BDX
Dark Matter search in a Beam Dump eXperiment at Jefferson Lab

Marzio De Napoli
on behalf of the BDX Collaboration
An extensive experimental program based on WIMPs paradigm is searching for DM. Up to now, no results from DM direct search and no evidence of new physics at the weak-scale from LHC.

**Physics Motivation**

**EXTENDING THE DM HUNTING TERRITORY TO UNEXPLORED REGIONS**

Light Dark Matter ($\chi$) in the 1-1000 MeV mass range

Requires a new Force - $U'(1)$ to achieve the correct thermal relic

Light DM couples to SM through the new Force

Mass range where (traditional) Direct Detection is (almost) impossible

High intensity beam makes accelerator-based DM search highly competitive

**Beam Dump eXperiment**

<table>
<thead>
<tr>
<th>Energy</th>
<th>Light Dark Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MeV</td>
<td></td>
</tr>
</tbody>
</table>

**Direct Detection**

<table>
<thead>
<tr>
<th>Energy</th>
<th>WIMPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 GeV</td>
<td></td>
</tr>
<tr>
<td>$M_{z0}$</td>
<td></td>
</tr>
<tr>
<td>10 TeV</td>
<td></td>
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AN OLD IDEA: IF THERE IS AN ADDITIONAL U(1) SYMMETRY, THE NEW VECTOR BOSON A’ KINETICALLY MIXES WITH THE SM PHOTON

TWO U(1)’S AND $\epsilon$ CHARGE SHIFTS

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$$\Delta L = \frac{\epsilon}{2} F_{\mu\nu}^Y F_{\mu\nu}^{'}$$

“Kinetic mixing”

Loops of heavy particles charged under photon and $A'$

$A'$ acts as a “portal” between the SM and the new sector

Standard Model

Dark Sector $A'$ (massive)
Mixing induces an effective weak coupling $\epsilon \cdot e$ to electric charge

**Heavy/Dark Photons**

Visible decay

$\sigma \propto \epsilon^2$

Invisible decay

$\Gamma_{\chi \bar{\chi}} \propto \alpha_D$

(not $\epsilon$-suppressed!)

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**BDX in a nutshell**

**LIGHT DARK MATTER SEARCH IN AN ELECTRON BEAM-DUMP EXPERIMENT**

- **High intensity beam**
  - Sensitivity scales linearly with the total number of EOT
  - \(0(10) \text{ GeV beam energy}\)
  - High energy helps cross-sections and kinematics

- **DM signature in the detector**
  - EM shower \(\sim\) GeV energy
  - High energy thresholds

**KINEMATICS: DM PARTICLES STRONGLY FORWARD FOCUSED**

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**BDX at JLAB**

*High energy beam available:* 11 GeV

The highest available beam current ~ 65 µA

Integrated charge: $10^{22}$ EOT in ~ 10 months

- BDX detector located downstream of Hall-A beam-dump (~ 8m µg)
- New underground experimental hall

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The BDX detector

**DM DETECTION**
modular EM Calorimeter
- 800 CsI(Tl) crystals (from BaBar EMCal)
- 8 modules 10x10 crystals each
- ~3 m long, ~50x50 cm² front face
- 6x6 mm² SiPM readout

**BACKGROUND REJECTION**
Two active veto layers
Plastic scintillators + WLS + SiPM

OUTER VETO:
- Plastic scint + Light guide + PMT

INNER VETO:
- Plastic scintillator paddle + WLS fibres + SiPM

4x4 BaBar Crystals

BDX-proto fully assembled at INFN-Catania

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Cosmic background measured with the BDX detector prototype in Catania and LNS (similar overburden expected at JLab) and conservatively projected to the full detector.

Expected cosmic background counts in the BDX lifetime:

<table>
<thead>
<tr>
<th>Energy Threshold (MeV)</th>
<th>Expected Counts (285 days meas.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>740 ± 300</td>
</tr>
<tr>
<td>250</td>
<td>57 ± 25</td>
</tr>
<tr>
<td>300</td>
<td>4.7 ± 2.2</td>
</tr>
<tr>
<td>350</td>
<td>0.037 ± 0.022</td>
</tr>
</tbody>
</table>
Beam-related Background - Simulations

Beam-dump and surrounding geometry/materials implemented in FLUKA and Geant4

**FLUKA vs GEANT4 at the beam-dump exit**

- High-energy muon production in the dump dominated by the $\gamma\rightarrow\mu^+\mu^-$ process
- Very good consistency between Geant4 and Fluka for $\mu$ production in the dump
- On-site measurement of muons downstream of the Hall-A beam dump to validate MC simulations

**FLUKA vs GEANT4 at different distances from the dump**

REASONABLE AGREEMENT ON HIGH-ENERGY PARTICLE FLUXES BETWEEN FLUKA AND GEANT4
Beam-related Background - Results

- FLUKA: **biasing techniques**

- **High statistics** simulations: 300 cores x 3 months simulating $\sim 10^{17}$ EOT equivalent at BDX detector location

  Particles produced in the BD by the 11 GeV beam are tracked to BDX detector location

- 6.6m iron shield + 2m concrete to stop high energy muons
- different shielding configuration tested

  ★ No n and γ with $E > 100$ MeV are found at the detector location

  ★ All the $\mu$ emitted forward and passing through the shielding are ranged-out

  ★ $\mu$ emitted at a large angle in the dump, propagating in the dirt, and then, after a hard interaction, re-scattering in the detector result to a non-zero background rate but they have a kinetic energy lower than 300 MeV

All high energy SM particles ranged-out except neutrinos

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Neutrino
• $\pi \rightarrow \mu + \nu_\mu$  $\mu \rightarrow e + \nu_\mu + \nu_e$
• Mainly low energy (<60MeV) from decay at rest
• Some $\nu$ produced in HadShower and boosted to BDX detector

Non-negligible contribution of high energy $\nu$ interacting in the BDX detector

Neutrino interactions in the detector

- **NC**
  - $\nu_\mu + N \rightarrow \nu_\mu + X$
  - $\nu_e + N \rightarrow \nu_e + X$
  - All rejected by the detector threshold (limited energy transfer to $N$)

- **CC**
  - $\nu_\mu + N \rightarrow X + \mu$
  - $\nu_e + N \rightarrow X + e$
  - All rejected by identifying scattered $\mu$

  Could produce an high energy $e$ in the detector that mimics the signal

Different scattered $e^-$ angle for signal and bg

Neutrino BG can be identified and suppressed

★ BDX only limited by the $\nu$ irreducible bg
★ Expected beam-related bg counts (after analysis cuts) $\sim$5 events
Measuring the flux of $\mu$ produced in the Hall-A beam-dump at the BDX location as a benchmark for simulations

- Two wells equipped with 10" pipes drilled at ~25m and ~28m from the dump
- A detector (BDX-Hodo) lowered into the pipes down to beam height to measure the $\mu$ flux when 11 GeV beam is on
Beam-related Background - On-site measurements

**BDX HODO** same technologies proposed in the final experiment

- **CRISTAL**
  - CsI(Tl) crystal (5x5 x 30 cm$^2$)
  - 6x6 mm$^2$ Hamamatsu SiPMs

- **SCINTILLATORS**
  - 13 plastic scintillator paddles 1 cm thick
  - 3x3 mm$^2$ SIPM coupled via WLS fibers

- **CONTAINER**
  - Cylindrical vessel (d=20cm, h=52cm)
  - Stainless steel, water-tight

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BDX muon test

Run: from Feb 22nd to May 2nd 2018

Hall-A beam parameters:

- $I_{\text{Beam}} \sim 22\mu\text{A}$
- $E_{\text{Beam}} = 10.6$ GeV
- Diffuser:ON

+ 1 week taken in Well II with $E_{\text{beam}}=4.3$ GeV

First muon signal on the scope

The BDX-Hodo lowered in well 1

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Beam-related Background: On-site measurements

**BDX Muon test**
**DATA/SIM comparison**

★ Absolute rates for data and simulations in agreement within the density-related uncertainty band

★ The shape of rates sampled at different heights is well reproduced by simulations (gaussian with the same $\sigma$)

Agreement between data and simulations proves:

✳ the BDX simulation framework is reliable

✳ no significant contribution from neutron bg (high energy n and/or pile-up effects)
BDX expected reach

- $10^{22}$ EOT (65 uA for 285 days)
- BDX can run parasitically to any Hall-A - 10GeV experiment

**BDX SENSITIVITY IS 10-100 TIMES BETTER THAN EXISTING LIMITS ON LDM**

![Beam-related background and Cosmic background graph]

**Elastic X-e⁻ scattering - BDX reach**

**Inelastic X-N scattering**

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Conclusions

✦ BDX is a beam-dump experiment at JLab aimed to investigate the existence of Light Dark Matter (1 MeV - 100 MeV)

✦ Collecting $10^{22}$ EOT in 285 days of parasitic running (~4y-calendar) at 10 GeV the BDX experiment can be 10-100 times more sensitive than previous experiments, excluding a significant area of the parameter space in case of null results.

✦ A new experimental hall, downstream of Hall-A beam-dump, will host the BDX detector based on ~800 CsI(Tl) crystals + InnerVeto + OuterVeto

✦ A BDX detector prototype was constructed and used to validate the proposed technology and measure cosmic background rates.

✦ We implemented two strategies for a reliable beam-related background estimate:
  ✓ high statistics simulations: biasing method in FLUKA, simulating $~10^{17}$ EOT (equivalent)
  ✓ measurement on site when the accelerator is running

✦ In July BDX has been approved by the JLab-PAC46 with the maximum scientific rate.
Thank you for your attention

BDX Collaboration

• More than 120 researchers signed the BDX proposal

BDX Institutions
INFN-Italy: Genova, Catania, Roma, Bologna, Torino, LNS, LNF, Padova, RomaTV, SassariU, Ferrara, Bari, Lecco
Jefferson Lab
BNL
FNAL
Occidental College
University of New Mexico
SLAC
Ohio University
Stony Brook
Canisius College
University of New Hampshire
George Washington University
Mississippi Stae University
Hampton University
Old Dominion University
Northwestern University
Mainz University
Gulch
GlasgowU
IPN-Orsay