BDX update

Marco Spreafico

On behalf of BDX collaboration

30 - 04 - 2025

1. Dark Matter
   - Light Dark Matter
   - Dark Matter search
2. BDX
   - Experimental setup
   - Physics reach
   - Status and perspective
3. BDX-MINI
   - Experimental setup
   - Results
   - AI Reach Optimization
4. Outlook

Dark Matter Problem

Astrophysical observations suggest existence of DM

→ Information only from gravitational interaction

⇒ No clue on DM nature

Common assumption: **thermal origin of DM**

→ DM we see comes from an epoch of thermodynamical equilibrium with SM

→ constrain on available mass range

→ strong constraint on viable DM → SM interaction

Thermal DM

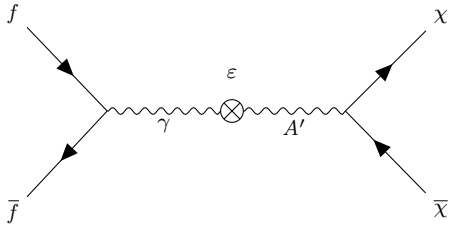
Light Dark Matter - Dark Photon model

Simplest possibility: "*vector portal*"

$\rightarrow$ $U(1)$ gauge boson (**dark photon**) coupling to electric charge

$$\mathcal{L}_{LDM} \sim g_D A'_\mu J^\mu_\chi + \varepsilon e A'_\mu J^\mu_{EM} + [...]$$

Annihilation in SM:



Model parameters:

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

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

arXiv:1607.01390

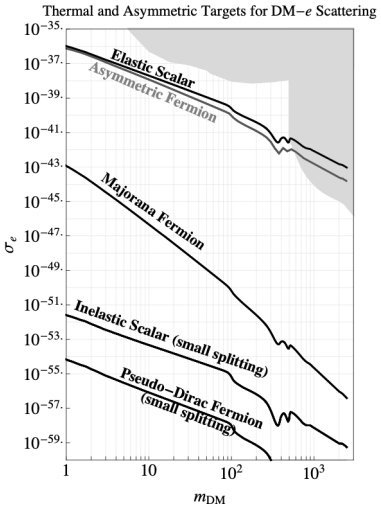
Light Dark Matter

Direct detection not suited for sub-GeV DM searches:

- DD experiments optimized for $m_\chi >$ GeV
  - $\rightarrow$ $E_R \propto m_\chi^2 / m_N$
  - $\Rightarrow$ very low recoil energy

- LDM-SM interaction cross section depends on impinging particle velocity
  - $\rightarrow$ DD sensitivity strongly model-dependent

- Inelastic DM almost impossible to probe
  - Upscattering kinematically forbidden



Light Dark Matter

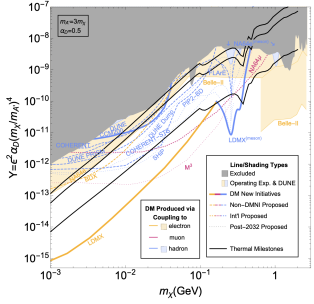
LDM at accelerators

Accelerator based experiments at the *intensity frontier* uniquely suited to search for LDM:

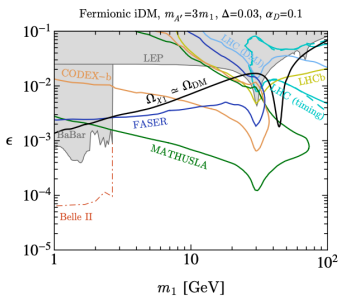
→ High intensity ⇒ increased possibility of DM production

→ Production of relativistic DM ⇒ testing different models

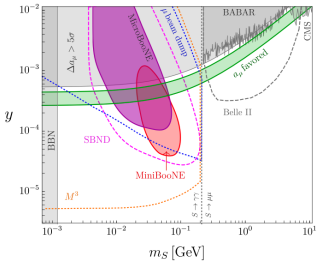
Light Dark Matter



Inelastic Light Dark Matter

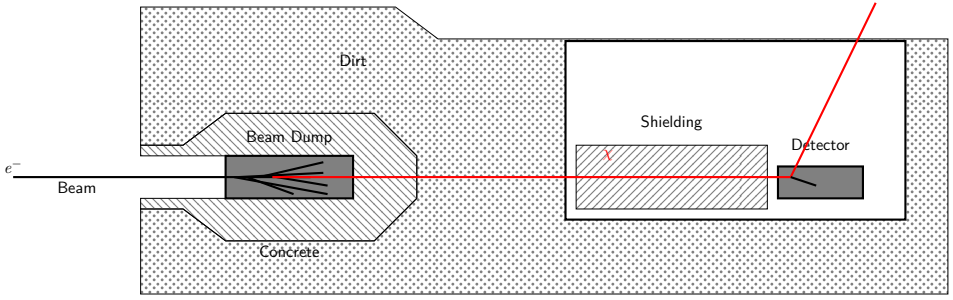


Muonphilic Dark Scalar



Beam Dump experiments

Beam dump experiments: direct detection of LDM produced by beam impinging on fixed target (beam dump)[1]



χ production

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

χ interaction

- χ propagate through shielding
- χ scattering through A' exchange

[1] Izaguirre et al., Phys. Rev. D 88, 114015 arXiv:1607.01390

BDX

BDX

JLab experiment approved by PAC46

- Run time: 2026-2029
- Fully optimized for LDM searches

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)

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

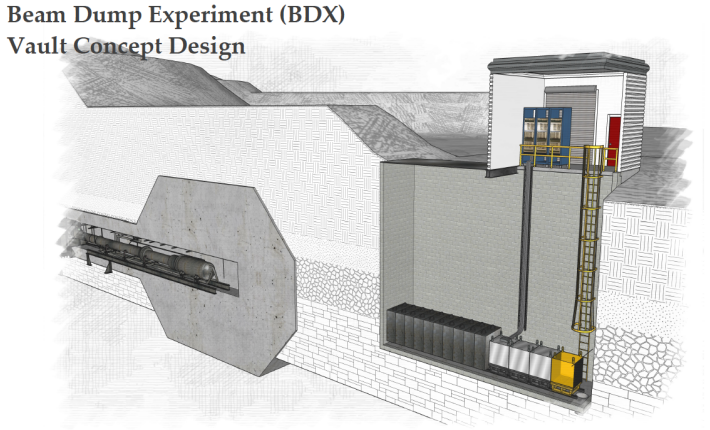
- New underground (~ 8 m) vault
- 25 m downstream of Hall-A beam dump
- passive shielding (~ 7 m steel) to reduce beam related background

arXiv:1607.01390

BDX - Vault

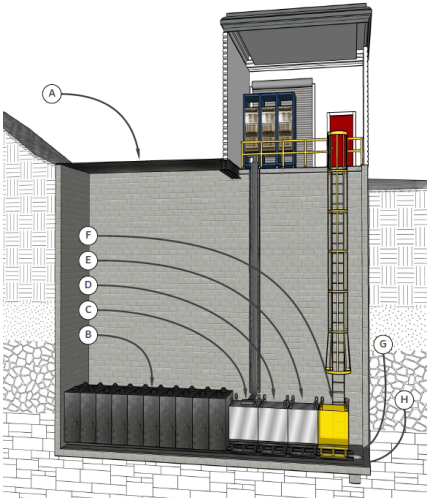
Finalized vault:

- Vault built ~ 15 m from the beam dump
- ~ 7 m Aluminum shielding
- Detector located ~ 22 m downstream the dump



BDX - Vault

- **A** Removable cover
- **B** Shielding Al block $\sim 1.5 \times 1.5 \times 7$ m
- **C** First module (BGO)
- **D** Second module ($PbWO_4$)
- **E** Third module ($PbWO_4$)
- **F** Space for extra module (considering CCD detector)
- **G** Support structure
- **H** Rails to mobilize detector



BDX - Detector

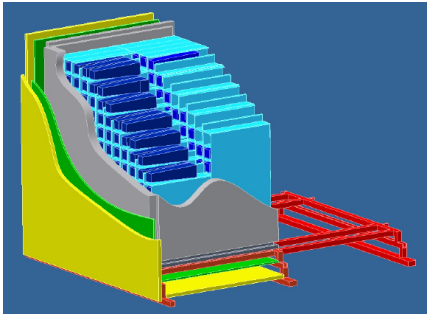
Detector design

Electromagnetic calorimeter:

- homogeneous 3 tons ECal

Veto system:

- hermetic multi layer veto
- 3 layer of plastic scintillator counters
- 5 cm lead vault between veto and calorimeter



Modular detector arrangement:

- ECal (BGO, $PbWO_4$)
- Multi-layer veto

$\rightarrow$ total: 3 modules (1 BGO, 2 $PbWO_4$)

Signal detection:

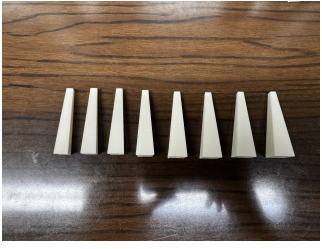
- EM shower ($\gtrsim$ 100 MeV) and no corresponding activity in the active veto

arXiv:1607.01390

BDX - BGO module

BGO crystals comin grom decommissioning of BGO-OD detector

- 480 crystals (mass 1.5 tons ~ 0.5 BDX mass)
- Tapered crystals
- Two crystals placed in a parallelepipedal alveolus to achieve regular shape
- Module made of 3 (9×9) alveoli matrix
- Central aveoli filled with $PbWO_4$ crystals (from BDX-MINI, POKER)



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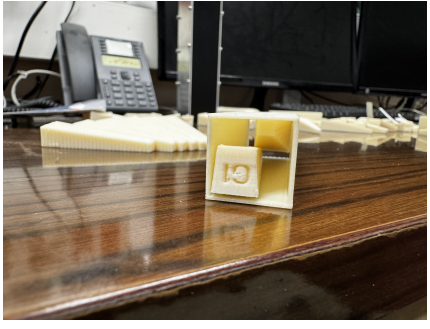
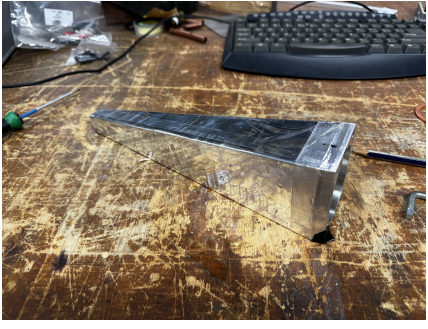


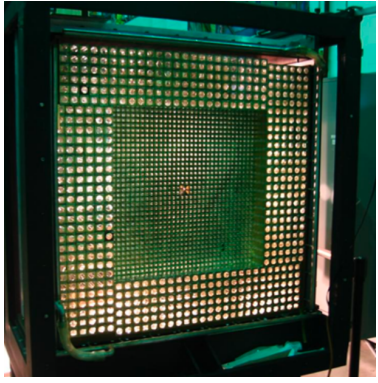


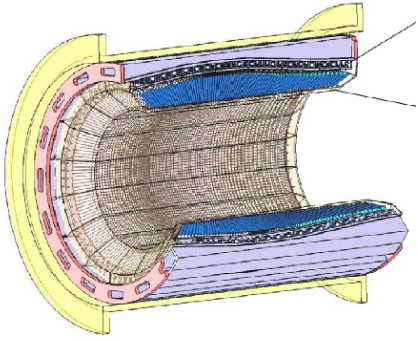
BDX - PbWO modules

Subsequent modules commissioned at later times

- First module made with $\sim$ 1200 $PbWO_4$ crystals from PRad HyCal
- Second module made with $\sim$ 800 $PbWO_4$ spare crystals from PANDA

Total mass with $PbWO_4$ modules $\sim$ BDX CsI proposed mass





BDX - CCD

Possibility for spare module: build a low-threshold detector (CCD)

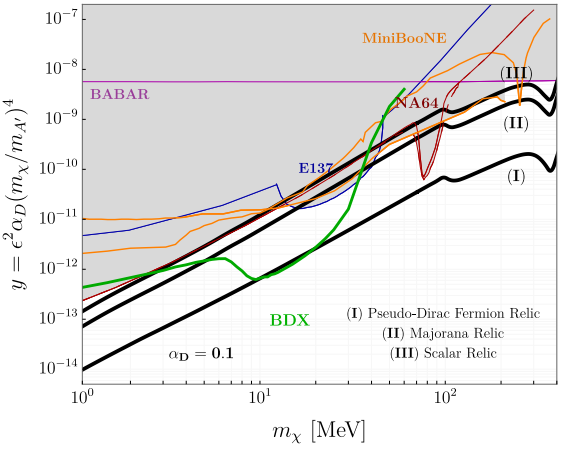
Skipper CCD: low (eV) threshold detector Exploits low energy DM interaction

- Expected clear signature from DM interaction
- Very low background (SM signal strongly different)

~ 30 CCDs could reproduce BDX results with a few grams detector

BDX - Reach

Thanks to CEBAF high luminosity and an optimized detector layout, BDX will be able to explore different LDM models



arXiv:1607.01390, arXiv:1910.03532, Phys.Rev.D 98 (2018) 11, 115022

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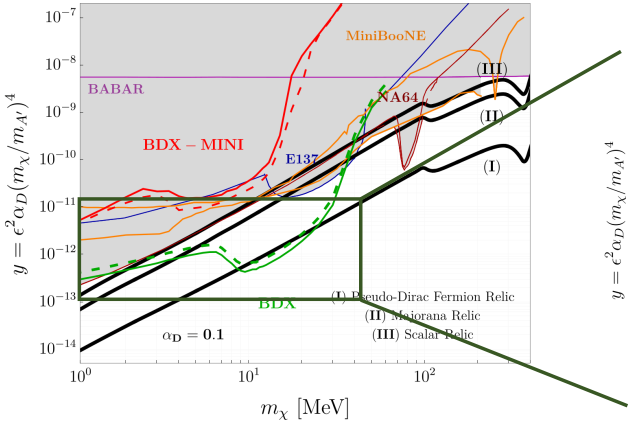
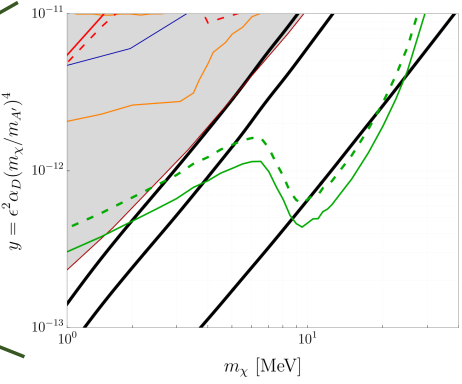


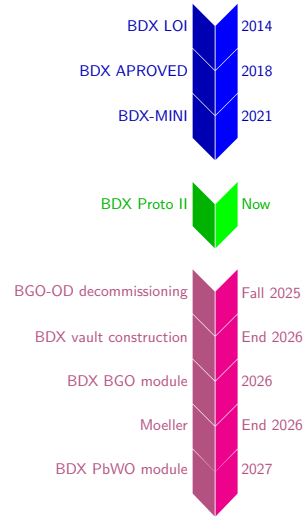


BDX - Status and perspective

→ 2014 - BDX Letter of Intent
→ 2015 - BDX Proto I: study of cosmic background
→ 2017 - BDX Hodo: study of beam-related background
→ 2018 - BDX approved at PAC46 with the highest scientific rating
→ 2021 - BDX-Mini: test of BDX technology

→ NOW - BDX Proto II: veto optimization

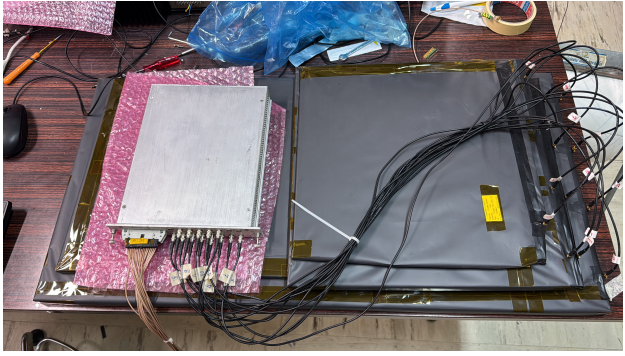
→ Fall 2025 - BGO-OD decommissioning
→ Mid 2026 - BDX Hall construction
→ End 2026 - BDX first module commissioning
→ End 2026 - Moeller: BDX running parassitically
→ 2027 - second and third module commissioning



BDX - Proto

Currently working on the construction of a small scale prototype to test BDX veto

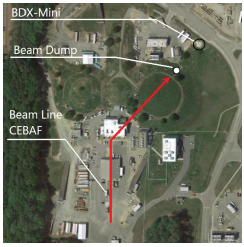
- Multi layer veto with plastic scintillator (EJ 200) read with WLS fibers and SiPM
- Crystals inside to mimic calorimeter (BGO, $PbWO_4$, CsI(Tl))
- Goal: measure veto detection efficiency and rejection capabilities

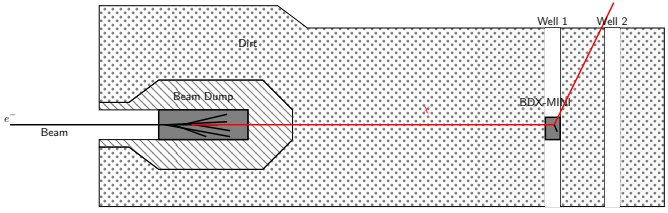


BDX-MINI - Experimental Setup

Pilot version of BDX:

- detector placed $\sim$ 25 m downstream of beam dump
- 2.56 GeV e^- beam
- current up to $150\ \mu$A
- measurement alternating beam on and beam off data (beam on time $\sim$ 50 %)
  - $\rightarrow$ Cosmogenic background studied with beam-off data
- accumulated 2.54×10^{21} EOT



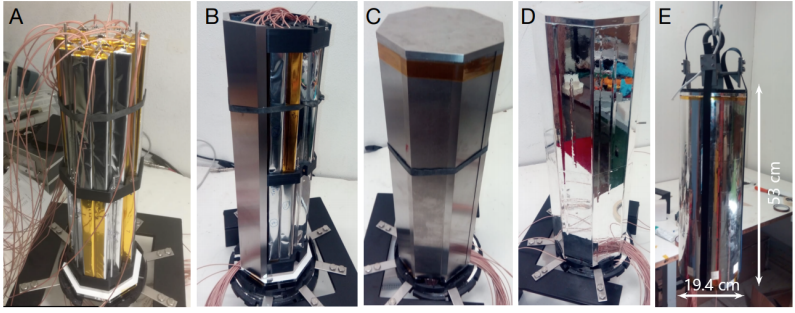


M. Battaglieri et al., Eur.Phys.J.C 81 (2021) 2, 164

BDX-MINI - Detector

Electromagnetic calorimeter (ECal):

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



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

BDX-MINI - Detector

Electromagnetic calorimeter (ECal):

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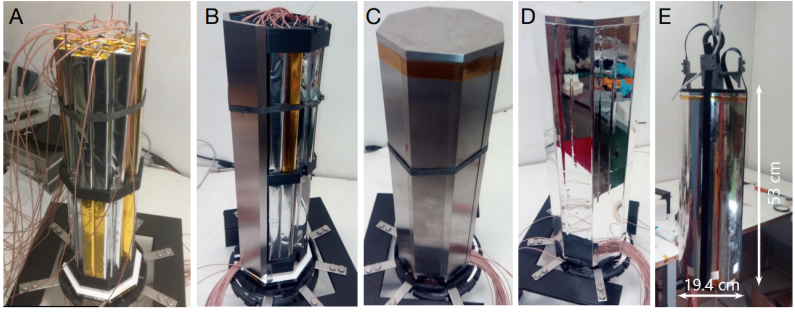
- SiPM readout

Veto system

- Active veto:
- Octagonal (IV) plastic scintillator
- Cylindrical (OV) plastic scintilaltor
- Passive tungsten shielding



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

BDX-MINI - Results

BDX-MINI analysis fully optimized for DM searches

- Cosmic background studied using beam-off data
- Signal cut optimized using beam-off data and signal MC simulation

Experimental results

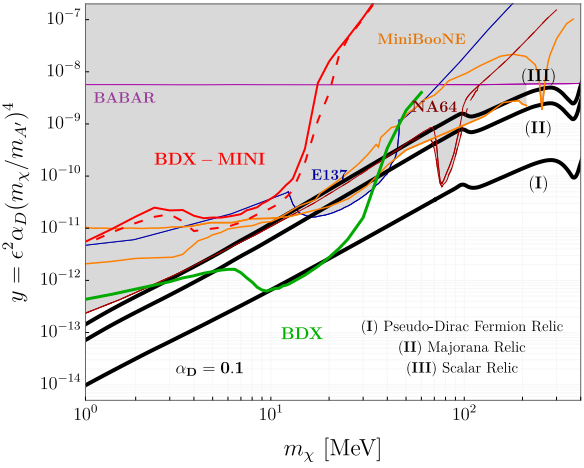
Yields (for $N_{EOT} = 2.54 \cdot 10^{21}$)

- $N_{on} = 3623$
- $N_{off} = 3822$ ($\tau = 1.054$)

No excess is observed

→ evaluated 90% exclusion limit in the LDM parameter space

→ results comparable with flagship experiments



M. Battaglieri et al., Phys.Rev.D 106 (2022) 7, 072011

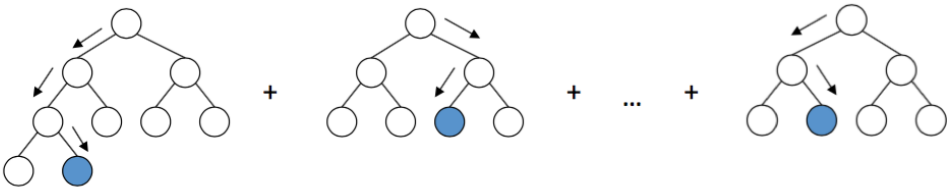
BDX-MINI - AI optimization

BDX-MINI impressive results due to analysis performed:

$\rightarrow$ signal cuts chosen to maximize signal-to-noise ratio

BDX-MINI selection cut: anti-coincidence with veto and $E_{tot} > 40$ MeV

$\rightarrow$ can AI provide better background rejection? $\Rightarrow$ BDT



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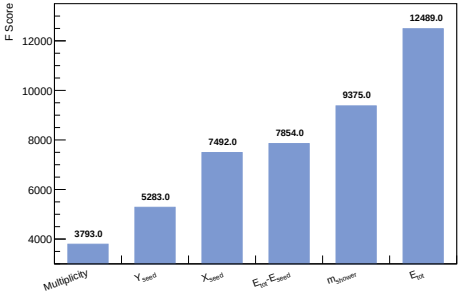

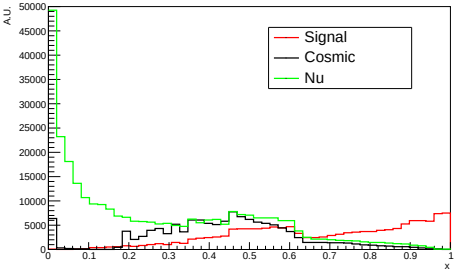

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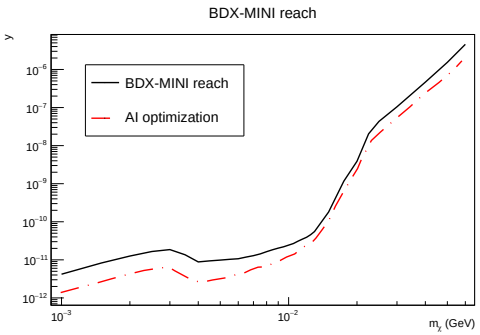
Expected significant improvement in BDX-MINI reach

- Significant improvement at low DM masses

AI based rejection algorithms can be used for BDX for better background rejection



Outlook

- Dark matter in the MeV-to-GeV range is largely unexplored

- **BDX**: search for Dark Sector particles in the MeV-GeV mass range
  - Technique viable to probe different DM candidates
  - JLab provides unique opportunities to probe different models
  - BDX ready to be commissioned
  - BDX vault excavation beginning in the next months
  - BDX detector commissioning starting by the end of the year
  - BDX start taking data in 2027 (with Moeller)

- **BDX-MINI**: pilot version of BDX
  - First modern beam dump experiment searching for Light Dark Matter
  - Detector optimized for LDM searches
  - Analysis aimed to LDM detection
  - Results can be improved with AI-based algorithms

- Beam dump experiment with e beam highly sensitive to Light Dark Matter in the MeV-GeV range

  $\rightarrow$ Sensitivity to large variety of models

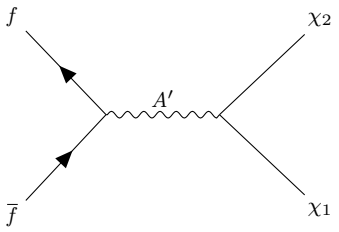
  $\rightarrow$ BDX-MINI remarkable results demonstrate that BDX is a mature, ready-to-run experiment (after the construction of a new underground experimental hall)

Backup slides

Light Dark Matter - Inelastic Dark Matter

Dark Sector may be composed of two states with different mass

$\rightarrow$ Stable low mass state χ_1 and unstable high mass state χ_2



Same parameter $y \equiv \frac{g_D^2 \epsilon^2 e^2}{4\pi} \left(\frac{m_\chi}{m_{A'}}\right)^4 \sim \langle \sigma v \rangle_{relic} m_\chi^2$ can be used to probe this model

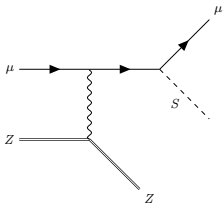
M. Battaglieri et al., arXiv:1910.03532

Light Dark Matter - Muonphilic Dark Scalar

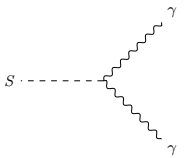
Dark Sector could explain SM anomalies, for example muon $(g-2)_\mu$ anomaly

$\rightarrow$ Simplest possibility: Dark Scalar coupled only to muons

Dark Scalar Production



DS decay



Model parameters:

- Dark Scalar mass m_S
- DS-muon coupling g_μ

C. Cesarotti et al., Phys.Rev.D 110 (2024) 5, 055032

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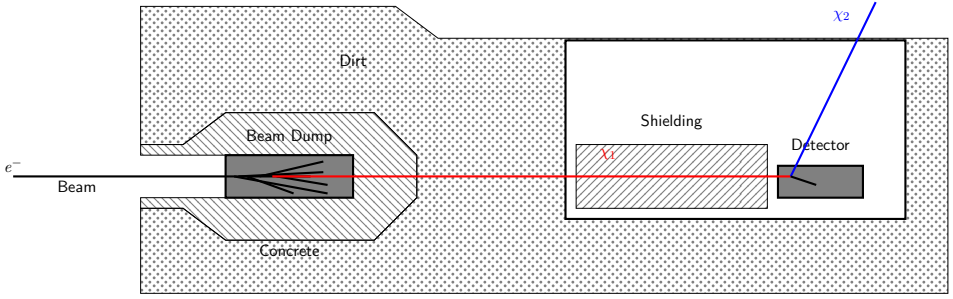

$\chi_{1,2}$ production

- e^- beam impinging on target
- $\chi_1\chi_2$ from decay of A' produced in the dump

$\chi_{1,2}$ interaction

- χ_1 scattering through A' exchange
- χ_2 decay in χ_1 and e^+e^-

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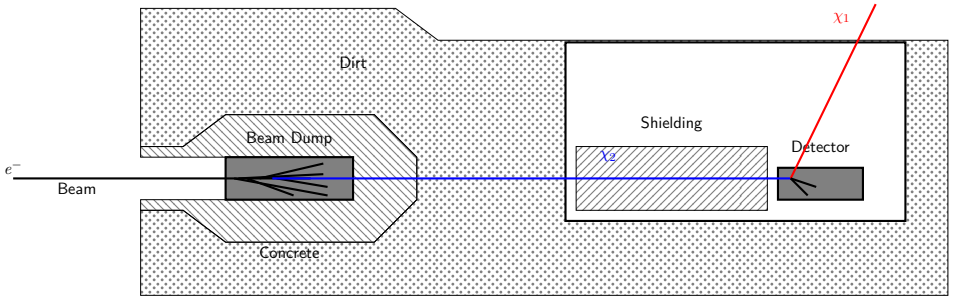

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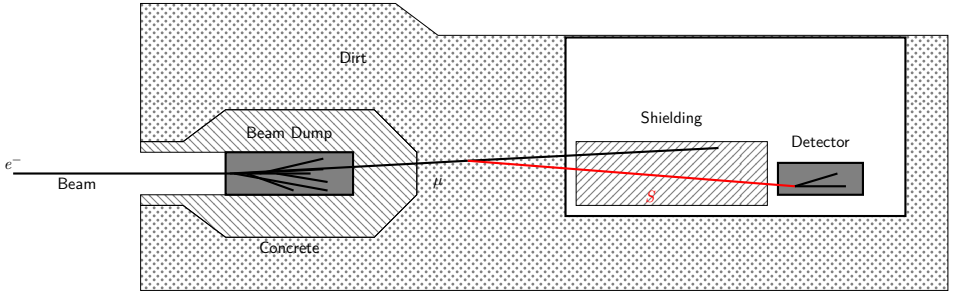

DS production

- Secondary μ cross different materials
- DS production from μ scattering

DS decay

- DS propagate over large distance
- DS decay identified as two high energy γs

[2] Phys.Rev.D 110 (2024) 5, 055032
L. Marsicano et al., Phys.Rev.D 98 (2018) 11, 115022

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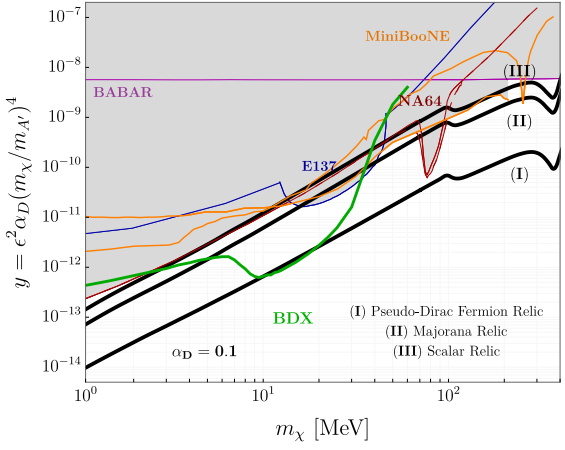

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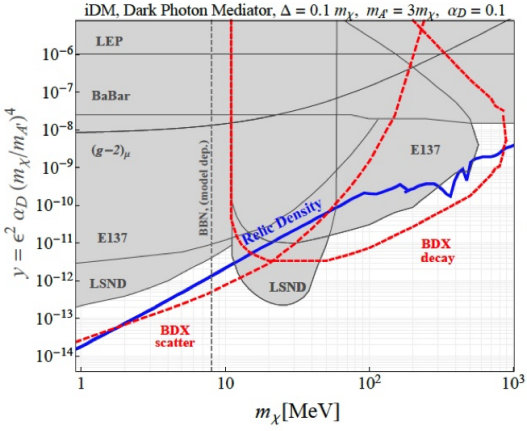

arXiv:1607.01390, arXiv:1910.03532, Phys.Rev.D 98 (2018) 11, 115022

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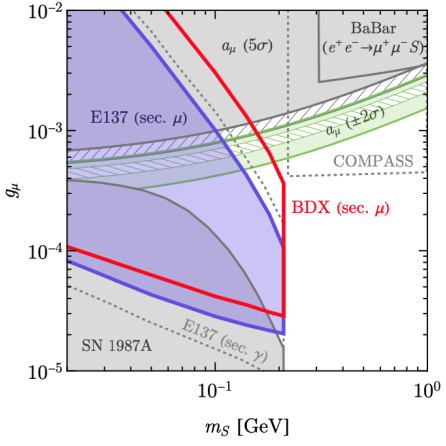

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