Proposal to Jefferson Lab PAC44
July 25 2016

BDX
Dark Matter search in a Beam Dump eXperiment

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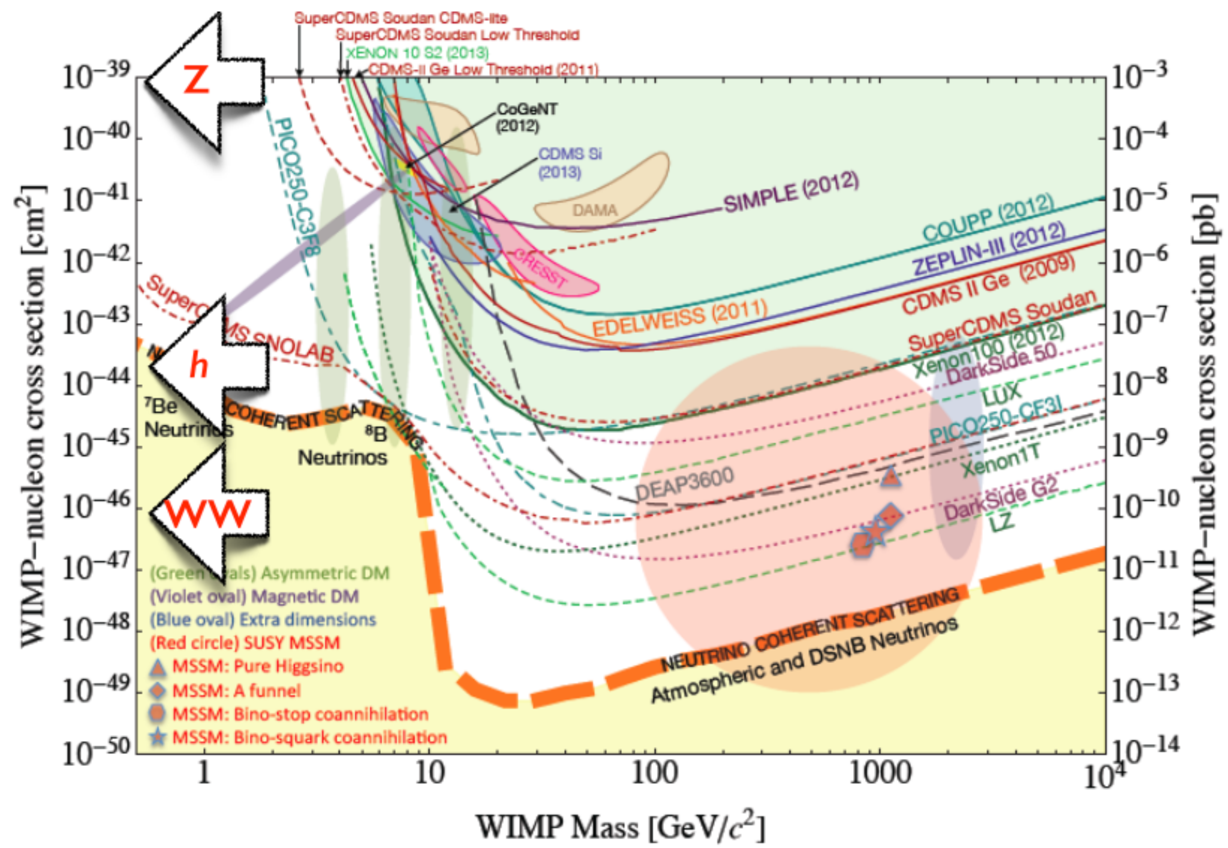
and the BDX Collaboration

★ Physics motivations
★ Proposed experimental setup
★ Background and signal rates
★ Beam time request and expected reach

Hunting Dark Matter

Limits on DM_{Xsec} vs DM_{Mass} from Direct Detection

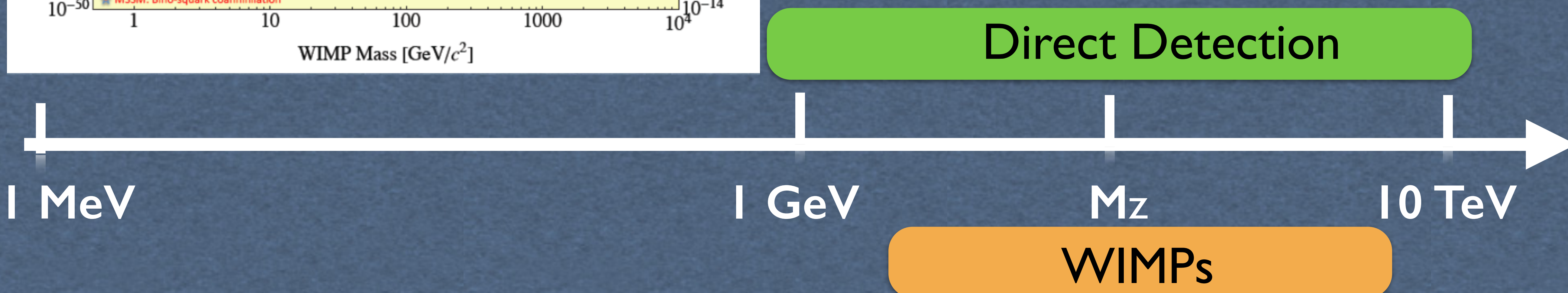


Compelling astrophysical indications of DM existence

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

The WIMPs paradigm:
- slow-moving cosmological Weakly Interacting Massive Particles interacting with the SM-Weak force
- DM detection by nuclear recoil
- Experiments optimised for heavy DM (M>10 GeV)

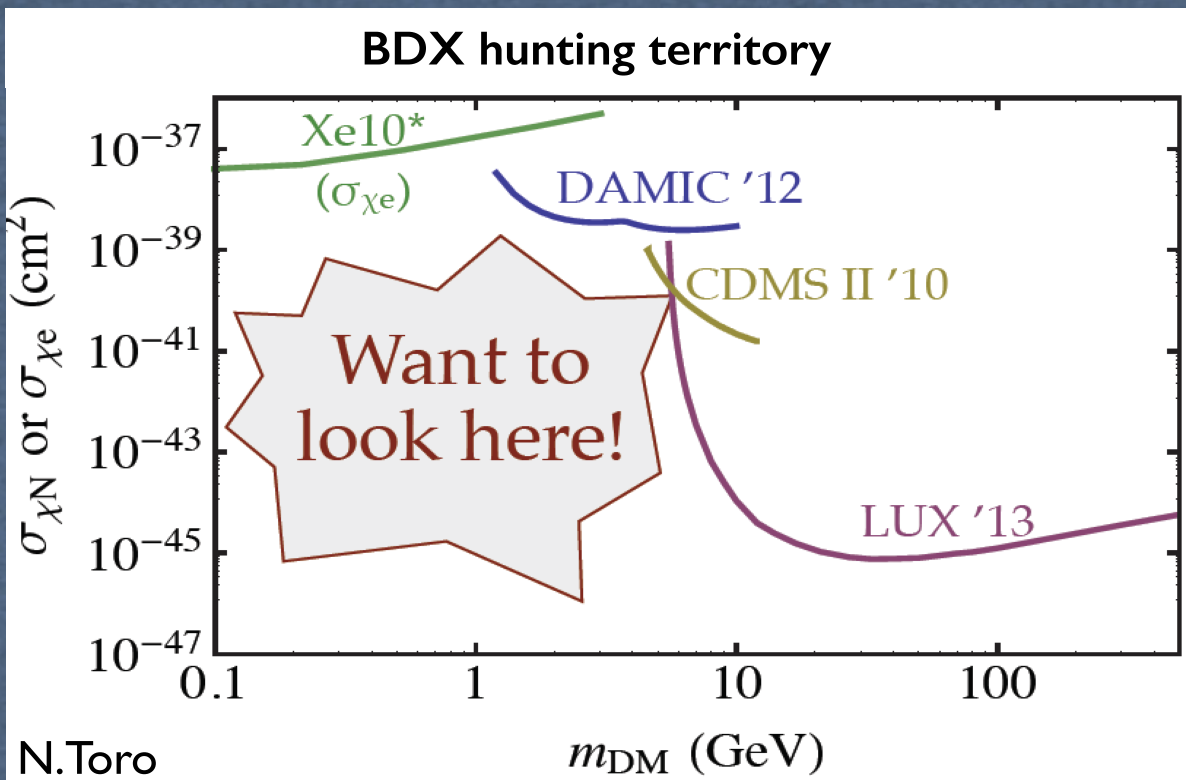
Null signal (so far)
- weak-interaction at tree level ruled-out
- exp limits close to irreducible neutrino background



WIMPs paradigm is not the only theoretically well-motivated option

Light DM: extending the search to unconventional (and unexplored!) territory

Hunting dark matter: Light DM



Dark/Hidden Sector

Light Dark Matter couples to SM with a new force

- Light Dark Matter (X) in 1-1000 MeV mass range
- New vector boson (A') responsible for DM-DM and DM-SM interaction
- (Traditional) Direct Detection is (almost) impossible

Accelerator-based DM search

- High intensity
- Moderate energy

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

BDX-Beam Dump eXperiment | Direct Detection

1 MeV — 1 GeV — Mz — 10 TeV

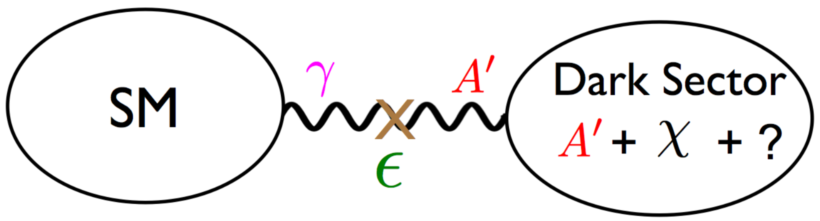
Light Dark Matter | WIMPs

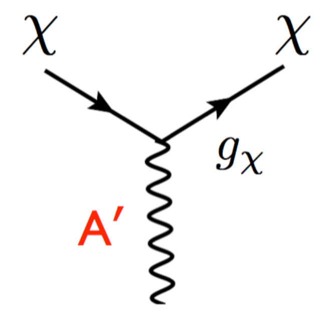
Dark Sector or Hidden Sector
DM not directly charged under SM interactions

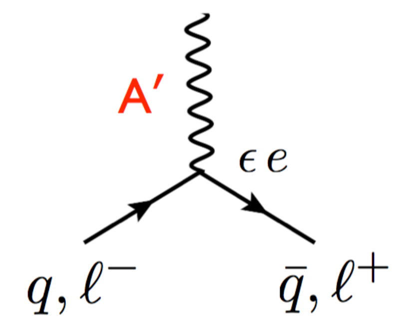
Can be explored at JLab!

Dark forces and dark matter

(Light DM - light mediators)



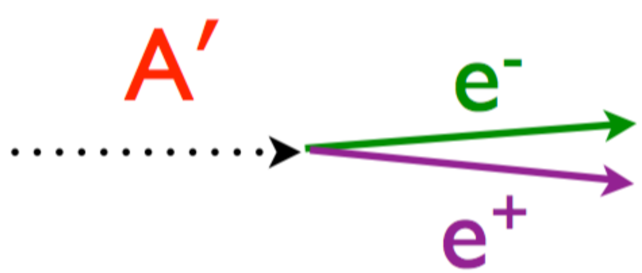




4 parameters: m_χ, $m_{A'}$, ε, α_D

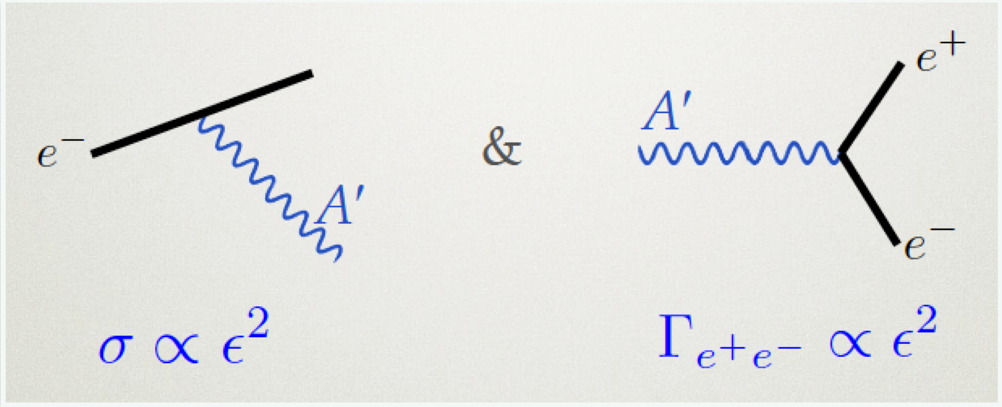
m_χ, ~ $m_{A'}$: MeV - GeV

Visible

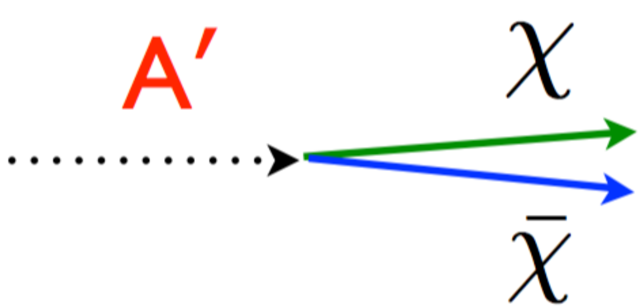


- *Minimal* decay
- Decay regulated by ε^2
- Independent of m_χ
- Requires $m_{A'}<2m_\chi$ (on-shell)

APEX, HPS, DARK LIGHT

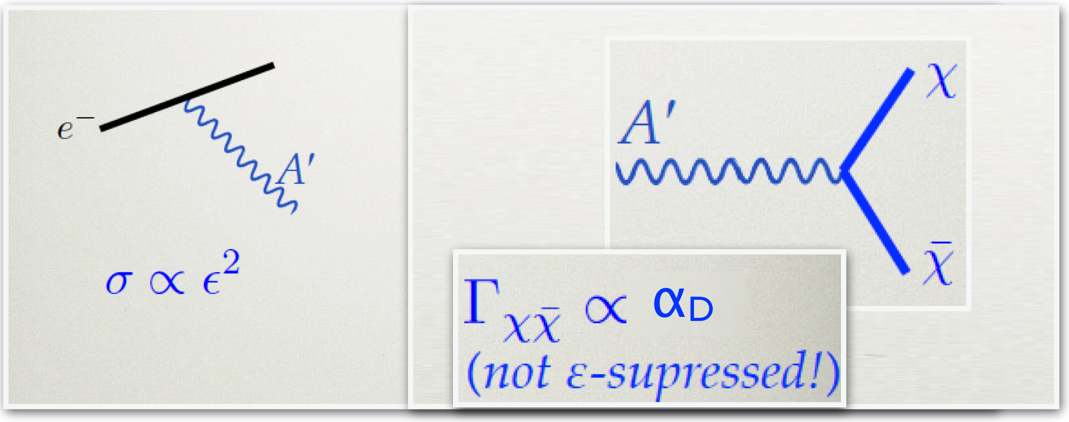


Invisible



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

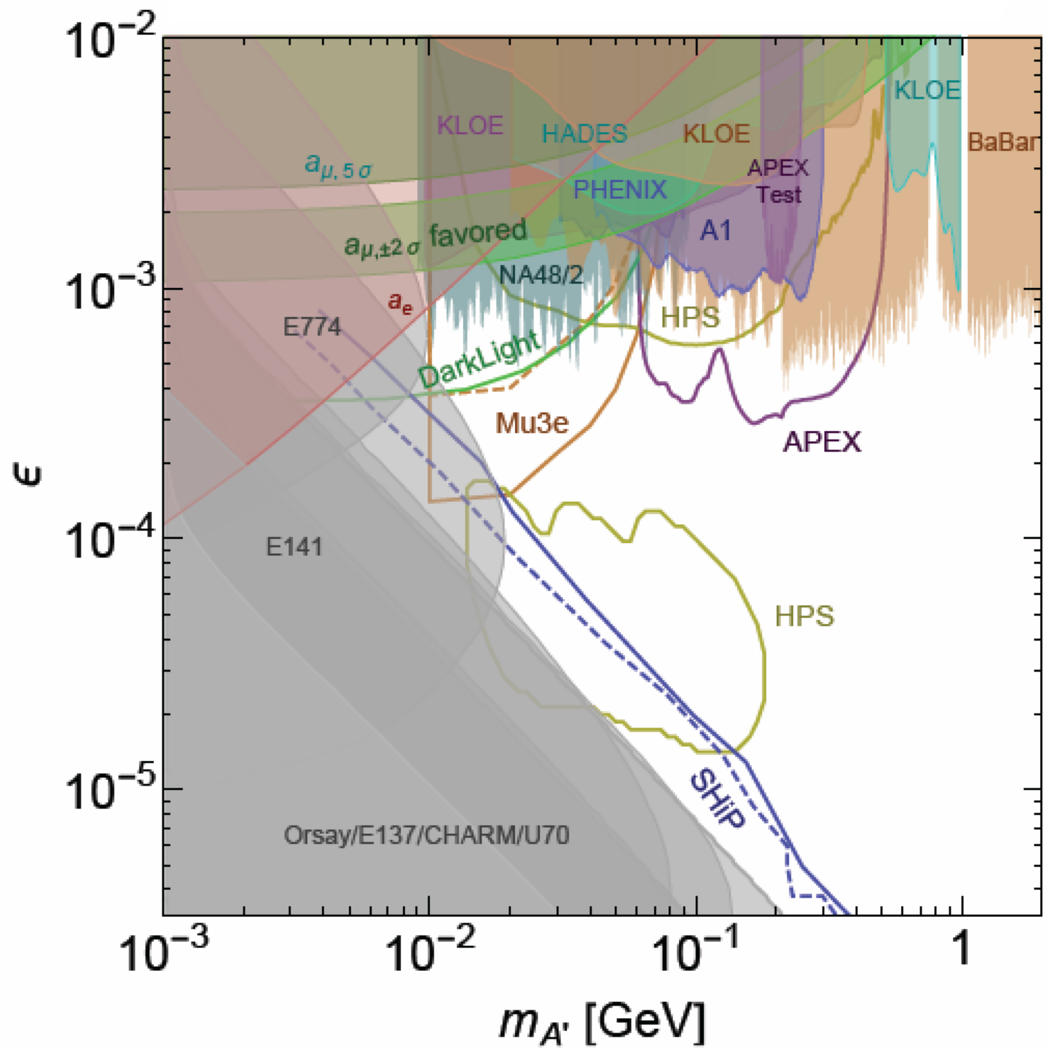
DARK LIGHT



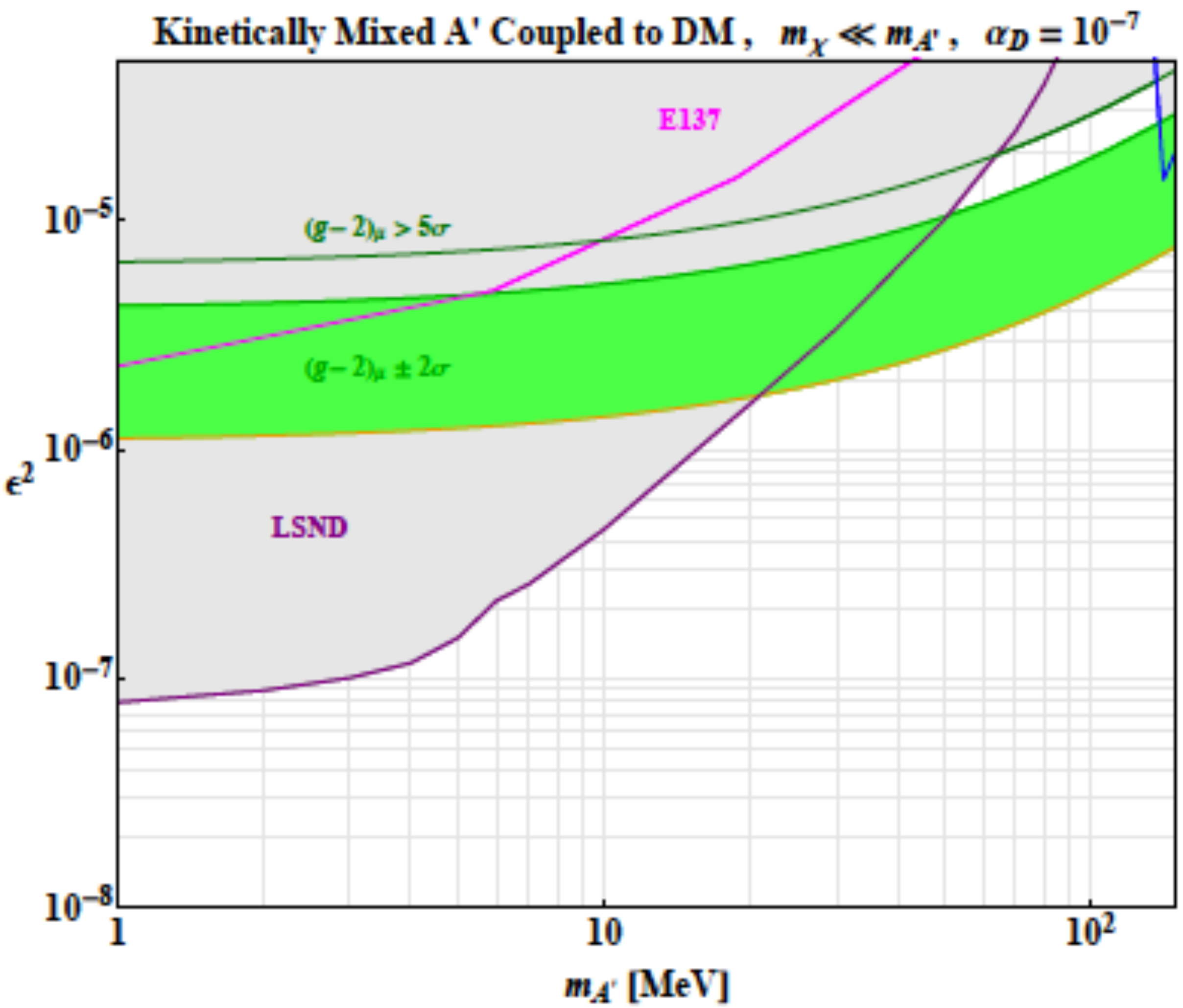
BDX is searching for the A' invisible decay to Light Dark Matter

Visible vs Invisible: complementarity

Visible decay



Invisible decay



Exclusion limits are model dependent: if invisible decay is included limits do not hold!

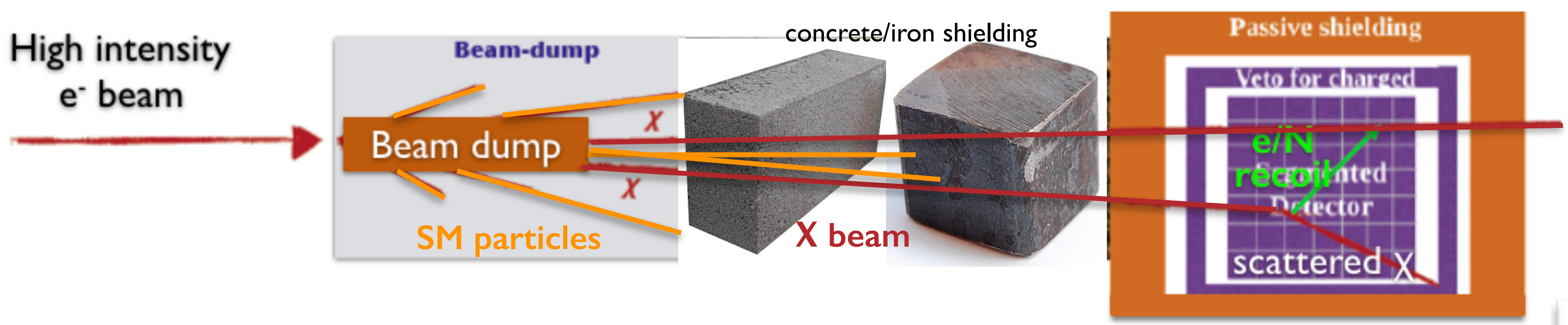
The BDX experiment

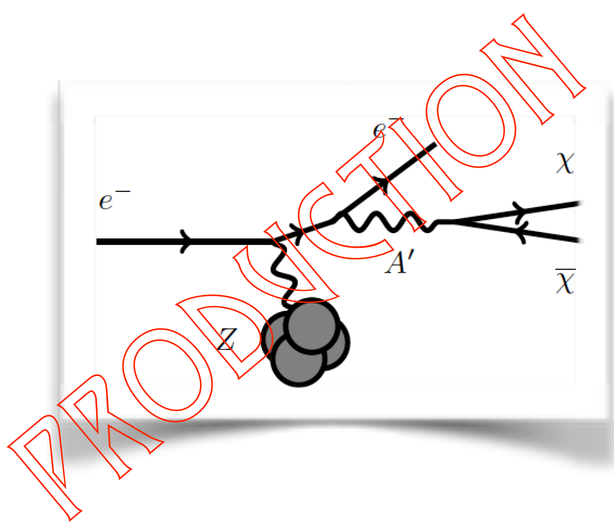
Two step process

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



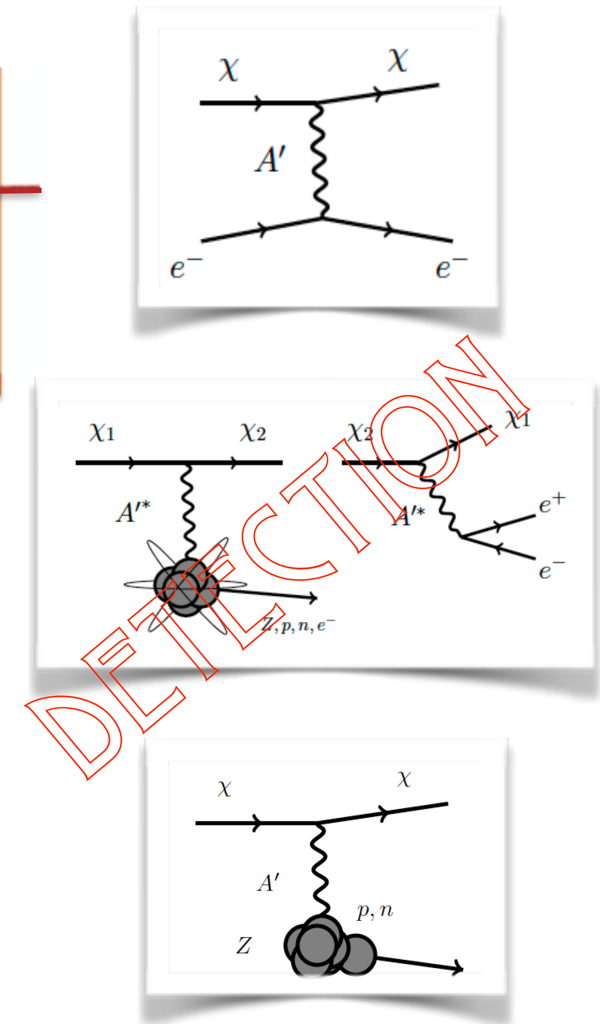


A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

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

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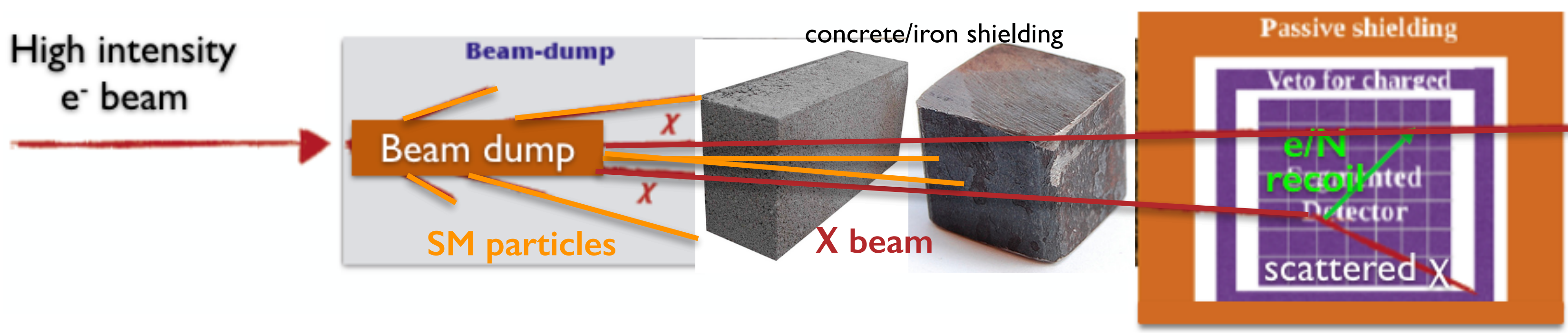

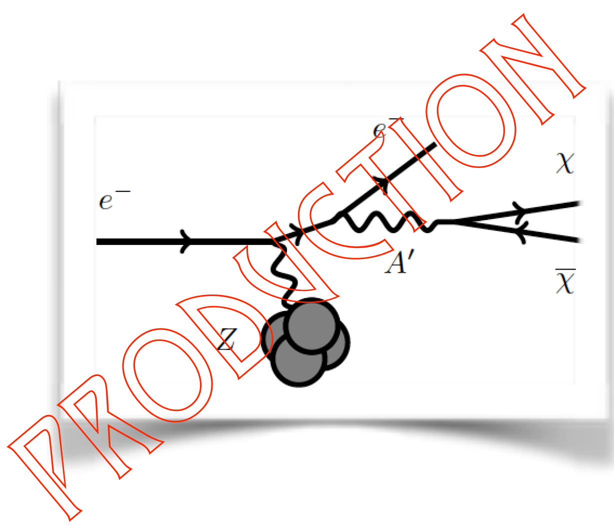

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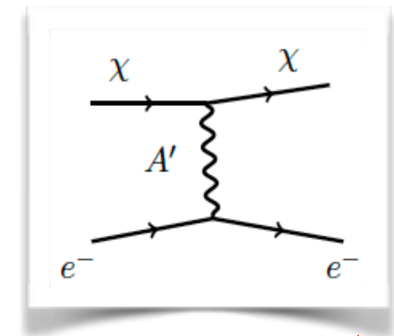
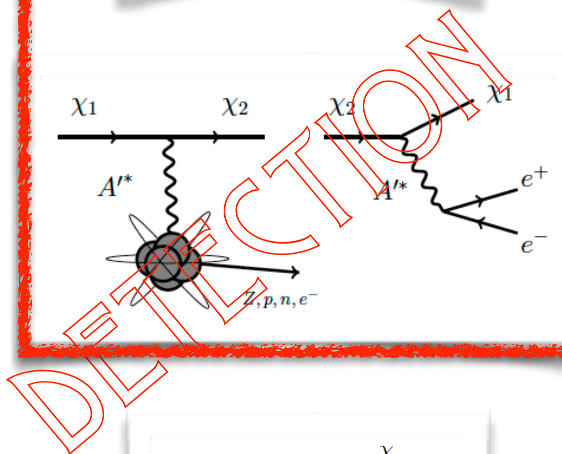
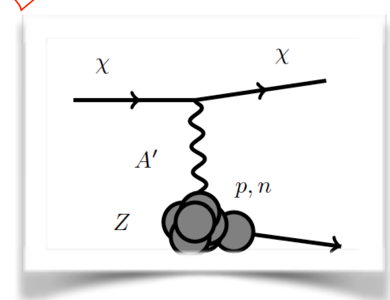


Elastic on electrons



Inelastic on nuclei



Elastic on nuclei

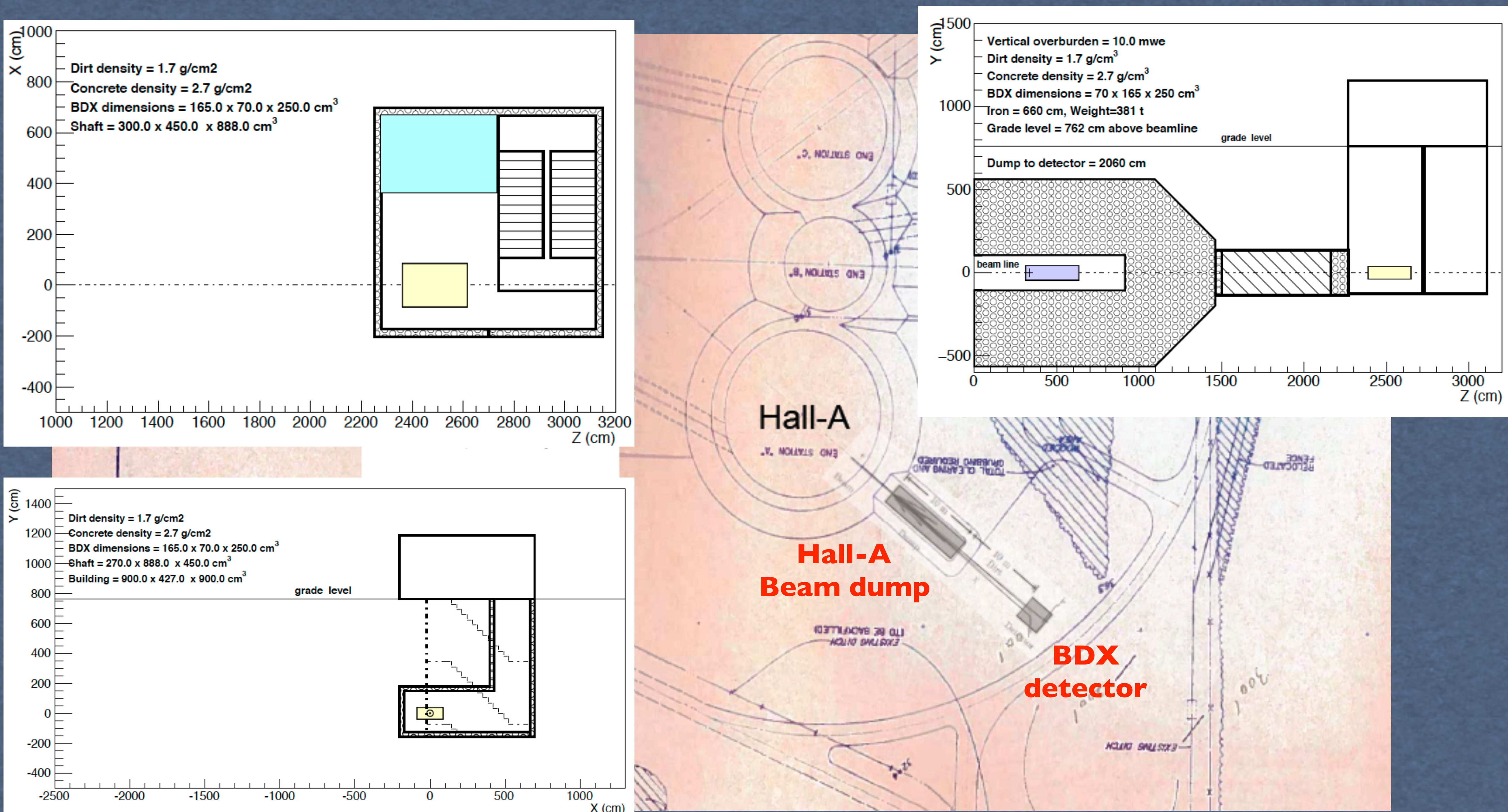
BDX@JLab

Experimental signature at JLab : 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)

BDX behind the JLab Hall-A

- ★ The highest available electron beam current: ~65 uA
- ★ The highest integrated charge: 10^{22} EOT (41 weeks)
- ★ High energy beam available: 11 GeV
- ★ BDX detector located downstream of Hall-A BD
- ★ New underground experimental hall
- ★ Realistic cost estimate: ~ $1.5M



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

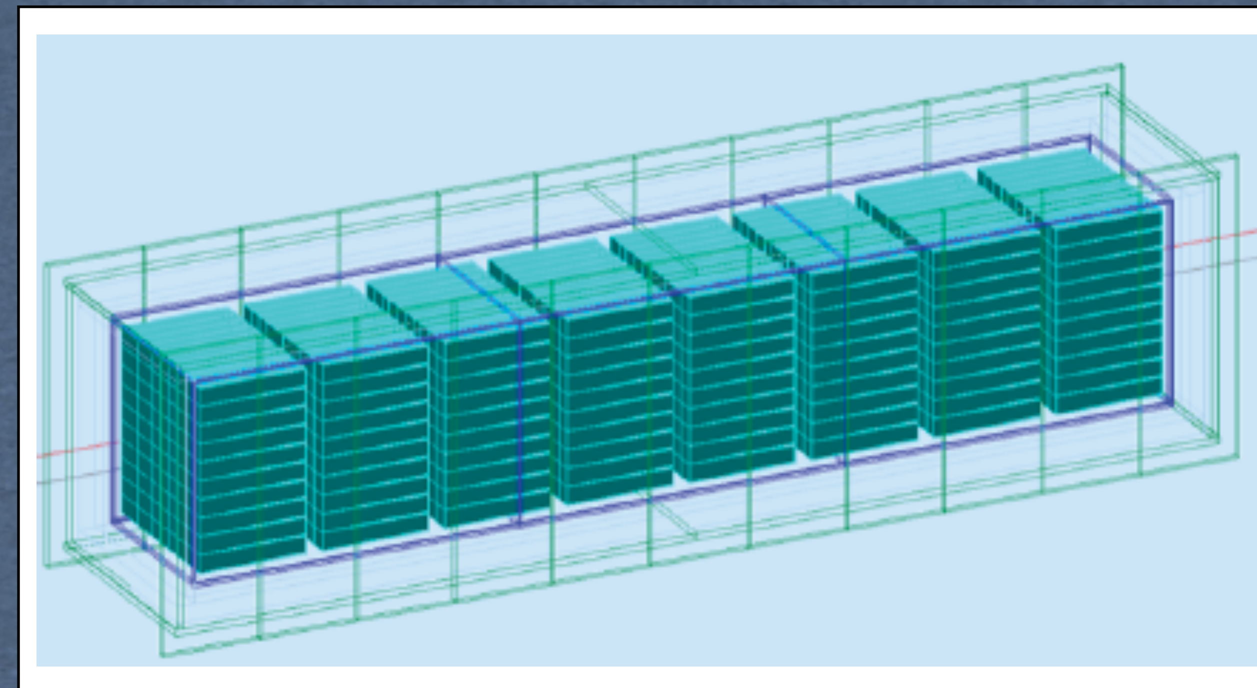
Active veto

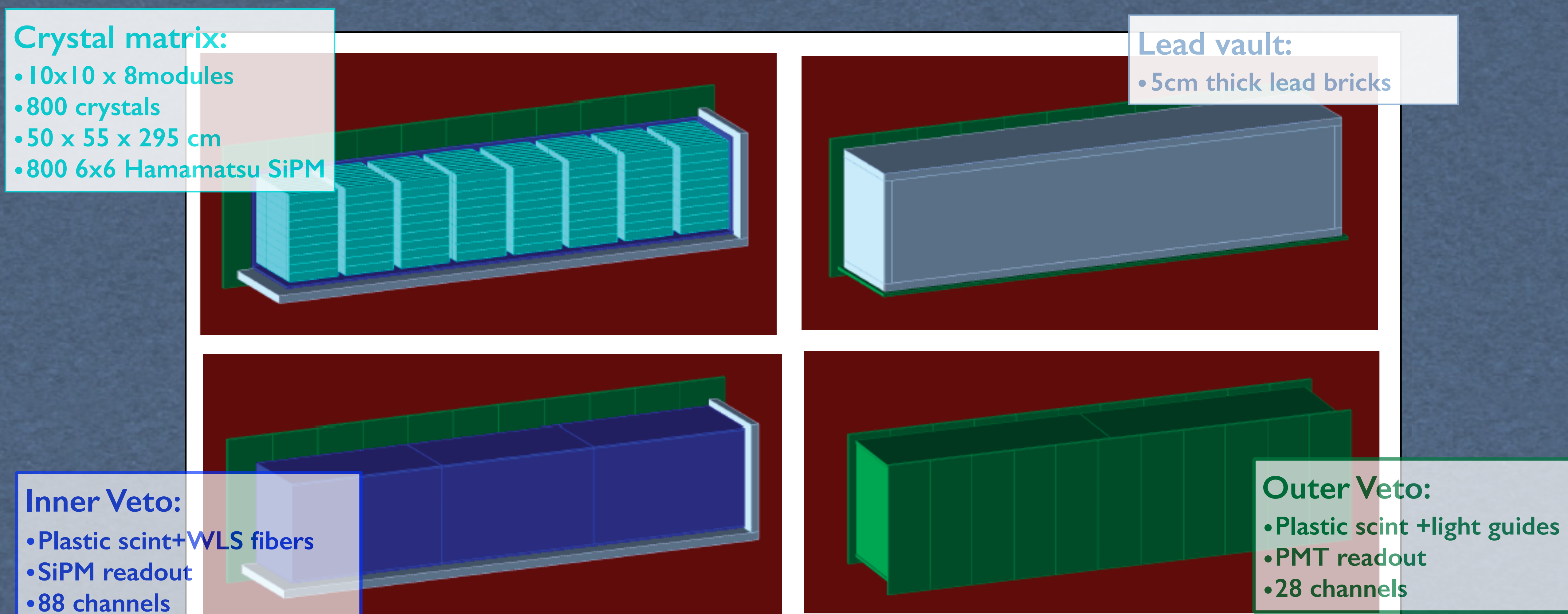
↓

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

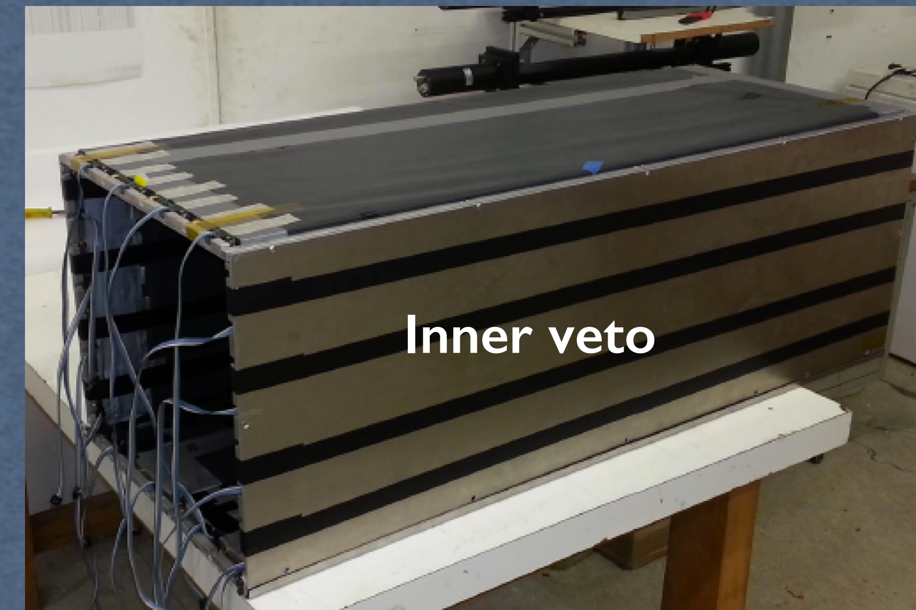
The BDX detector

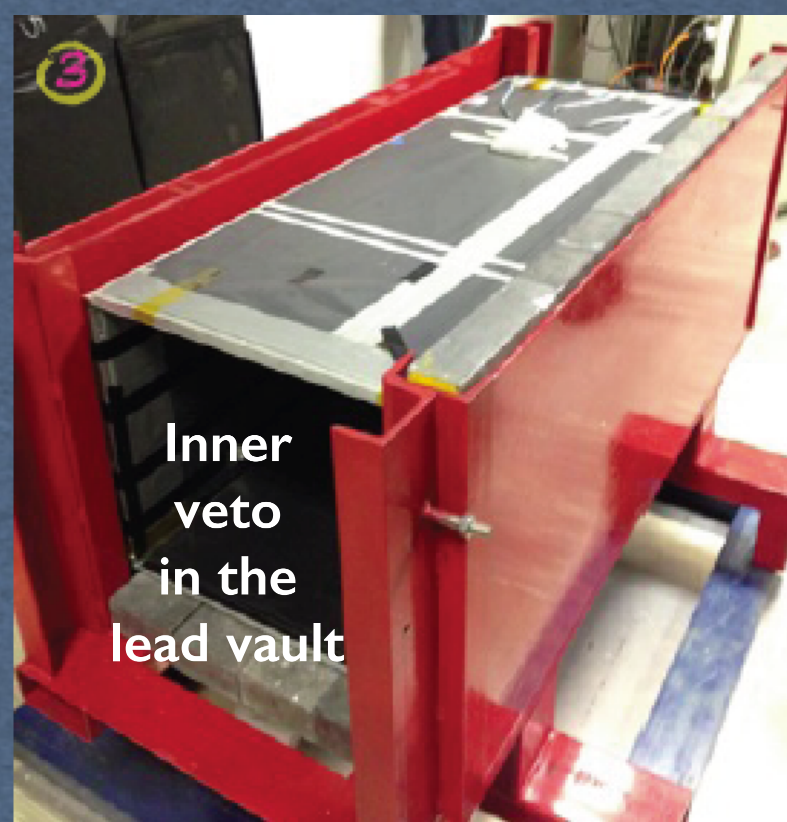
- ★ Modular EM calorimeter: 8 modules 10x10 crystals each
- ★ 800 CsI(Tl) crystals (former BaBar EMCal) + SiPM readout
- ★ Inner Veto: plastic scintillator + WLS + SiPM
- ★ Outer Veto: plastic scintillator + PMTs
- ★ Passive shielding: lead vault





The BDX prototype



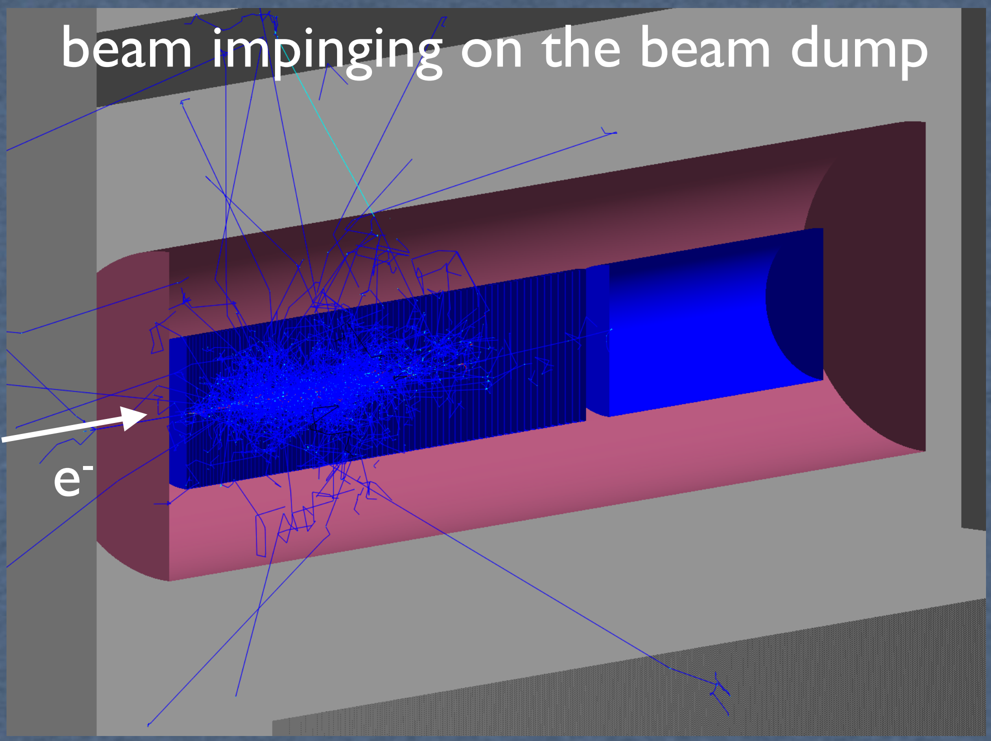


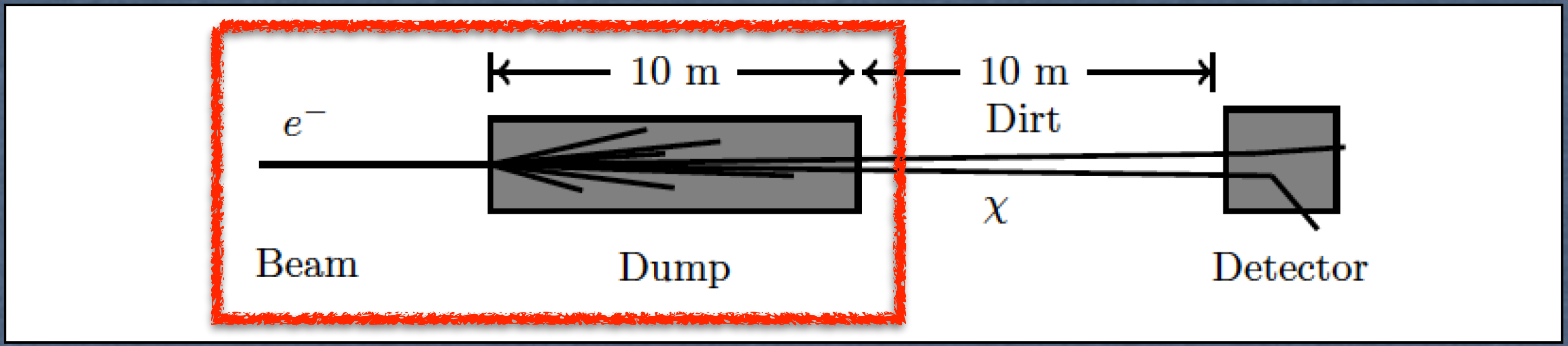
BDX-proto

EM Cal
CsI(Tl) crystal(s)
3x3/6x6 mm^2 SiPM

- Outer Veto
- Lead vault
- Inner Veto

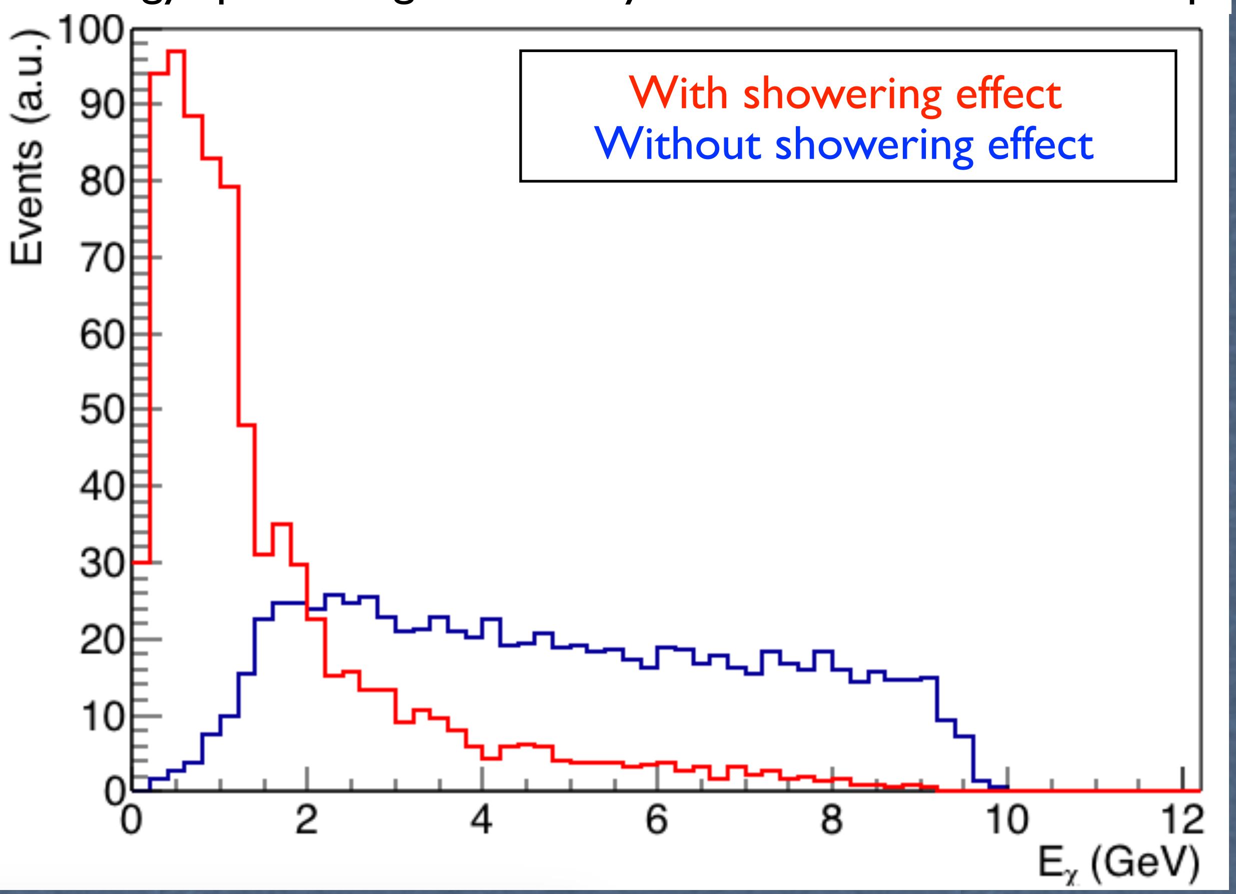
X production in the BD





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

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



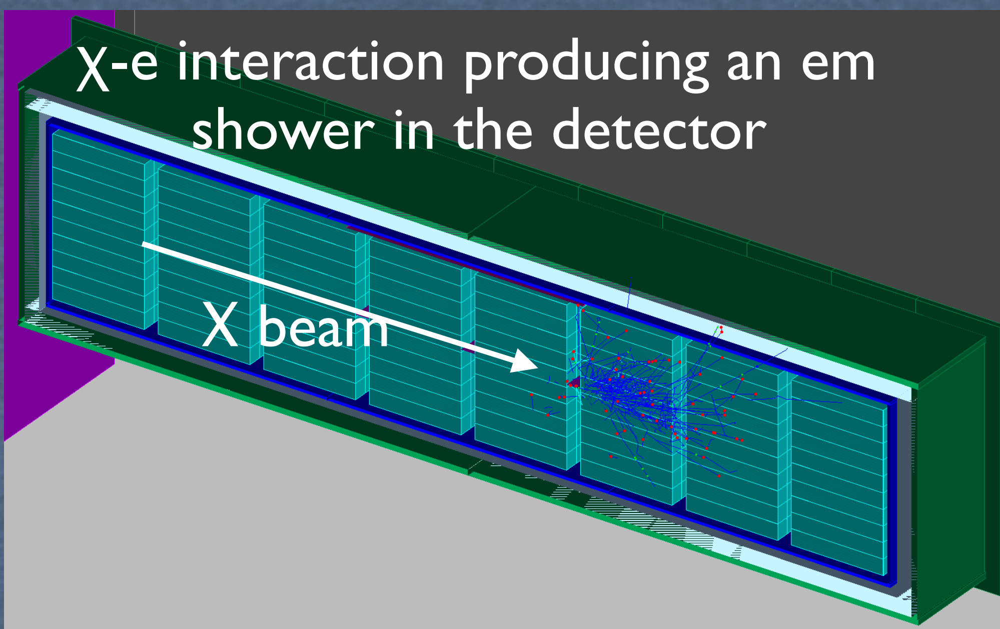
The em shower in the dump was neglected in previous works

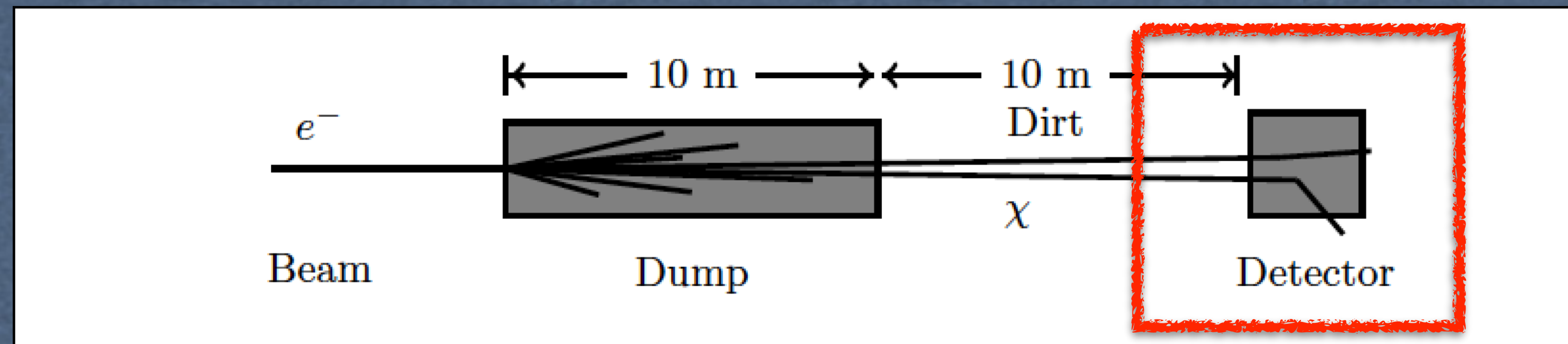
Significant effect on energy distribution and X production angle

JLab kinematics

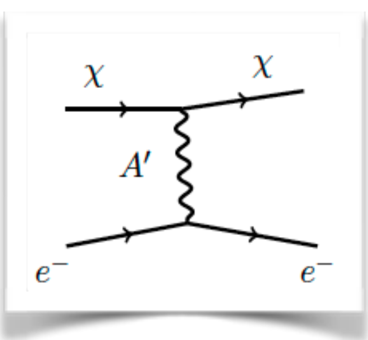
- X beam softer (significant)
- X beam defocused (less important)
- X beam intensity almost untouched

X detection in the BDX detector

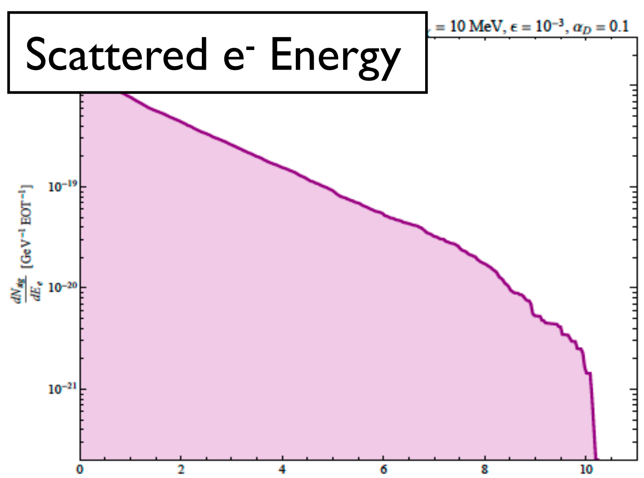


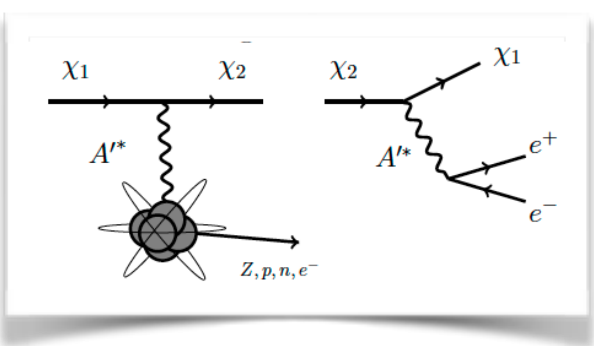


- GEANT4 simulations of X-e and X-N interaction
- Detection efficiency derived as a function of the energy threshold included in all BDX reach estimates

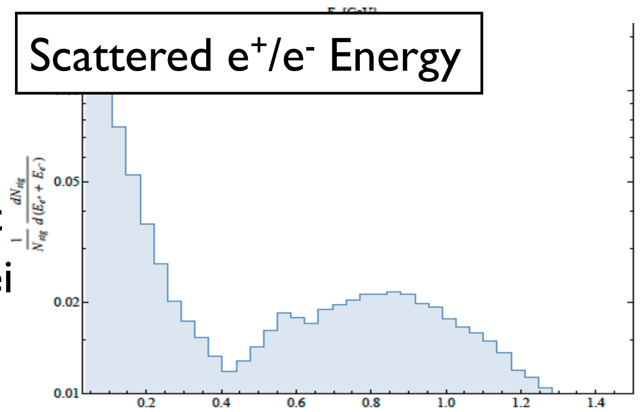


Elastic on electrons





Inelastic on nuclei



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

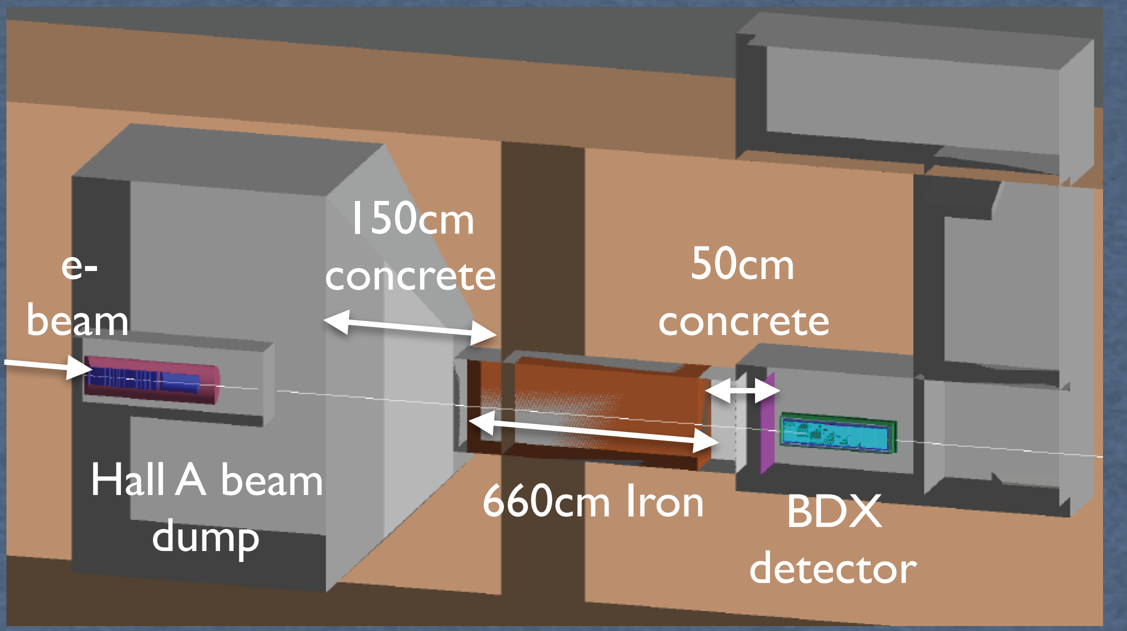
Parameters: m_X = 30 MeV $m_{A'}$ = 90 MeV	
X-e⁻ scattering inside the fiducial volume $E_{e^-} \geq 300$ MeV	**100%**
$E_{Seed} \geq 300$ MeV	**↓ 61%**
Veto anticoincidence	**↓ 13% (10% - 20%)**

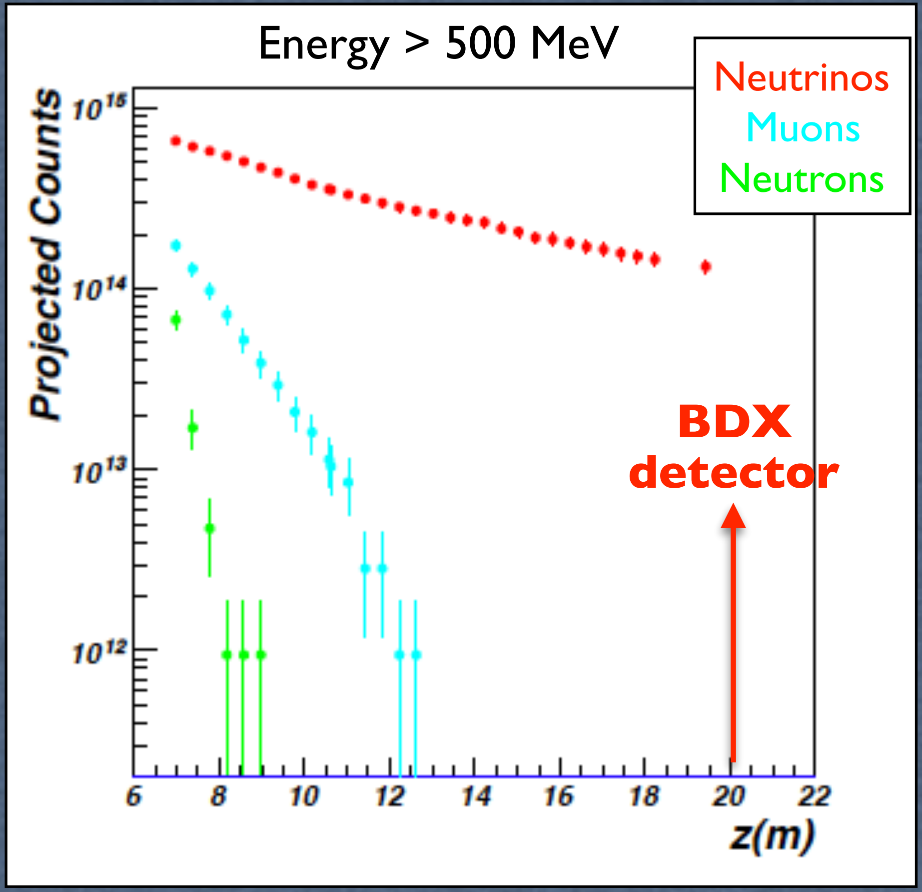
- E_{Seed} = max crystal energy in the em cluster
- Veto anti-coincidence to account for cosmic bg cut
- Consistent with prototype measurement
- Conservative (refined cuts on em shower will be possible)

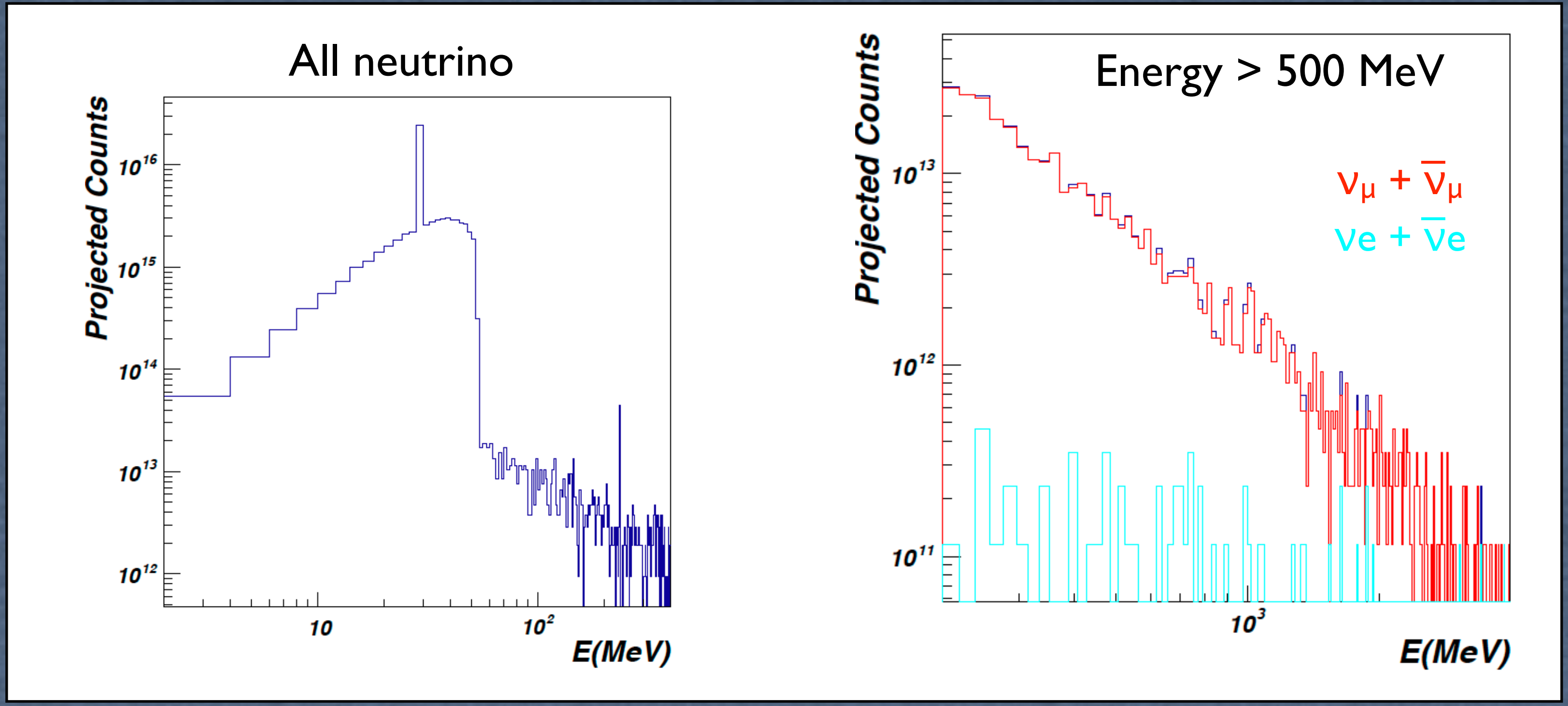
Beam-related background

★ **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







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

★ **Neutrino**

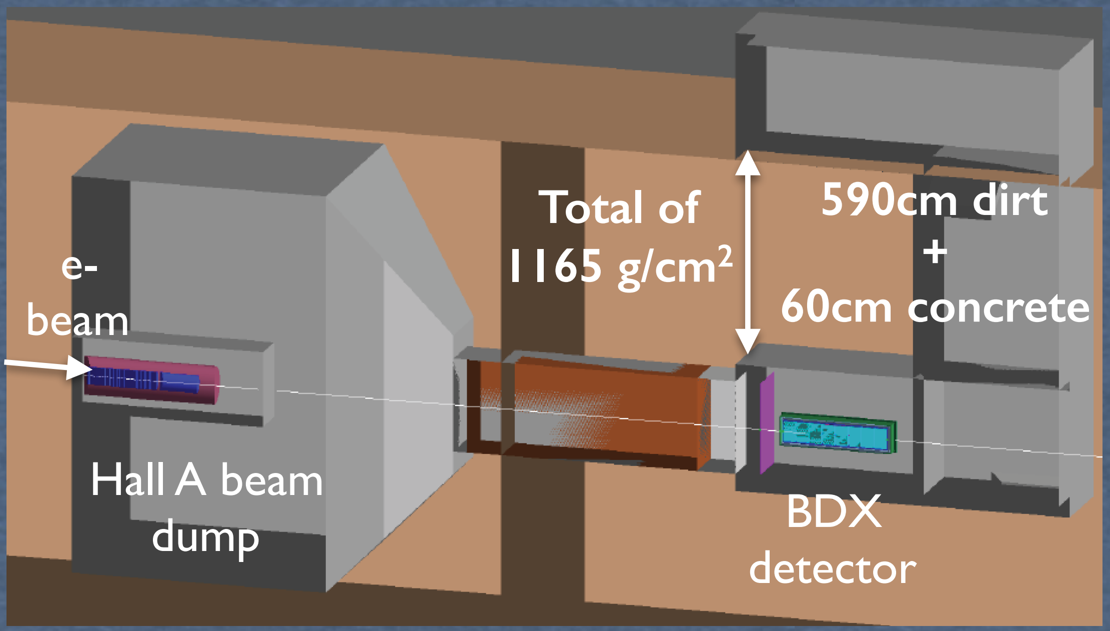
- $\pi \to \mu\, \nu_\mu$ $\mu \to e\, \nu_\mu\, \nu_e$
- Mainly low energy (<60 MeV)

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

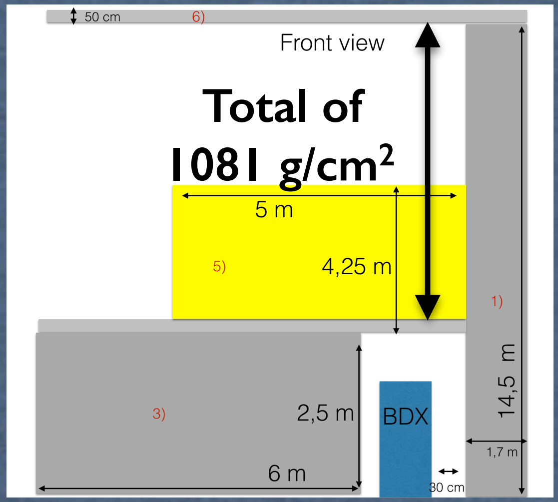
Neutrino *irreducible* bg represents the ultimate limitation for BDX

Cosmic background

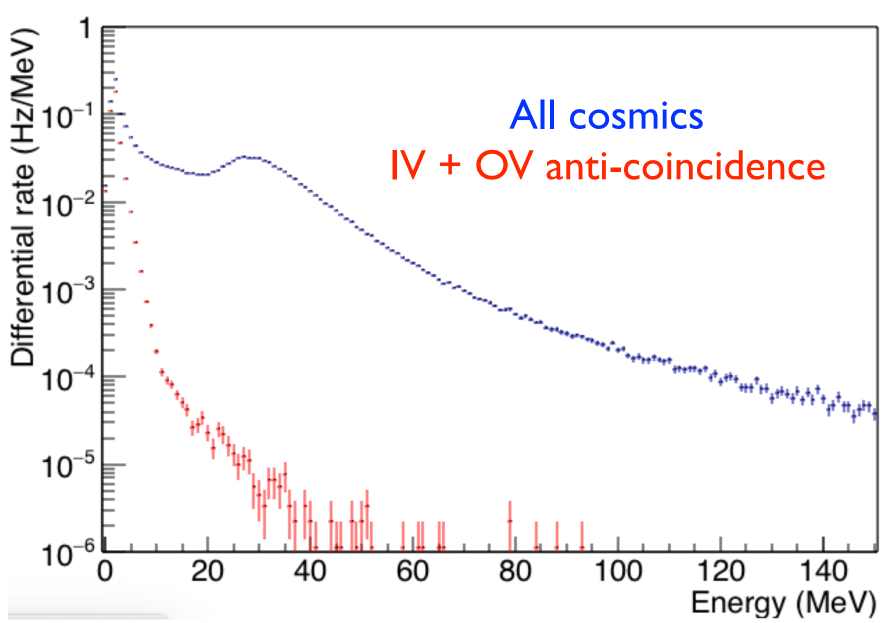
- ★ Cosmic background measured with the BDX detector prototype with similar overburden
- ★ GEANT4 simulations reproduce muon rate w/wo overburden
- ★ The majority of cosmic muons detected and rejected by the combination of the two veto detectors
- ★ The most part of cosmic neutrons are shielded by the 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)



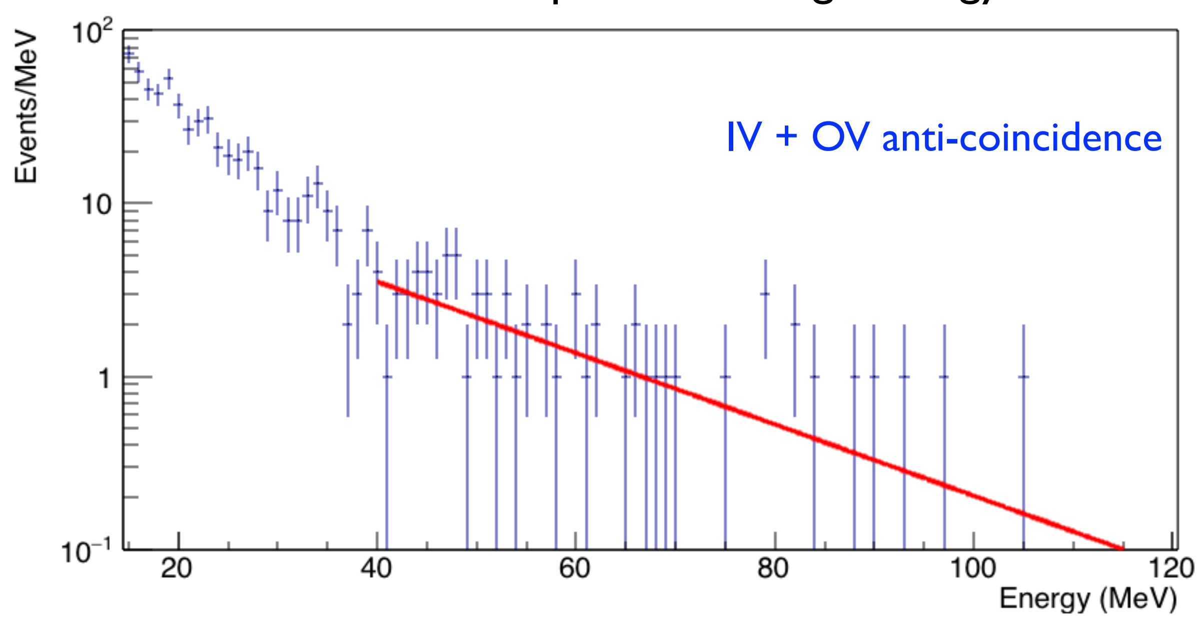
LNS set-up of BDX prototype



Count rate measured in 1 crystal



Count rate extrapolation to high energy



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

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 simulations

Brute force + other methods 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)

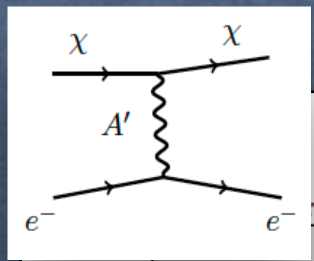
BDX reach calculation

- 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

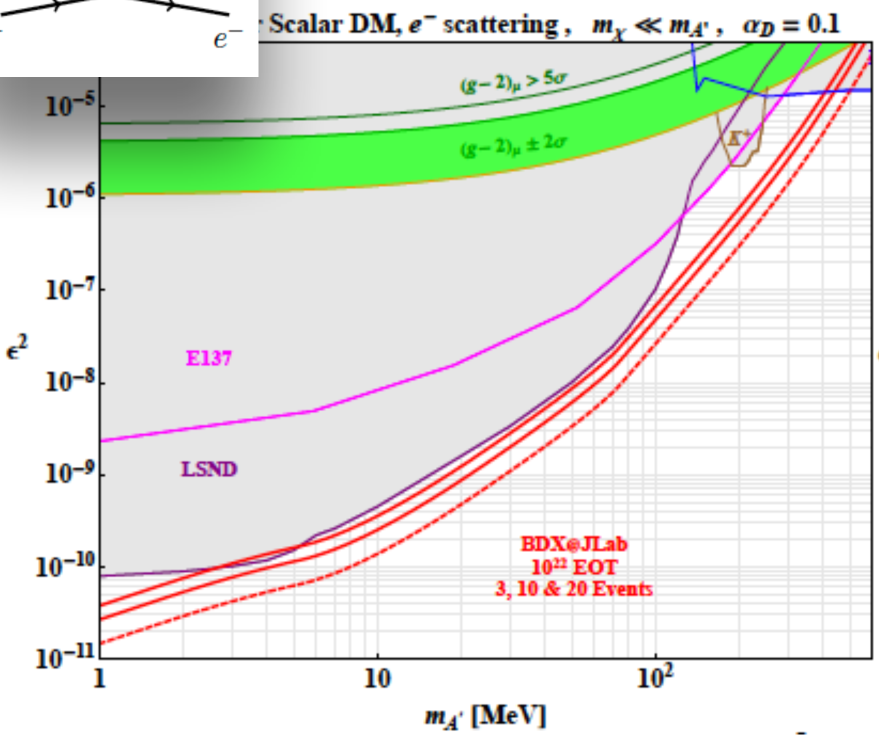
$N_{Signal} > 2\ \sigma_{bg} \sim 11 - 17$ counts

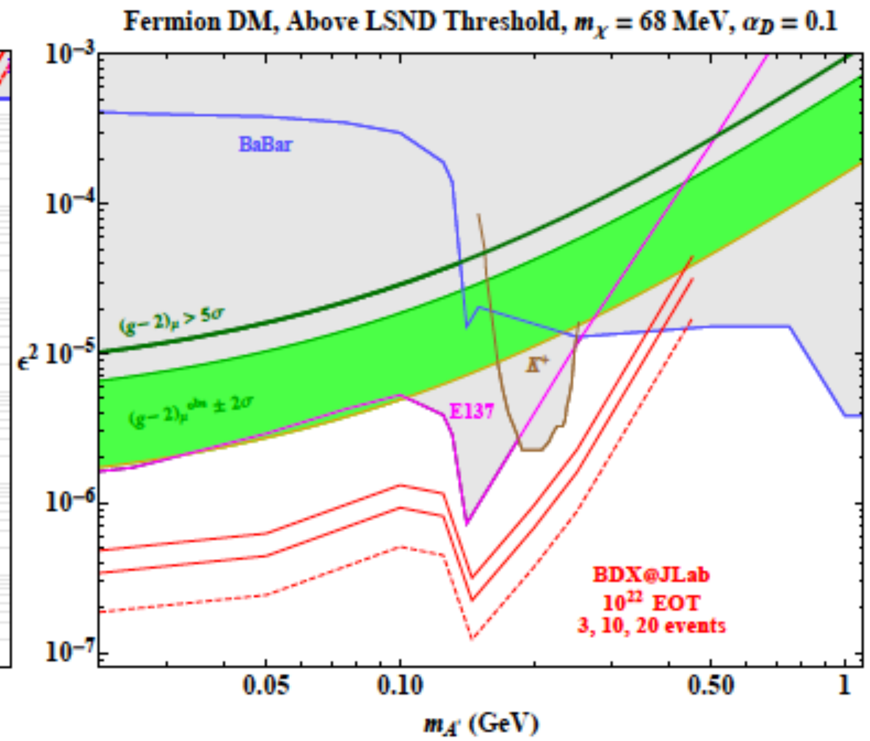
BDX reach reported for (3) 10 and 20 excess events

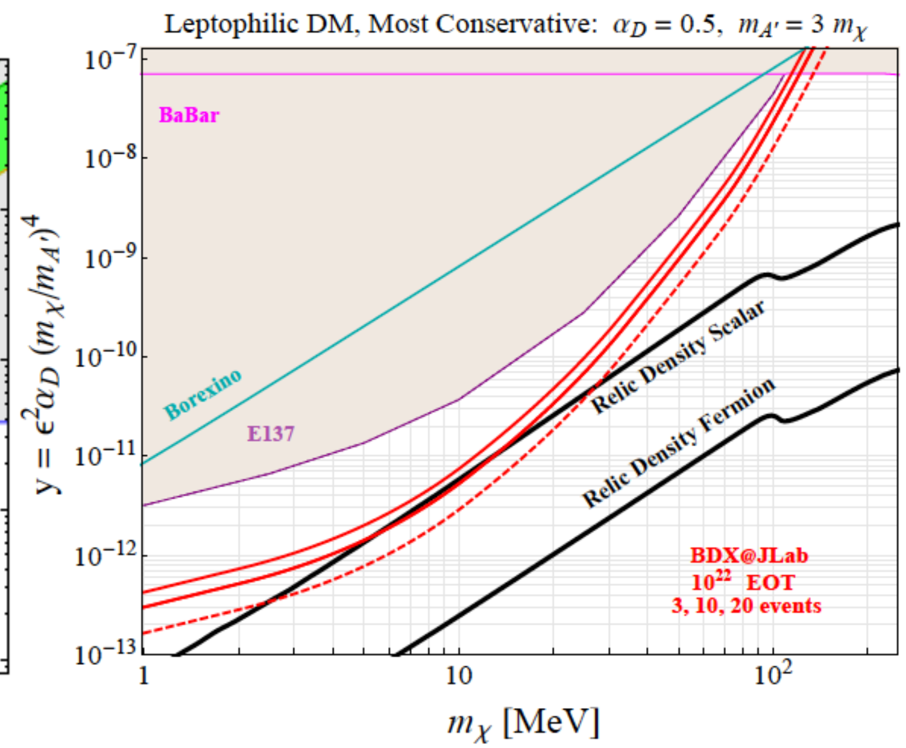
BDX expected reach



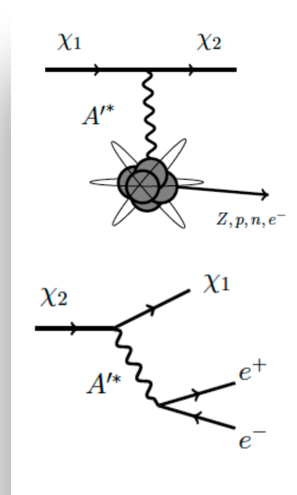
Elastic X-e⁻ scattering - BDX reach

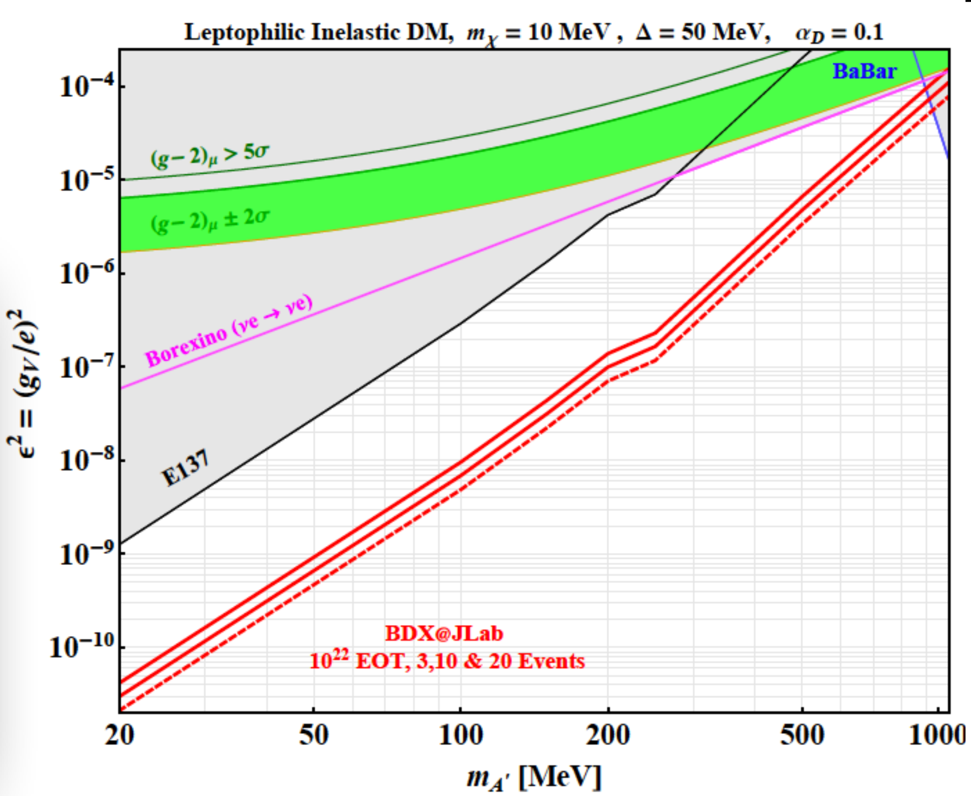




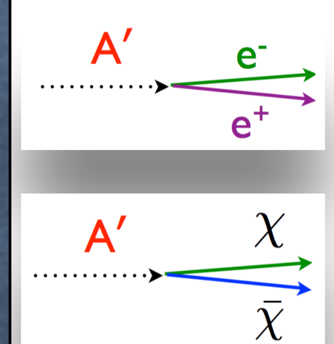


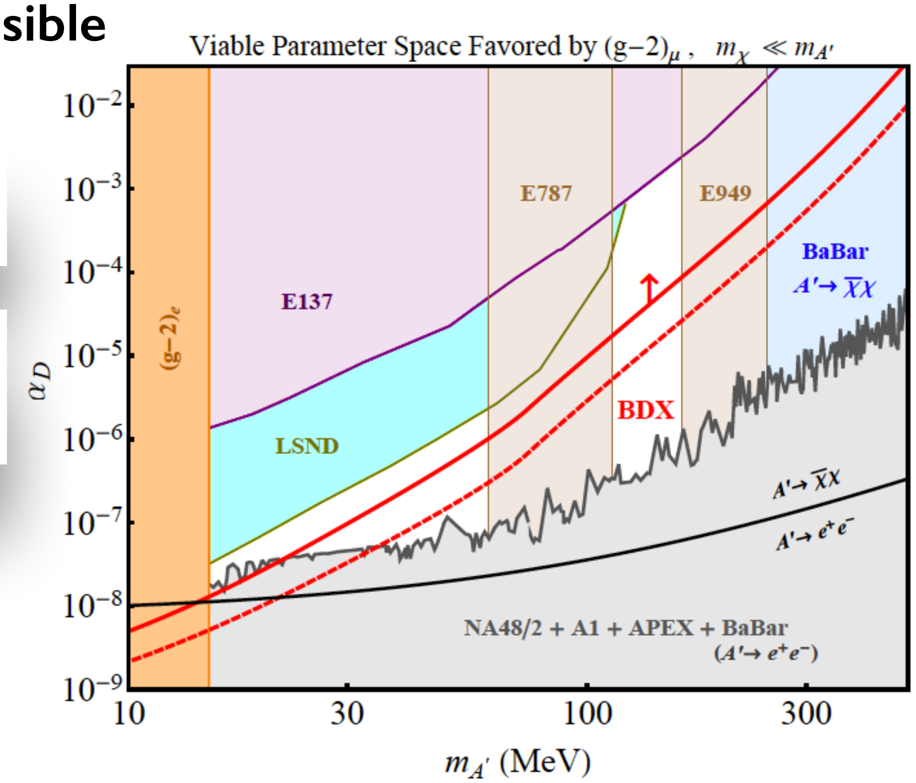
Inelastic X-N scattering





Visible + Invisible decay





Conclusions

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

✳ Theoretically well-motivated Light Dark Matter scenario(s) can be explored with the high-intensity/high-energy JLab beam with unprecedented precision

✳ A dedicated Beam-Dump eXperiment (BDX) will naturally complement the extensive program already running at the major electron- and proton-beam facilities (JLab, LNF, Cornell, Mainz, SLAC, FNAL and CERN)

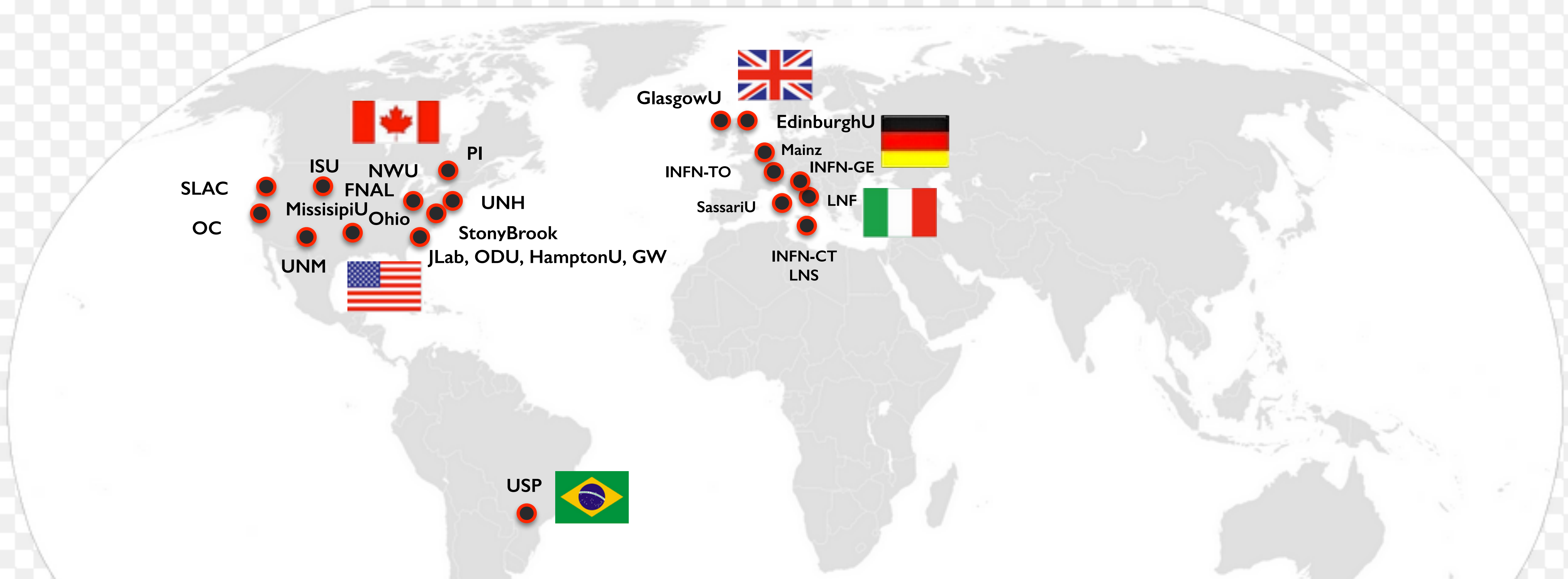
✳ A new experimental hall, downstream of Hall-A beam-dump, will host the BDX detector based on ~800 CsI(Tl) crystals + InnerVeto + Outer Veto

✳ Full GEANT4 simulations have been run to optimize the experimental set-up and estimate beam-related background(s)

✳ A BDX detector prototype, currently taking cosmic data at LNS-Italy, is being used to test the proposed technology, validate MC simulations and measure cosmic background rates

✳ The BDX experiment, collecting 10^{22} EOT in 285 days of parasitic running (~4y-calendar) would be 10-100 times more sensitive than previous experiments excluding a significant area of the the parameter space in case of null results

The BDX Collaboration



- 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

Back up slides

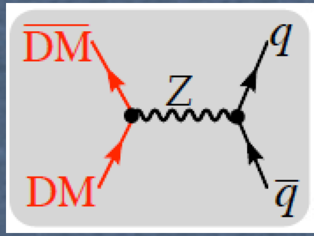
Any guess about the DM mass and interaction?

★ (Obvious) first guess: DM interaction in the range of the at the weak force scale (WIMPS) with DM mass in the range of TeV

WIMPs paradigm is not the only option

Light Dark Matter | Light Dark Matter (<TeV) naturally introduces light mediators | **New interaction**

★ DM as thermal relic from the hot early Universe



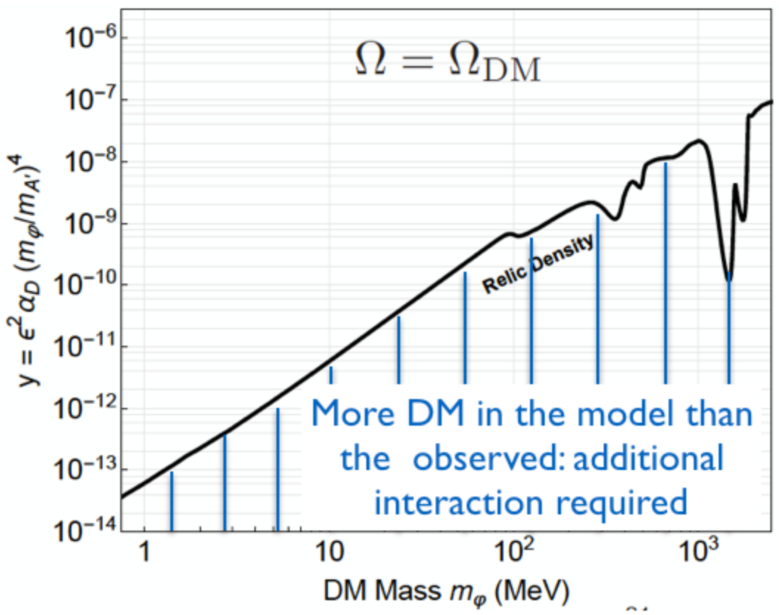
- DM annihilation in SM in the early Universe $\langle \sigma v \rangle \sim g^2_{Dark}\, g^2_{SM}\, M^2_{DM}/M^4_{mediator}$
- Minimal DM abundance is left over to the present day $\langle \sigma v \rangle \sim 3\times10^{-26}\ cm^3/s \sim 1/(20\ TeV)^2$

★ Definition of [adimensional] variable $y \sim g^2_{Dark}\, g^2_{SM}\, (M_{DM}/M_{mediator})^4 \sim \langle \sigma v \rangle\, M^2_{DM}$

$$\langle \sigma v \rangle \propto \epsilon^2 \alpha_D \frac{m_\varphi^2}{m_{A'}^4} = \epsilon^2 \alpha_D \frac{m_\varphi^4}{m_{A'}^4} \frac{1}{m_\varphi^2} = \frac{y}{m_\varphi^2}$$

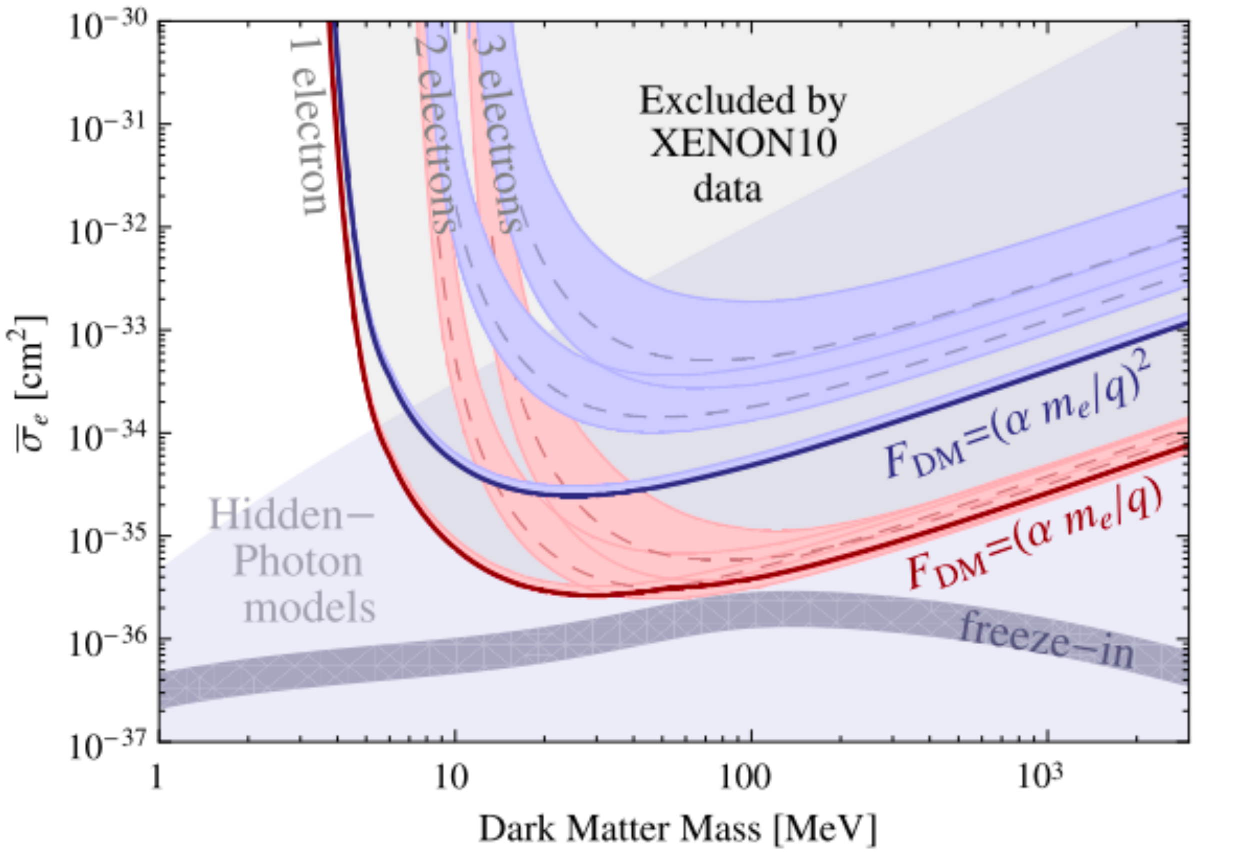
Computed for $m_{A'}/m_{\varphi/\chi} = 3$

But thermal target largely insensitive to this ratio



LDM - Direct Detection limits

Limits from XENON10

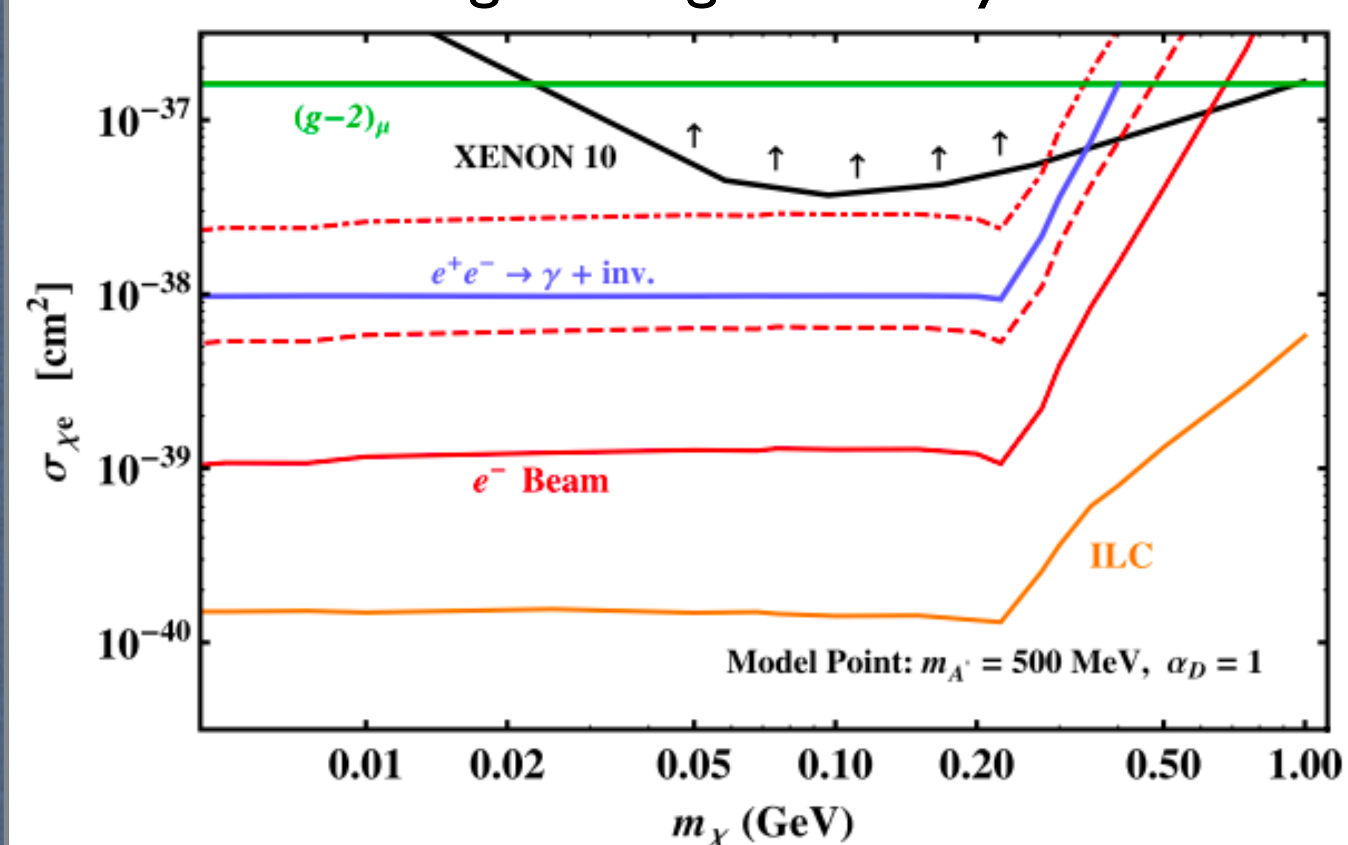


PhysRevLett. 109.021301 R.Essig, A.Manalaysay, J.Mardon, P.Sorensen, T.Volansky,

- 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

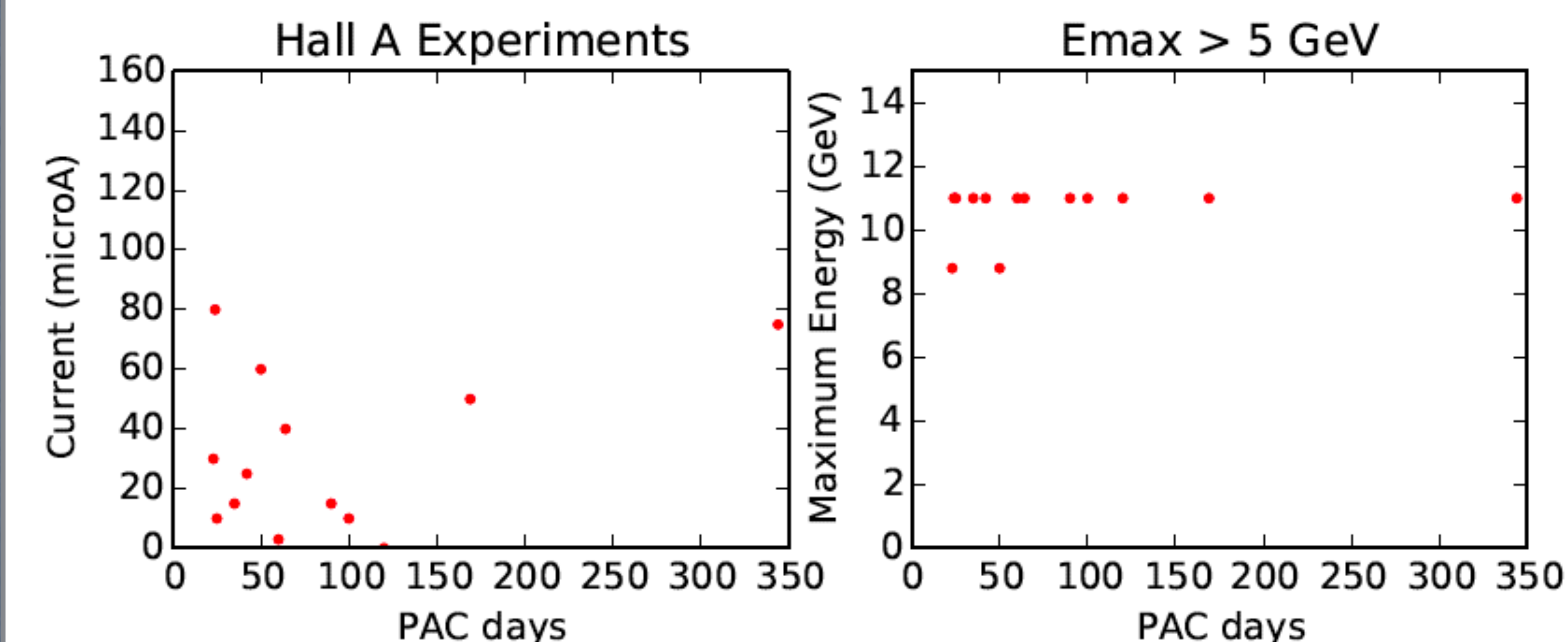
- Fixed target electron beam experiments can be 10^3 - 10^4 more sensitive in the 1 MeV - 1 GeV mass range
- No experiments were designed to measure LDM (all limits come from reinterpretation of old experiments)

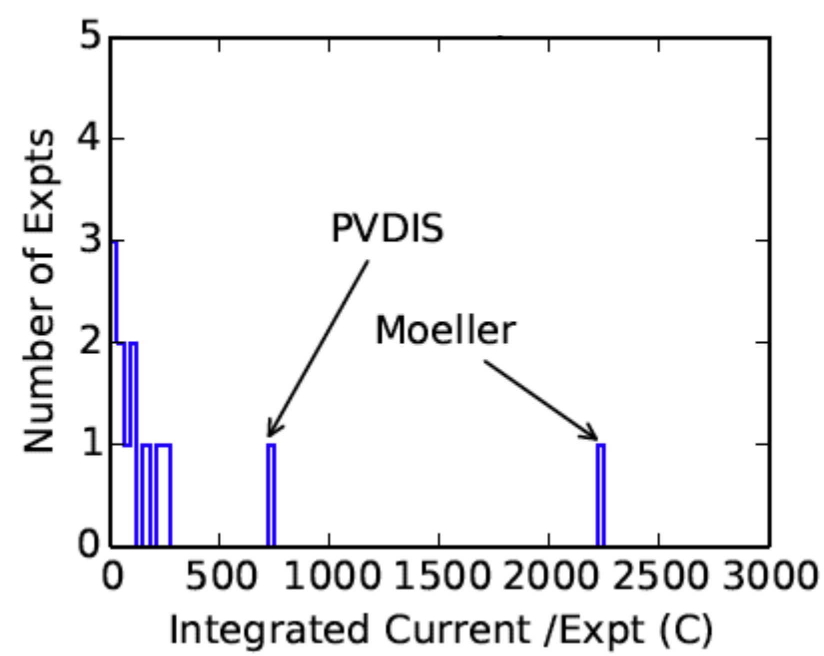
Fixed target & high intensity e⁻ beam



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

Hall A approved experiments





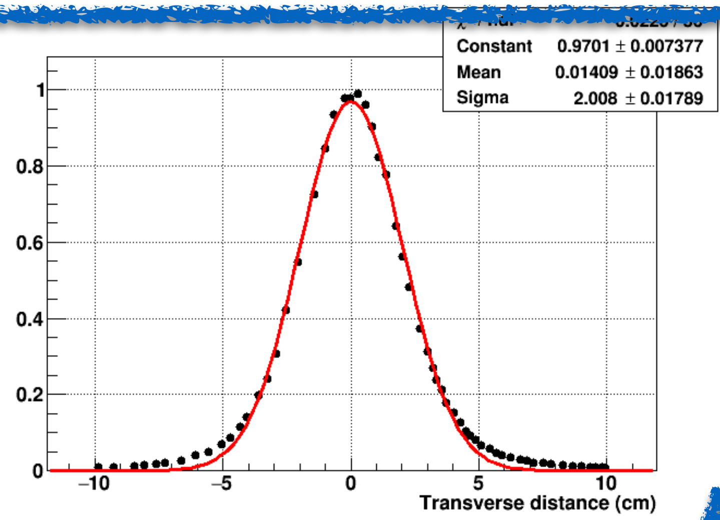
Total Charge = 4042 C
EOT = 2.5 10^{22} electrons

BDX beam-time request almost saturated by *Moeller* and *PVDIS (11GeV)* exps

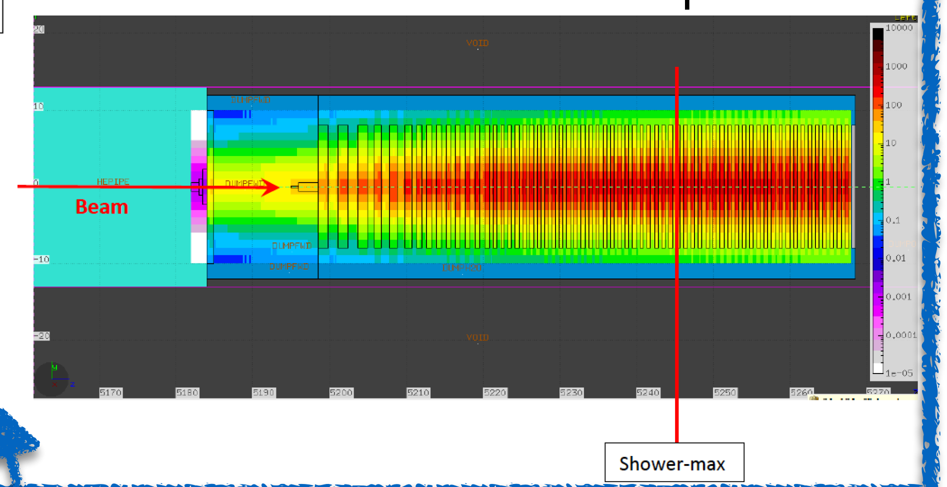
		Approved days	Energy1 (GeV)	Energy2 (GeV)	Energy3 (GeV)	Energy4 (GeV)	Current (microA)
E12-06-122	A1n	23	0	0	6,6	8,8	30
E12-07-108	ep elastic	24	0	6,6	8,8	11	80
E12-09-005	Moeller	344	0	0	0	11	75
E12-09-016	Gen/Gmn	50	0	4,4	6,6	8,8	60
E12-09-019	Gmn (SBS)	25	4,4	6,6	8,8	11	10
E12-10-007	PVDIS	169	0	0	6,6	11	50
E12-10-009	APEX A1	34	1,1	2,2	3,3	4,4	75
E12-10-103	F2n/F2p	42	0	0	0	11	25
E12-06-114	DVCS e-helicity	100	0	6,6	8,8	11	10
E12-10-018	Transversity 3He	64	0	0	8,8	11	40
E12-10-006	Trans tgt asym 3He	90	0	0	8,8	11	15
E12-11-007	SIDIS PI+ (SOLID)	35	0	0	8,8	11	15
E12-11-101	PREX II	35	0	0	0	1	70
E12-11-108	Trans tgt asym (SOLID)	120	0	0	8,8	11	0,1
E12-11-112	Isospin dep 2N, 3N SRC	19	0	0	2,2	4,4	25
E12-12-006	J/Psi	60	0	0	0	11	3
E12-12-004	CRES	45	0	0	0	1,1	150
E12-14-009	GE 3He/3H	1,5	0	0	0	1,1	5
E12-14-011	p, n moment distr A=3	12	0	0	0	4,4	25
E12-14-012	Spec Func 40Ar	9	0	0	0	2,2	100
		1301,5					

Running BDX in parallel with *Moeller* experiment

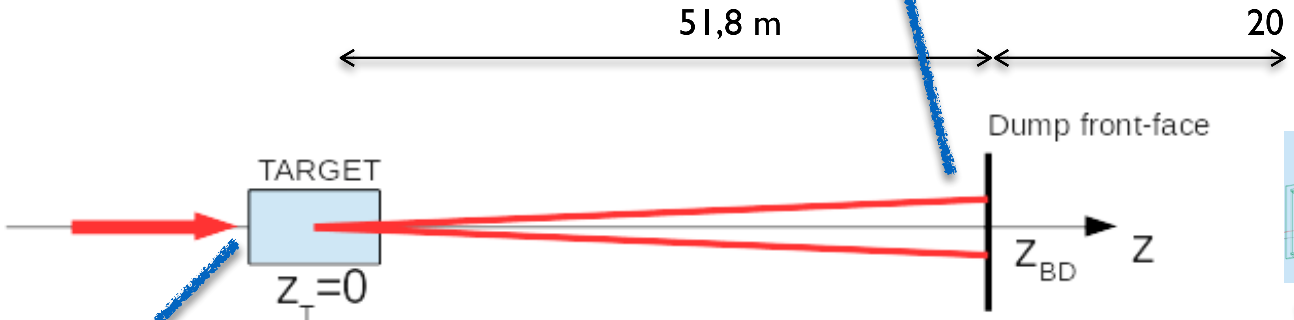
e-beam spot on beam dump front face



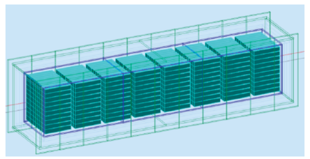
EM shower in beam dump



Hall-A *Moeller* exp target area



BDX detector



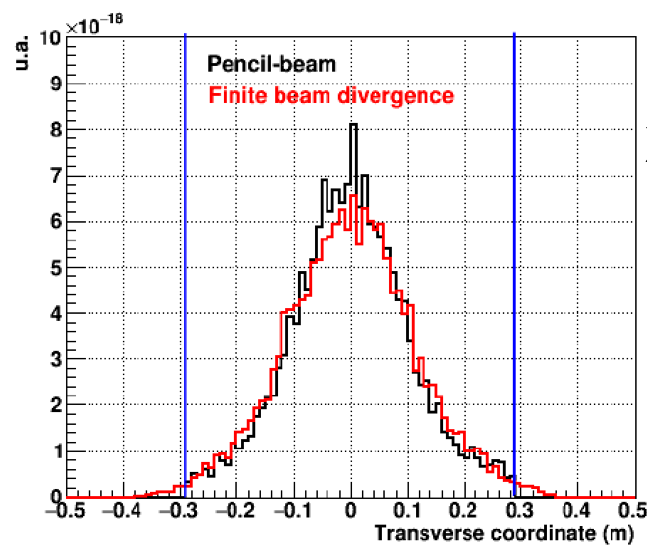
Moeller run conditions

- E_{beam}= 11 GeV
- I_{beam}=75uA
- Approved days: 344
- Target: 150cm LH_2

The electron beam is rastered on the target face over a 2x2 mm² area

- **Multiple scattering in LH2 target is the dominant factor in transverse spread**
- **No additional diffuser is needed to spread power on beam dump front face**
- **No significant difference between pencil and diffused beam**

Resulting X beam fully contained in BDX detector acceptance



X-beam spot on BDX detector front face

K.Welch, J.Benesh

The BDX crystals

Requirements:
- High density
- High light yield
- Cost-affordable for a ~ m^3 detector volume
- Good timing (desirable)

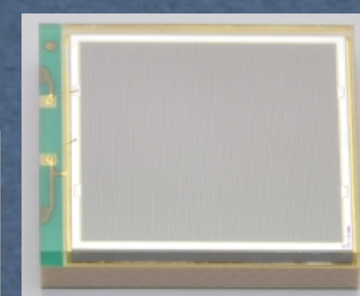
Possible options:

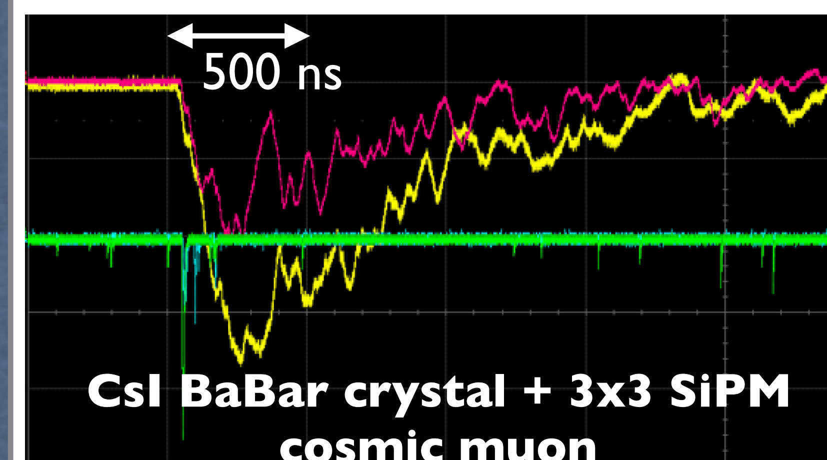
BaF2
CsI
BSO

A dedicated measurement campaign to characterise the crystal properties
- Light yield (with SiPM readout!)
- Intrinsic decay time / time resolution

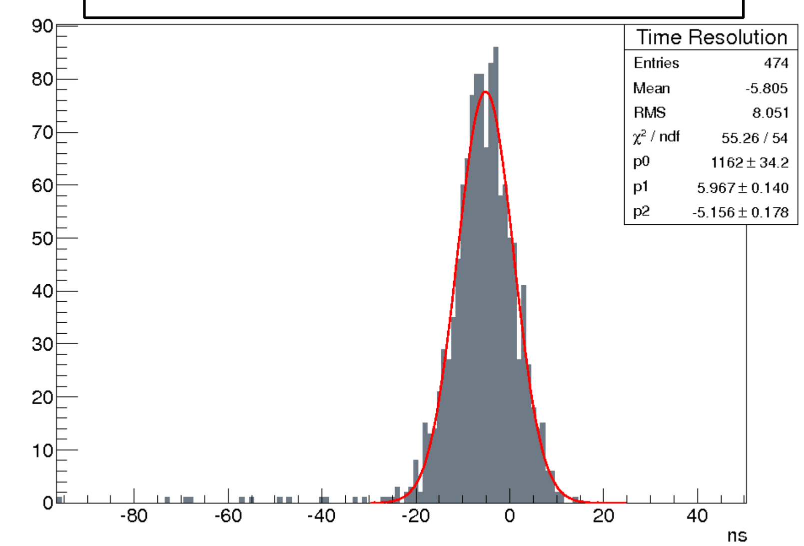
Parameter	Values
Radiation length	1.85 cm
Molière radius	3.8 cm
Density	4.53 g/cm^3
Light yield	50, 000 γ/MeV
Light yield temp. coeff.	0.28%/°C
Peak emission λ_{max}	565 nm
Refractive index (λ_{max})	1.80
Signal decay time	680 ns (64%)
	3.34 µs (36%)

CsI(Tl) + SiPM readout





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



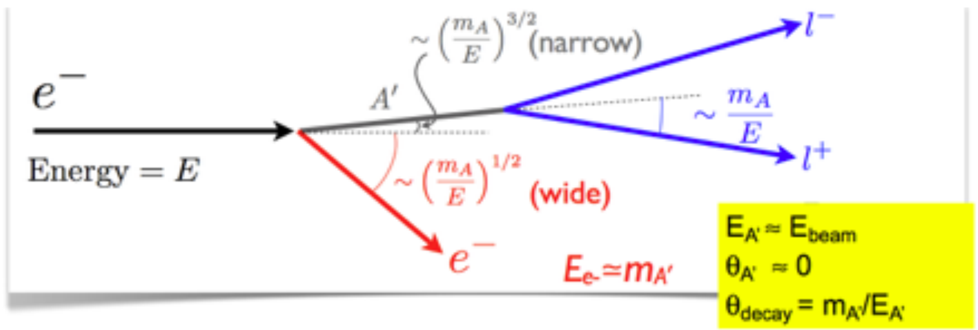
Crystals are available from BABAR em calorimeter
- Size: (5x5)cm^2 front face, (6x6)cm^2 back face, 30cm length
- 820 crystals available from end cap
- Decay time: fast 900ns, slow 4000ns
- LY= 50k γ/MeV

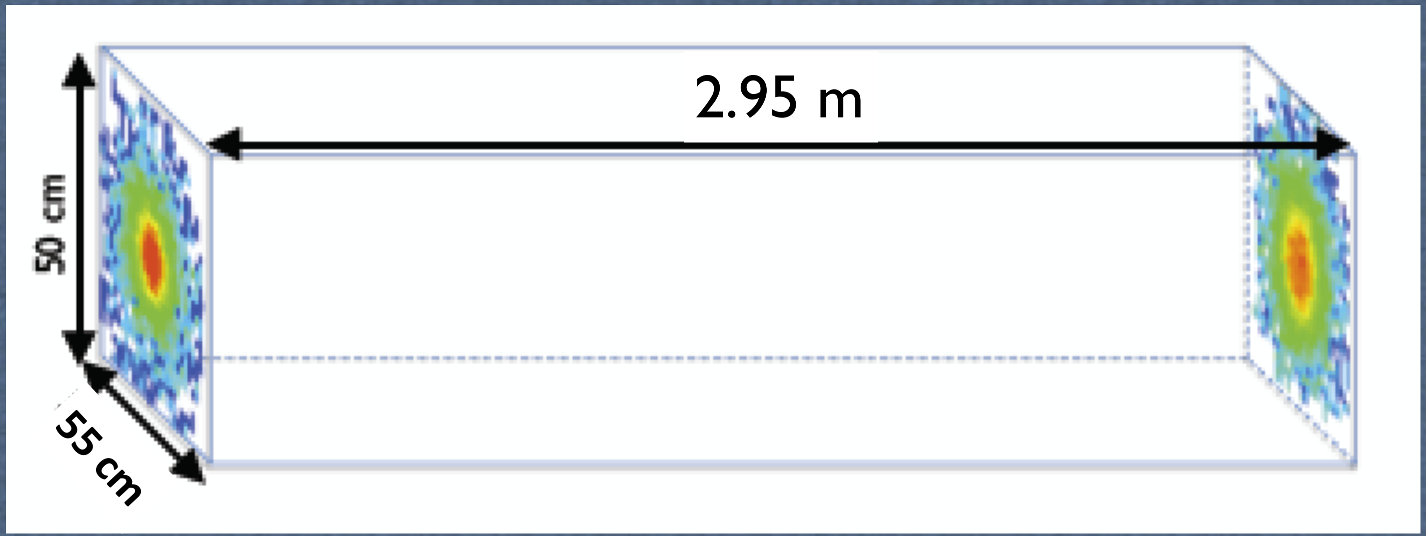
SiPM readout
- Size: (6x6) mm^2, 25µm, 57.6k cells, trenched, pde=25%
- SPE capability
- CsI(Tl): 40 pe/MeV
- Time resolution: ~5ns (MIPs)

★ 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

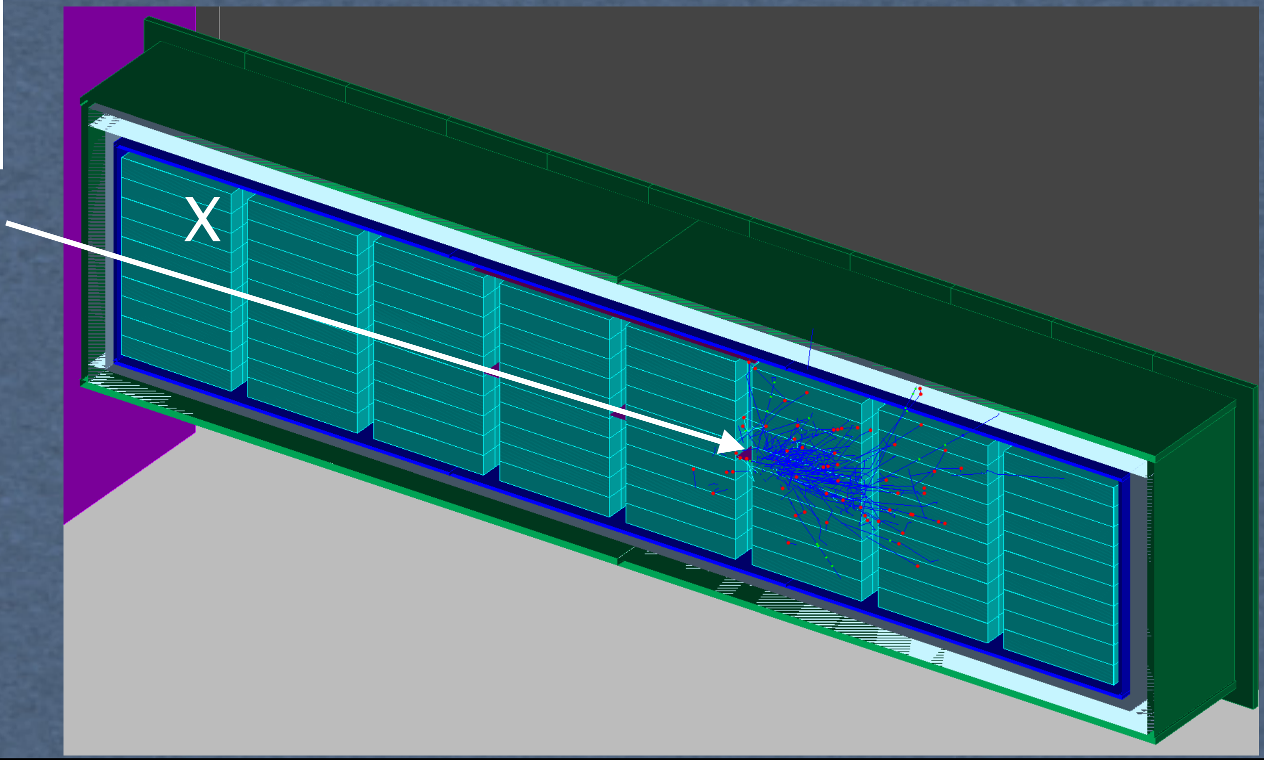
Strongly forward peaked kinematics
focused χ-beam !





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

★ Each crystal is read separately

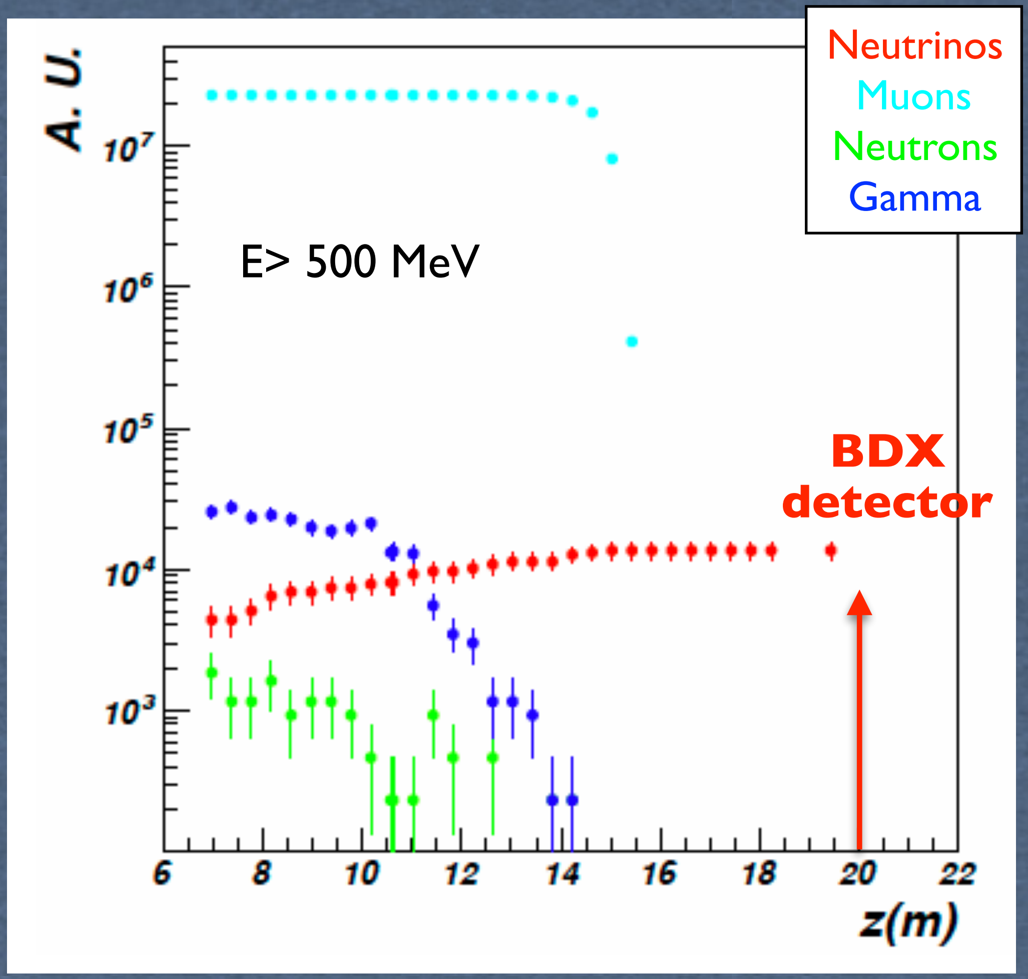


★ ~800 BaBar EndCup crystals
★ Simplified assembly mechanics
★ Modular detector
★ Final arrangement:
    10x10crystals (front face ~50x55 cm2)
    8 modules (active/total length: 260/295 cm)

GEANT4 simulation
of electron recoil bg (E>500MeV)

Low interacting particles produced with low rate in the BD that may reach the detector or produce secondaries close to the detector studied with dedicated simulations

10 GeV muons generated in the dump



Gamma and neutrons:

- energetic particles (~GeV) rapidly loose energy
- only low energy (<10 MeV) close to the detector

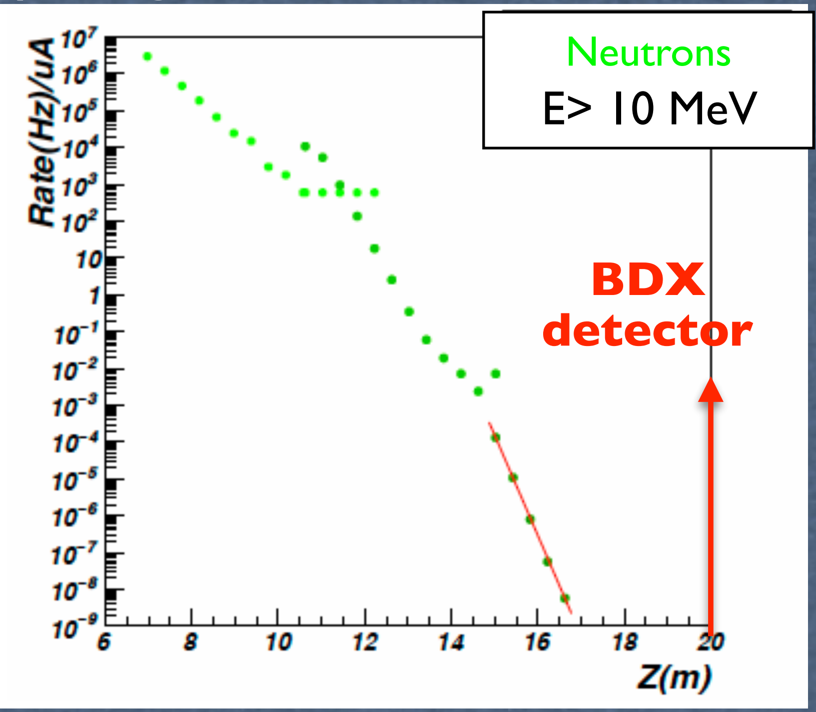
Muons:

- up to 10 GeV by asymmetric pair production
- range less than BDX absorber (concrete+iron) length
- secondaries die within the same range

No muons or secondaries with E ≥100 MeV or higher at the detector location

GEANT4 & MCNP simulations of low energy bg (>10MeV)

- Low energy secondaries studied with GEANT4 and MCNP
- Simulation of full statistics (10^{22} EOT) not feasible because of computing resources limitation [GEANT4: 1y, 2000 cores→10^{11}-10^{12} EOT]
- Extrapolation needed

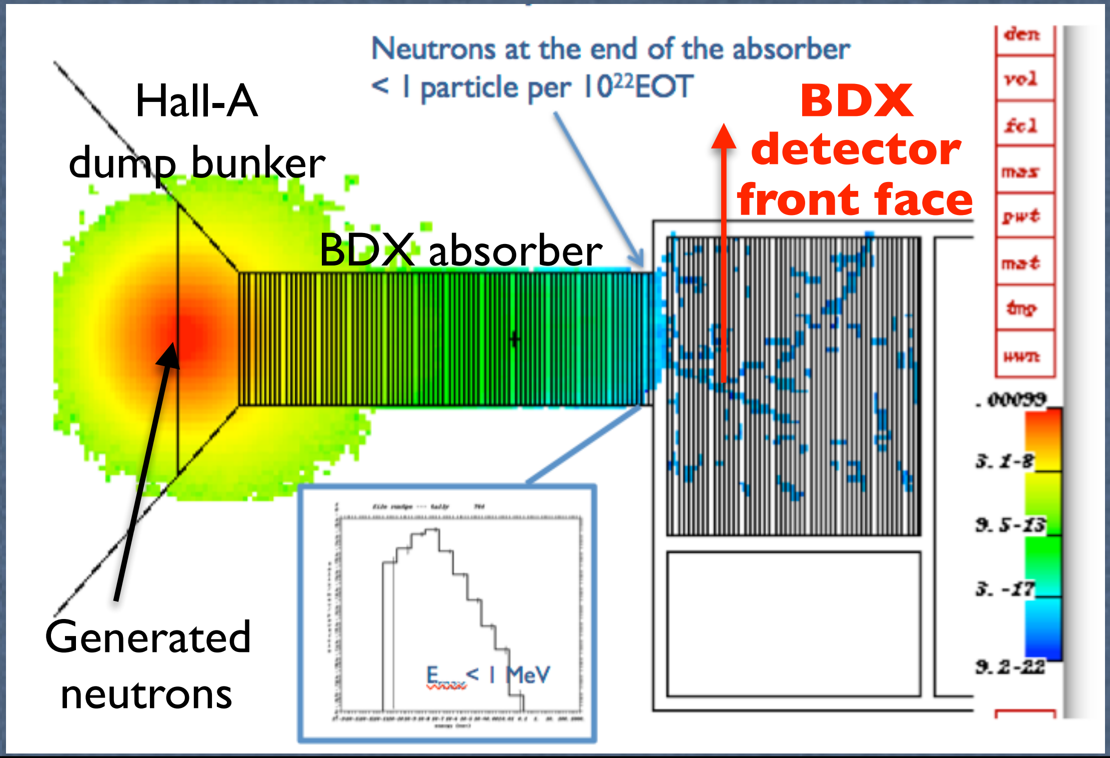


Neutron GEANT4 extrapolation

- Iterative approach
  - First iteration based on simulation of 10^9 EOT with no energy cut-offs
  - Estimate neutron counts at detector location by using neutron spectrum at deepest position with non-zero flux as input for next iteration
  - No significant neutron counts at the detector location

Neutron MCNP estimates

- Variation reduction technique
  - Input neutron spectrum from GEANT4 simulation of 10^9 EOT with no energy cut-offs
  - Progressively increasing neutron cell importance in BDX absorber to obtain non-zero statistics at detector location



No significant neutron counts at the detector location from both GEANT4 and MCNP simulations

Similar results for photons

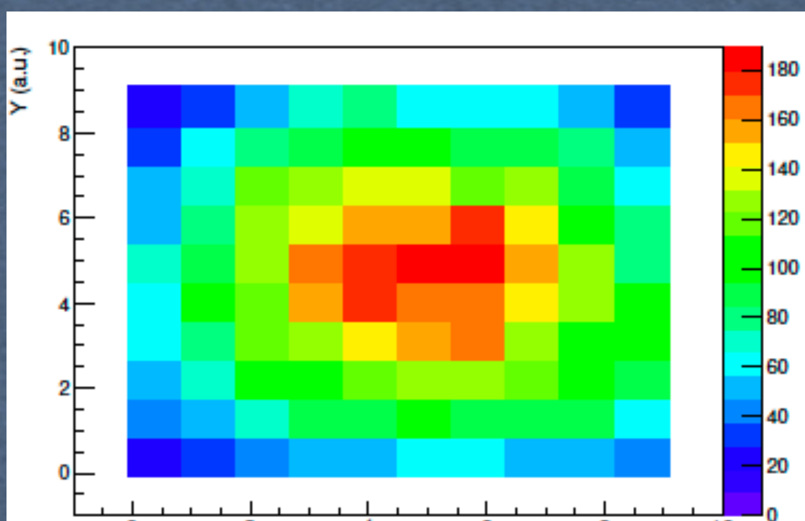
Signal vs cosmogenic background

- No time cuts applied (best timing with CsI ~ 10ns would require a dedicated matched beam structure)

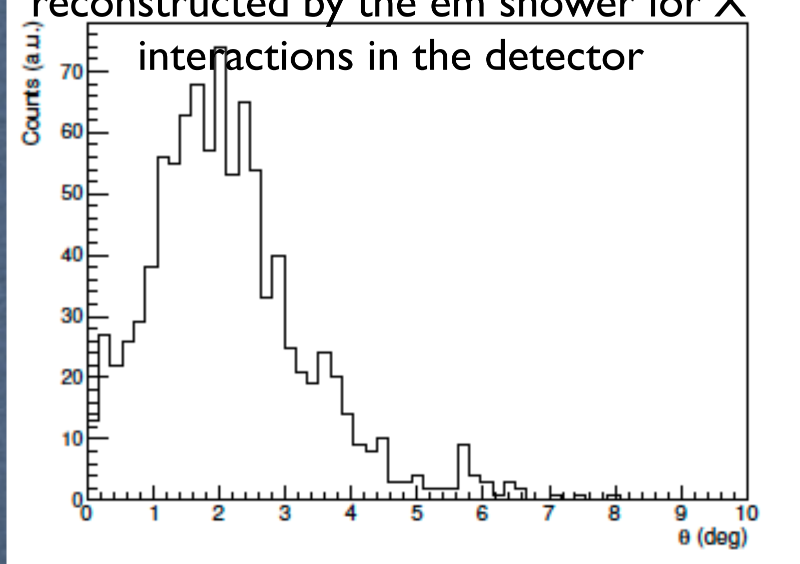
We can do better!

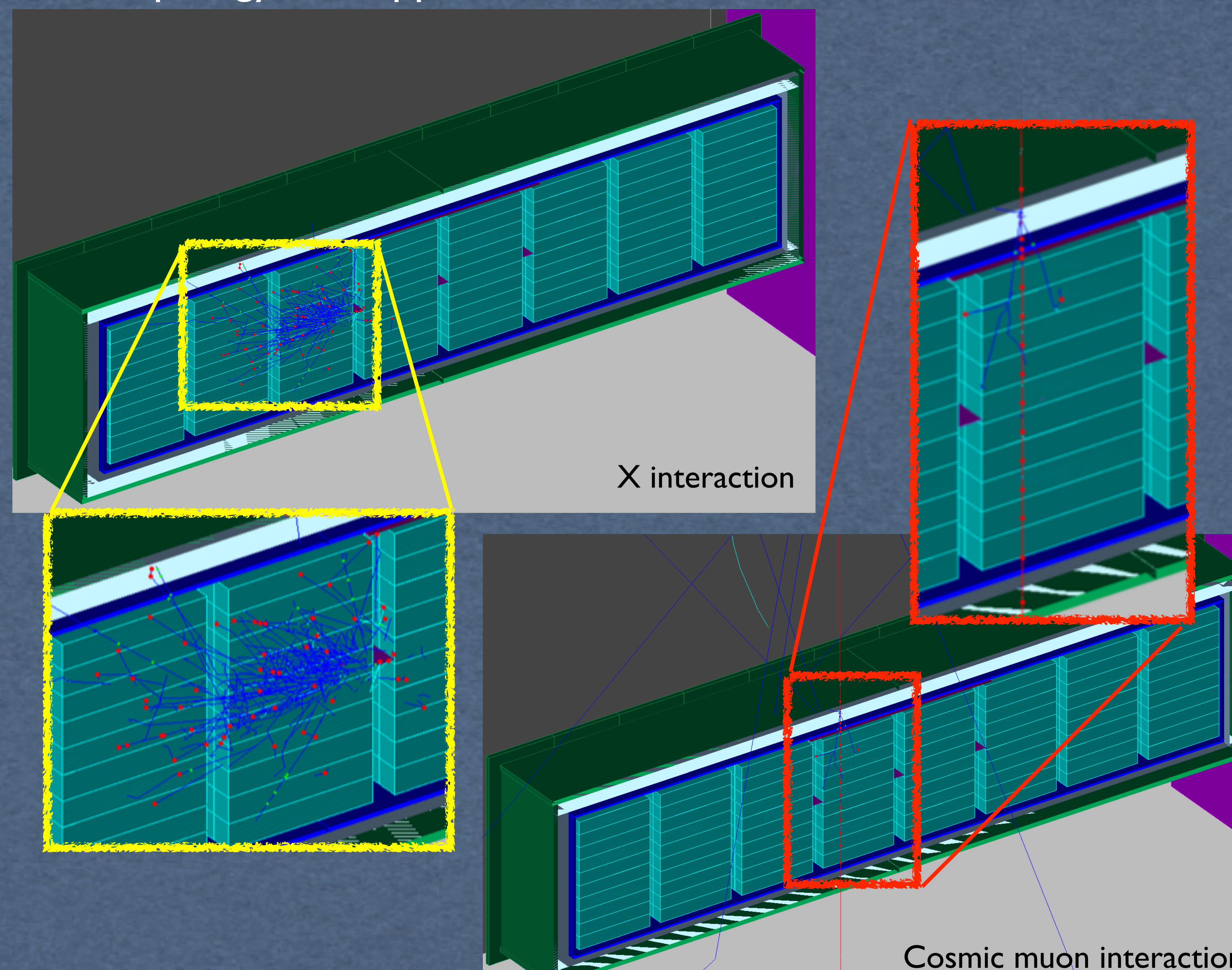
- No topology cuts applied

- No directionality cuts

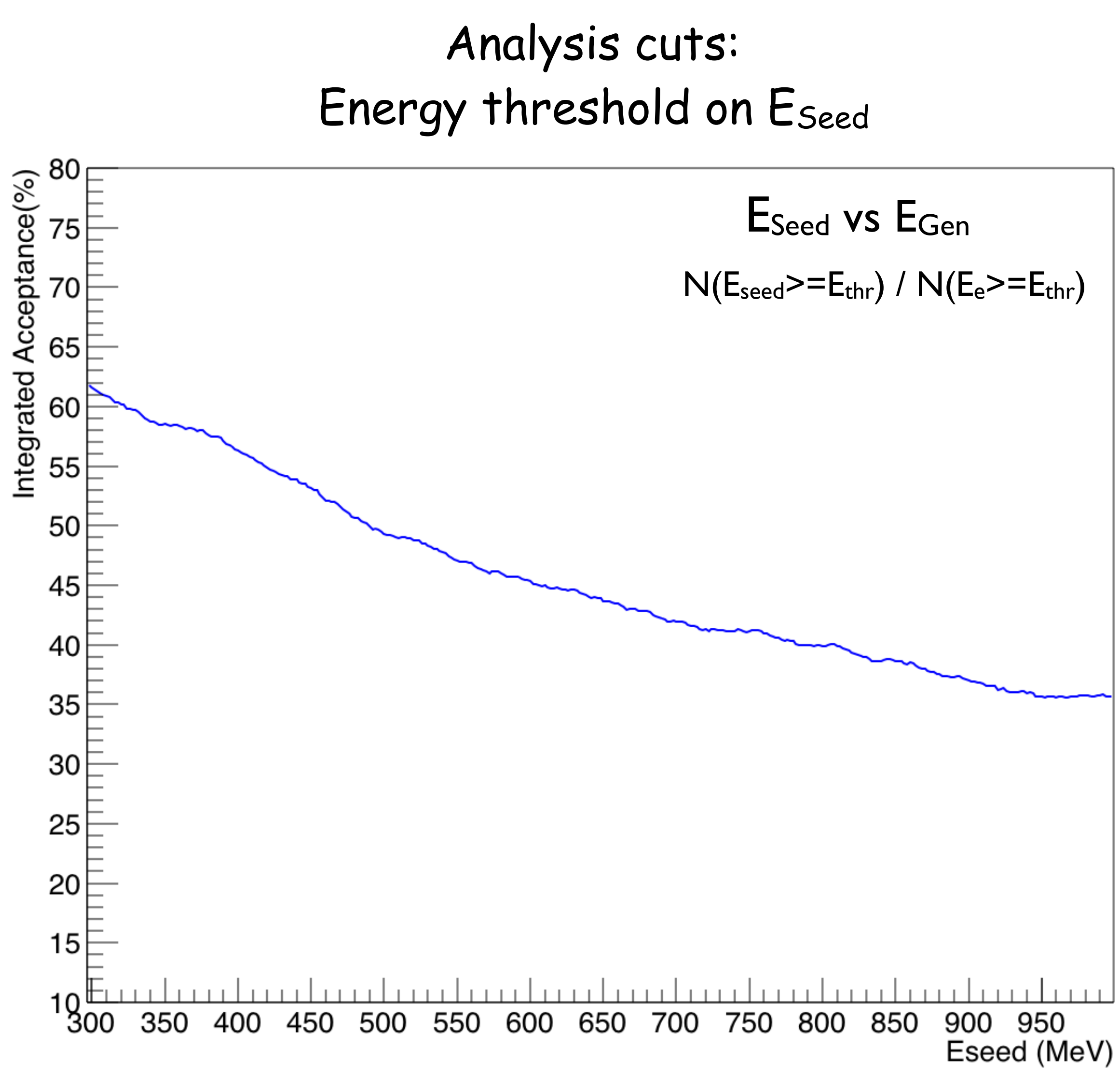


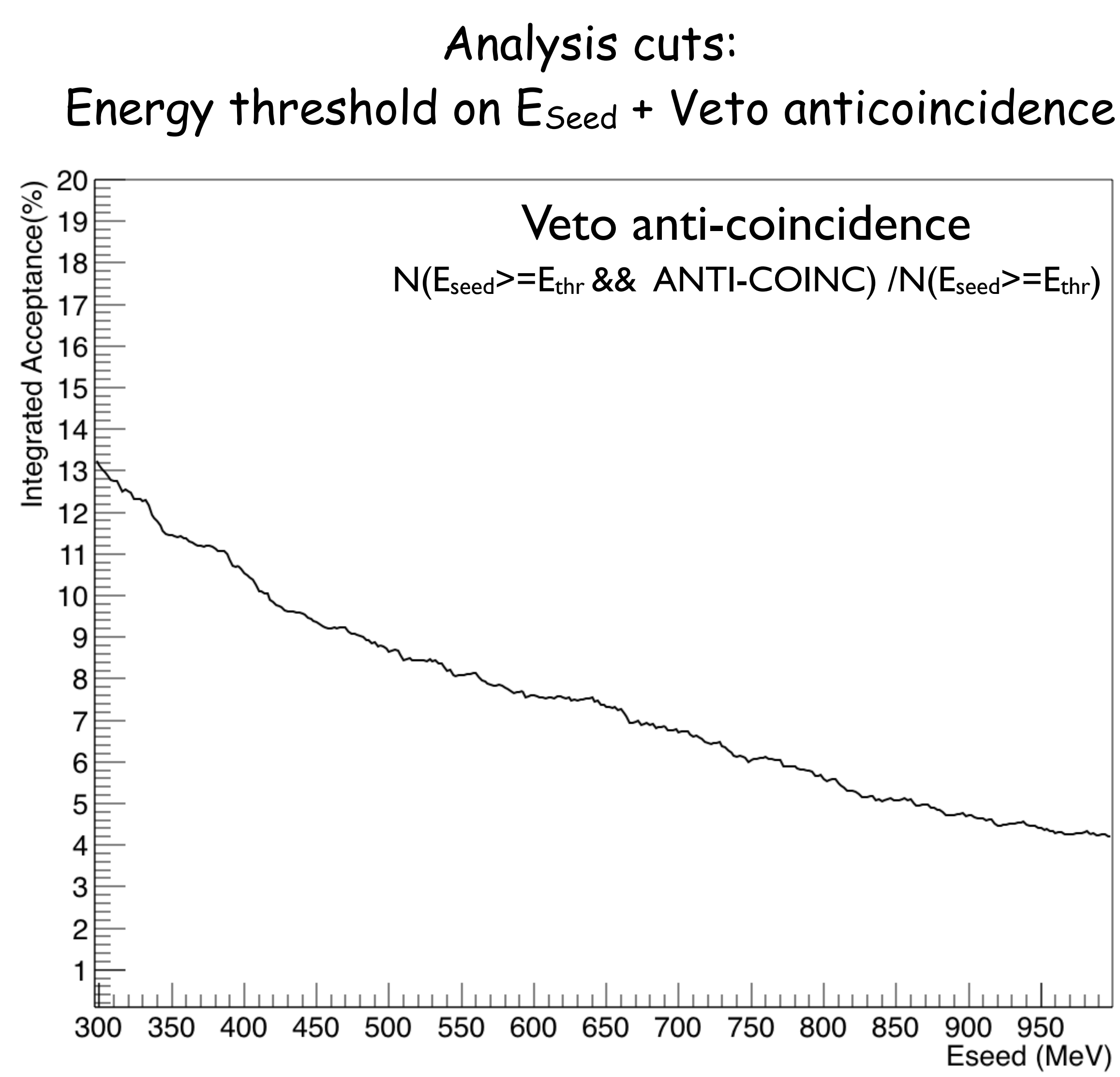
theta angle (from the beam direction) reconstructed by the em shower for X interactions in the detector





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

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

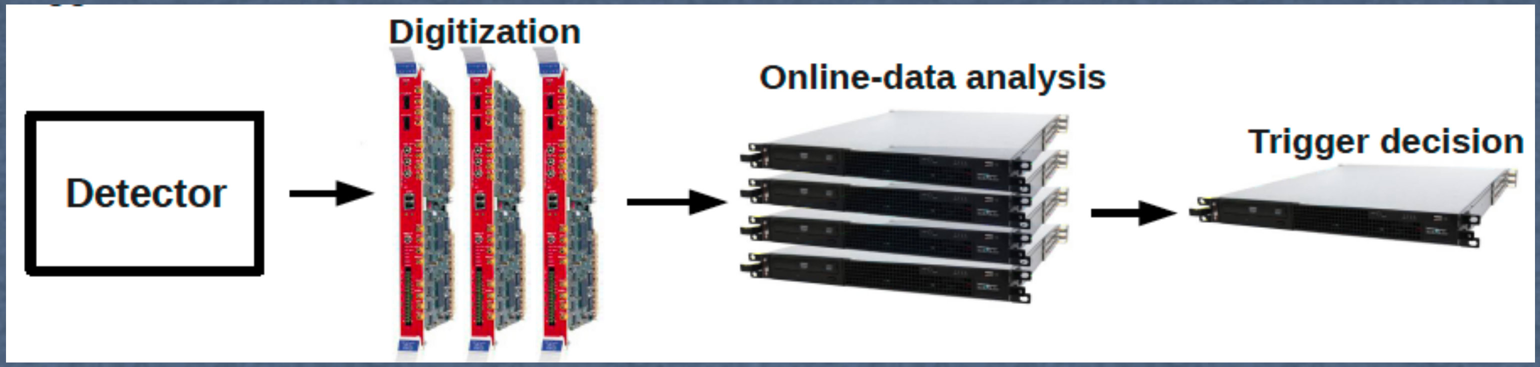
Different options under investigation:

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



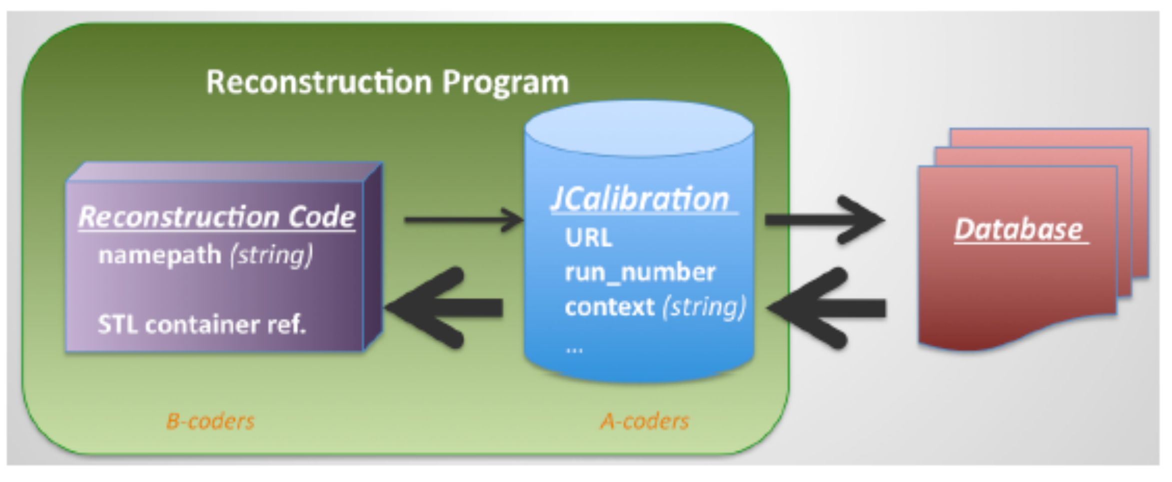
3) Trigger-less - custom

- 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 LOI: JLab *PAC42* report

Summary and Recommendation: BDX could become the definitive beam dump experiment at electron accelerators. Sited at Jefferson Lab, it would use the CEBAF high intensity beam and modern technologies for detector design, trigger, and data acquisition, to achieve the most stringent limits (or to make the first discovery) of a class of dark matter particles.

The collaboration is encouraged to proceed with a full proposal to the laboratory, but the PAC emphasizes that the collaboration needs to meet a high standard in order to be eventually approved. Experimentally, a fully fleshed-out detector design needs to be presented, including both simulations and measurements (with CORMORINO or otherwise) that demonstrate its sensitivity to both detection channels as well as its ability to reject cosmic ray backgrounds with whatever necessary overburden. Theoretically, it must be made clear what models and attendant assumptions motivate this particular measurement, as well as the extent to which these models are (or are not) addressed in other experiments at other laboratories. Finally, the PAC realizes that the infrastructure costs to build and instrument a pit that would house this experiment will be extensive, and recommends that the laboratory require an approved proposal before scheduling onsite tests with beam as part of the design process.

PAC42 recommendations	*BDX Collaboration response*
Full detector design	EMCal (800 CsI(Tl) crystals) +IV + OV, SiPM photosensor, fADC daq
Full simulations	GEMC (GEANT4), MCNP for detector response and beam bg evaluation
Background measurement	BDX detector prototype tacking cosmic data with similar overburden
Infrastructure cost estimate	Detailed cost estimate for a new underground facility at JLab
Theory and competition	Detailed theory motivation and comparison with other experiments