# DAEALUS and dark matter detection

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DAEδALUS and dark matter detection

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Among laboratory probes of dark matter, fixed-target neutrino experiments are particularly well suited to search for light weakly coupled dark sectors. In this paper, we show that the DAEδALUS source setup—an 800 MeV proton beam impinging on a target of graphite and copper—can improve the present LSND bound on dark photon models by an order of magnitude over much of the accessible parameter space for light dark matter when paired with a suitable neutrino detector such as LENA. Interestingly, both DAEδALUS and LSND are sensitive to dark matter produced from off-shell dark photons. We show for the first time that LSND can be competitive with searches for visible dark photon decays and that fixed-target experiments have sensitivity to a much larger range of heavy dark photon masses than previously thought. We review the mechanism for dark matter production and detection through a dark photon mediator, discuss the beam-off and beam-on backgrounds, and present the sensitivity in dark photon kinetic mixing for both the DAEδALUS/LENA setup and LSND in both the on- and off-shell regimes.

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I. INTRODUCTION

The gravitational evidence for dark matter (DM) is overwhelming [1,2], but most realistic DM scenarios predict some kind of nongravitational interactions between DM and ordinary matter. One ubiquitous prediction is that DM should have nonzero scattering cross sections off nuclei, which is the mechanism by which direct detection experiments search for DM in the galactic halo [3,4]. DM can also be produced in laboratory experiments, either at high energies at machines like the LHC [5] or at low energies through bremsstrahlung or rare hadron decays (see Ref. [6] for a review). This low-energy mode has been exploited to use fixed-target neutrino experiments such as LSND [7] and MiniBooNE [8] as production and detection experiments for sub-GeV DM [9–11], and it has been recently proposed to use the main injector beam at Fermilab paired with the NOvA detector [12] to search for GeV-scale DM [13]. A similar logic applies to electron beam fixed-target experiments [14–16].

In this paper, we propose conducting a DM search using DAEδALUS [17] in close proximity to a large-volume neutrino detector such as the proposed LENA detector [18]. DAEδALUS uses cyclotrons (peak power 8 MW, average power 1–2 MW) to produce a high-intensity 800 MeV proton beam incident on a graphite and copper target (1 m of graphite liner inside a 3.75 m copper beam stop), creating a decay-at-rest neutrino source from stopped charged pions. Proton-carbon scattering is also a rich source of neutral pions, and in scenarios involving a light weakly coupled dark sector, rare $\chi^0$ decays to an on-shell dark mediator $A'$ can produce pairs of DM particles $\chi\bar{\chi}$ when $2m_\chi < m_{A'}$. These DM particles can then be detected through neutral-current-like scattering in detectors designed to observe neutrinos, as illustrated in Figs. 1 and 2. A similar setup was the basis for existing LSND bounds on light DM [9,10], but we find that for light $\chi$ DAEδALUS can improve the reach of LSND by an order of magnitude in the visible-dark sector coupling $\delta^2$ after only one year of running. This DM search is therefore an important physics opportunity for the initial single-cyclotron phase of DAEδALUS.

We also find that both DAEδALUS and LSND are sensitive to DM production through off-shell mediators in two distinct regimes, a fact that has been overlooked in the literature. Surprisingly, in the lower regime ($m_{A'} < 2m_{\chi}$), sensitivity to an off-shell $A'$ can be superior compared to a heavier on-shell $A'$. In the upper regime ($m_{A'} > m_{\chi}$),
existing LSND limits are considerably stronger than previously reported, and the DAE\(\delta\)ALUS sensitivity can extend up to \(m_A^0 \simeq 800\) MeV rather than cutting off at \(m_A^0 \simeq m_{\pi^0}\). Indeed, the observation that DM produced from meson decays can probe \(A^0\) masses much heavier than the meson mass expands the sensitivity of the entire experimental program to discover DM in proton-beam fixed-target searches. As Figs. 3 and 4 illustrate, the combination of updated LSND bounds and projected DAE\(\delta\)ALUS sensitivity covers a broad range of DM and mediator masses and is even competitive with searches for visibly decaying mediators in certain regions of parameter space.

The search strategies for MeV-scale DM at both DAE\(\delta\)ALUS and LSND are very similar, so it is worth pointing out the potential advantages of DAE\(\delta\)ALUS compared to LSND:

(i) Higher energy range: The LSND \(\nu_e - e^-\) elastic scattering measurement [22], which has been used to set limits on light DM, focused on the recoil electron energy range \(E_e \in [18, 52]\) MeV, where a Čerenkov detector can use directionality to discriminate against decay-at-rest neutrino backgrounds. This strategy is optimal for a heavier DM search \((m_\chi \gtrsim 40\) MeV) where the kinetic energy available for scattering is smaller. Here, we propose a search with DAE\(\delta\)ALUS/LENA in the higher energy range \(E_e \in [106, 400]\) MeV, well above the thresholds from decay-at-rest backgrounds, which is optimal for lighter DM \((m_\chi \lesssim 20\) MeV). The specialized target at DAE\(\delta\)ALUS, designed to reduce the decay-in-flight component of the neutrino beam, makes such a high-energy search possible by reducing decay-in-flight backgrounds.\(^3\)

\(^3\)In principle, LSND could have done such a high-energy search as well. It may be possible to derive stronger limits than those from the LSND electron scattering measurement by using LSND’s measurement of \(\nu_e C \rightarrow e^- X\) at 60–200 MeV [23].
FIG. 3 (color online). Summary of DAEδALUS/LENA 3σ sensitivity to the kinetic mixing parameter $\epsilon^2$ assuming the on-axis configuration [see Fig. 2(c)] and a full year of run time with $7.5 \times 10^{22} \pi^0$ produced. We also display updated bounds from existing LSND data in both off-shell $A'$ regimes. Left column: DAEδALUS sensitivity as a function of $m_A$ for fixed DM mass $m_\chi = 1$ MeV (a), 20 MeV (c), and 40 MeV (e). Right column: DAEδALUS sensitivity as a function of $m_\chi$ for fixed dark photon mass $m_{A'} = 10$ MeV (b), 50 MeV (d), and 100 MeV (f). The thick green band is the region where $A'$ could resolve the longstanding $(g-2)_\mu$ anomaly to within $\pm 2\sigma$ [20]; see Sec. VI for information about the other projected sensitivities and constraints. Where applicable, the dashed vertical black line marks the transition between the on- and off-shell $A'$ regimes for $\pi^0 \rightarrow A' \gamma \chi \bar{\chi}$. Assuming such a $\chi$ exists, the dark gray region above the black LSND curve is excluded; this is the first demonstration that LSND can rule out a visibly decaying $A'$ by searching for DM produced via an off-shell $A'$. 
FIG. 4 (color online). Parameter space for the dark photon mass $m_A$ and dark coupling $\alpha_D$, taking $\epsilon$ to be the smallest value which resolves the $(g-2)_\mu$ anomaly for $m_\mu = 1$ MeV. The DAEδALUS/LENA curve shows $3\sigma$ sensitivity. The solid black curve is the boundary where $\text{Br}(A' \rightarrow e^+ e^-) = \text{Br}(A' \rightarrow \bar{\chi} \chi) = 50\%$. Note that for $\text{Br}(A' \rightarrow e^+ e^-) = 100\%$ (just below the black curve) recent (preliminary) results from NA48/2 [21] have ruled out the remaining parameter space for a visibly decaying $A'$ that explains the discrepancy.

(ii) Higher luminosity: A single DAEδALUS cyclotron with a 25% duty cycle and peak power 8 MW can deliver $4.9 \times 10^{23}$ protons on target per year, producing $7.5 \times 10^{22}$ $\pi^0$ per year, compared to $10^{22}$ $\pi^0$ over the life of the LSND experiment.

(iii) Larger acceptance: At LSND, the source was placed a distance of 30 m from the neutrino detector, whereas the DAEδALUS source can be placed as close as 20 m to the detector, increasing the angular acceptance for DM scattering. In addition, the detector length of LSND was 8.3 m, whereas DAEδALUS can be paired with a large neutrino detector like LENA in a geometry where the average path length through the detector is closer to 21 m and the maximum path length is over 100 m.

Because we consider a dedicated DM search with DAEδALUS, we will optimize our cuts for each point in the dark-sector parameter space. We will show that under conservative assumptions a light DM search at DAEδALUS/LENA is systematic-dominated. In particular, the improvements compared to LSND come almost exclusively from the optimized cuts rather than the higher luminosity and larger acceptance, though that conclusion could change with relatively modest improvements to the systematic uncertainties of neutrino-nucleon scattering cross sections.

The full DAEδALUS program [24] includes multiple cyclotron-based neutrino sources placed at three different distances from a single detector such as LENA. Because the earliest phase of DAEδALUS involves just a single “near” cyclotron-based neutrino source, we focus on pairing this neutrino source with a neutrino detector to perform a dedicated DM search. For studies of other physics opportunities with a near cyclotron, see Refs. [28–30].

To directly compare to previous studies [9–11,14–16,31–35], we will focus on vector portal models of the dark sector [36–38]. Here, a massive dark photon $A'$ from a new $U(1)_D$ kinetically mixes with the standard model hypercharge,

$$\mathcal{L} \supset \frac{e'}{2} F^\mu_\nu B^{\mu\nu} - \frac{1}{2} m_{A'}^2 A'^\mu A'^\nu + \bar{\chi}(iD - m_\chi)\chi,$$

and couples to a DM particle $\chi$, which carries unit charge under the $U(1)_D$. The DM can be either a scalar or a Dirac fermion; we focus in the text on the case of fermionic DM, leaving a discussion of scalar DM to the Appendixes.

Here, $D_\mu = \partial_\mu + i g_D A'_\mu$, where $g_D$ is the dark coupling constant. After electroweak symmetry breaking and diagonalizing the kinetic terms, the $A'$ inherits a universal coupling to electromagnetic currents with strength $e'\epsilon$, where $\epsilon \equiv \epsilon_Y \cos \theta_W$. This model has four free parameters,

$$\{m_{A'}, \epsilon, m_\chi, \alpha_D\},$$

namely the $A'$ mass $m_{A'}$, the kinetic mixing parameter $\epsilon$, the DM mass $m_\chi$, and the dark fine-structure constant $\alpha_D \equiv g_D^2/4\pi$. Many dark photon studies have explored the $\{m_{A'}, \epsilon\}$ portion of parameter space, but $m_\chi$ is an essential third dimension that introduces qualitatively different phenomenology. We focus primarily on the region of parameter space $\alpha_D \gg \epsilon^2 \alpha_{EM}$ where the $A'$ primarily decays into DM when kinematically allowed, rather than into visible-sector particles, though we do look at a wider range of $\alpha_D$ values in Fig. 4.

Due to its universal coupling to electromagnetism, the $A'$ can replace a photon in any kinematically allowed process, with an accompanying factor of $\epsilon$, such that the event rate for any tree-level process coupling the visible sector to the dark sector is proportional to $\epsilon^2$. Thus, as shown in Fig. 1, DM can be produced and detected via

$$\pi^0 \rightarrow \gamma A'(\gamma) \rightarrow \gamma \chi \bar{\chi}, \quad (3)$$

$$\chi e^- \rightarrow \bar{\chi} e^-,$$  

where the $A'$ can either be on or off-shell in the production process, and the scattering process proceeds through a

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4One could also pair DAEδALUS with the proposed JUNO [25], Hyper-K [26], or water-based liquid scintillator [27] detectors. While it may be possible to use an existing neutrino detector such as NOvA, beam-off backgrounds for an above-ground detector appear prohibitive.

5The $A'$ can acquire mass either through a Stückelberg field or a dark Higgs.

6Changing $\alpha_D$ results in a simple linear scaling of the sensitivity when the DM is produced via an on-shell $A'$ and a quadratic scaling when the DM is produced via an off-shell $A'$. We discuss scaling with $\alpha_D$ in Sec. VI.
t-channel $A^+$. The main detection backgrounds come from neutrinos, either elastic scattering off electrons or charged-current quasielastic (CCQE) scattering off nucleons, but because the spectra of neutrinos produced from decays at rest have sharp kinematic cutoffs, much of the neutrino background can be mitigated by a simple cut on the electron recoil energy in the detector.

While our benchmark dark sector is a viable, a renormalizable theory of DM in its own right, it is also useful to regard this scenario as a simplified model for an entire class of theories in which sub-GeV particles mediate interactions between dark and visible matter. Indeed, there is a vast literature which invokes light, weakly coupled particles to resolve anomalies in direct and indirect detection experiments, build models that relate dark and baryonic energy densities, resolve puzzles in simulations of cosmological structure formation, introduce new relativistic degrees of freedom during big bang nucleosynthesis, and resolve the proton charge-radius anomaly and other low-energy standard model anomalies [15]. That said, it has been observed that certain realizations of light ($\lesssim$ GeV) DM face strong constraints from out-of-equilibrium annihilation to charged leptons during cosmic microwave background freeze-out [73–77]. However, these bounds are model dependent and can be evaded if DM is asymmetric, scatters inelastically with the visible sector [15], has a velocity-suppressed annihilation cross section [78], or if the annihilating particles are a subdominant fraction of the DM abundance, none of which affect the projections for a fixed target search.3 We therefore consider the kinetically mixed dark photon as a simplified model of a portal to the dark sector for which the experimental constraints and future projections can be adapted to study a plethora of other, more elaborate scenarios.

The rest of this paper is organized as follows. In Sec. II, we describe the mechanism of DM production at the DAEδALUS source, for both on- and off-shell mediators. We describe the mechanism and signals of DM scattering at the LENA detector in Sec. III, and we survey the backgrounds to such a search in Secs. IV and V. In Sec. VI, we discuss the sensitivity of DAEδALUS/LENA to DM production in various regions of parameter space and compare with reevaluated bounds from LSND and limits from searches for $A' \to e^+e^-$. We conclude in Sec. VII. Details of the various production and scattering calculations can be found in the Appendixes.

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2A thorough analysis of model-dependent cosmological constraints is beyond the scope of this work, but see Ref. [14] for a more in-depth discussion of these issues. We simply note here that in the region of parameter space we consider $\alpha_D$ is typically large enough to make the relic density of $\chi$ a subdominant fraction of the observed total DM abundance.

3We thank Rouven Essig for pointing out the importance of on-shell $A'$ production from $\Delta$ decays.

4We used the “QGSB_BIC” physics list in GEANT4.
In the region of parameter space where \( \alpha_D \gg e^2 \alpha_{EM} \), \( \text{Br}(A' \to \chi \bar{\chi}) \approx 1 \). Then \( \text{Br}(\pi^0 \to \gamma \chi \bar{\chi}) \) is independent of \( m_\pi \) and \( \alpha_D \) and depends only on the A' mass and the kinetic mixing parameter \( \epsilon \). Since the kinematics of two-body decays are fixed by energy-momentum conservation, the double-differential angular and energy distribution \( d^2 N_{\chi^0}/(d\Omega dE_\gamma) \) (summed over the DM polarizations and the unobserved photon polarizations) of the DM is also independent of \( m_\pi \) and is inherited directly from the analogous distribution of the A's, which is, in turn, inherited from the parent pions. However, we caution that the narrow-width approximation breaks down if \( m_{A'} \) is sufficiently close to \( m_{\pi^0} \) from below [82–84]. In particular, there is no sharp kinematic threshold at \( m_{\pi^0} \).

If \( m_{A'} < 2m_\pi \) or \( m_{A'} \gtrsim m_{\pi^0} - 2\Gamma_{A'} m_{A'} \), the narrow-width approximation is not applicable, and DM is produced through a three-body decay.\(^{11}\) Details of our treatment of the narrow-width approximation are given in Apps. A 4 and A 5. The expression for the branching ratio involves a phase-space integral which cannot be computed analytically,

\[
\text{Br}(\pi^0 \to \gamma \chi \bar{\chi}) = \frac{2\alpha_D}{m_{\pi^0}} \int d\Phi_{\pi^0 \to \gamma A'} d\Phi_{A' \to \chi \bar{\chi}} \times \frac{\Gamma_{A'}}{4\pi} |A_{A' \to \chi \bar{\chi}}|^2 \quad \text{(off shell)},
\]

where \( s \) is the mass squared of the virtual A', \( \Gamma_{\pi^0} = 7.74 \text{ eV} \) is the total \( \pi^0 \) width, and \( A_{A' \to \chi \bar{\chi}} \) is the three-body decay amplitude normalized to \( e = \alpha_D = 1 \). This normalization was chosen to make the dependence of the branching ratio on \( e \) and \( \alpha_D \) explicit. In contrast to the on-shell case, the branching ratio now depends on both the dark fine structure constant \( \alpha_D \) and the DM mass \( m_\chi \). Full expressions for the three-body amplitudes for fermionic and scalar DM, as well as the A' width, are given in App. A. The double-differential distribution \( d^2 N_{\chi^0}/(d\Omega dE_\gamma) \) can be obtained in a straightforward manner from Eq. (7) by only performing the first phase-space integral, which gives the distribution in the \( \chi^0 \) rest frame, then boosting according to the \( \chi^0 \) lab-frame distribution.

\(^{11}\) This illustrates a subtlety of the narrow-width approximation. Although the A' can go on shell for \( m_{A'} < m_{\pi^0} \), the phase-space suppression means that the phase-space integral in Eq. (7) is actually dominated by the off-shell region of the amplitude, giving a smooth behavior through the \( \pi^0 \) threshold. The effect of near degeneracies on the efficacy of the narrow-width approximation in resonant three-body decays has been previously noted in Ref. [84], where it is shown that phase-space factors distort the shape of the Breit–Wigner distribution and lead to errors parametrically greater than \( \Gamma/M \).

### III. Dark Matter Scattering at LENA

The LENA detector [18] is a proposed cylindrical scintillator detector with a target volume of radius 13 m and height 100 m; we assume the target volume is filled with linear alkyl benzene (C\(_{18}\)H\(_{30}\)), giving a fiducial mass of 45.8 kton, though other choices of scintillator are under consideration. Dark sector particles produced at the DAE\( \delta \)ALUS target can travel unimpeded through the surrounding material to scatter in the LENA detector. For low mass mediators, the dominant channel is coherent scattering off detector nuclei, which enjoys an \( A^2 \) enhancement since small momentum transfers are unable to resolve nuclear substructure. However, this channel suffers from a severe form-factor suppression for momentum transfers in excess of our electron recoil cuts which are necessary to discriminate the signal from the beam-on neutrino backgrounds. DM particles can also scatter off atomic electrons in the detector, and it is this \( \chi e^- \rightarrow \chi e^- \) channel on which we will focus, though the discussion below can be adapted to a generic detector target.\(^{12}\)

The total scattering yield for the electron channel is

\[
N_{\text{sig}} = n_e \int_{E_{\text{min}}}^{E_{\text{max}}} dE_e \int_{E_{\text{min}}}^{E_{\text{max}}} dE_x \int_{L_{\text{ENA}}} d\Omega_e \left( \frac{d^2 N_e}{d\Omega dE_x} \right) dE_e,
\]

where our GEANT simulation yields \( N_{\chi^0} = 7.5 \times 10^{22} \pi^0/\text{yr} \) and \( \text{Br}(\pi^0 \to \gamma \chi \bar{\chi}) \) is given by Eq. (6) for on-shell production and Eq. (7) for off-shell production. The maximum energy of DM produced at DAE\( \delta \)ALUS as a function of its mass \( m_\chi \) is

\[
E_x^{\text{max}} = \frac{1}{2} \beta_{\text{max}} m_\chi \sqrt{1 - \frac{4m_e^2}{m_\chi^2}},
\]

where \( (\gamma_{\text{max}}, \beta_{\text{max}}) \approx (5, 0.98) \) are the maximum boost and velocity, respectively, for \( \pi^0 \)'s produced at DAE\( \delta \)ALUS.

\(^{12}\) If there are mass splittings in the dark sector and the A' coupling is off-diagonal between mass eigenstates, scattering inside the detector will be inelastic and may feature striking deexcitation signals that are not easily mimicked by neutrino or cosmic backgrounds [15]. Although this scenario is beyond the scope of this paper, we note that the experimental setups discussed in this work should have promising discovery potential for these signals as well, and in App. B we derive cross sections appropriate to this more general case.
where \( n_e = 3.0 \times 10^{23}/\text{cm}^3 \) is the number density of target electrons, \( \varphi(\Omega) \) is the DM path length through LENA, \( d\sigma/dE_e \) is the recoil electron energy distribution, and the angular integral is taken over the region covered by the LENA detector for the chosen geometry. \( E^\text{low}(m_\chi) \) and \( E^\text{high}(m_\chi) \) are electron recoil energy cuts which are chosen for each \( m_\chi \) to optimize signal-to-background sensitivity for that mass point; we discuss these cuts further in Sec. V. In principle, we should also include a factor accounting for any muon veto dead time or reconstruction efficiencies, but we neglect these here. The minimum incoming energy for \( \chi \) to induce an electron recoil of energy \( E_e \) is

\[
E^\text{min}_{\chi}(E_e) = \frac{T_e}{2} \left[ 1 + \sqrt{\left( 1 + \frac{2m_\chi}{T_e} \right) \left( 1 + \frac{2m_e^2}{m_\chi T_e} \right)} \right],
\]

where \( m_e \) is the electron mass and \( T_e \) is the electron kinetic energy. Another useful expression is the maximum possible recoil electron energy for a given DM mass,

\[
E^\text{max}_{\chi}(m_\chi) = m_e + \frac{2(E^\text{max}_{\chi})^2 - 2m_e^2}{2E^\text{max}_{\chi} m_e + m_e^2 + m_e^2},
\]

where \( E^\text{max}_{\chi} \) is given in Eq. (9). In App. B, we present the details of our numerical signal rate computation, including cross sections for scalar and fermion DM particles scattering off a generic target.

In terms of geometry, we consider three possible locations for DAE\( \delta \)ALUS relative to LENA, shown in Fig. 2:

(i) midpoint: pointed horizontally at the vertical midpoint of the detector, 16 m away from the cylindrical face;
(ii) oblique: pointed horizontally near the upper corner of the detector, at a lateral distance 16 m and height 5 m;
(iii) on axis: pointed downward into the end cap of the detector, 16 m above the top face.

The LENA design is self-shielding and includes a 2 m buffer and 2 m muon veto between the outer face and the target volume, so the effective source-detector distance in all three cases is at least 20 m. The signal yield for a 1 MeV DM particle for the three proposed geometries is shown in Fig. 5. The choice of geometry only affects the sensitivity in \( \varepsilon^2 \) by a factor of order 10\% The midpoint and on-axis geometries are essentially identical and provide superior sensitivity compared to the oblique geometry for the entire range of \( A' \) masses; the effective detector length and solid angle acceptance are larger for these geometries, and because the signal and background angular distributions are so similar after energy cuts are imposed [see Fig. 6(a) and the discussion below], no additional signal/background separation is achieved in the oblique configuration. For simplicity, we will focus on the on-axis configuration because it preserves cylindrical symmetry.

In terms of electron energy cuts, we consider three benchmark cuts on \( E_e \) based on avoiding various beam-on background thresholds:

(i) \( E^\text{low}_e = 106 \text{MeV} \), above the low-energy muon capture and stopped pion and muon backgrounds;
(ii) \( E^\text{low}_e = 147 \text{MeV} \), above the energy threshold for muon production from beam-on sources;
(iii) \( E^\text{low}_e = 250 \text{MeV} \), above the dominant decay-in-flight neutrino-electron scattering background.

Roughly speaking, the 106 MeV cut is optimal for heavy DM, the 147 MeV cut is optimal for medium-mass DM, and the 250 MeV cut is optimal for light DM. This can be seen from Eq. (12); for example, \( m_\chi = 42 \text{MeV} \) implies \( E^\text{max}_e = 146 \text{MeV} \), so the lowest of the energy thresholds (with all its additional backgrounds) is necessary to retain any signal acceptance at all. We give more details justifying these cuts in Sec. V below and discuss how to optimize them based on the various background spectra.

### IV. BEAM-OFF BACKGROUNDs

The signal process \( \chi e^- \rightarrow \chi e^- \) faces backgrounds from any process which results in an energetic lepton in the final state. There are two main sources of backgrounds, beam off and beam on. The principal advantage of using an underground detector such as LENA is the reduction in beam-off backgrounds from sources other than neutrinos. The target depth of LENA is approximately 4000 mwe with a cosmic muon flux of \( \approx 1 \times 10^{-4} \text{ m}^{-2} \text{ s}^{-1} \). Therefore, external backgrounds related to untagged cosmic muons interacting in the rock surrounding the detector are expected to be
The neutrino distribution is roughly isotropic, while the signal is strongly peaked in the forward direction ($\cos \theta = 1$). The slight excess of neutrino production in the backward direction is an artifact of the simplified target geometry used in the simulation; see the text for details. Above 106 MeV both the DM and neutrino distributions are strongly peaked in the forward direction; the relative normalizations of the curves with and without the cut show the reduction in signal and background due to this cut alone, though the actual signal is also determined by the geometric acceptance of LENA. For different DM masses, the normalization of the DM distribution changes, but not its shape. Although LENA cannot resolve electron-recoil angles for which $\cos \theta > 0.9$, imposing a stronger angular cut of $\cos \theta > 0.95$ would preserve an order-1 fraction of signal events and dramatically reduce both beam-off and beam-on backgrounds discussed in Secs. IV and V. To be conservative, we assume $\cos \theta > 0.9$ for all of our sensitivity projections, but this is a potential avenue for improving new-physics searches in the electron scattering channel. Right (b): Electron energy spectra due to various DM signal points. The $\nu_{\mu}$ CCQE distribution was only simulated above 100 MeV where it begins to dominate. The $\epsilon^2$ values for each signal point are chosen to match the minimum value for which the DAEδALUS/LENA setup has the 3σ sensitivity displayed in Fig. 3.

In principle, events with delayed vertex activity such as $\nu_e^{12}\mathrm{C} \rightarrow e^{-12}\mathrm{N}_{\alpha}$, $12\mathrm{N}_{\alpha} \rightarrow 12\mathrm{C}\beta^+$ can be tagged, but we do not consider event-by-event rejection of this class of events here.
keeping ≈99% of the signal over most of the kinematically allowed parameter space.\textsuperscript{14} The rates for these processes in three benchmark energy ranges of interest are given in Table I; more details of our beam-off estimates are given in Table C1. We note that with these cuts all the beam-off backgrounds are subdominant to the beam-on backgrounds, which we discuss below.

V. BEAM-ON BACKGROUNDS

We now consider the possible beam-on backgrounds. By imposing kinematic cuts which select for neutrino energies $E_{\nu} > 52.8$ MeV, we eliminate the large decay-at-rest neutrino background from

$$\pi^+ \rightarrow \mu^+ \nu_\mu, \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu,$$

(15)

A further cut at $E_{\nu} > 70$ MeV eliminates the neutrino background from helicity-suppressed $\pi^+$ decays at rest,

$$\pi^+ \rightarrow e^+ \nu_e,$$

(16)

which could pose a significant background because of the large number of stopped pions at DAE\textsuperscript{alus}. Finally, a cut at $E_{\nu} > m_\mu \approx 106$ MeV mitigates the neutrino background from muon capture,

$$\mu^- + \frac{A}{2} N \rightarrow \nu_\mu + \frac{A}{2-\lambda}N',$$

(17)

where $N$ is a nucleus in the DAE\textsuperscript{alus} target, either carbon or copper. The rate of muon capture is not well modeled by our GEANT simulation since the true DAE\textsuperscript{alus} target contains copper and the cross section for $\mu^-$ capture on copper is much higher than on graphite.

However, the neutrinos produced from muon capture have a sharp kinematic end point at or below the muon mass and suffer an acceptance penalty because they are produced isotropically, so we expect this background to be negligible above 106 MeV.

The remaining beam-on sources of neutrinos above 106 MeV are all decays in flight,

$$\pi^+ \rightarrow \mu^+ \nu_\mu, \quad (18)$$

$$\pi^+ \rightarrow e^+ \nu_e, \quad (19)$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu, \quad (20)$$

$$\pi^- \rightarrow e^- \bar{\nu}_e, \quad (21)$$

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e, \quad (22)$$

Note the inclusion of the helicity-suppressed pion decay modes to electrons and positrons, which will in fact pose the main backgrounds above 250 MeV. To estimate the beam-on backgrounds, we used the same GEANT simulation, which generated our signal events to generate the parent pions and muons, and GENIE \textsuperscript{[85]} to simulate the CCQE processes; details are given in Appendix C2. The simplified DAE\textsuperscript{alus} target geometry used in this simulation consisted of a single block of graphite with a flat face, whereas the full DAE\textsuperscript{alus} design consists of a graphite and copper target with a reentrant hole. Since the stopping power for copper is greater than for graphite, we expect the decay-in-flight background from this simulation to be an upper limit on the true decay-in-flight background from the DAE\textsuperscript{alus} neutrino source. Furthermore, we expect our simulation to overestimate the number of backscattered pions, since in the full DAE\textsuperscript{alus} target design some pions will stop in target material surrounding the reentrant hole. That said, since we focus on energies above the decay-at-rest neutrino spectrum, these backscattered pions do not pose a background in this analysis.

A few words are in order regarding our treatment of the muon decay-in-flight backgrounds. For the LSND

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\textsuperscript{14}LENA is able to resolve paths of outgoing electrons with energies above 250 MeV and muons with kinetic energies above 100 MeV to an accuracy of a few degrees \textsuperscript{[18]}. Extending this cut for electrons down to energies of 106 MeV is perhaps optimistic at LENA but may be possible with a future detector paired with the DAE\textsuperscript{alus} source.
experiment, the $\nu_e$ background from $\mu^-$ decays was of the same order of magnitude as that from $\pi^+$ decays, in the electron recoil range 60–200 MeV [23]. However, at DAEδALUS, we expect the $\nu_e$ background from $\pi^+$ decay to be dominant for a number of reasons. First, a significant number of the decay-in-flight $\mu^+$ at LSND were due to isotope stringers placed in the LAMPF beam upstream of the LSND target, whereas the DAEδALUS target will be optimized to suppress decay-in-flight backgrounds. Second, the spectrum of decay-in-flight $\mu^+$ at DAEδALUS is much softer than the $\pi^+$ spectrum due to the longer muon lifetime and correspondingly larger energy loss in the DAEδALUS target. Third, the daughter neutrinos are less energetic: 52.4 MeV in the muon rest frame, as compared to 70 MeV in the pion rest frame. Therefore, we expect this background to be subdominant to the $\pi^+$ decay-in-flight $\nu_e$ CCQE background for energies above 250 MeV and subdominant to the $\pi^+$ decay-in-flight $\nu_{\mu^*}$ electron elastic scattering background between 106 and 250 MeV. We attempted to directly simulate this background with GEANT, but statistics proved prohibitive; we leave a full simulation of this background to more detailed studies.

Exactly as with beam-off backgrounds, beam-on backgrounds consist of both $\nu - e^-$ elastic scattering and CCQE events. Elastic events tend to have the outgoing electron scattered at small angles with respect to the initial neutrino direction when $T_e > 106$ MeV, while CCQE events tend to have the lepton (electron or muon) produced more isotropically. As shown in Fig. 6a, the DM distribution is strongly peaked in the forward direction, such that much of the signal at large recoil energies will have electrons nearly parallel to the beamline. Thus, beam-on CCQE background events can be mitigated with the same cut on the outgoing charged lepton angle $\theta_{l^*} < 25^\circ$ as was used for beam-off events. The uncertainty for beam-on backgrounds is dominated by the systematic uncertainty in the neutrino flux. For each flavor of neutrino, a charged-current (CC) channel is available to measure the flux:

$$\nu_\mu^{12}\text{C} \rightarrow \mu^- X \quad (\text{tagged muon}),$$  
$$\nu_e^{12}\text{C} \rightarrow e^-\nu_{\text{gs}} \quad (\text{tagged }^{12}\text{N}_{\text{gs}} \beta \text{ decay}),$$  
$$\bar{\nu}_\mu p \rightarrow \mu^+ n \quad (\text{tagged muon and neutron}),$$  
$$\bar{\nu}_e p \rightarrow e^+ n \quad (\text{tagged neutron}).$$

There has been a considerable experimental effort to measure these CC cross sections [86], and recently it was proposed to measure the inclusive CC reaction in Eq. (23) with a monoenergetic 236 MeV $\nu_\mu$ beam from kaon decays [87]. When presenting the reach of DAEδALUS/LENA, we will assume a 20% uncertainty in all of these cross sections, translating to an approximate 20% uncertainty in all beam-on background rates, $\delta B = 0.2B$.

The elastic and CCQE rates for all beam-on backgrounds above 106 MeV with the angular cut imposed are summarized in Table II for the three benchmark energy ranges. The main irreducible background in the recoil energy range 106–147 MeV is $\nu_{\mu^*} - e^-$ elastic scattering. The main irreducible background in the recoil energy range 106–147 MeV is $\nu_{\mu^*} - e^-$ elastic scattering. The main

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\[ \text{TABLE II. One-year rates for all beam-on backgrounds resulting in an outgoing lepton } l^* = e^-, \mu^+ \text{ with kinetic energy } T_e > 106 \text{ MeV in the final state. “Elastic” refers to elastic neutrino-electron scattering, and “CCQE” refers to charged-current quasielastic neutrino-nucleon scattering. A cut } \cos \theta_{l^*} > 0.9 \text{ has been imposed on all outgoing charged leptons. Bolded entries are dominant backgrounds in their respective energy ranges. We expect backgrounds from } \mu^+ \text{ decay in flight (DIF) to be subdominant; see the text for details.} \]

<table>
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<tr>
<th>Source</th>
<th>Neutrino</th>
<th>Reaction Type</th>
<th>106–147 MeV</th>
<th>147–250 MeV</th>
<th>250–400 MeV</th>
<th>Tag</th>
</tr>
</thead>
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<td>Elastic</td>
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<td>316</td>
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<td>Michel</td>
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<td>331</td>
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<tr>
<td></td>
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<td>42</td>
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<tr>
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<td>CCQE</td>
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<tr>
<td></td>
<td>$\nu_e$</td>
<td>Elastic</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>&lt; 1</td>
<td>$\ldots$</td>
</tr>
</tbody>
</table>

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\[ ^{16}\text{The high statistics of the JPARC-MLF experiment [88], which should see nearly 200,000 CCQE events at 236 MeV, would give a much better than 20% uncertainty on the differential energy spectrum. However, there would still be considerable uncertainty on the overall normalization, since theoretical predictions for the inclusive CC cross section can differ up to 25% (see Ref. [87] for a discussion). That said, the exclusive channel in Eq. (24), which accounts for about 1% of the $\nu_e$ CCQE cross section, has a smaller \(<10%\) uncertainty and may be useful for determination of the absolute flux to 10%. We thank Joshua Spitz for bringing this point to our attention.} \]
reducible background is $\nu_\mu$ CCQE, which produces an outgoing muon; 70% of the time, this muon can be identified through its Michel electron decay product [18], which as described above also provides the channel with which to calibrate the $\nu_\mu$ flux. Above 147 MeV, muons can no longer be produced in CCQE events from beam-on neutrino sources, leaving the $\nu_\mu - e^-$ elastic background as the dominant irreducible background in the recoil energy range 147–250 MeV, with a significant contribution from $\nu_e$ CCQE. Above 250 MeV, the rate due to beam-on $\nu_\mu - e^-$ elastic scattering is less than 1 event per year. Here, the dominant background is $\nu_e$ CCQE. Amusingly, the source of these electron neutrinos is the helicity-suppressed decay $\pi^+ \rightarrow e^+ \nu_e$, which, despite its branching ratio of $1.23 \times 10^{-3}$, has a very broad $\nu_e$ energy spectrum and a large CCQE cross section. The corresponding decay $\pi^- \rightarrow e^- \bar{\nu}_e$ leads to a subdominant reducible background with a taggable neutron.

The optimal recoil cuts as a function of $m_\chi$ and $m_{A'}$ can now be determined based on the various background thresholds. For light $\chi$, Fig. 6(b) shows that the DM recoil spectrum is relatively flat and extends to high energies, so the optimal $E_{e}^{\text{low}}$ is around 210 MeV where the only significant background is $\nu_e$ CCQE. As $m_\chi$ increases, the DM distribution begins to fall more steeply with energy, such that for $m_\chi = 20$ MeV the signal and $\nu_e$ elastic background fall at approximately the same rate. Thus, one needs to apply a lower energy cut to retain a sufficient yield of signal events; this is true for both on- and off-shell DM production. Below 250 MeV the only new background is $\nu_\mu$ elastic scattering, so to keep the maximum number of signal events, the optimal $E_{e}^{\text{low}}$ should be close to 147 MeV. For heavier DM, $m_\chi \gtrsim 30$ MeV, the 147 MeV cut is too severe because the DM is not produced with enough kinetic energy to provoke recoils above 147 MeV at an appreciable rate. As described above, to avoid the numerous low-energy backgrounds, the lowest realistic energy cut is $E_{e}^{\text{low}} = 106$ MeV. We determined $E_{e}^{\text{high}}$ as a function of $m_\chi$ and $m_{A'}$ by optimizing signal-to-background sensitivity $S/\delta B$ using $\delta B = \sqrt{4B/3}$ (systematic and statistical errors combined) for beam off and $\delta B = 0.2B$ (systematic only) for beam on; the result for $m_{A'} = 50$ MeV is shown in Fig. 7. Due to the broad neutrino background spectra, the optimal signal window is as narrow as possible for all DM masses. However, the energy resolution at LENA is on the order of a few percent in the energy range we consider [18]. To be conservative, we use signal windows of 50 MeV or greater in electron recoil energy.

![Optimal Signal Window](image)

**FIG. 7** (color online). Optimal electron recoil cuts $E_{e}^{\text{low}}$ (green curve) and $E_{e}^{\text{high}}$ (red curve), which optimize the signal-to-background sensitivity $S/\delta B$ as a function of $m_\chi$ for fixed $m_{A'} = 50$ MeV, assuming a minimum signal window width of 50 MeV. The shaded region between the red and green curves defines the optimal signal window for each mass point. Also shown is the maximum electron recoil energy $E_{e}^{\text{max}}$ (black, dotted curve) for each $m_\chi$ assuming an initial proton energy of 800 MeV [see Eq. (12)]. The blue dashed lines at $E_e = 106, 147, and 250$ MeV, respectively, denote the electron energies beyond which beam-on backgrounds from $\mu^-$ capture, $\nu_\mu$ CCQE (from $\pi^+$ DIF) and $\nu_e$ elastic scattering (from $\pi^+$ DIF) become irrelevant; these lines can be regarded as a heuristic estimate of $E_{e}^{\text{low}}(m_\chi)$. Above 250 MeV, the only significant beam-on background is from the $\nu_e$ CCQE process (see Table II).

VI. SENSITIVITY

The main results of this paper are shown in Fig. 3, which give the $3\sigma$ sensitivity of the DAE$\delta$ALUS/LENA setup to the dark photon/DM parameter space. We also show updated results for the LSND exclusions, which extend the analysis of Ref. [10] into both off-shell $A'$ regimes. Our LSND exclusions are based on rescaling our GEANT simulation for the DM signal rates in DAE$\delta$ALUS/LENA to match the collision rate and target geometry of LSND. We make no attempt to simulate the backgrounds at LSND but instead assume that the 55-event upper limit quoted in Ref. [22] accounts for background subtraction. Our signal yields are expected to be very similar to the analysis in Ref. [10] because the $\pi^0$ spectrum depends very little on the target geometry; we verified that in the on-shell $A'$ regime we obtain nearly identical results to Ref. [10]. A key feature to note is the dark gray bands in Figs. 3(c) and 3(e), which indicate the region of parameter space where LSND can place bounds on $\pi^0 \rightarrow e^+ e^-$ decays by searching for DM produced in $\pi^0 \rightarrow \gamma A' \rightarrow \gamma \gamma \chi$ via an off-shell $A'$. The extended exclusion limits from LSND compared to the previously reported limits are demonstrated in Fig. 8 for $m_\chi = 20$ MeV; we discuss the reason for this extended coverage in more detail below.

Also plotted in Fig. 3 are constraints and projected sensitivities for a variety of dark photon searches; for a comprehensive review of this parameter space, see Ref. [6] and citations therein. The constraints are from E137 [89,90], Orsay [91], muon $g - 2$ [20,92], electron $g - 2$
true kinematic threshold for on-shell production of the $A'$ at $m_{A'} = 40$ MeV. Just above threshold, the phase-space suppression of DM particles produced nearly at rest in the on-shell $A'$ rest frame competes with the matrix element suppression of DM produced through an off-shell $A'$, and so the cut on electron recoil energy tends to shift the point of maximum sensitivity in $e^2$ to larger $A'$ masses. This results in a dip at $m_{A'} \gtrsim 40$ MeV rather than a sharp drop exactly at threshold. Second, in the lower off-shell regime $m_{A'} < 40$ MeV, both DAEδALUS and LSND are still sensitive to DM production and scattering, and in fact the sensitivity to very light off-shell $A'$s is superior to the on-shell sensitivity. This surprising observation has also been neglected in previous studies and is possible because the virtuality of the $A'$ does not generate all that much of a suppression in the decay $A^0 \to \gamma A' \to \gamma \chi \chi'$. Indeed, phase-space constraints at high $m_{A'}$ can be more restrictive than matrix element suppression at low $m_{A'}$, such that there is a region of parameter space at very low $m_{A'}$ where the off-shell reach of both experiments in $e^2$ is stronger than the on-shell reach.

Furthermore, because the $A'$ couples to electrons by assumption, if $A'$ decays to DM are kinematically forbidden, then the decay channel $A' \to e^+ e^-$ must be open. This leads to the key feature mentioned above that the sensitivity of DAEδALUS/LENA and LSND in the lower off-shell $A'$ regime can overlap with visible $A' \to e^+ e^-$ searches. Indeed, for $m_{\chi} = 20$ MeV, the reach of LSND and DAEδALUS/LENA is comparable to experiments like E141 [95] and HPS [104]. Of course, the visible limits are independent of $m_{\chi}$, whereas the LSND and DAEδALUS/LENA limits require a dark-sector state of the appropriate mass. Still, this emphasizes the importance of studying the full $\{m_{A'}, e, m_{\chi}, \alpha_D\}$ parameter space. Note that as $\alpha_D$ increases the LSND and DAEδALUS curves on these plots shift downward. DM production is independent of $\alpha_D$ in the on-shell regime but proportional to $\alpha_D$ in the off-shell regime, while DM scattering is proportional to $\alpha_D$ for any $m_{\chi}$ and $m_{A'}$ (see App. A and App. B). Thus, the scaling of the sensitivity with $\alpha_D$ is quadratic in the off-shell regime and linear in the on-shell regime. In contrast, the visible searches remain unaffected as $\alpha_D$ is changed since the on-shell $A' \to e^+ e^-$ process is independent of the dark coupling $\alpha_D$.

Going to even heavier DM, $m_{\chi} = 40$ MeV in Fig. 3(e), we see that constraints from LSND data already cover the entire region which would be probed by DAEδALUS in one year of running. This is due to the fact that LSND is a Čerenkov detector and can use directionality to discriminate against neutrino backgrounds at lower energies than LENA. For the DAEδALUS/LENA setup, the minimum recoil cut of 106 MeV which is necessary to mitigate the backgrounds also cuts out the majority of the signal, since the heavy DM is produced with relatively low kinetic energy. This also results in an even greater
degradation of sensitivity near the on-shell threshold at $m_A = 2m_\chi$ compared to LSND. Thus, we see that experiments like LSND, which have sensitivity to low electron recoil energies, are optimal for larger $m_\chi$.

The plots in the right column of Fig. 3 show the sensitivity in $e^2$ for fixed $(m_A', \alpha_0)$ as a function of $m_\chi$, where again the electron recoil cuts are chosen for each $m_\chi$ to optimize the sensitivity as in Fig. 7. The DAE\$\delta$ALUS/LENA reach improves on LSND by an order of magnitude for light $\chi$, but the improvement weakens for heavier $\chi$ for the same reasons discussed above: the LSND recoil cuts favor heavier DM because it is produced with less kinetic energy. The constraints from visible searches now appear as horizontal lines in the off-shell regime because they depend only on $m_A'$ and not on $m_\chi$.

Finally, Fig. 4 shows a different slice through parameter space. Here, we fix $m_\chi$ and show the sensitivity to $\alpha_0$ as a function of $m_A'$, where, for each $A'$ mass, $e$ assumes the lowest value consistent with the $(g - 2)_\mu$ preferred band [as shown in green in Fig. 3(a)]. We see that DAE\$\delta$ALUS/LENA can improve considerably on LSND bounds over the entire kinematically accessible parameter space of the dark photon model and nearly covers all of the remaining parameter space that resolves the $(g - 2)_\mu$ anomaly. The prospect of reconciling this anomaly with a dark photon is usually discussed for an $A'$ which decays purely to $e^+e^-$ or purely to dark-sector states (see Ref. [108] for a discussion of current constraints), but presenting the parameter space in this fashion shows that DAE\$\delta$ALUS/LENA is sensitive to dark photons that decay predominantly to visible states and that visible decay experiments already cover some regions in which the $A'$ decays invisibly.\footnote{We thank Natalia Toro for pointing out the sensitivity of visible searches in this region of parameter space.} Note that after including preliminary results from NA48/2 [21] the $(g - 2)_\mu$ window for a visibly decaying $A'$ is now fully closed [see also Fig. 3(e)].

### VII. CONCLUSION

A rich dark sector remains a well-motivated possibility, and light DM coupled to a kinetically mixed dark photon provides excellent opportunities for discovery. In this paper we have shown that intensity frontier experiments like DAE\$\delta$ALUS, in conjunction with a large underground neutrino detector such as LENA, will have unprecedented sensitivity to light (sub-50 MeV) DM, light (sub-400 MeV) dark photons, and other light, weakly coupled particles. Previous analyses have emphasized the $m_\chi > 2m_\chi$ region of parameter space where the $A'$ decays almost exclusively to the dark sector via $A' \to \chi \bar{\chi}$. This focus was motivated by the typical size of $e$, which ensures that if light dark-sector states exist then $\text{Br}(A' \to \chi \bar{\chi}) \approx 1$. Here, we have shown that existing LSND data place strong constraints on two additional regions, the $m_A' < 2m_\chi$ regime, where on-shell $A'$'s decay via the visible channel $A' \to e^+e^-$ but DM can be produced via an off-shell $A'$, and the $m_\chi > m_\chi > 2m_\chi$ regime, which does not actually contain a kinematic threshold forbidding DM production. Because DM can be produced through both on- and off-shell dark photons, the full four-dimensional parameter space $\{m_A', e, m_\chi, \alpha_0\}$ contains interesting regimes which are not captured in the usual $\{m_A', e\}$ plots. DAE\$\delta$ALUS is uniquely sensitive to this larger parameter space, even up to $A'$ masses of 500 MeV. We also encourage the current search at MiniBooNE to explore this expanded parameter space.

In addition to the potential advantages of higher luminosity and larger acceptance compared to previous experiments, a light DM search at DAE\$\delta$ALUS/LENA would not require a separate running mode, such as the off-target mode used for MiniBooNE. While the sensitivity is best in the on-axis configuration, the reach is relatively insensitive to the detector geometry, and so a DM search could run simultaneously with a decay-at-rest neutrino experiment, provided analysis cuts are performed offline after data taking. In fact, pairing DAE\$\delta$ALUS with a large-volume underground Čerenkov detector like the proposed Hyper-K, with sensitivity to both low and high electron recoil energies and good electron-muon separation to reduce CCQE backgrounds, could cover a broad region of the full four-dimensional parameter space of the dark photon model. The fact that both neutrino and DM experiments share essentially the same signals and backgrounds, though often well separated kinematically, is an advantageous feature of such a setup and suggests exciting opportunities for symbiosis between beyond-the-standard-model and neutrino physics in the coming years.

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APPENDIX A: DARK MATTER PRODUCTION RATES

For calculating the DM production rates and kinematics at DAE@ALUS in Sec. II, we need the three-body matrix element for \( \pi^0 \to \gamma A'(\gamma') \to \gamma \chi \bar{\chi} \), summed over photon polarizations and DM spins if necessary. The calculations below are sufficiently general to be used for either an on-shell or off-shell \( A' \), so we will keep the width \( \Gamma_{A'} \) in the \( A' \) propagator. We will give expressions both for complex scalar DM and Dirac fermion DM, though we only show plots for fermionic DM in the text.

### 1. Dark photon width

For the parameter space \( m_{A'} > 2m_\chi \) and assuming that \( \chi \) is the only dark-sector particle coupled to \( U(1)_D \), the \( A' \) width is

\[
\Gamma_{A',\text{tot}} = \begin{cases} 
\Gamma_{A'\to\gamma\chi\bar{\chi}} + \Gamma_{A'\to e^+e^-} & (m_{A'} > 2m_\chi), \\
\Gamma_{A'\to e^+e^-} & (m_{A'} < 2m_\chi).
\end{cases}
\]

\[
\Gamma_{A',\text{tot}} = \frac{1}{6m_{A'}^2} \times \left\{ \begin{array}{l}
\alpha_D(m_{A'}^2 - 4m_\chi^2)\sqrt{m_{A'}^2/4 - m_\chi^2} + 4e^2\alpha_{EM}(2m_\chi^2 + m_{A'}^2)\sqrt{m_{A'}^2/4 - m_\chi^2} & \text{(scalar)}, \\
4\alpha_D(m_{A'}^2 + 2m_\chi^2)\sqrt{m_{A'}^2/4 - m_\chi^2} + 4e^2\alpha_{EM}(2m_\chi^2 + m_{A'}^2)\sqrt{m_{A'}^2/4 - m_\chi^2} & \text{(fermion)}, \\
4e^2\alpha_{EM}(2m_\chi^2 + m_{A'}^2)\sqrt{m_{A'}^2/4 - m_\chi^2} & \text{(off-shell)},
\end{array} \right.
\]

where \( \alpha_D = g_D^2/4\pi \) and \( \alpha_{EM} = e^2/4\pi \) are the \( U(1)_D \) and electromagnetic fine structure constants, respectively. The last expression is valid when \( m_{A'} < 2m_\chi \) such that on-shell decays \( A' \to \chi \bar{\chi} \) are kinematically forbidden.

### 2. Scalar DM production

The matrix element for DM production can be obtained by replacing a photon leg with an \( A' \) leg in the \( \pi^0 \to \gamma \gamma \) effective vertex mediated by the chiral anomaly, with the \( A' \to \chi \bar{\chi} \) part of the diagram determined by the \( U(1)_D \) coupling to \( \chi \). For the case of scalar DM, the matrix element is

\[
A_{\pi^0\to\gamma\chi\bar{\chi}} = eg_D\frac{e^2}{4\pi f_\pi} \epsilon^{(\gamma)}_{\gamma'} P_\alpha q_\beta \frac{-i(g_{\mu\nu} - q_\mu q_\nu/m_{A'}^2)}{s - m_{A'}^2 + im_{A'}\Gamma_{A'}}(k_2^\mu - k_1^\mu)
\]

where \( p \) is the photon momentum, \( k_1 \) and \( k_2 \) are the DM momenta, \( q = k_1 + k_2 \) is the virtual \( A' \) momentum, \( s = q^2 \), and \( \epsilon^{(\gamma)}_{\gamma'} \) is the polarization vector of the outgoing photon, and \( f_\pi \) is the pion decay constant. Squaring and summing over the two photon polarizations gives

\[
\langle |A_{\pi^0\to\gamma\chi\bar{\chi}}|^2 \rangle = \frac{e^4 g_D^2 \alpha_{EM}}{\pi^2 f_\pi^2} g_{\mu\nu} \epsilon^{\mu\nu\rho\sigma\tau} P_\alpha q_\beta P_{\gamma'} q_\delta \frac{(g_{\mu\nu} - q_\mu q_\nu/m_{A'}^2)(g_{\sigma\tau} - q_\sigma q_\tau/m_{A'}^2)}{(s - m_{A'}^2)^2 + m_{A'}^2\Gamma_{A'}^2}(k_2^\rho - k_1^\rho)(k_2^\sigma - k_1^\sigma)
\]

where the two-body widths are given by

\[
\Gamma_{A'\to\chi\bar{\chi}} = \frac{|\mathbf{p}|}{8\pi m_{A'}} \langle |\mathcal{A}|^2 \rangle,
\]

with \( |\mathbf{p}| = \sqrt{m_{A'}^2/4 - m_\chi^2} \), and \( m_\chi = m_\chi \) or \( m_\chi \) as appropriate. The spin-averaged squared amplitudes for \( A' \) decay to DM and leptons are

\[
\langle |\mathcal{A}_{A'\to\chi\bar{\chi}}|^2 \rangle = \frac{g_D^2}{3} \times \left\{ \begin{array}{l}
m_{A'}^4 - 4m_\chi^4 & \text{(scalar)}, \\
4m_{A'}^2 + 8m_\chi^2 & \text{(fermion)}, \\
4e^2 & \text{(off-shell)},
\end{array} \right.
\]

The last expression is valid when \( m_{A'} < 2m_\chi \) such that on-shell decays \( A' \to \chi \bar{\chi} \) are kinematically forbidden.

\[ m_{A'} > 2m_\chi \]

\[ m_{A'} < 2m_\chi \]
which leads to the final result

$$\langle |A_{\pi^{-}\rightarrow \pi \pi}^{\pi}|^2 \rangle = \frac{e^2 \alpha_{EM}^{2} \alpha_{D}}{\pi f_{\pi}^{2}} \frac{m_{A}^{2}}{s - m_{A}^{2} + i m_{A} \Gamma_{A}} \left[ (s - 4m_{Z}^{2} - s)^{2} - 4s(p \cdot k_{1} - p \cdot k_{2}) \right]^{2} \quad \text{(scalar)}. \quad (A9)$$

If $m_{A} < 2m_{Z}$, the $A'$ is off-shell, and the $A'$ width (which is proportional to $e^2$) can be neglected in the denominator; see Eq. (A5).

### 3. Fermionic DM production

The matrix element for fermionic DM is identical to the scalar case apart from the external spinors which replace the momentum factor $k_2 - k_1$. The matrix element is

$$A_{\pi^{-}\rightarrow \pi \pi}^{\pi} = e g_{D} \frac{e^{2}}{4 \pi f_{\pi}} \frac{1}{4} \varepsilon_{\mu} \varepsilon_{\rho} \varepsilon_{\sigma} \varepsilon_{\nu} \delta_{\mu \rho} p_{\sigma} q_{\rho} - i \frac{g_{\mu} - g_{\rho} q_{\rho}/m_{A}^{2}}{s - m_{A}^{2} + i m_{A} \Gamma_{A}} (\bar{v}(k_{2}) \gamma_{\nu} u(k_{1})) \quad \text{(fermion).} \quad (A10)$$

The additional spin sum is straightforward:

$$\langle |A_{\pi^{-}\rightarrow \pi \pi}^{\pi}|^2 \rangle = - \frac{4e^{2} g_{D} \alpha_{EM}^{2}}{\pi f_{\pi}^{2}} \frac{m_{A}^{2}}{s - m_{A}^{2} + i m_{A} \Gamma_{A}} \left[ (s + 2m_{Z}^{2})(m_{A}^{2} - s)^{2} - 8s(p \cdot k_{1})(p \cdot k_{2}) \right] \quad \text{(fermion).} \quad (A12)$$

Again, if $m_{A} < 2m_{Z}$, the $A'$ width can be neglected.

### 4. On-shell regime

If the pole of the $A'$ propagator is well within the physical kinematical region $s \in [4m_{Z}^{2}, m_{A}^{2}]$, we can use the narrow-width approximation [81],

$$\frac{1}{(s - m_{A}^{2})^{2} + m_{A}^{2} \Gamma_{A}^{2}} \rightarrow \frac{\pi}{m_{A} \Gamma_{A}} \delta(s - m_{A}^{2}). \quad (A13)$$

Making this substitution in the appropriate matrix elements and integrating over the phase space gives Eq. (6) in the text. In particular, when $\alpha_{D} \gg e^{2} \alpha_{EM}$, $\Gamma_{A} \propto \alpha_{D}$ [see Eq. (A5)], so the factors of $\alpha_{D}$ cancel, and $\Gamma_{\pi^{-}\rightarrow \pi \pi}$ is independent of $\alpha_{D}$. However, if $\alpha_{D} \ll e^{2} \alpha_{EM}$ (as in a portion of parameter space that we consider in Fig. 4), then $\Gamma_{A} \propto e^{2}$ since the visible width dominates; in that case the factors of $e^{2}$ cancel, and $\Gamma_{\pi^{-}\rightarrow \pi \pi}$ is proportional to $\alpha_{D}$ but independent of $e$.

As a check of the narrow-width approximation, we find the expected result

$$\Gamma_{\pi^{-}\rightarrow \pi \pi} = \Gamma_{\pi^{-}\rightarrow \pi A'} \propto \text{Br}(A' \rightarrow \chi \bar{\chi}) \quad \text{(on-shell).} \quad (A14)$$

valid for both fermionic and scalar DM.

### 5. Pion threshold regime

If the pole of the $A'$ propagator is sufficiently close to $m_{Z}^{2}$, the narrow-width approximation breaks down because the Breit–Wigner distribution is no longer completely contained in the physical kinematical region $s \in [4m_{Z}^{2}, m_{A}^{2}]$. In that case, we must integrate the appropriate full three-body matrix element over phase space as in Eq. (7) to obtain the branching ratio $\text{Br}(\pi^{0} \rightarrow \gamma \pi \pi)$. Now, however, the width must be included in the denominator because it is not parametrically small with our choice of parameters; it is proportional to $\alpha_{D}$ rather than $e^{2}$. In practice, the three-body matrix element must be used for $|m_{A}^{2} - m_{Z}^{2}| \lesssim 10 \Gamma_{A} m_{A}$; for $\alpha_{D} = 0.1$ and $m_{Z} = 1$ MeV, this translates to 120 MeV $\lesssim m_{A} \lesssim 140$ MeV.

In the limit of large $m_{A}$ and small $m_{Z}$, the decay width for $\pi^{0} \rightarrow \gamma \pi \pi$ can be written as

$$\Gamma_{\pi^{0} \rightarrow \pi \pi} = \frac{m_{A}^{4}}{120} \left( \frac{e g_{D}}{m_{A}^{2}} \right)^{2} \Gamma_{\pi^{0} \rightarrow \gamma \pi} \quad \text{(A15)}$$

Thus, we can view $e g_{D}/m_{A}^{2}$ as a “Fermi constant” for the dark sector arising from integrating out the $A'$, analogous to integrating out the $W$ boson in the weak sector. This
APPENDIX B: DARK MATTER SCATTERING RATES

For calculating the scattering of DM at LENA in Sec. III, we need to calculate the $\chi e^- \rightarrow \chi e^-$ differential cross section $d\sigma/dE_e$. While we have in mind elastic scattering off electrons, we will present formulas that are sufficiently general to apply to any pointlike (fermionic) target $T$ and any inelastic splittings between DM masses which could lead to alternative signals. We let the incoming (outgoing) DM have four-momentum $p_1$ ($k_1$) and mass $m_1$ ($m_2$). We assume the target $T$ is initially at rest in the lab frame.

\[
\langle |A|^2 \rangle = \frac{32\pi^2 e^2 \alpha_{EM} \alpha_D}{(t - m_X^2)^2} \left[ (k_2 \cdot p_1) (p_2 \cdot p_1) + (k_2 \cdot p_1) (p_2 \cdot p_1) - (k_2 \cdot p_2) (p_1 \cdot p_1) + (k_2 \cdot p_1) (p_2 \cdot k_1) + (k_2 \cdot k_1) (p_2 \cdot p_1) \right.
\]
\[
- (k_2 \cdot p_2) (p_1 \cdot k_1) + (k_2 \cdot k_1) (p_2 \cdot k_1) + (k_2 \cdot k_1) (p_2 \cdot k_1) - (k_2 \cdot p_2) (k_1 \cdot k_1) + (k_2 \cdot k_1) (p_2 \cdot p_1) + (k_2 \cdot p_1) (p_2 \cdot k_1) - (k_2 \cdot p_2) (k_1 \cdot p_1) + m_2^2 \left[ m_1^2 + m_2^2 + 2 (p_1 \cdot k_1) \right] \] (scalar).

where $t = (k_1 - p_1)^2 = (k_2 - p_2)^2 = 2m_X^2 - 2m_T E_{k_2}$ and $E_{k_2} = k_2^0$ in the lab frame. All quantities can now be written in terms of the incoming $\chi_1$ energy $E_{p_1}$ and the target recoil energy $E_{k_2}$ in the lab frame.

For fermionic DM, the analogous matrix element is

\[
\langle |A|^2 \rangle = \frac{e^2 g_D}{(t - m_X^2)} \left[ \bar{u}(k_2) \gamma_\mu u(p_2) \right] \left[ \bar{u}(k_1) \gamma^\mu u(p_1) \right] (\text{fermion}).
\]

(B3)

Squaring and averaging/summing over the spin states gives

\[
\langle |A|^2 \rangle = \frac{128\pi^2 e^2 \alpha_{EM} \alpha_D}{(t - m_X^2)^2} \left[ (k_1 \cdot k_2) (p_1 \cdot p_2) + (k_2 \cdot p_1) (p_2 \cdot k_1) - m_1 m_2 (k_2 \cdot p_2) - m_2^2 (p_1 \cdot k_1) + 2m_1 m_2 m_2^2 \right] \] (fermion).

(B4)

2. Differential distributions

From the amplitudes above, we can obtain the differential cross section. Letting $^\ast$ denote quantities in the c.m. frame, the angular distribution is

\[
\frac{d\sigma}{d\Omega} = \frac{1}{2\pi} \frac{d\sigma}{d\cos\theta^\ast} = \frac{\langle |A|^2 \rangle \left[ \hat{k} \cdot \hat{p} \right]}{64\pi^2 s \left| \hat{p} \right|^4},
\]

(B5)

where the initial and final state three-momenta in the c.m. frame are

with mass $m_T$ and initial (final) four-momentum $p_1$ ($k_2$). The case of $\chi e^- \rightarrow \chi e^-$ in the text is obtained with $m_1 = m_2 \equiv m_\chi$ and $T = e^-$. For scalar DM and a fermionic target $T$ (i.e. electron or nucleon), the amplitude for scattering via a $t$-channel kinetically mixed photon is

\[
\mathcal{A} = \frac{ee g_D}{(t - m_X^2)} \bar{u}(k_2) \gamma_\mu (p_1 + k_1) u(p_2) \text{ (scalar)}. \quad \text{(B1)}
\]

Unlike in the production case, here we can always ignore the $A^\ast$ width. Squaring and averaging (summing) over the initial (final) state target spins gives

\[
\left| \hat{p}^\ast \right|^2 = \frac{(s - m_1^2 - m_2^2)^2 - 4m_1^2 m_2^2}{4s},
\]

\[
\left| \hat{k}^\ast \right|^2 = \frac{(s - m_1^2 - m_2^2)^2 - 4m_1^2 m_2^2}{4s}. \quad \text{(B6)}
\]

To go to the lab frame (without $^\ast$ss), we can use the relations

\[
s = (p_1 + p_2)^2 = m_1^2 + m_2^2 + 2m_T E_{p_1}, \quad \text{(B7)}
\]

\[
k_1 \cdot p_1 = -\frac{1}{2} (2m_1^2 - m_1^2 - m_2^2 - 2m_T E_{k_2}) = E_{p_1}^\ast E_{k_2} - \left| \hat{p}^\ast \right| \left| \hat{k}^\ast \right| \cos\theta^\ast. \quad \text{(B8)}
\]

where the incoming DM energy in the lab frame $E_{p_1}$ is known. This allows us to obtain simple expressions for the flux factor $\left| \hat{k}^\ast \right| / \left| \hat{p}^\ast \right|$ and the scattering angle $\cos\theta^\ast$, giving

\[
d \cos\theta^\ast = \frac{m_T}{\left| \hat{p}^\ast \right| \left| \hat{k}^\ast \right|} dE_T. \quad \text{(B9)}
\]

where $E_T \equiv E_{k_2}$ is the energy of the recoiling target. The recoil energy distribution is

\[
\frac{d\sigma}{dE_T} = \frac{m_T \langle |A|^2 \rangle}{32\pi s \left| \hat{p} \right|^4}, \quad \text{(B10)}
\]

which contains the particle physics information about $d\sigma/dE_e$ needed to evaluate the signal yield in Eq. (10). In particular, the cross section is proportional to $e^2 \alpha_{EM} \alpha_D$.  

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3. Numerical signal rate

Specializing to the case of elastic electron scattering \( T = e^- \), \( m_1 = m_2 \equiv m_e \), we can obtain the DM signal yield in Eq. (10) given a total production rate of \( N_{\nu e} \) neutral pions by

\[
N_{\text{sig}} = 2N_{\nu e} \text{Br}(\pi^0 \rightarrow \chi \chi)n_e \frac{1}{N_\chi} \sum_{i=1}^{N_\chi} \epsilon(\vec{p}_\chi^i) \int_{E_{\text{min}}}^{E_{\text{max}}} dE_e \frac{d\sigma}{dE_e} \times (E_e, E_\chi) \Theta [E_\chi - E_{\text{min}}(E_e)]. \tag{B11}
\]

Here \( n_e \) is the target electron density, and we have used our GEANT simulation to generate a population of \( N_\chi \) DM four-vectors \( \{E_\chi, \vec{p}_\chi\} \). The sum is over all \( N_\chi \) events passing geometric cuts; the path length through the detector for event \( i \) is \( \epsilon(\vec{p}_\chi^i) \), and the total geometric acceptance is \( N_\chi/N_\chi \). To induce an electron recoil of magnitude \( E_e \), the DM energy must be above the \( E_{\text{min}}(E_e) \) threshold defined in Eq. (11).

For a LENA-like cylindrical detector of radius \( R \) and height \( h \) as discussed in Sec. III, we can compute the path length through the detector for a DM particle or neutrino. For each geometry, we take the \( z \) axis to point in the beam direction. For the midpoint scenario depicted in Fig. 2(a), we define the \( y \) axis to be parallel to the cylindrical detector axis. The path length is

\[
\epsilon(\vec{p}_\chi) = \begin{cases} 
\left[ (h + D \cos \theta_0) \tan(\theta_0 - \theta_d) - L \right] \csc(\theta_0 - \theta_d) & (\chi \text{ enters top/exits side}), \\
\left[ (D \cos \theta_0 + h) - L \cot(\theta_0 - \theta_d) \right] \sec(\theta_0 - \theta_d) & (\chi \text{ enters side/exits bottom}), \\
S \csc(\theta_0 - \theta_d) & (\chi \text{ exits through bottom}), \\
S \csc(\theta_0 - \theta_d) & (\chi \text{ exits through top/bottom}), \\
\end{cases}
\]

(B12)

where \( \tan \theta_0 = 2R/h \) and \( \theta_d \) is the angle with respect to the beam in the plane spanned by the beam line and the detector’s cylindrical axis.

Finally, for the on-axis scenario in Fig. 2(c), the cylindrical detector axis is aligned with the \( z \) axis (i.e. the beam direction). The path length is

\[
\epsilon(\vec{p}_\chi) = \begin{cases} 
h \sec \theta_z & (\chi \text{ exits through bottom}), \\
(R - D \tan \theta_z) \csc \theta_z & (\chi \text{ exits through side}), \\
\end{cases}
\]

(B13)

where \( \tan \theta_z = \sqrt{p_x^2 + p_y^2/p_z} \) is the DM angle with respect to the \( z \) axis. Here \( D \) is the (vertical) distance between the DAEsALUS source and the detector.

APPENDIX C: NEUTRINO BACKGROUNDS

1. Beam-off backgrounds

The irreducible background due to neutrino-electron scattering from atmospheric neutrinos is estimated from the calculated spectra of Gaisser et al. [109] with a latitude-dependent scaling factor applied to translate the flux from Kamioka to Pyhasalmi as in Ref. [110]. To determine this rate, we convolved the neutrino flux with the elastic scattering cross section. The resulting event rates were less than 1 event per year for each neutrino flavor in each energy range 106–147, 147–250, and 250–400 MeV. The CCQE scattering of atmospheric electron and muon neutrinos and antineutrinos poses an additional beam-off background. For this channel, we generated 1 million sample events on C18H30 using GENIE 2.8.0 [85], with atmospheric flux spectra from Ref. [111] as input. The event sample was reweighted to match the expected number of \( \nu - e \) events calculated above. After a cut requiring the outgoing lepton \( \ell = e, \mu \) to be within 25° of the beam direction, \( \cos \theta_\ell < 0.9 \) (which we take to reduce the nearly isotropic CCQE backgrounds by a factor of 20), the raw rates for these processes are given in Table I. We then assumed a 70% reduction in the \( \nu_\mu \) and \( \bar{\nu}_\mu \) CCQE background rate by rejecting events followed by a Michel electron candidate, as described in Ref. [18]. Furthermore, roughly 25% of the CCQE events for \( \bar{\nu}_\mu \) and \( \bar{\nu}_e \) are on hydrogen and produce a neutron that can be tagged to reject the event; we assumed an 80% neutron tagging efficiency. After these reductions, the dominant process in each energy...

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range is $\nu_e$ CCQE. Using the 75% beam-off time of DAE2ALUS to measure this background gives a statistical uncertainty of $\sqrt{B}$ and a systematic uncertainty of $\sqrt{B/3}$, for a total uncertainty of $(\delta B)^2 = 4B/3$. We have checked that additional backgrounds such as excited resonances, coherent scattering, and deep inelastic scattering also have negligible rates compared to CCQE; in addition, these backgrounds are reducible if one can identify vertex activity or pions in the final state.

### 2. Beam-on backgrounds

There are two main types of beam-on backgrounds, neutral-current elastic muon neutrino-electron scattering and CCQE neutrino-nucleon scattering. For neutrino energies $E_\nu \ll m_\pi$, the differential cross section for elastic muon neutrino-electron scattering ($\nu_e e^- \to \nu_e e^-$) is

$$\frac{d\sigma_{\nu e}}{dE_{e}} = \frac{G_F^2 s}{4\pi E_{\nu}} \left[ g_L^2 + g_R^2 \left( 1 - \frac{E_{e}}{E_\nu} \right)^2 \right],$$  \hspace{1cm} (C1)

where $G_F$ is the Fermi constant, $s = m_e^2 + 2m_eE_\nu$, and $g_{L,R} = g_V \pm g_A$, where $g_V = -\frac{1}{2} + 2\sin^2 \theta_W$, $g_A = -\frac{1}{2}$. For antineutrino scattering ($\bar{\nu}_e e^- \to \bar{\nu}_e e^-$), $g_L$ and $g_R$ are interchanged.

As outlined in Sec. V, we used population of decay-in-flight pions generated in GEANT to simulate our neutrino background events. Given a total flux $N_{e^\pi}$ of decay-in-flight $\pi^+$, each of which produces one $\nu_\mu$, the total $\nu_\mu$ background count is

$$N_{bg} = N_{e^\pi} n_e \frac{1}{N_{\nu}^e} \sum_{i=1}^{N_{\nu}^e} \ell(\tilde{p}_i^\nu)$$

$$\times \int_{E_{\nu}^{low}}^{E_{\nu}^{high}} dE_{\nu} \frac{d\sigma_{\nu e}}{dE_{e}} (E_{\nu}, E_e) \Theta [E'_e - E_{\nu}^{min}(E_\nu)],$$  \hspace{1cm} (C2)

where as above $n_e$ is the detector electron density, $N_{\nu}^e$ is the number of sample neutrino events generated, $N_{\nu}$ is the number of neutrino events passing geometric cuts, $\ell(\tilde{p}_i^\nu)$ is the path length through the detector for a muon-neutrino with three-momentum $\tilde{p}_i^\nu$, and

$$E_{\nu}^{min}(E_\nu) = \frac{T_e}{2} \left( 1 + \sqrt{1 + \frac{2m_e}{T_e}} \right), \quad T_e = E_e - m_e.$$

(C3)

is the minimum neutrino energy to trigger an electron recoil of energy $E_e$. For neutrinos produced from incident $\pi^-$ or $\mu^-$, we replace $N_{e^\pi}$ by the flux of the particle in question. We have checked that the neutrino events produced by GEANT, and neutrinos obtained from manually decaying a sample of energetic pion events from GEANT, give the same results.

zFor the CCQE events, we used the same GENIE simulation [85] as for beam-off backgrounds, with an input neutrino flux spectrum generated from our GEANT simulation. We manually decayed the GEANT sample of decay-in-flight pions to obtain the spectrum for the relevant neutrino flavors, input the neutrino spectrum into GENIE with the angle-dependent path length appropriate for the geometry in question, and reweighted the event sample to match our elastic scattering simulations. The resulting raw rates are given in Table II; the same Michel electron and neutron tagging reductions apply for the background rates. We cross-checked the GENIE results by implementing the Llewellyn Smith CCQE parametrization [112] in our own simulation. We find excellent agreement with GENIE, which is somewhat surprising as it implies that Pauli blocking is not significant in this energy range. We leave a detailed study of the kinematics of the CCQE background to future work. We attempted to directly simulate the background from $\mu^+$ decays with GEANT, but limited statistics proved prohibitive; as explained in the text, we expect this background to be subdominant to the other processes we have considered.

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