Light Dark Matter Factory @ JLAB

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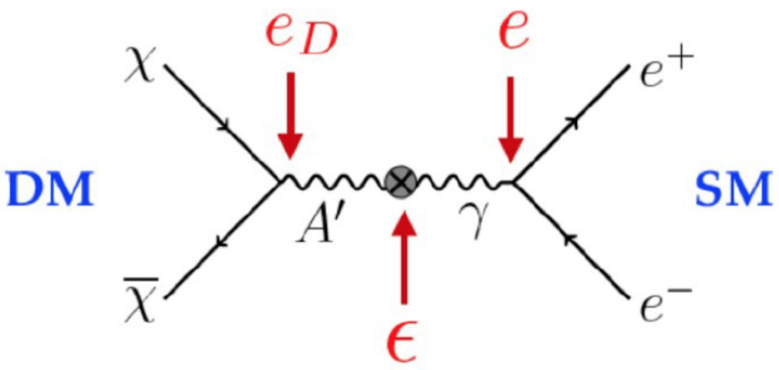
Outline

- Introduction
- The BDX experiment @ JLAB
- BDX-MINI pilot experiment @ JLAB
- Summary

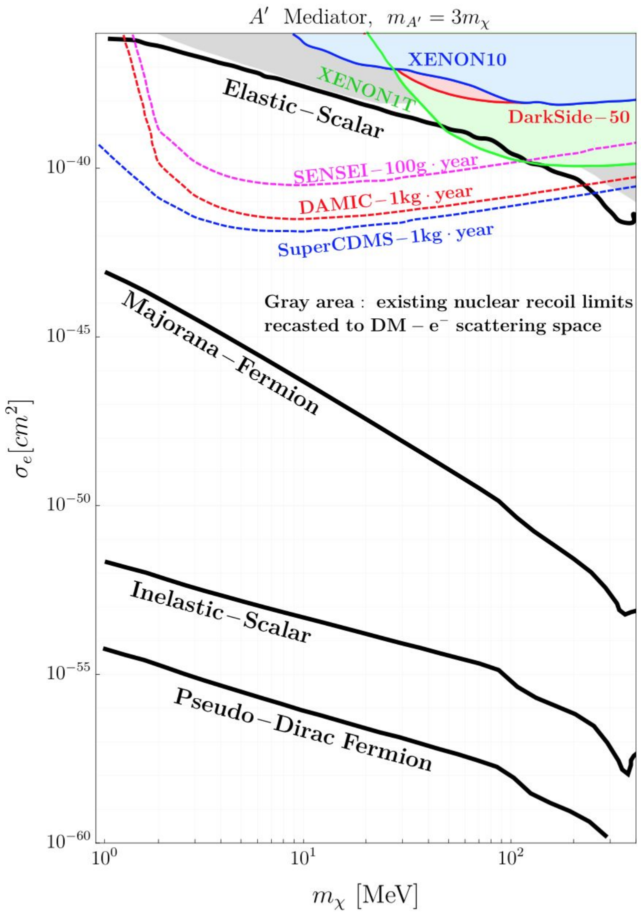
Light Dark Matter search

- Dark Matter is there but **we know nothing about the particle content of DM**
- **New promising hypothesis: Light Dark Matter in the mass range 1MeV - 1GeV**
- Simplest possibility**: vector-portal:** DM-SM interaction through a new U(1) gauge-boson ("dark photon") coupling to electric charge
- Model parameters:
  - Dark-photon mass, $M_{A'}$ and coupling to electric charge ε
  - Dark matter mass, M_x and coupling to dark photon g_D



Light Dark Matter search @ the intensity frontier

- Dark Matter direct detection experiments, typically optimized for Mx > 1GeV have a limited sensitivity in the sub-GeV range
    - DM detection by nuclear recoil: $E_R \propto M^2_X/M_N$
- LDM-SM interaction cross section at low energy has a sizable dependence on impinging particle velocity, with a drastic reduction for specific models
- **Accelerator-based experiments** at the intensity frontier ar uniquely suited to explore the LDM hypothesis
    - **World-leading capability of JLAB-CEBAF's intense beam offers unique opportunity to probe LDM scenario**



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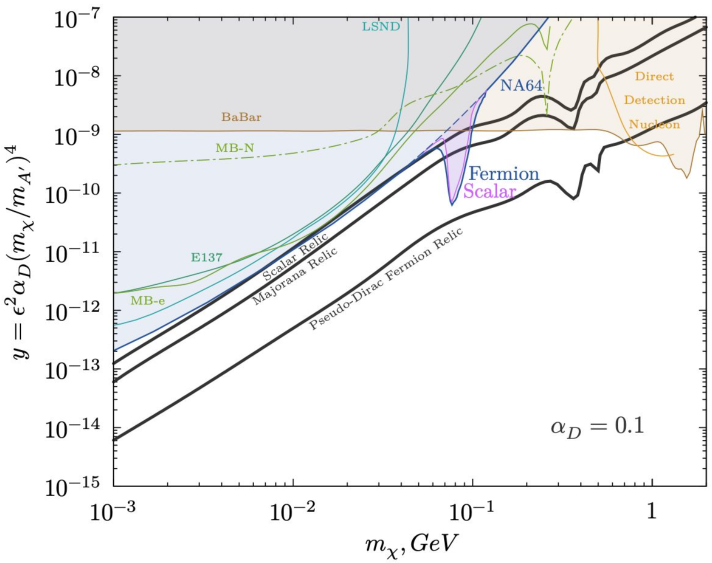
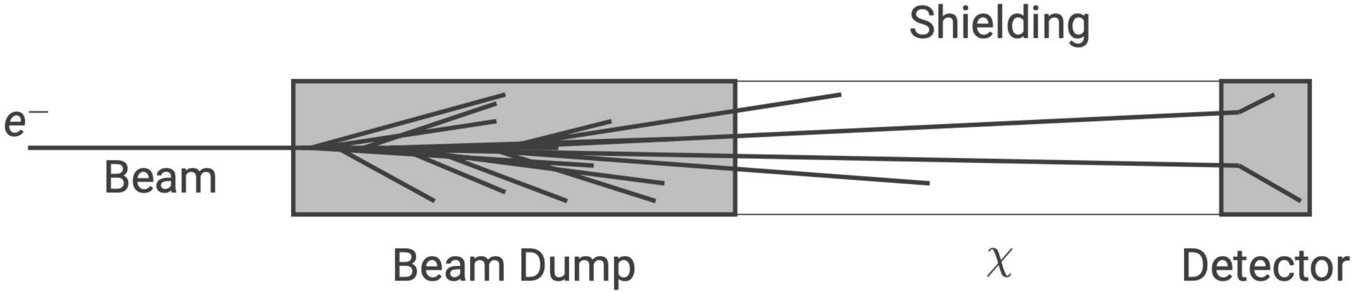


LDM search in Beam Dump Experiments



LDM production:

- High-energy, high-intensity e- beam impinging on a thick target
- X particles production: radiative A' emission, e-e+ annihilation

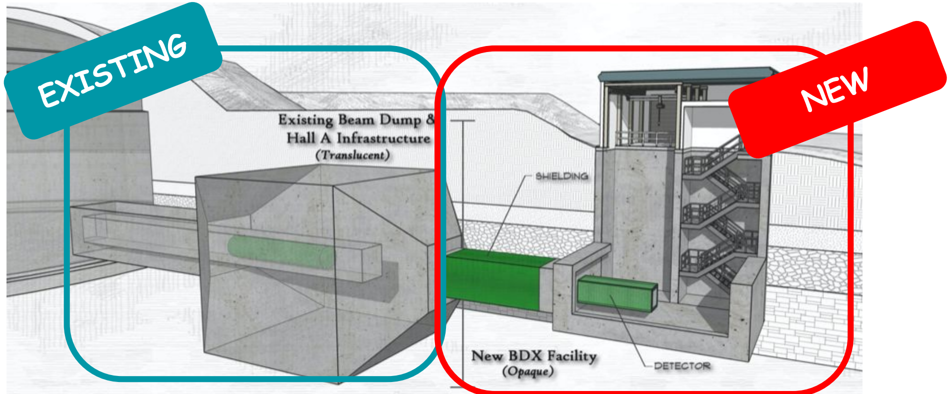
Number of signal events scales as: $S \propto \frac{\alpha_D \varepsilon^4}{m_A^4}$

LDM detection:

- Detector placed behind the dump O(10-100)m
- Neutral-current LDM scattering through A' exchange, recoil releasing visible energy
- Different signals depending on the interaction
  - BDX: LDM - e- scattering -> e.m shower

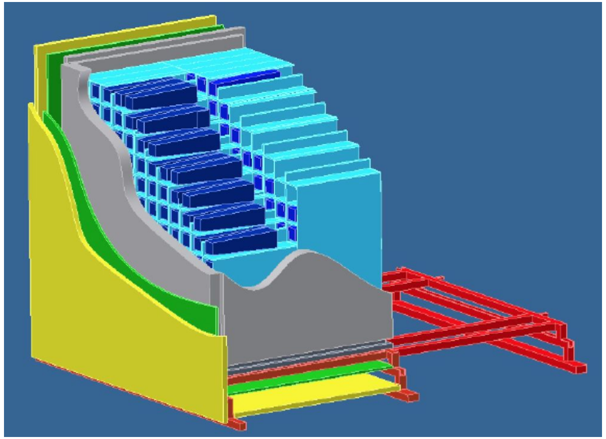
Beam Dump eXperiment @ JLAB

- **JLAB offers the best condition for BDX**
  - A high energy beam: 11 GeV
  - The highest available electron beam current: ~65uA (currently)
  - Charge : 10^22 EOT
  - Fully parasitic wrt Hall-A physics program
- **New facility to be built** in front of Hall-A beam dump
  - Passive shielding layer between beam dump and detector to reduce SM beam-related background
  - Sizeable overburden (~10 m water-equivalent) to reduce cosmogenic background
  - New underground hall (~8m) at 25 m downstream hall-A beam dump that will host the detector
- **Detector with 2 components:** Ecal + Veto system

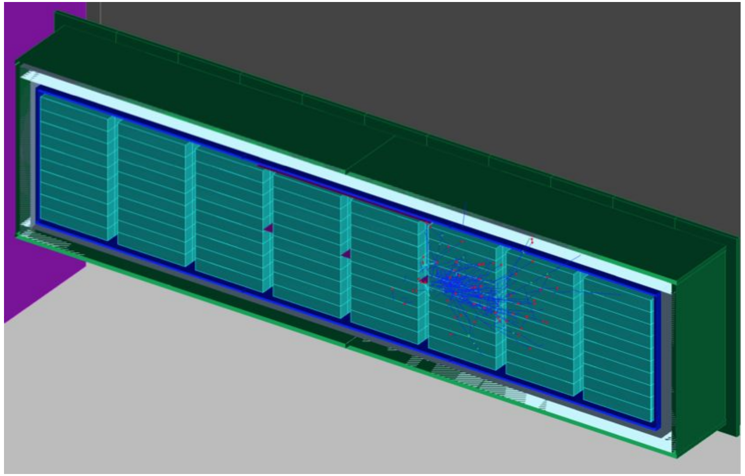


BDX detector

- **Electromagnetic Calorimeter**
  - Sensitivity to high-energy EM shower
  - Homogeneous EM calorimeter ($0.5 m^3$) made with CsI(TI) crystals and SiPM readout
    - Modular arrangement: 8 modules 10x10 crystals each
    - Reuse BaBar crystals



- **Veto system**
  - 2 layers of plastic scintillator counters read by WLS fibers and SiPMs
  - 5 cm lead vault between veto and ECAL

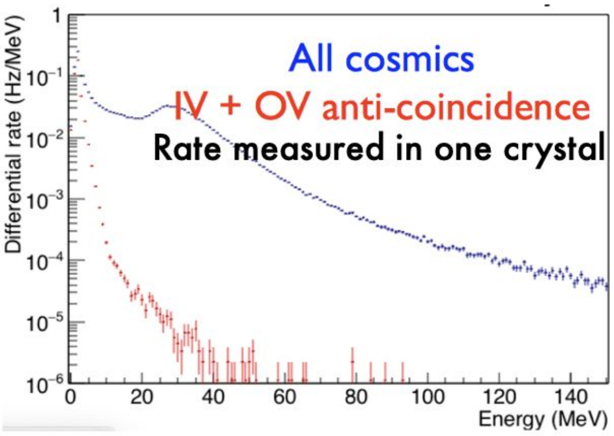


BDX backgrounds

❖ **Cosmogenic Background**

➢ Measured with the BDX prototype at INFN-LNS, with similar overburden as expected at JLAB

➢ Using vetos in anti-coincidence and high energy threshold O(350MeV), cosmic background is negligible



Threshold	Projected counts
250 MeV	(57 ± 25)
300 MeV	(4.7 ± 2.2)
350 MeV	(0.037 ± 0.022)

❖ **Beam-related Background**

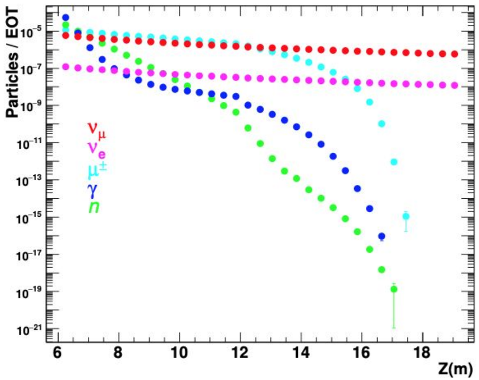
➢ Estimated through MC simulations

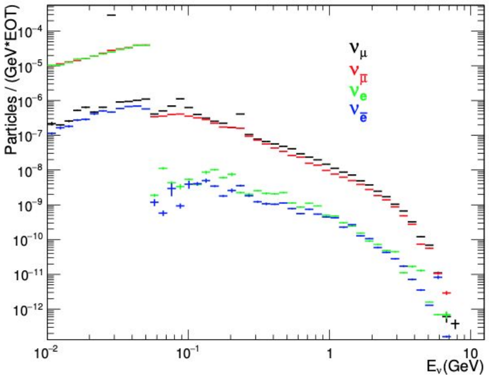
- ■ MC simulations validated with on-site measurement

➢ 6.6 iron shield +2m concrete enough to range-out high energy muons

➢ **Neutrinos**: only particles reaching the detector

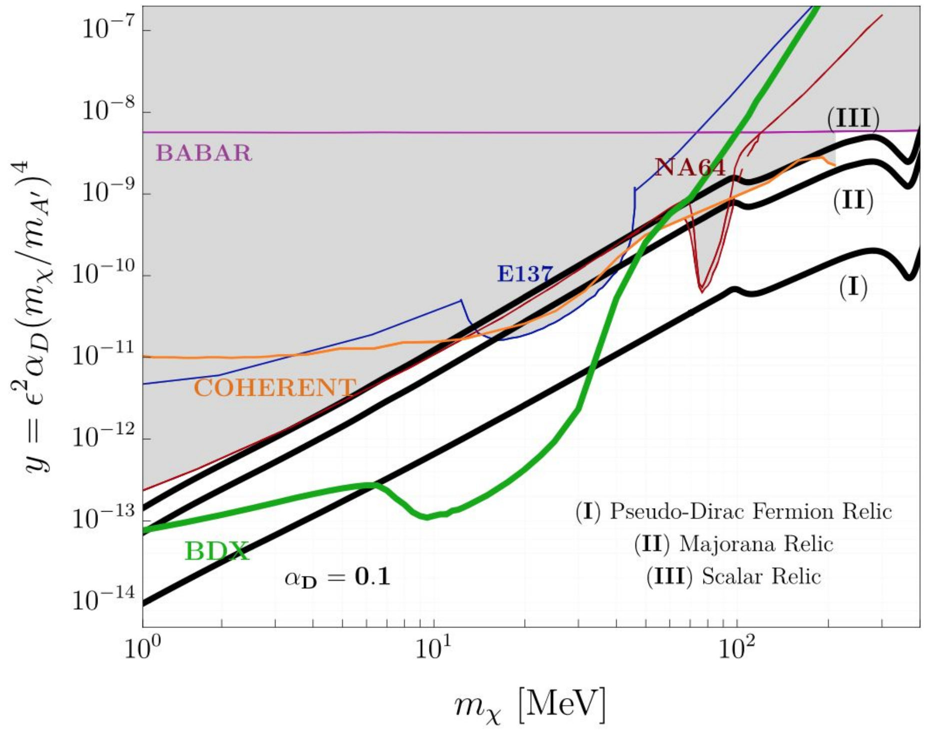
- ■ High-energy v from in-flight decays of pion and kaon
- ■ Possible background contribution from ve interaction via CC in the detector
- ■ Estimate: Nv = 5 counts for 10^22 EOT





BDX sensitivity and experiment status

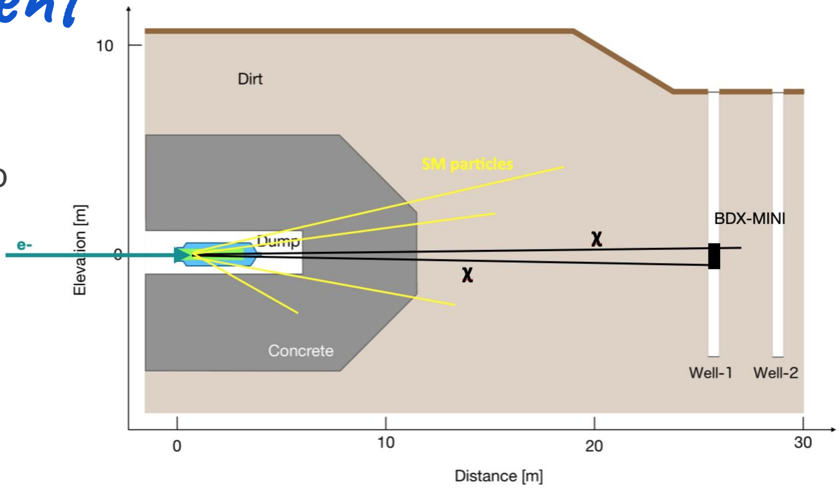
BDX will improve of 2 orders of magnitude current exclusion limits in LDM parameter space



- **BDX status**
  - Full proposal presented to JLab PAC46 (2018), **approved with the highest scientific rating**
  - Currently negotiating with laboratory management to build the new experimental hall

BDX - Mini @ JLAB: pilot experiment

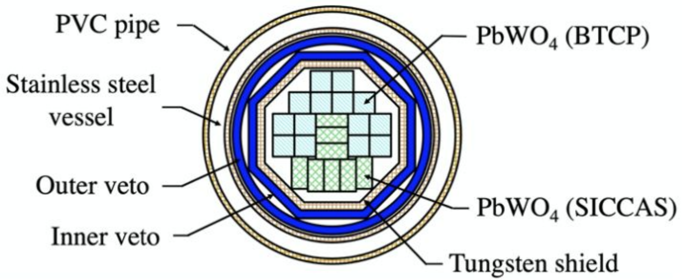
Small-scale, low-energy version of full BSX experiment

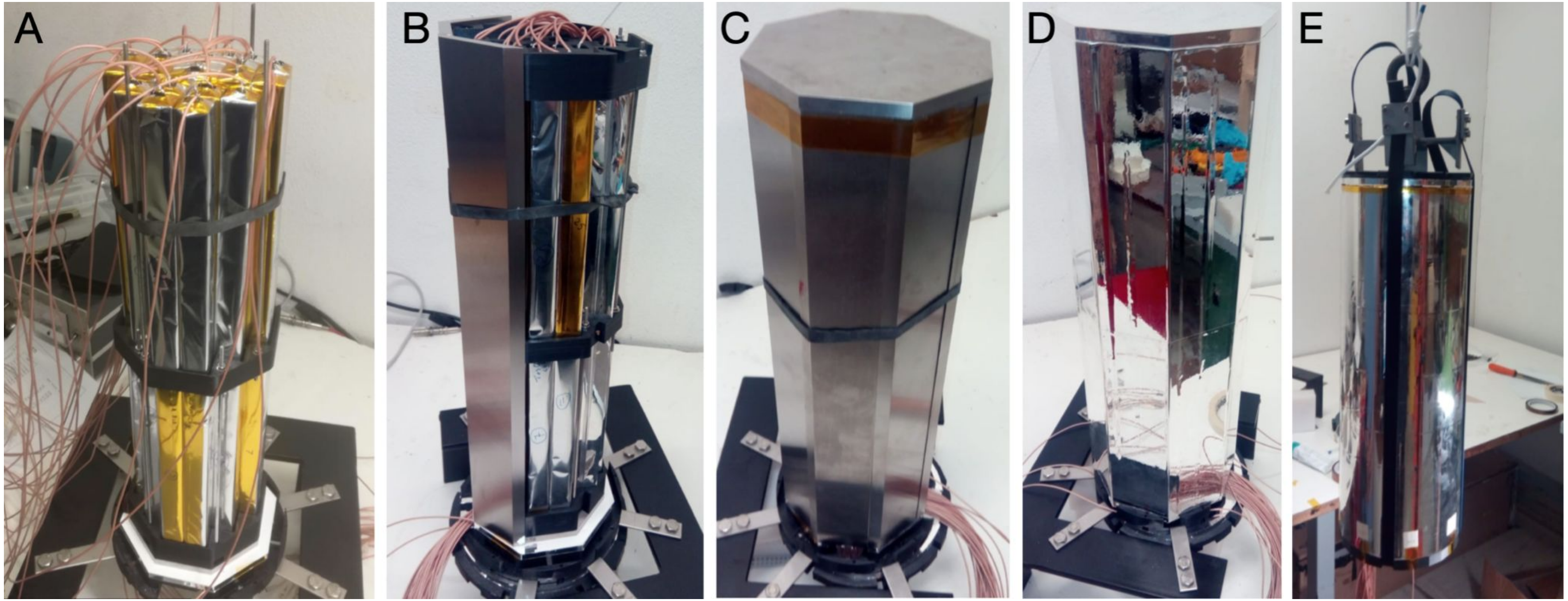


- **Experimental set-up**
  - ➢ 2.2 GeV, 150 uA e- beam impinging on Hall-A beam dump
  - ➢ SM particles shielded by concrete and soil
  - ➢ Detector installed in a well 25-m downstream
- **Data taking**
  - ➢ December 2019: 11 GeV calibration sample
  - ➢ 2020: 2.2 GeV e-beam - 2.54E21 EOT

BDX - Mini detector

- PbWO4-based EM calorimeter (44 crystals), SiPM readout
  - 0.15% of BDX active volume
- 8 mm passive tungsten shielding
- 2 plastic scintillator active veto layers, SiPM readout

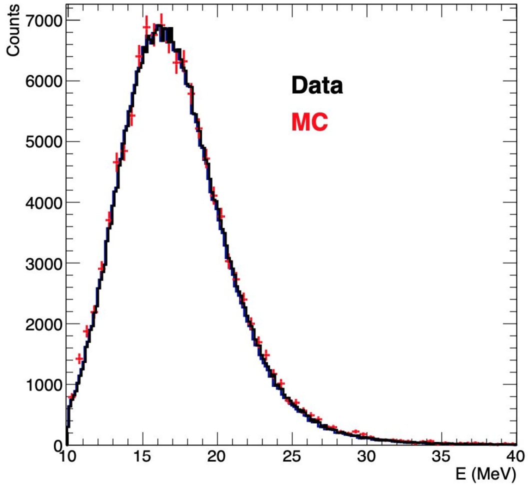


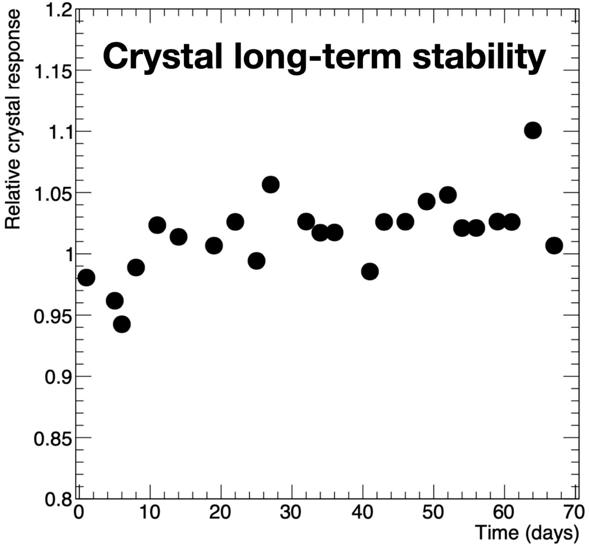


BDX - Mini detector performance

- **ECAL calorimeter**
  - Energy calibration determined from 11 GeV data exploiting secondary muon from beam-dump
    - Compared energy spectra between data and MC
  - Detector stability monitored with cosmic muon during beam-off period

- **Veto system**
  - VETO efficiency monitored with cosmic muons, using a tag-and-probe method. Trajectories selected via ECAL crystals energy deposition.
  - VETO systems characterized by high cosmic-ray rejection efficiency





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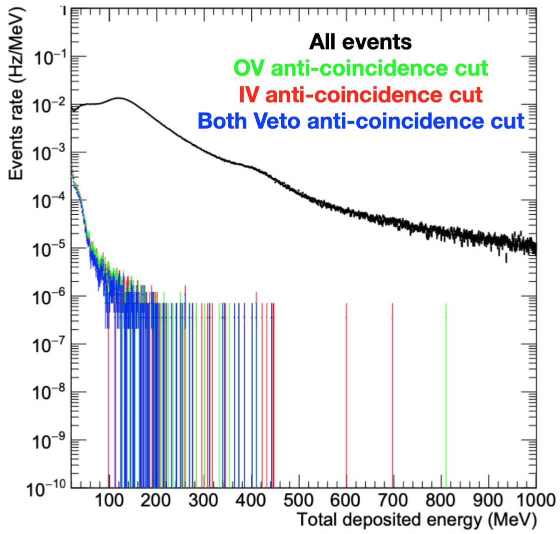

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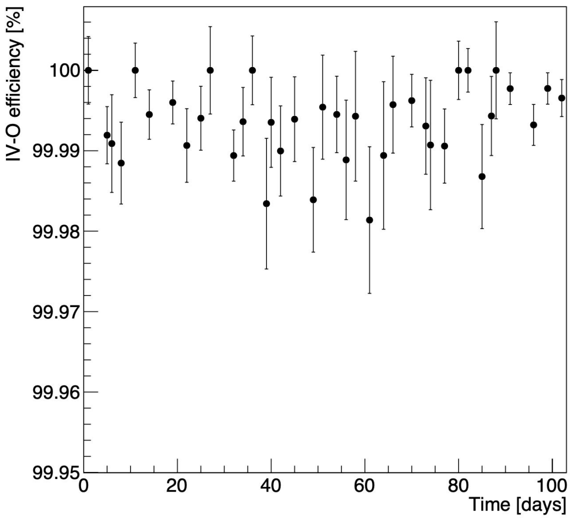

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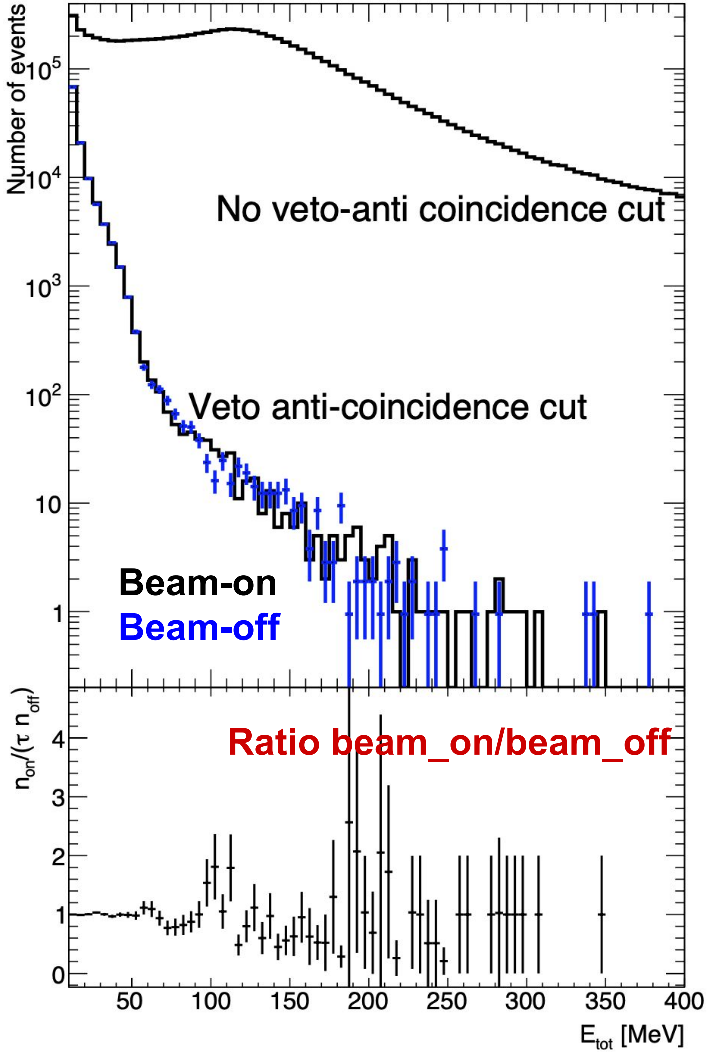
BDX - Mini Data samples

- **2 samples** collected at almost the same time
  - **Beam-on :** which corresponded to more than 10 μA requirement on current in Hall A
  - **Beam-off**
    - Used to determine the cosmic-ray background in the beam-on sample after normalizing by the corresponding time.
- Ratio between beam-on and beam-off distributions showing that there is **no statistical difference** between the 2 data sets



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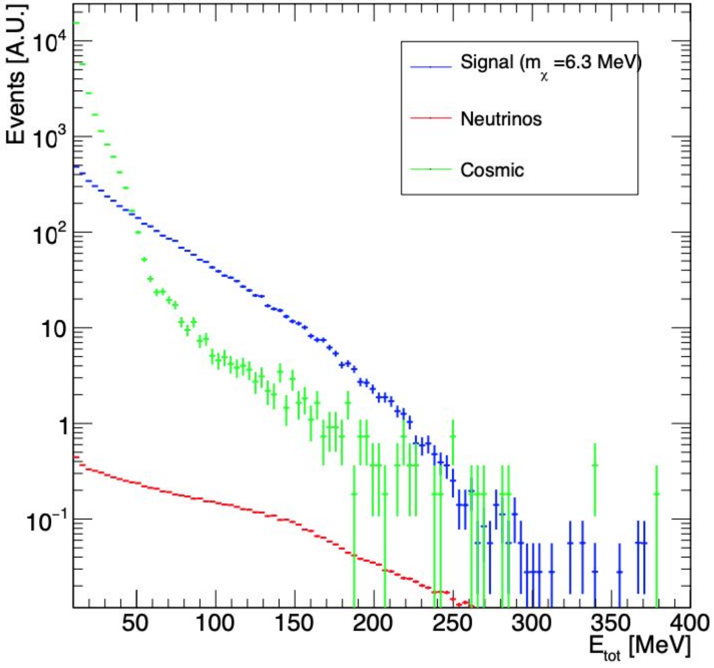
BDX - Mini Backgrounds

- **Beam-unrelated background (cosmic rays):**
  - Cosmic background was **measured** during beam-off data
  - Cosmic rate for an ECAL threshold ~40 MeV is 1.9 Hz, **suppressed by 4 order of magnitude** when no activity in both veto are required

- **Beam-related Background (neutrinos)**
  - Estimated through MC simulations
  - Except neutrinos, no other SM particles propagate from the dump to the BDX-MINI detector.
  - Neutrinos background is negligible: less then 1 neutrino event detected in the the entire BDX-MINI run.



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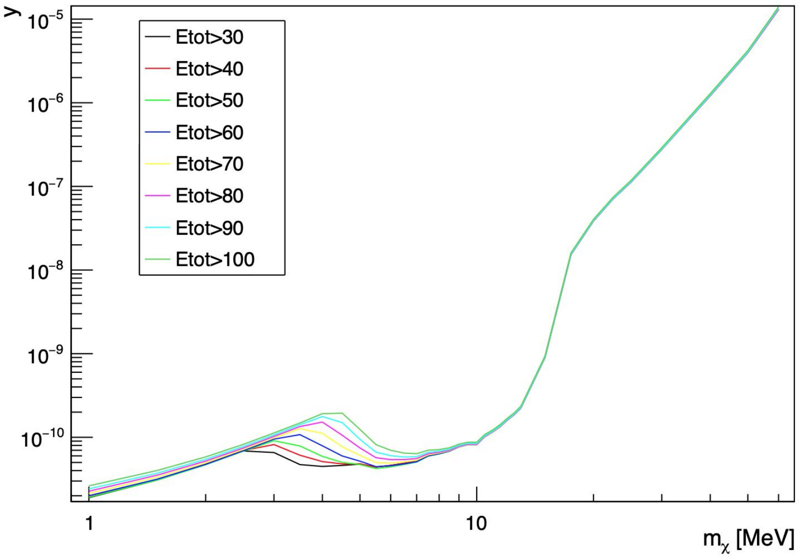
BDX - Mini Data analysis

- **Approach:** blind analysis. Fix the selection cuts by optimizing the experiment sensitivity (looking the beam-off data set)
- **Model:** ON-OFF problem, described by:

$$\mathcal{L} = P(n_{on}, S + B_\nu + B_c) \cdot P(n_{off}, \tau \cdot B_c)$$

  - n_{on}, n_{off} measured number of events during beam-on/beam-off intervals (τ = Toff/Ton)
  - Bc/Bv expected number of cosmogenic/beam-related background events. Bv evaluated via MC. Bc threated as nuisance parameter.
- Refined this model in order to include in the upper-limit evaluation procedure the measured energy deposition in the BDX-MINI detector for each event
- Extract the upper limit on S through an one-side profile-likelihood test statistics
- Systematic uncertainties described via ancillary pseudo-measurement factor in L with Gaussian constraint.

Expected sensitivity



- **Best sensitivity**: the energy range between 40 and 355 MeV was split into seven equally spaced 45 MeV-wide bins, and a single bin was used for all events from 355 to 600 MeV.
  - only used events accepted by the anti-coincidence condition

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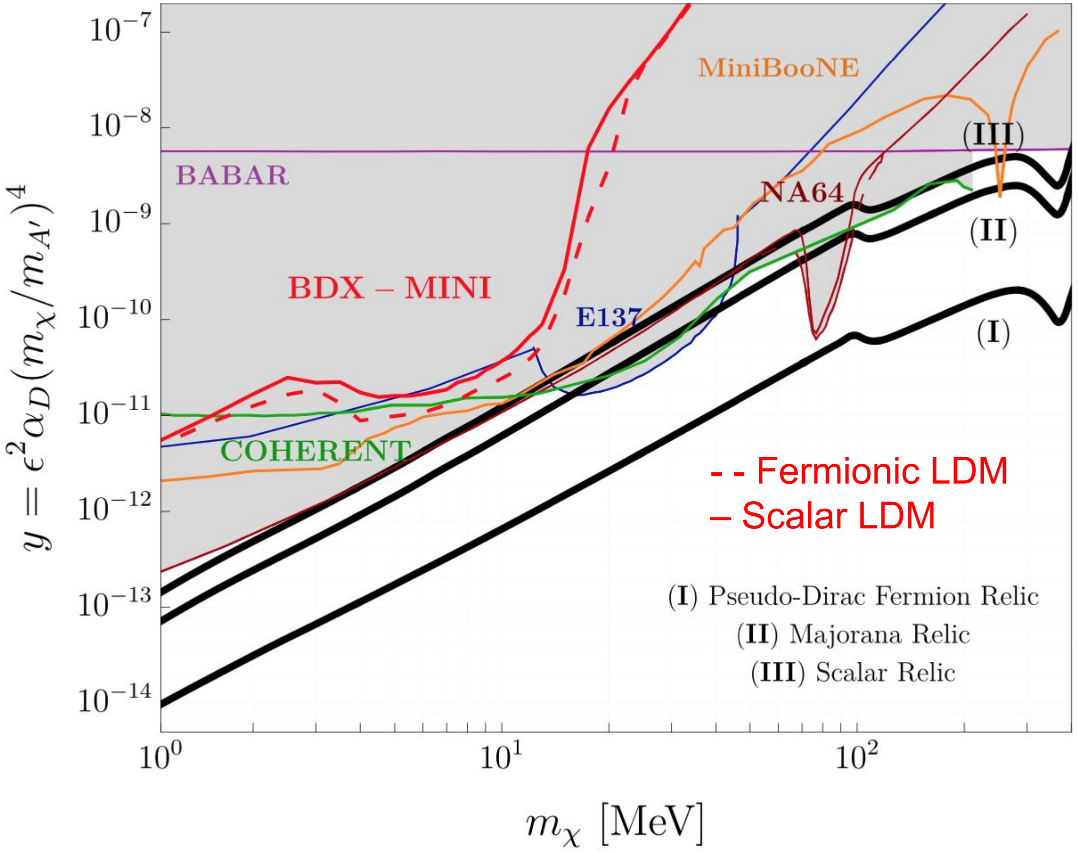
BDX - Mini results:

- **Umbliding:** we applied the procedure optimized on the beam-off data set only to the whole beam-on data set
- **Upper limit** derived on parameters space
- This pilot experiment is sensitive to the parameter space covered by some of the most sensitive experiments to date



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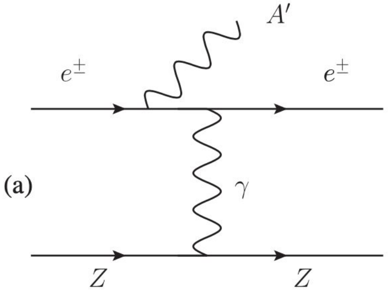
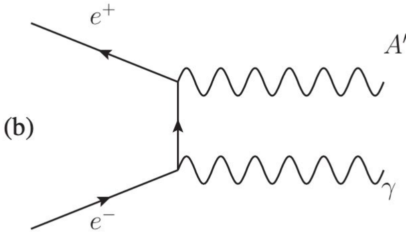
Summary

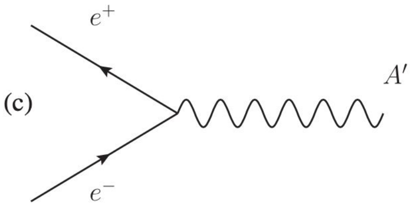
- ❖ Dark Matter in the MeV-to-GeV range is largely unexplored
- ❖ **Be**am **D**ump e**X**periment @ JLAB is sensitive to **Dark Matter** with masses **~1-100 MeV.**
  - ➢ High intensity (10^{22} EOT/year) 11-GeV e- beam
  - ➢ Detector: 800 CsI(Tl) calorimeter + 2 layers active veto + shielding
- ❖ BDX was **approved** by JLAB-PAC with **highest scientific rating.** The full experiment is awaiting funding
- ❖ A pilot experiment, **BDX-MINI**, took data for ~6 months:
  - ➢ Small-scale version of the full-BDX effort, including all the key components
  - ➢ Measurement campaign with 2.184 GeV beam, accumulating 2.51E21 EOT
  - ➢ BDX-MINI **set limits close to existing boundaries** in the parameter space

LDM production mechaninsms

In the “dark sector” scenario, 3 main LDM production mechanisms in fixed-target, lepton-beam experiments







❖ **A) A’-strahlung**:
- ➢ Radiative A’ emission in nucleus EM field followed by A’->XX
- ➢ Scales as $Z^2\alpha^3$
- ➢ Forward-boosted, high-energy A’ emission

❖ **B) Non-resonant e+e- annhilation**:
- ➢ e+e- -> A’γ followed by A’->XX
- ➢ Scales as $Z\alpha^2$
- ➢ Forward-backward A’ emission in the CM

❖ **C) Resonant e+e- annhilation**:
- ➢ e+e- -> A’->XX
- ➢ Scales as Zα
- ➢ Breit-Wigner like cross section with $M_{A'} = \sqrt{2m_eE}$