HPS Collaboration meeting

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

Nov 17 2021
HPS Collaboration Meeting

Update on BDX

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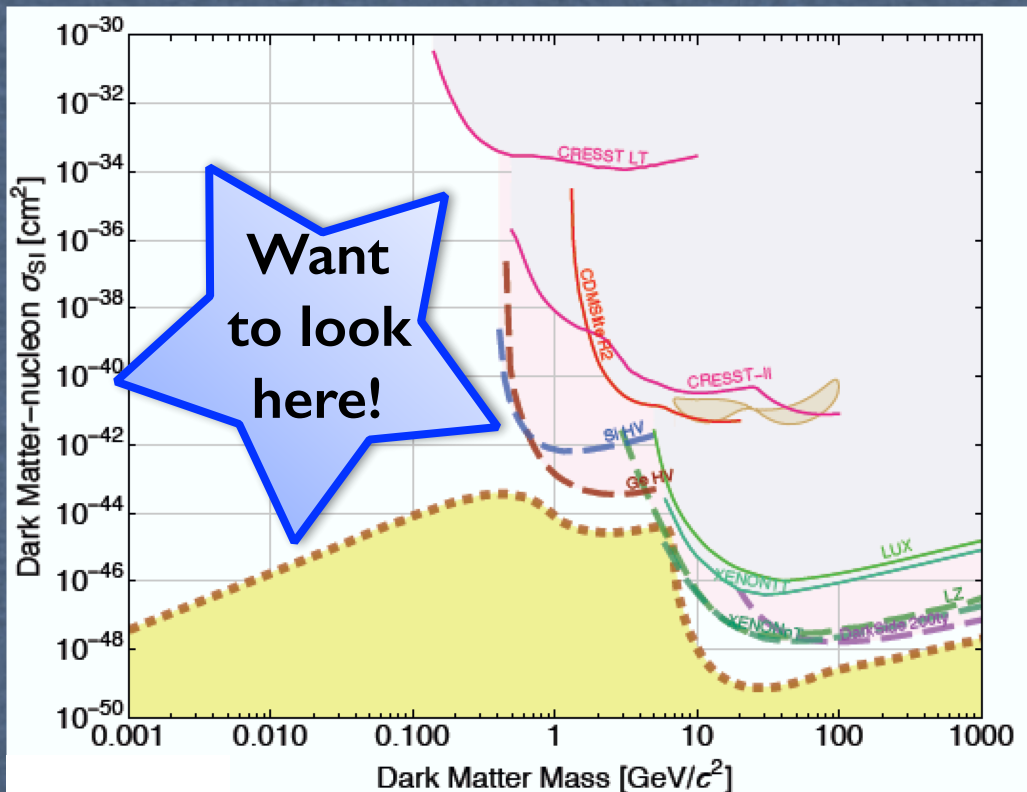
Light Dark Matter

★ 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

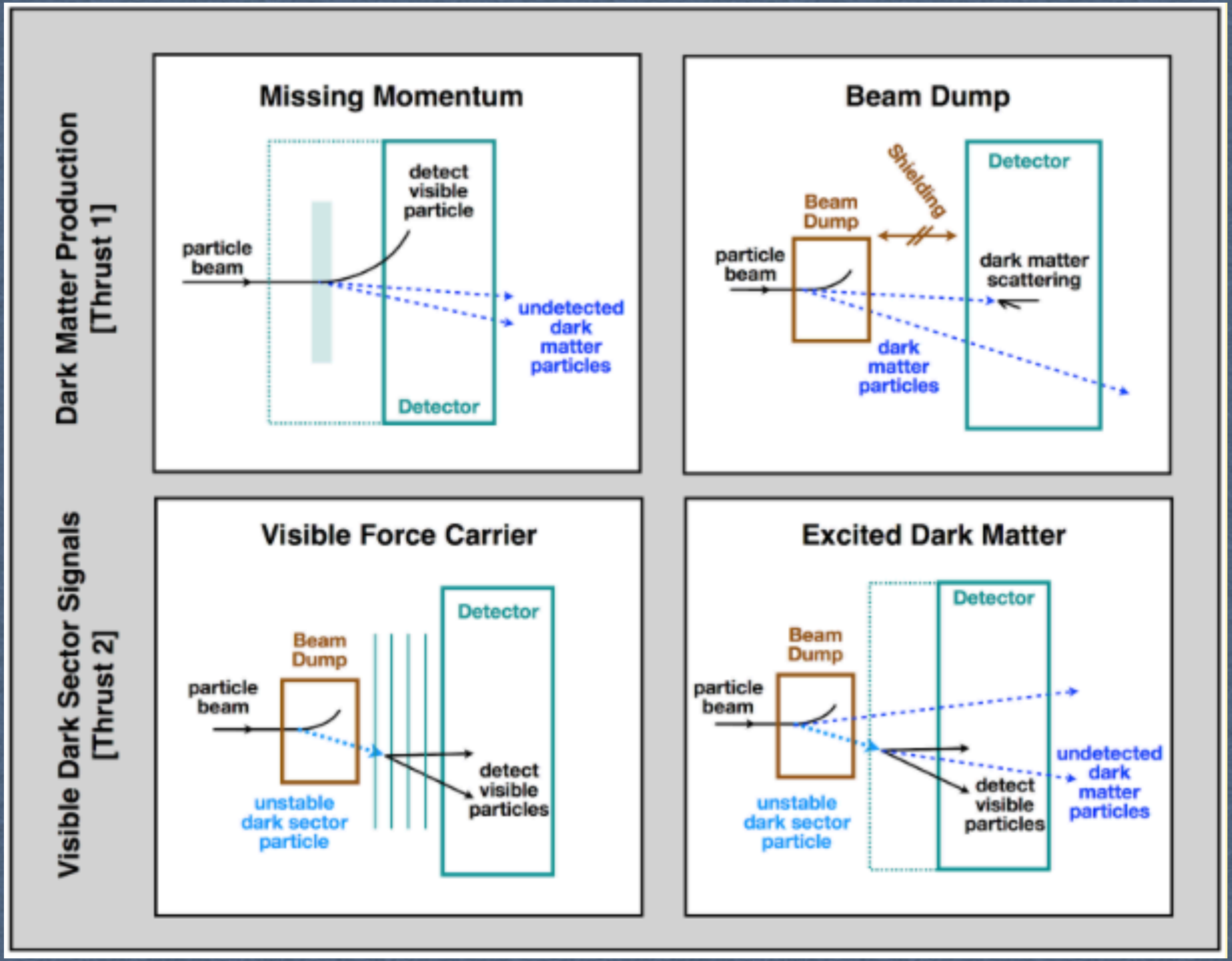
1 MeV — 1 GeV — Mz — 10 TeV

WIMPs

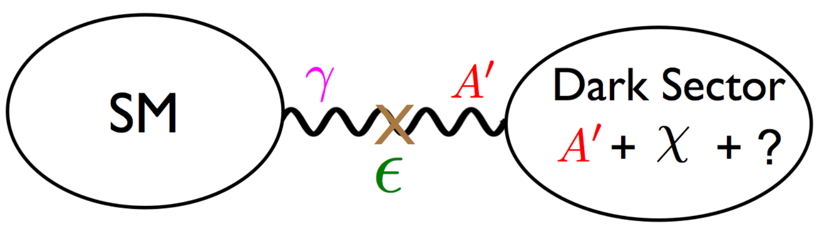
Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

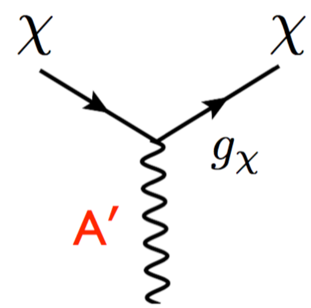
Can be explored at accelerators!

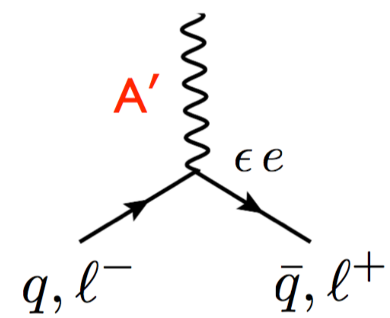
Experimental techniques



Dark forces and dark matter
(Light WIMPs - light mediators)



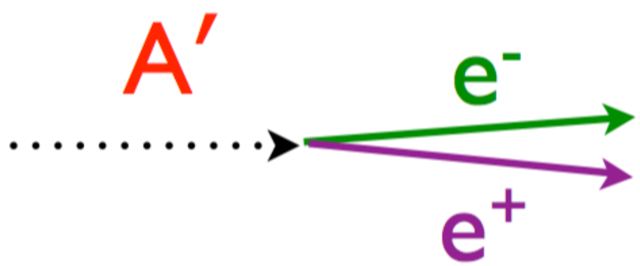




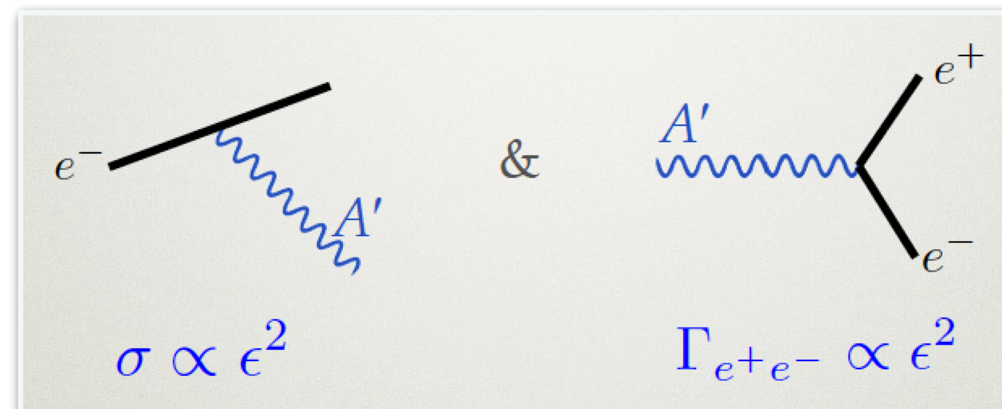
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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

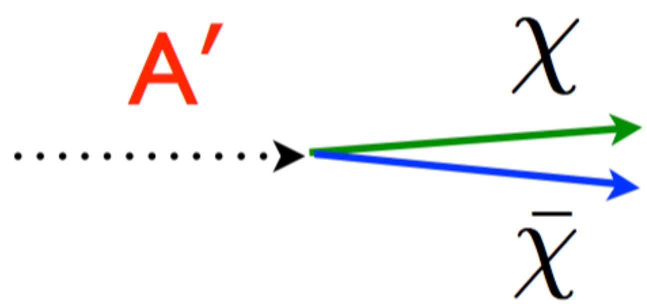
Visible



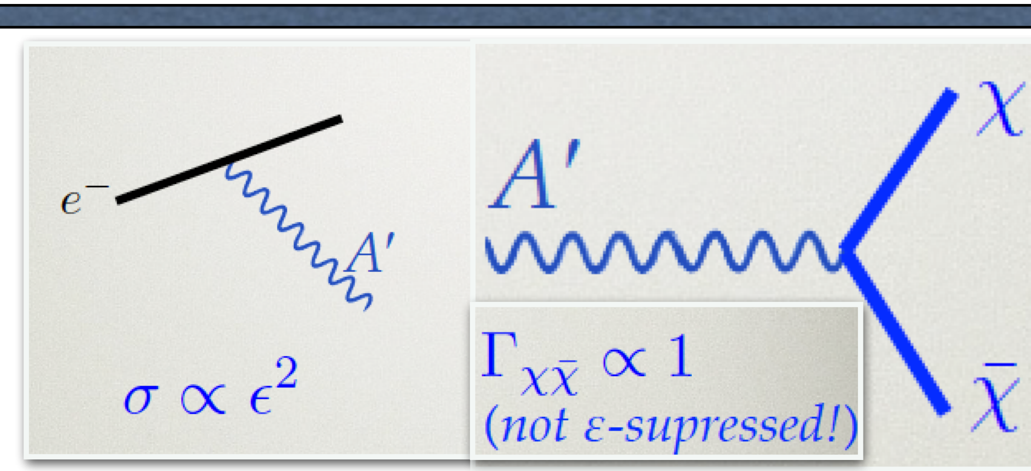
- *Minimal* decay
- Decay regulated by ε^2
- Independent of m_χ
- Requires $m_{A'} < 2m_\chi$



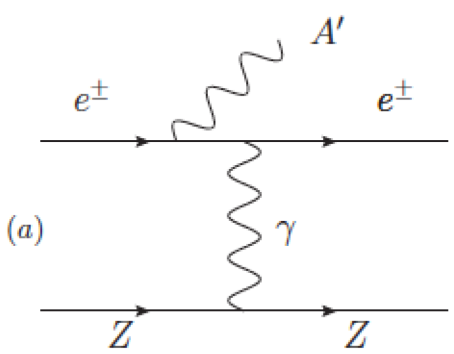
Invisible



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



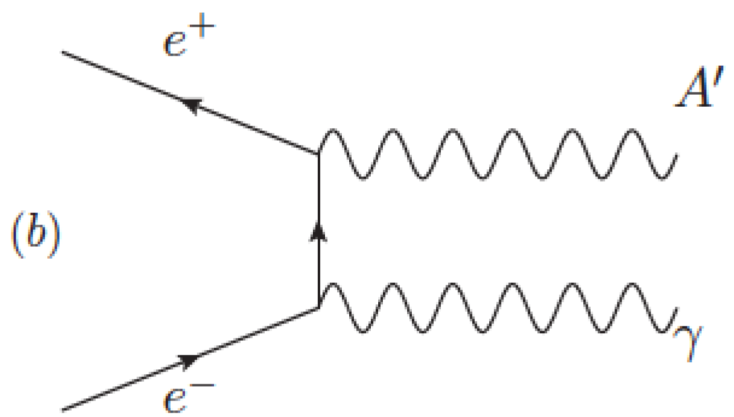
DM interaction in fixed target experiments



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

The Weizsacker-Williams approximation (*A'-strahlung*)

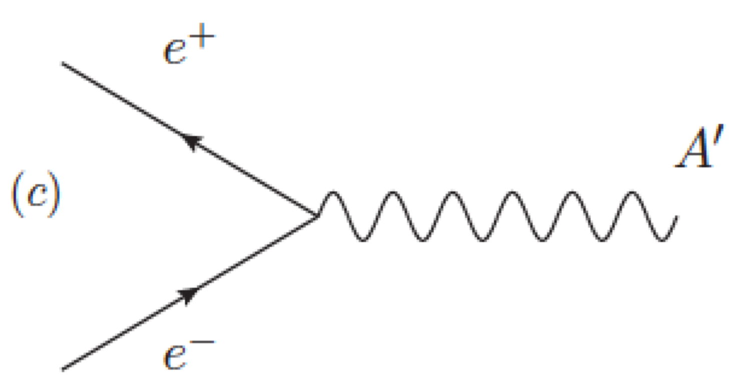
- The incoming electron 'see' a fast-moving cloud of effective photons to scatter from
- Photons are almost on-shell (low Q2) → transverse photons ~ $e^- \gamma_{Real}$ scattering
- Same treatment as the regular *bremsstrahlung*
- Effective photon flux χ is critical, accounting for nuclear effect using FF
- Forward-boosted, high-energy *A'* emission



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

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

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



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

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

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

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

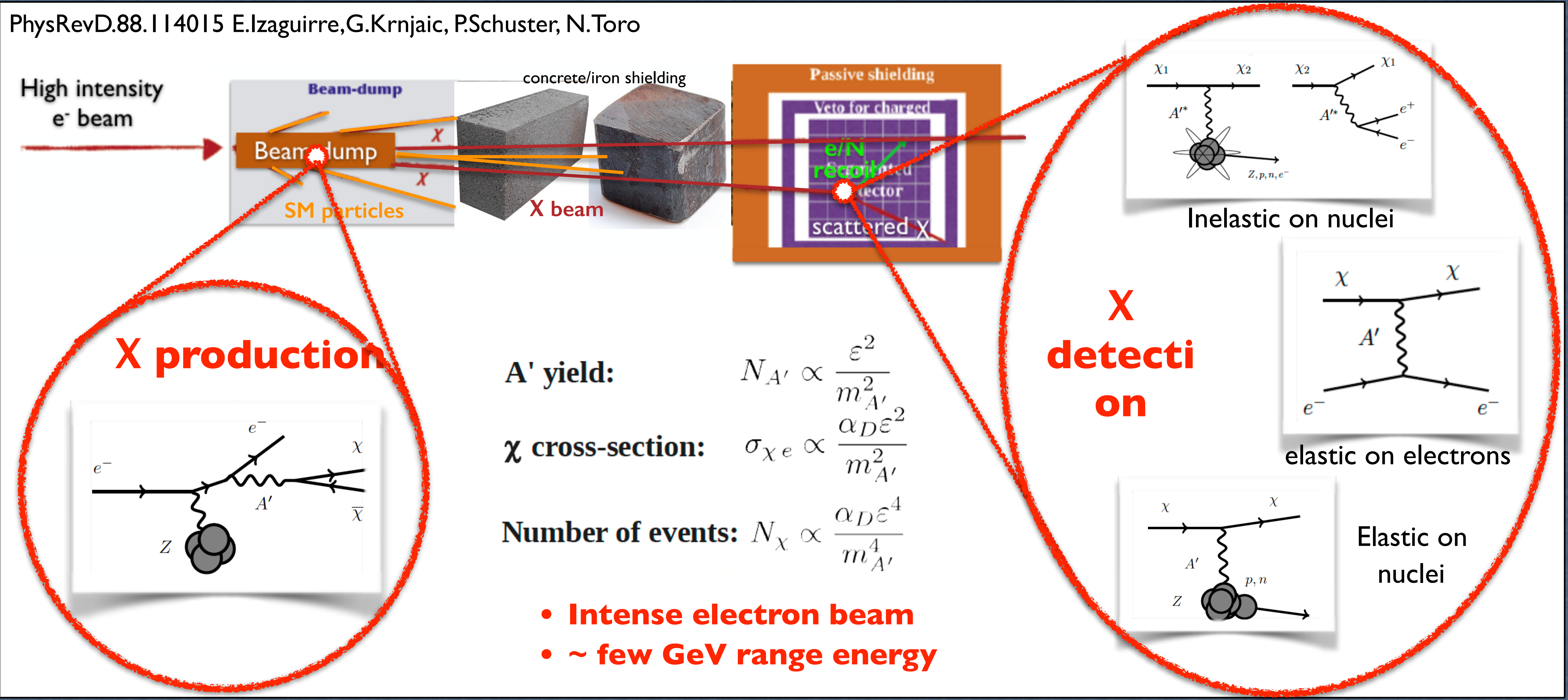
The BDX experiment

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



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

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

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

- **Intense electron beam**
- **~ few GeV range energy**

The BDX experiment

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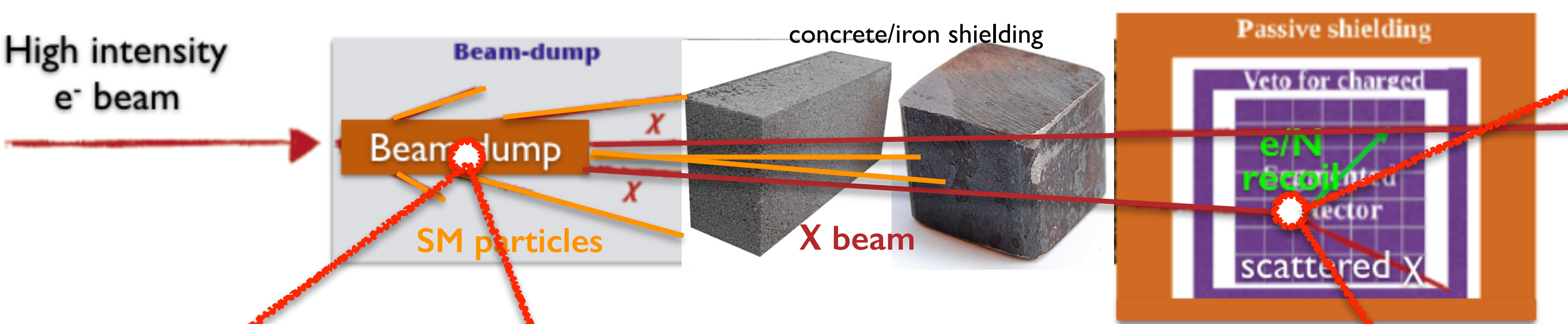

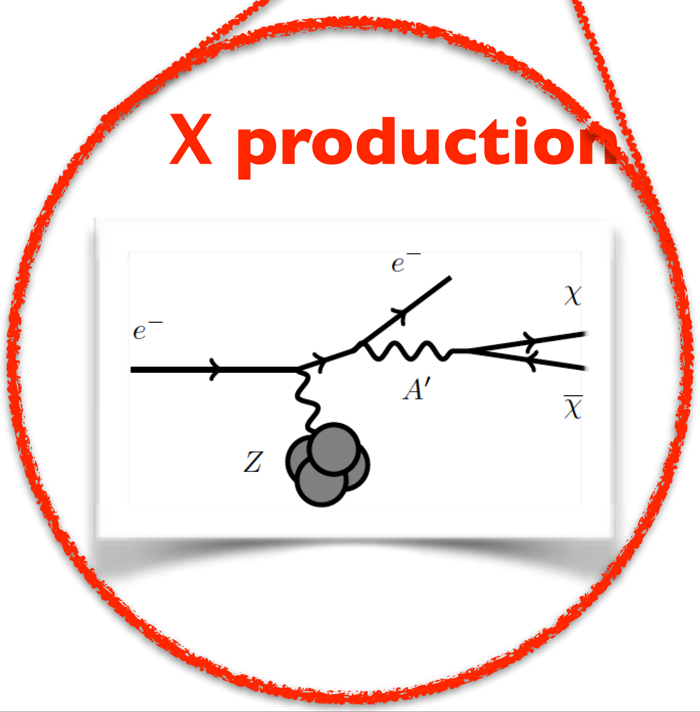

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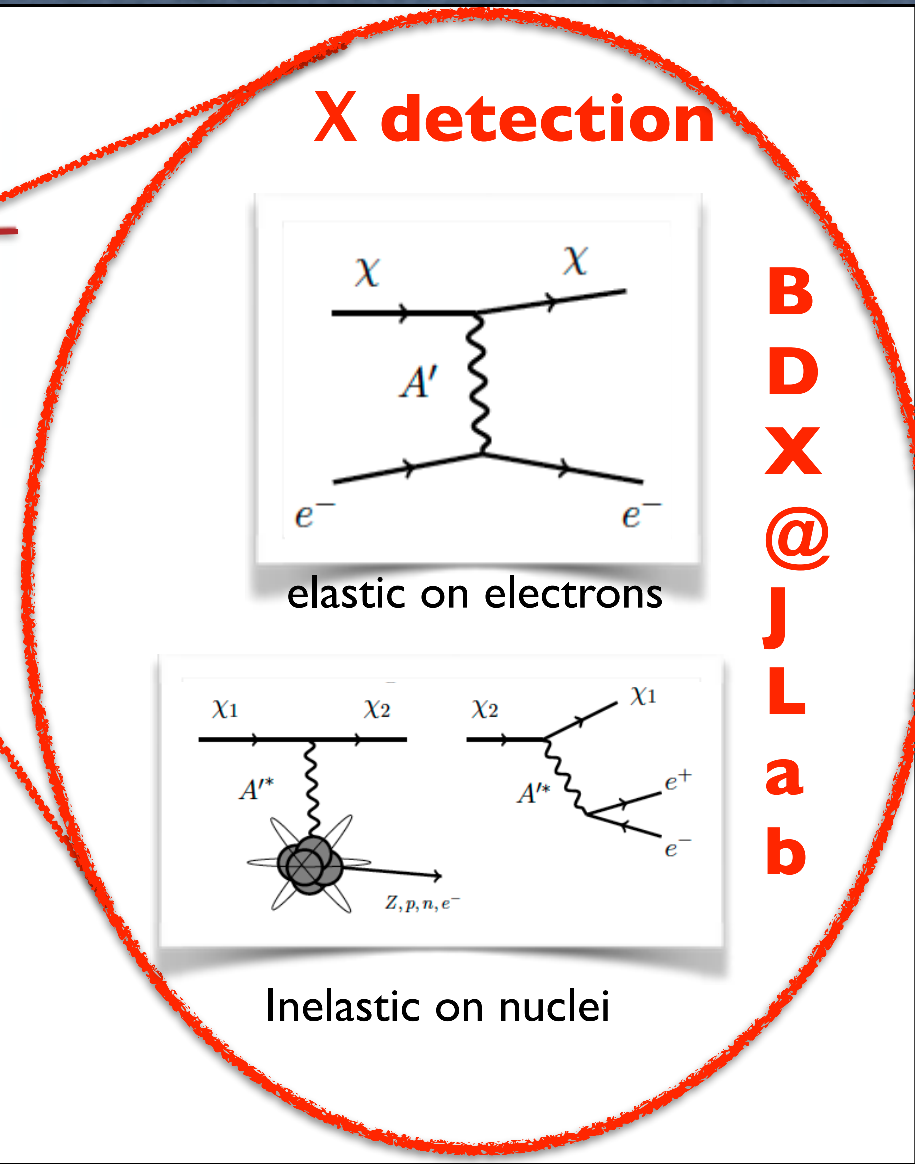


B D X @ J L a b

Experimental signature in the detector:

X-electron → EM shower ~GeV energy

The BDX detector

Detecting the X

Detector requirements

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

Rejecting the bg

- Beam-related
- Cosmic

Active veto requirements

- High efficiency (>99%) to MIPs
- Fast (~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

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 ~ m^3 detector volume
- Good timing (desirable)

Possible options:

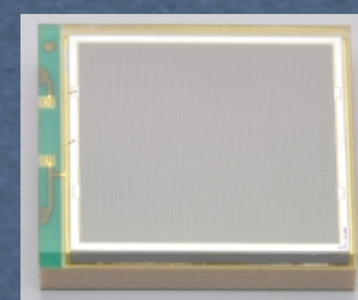
BaF2
CsI
BSO

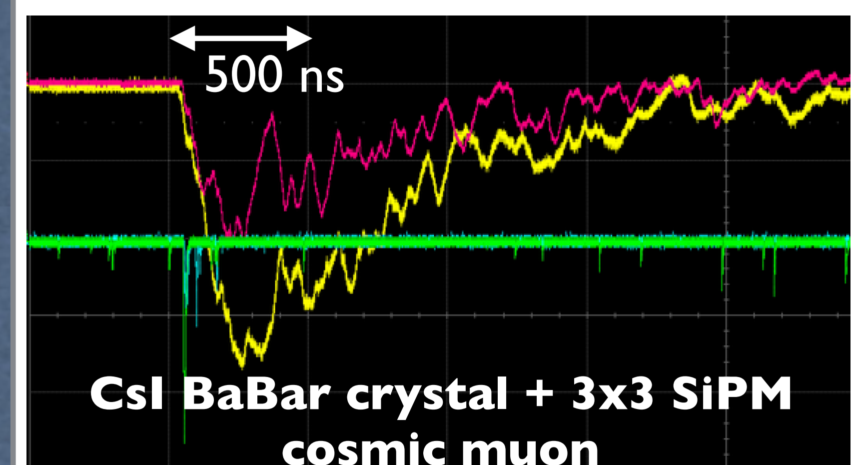
A dedicated measurement campaign to characterise the crystal properties

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

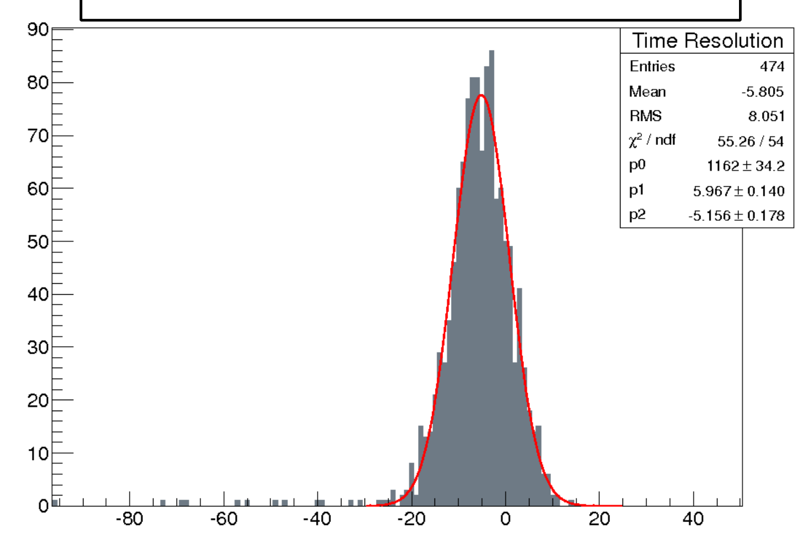
Parameter	Values
Radiation length	1.85 cm
Molière radius	3.8 cm
Density	4.53 g/cm^3
Light yield	50,000 γ/MeV
Light yield temp. coeff.	0.28%/°C
Peak emission λ_{max}	565 nm
Refractive index (λ_{max})	1.80
Signal decay time	680 ns (64%)
	3.34 µs (36%)

CsI(Tl) + SiPM readout





CsI BaBar crystal + 3x3 SiPM
Time resolution: σ = 6ns



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, 25µm, 57.6k cells, trenched, pde=25%
- SPE capability
- CsI(Tl): 40 pe/MeV
- Time resolution: ~6ns (MIPs)

★Due to the large LY signals at ~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 m^2 detector surface
- Good timing (desirable)

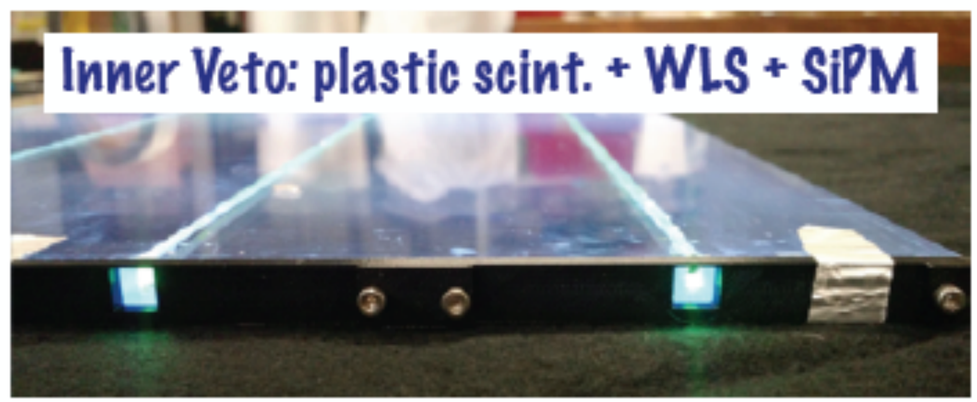
Possible options:

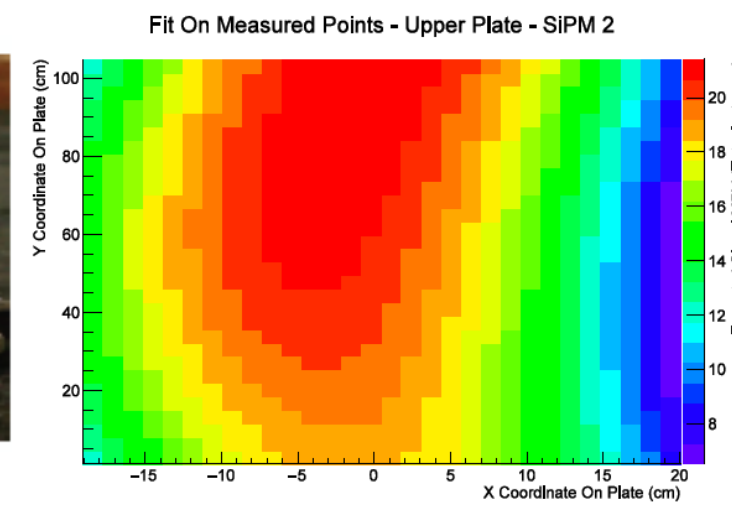
plastic scintillator
liquid scintillator
passive vetos

R&D on different technologies:
- Plastic scintillator + light guide + PMT
- Plastic scintillator + WLS + PMT
- Plastic scintillator + WLS + sipm

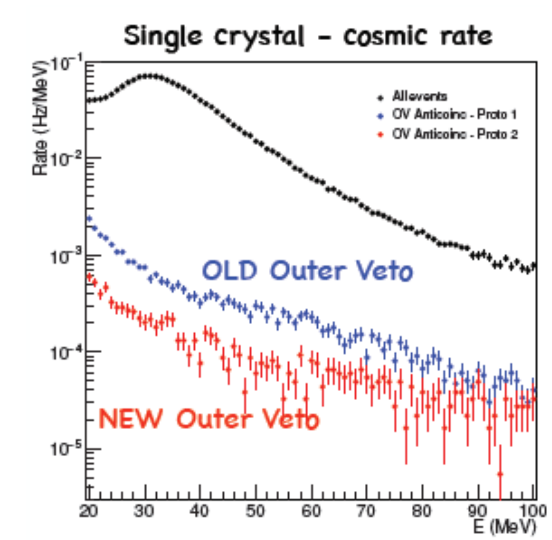
Plastic scintillator + WLS and SipM/PMT readout

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





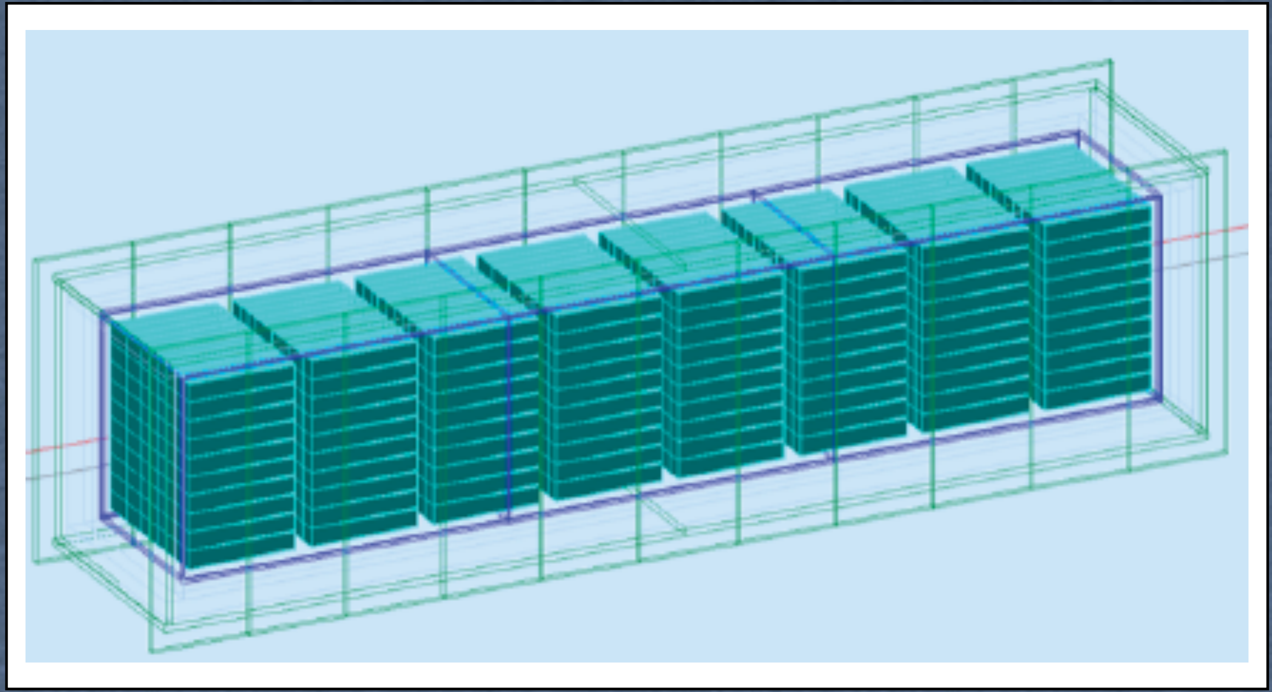
Outer veto:
- Plastic scintillator + Light guide + PMT
- Plastic scintillator +WLS fiber

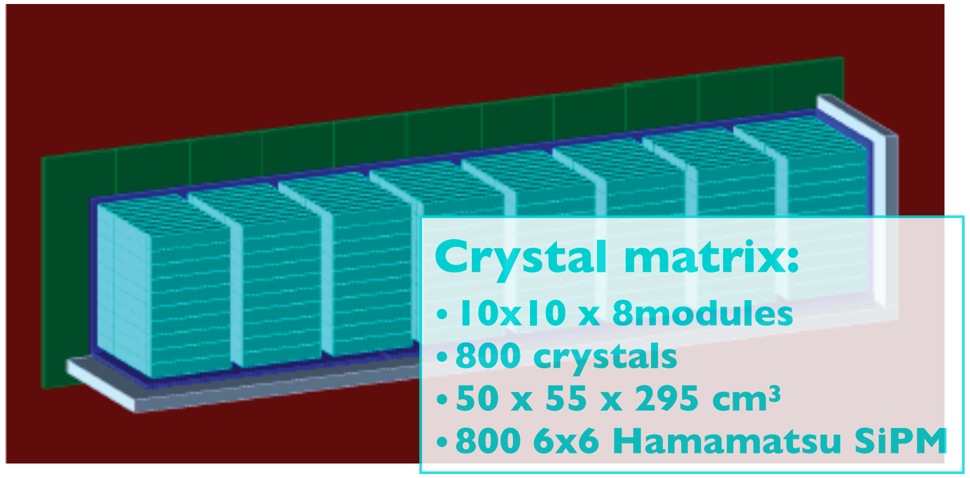


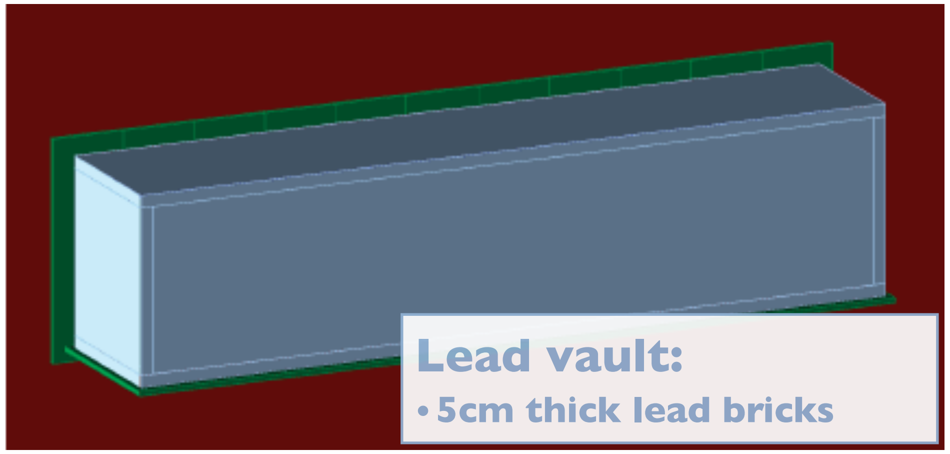
★High efficiency to MIPs (>99%)
★Robust and simple technology

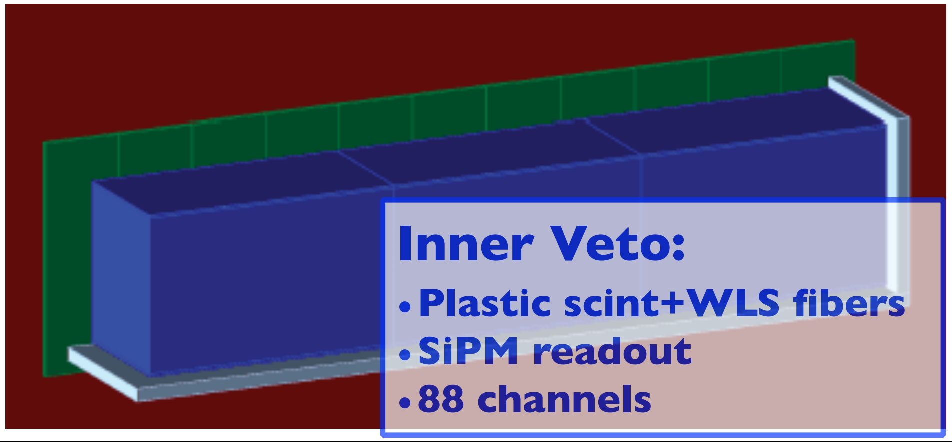
The BDX detector

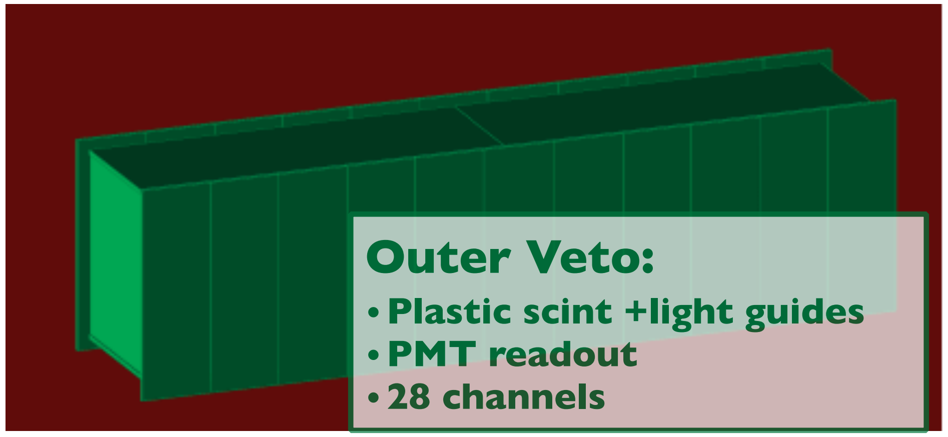
- ★ Modular EM calorimeter: 8 modules 10x10 crystals each
- ★ 800 CsI(Tl) crystals (former BaBar EMCal) + SiPM readout
- ★ Inner Veto: plastic scintillator + WLS + SiPM
- ★ Outer Veto: plastic scintillator + PMTs
- ★ Passive shielding: lead vault



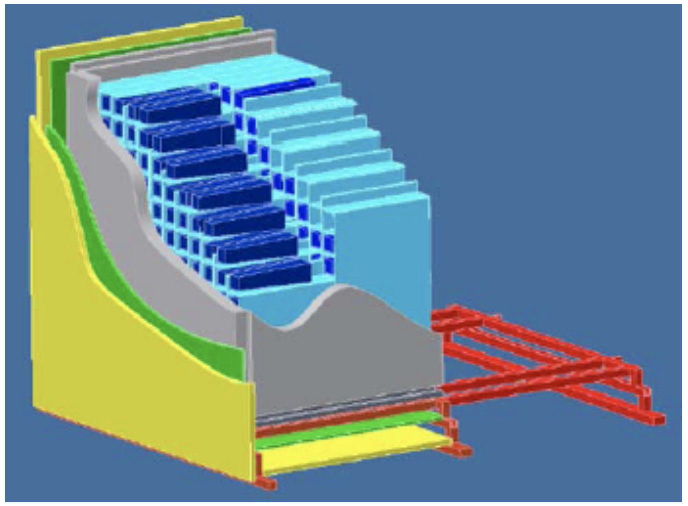




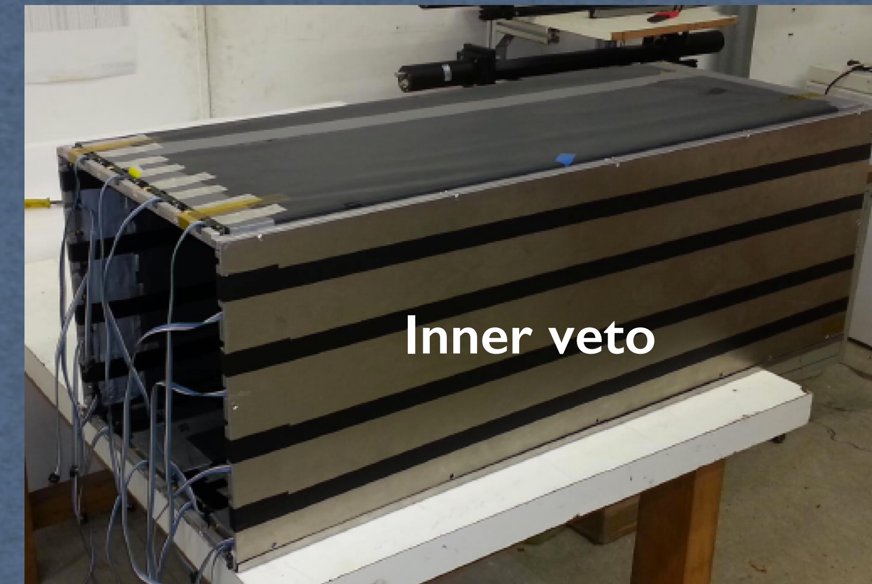


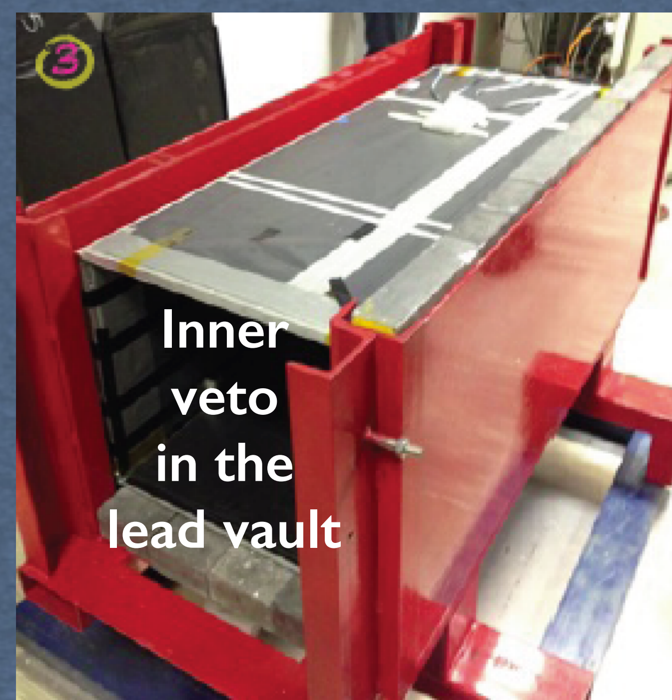


Calorimeter module



The BDX prototype



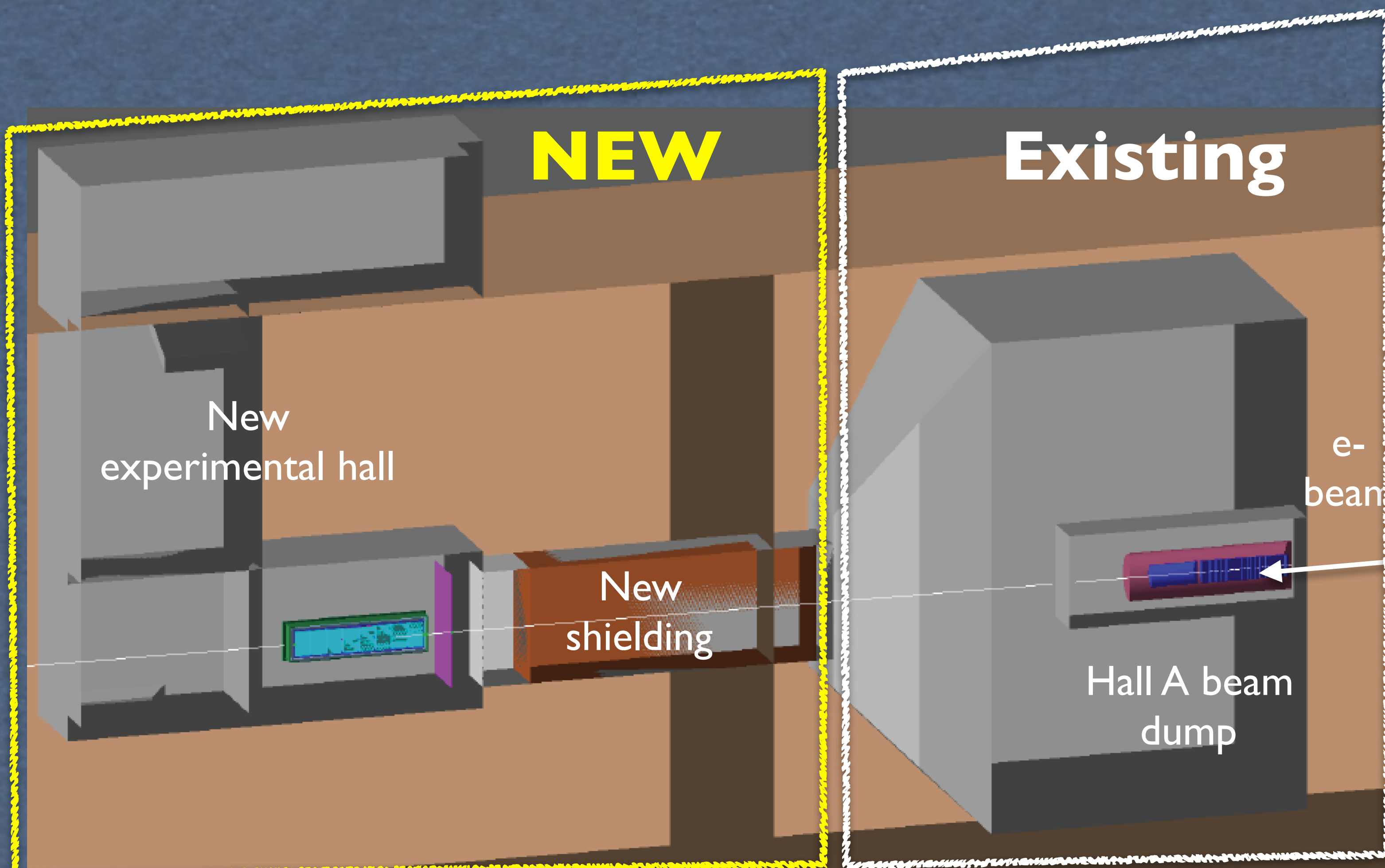


- EM Cal
  - 4x4 CsI(Tl) crystals
  - 6x6 mm^2 SiPM
- Outer Veto
- Lead vault
- Inner Veto

BDX at JLab

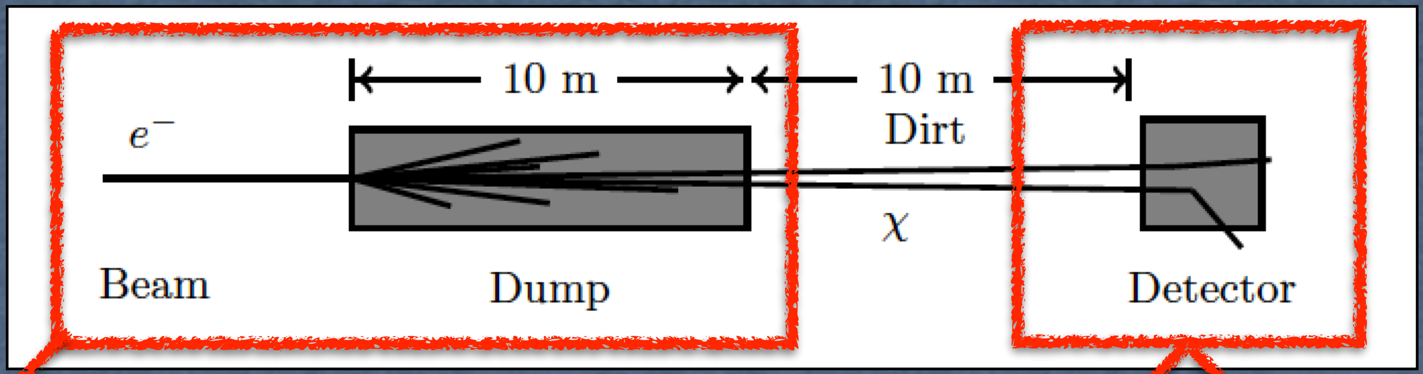
★ High energy beam available: 11 GeV
★ The highest available electron beam current: ~65 uA
★ The highest integrated charge: 10^{22} EOT (41 weeks)

★ BDX detector located downstream of Hall-A beam dump
★ New underground experimental hall

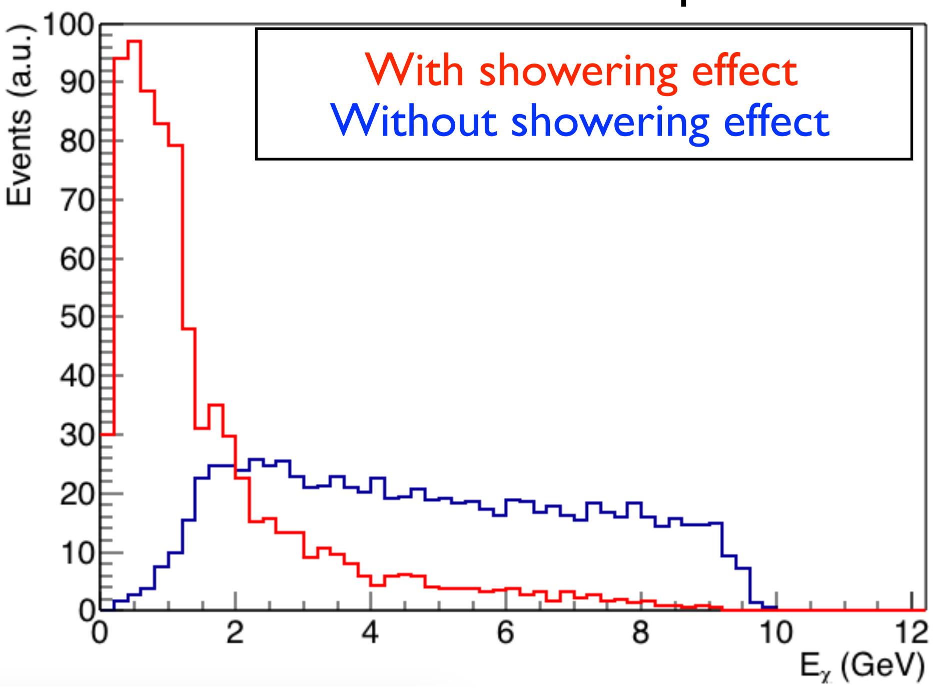


X production and detection

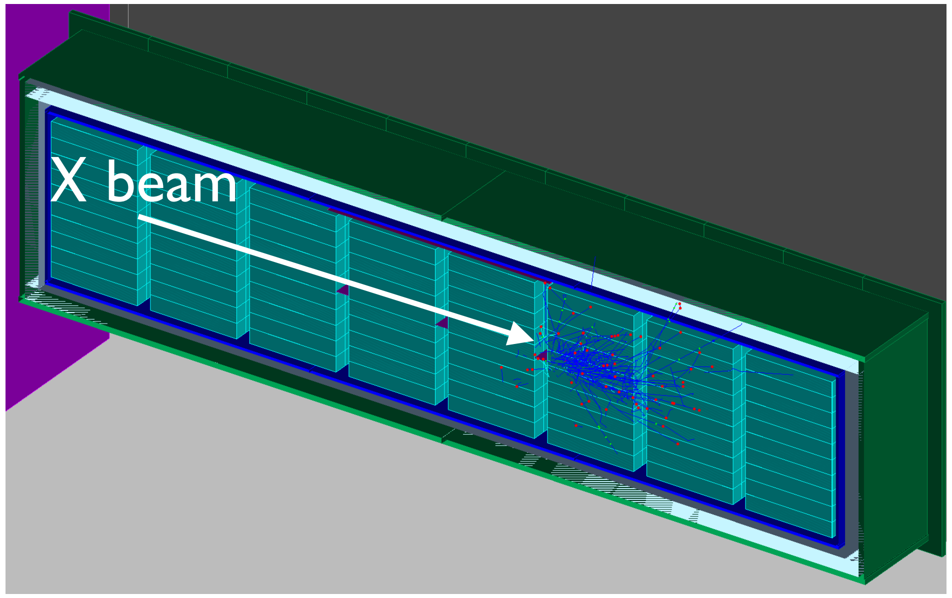
- Detailed simulations using ad-hoc MC code to describe the A' production, decay (A' →χ χ) and interaction in the BDX detector (X-e)
- Detailed description of Hall-A beam dump (production) and BDX detector (detection) using GEANT4



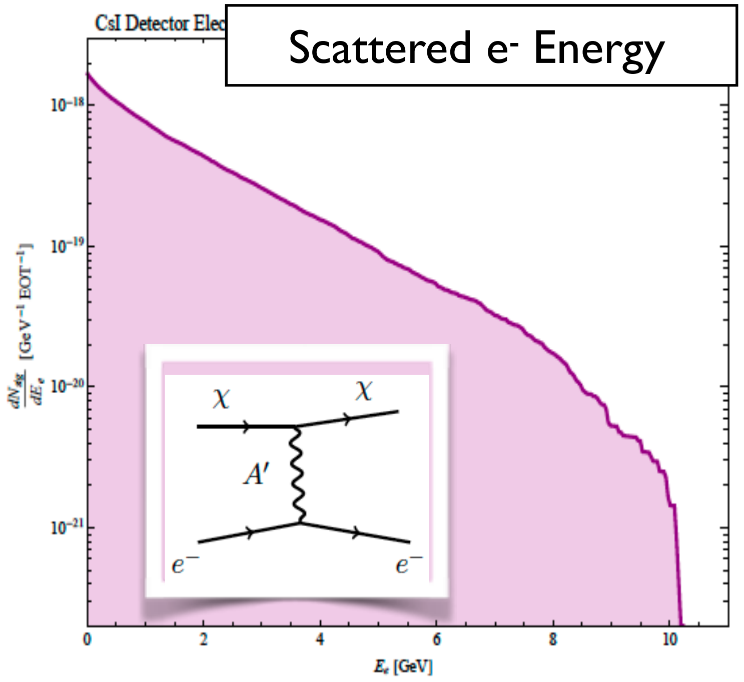
X energy spectrum generated by 11 GeV e-beam in the dump



χ-e interaction producing an em shower in the detector



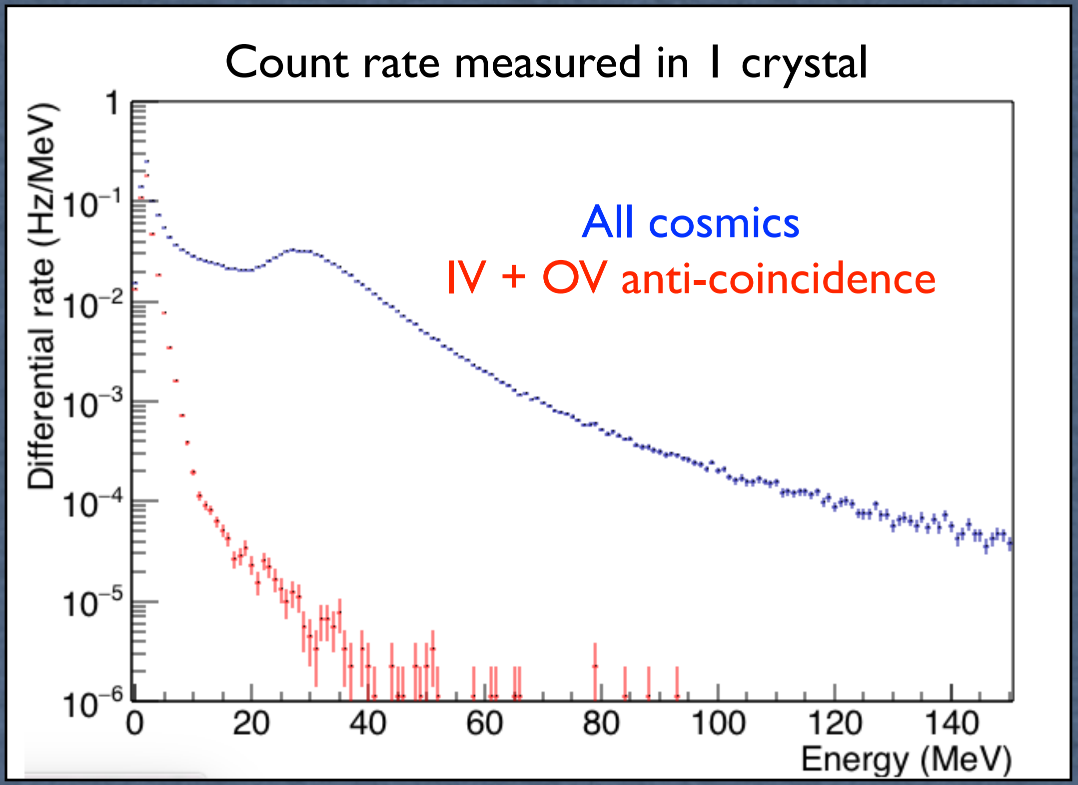
Elastic on electrons



Background

Cosmic

★ Cosmic background measured with the BDX detector prototype in CT



Expected cosmic bg counts in BDX lifetime < 2 counts

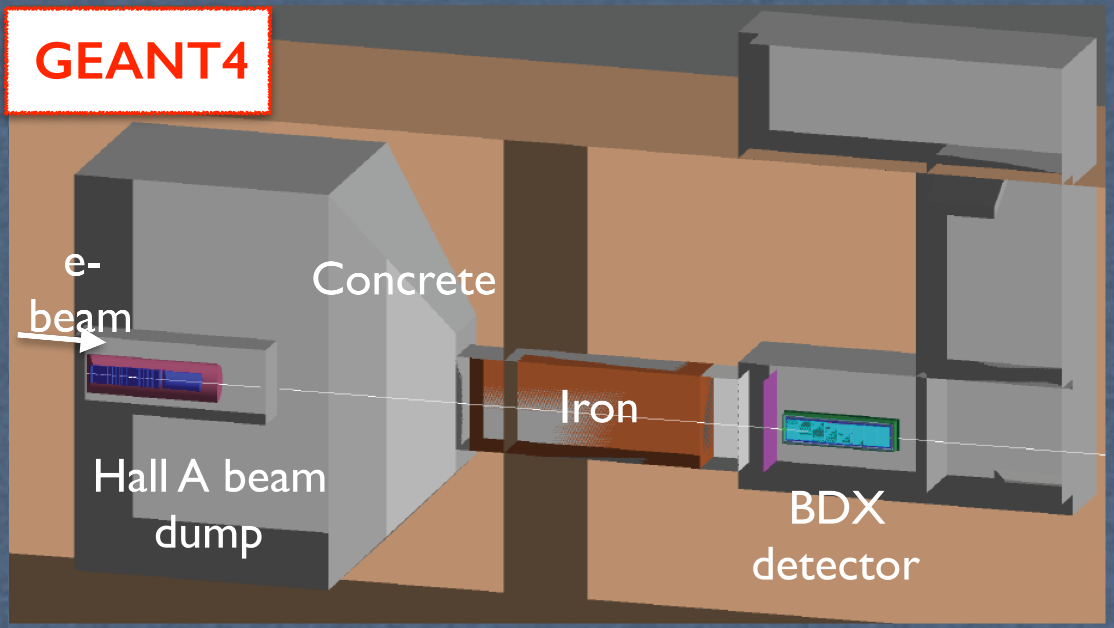
Beam-related

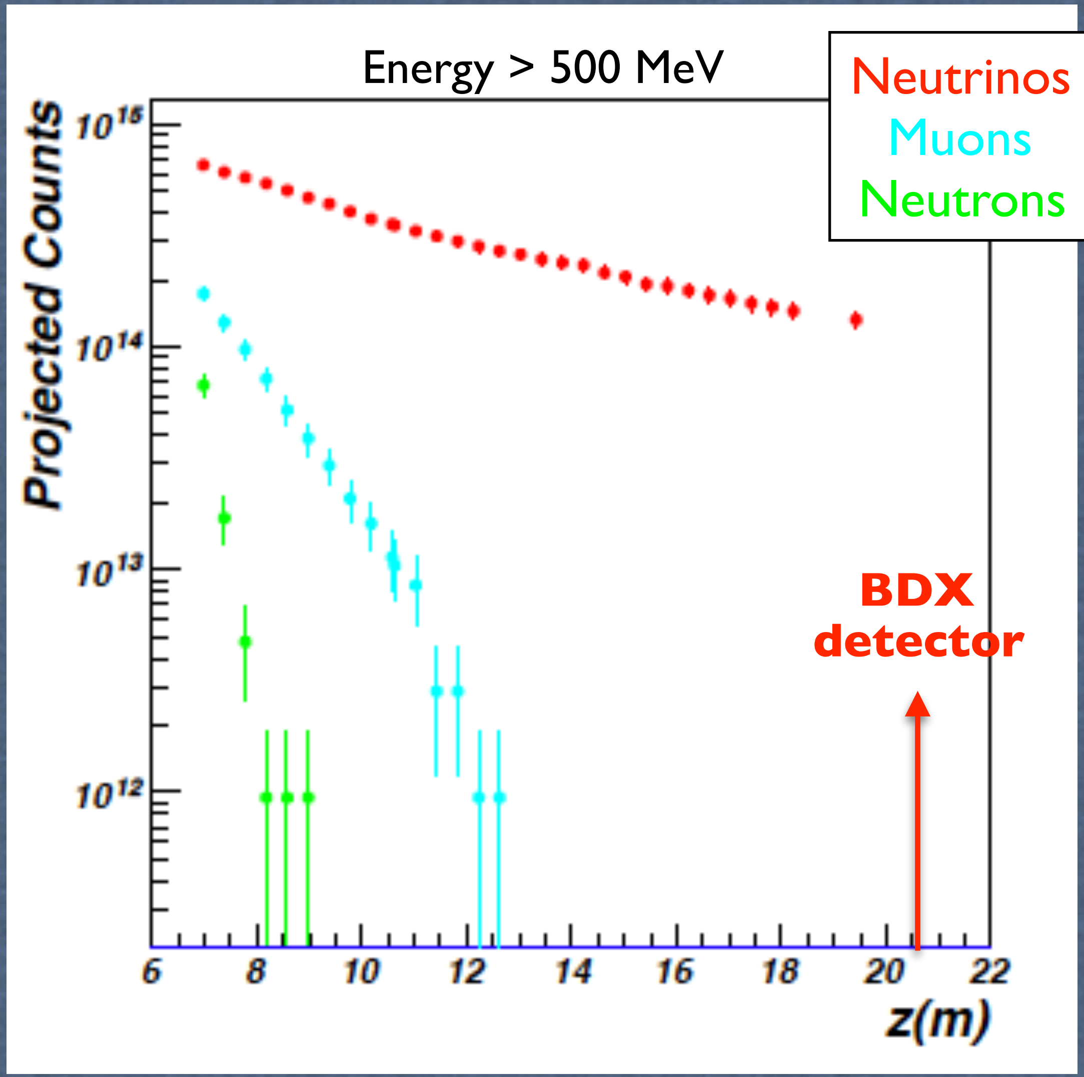
Bg estimated using GEANT4, tracking particles with $E>E_{Thr}$

★ 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

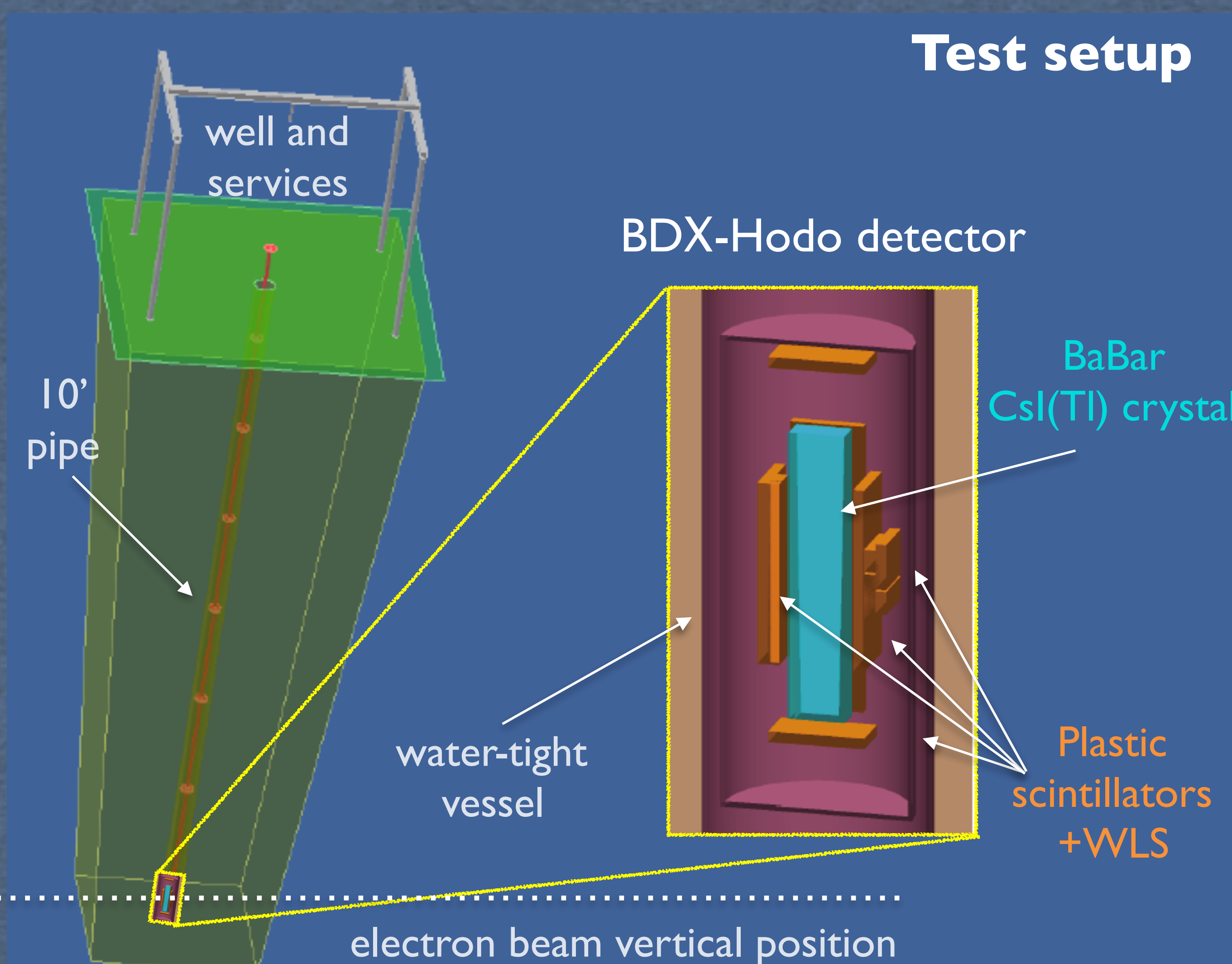




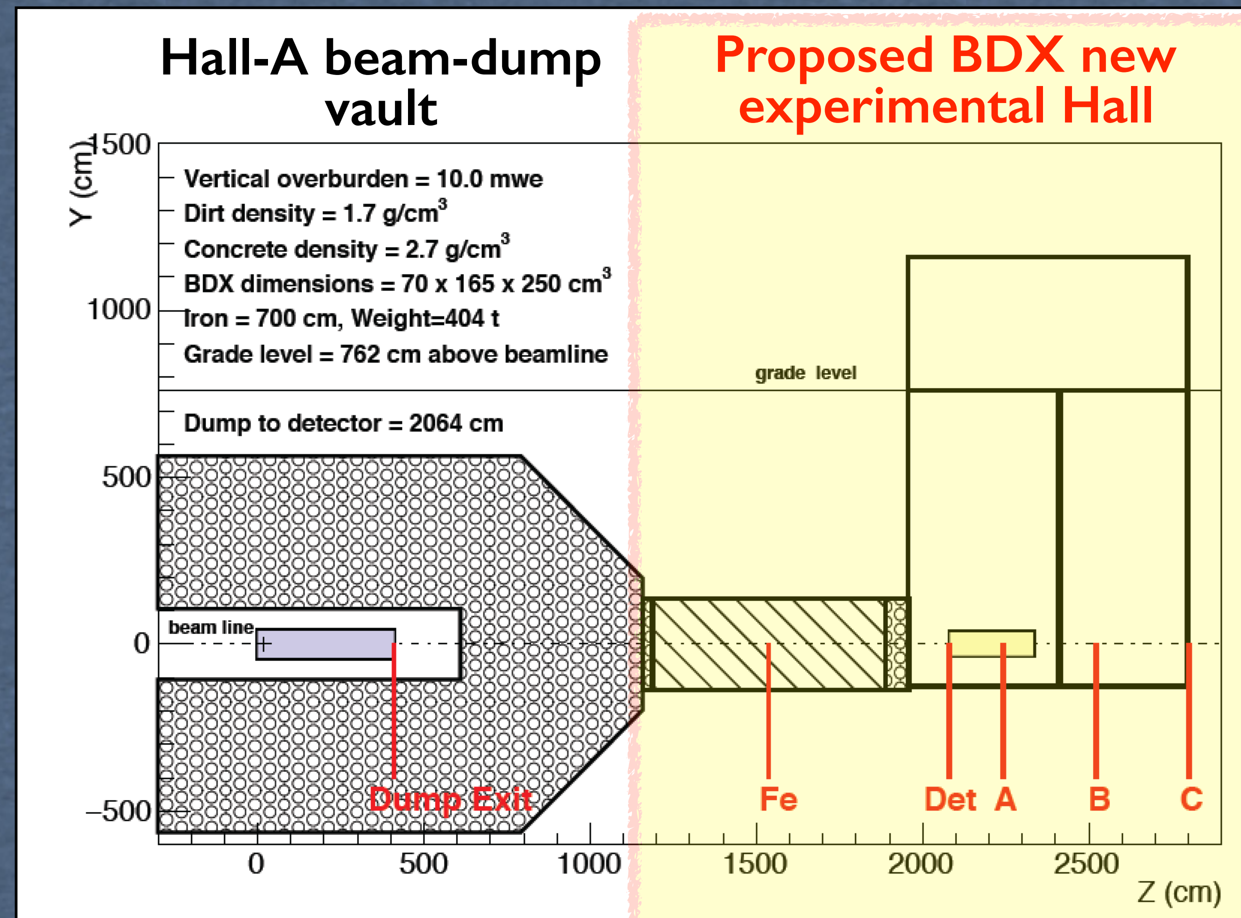
Tests to measure the beam-on background

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



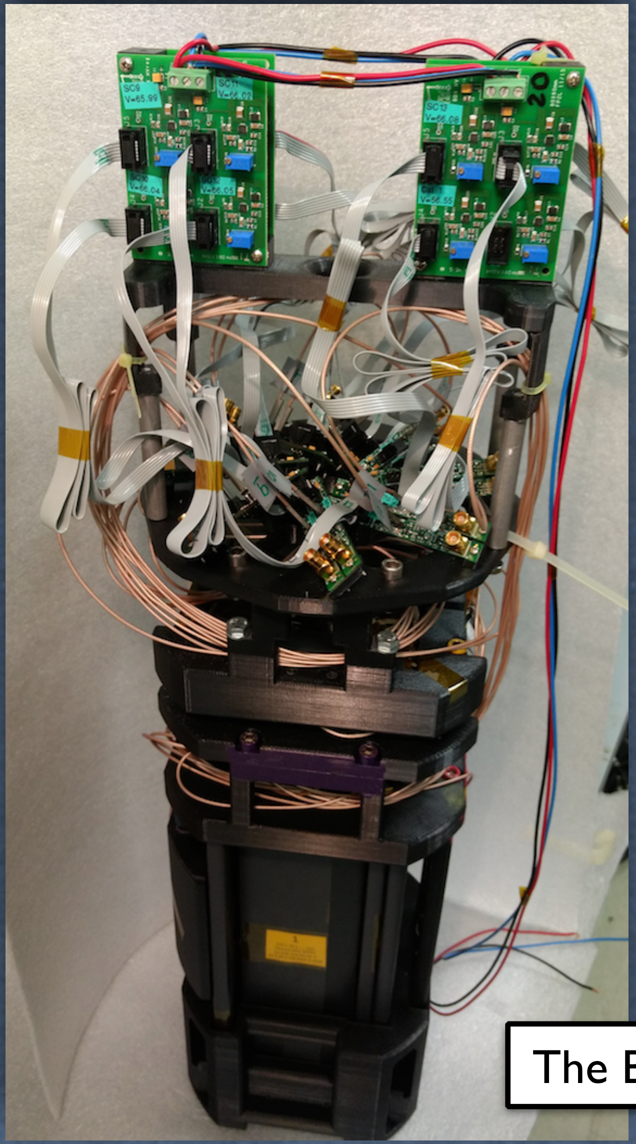
Downstream of the Hall-A beam dump - TODAY -



BDX-Hodo tests at JLab

Two wells


The tent

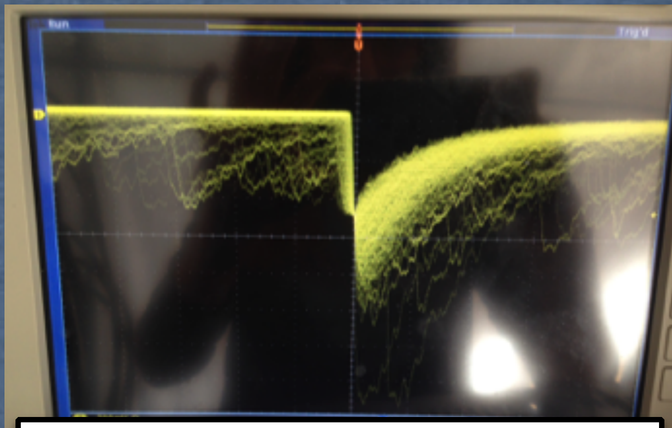

The BDX-Hodo


BDX-Hodo in the tent

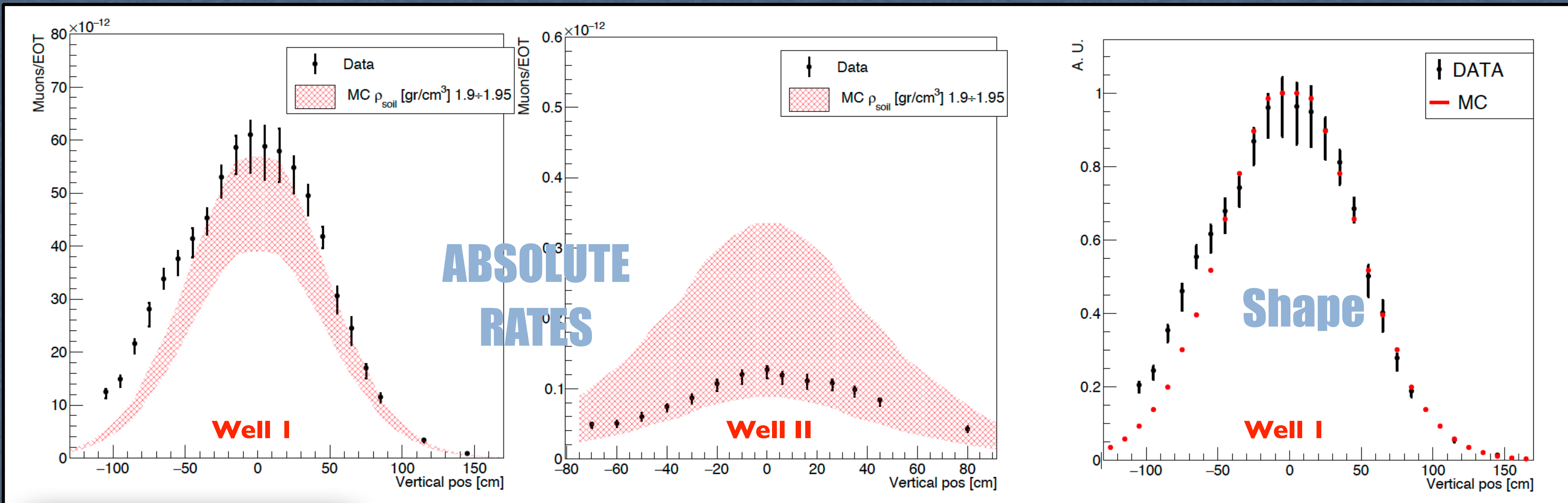

The BDX-Hodo lowered in well 1

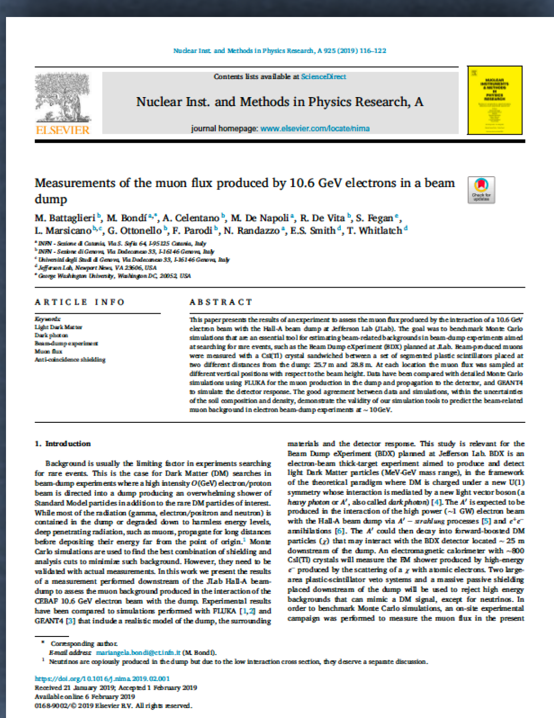
- Run: from Feb 22nd to May 2nd 2018
- Hall-A beam parameters
  - I_{Beam} ~ 22uA
  - E_{Beam} = 10.6 GeV
  - Diffuser: ON

+ 1 week taken in Well II with E_{beam}=4 .3 GeV


The first muon signal on the scope

Data/Sim comparison




Nuclear Inst. and Methods in Physics Research, A

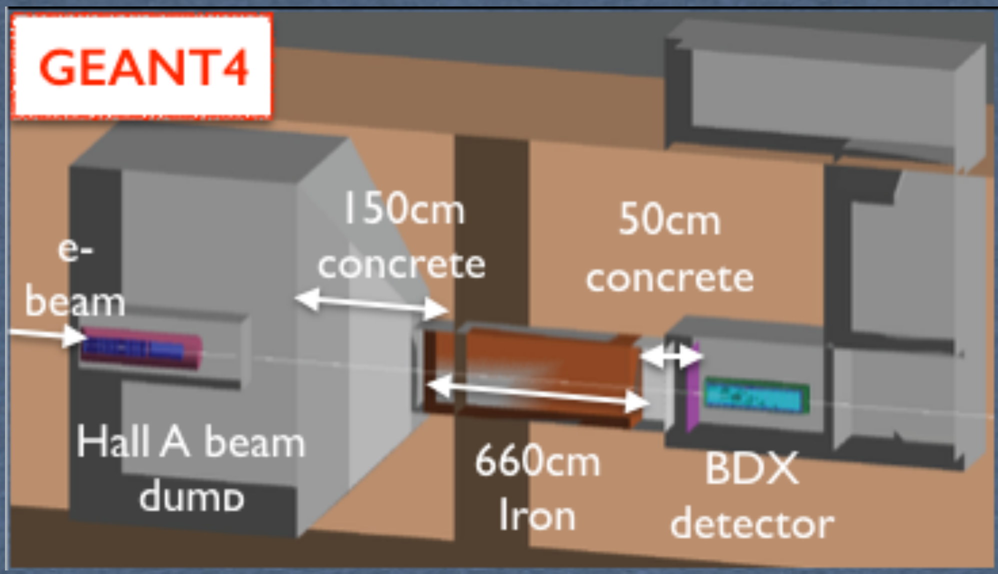
Measurements of the muon flux produced by 10.6 GeV electrons in a beam dump

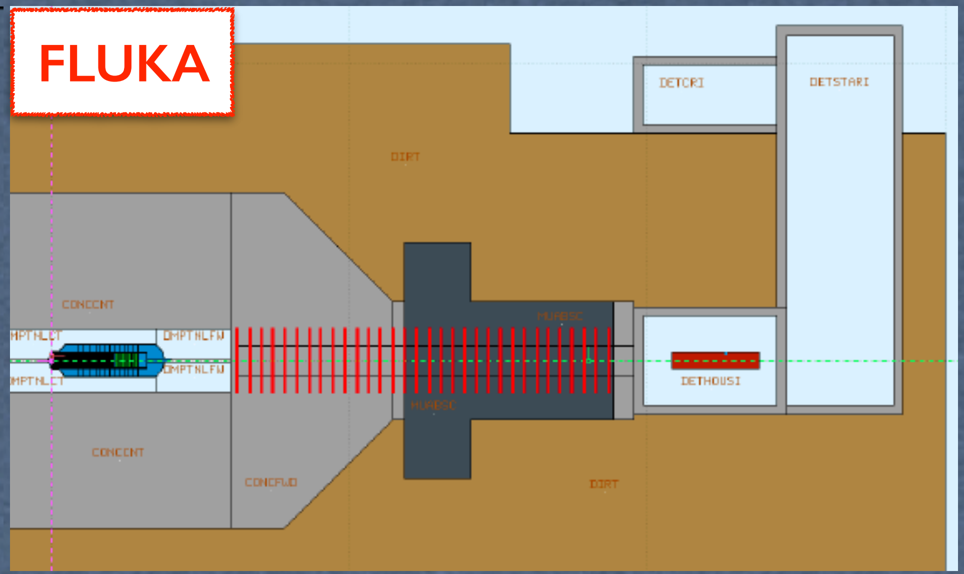
- ★ **Absolute rates** for data and simulations in agreement within the density-related uncertainty band
- ★ The **shape** of rates sampled at different heights is well reproduced by simulations (gaussian with the same σ)

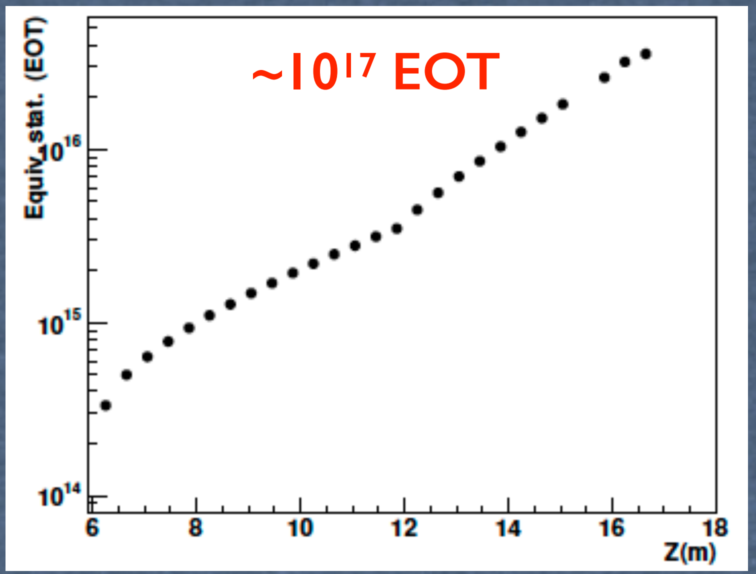
Good agreement between data and simulations prove:

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

High statistics MC sim the BDX set-up



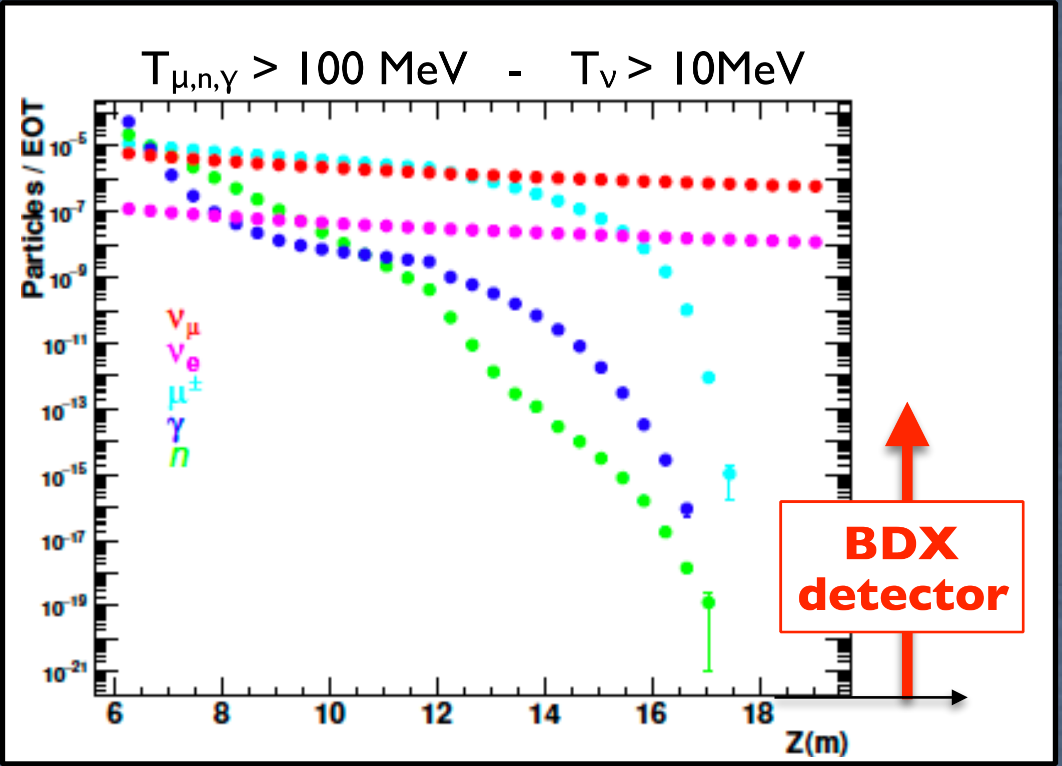




★ **Particles produced in the BD by the 11 GeV beam are tracked to BDX detector location**

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

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



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

★ **Muons**

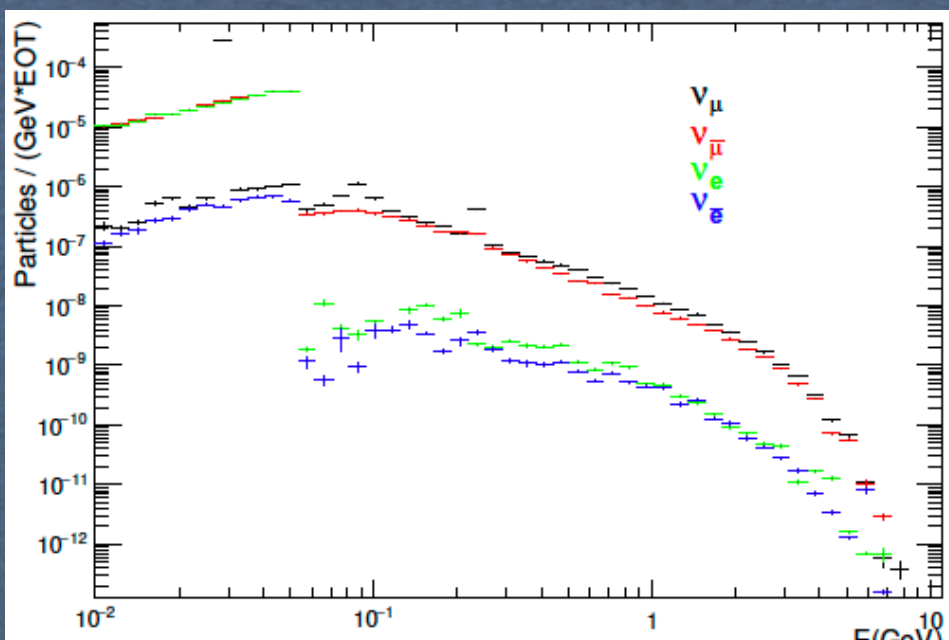
- All forward-going muons are ranged out
- Large angle μs may enter in BDX volume (R~0.02 Hz)
- They are rejected by combination of veto and threshold
- Shielding configuration leading to 0 bg events found
- An optimized shielding will be defined at the time of the new experimental Hall design

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

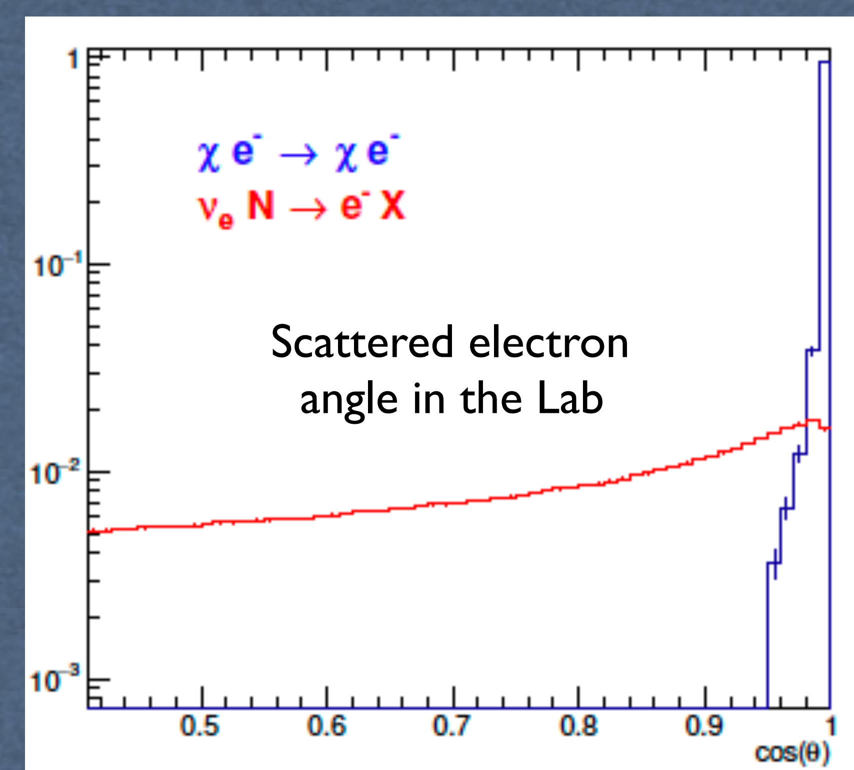
NC
$\nu_\mu + N \rightarrow \nu_\mu\, X$: all rejected by the det. threshold (limited energy transfer to N)
$\nu_e + N \rightarrow \nu_e\, X$: all rejected by the det. threshold (limited energy transfer to N)

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

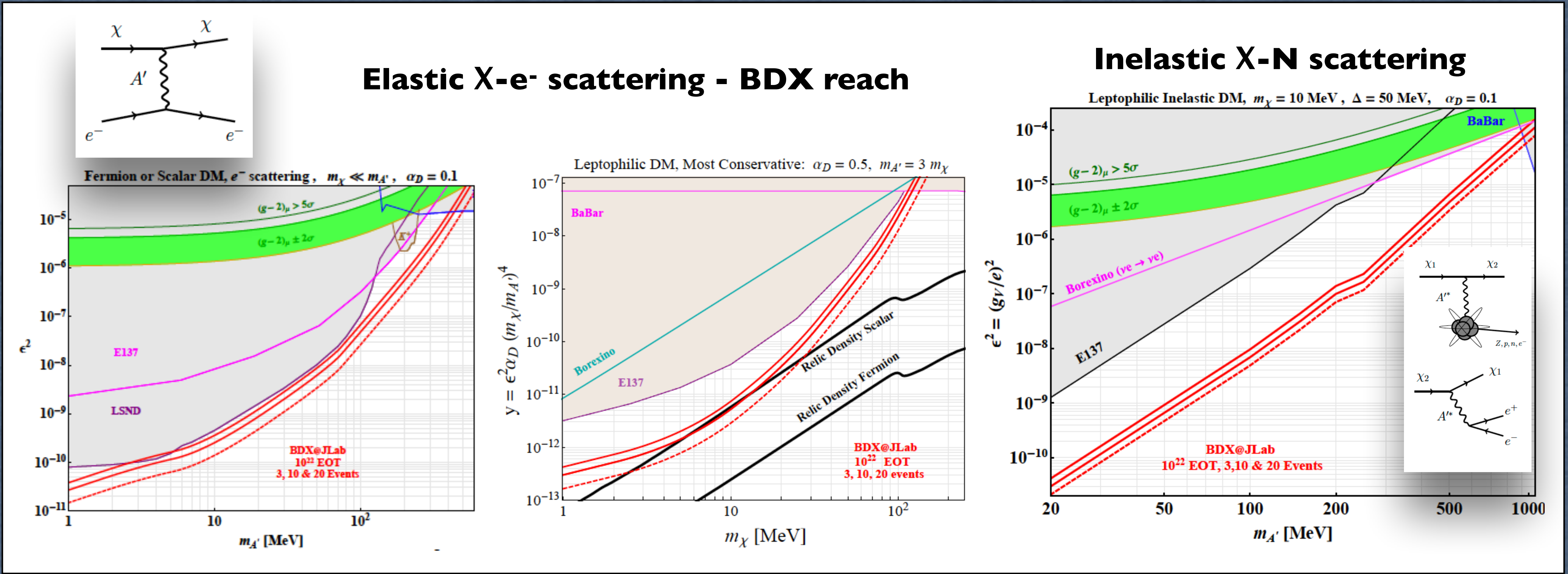
Beam time request

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

Beam-related background	
Energy threshold	N_ν (285 days)
300 MeV	~10 counts

Cosmic background	
Energy threshold	√ Bg (285 days)
300 MeV	<2 counts

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



BDX expected reach

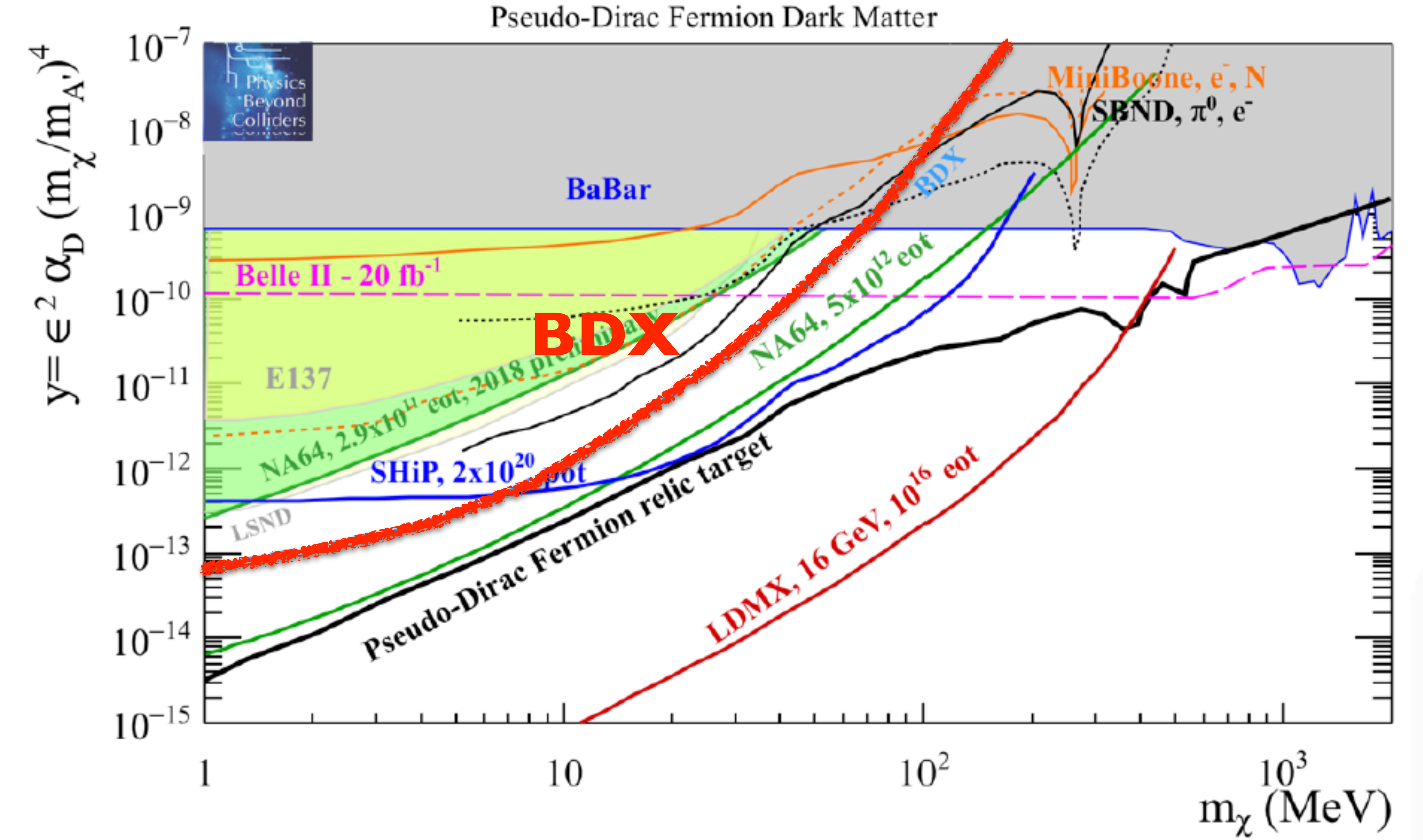
BDX continues to be competitive in the current LDM landscape

Bea

- 10^{2}
- BD
  E_{bea}

BD

ys)

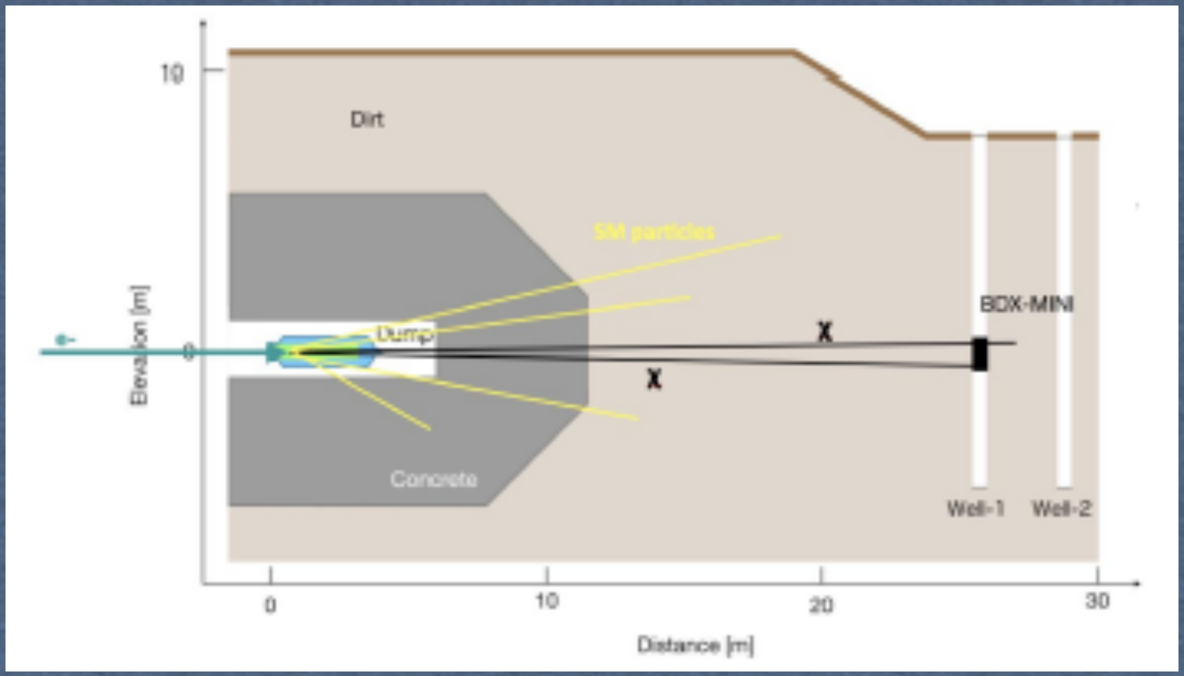


$m_{A'}$ [MeV]

m_χ [MeV]

$m_{A'}$ [MeV]

BDX-MINI @ JLab



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- E_{beam}=2.2 GeV, no muons
- Limited reach but first physics result!

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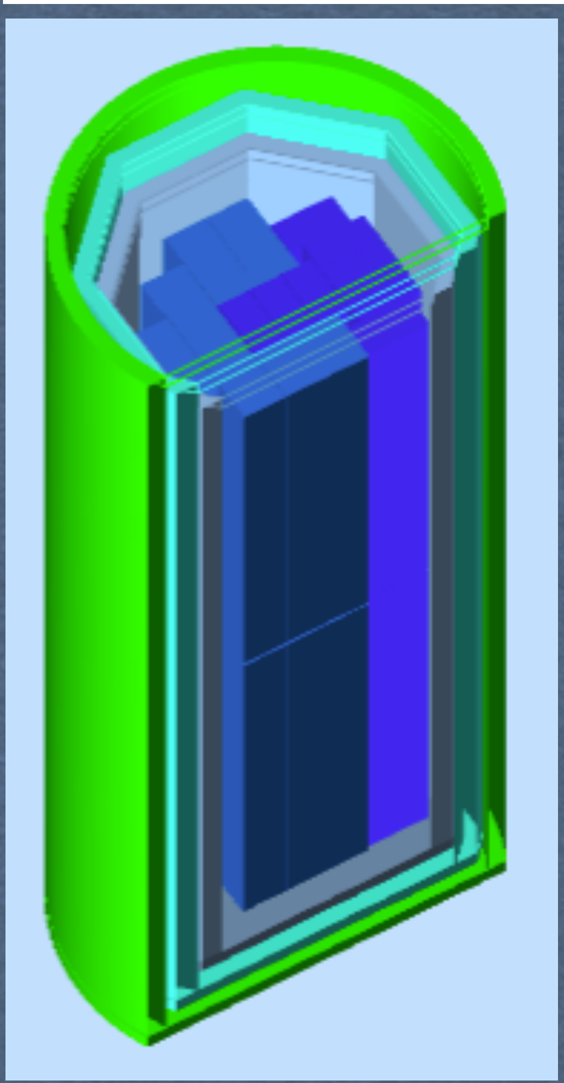
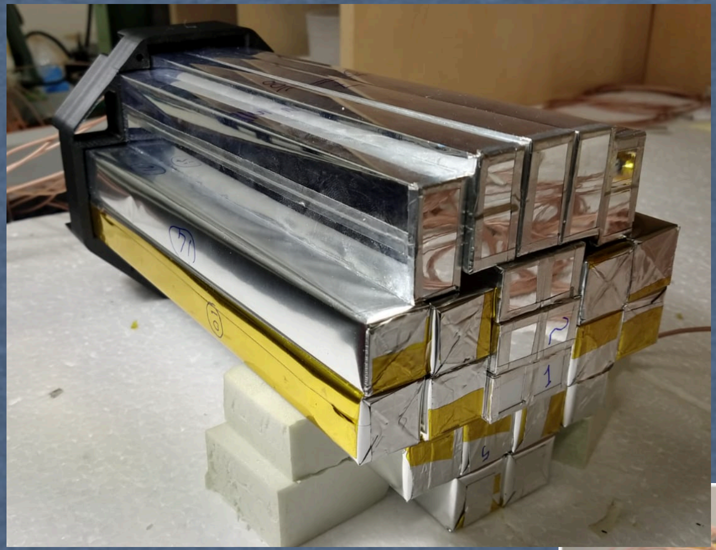
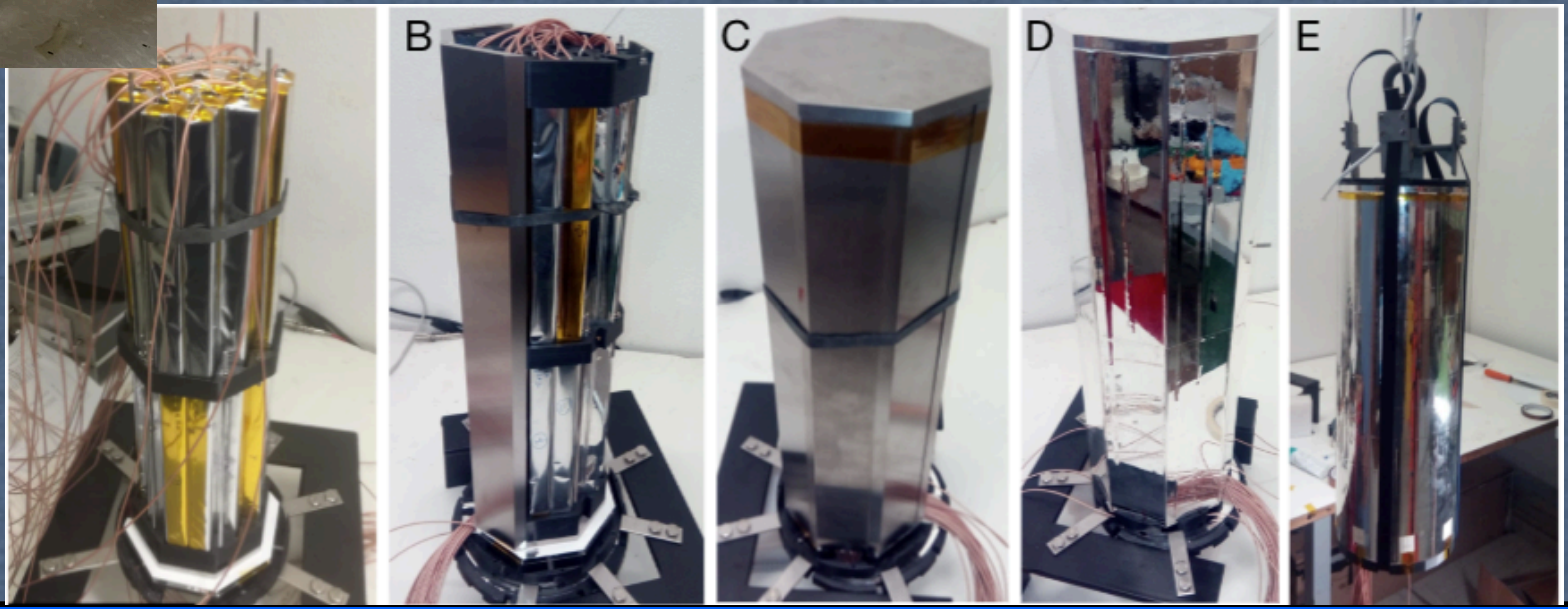




- 44 PbWO4 PANDA/FT-Cal crystals (~1% BDX volume)
- 6x6 mm2 SiPM readout
- 2 active plastic scintillator vetos: cylindrical and octagonal (8 sipm each) + 2x lids + Passive W shielding



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Regular Article - Experimental Physics

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 $PbWO_4$ 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 μA) 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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BDX-MINI @ JLab

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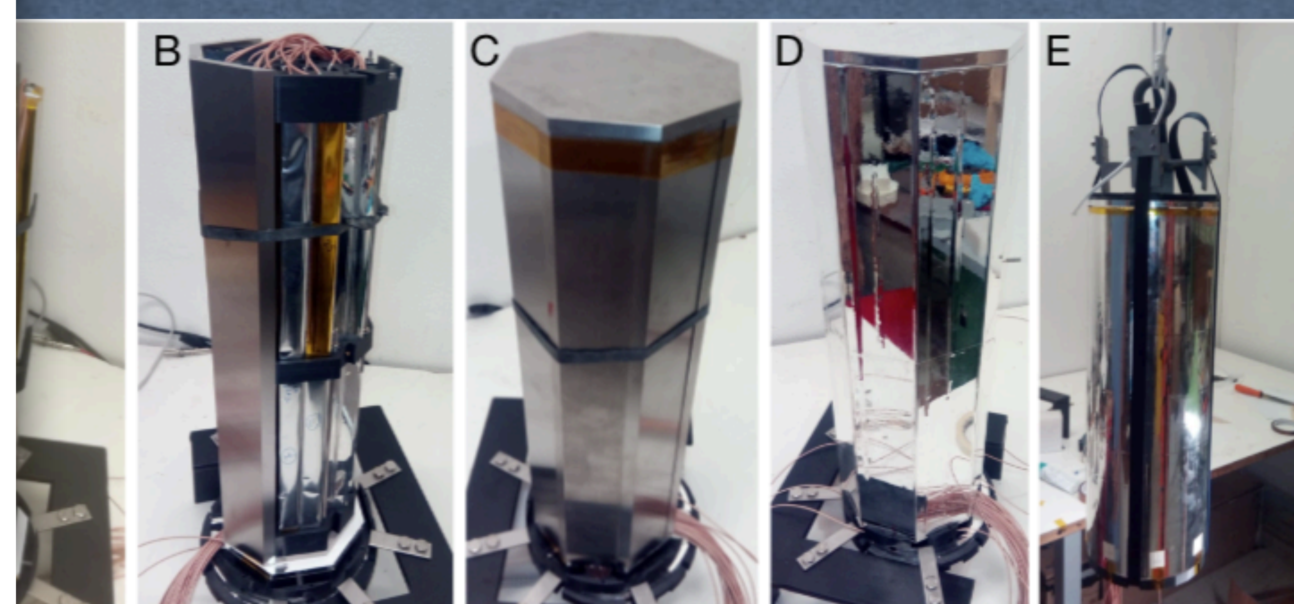
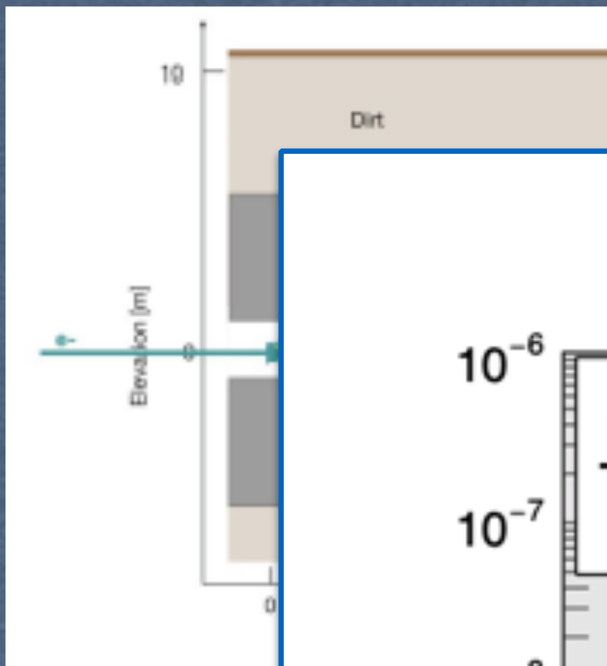
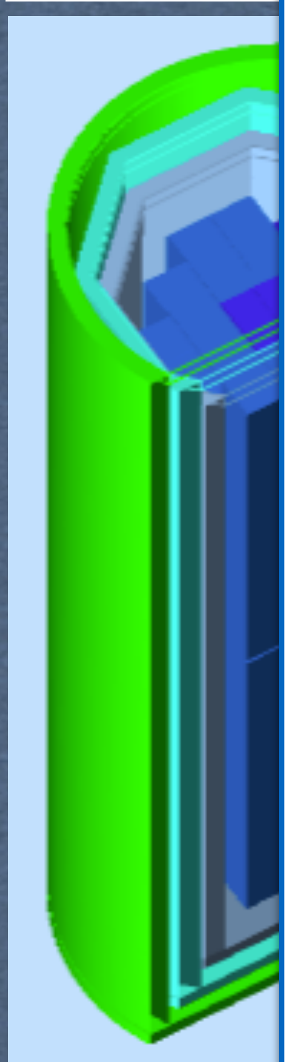
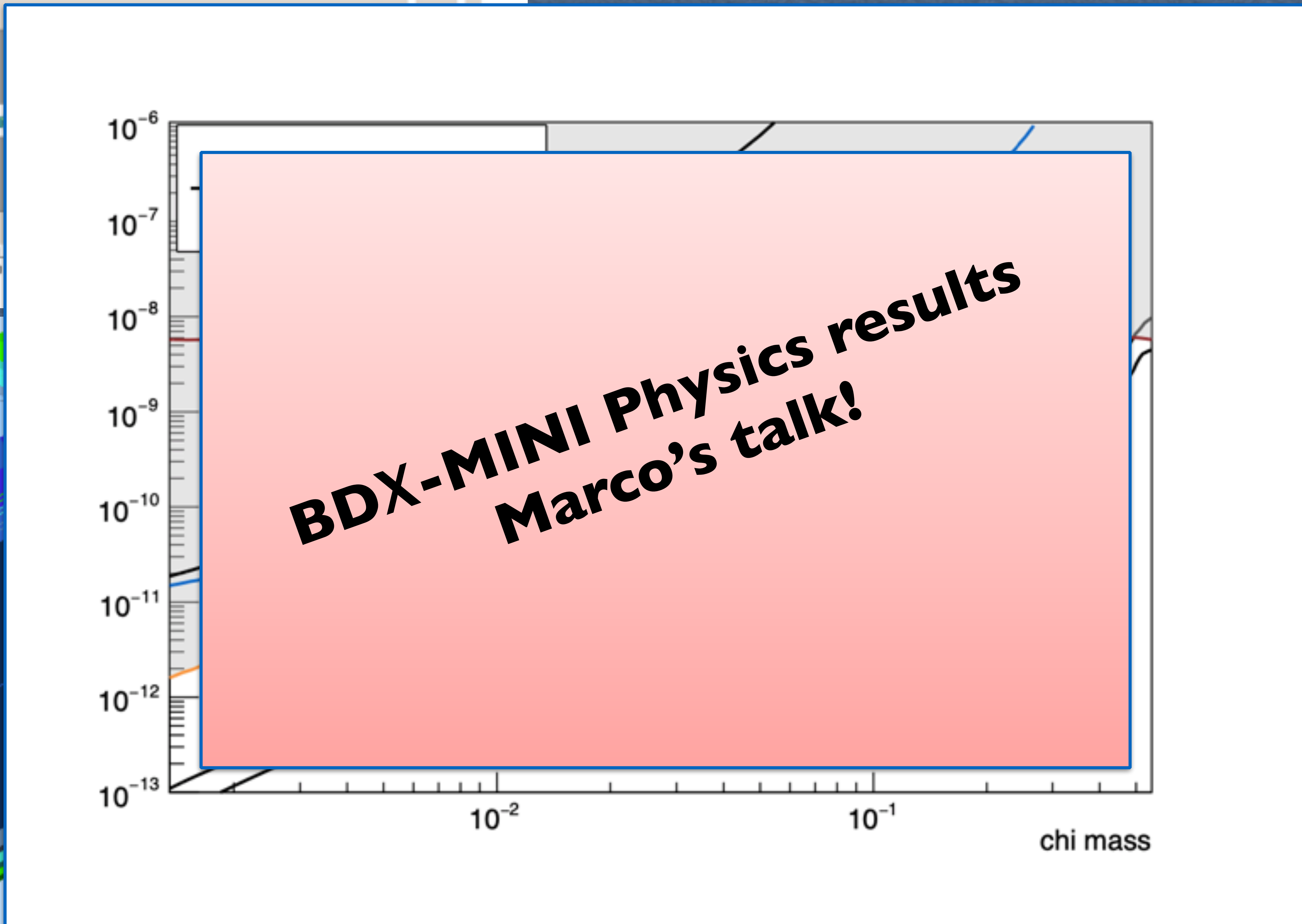


BDX-MINI @ JLab







BDX-MINI Physics results
Marco's talk!

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