Università di Genova

INFN GENOVA

Dark Matter search with the BDX-MINI experiment

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On behalf of BDX Collaboration

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Jefferson Lab

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   - Dark Photon model
   - Beam Dump Experiments
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Dark Matter Problem

Astrophysical observations suggest existence of DM

$\rightarrow$ Information only from gravitational interaction

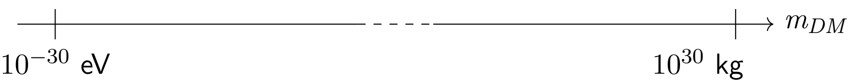
$\Rightarrow$ No clue on DM nature

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



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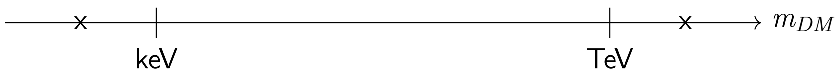

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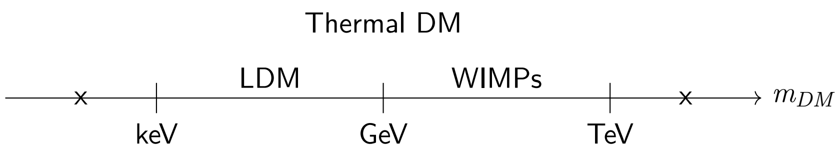

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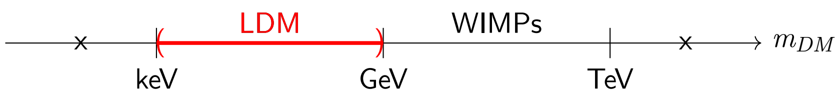


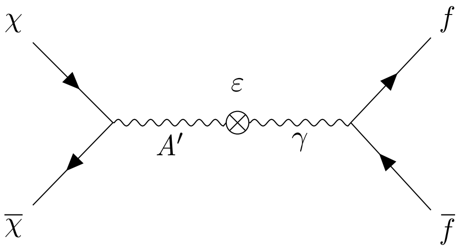
Light Dark Matter - Dark Photon model

Simplest possibility: "*vector portal*"[1]

→ $U(1)$ 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:



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

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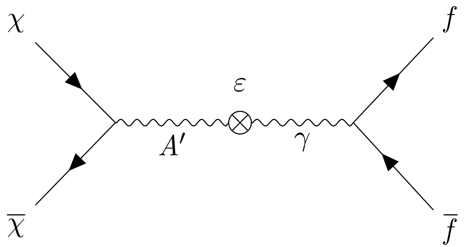

Model parameters:

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

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

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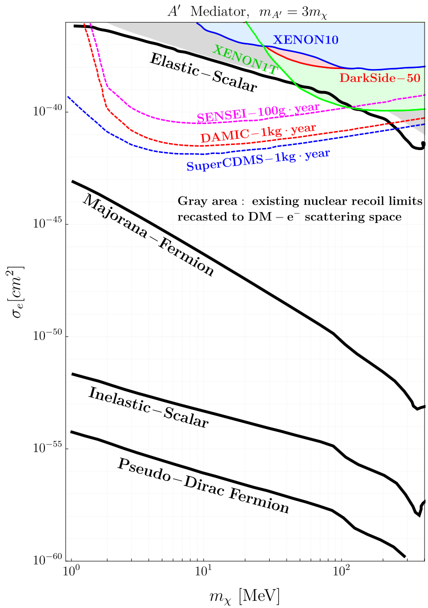
Light Dark Matter

Direct detection not well 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



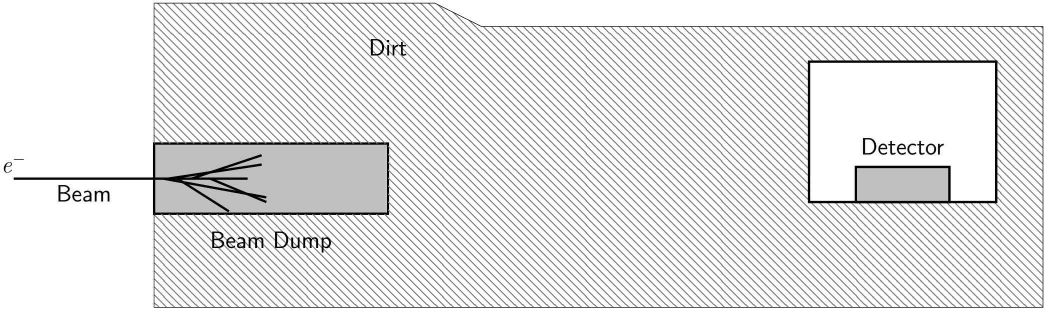
LDM at accelerators

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

Beam Dump experiments

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



χ production

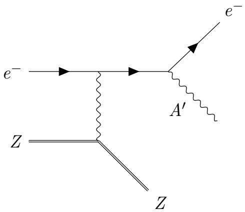
- e^- beam impinging on target
- χ from decay of A' produced in the dump

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

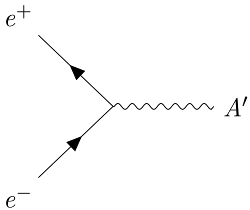
Dark Photon model

Dark Matter production[3]

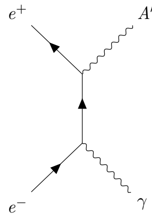
A'-strahlung



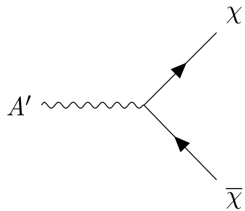
Resonant e^+e^- annihilation



Non-resonant e^+e^- annihilation



A' decay



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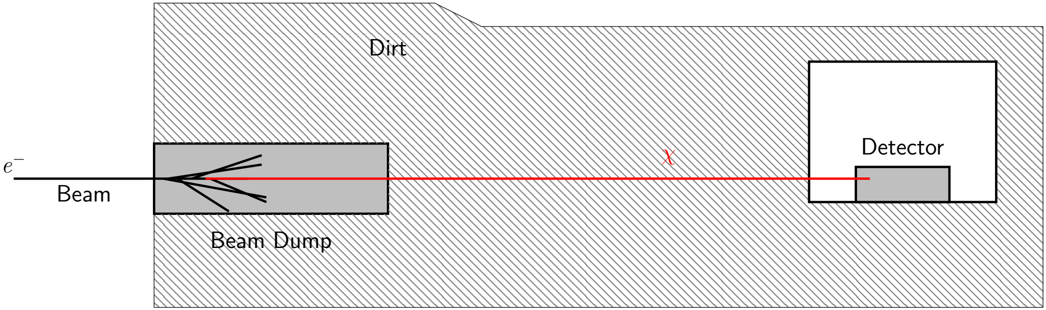

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χ interaction

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

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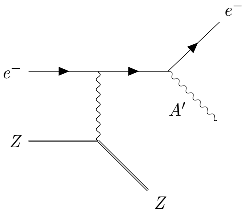

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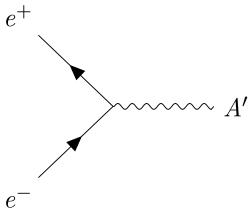

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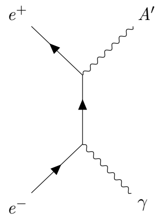

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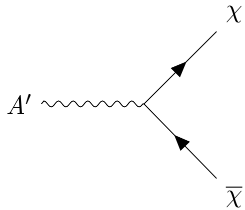
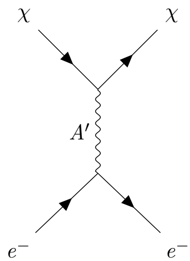


Dark Matter interaction

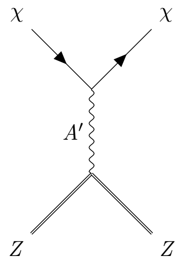
With $\sim$ GeV DM recoil energy:

- $E^e_{rec} \sim 100$ MeV
- $E^N_{rec} \sim$ MeV

Scattering on e^-



Scattering on nuclei



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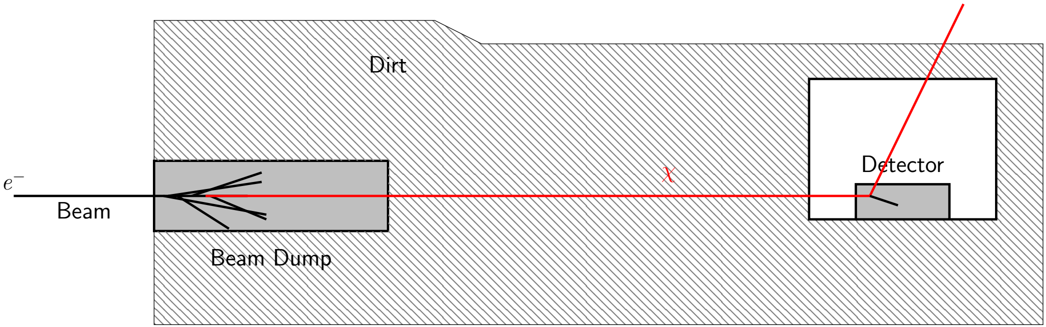

χ production

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

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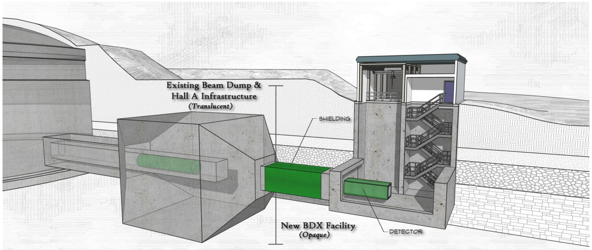
BDX

BDX is a **JLab experiment** approved by PAC46

→ unique experiment able to produce and detect LDM

→ beam dump experiment specifically aimed at LDM searches



Experiment designed with two goals:

LDM production and detection

→ Exploit CEBAF high-intensity beam

→ Medium-high energy beam

→ EM shower detection capability

→ Fully parasitic

Minimize background

→ Shielding to filter beam-related background

→ Multi layer veto for cosmogenic background

→ Segmented detector

→ Time resolution for detector-veto coincidence

arXiv:1607.01390

BDX - Experimental Setup

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 (~ 6.6 m iron) to reduce beam related background
- $\sim$ 10 m water equivalent overburden to reduce cosmogenic background

arXiv:1607.01390

BDX - Detector

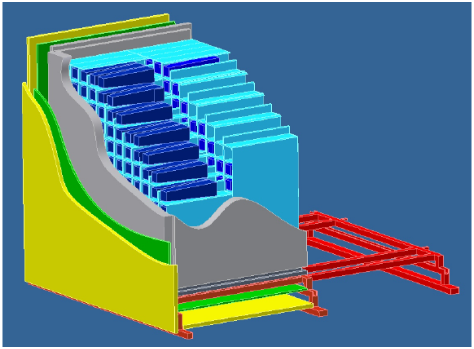
Detector design

Electromagnetic calorimeter:

- homogeneous calorimeter made with CsI(Tl) crystals read by SiPM

Veto system:

- hermetic multi layer veto
- 2 layer of plastic scintillator counters read by WLS fibers and SiPM
- 5 cm lead vault between veto and calorimeter



Modular detector arrangement:

- 1 module: 10×10 crystals
  - 50×50 cm^2 front face, 30 cm long
  - Module surrounded by veto

$\rightarrow$ total: 8 modules (~ 2.6 m length)

Signal detection:

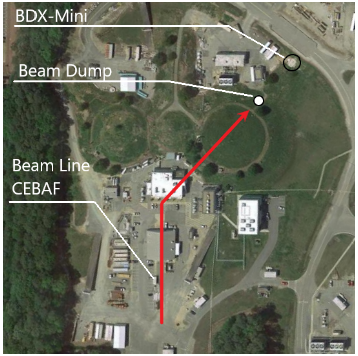
- EM shower ($\gtrsim 100$ MeV) and no corresponding activity in the active veto
- Signal efficiency $\sim 20\%$

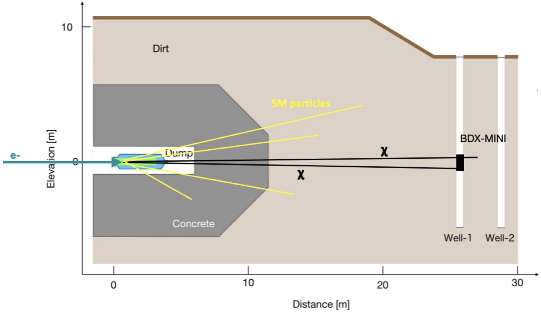
BDX-MINI experiment

Pilot version of BDX:

- 2.56 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

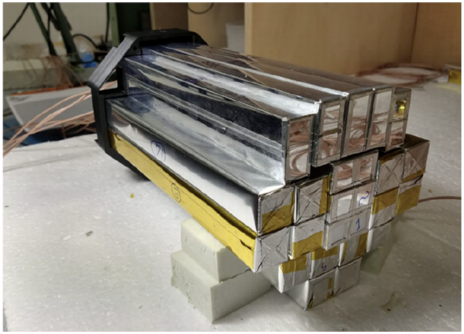




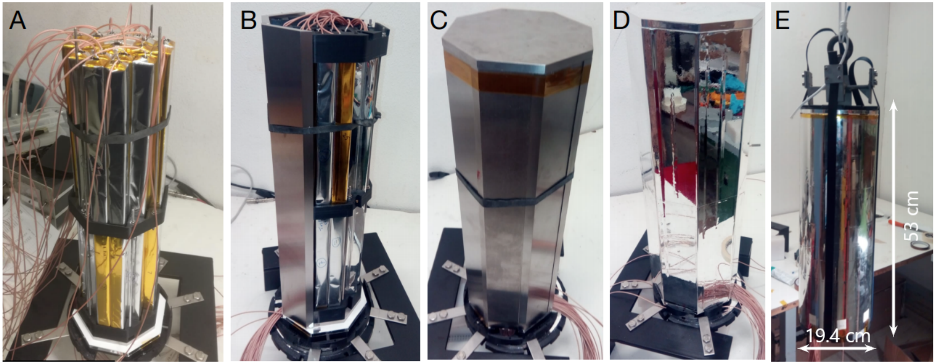
M. Battaglieri et al., Eur.Phys.J.C 81 (2021) 2, 164

BDX-MINI detector

Electromagnetic calorimeter (ECal):



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



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BDX-MINI detector

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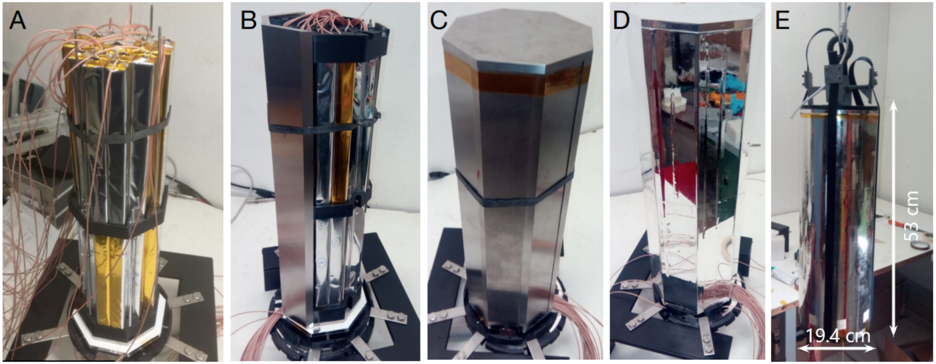
- SiPM readout

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



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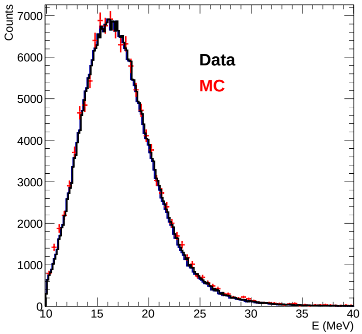
Detector performance

Detector performance:

- Calibration with special 10 GeV run
- Stability monitored with cosmic μ

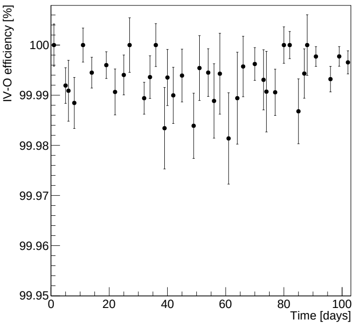
ECal energy response

- Energy calibration determined from 10 GeV data
  - $\rightarrow$ compared secondary μ between data and MC
- Stability monitored with beam off data
  - $\rightarrow$ Selected penetrating μ with Landau peak



VETO stability

- Veto efficiency monitored with cosmic muons
  - $\rightarrow$ *tag-and-probe* method
  - $\rightarrow$ trajectories selected with ECal energy deposition



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Backgrounds

Two main sources of background:

Beam related background

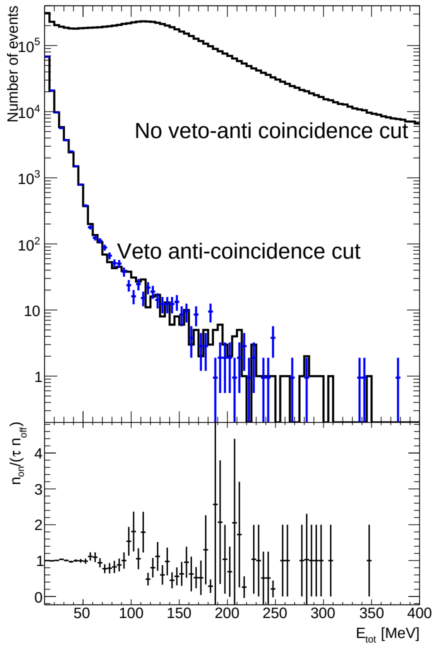
Yield estimate through MC simulations (FLUKA+GENIE+Geant4)

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

Cosmogenic background

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

Measured cosmic background



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

Data analysis

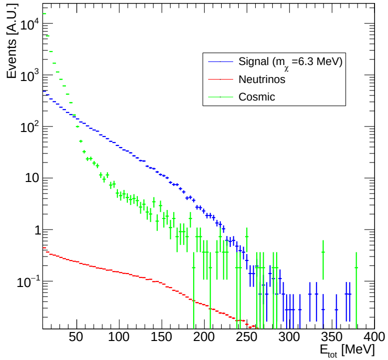
Approach

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

Model: ON-OFF problem

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

- 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

→ one-sided profile-likelihood test statistics to evaluate upper limit on S

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

Sensitivity optimization

Idea: improve sensitivity considering effect of data analysis cuts on background minimization and signal maximization

→ beam-on data extrapolated from beam-off data

→ used only events in anti-coincidence with veto

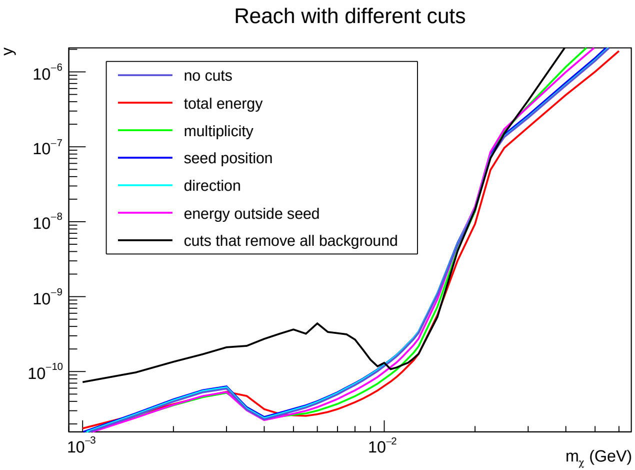
→ evaluated upper limit on signal yield with different cuts and converted to exclusion limit

Tested different cuts

Best condition

- Anti-coincidence with veto
- $E_{tot} > 40$ MeV
- Data split into 8 energy bins

⇒ Sensitivity highly enhanced



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

Unblinding

Last step: unblinding and analysis of beam on data

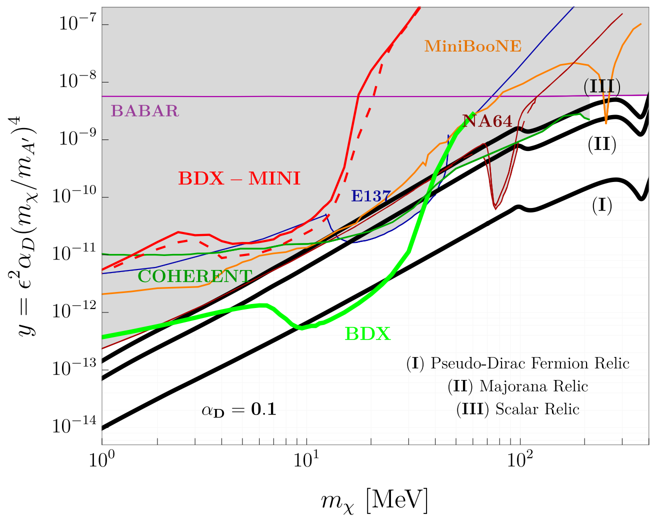
Experimental results

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

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

No excess is observed

$\rightarrow$ evaluated 90% exclusion limit in the LDM parameter space



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Conclusions

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

- Beam dump experiments at the intensity frontier uniquely suited for DM searches
  - **Beam Dump eXperiment** at JLab: search for Dark Sector particles in the MeV-GeV mass range

- **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

- 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)