The Beam Dump eXperiment @ JLAB

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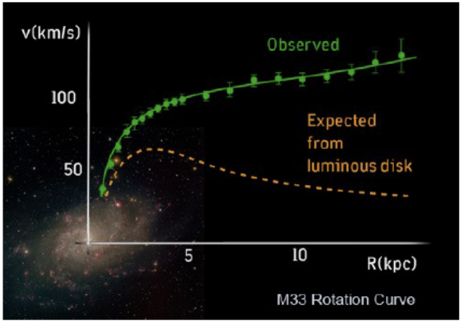
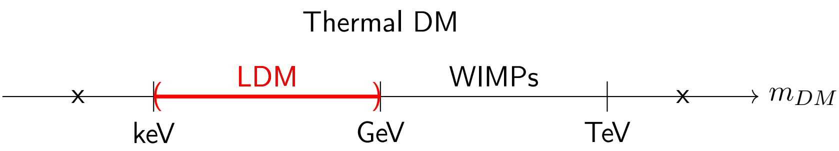
October 1, 2024

Dark Matter

- Dark Matter is there but **we know nothing about the particle content of DM**
  - Plenty of cosmological/ astrophysical observations: CMB anisotropies, galaxy rotation curves, gravitational lensing,cluster collisions...
- No hints on DM particle properties (mass, cross section)
- Common assumption: **thermal origin of DM**:
  - DM in thermal equilibrium with SM in early Universe. Current relic abundance set by the strength of the SM-LDM interaction ("freeze-out mechanism")
  - constrain on available mass range
- Light Dark Matter: mass range 1 MeV÷1 GeV

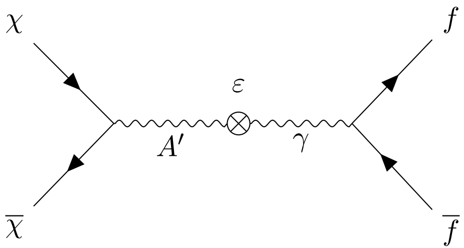




Light Dark Matter - Dark Photon model

Light Dark Matter: DM is made by sub-GeV particles, interacting with SM via a new force (acting as a "portal" between SM and the new "Dark Sector").

- **"vector-portal"**"[1]: DM-SM interaction trough a new U(1) gauge-boson ("dark-photon") coupling to electric charge



Model parameters:

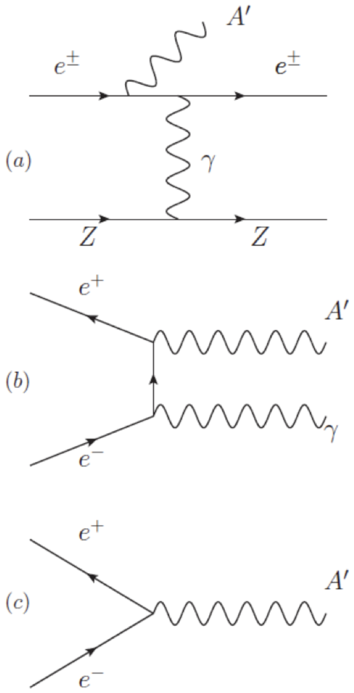
- Dark Photon mass $m_{A'}$, coupling to SM ε
- Dark Matter mass m_χ, coupling to DM g_D ($\alpha_D \equiv g_D^2/4\pi$)

$$y \equiv \frac{g_D^2 \epsilon^2 e^2}{4\pi} \left(\frac{m_\chi}{m_{A'}} \right)^4 \sim \langle \sigma v \rangle_{relic} m_\chi^2$$

[1] For a comprehensive review: 1707.04591, 2005.01515, 2011.02157

Dark Photon Production Mechanisms With Lepton Beams

Three main production mechanisms in fixed targets, lepton beam experiments:



a) **A'-strahlung**:

- Radiative A emission in nucleus EM field
- Scales as $Z^2\alpha_{EM}^3$.
- Forward-boosted, high-energy A emission

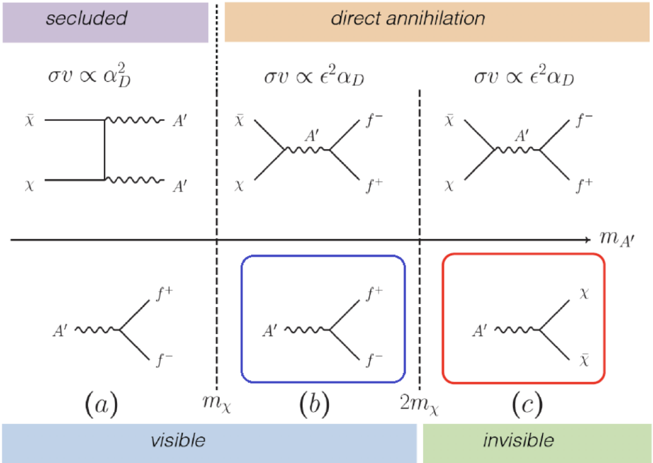
b) e+e− annihilation:

- scales as $Z\alpha_{EM}^2$.
- Forward-backward A' emission in the CM

c) **Resonant** e+e− annihilation

- scales as $Z\alpha_{EM}$.
- resonant Breit-Wigner like cross section with $mA' = \sqrt{2m_e E}$

Mass Hierarchy Determines Search Strategy and Interpretation



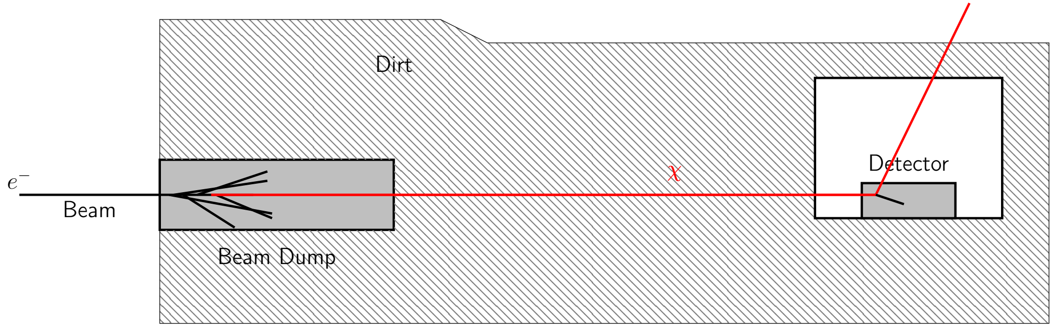
(a) Secluded scenario: does not lend itself to decisive laboratory tests.

(b) Visible decay scenario. Experiments @ JLAB: HPS, APEX

(c) Invisible decay scenario. Experiments @ JLAB: BDX, BDX-MINI

Beam Dump experiments

Beam dump experiments: direct detection of LDM produced by beam impinging on fixed target (beam dump)[2]



χ production

- e^- beam impinging on target
- χ from decay of A' produced in the dump

χ interaction

- Detector placed behind the dump ($\sim$ 10 m)
- χ scattering through A' exchange

Number of signal events: $S \propto \frac{\alpha_D \varepsilon^4}{m_{A'}^4}$

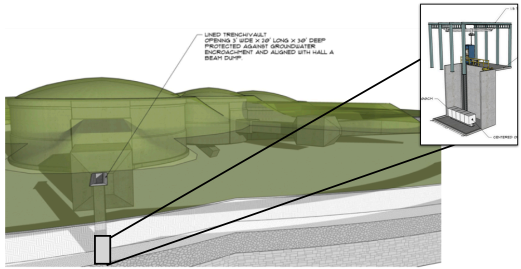
[2] Izaguirre et al., Phys. Rev. D 88, 114015

BDX: Beam Dump eXperiment

- BDX was approved by JLab PAC-46 in July 2018 (reconfirmed in 2023 by PAC-51) with maximum scientific rating (A) and waiting for scheduling.
- the experiment is designed with two goals:
  - Producing and detecting LDM;
  - Reducing cosmic and beam-related background

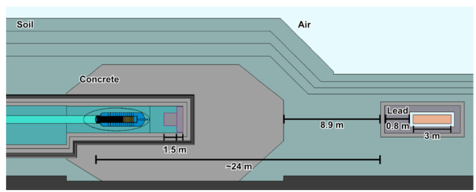
JLAB offers the best condition for BDX:

- Medium high energy beam (11 GeV)
- High electron beam current (65 μA)
- Fully parasitic wrt Hall-A physic program (Moeller)
- Electron on target: 10^{22}



New facility to be built in front of Hall-A beam dump:

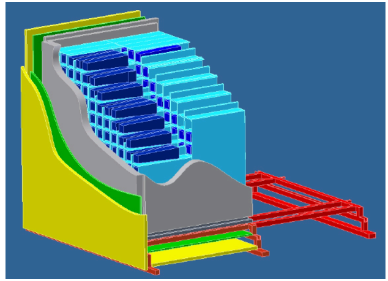
- new underground (~ 8 m) pit
- 25 m downstream of Hall-A beam dump
- passive shielding ($\sim$1.5 m lead in downstream BD and $\sim$0.8 m upstream detector) to reduce beam related background

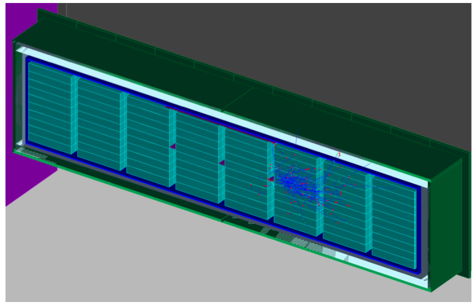


BDX-detector

Electromagnetic Calorimeter:

- Sensitivity to high energy ($\gtrsim 100$ MeV) EM shower;
- Homogeneous EM calorimeter (0.5 m^3) made with high-density crystals and SiPM readout;
  - negotiationg BDX crystal's calorimeter with FAIR (PbWO4), ~~SLAC (CsI(Tl))~~, CERN (BGO)
  - Modular arrangement: 8 modules 10x10 crystals each.





Veto System:

- 2 layers of plastic scintillator counters read by WLS fibers and SiPM ;
- 5 cm lead vault between veto and ECAL.

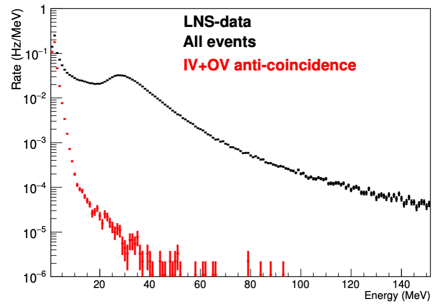
Signal detection:

- EM shower ($\gtrsim$ 100 MeV) and no corresponding activity in the active veto

BDX backgrounds

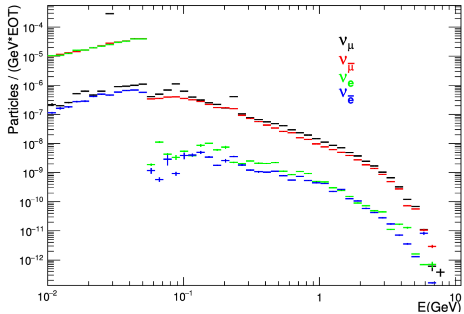
Cosmic background: data-driven estimate.

- Result extrapolated from cosmic-ray data acquired with a small-scale BDX prototype installed at INFN-LNS/INFN-CT[a];
- cosmic muons are detected and rejected by the two veto detectors:
  - $E_{thr} \sim$ 300 MeV; B_c ∼10 (1 year).



Beam-related: yield estimate through MC simulations (FLUKA+Geant4+GENIE)

- MC simulations validated with an on-site measurement[b];
- ν-induced background from ν_e CC interactions in the detector, with a high-energy e- resulting to an EM shower. B_ν ∼10 for 10^{22} EOT.
- All other SM particles are absorbed by passive shielding.

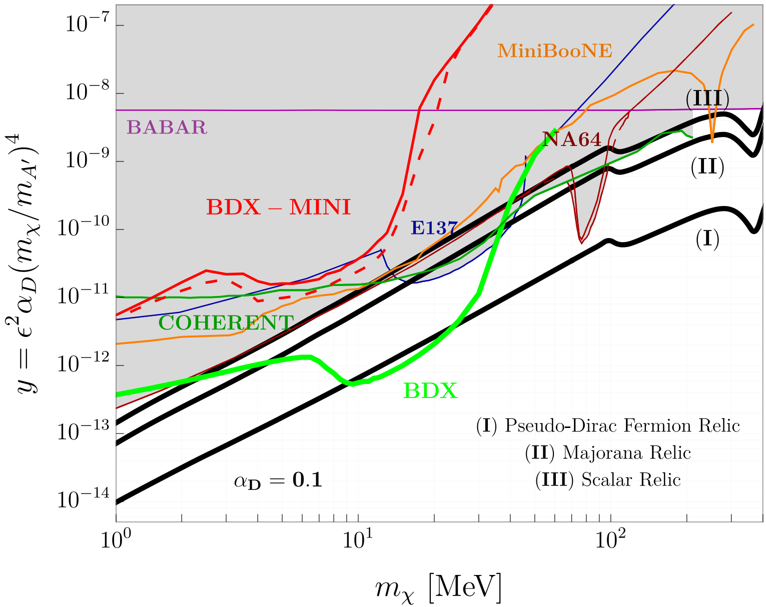


[a] M.Bondi et al., JINST 15 C04022

[b] M. Battaglieri et al., NIM A 925(2019) 16

BDX sensitivity

BDX sensitivity considering 10^{22} EOT, a 20% detection efficiency and 300 MeV detection thresholds in the ECAL



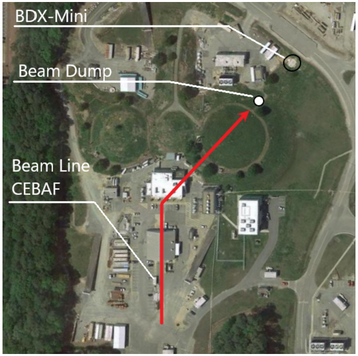
BDX will improve of 2 orders of magnitude current exclusion limits in LDM parameter space

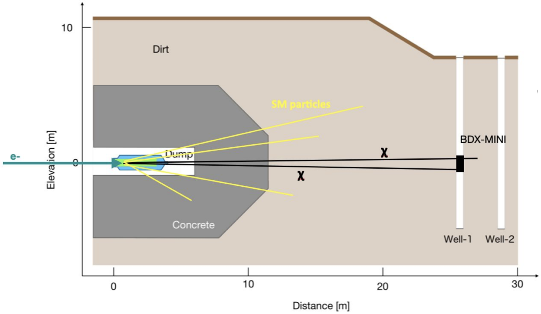
BDX-MINI@JLAB: Pilot experiment

Small-scale, low energy version of full BDX experiment:

- ∼2.2 GeV e^- beam (10 GeV beam used for calibration)
- current up to $150\ \mu$A
- measurement alternating beam on and beam off data (beam on time $\sim$ 50 %)
- accumulated 2.54×10^{21} EOT

- beam off measurements for cosmic background characterization





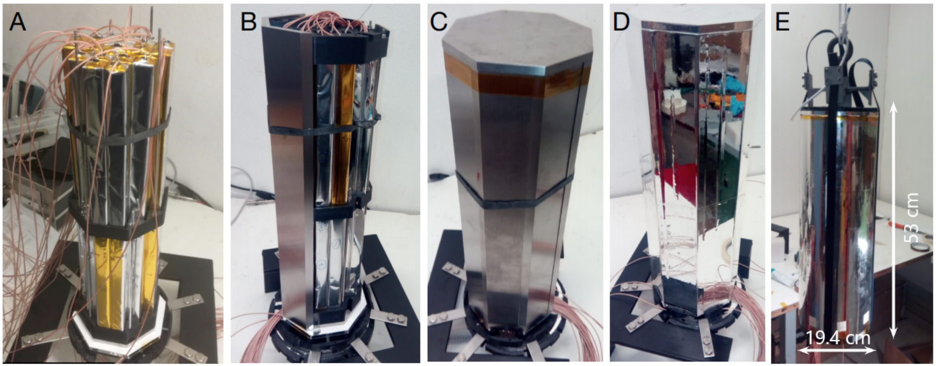
BDX-MINI detector

Electromagnetic calorimeter (ECal):

- 44 $PbWO_4$ crystals (4×10^{-3} m^3 active volume), read by SiPM

Veto system

- Active veto:
  - Octagonal (IV) and cylindrical (OV) plastic scintillator
  - Optically continuous
  - SiPM readout + WLS fibers light collection
- Passive tungsten shielding
  - 0.8 cm thick



M. Battaglieri et al., Eur.Phys.J.C 81 (2021) 2, 164

BDX-MINI Backgrounds

Two main sources of background [a]:

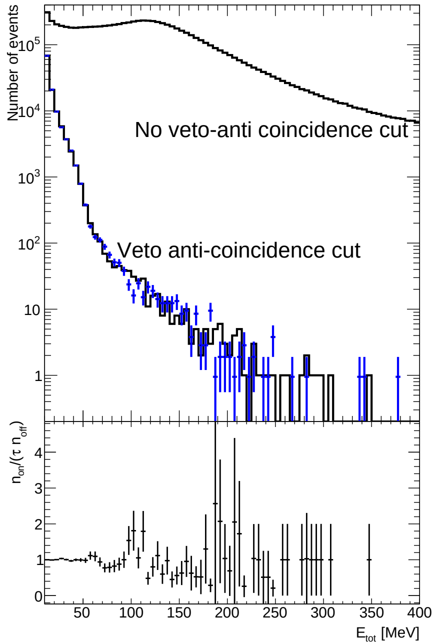
Beam related background: Yield estimate through MC simulations (FLUKA+GENIE+Geant4)

- MC simulation validated with in-situ measurement
- ν only background $\rightarrow$ negligible: 5.8x10^{-23} ν/EOT

Cosmogenic background

- Continuous measurement $\Rightarrow$ no rejection
- Charged particles rejected requiring veto anti-coincidence
- Further suppression can be achieved using energy cut

Measured cosmic background



[a] M. Battaglieri et al., Phys.Rev.D 106 (2022) 7, 07201

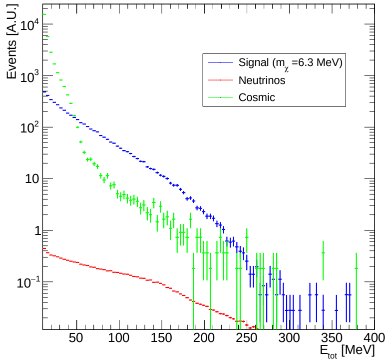
BDX-MINI Data analysis

Blind analysis[3]: experiment sensitivity optimized with MC simulations and beam-off data

Model: ON-OFF problem

$$\mathcal{L} = \prod_j \left[P(n^j_{\rm on}; \mu^j_c + \mu^j_\nu + \alpha^j \cdot S) \cdot P(n^j_{\rm off}; \mu^j_c \cdot \tau) \right]$$

- n^j_{on}, n^j_{off}: measured number of events during beam-on/beam-off intervals ($\tau = T_{off}/T_{on}$)
- μ^j_c/μ^j_ν: expected number of cosmogenic/beam-related backgrounds events
- μ^j_ν evaluated via MC, μ^j_c treated as nuisance parameter
- Data binned according to total energy deposition in ECal



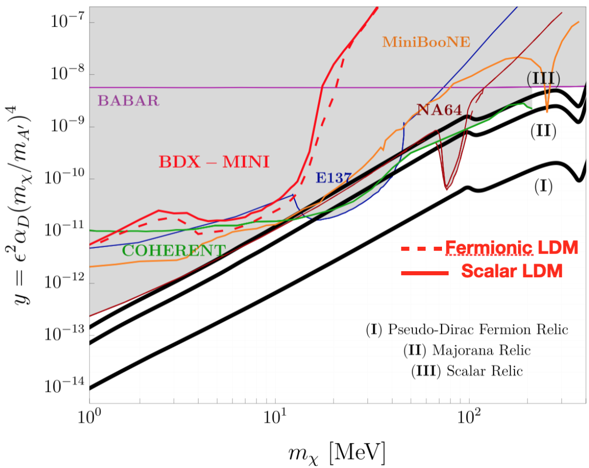
Systematic uncertainties: described via ancillary pseudo-measurement factors in $\mathcal{L}$ with Gaussian constraint

$\rightarrow$ one-sided profile-likelihood test statistics to evaluate upper limit on S

3 M. Battaglieri et al., Phys.Rev.D 106 (2022) 7, 07201

BDX-MINI Results

- **Blind approach:** fix the selection cuts by optimizing the experiment sensitivity.
- The signal window optimizing the BDX-mini sensitivity is defined by Ethr = 40 MeV;
- Unblinding and analysis of beam on data: **No excess is observed: an upper limit is derived in the LDM parameters space**
- This pilot experiment[a] is sensitive to the parameter space covered by some of the most sensitive experiments to date.



[a] M.Battaglieri and et al, Phys. Rev. D 106, 072011

BDX-MINI AI-based data analysis

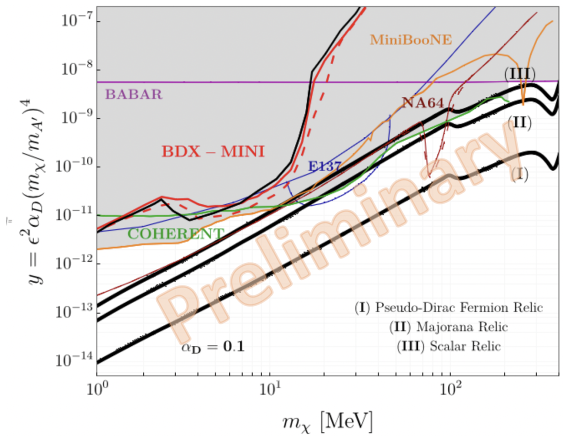
Re-evaluation of BDX-MINI reach using AI-based techniques.

Boosted Decision Tree (BDT)

- Multiple variables as input (Etot, multiplicity, seed position, energy distribution, . . .)
- Evaluation of a new variable that efficiently discriminates between signal and background

Training over BDX-MINI data and MC simulations (DM, neutrinos)

- Training over events in anti-coincidence with veto
- Evaluation of new cut to reduce background



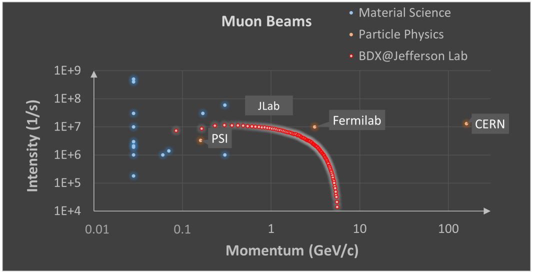
BDX spin-off: Secondary beams

High-intensity secondary beams are produced by the interaction of 11 GeV e- beam with dump (muons, neutrinos).

Secondary beam fluxes [a] were evaluated performing detailate MC simulation.

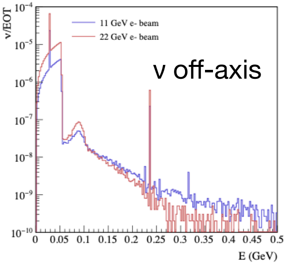
Muon beam

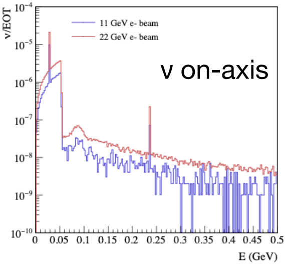
- Bremmstrahlung-like energy spectrum extending up to 5 GeV;
- Flux on-axis: 9E-7 μ/EOT corresponding to a yield of 10^8 μ/s.



Neutrino beams

- Flux on-axis integrating the integrating the neutrino flux in the energy range 0–500 MeV: ~3E-5 $\nu/EOT/\mathrm{m}^2$
- Flux off-axis integrating the integrating the neutrino flux in the energy range 0–500 MeV: ~7E-5 ν/EOT/m^2
  - comparable to the integrated flux of the flagship DAR-neutrino facility SNS@Oak Ridge National Lab.





[a] M. Battaglieri et al, Instruments 2024, 8(1)

Conclusions

- Dark matter in the MeV-to-GeV range is largely unexplored;
- Beam Dump eXperiment at JLab: search for Dark Sector particles in the 1 - 1000 MeV mass range;
- BDX was approved by JLAB PAC with the highest scientific rating, currently discussing with laboratory to define a strategy to build the new experimental Hall;
- BDX-MINI pilot experiment:
  - Small-scale version of the full-BDX effort, including all the key components;
  - Evaluated exclusion limit is competitive to flagship experiments;
  - BDX-mini result demonstrates the potentialities of the new generation of beam-dump experiments in LDM searches.
- Spin-off of BDX: from the beam-related backgrounds to the secondary beams exploration.