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Light Dark Matter Searches at Electron Beam-Dumps

International Workshop On Light Dark Matter At Accelerators

20-22 November, Fondazione Querini Stampalia - Venice

L. Marsicano (INFN Genova, Università di Genova)

Overview

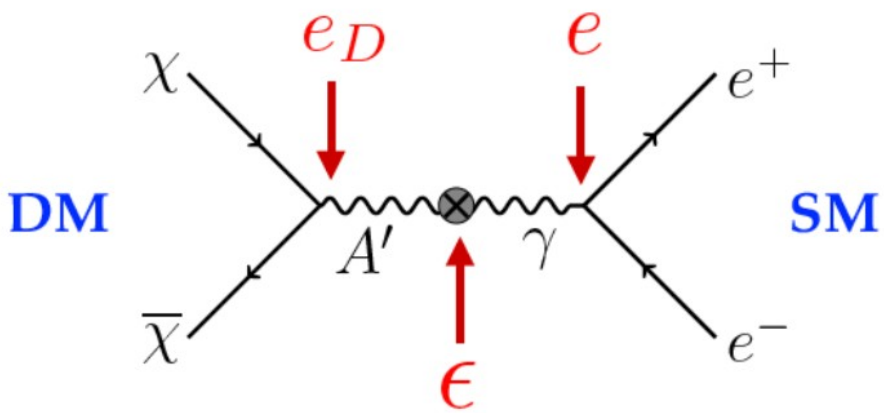
- **SLAC E137 Reanalysis**
  - E137 - visible
  - E137 - invisible
- **BDX @ JLab**
  - BDX Detector
  - Background Assessment
  - Sensitivity
  - BDX - Drift
  - BDX – BDX Mini
- **Conclusions**

Vector Mediated LDM

Light Dark Matter (mass in the MeV – GeV range) requires new mediator to reproduce the observed **DM relic density** in the **thermal DM hypothesis**

- Simplest scenario: new massive vector gauge boson (d*ark photon, A'*) mediates the interaction between DM and SM:

$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$



$$\alpha \equiv \frac{e^2}{4\pi}$$

DM charged under new mediator: e_D ~ e

Small A'-photon mixing: ε << 1

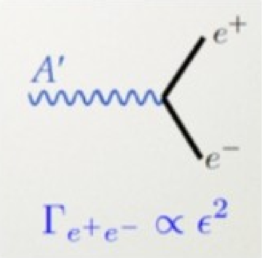
$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\,\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F_{\mu\nu} + \frac{m_{A'}^2}{2}A'_{\mu}A'^{\,\mu} + g_D A'_{\,\mu}J_D^{\mu}$$

Dark Photon Signatures

Two possible signatures for **on-shell** dark photon:

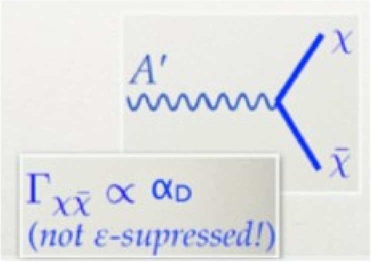
Visible: $A' \to e^+e^-$

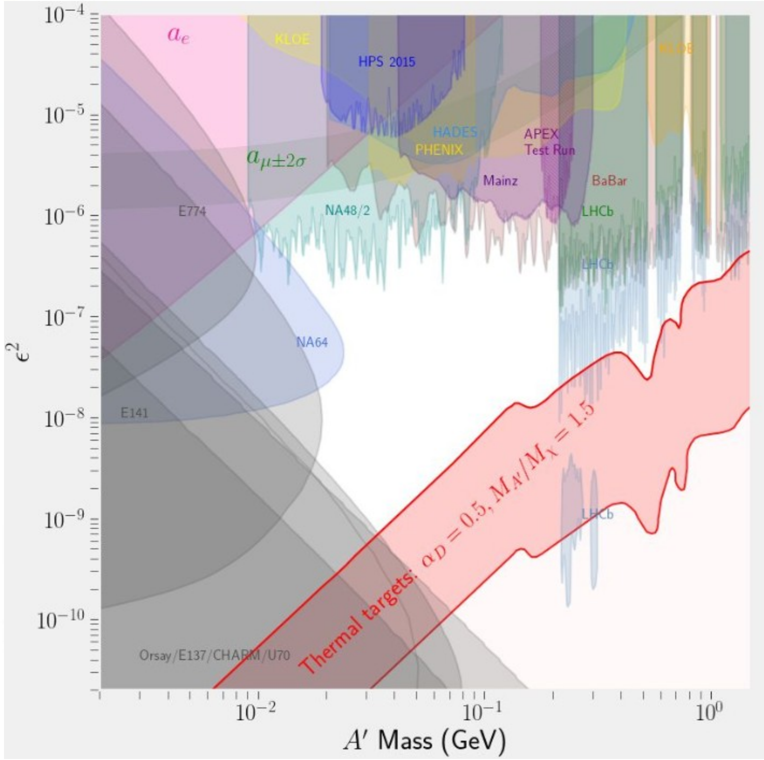
- $m_{A'} < 2m_\chi$
- Decay time depending on ε^2

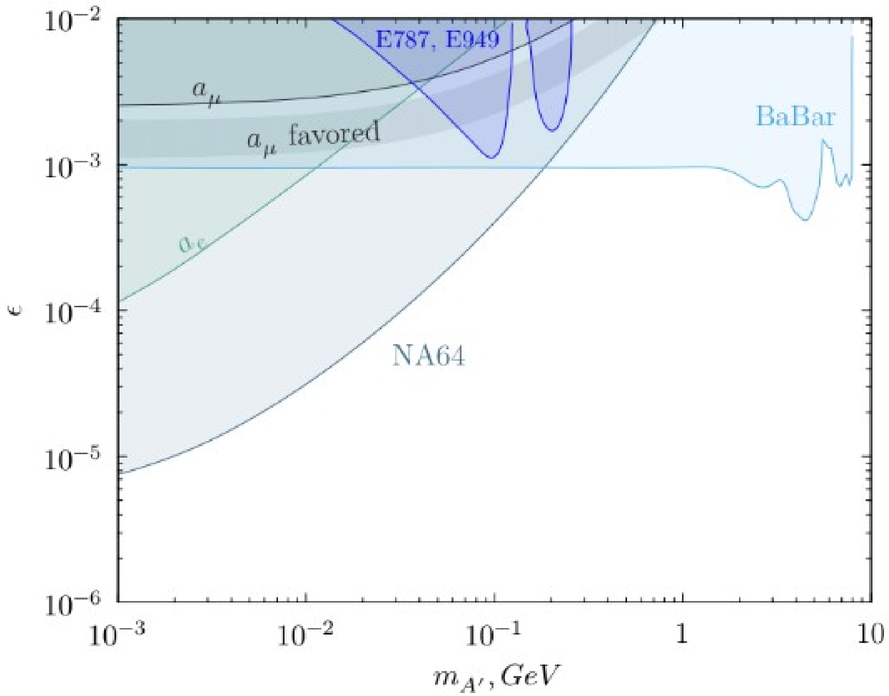


Invisible: $A' \to \chi\chi$

- $m_{A'} > 2m_\chi$
- Not depending on ε



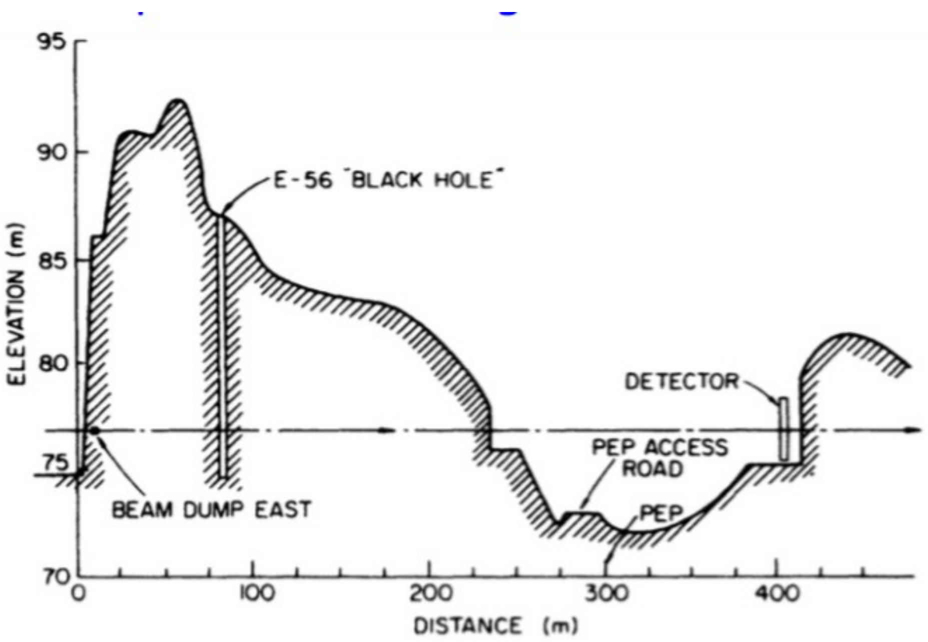




SLAC E137

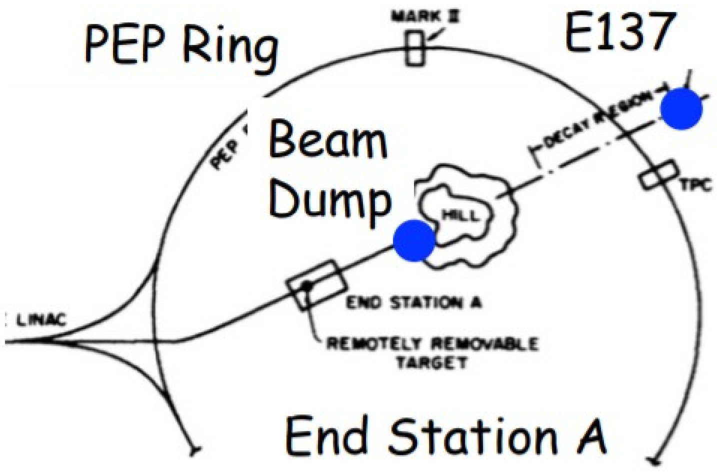
SLAC E137: electron beam-dump experiment from the ‘80s searching for long-lived axion-like particles

- Beam: 20 GeV, ~2 X10^{20} EOT
- Target: Aluminum-water beam-dump
- Shielding: 179 m of dirt (hill)
- Decay volume length: 204 m (air)
- Detector: EM calorimeter + MWPC



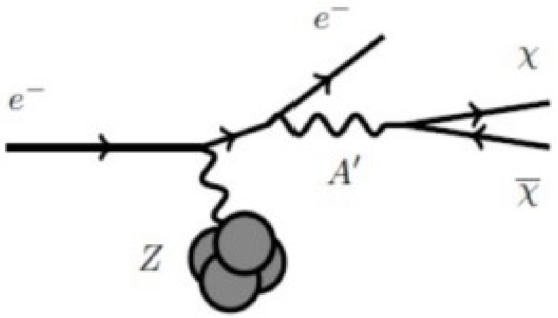
Results:

- No events observed: exclusion limits at 95% CL at 2.3 signal events
- Null result can be interpreted both in visible and invisible decay scenario
- Reanalysis suffer from **systematic errors** due to missing data concerning the experimental setup (e.g. the beam-dump materials)

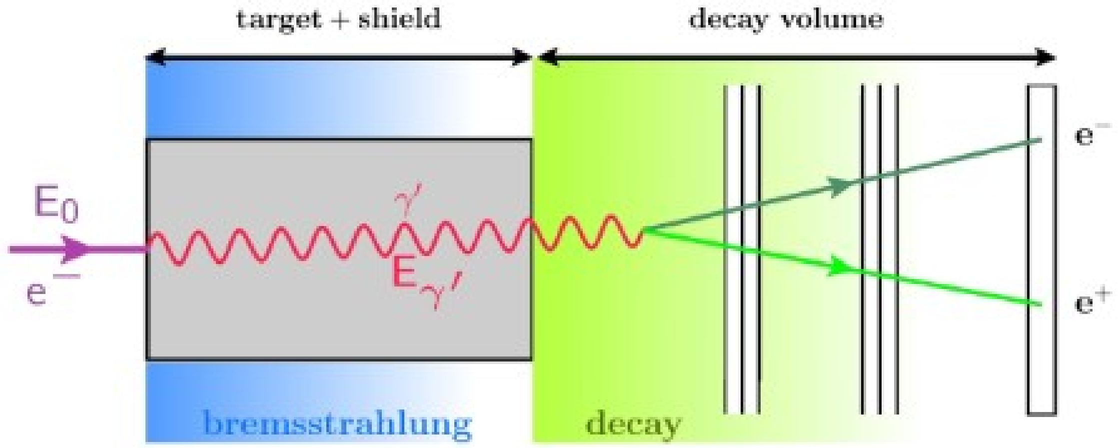


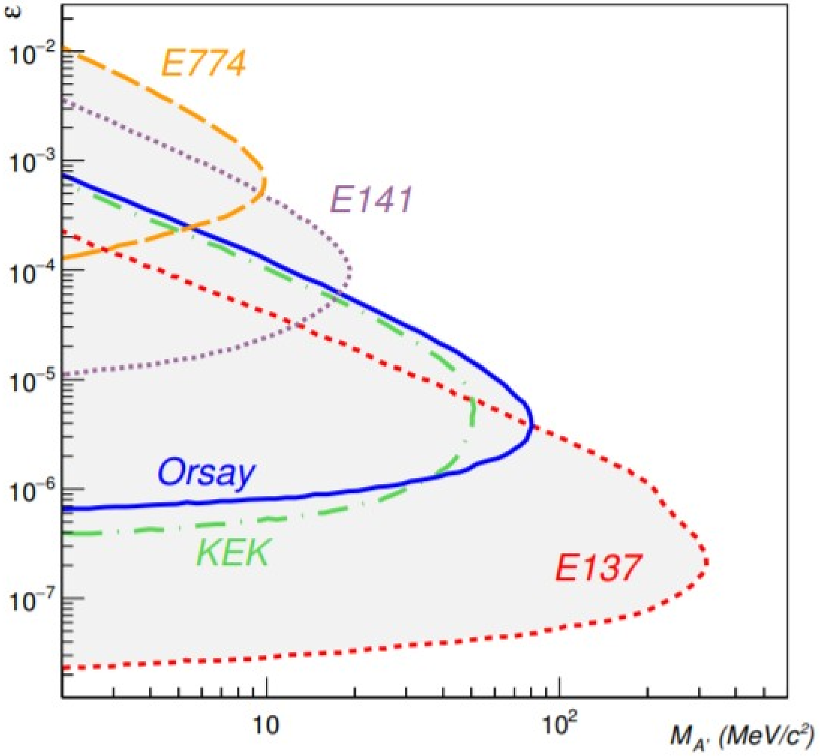
E137 Reanalysis - Visible Decay

- **Production:** radiative A’ emission (*A’-strahlung*)
- **Propagation and Decay:** long lived A’→ detached decay vertex
- **Detection:** e^+e^- pair result of A’ decay is measured in the downstream detector

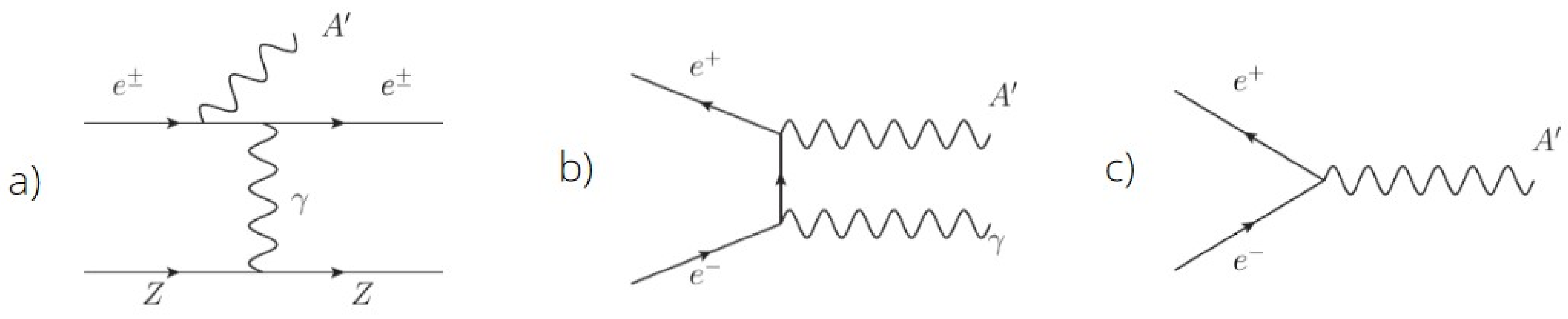


Two reanalysis (Miller,Andreas) resulting in similar exclusion limits

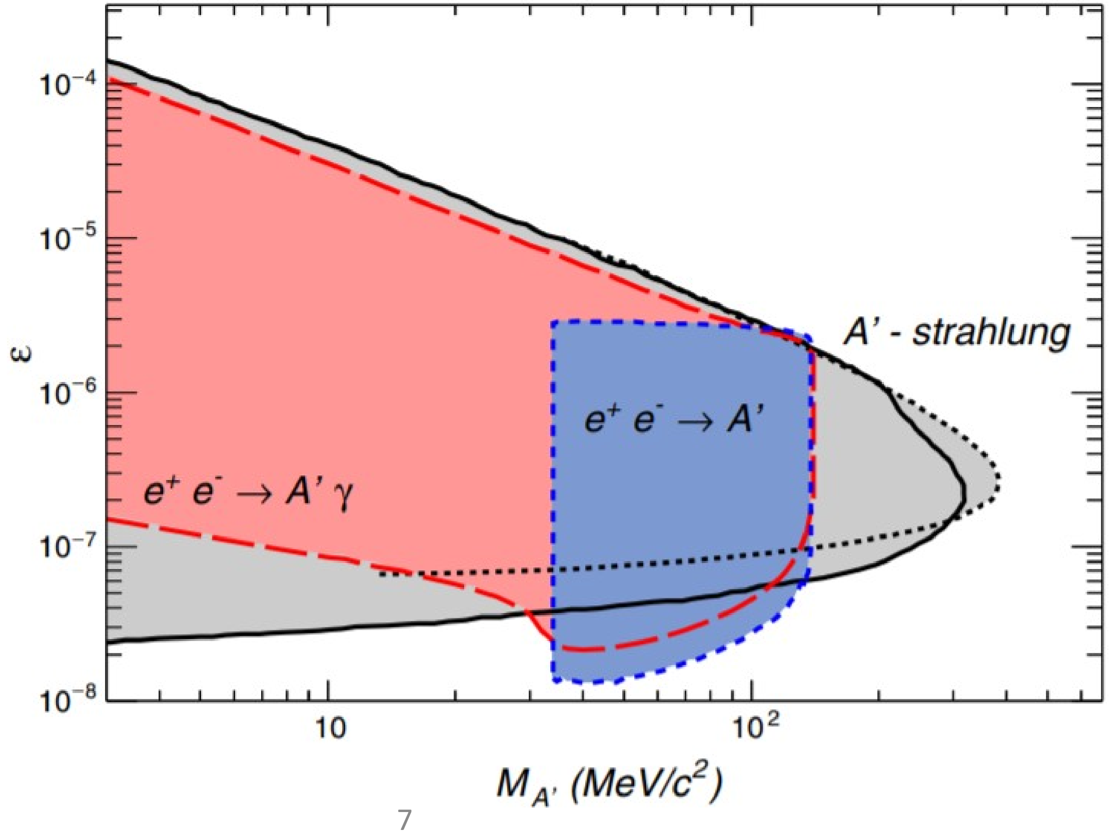




E137 Reanalysis – Secondary e+ Contribution



L.Marsicano *et al.* Phys. Rev. D 98, 015031 (2018)



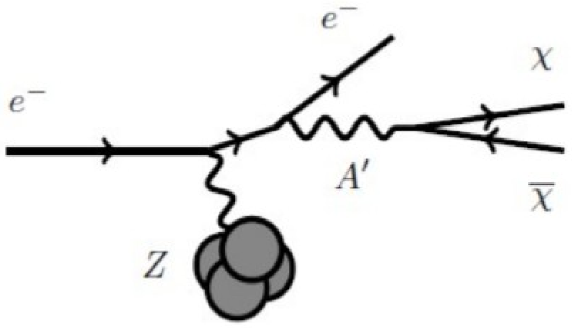
- Due to EM showering, an electron beam-dump is a positron rich environment
- e^+ contribute to the total χ yield with the resonant and non-resonant annihilation processes b) and c):
- Positron annihilation into A' scales as **$\varepsilon^2\alpha^2$** (b) or **$\varepsilon^2\alpha$** (c) compared to the **$\varepsilon^2\alpha^3$** scaling of the A'-strahlung

Secondary e^+ contribution to A' yield included in recent reanalysis (Marsicano)

Electron Beam Dumps – Invisible Decay

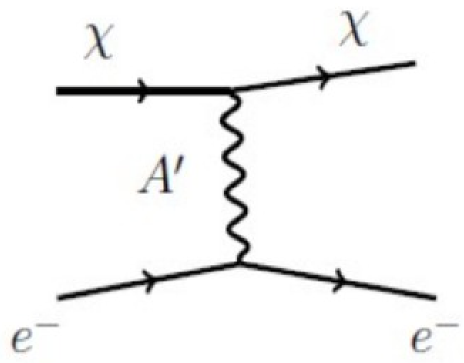
LDM Production:

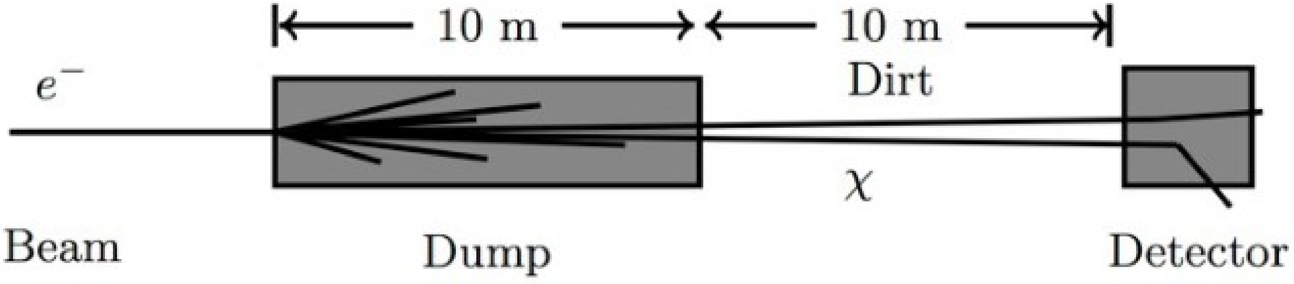
- High-energy, high-intensity e^- beam impinging on the dump
- Dark photons produced radiatively through **A'-strahlung** and **secondary positron annihilation**
- A' decay to LDM particle pairs



LDM Detection:

- Detector placed O(20-100 m) behind the dump
- Neutral-current scattering on atomic e- through A' exchange, recoil releasing visible energy
- Signal O(100 MeV) electromagnetic shower





A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

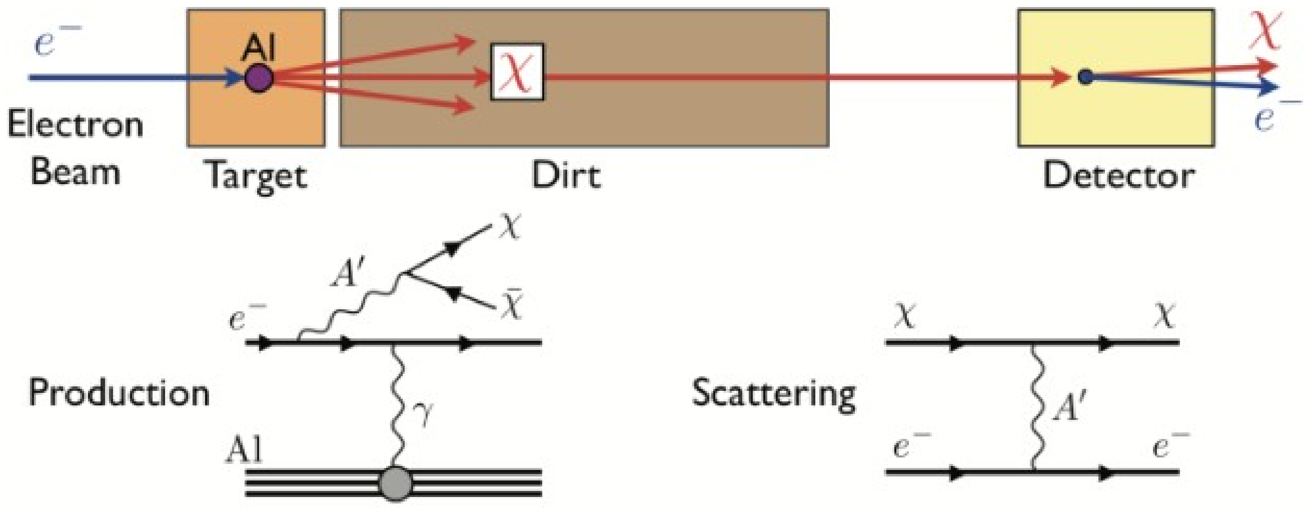
χ cross-section: $\sigma_{\chi e} \propto \frac{\alpha_D \varepsilon^2}{m_{A'}^2}$

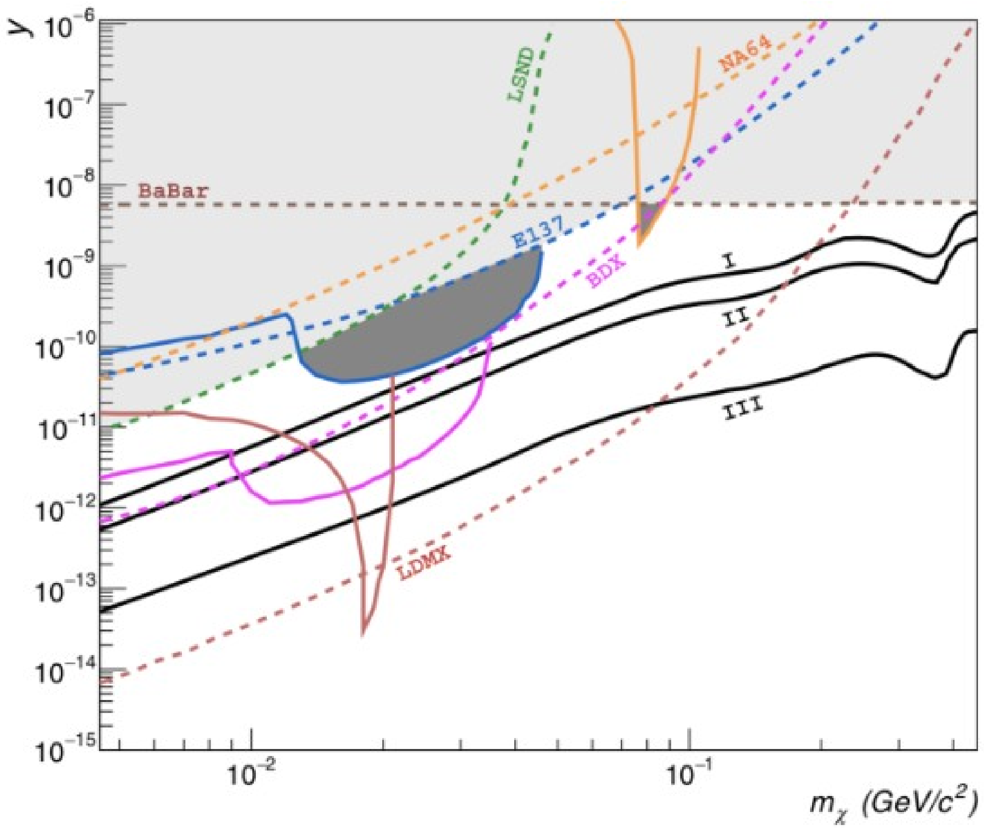
Number of events: $N_\chi \propto \frac{\alpha_D \varepsilon^4}{m_{A'}^4}$

E137 Reanalysis – Invisible Decay

- **E137** results have been reanalyzed also in the invisible A' scenario
- First analysis (Batell) focused on A′-strahlung production mechanism
- Recent analysis (Marsicano) included the contribution of secondary positron annihilation **e^+e^- → A'** to the total A' yield

L. Marsicano *et al.*, Phys. Rev. Lett. 121, 041802 (2018)

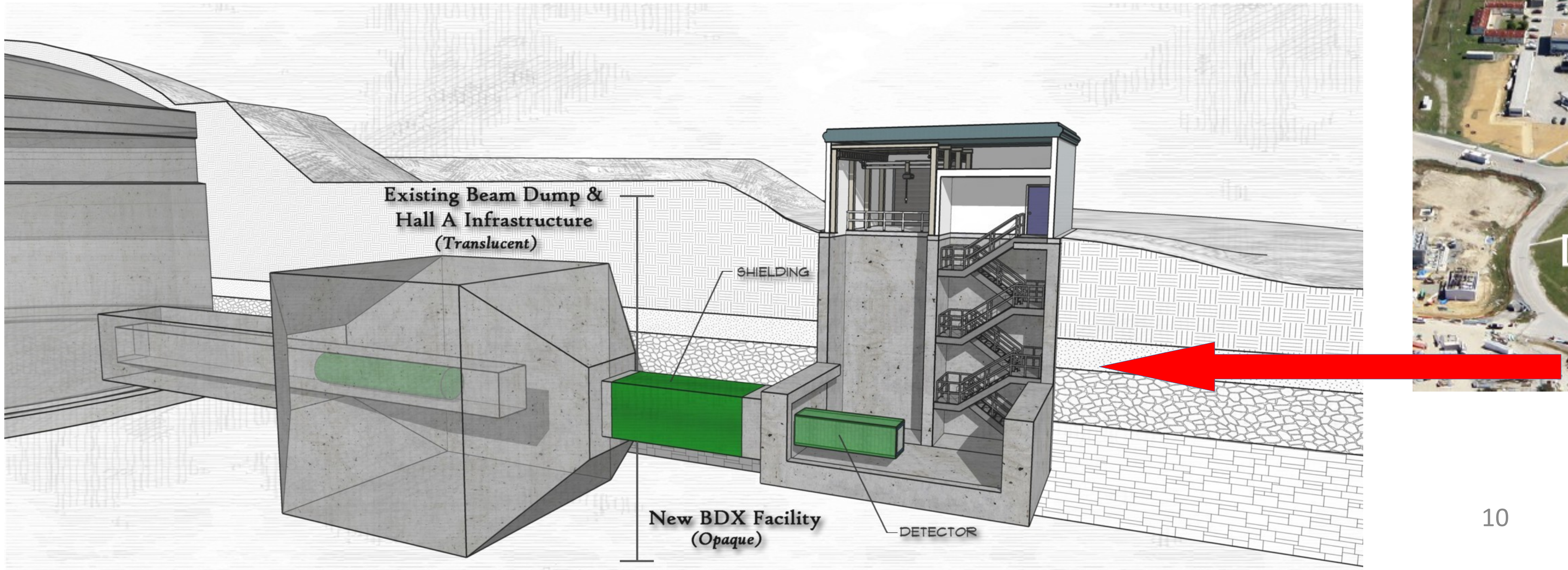


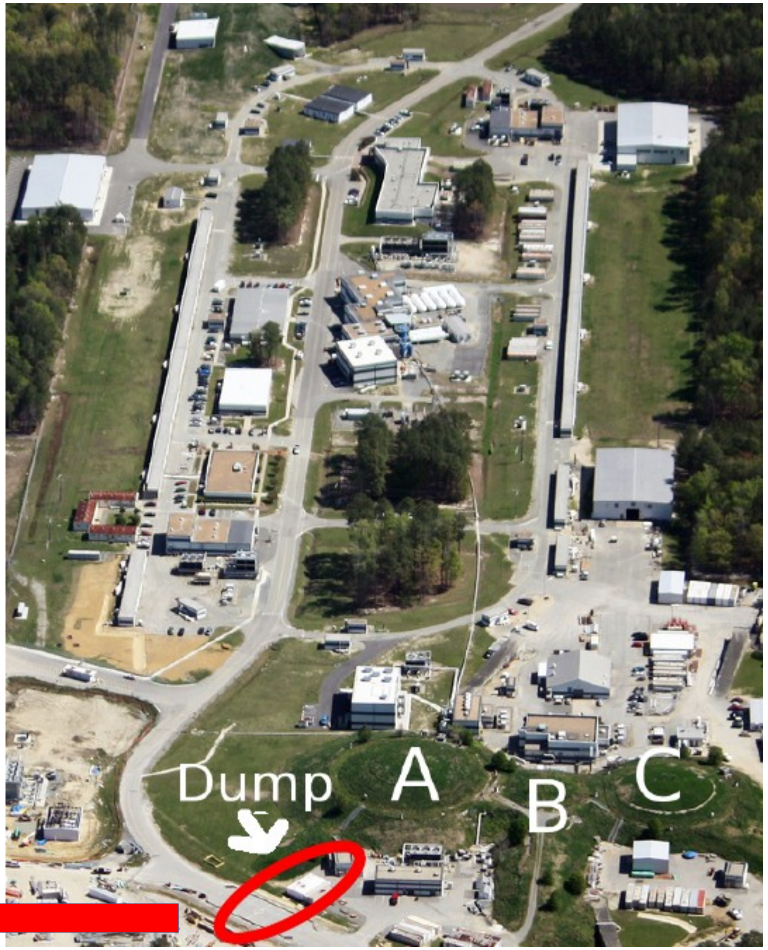


The Beam Dump eXperiment

BDX: modern beam-dump experiment at **Jefferson Lab** – CEBAF 11 GeV e^- beam, Al-H_2O beam-dump. 10^{22} EOT in ~285 days.

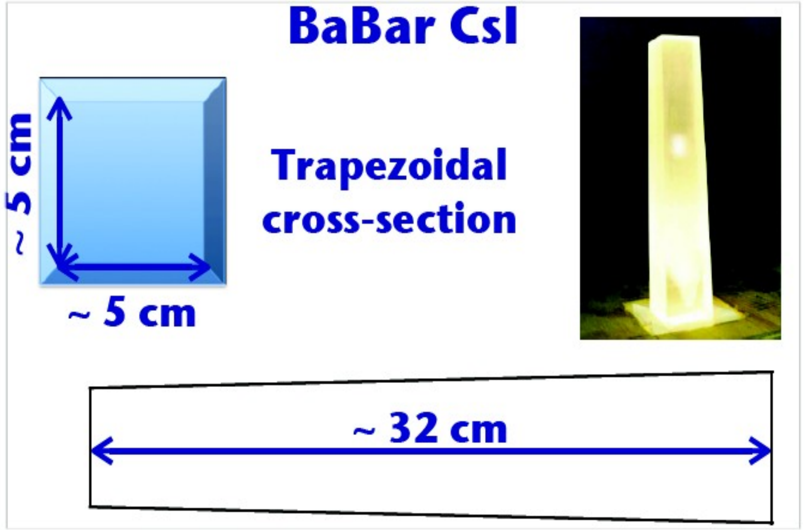
- Detector installed O(20 m) behind Hall-A beam-dump, in a **new experimental hall**
- Passive shielding layer between beam-dump and detector to reduce SM beam-related background
- Sizable overburden (10 m water-equivalent) to reduce cosmogenic background





The BDX Detector

BDX detector: state-of-the-art EM calorimeter, CsI(Tl) crystals with SiPM-based readout, surrounded by active veto layers and a passive lead shielding to reduce cosmic background



Detector design:

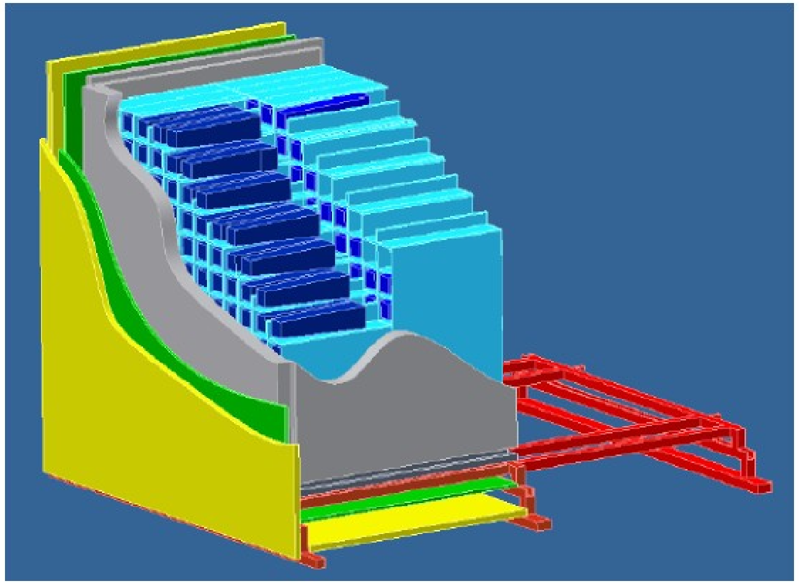
- 800 CsI(Tl) crystals, total interaction volume 0.5 m^3
- 5 cm thick lead shielding
- Dual active-veto layer (IV and OV), made of plastic scintillator counters with SiPM readout

Calorimeter arrangement:

- 1 module: 10x10 crystals, 30-cm long; front face: 50x50 cm^2
- 8 modules: interaction length 2.6 m

Signal:

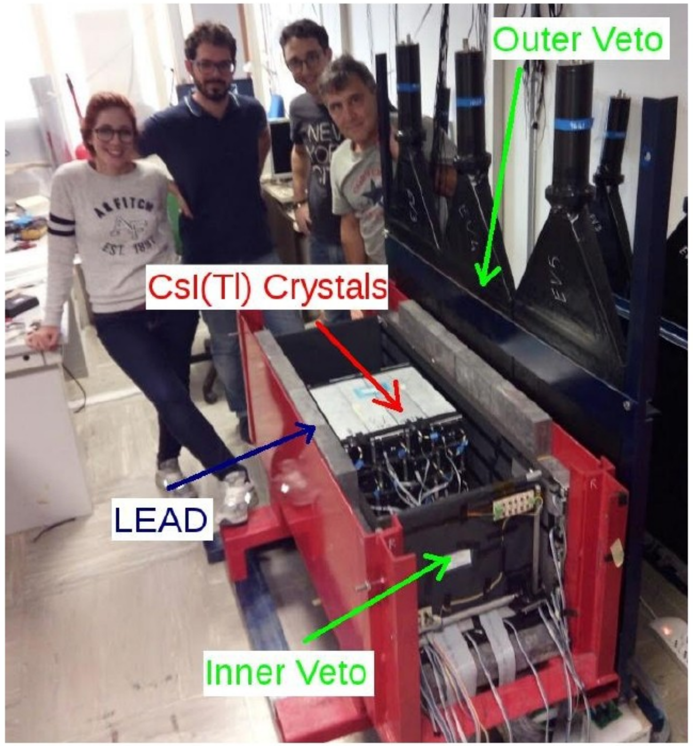
- EM-shower, (threshold: 350 MeV), anticoincidence with IV and OV
- Efficiency (conservative): O(10% – 20%) – dominated by EM shower splash back to veto counters



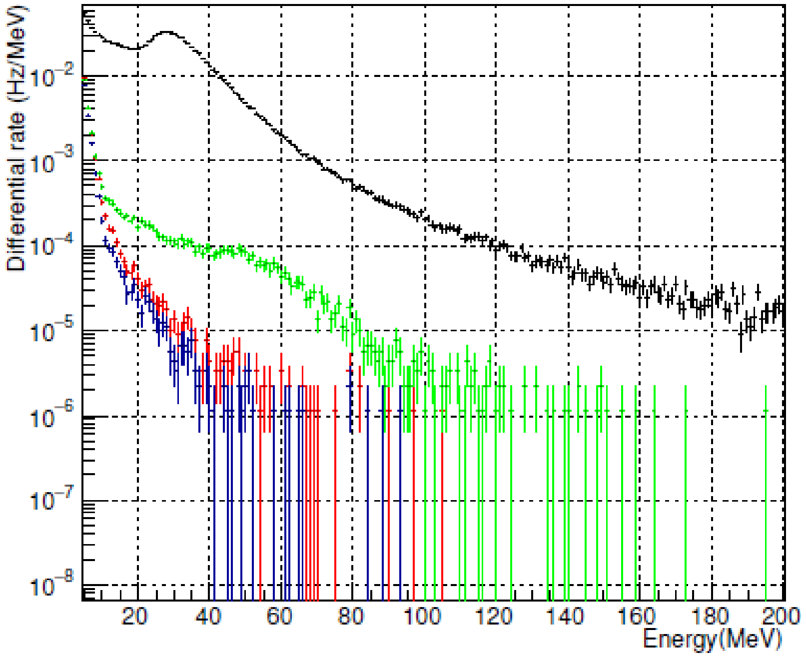
Cosmic Background Assessment

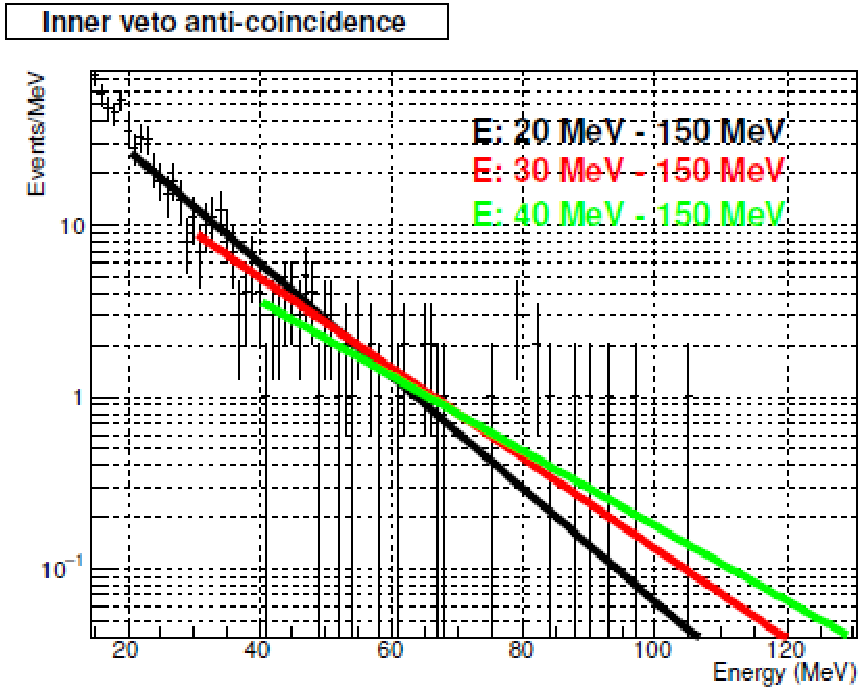
Cosmic background was measured with a small-size **Prototype detector** assembled in a bunker at **Laboratori Nazionali del Sud** (Catania), in order to reproduce similar conditions to those expected at JLab

Results were used to extrapolate the expected background rates of the final BDX experiment, scaling the measured experimental rates to the 800 crystals comprising the full detector



Energy threshold	Extrapolated rate
200 MeV	$(3.6 \pm 1.5) \cdot 10^{-8}$ Hz
250 MeV	$(2.9 \pm 1.3) \cdot 10^{-9}$ Hz
300 MeV	$(2.4 \pm 1.1) \cdot 10^{-10}$ Hz
350 MeV	$(1.9 \pm 0.9) \cdot 10^{-12}$ Hz



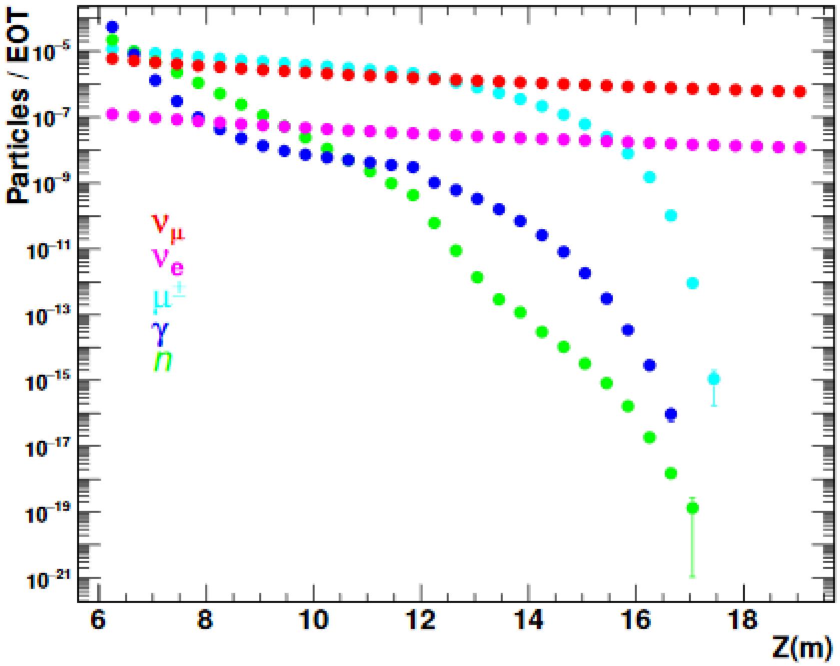


0 cosmic background events expected with an energy threshold over 350 MeV

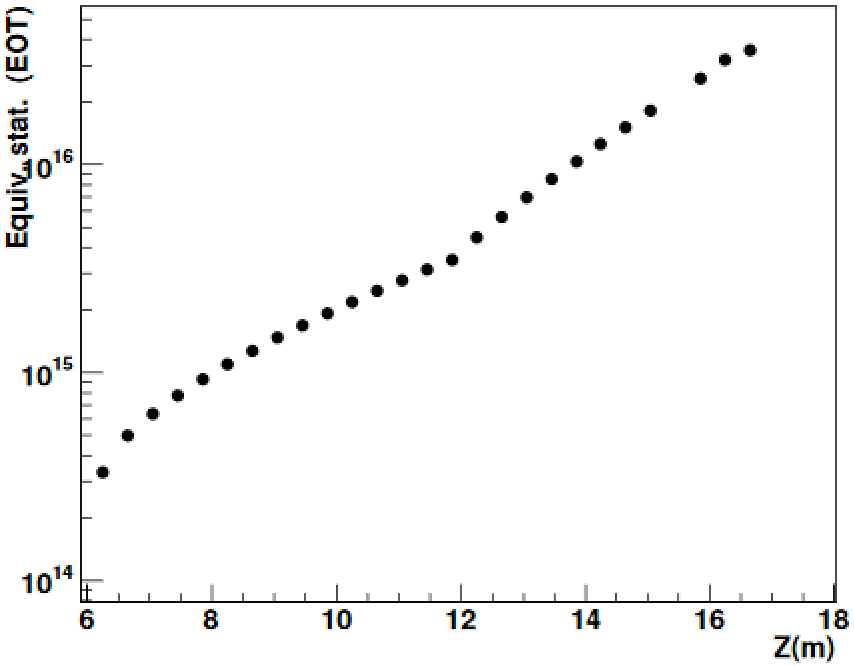
Beam-Related Background Evaluation

- Penetrating SM particles produced in the dump (muons, neutrons, neutrinos) can hit the detector mimicking the LDM signal
- This background can be evaluated only with simulations
- The large charge collected by BDX (10^{22}) EOT makes impossible to simulate the whole experiment
- Heavy use of biasing with **FLUKA** to achieve the highest possible statistic (~10^{17} equiv. EOT)
- Unbiased **GEANT4** simulations used as a benchmark

Flux of SM Particles at different depths in the shielding



Equivalent number of electron in the FLUKA simulation



Neutrino Induced Background Events

- Neutrinos are produced in muon decays and hadronic showers in the dump
- A sizable number of neutrinos propagate to the BDX detector
- A not negligible part of the ν spectrum has energy greater than 100 MeV

ν background evaluated through multi-step procedure:

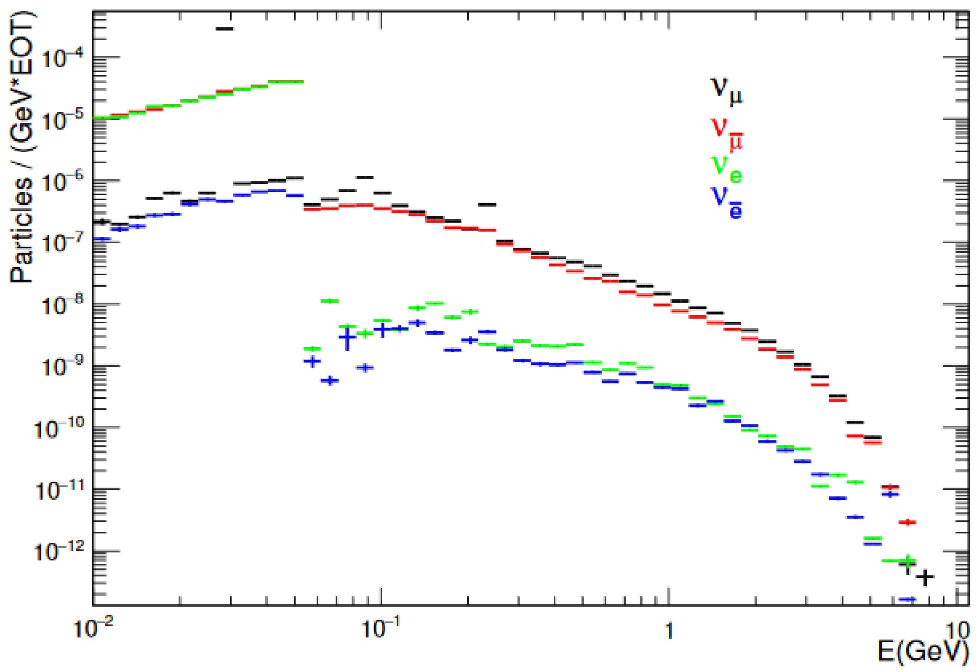
1. ν flux, obtained through a FLUKA simulation is sampled on a surface in front of the BDX detector

2. ν are propagated to the detector volume; interaction with the Cs/I nuclei is forced; secondary particles produced in the interaction are sampled

3. The response of the detector to neutrino secondaries is obtained from a dedicated GEANT4-based simulation

RESULT: with an energy threshold of 300 MeV, the number of foreseen neutrino events is ~5

Differential energy spectrum of neutrinos impinging on the BDX detector



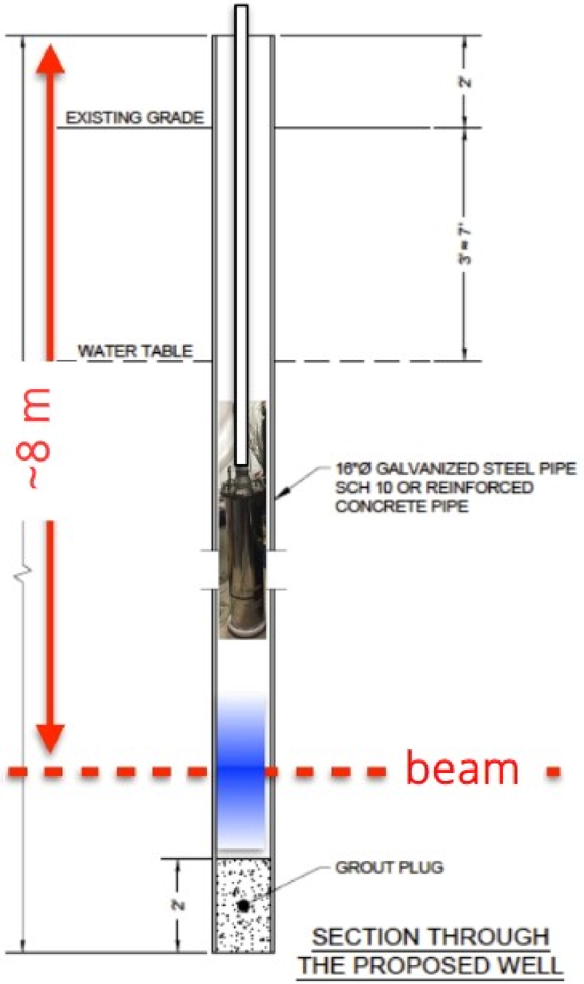
BDX Muon Test

Test to measure the beam on background

- Measure muon flux in the proposed BDX location
- Use results to validate simulations
- Check effects of beam-on background not accounted for in the simulations (low energy neutrons pile-up?)

BDX hodo:

- 1 CsI(Tl) crystal readout by a 6X6 mm^3 Hamamatsu SiPM
- 13 scintillator paddles 1 cm thick (readout by 3X3 mm^3 SipM + WLS fibers)
- Water-tight cylindrical vessel

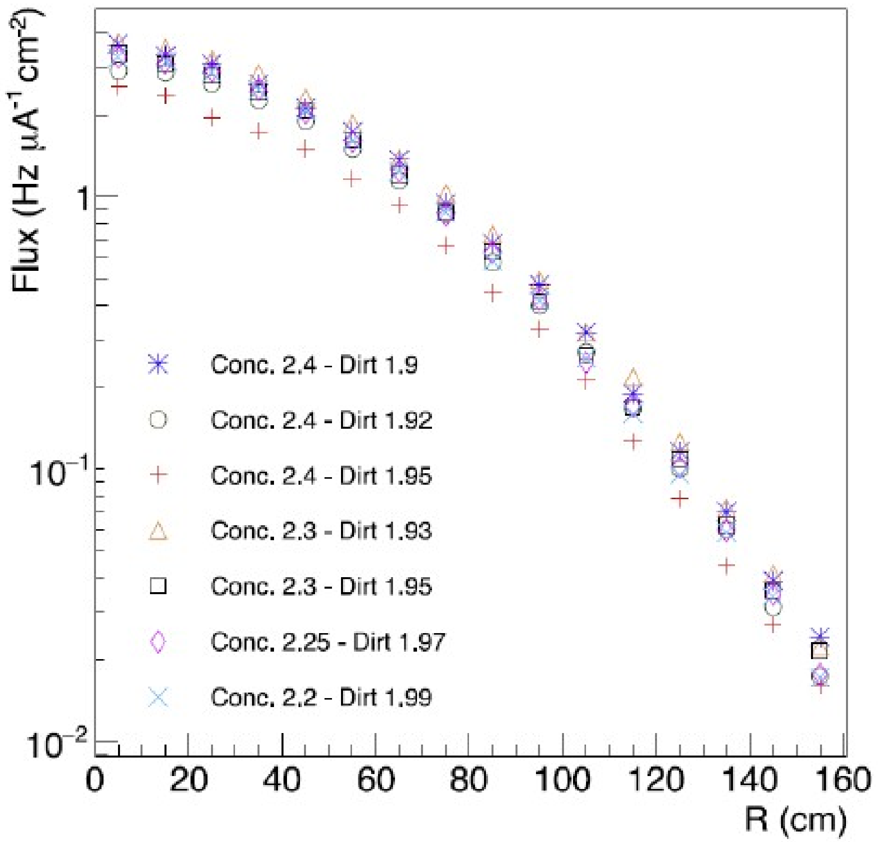


BDX Muon Test - Simulations

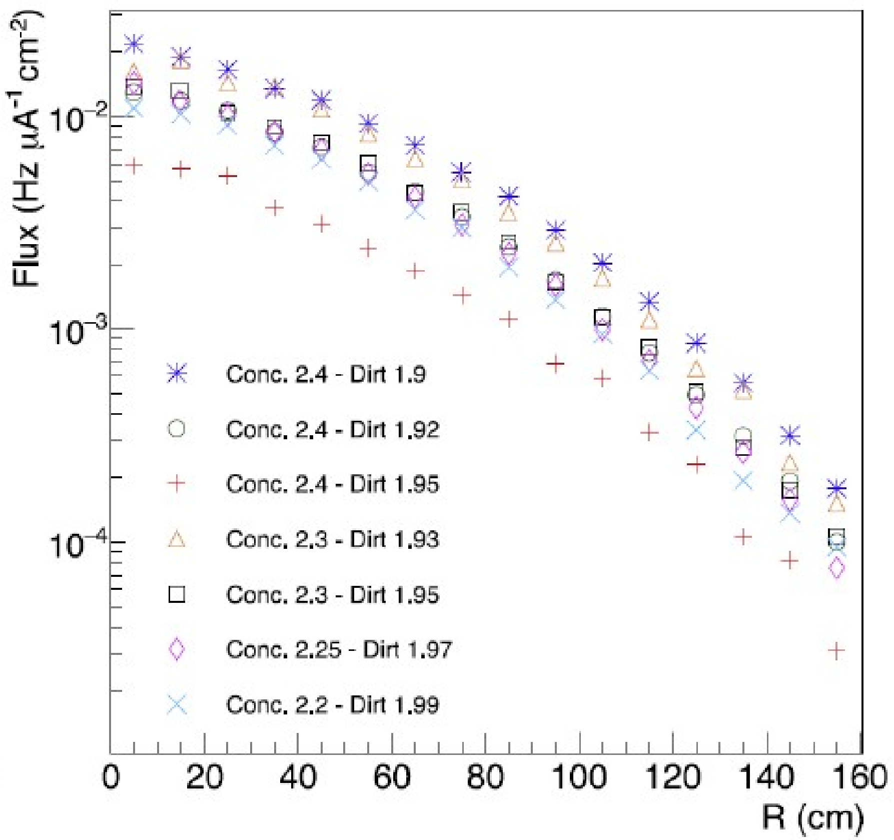
- The position of the measurement is close to muons range out distance
- Fluxes show critical dependence on the **dirt/bunker concrete density** value (known with a ~2 % uncertainty)

Sizable systematic error on the data/simulation comparison

Position B

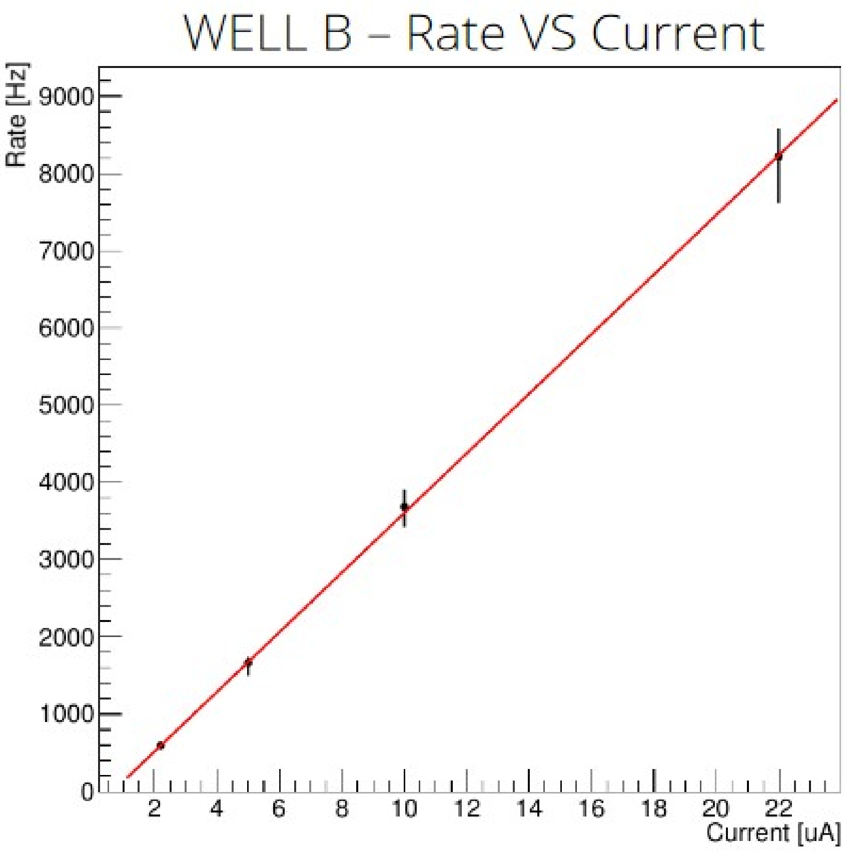


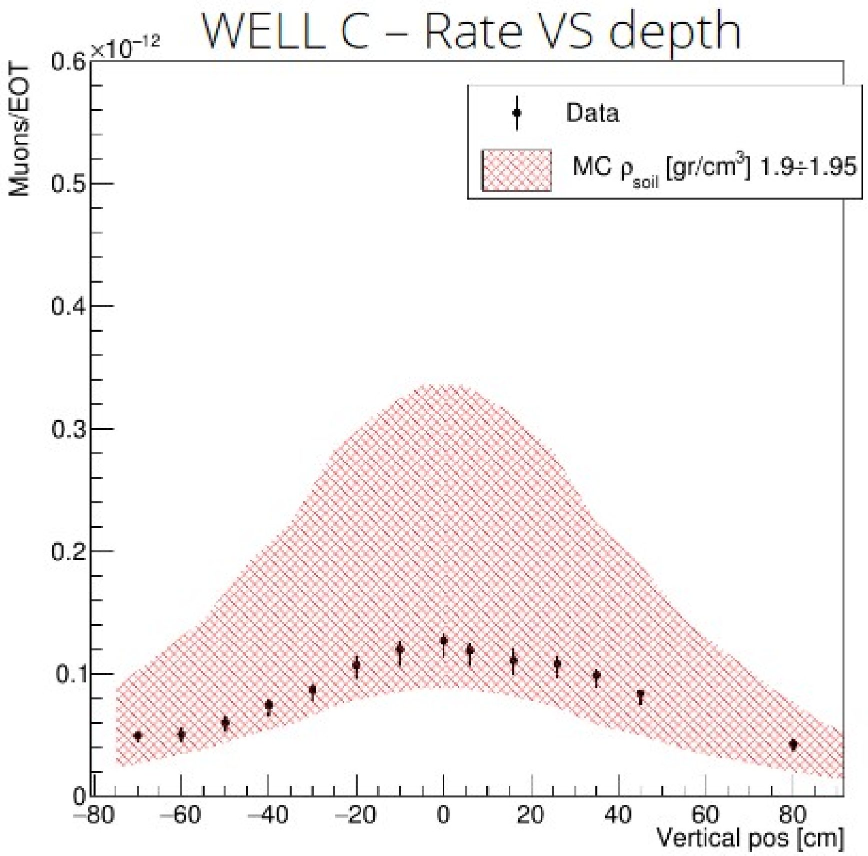
Position C



BDX Muon Test - Results

- The red band indicates the systematic error due to the dirt and concrete density uncertainity
- ρ_D measured in the position of the two wells, at beam height: 1.93-1.95 g/cm^3; no measurement of the bunker concrete density was available
- **Accounting for dirt and concrete density uncertainty, the agreement between data and simulations is reasonable**
- **NO neutrons pile-up effect was observed**





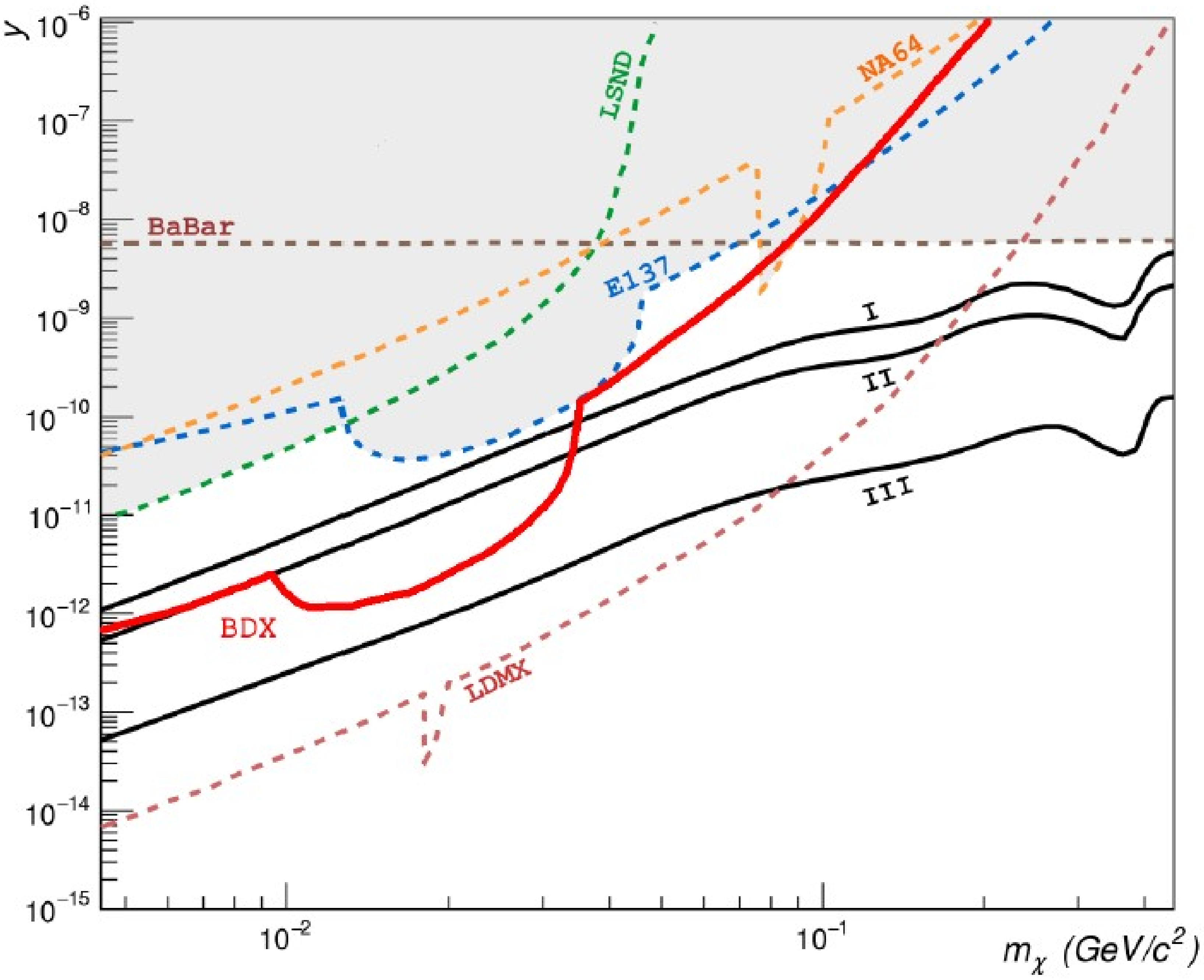
BDX Sensitivity

Beam Request:

- 10^{22} EOT (285 days @ 65 µA)
- Possible to run parasitically to any Hall-A 11 GeV experiment

Expected Backgrounds:

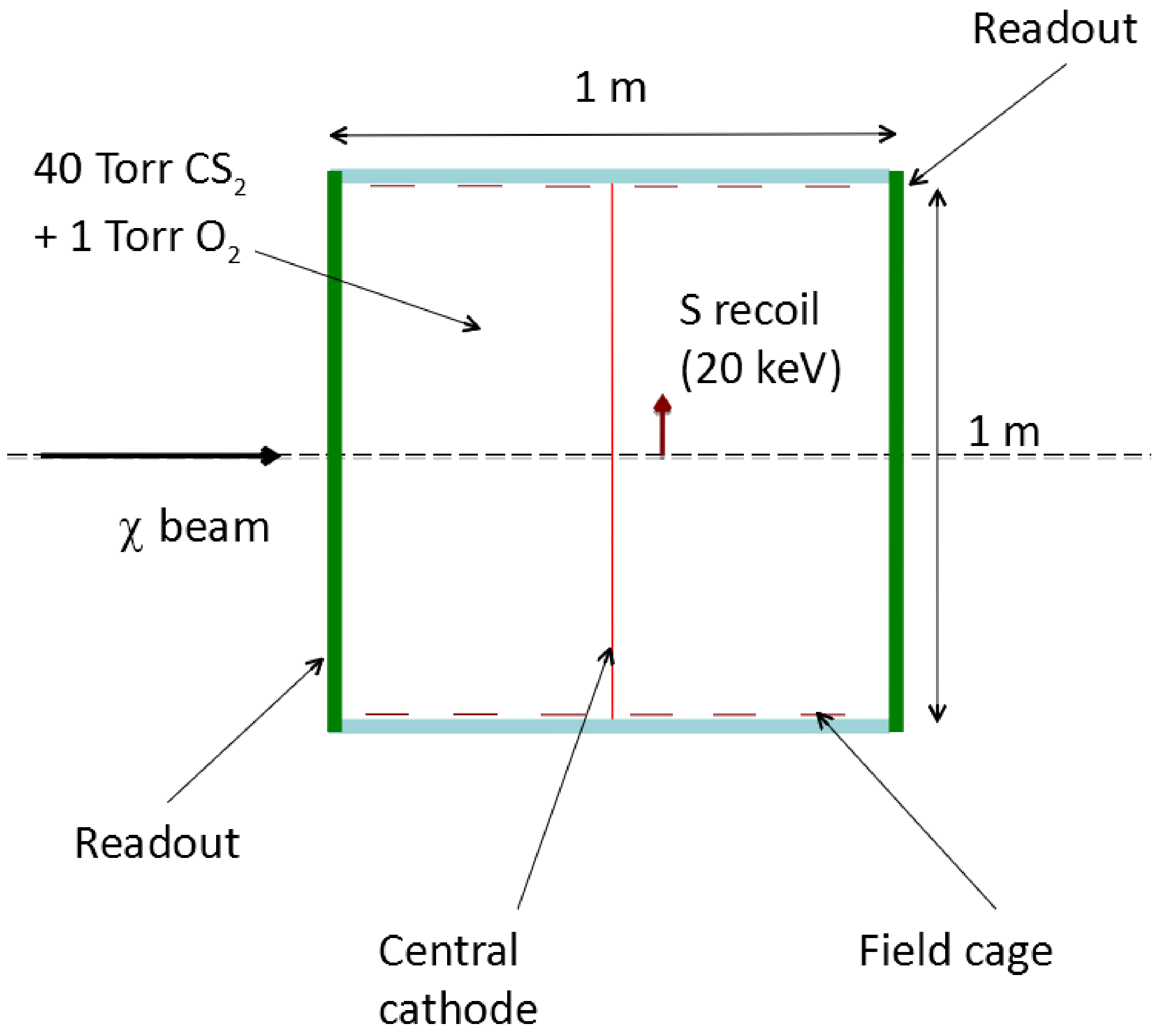
- Energy threshold: 350 MeV
- Neutrino background events: ~5 ev.
- Cosmic background events: ~0 ev.



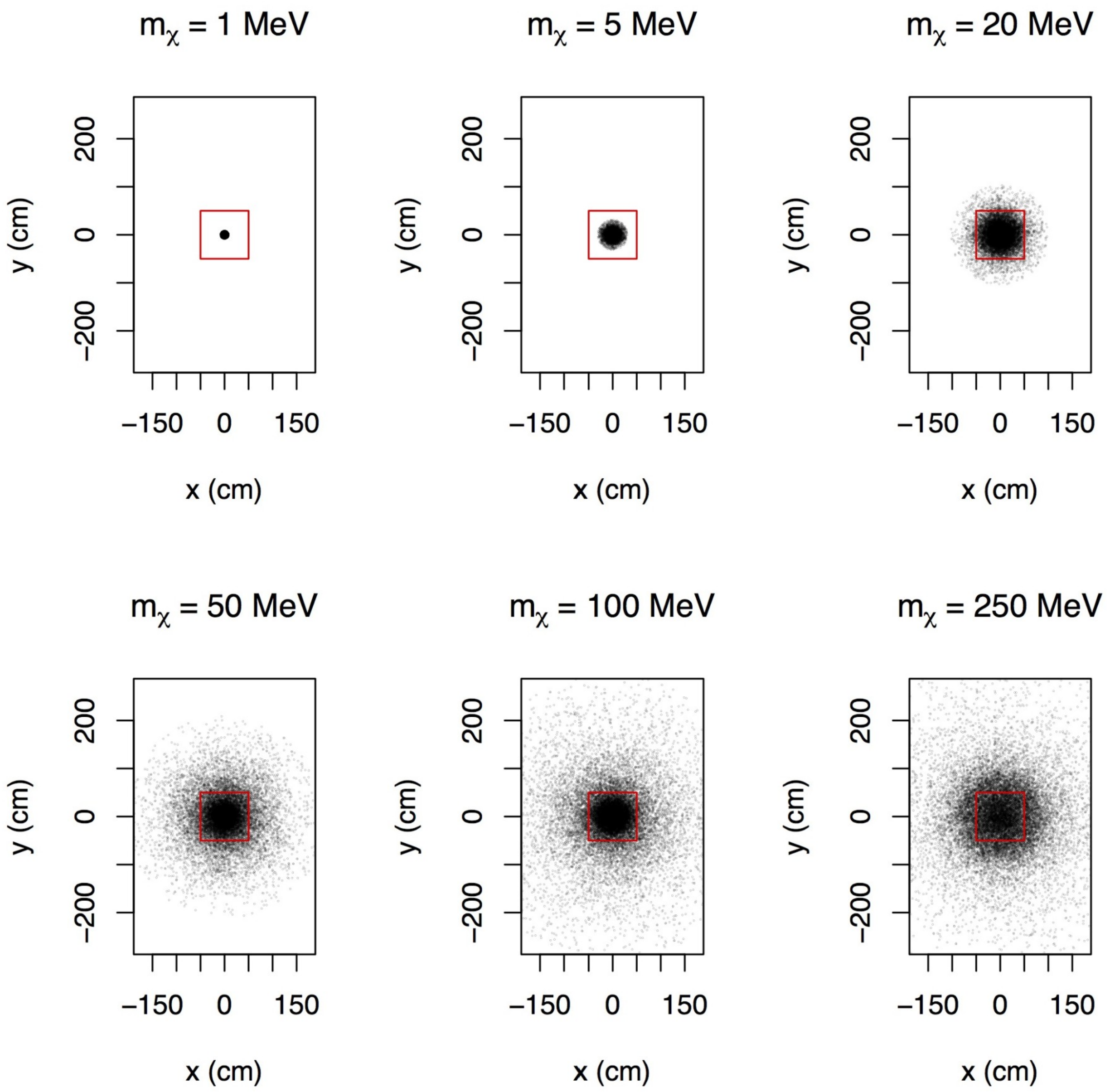
BDX-Drift

BDX Drift: unique, proven, halo-dark-matter detector running in parallel with BDX

- Low-pressure, directional TPC placed behind the BDX detector
- 10 modules 1 m each aligned along the LDM beam direction
- **Expected Signal**: S recoil (order 20 KeV) parallel to readout plane

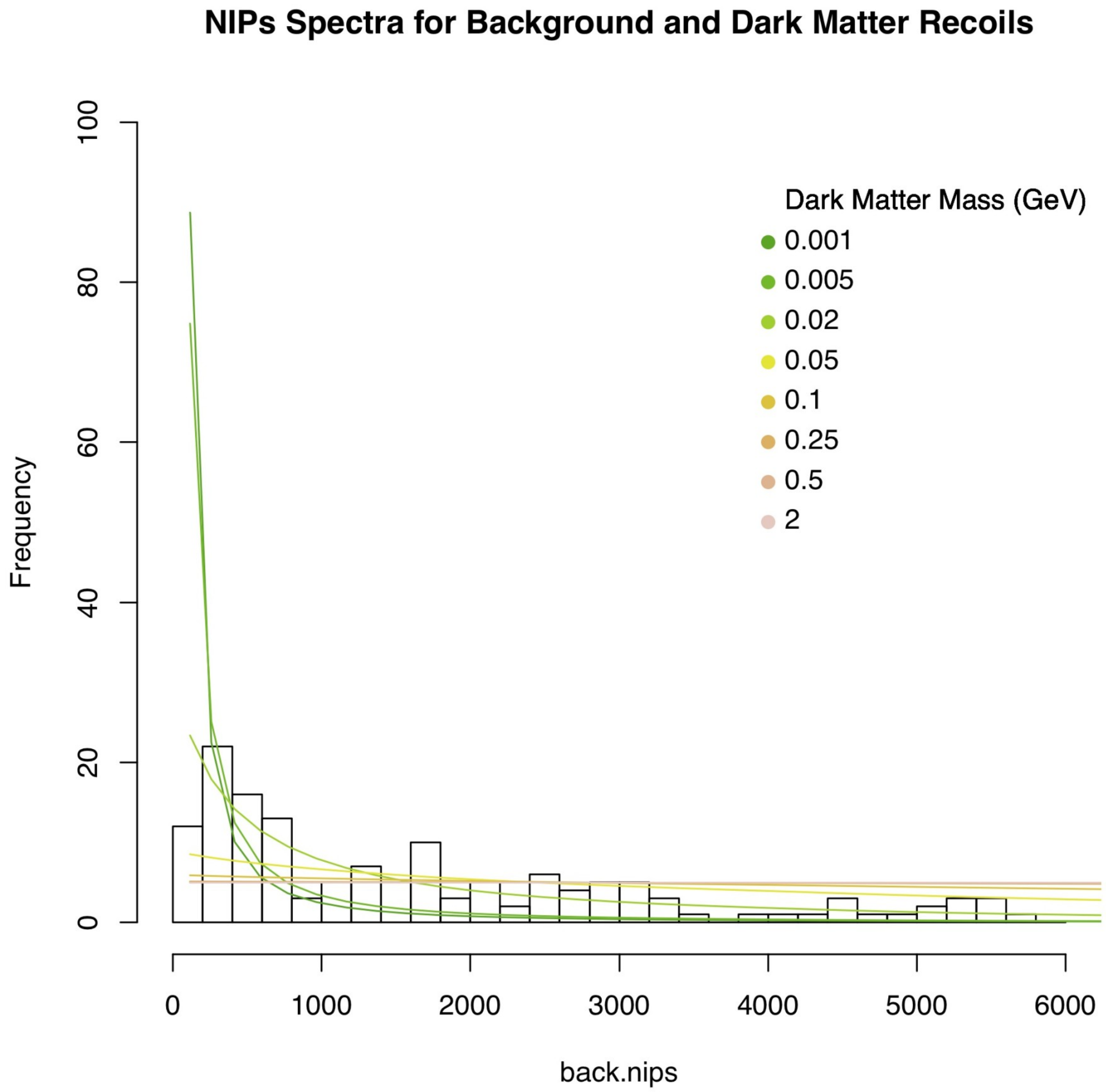


BDX-Drift Signatures - Position



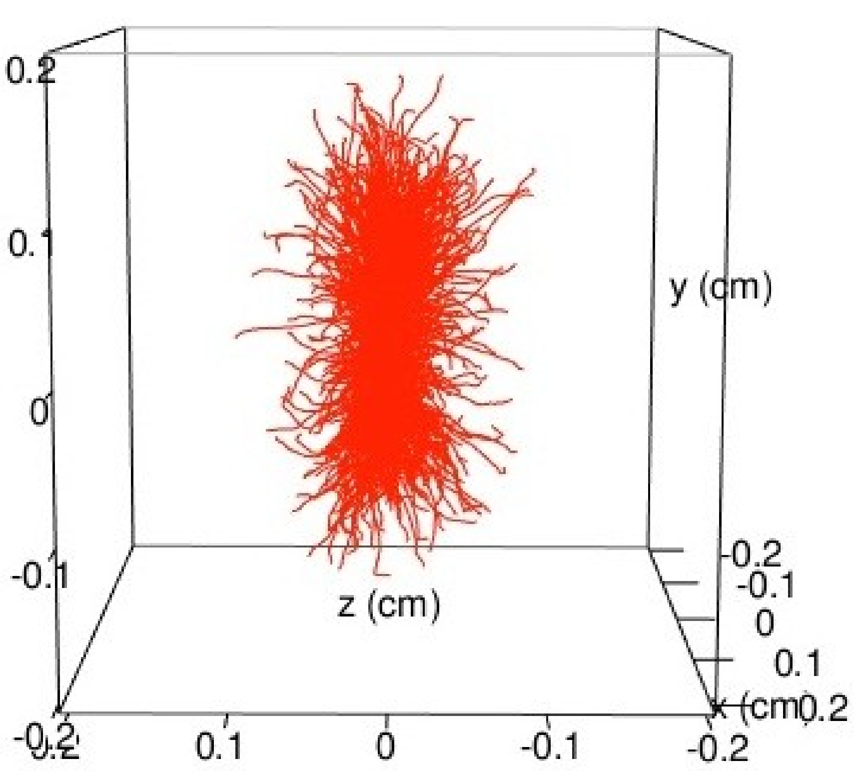
- Red box shows extent of the BDX-DRIFT detector
- Recoil distribution depends on m_χ
- Can be used to detect dark matter or reject background
- Off-axis measurements could be made to reject ν backgrounds

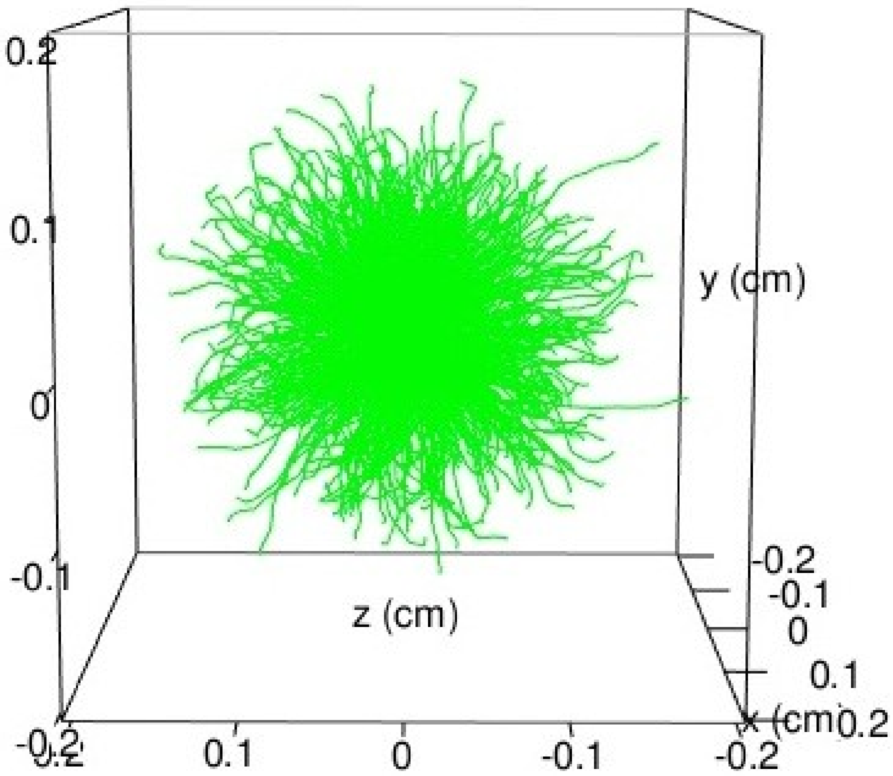
BDX-Drift Signatures - Ionization



- Histogram shows background ionization distribution
- Colored curves indicate predicted ionization distribution from dark matter according to mass
- For most masses one could discriminate

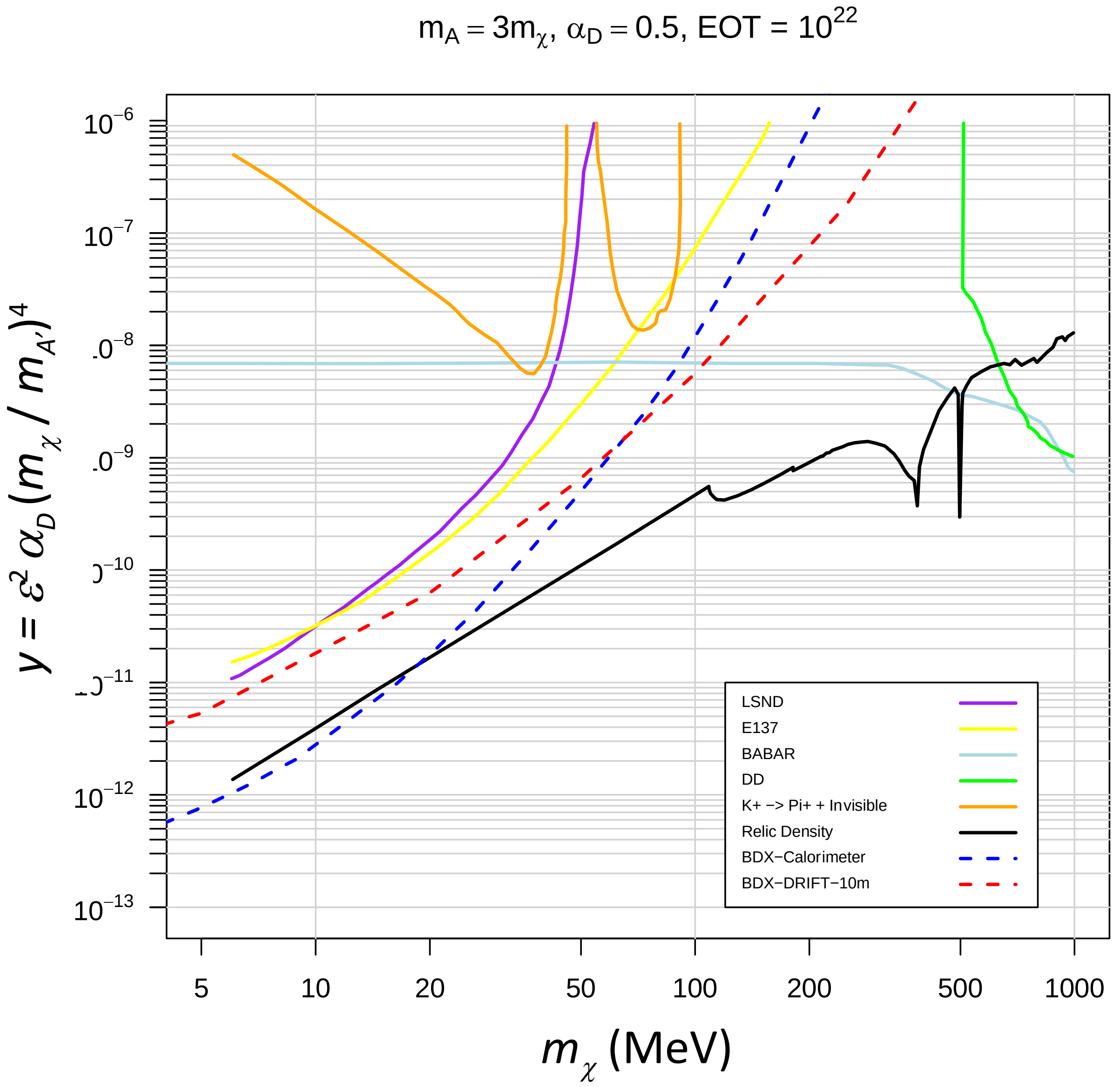
BDX-Drift Signatures - Direction





Different directional responses provide a strong signature

BDX-Drift Sensitivity



BDX Status

- R&D effort ongoing from 2014 (first LOI presented to JLab PAC42)
- Full proposal presented to PAC44 (2016) approved conditionally to benchmarking simulation with on-site measurement (bdx-hodo) and to detector optimization
- Measurement of the muon flux have been performed on site (spring 2018) with the endorsement and support of JLab; simulations proved to be in reasonable agreement with data
- Results have been presented to PAC46, which **approved the experiment with the highest scientific rating**

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

The BDX Collaboration

M. Battaglieri*†, A. Bersani, B. Caiffi, A. Celentano†, R. De Vita†, E. Fanchini, L. Marsicano, P. Musico, M. Osipenko, F. Panza, M. Ripani, E. Santopinto, M. Taiuti
Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dell'Università, 16146 Genova, Italy

V. Bellini, M. Bondí, M. De Napoli†, F. Mammoliti, E. Leonora, N. Randazzo, G. Russo, M. Sperduto, C. Sutera, F. Tortorici
Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Catania, Italy

N.Baltzell, M. Dalton, A. Freyberger, F.-X. Girod, V. Kubarovsky, E. Pasyuk, E.S. Smith†, S. Stepanyan, M. Ungaro, T. Whitlatch
Jefferson Lab, Newport News, VA 23606, USA

E. Izaguirre†
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada, N2L 2Y5

G. Krnjaic†
Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510

D. Snowden-Ifft
Occidental College, Los Angeles, California 90041, USA

*Contact Person, email: Marco.Battaglieri@ge.infn.it
†Spokesperson

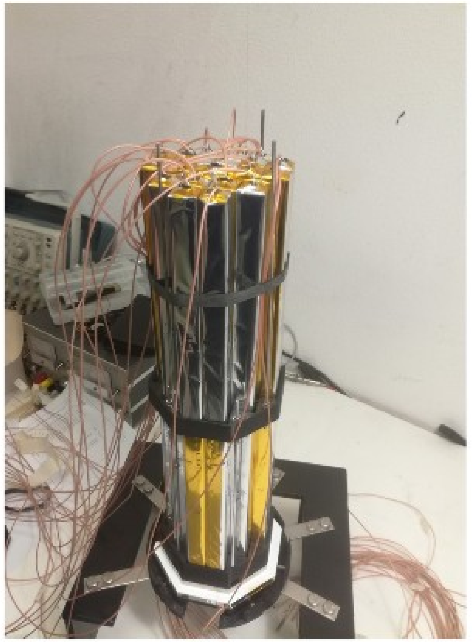
BDX-mini

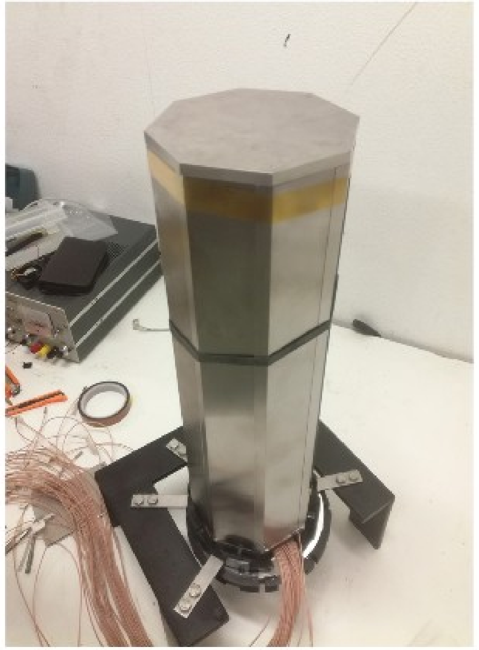
Waiting for the new experimental hall...

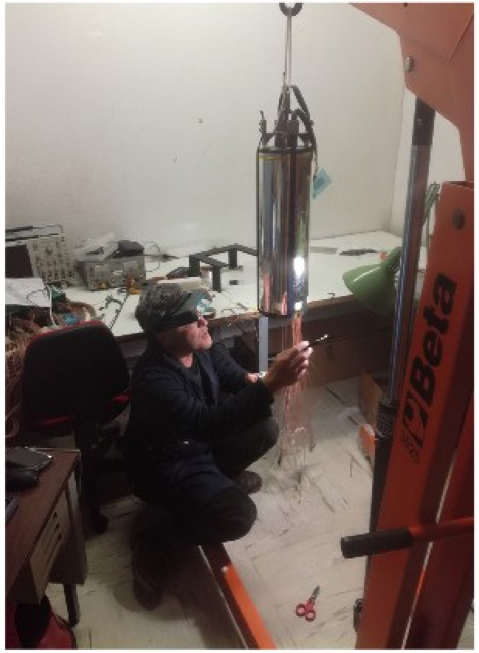
→ **BDX-mini**: small scale prototype for detector design and technology validation

Detector Components:

- 44x $PbWO_4$ crystals read by SiPMs (total volume about 0.004 m^3)
- 0.8 cm thick tungsten shielding
- double plastic scintillator layer read by SiPM + WLS fibers (20 channels in total)
- water tight stainless steel vessel





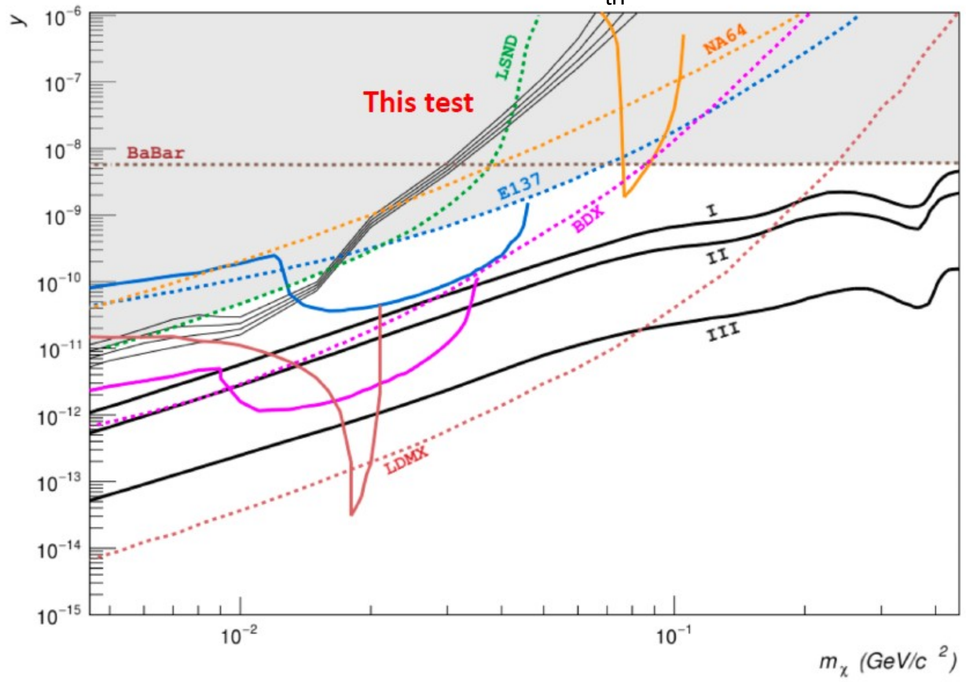


BDX-mini tests @JLab

BDX-mini measurement campaign @JLab:

- Detector lowered at beam height in a pipe drilled 25 m behind Hall A beam-dump
- Beam-on measurement foreseen fall 2019 (beam energy 2 GeV ; current 150 μA)
- Currently data-taking ongoing

BDX-mini Preliminary Reach – E_{th} = 100, 200,..,500 MeV



Conclusions

- Beam-dump experiments are sensitive to both visible and invisible decays of dark photons.
- Recent E137 reanalysis prove the importance of secondary particles contribution to the dark photon yield of beam dump experiments
- BDX is a modern electron beam-dump experiment optimized to search for LDM particles in the dark photon theoretical scenario using CEBAF e- beam and an electromagnetic calorimeter
- BDX-drift is a halo-dark-matter detector optimized to search for LDM. It will run in parallel to the approved BDX experiment, increasing its reach and adding new, powerful signatures to the search for dark matter at Jlab.