HPS Collaboration Meeting
June 18th 2014

BDX
Dark matter search in a Beam Dump eXperiment at Jefferson Lab

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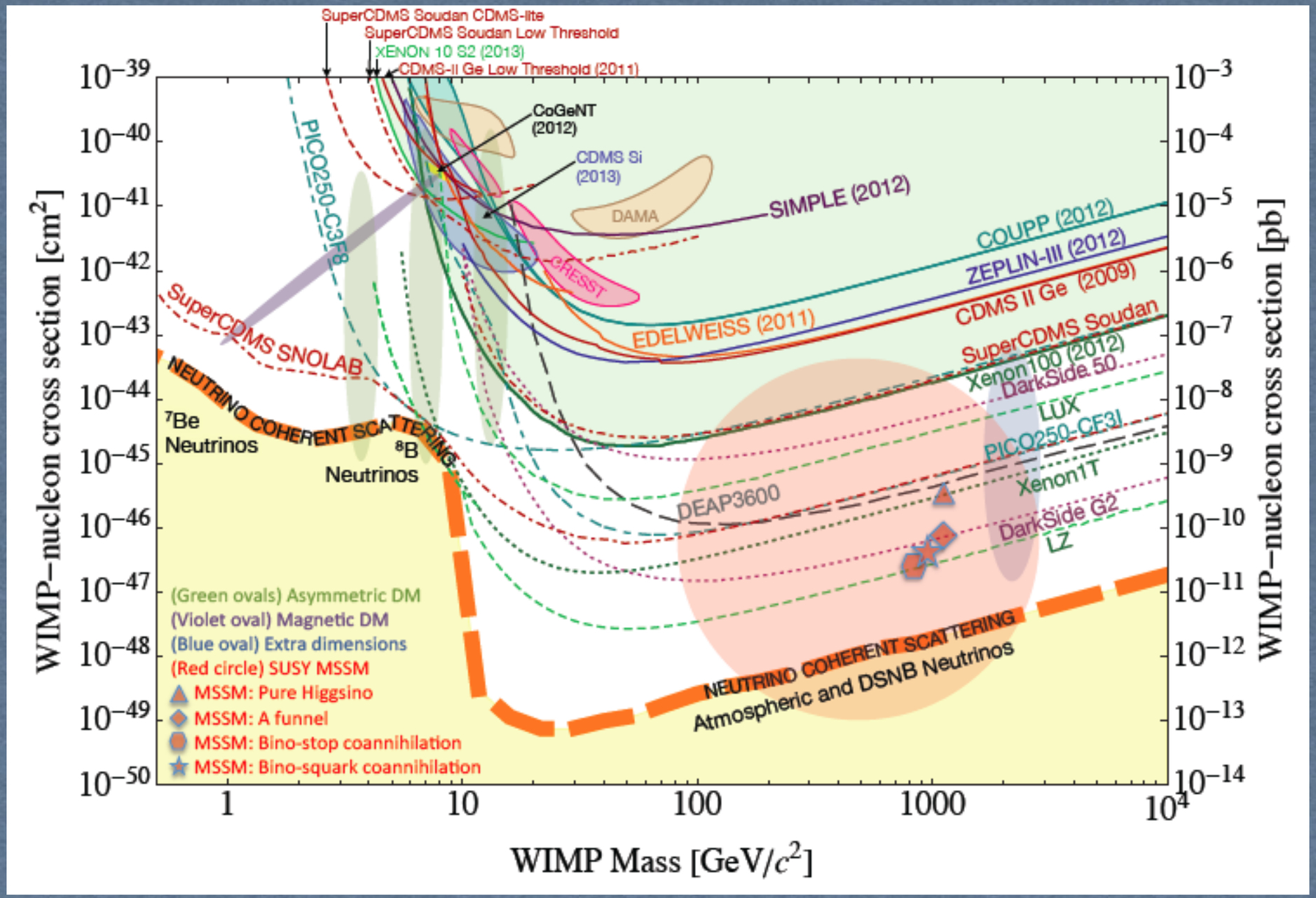
INFN-GE Italy

Physics Motivations

Dark matter (DM) direct search mainly focused in the mass region 10 GeV -10 TeV

- WIMP: weakly interacting massive particles with weak scale mass provides the correct DM relic abundance
- No signal in direct detection



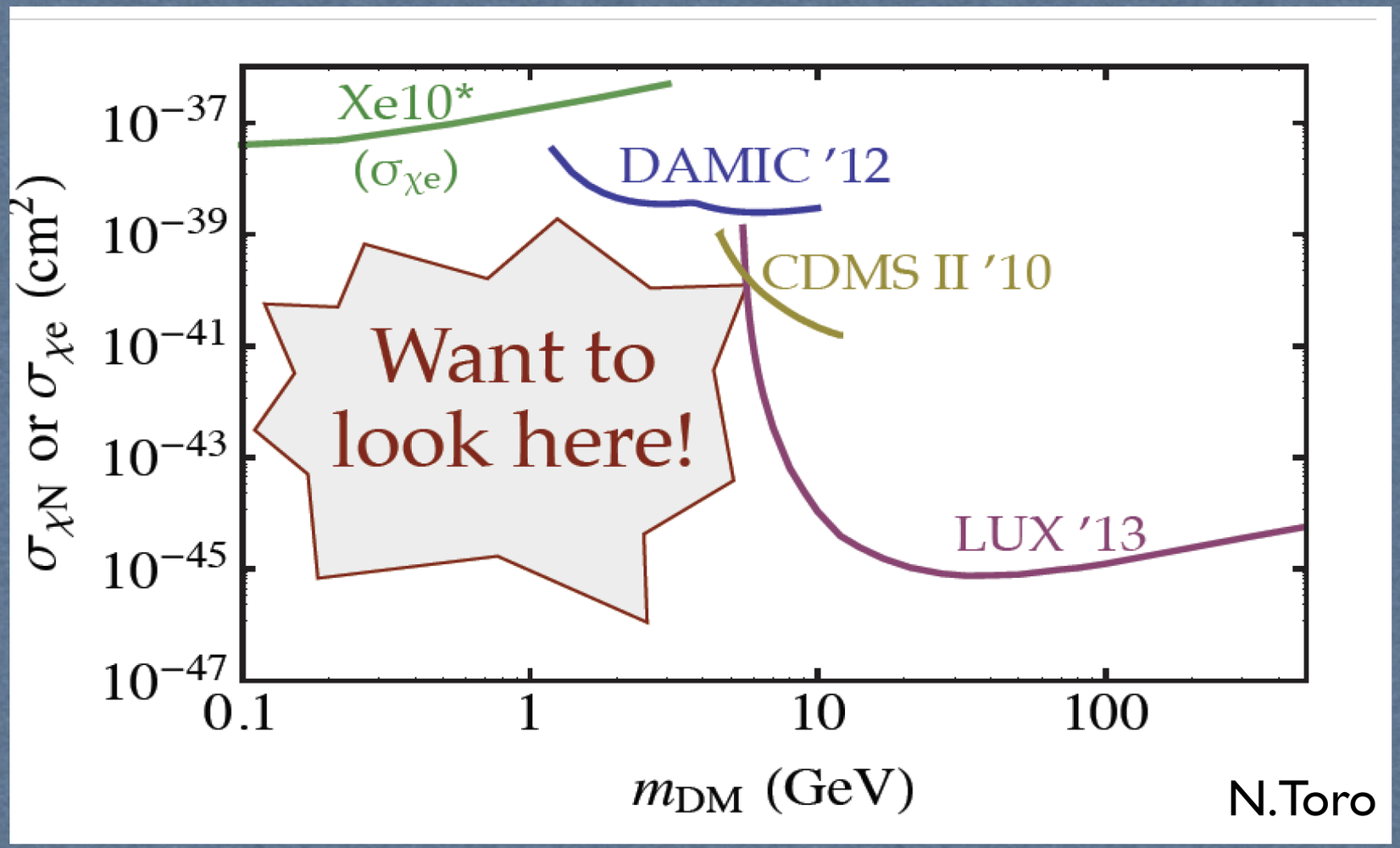
DM detection by measuring the (heavy) nucleus recoil of slow moving cosmological DM
→ no experimental sensitivity to light DM (<1 GeV)

Physics Motivations

Accelerators-based DM search is covering a similar mass region but can extend the reach outside the classical DM hunting territory

Many theoretical suggestions and experimental attempts to extend the search region to:

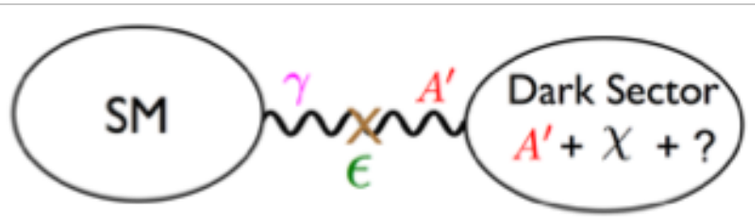
- **Higher mass (> 10 TeV)**
  LHC, Rare decays, …
- **Lower Mass (<10 GeV)**
  MiniBoone@FNAL, SPS@CERN, PADME@LNF

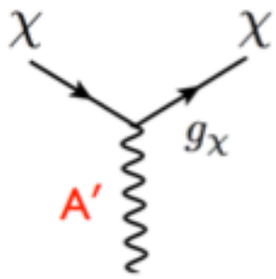


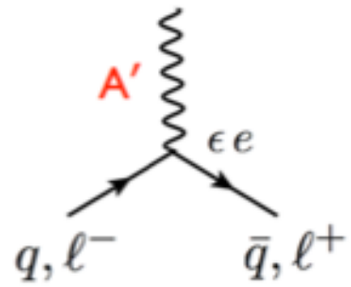
Beam dump (e^-) experiments can provide unprecedented sensitivity to light dark matter
Jefferson Lab can play a significant role in light DM search

Physics Motivations

Theory suggests scenarios where light DM (χ) interacts with SM particle by a light mediator (A')



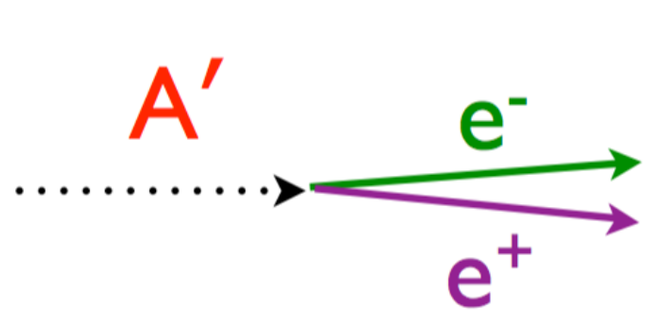




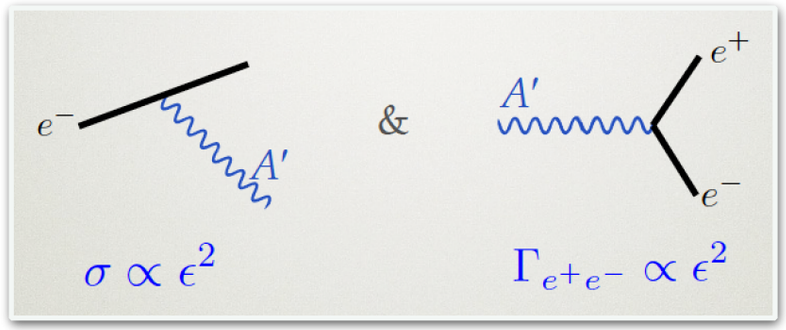
4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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

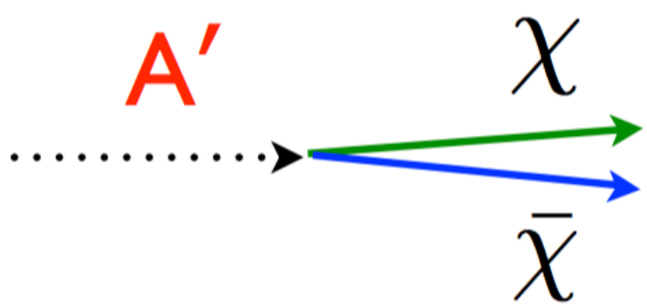
Visible



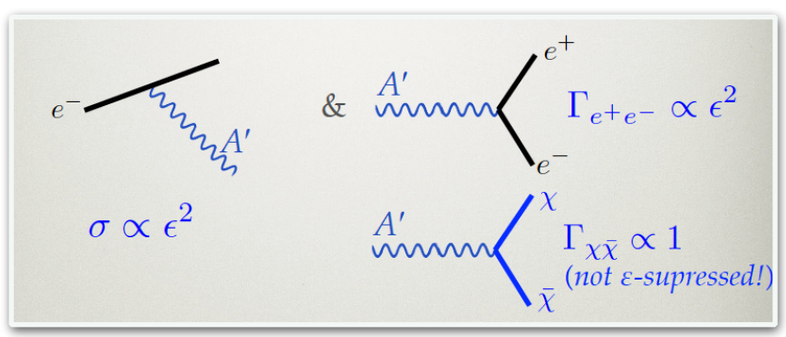
- *Minimal* decay
- Decay ∝ ε^2
- It does not depend on m_χ
- It requires $m_{A'} < 2m_\chi$



Invisible



- Natural extension of the model
- $m_\chi < 2m_{A'}$
- stable and invisible
- It does not depend on ε



Physics Motivations

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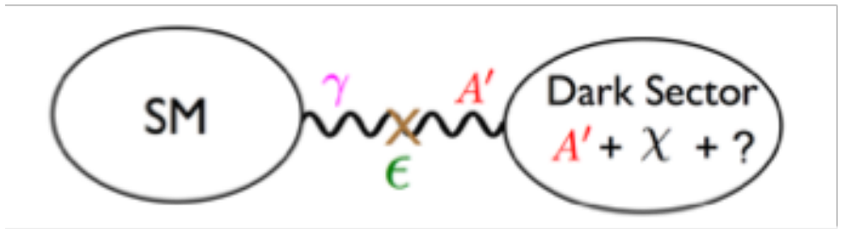

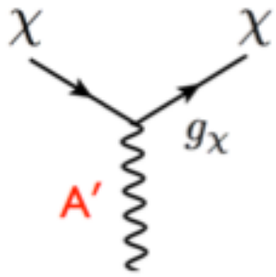

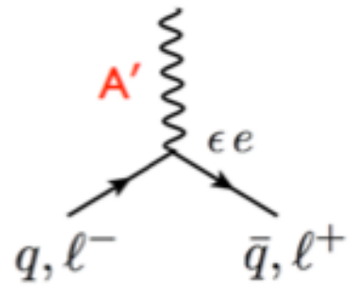

4 parameters: $m_\chi, m_{A'}, \epsilon, g_\chi$

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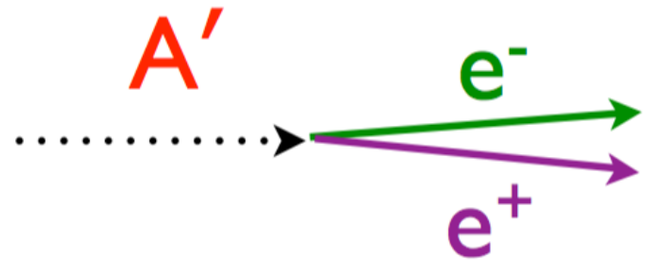
Visible

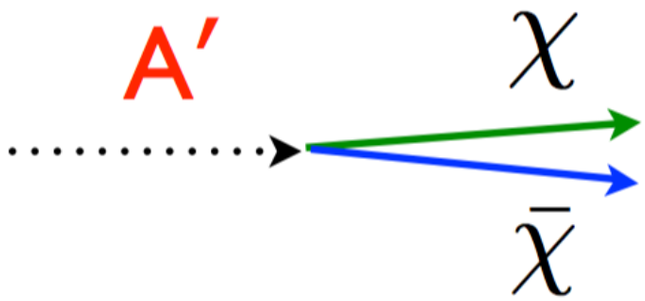


- *Minimal* decay
- Decay $\propto \varepsilon^2$
- It does not depend on m_χ
- It requires $m_{A'} < 2m_\chi$

HPS, APEX, DarkLight

Approved experiments at JLab

Invisible



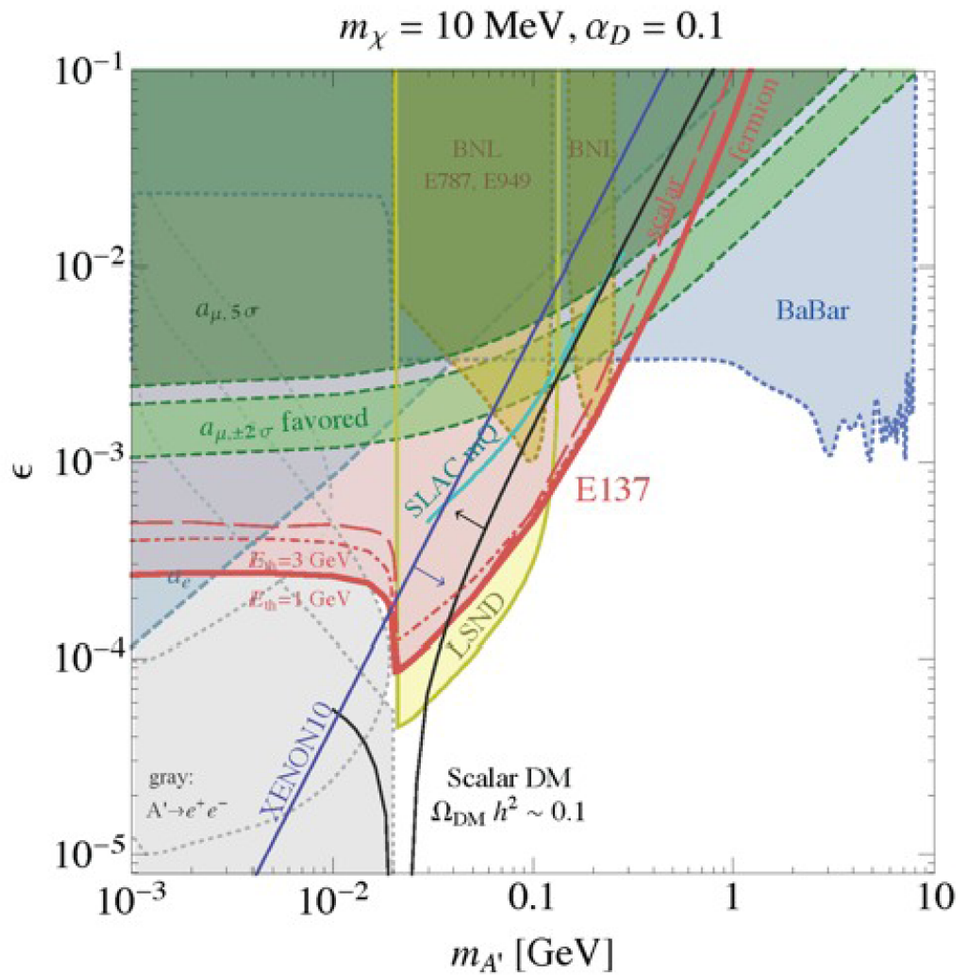
- $m_\chi < 2m_{A'}$
- i) stable and invisible
- ii) decay to SM particles
- It does not depend on ε

Beam Dump eXperiment (BDX)

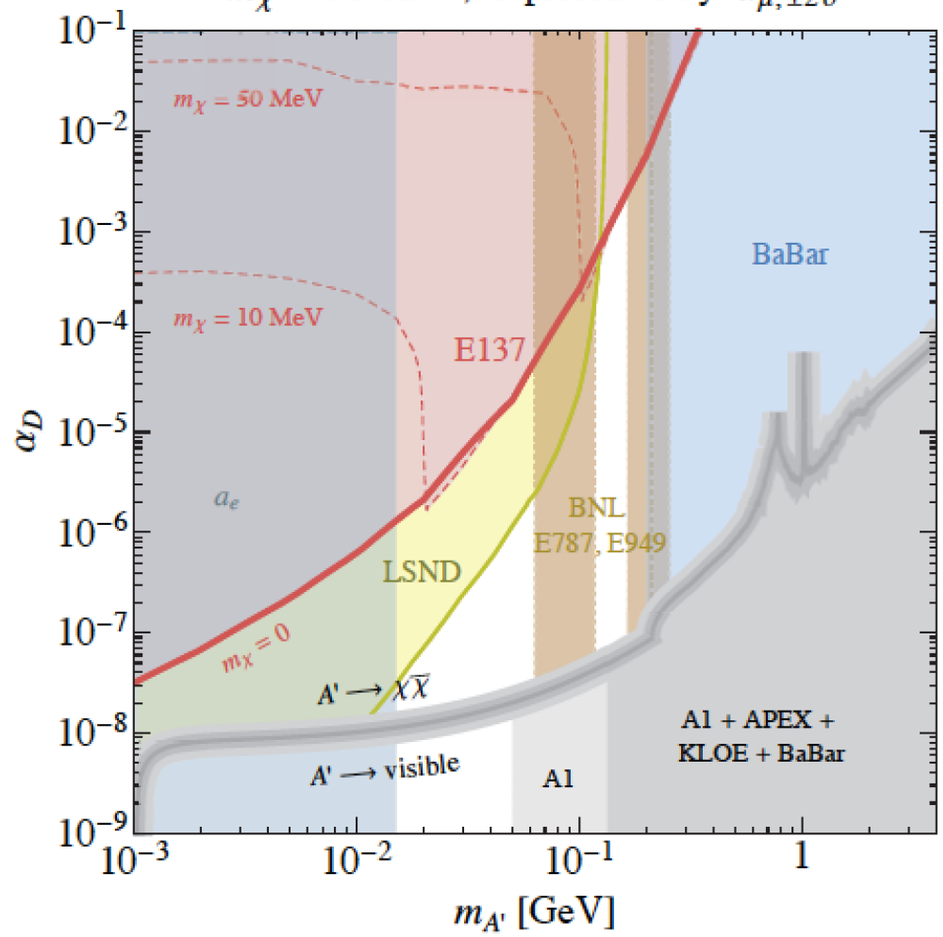
Letter of Intent to JLab PAC42

Visible vs Invisible: complementarity
$(g\text{-}2)_\mu$

Visible only



Visible + Invisible



Strong Constraints on Sub-GeV Dark Matter from SLAC Beam Dump E137
http://arxiv.org/abs/1406.2698 Brian Batell, Rouven Essig, Ze'ev Surujon

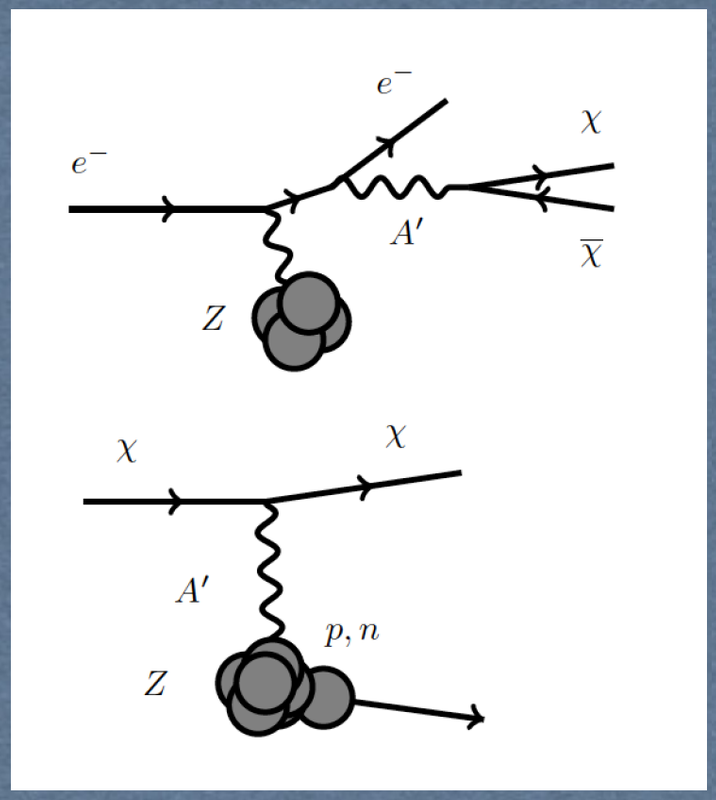
- Reinterpretation of existing data are ruling out $(g\text{-}2)_\mu$ favoured region
- Exclusion limits are model dependent: if invisible decay is included limits do not hold!

Physics Motivations

How to experimentally access **invisible decay**?

I) Elastic scattering on nucleon

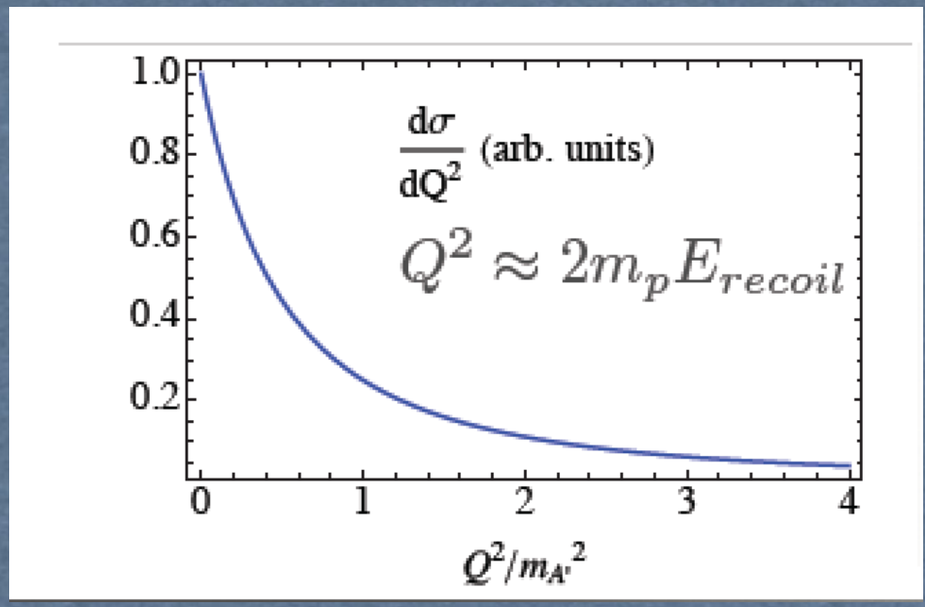
Two steps process:



An electron irradiates an A'
The A' decays to a χ pair

The χ elastically elastically scatters on a nucleon in the detector producing a visible recoil (~MeV)

Nucleon recoil: sizeable cross section for T_N>1-10 MeV



Experimental requirements:

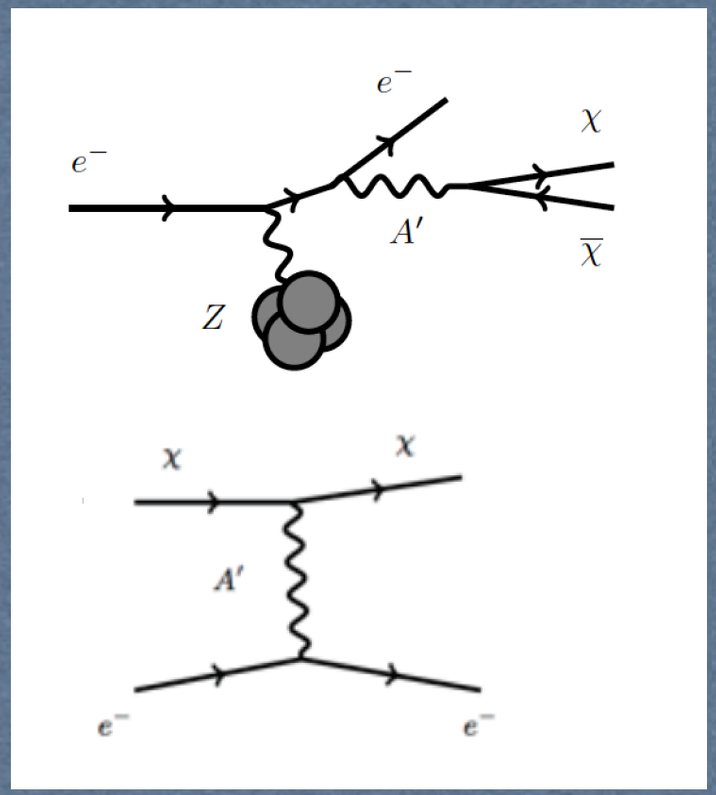
- sensitivity to ~MeV nucleon recoil (low detection thresholds)
- low energy background rejection capability

Physics Motivations

More favourable scenarios:

II) Elastic scattering on electrons

Two steps process:

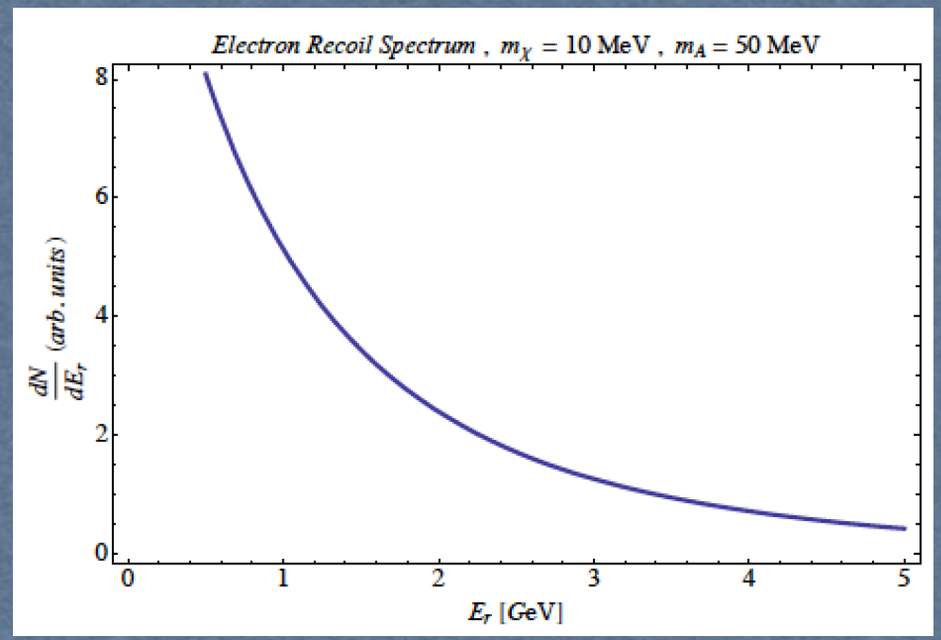


An electron irradiates an A'

The A' decays to a χ pair

The χ elastically elastically scatters on an electron in the detector producing a visible recoil (~GeV)

Electron recoil



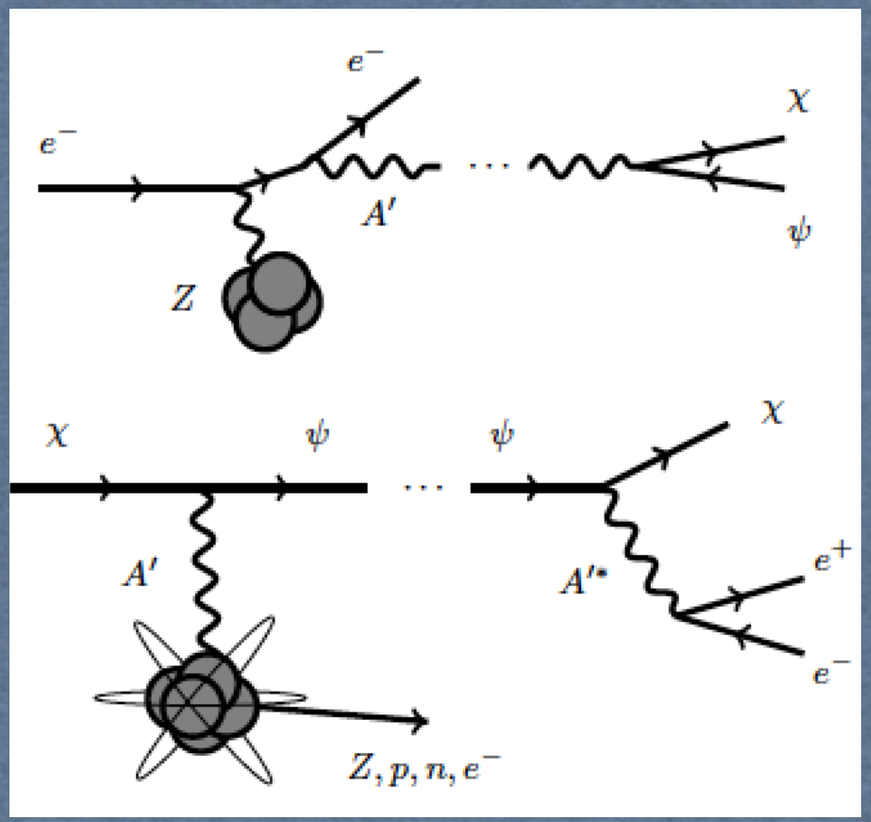
Experimental requirements:

- sensitivity to ~GeV electrons (electromagnetic showers)
- easy background rejection

Physics Motivations

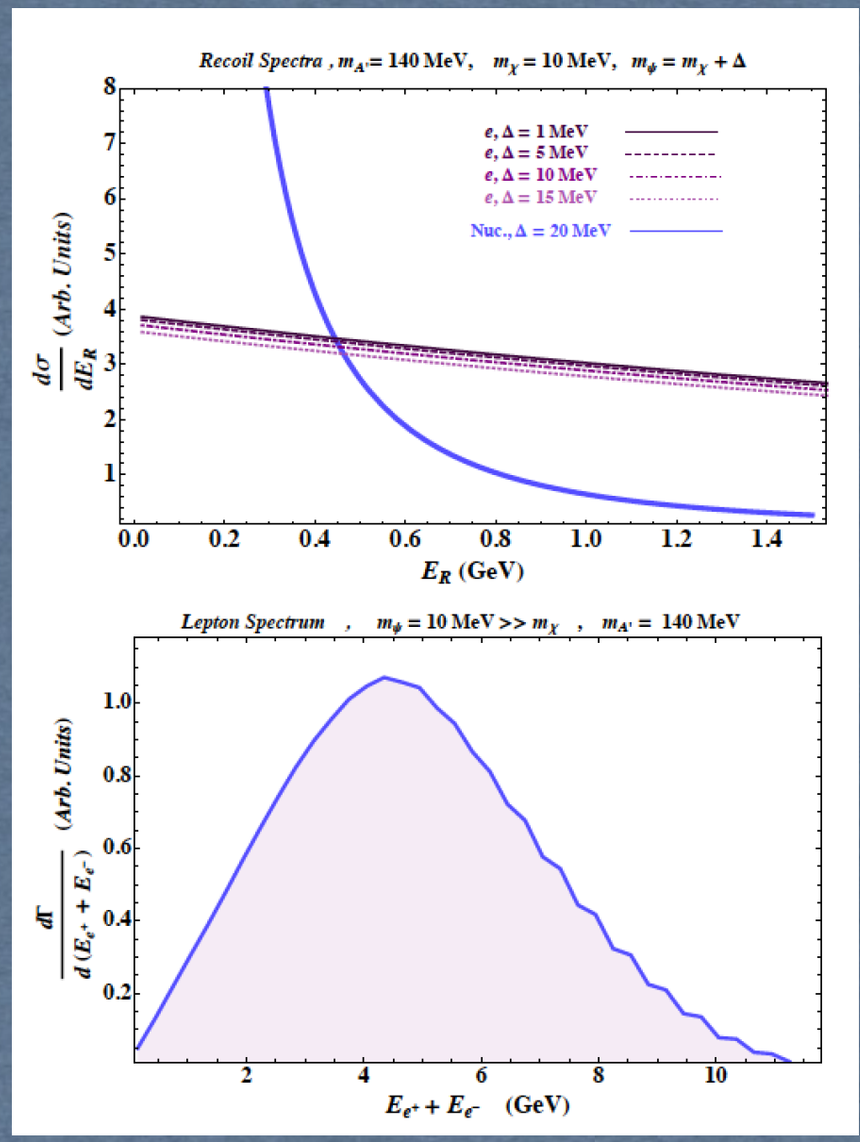
More favourable scenarios:

III) Inelastic χ-N,e⁻ scattering



An electron irradiates an A'
The A' decays to a χ Ψ pair
(where Ψ is an excited χ)
and the Ψ decays promptly to
χ e^+e^-

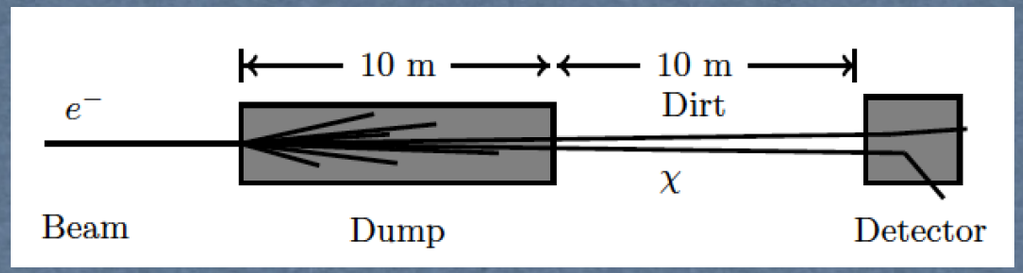
The χ scatters inelastically off the nucleon/electrons of the detector producing a Ψ that subsequently decays to χ e^+e^- in the detector

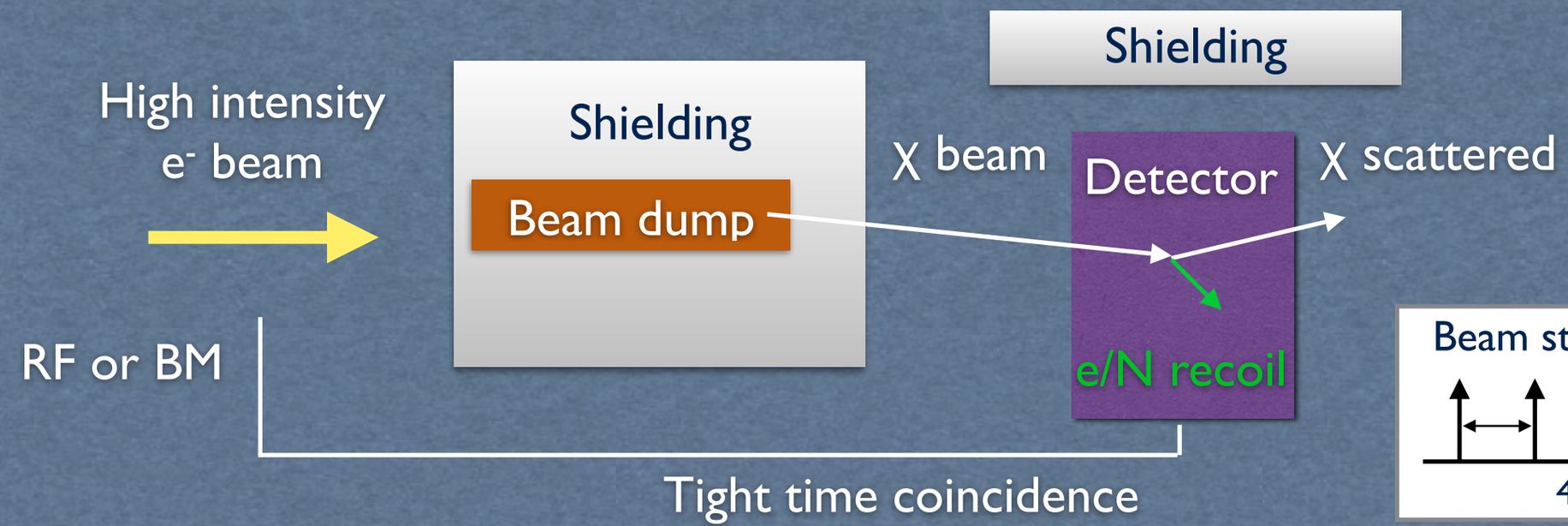


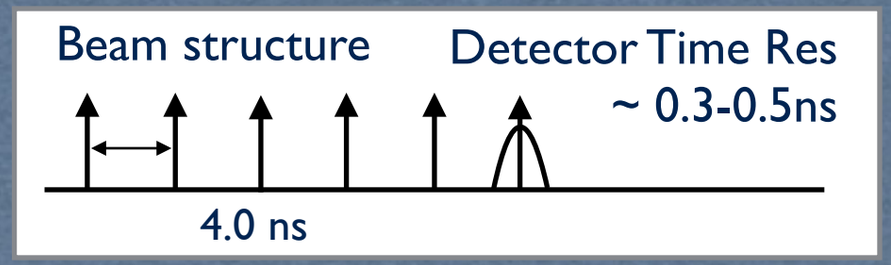
Experimental requirements:

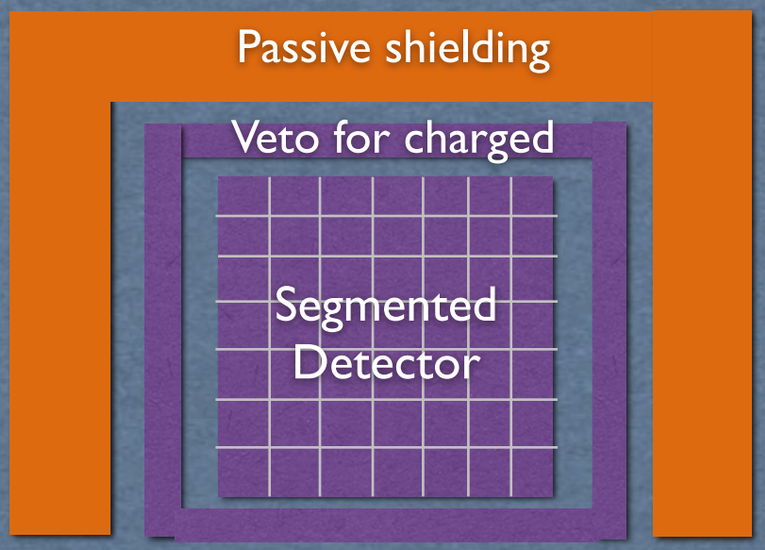
- sensitivity to ~100 MeV nucleon recoil and ~ GeV electrons (em showers)
- low background

Experimental technique









Detector requirements

- Good time resolution to reject beam-uncorrelated background
- Segmentation for bg rejection
- Active veto
- Passive shielding
- Low threshold for nucleon recoil detection (~MeV)
- EM showers detection capability

~1 m^3 segmented plastic scintillator + lead foils

JLab electron beam-dumps

Hall-A/Hall-C

- E~11GeV
- high current (~100-200uA)
- Parasitic run
- No room behind the beam dump enclosure
- Ideal place for a full experiment

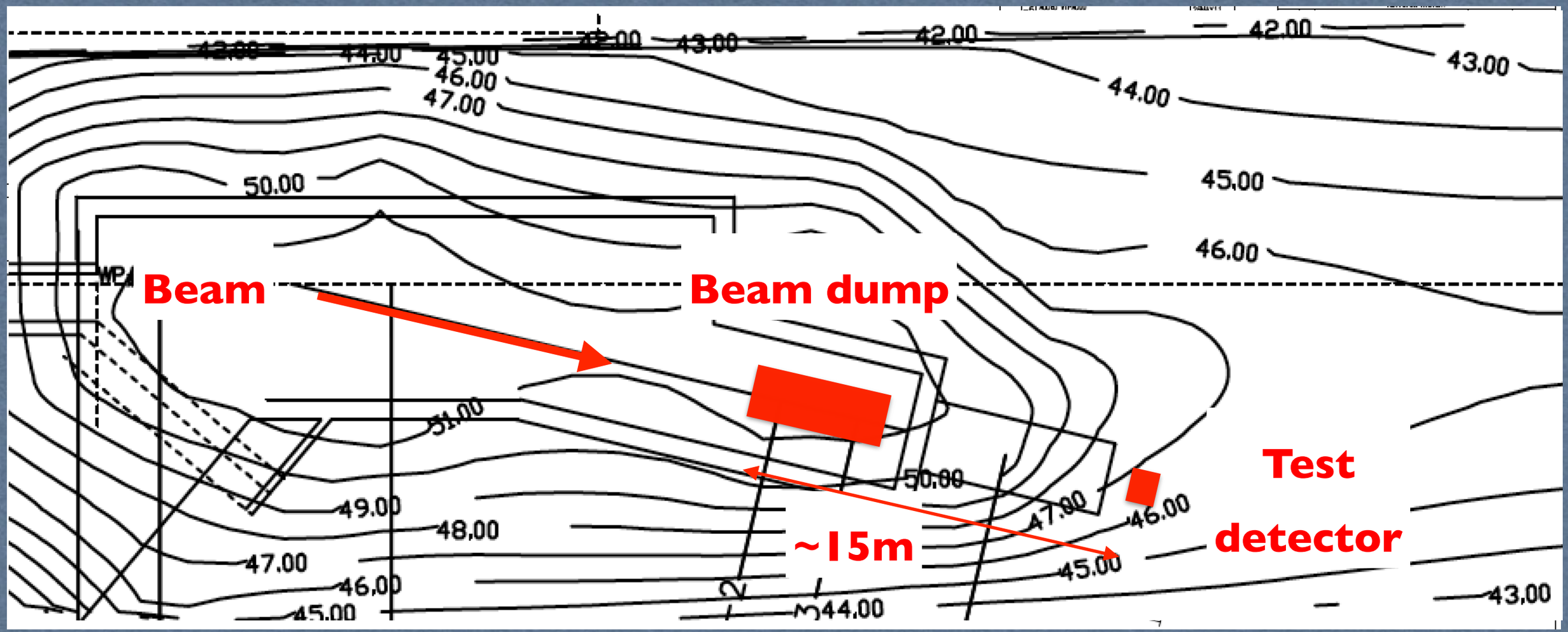
Hall-B

- E~11GeV
- moderate current (~200nA)
- Same area as HPS setup
- Difficult access to beam dump enclosure
- interference with HPS magnet

JLab electron beam-dumps

Hall-D

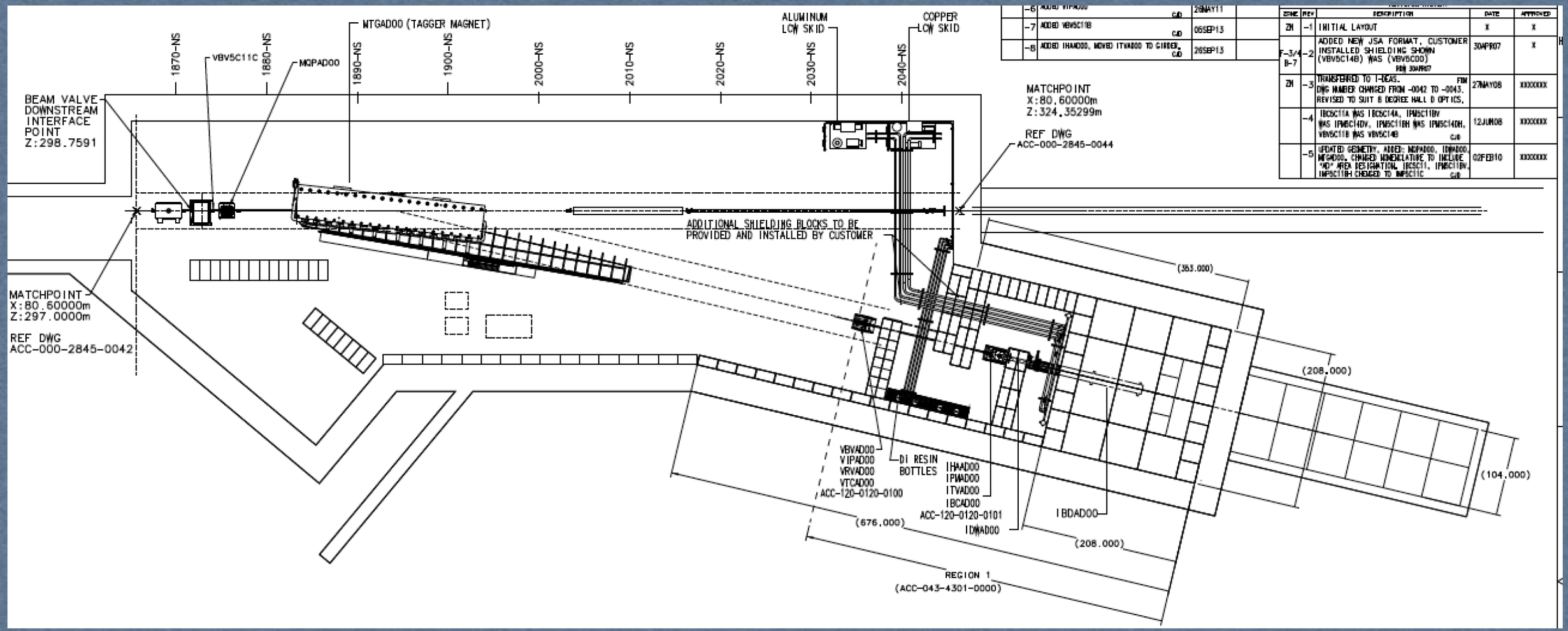
- E~12GeV
- moderate current ~200nA (may be increased up to 8 uA!)
- Over-the-ground beam dump
- Easy access to the back of the BD enclosure
- Simplified logistic: (shielded roof) hut, power, network, A/C



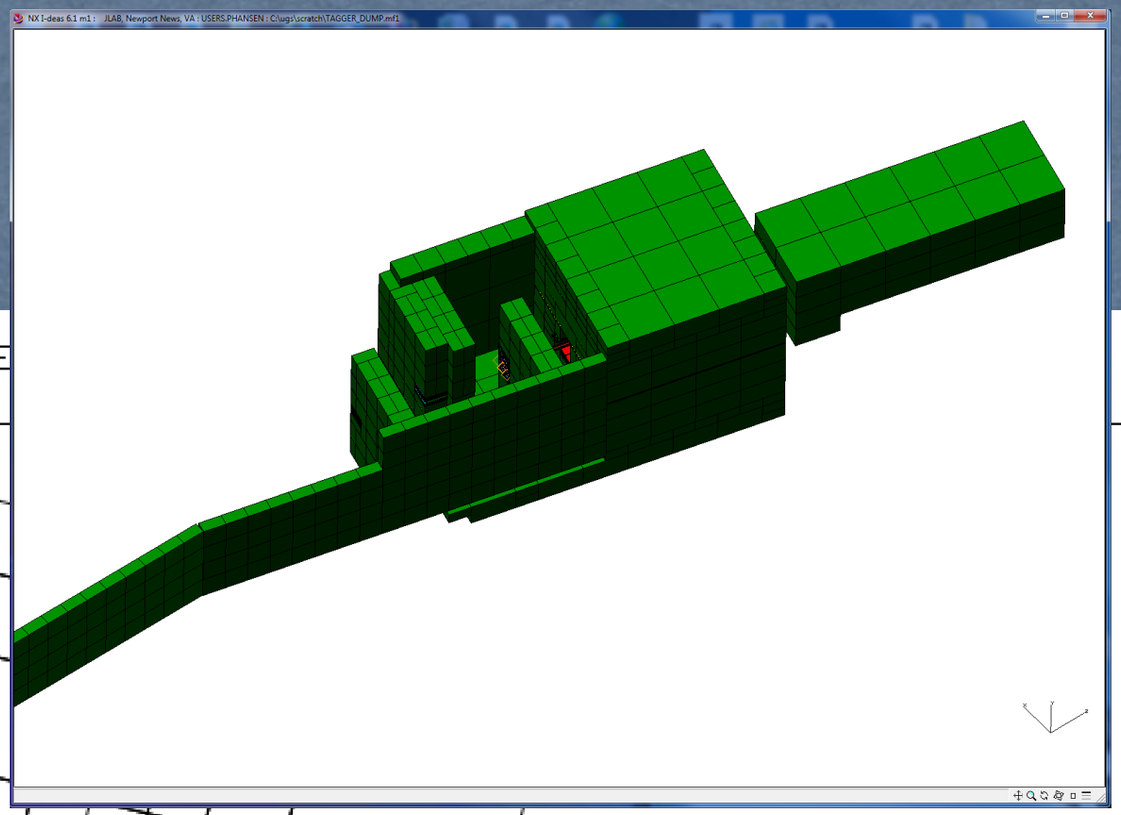
JLab Hall-D option

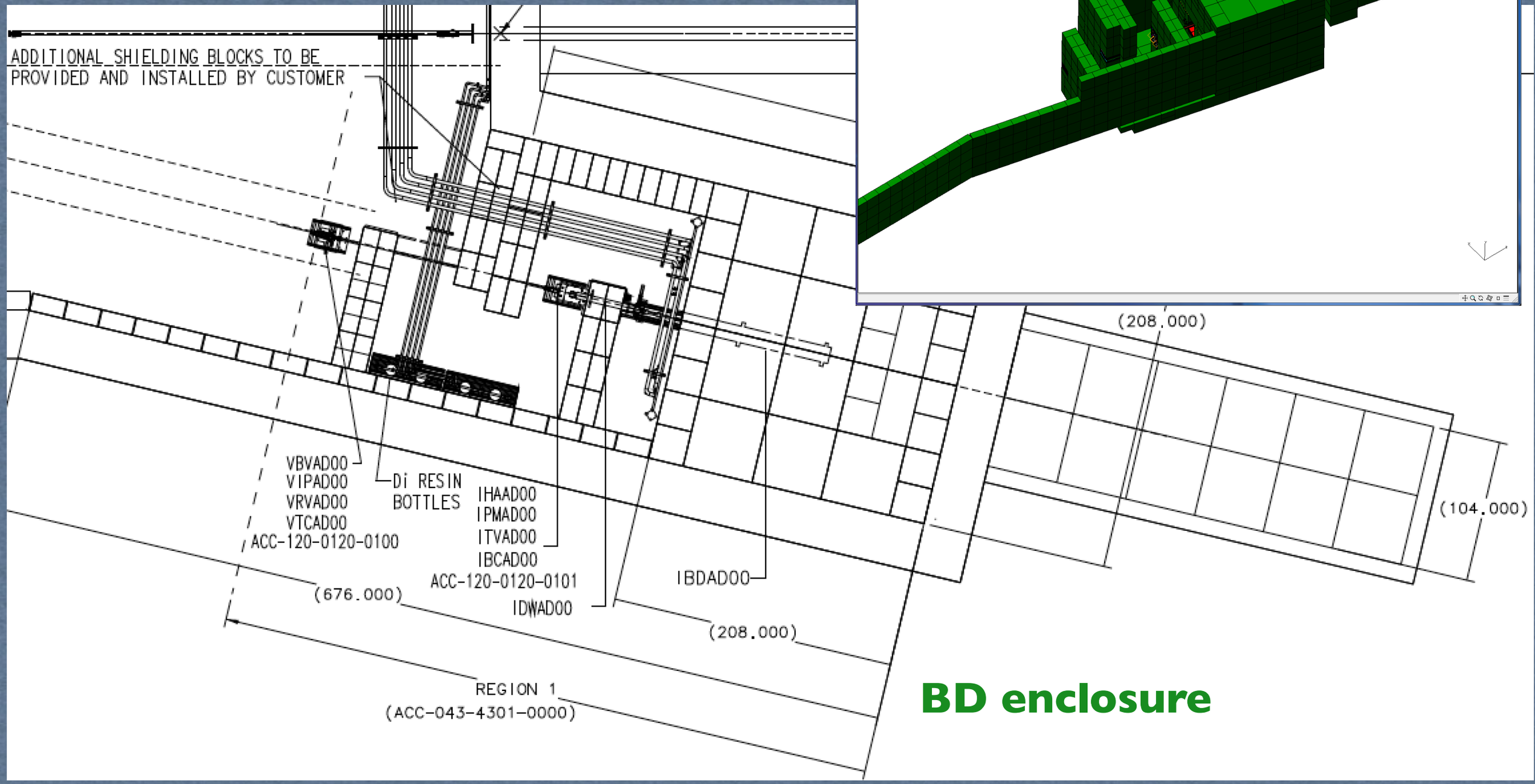
Hall-D

- E~12GeV
- moderate current ~200nA (may be increased up to 8 uA!)
- Over-the-ground beam dump
- Easy access to the back of the BD enclosure
- Simplified logistic: (shielded roof) hut, power, network, A/C



Hall-D Beam Dump

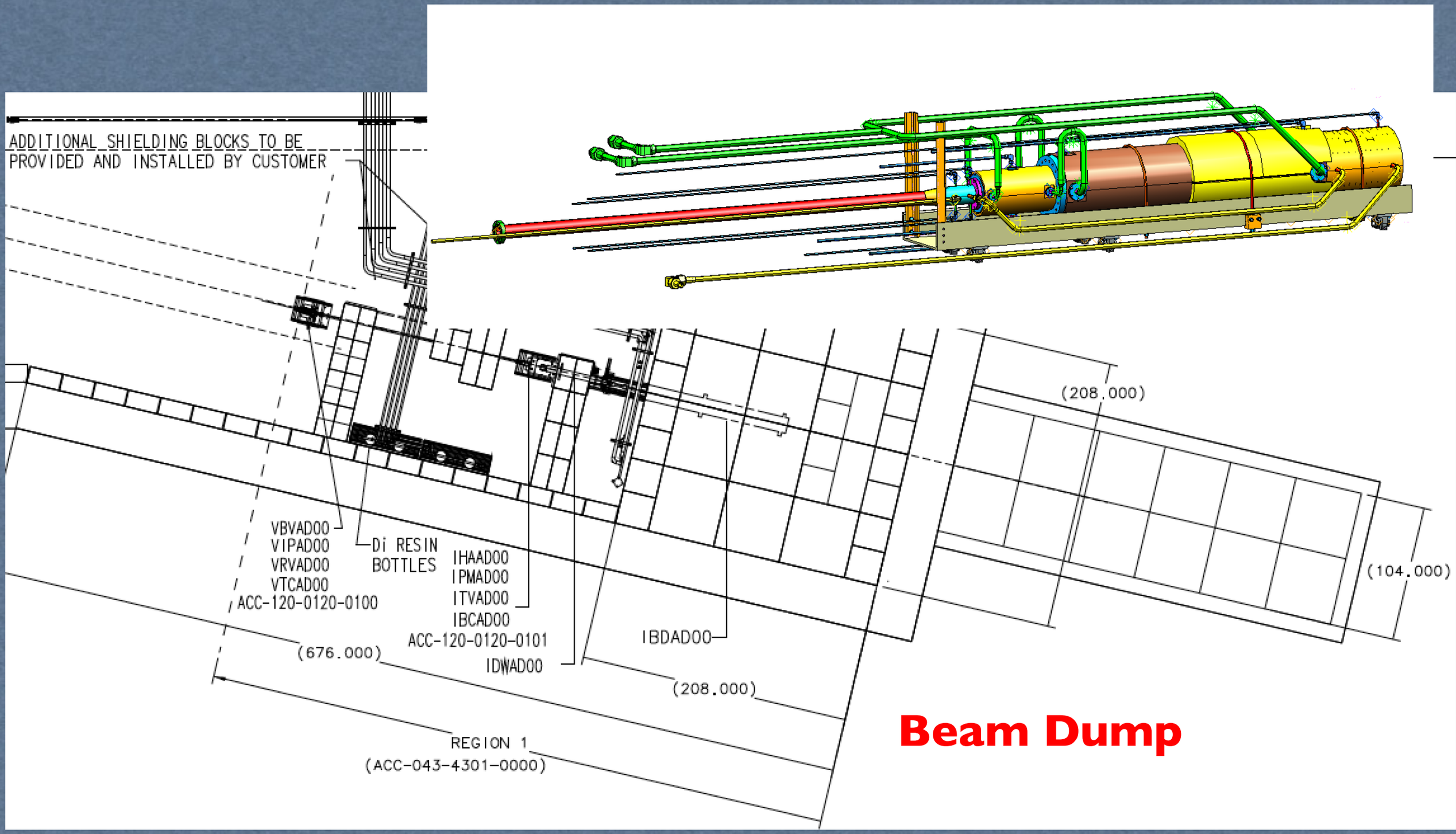




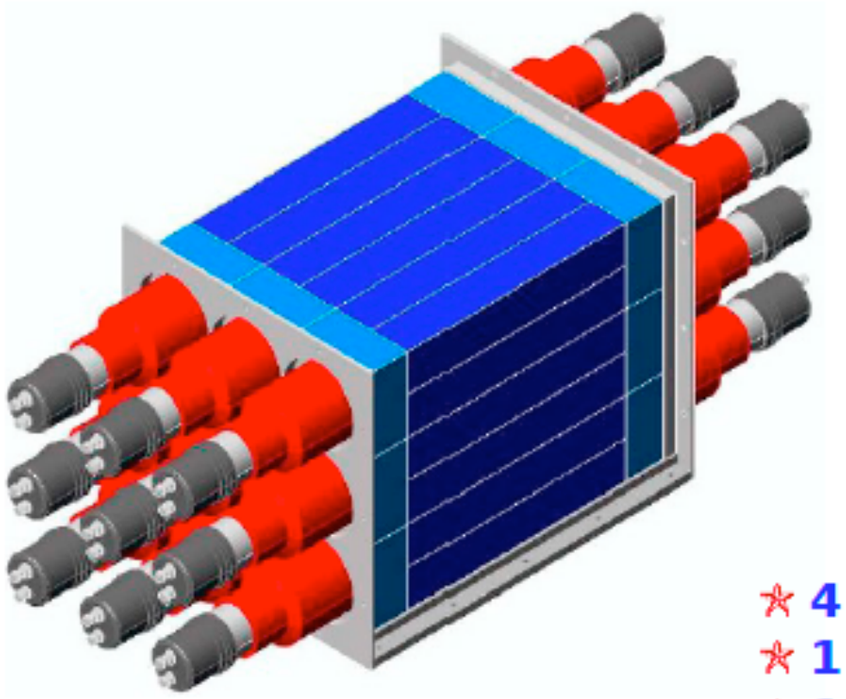
BD enclosure

A.Freyberger and E.Smith

Hall-D Beam Dump



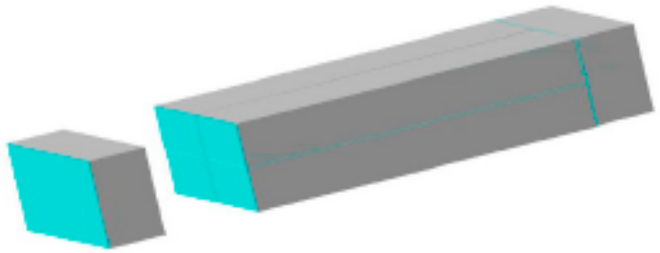
Full detector prototype: CORMORINO

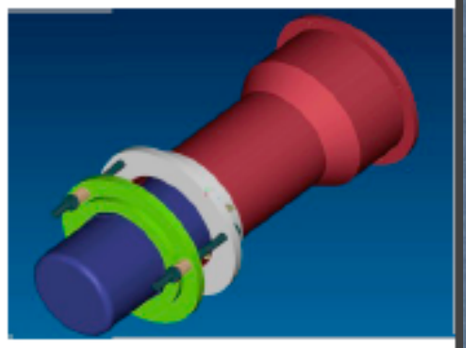


CORMORAD prototype

CORMORINO

scale $(1:3)^3$ ~3% m^3



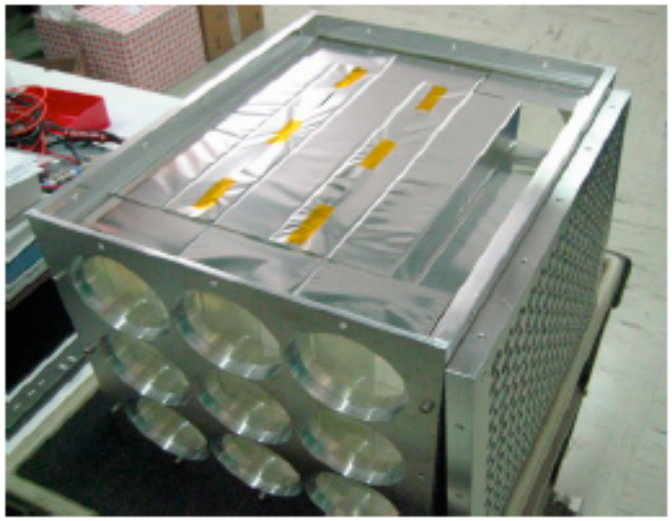


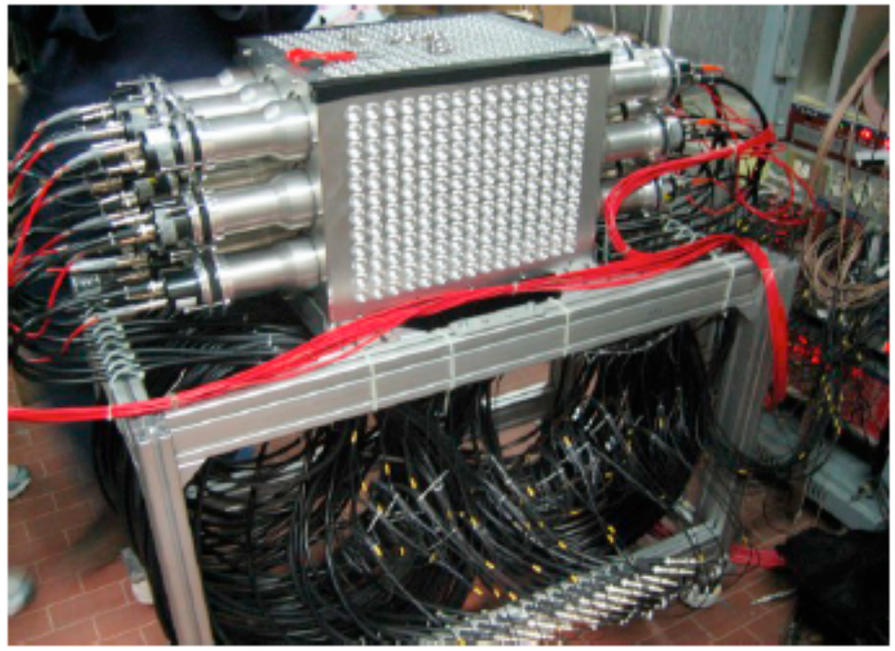
Prototype cell

- 4 30x5x5 cm^3 NE110 bars
- 1 5x10x10 cm^3 NE110 block
- 12.5 μm Gd foils wrapping

- Light read-out: 18 Photonis XP2312 3" PMTs

- Size: 40 x 30 x 30 cm^3





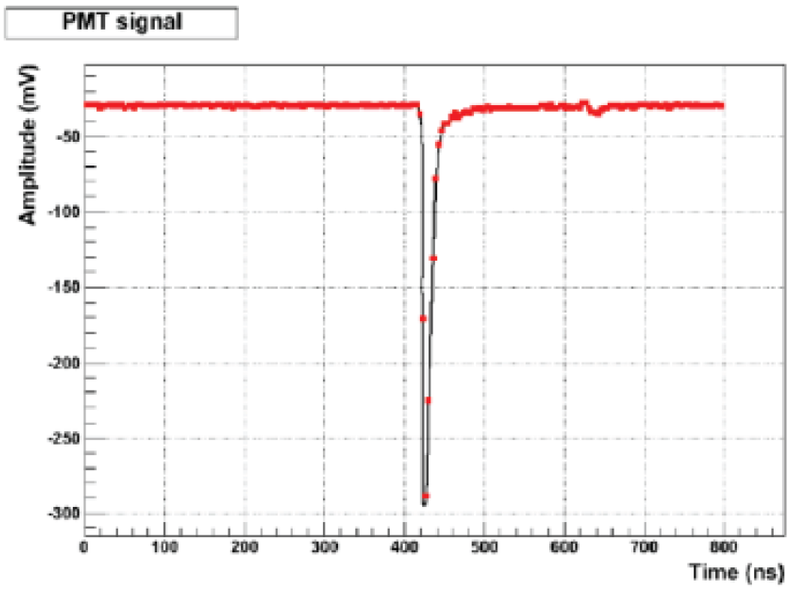
Mounted in a van and operated remotely for 1 month in a NPP

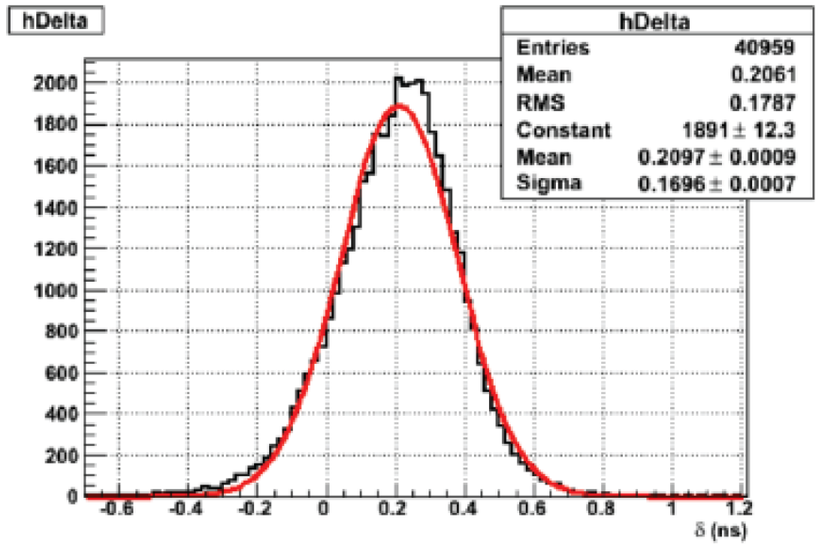
CORMORINO is a full working prototype of the full scale detector

Used to validate design, bg rates, shielding …

Full detector prototype: CORMORINO

A. Celentano

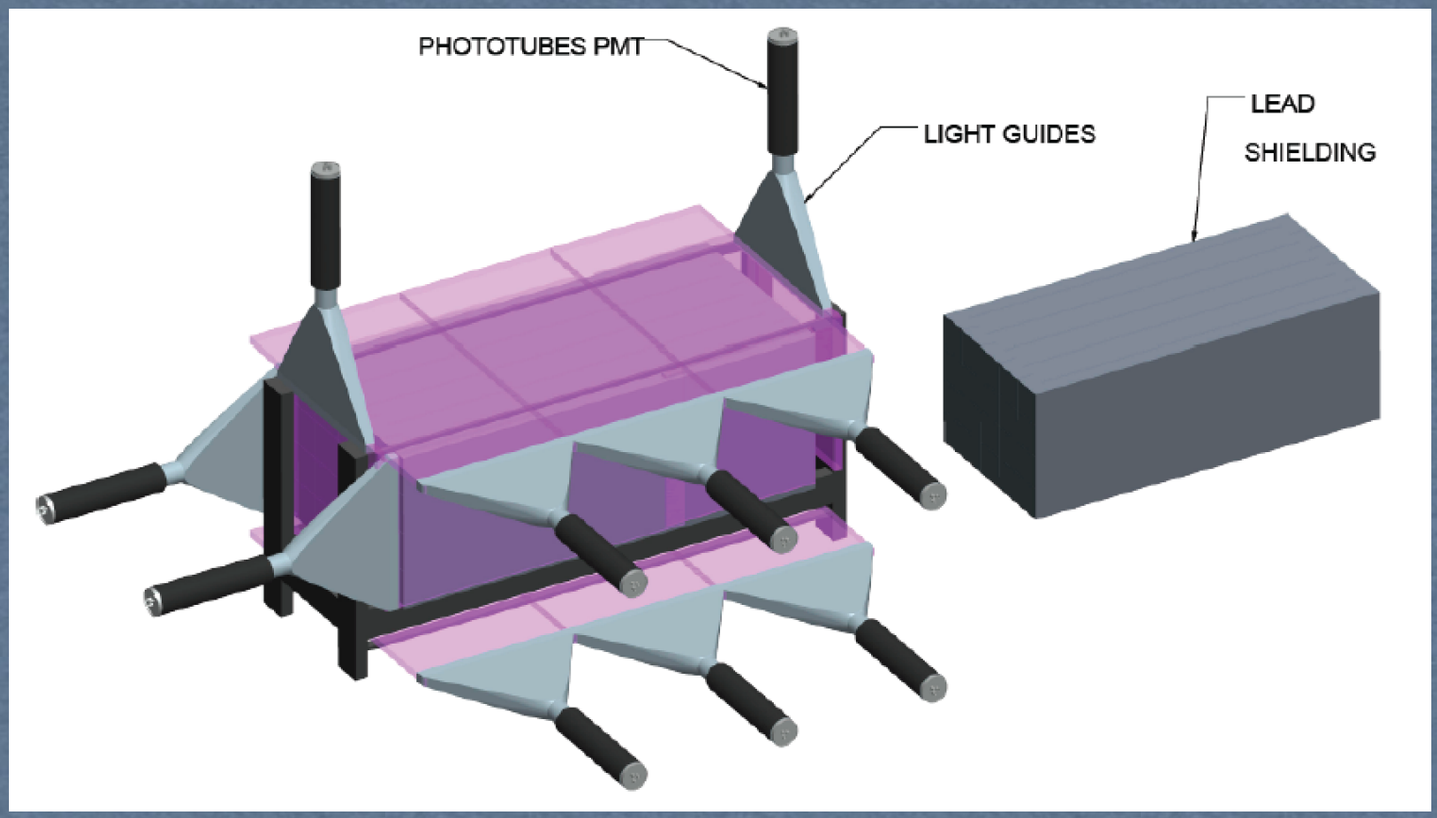




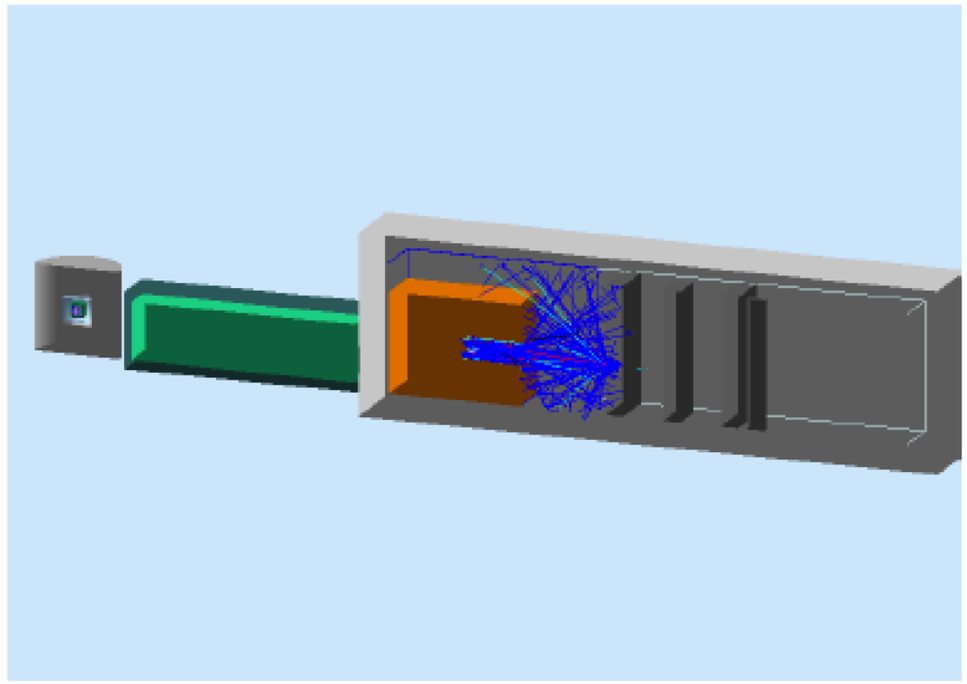
- Measured fACD signal
- Time resolution:
  σ_T ~110 ps/MIP

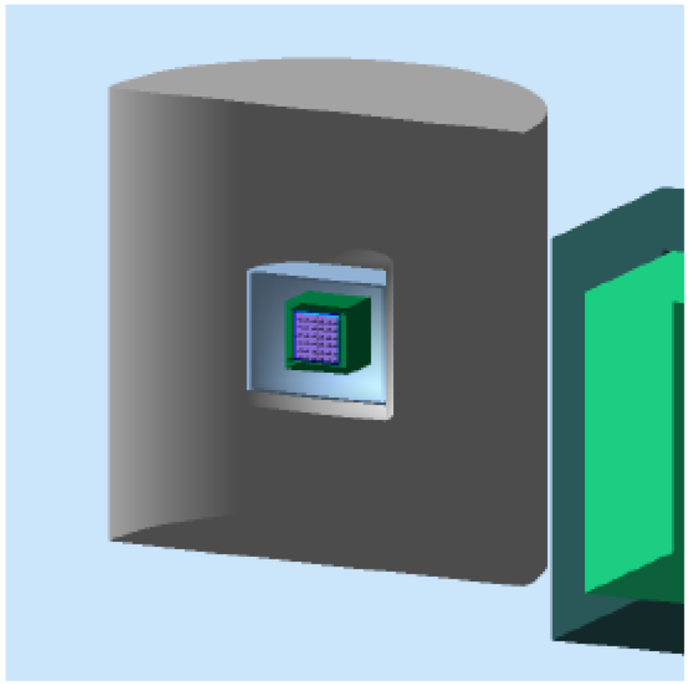
- Adding an active veto
  plastic scintillators paddles 2cm thick + single-side PMT readout
- Adding a passive shielding
  5cm-thick lead bricks
- We may also add a second active veto between CORMORINO and the lead shielding
  extruded plastic scintillator paddles + WLS fibers + single side simp readout

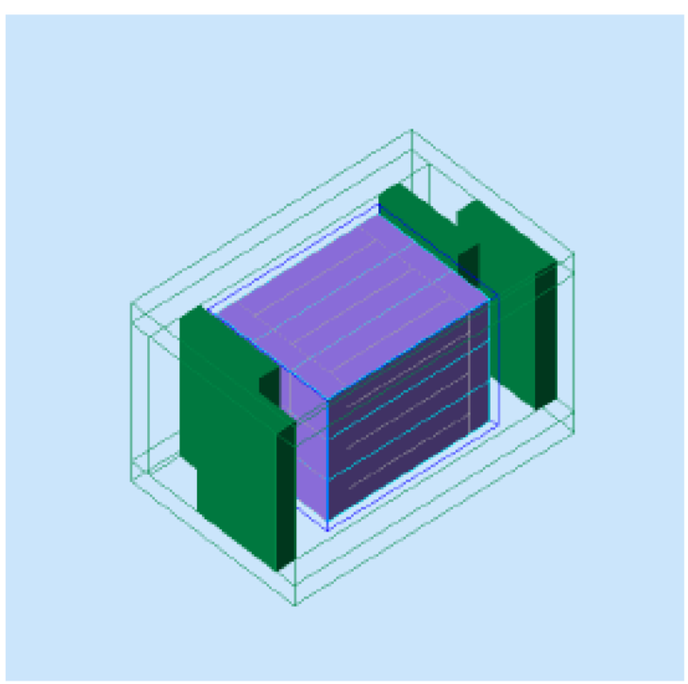
A. Celentano, F. Parodi, V. Vigo



MC implementation: GEANT4 - GEMC



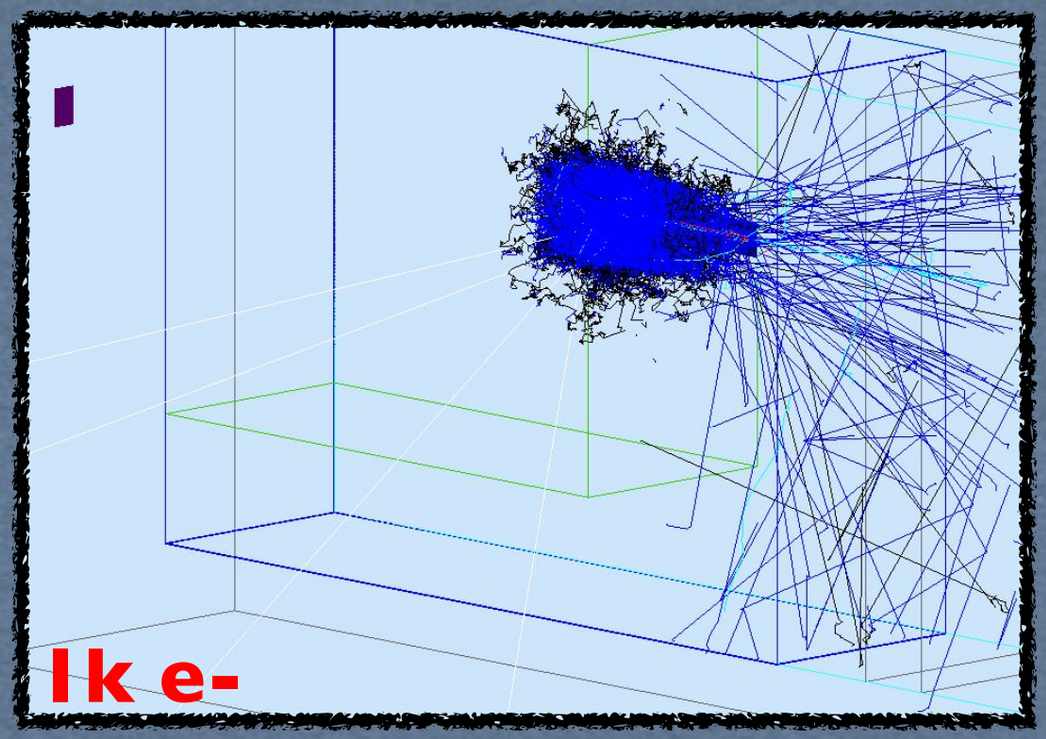




- Process time = 0.2 s/ev (no Thr)

- I=200 nA →1250 e^-/ns
- 4.0 nA bunch separation
- 1M events ↔ 0.8us bea-time needs 2.5 (0.8) cpu-days

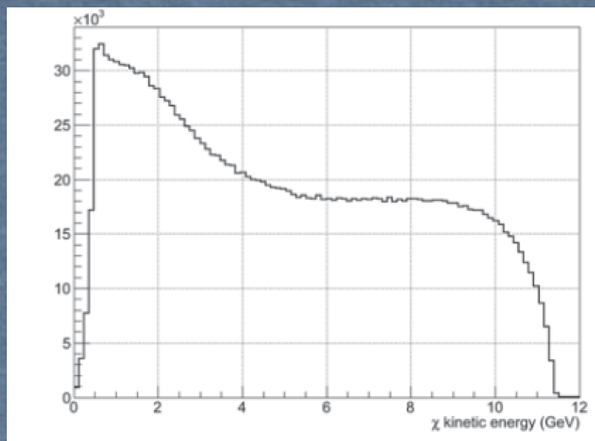
- Simulated 1.6 10^9 EOT (1.2 ms)
- Only neutrinos ($\bar{\nu}_\mu$, ν_μ, and ν_e) pass the beam dump and cross the detector

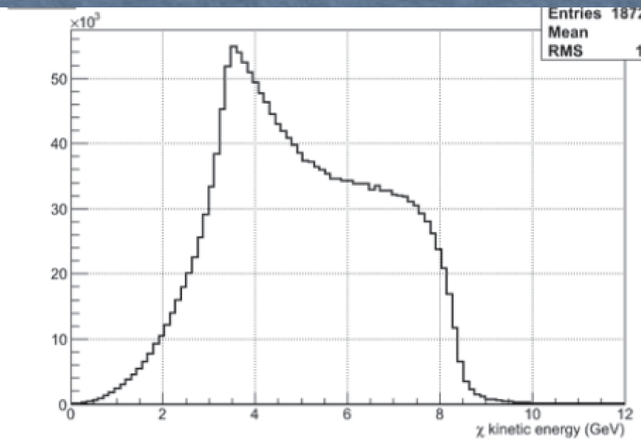


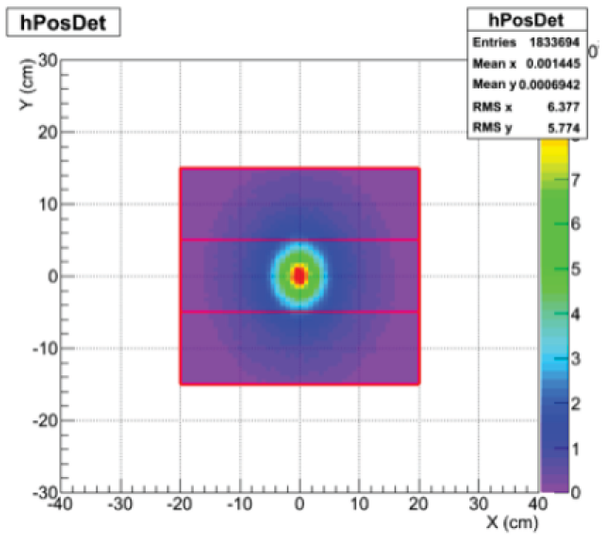
A. Celentano, P. Degtiarenko, M. Osipenko, R. De Vita

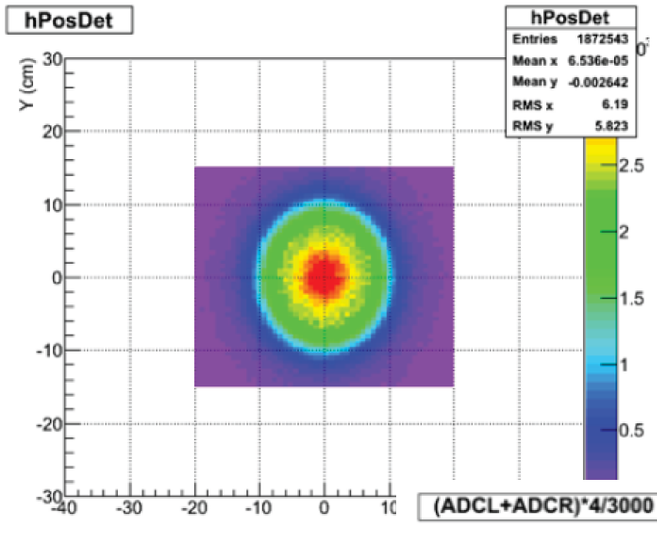
Expected signal

- Detailed estimates for the more challenging χ detection case (elastic scattering on nucleon)







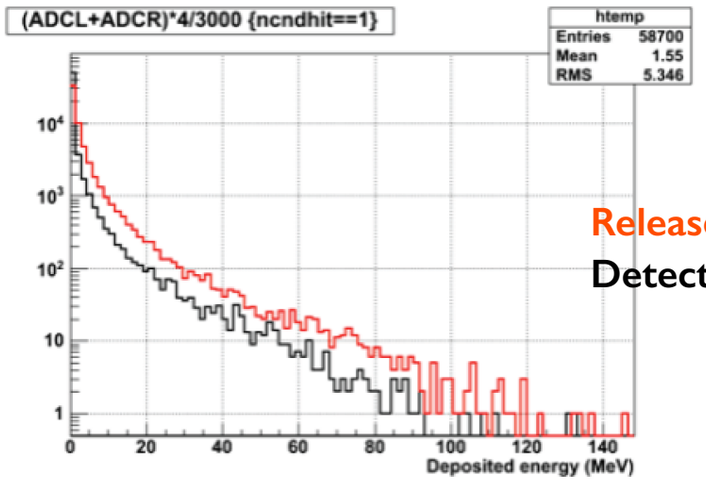


- Two sets of model parameters

	S.I	S.II
M_χ	10 MeV	68 MeV
$M_{A'}$	50 MeV	150 MeV
ϵ	10^{-3}	10^{-3}
α_{Dark}	0.1	0.1
N_χ pairs produced per EOT	$3.4\ 10^{-10}$	$3.4\ 10^{-11}$
$\sigma_{\chi-p}$	1.4 nb	0.14 nb

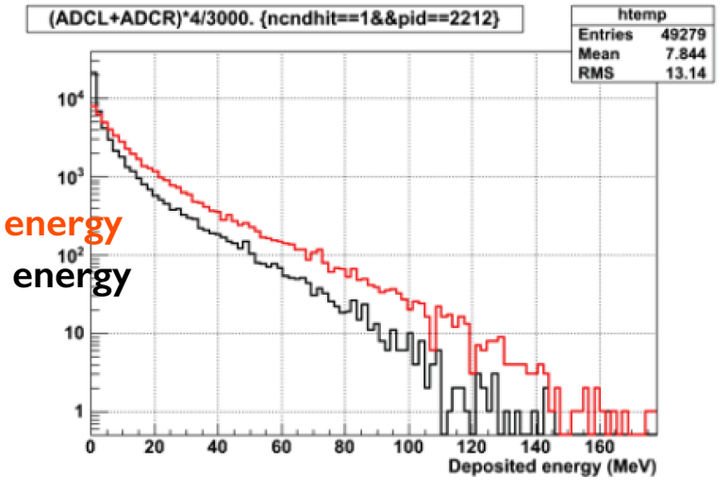
- Detected energy includes attenuation length and light quenching effect
- Two detection thresholds studied: 1 MeV and 10 MeV (el-equiv)

A. Celentano, E. Izaguirre, G. Krnjaic, P. Schuster, N.Toro



Released energy

Detected energy

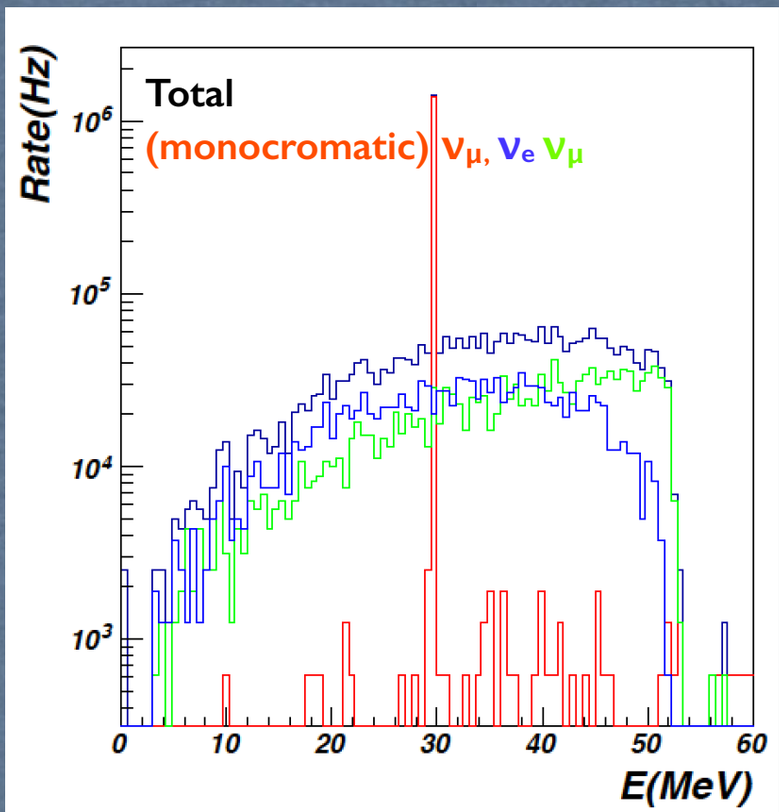


Backgrounds

Beam related background

I) Beam neutrinos **negligible**

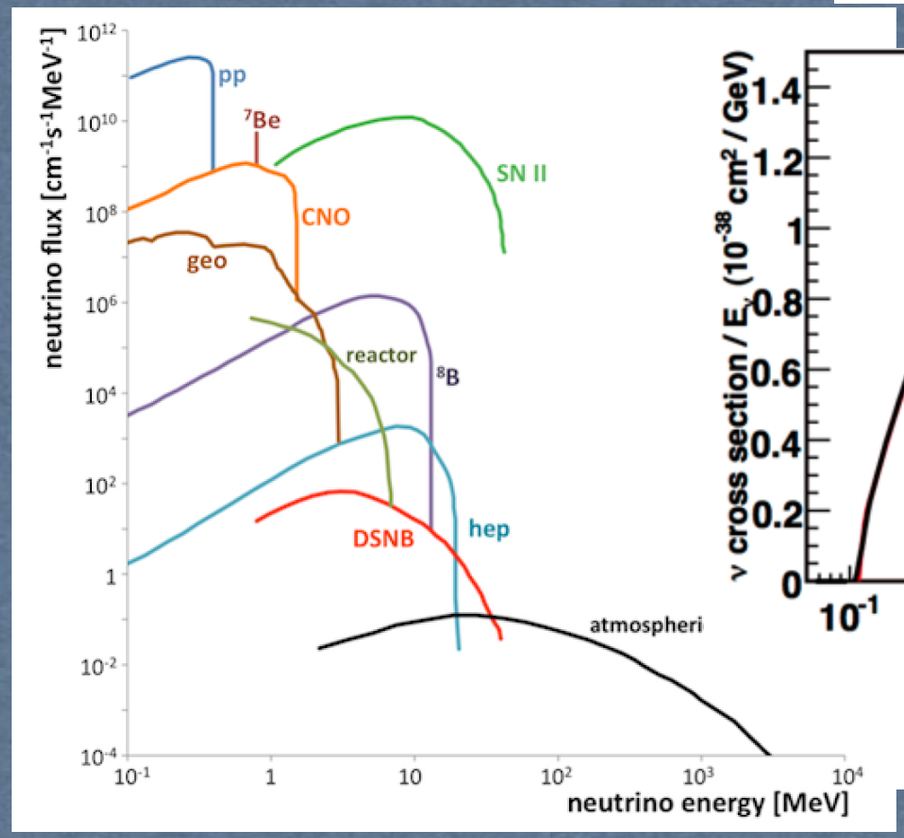
- Only neutrinos exit from the beam-dump
- $\pi^+ \rightarrow \mu^+ \nu_\mu$ (π^- are mainly captured by nuclei)
- $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$

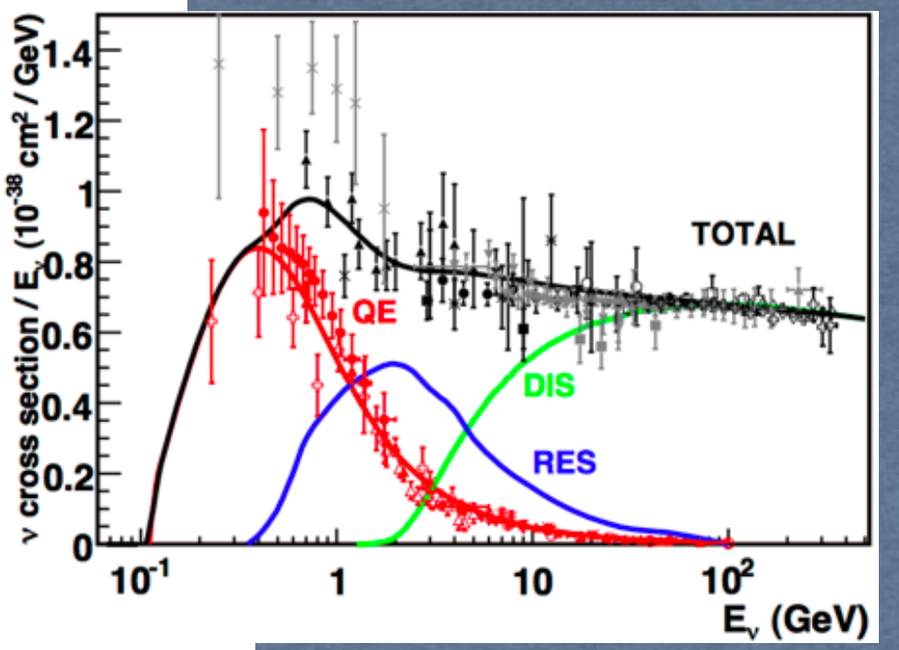


Beam un-related background (cosmogenic)

I) Cosmic neutrinos **negligible**

- Considering flux, interaction cross sections and 1MeV (10 MeV) detection threshold the number of detected cosmic neutrinos is negligible

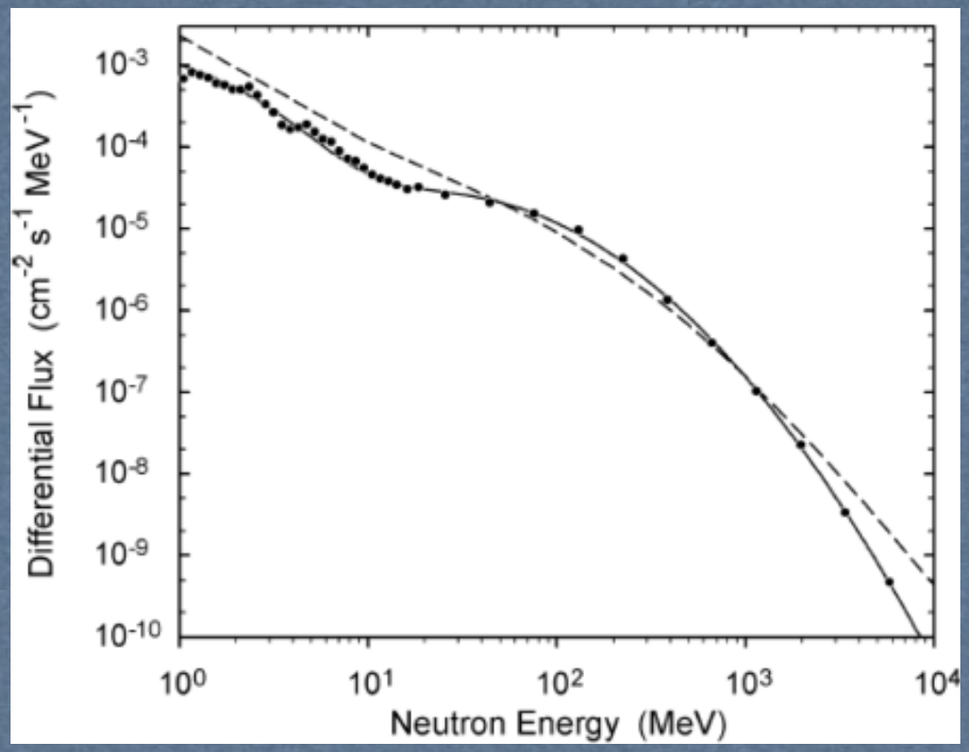




Backgrounds

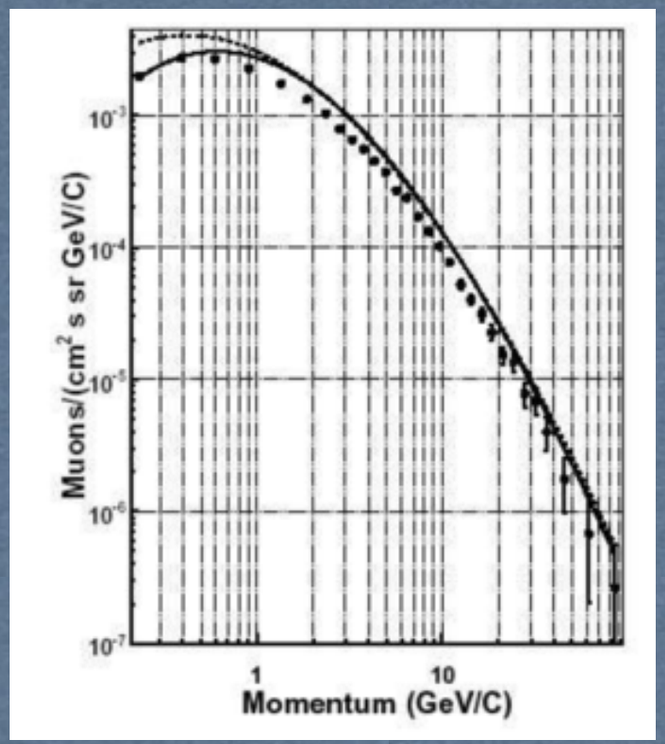
II) Cosmic neutrons sizeable

- A high energy neutron can penetrate the shielding and interact inside the detector mimicking a χ-N interaction
- 1m iron shield + detection energy threshold introduce a neutron energy cutoff (detection efficiency = 0 for T_N< 50 (100) MeV)



III) Cosmic muons

- Crossing muons are rejected by the veto
- Crossing muons can produce a fake signal for veto inefficiency (~ 5%) sizeable
- Muons decaying inside the detector not rejected for veto inefficiency sizeable
- Muons decaying inside the lead shielding not rejected for veto inefficiency sizeable
- Muons decaying between iron and veto negligible
  - for the standard decay $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$ e+ is detected by the veto
  - for the rare decay $\mu^- \rightarrow e^- \nu_\mu \nu_e \gamma$ (Br~1.5%) the 10-100 MeV photon could by-pass the veto and interact in the detector but the rate is negligible



Expected rates in CORMORINO

	Rate $_{Thr=1\text{MeV}}$ (Hz/μA))	Rate $_{Thr=10\text{MeV}}$ (Hz/μA))
χ detection - S.I	$1.0\ 10^{-5}$	$1.2\ 10^{-6}$
χ detection - S.II	$2.0\ 10^{-7}$	$0.7\ 10^{-7}$
B-rel ν	$2.0\ 10^{-9}$	$2.0\ 10^{-10}$
B-rel neutron	0	0

	Rate $_{Thr=1\text{MeV}}$ (Hz)	Rate $_{Thr=10\text{MeV}}$ (Hz)
B-unrel ν	$2.0\ 10^{-6}$	$2.0\ 10^{-7}$
B-unrel neutron	$2.7\ 10^{-3}$	$0.6\ 10^{-3}$
Crossing muons	$3.3\ 10^{-3}$	$3.5\ 10^{-3}$
Captured μ^+	$1.4\ 10^{-3}$	$2.4\ 10^{-3}$
Decaying μ^- (CORM)	$2.9\ 10^{-3}$	$4.8\ 10^{-3}$
Stopped μ in lead	$7.0\ 10^{-3}$	$4.3\ 10^{-3}$
μ^- rare decay	$2.0\ 10^{-5}$	$8.0\ 10^{-6}$
Total Beam-unrelated bg	$1.7\ 10^{-2}$	$1.5\ 10^{-2}$

- Expected signal rates is reported for the two theoretical χ-N elastic scattering scenarios
- Detection thresholds:1 MeV, 10 MeV
- Background is negligible for em showers produced by 0.5 GeV electron (150 MeV deposited if the sampling fraction is 30%)

- **Beam-related bg does not seem to be an issue**
- **Cosmogenic (reducible) bg's estimates need to be validate by real measurements**

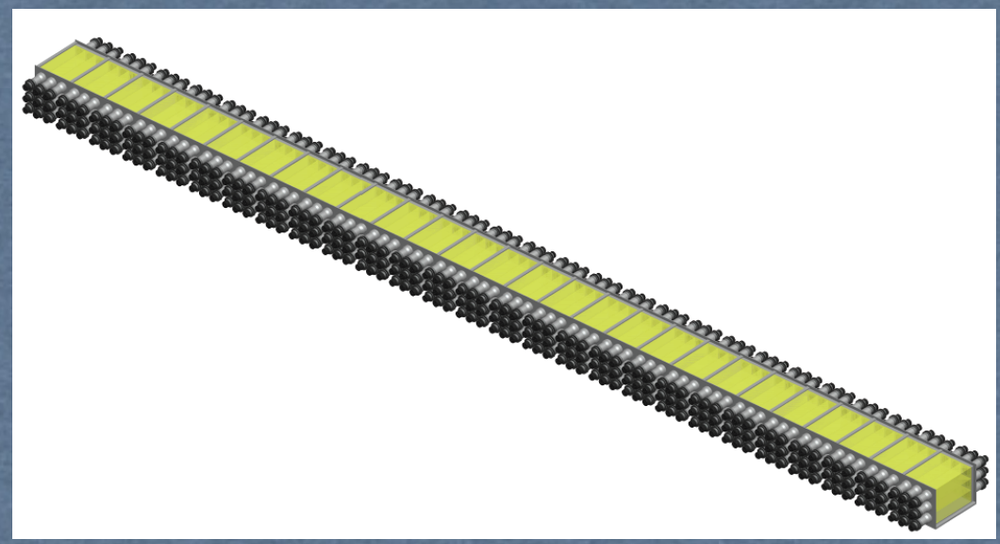
The (full) BDX experiment

BDX detector size: 30x CORMORINO

- Exploiting the χ production kinematics the detector front size is the same as CORMORINO (~45x50 cm^2)
- Each optical channel (coupled to L-R PMTs) is made by a matrix of 3x3 (5x5x50) cm^3 paddles
- A CORMORINO-like module is made by 3x3 optical channels (18 PMTs) with volume 0.1m^3
- 20 modules (360 PMTs and electronic channels) provides a factor of 30x in counts
- Each scintillator bar is interleaved with 1mm lead foils to increase the overall em radiation length

BDX charge: 10^{22} EOT (Electron On Target)

- Beam current: 100 uA (HAll-A or HAll-C option)
- Accelerator availability: 50%
- Run time: 1 (calendar) year



BDX cosmogenic bg rejection factor: 5x

- Time coincidence between the 4ns RF signal and the detector

This is a conservative estimate since:

★ **the cosmic bg could be reduced by increasing the passive shielding**

★ **the veto inefficiency cured by adding a second active veto**

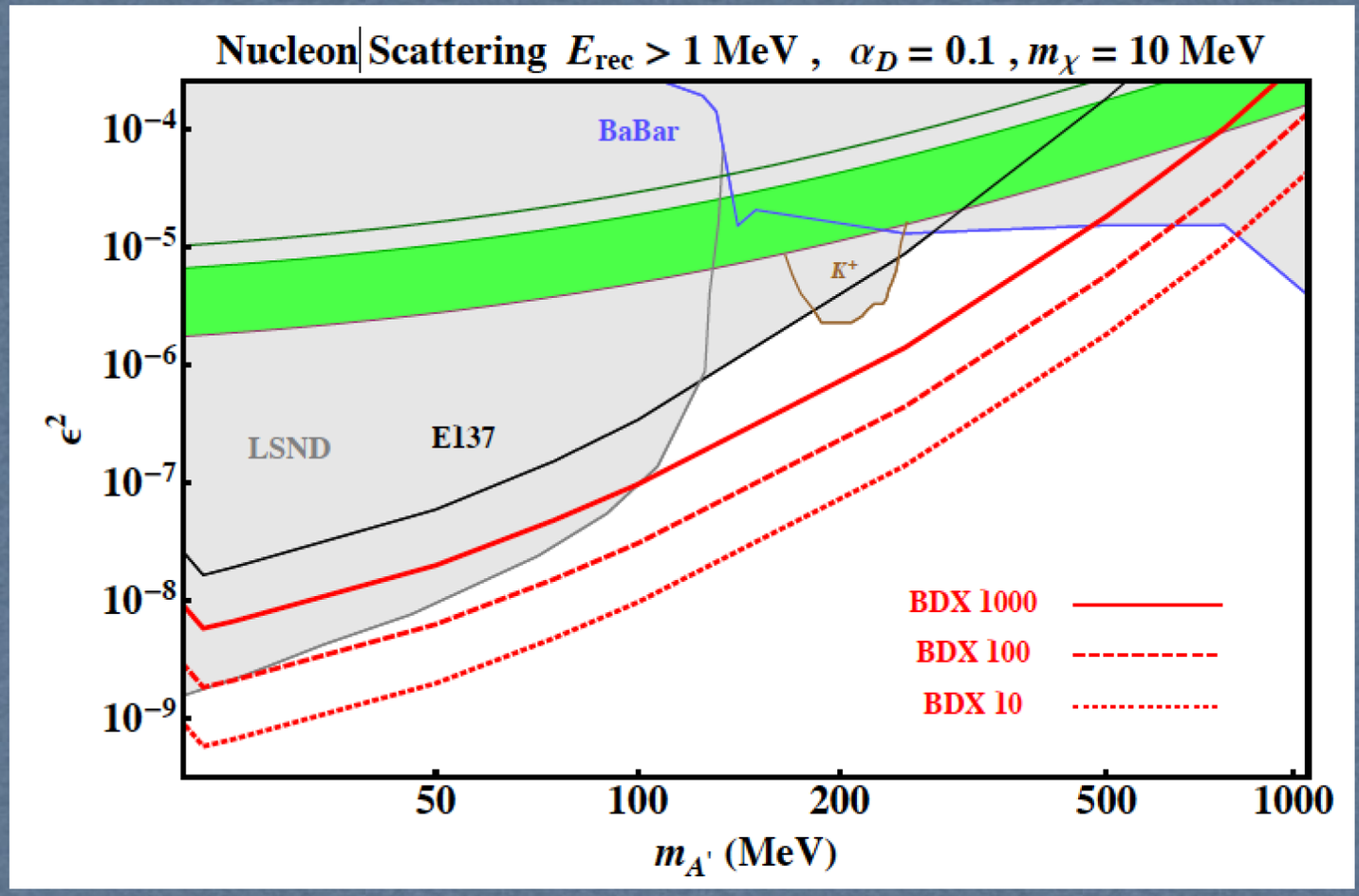
★ **the time coincidence can be tightened**

★ **the detection thresholds further reduced (from 1 MeV to 0.5 MeV)**

The (full) BDX experiment

	Counts $_{Thr=1\text{MeV}}$	Counts $_{Thr=10\text{MeV}}$
χ detection - S.I	$0.5\ 10^6 \pm 700$	$5.7\ 10^4 \pm 240$
χ detection - S.II	$1.0\ 10^4 \pm 100$	$3.3\ 10^3 \pm 60$
Beam-rel bg	100 ± 10	10 ± 3
Beam-unrel bg	$1.6\ 10^6 \pm 1300$	$1.4\ 10^6 \pm 1200$

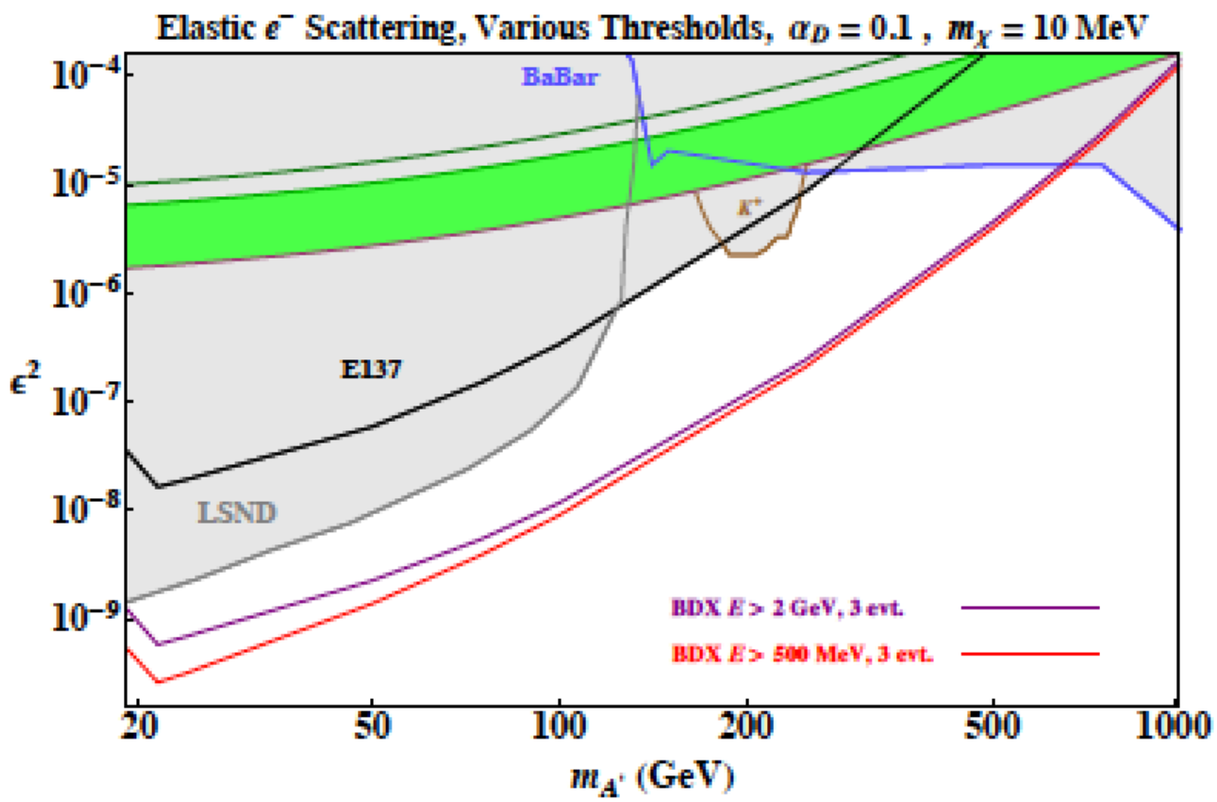
Elastic X-N scattering
BDX reach

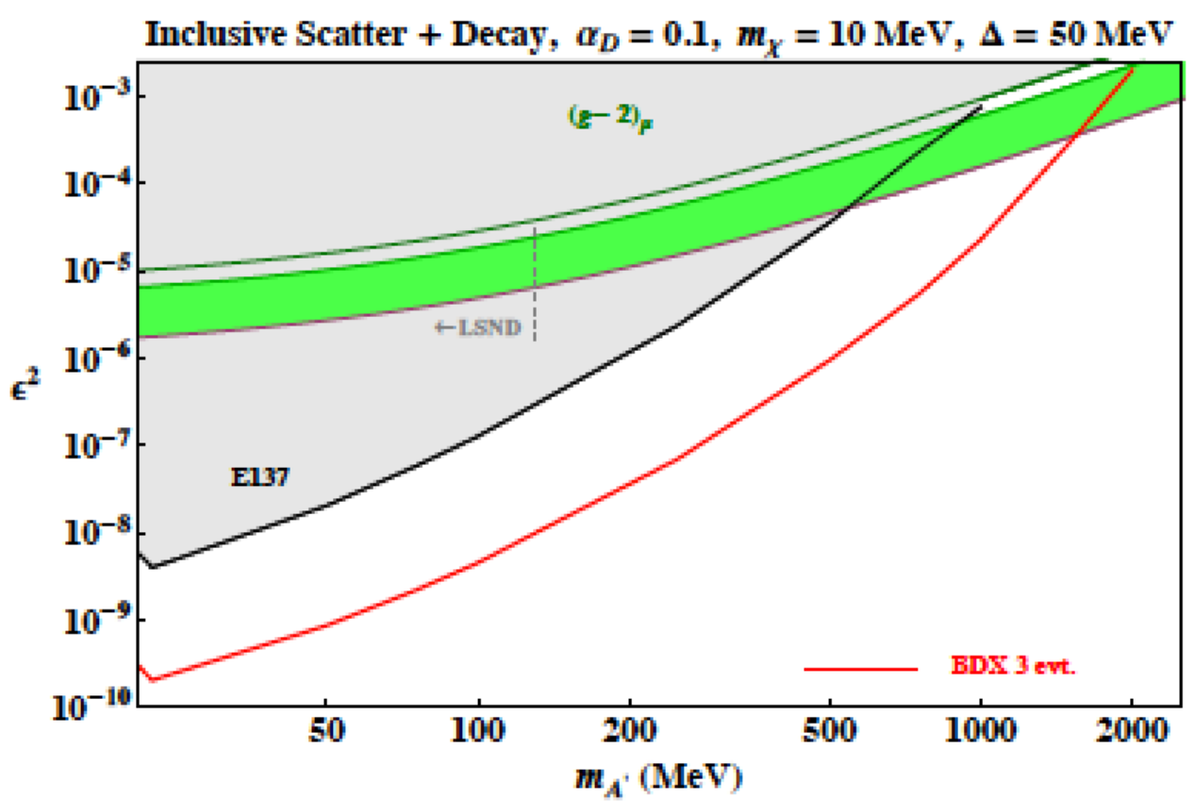


The (full) BDX experiment

	Counts $_{Thr=1\text{MeV}}$	Counts $_{Thr=10\text{MeV}}$	EM shower Thr=150 MeV
χ detection - S.I	$0.5\ 10^6 \pm 700$	$5.7\ 10^4 \pm 240$	
χ detection - S.II	$1.0\ 10^4 \pm 100$	$3.3\ 10^3 \pm 60$	
Beam-rel bg	100 ± 10	10 ± 3	~0 (<3)
Beam-unrel bg	$1.6\ 10^6 \pm 1300$	$1.4\ 10^6 \pm 1200$	~0 (<3)

Elastic X-e$^-$ scattering and inelastic BDX reach





BDX LOI

V1.8
June 13, 2014

Letter of Intent to PAC 42

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

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arXiv:1406.3028v1 [physics.ins-det] 11 Jun 2014

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Abstract

MeV-GeV dark matter (DM) is theoretically well motivated but remarkably unexplored. This Letter of Intent presents the MeV-GeV DM discovery potential for a 1 m^3 segmented plastic scintillator detector placed downstream of the beam-dump at one of the high intensity JLab experimental Halls, receiving up to 10^{22} electrons-on-target (EOT) in a one-year period. This experiment (Beam-Dump eXperiment or BDX) is sensitive to DM-nucleon elastic scattering at the level of a thousand counts per year, with very low threshold recoil energies (~1 MeV), and limited only by reducible cosmogenic backgrounds. Sensitivity to DM-electron elastic scattering and/or inelastic DM would be below 10 counts per year after requiring all electromagnetic showers in the detector to exceed a few-hundred MeV, which dramatically reduces or altogether eliminates all backgrounds. Detailed Monte Carlo simulations are in progress to finalize the detector design and experimental set up. An existing 0.036 m^3 prototype based on the same technology will be used to validate simulations with background rate estimates, driving the necessary R&D towards an optimized detector. The final detector design and experimental set up will be presented in a full proposal to be submitted to the next JLab PAC. A fully realized experiment would be sensitive to large regions of DM parameter space, exceeding the discovery potential of existing and planned experiments by two orders of magnitude in the MeV-GeV DM mass range.

2

- BDX LOI submitted to PAC42
- BDX LOI published **http://arxiv.org/abs/1406.3028**
- Spokespersons:
  M.Battaglieri, A.Celentano, R. De Vita, E.Izaguirre, G.Krnjaic, E.Smith, S.Stepanyan

✳A significant interested for BDX LOI

✳The Letter of Intent is only the first step in the (long) way to run the experiment

ToDo list (very partial)

- Complete CORMORINO veto
- Measure cosmogenic bg rate
- Define the full detector design
- Look for detector financing
- Prepare the full proposal for '15 July PAC
- Set full simulations
- Build the detector
- Prepare the JLab bed
- Install the detector
- Run the experiment !!!!

✳A lot of work to do!

✳ A lot of opportunities for new collaborators and students!

Putting BDX into context

Report of the Particle Physics Project Prioritization Panel (P5) (May '14)

Premises

… The dark matter may be composed of ultra-light (less than a GeV), very weakly interacting particles. Searches for such states can be carried out with high-intensity, low-energy beams available at Jefferson Lab or with neutrino beams aimed at large underground detectors.

Recommendations

Dark Matter

The experimental challenge of discovery and characterization of dark matter interactions with ordinary matter requires a multi-generational suite of progressively more sensitive and ambitious direct detection experiments. This is a highly competitive, rapidly evolving field with excellent potential for discovery. **The second-generation direct detection experiments are ready to be designed and built, and should include the search for axions, and the search for low-mass (<10 GeV) and high-mass WIMPs.** Several experiments are needed using multiple target materials to search the available spin-independent and spin-dependent parameter space. This suite of experiments should have substantial cross-section reach, as well as the ability to confirm or refute current anomalous results. Investment at a level substantially larger than that called for in the 2012 joint agency announcement of opportunity will be required for a program of this breadth.

Recommendation 19: Proceed immediately with a broad second-generation (G2) dark matter direct detection program with capabilities described in the text. Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity.

Conclusions

★ The dark sector may be more complex than originally expected

★ Extensive search for low mass DM (direct search, acc-based experiments)

★ Natural extension of the heavy photon model to include light DM via invisible decay

★ Beam Dump eXp at JLab to search for light DM particles (X) with mass <1 GeV

★ BDX: High intensity e-beam for 1 year (10^{22} EOT) & 1 m^3-size solid/liquid detector

★ Sensitivity to: elastic X-N scattering, elastic X-e^- scattering, and inelastic interaction

★ Cosmogenic bg (neutron and muons) can be tested on a prototype (CORMORINO)

★ BDX would extended the exclusion region by x100 in case of negative results and put an end to the possible A' involvement in $(g-2)_\mu$ anomaly

★ LOI submitted to PAC42 and full proposal in preparation

★ International competition (CERN, LNF, MAINZ, …) and strong interest from the HEP/DM community and funding agencies (P5)

★ The navy crossing is just at the beginning: new collaborators are welcome!