The BDX experiment at Jefferson Laboratory MonteCarlo tools for signal simulation

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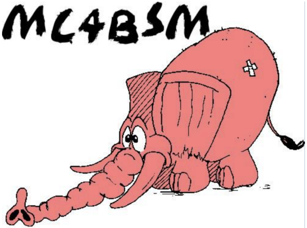
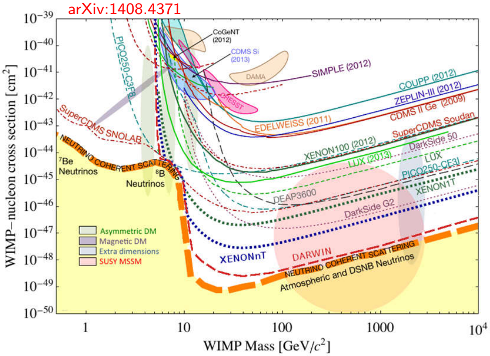


Outline

The dark sector

Dark matter: it is there, but very little is known about it! What is it? Where did it came from?

- "WIMP miracle:" electroweak scale masses ($\simeq$100 GeV) and DM annihilation cross sections (10^{-36} cm^2) give correct dark matter density / relic abundances. No need for a new interaction!
- Intense experimental program searching for a signal in this mass region. So far, no positive evidences have been found.
- What about **light dark matter**, in the mass range 1 MeV $\div$ 1 GeV?



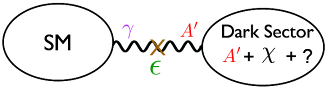
Light dark matter

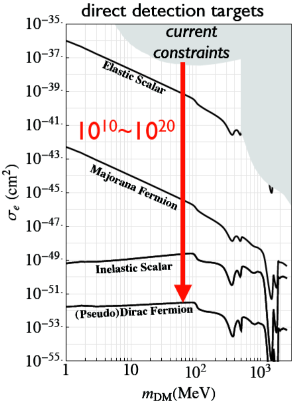
The light dark matter hypothesis can explain the (gravitationally) observed relic abundance, **provided a new interaction mechanism between SM and dark sector exists**.

- Simplest possibility: “vector-portal”. DM-SM interaction trough a new U(1) gauge-boson (“dark-photon”) coupling to electric charge.
- Model parameters: Dark-photon mass, M'_A and coupling to electric charge ε. Dark matter mass, M_χ and coupling to dark photon, g_D $(\alpha_D \equiv g_D^2/4\pi)$.

LDM direct detection
Non-relativistic thermal LDM:

- Hard to measure in direct detection (although DD is crucial to probe cosmogenic origin!) due to kinematic effects (low recoil energy)
- Huge parameters space due to different low-energy behavior of different mediators





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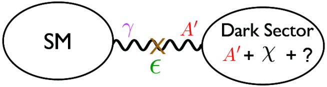
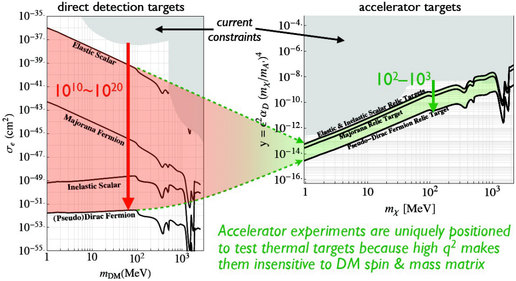


LDM at accelerators

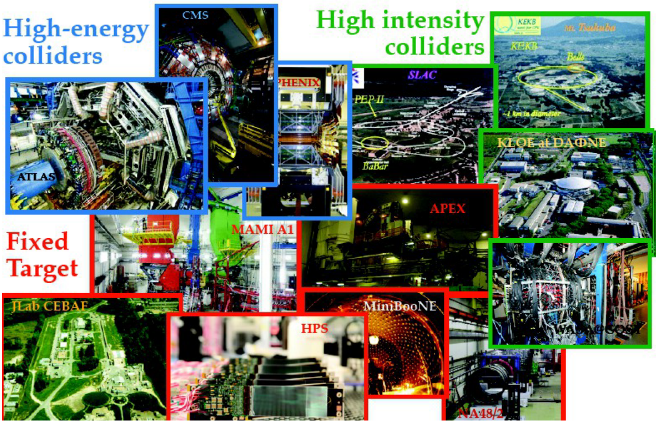


Natural parameters space to test thermal targets at accelerators:

- m_χ
- $y = \varepsilon^2 \alpha_D (m_\chi/m_{A'})^4$
- Fixed $m_\chi/m_{A'}$ ratio

Light dark matter searches at accelerators

In the past few years, many different and complementary programs were proposed (and some already started) to search for LDM at accelerators, looking both for LDM particles and for mediators



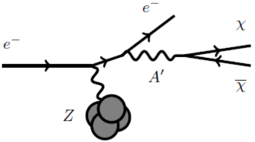
A fixed target, e^- beam LDM experiment

Beam Dump eXperiment: Light Dark Matter (LDM) direct detection in a e^- beam, fixed-target setup[1]

LDM parameters space:
M'_A, M_χ, ε, α_D
$M'_A \simeq 10 \div 1000$ MeV
$M_\chi \simeq 1 \div 100$ MeV

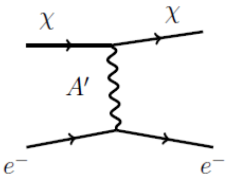
χ production

- High-energy, high-intensity e^- beam impinging on a dump
- χ particles pair-produced radiatively, trough A' emission

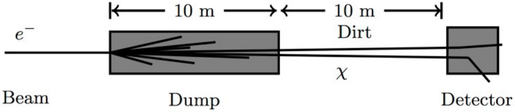


χ detection

- Detector placed behind the dump, $\simeq 20m$
- Neutral-current χ scattering on atomic e^- trough A' exchange,recoil releasing visible energy
- Signal: high-energy - O(GeV) - EM shower

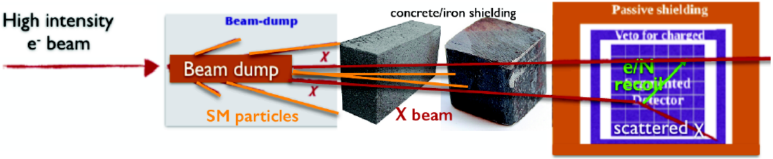


Number of events scales as: $N \propto \frac{\alpha_D \varepsilon^4}{m_A^4}$



[1] For a comprehensive introduction: E. Izaguirre *et al*, Phys. Rev. D 88, 114015

BDX experiment layout



The experiment is designed with two goals:

Producing and detecting LDM

- High-intensity e^- beam, $\simeq 10^{22}$ electrons-on-target (EOT)/year
- Medium-high energy, >10 GeV
- $\simeq 1\ m^3$ (1-5 tons) detector
- EM-showers detection capability

Reducing background

- Passive shielding between beam-dump and detector to filter beam-related backgrounds (except νs)
- Passive shielding and active vetos surrounding the active volume to reduce and identify cosmogenic backgrounds
- Segmented detector for background discrimination based on event topology
- Good time resolution to perform detector-veto coincidence

BDX detector

BDX detector: state-of-the-art EM calorimeter, CsI(Tl) crystals with SiPM-based readout.

Detector design:

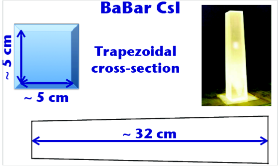
- $\simeq$ 800 CsI(Tl) crystals, total interaction volume $\simeq 0.5m^3$
- Dual active-veto layer, made of plastic scintillator counters with SiPM readout

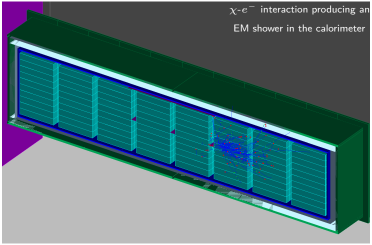
Calorimeter arrangement:

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

Signal:

- EM-shower, $E_{thr} \simeq 300$ MeV, anti-coincidence with IV and OV
- Efficiency (conservative): O($10\% - 20\%$) - dominated by EM shower splash-back to veto counters





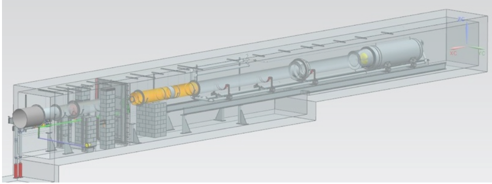
Jefferson Laboratory

Jefferson Laboratory (Newport News, VA) is home for the CEBAF electron accelerator, based on superconducting RF technology.

Plan to run BDX behind Hall-A beam-dump

- Ideal beam conditions for the experiment: $E_0 = 11 GeV$, I up to $\simeq$ 60 μA
- Already-approved experiments with more than 10^{22} EOT (Moller, PVDIS)
- BDX is compatible with these planned experiments and can run parasitically with them

Hall-A beam-dump: Aluminum plates immersed in water for cooling.

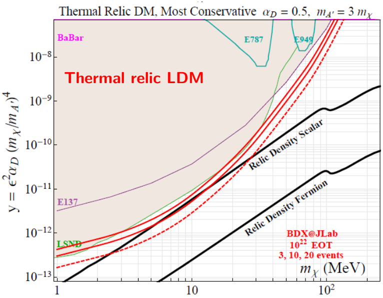


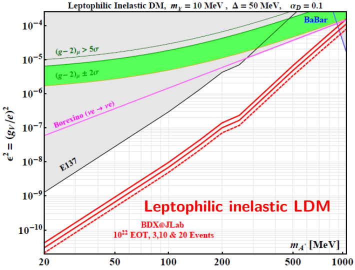
BDX@JLab: reach

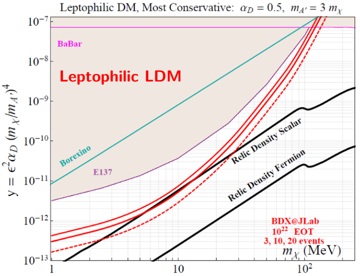
BDX reach: determined by foreseen backgrounds. Dominant contribution: beam-related ν_e, CC scattering in the detector. O(few) counts per 10^{22} EOT.

The BDX sensitivity for different LDM models has been evaluated - 10^{22} EOT:

- Thermal relic LDM
- Leptophilic LDM
- Leptophilic inelastic LDM



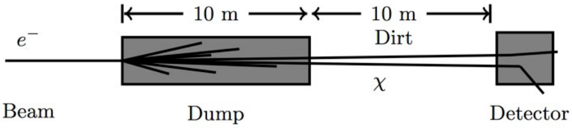




Overview

Goal: determine the total number of signal events in the detector for a given combination of model parameters
Strategy: factorize the event generation, as in the real physical process

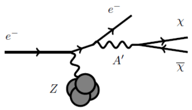
- χ-beam generator: simulate the interaction of the primary e^- beam in the dump (thick-target) and produce the secondary χ beam, with absolute normalization per EOT.
- Recoils generator: given the secondary χ-beam, produces the scattered e^- in the detector.
- Detector simulation: given the scattered e^-, simulates the detector response.



χ generator

Process: $e^- + Al \rightarrow e^- + Al + \chi + \overline{\chi}$
Goal:

- Compute the total $\chi-$flux per electron-on-target
- Generate final state 4-momenta according to dσ



Code: customized version of MadGraph/MadEvent 4 to simulate fixed-target process

- Initial state particle masses
- New particles (A', χ) and new couplings $(A' - e$ and $A' - \chi)$
- New momentum-dependent form factor for photon-nucleus interactions

Momentum-dependent FF: accounts for nuclear effects in *coherent* $e^- - Al$ interaction

- $G_{2,el}(t)$: elastic form factor
- $G_{2,in}(t)$: quasi-elastic form factor

$$G_{2,el}(t) = \left(\frac{a^2 t}{1 + a^2 t}\right)^2 \left(\frac{1}{1 + t/d}\right)^2 Z^2$$

$$G_{2,in}(t) = \left(\frac{a'^2 t}{1 + a'^2 t}\right)^2 \left(\frac{1 + \frac{t}{4m_p^2}(\mu_p^2 - 1)}{(1 + \frac{t}{0.71\,\mathrm{GeV}^2})^4}\right)^2 Z$$

Particles.dat:

```
f-    f+    F    S    FMASS   FWIDTH    S   f    611
x     x     V    W    APMASS  APWIDTH   S   A'   622
N-    N+    F    S    HPMASS  HPWIDTH   S   P    623
```

Interactions.dat:

```
N-  N-  a   GAN   QND
f-  f-  x   GEAPX QDS
e-  e-  x   GEAP  QDS
```

Couplings.f:

```
      Anuc = 26.98
      aval = 111.0/( elemass*Znuc**(1.0/3.0) )
      dval = 0.164/Anuc**(2.0/3.0)
      apval = 773.0/( elemass*Znuc**(2.0/3.0) )

      tval = -(pp(0,Nin)-pp(0,Nout))**2
     $       +(pp(1,Nin)-pp(1,Nout))**2
     $       +(pp(2,Nin)-pp(2,Nout))**2
     $       +(pp(3,Nin)-pp(3,Nout))**2

      fullcoupling = ee * (Znuc**2 *aval**4 *
     $     tval**2/((1+aval**2*tval)*(1+tval/dval))**2 +
     $     Znuc * apval**4 * tval**2 * (1+1.9276*tval)**2 /
     $     ((1+apval**2*tval)*(1+1.40845*tval)**4)**2 )**0.5
```

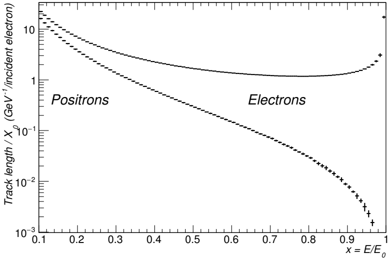
χ generator: thick-target effects

Thin target kinematics (on-shell A'):

- A' emitted forward, $E_A \simeq E_0$
- χ beam forward peaked

e^- in the dump:

- Energy loss: χ kinematics gets broader
- Secondary e^-/e^+ are produced: more χ particles are emitted

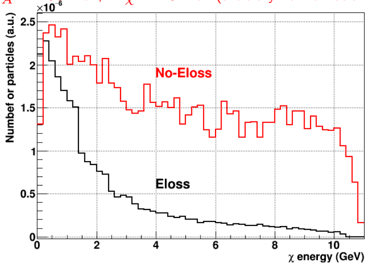


To account for this:

$$\frac{dN}{dE_{A'}} \propto \int_{E_{min}}^{E_0} dE_e T_+(E_e) \frac{d\sigma(E_e)}{dE_{A'}}$$

- "Traditional" approach: $T_+ = X_0 \delta(E_0 - E_e)$
- Our approach: perform full calculation.
  - Evaluate $T_+(E_e)$ with MonteCarlo (G4)
  - Perform multiple MG4 runs, with different primary beam energy
  - Sum runs with weight $T_+(E_e)$
  - Implementation: external python script calling MG4 with proper cards

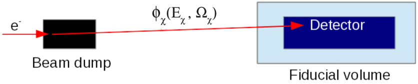
χ energy distribution for $E_0 = 11$ GeV
$M_A = 100$ MeV, $M_\chi = 10$ MeV (arbitrary normalization)



Recoil generator

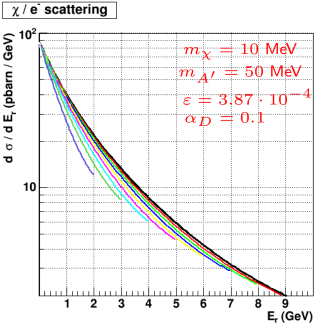
Process: $\chi + e^- \rightarrow \chi + e^-$
Goal:

- Compute the total number of scattering events in the detector
- Generate final state 4-momenta according to dσ



Input from χ generator: $\Phi_\chi(E_\chi, \Omega_\chi)$
Code: standalone C++ code
Interaction cross-section:

$$\frac{d\sigma_{\chi e}}{dE_R} = 4\pi\alpha\alpha_D\varepsilon^2 m_e \frac{4m_e m_\chi^2 E_R + \left[m_\chi^2 + m_e(E_\chi - E_R)\right]^2}{(m_{A'}^2 + 2m_e E_R)^2(m_\chi^2 + 2m_e E_\chi)^2}$$



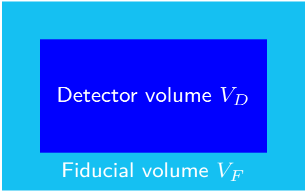
- Smooth 1-dimensional function, easy to integrate and to sample.
- Function depends on incoming χ energy E_χ:
  - To avoid function integration event by event, bin in E_χ before generating events (from 0 to Ebeam)
  - For each event, use the cross-section computed at the bin center

Recoil generator

Decouple the $\chi - e^-$ interaction simulation from the detector response simulation, and use Geant4 for the latter.

$$N_D = \int_{V_D} \frac{d\Phi_\chi}{dE_\chi d\Omega_\chi} \frac{d\sigma_I(E_\chi)}{dE_r} n_p dE_\chi d\Omega_\chi dE_r$$

- Define a fiducial volume V_F, with $V_F > V_D$ (also include E_r in this)
- Use V_F to calculate N_F and to generate 4-vectors
  - $\lambda_\chi \gg L_D$: generate events uniformly. For each χ generate the interaction vertex uniformly along the part of the trajectory that lies within V_F
  - Following G4 simulation is designed to ignore cases with recoil generated in V_F but not in V_D
- Compute the detector response as: $N_D = N_F \cdot \varepsilon$
- ε is calculated trough G4 simulation



Detector simulation

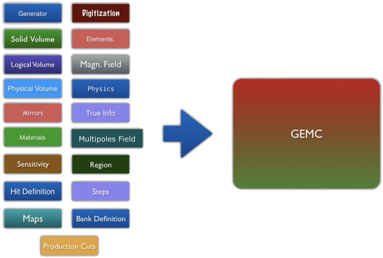
Process: e^- interaction with detector material (EM shower)
Goal:

- Simulate the detector response, in terms of measured observables
- Compute the overall detector efficiency

Input from recoil generator: scattered electrons 4-momenta and vertexes
Code: GEant4 Monte-Carlo (GEMC) software[2], developed by M. Ungaro @ JLAB

GEMC is a C++ program that simulates particles through matter using Geant4 libraries.

- User specifies materials and geometry (volumes / surfaces) in a perl script, using a GEANT4-classes like syntax
- Materials and geometry are uploaded to a database
- GEMC loads the geometry and automatically constructs the detector.
- Similar procedure for detector response/digitization



[2] http://gemc.jlab.org

Conclusions

- Dark matter in the MeV-to-GeV range is largely unexplored
- **Beam Dump eXperiment** at JLab: search for Dark sector particles in the 1 $\div$ 1000 MeV mass range
  - High intensity ($\simeq 10^{22}$ EOT/year), high energy (11 GeV) e^- beam
  - Detector: $\simeq 800$ CsI(Tl) calorimeter + 2-layers active veto + shielding
  - BDX proposal submitted to JLab PAC 44 (2016) - **conditionally approved**.
- Strategy for signal yield evaluation follows the "dual-step" nature of the experiment:
  - Factorize χ production in the beam-dump, $\chi - e^-$ scattering in the detector, and detector response evaluation
  - Use specific code for each step: where possible, adapt existing tools to the specific experimental setup

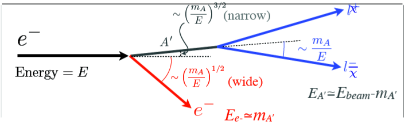
Backup slides

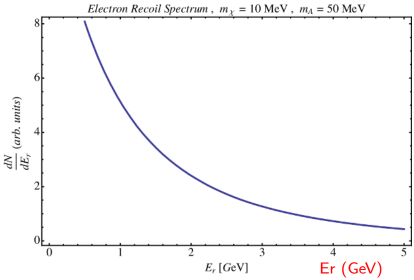
Production: Main features follows from thin-target kinematics $*$ e^- energy loss and secondaries emission in the dump

- Thin target kinematics:
  - A' emitted with forward kinematics, $E'_A \simeq E_0$
  - High-energy χ beam strongly focused along primary beam direction - allowing a compact detector
- e^- in the dump: e^- loses energy by ionization and Bremsstrahlung, χ kinematics gets broader

Detection: $\chi - e^-$ elastic scattering

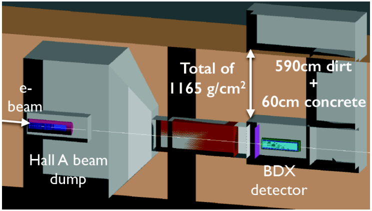
- e^- recoil: EM shower (O(GeV))
- Background rejection is not critical

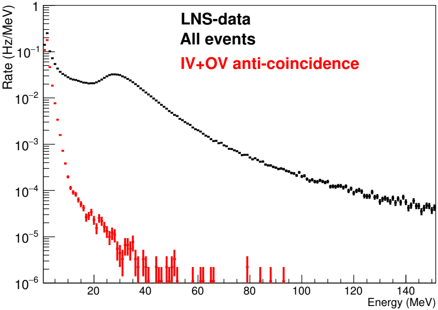




Cosmogenic backgrounds

- Cosmic backgrounds have been measured with a small-scale prototype in a similar overburden configuration as foreseen in BDX
- The majority of cosmic muons are detected and rejected by the veto counters, while cosmic neutrons are shielded by the overburden
- Measured anti-coincidence rate ($E_{thr} \simeq 300$ MeV) < 2 counts: results obtained by conservatively extrapolating from the lower-E, non-zero counts region, projecting to the JLab setup (800 crystals)





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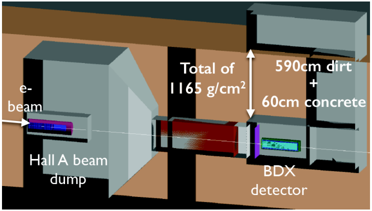
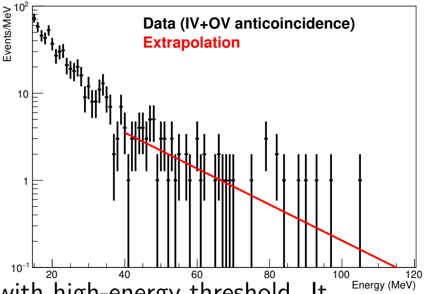
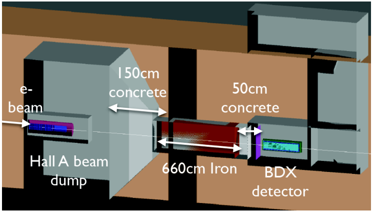


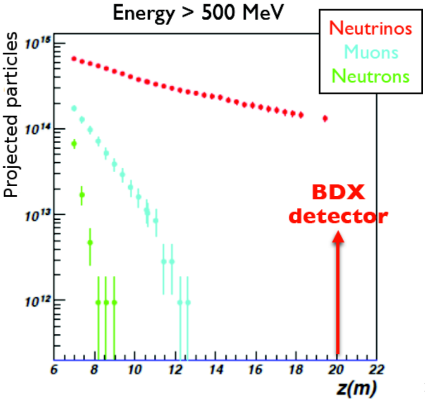


Cosmogenic background is negligible with high-energy threshold. It will be measured on-site when beam is off

Beam-related backgrounds estimated trough MC simulations (Geant4/Fluka) Challenge: very high EOT. Solutions:

- Sample non-zero flux as a function of depth and propagate to detector location (G4)
- Use biasing (Fluka)





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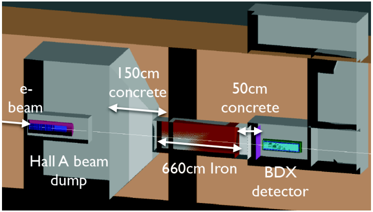
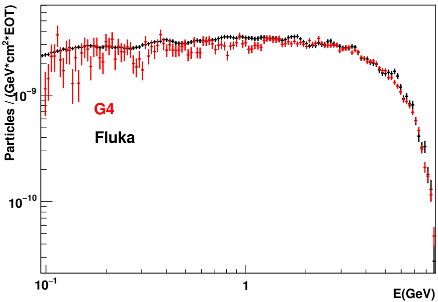
Muons

- High-energy muon production in the dump dominated by the $\gamma \to \mu^+\mu^-$ 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 is foreseen (see next slide)
- 6.6m iron shield (+2 m concrete) enough to range-out high energy muons: no particles at the detector location





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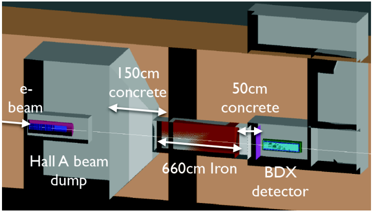
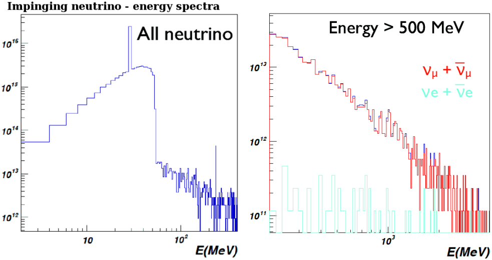
Neutrinos: only particles reaching the detector

- Spectrum mainly at low-energy, dominated by μ^+ decay / μ^- capture on nuclei
- High-energy part from in-flight decays and prompt production processes





Possible background contribution from ν_e interacting via CC in the detector, producing a high-energy $e^\pm$ resulting in a EM shower

Neutrino irreducible background is the ultimate limitation for BDX.

Estimate ($E_{thr} \simeq 300$ MeV): $N_{\nu_e+\overline{\nu}_e} = O(1)$ counts for 10^{22} EOT