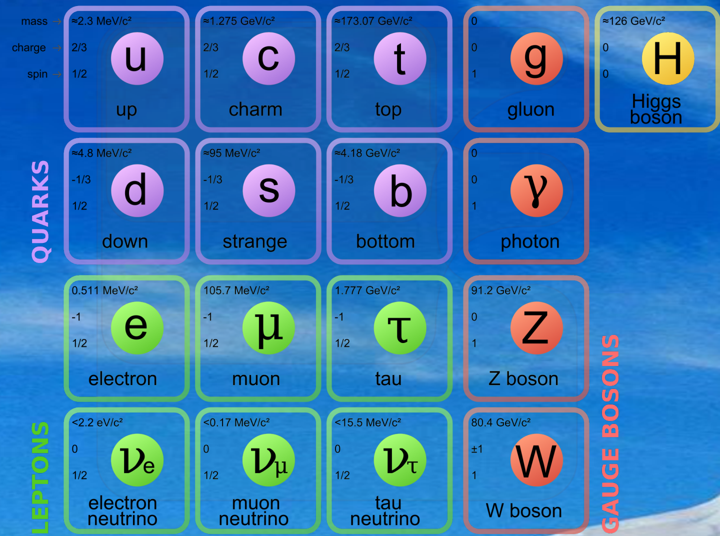
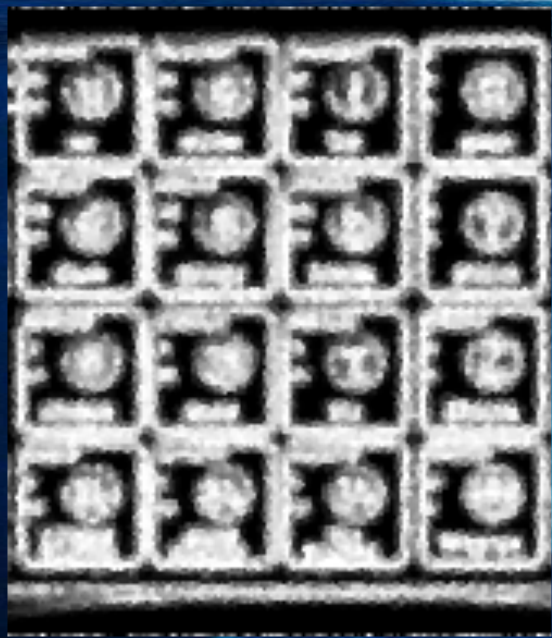
13th Rencontres du Vietnam July 23-29
ICISE
Exploring the Dark Universe 2017

# Review on searches for light dark matter at fixed target electron accelerators

INFN Sez. CATANIA
Mariangela Bondì
on behalf of the BDX collaboration

25 July 2017



# Hidden Sectors

Is it made by a "Dark Sector" of new particles and interactions ?

A Hidden Sector not charged under SM gauge groups :

- Light Dark Matter $\chi$ in MeV - GeV mass range
- "New" interaction between LDM and SM particles in order to be compatible with the DM thermal origin
- Can explain some puzzling observations

# Possible connection between Hidden sector and SM: "Vector" portal

Consider a theory in which nature contains an additional Abelian gauge symmetry U'(1)

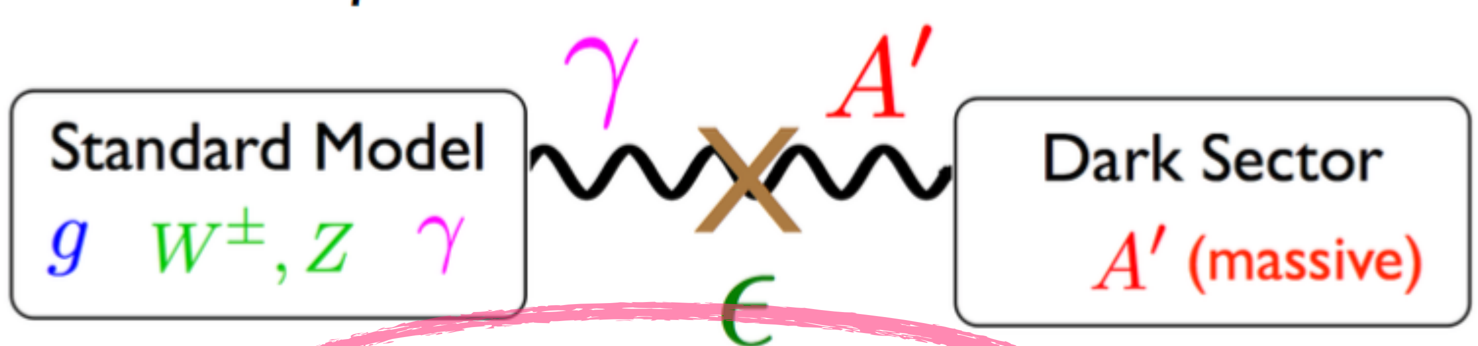
B. Holdom, Phys. Lett., B166:196-198, 1986

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F_{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'^\mu + g_D A'_\mu J^\mu_\chi + eA_\mu J^\mu_{\rm EM}$$

This gives rise to a Kinetic Mixing term where the photon mixes with a new gauge boson ( "Dark/Heavy Photon" or A') through the interactions of massive fields:

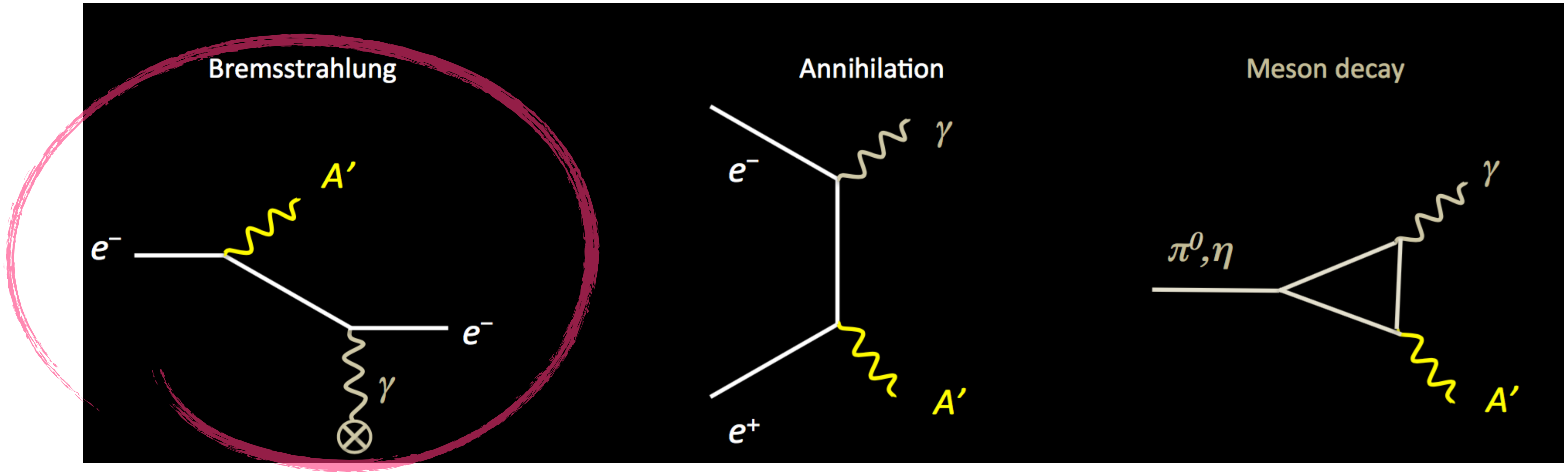
Mixing induces an effective weak coupling εe to electric charge

*A' acts as a "portal" between the SM and the new sector*




4 parameters: $M_{A'}$ , $M_X$, ε, $g_d$

Since dark photons couple to electric charge, they can be produced through…..



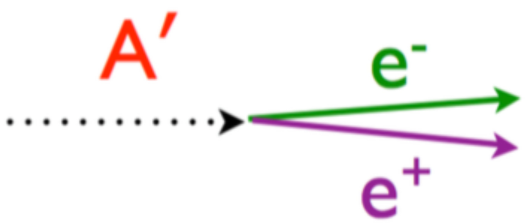

A' can be produced in electron collision on target by:

- Bremsstrahlung eN -> eNA'. In a fixed target configuration the A' is produced very forward, carrying most of the beam energy, while e⁻ emerges at a larger angle

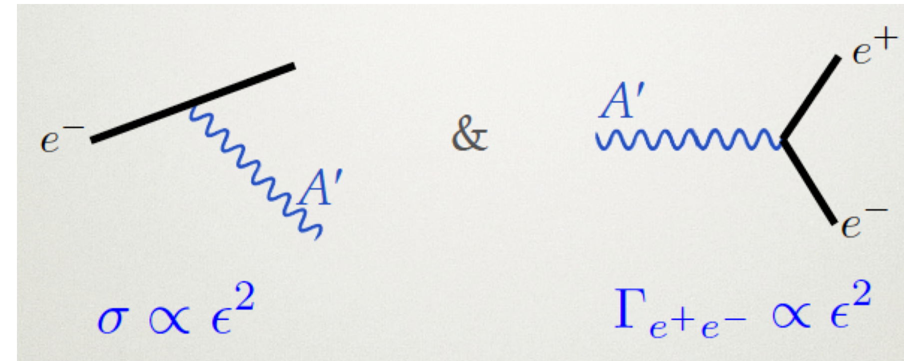
- Annihilation -> $e^+e^-$ -> $\gamma A'$

- Meson decays

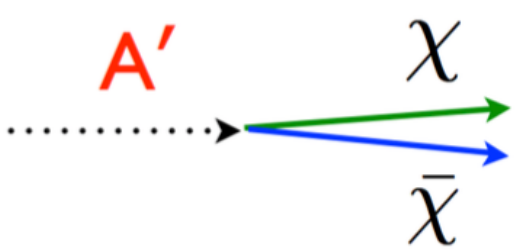
## Visible decay



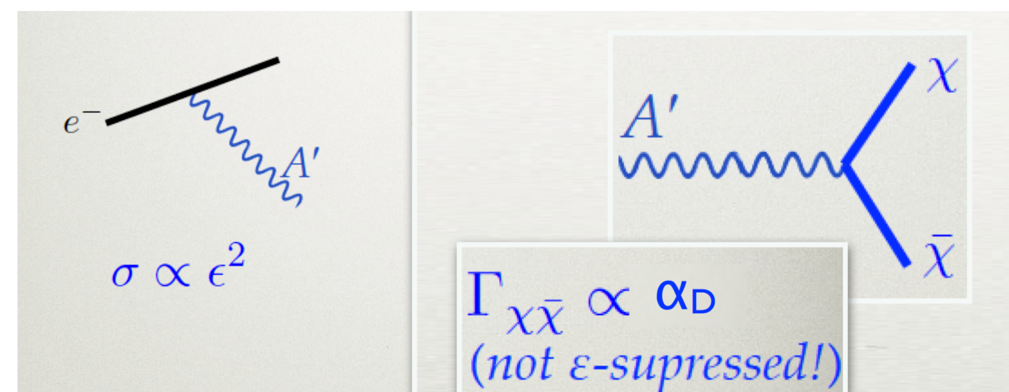

- Decay regulated by $\varepsilon^2$
- Independent on $m_\chi$
- Requires $m_{A'} < 2\ m_\chi$




## Invisible decay




- Requires $m_{A'} > 2\ m_\chi$
- Independent on $\varepsilon$




**A broad international program of accelerator experiments is currently focused on exploring light dark matter and associated new force**

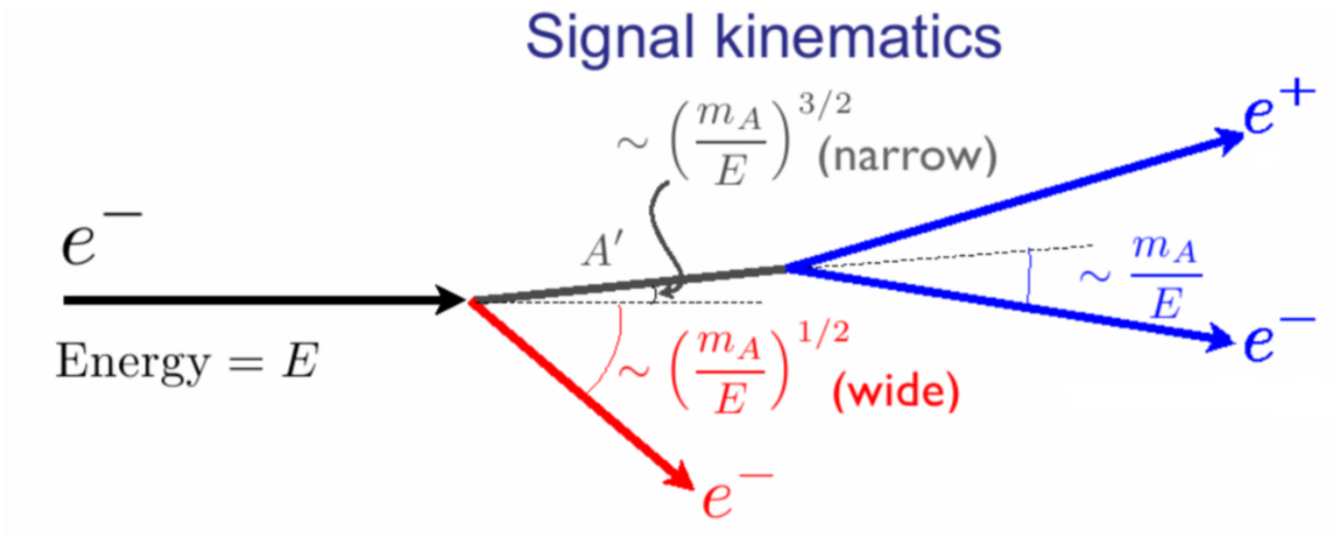
**Direct dark photon searches:** focused on **identifying the mediator through its decay into SM particles.** The production mechanism is eZ -> eZA′ or neutral meson decays, and the mediator is reconstructed through its leptonic decays A′ -> $e^+e^-$

**Missing mass:** The DM is produced in exclusive reactions and identified as a narrow resonate over a smooth background in the recoil mass distribution

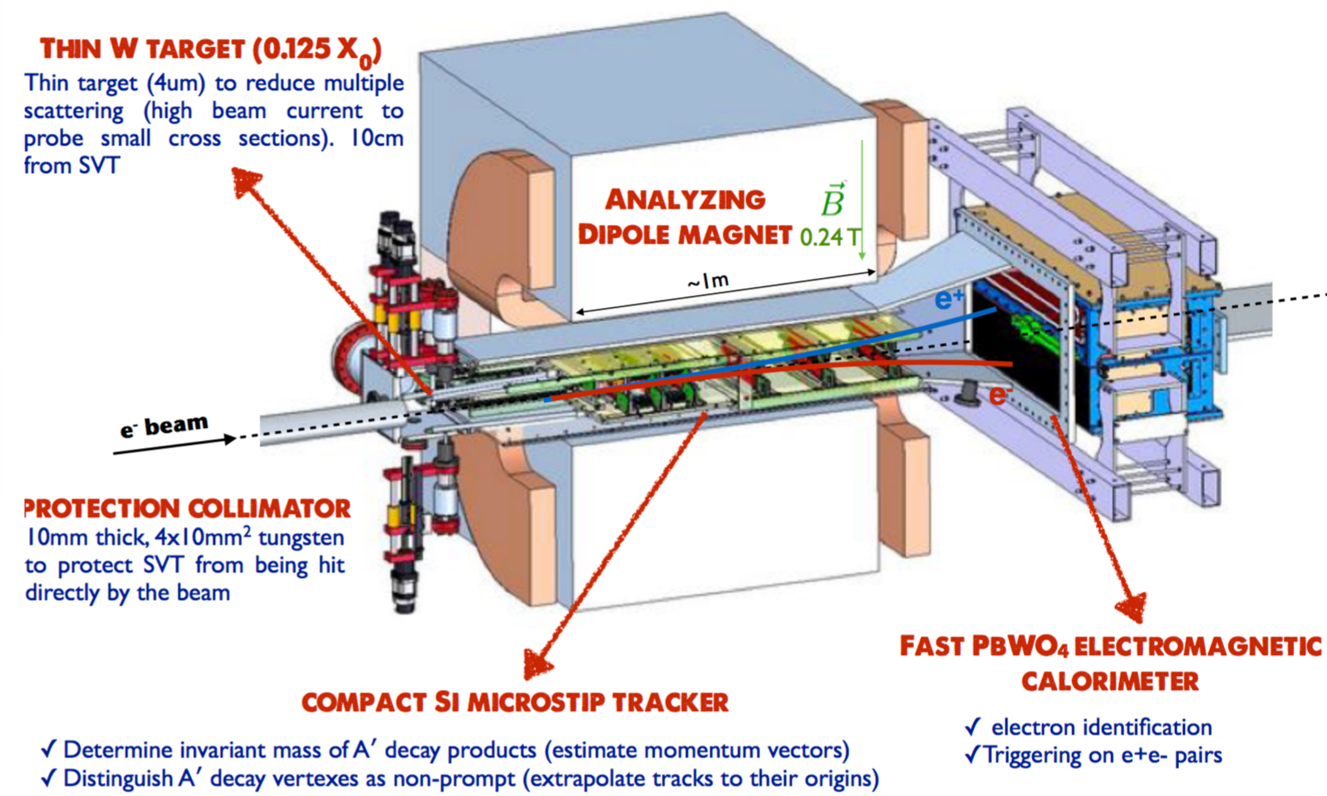
**Missing momentum/energy:** The DM is produced in eZ -> eZ(A′ -> XX) and identified through the missing energy/momentum carried away by the escaping DM particles

**Electron Beam Dump:** The DM is produced via eZ -> eZ(A′ -> XX) and typically detected via eX -> eX or NX-> NX scattering in a downstream detector

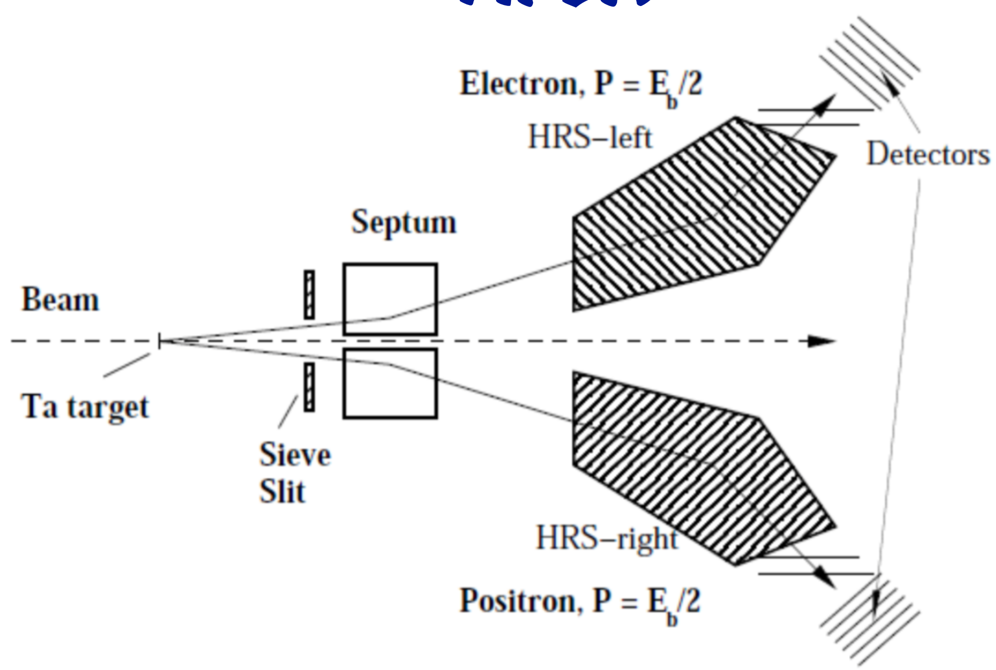
# Direct Dark Photon search




## HPS




## APEX



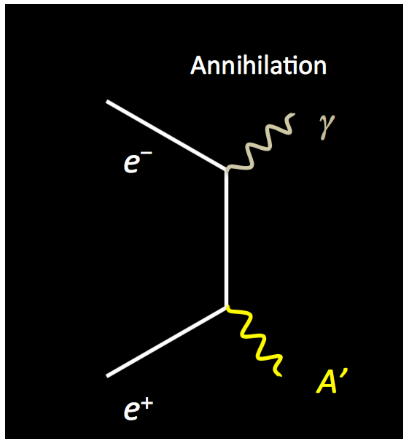

- Fixed target experiment at HALL B @ JLAB
- Detector: SVT + ECAL (I. Ballossino et al. (HPS coll.) NIMA 854 (2017) 89)
- Two complementary search techniques: resonance search and detached vertexing .
- Sensitivity: $10^{-10}<\varepsilon^2<10^{-5}$ in the mass range 20 MeV < $m_{A'}$ < 1 GeV
- Full approval from the laboratory for a 180-day run with different beam energy configurations
- Two data-taking periods have been completed: in 2015, 1.7 days (10 mC) at 1.06 GeV and in 2016, 5.4 days (92.5 mC) at 2.3 GeV

- Fixed target experiment at HALL A @ JLAB
- Detection strategy is $m_{A'}$ bump hunt
- Engineering run to demonstrate method done (2010)
- Sensitivity: $\varepsilon^2>10^{-7}$ in the mass range 60 MeV < $m_{A'}$ < 550 MeV

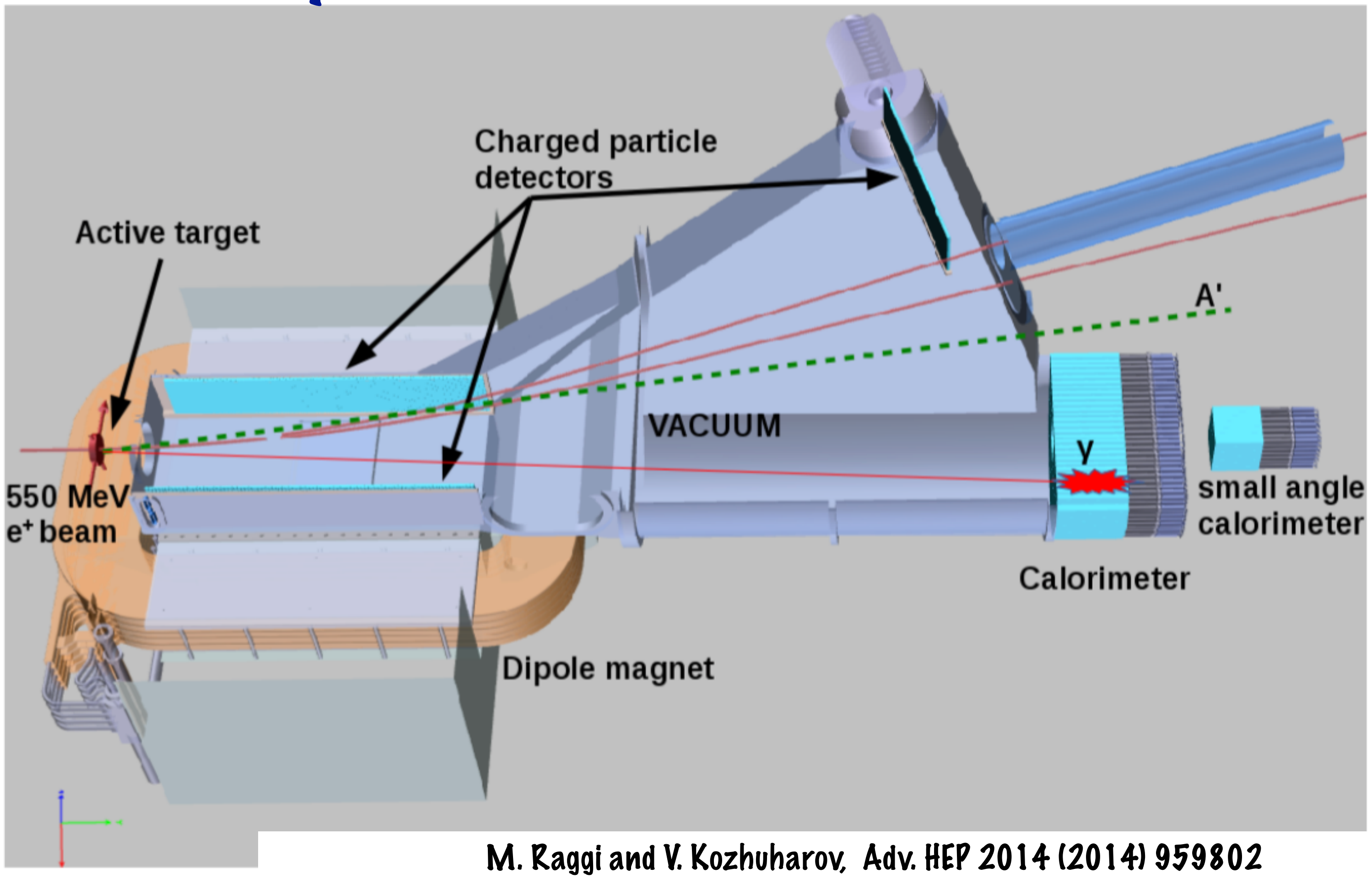
S. Abrahamyan et al. (APEX), Phys. Rev. Lett. 107, 191804 (2011), 1108.2750.

# Missing Mass

It aims to use annihilation production ($e^+e^-$ -> $\gamma$(A'->XX) ) and missing mass searches.




## PADME experiment

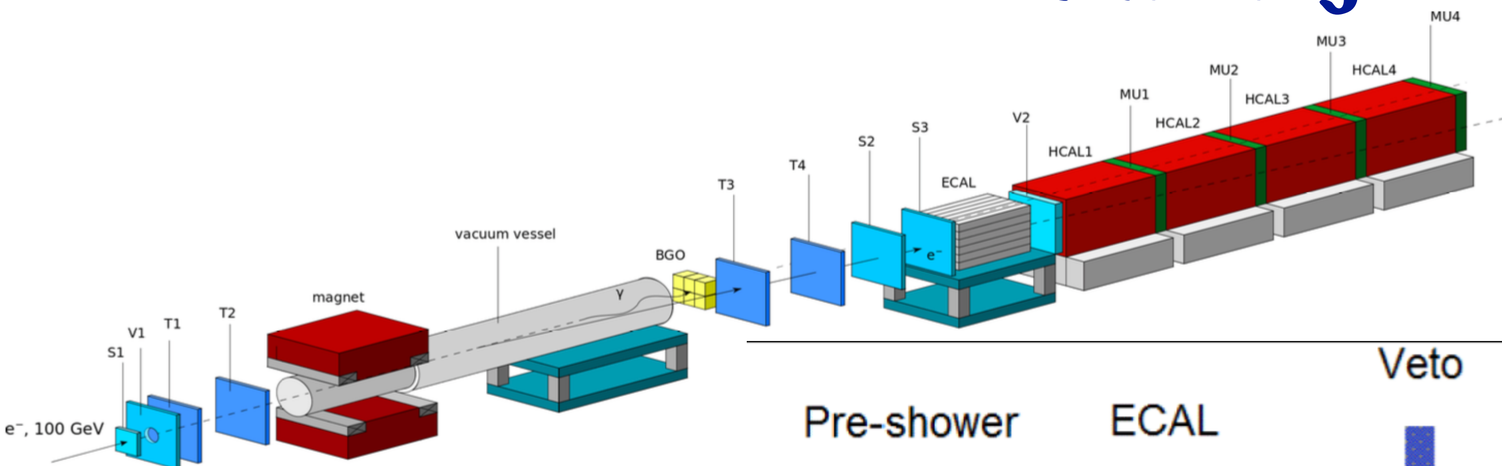



M. Raggi and V. Kozhuharov, Adv. HEP 2014 (2014) 959802

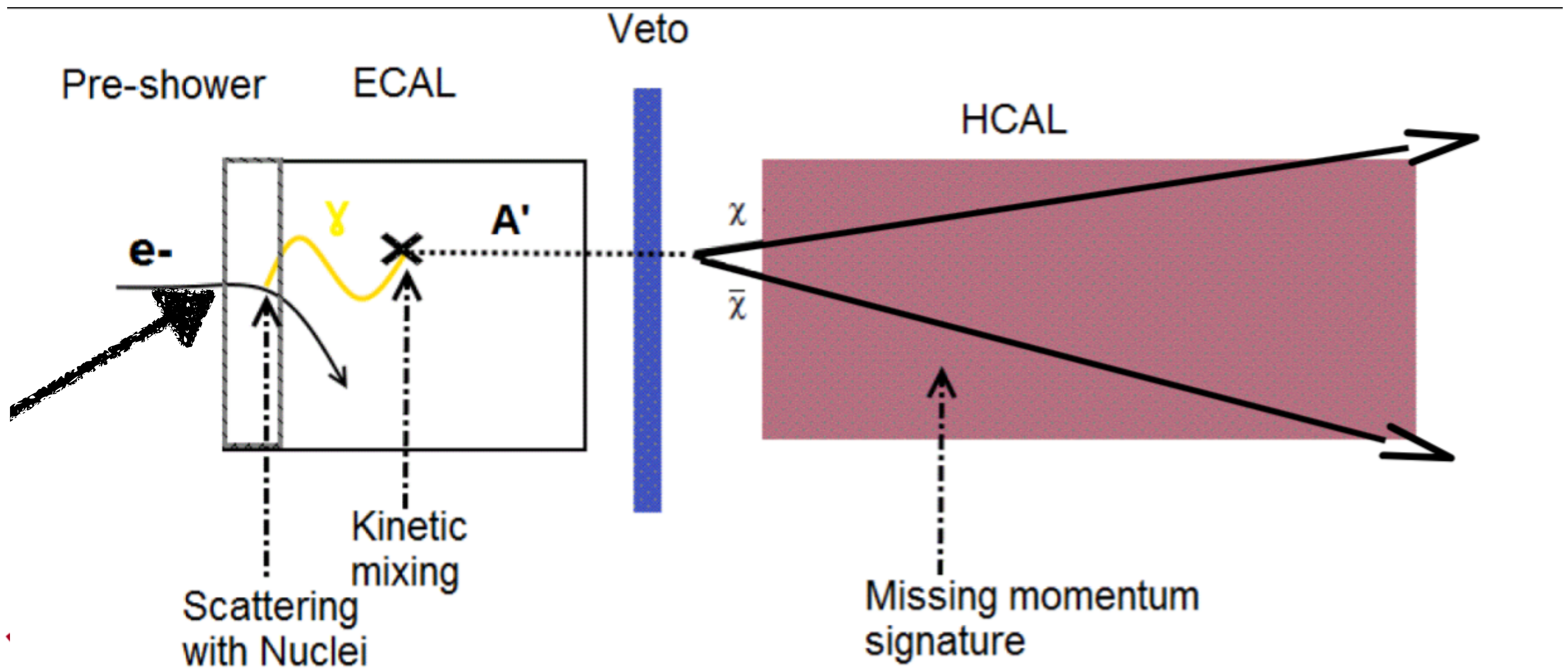
- Small scale fixed target experiment
- 550 MeV $e^+$ @ BTF in INFN-LNF
- Thin active diamond target
- Charged particle detectors
- Calorimeter
- Expected to collect >=$10^{13}$ positron on target

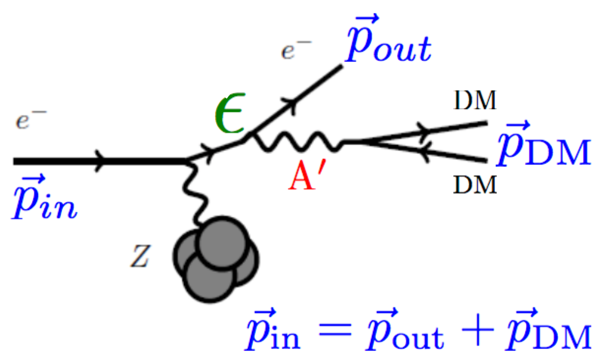
**Sensitivity:** $\varepsilon^2 > 10^{-7}$ in the mass range $m_{A'}$ < 24 MeV in a complete model independent way (Independent from the A' decay mechanism, A' lifetime, nature and mass of the dark matter ).

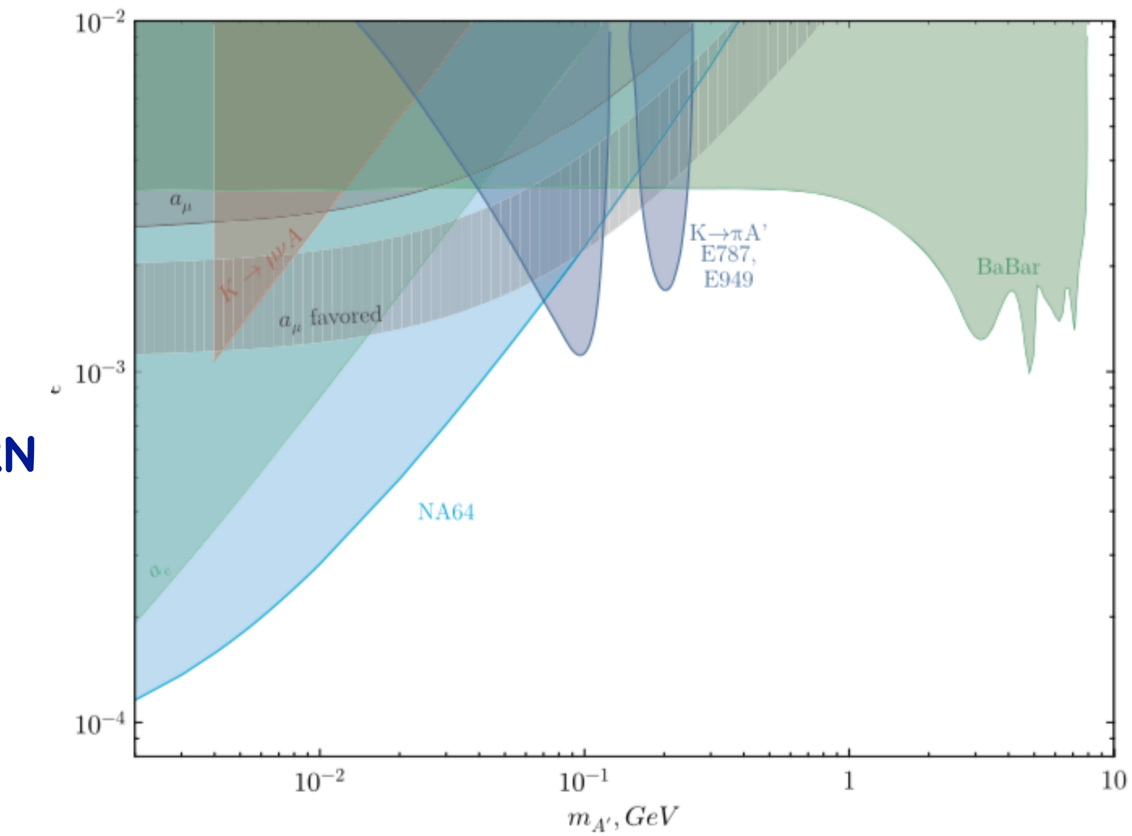
# Missing energy:




## NA64 experiment




- Fixed target experiment combining the active beam dump technique with missing energy measurement
- 100 GeV e- secondary beam from the SPS beam line @ CERN
- A typical signature for a signal will be missing energy in the ECAL and no activity in the the VETO and HCAL.

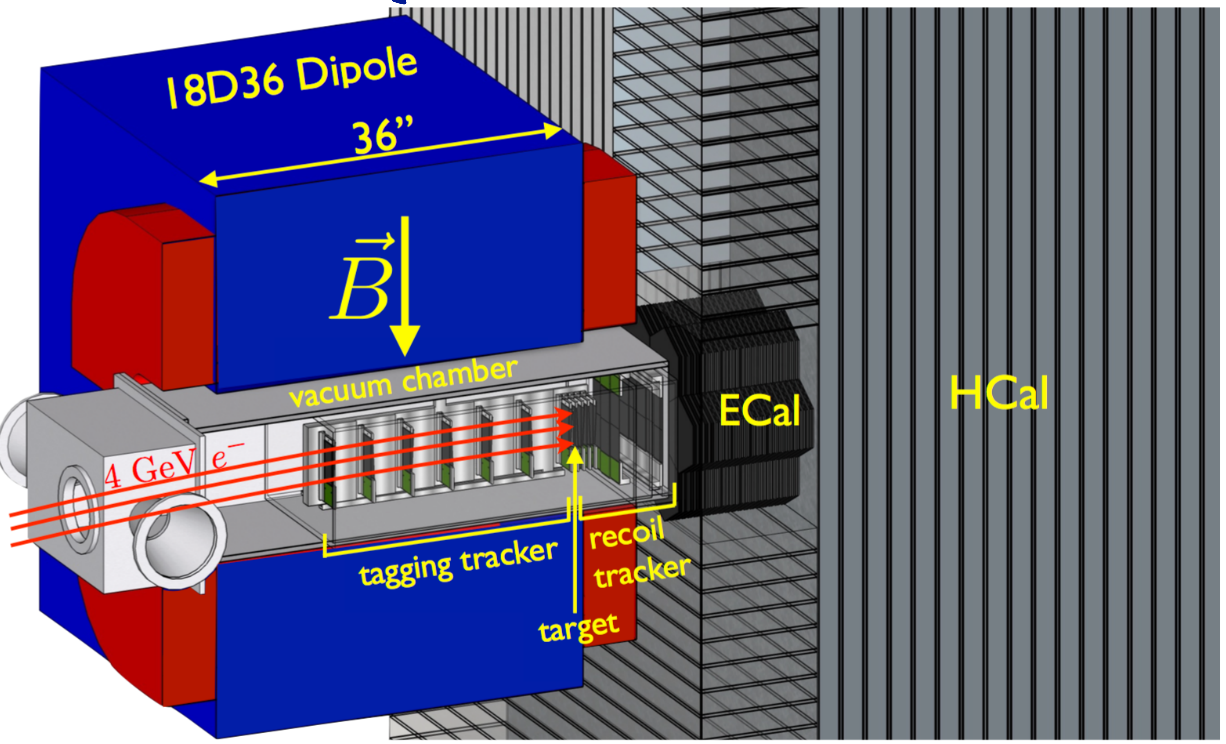
D. Banerjee et al. (NA64), Phys. Rev. Lett. 118, 011802 (2017), 1610.02988.

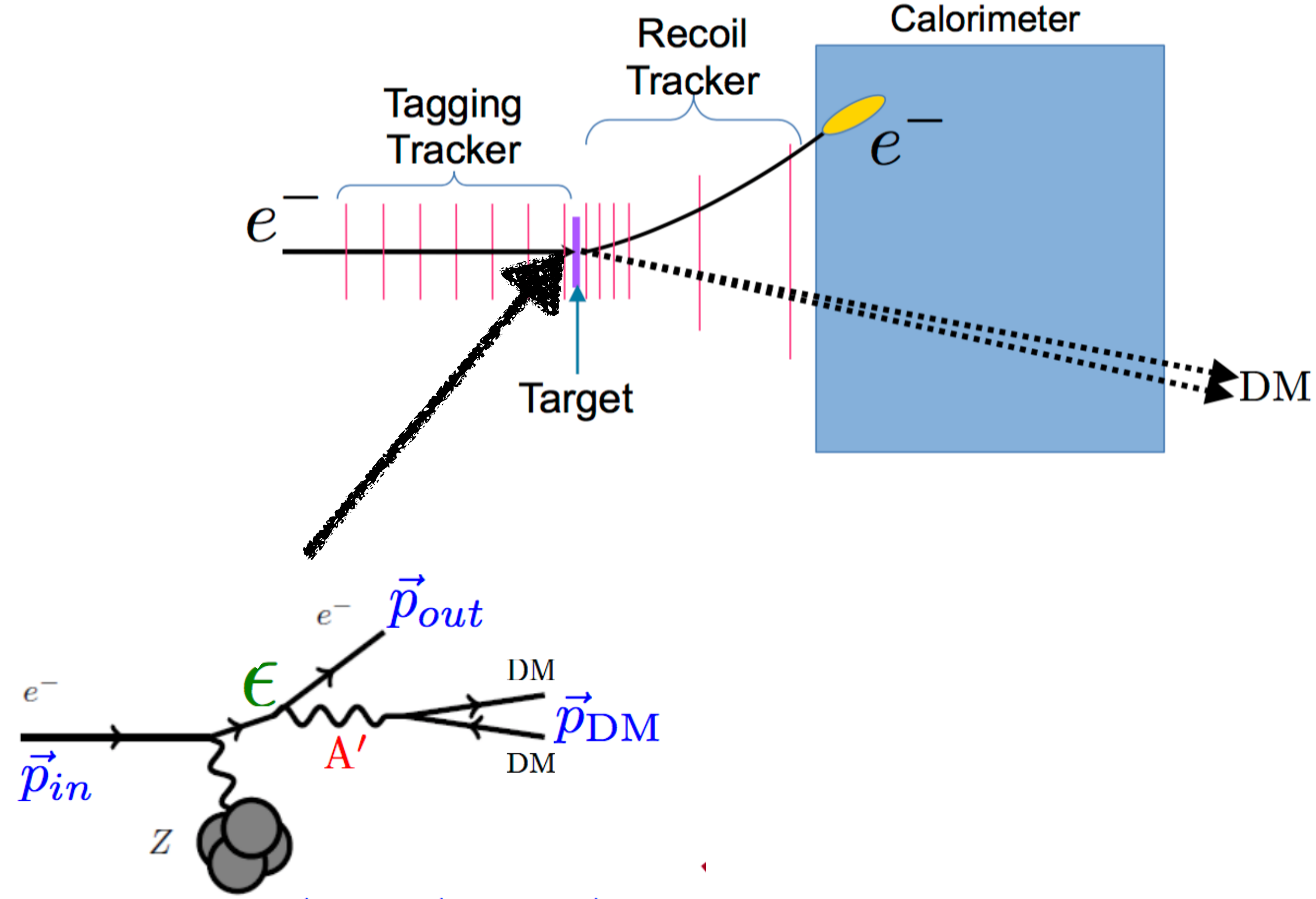
# Missing momentum/energy

J. Mans, EPJ Web of Conferences 142, 01020 (2017)

LDMX collaboration: https://confluence.slac.stanford.edu/display/MME/Light+Dark+Matter+Experiment

## LDMX experiment




$$\vec{p}_{\rm in} = \vec{p}_{\rm out} + \vec{p}_{\rm DM}$$

- Missing momentum experiment
- A Low current, multi-GEV e- beam with high-repetition rate
- The experimental signature consists of a soft wide angle scattered electron, characteristic of DM production at an electron fixed-target reaction, plus missing energy

# $e^-$ - Beam dump experiment


PHYSICAL REVIEW D 88, 114015 (2013)

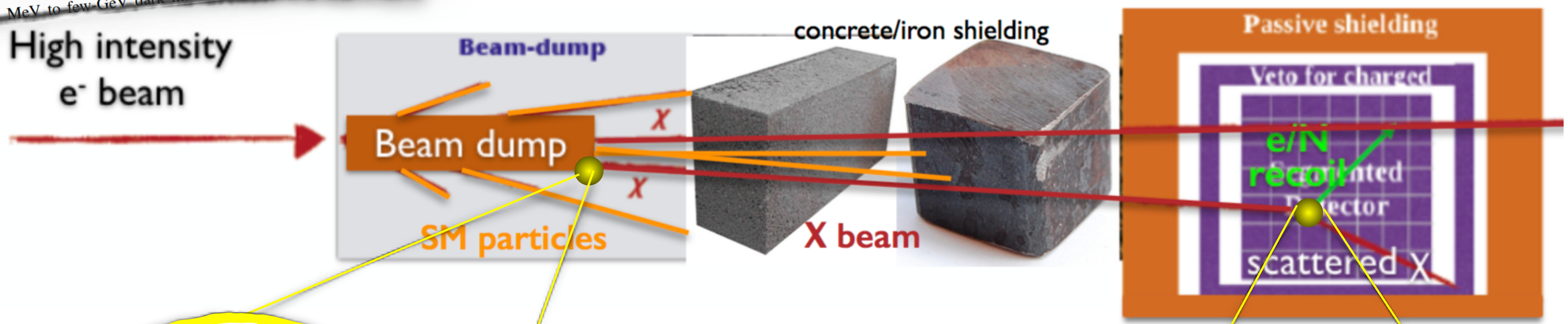
**New electron beam-dump experiments to search for MeV to few-GeV dark matter**

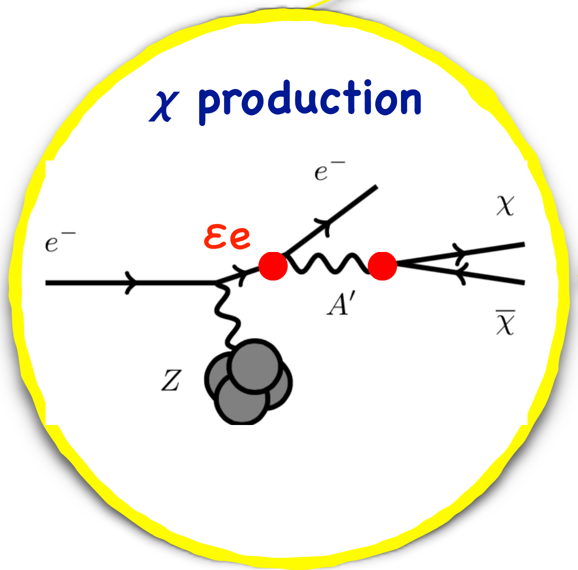
Eder Izaguirre, Gordan Krnjaic, Philip Schuster, and Natalia Toro

*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

(Received 9 August 2013; published 3 December 2013)

In a broad class of consistent models, MeV to few-GeV dark matter interacts with ordinary matter

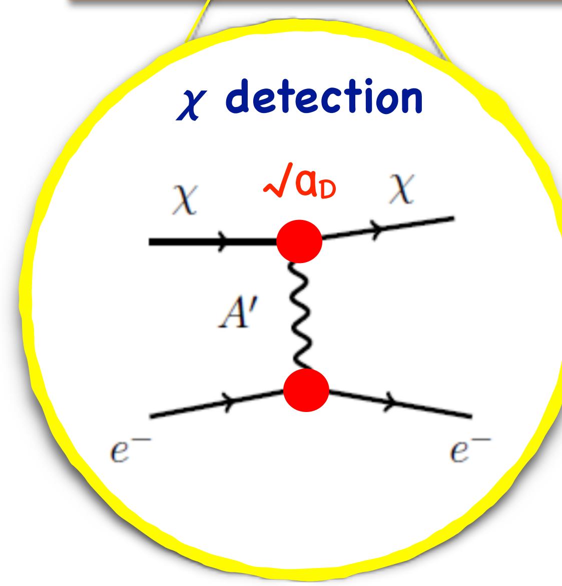



A' yield: $N_{A'} \propto \frac{\varepsilon^2}{m_{A'}^2}$

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

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




**1 Step: LDM production**

- Xs produced via A' emission and invisible decay
  - ➡ GeV - high intensity e- beam

**2 Step: LDM detection**

- X scatter off nucleons, nuclei, or electrons in the detector volume, giving rise to a detectable signal.

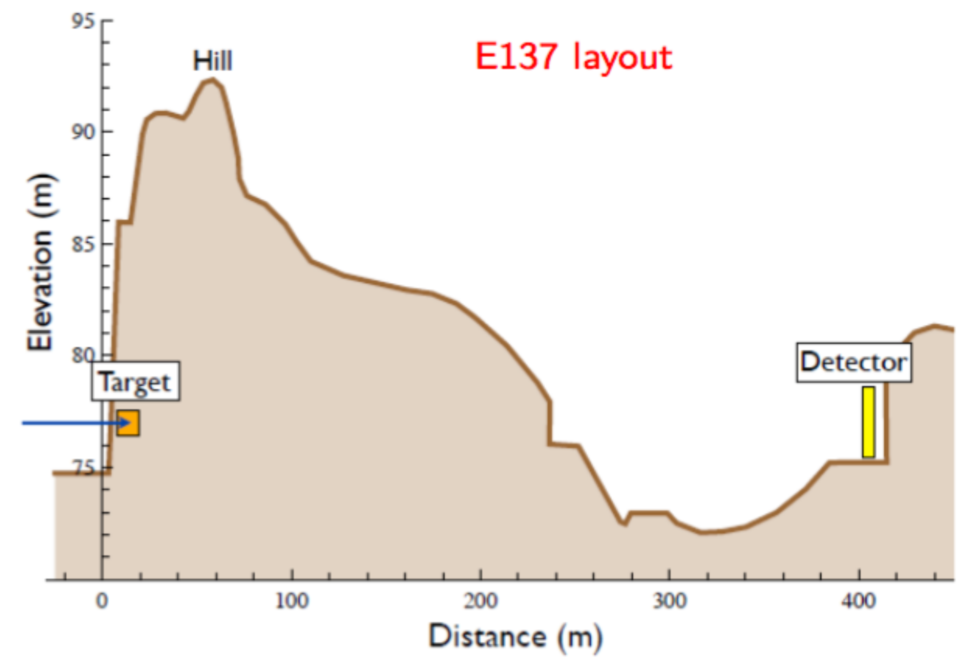
**the eternal fight in physics: signal vs background**

# The Beam Dump eXperiment (BDX)

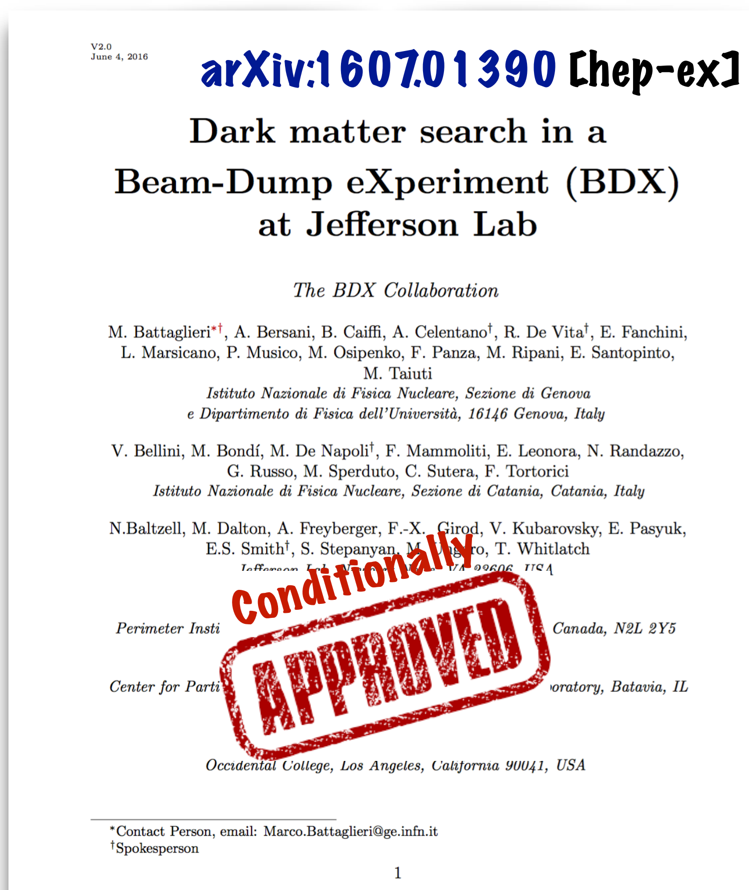
## Past e- beam dump experiment: E137 @ SLAC

PRL 113, 171802 (2014)

LDM results are a re-analysis of old data
the experiment itself was not optimized for this research




An optimized e- beam-dump experiment can explore new territories in the LDM space:
**BDX**


V2.0
June 4, 2016

arXiv:1607.01390 [hep-ex]

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

*The BDX Collaboration*

M. Battaglieri*†, A. Bersani, B. Caiffi, A. Celentano†, R. De Vita†, E. Fanchini, L. Marsicano, P. Musico, M. Osipenko, F. Panza, M. Ripani, E. Santopinto, M. Taiuti
*Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dell'Università, 16146 Genova, Italy*

V. Bellini, M. Bondí, M. De Napoli†, F. Mammoliti, E. Leonora, N. Randazzo, G. Russo, M. Sperduto, C. Sutera, F. Tortorici
*Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Catania, Italy*

N.Baltzell, M. Dalton, A. Freyberger, F.-X. Girod, V. Kubarovsky, E. Pasyuk, E.S. Smith†, S. Stepanyan, M. Ungaro, T. Whitlatch

*Perimeter Insti ... Canada, N2L 2Y5*

*Center for Parti ... oratory, Batavia, IL*

*Occidental College, Los Angeles, California 90041, USA*

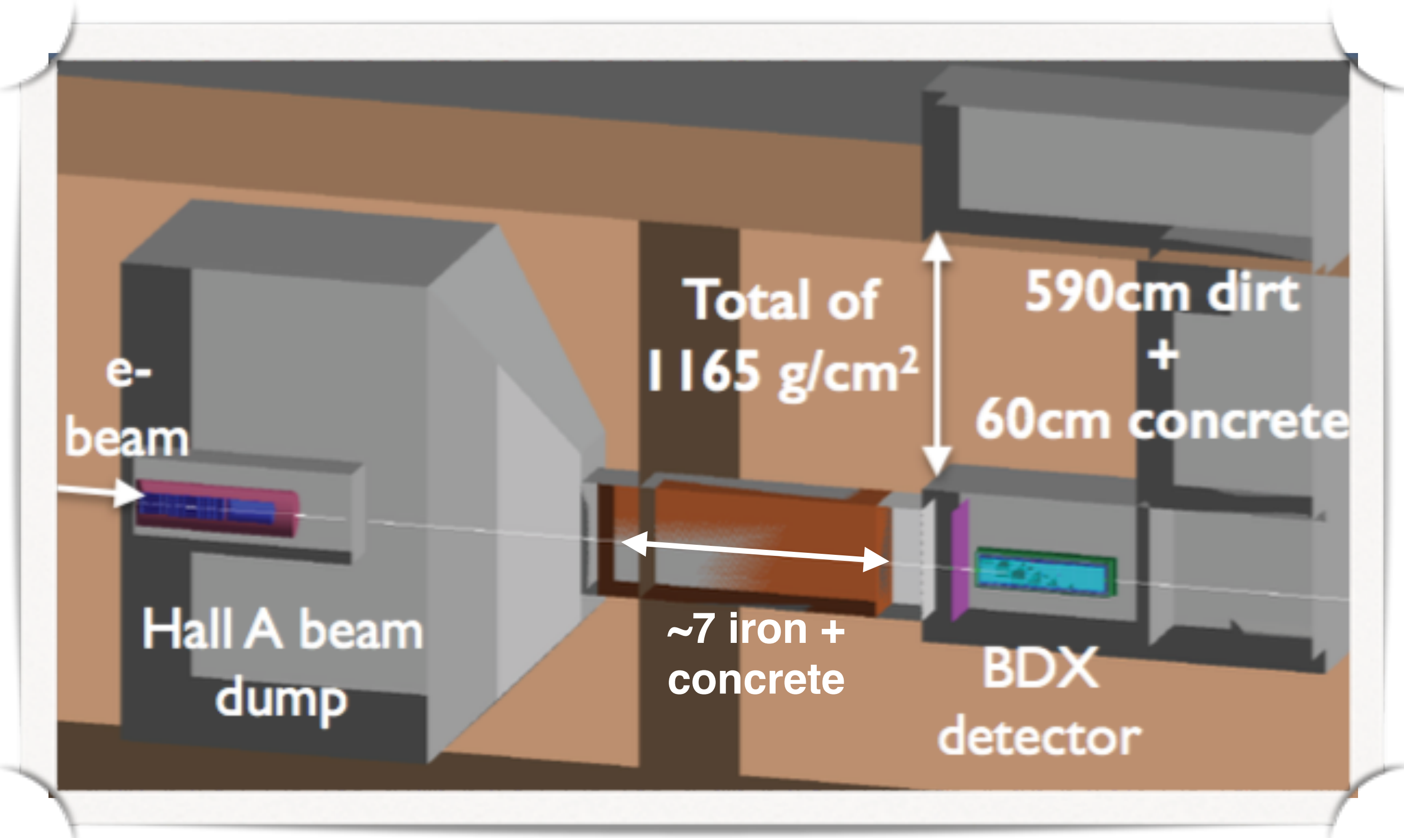
*Contact Person, email: Marco.Battaglieri@ge.infn.it
†Spokesperson

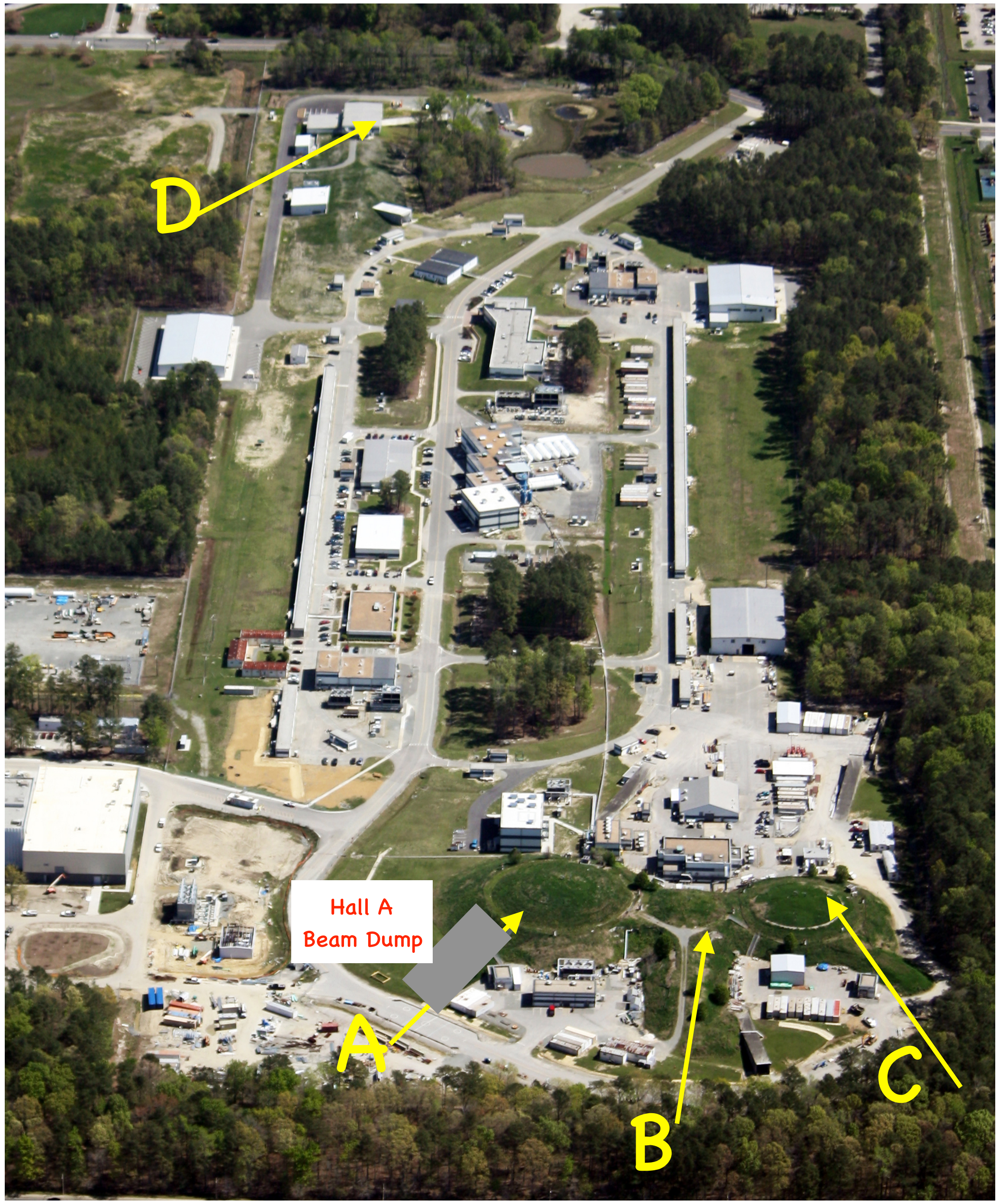
1

Conditionally APPROVED


BDX collaboration

- ✓ High electron beam current ~ 65 μA (integrated charge $10^{22}$ EOT in 41 weeks)
- ✓ Energy beam available: 11 GeV
- ✓ Parasitic to experimental program. Use electrons that are otherwise thrown away.
- ✓ New underground experimental Hall



# BDX detector

**χ detection**

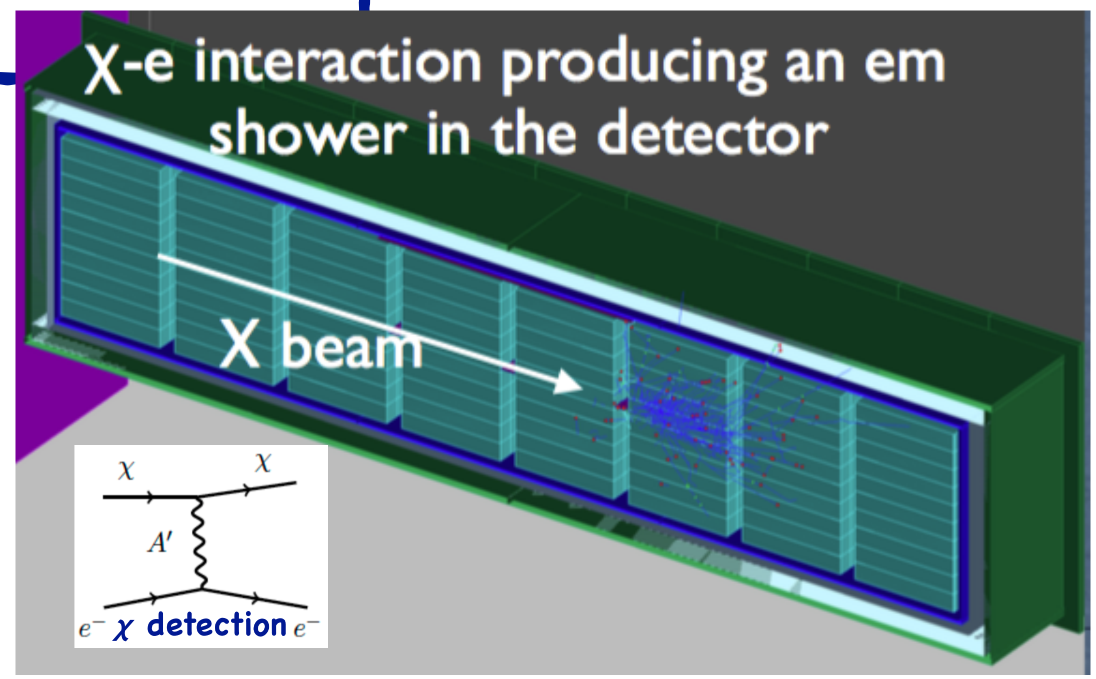
**What?** BDX experimental signatures : χ-e⁻—> EM shower ~ GeV energy

**How?** EM Calorimeter: A homogenous crystal-based detector

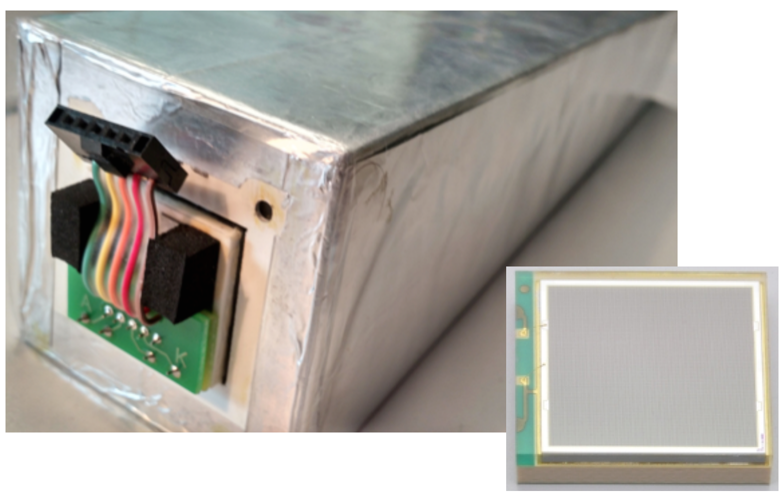
**Background rejection**

**What?** Cosmic and Beam-on backgrounds

**How?** Active Veto: Two layers of plastic scintillator

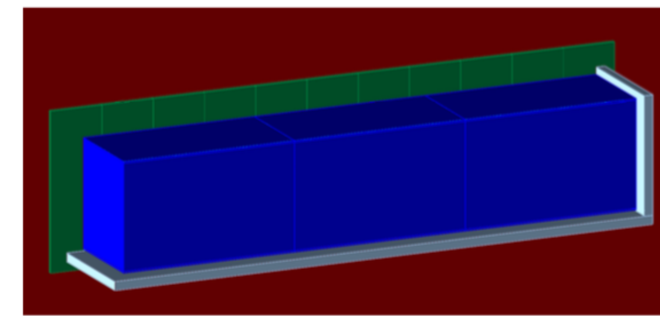



## EM Calorimeter



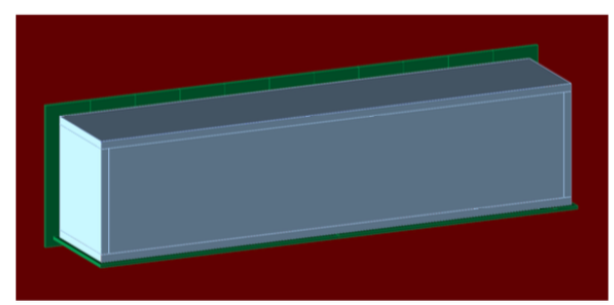
- 8 Blocks (10x10 crystals each)
- 800 CsI(Tl) crystals
- 50 x 55 x 295 $cm^3$
- 6x6 mm2 Hamamatsu SiPMs

## Inner Veto



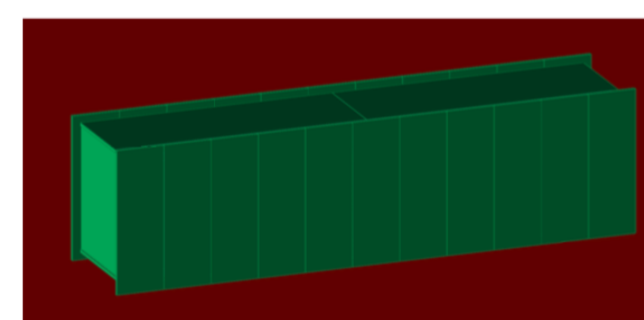
- Plastic scint + WLS fibers
- SIPM readout

## Passive shielding



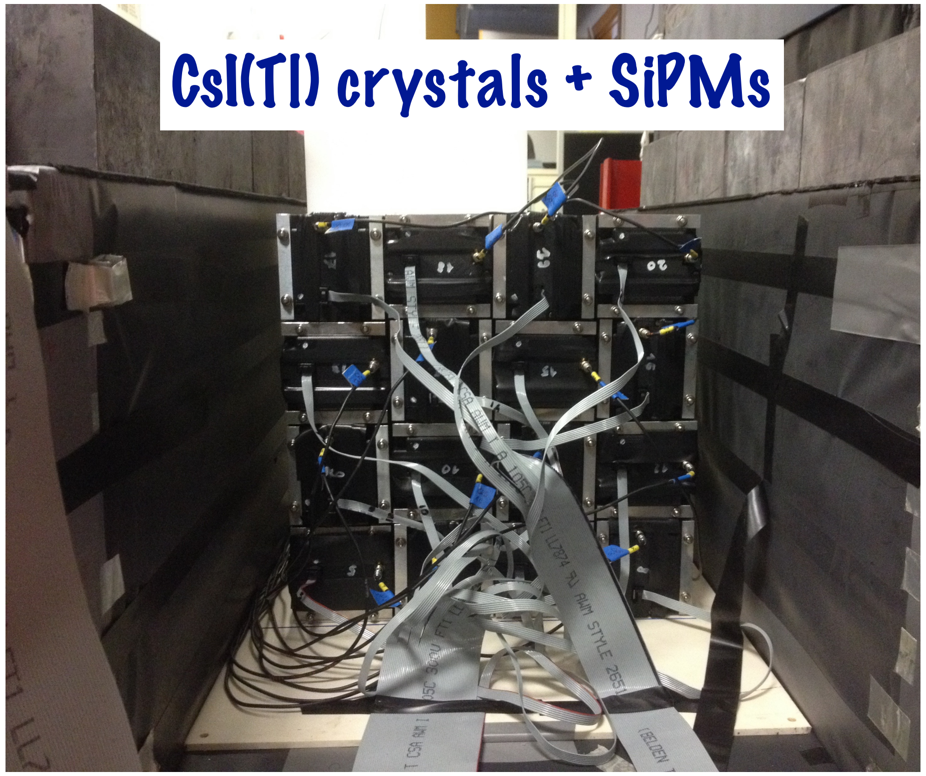
- 5 cm thick lead bricks

## Outer Veto



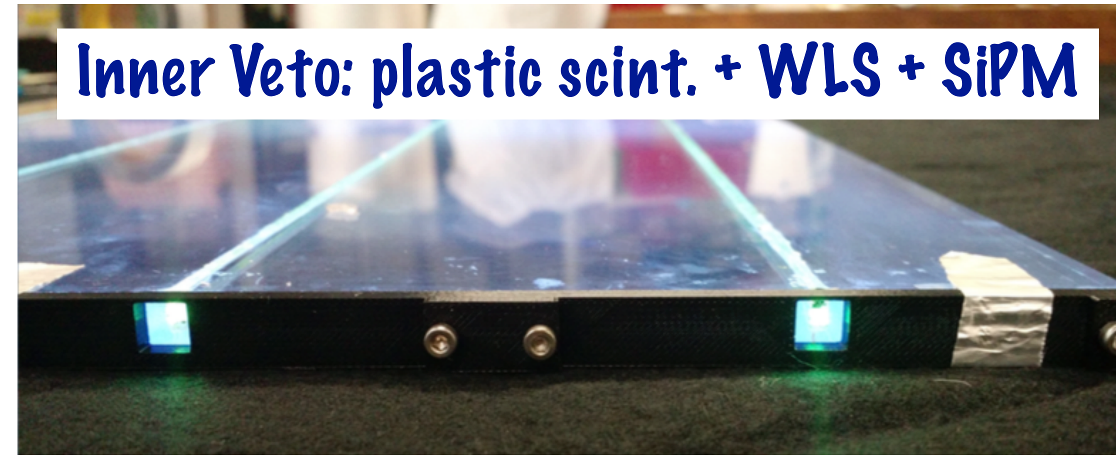
- Plastic scint
- light guide + PMT readout
- WLS + PMT/SiPM

# BDX prototype

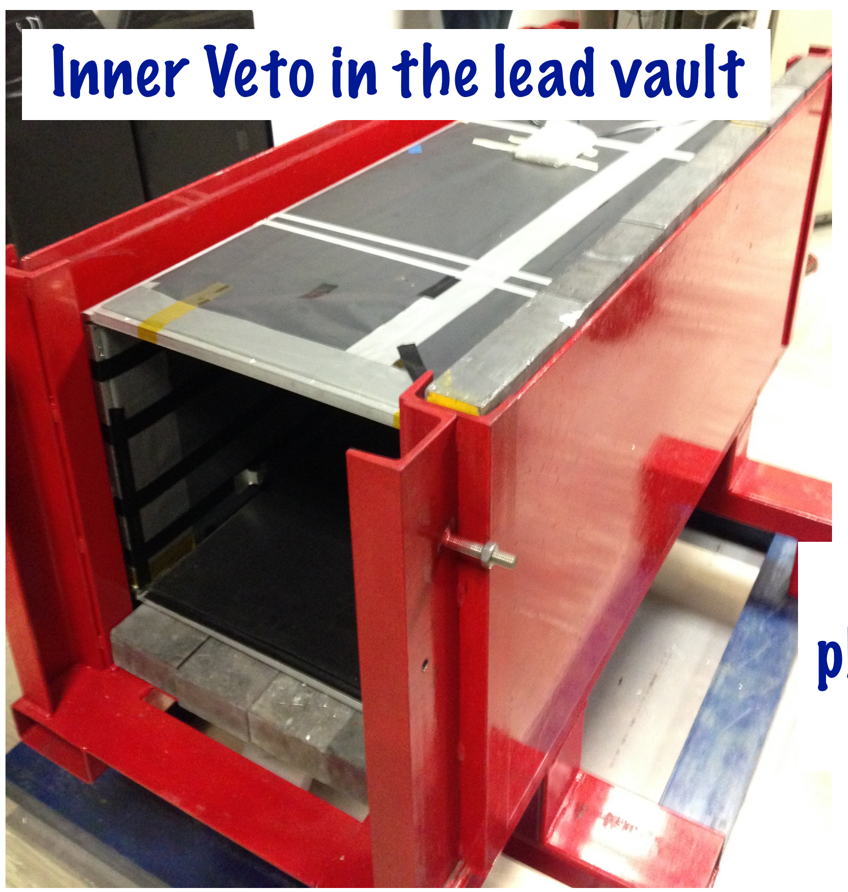


CsI(Tl) crystals + SiPMs

Outer Veto:
plastic scint. + Light guide + PMT



Inner Veto: plastic scint. + WLS + SiPM

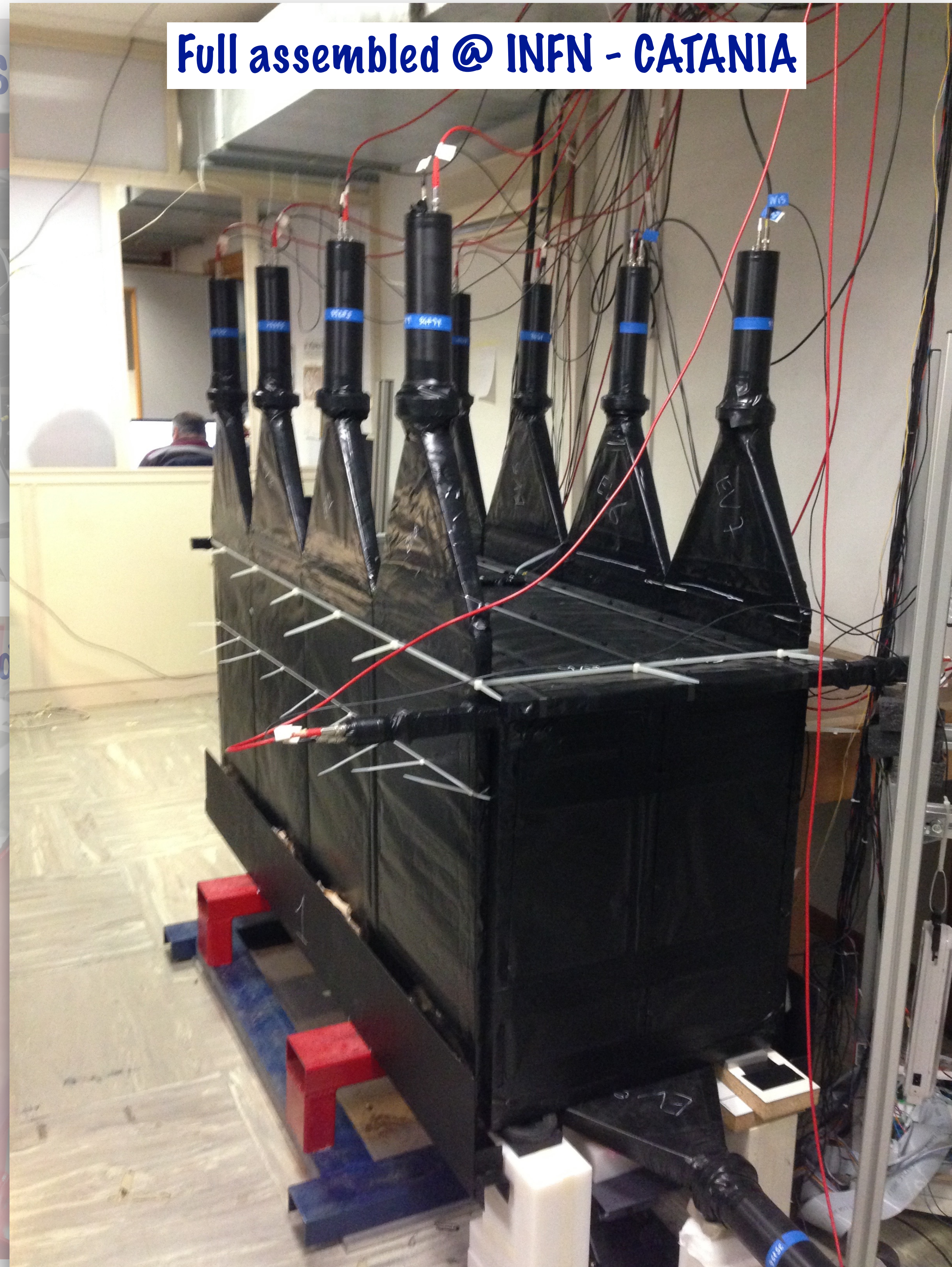


Inner Veto in the lead vault

Outer Veto:
plastic + WLS plastic + PMT

# BDX prototype

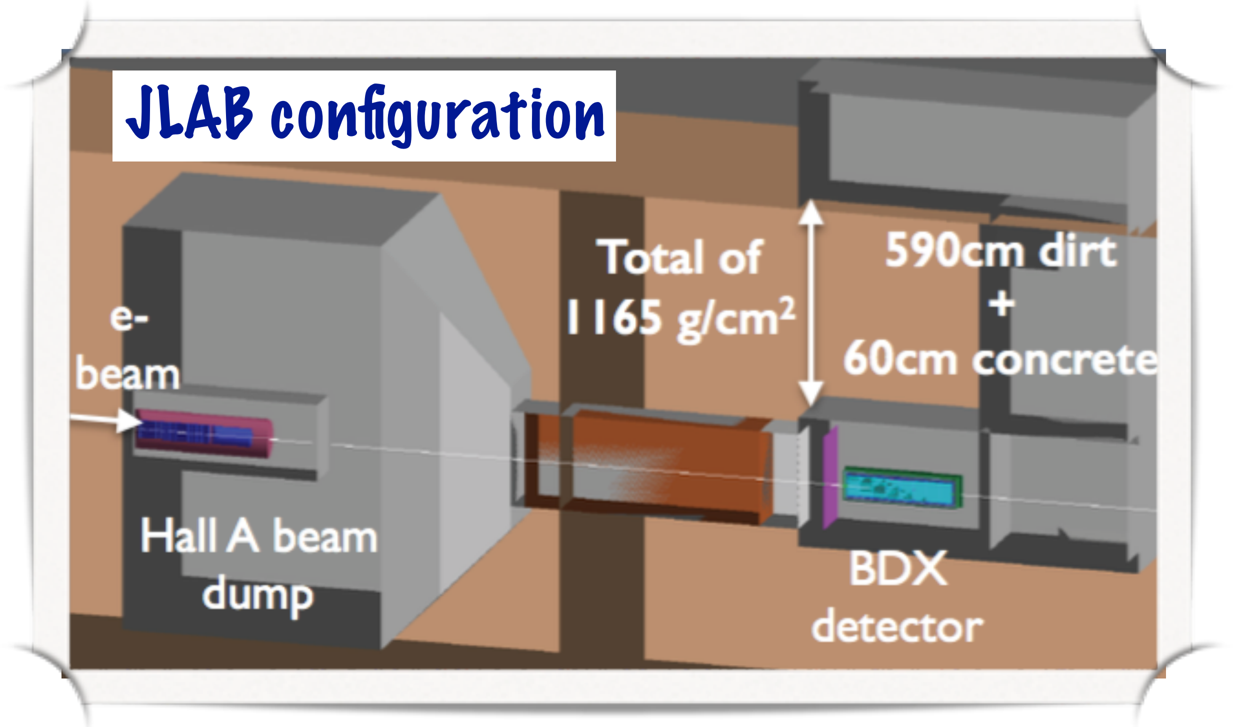


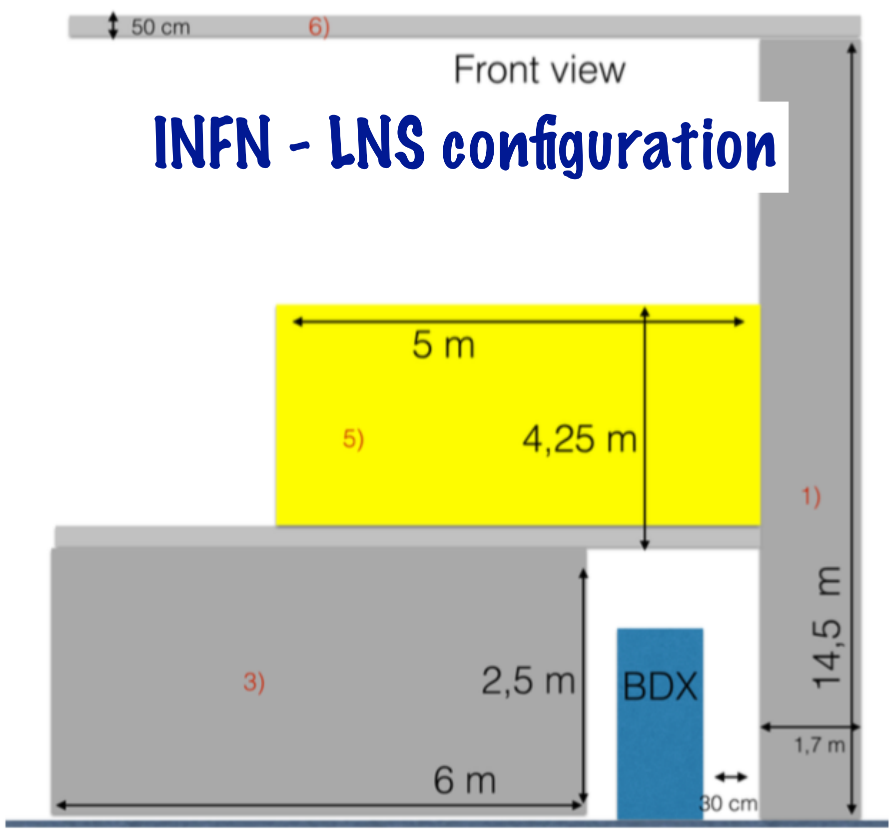




# Cosmic-ray backgrounds

- Cosmic background measured with the BDX detector prototype at INFN -CT and INFN -LNS, with similar overburden of the JLAB configuration
- Geant4 simulations (GEMC framework) in very good agreement with data
- The majority of cosmic muons are detected and rejected by the two veto detectors
- Cosmogenic background eliminated with Veto anticoincidence and Ethresh>0.3 GeV: results obtained by conservatively extrapolating from the lower-E, non-zero counts region, projecting to the JLAB setup



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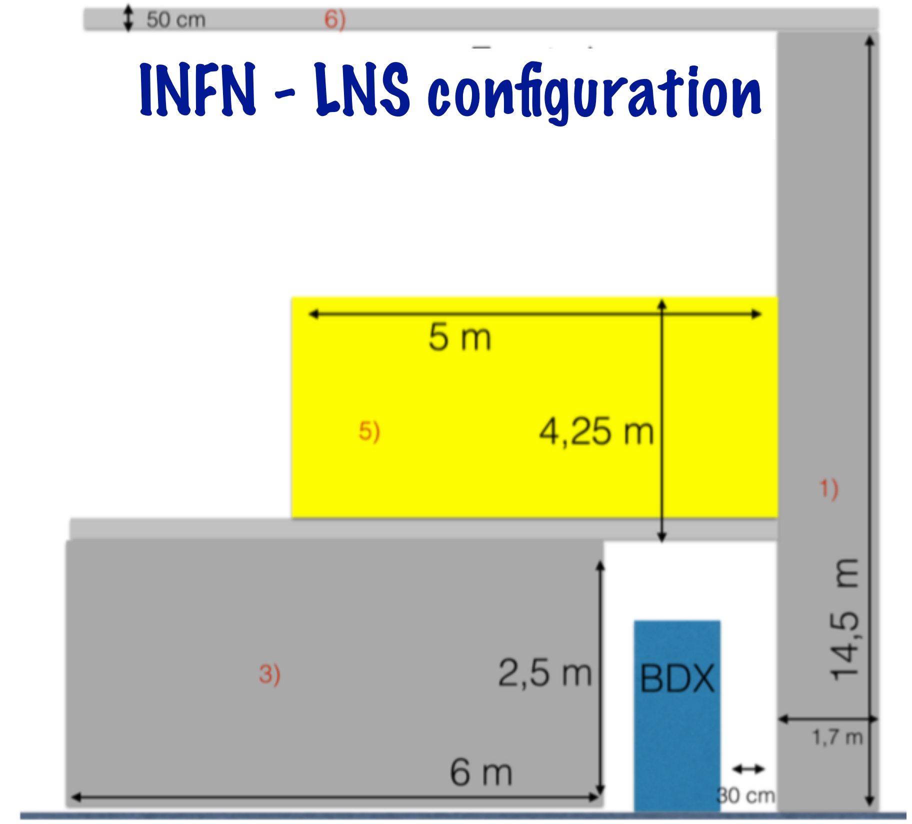
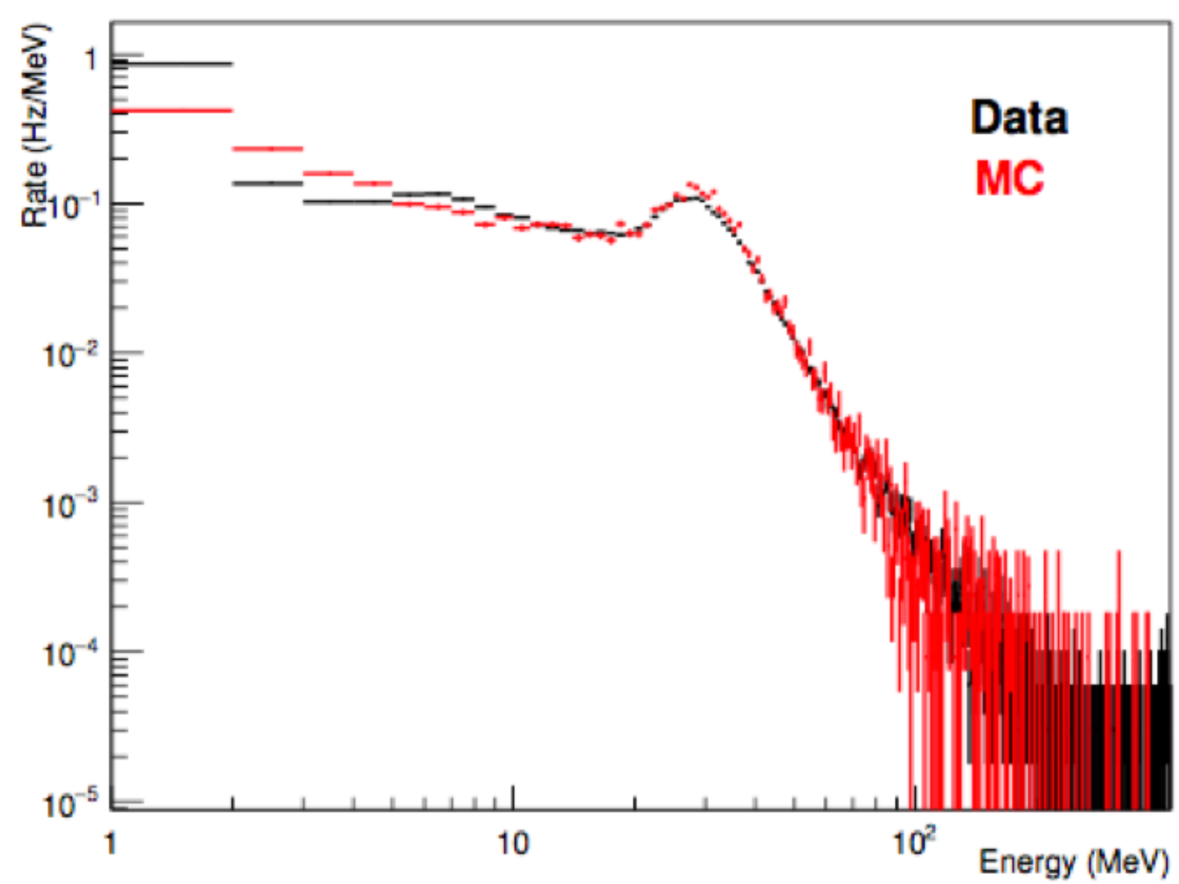



Crystal energy deposition



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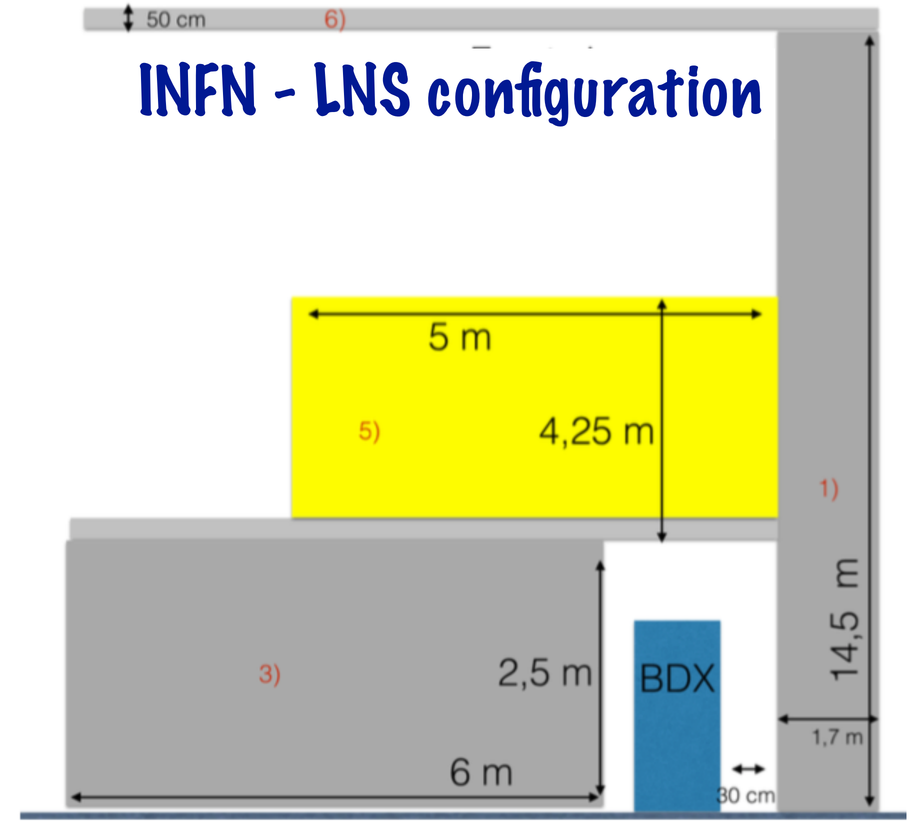
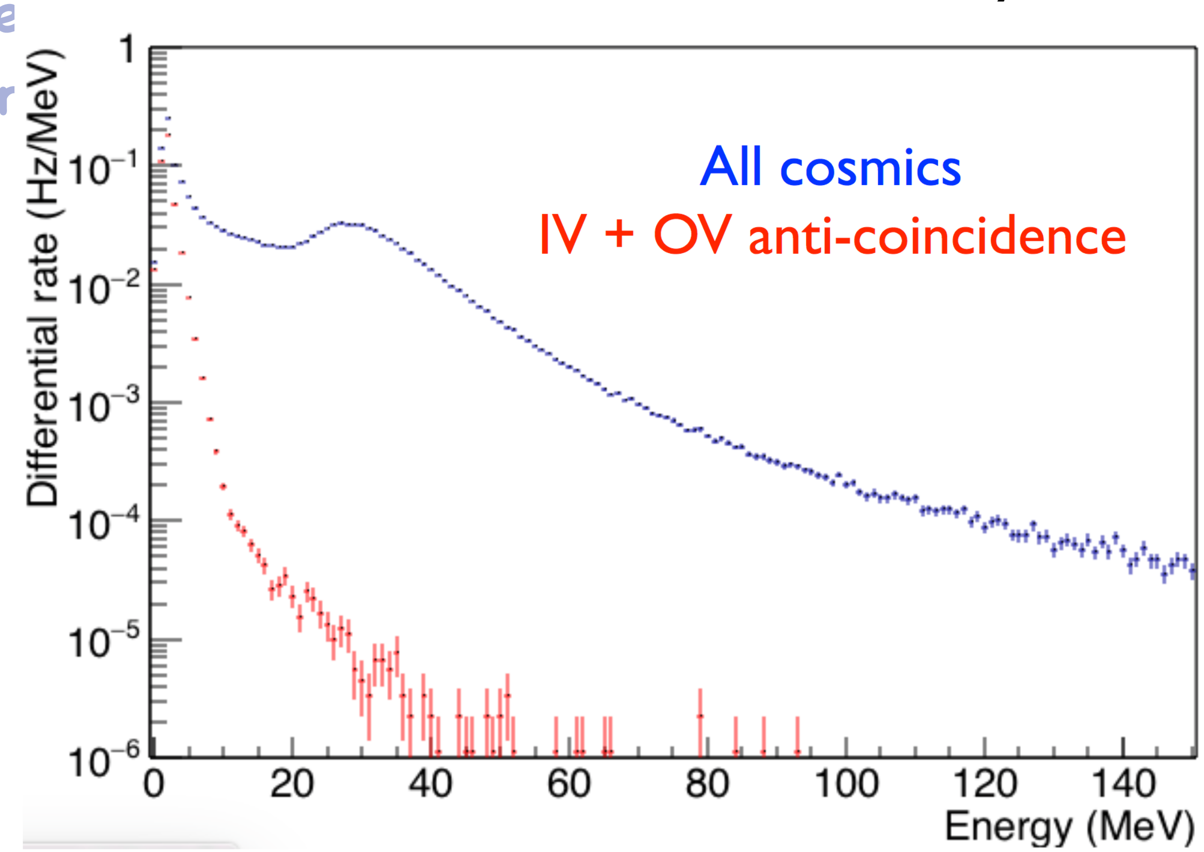



Count rate measured in 1 crystal



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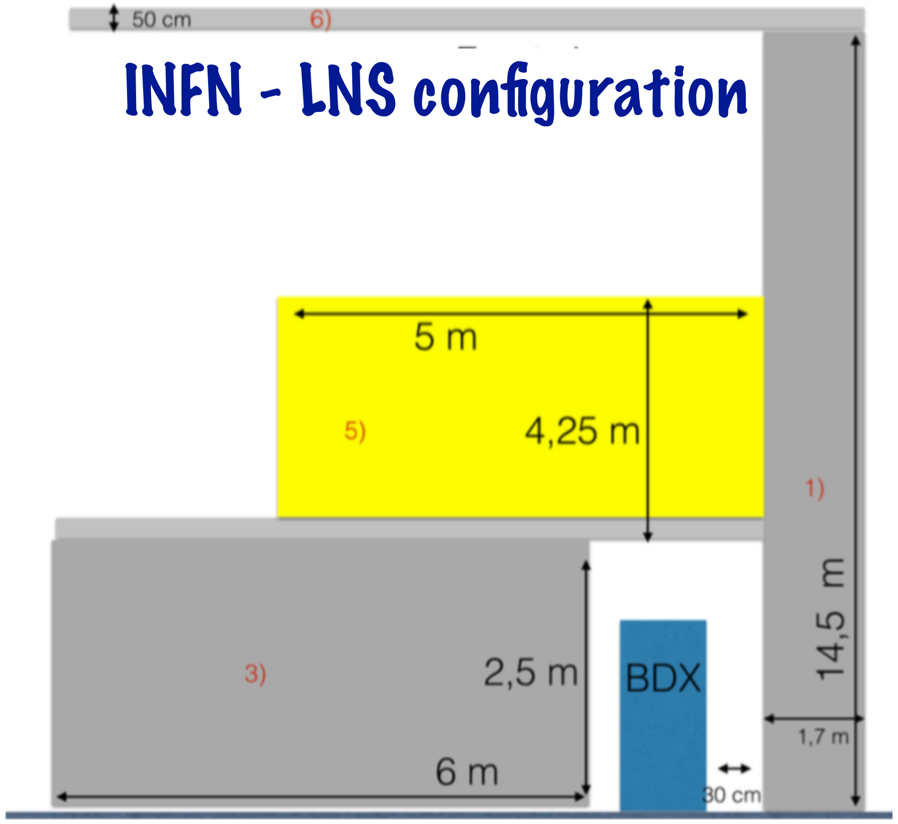
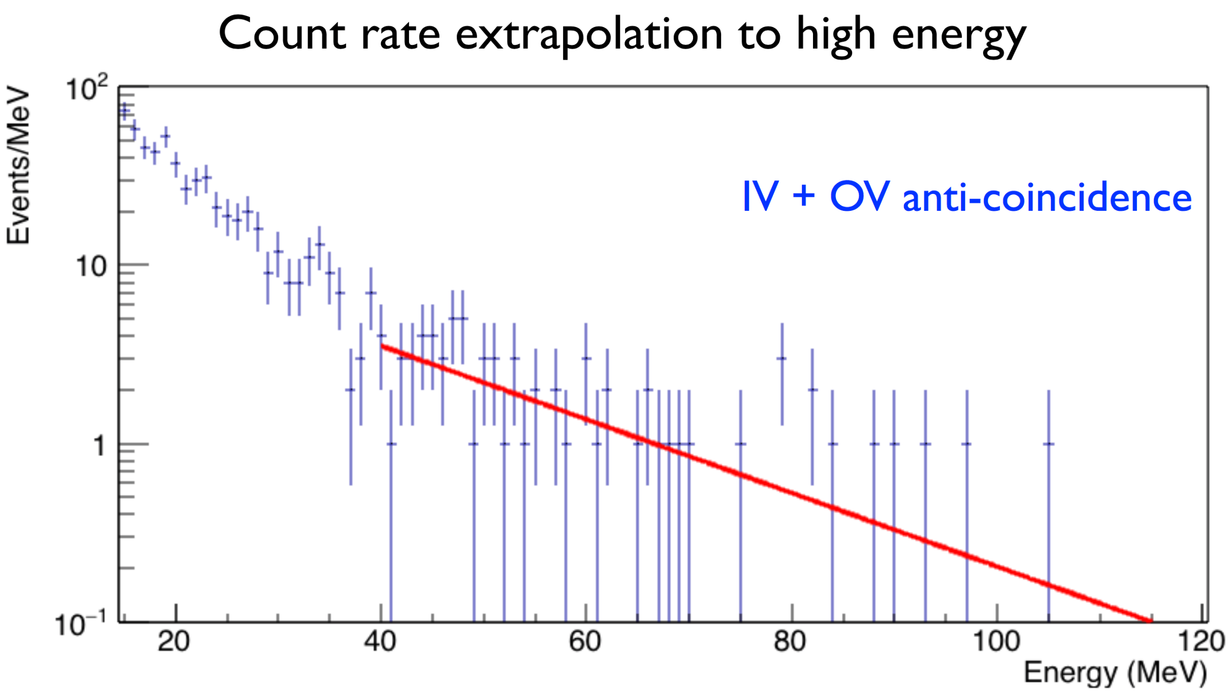
- Cosmogenic background eliminated with Veto anti-coincidence and Ethresh>0.3 GeV: results obtained by conservatively extrapolating from the lower-E, non-zero counts region, projecting to the JLAB setup (800 CsI(Tl) crystals)

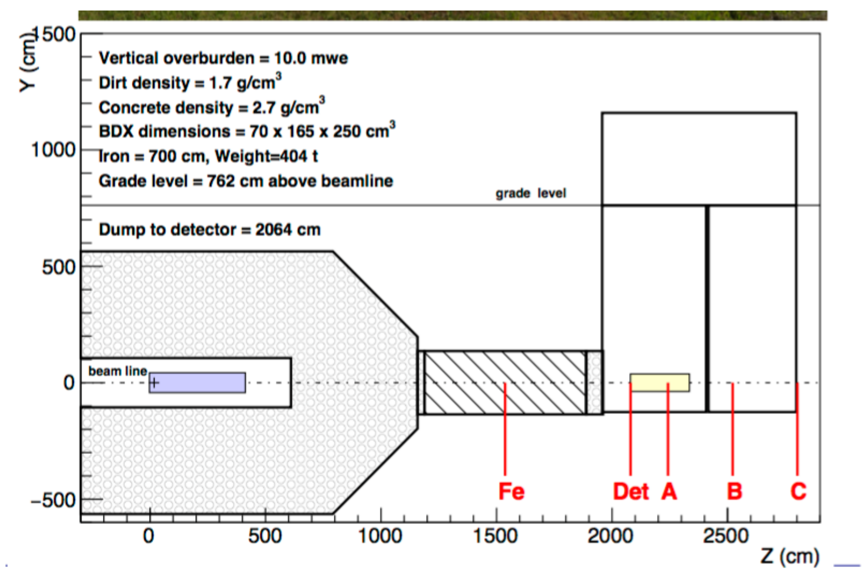


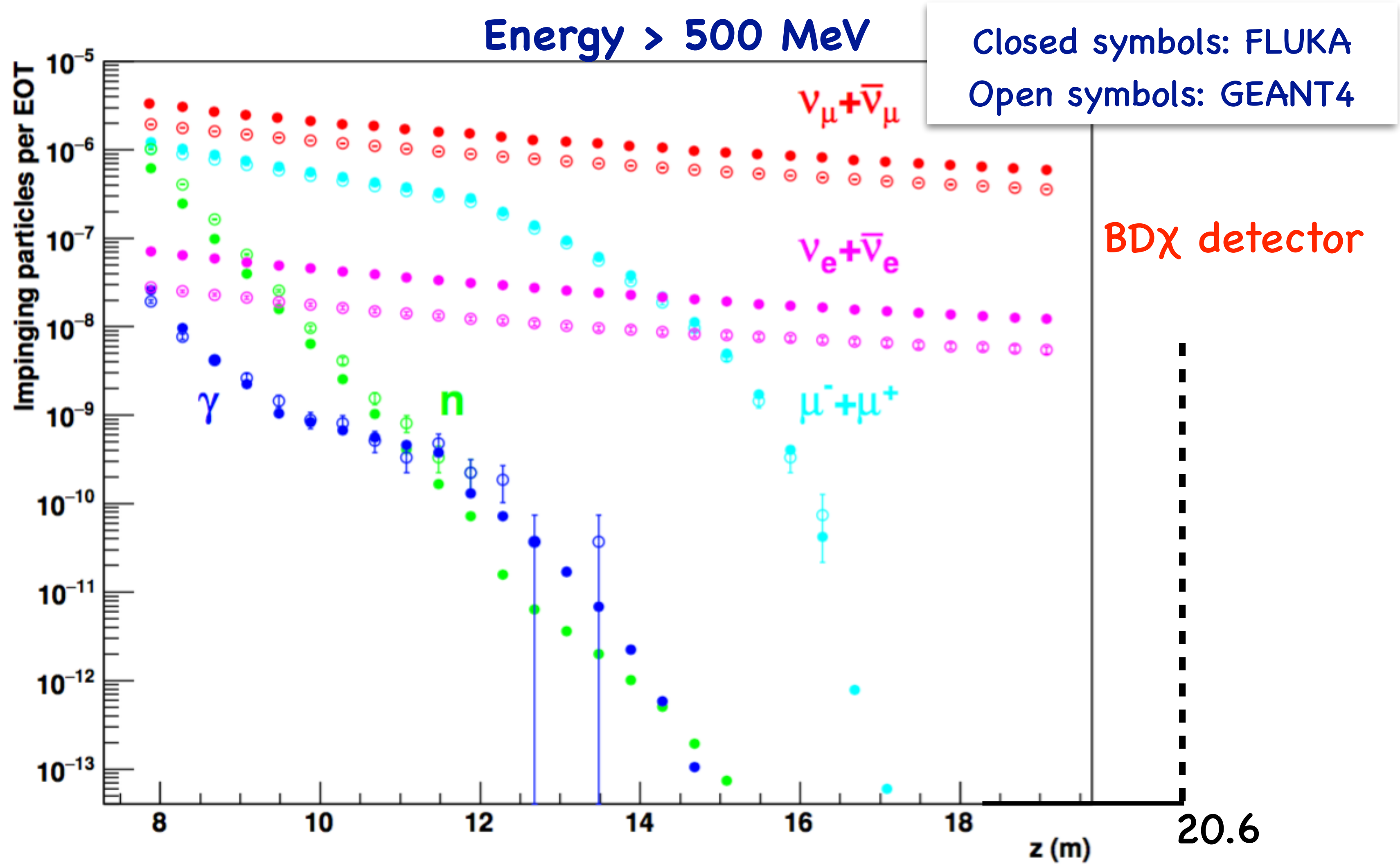




**Cosmogenic background is negligible**
**with high-energy threshold.**
It will be measured on-site when beam is off

# Beam-related backgrounds: GEANT4 vs FLUKA

The interaction of the 11 GeV electron beam in the dump was simulated and the flux of secondaries was studied as a function of the distance from the dump



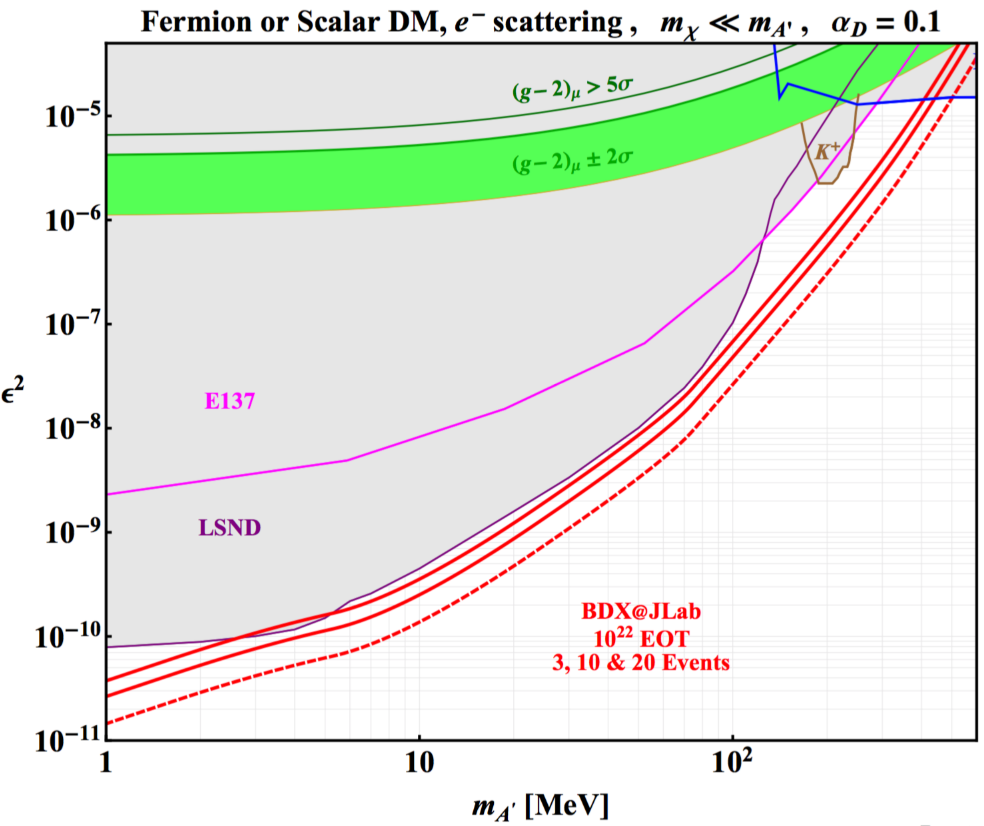




- Photon and neutron cascades absorbed in shielding
- Muons ranged out in Fe
- Neutrinos survives to the detector -> For a simulated statistics of $2.2\times10^8$ EOT we obtained, after all rejection cuts and extrapolation to $10^{22}$ EOT ~ 10 ν.

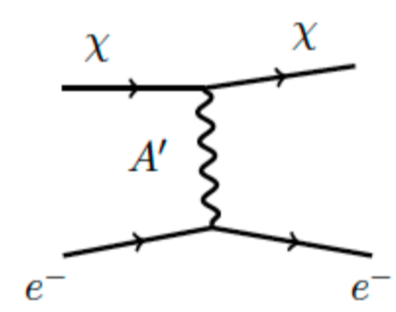
**Neutrino irreducible background** is the ultimate limitation for BDX.

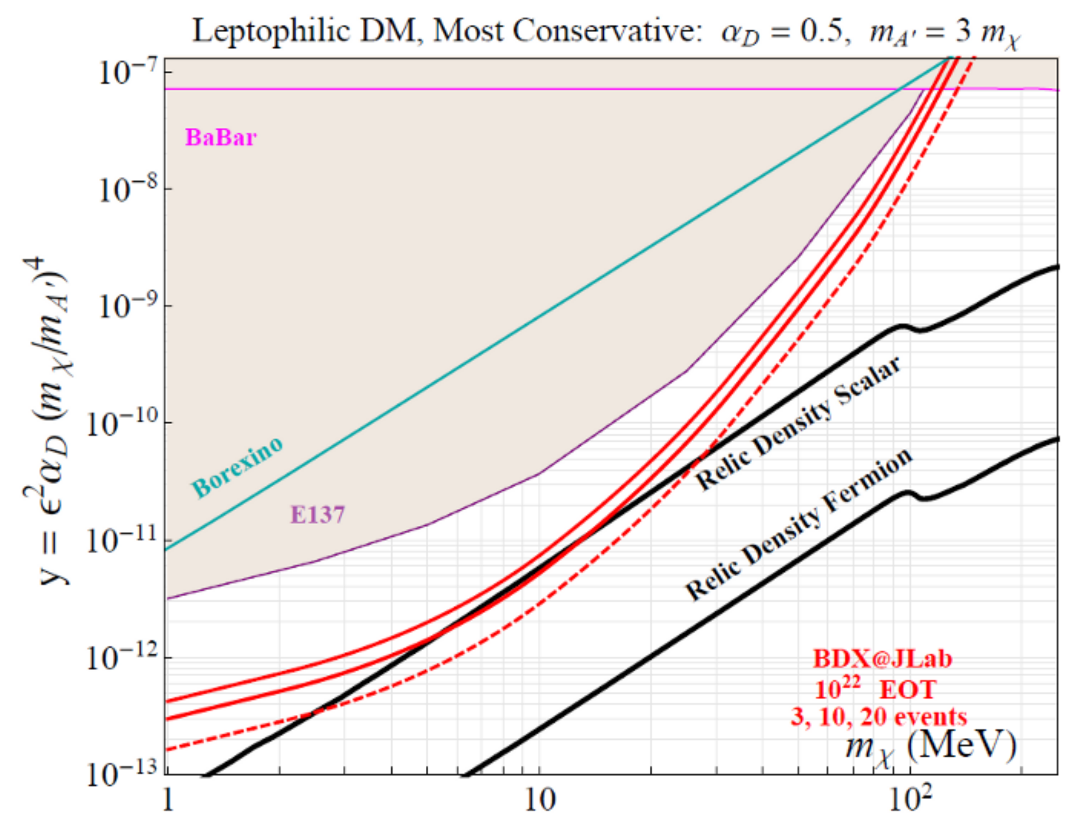
# BDX @ JLAB: Reach

**BDX is an optimized beam-dump experiment that can be conclusive for some Light Dark Matter scenarios. Obtained results will guide future second-generation experiments**

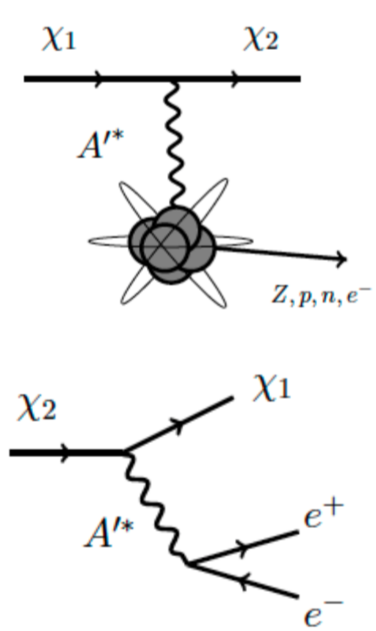


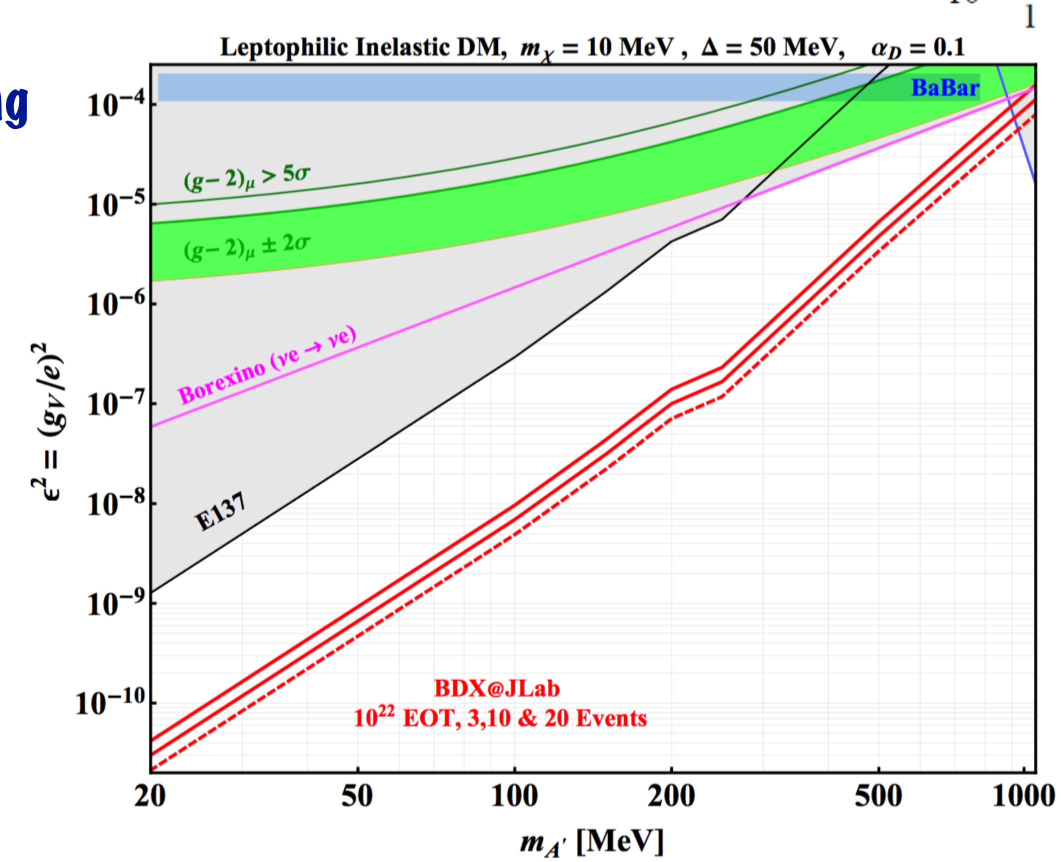

## $\chi$ - e elastic scattering




## $\chi$ - N inelastic scattering




**BDX** can be 10-100 times more sensitive than previous experiments excluding a significant area of the parameter space

## Dark matter in the MeV-to-GeV range is largely unexplored.

- Growing worldwide interest for LDM searches: many on-going experiments and future initiatives
- Beam Dump eXperiment at JLab: search for Dark sector particles in the 1 ÷ 1000 MeV mass range.
  - ✓ Full proposal submitted to JLab PAC 44 - conditionally approved: to run parasitically at Jefferson Lab for 41 weeks at ~11 GeV, which will allow it to collect ~$10^{22}$ electrons on target.
  - ✓ BDX can be 10-100 times more sensitive than previous experiments
  - ✓ BDX update submitted to JLAB-PAC45: Test plan to measure muon flux behind HALL A beam dump to validate MC

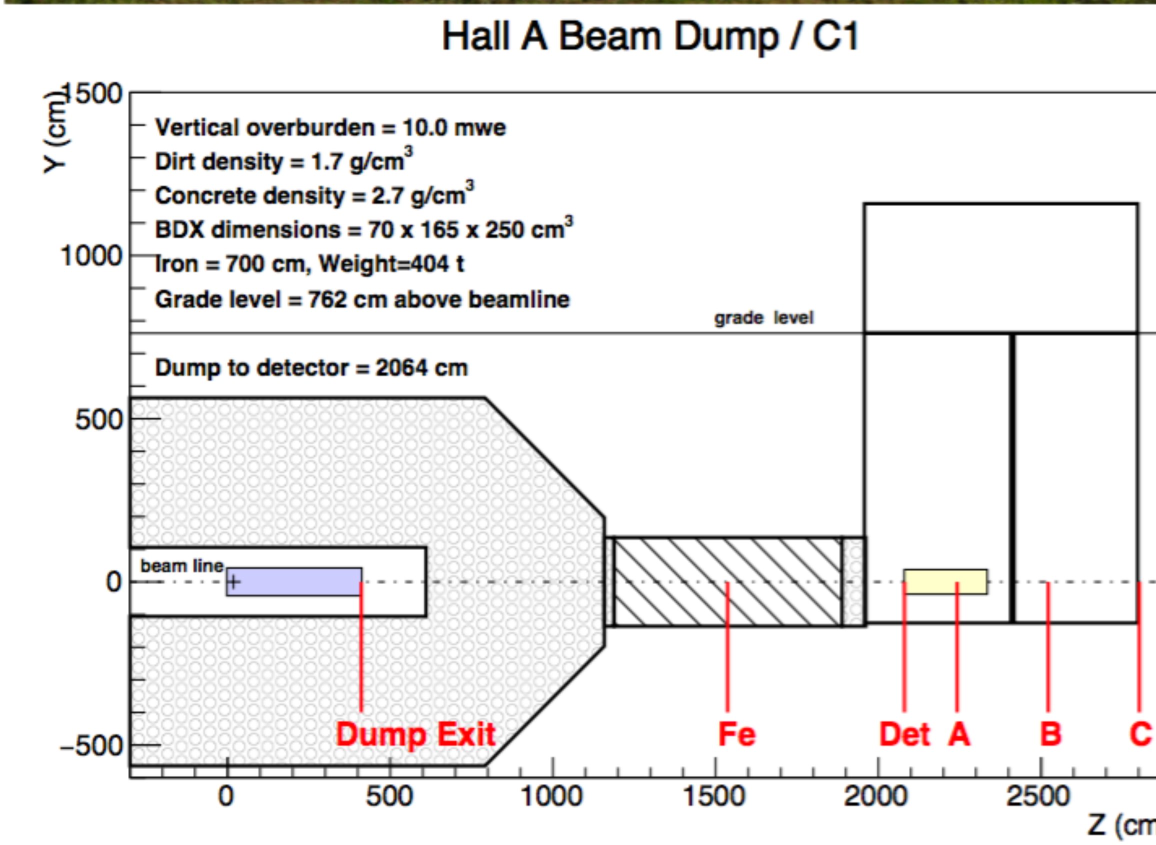
**BDX can produce important physics results, exploring unknown territories in the LDM space, and providing directions for future activities in this field**

# Beam-related μ: on-site measurement

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

**GOAL: validate MC simulations**

- Measure the muon flux behind the Hall A beam-dump in 2 different positions (B and C) with BDX-HODO
- BDX-HODO: 1 CsI(Tl) coupled 6x6 $mm^2$ Hamamatsu S13360-6025 and sandwiched between a set of segmented plastic scintillators.
- From the FLUKA (GEANT4) simulations a drop in rate by about one order of magnitude when moving from one location to the next
- **Rate of beam-on muons** measured by BDX-Hodo are expected to be sizable for a beam current of **10 μA: ~3.7kHz for B and ~0.5kHz for C.**


**BDX - HODO concept**