

HPS Collaboration meeting

📅 15 Nov 2021, 11:30 → 17 Nov 2021, 15:00 US/Eastern

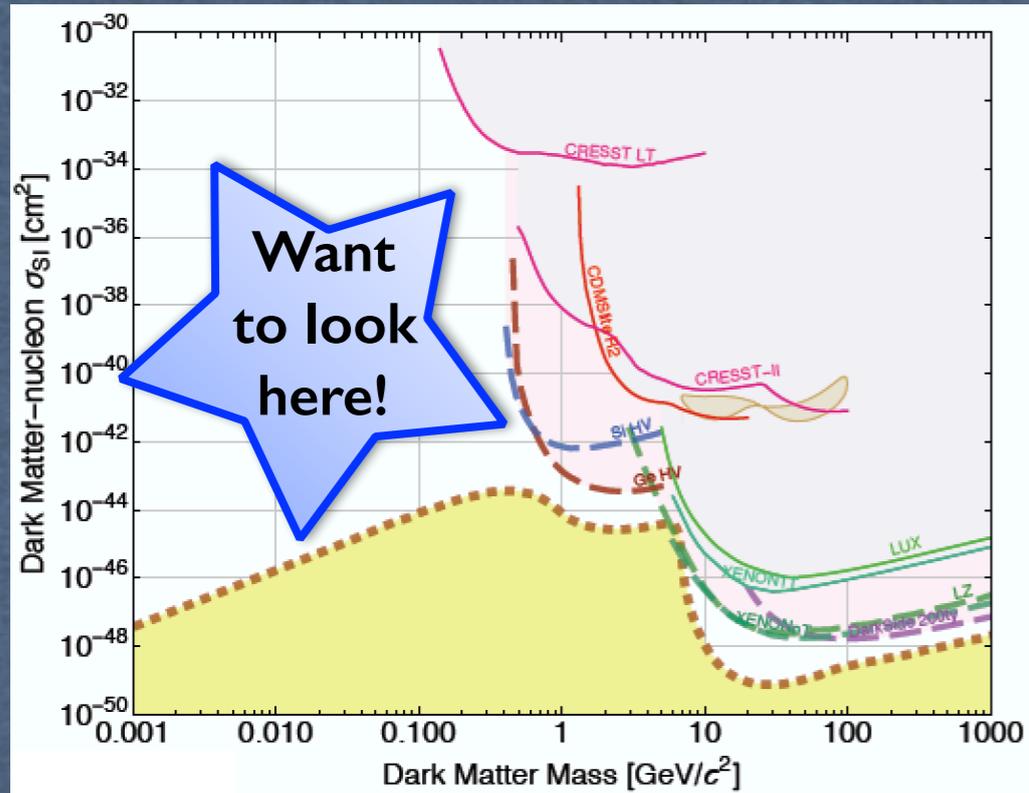
Nov 17 2021
HPS Collaboration Meeting

Update on BDX

M.Battaglieri, M.Spreafico
INFN-GE Italy

Light Dark Matter

★ Experimental limits



Light Dark Matter with a (almost) weak interaction (new force!)

- Direct Detection is (almost) impossible
 - Low mass elastic scattering on heavy nuclei produces small recoil
 - eV-range recoil requires a different detection technology
 - Directionality may help to go behind existing limits at large masses

Accelerators-based DM search

covers an unexplored mass region extending the reach outside the classical DM hunting territory

- **High intensity**
- **Moderate energy**

Light Dark Matter

Direct Detection

1 MeV

1 GeV

Mz

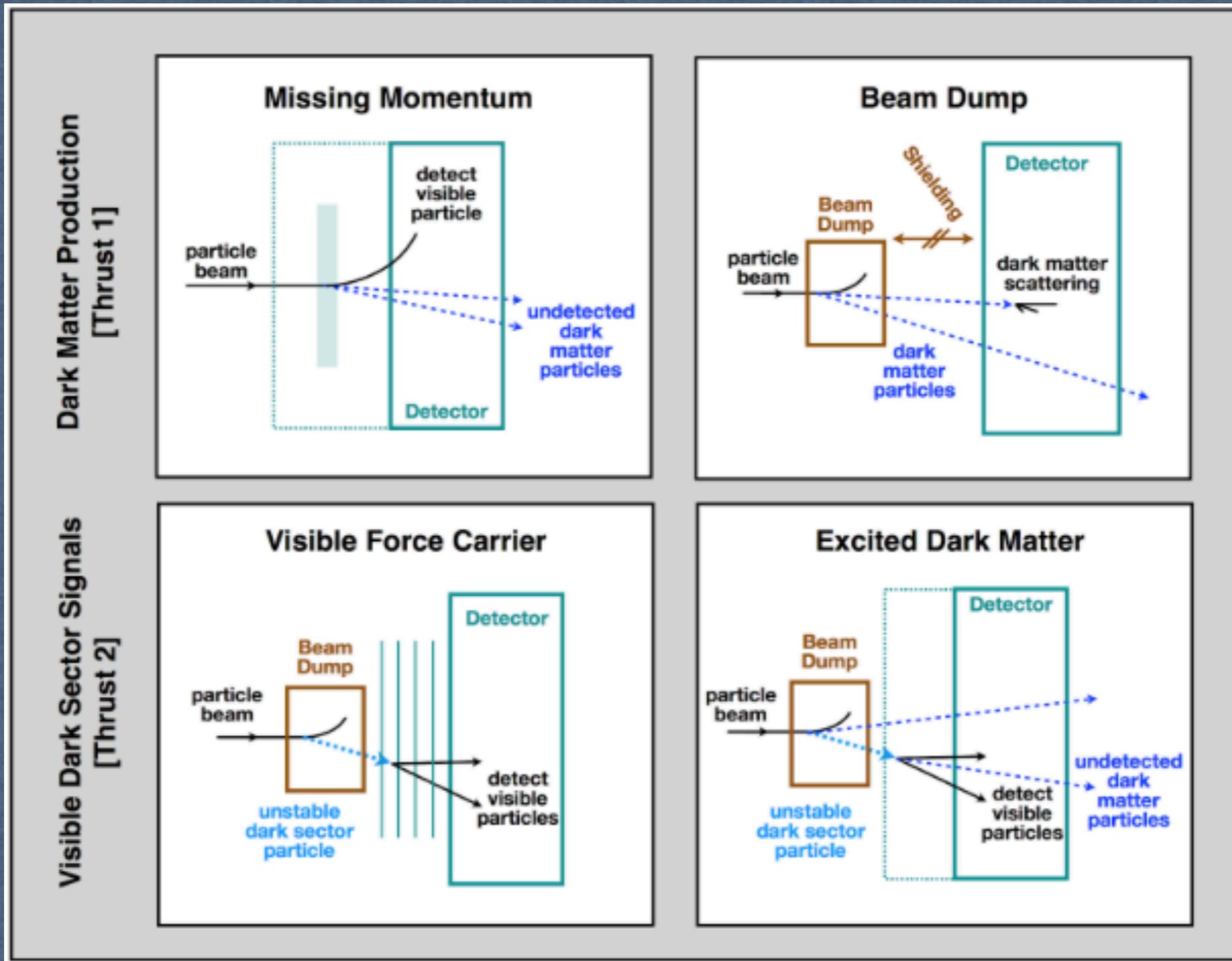
10 TeV

WIMPs

Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

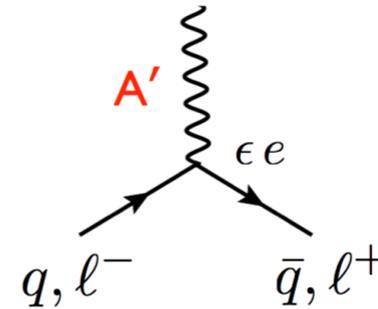
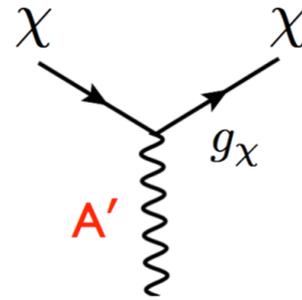
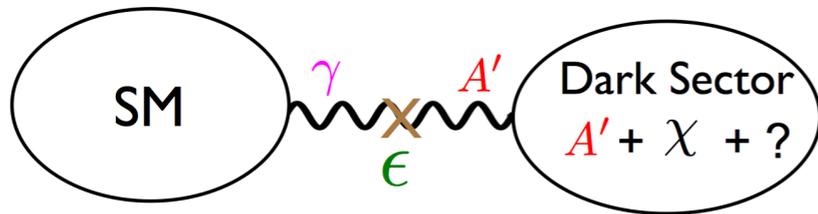
Can be explored at accelerators!

Experimental techniques



Dark forces and dark matter

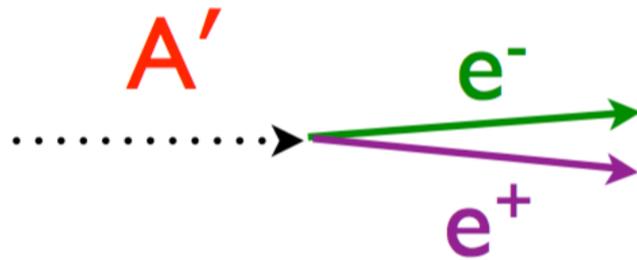
(Light WIMPs - light mediators)



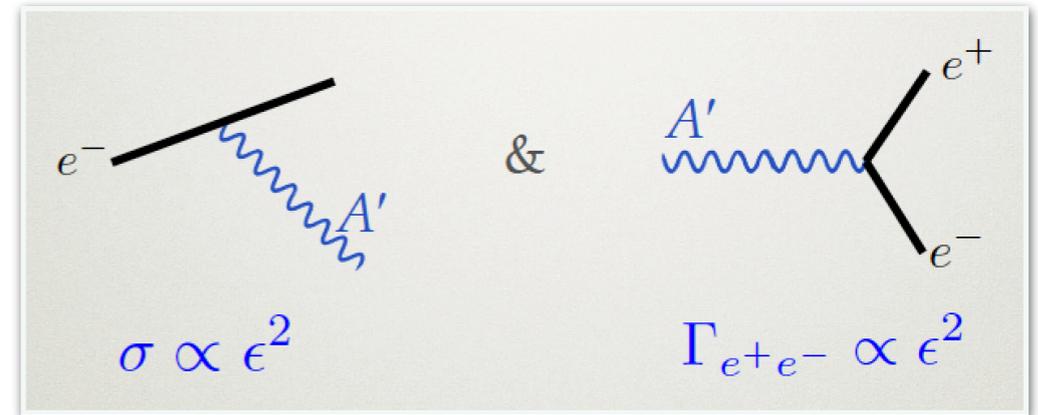
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

$$m_\chi \sim m_{A'} \sim \text{MeV} - 5 \text{ GeV}$$

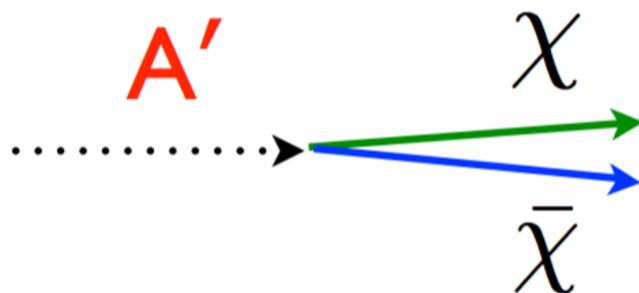
Visible



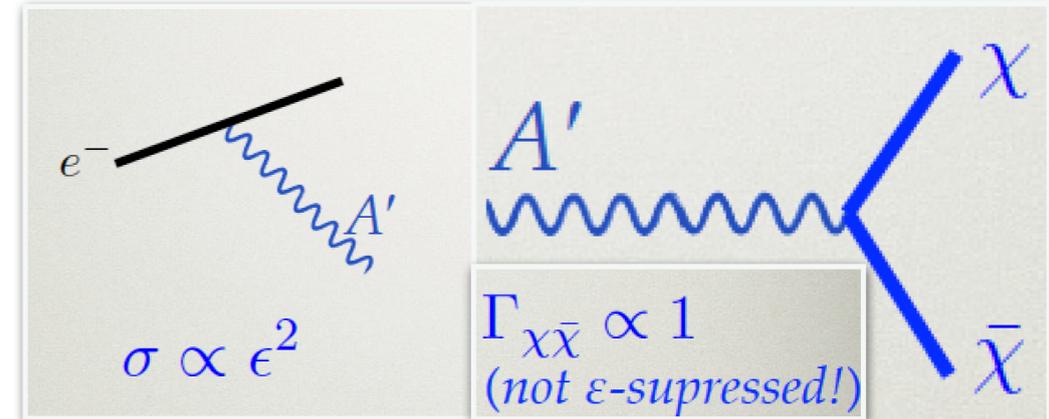
- Minimal decay
- Decay regulated by ϵ^2
- Independent of m_χ
- Requires $m_{A'} < 2m_\chi$



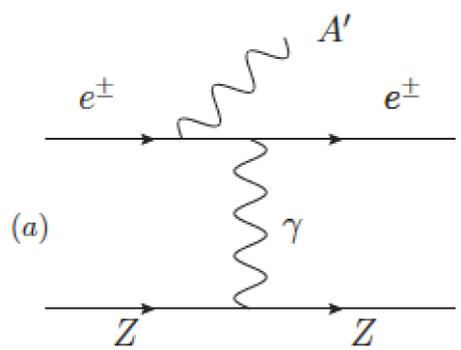
Invisible



- Depends on 4 parameters
- $m_{A'} > 2m_\chi$ (on-shell)
- $\alpha_D = g_\chi^2/4\pi \gg \epsilon^2 \alpha_{EM}$



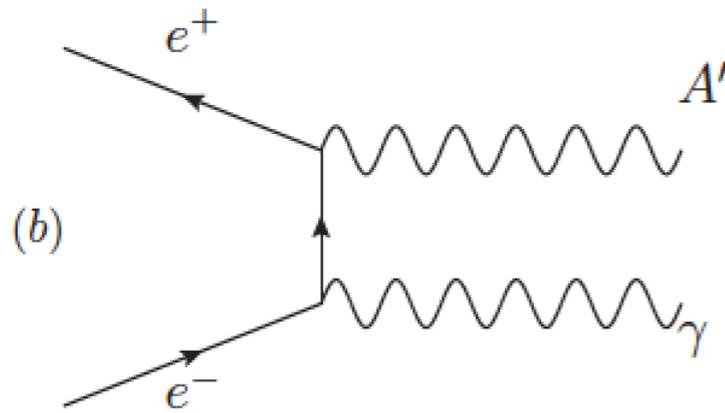
DM interaction in fixed target experiments



$$\sim \epsilon^2 \alpha^3_{EM}$$

The Weizsacker-Williams approximation (A' -strahlung)

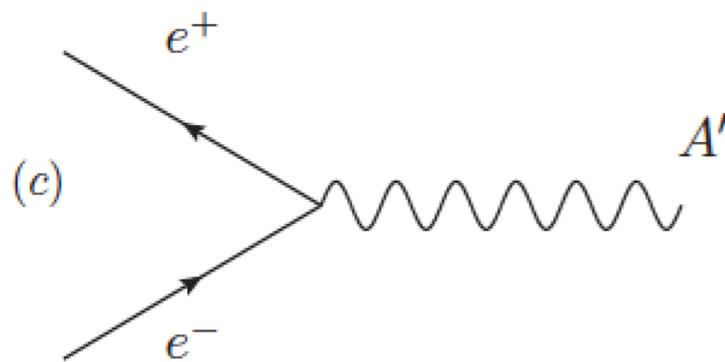
- The incoming electron 'see' a fast-moving cloud of effective photons to scatter from
- Photons are almost on-shell (low Q^2) \rightarrow transverse photons $\sim e^- \gamma_{Real}$ scattering
- Same treatment as the regular *bremsstrahlung*
- Effective photon flux χ is critical, accounting for nuclear effect using FF
- Forward-boosted, high-energy A' emission



- **NON-RESONANT annihilation** $\sim \epsilon^2 \alpha^2_{EM}$

$$\sigma_{nr} = \frac{8\pi\alpha^2\epsilon^2}{s} \left[\left(\frac{s - m_{A'}^2}{2s} + \frac{m_{A'}^2}{s - m_{A'}^2} \right) \log \frac{s}{m_e^2} - \frac{s - m_{A'}^2}{2s} \right]$$

- A' along (e^+e^-) direction
- Forward/backward emission



- **RESONANT annihilation** $\sim \epsilon^2 \alpha_{EM}$

$$\sigma_r = \sigma_{\text{peak}} \frac{\Gamma_{A'}^2/4}{(\sqrt{s} - m_{A'})^2 + \Gamma_{A'}^2/4},$$

$$\Gamma_{A'} = \frac{1}{3} m_{A'} \epsilon^2 \alpha \quad \sigma_{\text{peak}} = \frac{12\pi}{m_{A'}^2}$$

- Two-body process
- A' forward-peaked along e^+ direction
- $E_{A'} = E_R = m_{A'}/2m_e$

The BDX experiment

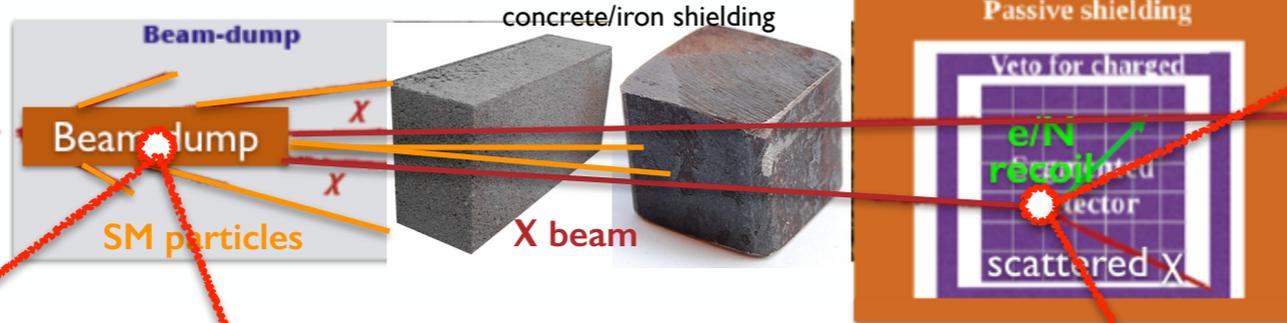
Two step process

I) An electron radiates an A' and the A' promptly decays to a χ (DM) pair

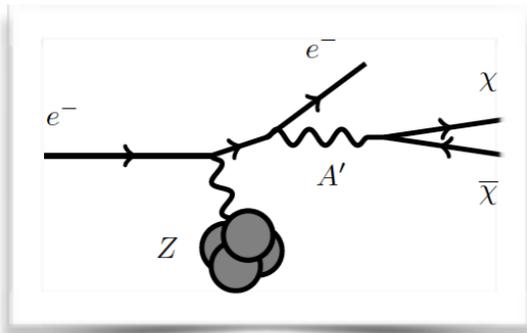
II) The χ (in-)elastically scatters on a e-/nucleon in the detector producing a visible recoil (GeV)

PhysRevD.88.114015 E.Izaguirre, G.Krnjaic, P.Schuster, N.Toro

High intensity e^- beam



X production



A' yield:

$$N_{A'} \propto \frac{\epsilon^2}{m_{A'}^2}$$

χ cross-section:

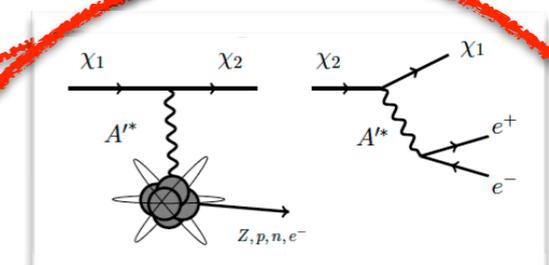
$$\sigma_{\chi e} \propto \frac{\alpha_D \epsilon^2}{m_{A'}^2}$$

Number of events:

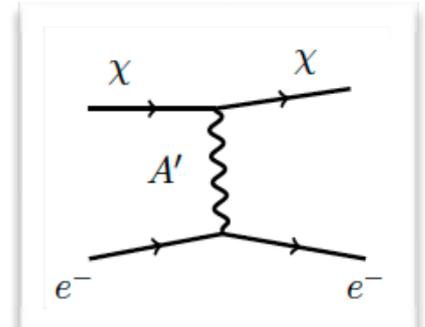
$$N_\chi \propto \frac{\alpha_D \epsilon^4}{m_{A'}^4}$$

- Intense electron beam
- ~ few GeV range energy

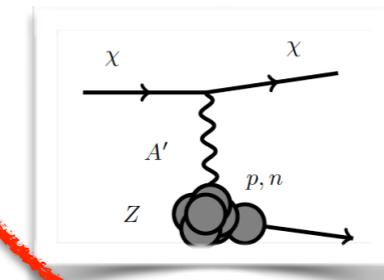
X detection on



Inelastic on nuclei



elastic on electrons



Elastic on nuclei

The BDX experiment

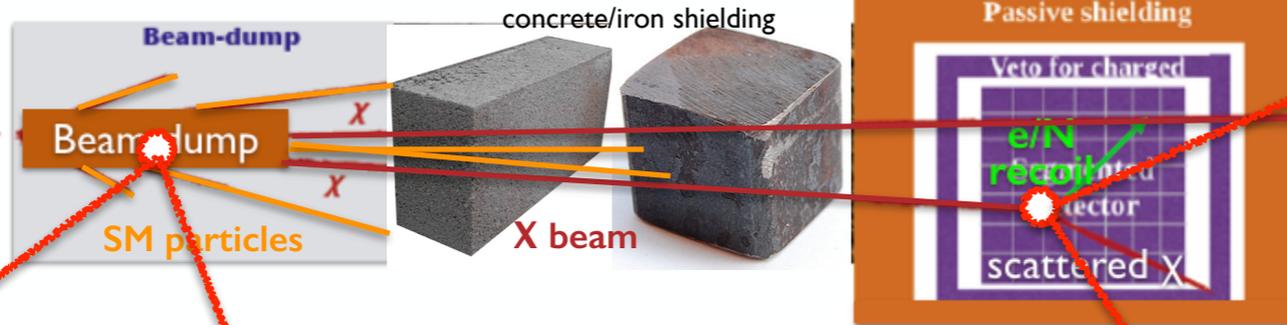
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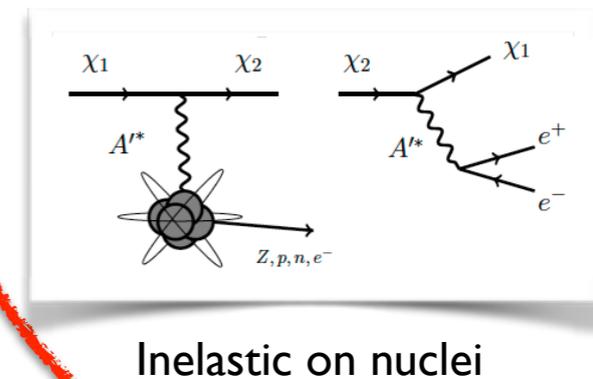
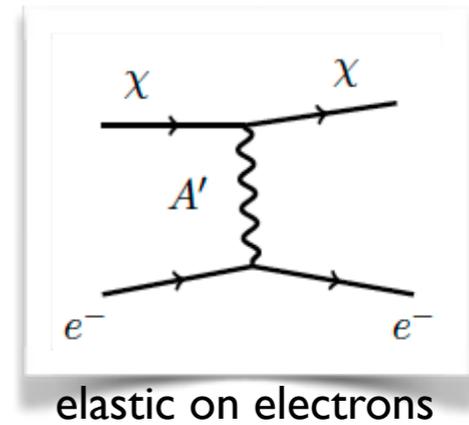
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PhysRevD.88.114015 E.Izaguirre, G.Krnjaic, P.Schuster, N.Toro

High intensity e^- beam

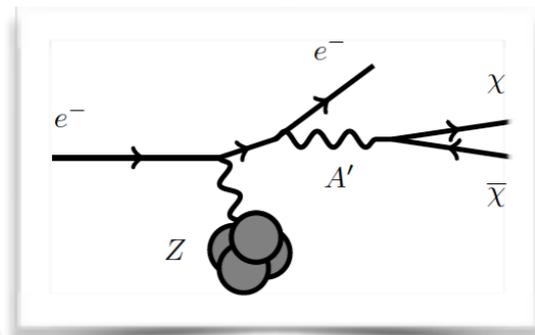


X detection



BDX @ JLab

X production



A' yield:

$$N_{A'} \propto \frac{\epsilon^2}{m_{A'}^2}$$

χ cross-section:

$$\sigma_{\chi e} \propto \frac{\alpha_D \epsilon^2}{m_{A'}^2}$$

Number of events:

$$N_\chi \propto \frac{\alpha_D \epsilon^4}{m_{A'}^4}$$

- Intense electron beam
- ~ few GeV range energy

Experimental signature in the detector:

X-electron \rightarrow EM shower ~GeV energy

The BDX detector

Detecting the X

Detector requirements

- EM showers detection capability (\sim GeV)
- Compact foot-print
- Low DAQ threshold to include nucleon recoil detection (\sim MeV)
- Segmentation for topology id

Active veto requirements

- High efficiency ($>99\%$) to MIPs
- Fast (\sim ns) for time coincidence with the calorimeter
- Segmentation for bg rejection

Passive veto made by lead bricks

- Lead vault between active layers for low energy gamma

Rejecting the bg

- Beam-related
- Cosmic

BDX technology

E.M. calorimeter



A **homogeneous crystal**-based detector combines all necessary requirements

Active veto



Two layers: of **plastic scintillator**
OV: light guide + PMT
IV: WLS + SIPM

The BDX crystals

Requirements:

- High density
- High light yield
- Cost-affordable for a $\sim \text{m}^3$ detector volume
- Good timing (desirable)

Possible options:

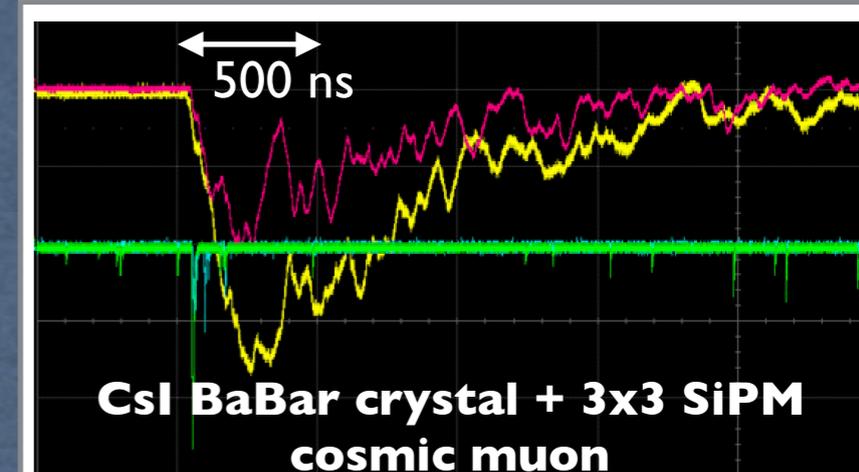
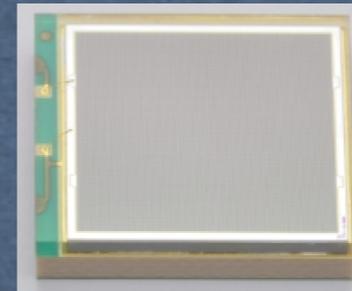
BaF2
CsI
BSO

A dedicated measurement campaign to characterise the crystal properties

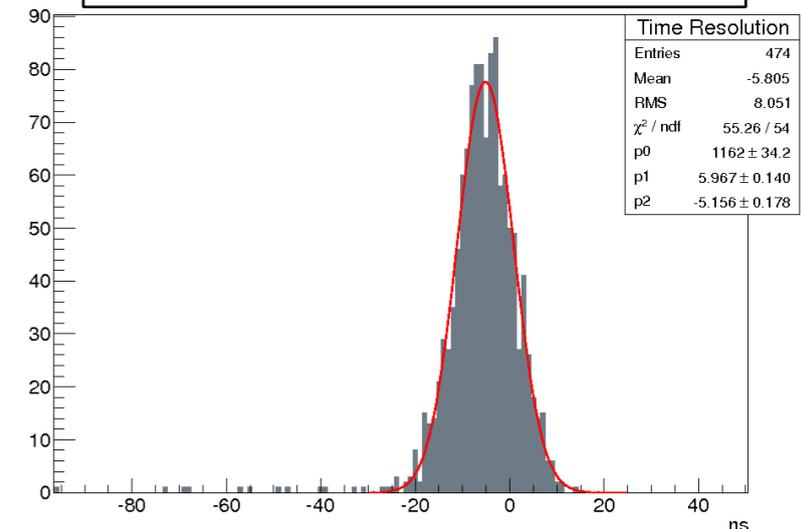
- Light yield (with SiPM readout!)
- Intrinsic decay time / time resolution

Parameter	Values
Radiation length	1.85 cm
Molière radius	3.8 cm
Density	4.53 g/cm ³
Light yield	50,000 γ /MeV
Light yield temp. coeff.	0.28%/°C
Peak emission λ_{max}	565 nm
Refractive index (λ_{max})	1.80
Signal decay time	680 ns (64%) 3.34 μ s (36%)

CsI(Tl) + SiPM readout



CsI BaBar crystal + 3x3 SiPM
Time resolution: $\sigma = 6\text{ns}$



Crystals are available from BABAR em calorimeter

- Size: (5x5)cm² front face, (6x6)cm² back face, 30cm length
- 820 crystals available from end cap
- Decay time: fast 900ns, slow 4000ns
- LY= 50k γ /MeV

SiPM readout

- Size: (6x6) mm², 25 μ m, 57.6k cells, trenched, pde=25%
- SPE capability
- CsI(Tl): 40 pe/MeV
- Time resolution: $\sim 6\text{ns}$ (MIPs)

★ Due to the large LY signals at $\sim \text{MeV}$ level are detectable

★ Despite a long scintillation time a few ns time coincidence is possible

The BDX active veto

Requirements:

- Hermeticity
- Segmentation
- Cost-affordable for several m² detector surface
- Good timing (desirable)

Possible options:

- plastic scintillator
- liquid scintillator
- passive vetos

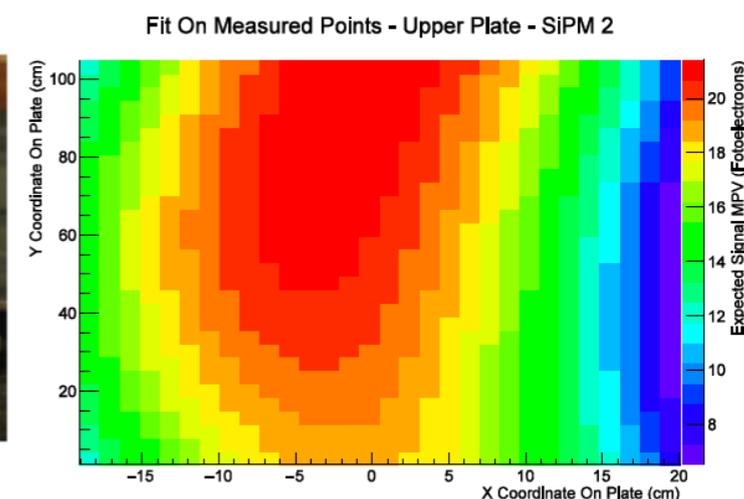
R&D on different technologies:

- Plastic scintillator + light guide + PMT
- Plastic scintillator + WLS + PMT
- Plastic scintillator + WLS + sipm

Plastic scintillator + WLS and SipM/PMT readout

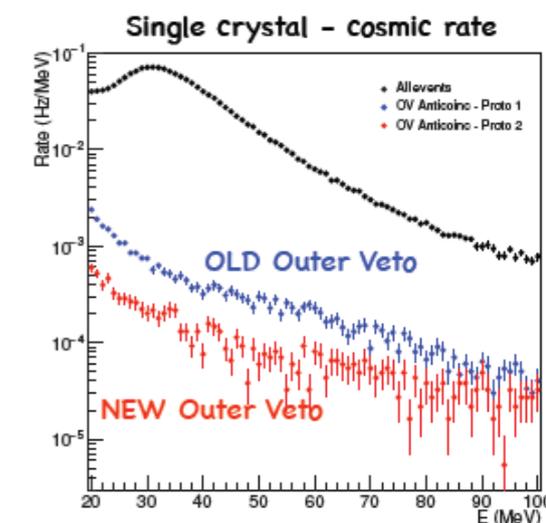
Inner veto:

- 1cm (all clear) Plastic scintillator +WLS fiber placed in grooves
- 3x3 SiPM readout
- LY= 15-50 pe/MIP



Outer veto:

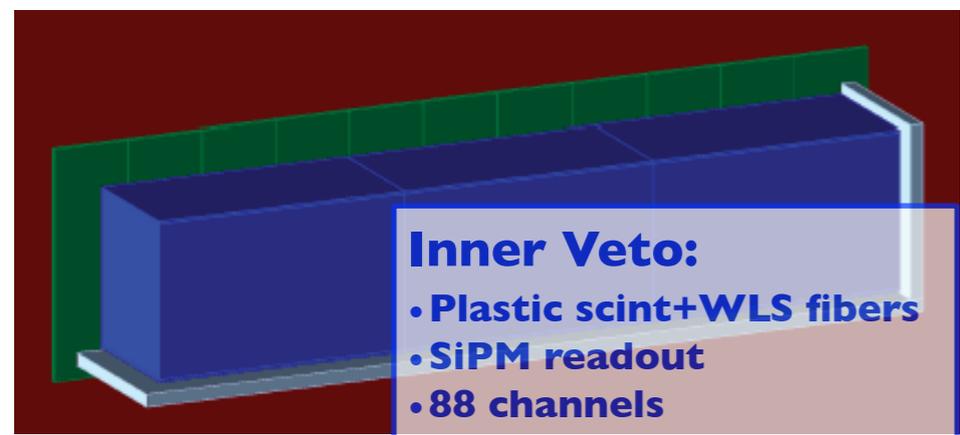
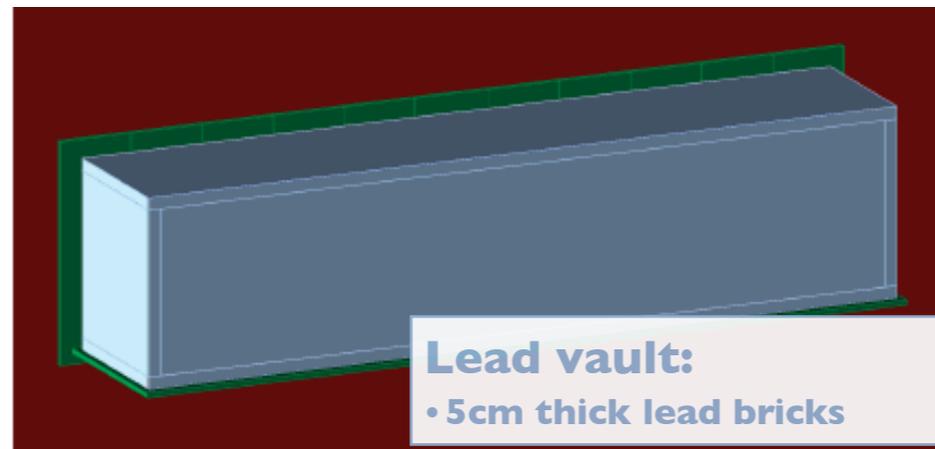
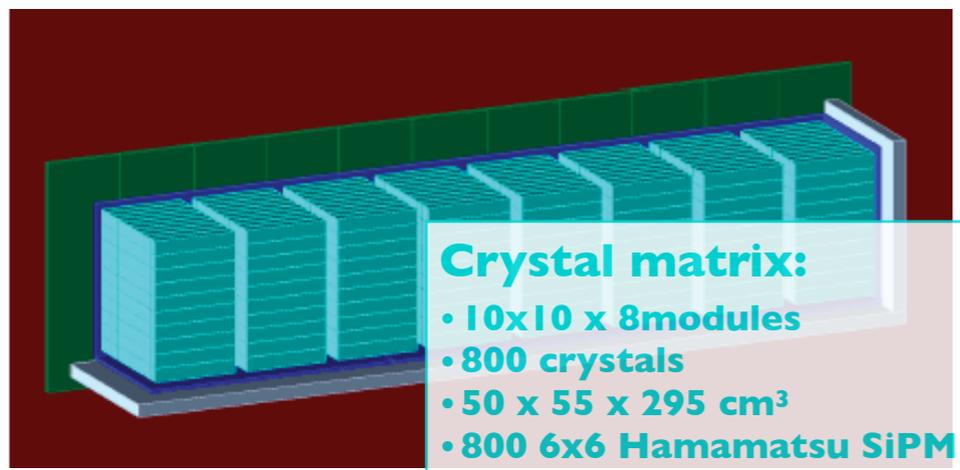
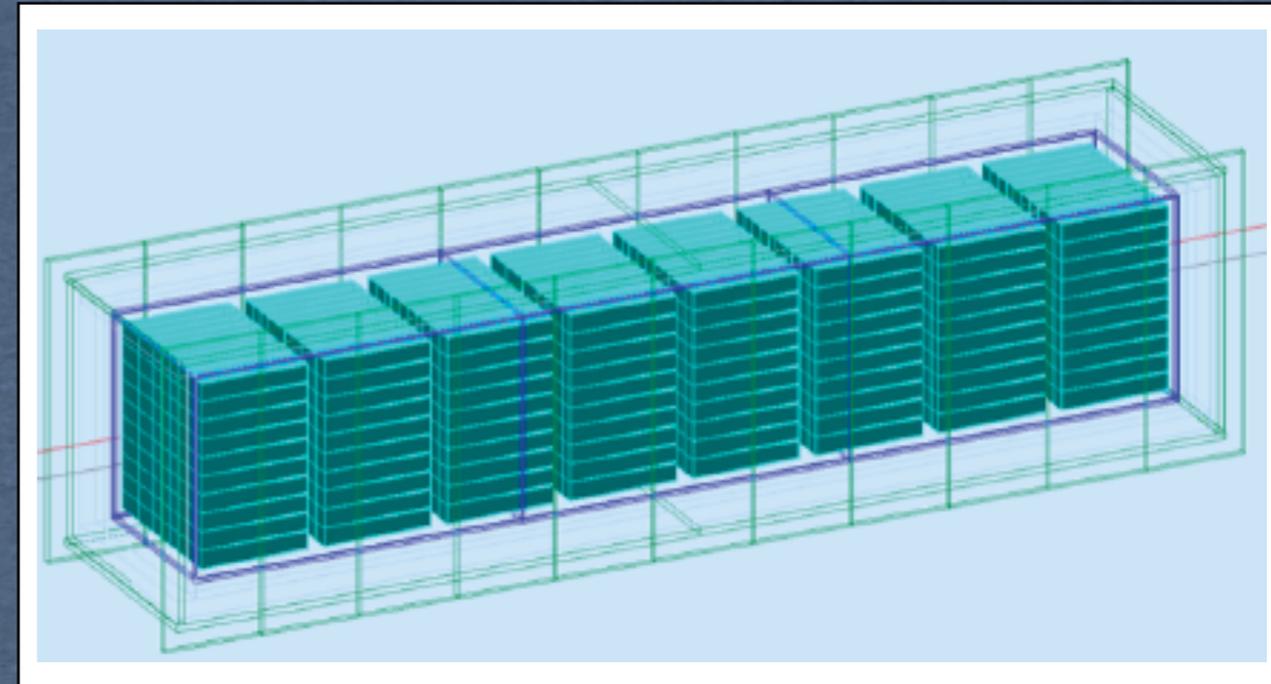
- Plastic scintillator + Light guide + PMT
- Plastic scintillator +WLS fiber



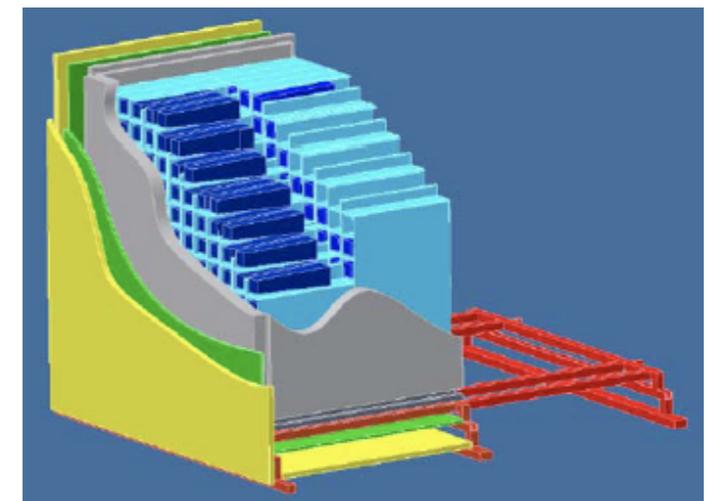
- ★ High efficiency to MIPs (>99%)
- ★ Robust and simple technology

The BDX detector

- ★ Modular EM calorimeter: 8 modules 10x10 crystals each
- ★ 800 CsI(Tl) crystals (former BaBar EMCal) + SiPM readout
- ★ Inner Veto: plastic scintillator + WLS + SiPM
- ★ Outer Veto: plastic scintillator + PMTs
- ★ Passive shielding: lead vault



Calorimeter module



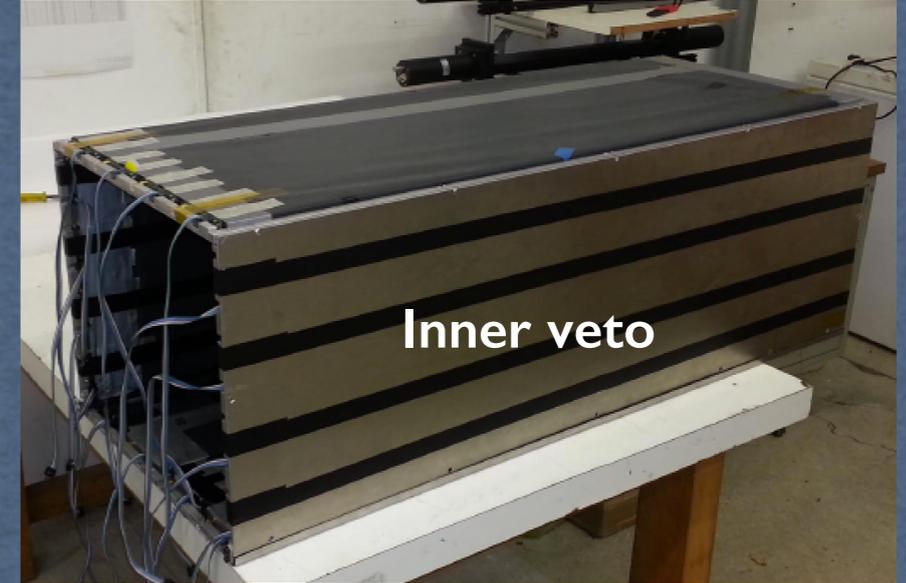
The BDX prototype



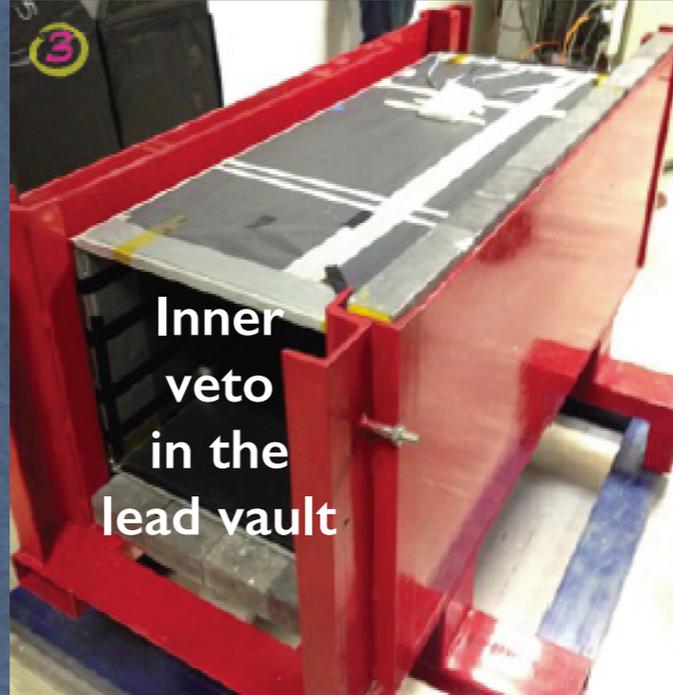
Outer veto
plastic scintillators
paddle
+ light guide +
PMT



Inner veto
plastic scintillators paddle
+ WLS + SiPM



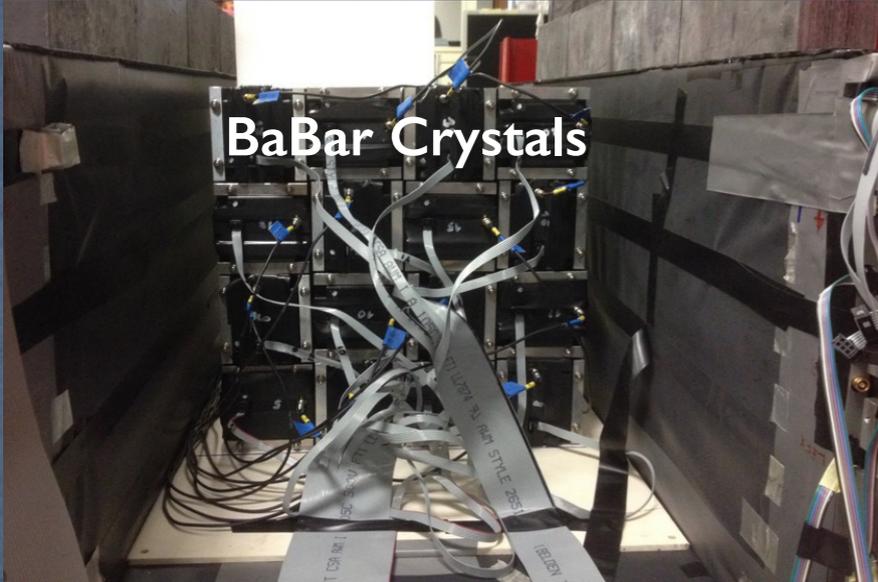
Inner veto



Inner
veto
in the
lead vault



BDX-proto
fully assembled
at INFN-CT

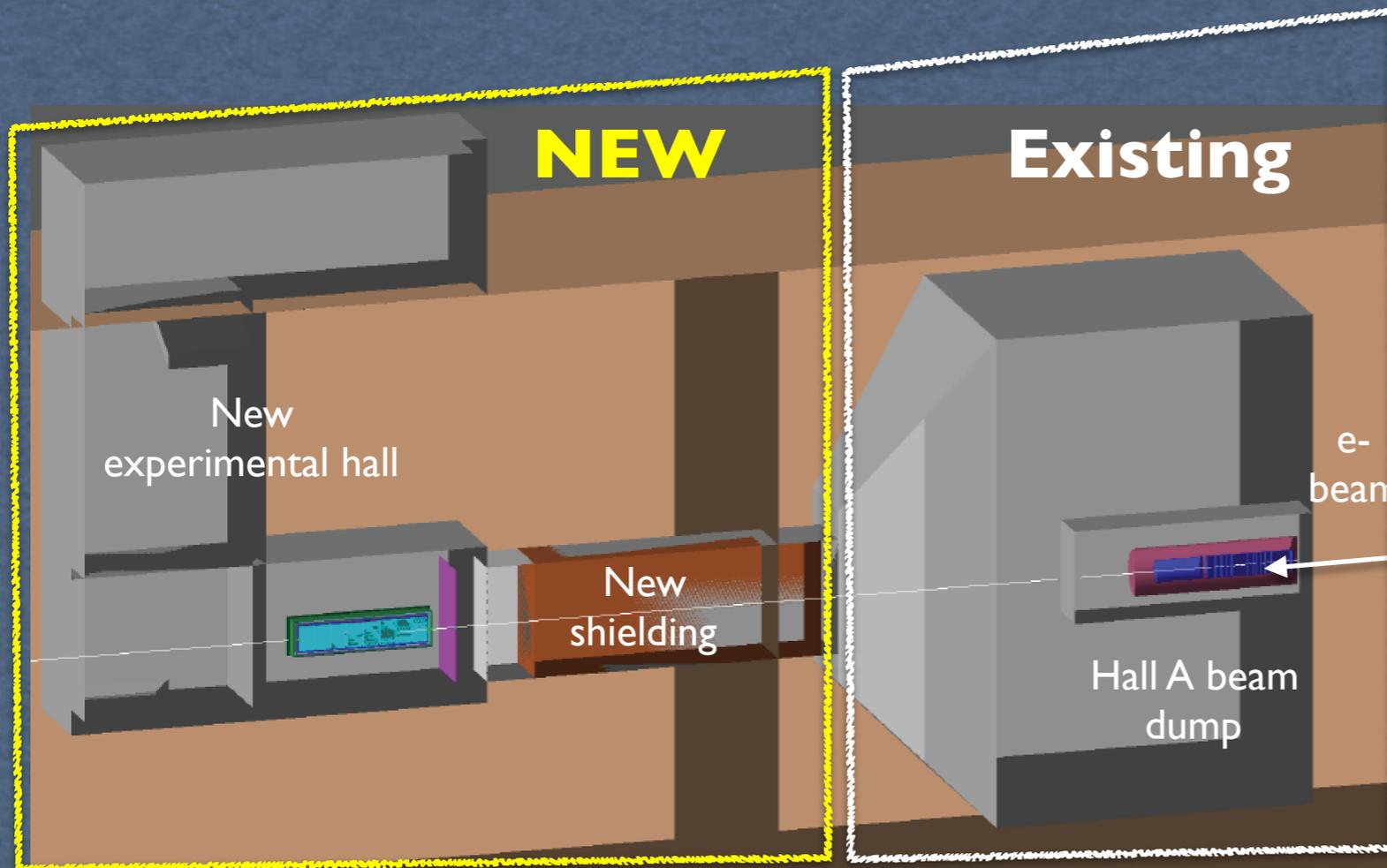


BaBar Crystals

- EM Cal
 - 4x4 CsI(Tl) crystals
 - 6x6 mm² SiPM
- Outer Veto
- Lead vault
- Inner Veto

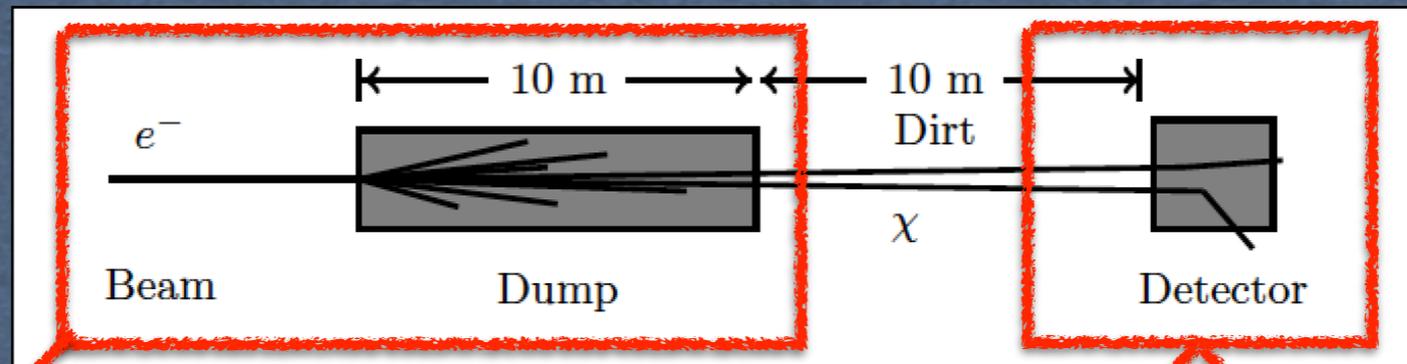
BDX at JLab

- ★ High energy beam available: 11 GeV
- ★ The highest available electron beam current: $\sim 65 \mu\text{A}$
- ★ The highest integrated charge: 10^{22} EOT (41 weeks)
- ★ BDX detector located downstream of Hall-A beam dump
- ★ New underground experimental hall

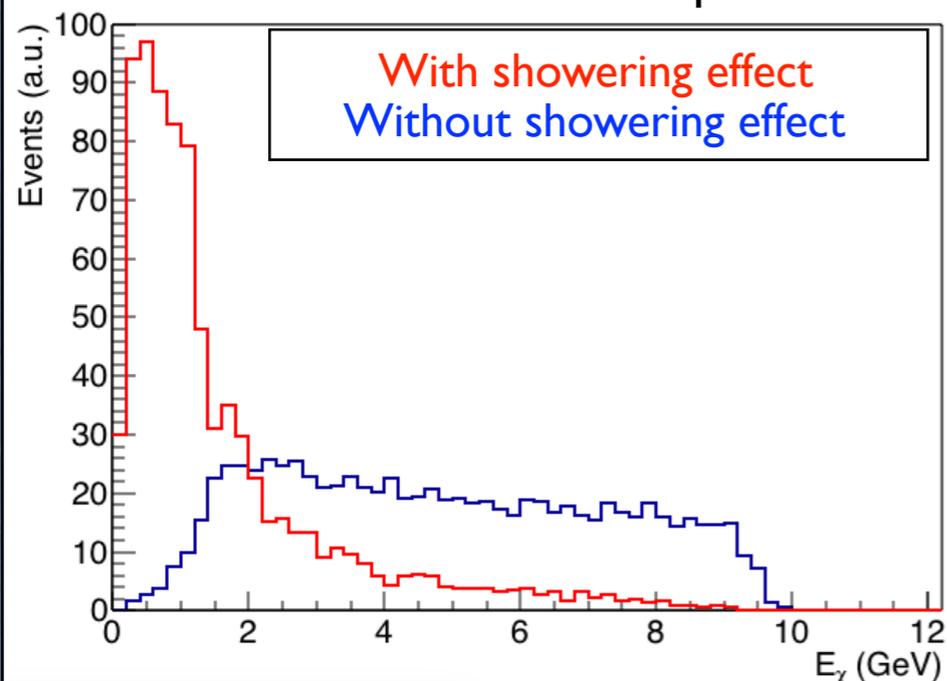


X production and detection

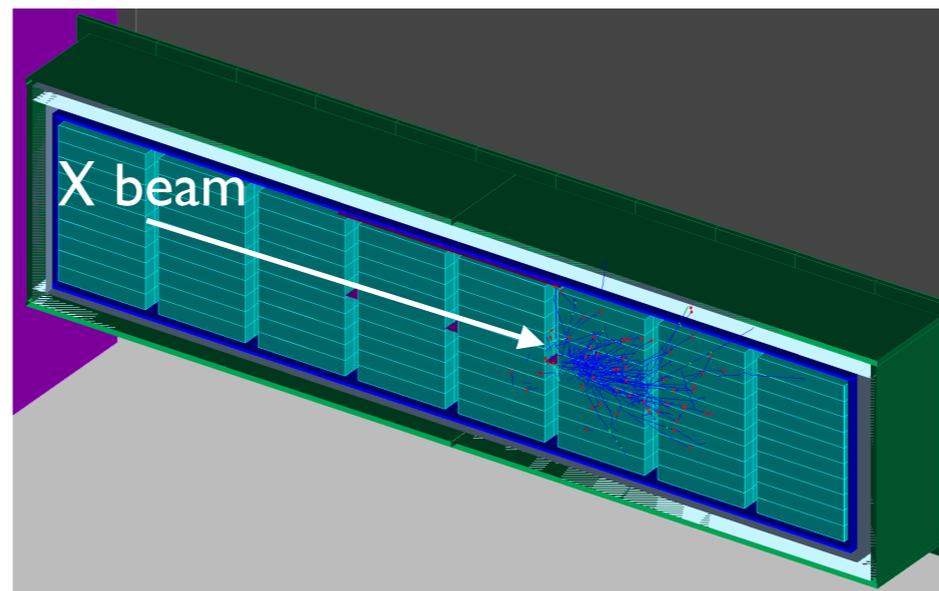
- Detailed simulations using ad-hoc MC code to describe the A' production, decay ($A' \rightarrow \chi \chi$) and interaction in the BDX detector (χ -e)
- Detailed description of Hall-A beam dump (production) and BDX detector (detection) using GEANT4



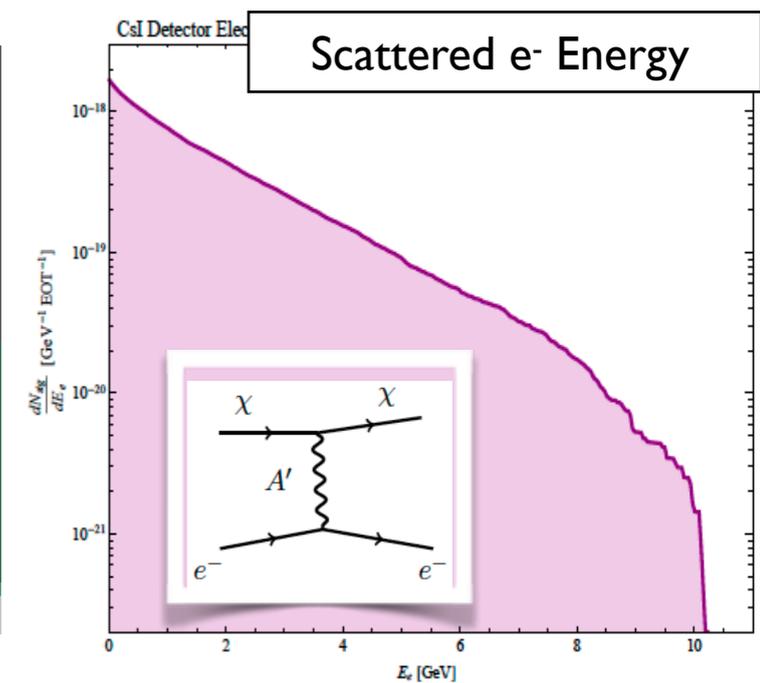
X energy spectrum generated by 11 GeV e-beam in the dump



χ -e interaction producing an em shower in the detector



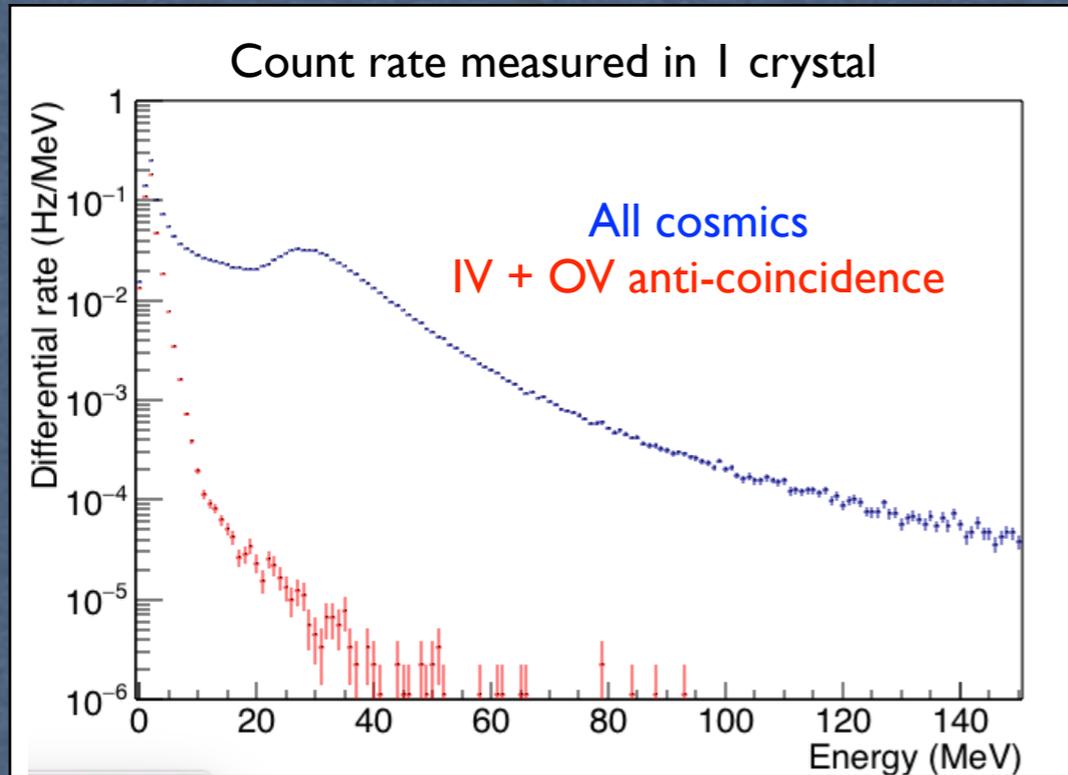
Elastic on electrons



Background

Cosmic

- ★ Cosmic background measured with the BDX detector prototype in CT



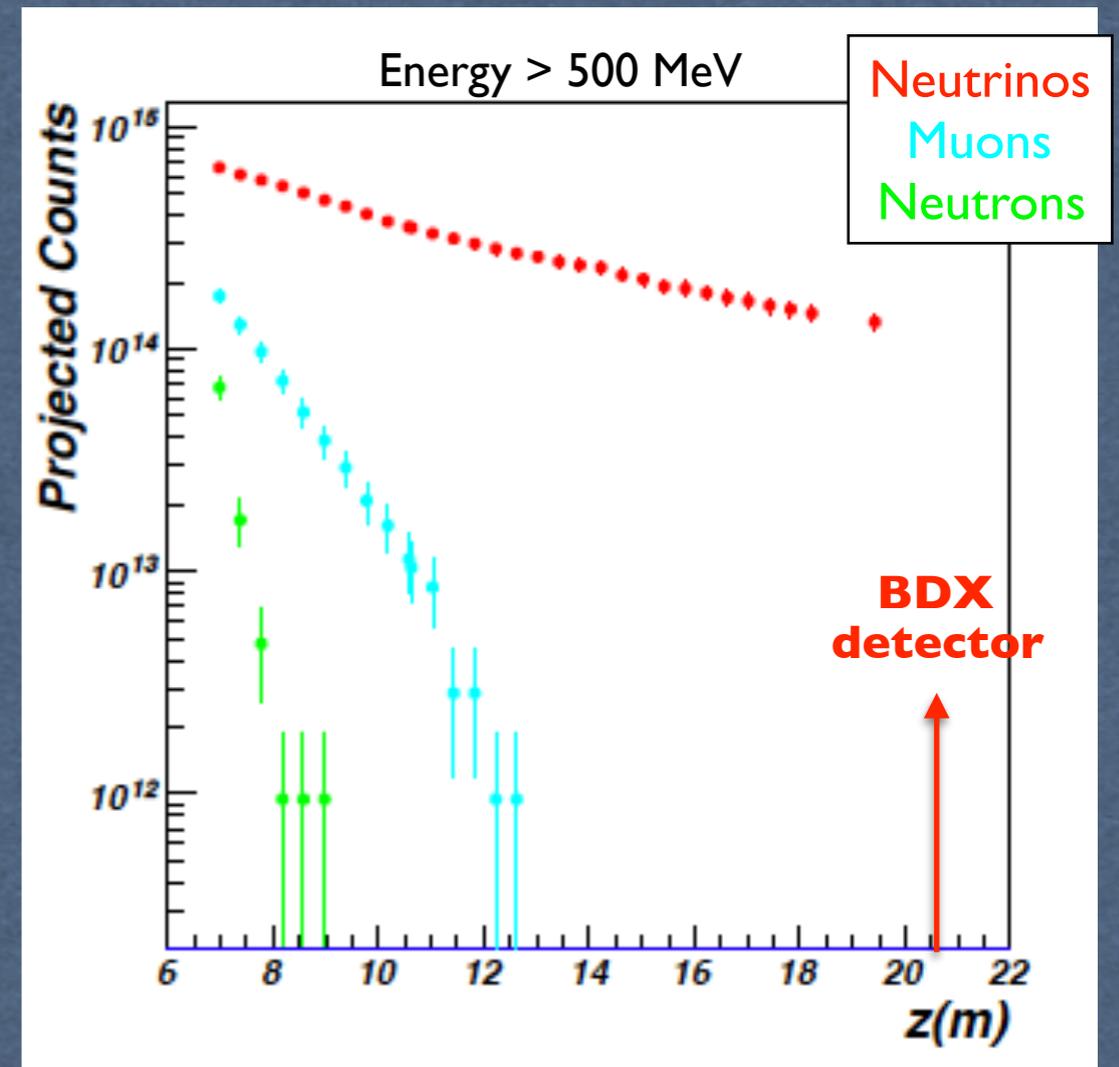
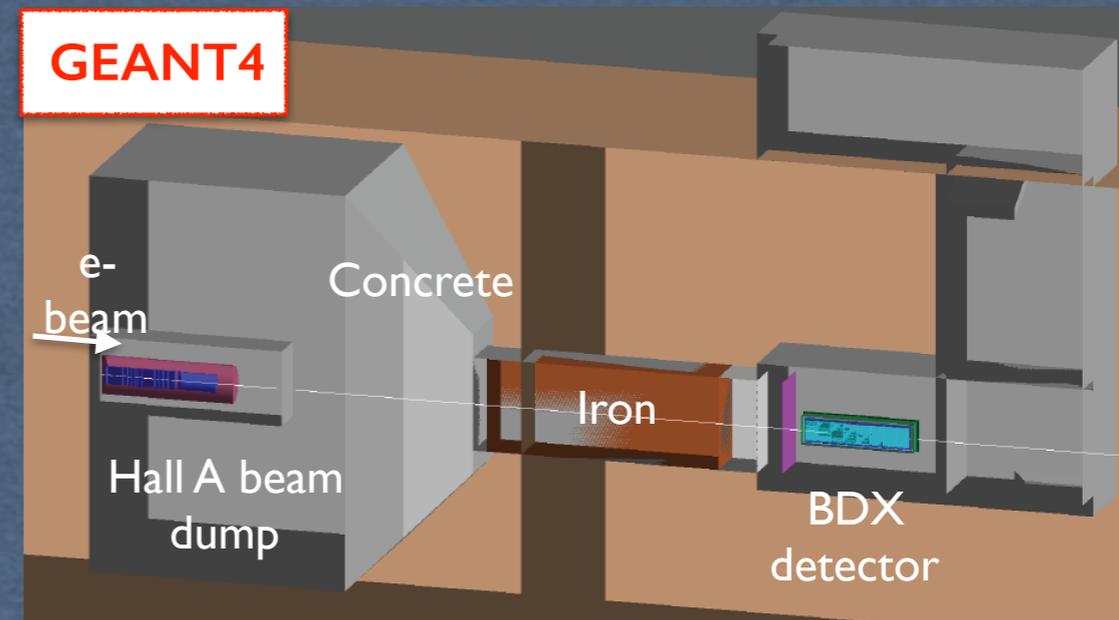
Expected cosmic bg counts in BDX lifetime < 2 counts

Beam-related

Bg estimated using GEANT4, tracking particles with $E > E_{Thr}$

- ★ Muons are ranged out by the iron shielding
- ★ Non-negligible contribution of high energy neutrino interacting in the detector by CC: $\nu + N \rightarrow X + e^-$

Expected beam-related counts in BDX lifetime ~ 10 counts

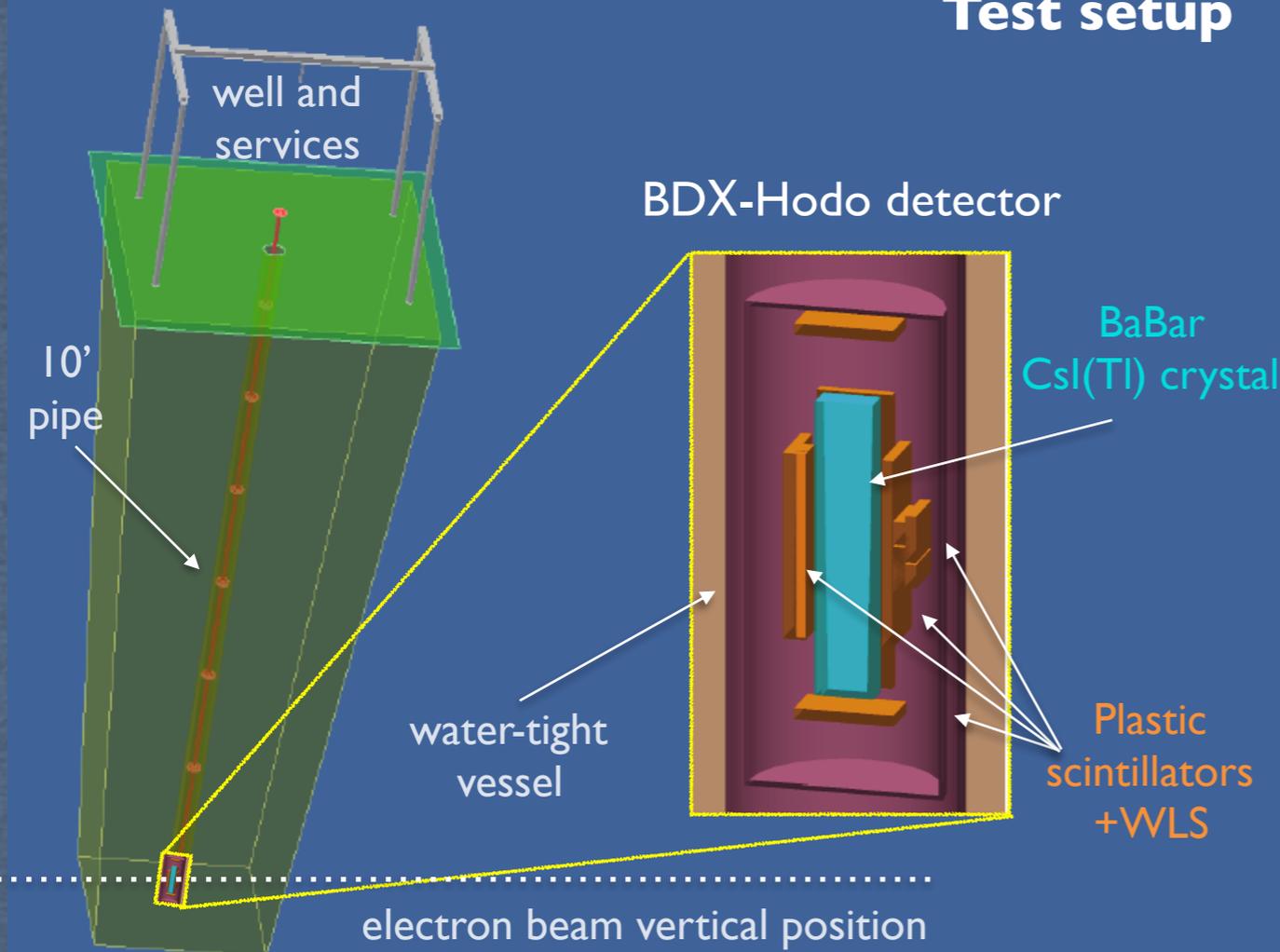


Tests to measure the beam-on background

Measurement campaign to characterize the flux of high-energy μ produced in the Hall-A beam dump

- Pipe downstream of Hall-A beam-dump at BDX location
- Insert a CsI(Tl) crystal surrounded by plastic scintillators
- Same detector technology proposed for BDX detector
- Measure μ flux when 11-GeV beam is on

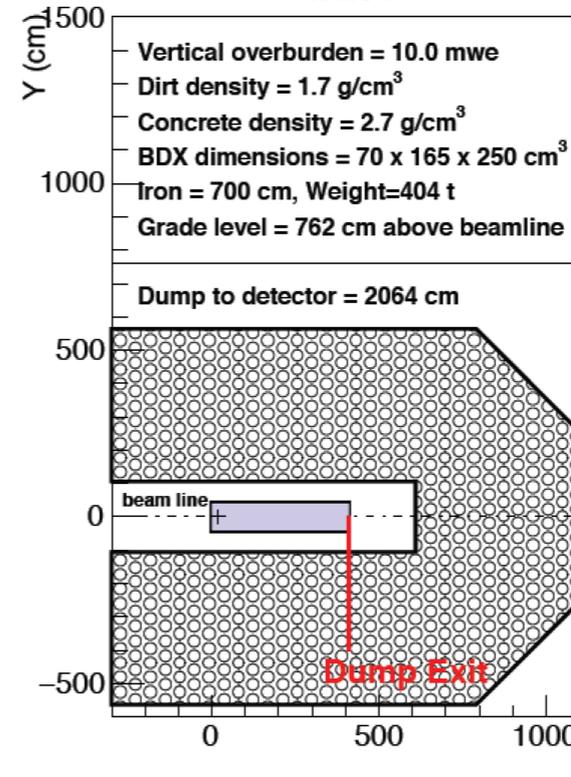
Test setup



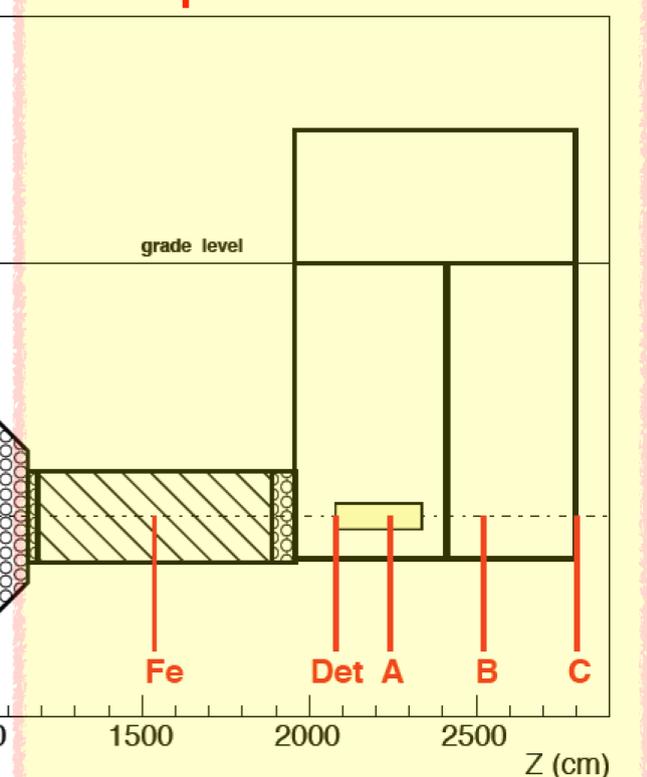
Downstream of the Hall-A beam dump - TODAY -



Hall-A beam-dump vault



Proposed BDX new experimental Hall



BDX-Hodo tests at JLab

Two wells

Well 1 (~25m)

Well 2 (~28m)

The tent

The BDX-Hodo

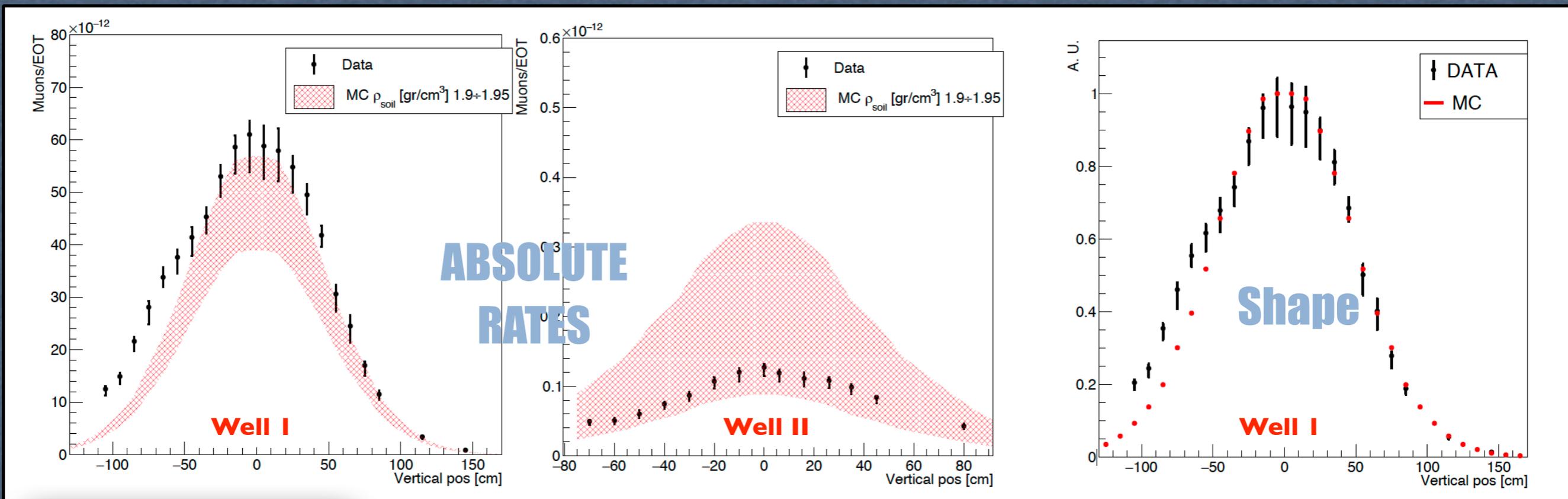
BDX-Hodo in the tent

The BDX-Hodo lowered in well 1

The first muon signal on the scope

- Run: from Feb 22nd to May 2nd 2018
- Hall-A beam parameters
 - $I_{\text{Beam}} \sim 22\mu\text{A}$
 - $E_{\text{Beam}} = 10.6 \text{ GeV}$
 - Diffuser: ON
- + 1 week taken in Well II with $E_{\text{beam}} = 4.3 \text{ GeV}$

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 σ)

Good agreement between data and simulations prove:

- * the **BDX simulation framework is reliable**
- * **no significant contribution from n bg (high energy n and/or pile-up effects)**

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Measurements of the muon flux produced by 10.6 GeV electrons in a beam dump

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ARTICLE INFO

ABSTRACT

Keywords: Light Dark Matter; Dark Matter; Beam-Dump experiments; Monte Carlo

This paper presents the results of an experiment to assess the muon flux produced by the interaction of a 10.6 GeV electron beam with the Hall A beam dump at Jefferson Lab (JLab). The goal was to benchmark Monte Carlo simulations that are an essential tool for estimating beam-induced backgrounds in beam dump experiments aimed at searching for new events, such as the Neutrino Dump Experiment (NDX) planned at JLab. Muon-produced muons were measured with a CsI(Tl) crystal sandwiched between a set of segmented plastic scintillators placed at two different distances from the dump: 25.7 m and 28.8 m. At each location the muons that were sampled at different vertical positions with respect to the beam height. Data have been compared with detailed Monte Carlo simulations using FLUKA for the muon production in the dump and propagation to the detector, and GEANT4 to simulate the detector response. The good agreement between data and simulations, with the uncertainty of the soil composition and density, demonstrates the validity of our simulation tools to predict the beam-induced muon background in electron beam-dump experiments at ~ 10 GeV.

1. Introduction

Background is usually the limiting factor to experiments searching for rare events. This is the case for Dark Matter (DM) searches in beam-dump experiments where a high intensity O(GeV) electron/proton beam is directed into a dump producing an overwhelming shower of Standard Model particles in addition to the rare DM particles of interest. While most of the radiation (gamma, electron/positron and neutron) is contained in the dump or degraded down to harmless energy levels, deep penetrating radiation, such as muons, propagates for long distances before depositing their energy far from the point of origin. Monte Carlo simulations are used to find the best combination of shielding and analysis cuts to minimize such background. However, they need to be validated with actual measurements. In this work we present the results of a measurement performed downstream of the JLab Hall A beam-dump to assess the muon background produced in the interaction of the CEBAF 10.6 GeV electron beam with the dump. Experimental results have been compared to simulations performed with FLUKA [1,2] and GEANT4 [3] that include a realistic model of the dump, the surrounding materials and the detector response. This study is relevant for the Neutrino Dump Experiment (NDX) planned at Jefferson Lab. NDX is an electron-beam thick-target experiment aimed to produce and detect light Dark Matter particles (MeV GeV mass range), in the framework of the Higgs portal paradigm where DM is charged under a new U(1) symmetry whose interaction is mediated by a new light vector boson (a Higgs photon or A' , also called dark photon) [4]. The A' is expected to be produced in the interaction of the high power (~1 CW) electron beam with the Hall A beam dump via A' - $\nu\bar{\nu}$ processes [5] and e^+e^- annihilation [6]. The A' could then decay into forward-scattered DM particles [4] that may interact with the NDX detector located ~25 m downstream of the dump. An electromagnetic calorimeter with ~800 CsI(Tl) crystals will measure the DM shower produced by high-energy e^+ produced by the scattering of e^- with atomic electrons. Two large-area plastic-scintillator veto systems and a massive passive shielding shield downstream of the dump will be used to reject high energy backgrounds that can mimic a DM signal, except for neutrons. In order to benchmark Monte Carlo simulations, an on-site experimental campaign was performed to measure the muon flux in the present

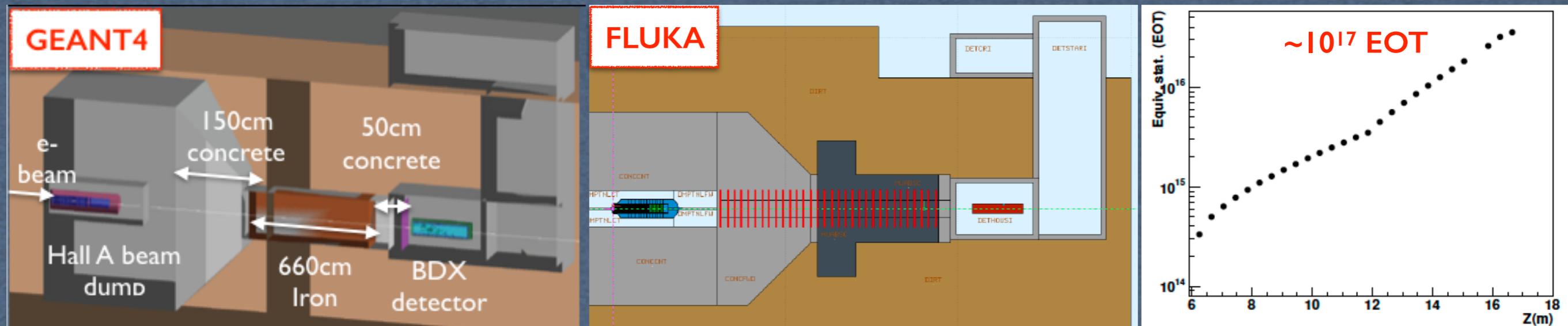
* Corresponding author.
E-mail address: m.battaglieri@infn.it (M. Battaglieri).

Neutrons are copiously produced in the dump but due to the low interaction cross section, they deserve a separate discussion.

<https://doi.org/10.1016/j.nimpr.2019.02.001>

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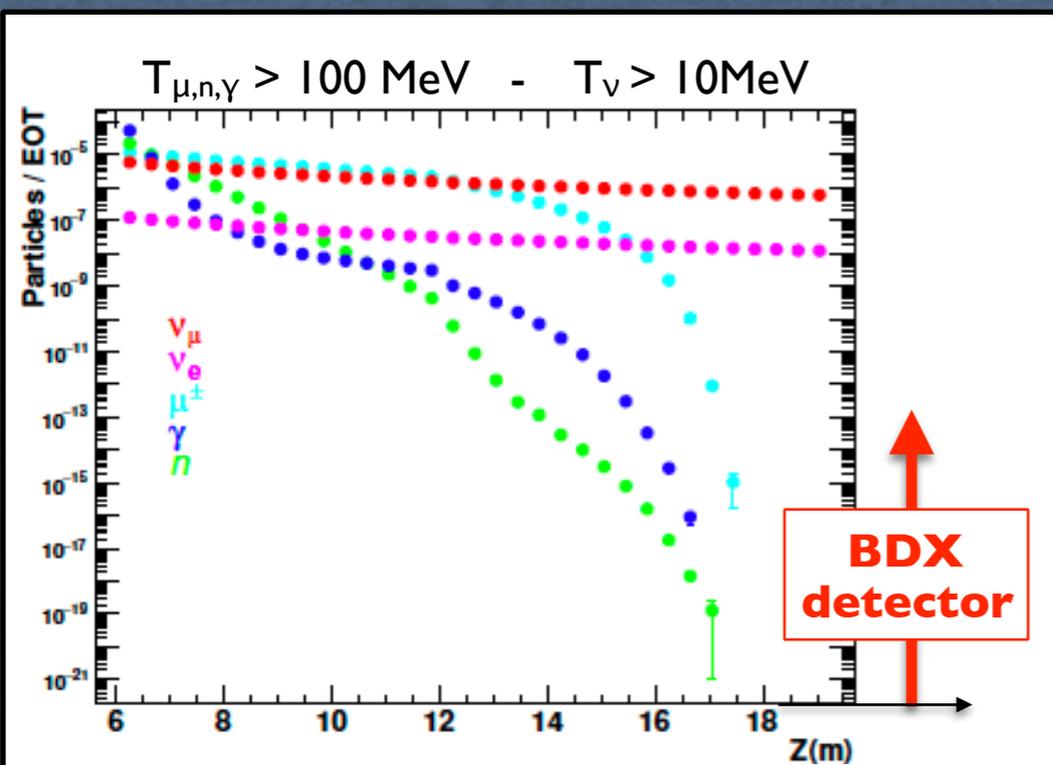
High statistics MC sim the BDX set-up



★ 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

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



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

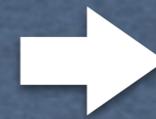
★ **Muons**

- All forward-going muons are ranged out
- Large angle μ s may enter in BDX volume ($R \sim 0.02$ Hz)
- They are rejected by combination of veto and threshold
- Shielding configuration leading to 0 bg events found
- An optimized shielding will be defined at the time of the new experimental Hall design

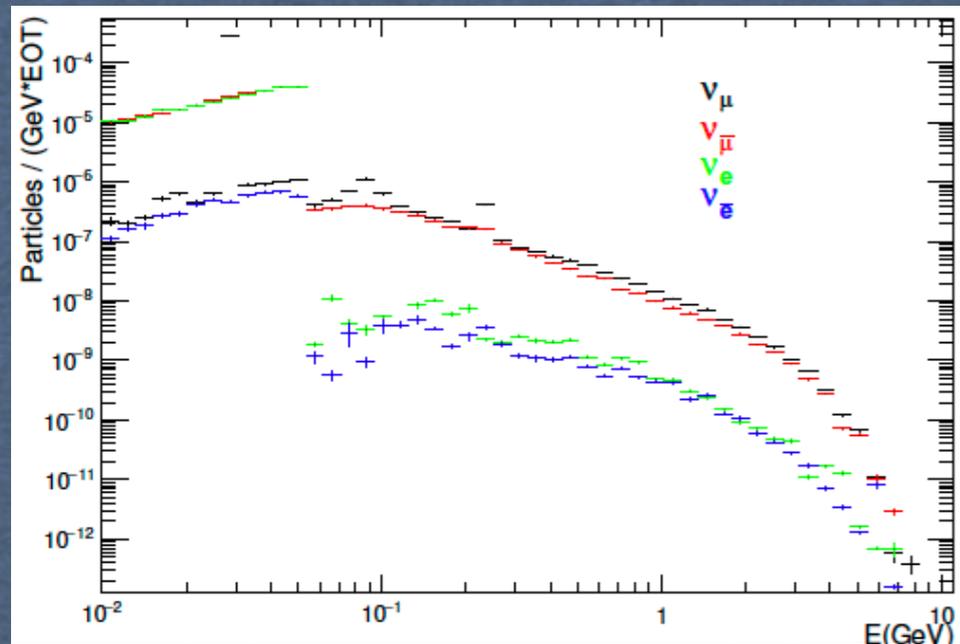
MC Simulations: neutrino background

★ Neutrino

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



Non-negligible contribution of high energy ν interacting in the BDX detector



- FLUKA to generate and propagate ν (1.5x ν flux obtained by G4)
- FLUKA NUNDIS/NUNRES to simulate ν interaction with CsI(Tl) BDX crystals
- G4 to simulate the detector response to ν -CsI(Tl) interaction products

- NC**
- $\nu_\mu + N \rightarrow \nu_\mu X$: all rejected by the det. threshold (limited energy transfer to N)
 - $\nu_e + N \rightarrow \nu_e X$: all rejected by the det. threshold (limited energy transfer to N)
- CC**
- $\nu_\mu + N \rightarrow X + \mu$: all rejected by identifying the scattered muon
 - $\nu_{e^-} + N \rightarrow X + e^-$: the largest contribution to over-tresh. hits in BDX

Different scattered e^- angle for signal and bg:

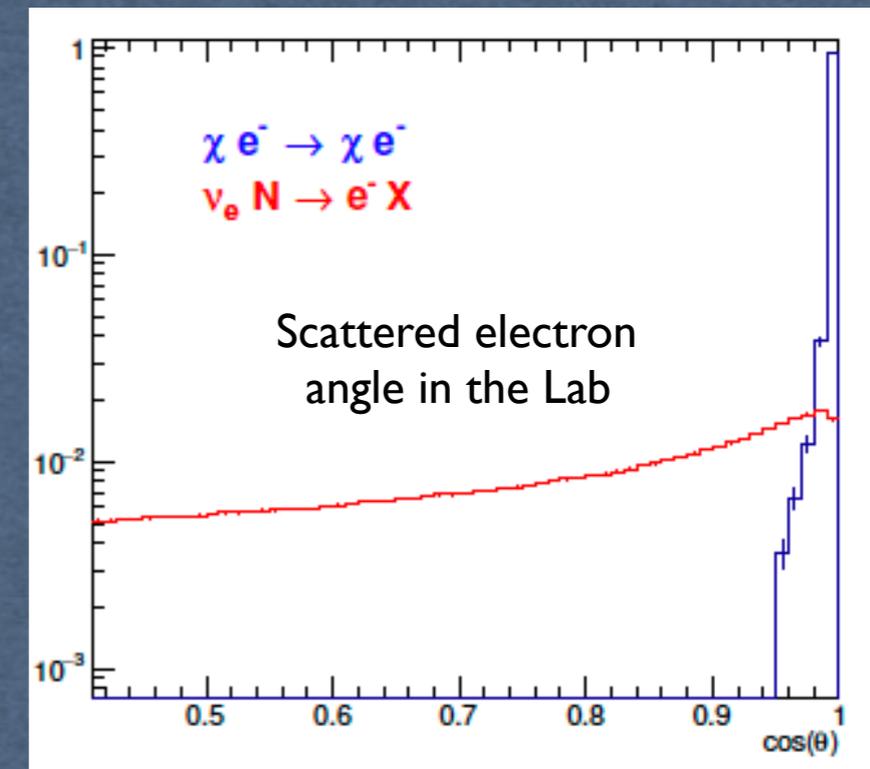
- $X_{DM} + e^- \rightarrow X_{DM} + e^-$: forward peaked for
- $\nu_{e^-} + N \rightarrow X + e^-$: spread over all angles



neutrino BG can be identified and suppressed!

High-stats FLUKA simulations demonstrate:

- * BDX only limited by the ν irreducible bg
- * Expected beam-related bg counts ~ 5 events



BDX expected reach

Beam time request

- 10^{22} EOT (65 uA for 285 days)
- BDX can run parasitically to any Hall-A $E_{\text{beam}} > 10$ GeV experiments (e.g. Moeller)

Beam-related background

Energy threshold | N_v (285 days)

300 MeV

~10 counts

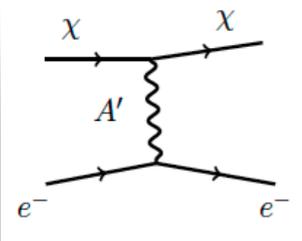
Cosmic background

Energy threshold | \sqrt{Bg} (285 days)

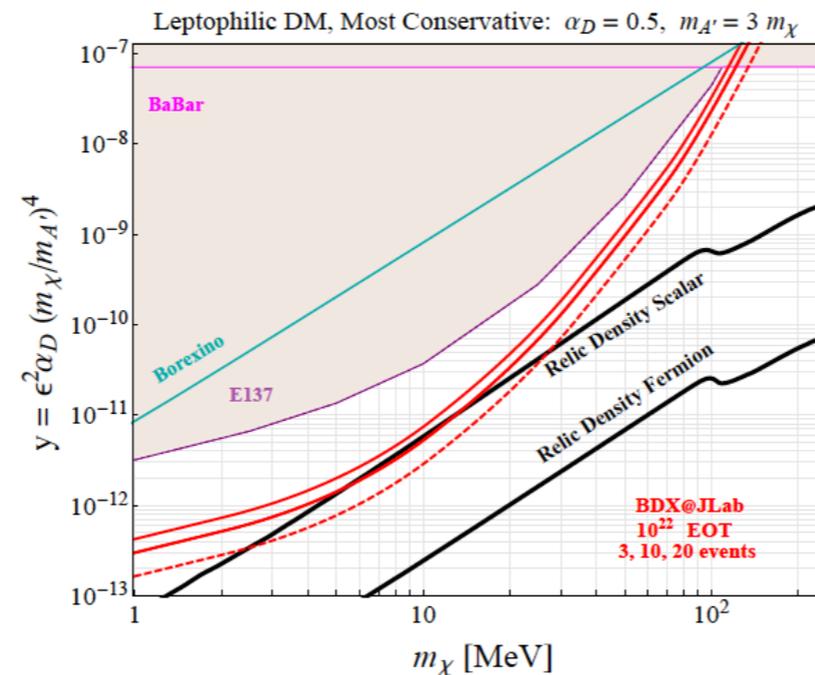
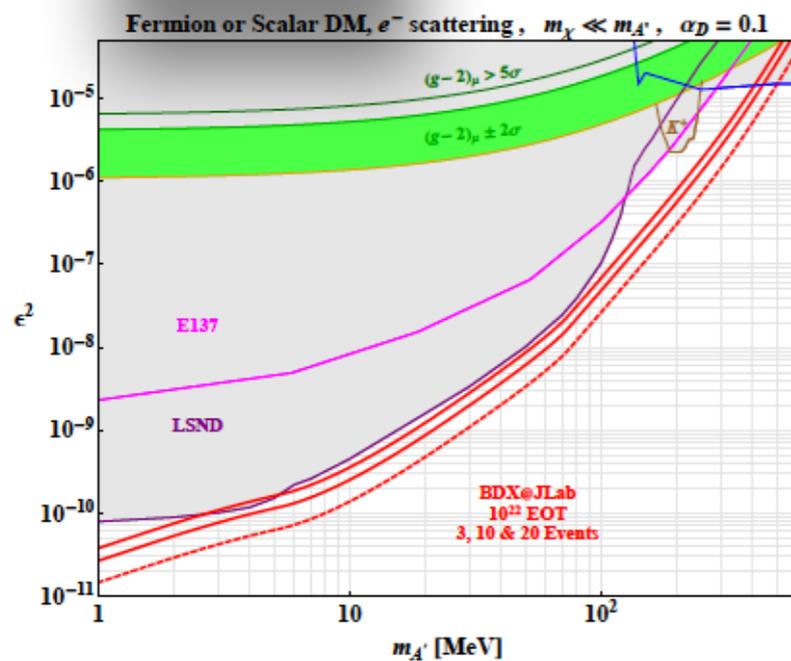
300 MeV

<2 counts

BDX sensitivity is 10-100 times better than existing limits on LDM

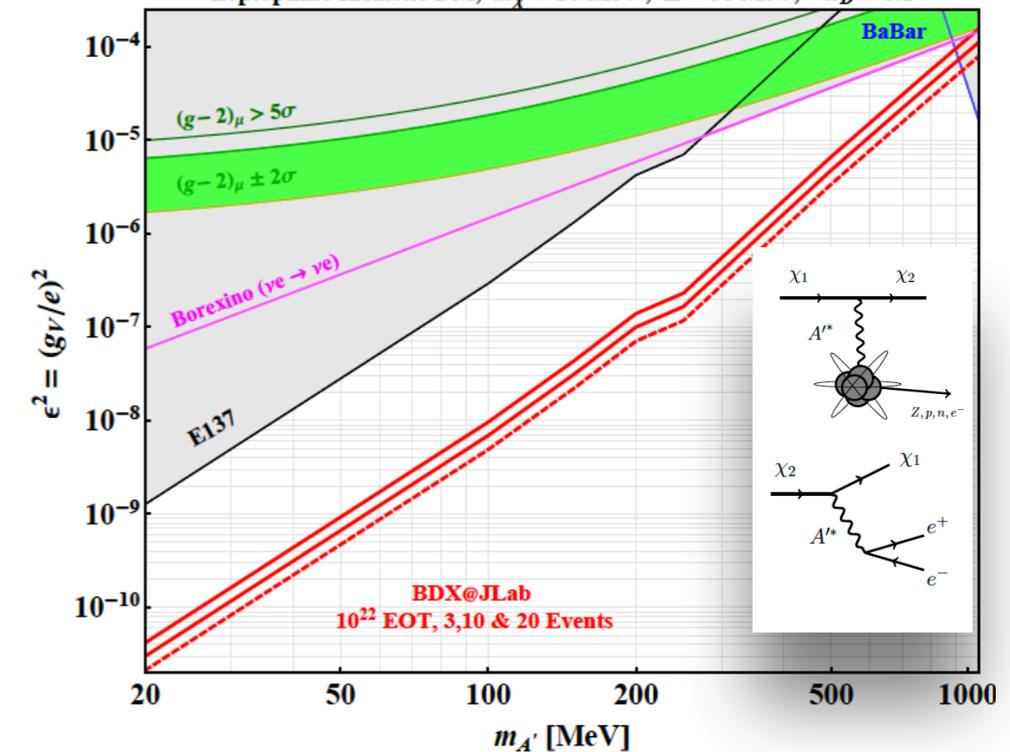


Elastic X-e scattering - BDX reach



Inelastic X-N scattering

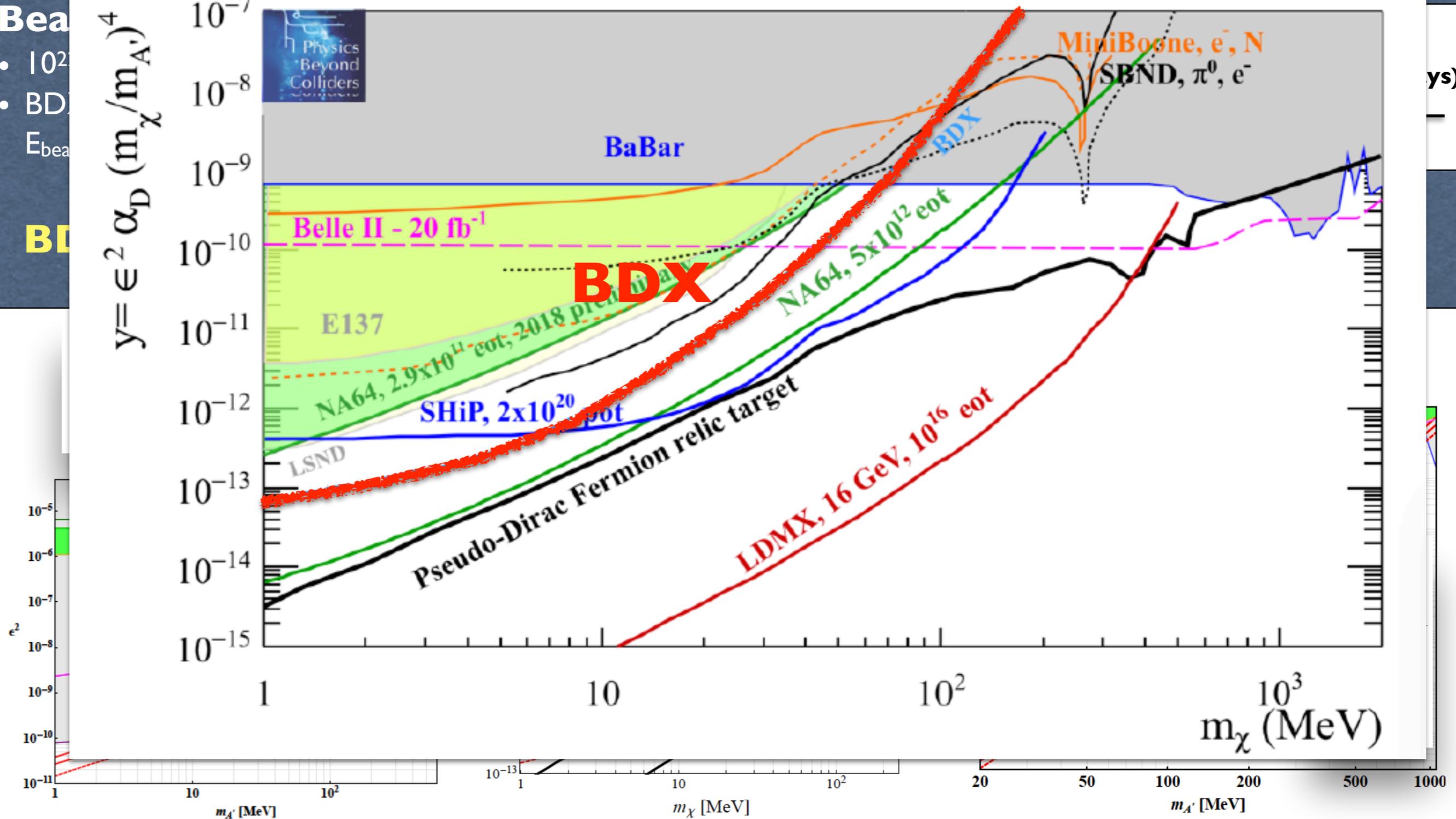
Leptophilic Inelastic DM, $m_\chi = 10$ MeV, $\Delta = 50$ MeV, $\alpha_D = 0.1$



BDX expected reach

BDX continues to be competitive in the current LDM landscape

Pseudo-Dirac Fermion Dark Matter



Bea
• 10²
• BD
E_{bea}
BD

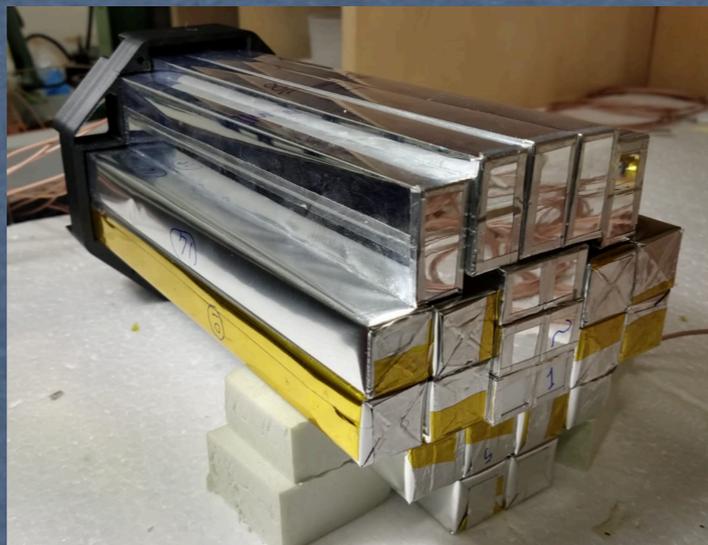
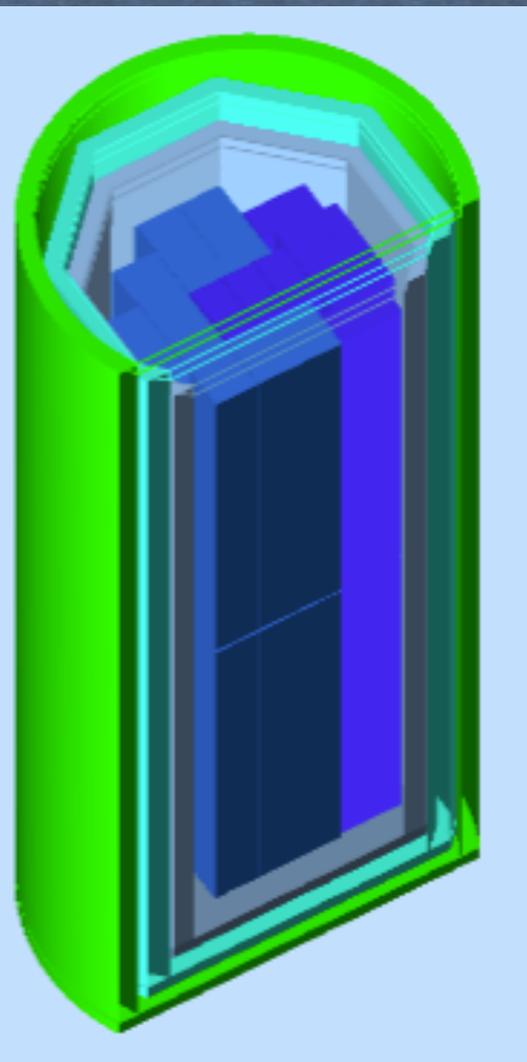
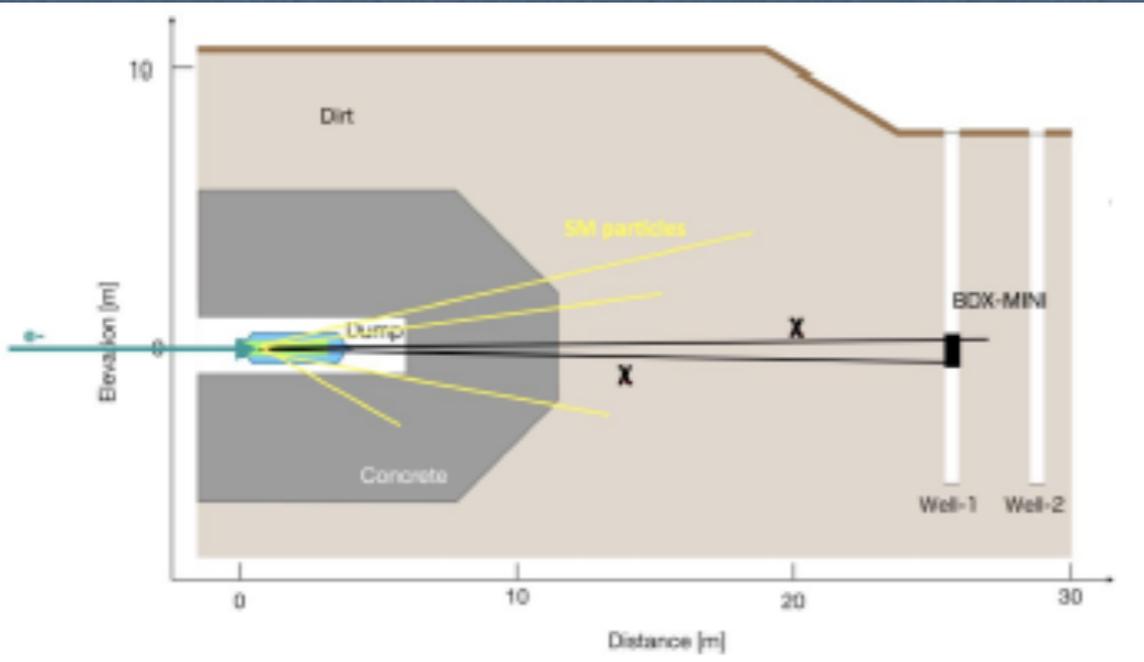
ys)

10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹

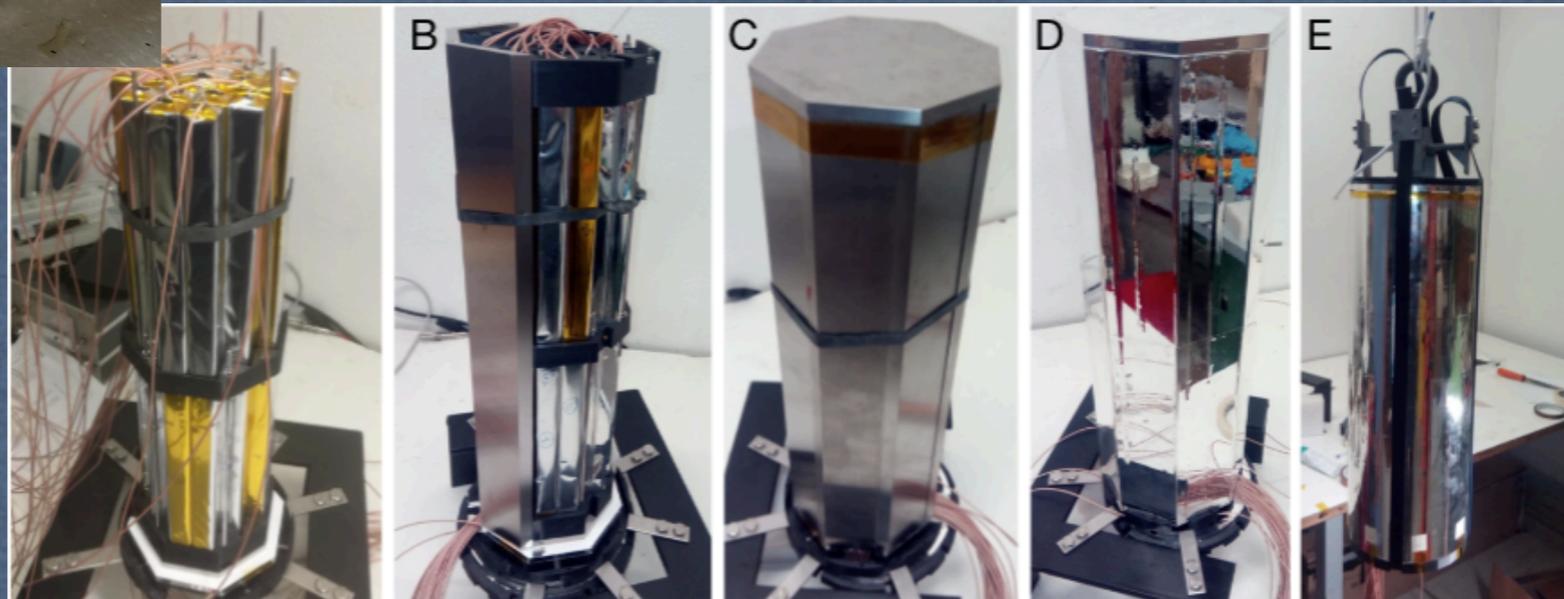
10⁻¹¹
10⁻¹⁰
10⁻⁹
10⁻⁸
10⁻⁷
10⁻⁶
10⁻⁵

BDX-MINI @ JLab

- Two wells dug for bg muon tests
- $E_{\text{beam}}=2.2$ GeV, no muons
- Limited reach but first physics result!
- Installed in March 2019
- Run from Dec 2019 to Aug 2020
- Collected $4e21$ EOT (40% BDX!) in ~4 months (+ cosmics)
- Good detector performance with high duty factor
- Data analysis in progress



- 44 PbWO4 PANDA/FT-Cal crystals (~1% BDX volume)
- 6x6 mm² SiPM readout
- 2 active plastic scintillator vetos: cylindrical and octagonal (8 sipm each) + 2x lids + Passive W shielding





The BDX-MINI detector for Light Dark Matter search at JLab

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Abstract This paper describes the design and performance of a compact detector, BDX-MINI, that incorporates all features of a concept that optimized the detection of light dark matter in the MeV-GeV mass range produced by electrons in a beam dump. It represents a reduced version of the future BDX experiment expected to run at JLAB. BDX-MINI was exposed to penetrating particles produced by a 2.176 GeV electron beam incident on the beam dump of Hall A at Jefferson Lab. The detector consists of 30.5 kg of PbWO₄ crystals with sufficient material following the beam dump to eliminate all known particles except neutrinos. The crystals are read out using silicon photomultipliers. Completely surrounding the detector are a passive layer of tungsten and two active scintillator veto systems, which are also read out using silicon photomultipliers. The design was validated and the performance of the robust detector was shown to be stable during a six month period during which the detector was operated with minimal access.

1 Introduction

BDX is a Beam Dump eXperiment searching for Light Dark Matter particles in the MeV-GeV mass range produced by the interaction of the Jefferson Lab (JLab) multi-GeV, high-intensity electron-beam with the experimental Hall-A beam dump [1]. BDX will have the requisite sensitivity to explore an entirely new physics regime (“Dark Sector”), where light dark matter (LDM) is the lightest stable state. LDM particles χ are charged under a new U(1)_D broken symmetry, whose mediator is a massive vector boson called A' or “dark

photon”. The dark photon can be kinetically mixed with the Standard Model (SM) hypercharge field, resulting in SM-DM interaction. We refer the reader to the recent review works [2–4] for a comprehensive discussion of the LDM theory and the corresponding ongoing experimental effort.

In the BDX experiment, a high-current (up to 150 μ A) e^- beam will be accelerated to an energy of 11 GeV by CEBAF will hit the experimental Hall-A Al/water beam dump [5], potentially producing, together with a large number of SM particles, a “dark beam” of χ particles. Given the time structure of the CEBAF accelerator, with beam bunches impinging on the target at \simeq 500 MHz, the hypothetical secondary “dark beam” is almost continuous. LDM is predicted to be produced in the beam dump via two main mechanisms: A' -strahlung [6,7], which is conceptually akin to bremsstrahlung for SM, and e^+e^- resonant annihilation [8]. The beam dump is heavily shielded with 20 m of concrete, iron and dirt, acting as a filter for almost all SM particles. Only weakly interacting particles (SM ν and LDM χ) propagate through the shielding to the BDX detector that is designed to identify rare interactions. The BDX detector is a homogeneous electromagnetic calorimeter, surrounded by a dual-layer veto system to reject the cosmogenic background [9]. The χ interaction with the atomic electrons in the calorimeter results in a high-energy scattered e^- , up to 1 GeV (few hundreds MeV) for 11 GeV (2.176 GeV) primary electron beam energy, that can be easily measured in the BDX detector. The scattering is identified by detecting a high-energy electromagnetic shower with no associated activity in the surrounding veto systems. Considering the low probability of LDM production and detection, beam-dump experiments require intense beams and a large accumulated charge. With more than 10^{22} electrons-on-target (EOT) expected in one year of running,

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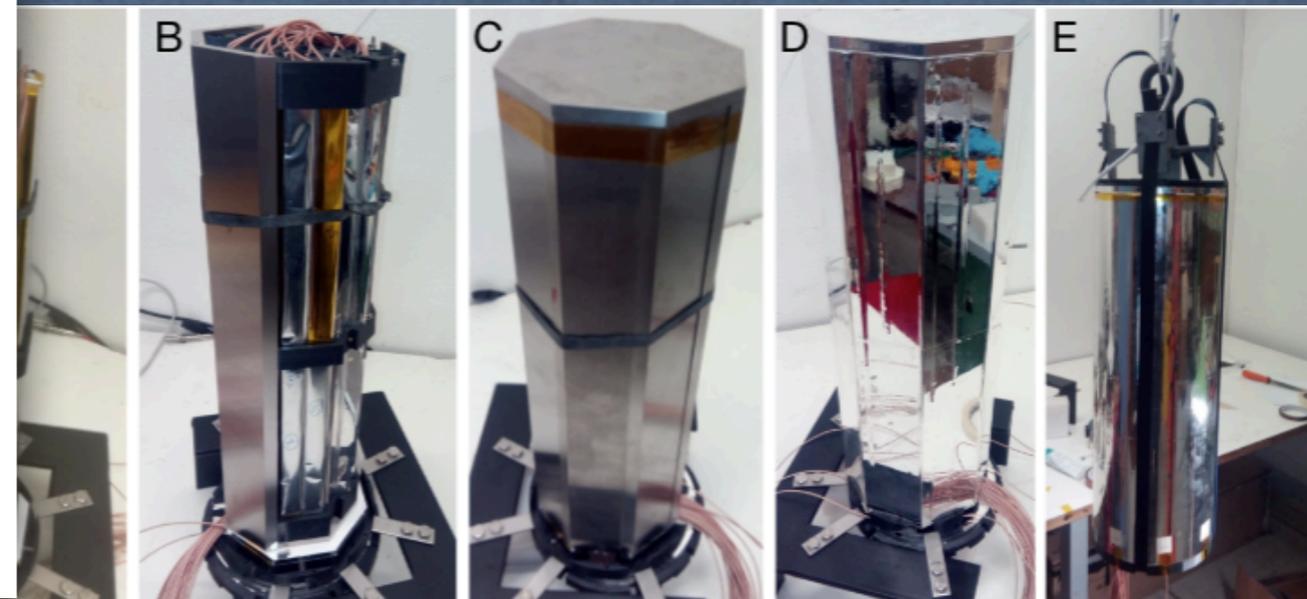
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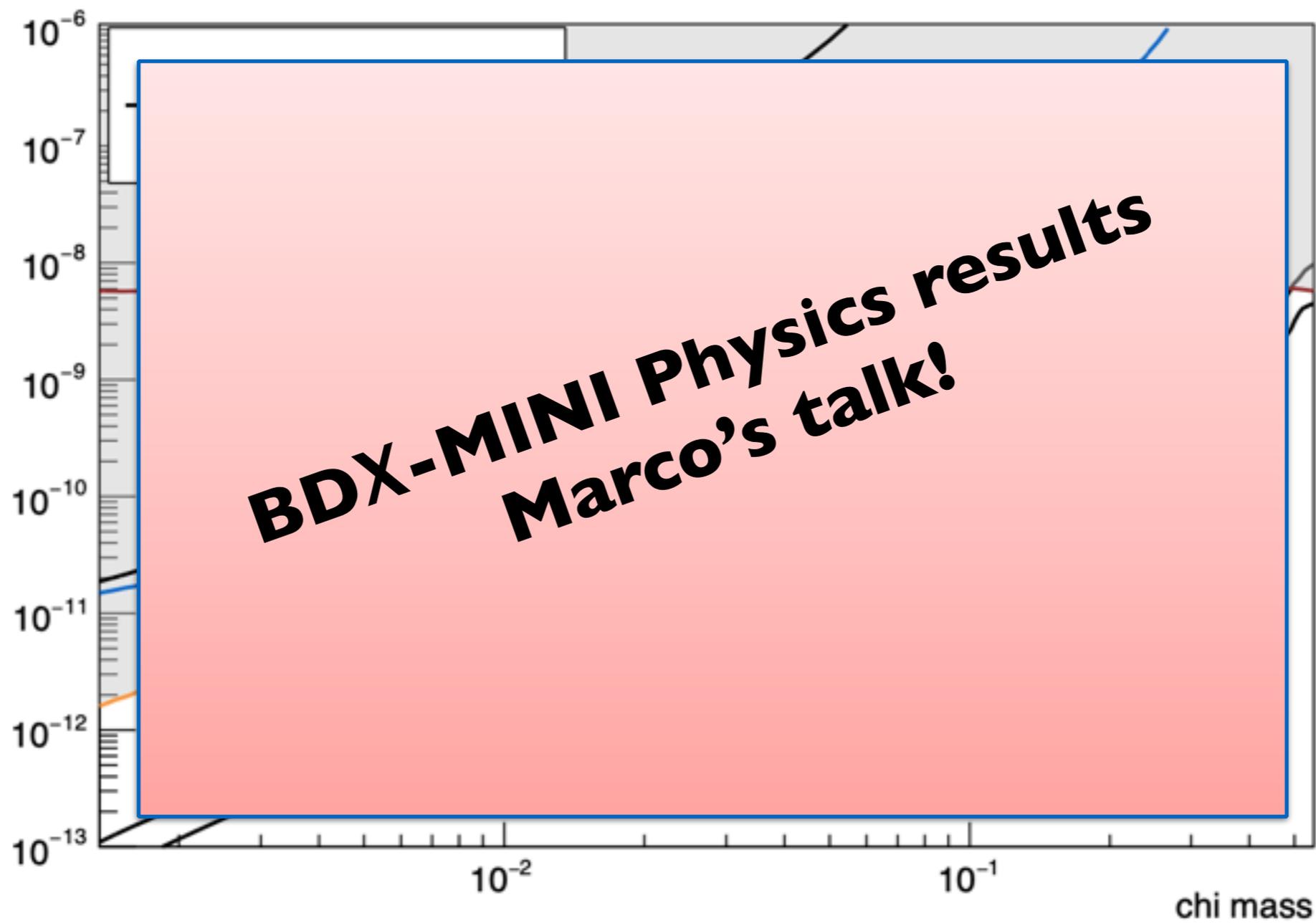
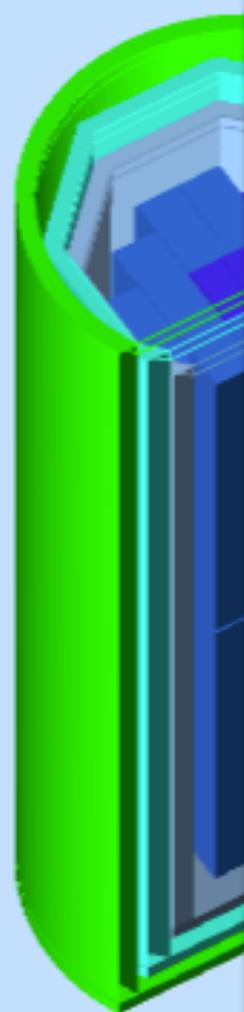
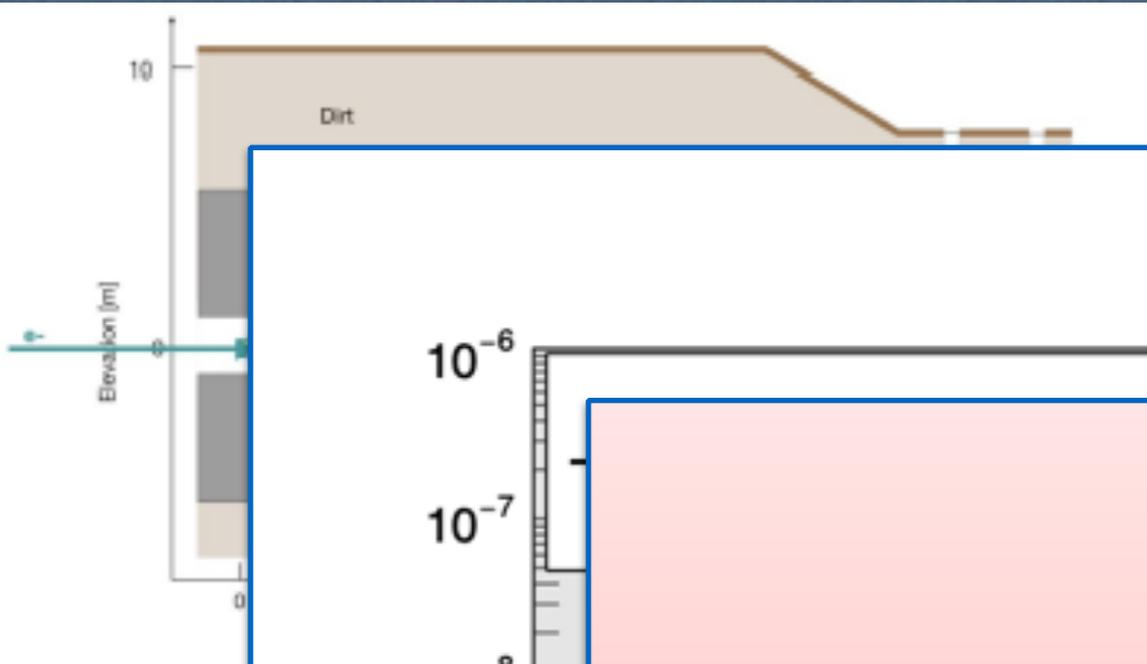
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6x6 mm² SiPM readout

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BDX-MINI @ JLab



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