The BDχ detector prototype for Dark Matter searches in a Beam Dump eXperiment @ JLAB

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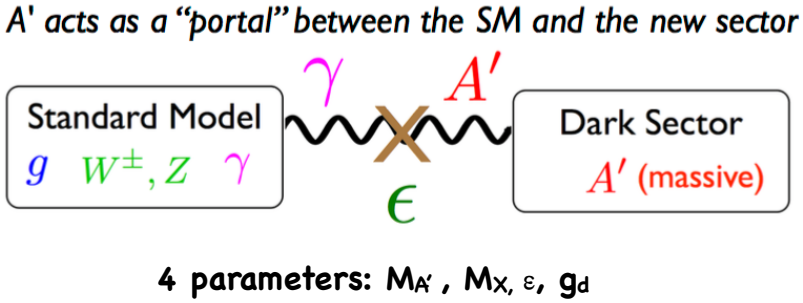
Search for Light Dark Matter

LDM (MeV - GeV) is a new hypothesis to explain the observed relic abundance, alternative to the traditional WIMP (GeV - TeV range) hypothesis.

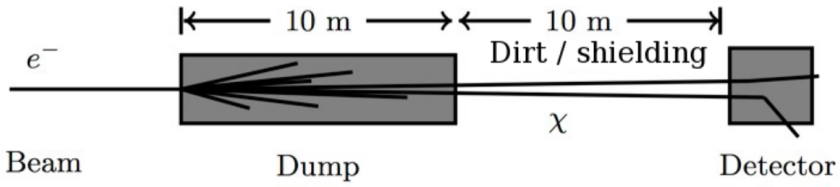
- LDM requires a "new" interaction mechanism between the SM and LDM. The simplest: LDM-SM interaction through a new U(1) gauge-boson ("dark- photon")



- Accelerator based experiments in the GeV energy range are the ideal tool to search for LDM (direct-detection experiments have limited sensitivity to LDM – too low energy recoil)

Beam Dump eXperiment

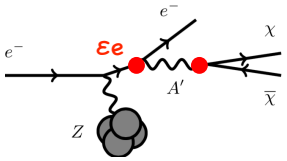
LDM is direct detected in a e^- beam, fixed target setup. It consists in two step:



E. Izaguirre et al, Phys. Rev. D 88, 114015

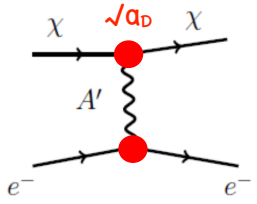
χ production

- GeV - high intensity - e^- beam impinging on a dump
- χ particles pair produced via A' emission and invisible decay

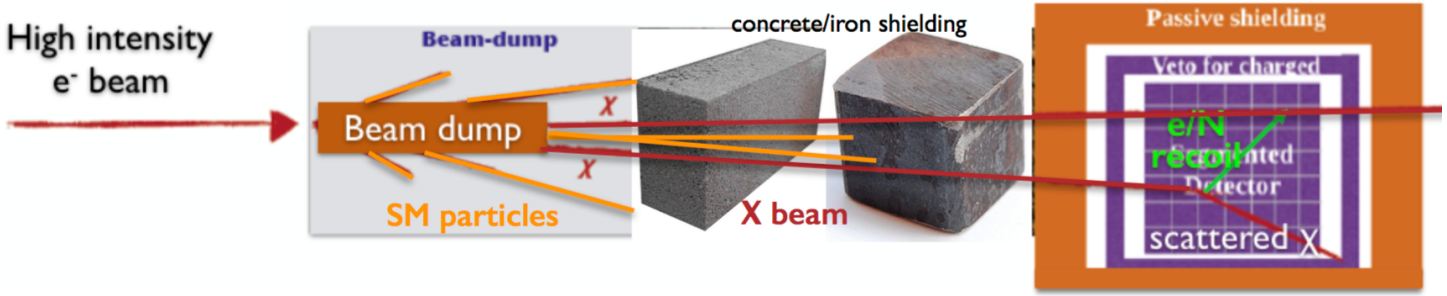


χ detection

- Detector placed behind dump $O(10\,\mathrm{m})$
- χs scattering on atomic e- through A' exchange, recoil releasing visible energy
- Signal: $O(100\,\mathrm{MeV})$ - EM shower



BDχ experiment layout



The experiment is designed with two goals:

Producing and detecting χ

- High intensity e^--beam $\simeq 10^{22}$ EOT/year
- Energy e^--beam ≥ 10 GeV
- $\simeq 1\,m^3$ detector
- BDχ signal: χ-e^- scattering $\rightarrow$ GeV electromagnetic shower

Reducing Background

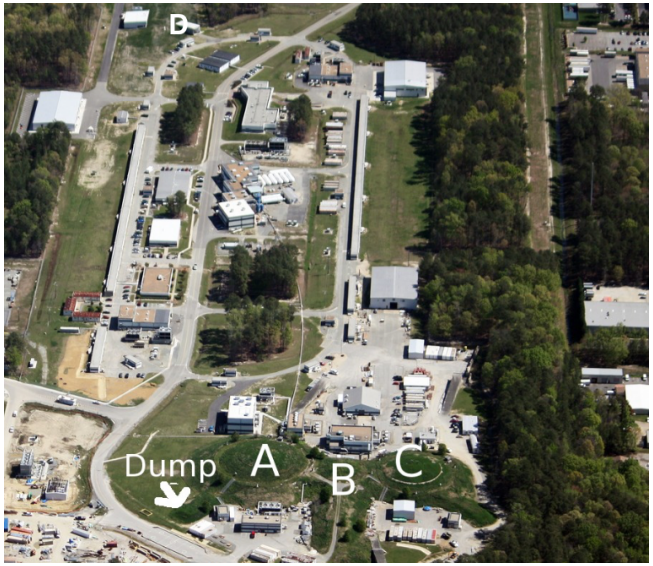
- Passive shielding between beam-dump and detector to filter beam-related backgrounds (except νs)
- Passive shielding and active vetos surrounding the active volume to reduce backgrounds
- Segmented detector for background discrimination based on event topology

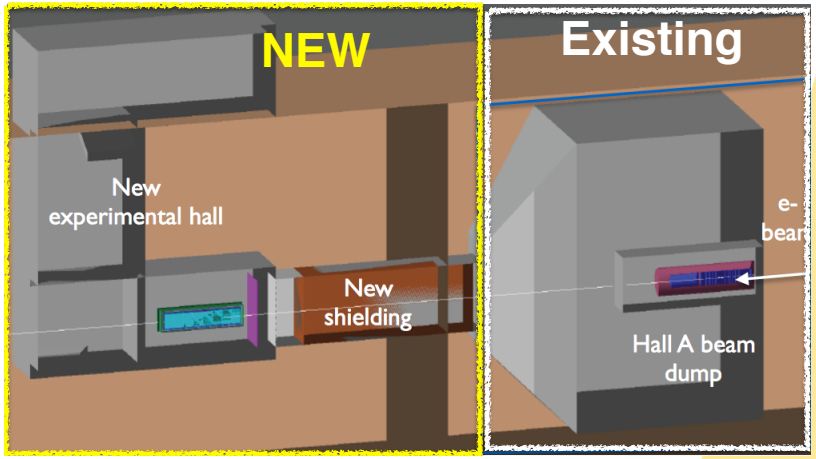
BDχ setup @ JLAB

Jefferson Laboratory is home for the CEBAF electron accelerator

Plan to run BDχ behind Hall-A beam-dump in a new, dedicated experimental Hall

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





BDχ detector

Detector design:

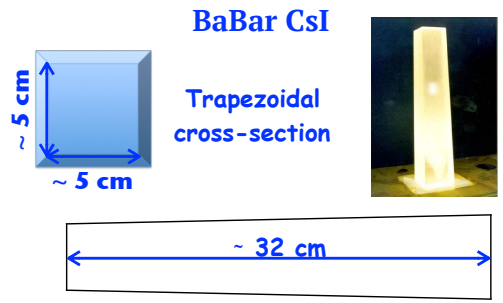
- 800 CsI(Tl) crystals, total interaction $0.5\,\mathrm{m}^3$
- Dual active-veto layer, made of plastic scintillator counters with SiPM redaout

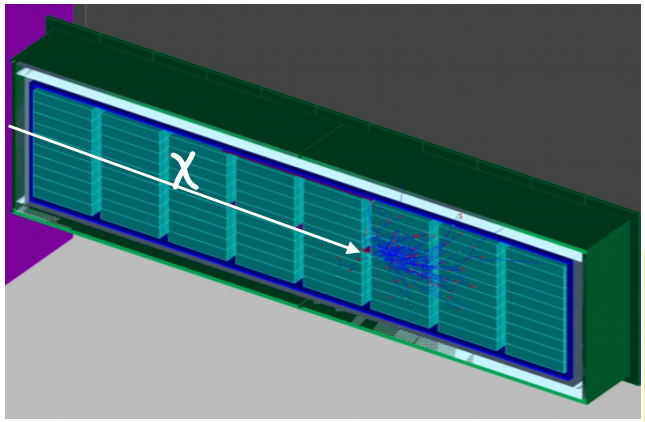
Calorimeter footprint:

- 1 module: 10×10 crystals, 30-cm long. Front face: $50 \times 50\,\mathrm{cm}^2$
- 8 modules: interaction length 2.6 m
- each crystal read by SiPM

Signal:

- EM-shower (threshold: 300 MeV), anti-coincidence with IV and OV



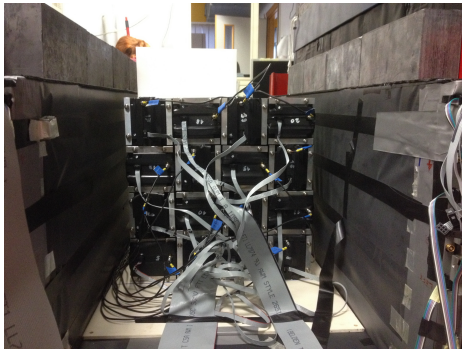


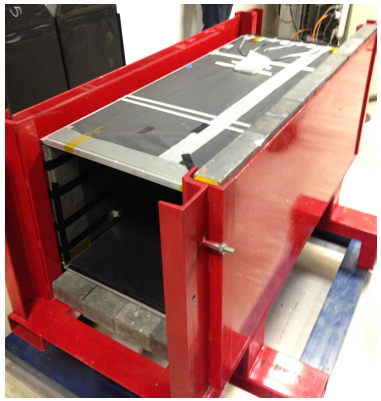
BDχ Proto

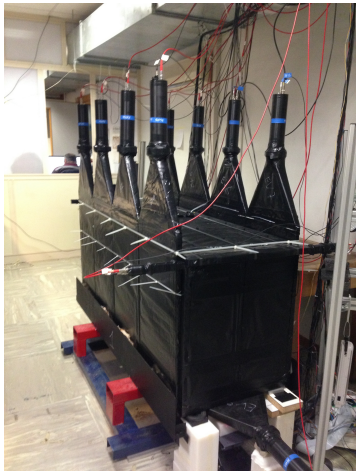
Small scale prototype for detector design and technology validation in a cosmic measurement campaing @ INFN-CT and INFN-LNS

Detector components:

- EM-Calorimeter (ECal):16 CsI(Tl) crystals read by SiPM
- Inner Veto (IV): active-veto layer, made of plastic scintillator counters with SiPM redaout
- Passive shielding: 5 cm lead vault
- Outer Veto (OV): active-veto layer, made plastic scintillator counters. Tested different light read-out systems
- The dimensions of the whole setup are: $\sim 1 \times 1.1 \times 1.8\,\mathrm{m}^3$

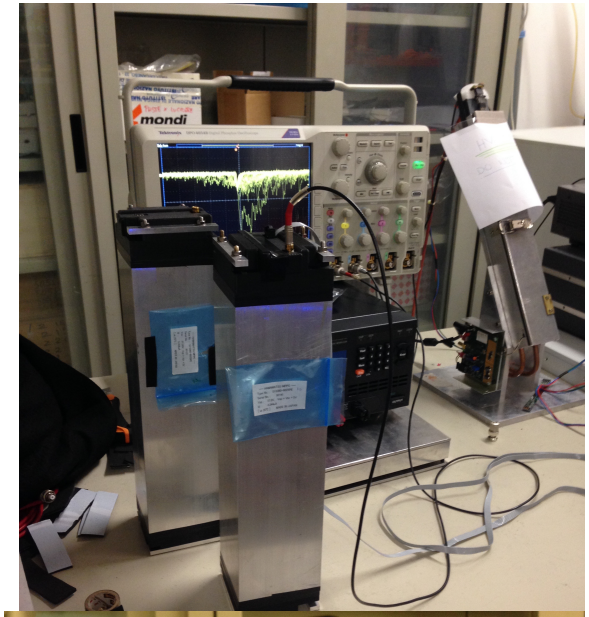


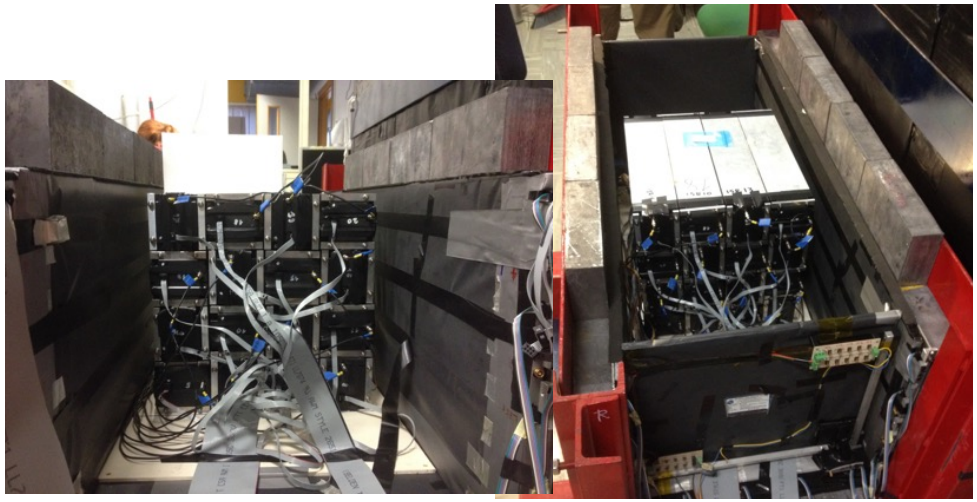


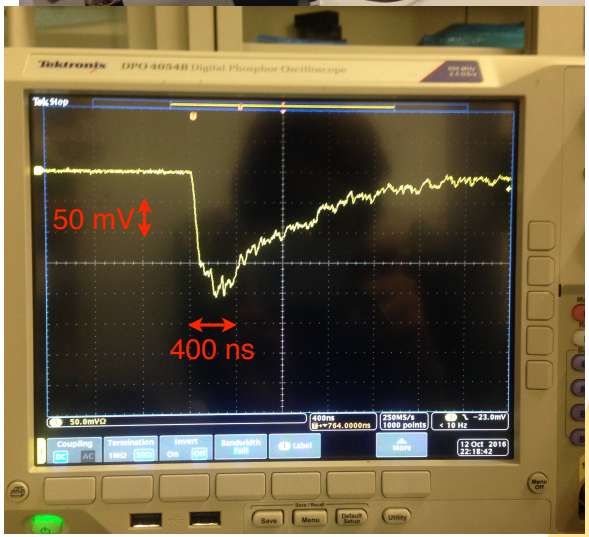


BDχ Proto: ECal

- 16 CsI(Tl)[a] crystals assembled in a 4 x 4 matrix
- SiPM: 6 x 6 mm^2 Hamamatsu MPPC (S13360-6025PE)
- Each crystal is inserted inside a regular-parallelepiped aluminum holder (5 x 5.5 x 33 cm3)



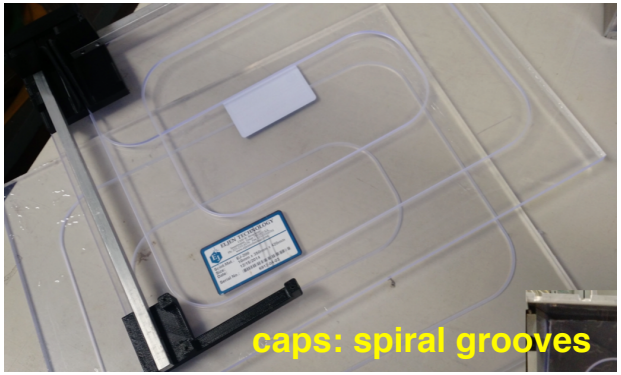


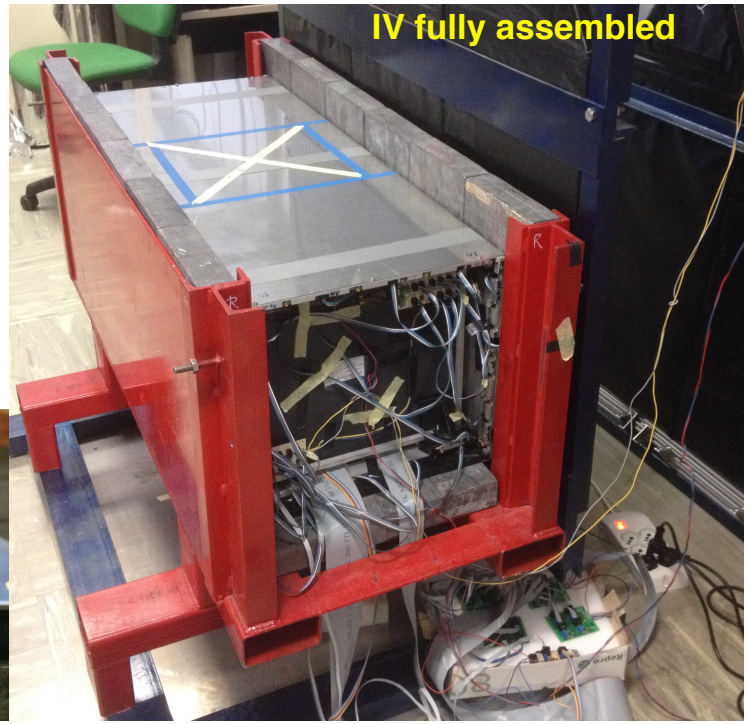


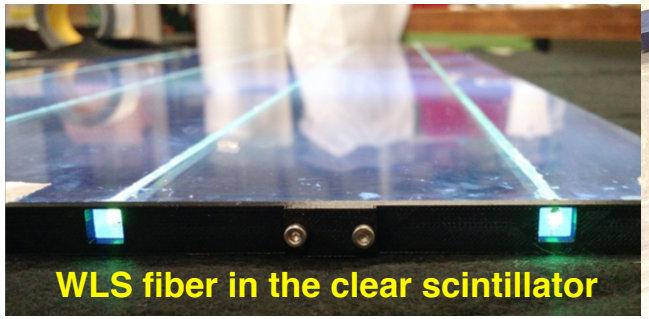
[a] Each crystal was assembled and tested @ INFN-GE

BDχ Proto: Inner Veto

- 6 EJ200 plastic scintillator padddles, 1-cm thick, forming a nearly hermetic parallelepiped[a]
- Top, bottom, left and right sides of the veto: 4 scintillators $35 \times 140\,\mathrm{cm}^2$
- Upstream and downstream caps: 2 scintillators $35 \times 42\,\mathrm{cm}^2$
- Grooves on the surface of the scintillators host two WLS fibers each (Φ=1mm) to convoy the scintillation light to SiPMs, mounted at the edges.
- SiPM: $3 \times 3\,\mathrm{mm}^2$ Hamamatsu MPPC (S12572-100C)



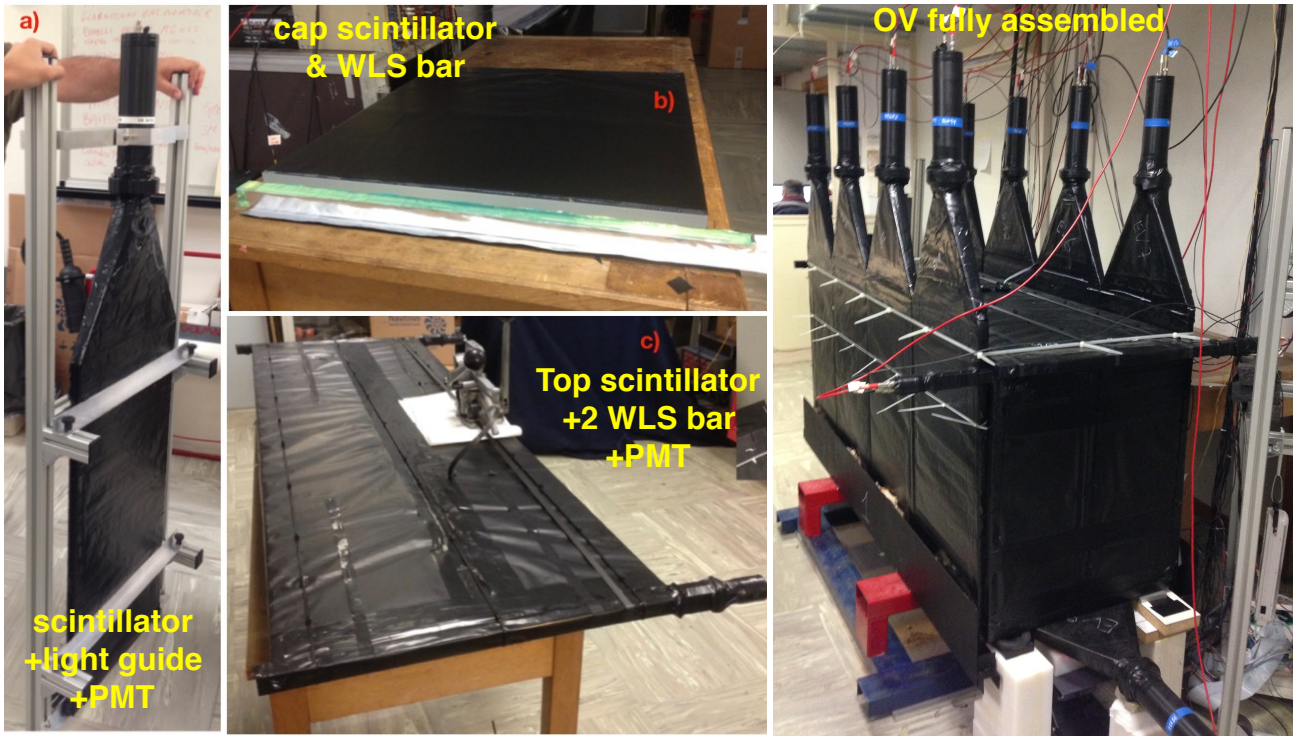




[a] IV was assembled and tested @ INFN-GE

BDχ Proto: Outer Veto

- Different light read-out systems
- Bottom and lateral sides are made by $80 \times 40 \times 2\,\mathrm{cm}^3$ NE110 scintillators
  - A fish-tail shaped PMMA light-guide + 2 inch PMT (Thorn EMI 9954A)
- Top ($184 \times 54 \times 2.5\,\mathrm{cm}^3$), upstream and downstream ($58 \times 66 \times 2.5\,\mathrm{cm}^3$) caps are made by EJ200 scintillators
  - EJ280 WLS bar + PMT(Hamamatsu R1924A)



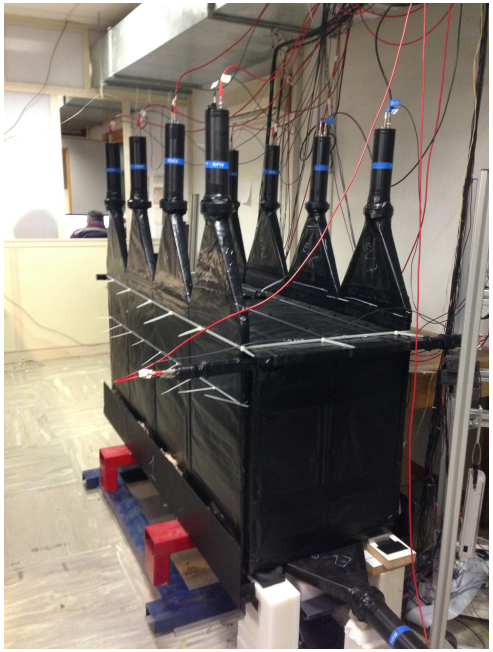
[a] OV was assembled and tested @ INFN-CT

Measurement campaign @ INFN-CT and INFN-LNS

Main goals: to finalize the design of the full detector, make realistic predictions of its expected performance and estimate the cosmic background contribution

INFN-CT

- Minimal shielding: concrete roof 15 cm thick
- Detector commissioning
- Characterization of cosmic events in the ECAL
- IV and OV performances



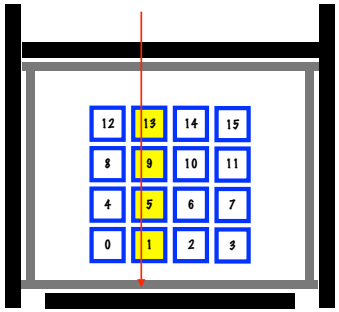
INFN-LNS

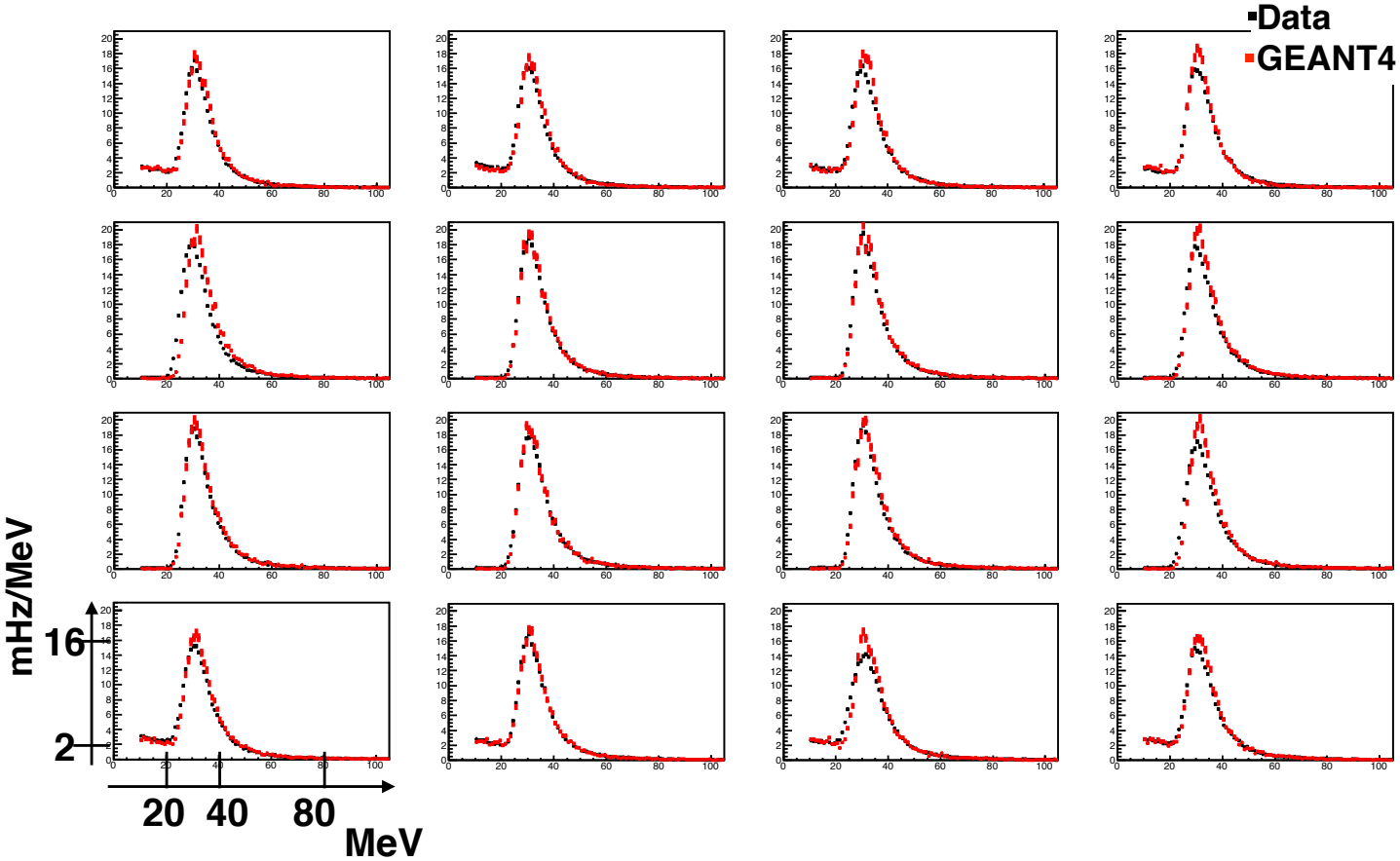
- Similar overburden as expected @ JLab
- First version of prototype: just 1 crystal and OV no optimaized
- Study of the cosmogenic background reduction in a realistic condition

Measurement campaign @ INFN-CT:
Characterization of cosmic events (1)

Comparison between the rate of cosmic muons as a function of the deposited energy in each crystal and the expected values (GEANT 4 simulations)

- perpendicular muons crossing ECAL

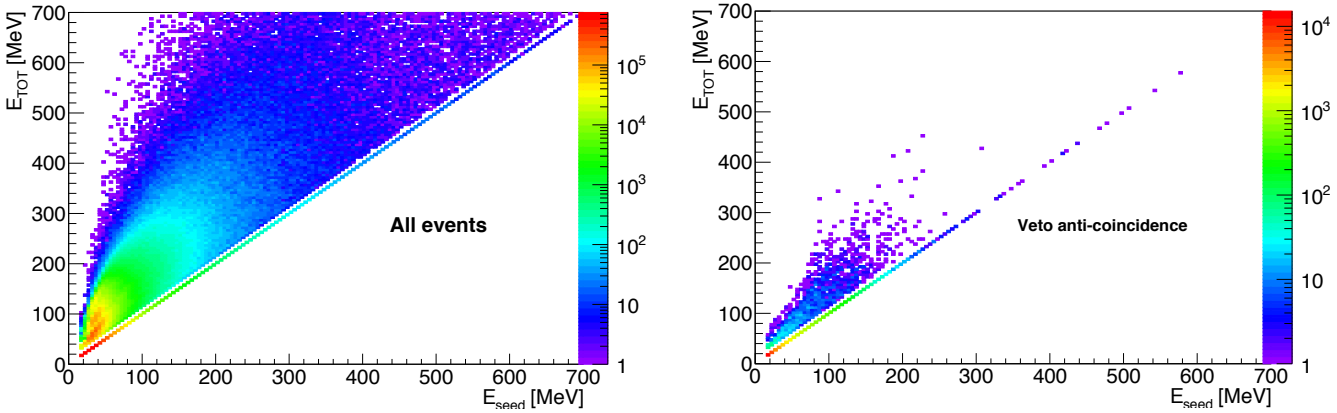




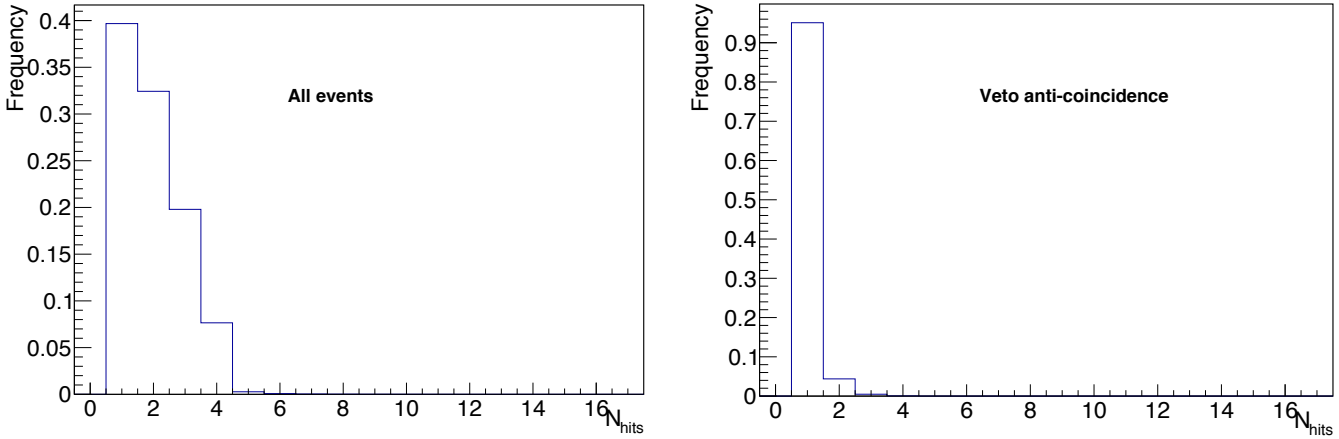
Measurement campaign @ INFN-CT:
Characterization of cosmic events (2)

Looking at three different measurable quantities...

- E_{seed}: the highest energy measured in a single crystal per event
- E_{TOT}: total energy measured in ECAL per event



- N_{hits}: number of crystals fired (signal over threshold)

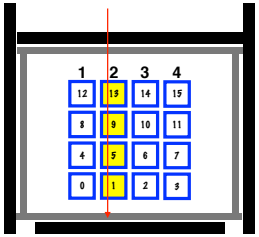


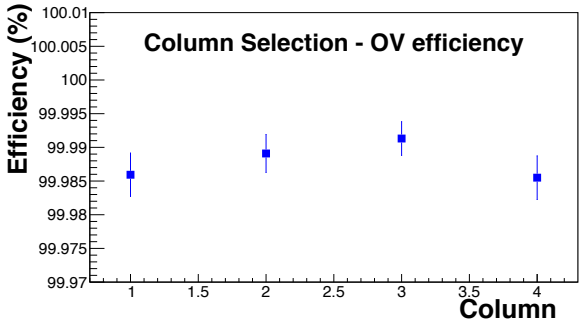
high energy && veto anti-coincidence: **most of the E contained in just 1 crystal**

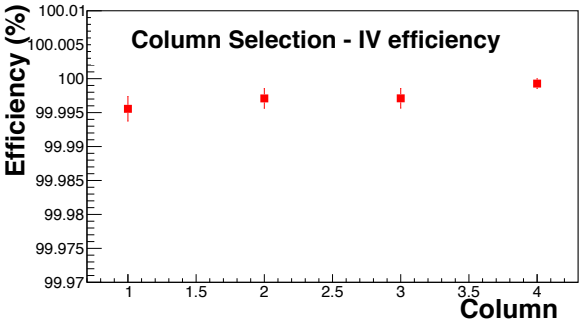
Measurement campaign @ INFN-CT:
IV and OV performances (1)

Veto efficiency has been studied for two class of events with a well-defined topology in the ECAL

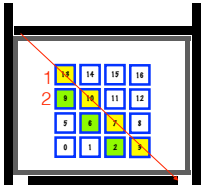
- **Vertical selection**

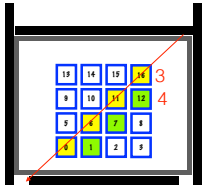


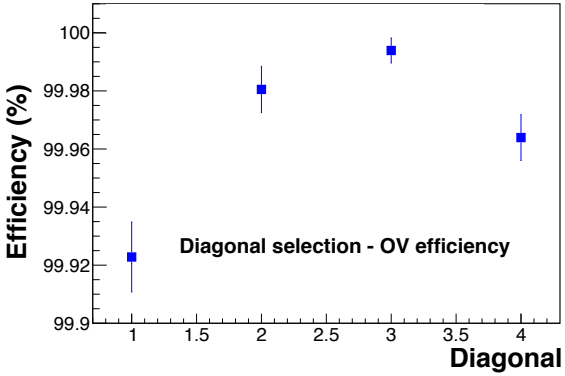


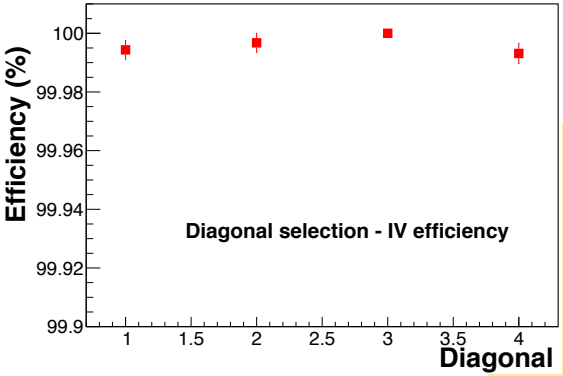


- **Diagonal selection**





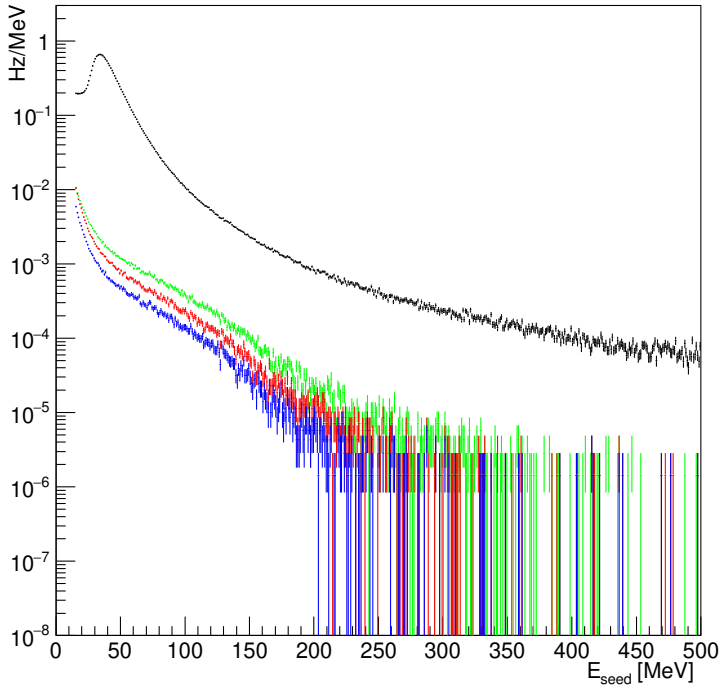




Efficiency$_{OV,IV} > 99.9\%$ is an index of the overall goodness of both systems in terms of hermeticity and technologies

Measurement campaign @ INFN-CT:
IV and OV performances (2)

The background rejection efficiency as a function of event energy has been studied



- All events
- Events with OV in anti-coincidence
- Events with IV in anti-coincidence
- Events with both OV and IV in anti-coincidence

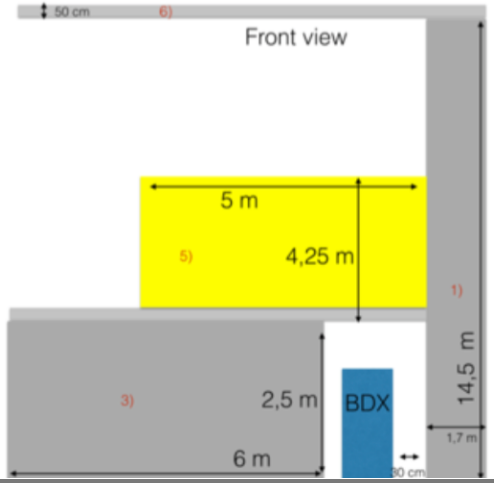
- At the MIP energy the differential counting rate is reduced by a factor: ~ 700 when OV and IV in anti-coincidence
- At higher energy (i.e. $E_{seed} > 350$ MeV) the integrated background rate is suppressed by ~ 3 orders of magnitude

Measurement campaign @ INFN-LNS

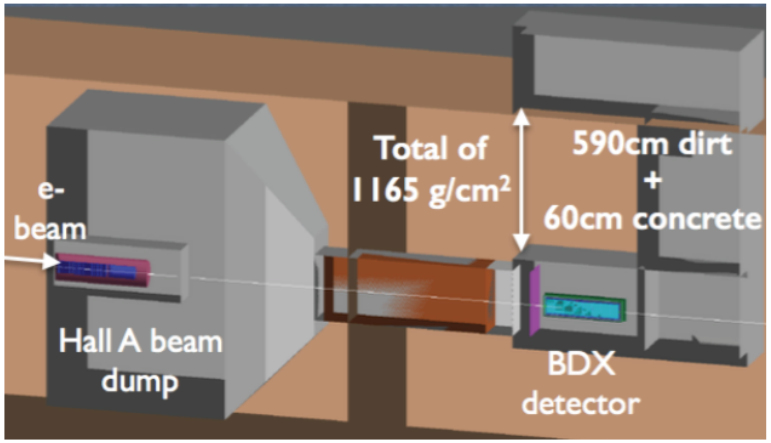
Main goal: to estimate conservatively the total number of cosmogenic background events expected in the full experiment

- First version of prototype: one crystal
- Detector placed inside a bunker with a surrounding overburden similar to that expected @ JLab

Bunker @ INFN-LNS

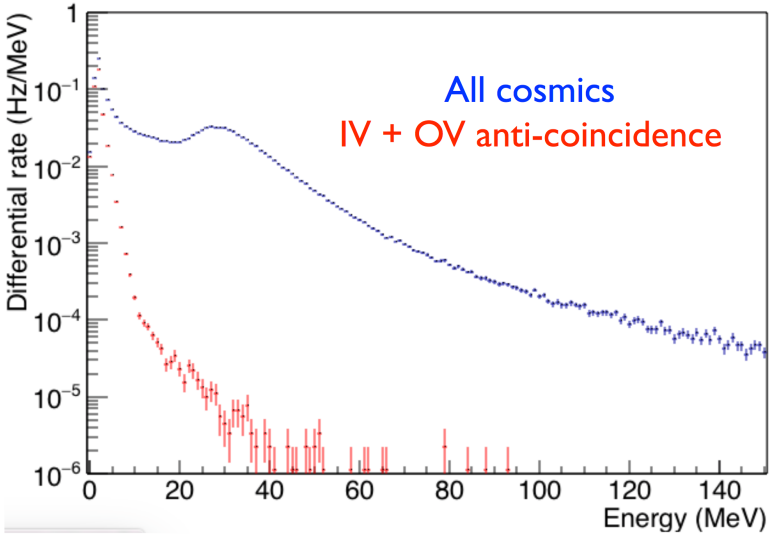


Future BDX Facility @JLAB

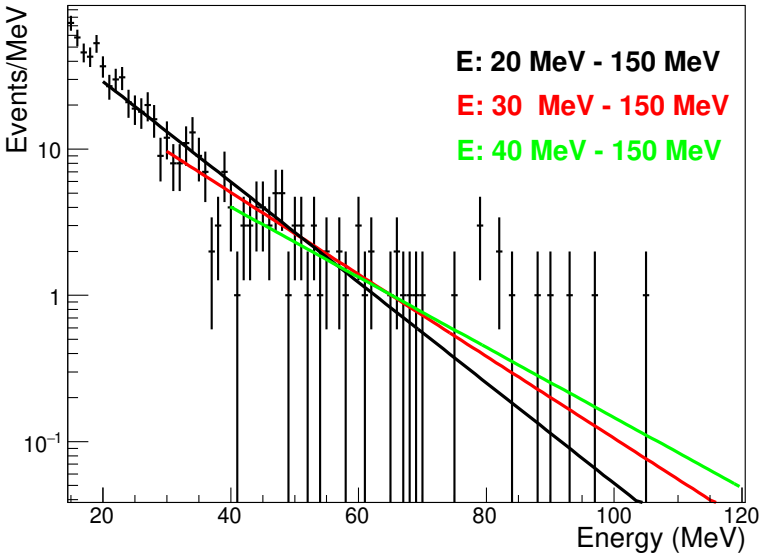


Measurement campaign @ INFN-LNS

Count rate measured in 1 crystal



- The majority of cosmic muons are detected and rejected by the two veto detectors



- Measured anti-coincidence rate (E_{thr}~300 MeV)~ 10^{-12} Hz
  - results obtained by conservatively extrapolating from the lower-E, non-zero counts region
- **Expected cosmic bg in the BDX lifetime $<$ 2 counts:)**
  - projecting to the JLAB setup (800 CsI(Tl) crystals)
  - integrating over the expected beam-on time (285 days).

Conclusions

- A prototype of the future BDχ detector was designed and constructed
- A dedicated campaign of measurements @ INFN-CT allowed us **to validate the technological solution proposed for the future detector and to study the performances of the prototype**
- A dedicated campaign of measurements @ INFN-LNS, performed with the first version of the BDX-PROTO, allowed us **to demonstrate the possibility to reject the cosmic background**