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The BDX experiment

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On behalf of BDX collaboration

25 - 10 - 2024

1. Light Dark Matter
2. BDX
   - Experimental setup
   - Physics reach
3. BDX-MINI
   - Experimental setup
   - Results
4. BDX@22 GeV
   - Background@22 GeV
   - Physical reach @ 22 GeV
5. Outlook

Dark Matter Problem

Astrophysical observations suggest existence of DM

$\rightarrow$ Information only from gravitational interaction

$\Rightarrow$ No clue on DM nature

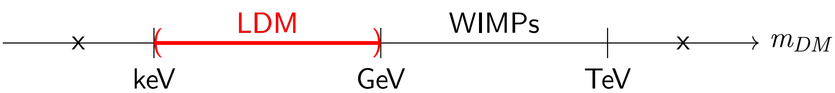
Common assumption: **thermal origin of DM**

$\rightarrow$ DM we see comes from an epoch of thermodynamical equilibrium with SM

$\rightarrow$ constrain on available mass range

$\rightarrow$ strong constraint on viable DM $\rightarrow$ SM interaction

Thermal DM



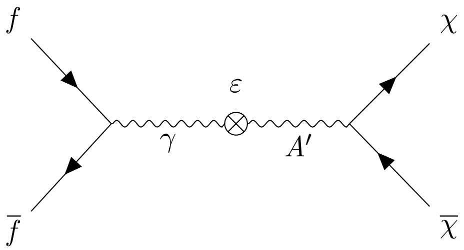
Light Dark Matter - Dark Photon model

Simplest possibility: "*vector portal*"

→ $U(1)$ 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 ($\alpha_D \equiv g_D^2/4\pi$)

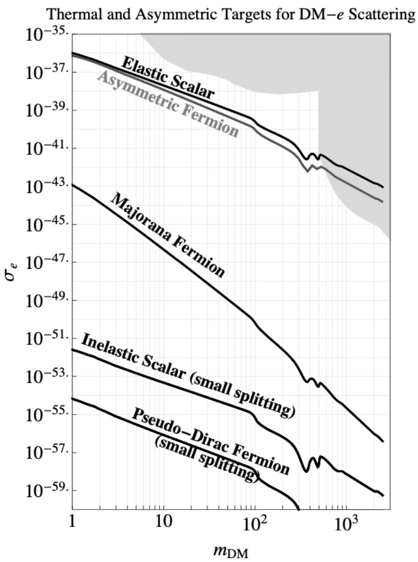
$$y \equiv \frac{g_D^2 \epsilon^2 e^2}{4\pi} \left(\frac{m_\chi}{m_{A'}}\right)^4 \sim \langle \sigma v \rangle_{relic} m_\chi^2$$

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

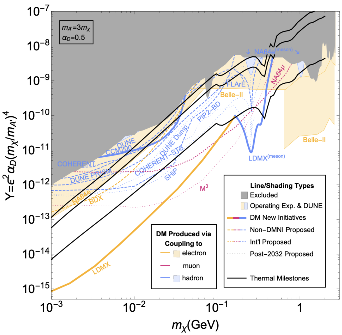
LDM at accelerators

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

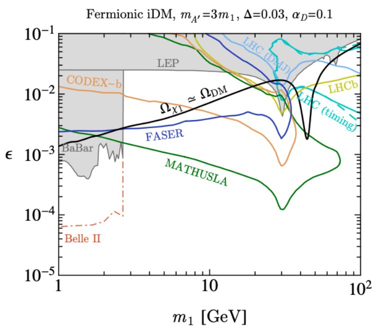
$\rightarrow$ High intensity $\Rightarrow$ increased possibility of DM production

$\rightarrow$ Production of relativistic DM $\Rightarrow$ testing different models

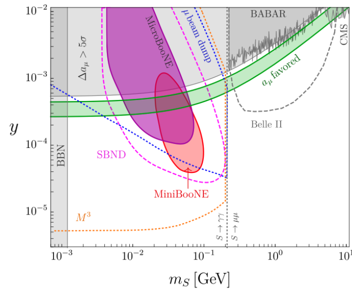
Light Dark Matter



Inelastic Light Dark Matter

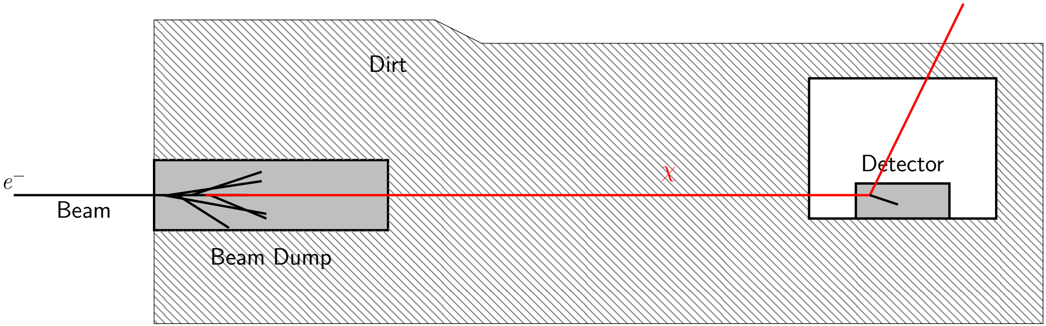


Muonphilic Dark Scalar



Beam Dump experiments

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



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

Izaguirre et al., Phys. Rev. D 88, 114015

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) hall
- 25 m downstream of Hall-A beam dump
- passive shielding (~ 3 m lead) to reduce beam related background

arXiv:1607.01390

BDX - Detector

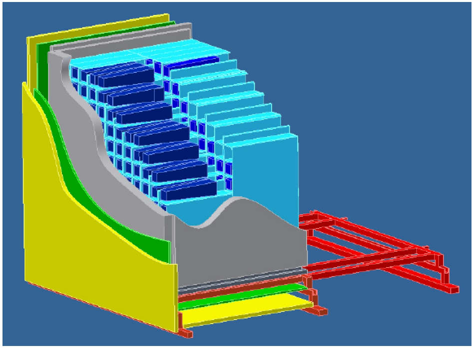
Detector design

Electromagnetic calorimeter:

- homogeneous 4 tons ECal

Veto system:

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



Modular detector arrangement:

- 1 module: $10\times10\times2$ alveoli
  - Good coverage of DM flux
  - Module surrounded by veto

$\rightarrow$ total: 4 modules

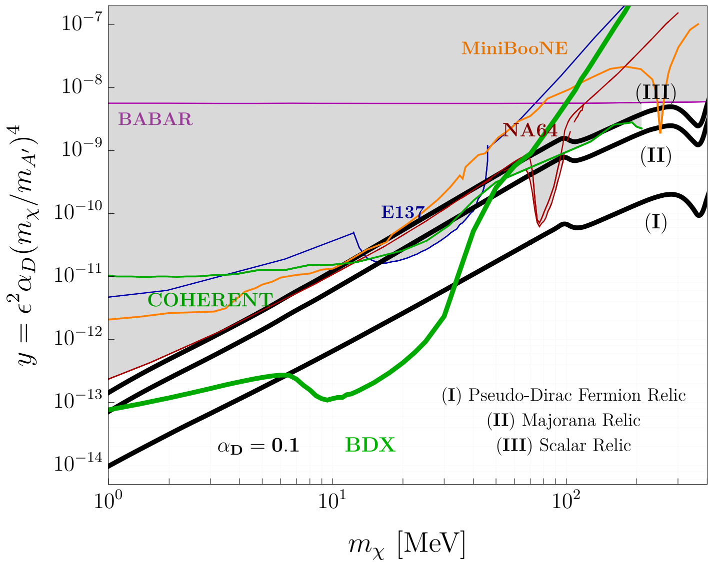
Signal detection:

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

arXiv:1607.01390

BDX - Reach

Thanks to CEBAF high luminosity and an optimized detector layout, BDX will be able to efficiently explore a large portion of LDM parameter space

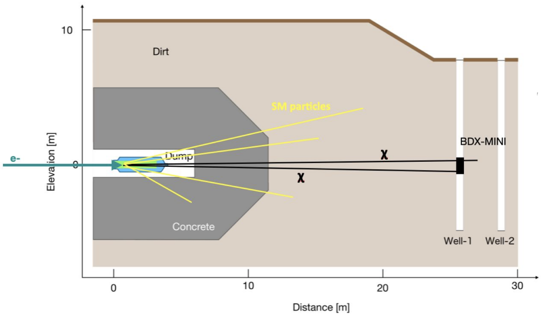


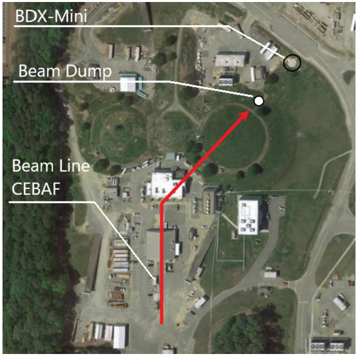
BDX-MINI - Experimental Setup

Pilot version of BDX:

- 2.56 GeV e^- beam
- 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

- cosmic background studied with beam off data



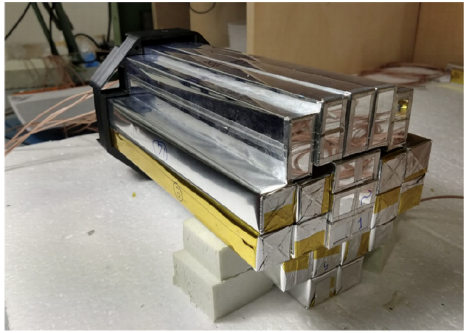


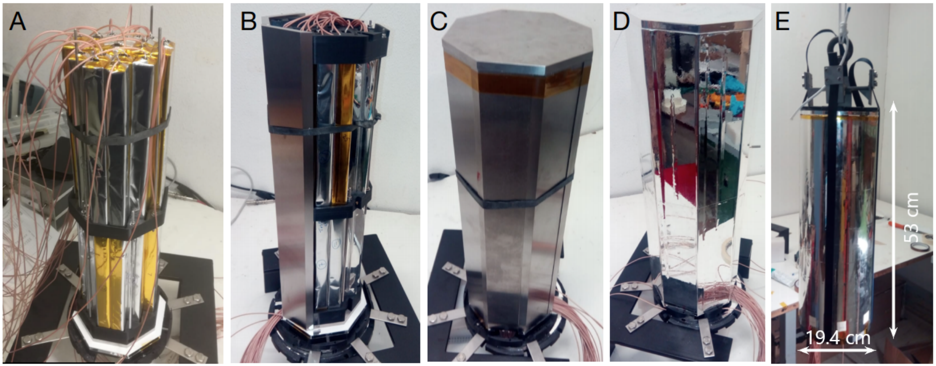
M. Battaglieri et al., Eur.Phys.J.C 81 (2021) 2, 164

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

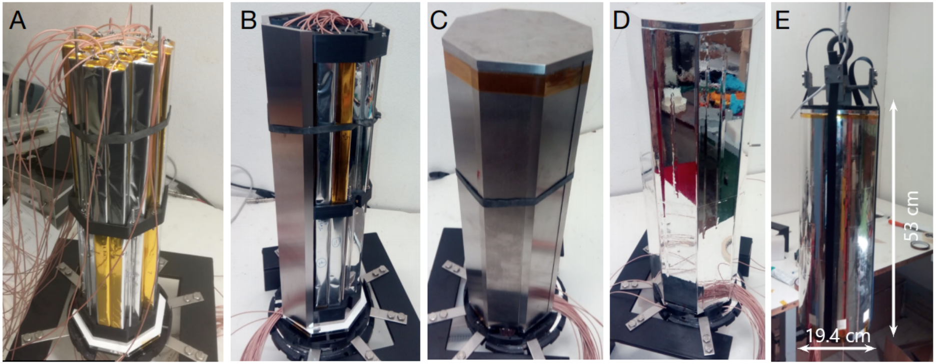
BDX-MINI - Detector

Electromagnetic calorimeter (ECal):

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

Veto system

- Active veto:
- Octagonal (IV) plastic scintillator
- Cylindrical (OV) plastic scintillator
- 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

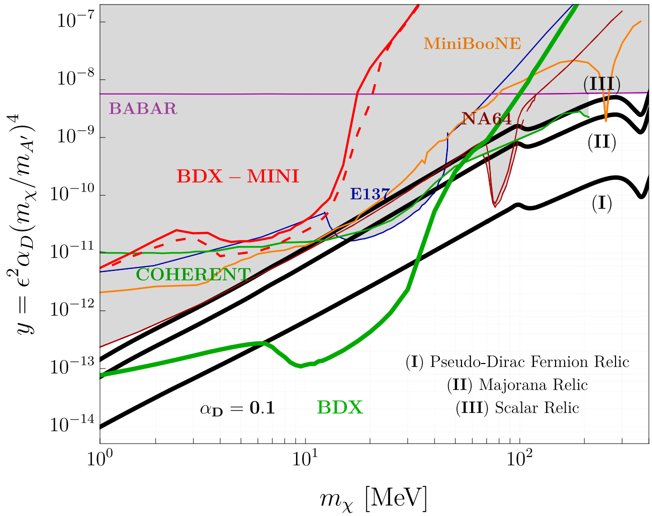
Yields (for $N_{EOT} = 2.54 \cdot 10^{21}$)

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

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 @ 22 GeV - Overview

What changes with a 22 GeV beam?

Higher beam energy

Higher secondary particle energy:

- Higher masses can be probed
- Resonant enhancement shifted to higher masses ($\propto \sqrt{E_{beam}}$)

Higher secondary flux

- Higher $e^{\pm}$ flux $\rightarrow$ enhancement DM production probability
- Higher secondary flux $\rightarrow$ study of different Dark Sector possibilities

Enhanced secondary particle flux

Increased overall beam-related background:

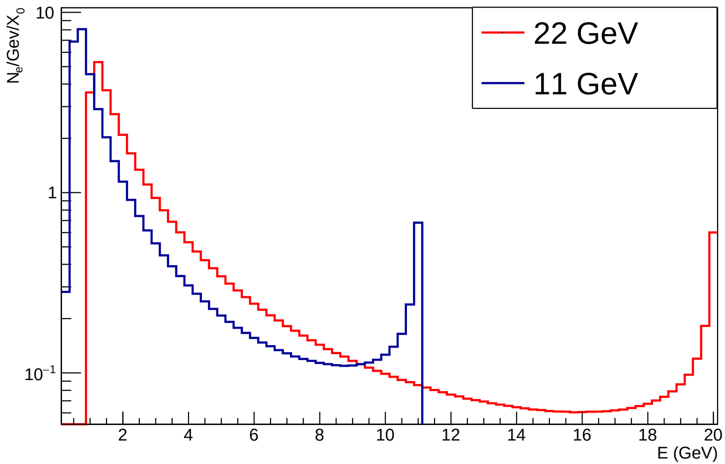
- μ $\rightarrow$ can be rejected using veto
- n $\rightarrow$ non rejectable using veto but low energy contribution
- ν $\rightarrow$ not rejectable

BDX optimized for 10 GeV beam

$\rightarrow$ exploit Hall-A 22 GeV run to extend reach

BDX @ 22 GeV - $e^{\pm}$ flux

Increased beam energy $\rightarrow$ increased number of secondary $e^{\pm}$



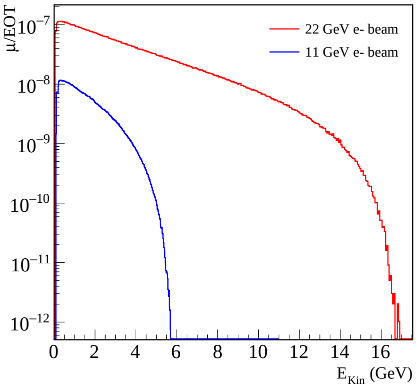
$$N_{e^{\pm}}/EOT|_{10GeV} = 189 \quad \Rightarrow \quad N_{e^{\pm}}/EOT|_{10GeV} = 300$$

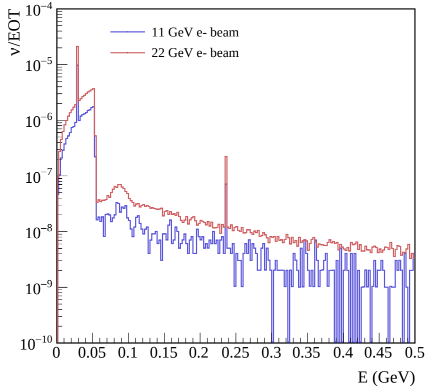
Warning!

Estimates are made using the current beam dump configuration, but the layout will have to change to absorb a higher energy beam

BDX @ 22 GeV - Beam-related background

Increased beam energy ⇒ increased number of secondary particles:





$$N_\mu/EOT|_{10GeV} = 9.8\times10^{-7} \quad \Rightarrow$$
$$N_\mu/EOT|_{22GeV} = 7.6\times10^{-6}$$

$$N_\nu/EOT|_{10GeV} = 2.9\times10^{-5} \quad \Rightarrow$$
$$N_\nu/EOT|_{22GeV} = 6.3\times10^{-5}$$

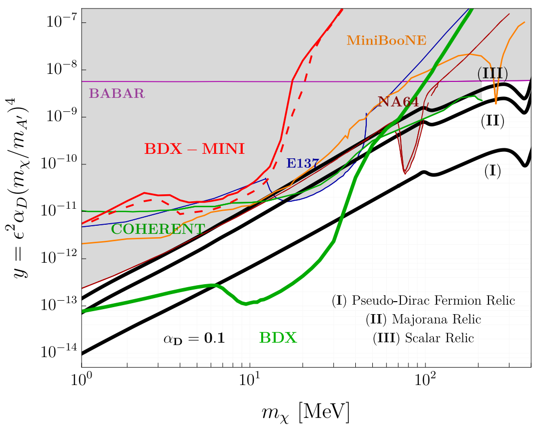
Warning!

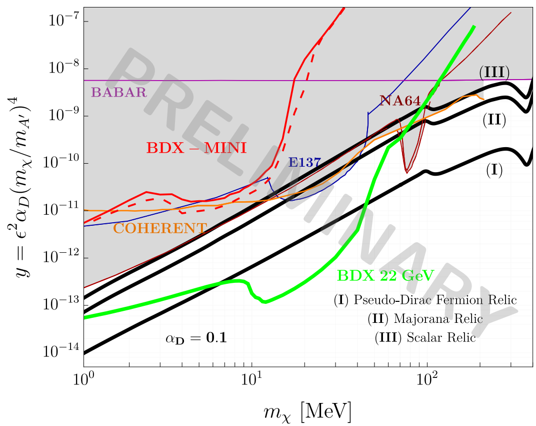
Different beam dump layout and a more optimized shielding may greatly affect the expected secondary fluxes

A. Fulci et al., Instruments 8 (2024) 1

BDX @ 22 GeV - Reach

Data with 22 GeV beam can extend BDX reach to higher masses:





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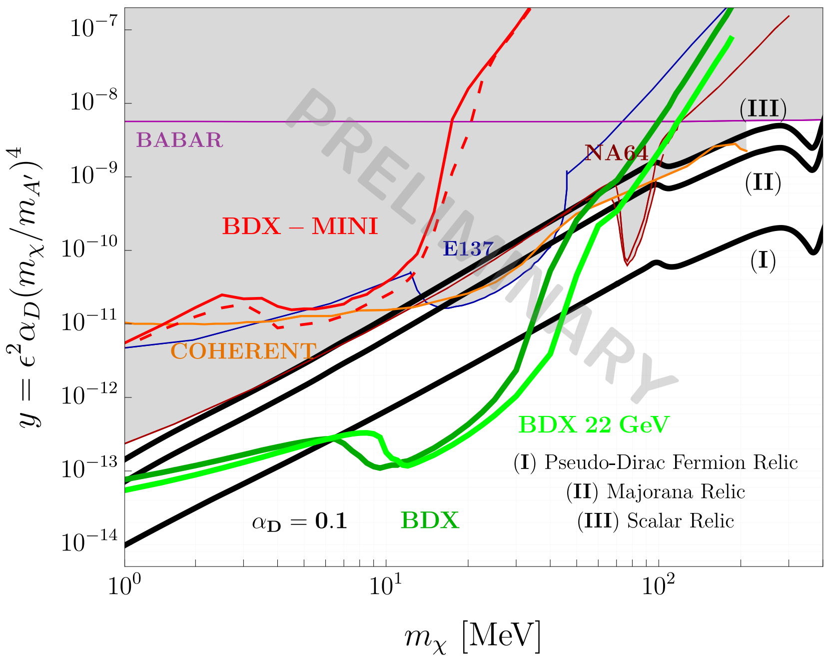


Outlook

- 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-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
  - Evaluated exclusion limit $\rightarrow$ competitive to flagship experiments

- **BDX@22 GeV**: extend BDX results but more difficult run conditions

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

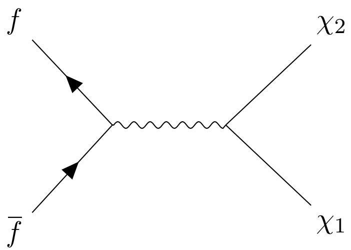
  $\rightarrow$ BDX-MINI remarkable results demonstrate that BDX is a mature, ready-to-run experiment (after the construction of a new underground experimental hall)

Backup slides

Light Dark Matter - Inelastic Dark Matter

Dark Sector may be composed of two states with different mass

→ 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

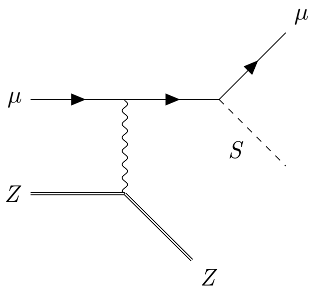
M. Battaglieri et al., arXiv:1910.03532

Light Dark Matter - Muonphilic Dark Scalar

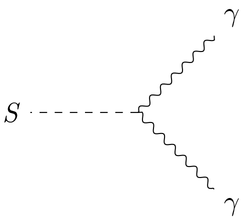
Dark Sector could explain SM anomalies, for example muon $(g-2)_\mu$ anomaly

→ Simplest possibility: Dark Scalar coupled only to muons

Dark Scalar Production



DS decay



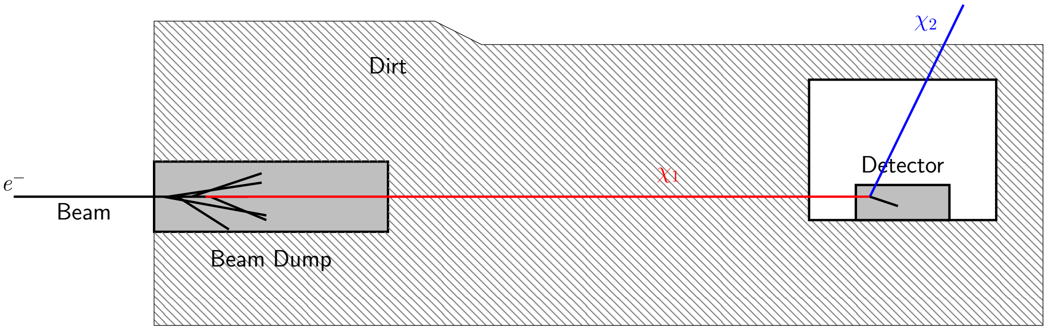
Model parameters:

- Dark Scalar mass m_S
- DS-muon coupling g_μ

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

Beam Dump experiments

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



$\chi_{1,2}$ 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 $e^= e^-$

M. Battaglieri et al., arXiv:1910.03532

Beam Dump experiments

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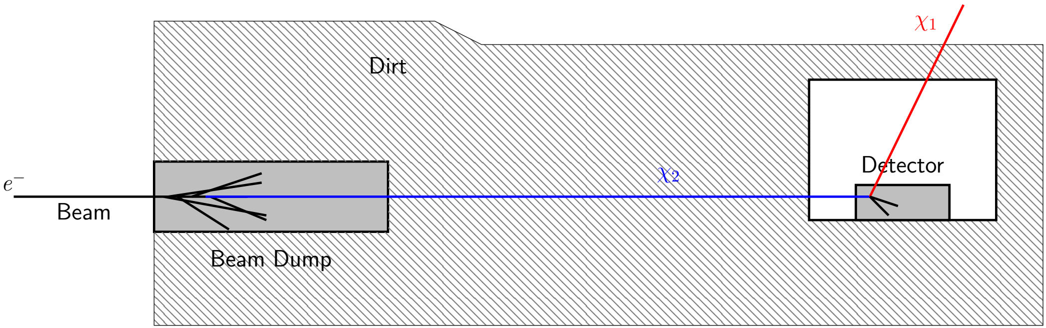

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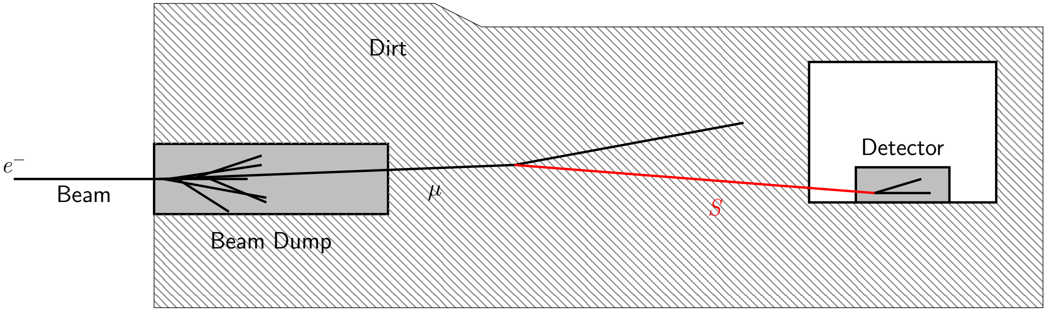
Beam Dump experiments

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



DS production

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

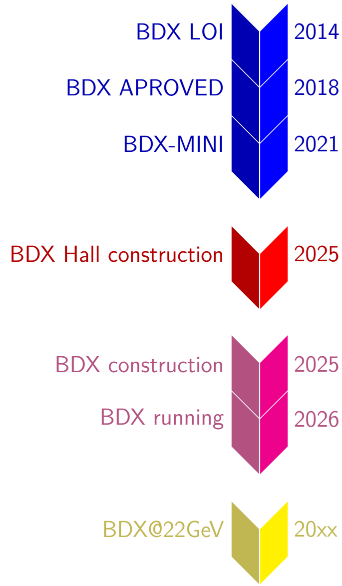
DS decay

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

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

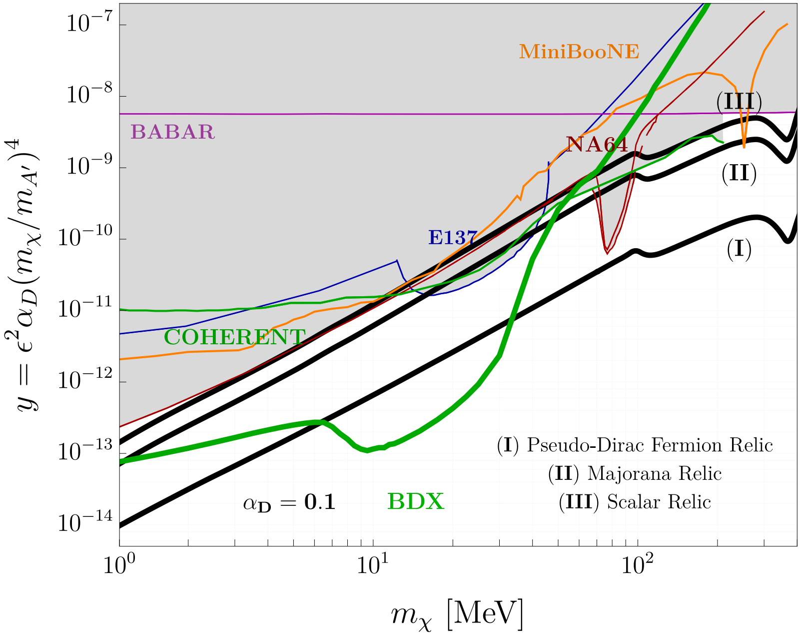
BDX - Status and perspective

- → 2014 - BDX Letter of Intent
- → 2015 - BDX Proto: 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
- → 2025 - BDX Hall construction?
- → 2025 - BDX construction
- → 2026 - Moeller: BDX running parasitically
- → 20xx - BDX@22 GeV



BDX - Reach

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



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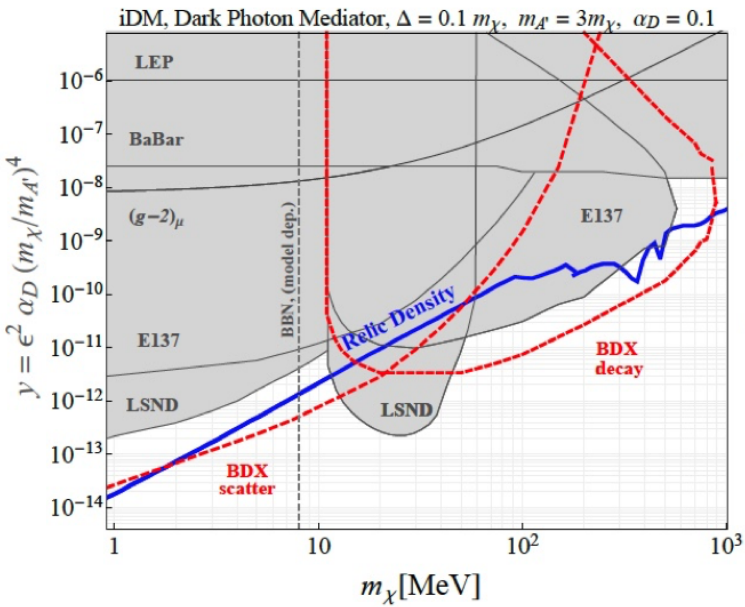

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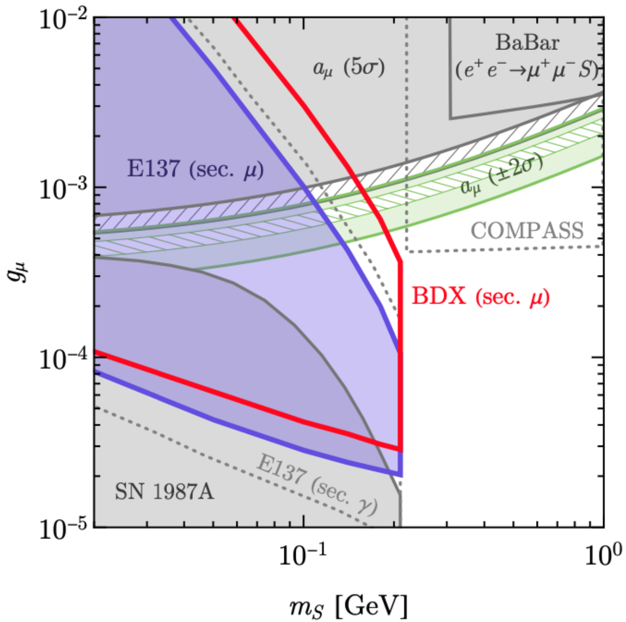

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