The BDX experiment at Jefferson Laboratory

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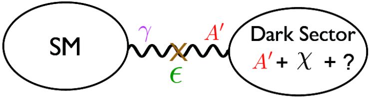
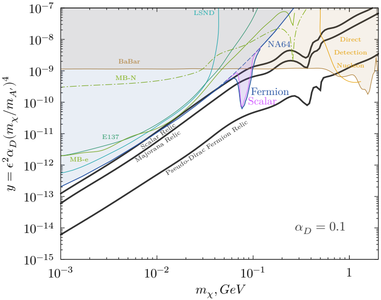
Outline

Light dark matter

The light dark matter hypothesis predicts that DM is made by sub-GeV particles interacting with SM via a new force.[1]





Simplest possibility: "vector-portal". DM-SM interaction trough a new U(1) gauge-boson ("dark-photon") coupling to electric charge

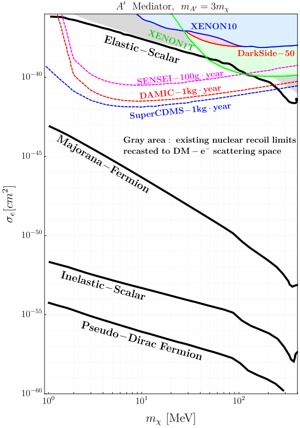
Model parameters:

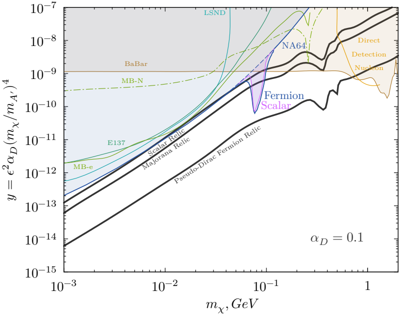
- Dark-photon mass, $M_{A'}$ and coupling to electric charge ε
- Dark matter mass, M_χ and coupling to dark photon, g_D ($\alpha_D \equiv g_D^2/4\pi$)

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

Light dark matter searches at the intensity frontier

- Dark Matter direct detection experiments, typically optimized for $M_\chi \geq 1$ GeV, have a limited sensitivity in the sub-GeV range
  - $E_R \propto M_\chi^2 / M_N$
  - Many ongoing efforts to overcome this limitation
- LDM-SM interaction cross section at low energy has a sizable dependence on the impinging particle velocity, with a drastic reduction for specific models





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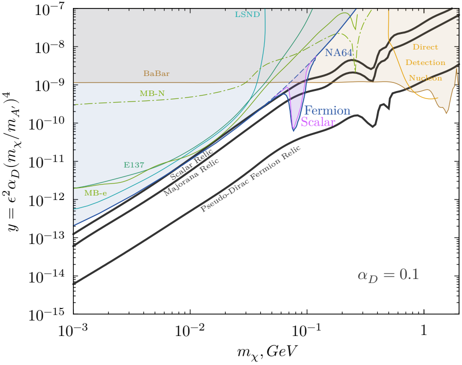


LDM at accelerators

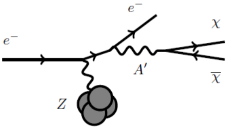
Accelerator-based experiments at the *intensity frontier* are uniquely suited to explore the light dark matter hypothesis

LDM search in beam-dump experiments

Beam dump experiments: LDM direct detection in a e^- beam, fixed-target setup[2]

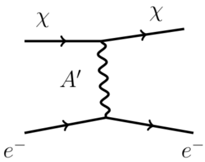
χ production

- High-energy, high-intensity e^- beam impinging on a dump
- χ particles production: radiative A' emission (both on-shell or off-shell) / e^+e^- annihilation

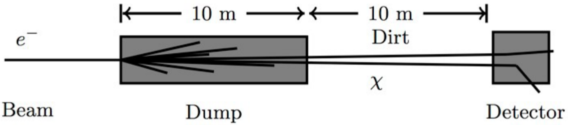


χ detection

- Detector placed behind the dump, O(10-100) m
- Neutral-current χ scattering trough A' exchange, recoil releasing visible energy
- Different signals depending on the interaction (BDX channel: $\chi - e^-$ elastic scattering)



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

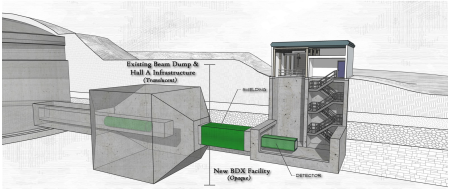


[2]For a comprehensive introduction: E. Izaguirre *et al.*, Phys. Rev. D 88, 114015

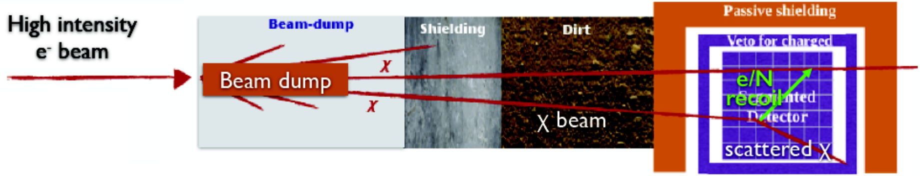
BDX: **B**eam **D**ump e**X**periment at Jefferson Laboratory

Experimental setup

- 11 GeV, $100\ \mu$A CEBAF e^- beam impinging on the Hall-A beam dump
- Detector installed 20 m downstream, in a new experimental hall
- Passive shielding layer between beam dump and detector to shield beam-related background (except ν)
- Sizable overburden ($\simeq 10$ m water-equivalent) to reduce cosmogenic background



BDX experiment layout



The experiment is designed with two goals:

Producing and detecting LDM

- High-intensity e^- beam, $\simeq 10^{22}$ electrons-on-target (EOT)/year
- Medium-high energy, >10 GeV
- $\simeq 1\ m^3$ (1-5 tons) detector
- EM-showers detection capability

Reducing background

- Passive shielding between beam dump and detector to filter beam-related backgrounds (except ν)
- Passive shielding and active vetos surrounding the active volume to reject cosmogenic backgrounds
- Segmented detector for background discrimination based on event topology
- Good time resolution to perform detector-veto coincidence

The BDX detector

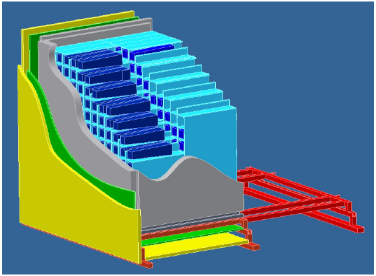
Detector design: 800 CsI(Tl) crystals, total interaction volume $\simeq 0.5m^3$.

Modular detector arrangement:

- 1 module: 10x10 30-cm long crystals, module front face: 50x50 cm^2
- Crystals are surrounded by a 1-cm thick W shielding layer and by two plastic scintillator active veto layers (IV / OV)
- 8 modules, total interaction length 2.6 m

Signal detection:

- EM-shower, $E_{thr} \simeq 300$ MeV, anti-coincidence with IV and OV
- Signal efficiency (conservative) $\simeq 10\%$ - ongoing studies to exploit EM shower directionality to improve this.



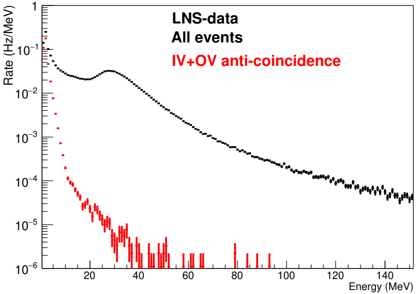
BDX backgrounds

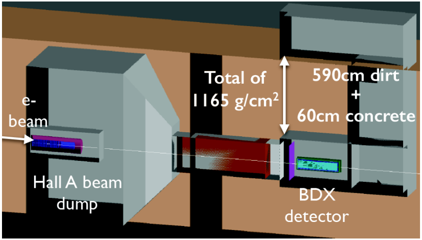
Cosmogenic: data-driven estimate

- μ: rejected by IV/OV. Neutrons: absorbed by the overburden.
- Result extrapolated from cosmic-ray data acquired with a small-scale BDX prototype installed at INFN-LNS (similar overburden).
    - $E_{thr} = 300$ MeV: $B_c \simeq$ 5 (1 year).

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

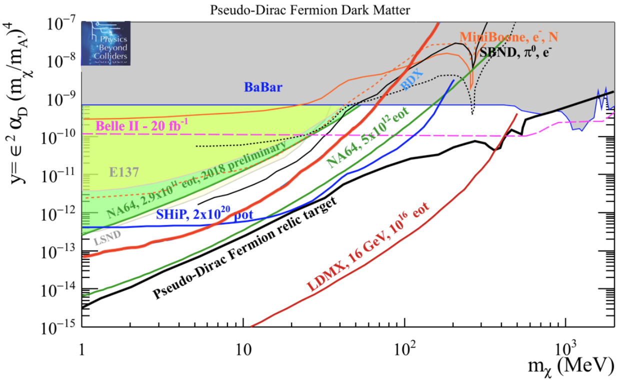
- ν-induced background from ν_e CC interactions in the detector, with a high-energy $e^{\pm}$ resulting to an EM shower. $B_\nu \simeq 10$ for 10^{22} EOT.
- All other SM particles are absorbed by 6.6 m of iron + 2 m concrete shielding.





BDX sensitivity and experiment status

With 10^{22} EOT (1-year running time), BDX will be capable of exploring a large area of the LDM parameters 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

The BDX-MINI experiment

Small-scale, low-energy version of the full BDX experiment.

Experimental setup

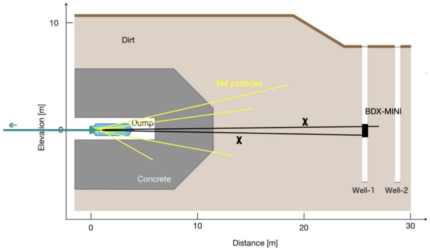
- 2.2 GeV, 150 μA e^- beam impinging on Hall-A beam dump
- SM particles shielded by concrete and soil
- Detector installed in a well 25-m downstream

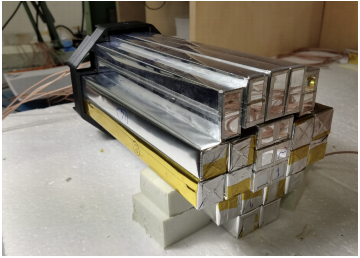
BDX-MINI detector

- $PbWO_4$-based EM calorimeter (44 crystals), SiPM readout
- 8 mm passive Tungsten shielding
- 2 plastic scintillator active veto layers, SiPM readout

Data-taking

December 2019: 11 GeV calibration sample
2020: $2.54 \cdot 10^{21}$ 2.184 GeV EOT

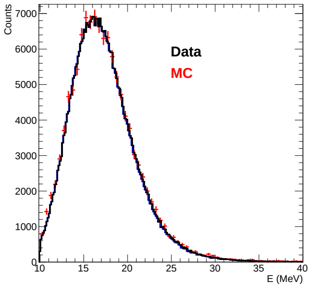




BDX-MINI detector performances (Eur.Phys.J.C 81 (2021)

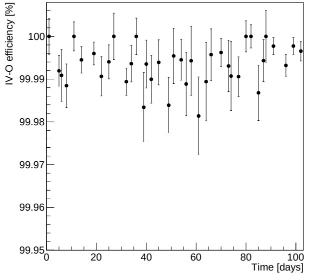
EM calorimeter energy response

- Energy calibration determined from 11 GeV data exploiting secondary μ from beam dump: compare energy spectra between data and MC
- Detector stability monitored with cosmic muons during beam-off time



VETO stability

- VETO efficiency monitored with cosmic muons, using a *tag-and-probe* method. Trajectories selected via ECAL crystals energy deposition.



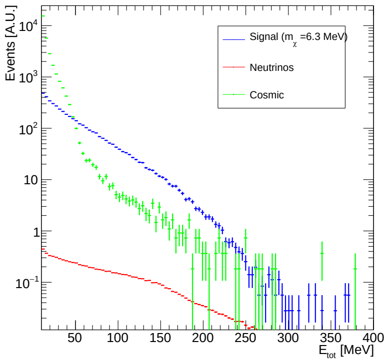
BDX-mini data analysis

Approach: blind-analysis. Fix the selection cuts by optimizing the experiment sensitivity.

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 ($\tau = T_{off}/T_{on}$).
- B_c/B_ν: expected number of cosmogenic/beam-related backgrounds events. B_ν evaluated via MC, B_c threated as nuisance parameter.



Extract the upper limit on S through a a one-sided profile-likelihood test statistics.

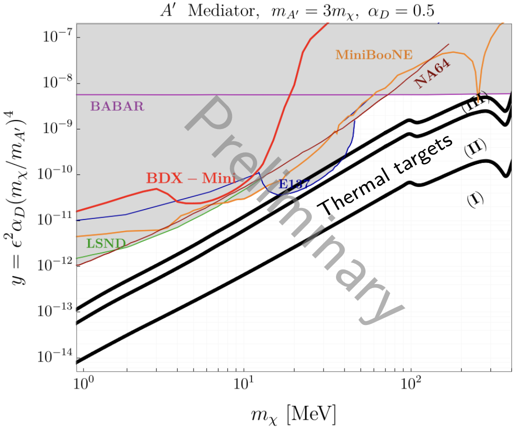
Systematic uncertainties described via ancillary pseudo-measurement factors in $\mathcal{L}$ with Gaussian constraint.

BDX-mini results

The signal window optimizing the BDX-mini sensitivity is defined by $E_{thr} = 40$ MeV. No further cuts are applied.

Experimental results

Yields: for $N_{EOT} = 2.54 \cdot 10^{21}$ and $\tau \simeq 1$, $n_{on} = 1347$ and $n_{off} = 1416$.
No excess is observed: an upper limit is derived in the LDM parameters space



Conclusions

- Dark matter in the MeV-to-GeV range is largely unexplored.
- **Beam Dump eXperiment** at JLab: search for Dark Sector particles in the $1 \div 1000$ MeV mass range.
    - High intensity ($\simeq 10^{22}$ EOT/year), high energy (11 GeV) e^- beam
    - Detector: $\simeq 800$ CsI(Tl) calorimeter + 2-layers active veto + shielding.
- 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
    - Measurement campaign with 2.184 GeV beam completed in 2020, data analysis in progress