamical prediction. The factor $(1 - m_{A'}^2/m_{D^0}^2)^2$ displays the momentum dependence generated by the radiative dipole structure, while the unknown strong-interaction normalization is kept in $F_{D^0\gamma}$. With this convention, lattice QCD calculations, light-cone sum rule estimates, vector-meson dominance inputs, or data driven normalizations can be incorporated simply by replacing $F_{D^0\gamma}(q^2)$, without changing the kinematic conversion used later.

The experimentally reconstructed final state is γe^+e^- , rather than the intermediate state A' alone. The observable rate must therefore include the probability for A' to decay into an electron and positron pair. We combine the coupling associated with the short distance transition, the hadronic normalization, and the visible branching fraction into a coupling used at the search level,

$$g_{\text{vis}}(m_{A'}) \equiv |F_{D^0\gamma}(m_{A'}^2)| \sqrt{\mathcal{B}(A' \rightarrow e^+e^-)} g_{\text{eff}}. \quad (4)$$

The quantity g_{vis} has the same mass dimension as g_{eff} , namely GeV^{-1} . All projected rates in the following analysis are expressed in terms of g_{vis} . If a particular model later specifies both $F_{D^0\gamma}(q^2)$ and $\mathcal{B}(A' \rightarrow e^+e^-)$, the same results can be translated back to g_{eff} , and then to the microscopic parameters of that model.

Although the present benchmark is formulated explicitly for the $A' \rightarrow e^+e^-$ final state, the same visible-coupling construction can be applied to the dimuon channel when $m_{A'} > 2m_\mu$. This extension is obtained by replacing $\mathcal{B}(A' \rightarrow e^+e^-)$ with $\mathcal{B}(A' \rightarrow \mu^+\mu^-)$ in the definition of g_{vis} , while the relation between g_{vis} and the signal branching fraction retains the same form. The relative sensitivity of the two channels is experiment-dependent. In particular, at e^+e^- colliders, selection criteria used to suppress Bhabha backgrounds may reduce the electron efficiency, so the dimuon channel can provide complementary sensitivity. A quantitative comparison should therefore be performed separately for each channel, using its corresponding detector response and background treatment.

3. Signal Branching Fraction from Two-Body Kinematics

After the visible normalization has been specified, the signal rate can be obtained from the two body decay $D^0 \rightarrow \gamma A'$. In the rest frame of the D^0 meson, and treating the photon as massless, the common momentum of the two final state particles is

$$|\vec{p}_\gamma| = |\vec{p}_{A'}| = \frac{m_{D^0}^2 - m_{A'}^2}{2m_{D^0}} = \frac{m_{D^0}}{2} \left(1 - \frac{m_{A'}^2}{m_{D^0}^2} \right). \quad (5)$$

This expression is purely kinematic. It shows that the available momentum vanishes when the mass of A' approaches the D^0 mass.

Throughout this benchmark we consider the visible massive- A' range

$$2m_e < m_{A'} < m_{D^0}. \quad (6)$$

The lower bound follows from the requirement that the intermediate state can decay into an e^+e^- pair, while the upper bound is set by the two-body kinematics of $D^0 \rightarrow \gamma A'$. In practice, the experimentally useful region is further restricted by reconstruction thresholds, conversion backgrounds, resonance regions, and endpoint phase-space loss, as discussed below.

The partial width is obtained by multiplying the squared amplitude by the two body phase space. Since the parent D^0 meson has spin zero, no average over initial spin states is required. After summing over the final state polarizations, one obtains

$$\Gamma(D^0 \rightarrow \gamma A') = \frac{|\vec{p}_\gamma|}{8\pi m_{D^0}^2} \sum_{\text{pol}} |\mathcal{M}(D^0 \rightarrow \gamma A')|^2. \quad (7)$$

Substituting the amplitude normalization introduced in Equation (3) and the momentum in Equation (5) gives

$$\Gamma(D^0 \rightarrow \gamma A') = \frac{m_{D^0}^3}{8\pi} \left| F_{D^0\gamma}(m_{A'}^2) \right|^2 g_{\text{eff}}^2 \left(1 - \frac{m_{A'}^2}{m_{D^0}^2} \right)^3. \quad (8)$$

Here the transition factor is evaluated at $q^2 = m_{A'}^2$. The cubic dependence has a clear kinematic origin: one power arises from the two body phase space, while the remaining two powers are supplied by the radiative dipole structure of the amplitude.

The experimentally visible final state also requires the decay of A' into an electron pair. Therefore, the partial width must be multiplied by $\tau_{D^0}/\hbar$ and by the visible branching fraction. Using the definition of g_{vis} , the visible signal branching fraction becomes

$$\mathcal{B}_{\text{sig}} \equiv \mathcal{B}(D^0 \rightarrow \gamma A' \rightarrow \gamma e^+e^-) = \frac{\tau_{D^0}}{\hbar} \frac{m_{D^0}^3}{8\pi} g_{\text{vis}}^2(m_{A'}) \left(1 - \frac{m_{A'}^2}{m_{D^0}^2} \right)^3. \quad (9)$$

For this benchmark, Equation (9) is the main conversion between the coupling used at the search level and the visible branching fraction. It shows that the rate is proportional to g_{vis}^2 and that the rate is suppressed when the available two-body momentum becomes small near the endpoint. The corresponding benchmark branching fraction curves, which visualize the g_{vis}^2 scaling and the endpoint suppression implied by Equation (9), are shown in Appendix A.

The same branching fraction fixes the area of the peak in the reconstructed dielectron mass spectrum. If the intrinsic width of A' is much smaller than the detector mass resolution, the observed signal is controlled by the detector response. For a normalized resolution function G ,

$$\frac{d\mathcal{B}}{dm_{e^+e^-}} = \mathcal{B}_{\text{sig}} G(m_{e^+e^-}; m_{A'}, \sigma_m), \quad \int G(m_{e^+e^-}; m_{A'}, \sigma_m) dm_{e^+e^-} = 1. \quad (10)$$

where the normalization of G ensures that the integral of the peak is $\mathcal{B}_{\text{sig}}$. If the intrinsic width is not negligible compared with the mass resolution, the physical line shape should first be described by a normalized Breit Wigner function and then smeared with the detector response,

$$\frac{d\mathcal{B}}{dm_{e^+e^-}} = \mathcal{B}_{\text{sig}} [BW(m_{e^+e^-}; m_{A'}, \Gamma_{A'}) \otimes G(m_{e^+e^-}; \sigma_m)]. \quad (11)$$

The narrow peak expression in Equation (10) is used as a transparent benchmark for a weakly coupled visible state. It fixes the signal yield and the local peak shape, but it does not replace the background model of a real analysis. In an experimental study, the smooth continuum, sidebands, reconstruction efficiency, and the ρ/ω , ϕ resonance regions should be treated with experiment-specific templates or vetoes.

4. Coupling Reach and Interpretation

The preceding section gives a direct relation between the visible branching fraction and the coupling used at the search level. This relation can be inverted to express the coupling reach in terms of the detector-level sensitivity to the visible branching fraction. Here, $\mathcal{B}_{\text{sens}}(m_{A'})$ denotes the minimum visible signal branching fraction required to satisfy the adopted experiment-specific exclusion or discovery criterion at the tested mass. At the sensitivity boundary, the predicted branching fraction is set equal to this sensitivity, $\mathcal{B}_{\text{sig}} = \mathcal{B}_{\text{sens}}$. Solving Equation (9) for g_{vis} then gives

$$g_{\text{vis}}^{\text{lim}}(m_{A'}; \mathcal{B}_{\text{sens}}) = \left[\frac{8\pi\hbar \mathcal{B}_{\text{sens}}}{\tau_{D^0} m_{D^0}^3} \right]^{1/2} \left(1 - \frac{m_{A'}^2}{m_{D^0}^2} \right)^{-3/2}. \quad (12)$$

This expression is the conversion used to draw the coupling reach curves. The square root dependence reflects the fact that rates are proportional to squared amplitudes. As a result, an improvement of the branching fraction sensitivity by a factor of 10 improves the coupling reach by a factor of $\sqrt{10}$. The last factor shows the loss of reach near the kinematic endpoint, where the two body phase space becomes small.

Figure 2 shows the reach in g_{vis} obtained from representative values of $\mathcal{B}_{\text{sens}}$. The curves depend only on the visible branching fraction sensitivity and on the kinematic factor in Equation (12). The rise at large $m_{A'}$ is therefore not a consequence of an assumed background model, but follows from the closing of the available phase space.

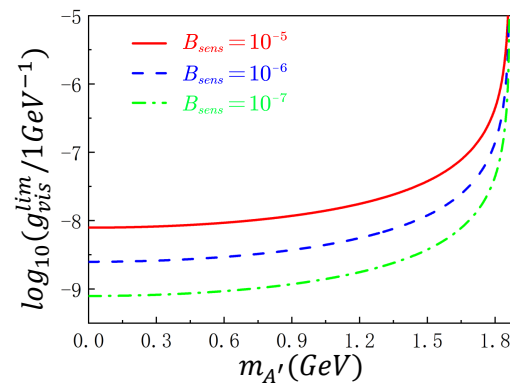


Figure 2. Coupling reach obtained by converting detector-level branching-fraction sensitivities into $g_{\text{vis}}^{\text{lim}}$. The curves correspond to $B_{\text{sens}} = 10^{-5}$, 10^{-6} , and 10^{-7} .

Table 1 gives representative numerical values of the converted coupling reach. These values are evaluated using Equation (12), with masses expressed in GeV, the D^0 lifetime in seconds, and $\hbar$ in GeV·s. The table is intended as a benchmark for rescaling rather than as a substitute for an experiment specific limit.

Table 1. Representative values of the converted coupling reach $g_{\text{vis}}^{\text{lim}}$ in GeV^{-1} .

$m_{A'}$ [GeV]	$B_{\text{sens}} = 10^{-5}$	$B_{\text{sens}} = 10^{-6}$	$B_{\text{sens}} = 10^{-7}$
0.2	8.02×10^{-9}	2.54×10^{-9}	8.02×10^{-10}
0.6	9.29×10^{-9}	2.94×10^{-9}	9.29×10^{-10}
1.2	1.76×10^{-8}	5.56×10^{-9}	1.76×10^{-9}
1.5	3.76×10^{-8}	1.19×10^{-8}	3.76×10^{-9}

Expressing the reach in terms of g_{vis} keeps the detector-level sensitivity separated from the hadronic normalization and from the visible decay probability of the intermediate state. The quantity g_{vis} should therefore not be read as a microscopic coupling by itself. It already contains the hadronic transition factor and the visible branching fraction of A' . Once a specific model or a data driven input provides these quantities, the corresponding effective coupling is obtained from

$$g_{\text{eff}}^{\text{lim}}(m_{A'}) = \frac{g_{\text{vis}}^{\text{lim}}(m_{A'}; B_{\text{sens}})}{|F_{D^0\gamma}(m_{A'}^2)| \sqrt{B(A' \rightarrow e^+e^-)}}. \quad (13)$$

Here the transition factor is evaluated at $q^2 = m_{A'}^2$. This equation separates the experimental result from the external physics inputs. The experimental analysis constrains g_{vis} , while the conversion to g_{eff} requires information on the hadronic normalization and on the decay probability of A' into the electron pair. In this sense, g_{vis} is the directly constrained search level quantity, whereas g_{eff} should be reported only after specifying $F_{D^0\gamma}(q^2)$ and $B(A' \rightarrow e^+e^-)$. Different choices of these two inputs therefore rescale the same g_{vis} reach multiplicatively, without changing the detector-level conversion in Equation (12).

Figure 3 visualizes the reinterpretation step encoded in Equation (13). For a fixed detector level reach on the search level coupling g_{vis} , the inferred constraint on the underlying effective flavor changing coupling g_{eff} depends on two external inputs: the hadronic transition normalization $|F_{D^0\gamma}(m_{A'}^2)|$ and the visible decay probability $B(A' \rightarrow e^+e^-)$. The color scale therefore represents the multiplicative factor that converts a quoted g_{vis} limit into an input-dependent g_{eff} limit. Smaller values of either input weaken the inferred constraint on g_{eff} , even when the experimental sensitivity to g_{vis} is unchanged. Thus, Figure 3 should not be interpreted as imposing a particular form factor model or dark sector decay scenario.

Instead, it provides a rescaling map that allows future theoretical or phenomenological inputs to be applied to the same experimental search level result. This makes explicit the central separation of the present framework: detector level sensitivity is encoded in g_{vis} , whereas the translation to g_{eff} is left to external theoretical input.

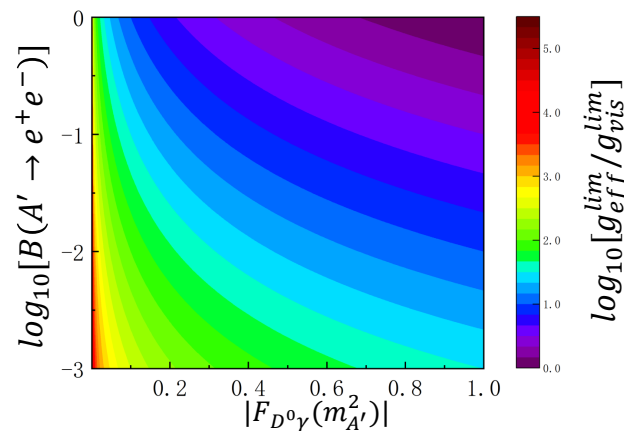


Figure 3. Rescaling from the visible search level coupling g_{vis} to the effective flavor changing coupling g_{eff} . The color scale shows $\log_{10}(g_{\text{eff}}^{\text{lim}}/g_{\text{vis}}^{\text{lim}})$ as a function of the hadronic transition normalization $|F_{D^0\gamma}(m_{A'}^2)|$ and the visible branching fraction $\mathcal{B}(A' \rightarrow e^+e^-)$.

With this separation made explicit, the g_{vis} representation provides a useful way to position the present framework relative to other research perspectives. Unlike the conventional ϵ versus $m_{A'}$ plane used in ordinary dark photon searches, the present benchmark is organized around a charm transition with changing flavor and a visible intermediate state. Table 2 summarizes this distinction and compares the role of the g_{vis} framework with related approaches.

Table 2. Positioning of this work relative to existing research perspectives.

Research Perspective	Core Object	Main Question	Relation to This Work
Ordinary dark photon searches	ϵ versus $m_{A'}$; visible or invisible A' decays	Production or decay through kinetic mixing	Complementary context; conversion to the flavor-changing charm amplitude requires external model input.
Rare charm constraints	Branching fractions and Wilson coefficients	Deviation in rare $c \rightarrow u$ processes	Closest in motivation; sensitive to long distance hadronic effects.
$D^0 \rightarrow \gamma e^+e^-$ Standard Model background	$m_{e^+e^-}$ spectrum and resonance templates	Continuum and vector meson backgrounds	Provides the background model, sidebands, and veto strategy.
This g_{vis} framework	$g_{\text{vis}}, \mathcal{B}_{\text{sens}}, E_{\text{eff}}, N_{\text{sig}}$	Visible coupling reach from branching fraction sensitivity	Keeps hadronic normalization explicit and allows rescaling.

This comparison clarifies the scope of the benchmark. Ordinary dark photon searches and the present benchmark constrain different search-level quantities and require different external inputs for their interpretation. Translating conventional constraints on ϵ into a constraint on the flavor-changing $c \rightarrow uA'$ amplitude requires a model that relates kinetic mixing to the flavor-changing production vertex. Rare charm studies are closer in motivation, although they are often sensitive to long distance hadronic effects. Standard Model studies of the visible D^0 decay spectrum are essential for modeling the continuum, sidebands, and resonance regions. Conversely, translating the g_{vis} reach obtained in the present framework into g_{eff} , microscopic couplings, or ϵ requires external input for the hadronic transition factor $F_{D^0\gamma}(m_{A'}^2)$ and the visible branching fraction $\mathcal{B}(A' \rightarrow e^+e^-)$. The purpose of the g_{vis} formulation is therefore not to eliminate model dependence, but to separate

these external physics inputs from the detector-level sensitivity and to make the required rescaling explicit.

5. Yield, Sensitivity, and Resonance Treatment

The visible branching fraction is converted into an expected signal yield through the effective exposure. N_{D^0} denotes the number of D^0 mesons produced within the parent-level fiducial phase space of the analyzed data sample, before detector response and signal side selection requirements are applied. The effective exposure is defined as

$$\mathcal{E}_{\text{eff}} = N_{D^0} \epsilon_{\text{rec}}, \quad N_{\text{sig}} = \mathcal{E}_{\text{eff}} \mathcal{B}_{\text{sig}}, \quad (14)$$

where ϵ_{rec} denotes the efficiency for signal decays within the fiducial D^0 sample to fall within the detector acceptance and satisfy the trigger, reconstruction, particle identification, and baseline selection requirements. N_{sig} denotes the signal yield after the baseline selection and before application of the mass window requirement. The latter is accounted for separately through the mass window fraction $\epsilon_W(m_{A'})$. Any dependence of ϵ_{rec} and $\mathcal{E}_{\text{eff}}$ on $m_{A'}$ is left implicit.

For a search at a fixed value of $m_{A'}$, the expected signal and background yields in a mass window W centered on the tested mass are written as

$$S = \mathcal{E}_{\text{eff}} \mathcal{B}_{\text{sig}} \epsilon_W(m_{A'}), \quad B = \int_W b_{\text{tot}}(m_{e^+e^-}) dm_{e^+e^-} \quad (15)$$

where $\epsilon_W(m_{A'})$ denotes the fraction of the normalized signal line shape contained within the selected mass window, and $b_{\text{tot}}(m_{e^+e^-}) \equiv dN_{\text{bkg}}/dm_{e^+e^-}$ denotes the total detector-level background event density after the baseline event selection and before imposing the mass window requirement. Contributions from genuine D^0 decays may be normalized to N_{D^0} using the corresponding differential branching fractions and efficiencies defined relative to the same fiducial phase space. Background components not naturally normalized to the produced D^0 yield are included directly in b_{tot} and may be constrained using data driven estimates, supplemented where necessary by simulation or fits to the reconstructed spectrum.

For each tested value of $m_{A'}$, the window yields S and B are converted into a local sensitivity according to an experiment-specific statistical criterion. Since this work is intended as a normalization benchmark, we do not prescribe a unique discovery or exclusion test. Instead, we define $S_{\text{min}}(m_{A'})$ as the minimum signal yield required by the adopted counting or likelihood procedure. This quantity may depend on the expected background, systematic uncertainties, the mass window definition, and, in a mass scan, the treatment of the look-elsewhere effect.

The same counting setup also determines the branching fraction sensitivity that enters Equation (12). Solving Equation (15) for $\mathcal{B}_{\text{sig}}$ and setting $S = S_{\text{min}}(m_{A'})$ gives

$$\mathcal{B}_{\text{sens}}(m_{A'}) = \frac{S_{\text{min}}(m_{A'})}{\mathcal{E}_{\text{eff}} \epsilon_W(m_{A'})}. \quad (16)$$

In the background-free 90% C.L. limit, one may use $S_{\text{min}} \simeq 2.3$. In the background-dominated case, S_{min} is obtained by solving the chosen local significance or exclusion condition using the statistical model specified above. The resulting $\mathcal{B}_{\text{sens}}$ is therefore a sensitivity at the tested mass point. In a mass scan, this local sensitivity should be distinguished from a global exclusion or discovery criterion, since scanning many tested masses increases the probability of finding a background fluctuation somewhere in the spectrum.

A schematic mass spectrum can then be written as a sum of normalized templates,

$$\frac{dN}{dm_{e^+e^-}} = N_{\text{cont}}f_{\text{cont}}(m_{e^+e^-}) + \sum_{V=\rho/\omega, \phi} N_V T_V(m_{e^+e^-}) + N_{\text{sig}} G(m_{e^+e^-}; m_{A'}, \sigma_m), \quad (17)$$

where f_{cont} describes the smooth continuum, T_V denotes the vector meson templates for $V = \rho/\omega, \phi$, and G denotes the detector resolution template for the A' signal. The coefficients N_{cont} , N_V , and N_{sig} are the corresponding event yields. The structure of Equation (17) is illustrated schematically in Figure 4.

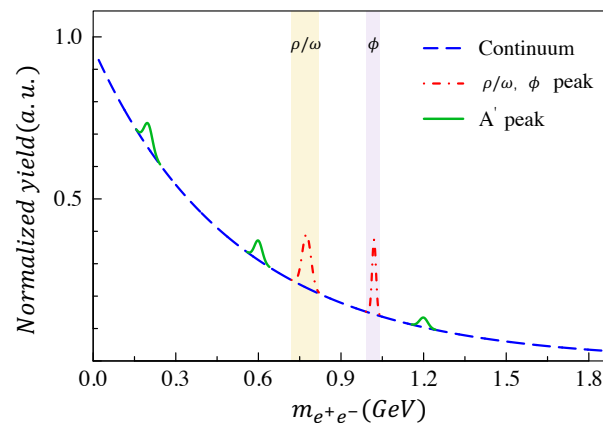


Figure 4. Schematic normalized dielectron invariant-mass spectrum for the visible A' search in $D^0 \rightarrow \gamma e^+ e^-$.

Figure 4 provides a visual representation of the template decomposition in Equation (17). The blue dashed curve represents the smooth continuum component $N_{\text{cont}}f_{\text{cont}}(m_{e^+e^-})$, while the red dot-dashed structures indicate the vector-meson contributions associated with the ρ/ω and ϕ regions. The green narrow peaks illustrate potential A' signal contributions at possible mass values. The shaded vertical bands emphasize the resonance-dominated mass intervals, where the interpretation of a narrow visible A' signal is expected to be most analysis-dependent.

Equation (17) is intended only as a schematic description of the mass spectrum. It should not be read as a unique Standard Model background prediction. In a real analysis, the continuum shape, sidebands, reconstruction efficiency, and resonance regions should be treated with experiment specific templates or vetoes. If interference among resonant and continuum amplitudes is relevant, the template sum should be replaced by an amplitude level model.

The ρ/ω and ϕ regions are therefore the main limitations for a visible-spectrum interpretation. In the benchmark presentation, the intervals near 0.72–0.82 GeV and 0.99–1.04 GeV can be treated either as veto regions or as regions that require dedicated vector-meson templates. This treatment preserves the usefulness of the signal normalization while avoiding an overinterpretation of the schematic spectrum in regions dominated by known hadronic structures.

Taken together, the yield, significance, and spectrum relations provide a practical way to reinterpret a detector-level search in terms of the visible coupling defined above. Their cleanest use is in regions where the intermediate state is narrow compared with the experimental mass resolution and where the visible decay can be treated as prompt, so that the acceptance effects are contained in ϵ_{rec} . Near the ρ/ω and ϕ bands, the same normalization can still be used, but the spectral interpretation should be tied to experiment-specific vetoes or resonance templates. With these qualifications, the framework provides a reusable conversion between visible branching fraction sensitivity, g_{vis} reach, and exposure

scaling, while translations to g_{eff} or to the ordinary kinetic-mixing parameter require additional hadronic or model input. Representative detector-level inputs for BESIII-like, Belle II-like, and LHCb-like massive A' searches are summarized in Appendix B. These inputs are used only for rescaling purposes and are not treated as existing limits on the specific decay chain.

6. Conclusions

Rare charm searches with visible narrow structures are difficult to interpret in a single microscopic parameter because the observed rate depends simultaneously on the short-distance transition, the non-perturbative $D^0 \rightarrow \gamma$ matrix element, and the visible decay probability of the intermediate state. In this work, we have organized these ingredients into a visible coupling benchmark for the decay chain $D^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$. The definition of g_{vis} keeps the detector level sensitivity separated from the hadronic and visible decay inputs, so that experimental branching fraction sensitivities can be compared without committing to a specific ultraviolet completion.

Within this normalization, the visible branching fraction is controlled by g_{vis}^2 and by the cubic two-body phase space factor. The inverse relation then converts a representative sensitivity B_{sens} into a reach on g_{vis} , with the expected degradation near the kinematic endpoint. The same framework also connects the branching fraction reach to event yields through the effective exposure $\mathcal{E}_{\text{eff}}$, making it straightforward to rescale the benchmark to different reconstructed charm samples, efficiencies, and mass resolutions.

The resulting formulation is intended as a rescaling tool rather than as a universal bound on the kinetic mixing parameter. Once experiment-specific efficiencies, background templates, resonance vetoes, and mass scan procedures are specified, the formulae can be used to compare BESIII-like, Belle II-like, LHCb-like, or future charm samples in a common visible coupling language. A further translation from g_{vis} to g_{eff} or to microscopic dark sector parameters requires additional input on $F_{D^0\gamma}(q^2)$ and $\mathcal{B}(A' \rightarrow e^+ e^-)$.

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Appendix A

Figure A1 illustrates the benchmark branching fraction implied by the visible coupling normalization. For a fixed g_{vis} , the signal branching fraction is controlled entirely by the quadratic coupling dependence and by the cubic two-body phase space factor. The three curves are separated by two orders of magnitude in $\mathcal{B}_{\text{sig}}$ for each one order of magnitude change in g_{vis} , reflecting the scaling $\mathcal{B}_{\text{sig}} \propto g_{\text{vis}}^2$. The common downward turn as $m_{A'}$ approaches the D^0 mass is the endpoint suppression from $(1 - m_{A'}^2/m_{D^0}^2)^3$. This figure therefore shows the clean kinematic part of the benchmark normalization, while the translation to g_{eff} requires the external inputs $F_{D^0\gamma}(m_{A'}^2)$ and $\mathcal{B}(A' \rightarrow e^+ e^-)$.

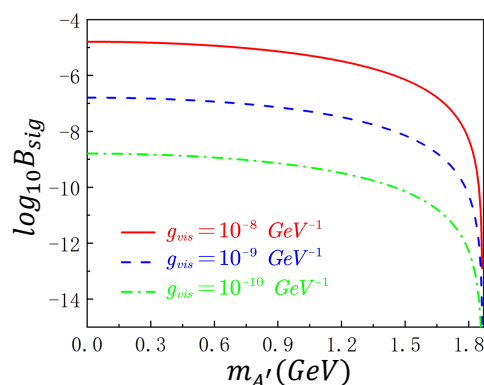


Figure A1. Benchmark signal branching fraction for $D^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$ as a function of the dark photon mass $m_{A'}$.

Appendix B

Table A1 summarizes representative detector level benchmark inputs for BESIII-like, Belle II-like, and LHCb-like massive visible- A' searches.

Table A1. Detector-level benchmark scenarios for a massive visible A' search in $D^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$ [31,32,35].

Scenario	Massive A' Relevance	Benchmark Input	Useful $m_{A'}$ Region	Main Experimental Issue
BESIII-like	Tagged $D\bar{D}$ environment; suitable for a prompt $A' \rightarrow e^+ e^-$ narrow peak recoiling against a photon.	$\mathcal{E}_{\text{eff}} = 10^7\text{--}10^8$; $\sigma_m = 3\text{--}8$ MeV	Low and intermediate masses, away from vector meson regions.	Statistics, photon reconstruction, conversion background, and ρ/ω , ϕ treatment.
Belle II-like	High luminosity $e^+ e^-$ environment with large charm samples; useful for a broad $m_{e^+ e^-}$ scan.	$\mathcal{E}_{\text{eff}} = 10^8\text{--}10^9$; $\sigma_m = 4\text{--}10$ MeV	Broad range below the kinematic endpoint.	Continuum background, photon efficiency, bremsstrahlung recovery, and mass-dependent efficiency.
LHCb-like	Large prompt charm yield and rare charm experience with $e^+ e^-$ final states; useful in selected prompt windows.	$\mathcal{E}_{\text{eff}} = 10^8\text{--}10^9$; $\sigma_m = 5\text{--}15$ MeV	Selected prompt windows outside resonance dominated regions.	Selection efficiency, low mass electron reconstruction, nonuniform acceptance, and template control.

For a given scenario in Table A1, the quoted $\mathcal{E}_{\text{eff}}$ and σ_m do not by themselves determine $\mathcal{B}_{\text{sens}}$. The latter also depends on the mass window fraction $\epsilon_W(m_{A'})$, the background level in the tested window, the treatment of resonance regions, and the adopted statistical criterion. For a background-free estimate at 90% C.L., taking $S_{\text{min}} \simeq 2.3$ in Equation (16) gives $\mathcal{B}_{\text{sens}}(m_{A'}) \simeq \frac{2.3}{\mathcal{E}_{\text{eff}} \epsilon_W(m_{A'})}$.

These benchmark scenarios are designed for a massive visible dark photon, reconstructed as a narrow structure in the $m_{e^+ e^-}$ spectrum. They should not be interpreted as published limits on $D^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$. Instead, they provide representative detector-level inputs for applying the conversion in Equation (12). Since the reach scales with the phase space factor $(1 - m_{A'}^2/m_{D^0}^2)^{-3/2}$, the sensitivity deteriorates as $m_{A'}$ approaches the D^0 endpoint. In addition, the regions around the ρ/ω and ϕ resonances require either vetoes or dedicated vector meson templates.

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