Dark Photon and Muon $g-2$ Inspired Inelastic Dark Matter Models at the High-Energy Intensity Frontier

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We study hidden-sector particles at past (CERN-Hamburg-Amsterdam-Rome-Moscow Collaboration and NuCal), present (NA62, SeaQuest, and DarkQuest), and future (LongQuest) experiments at the high-energy intensity frontier. We focus on exploring the minimal vector portal and the next-to-minimal models in which the productions and decays are decoupled. These next-to-minimal models have mostly been devised to explain experimental anomalies while avoiding existing constraints. We demonstrate that proton fixed-target experiments provide one of the most powerful probes for the MeV to few GeV mass range of these models, using inelastic dark matter (iDM) as an example. We consider an iDM model with a small mass splitting that yields the observed dark matter relic abundance, and a scenario with a sizable mass splitting that can also explain the muon $g-2$ anomaly. We set strong limits based on the CERN-Hamburg-Amsterdam-Rome-Moscow Collaboration and NuCal experiments, which come close to excluding iDM as a full-abundance thermal dark matter candidate in the MeV to GeV mass range. We also make projections based on NA62, SeaQuest, and DarkQuest and update the constraints of the minimal dark photon parameter space. We find that NuCal sets the only existing constraint in $\epsilon \sim 10^{-8}$–10^{-4} regime, reaching ~800 MeV in dark photon mass due to the resonant enhancement of proton bremsstrahlung production. These studies also motivate LongQuest, a three-stage retooling of the SeaQuest experiment with short ($\lesssim$5 m), medium (~5 m), and long ($\gtrsim$35 m) baseline tracking stations and detectors as a multipurpose machine to explore new physics.

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Introduction.—Given the nonobservation of new physics at the TeV scale and the ever-stronger constraints on weakly interacting massive particle dark matter (DM) [1], many physicists have shifted their attention to the study of dark-sector particles with sub-GeV to few GeV masses. This regime is also of great interest due to a number of experimental anomalies, including the muon $g-2$ anomaly [2,3] and the Land Scintillator Neutrino Detector and Mini Booster Neutrino Experiment excesses [4,5].

Proton fixed-target machines are among the most powerful and robust probes of dark-sector and long-lived particles in the MeV to ~10 GeV regime (e.g., [6–18]). First, the searches benefit from the combination of high energy and high intensity that the proton beams provide. Second, these accelerator-based probes do not depend on DM abundance, velocity distribution, or cosmic history. The constraints and sensitivity reach also do not depend on complicated astrophysics or rare events. As our theoretical understanding of the dark sector advances, it is crucial to look back at the highest-energy experiments of the intensity frontier. These include past experiments like the CERN-Hamburg-Amsterdam-Rome-Moscow Collaboration (CHARM) and NuCal (ν-Cal I) and ongoing experiments like NA62, SeaQuest, and SpinQuest and their beam-dump and upgrade proposals (the NA62 beam-dump run and the DarkQuest proposal [19]). It is also important to look closely at the existing facilities to see if low-cost repurposing or upgrades can help further explore beyond-the-standard-model physics [20,21].

To demonstrate the strength of proton fixed-target experiments, we first revisit several of the existing constraints of the vector portal [8,11,22–81], fill in the missing relevant production channels, and conduct a robust reanalysis based on the available data. Furthermore, we study a next-to-minimal class of models considered to have a certain range of lifetimes or decay lengths to avoid experimental or observational bounds while explaining specific anomalies. One of the best examples of this class of models is the inelastic dark matter (iDM) model [10,82–87]. In the case of iDM, the production of the dark-sector particles is predominantly through small standard model (SM) coupling, but the decay length of the dark-sector particles in the search is also determined by the mass splitting of nearly degenerate dark particle states. iDM provides one of the few viable GeV and sub-GeV thermal DM scenarios that freezes out to the right relic abundance, also called "thermal targets" (thermal DM that can be probed in near-future experiments) [88–103]. iDM was also studied as one of the last viable vector-portal explanations of the muon $g-2$ anomaly [2,86,104].

We set strong new constraints on iDM model parameters in the MeV to GeV regime, based on CHARM and NuCal beam-dump experiments, for both small and sizable iDM mass splitting, ruling out a large portion of the parameter space for iDM to account for the total DM abundance. We also revisit and improve the minimal dark photon bounds set by the pioneering analyses [51,53,54]. In addition, we perform the first dark photon and iDM sensitivity projections based on the NA62 beam-dump run. NA62 can further extend the sensitivity of the two scenarios and help to close the window of parameter space for which iDM models can explain the muon $g-2$ anomaly. Finally, we conduct a study of iDM in the muon $g-2$ regime based on the DarkQuest upgrade of the SeaQuest experiment [8,13,105]. We demonstrate a general point that high-energy proton fixed-target machines provide strong probes of models that would otherwise escape the bounds from other experiments.

Inspired by the studies of SeaQuest and DarkQuest (SQ-DQ), we consider a complete retooling of the SeaQuest and SpinQuest experiments as a dedicated and multipurpose experiment to conduct dark-sector searches with short ($\lesssim 5$ m), medium ($\sim$5–12 m), and long ($\gtrsim 35$ m) baseline detectors. We designate all these new installations as "LongQuest" and discuss the three-stage retooling in the Supplemental Material [106].

Models and signatures.—Dark photon from kinetic mixing: A minimal model of a visibly decaying dark photon through the kinetic mixing between SM $U(1)_Y$ and a dark $U(1)$ gauge field is given by

$$\mathcal{L}_{\text{kinmix}} = \frac{\epsilon}{2\cos\theta_W} A'_{\mu\nu} B^{\mu\nu}, \tag{1}$$

where θ_W is the Weinberg angle. The crucial interaction term between dark photon and SM particles can be expressed as

$$\mathcal{L}_{\text{int}} \supset \epsilon e A'_\mu \mathcal{J}^\mu_{\text{EM}}, \tag{2}$$

where $\mathcal{J}^\mu_{\text{EM}}$ is the SM electromagnetic current. We consider the case of a massive A' where the mass $m_{A'}$ can be generated through the Higgs or Stueckelberg mechanisms.

There are three main production channels considered in the literature for kinetically mixed dark photons: meson decays, proton bremsstrahlung, and Drell-Yan and QCD processes. Each of these processes dominates dark photon production for different dark photon masses. Among these, the Drell-Yan and QCD productions suffer large uncertainties in the sub-GeV energy regime given the uncertainty in the parton distribution functions [77,107] and thus were not included in our analysis. All the other relevant production processes were considered in our analysis.

Inelastic DM: Here, we study iDM composed of a Dirac pair of two-component Weyl spinors, η and ξ, charged under a new $U(1)_D$ gauge symmetry. We include the DM interaction term as

$$\mathcal{L}_{\text{int}} \supset \epsilon e A'_\mu \mathcal{J}^\mu_{\text{EM}} + g_D A'_\mu \mathcal{J}^\mu_{\mathcal{D}}. \tag{3}$$

$\mathcal{J}^\mu_{\mathcal{D}}$ is the dark-sector current to which the dark photon A' couples. We express $g_D \equiv \sqrt{4\pi\alpha_D}$. This dark-sector current consists of a four-component fermionic state $\Psi = (\eta \xi^\dagger)$ with two-component Weyl spinors η and ξ. Again, A' is massive and $U(1)_D$ is broken, and one can write down the Majorana and Dirac mass terms as

$$\mathcal{L} \supset -m_D \eta\xi - \frac{1}{2}\delta_\eta \eta^2 - \frac{1}{2}\delta_\xi \xi^2 + \text{H.c.} \tag{4}$$

$\delta_\eta, \delta_\xi \ll m_D$ are technically natural because they break the $U(1)$ symmetry explicitly. After the mass diagonalization $m_{12} \simeq m_D \mp \frac{1}{2}(\delta_\eta + \delta_\xi)$, we have $\chi_1 \simeq i(\eta - \xi)/\sqrt{2}, \chi_2 \simeq (\eta + \xi)/\sqrt{2}$.

The relevant parts of the Lagrangian in terms of the mass eigenstates χ_1 and χ_2 are

$$\mathcal{L} \supset \sum_{i=1,2} \bar{\chi}_i (i\not{\partial} - m_{\chi_i})\chi_i - (g_D A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2 + \text{H.c.}). \tag{5}$$

The elastic interactions are suppressed by a factor of δ/m_D. $\delta \ll m_D$ is again technically natural because the $U(1)$ explicit breaking would be restored when $\delta \to 0$. Note that the elastic interaction vanishes as $\delta_\eta = \delta_\xi$.

The particle χ_1, which we take to be lighter than χ_2, can account for the current-day DM abundance. The mass splitting is defined as

$$\Delta \equiv \frac{m_2 - m_1}{m_1}. \tag{6}$$

An approximate analytical expression for the A' dominantly decays to $\chi_1\chi_2$ when the mass splitting Δ and the elastic coupling terms are small is

$$\Gamma(A' \to \chi_1\chi_2) \simeq \frac{\alpha_D m_{A'}}{3} \sqrt{1 - \frac{4m_1^2}{m_{A'}^2}} \left(1 + \frac{2m_1^2}{m_{A'}^2}\right). \tag{7}$$

An approximation for the width of the χ_2 decay also exists in the small Δ limit when $m_{A'} \gg m_1 \gg m_l$:

$$\Gamma(\chi_2 \to \chi_1 l^+ l^-) \simeq \frac{4\epsilon^2 \alpha_{\rm em} \alpha_D \Delta^5 m_1^5}{15\pi m_{A'}^4}. \qquad (8)$$

We would like to emphasize that, in our analysis, we simulated the three-body decay $\chi_2 \to e^+e^-\chi_1$ by sampling the full decay width, calculated in the Supplemental Material [106], rather than using the approximations here.

The dark photon has been proposed as an explanation of the muon $g-2$ anomaly [2,104,108–117]. The minimal models assume that the dark photon either decays completely visibly [30,39–41,56,62] or invisibly to DM particles [88,108] and are excluded by various experiments when they assume large enough kinetic mixing to account for the muon $g-2$ anomaly [62,118,119]. These constraints can be weakened if the dark photon is allowed to decay semivisibly, as is possible in iDM models [86]. If Δ is sufficiently large, the χ_2 will decay inside the detector and thus avoid the invisible decay bounds on elastic DM [118–120].

iDM thermal target and muon $g-2$ window: The search strategy in this Letter is to look for the decay of the dark photon through $A' \to \ell^+\ell^-$ or the three-body semi-visible decay $\chi_2 \to \chi_1\ell^+\ell^-$, described in detail in the Supplemental Material [106]. The decay signature is a lepton-antilepton pair, and the best probes are "decay detectors" in a fixed-target setup. In this addition, we discuss each of the experiments considered in detail—including CHARM, NA62, NuCal and U70, and SeaQuest and DarkQuest—in the Supplemental Material [106] and summarize some useful experimental information for comparison in Table I of the Supplemental Material [106].

One of the main goals of this Letter is to provide constraints on the canonical iDM with a small mass splitting: $\Delta \ll 1$. We consider fermionic iDM and fix the mediator to DM mass ratio to be $m_{A'} = 3m_1$. In the small mass-splitting regime, we consider fractional mass differences $\Delta = 0.1$ with $\alpha_D = 0.1$ and $\Delta = 0.05$ with $\alpha_D = 0.5$ as examples. Also, we fix the value of the kinetic mixing ϵ, while varying α_D such that the model produces the observed relic abundance. We show the new constraints and projections for the small mass splitting, for $\Delta = 0.1$ with $\alpha_D = 0.1$ iDM parameter space, in Fig. 2 and the results of other choices of parameters in the Supplemental Material [106].

In addition, we present a detailed discussion of the sensitivity of proton-beam fixed-target facilities to study iDM with $\Delta \gtrsim 0.4$ comprising a parameter regime that could explain the muon $g-2$ anomaly and avoid other experimental constraints. The existing data from CHARM and NuCal are considered, and we also include studies based on the NA62 beam-dump mode as well as the SQ-DQ configuration. We consider iDM with a sizable mass-splitting regime, $\Delta = 0.4$, and coupling $\alpha_D = 0.1$. Then, we fix the ϵ to the value that gives the correct muon $g-2$ value while varying α_D to compare the current constraints and future sensitivity reach. The results are shown in Fig. 3. Although strong constraints can be set, the muon $g-2$ target regime cannot be excluded because the distances between the targets and the decay regions are too large, and χ_2 decays before reaching the fiducial detector region. This provides a motivation to consider the LongQuest upgrade of SQ-DQ to probe this regime.

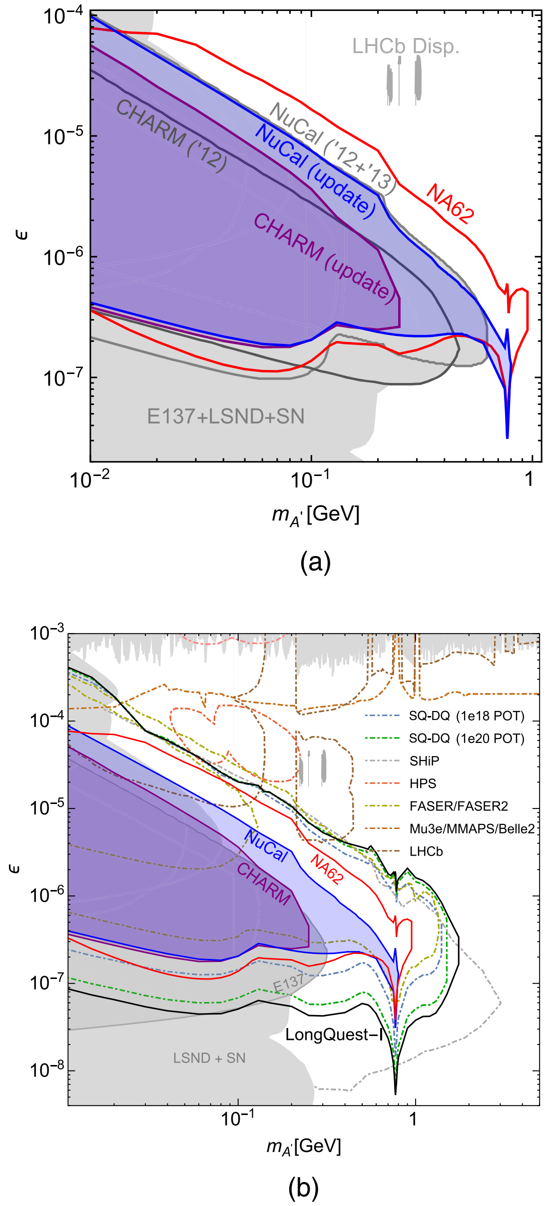

FIG. 1. We show updates on the kinetically mixed visibly decaying dark photon constraints and projections. In (a), gray contours are the previous bounds set based on analyses of the NuCal [51,54] and CHARM [53] experiments. In (b), projections for future experiments are shown in dot-dashed curves with color and also labeled in the plot. In both (a) and (b), our updated bounds on CHARM (purple) and NuCal (blue) and our new projections of NA62 (red) and LongQuest-I (black) are shown. (a) Updates on dark photon bounds and the NA62 projection. (b) Compilation of projections and constraints on dark photon.

Results and discussions.—Minimal dark photon: We update the dark photon bounds from CHARM and

NuCal in Fig. 1(a), taking into account additional relevant production channels (production of dark photons from η meson decays for NuCal and proton bremsstrahlung for CHARM). Interestingly, the bound does not get stronger for most parameter spaces in our consideration, except for the high mass regime, even though we take into account new relevant production channels. This is because the strength of the bounds in the meson-decay dominated regime ($m_{A'} \ll m_\eta$) are highly dependent on the estimate of the overall meson production rate, and ours are conservative (see Ref. [121] for comparisons between different methods of estimating π^0 production).

At large masses, there is an improvement from our handling of the proton bremsstrahlung, which considers a timelike form factor [9,131] with resonant enhancement from mixing with the ρ and ω mesons, visible in the constraint plots as a sharp peak. The NuCal contour is also the first constraint of this kind with a dark photon mass reach close to 1 GeV, as shown in Fig. 1. CHARM's production is not enhanced to the same extent due in part to its off-axis position and the highly collimated nature of bremsstrahlung. We also studied NA62's projected sensitivity in its proposed beam-dump mode based on [121] and found that it could explore stronger couplings due in large part to the higher energy beam and that the same ρ peak exhibited by NuCal appears at larger masses.

Finally, we make projections for the sensitivity of SQ-DQ and LongQuest-I with a simplified detector simulation. The short baseline relative to the length of the decay volume renders the detector particularly sensitive to the lifetime of the dark photon, which combined with the SeaqQuest detector simulation resulted in some statistical noise in the sensitivity. In Fig. 1(b), we show the sensitivity projections of the 10^{20} protons on target (POT) runs for SQ-DQ and LongQuest-I. We demonstrate the potential advantage of such an improved decay detector and the reduction of background rate to a 10% level by comparing the SQ-DQ and LongQuest-I curves.

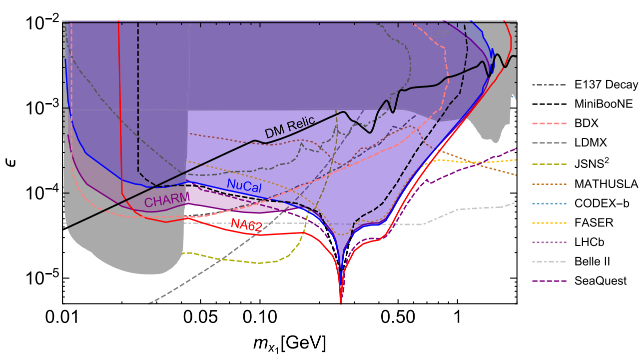

FIG. 2. We show new constraints on iDM based on the data of CHARM (purple) and NuCal (blue), and the projected sensitivity of the NA62 beam-dump run (red). The gray shaded regions are previously existing constraints (see Sec. I B). We also include the potential E137 decay constraint [10,13,40] along with future projections [10,13,32,73,76,77,85,122–130]. One can see the E137, Mini Booster Neutrino Experiment, and Beam Dump Experiment (BDX) projections are already covered by CHARM and NuCal. (a) Compilation of constraints and sensitivity projections for iDM with $m_{A'} = 3m_1$, $\alpha_D = 0.1$, and $\Delta = 0.1$.

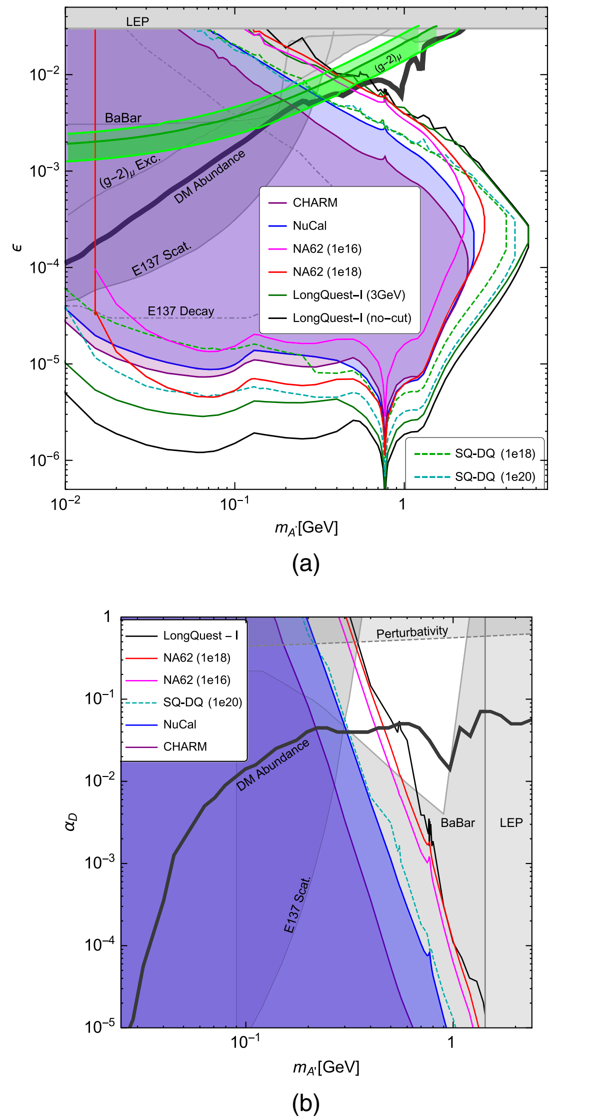

FIG. 3. These plots show constraints and sensitivity projections for iDM within the muon $g-2$ motivated regime. Here we consider $m_{A'} = 3m_1$ for demonstration. The muon $g-2$ favored regime is the light-green band in (a), while the thick-black curves are again the parameter contour yielding the correct DM relic abundance. We considered the bounds from CHARM (purple) and NuCal (blue) and projections from NA62 [10^{18} POT (red), 1.3×10^{16} POT (magenta)], SQ-DQ [10^{20} POT (dashed-cyan), 1.4×10^{18} POT (dashed-pine green), and LongQuest-I (3-GeV cut: darker green; no-cut: black)]. In (b), we only plot the LongQuest-I no cut curve because it is basically identical to the 3-GeV cut result. The gray region denotes the previously existing constraints. (a) iDM: $\Delta = 0.4$, $\alpha_D = 0.1$. With muon $g-2$ and DM regimes. (b) iDM Muon $g-2$ Target: $\Delta = 0.5$, $\epsilon = \epsilon_{(g-2)_\mu}$.

iDM thermal and $(g-2)_\mu$ targets: The constraints and sensitivity projections for iDM with $\Delta = 0.1$, $\alpha = 0.1$ are shown in Fig. 2 and the parameter space to explain the muon $g-2$ anomaly in Fig. 3. Other iDM constraints and projections are plotted in Fig. 6 of the Supplemental Material [106]. All previously considered experimental constraints in this parameter space are included and labeled in the plots [6,13,40,73,119,132–137], with the exception of the potential constraints from the recast of the E137 analysis [40], discussed in the Supplemental Material [106]. Below 10 MeV, the iDM model is subject to bounds on $N_{\rm eff}$ [138,139], and the proton fixed-target probes become suppressed by the limited phase space available to the $\chi_1 l^+ l^-$ states. We therefore choose to focus on iDM masses larger than 10 MeV.

As shown in Fig. 2, CHARM and NuCal provide strong constraints on iDM with small mass splittings, excluding almost all of the regimes that predict the correct DM relic abundance. NA62 can further improve the exploration of these iDM scenarios. Other future probes of iDM [10,13,32,73,76,77,85,122–130] relevant for the regime of interest are also included in Fig. 2. The benchmark thermal relic curve we consider in Fig. 2 of relic iDM is already ruled out by previous experiments. In the Supplemental Material [106], we show that there is still a small region of parameter space when the kinetic mixing and masses are small in the small mass-splitting case (e.g., $\delta = 0.05$ is picked to demonstrate that), in when that the relic abundance line survives current constraints.

For the large mass-splitting iDM parameter space motivated by the muon $g-2$ anomaly, proton fixed-target experiments provide strong new constraints, as shown in Fig. 3. However, in order to resolve the muon $g-2$ discrepancy, there must be large kinetic mixing between the dark and SM photons, and the dark photon must have a mass $\gtrsim 300$ MeV to escape existing constraints. The CHARM and NuCal analyses poorly constrain the open muon $g-2$ favored parameter space because the large mass and strong coupling to the SM leads the χ_2 particles to decay before they reach the decay regions.

In Fig. 3, we also show the first study of the iDM muon $g-2$ regime in SQ-DQ assuming a sizable mass splitting: $\Delta = 0.4$. We place a contour on more than ten events for the sensitivity of SQ-DQ 10^{18} POT run. For the SQ-DQ 10^{20} POT run, we assume 10^3 background events (a rough estimation from long-lived kaon decays) to set a sensitivity projection. One can see that SQ-DQ does improve the sensitivity to smaller couplings with a 10^{20} POT run. However, as can be seen in this figure, the sensitivity to iDM in the $(g-2)_\mu$ valid regime is not improved by SQ-DQ phase I and II.

In principle, SQ-DQ should provide the best sensitivity probes in this regime, given that it has the shortest distance between the target and the fiducial decay region among all the experiments we consider. However, we found that the sensitivity to this regime is only comparable to that of CHARM and NuCal because the strong magnetic field in the KMAG suppresses new physics events by kicking the visible charged products out of the decay volume [13]. This effect is particularly significant for iDM because the lepton pairs from χ_2 decays are soft, given that the χ_1 takes a large fraction of the χ_2 energy. The signal suppression from the KMAG effectively cancels out the benefit of a shorter baseline of SQ-DQ.

Finally, we show that the proposed LongQuest-I upgrades with reduced background and no KMAG magnetic field would help explore the iDM muon g-2 regime in Fig. 3. For the LongQuest-I analysis, we assume the background is reduced to 10% of the SQ-DQ background. Given the removal of KMAG and the potential soft SM background, we consider the sensitivity of a 3-GeV energy threshold cut and a projection with no energy threshold cut. Further discussions can be found in the Supplemental Material [106], which also includes Refs. [6–9,11,12,14, 17–20,40,43,44,51,53,54,71,80,86,105,109,121,122,137, 140–161]. A realistic analysis may need to apply an energy cut between these choices.

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