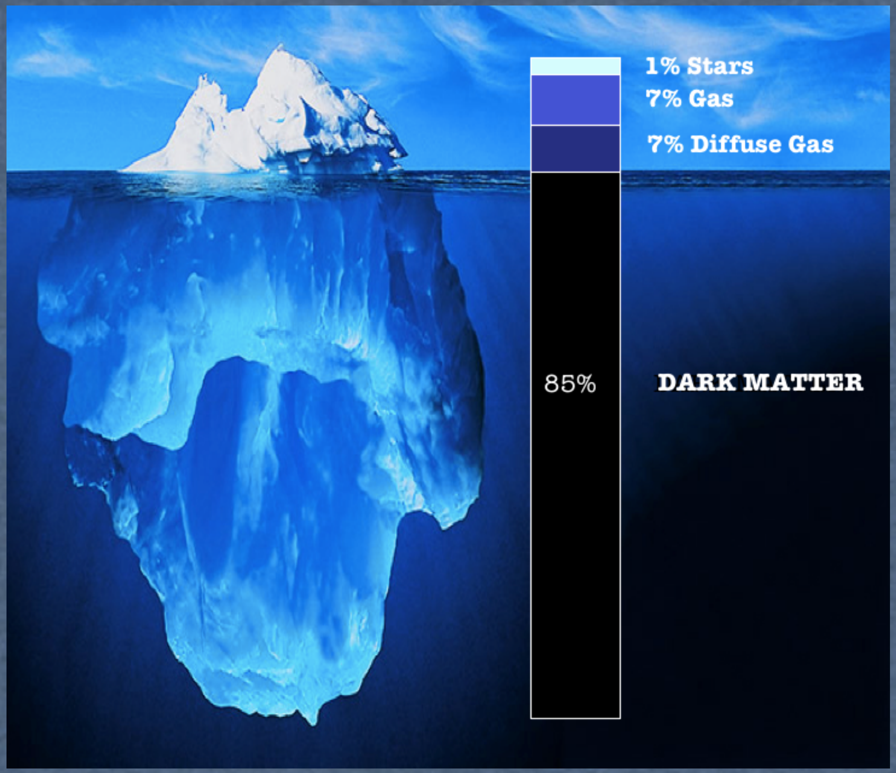
The BDX experiment

M.Battaglieri
INFN-GE Italy

Dark Matter (DM) vs Baryonic Matter (BM)

Compelling astrophysical indications about DM existence

★ How much DM w.r.t. BM?

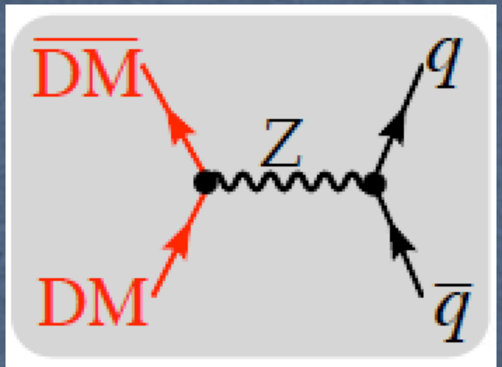


★ Does DM participate to non-gravitational interactions?
★ Is DM a new particle?

Two options:

- ★ New matter interacting trough the same forces
- ★ New matter interacting through new forces

Any guess about the DM mass and interaction?



$\langle \sigma v \rangle \sim M^2_{DM}/M^4_{mediator}$

Yes, if we do a couple of assumptions:

★ DM thermal origin

in the early Universe DM was in thermal equilibrium with regular matter (via annihilation)

★ DM as thermal relic from the hot early Universe

Minimal DM abundance is left over to the present day

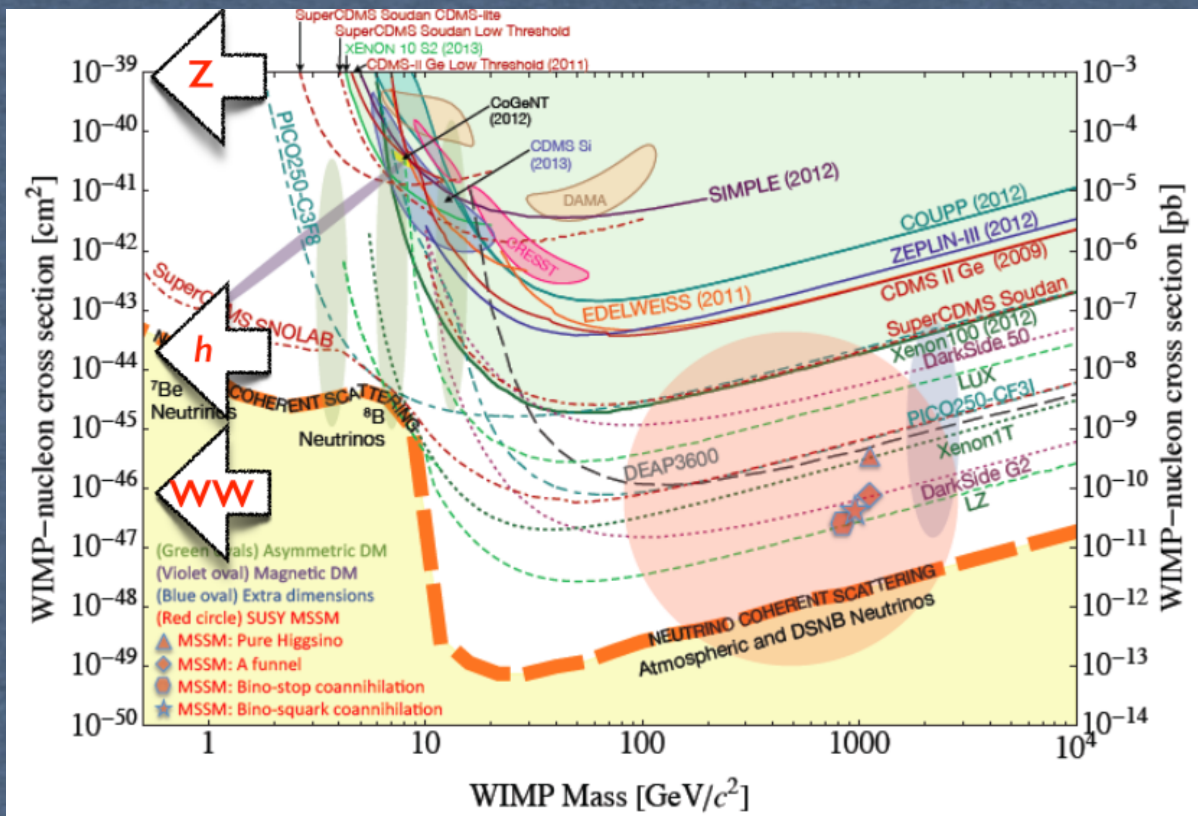
Correct DM density for an annihilation xsec:

$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ cm^3/s \sim 1/(20\ TeV)^2$

Thermal origin suggests DM interactions and mass in the vicinity of the weak-scale

Exploring the WIMP's option

★ Experimental limits



Slow-moving cosmological weakly interacting massive particles

- DM detection by measuring the (heavy) nucleus recoil
- Constraints on the interaction strength from the DM Direct Detection limits
  - Scattering through Z boson ($\sigma \sim 10^{-39}$cm^2): ruled out
  - Approaching limits for scattering through the Higgs ($\sigma \sim 10^{-45}$cm^2)
  - Close to irreducible neutrino background

Direct Detection

1 MeV — 1 GeV — M_Z — 10 TeV

WIMPs

✳ No signal in direct detection

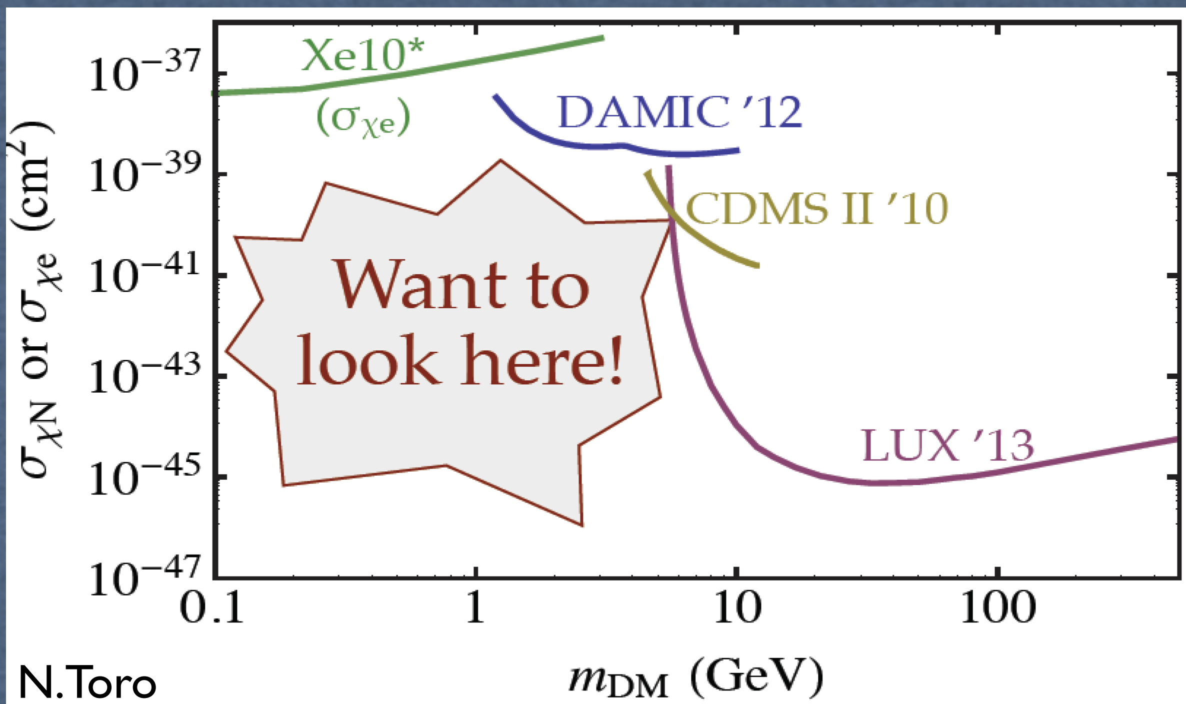
✳ Experiments have (almost) no sensitivity to (light) DM (<1 GeV)

WIMPs paradigm is not the only option (keeping the DM thermal origin)

Light Dark Matter + New interaction

Light Dark Matter

★ Experimental limits



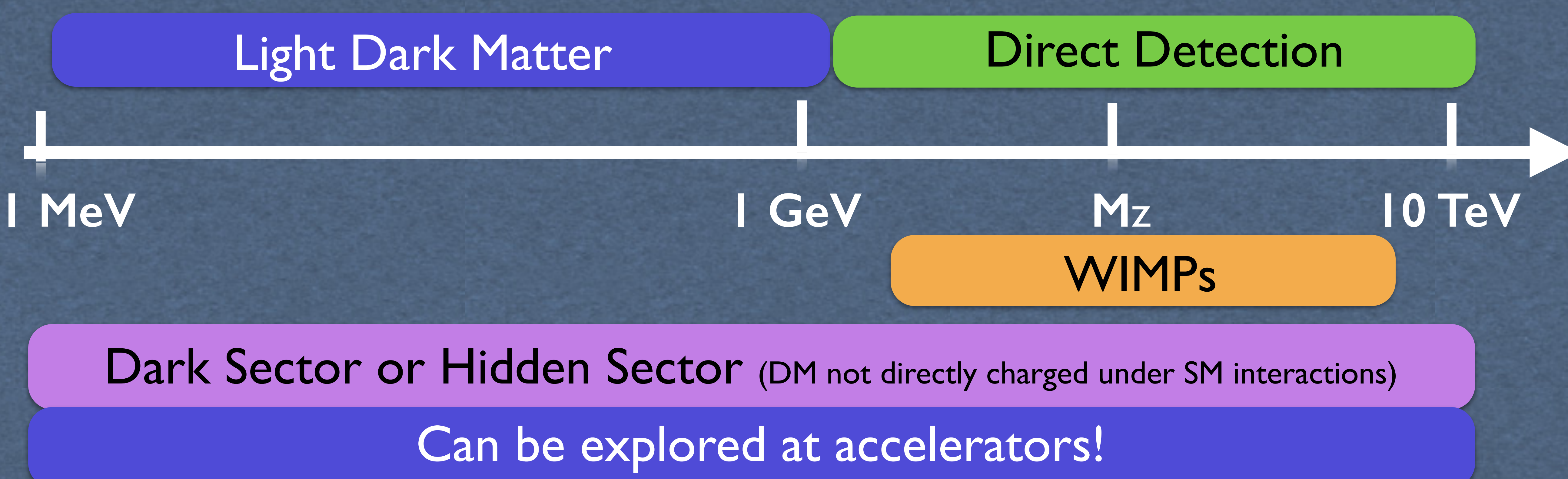
Light Dark Matter with a (almost) weak interaction (new force!)

- 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

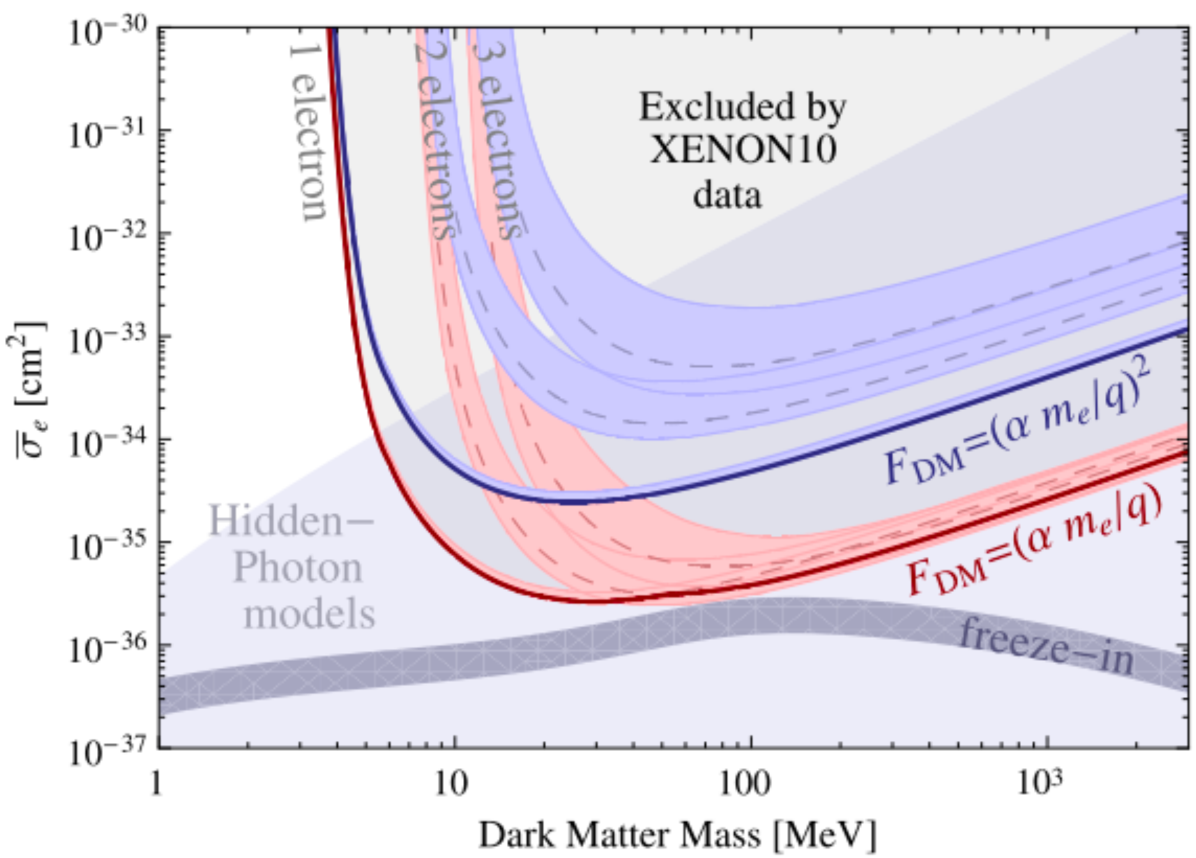
covers an unexplored mass region extending the reach outside the classical DM hunting territory

- High intensity
- Moderate energy



LDM - Direct Detection limits

Limits from XENON10



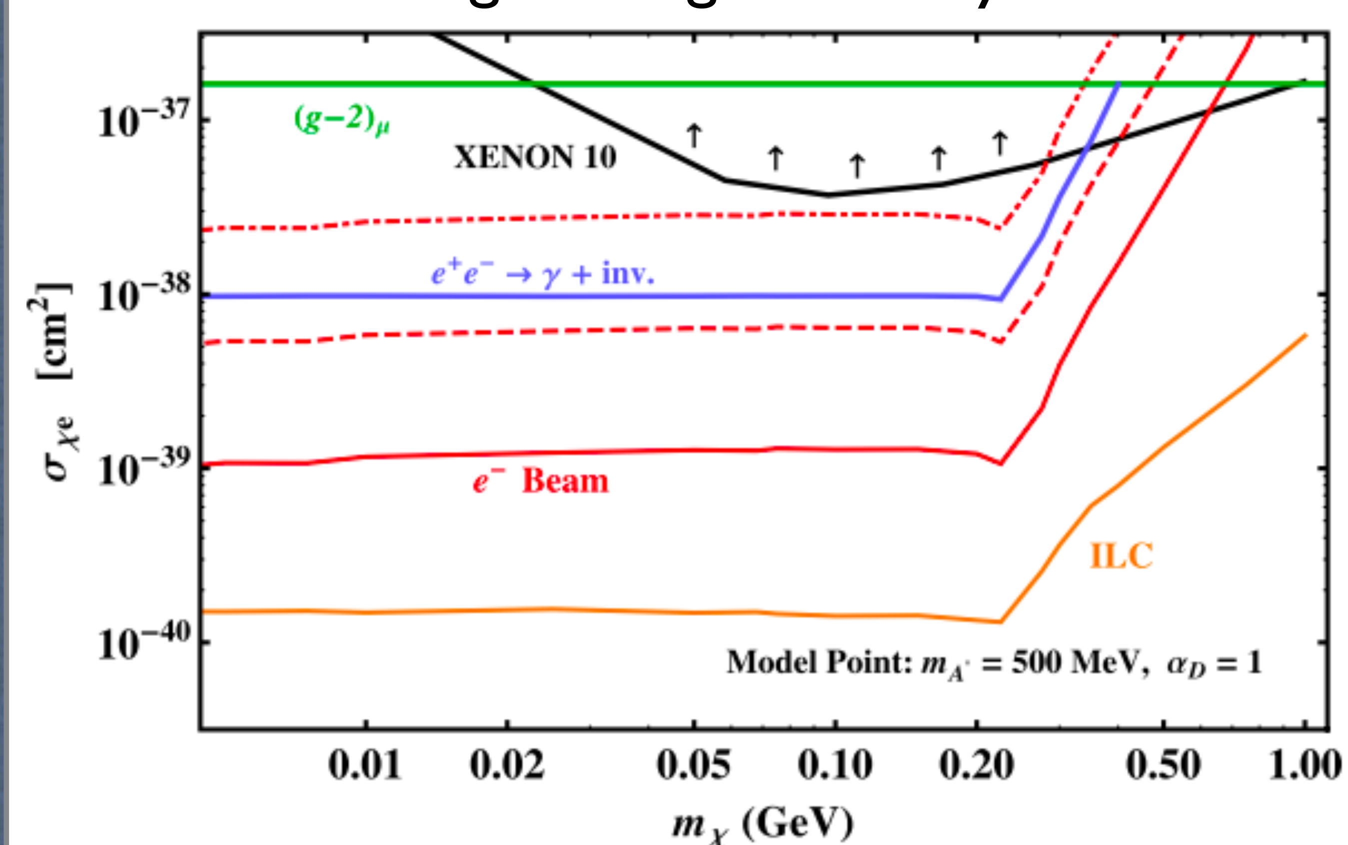
PhysRevLett. 109.021301 R.Essig, A.Manalaysay, J.Mardon, P.Sorensen, T.Volansky,

- Best limits on LDM interaction cross section obtained by direct DM detection (XENON10 and LUX)
  - χ_{cosmic}-e scattering
  - 1-electron ionization sensitivity
  - No FF for the scattering

- Fixed target electron beam experiments can be 10^3 - 10^4 more sensitive in the 1 MeV - 1 GeV mass range

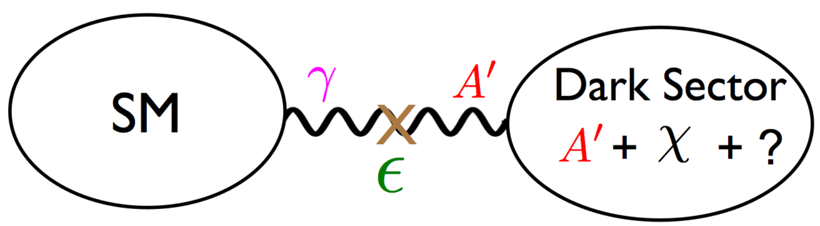
- No experiments were designed to measure LDM (all limits come from reinterpretation of old experiments)

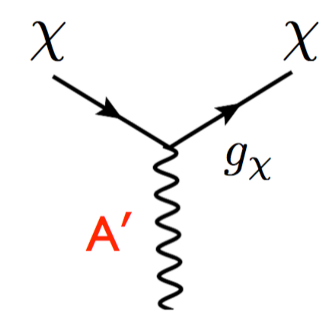
Fixed target & high intensity e$^-$ beam

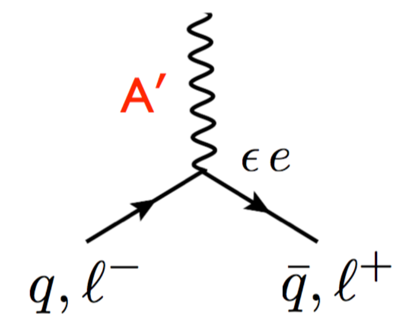


PhysRevD.88.114015 E.Izaguirre, G.Krnjaic, Gordan, P.Schuster, N.Toro

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



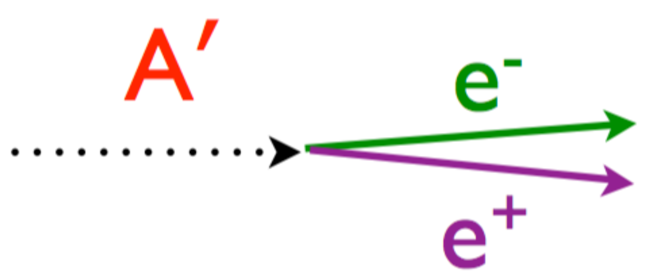




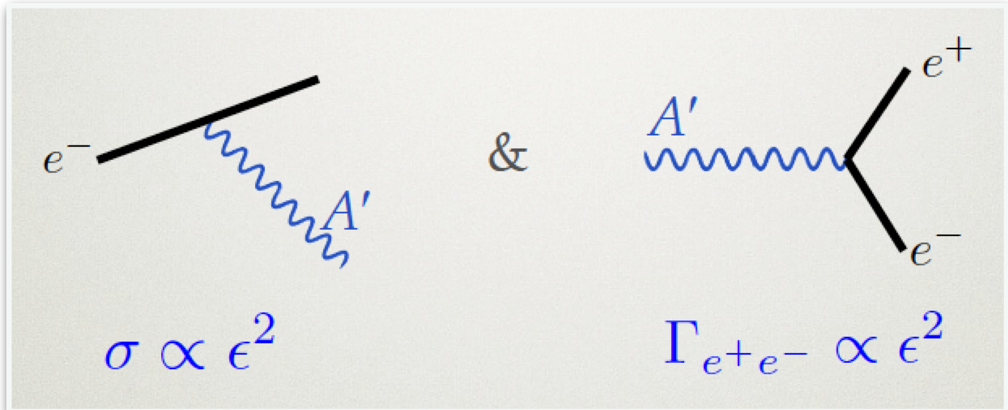
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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

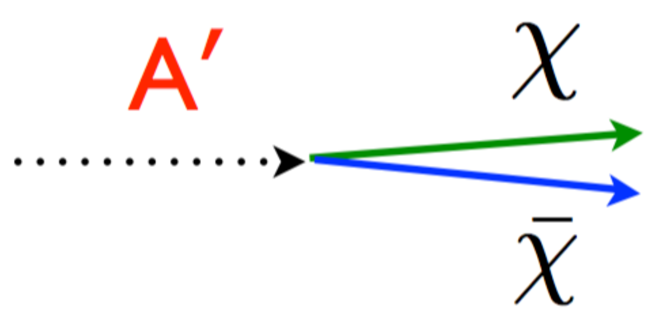
Visible



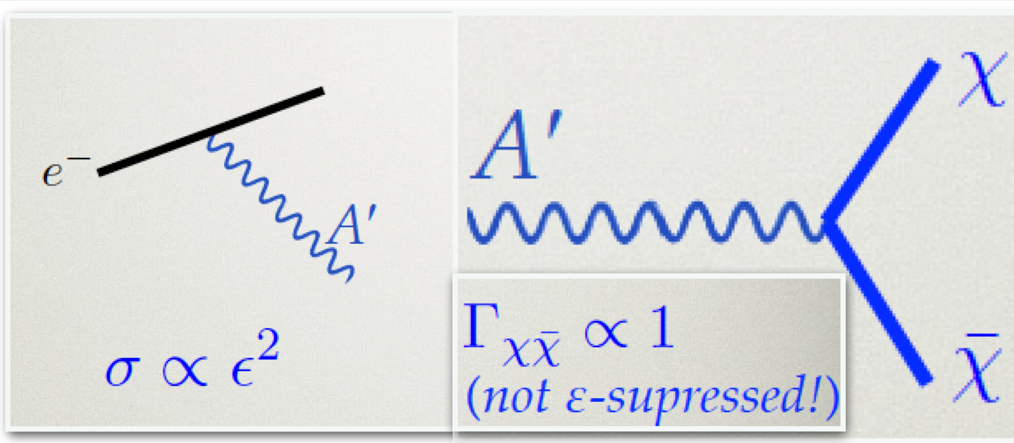
- *Minimal* decay
- Decay regulated by ε^2
- Independent of m_χ
- Requires $m_{A'} < 2m_\chi$



Invisible



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



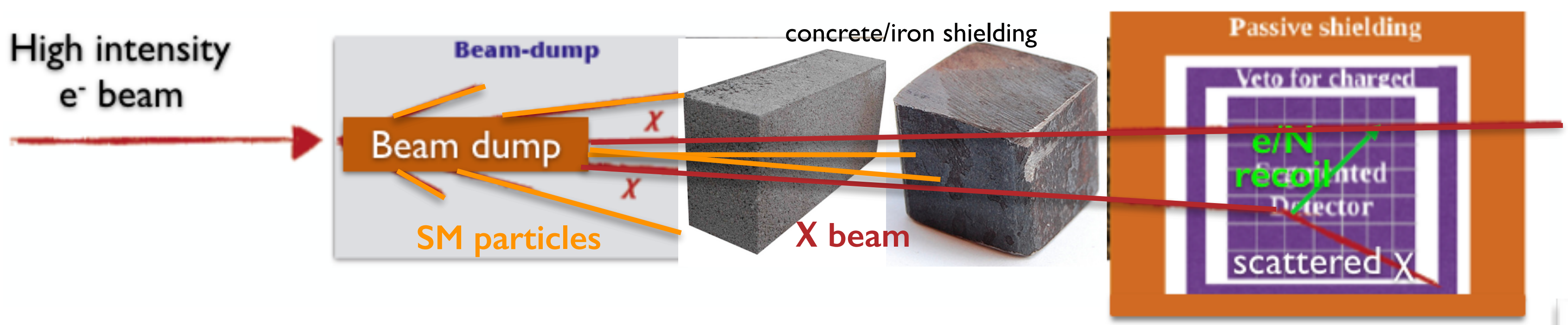
Fixed target DM production

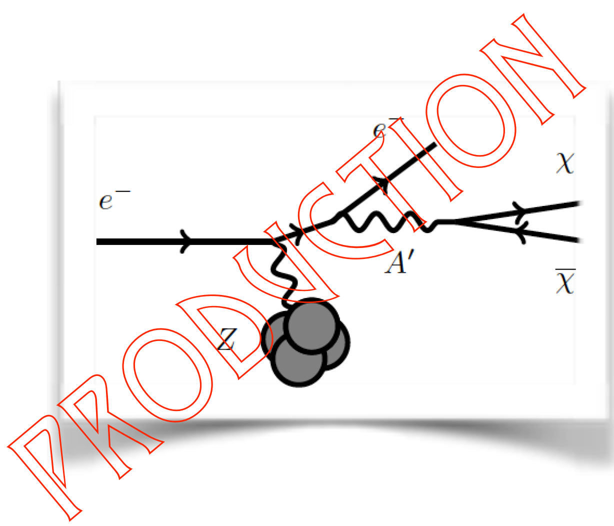
Two step process

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



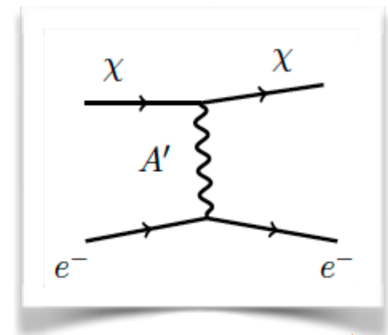


A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

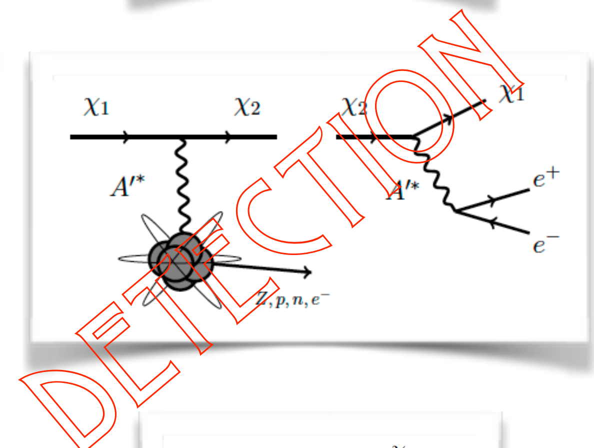
χ cross-section: $\sigma_{\chi e} \propto \frac{\alpha_D \varepsilon^2}{m_{A'}^2}$

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

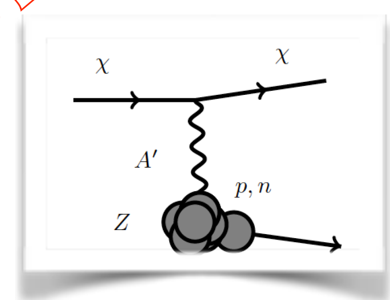
- Intense electron beam
- ~ few GeV range energy



Elastic on electrons



Inelastic on nuclei



Elastic on nuclei

The BDX experiment

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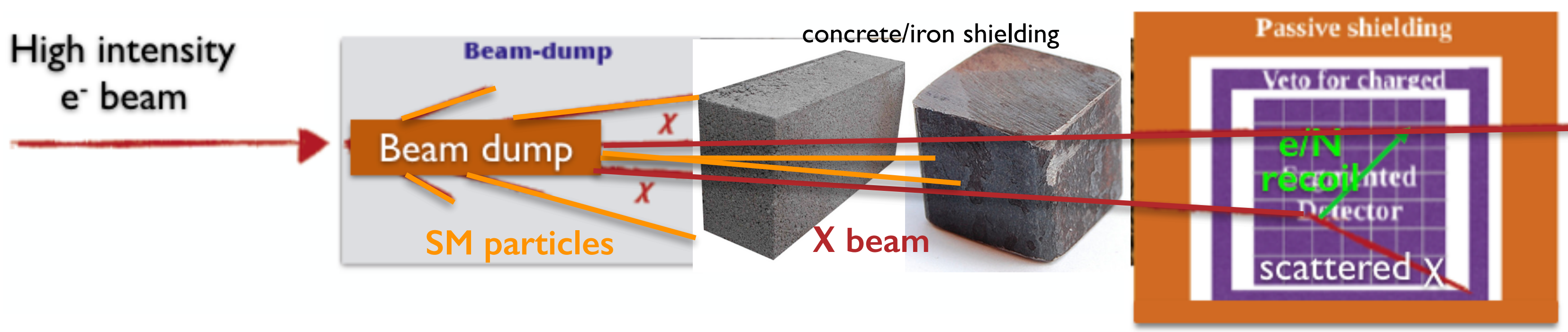

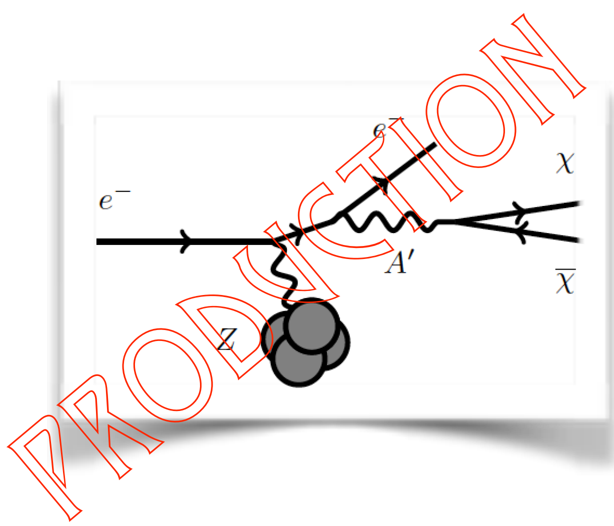

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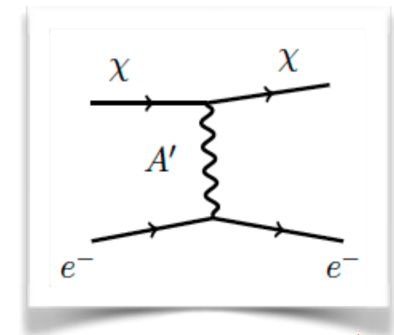
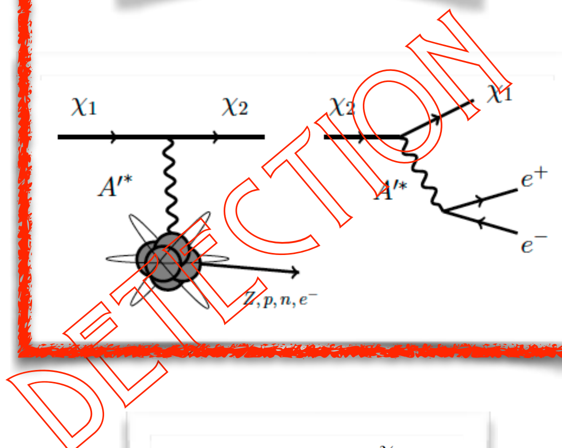
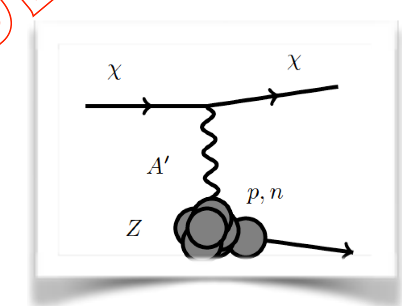


Elastic on electrons



Inelastic on nuclei

BDX@JLab



Elastic on nuclei

BDX experimental signature: X-electron/X-N inelastic → em shower ~GeV energy

- The X-Nucleon elastic scattering transfers a limited energy (few MeV)
- It can be used to check systematics
- We are investigating other experimental techniques less affected by bg (BDX-DRIFT)

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

BDX technology

E.M. calorimeter

↓

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

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

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:

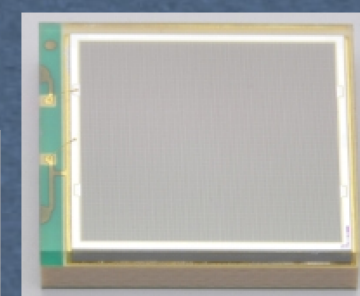
BaF2
CsI
BSO

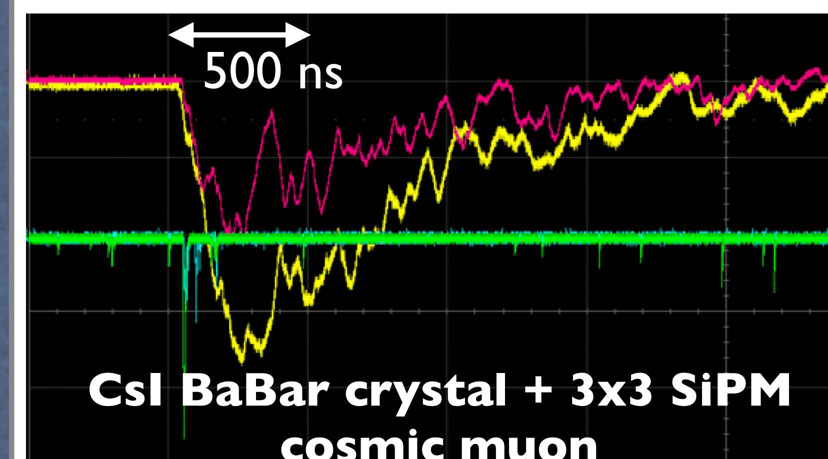
A dedicated measurement campaign to characterise the crystal properties

- 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





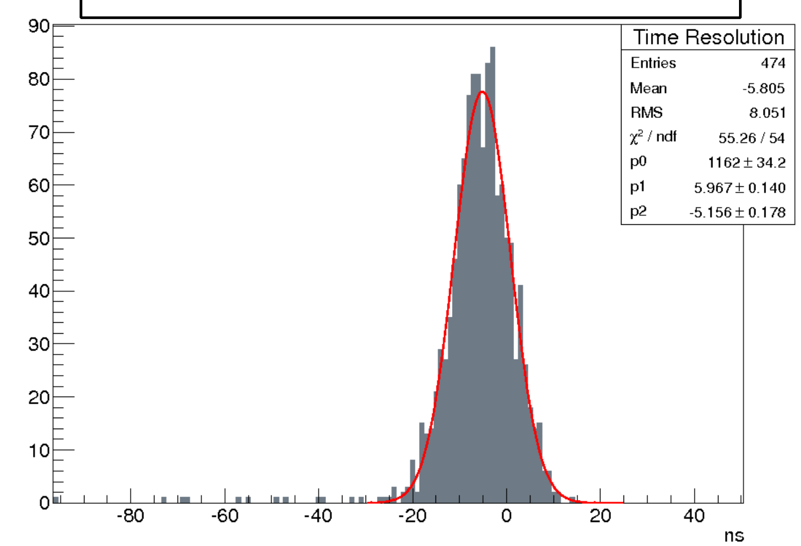
Crystals are available from BABAR em calorimeter

- Size: (5x5)cm^2 front face, (6x6)cm^2 back face, 30cm length
- 820 crystals available from end cap
- Decay time: fast 900ns, slow 4000ns
- LY= 50k γ/MeV

SiPM readout

- Size: (6x6) mm^2, 25μm, 57.6k cells, trenched, pde=25%
- SPE capability
- CsI(Tl): 40 pe/MeV
- Time resolution: ~6ns (MIPs)

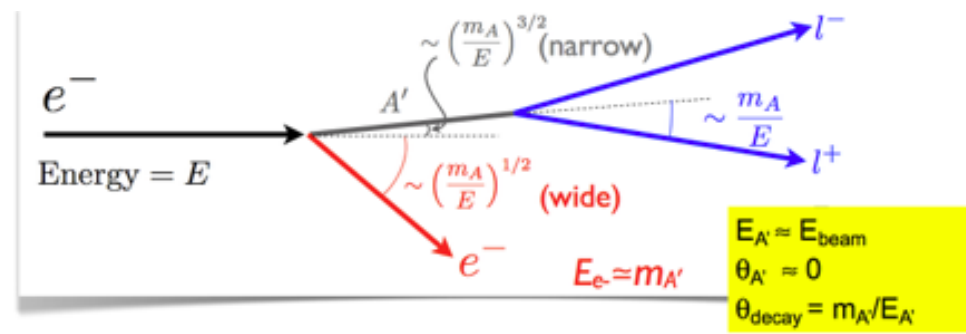
CsI BaBar crystal + 3x3 SiPM
Time resolution: σ = 6ns

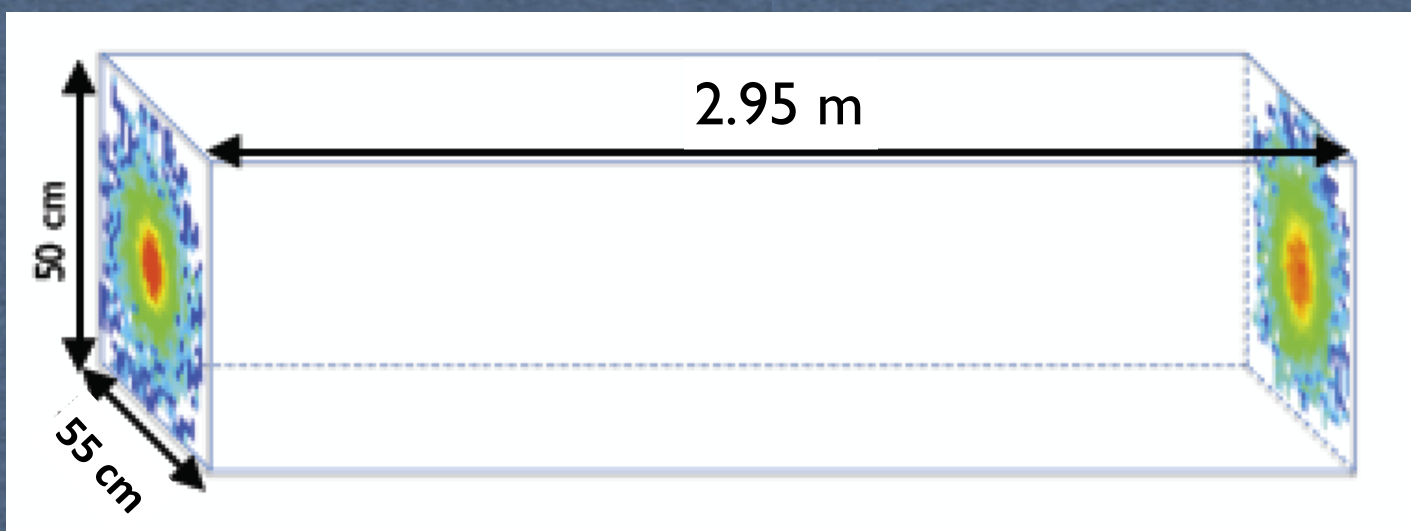


★ Due to the large LY signals at ~MeV level are detectable
★ Despite a long scintillation time a few ns time coincidence is possible

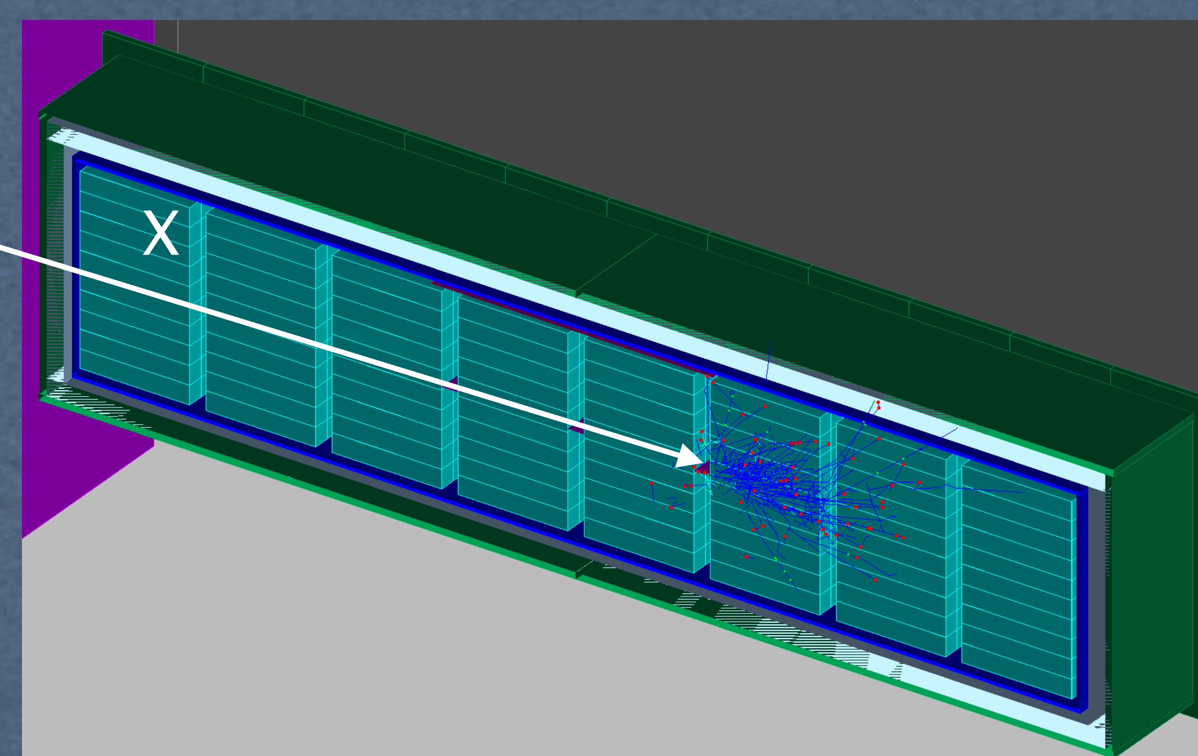
Detector layout

Strongly forward peaked kinematics
focused χ-beam !





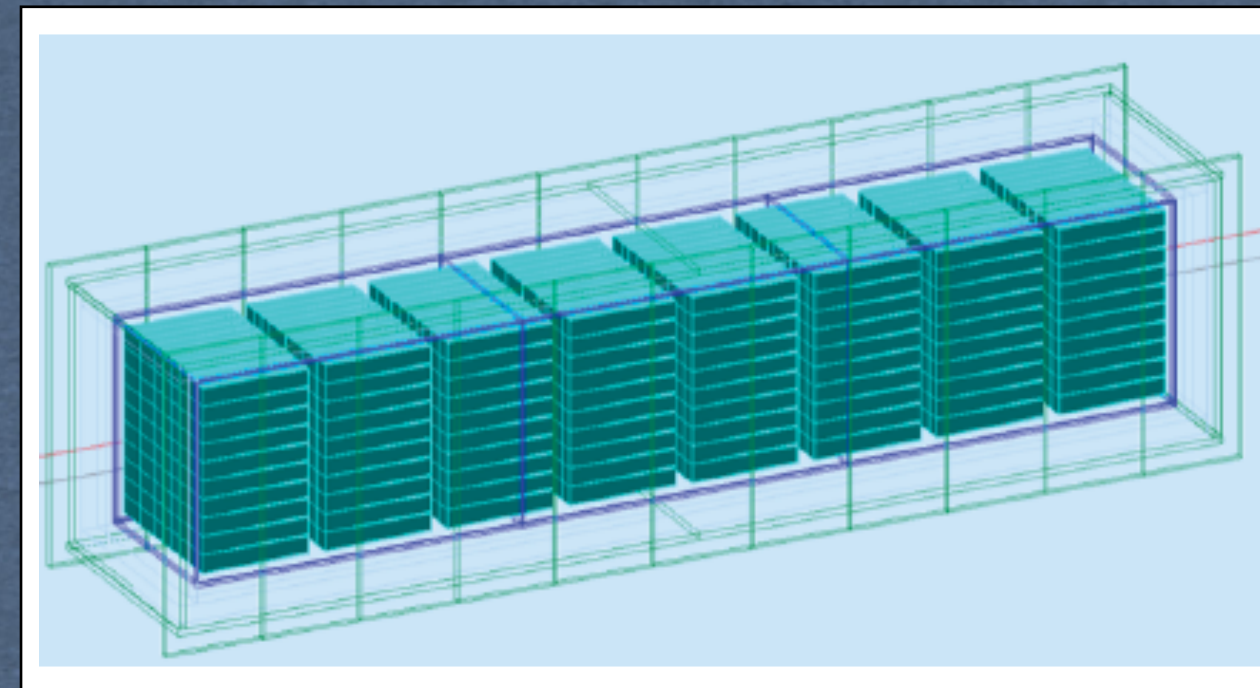
- ★ Each module is made by an array of 10x10 (front face ~50x55 cm2) crystals matrix
- ★ Each crystal is read separately

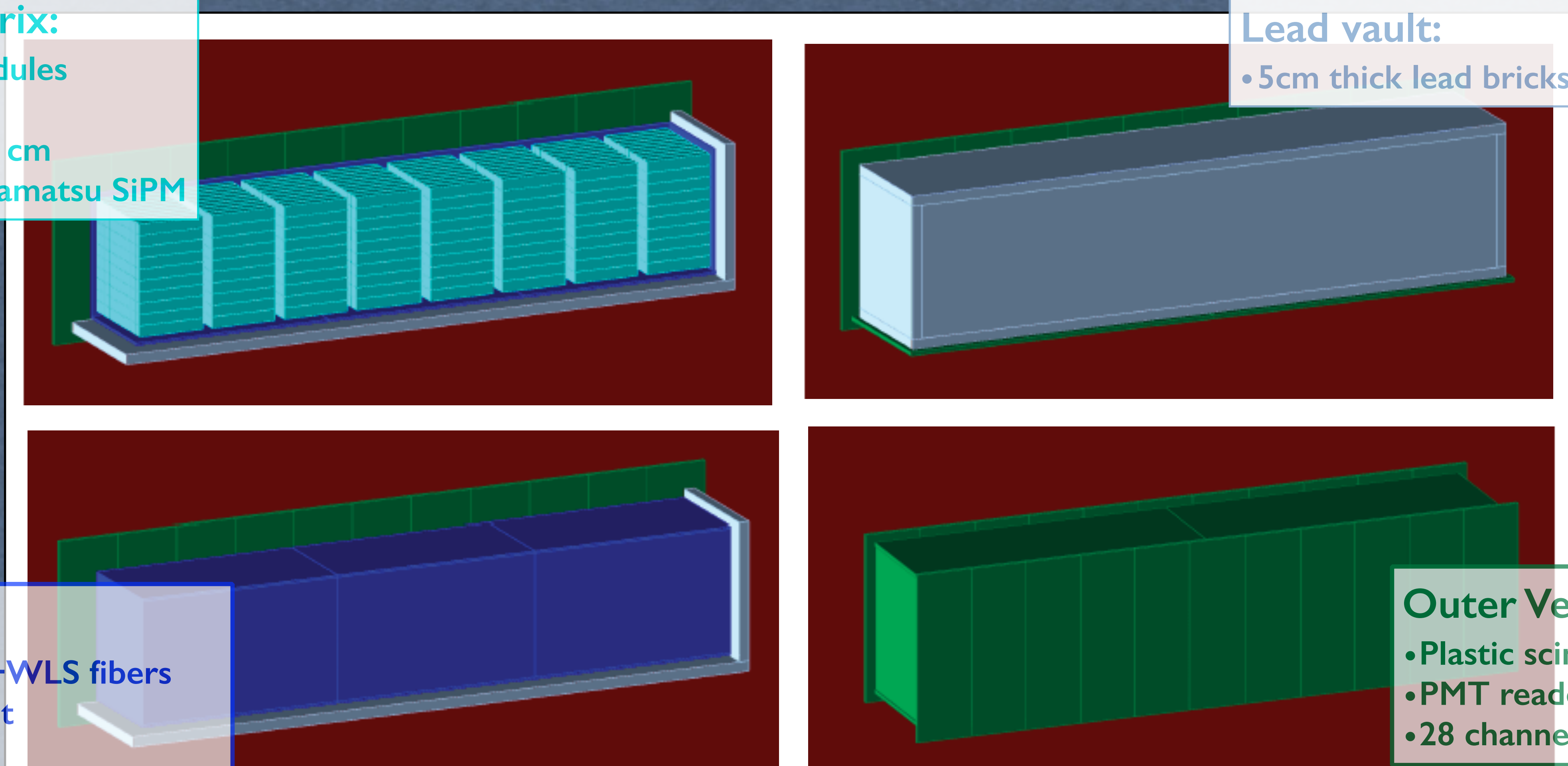


- ★ ~800 BaBar EndCup crystals
- ★ Simplified assembly mechanics
- ★ Modular detector
- ★ Final arrangement:
  - 10x10crystals (front face ~50x55 cm2)
  - 8 modules (active/total length: 260/295 cm)

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





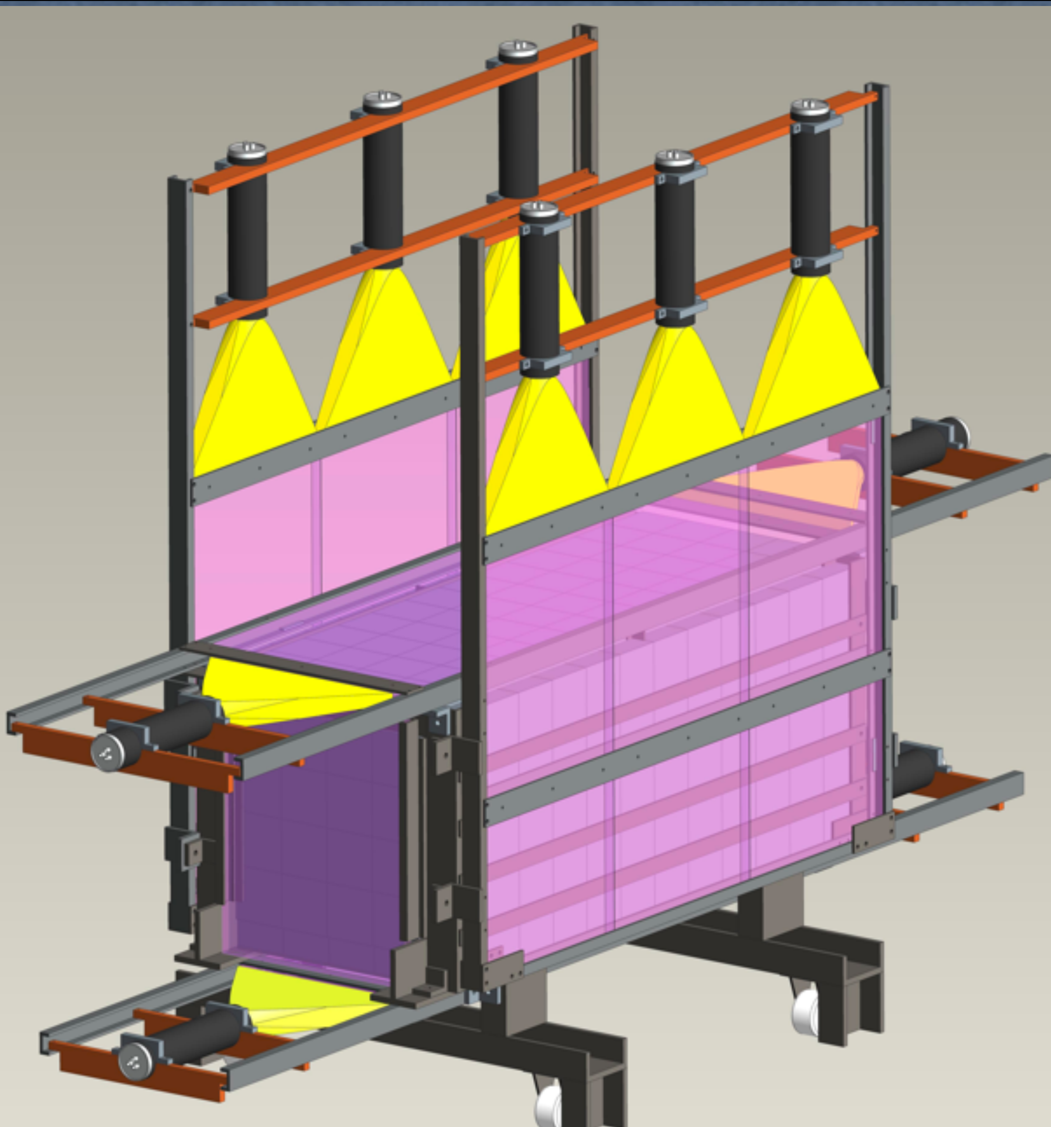
Crystal matrix:
- 10x10 x 8modules
- 800 crystals
- 50 x 55 x 295 cm
- 800 6x6 Hamamatsu SiPM

Lead vault:
- 5cm thick lead bricks

Inner Veto:
- Plastic scint+WLS fibers
- SiPM readout
- 88 channels

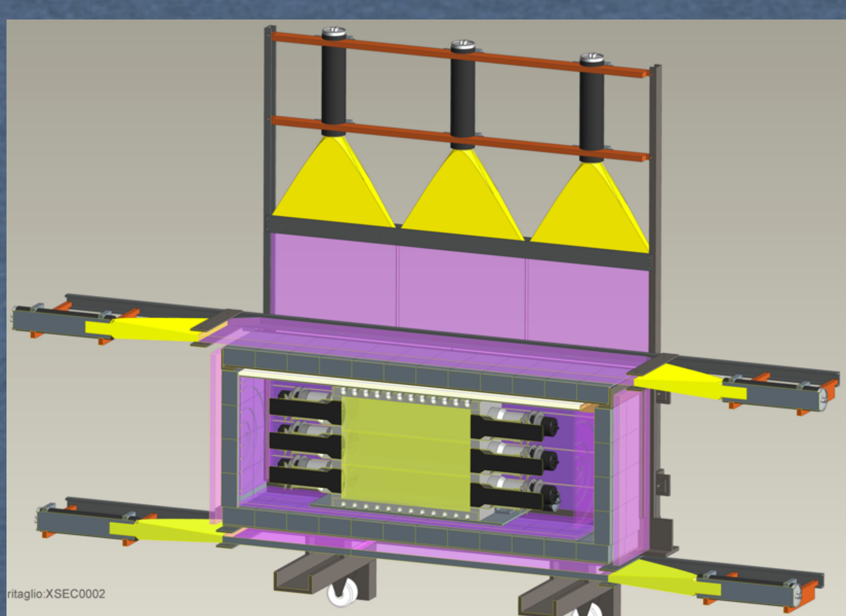
Outer Veto:
- Plastic scint +light guides
- PMT readout
- 28 channels

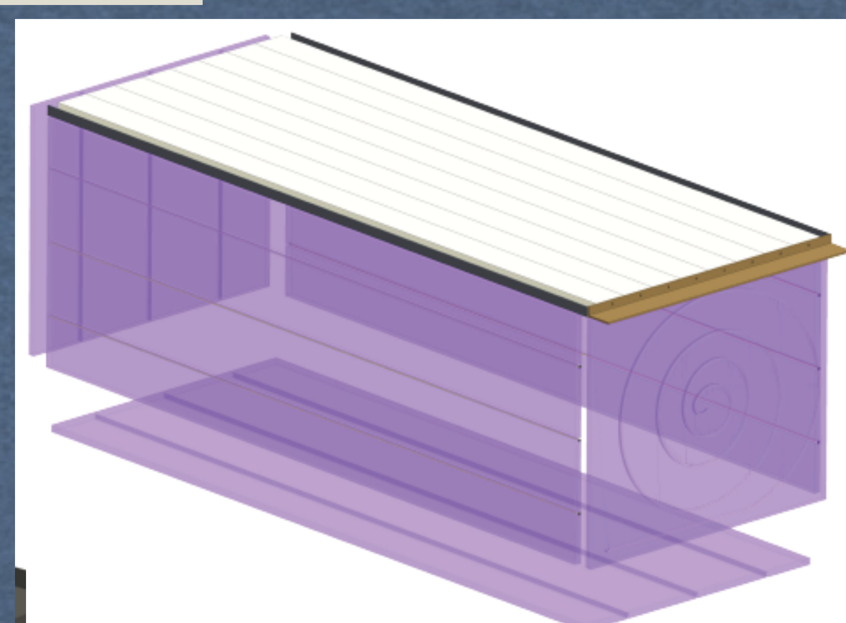
The BDX prototype

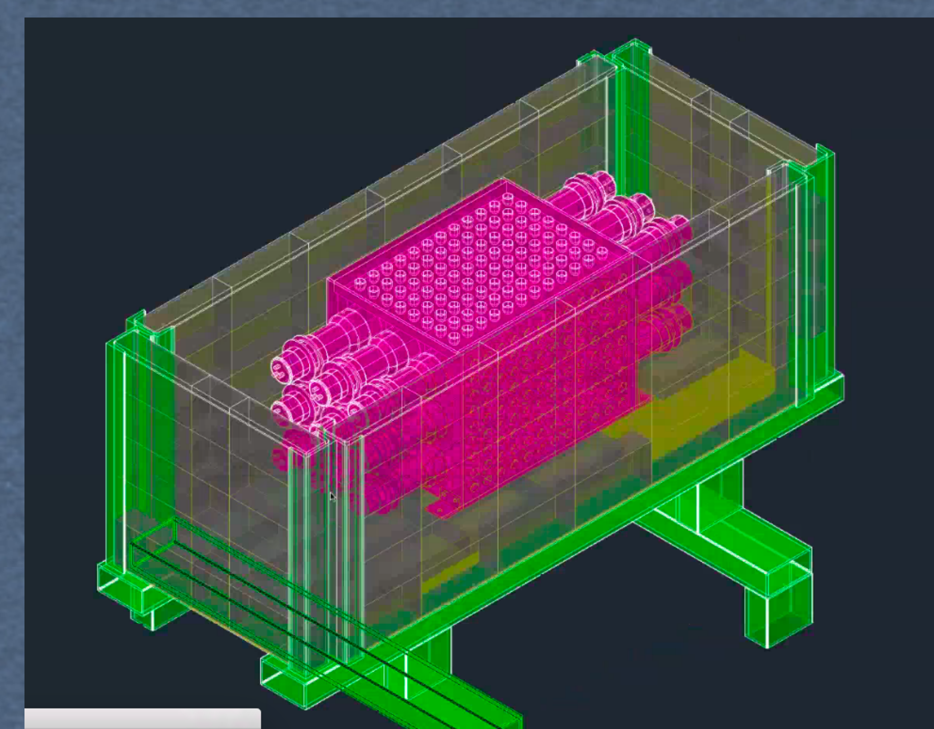


★ Reduced scale detector (2x1x0.5 m3)

★ InnerVeto + OuterVeto + Lead Vault surrounding 1/16 CsI(Tl) crystals calorimeter







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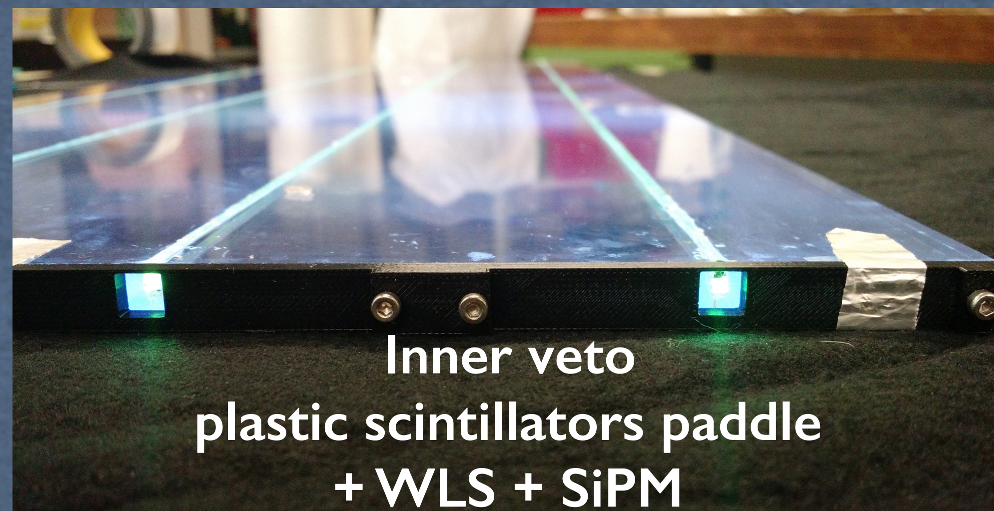
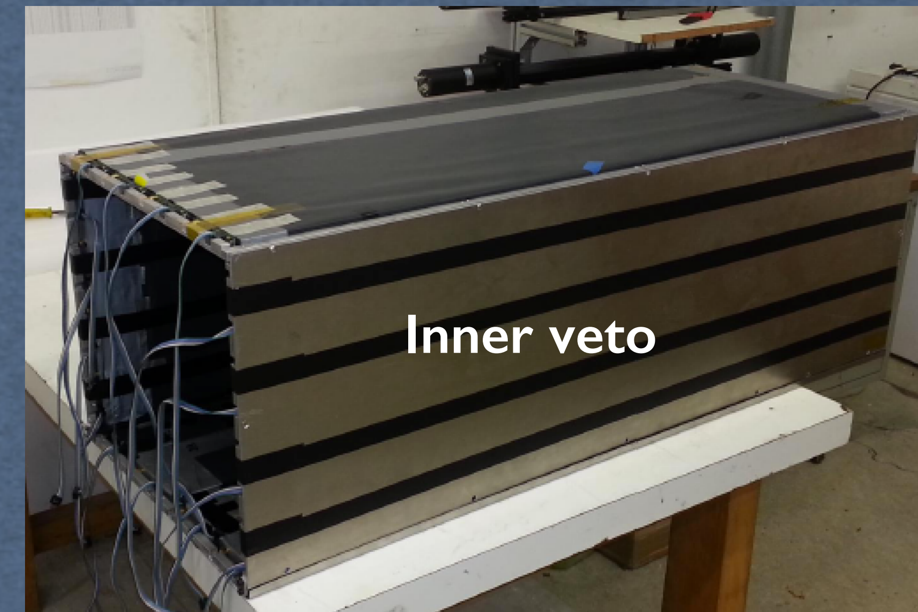
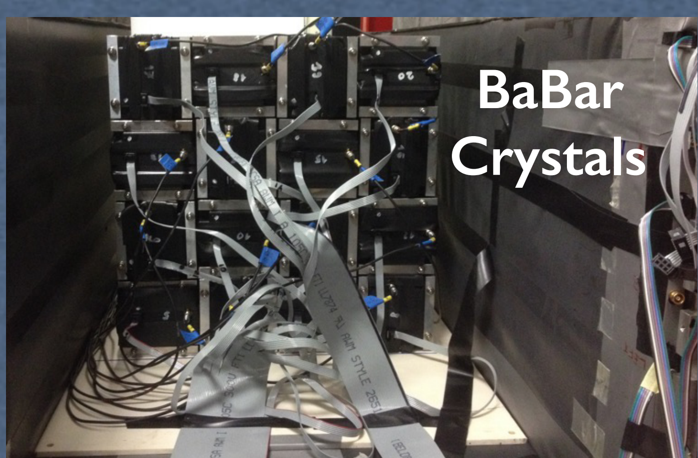






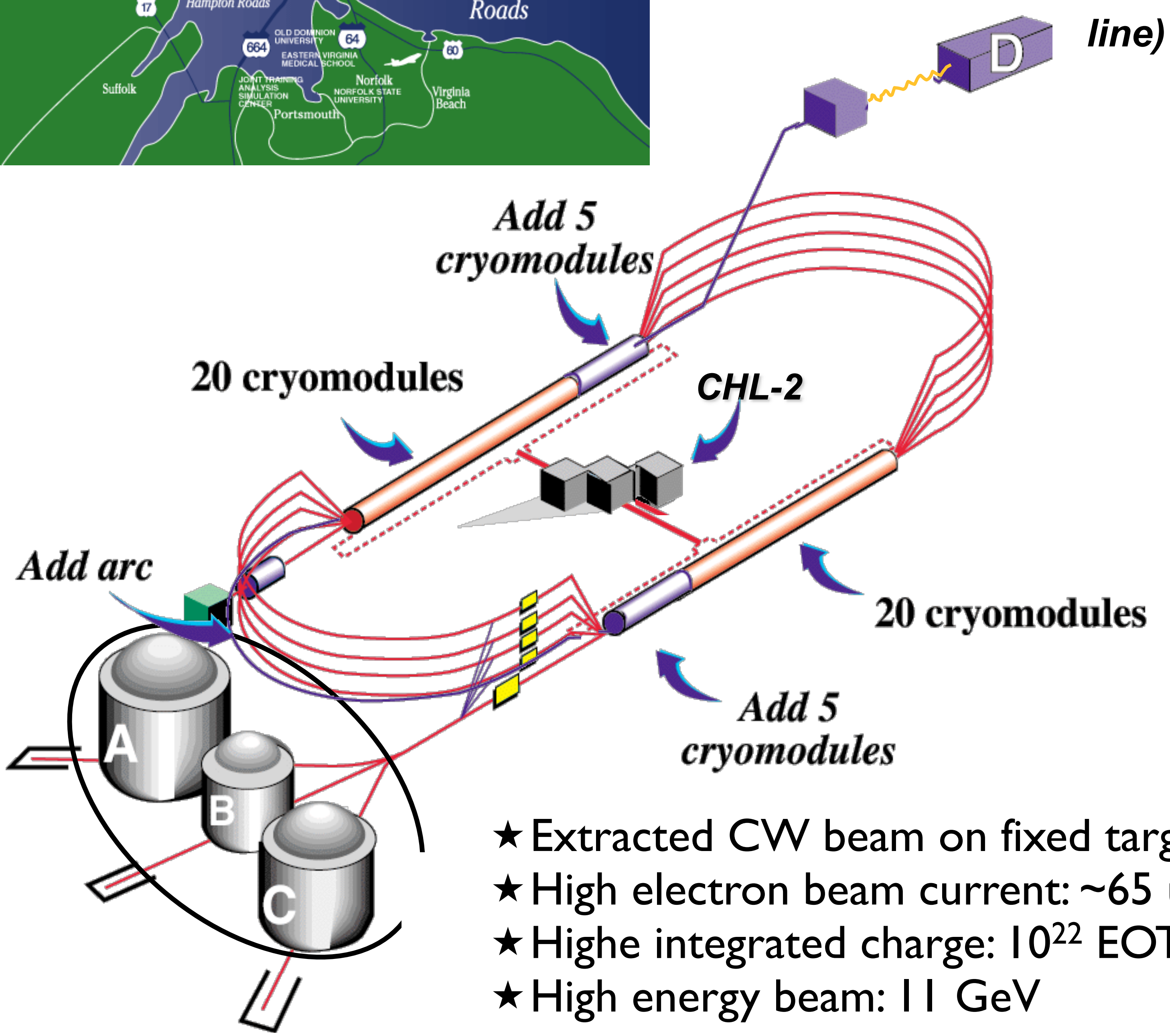
BDX-proto

- Outer Veto
- Lead vault
- Inner Veto

EM Cal
16x CsI(Tl)
crystal(s)
6x6 mm^2 SiPM

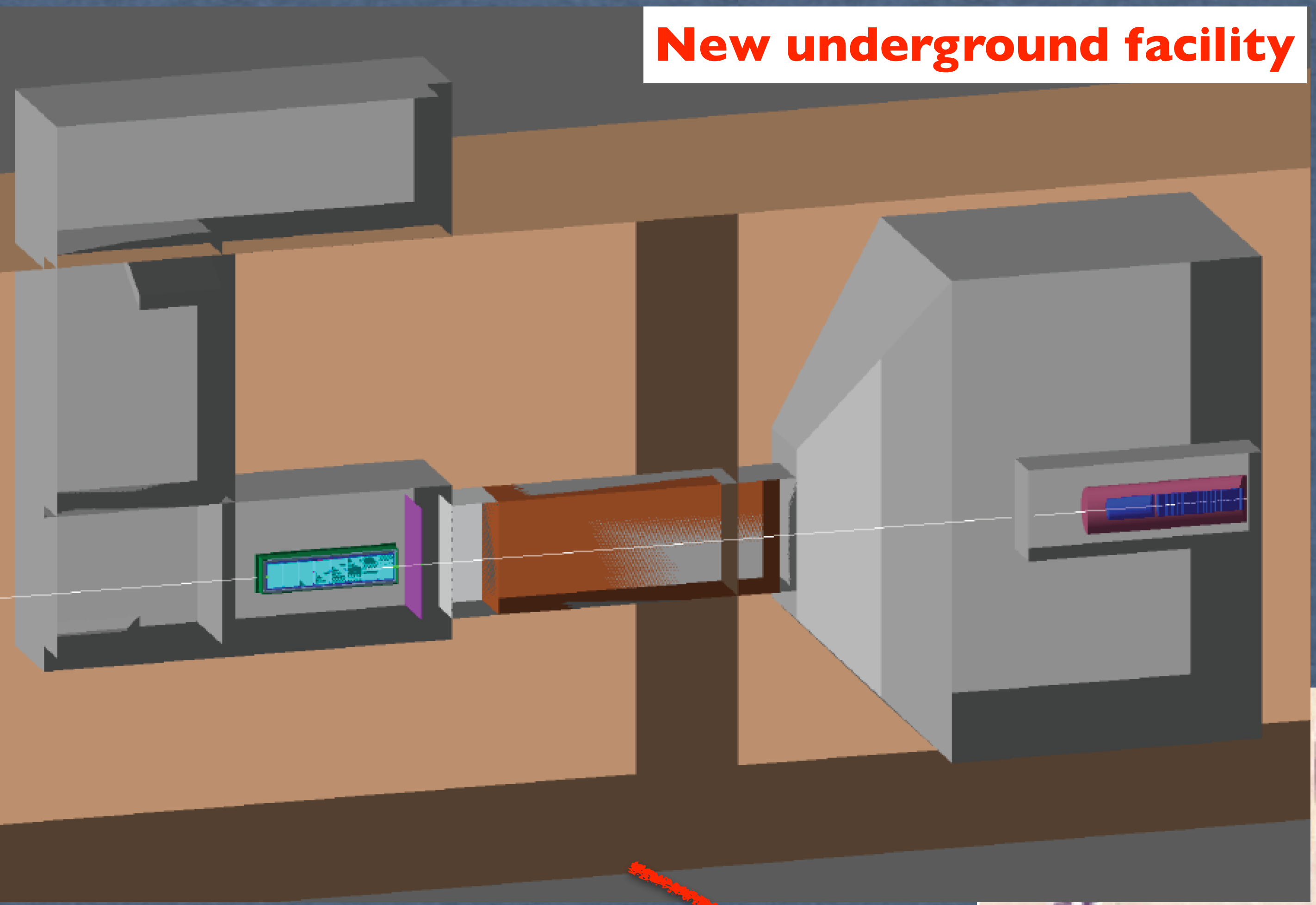
BDX@JLab

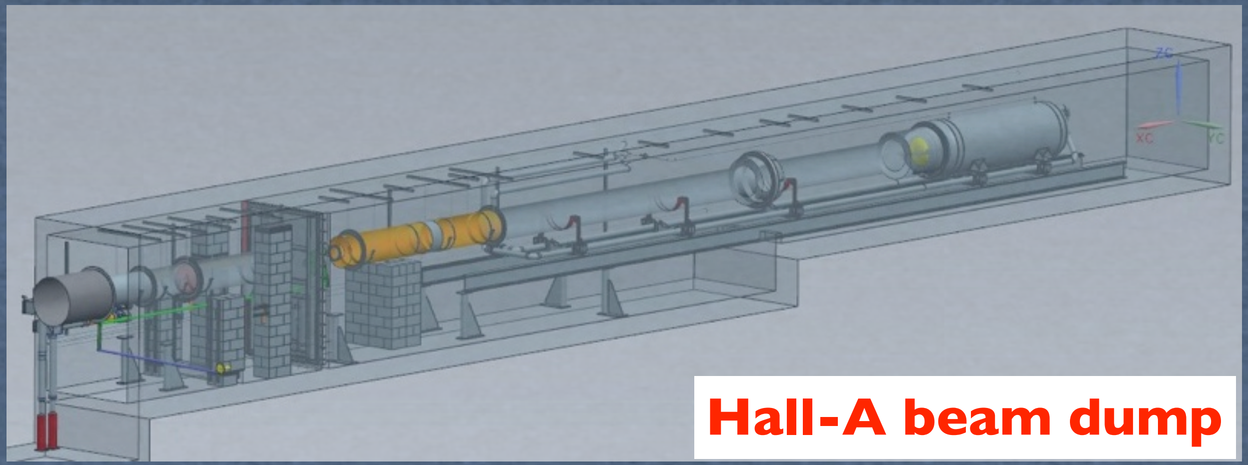
JLab is the ideal facility to run the BDX experiment

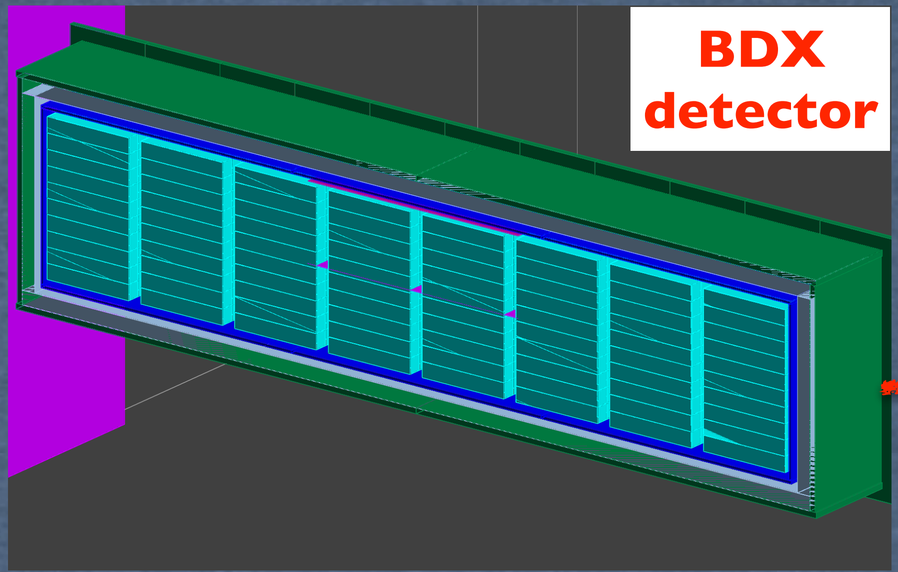


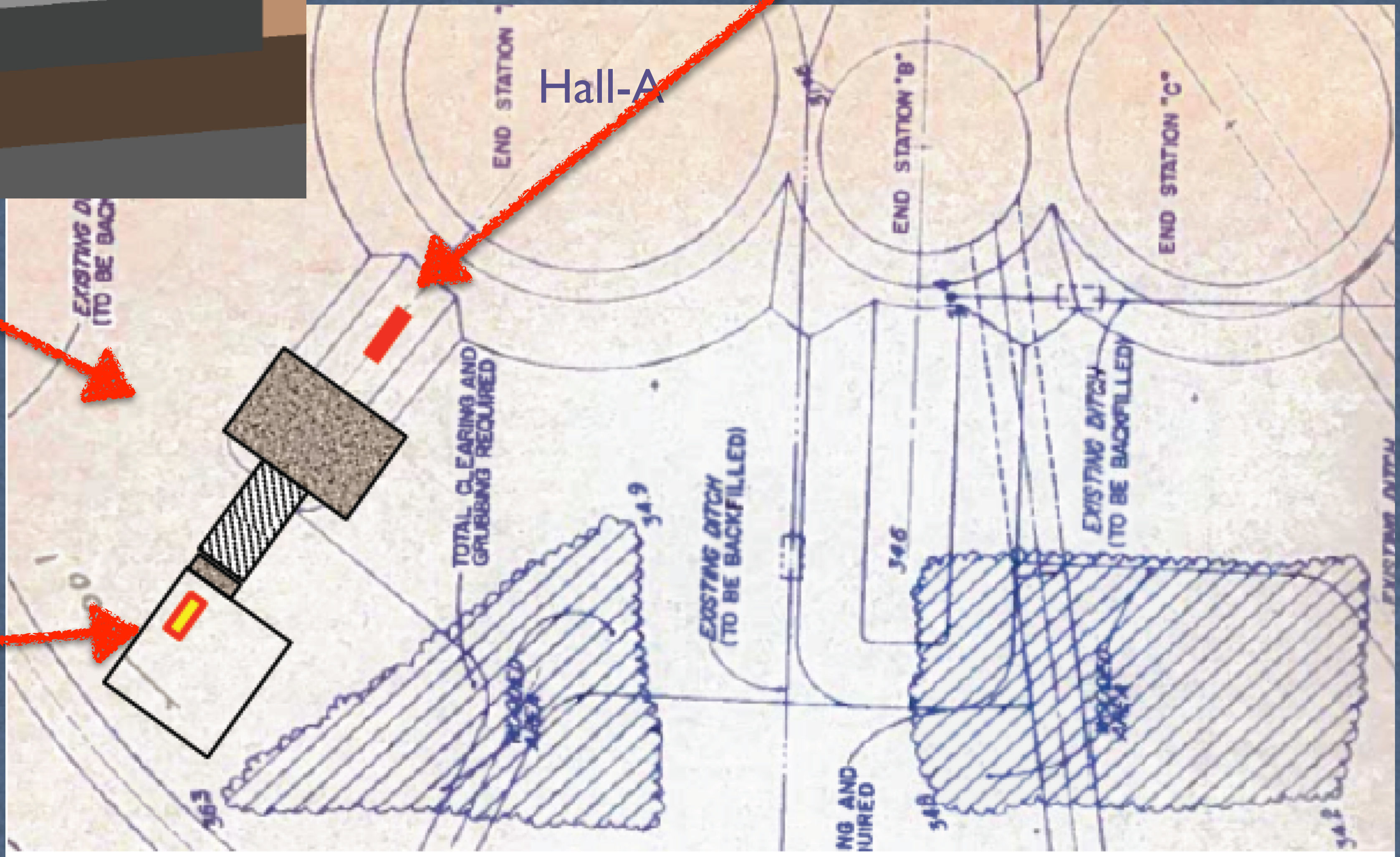
- ★ Extracted CW beam on fixed target
- ★ High electron beam current: ~65 uA
- ★ Highe integrated charge: 10^{22} EOT
- ★ High energy beam: 11 GeV

BDX@JLab

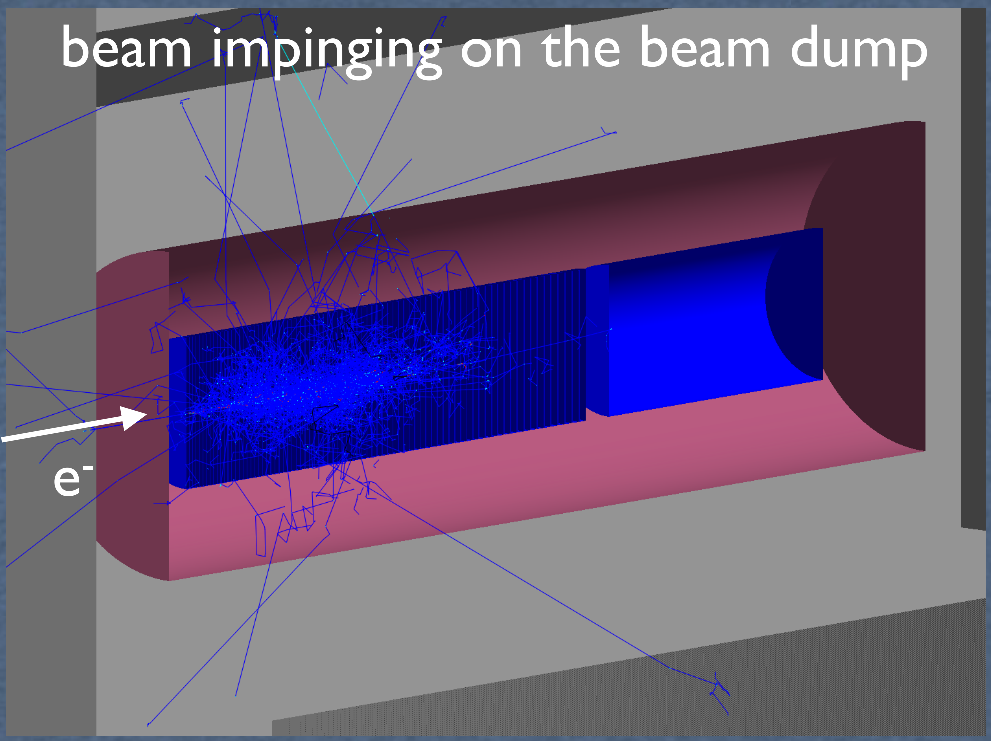

New underground facility

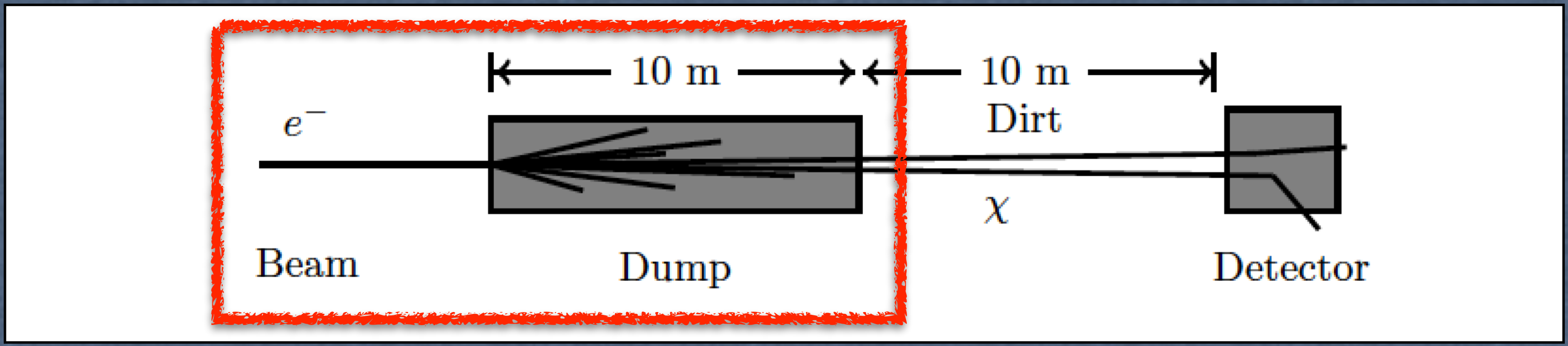

Hall-A beam dump


BDX
detector


Hall-A
END STATION "B"
END STATION "C"
TOTAL CLEARING AND GRUBBING REQUIRED
EXISTING DITCH (TO BE BACKFILLED)

X production in the BD





- MadGraph to describe the A' production and decay (A' → $\chi\bar{\chi}$)
- Detailed description of Hall-A beam dump (aluminium and water)
- Sampling of em shower simulated with GEANT4/FLUKA

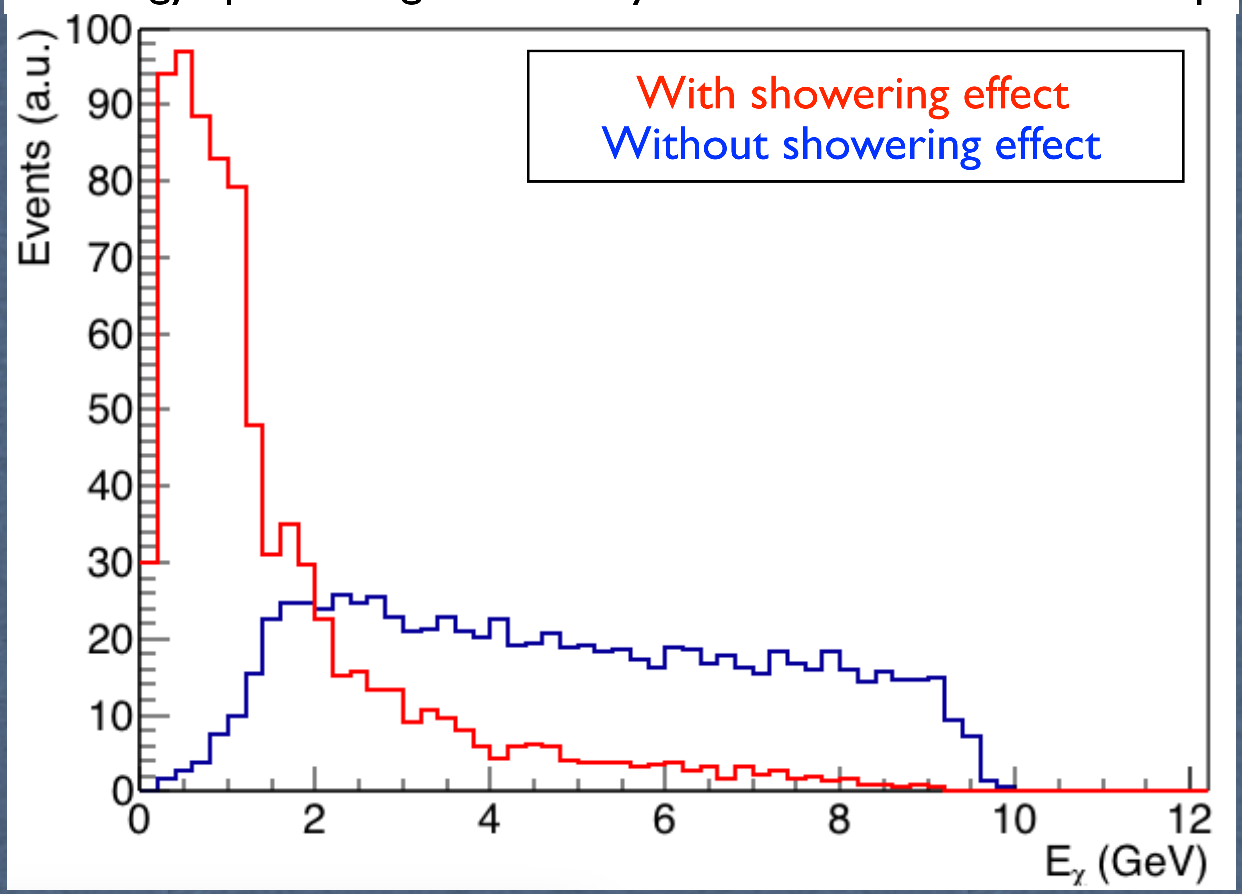
The em shower in the dump was neglected in previous works

Significant effect on energy distribution and X production angle

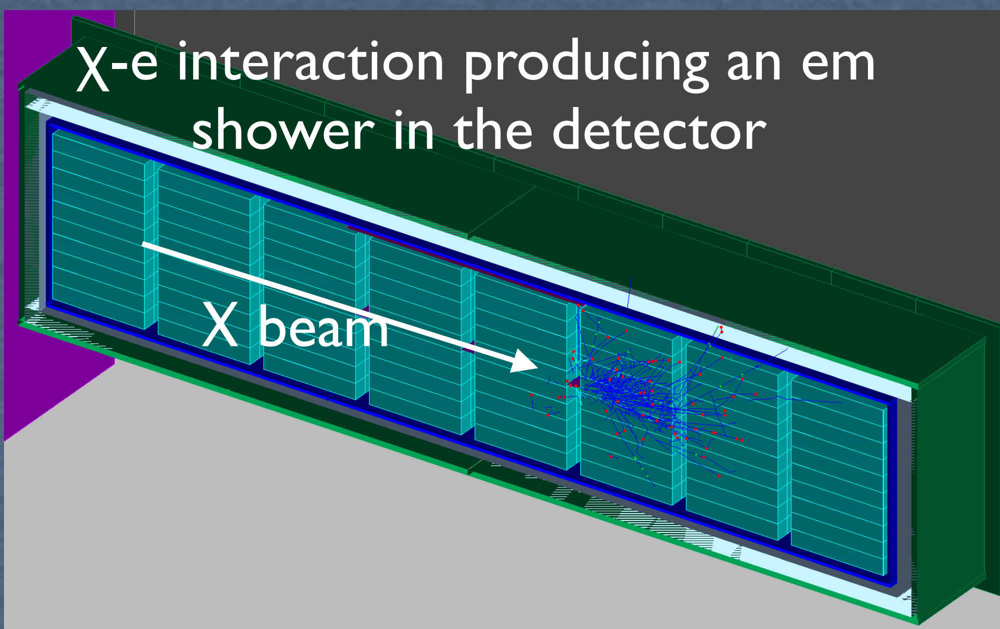
JLab kinematics

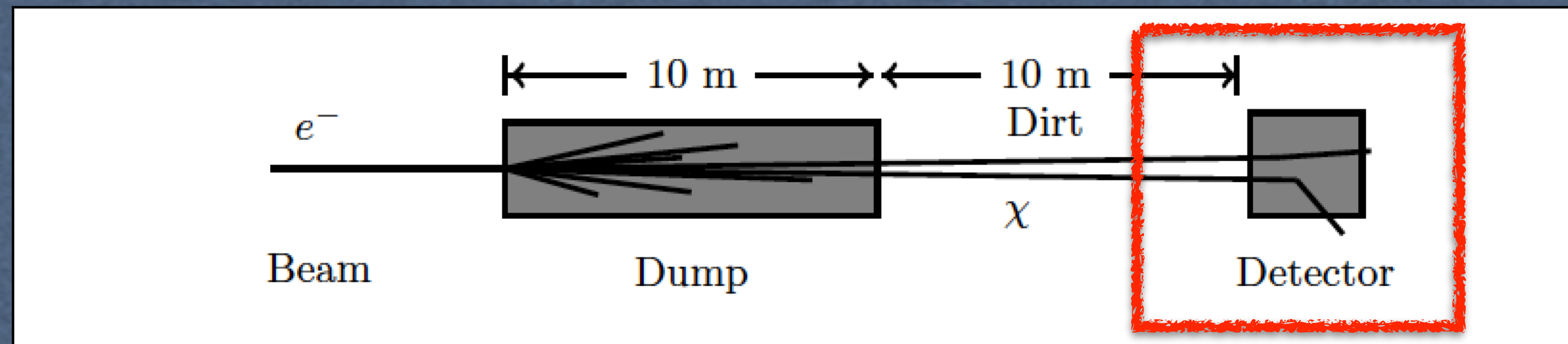
- X beam softer (significant)
- X beam defocused (less important)
- X beam intensity almost untouched

X energy spectrum generated by 10 GeV e-beam in the dump

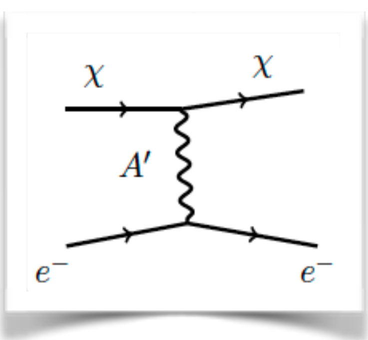


X detection in the BDX detector

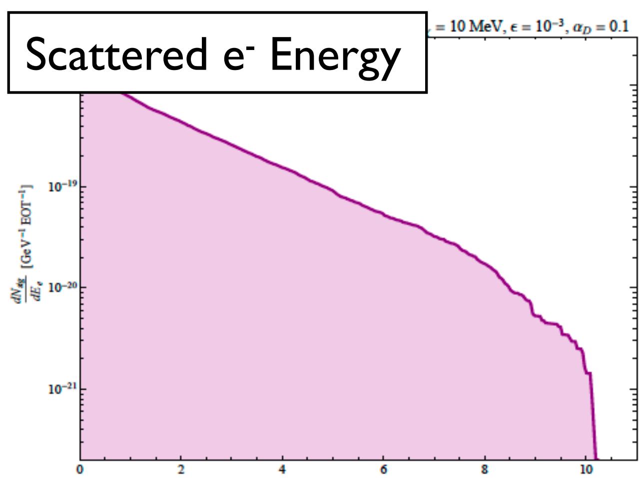


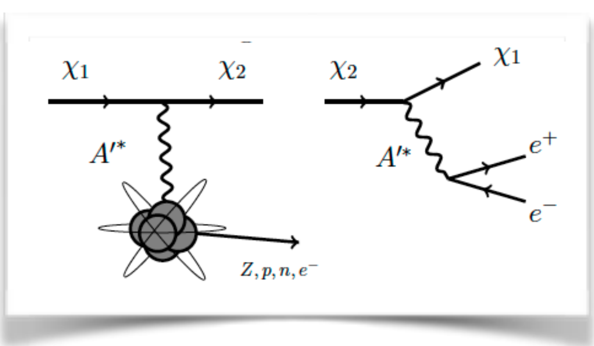


- GEANT4 simulations of X-e and X-N interaction
- Detection efficiency derived as a function of the energy threshold included in all BDX reach estimates

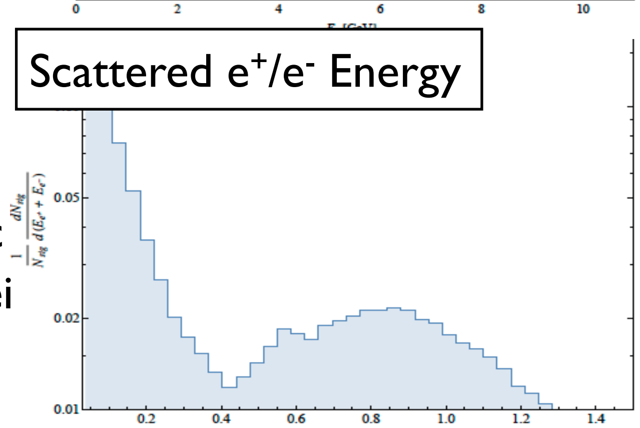


Elastic on electrons





Inelastic on nuclei



BDX detector response to X-e⁻ elastic and X-N inelastic scattering (em shower)

Parameters: m_X = 30 MeV $m_{A'}$ = 90 MeV	
X-e⁻ scattering inside the fiducial volume $E_{e^-} \geq 300$ MeV	100%
$E_{Seed} \geq 300$ MeV	61%
Veto anticoincidence	13% (10% - 20%)

- E_{Seed} = max crystal energy in the em cluster
- Veto anti-coincidence to account for cosmic bg cut
- Consistent with prototype measurement
- Conservative (refined cuts on em shower will be possible)

Cosmic background

★ Cosmic background measured with the BDX detector prototype with similar overburden

★ GEANT4 simulations reproduce muon rate w/wo overburden

★ The majority of cosmic muons detected and rejected by the combination of the two veto detectors

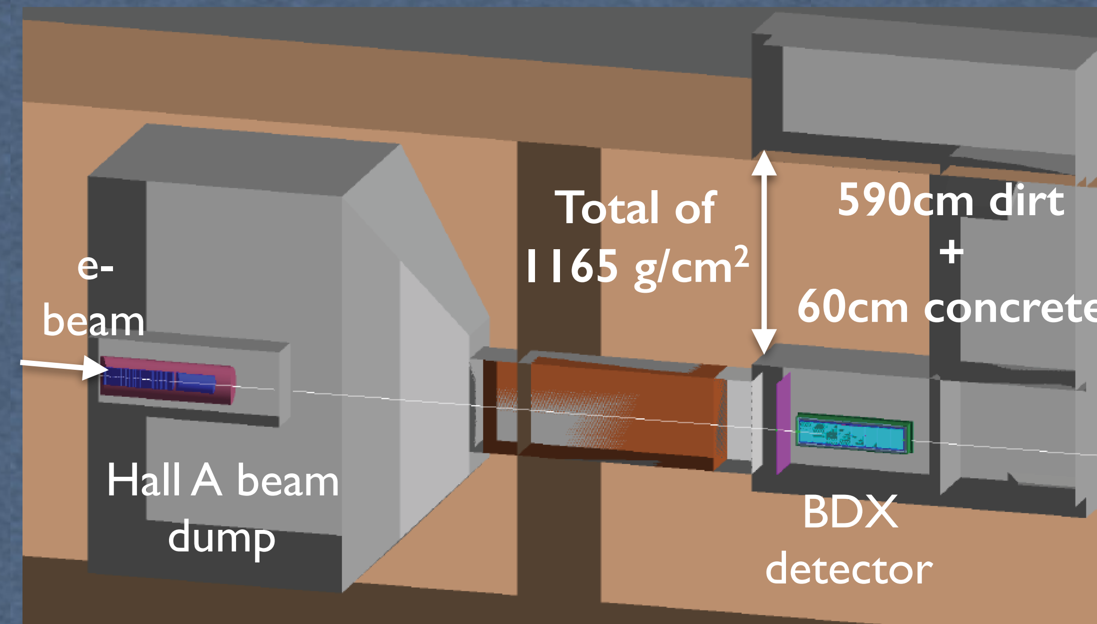
★ The most part of cosmic neutrons are shielded by the overburden

★ Low energy (<100 MeV) background due to neutrals

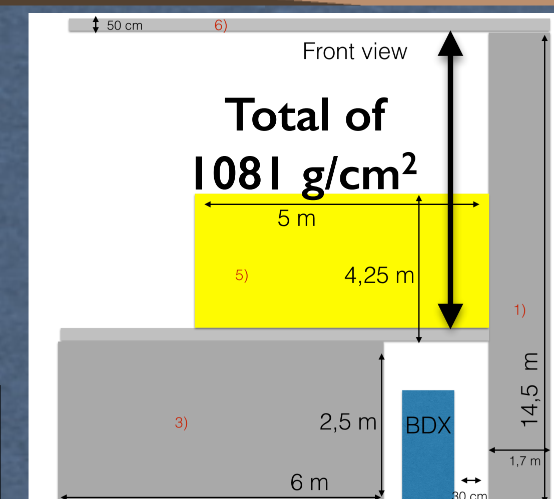
★ Measured Rate (E_{Thr}~300MeV) < 2 counts

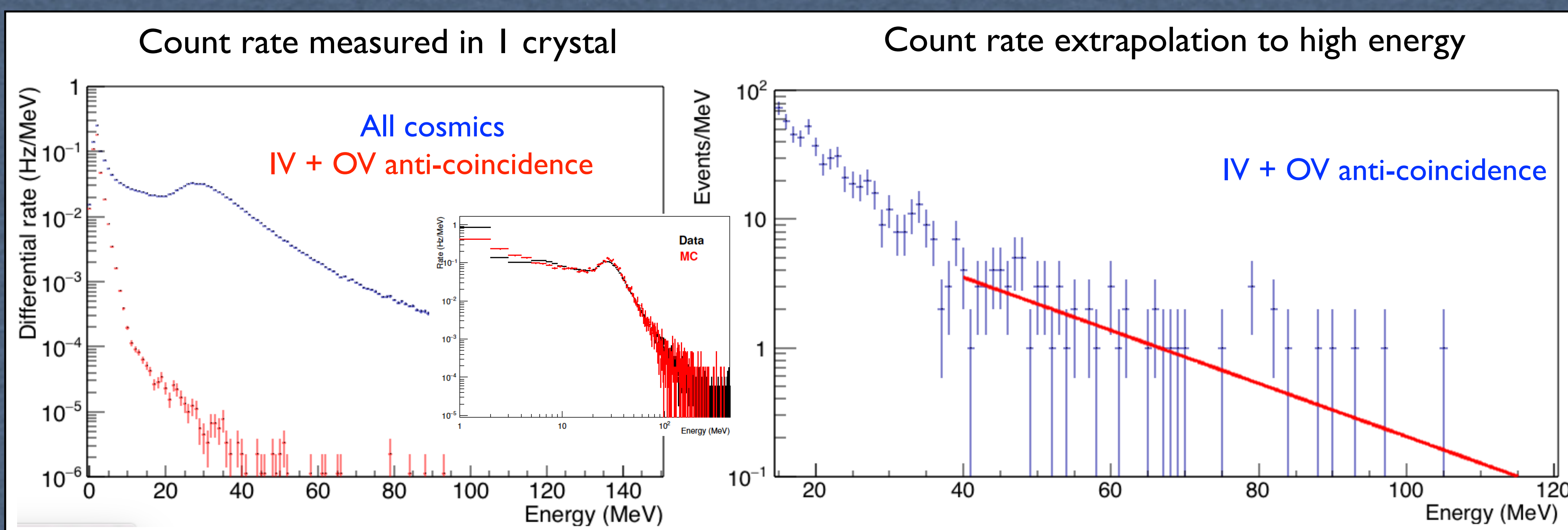
- Conservatively extrapolated from the (lower E) non-0 counts region
- Measured rate scaled to the JLab set-up (x800 crystals)

★ Perfect agreement with MC simulation



LNS set-up of BDX prototype



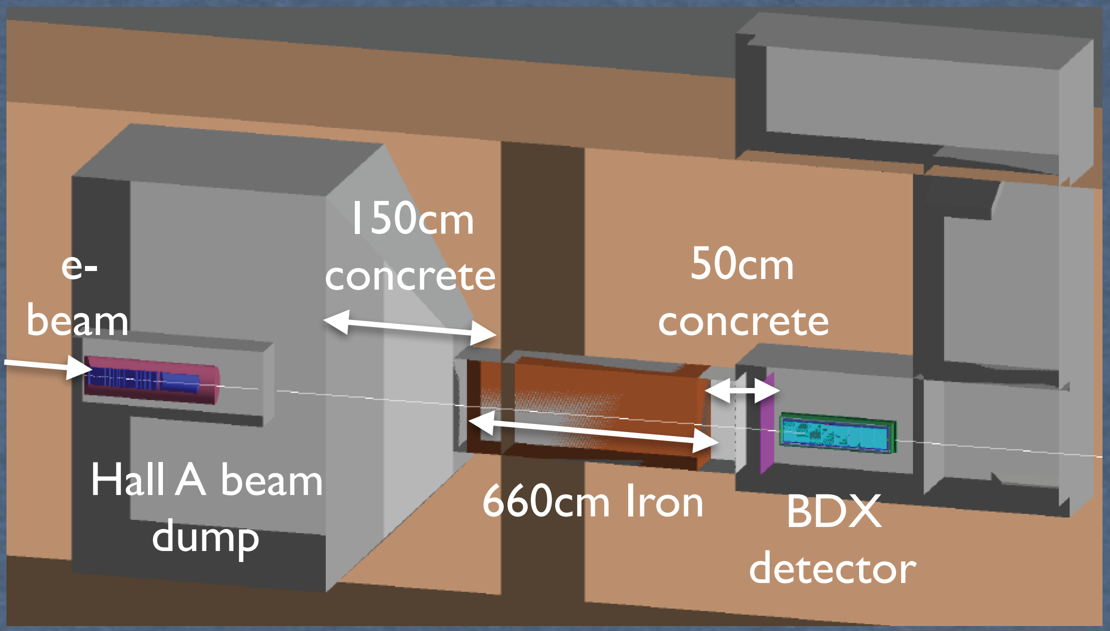


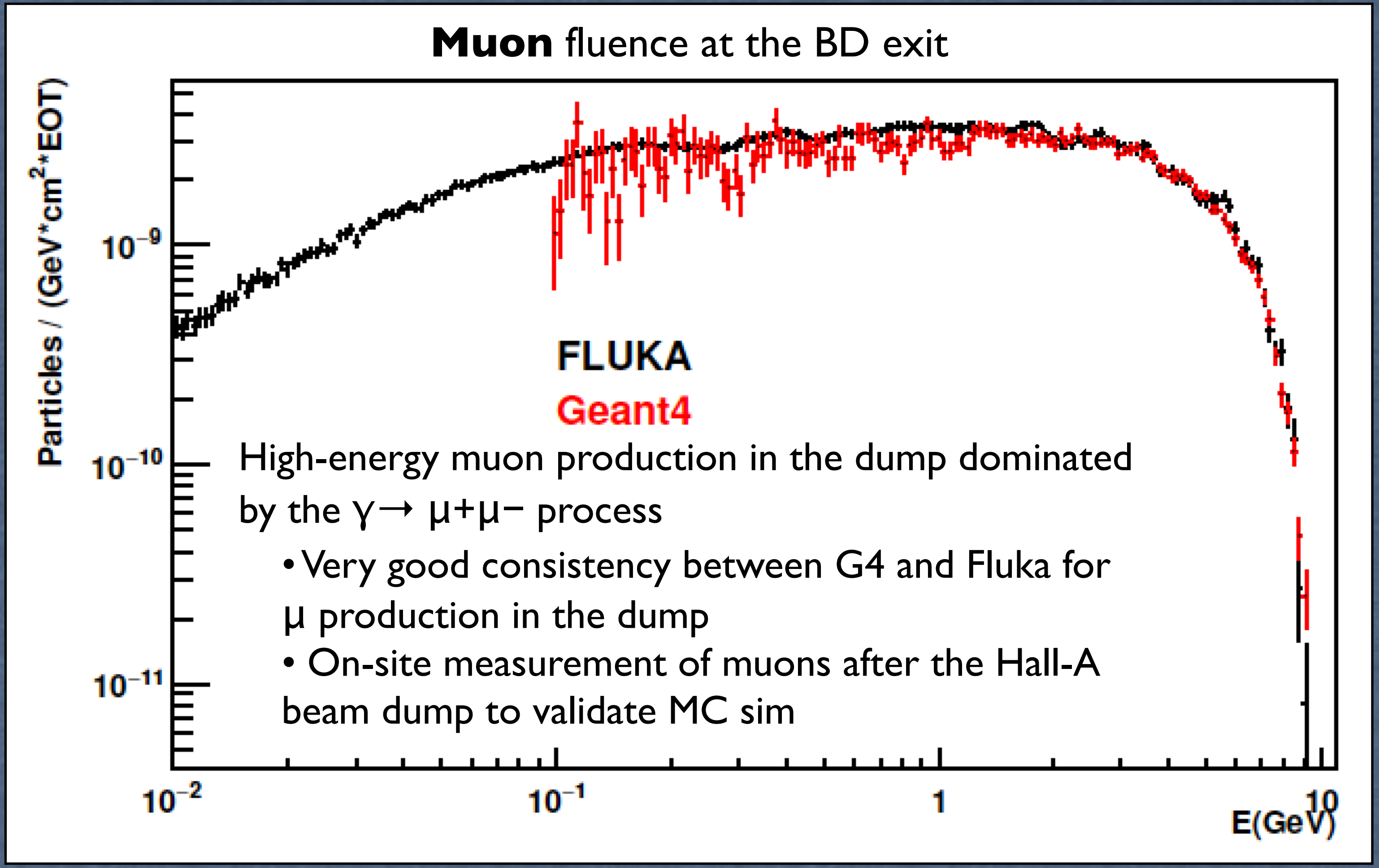
Cosmic background will be continuously and accurately measured during the experiment with **4x more** statistics

Beam-related background

★ **Muons produced in the BD by the 11 GeV beam**

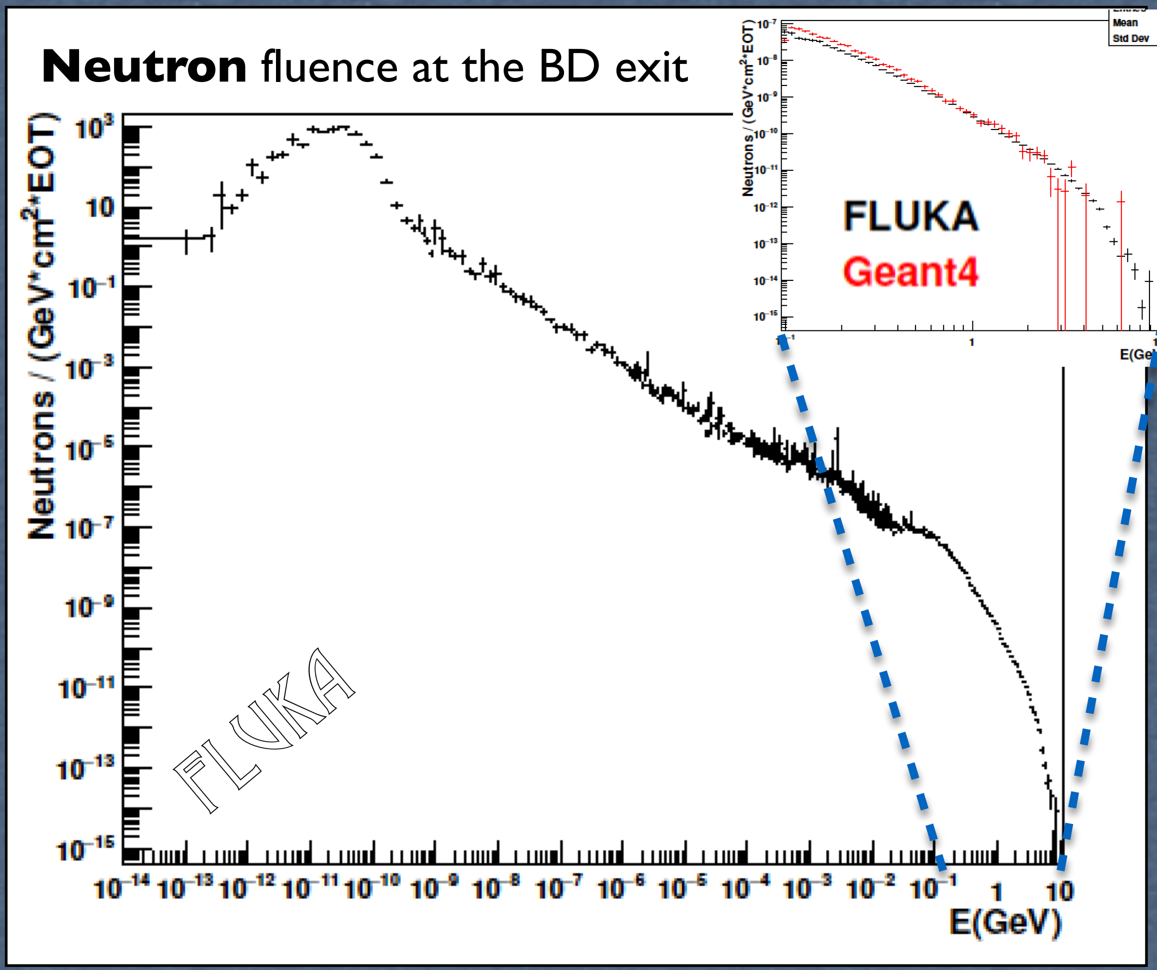
- 6.6m iron shield (+2m concrete) to stop high energy muons
- No muons at the detector location
- Propagating the non-negligible flux at different distances, no n and γ with E>10 MeV are found at the detector location





High-energy muon production in the dump dominated by the $\gamma \rightarrow \mu^+\mu^-$ process

- Very good consistency between G4 and Fluka for μ production in the dump
- On-site measurement of muons after the Hall-A beam dump to validate MC sim



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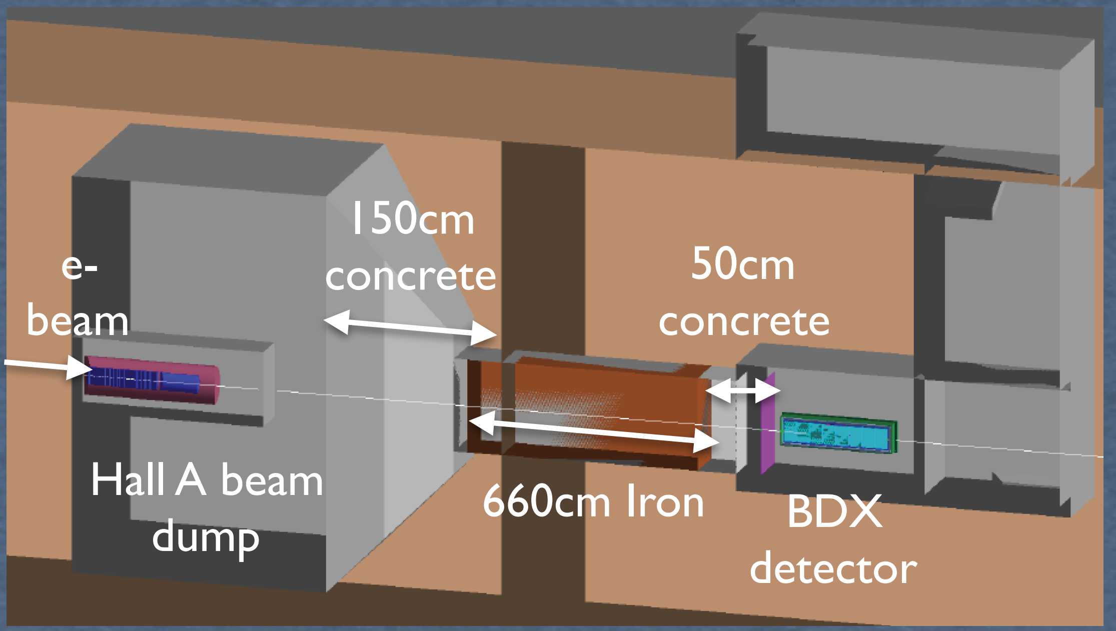
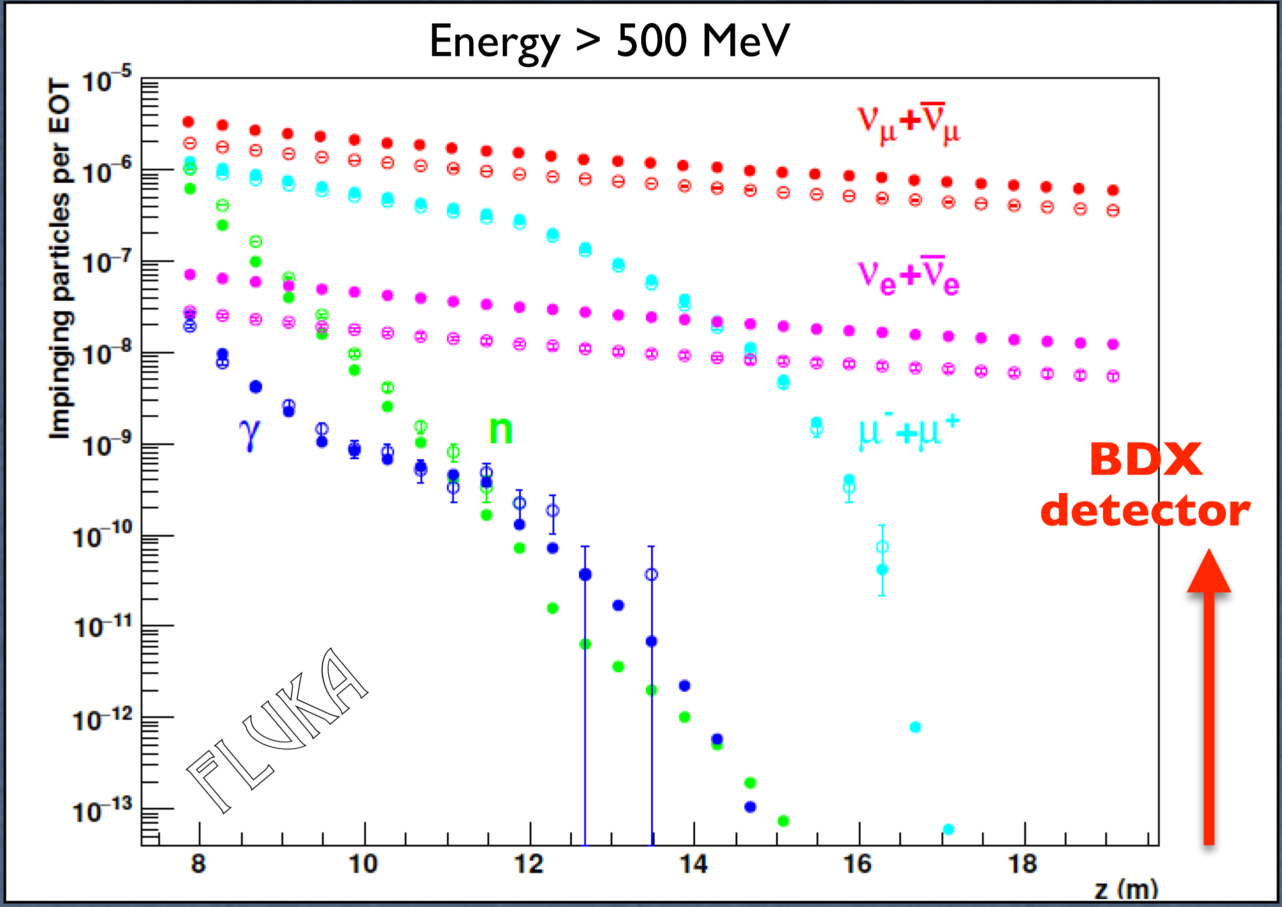
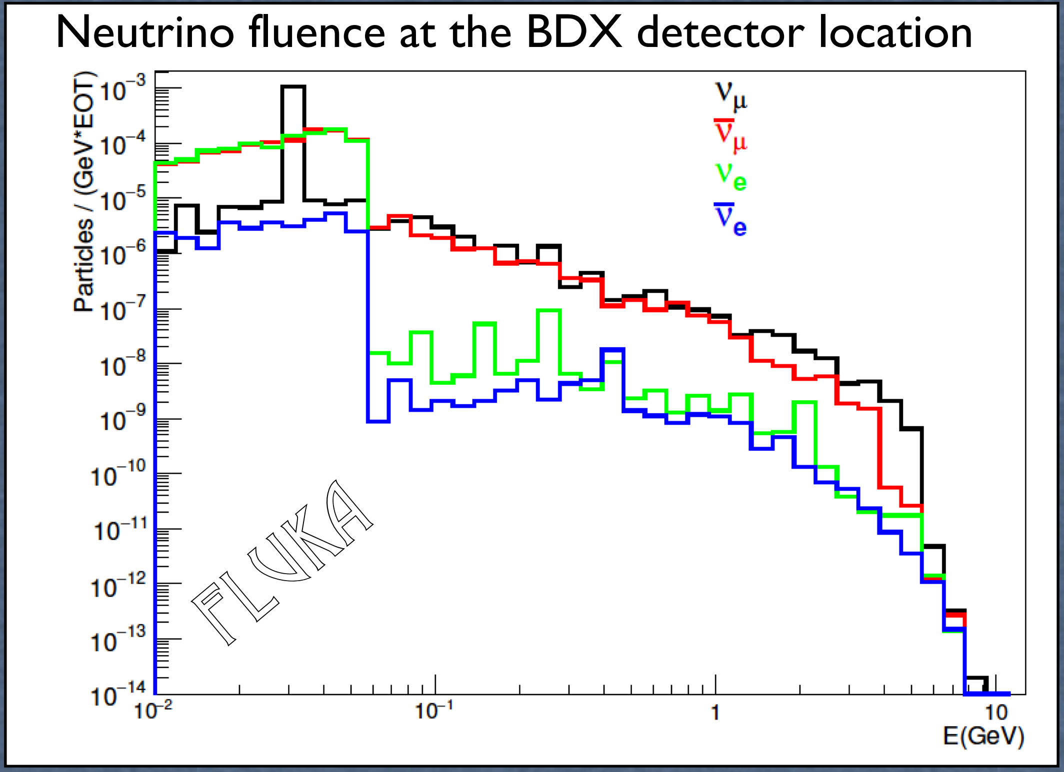






- For E> 500MeV only ν reach the detector
- Other particles lose energy via multiple interaction in the absorber

★ **Neutrino**

- $\pi \to \mu\, \nu_\mu \quad \mu \to e\, \nu_\mu\, \nu_e$
- Mainly low energy (<60 MeV)

- Non-negligible contribution of high energy neutrino interacting in the detector by CC: $\nu + N \to \nu + e^-$

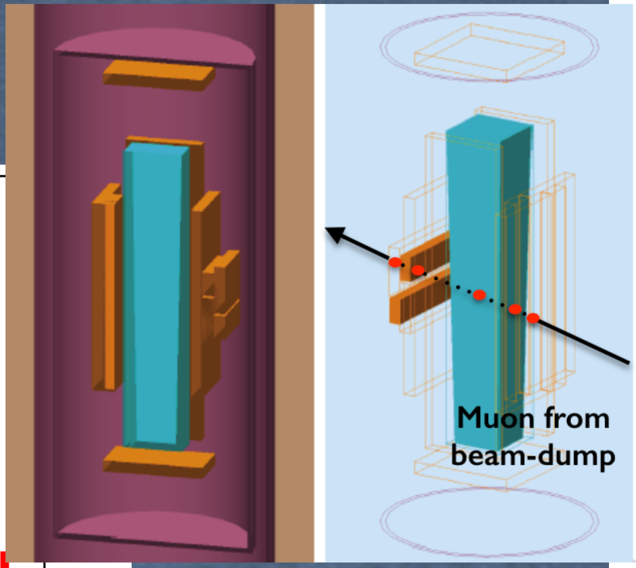
Neutrino *irreducible* bg represents the ultimate limitation for BDX

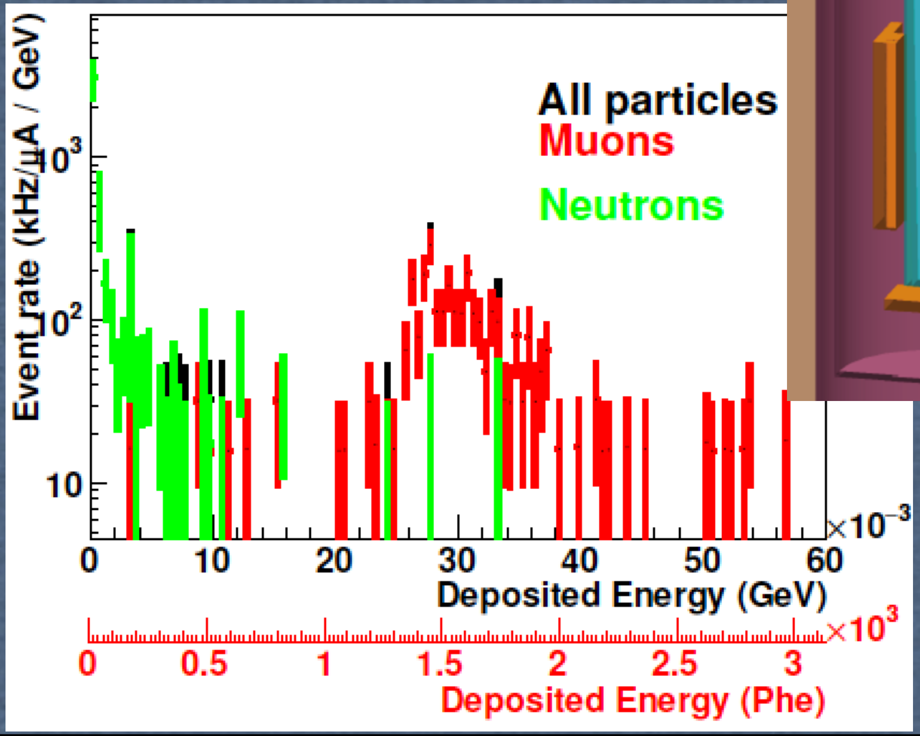
Test to measure the beam-on background

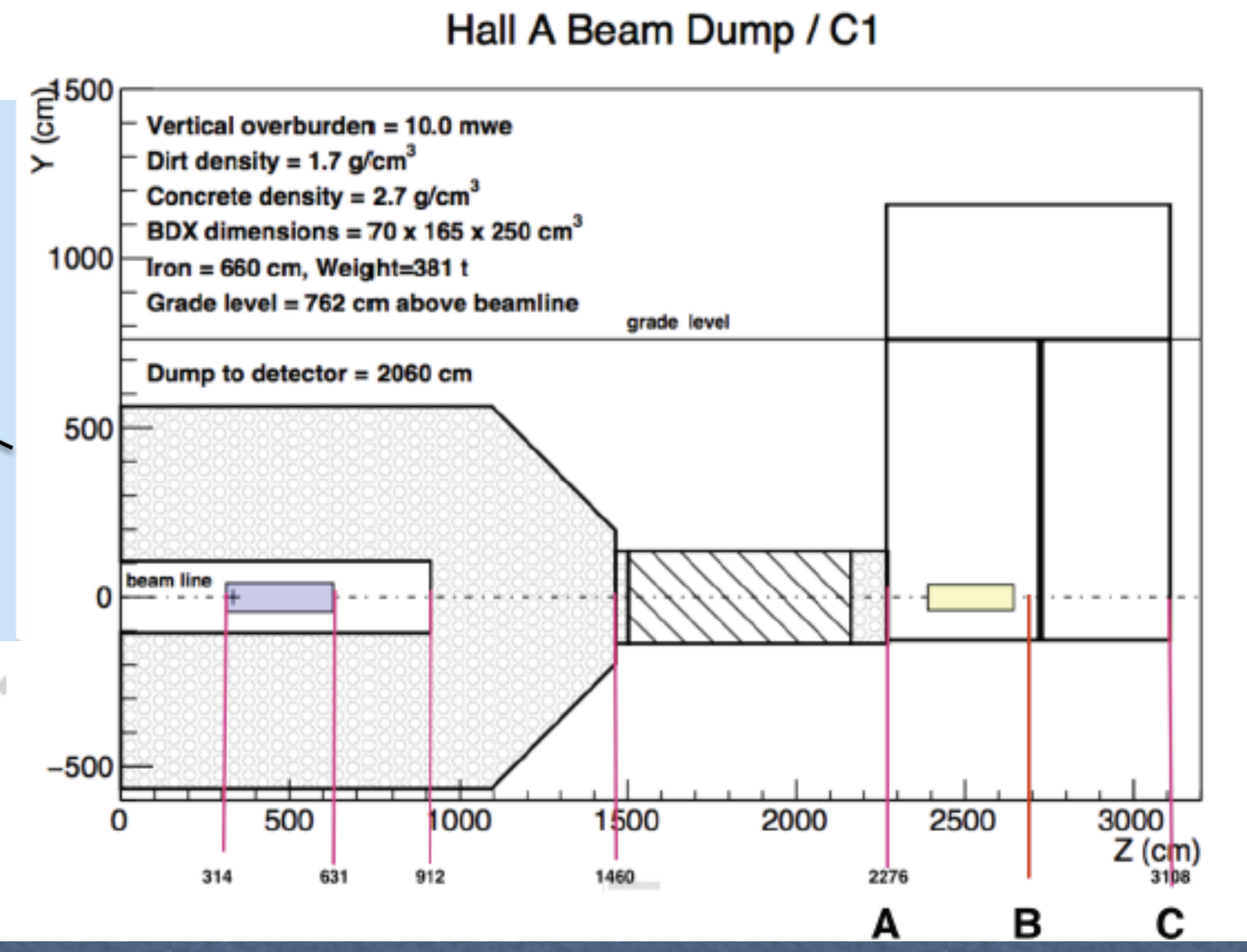
Measurement campaign to characterize the flux of high-energy μ produced in the Hall-A beam dump.

Goal: validate MC for forward particles production with an absolute normalization point

Setup:
- Pipe downstream of Hall-A beam-dump at BDX location
- Insert a CsI(Tl) crystal surronded by plastic scintillators
- Measure μ flux when 11-GeV beam is on







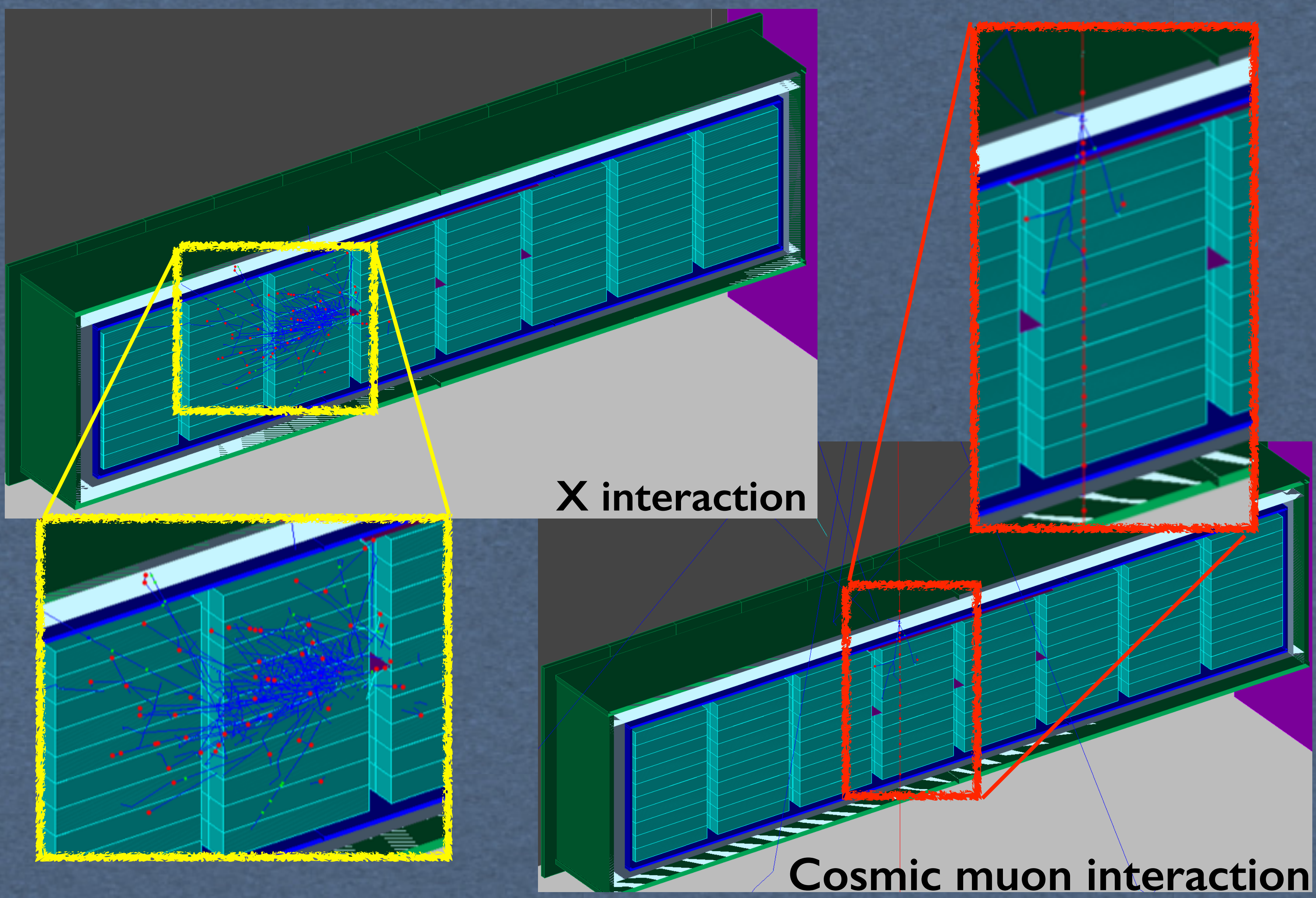
Signal vs background

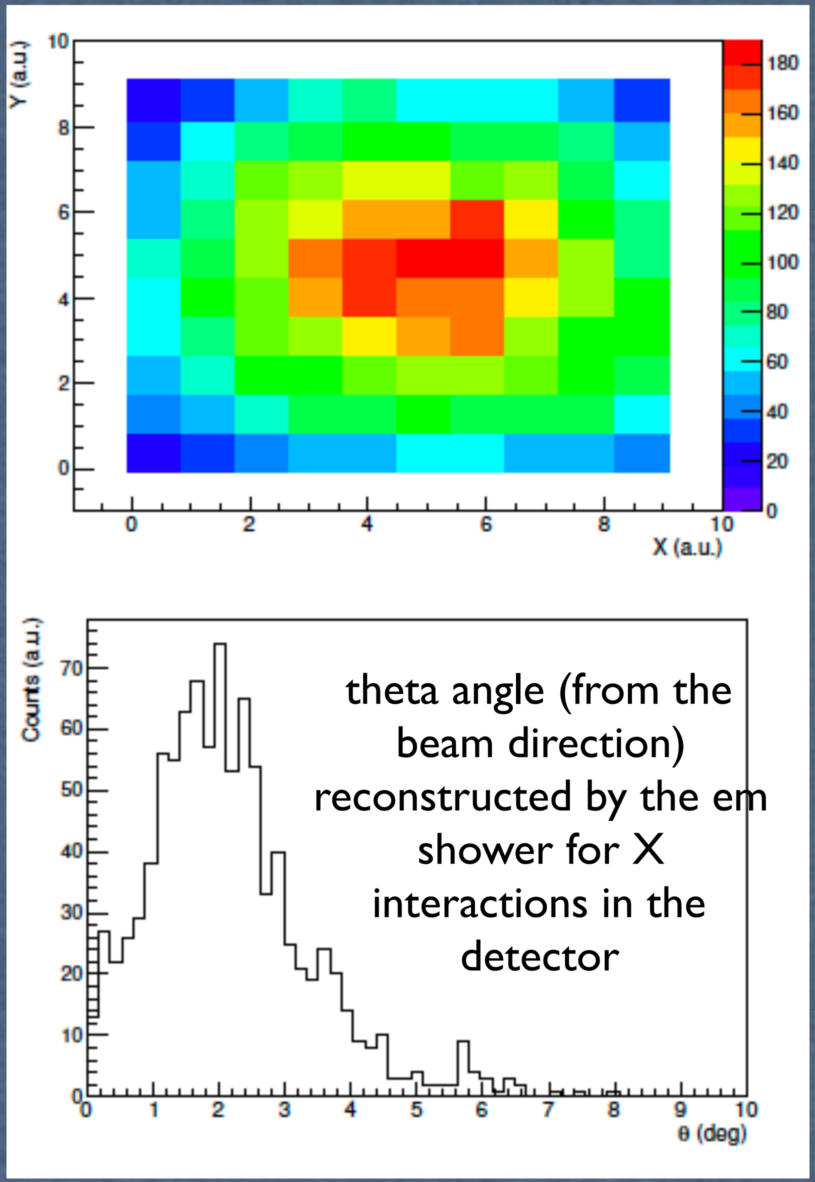
✳Additional rejection can be obtained by selecting the topology of different interactions

- SIGNAL: EM shower propagating along the beam-line
- Cosmic BG - muons clear track (mainly top-bottom)
- Cosmic BG - neutrons: hadronic shower pointing down
- μ-neutrinos: muon (a track) pointing to the BD
- e-neutrinos (DIS)

✳Further cuts:

- Directionality
- timing
- Multivariate analysis





Background(s)

I) Backgrounds associated to the beam (beam-related)

- detection thresholds define the bg level
- charged particle easy to shield, neutrals more difficult
- low energy particles produce signals below threshold

GEANT4/FLUKA simulations
Brute force + weight biases to deal with high flux of (low energy) particles

Beam-related background

Energy threshold	N_ν (285 days)
300 MeV	~10 counts

II) Cosmic background (beam-unrelated)

- measured (beam-off) and subtracted
- accelerator location usually prevents deep underground installation
- Few meters of overburden (dirt, concrete, heavy material)
- Time uncorrelated bg (CW beam prevents fast time coincidence)

Measurement with BDX prototype
Similar experimental set-up (same overburden) + extrapolation to JLab location

Cosmic sensitivity

Energy threshold	$\sqrt{Bg}$ (285 days)
300 MeV	<2 counts

For an energy threshold high enough (>2-300 MeV)
BDX hits the ultimate limit from ν interactions

Beam time request and expected reach

Experimental set-up

- CsI(Tl) calorimeter (~800 crystal, 50x55x295 cm^3)
- Plastic scintillator based Outer and Inner veto + Lead vault
- BDX detector placed in a new dedicated experimental hall downstream of Hall-A beam-dump

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)

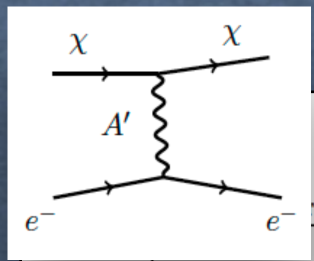
BDX reach calculation

- Signal determined as events excess wrt know background (beam + cosmic)
- BDX reach depends on precision of background determination
  - Beam bg: estimates depends on ν induced counts
  - Cosmic bg: measured during beam-off: 4x beam-on

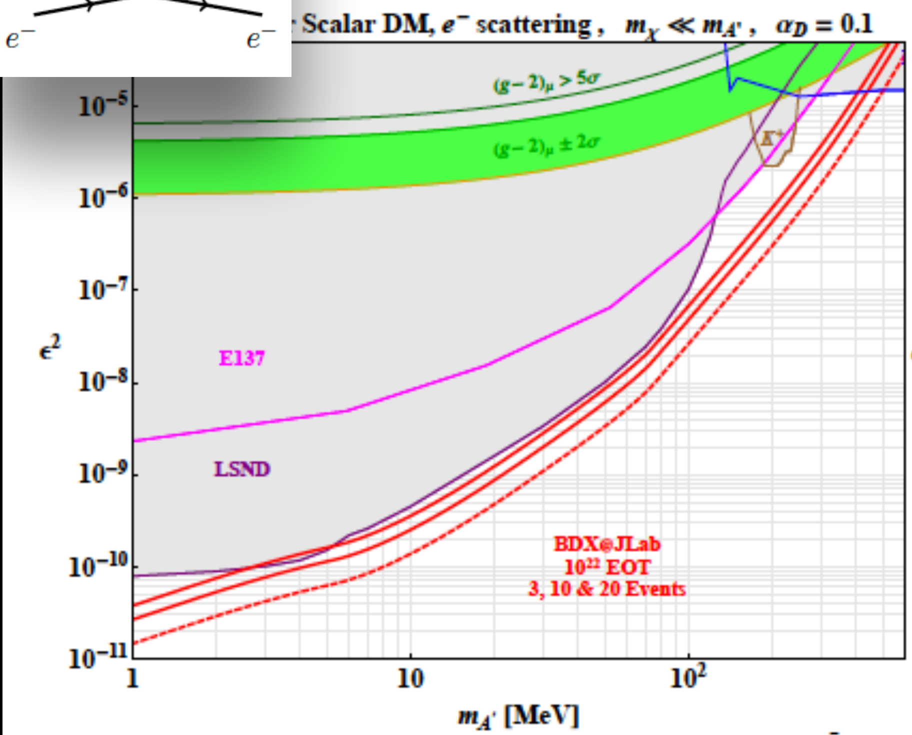
$N_{Signal} > 2\ \sigma_{bg} \sim 11 - 17$ counts

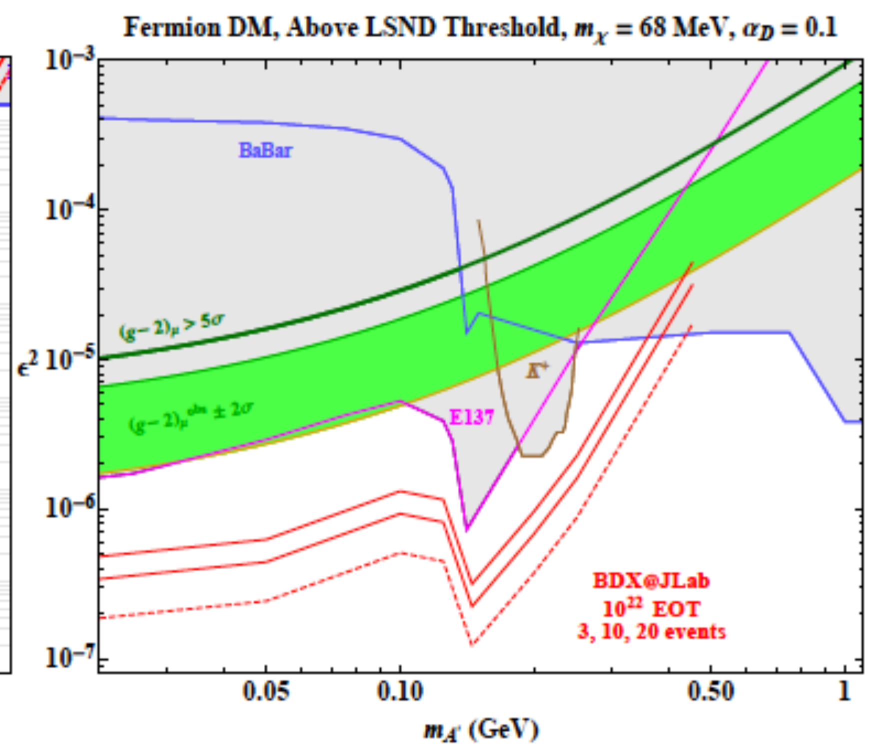
BDX reach reported for (3) 10 and 20 excess events

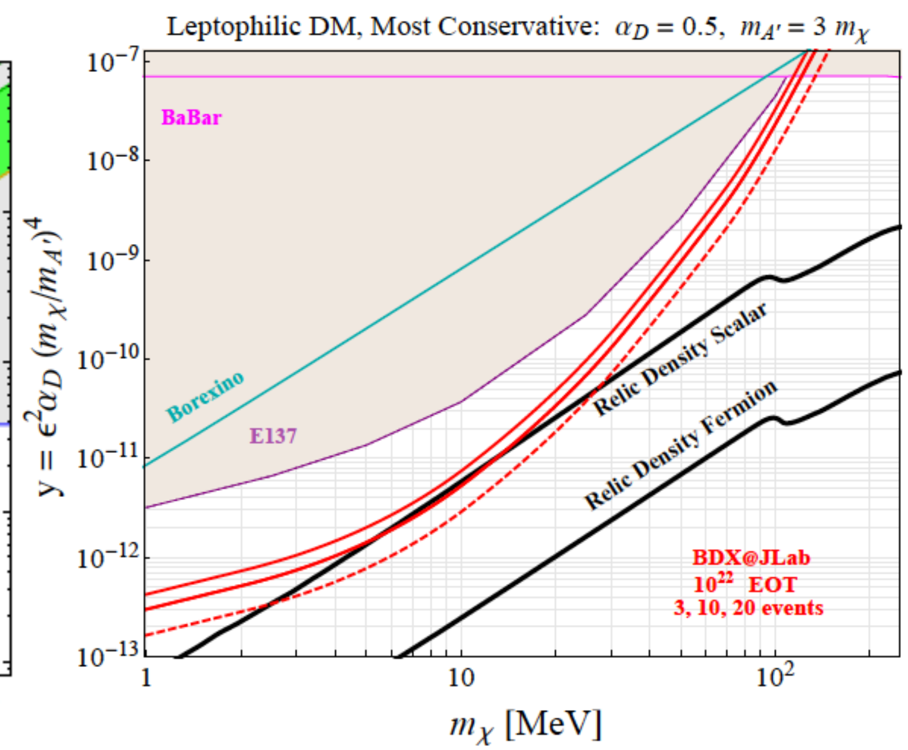
BDX expected reach



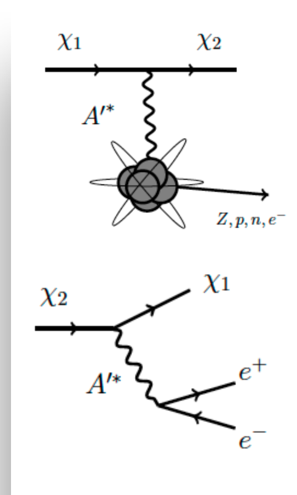
Elastic X-e⁻ scattering - BDX reach

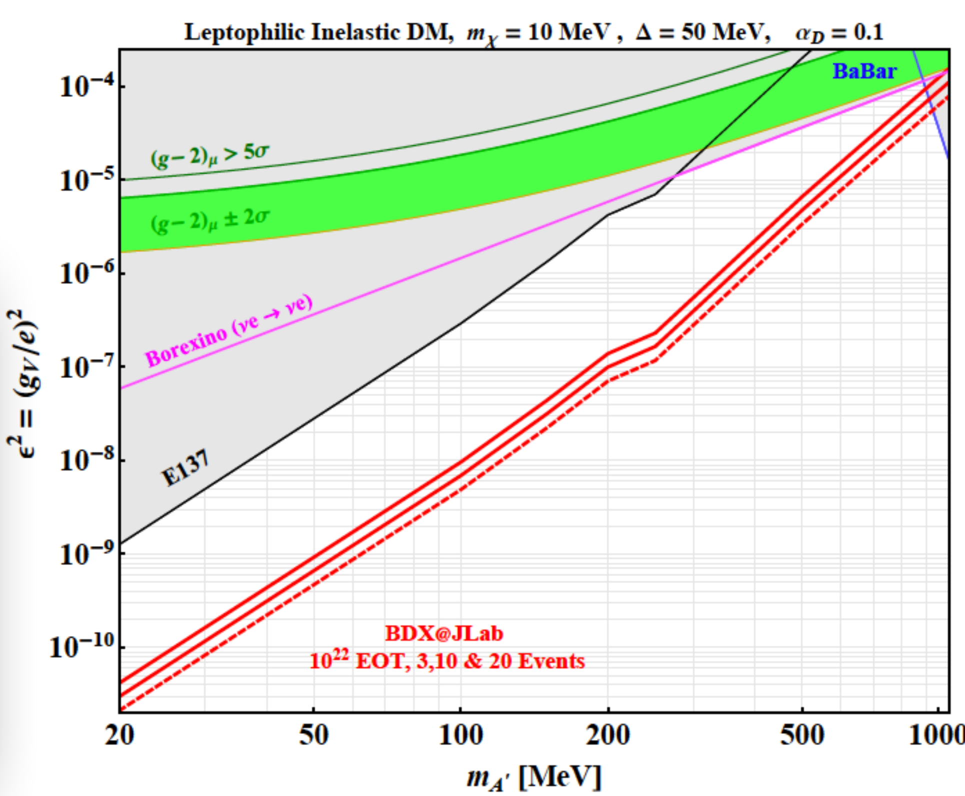




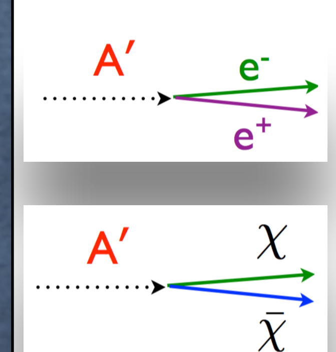


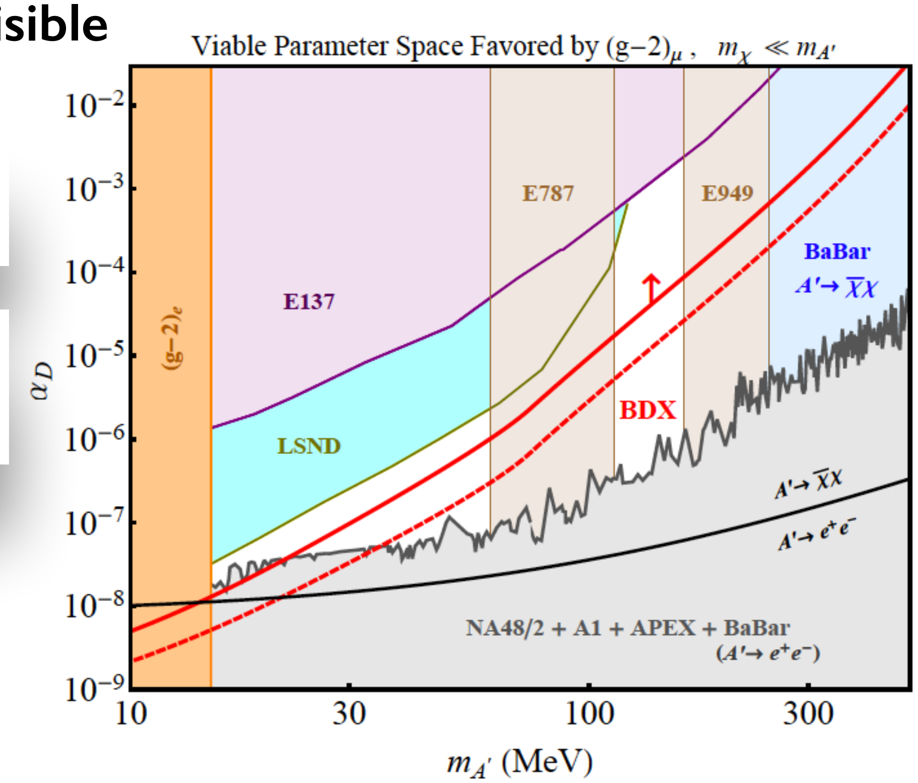
Inelastic X-N scattering





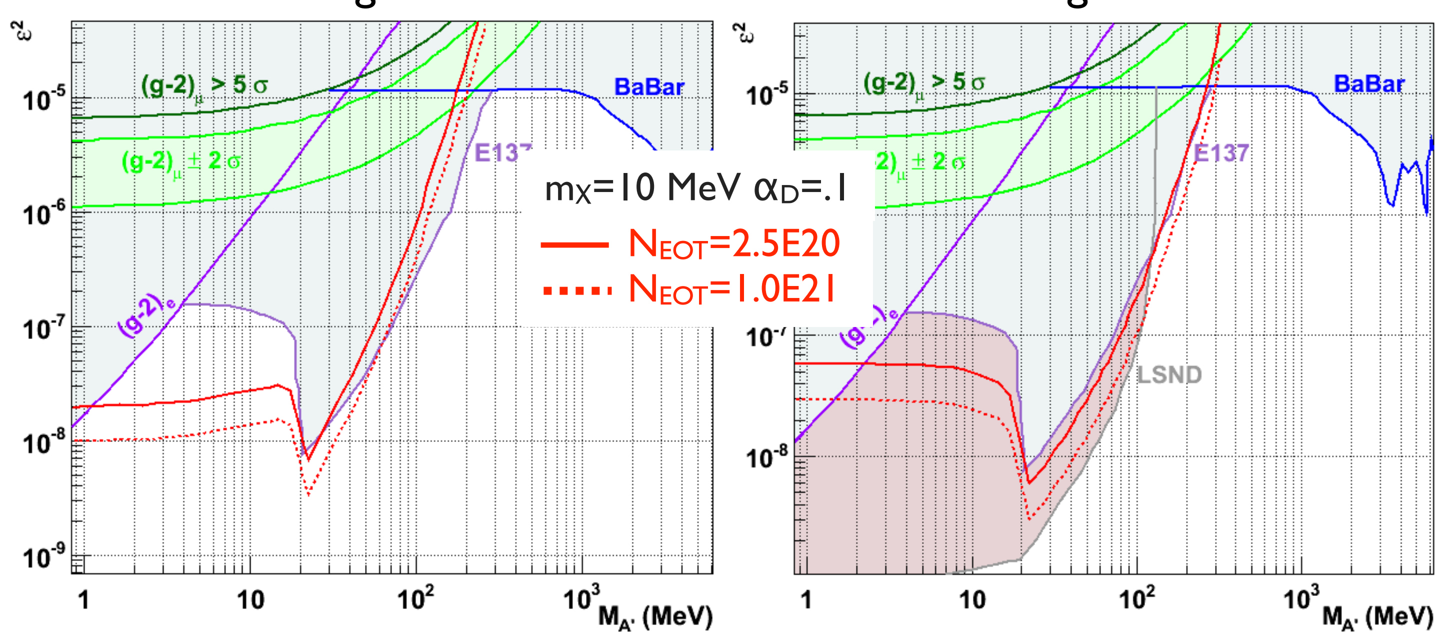
Visible + Invisible decay





Competition with other facilities

El scattering on electrons   El scattering on nucleon



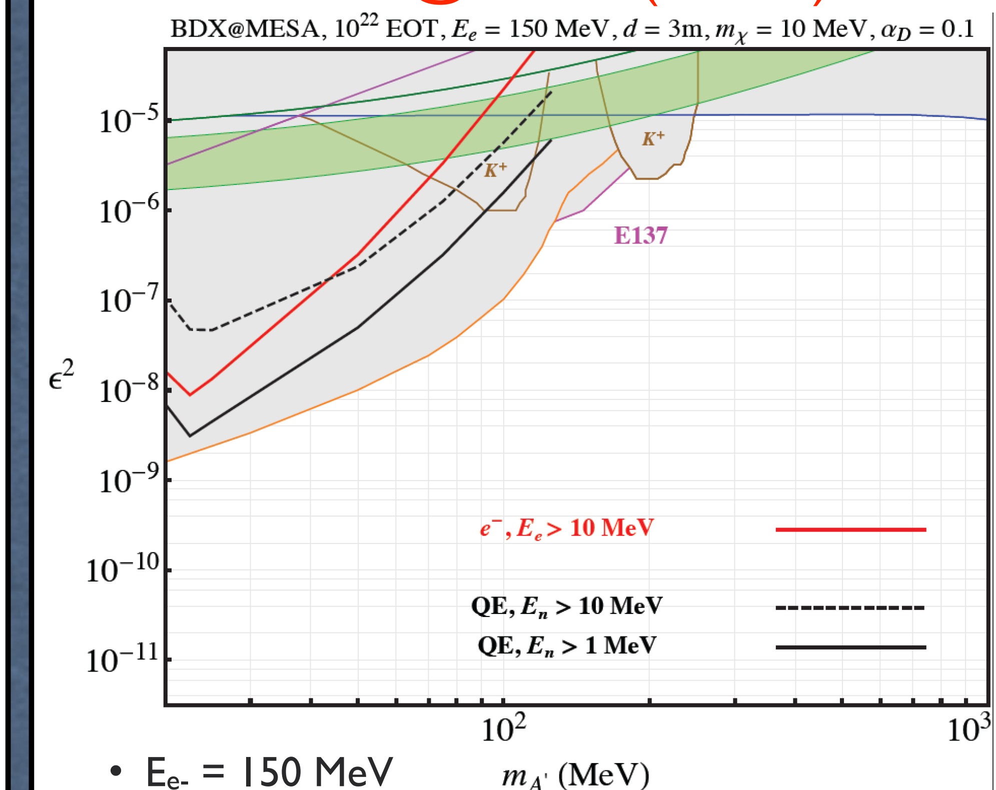
BDX @ LNF

- E_{e-} = 1.250 GeV (now 0.75GeV)
- EOT ~ 10^{20}-10^{21} $year^{-1}$ (now 10^{19})
- Pulsed beam 50Hz
- Minimal infrastructure costs

- Re-use of BaBar crystals (~1080)
- Detector: 60x60x225 cm3 at 5m from the dump
- 1y run (within PADME Experiment)
- 2-3y from now

P.Valente

BDX@Mainz (MESA)



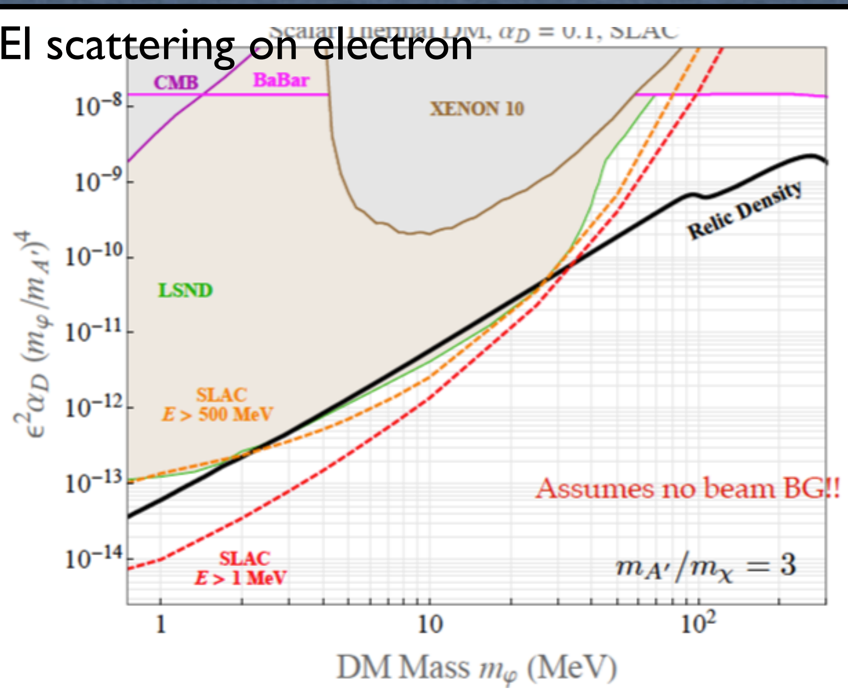
- E_{e-} = 150 MeV
- EOT ~ 10^{22}
- CW beam (3ns)
- Infrastructure costs limited
- Time line ?

- Re-use of BaBar crystals (~1080)
- Detector: 60x60x225 cm3 at 3m from the dump
- 3y run (parasitic to PV exp)

- Proposal accepted

A.Denig

El scattering on electron



BDX@SLAC LCLSII

- E_{e-} = 4 (8) GeV
- EOT ~ 3 10^{21}
- Pulsed beam ~1MHz
- Reduced cosmogenic bg
- Beam dump area clear
- Infrastructure costs limited
- May be some bg from the X-ray line
- Time line: 2020

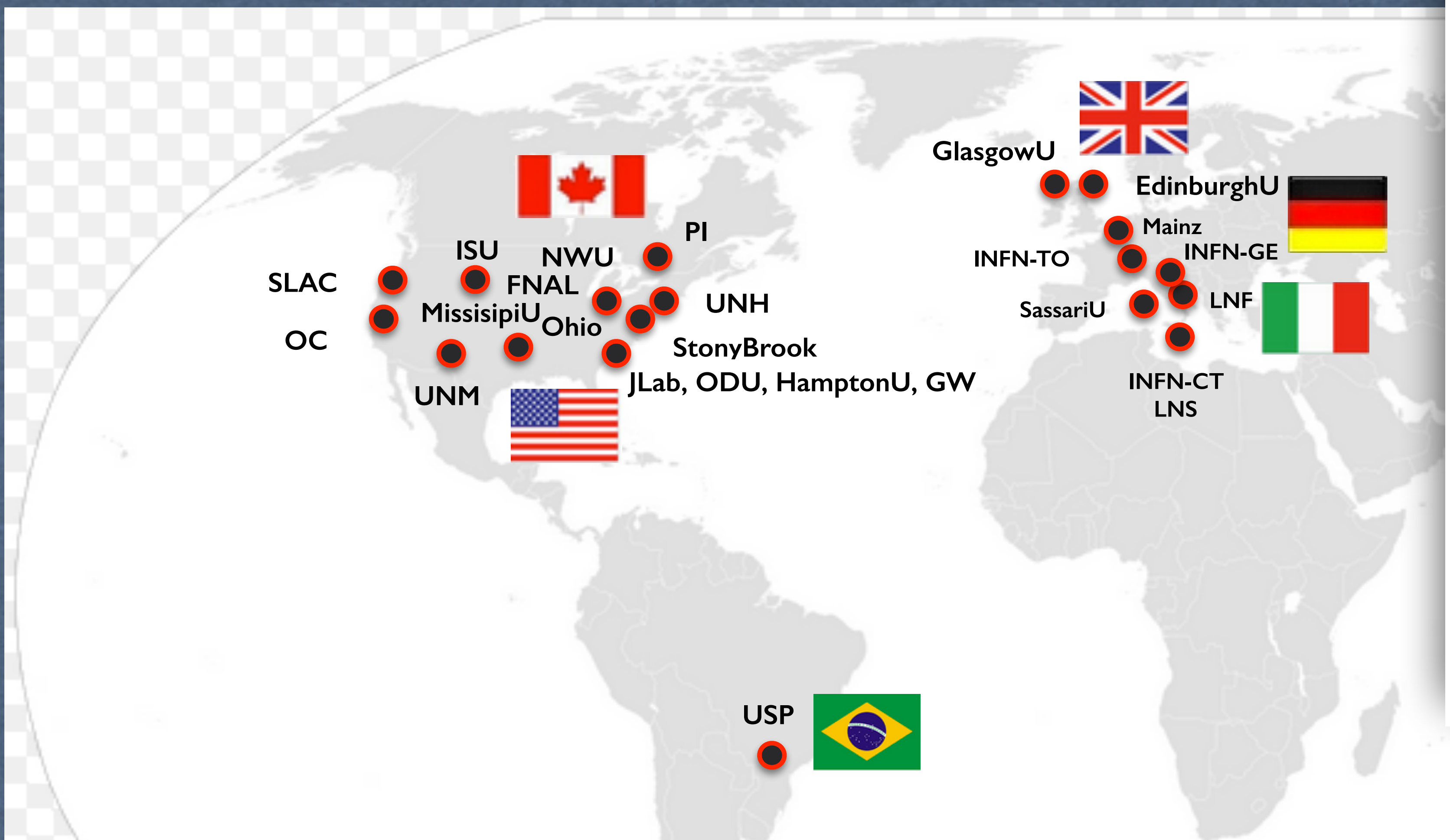
G.Krnjaic

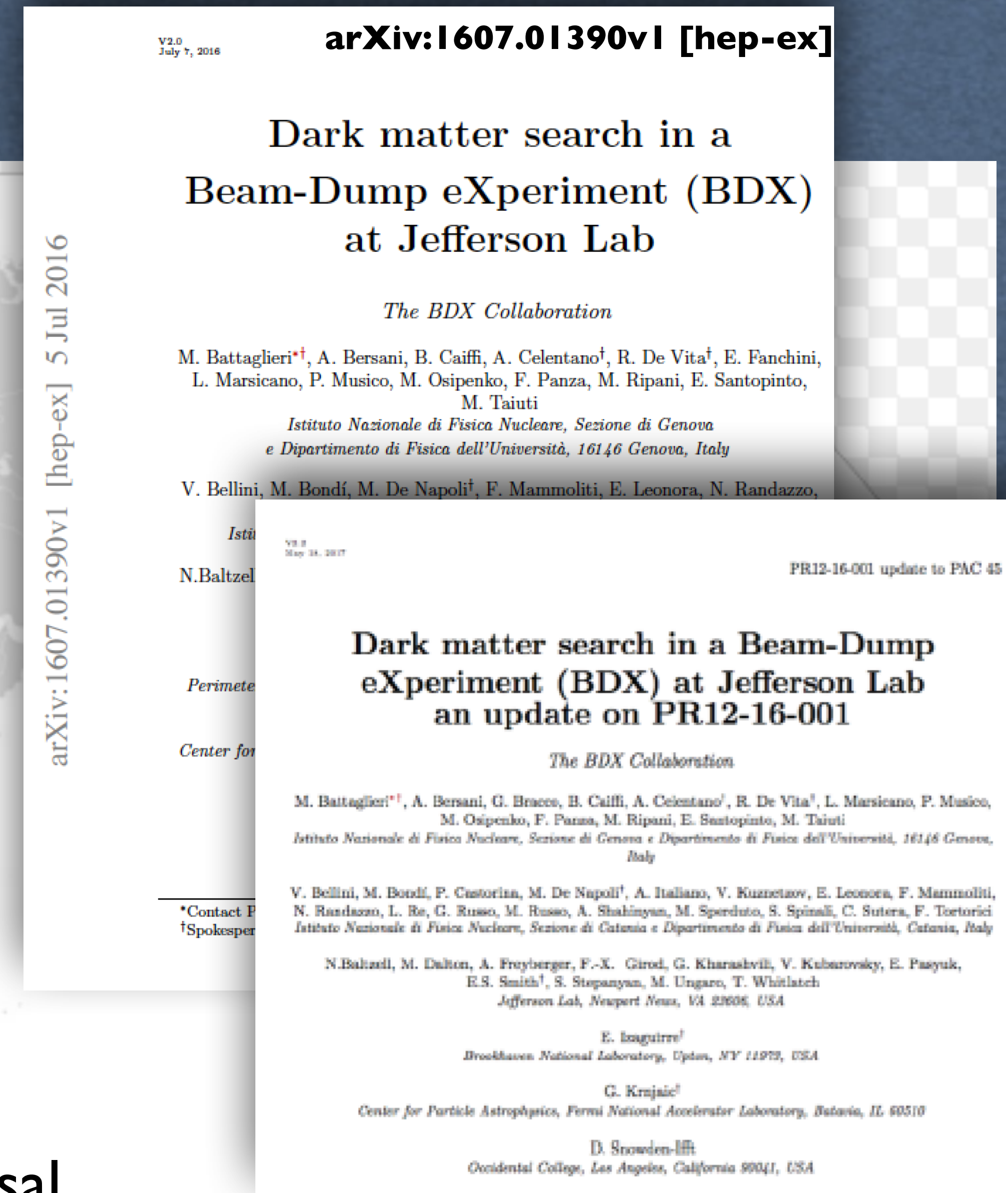
BDX@Cornell

- E_{e-} = 200 MeV
- EOT ~ 2.5 10^{22}
- Energy Recovery machine with extracted beam
- Some interest for a BDX-like experiment
- Time line: 2019

J.Alexander

The BDX Collaboration





V2.0
July 7, 2016

arXiv:1607.01390v1 [hep-ex]

arXiv:1607.01390v1 [hep-ex] 5 Jul 2016

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,

PR12-16-001 update to PAC 45

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab an update on PR12-16-001

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Istituto Nazionale di Fisica Nucleare, Sezione di Catania e Dipartimento di Fisica dell'Università, Catania, Italy

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

E. Izaguirre†
Brookhaven National Laboratory, Upton, NY 11973, USA

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

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

- More than 100 researchers signed the BDX proposal
- Connection with groups involved in similar projects at SLAC, CERN, Mainz and LNF
- Core group working on different aspects: physics, detector, simulations
- Weekly meeting to check progresses and share information
- Wiki page to store documents and meetings minutes
- Organisation of dedicated workshops and satellite meetings at major venues
- R&D funds from INFN and grant requests submitted

Conclusions

✳Existence of Dark Matter is a compelling reason to investigate new forces and matter over a broad range of mass

✳ Accelerator-based (Light)DM search provides unique feature of distinguish DM signal from any other cosmic anomalies or effects

✳Extensive experimental plans at high intensity e-facility: JLab, LNF, Cornell, Mainz, SLAC (+ p beam at FNAL and CERN)

✳ A detector based on CsI crystals + InnerVeto + Outer Veto running parasitically downstream of JLab Hall-A beam dump in 1y would set 10-100 times better limits

✳ A BDX prototype is currently taking cosmic data. Results have be used to validate MC simulations and cosmic bg estimates

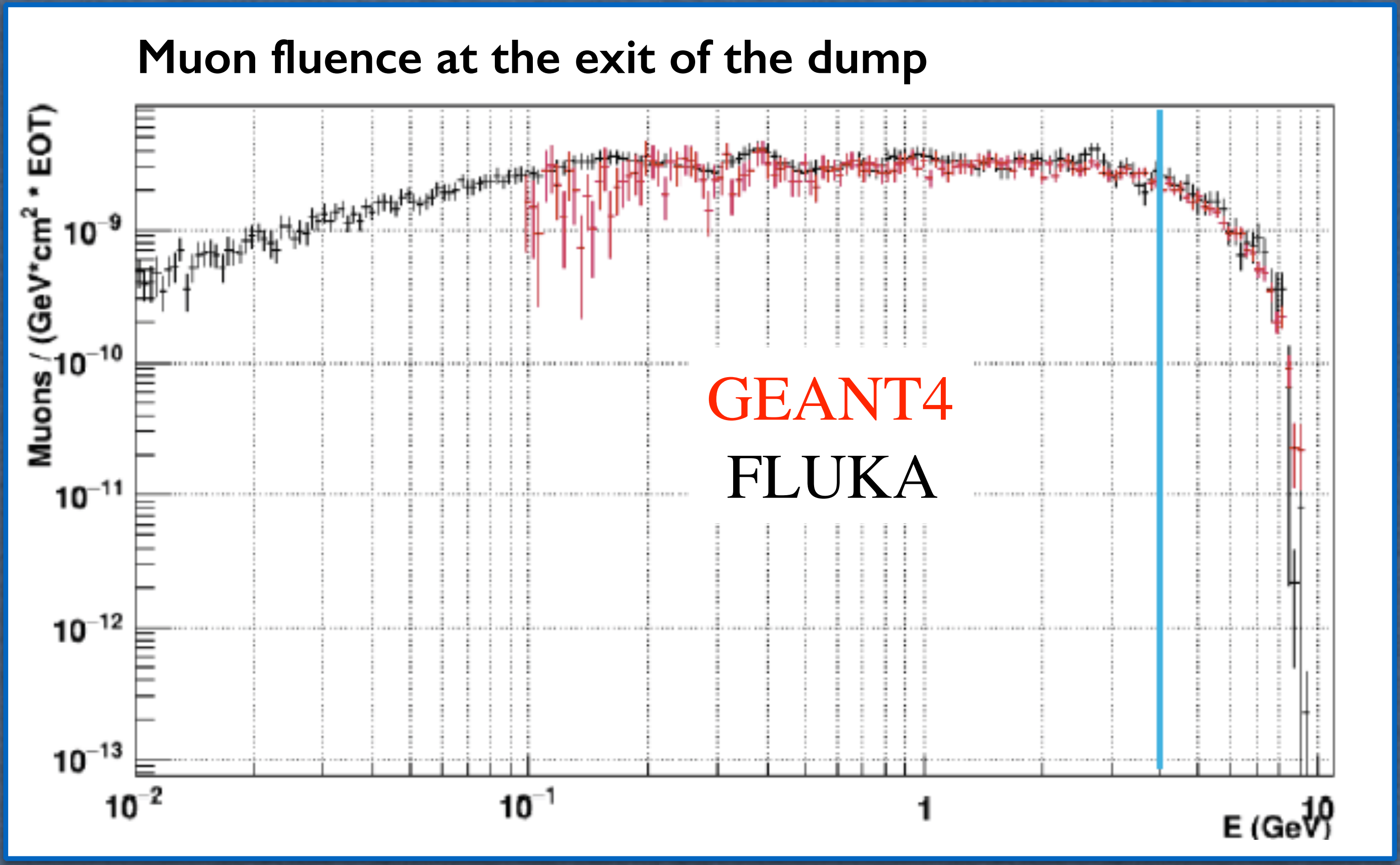
✳ A dedicated on-site test planned to validate MC projections for beam-on bg

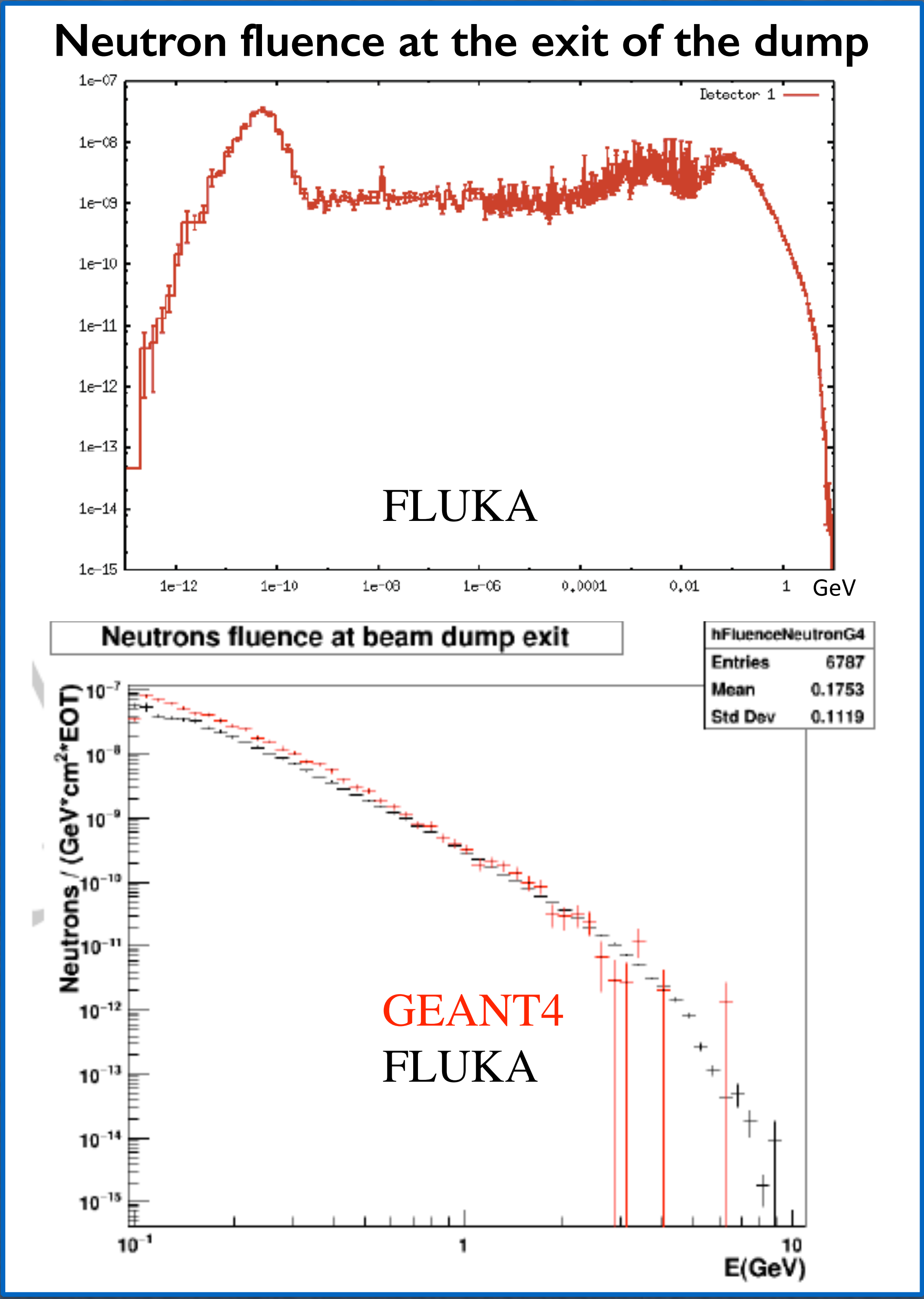
✳ Discovery or decisive tests of simplest scenarios will possible in the next ~5-8 years!

Backup

Beam / beam-dump interaction

- The 11 GeV beam interaction with the Hall-A beam dump has been studied using FLUKA and GEMC (GEANT4)
- Beam-dump geometry/material implemented in FLUKA by JLab RadCon Group imported in GEMC
- Surrounding material/geometry implemented in both FLUKA and GEMC
- All energies simulated in FLUKA; E>100 MeV in GEMC





- GEMC and FLUKA agrees (E>100MeV)
- FLUKA (weight biasing): better results in terms of statistics and run-time
- GEMC: 4-vectors of particles, easier to implement geometries and detector response

In this study we used both!

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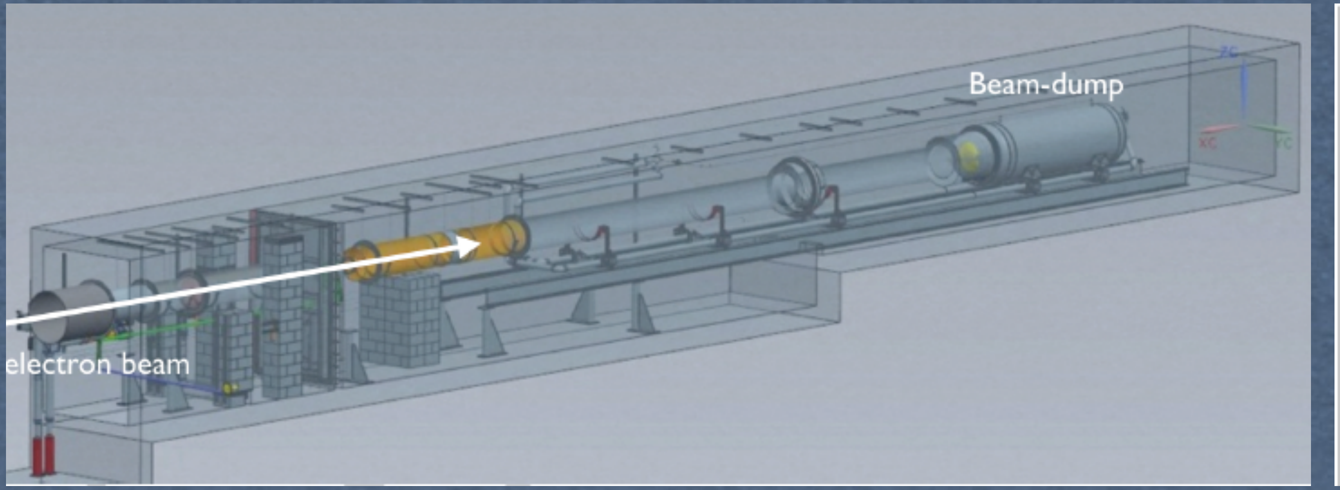
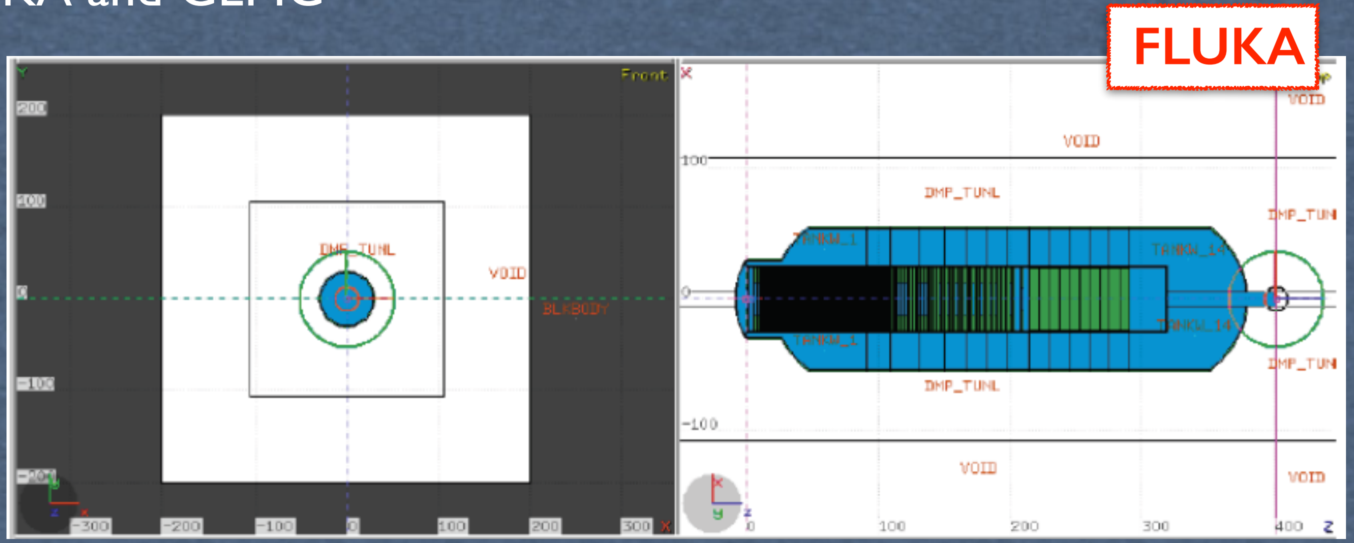
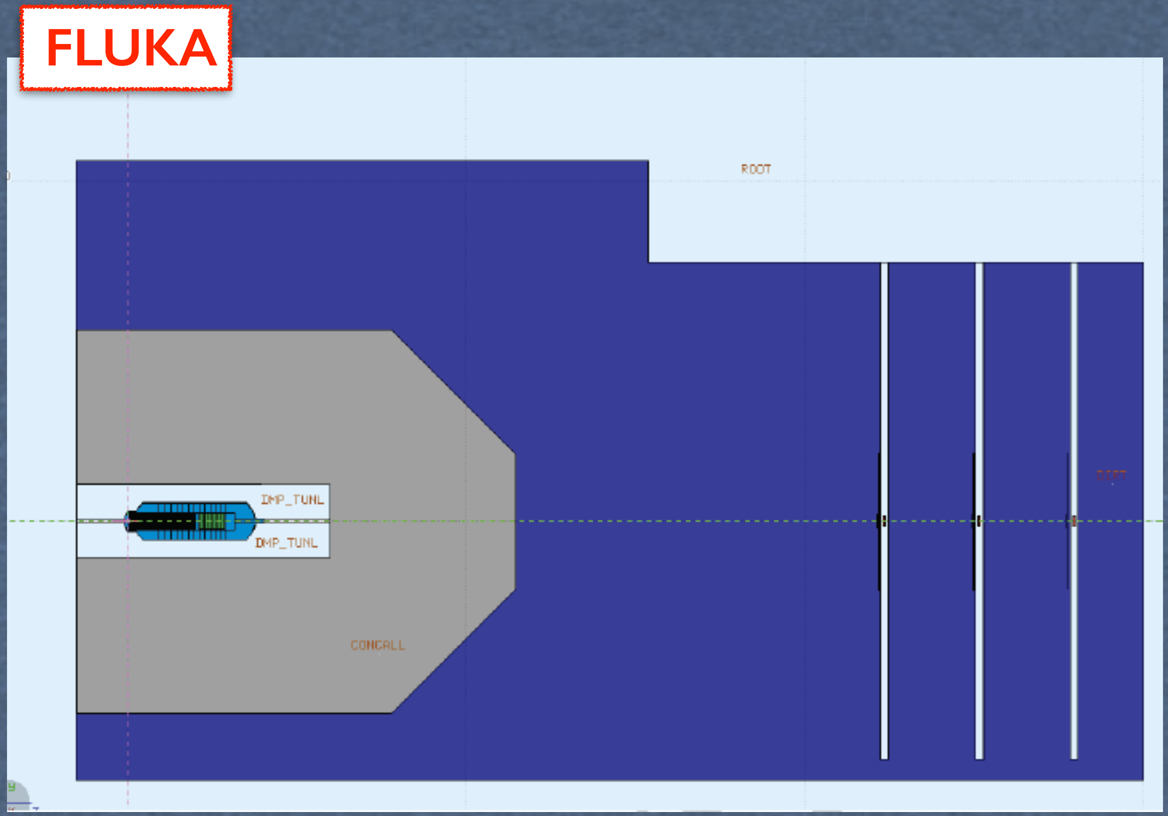
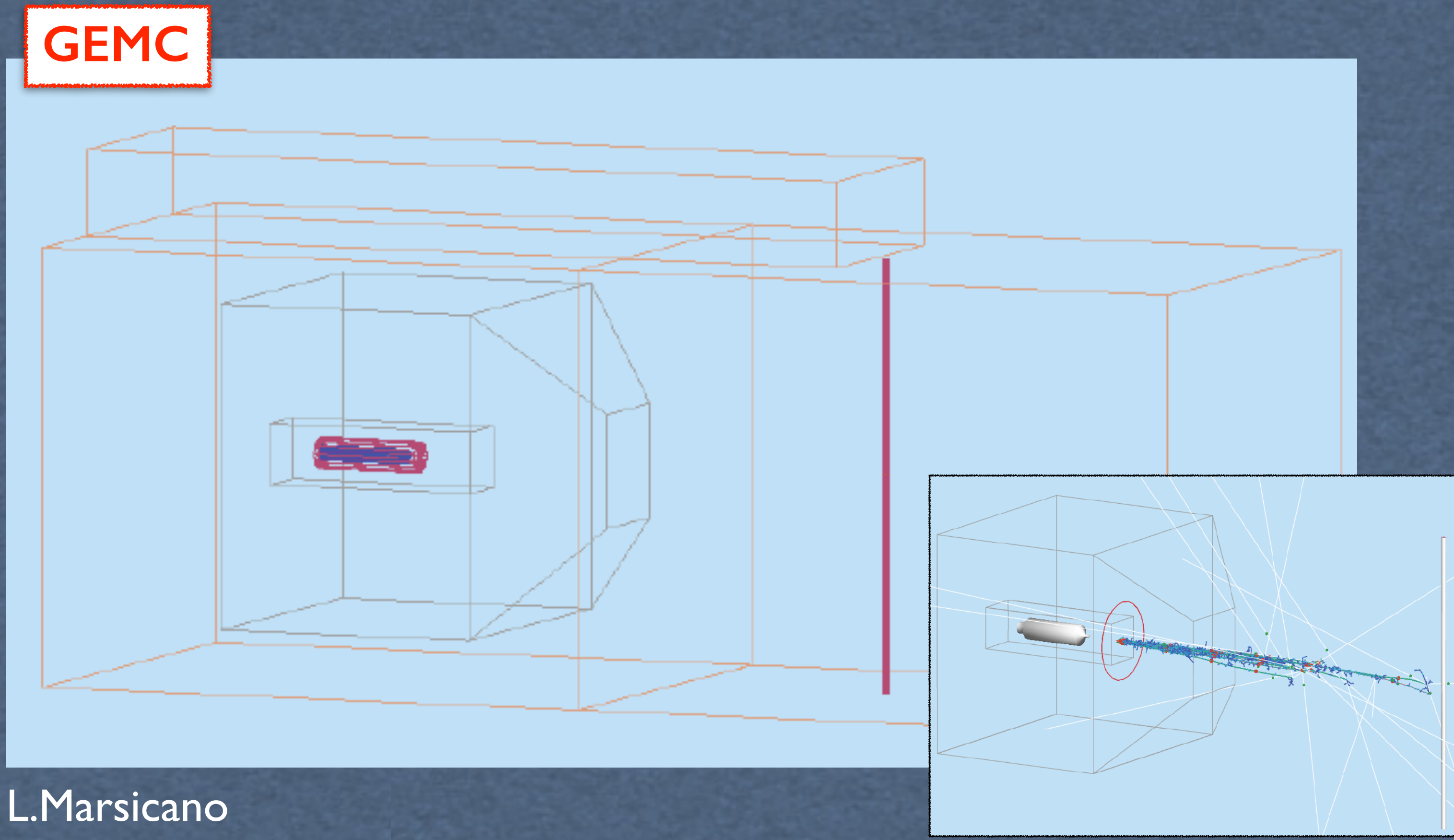




G.Kharashvili



A.Celentano



L.Marsicano

BDX Read-Out electronic scheme

BDX DAQ will be based on fADCs

- CsI(Tl) decay time & low thresholds are incompatible with "traditional" (TDC+QDC)-based DAQ
- Full waveform recording: reduce backgrounds and allow detailed off-line analysis
- Expected 16 MB/s data rate

16MB/s = 5Hz x 1000 crystals x 2048samples x 12 bit

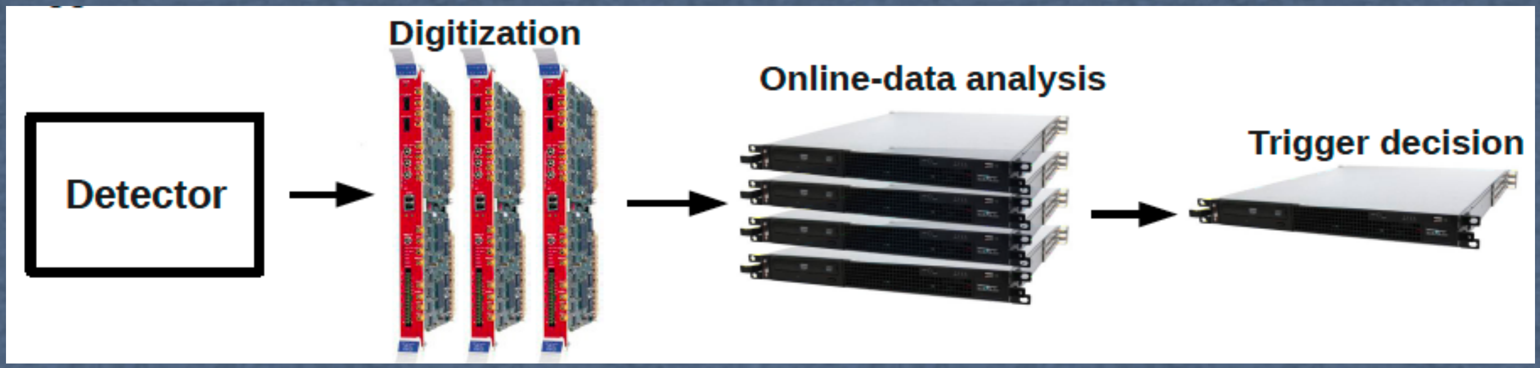
Different options under investigation:

1) Triggered - commercial

- trigger formed as OR of all crystals over thresholds (OVT)
- when trigger is released every channel with a signal in 10us window is recorded
- The simplest option (boards already available: e.g. CAEN V1725 or JLAB fa250) but expensive!

2) Trigger-less - commercial

- trigger-less system, based on existing fADC + Trigger Boards (e.g. JLab fADCs and VTP boards)
- Pipe-line data transferred to a central trigger CPU and then moved to
- Requires ad-hoc firmware and software development
- Not clear if cheaper than 1) but may be more matched on BDX requirements



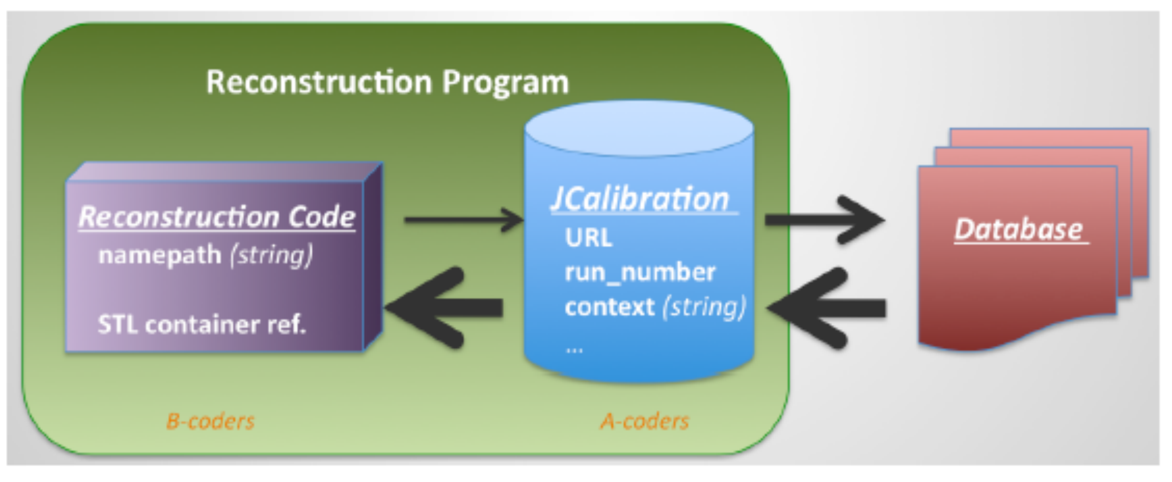
3) Trigger-less - custom

- trigger-less, based on a custom DAQ: single-channels digitizers, integrated in the front-end electronic
- Sophisticated solution matched to the experimental setup
- Requires ad-hoc hardware, firmware, and software development
- Similar approach used in other experiments (KM3, PANDA)
- May benefit of technology/solutions sharing with reduced costs

BDX data analysis and computing resources

Requirements for data analysis:

- Modularity
- Support for multiple event sources: EVIO file / ET-ring
- State-of-the art computer-science tools: parallel computing, plugins support
- Easily interface with other common tools: ROOT, GEMC



BDX solution:
the JANA framework
(D. Lawrence, https://www.jlab.org/JANA)

BDX event reconstruction:

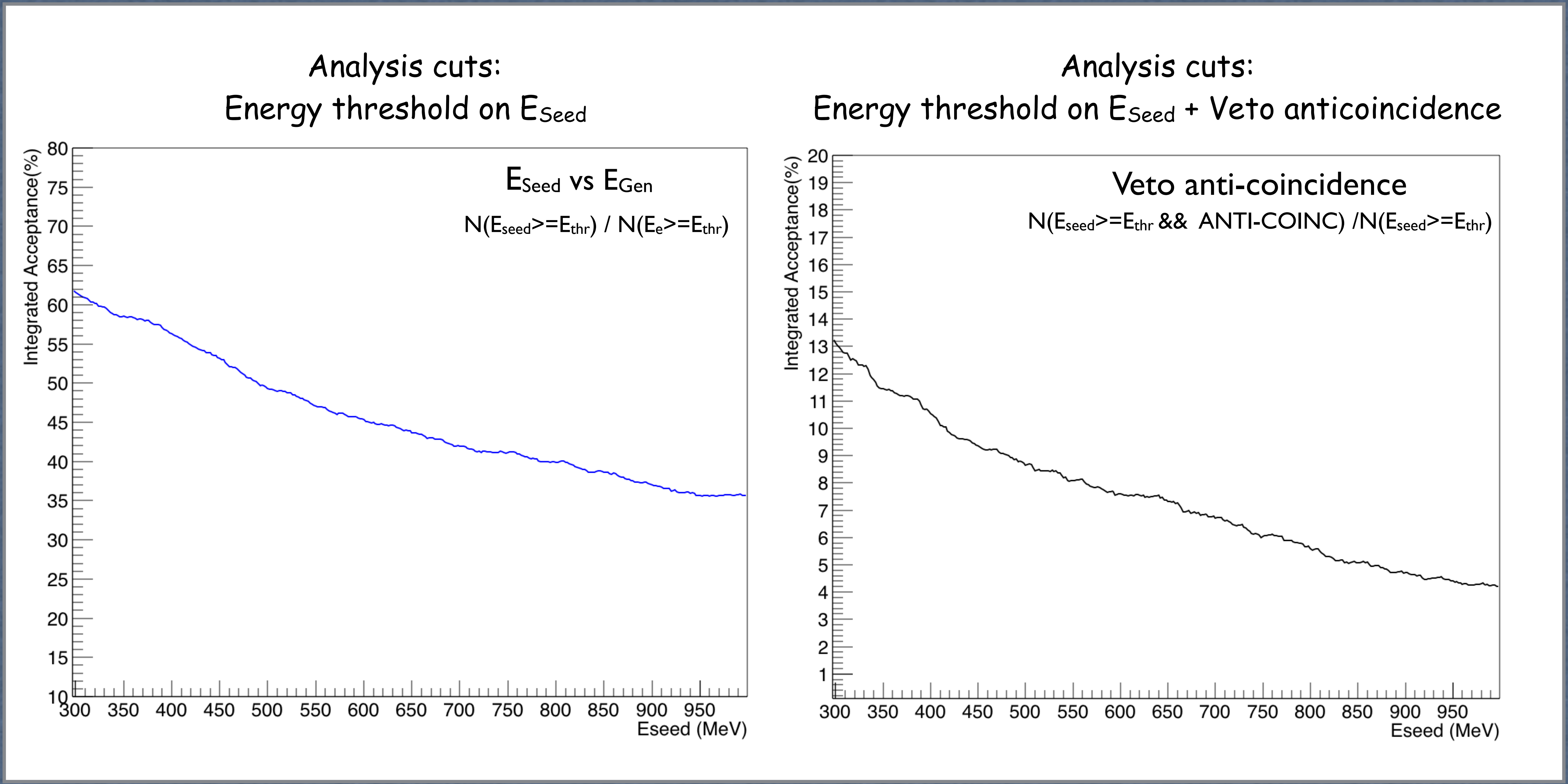
- identify events with above-threshold energy deposition in the calorimeter, with no activity in the veto systems
- For these "signal-like" events need to perform an intense scrutiny, by possibly looking at the raw information (waveforms)
- Different signal topologies may require different selection strategies

Strategy:
Event reconstruction and analysis with different, interchangeable, plugins (i.e. pieces of codes that can be activated on-demand when reconstruction starts)

Computing resources:

- data rate: 5kHz (single crystal trigger with low thr)
- 600TB storage: 400TB for 20% raw data w/o filtering + 100TB for 80% raw data with filtering + 100 TB reconstructed data and MC
- 6M CPU's hours: 10^{11} EOT simulated (10 sets of simulated data with different parameters) in next 5-7 years

BDX acceptance



X detection studies performed as a function of the em shower seed energy (crystal with the maximum energy deposited) to be consistent with the BDX prototype cosmogenic measurement