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# Production and Detection of Light Dark Matter at Jefferson Lab: The BDX Experiment

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**Abstract:** The Beam Dump eXperiment (BDX) is a an electron-beam thick-target experiment aimed to investigate the existence of light Dark Matter particles in the MeV-GeV mass region at Jefferson Lab. The experiment will make use of a 10.6 GeV high-intensity electron-beam impinging on the Hall-A beam-dump to produce the Dark Matter particles ($\chi$) through the Dark Photon portal. The BDX detector located at ∼20 m from the dump consists of two main components: an electromagnetic calorimeter to detect the signals produced by the $\chi$-electron scattering and a veto system to reject background. The expected signature of the DM (Dark Matter) interaction in the Ecal (Electromagnetic calorimeter) is a ∼GeV electromagnetic shower paired with a null activity in the surrounding active veto counters. Collecting $10^{22}$ electrons on target in 285 days of parasitic run at 65 µA of beam current, and with an expected background of O(5) counts, in the case of a null discovery, BDX will be able to lower the exclusion limits by one to two orders of magnitude in the parameter space of dark-matter coupling versus mass. This paper describes the experiment and presents a summary of the most significant results achieved thus far, which led to the recent approval of the experiment by JLab-PAC46.

**Keywords:** Dark Matter; Dark Photon; beam dump experiment

## 1. Introduction

The existence of a copious quantity of Dark Matter (DM) in the Universe is proved by a rich collection of astrophysical and cosmological observations. Nevertheless, its elementary properties remains largely elusive [1], making the search for DM one of the hottest topics in physics today. At the same time, the Standard Model (SM) of particle physics does not explain some experimental facts, such as neutrino masses, the cosmological baryon asymmetry and, of course, the existence of DM, which is, itself, an overwhelming evidence of physics beyond the SM. Various extensions of the SM have the merit to propose also candidates for the role of DM particles, such as the popular Weakly Interacting Massive Particles (WIMPs) (∼10 GeV–10 TeV mass range) expected to weakly interact with SM [1]. Due to the lack of evidence for WIMPs either from LHC or direct DM searches, other well motivated models of DM gained recently the interest of the physics community [2]. Physics beyond the SM might eventually emerge as a whole new sector containing new particles as well as new interactions. These new states do not need to be particularly heavy, with masses below 1 GeV/c$^2$, and would have easily escaped detection by underground experiments seeking for halo DM. Thus complementary searches attempting to explore these new scenarios are well motivated.

In a popular scenario, light Dark Matter (LDM) with mass in the ∼1 MeV–1 GeV range is charged under a new $U(1)_D$ broken symmetry, whose vector boson mediator $A'$ (heavy photon, also called Dark Photon) is massive. The Dark Photon can be kinetically mixed with the SM photon field, resulting in SM–DM interaction through an effective weak coupling of $A'$ to electric charge $\epsilon e$ [3]. The kinetic mixing parameter $\epsilon$ is expected to be in the range of $\sim 10^{-4}$–$10^{-2}$ ($\sim 10^{-6}$–$10^{-3}$) if the mixing is generated by one-loop (two-loop) interaction [4–6]. The minimal parameter space of vector-mediated LDM is characterized by $\epsilon$, the coupling $\alpha_D$ of the $A'$ to the LDM particle $\chi$ and two masses $m_{A'}$ and $m_\chi$.

Depending on the relative mass of the $A'$ and $\chi$, $A'$ can decay only into SM particles (visible decay) or dominantly to LDM states (invisible decay). In particular, if $m_\chi < m_{A'}/2$, and provided that $\alpha_D > \epsilon e$, the latter scenario dominates. This picture is compatible with the well-motivated hypothesis of DM thermal origin, a hypothesis which provides constraints to model parameters from the observed DM density in the Universe [2].

LDM received strong attention in recent years, motivating many theoretical and phenomenological studies. It also stimulated the reanalysis and interpretation of old data and promoted new experimental programs to search both for the $A'$ and LDM states [2,7]. In this context, accelerator-based experiments that make use of a lepton beam of moderate energy ($\sim$10 GeV) on a thick target or a beam-dump show a sizable sensitivity to a wide area of LDM parameter space [8,9]. Different experimental approaches are possible, each affected by different backgrounds, and with specific sensitivity to model parameters. In particular, high intensity $\sim$ GeV electron-beam fixed-target experiments offer large sensitivity to a broad class of Dark Sector scenarios that feature particles in the elusive MeV-GeV mass range [10].

## 2. BDX Overview

The Beam Dump experiment (BDX) at Jefferson Lab [11,12] aims to produce and detect LDM, assuming valid the above cited theoretical paradigm. Taking advantage of the high-intensity electron beam available at JLab, BDX has the unique capability of significantly improve the sensitivity to MeV–GeV DM, extending well beyond the reach of existing experiments. BDX will take advantage of the CEBAF (Continuous Electron Beam Accelerator Facility) beam, impinging on the JLab Hall-A beam-dump, which is enclosed in a concrete tunnel at the end of the beam transport line. The Hall-A can receive from CEBAF a 11 GeV electron beam with a current up to 65 μA. Such a beam intensity will allow BDX to collect $\sim 10^{22}$ electron-on-target (EOT) in 285 days, in full parasitic runs. The interaction between the energetic electrons and the atoms of the dump leads to the production of Dark Photons through a Bremsstrahlung-like radiative process ($A' - strahlung$, Figure 1, left) [10] and $e^+e^-$ annihilations [13,14]. The $A'$ could then decay into forward-boosted DM particles ($\chi$) (Figure 1, left). Having a small coupling to ordinary matter, LDM particles propagate through the dump and the shielding region up to the BDX detector.

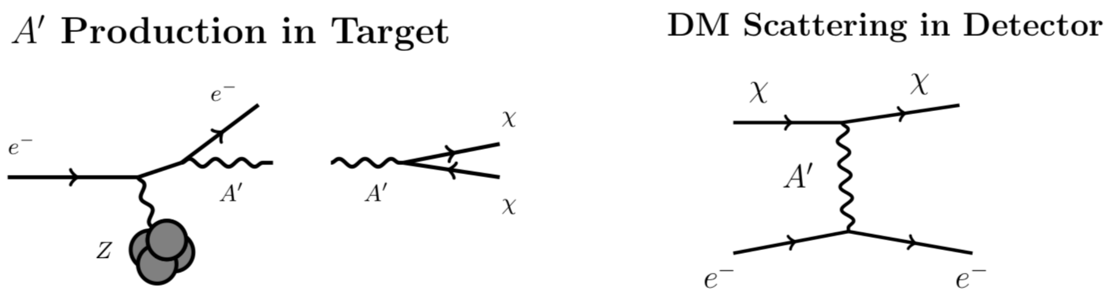


**Figure 1.** (**Left**). production of Dark Photons through a Bremsstrahlung-like radiative process and decay of $A'$ into a pair of DM particles; (**Right**) the $\chi$-e$^-$ scattering is also mediated by $A'$.

The detector will be placed along the LDM beam trajectory $\sim$8 m underground, i.e., at the beam-dump level, in a new underground facility located $\sim$20 m downstream of the Hall-A dump (Figure 2). A specific shielding configuration made by $\sim$7 m of iron plus $\sim$7 m of concrete and installed between the dump and the detector will be used to suppress the high-energy component of the beam-related background.

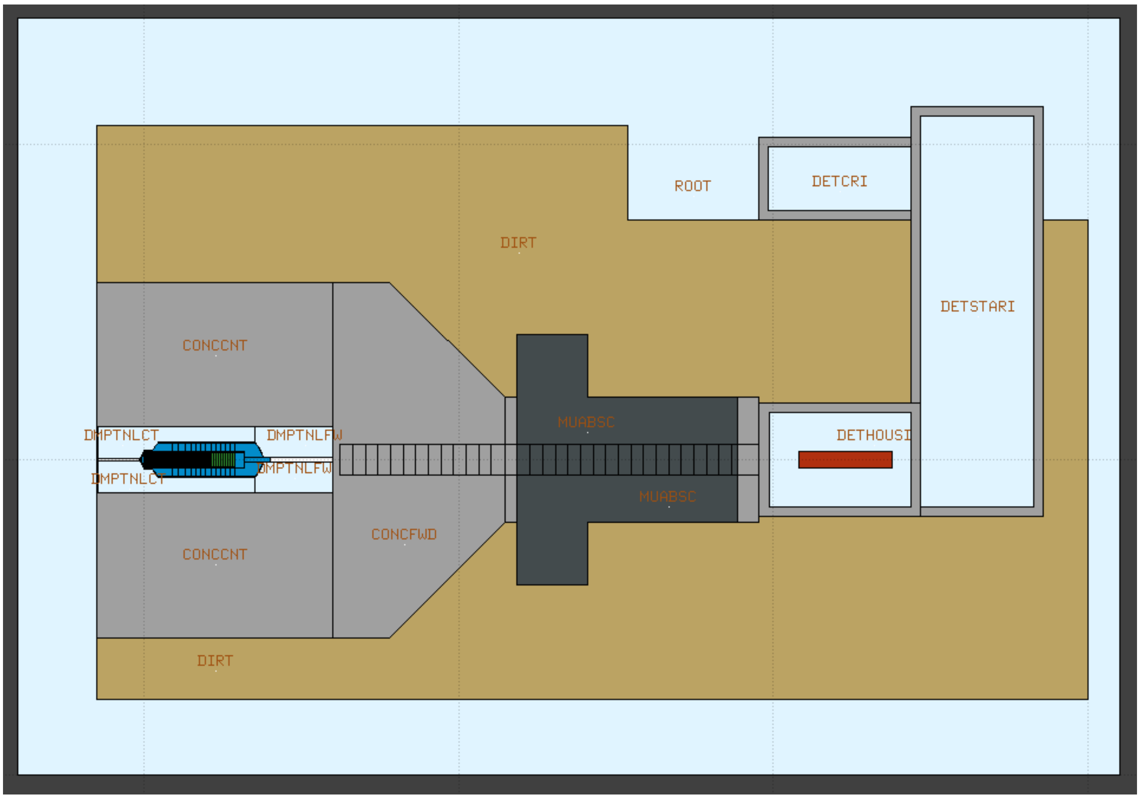


**Figure 2.** The BDX experimental setup, as implemented in FLUKA [15]. From left to right: the Hall-A beam dump (blue), the concrete (light-gray) and iron (dark-gray) shielding, and the BDX detector (red) located inside the new underground facility.

A fraction of DM particles will then scatter on the electrons of the BDX detector active material (Figure 1, right). For $\chi$-e$^-$ interaction, since $m_e << m_\chi$, the typically scattered electron carries GeV-scale energy producing an electromagnetic shower in the GeV energy range, generated by the recoiling electron, that represent an easily detectable signal in the BDX electromagnetic calorimeter. To identify and reduce the SM background that could mimic the expected Dark Matter signals, a combination of passive shielding, active vetos and analysis cuts will be applied.

## 3. The BDX Experimental Setup

The BDX detector is made of two main components: an electromagnetic calorimeter used to detect signals produced by the interacting DM particles, and an active veto system used to reject the background (see Figure 3 for a sketch of the detector). A signal event in BDX is characterized by the presence of an electromagnetic shower in the Ecal coupled with a null activity in the veto system.

The calorimeter consists of $\sim$800 CsI(Tl) crystals, arranged in eight modules of $10 \times 10$ CsI(Tl) crystals each, with the long size along the beam direction. The average size of each crystal is $4.7 \times 5.4 \times 32.5$ cm$^3$. This arrangement results in a cross section of $\sim$$50 \times 55$ cm$^2$ for a total length of $\sim$3 m. Light generated in the crystals will be read-out by Silicon Photomultipliers (SiPM); a rapidly growing technology for the detection of visible photons that is substituting more traditional PMTs and APDs in many physics fields. The good performance of SiPMs as the light readout system of a large-size CsI(Tl) crystal, same size as the BDX Ecal crystals, has been recently proved in Ref. [16]. The BDX Ecal is operated inside two hermetic layers of active veto counters, made of plastic scintillators: the outermost called Outer Veto (OV) and the innermost Inner Veto (IV). Both vetos consists of 1/2 cm-thick plastic scintillators. Due to the relatively large volume to cover, they are divided in paddles. The light from each of them is readout by one or more SiPMs, depending on the paddle size, through wavelength shifting plastic scintillators and scintillating fibers. Between the Ecal and the vetos, a layer of lead

$\sim$5 cm thick will reduce the number of events where the EM shower is not entirely contained in the Ecal and a fraction of its energy is deposited in the vetos, increasing, in this way, the detection efficiency to DM signals. Signals fromt the SiPMs will be amplified by custom charge amplifiers and digitized in the framework of a triggerless data acquisition system. For this purpose, a dedicated front-end board has been recently developed [17]. This highly configurable digitizer board includes 12 complete acquisition channels: the analog-to-digital converter components no the board can be chosen to fit the needs of the specific application within the range from 12 bits at 65 MHz to 14 bits at 250 MHz. The board allows time synchronization using various methods including GPS and White Rabbit. The configurability of the board and the various options implemented permit its use in a triggerless data acquisition system. Up to 240 channels can be hosted in a single 6U crate.

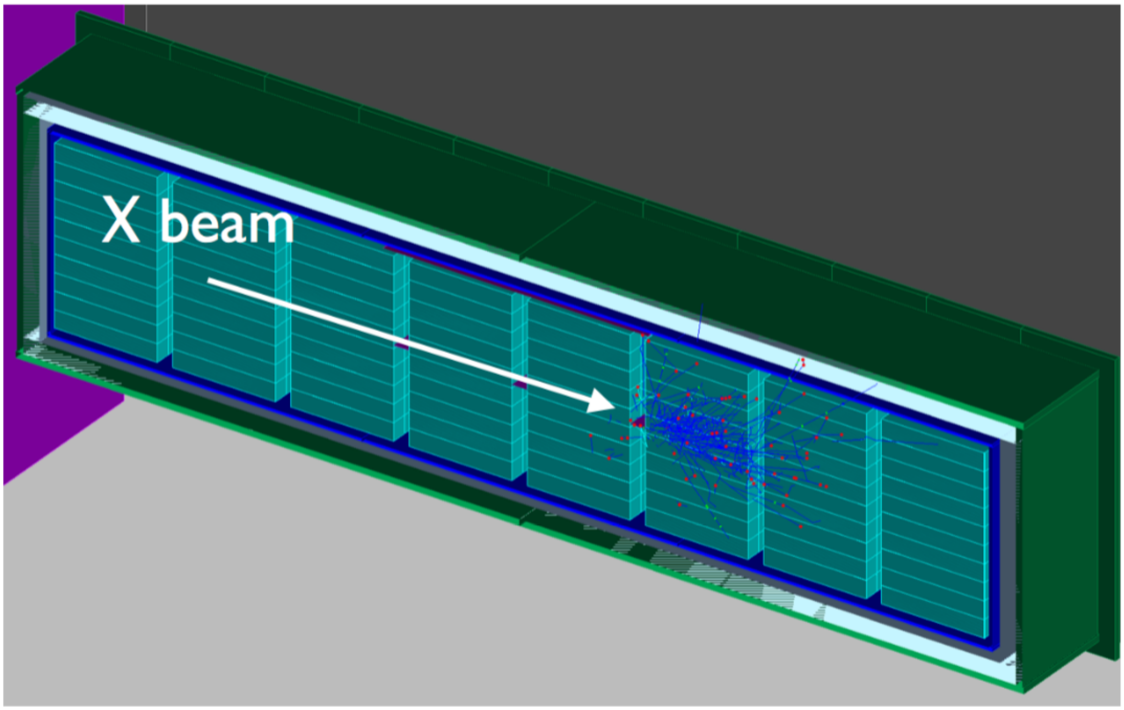


**Figure 3.** The BDX detector as implemented in GEANT4 [18]. The outer veto is shown in green, the inner veto is gray and the lead vault in blue. Crystals arranged in eight blocks of 10 × 10 are shown in light blue. A simulated electromagnetic shower from a $\chi$-e$^-$ scattering in the Ecal is also shown.

## 4. Background

Background is usually the limiting factor in experiments searching for rare events. This is the case for BDX where the low signal rate expected due to the two-step processes involving weak mixing between the SM photon and $A'$ (see Figure 1), makes background rejection a critical issue. Even though BDX will search for electromagnetic showers with energies on the range of hundreds of MeV, thus not requiring the low energy thresholds needed in standard DM direct searches, it is nevertheless mandatory to identify and reject the SM particles that can mimic a DM signal in the Ecal.

### *4.1. Beam-Related Background*

In beam-dump experiments, where a high intensity $O$(GeV) electron/proton beam is directed into a dump, an overwhelming shower of standard model particles is produced in addition to the rare DM particles of interest. While most of the radiation (gamma, electron/positron and neutron) is contained in the dump or degraded down to harmless energy levels, deep penetrating radiation propagate for long distances before depositing their energy far from the point of origin. In BDX, we used Monte Carlo simulations to find the best combination of shielding and analysis cuts to minimize such background. A summary of the most significant results found is reported in the following. Details on BDX simulations can be found in Refs. [11,19,20].

We simulated an 11 GeV electron-beam interacting with the beam-dump and propagated all particles to the location of interest sampling the flux in different locations. Exploiting biasing techniques available in FLUKA an equivalent statistics of $\sim$0.5 $\times 10^{17}$ EOT is obtained. In order to estimate the number of expected background events, the number of particles per EOT was multiplied by $10^{22}$ EOT. Figure 4 shows the particle rate per EOT at different depths in the shielding.

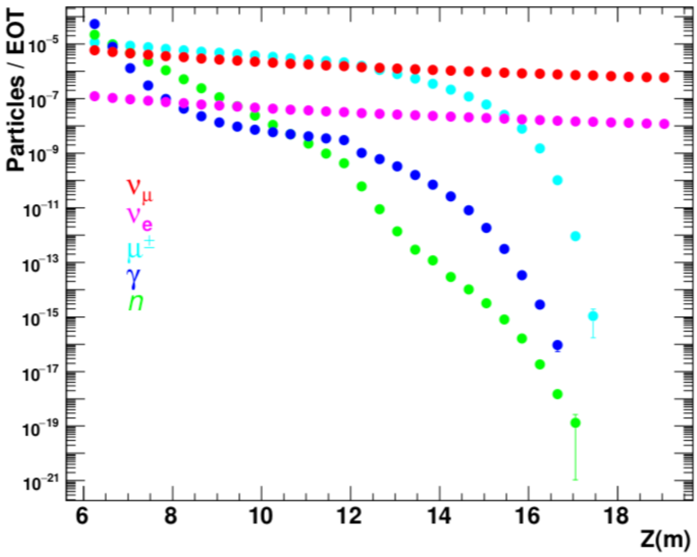


**Figure 4.** Particle rates per EOT at different depths in the shielding. Particle transport threshold was fixed to 100 MeV (10 MeV for neutrinos).

Results from simulations show that no neutrons or photons above 100 MeV transport threshold hit the detector; muons emitted forward and passing through the shielding are ranged-out; muons emitted at large angles in the dump, propagating in the dirt and then, after a hard interaction, re-scattering in the detector, result in a non-zero background rate. However, they have a kinetic energy lower than 300 MeV and the expected rate is much lower (about a factor 1000) than the rate of cosmic muons that we proved can be efficiently identified and removed with the veto system (see next paragraph) and using an energy threshold in the single crystal of $\sim$350 MeV.

Neutrinos are produced in muon decays and hadronic showers (pion decay). The majority come from pion and muon decay at rest but a non negligible fraction, due to in-flight pion decay, experience a significant boost to several GeV energy. High energy neutrinos interacting with BDX detector by elastic and inelastic scattering may result in a significant energy deposition O(300) MeV that may mimic an EM shower produced by the $\chi$–atomic electron interaction. The $\nu_\mu N \to \mu X$ CC interaction produces a $\mu$ in the final state (beside the hadronic state X). This reaction can be identified and used to provide an experimental assessment of the $\nu_\mu$ background (and therefore estimate the $\nu_e$ contribution) by detecting a $\mu$ scattering in the detector (a MIP signal inside the calorimeter with or without activity in IV and OV).

The NC $\nu_\mu N \to \nu_\mu X$ and $\nu_e N \to \nu_e X$ interactions produce an hadronic state X that may interact in the detector (while the scattered $\nu$ escapes detection). This can mimic an EM shower if $\pi_0$ ($\gamma$s) are produced. However, due to the difference in mass, the scattered $\nu$ carries most of the available energy providing a small transfer to the hadronic system and reducing the probability of an over-threshold energy deposition.

The critical background source for the experiment is the $\nu_e N \to eX$ process since the CC interaction could produce a high energy electron/positron into the detector that mimics the signal.

This background can be rejected considering the different kinematics of the $\nu$ interaction with respect to the $\chi$-electron scattering. The significant difference in the polar angle of the scattered electron (with respect to the beam direction) allows defining a selection criterion to identify $\nu_e$ and separate from the $\chi$. This difference is shown in Figure 5, reporting the angular distribution of scattered $e^-$ from $\nu_e$ CC, compared to the characteristics kinematics of the $\chi e^- \to \chi e^-$ kinematics.

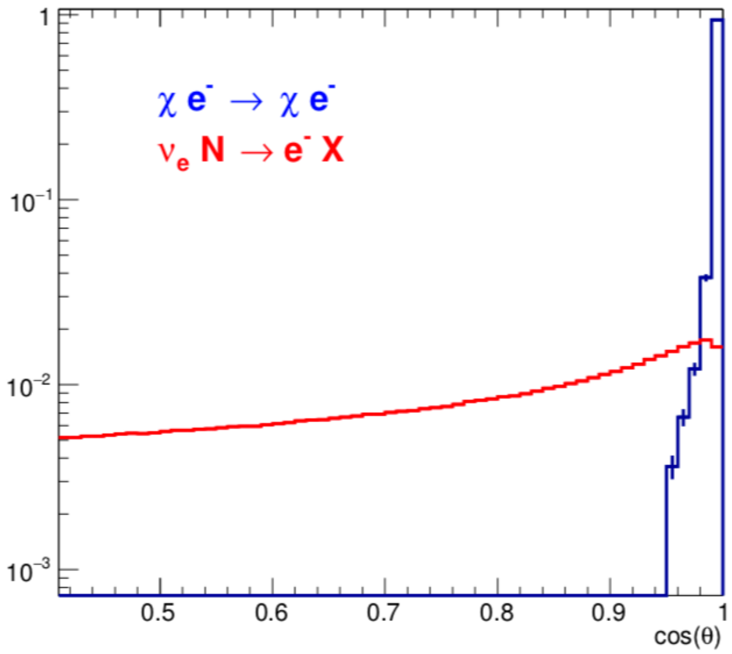


**Figure 5.** Scattered electron angle distribution for the signal $\chi e^- \to \chi e^-$ and $\nu_e$ CC background. The two histograms have been scaled to the same unitary area.

Indeed, such difference in the kinematics has an effect on the shower transverse dimension $R$, quantity indicating the shower deviation from the beam direction [20], which can consequently be used as an efficient analysis cut to reduce the neutrino background. By using an energy threshold on the single crystal of 350 MeV, the vetoes in anticoincidence and a cut of $R < 0.6$, the number of expected beam-related background (from neutrinos) is ∼5.

To validate our MC simulations with real data, an on-site experimental campaign was performed to measure the muon flux in the present unshielded configuration at the location of the future BDX detector [21]. The measurement used an electron beam with the proposed energy (10.6 GeV) and one third the current (∼ 20 µA) expected in the BDX experiment. We measured the fluence of muons produced by interactions of 10.6 GeV electron beam with the JLab Hall-A beam-dump. Beam-produced muons were measured with a CsI(Tl) crystal sandwiched between a set of segmented plastic scintillators placed at two different distances from the dump: 25.7 m and 28.8 m. At each location, the muon flux was sampled at different vertical positions with respect to the beam height. Data were compared with detailed Monte Carlo simulations using FLUKA for the muon production in the dump and propagation to the detector, and GEANT4 to simulate the detector response. The good agreement in absolute value and shape demonstrates that the simulation framework can safely be used to estimate the beam-related muon background in the BDX experimental set-up.

### 4.2. Cosmogenic Background

Beam-unrelated background is mainly due to cosmic neutrons, cosmic muons and their decay products. Both direct cosmic flow and secondary particles contribute to the beam-unrelated background rate in the detector.

To validate the BDX detector concept and prove the capability of rejecting high energy cosmic background, we performed an experimental campaign of cosmic-ray measurements at INFN-Sezione di Catania and LNS (Laboratoi Nazioni del SUd (INFN), Catania, Italy), using a prototype of the proposed BDX detector [19]. The BDX-Proto incorporates all the elements of the final detector, built using the same proposed technologies. One of the CsI(Tl) crystals that will be used for the final detector readout by a SiPM was placed inside two layers of plastic scintillator paddles forming the inner and outer vetos and a 5 cm lead vault. Cosmic ray data were taken for about one year inside and outside a similar overburden as the one expected in the BDX experiment. Details of the experimental conditions and data analysis are reported in Ref. [16]. The extrapolation of the expected cosmogenic background was performed by conservatively scaling the experimental rates of a single crystal observed in anticoincidence with the veto systems, to the 800 crystals comprising the full detector. This is certainly an upper limit on the expected rates since this assumes crystal-to-crystal fully uncorrelated counts, which overestimates the case for $\chi$-$e^-$ scattering. The results show that, for energy thresholds high enough, 300–350 MeV, the number of expected cosmogenic background counts in 285 days reduces to zero.

## 5. Status and Perspectives

The Beam Dump eXperiment (BDX) is an electron-beam thick-target experiment aimed to investigate the existence of light Dark Matter (LDM) particles in the MeV-GeV mass range at Jefferson Lab. The experiment has been approved last year with the maximum scientific grade (A) by JLab PAC46 and is expected to run in a dedicated underground facility located $\sim$ 20 m downstream of the Hall A beam-dump. It will make use of a 10.6 GeV $e^-$ beam collecting up to $10^{22}$ electrons on target. The detector consists of two main components: a CsI(Tl) electromagnetic calorimeter (Ecal) and a veto system used to reject the background. The expected signature of the DM interaction in the Ecal is a GeV electromagnetic shower paired with a null activity in the surrounding active veto counters. In addition to the veto system, a specific shielding configuration installed between the dump and the detector will be used to suppress the high-energy component of the beam-related background. Indeed, simulations have shown that, provided enough shielding is installed between the beam-dump and the detector, neutrinos are the only source of beam-related background (O(5) background events expected)—considering a detection threshold of O(300) MeV. Using similar energy thresholds coupled with vetos in anticoincidence, the expected cosmogenic background can be considered negligible, as demonstrated by the BDX-Prototype. With 285 days of a parasitic run at 65 μA (corresponding to $10^{22}$ EOT). the BDX experiment will lower the exclusion limits in the case of no signal by more than one order of magnitude in the parameter space of dark-matter coupling versus mass (Figure 6).

Very recently, a proof of concept measurement has already started at JLAB in the present unshielded configuration. It is using a 2.2 GeV $e^-$ beam and is expected to run parasitically for one year. The compact detector used, called BDX-Mini, is made by a PbWO4 electromagnetic calorimeter, surrounded by a layer of tungsten shielding and two hermetic plastic scintillator veto systems. BDX-Mini is currently lowered in a well, dug downstream of Hall-A at the location of the proposed BDX facility. Although it is an early stage experiment, it represents the first dedicated new-generation beam-dump experiment whose physics reach could almost cover a kinematic region measured by summing up old not-optimized experiments.

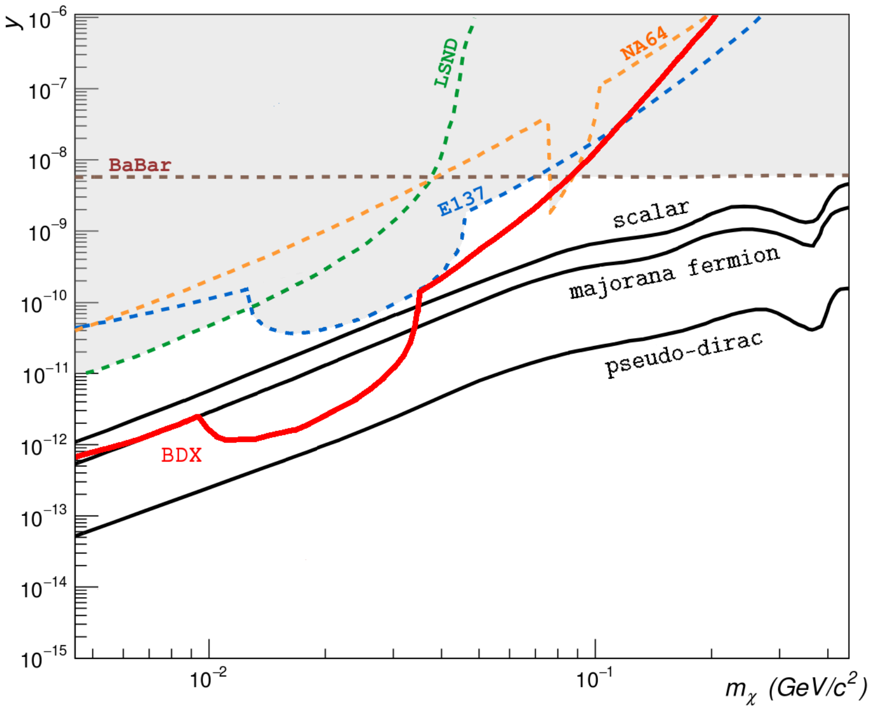


**Figure 6.** BDX exclusion limits (red line) from Ref. [14]. Limits are given for the parameter $y = \alpha_D \epsilon^2 (m_\chi / m_{A'})^4$ as a function of $m_\chi$, assuming $\alpha_D$ = 0.5 and $m_{A'} = 3m_\chi$. Black lines indicate various thermal relic targets.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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