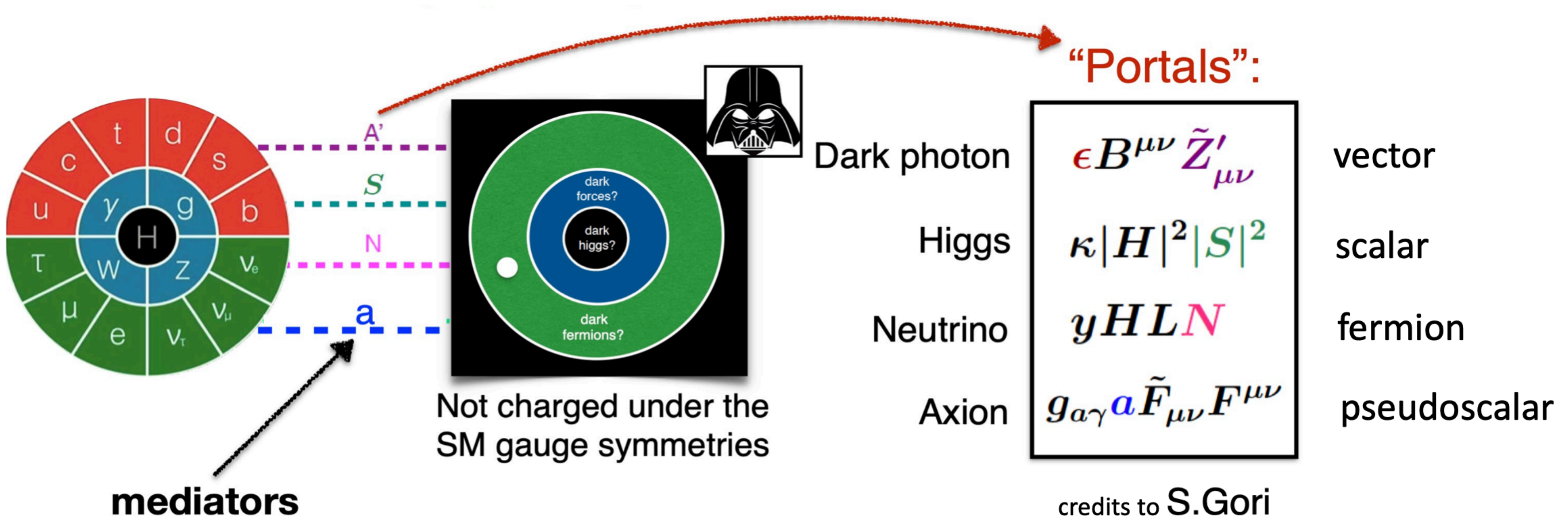
Experimental overview of Sub-GeV Physics in the Dark Sector

Mariangela Bondì

INFN - Sezione di Catania

Outline

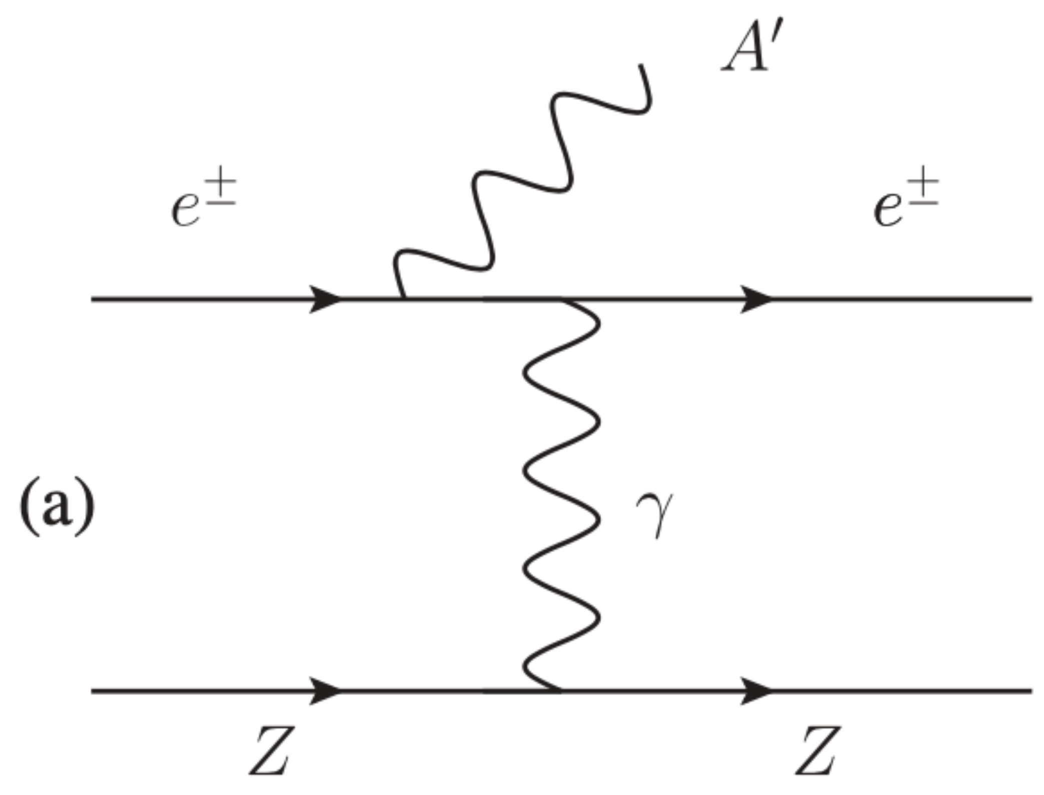
- *JLAB already features a significant experimental program dedicated to Dark Sector*
  - *Exploiting CEBAF unique capabilities to produce and detect Dark Photons*
    - *Current experiment: APEX, HPS, BDX-MINI*
    - *Experiments running in near future: X17, BDX*
- *Future upgrade of the facility offer even more opportunities*
  - *Secondary beam @ 11 GeV*
  - *Secondary beam @ 22 GeV*
  - *Positron Beam*



Dark Photon production mechanisms

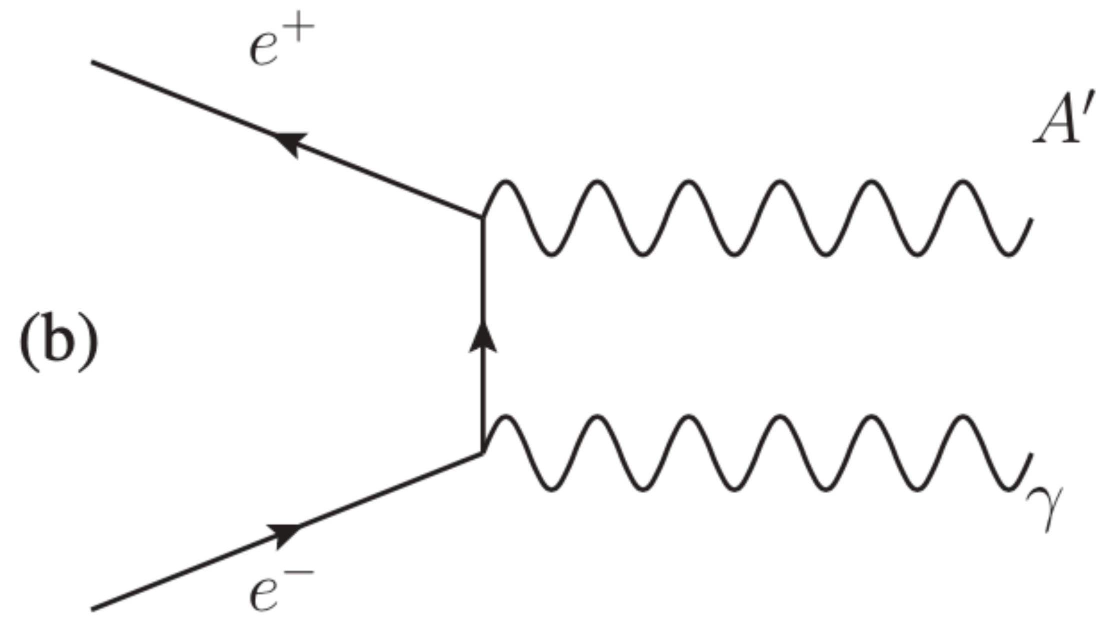
a) A'-strahlung:

- Radiative A' emission in nucleus EM field followed by A'->XX
- Scales as $Z^2\alpha^3$
- Forward-boosted, high-energy A' emission



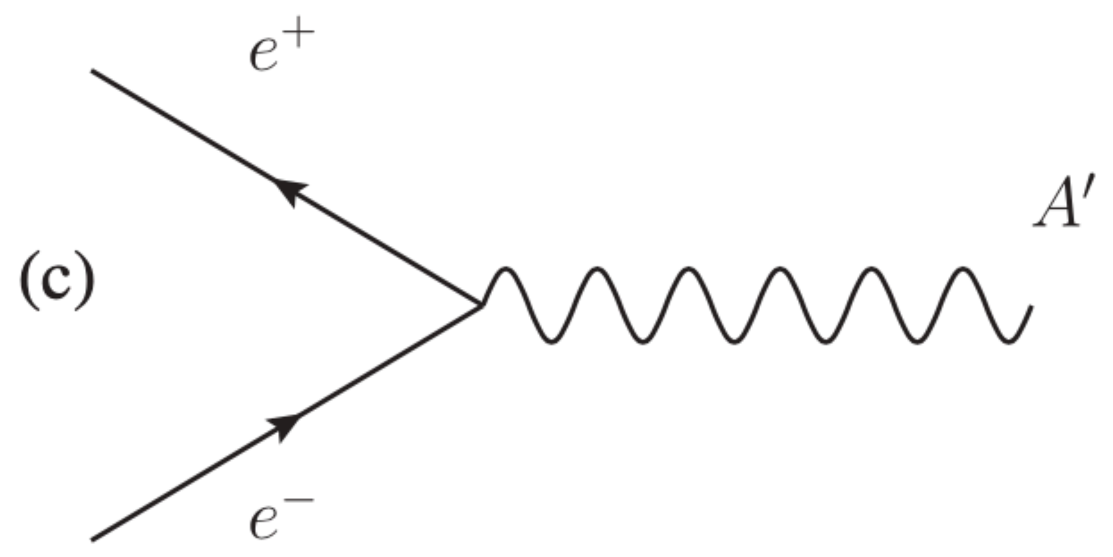
b) Non-resonant e+e- annhilation:

- e+e- -> A'γ followed by A'->XX
- Scales as $Z\alpha^2$
- Forward-backward A' emission in the CM



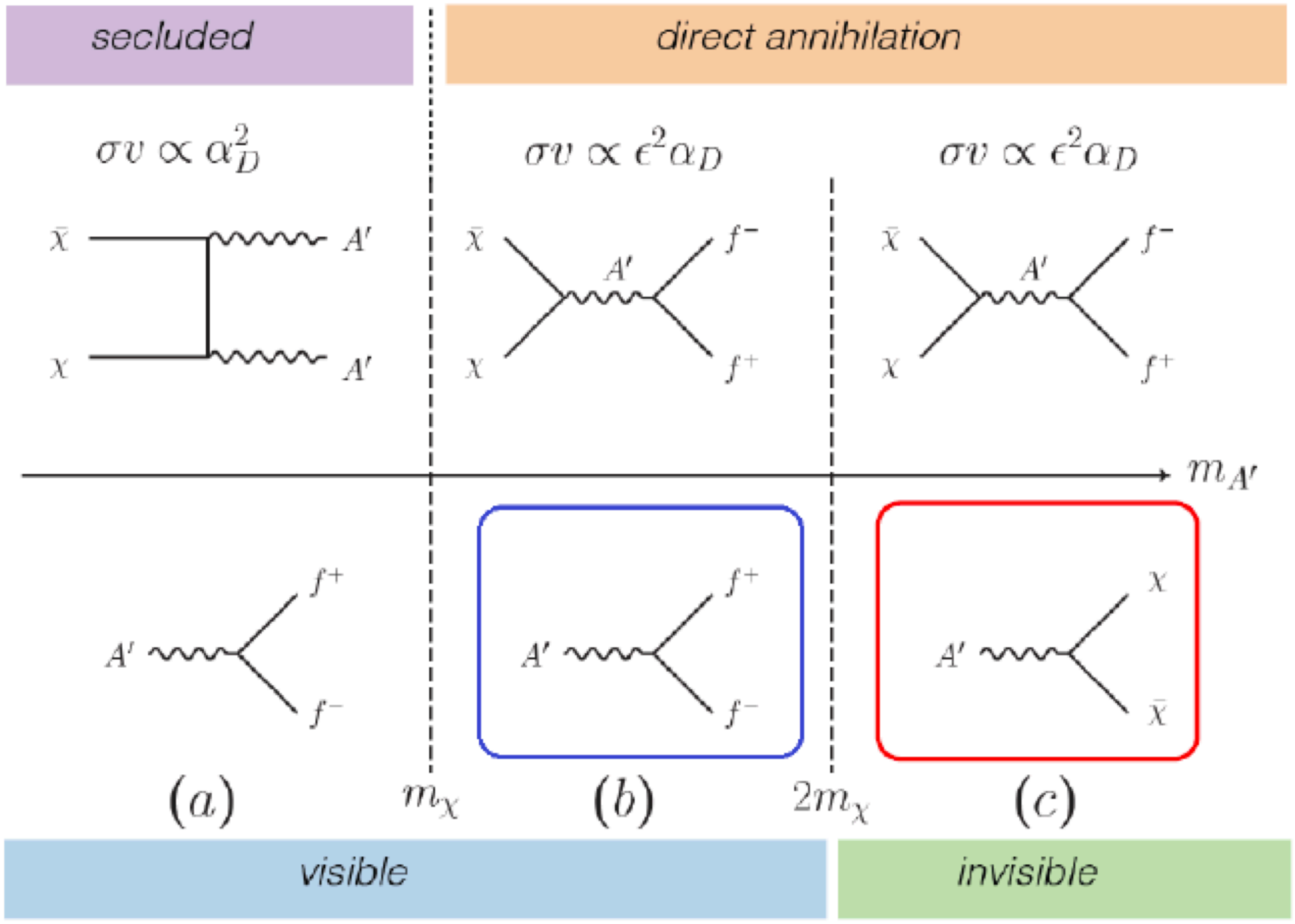
c) Resonant e+e- annhilation:

- e+e- -> A'->XX
- Scales as $Z\alpha$
- Breit-Wigner like cross section with mA' = sqrt(2meE)



Dark Photon signatures

- **Secluded:** no constraints for accelerator based experiments. Any ε is allowed
- **Visible decay:** final state contains SM particles:
  - Current experiments: APEX, HPS
  - Near Future experiments: X17, μBDX
- **Invisible decay:** final state contains Dark sector particles
  - Current experiments: BDX-MINI
  - Near Future experiments: BDX
  - Far Future experiments: μ[3]BDX, A' search with positron



Mass Hierarchy Determines Search Strategy and Interpretation

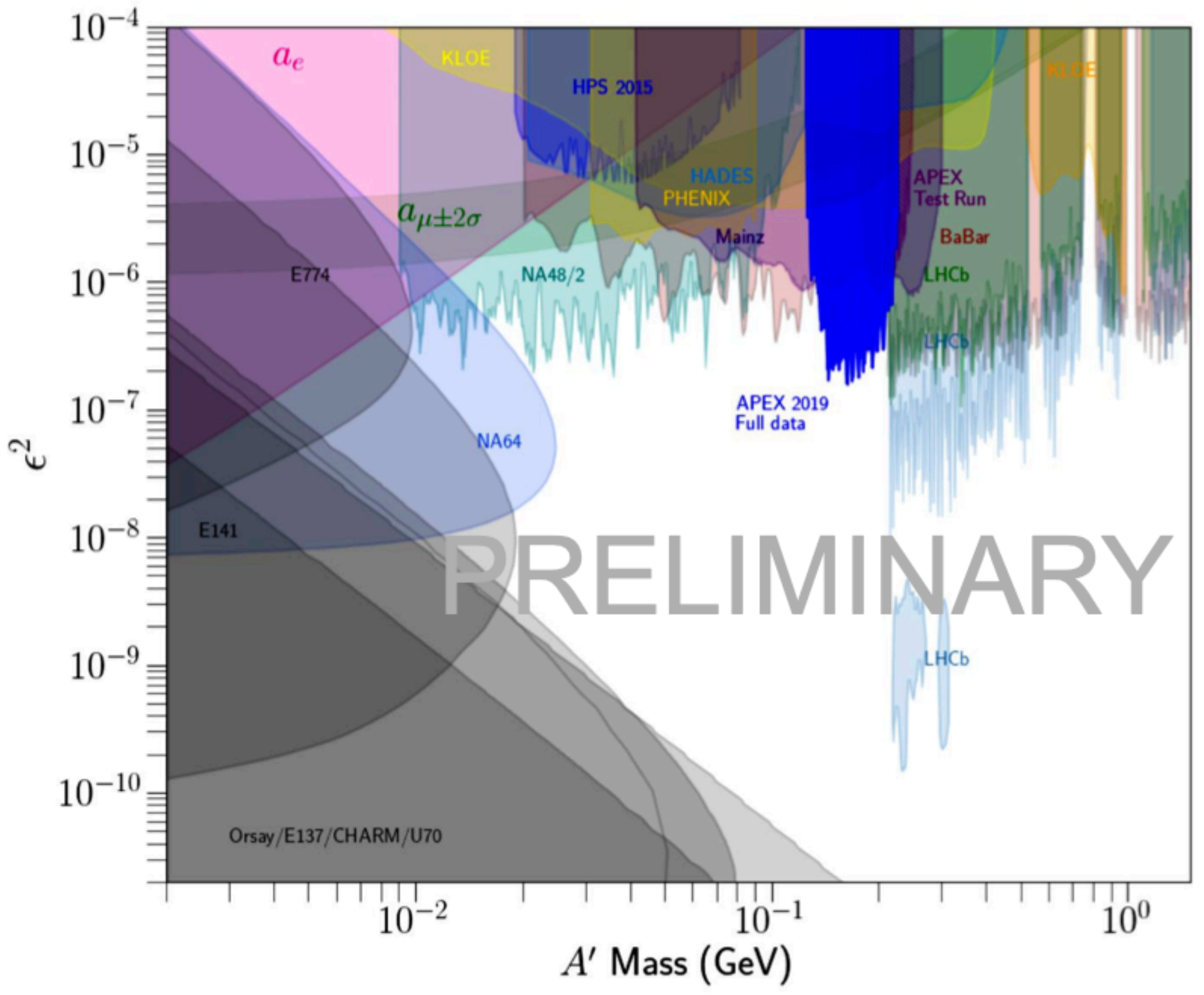
Current Dark Sector search @ JLAB: Dark photon visible decay

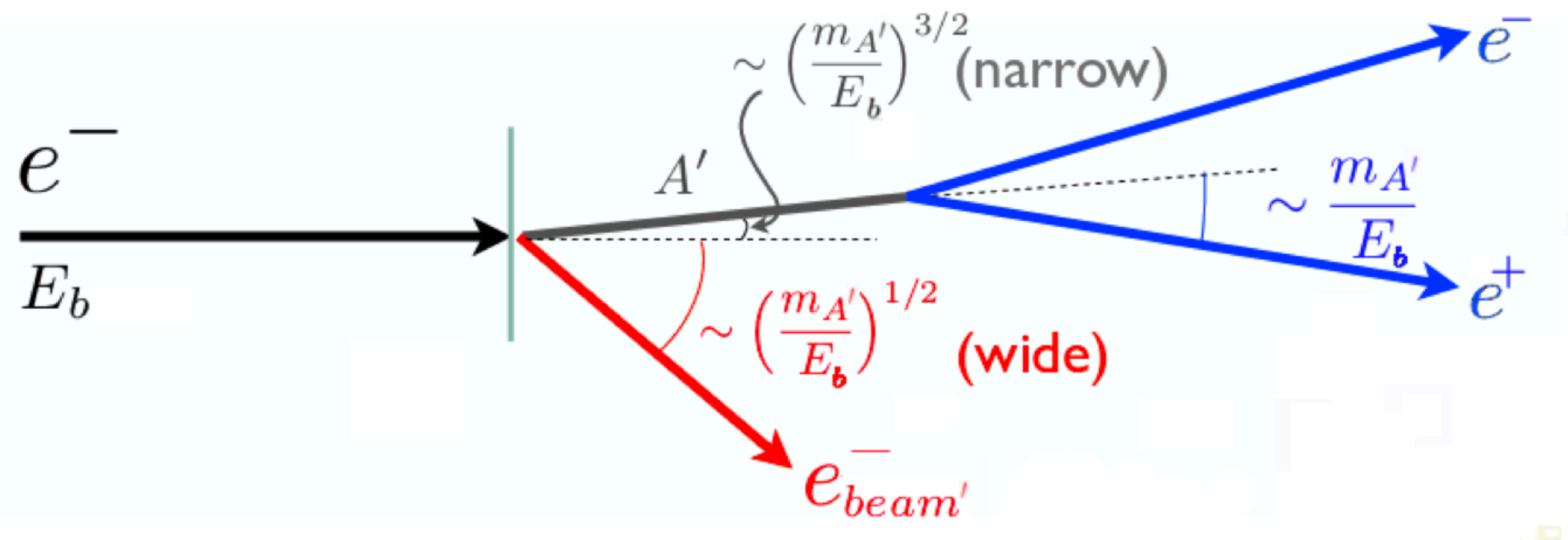
APEX: A-Prime EXperiment @HALL A

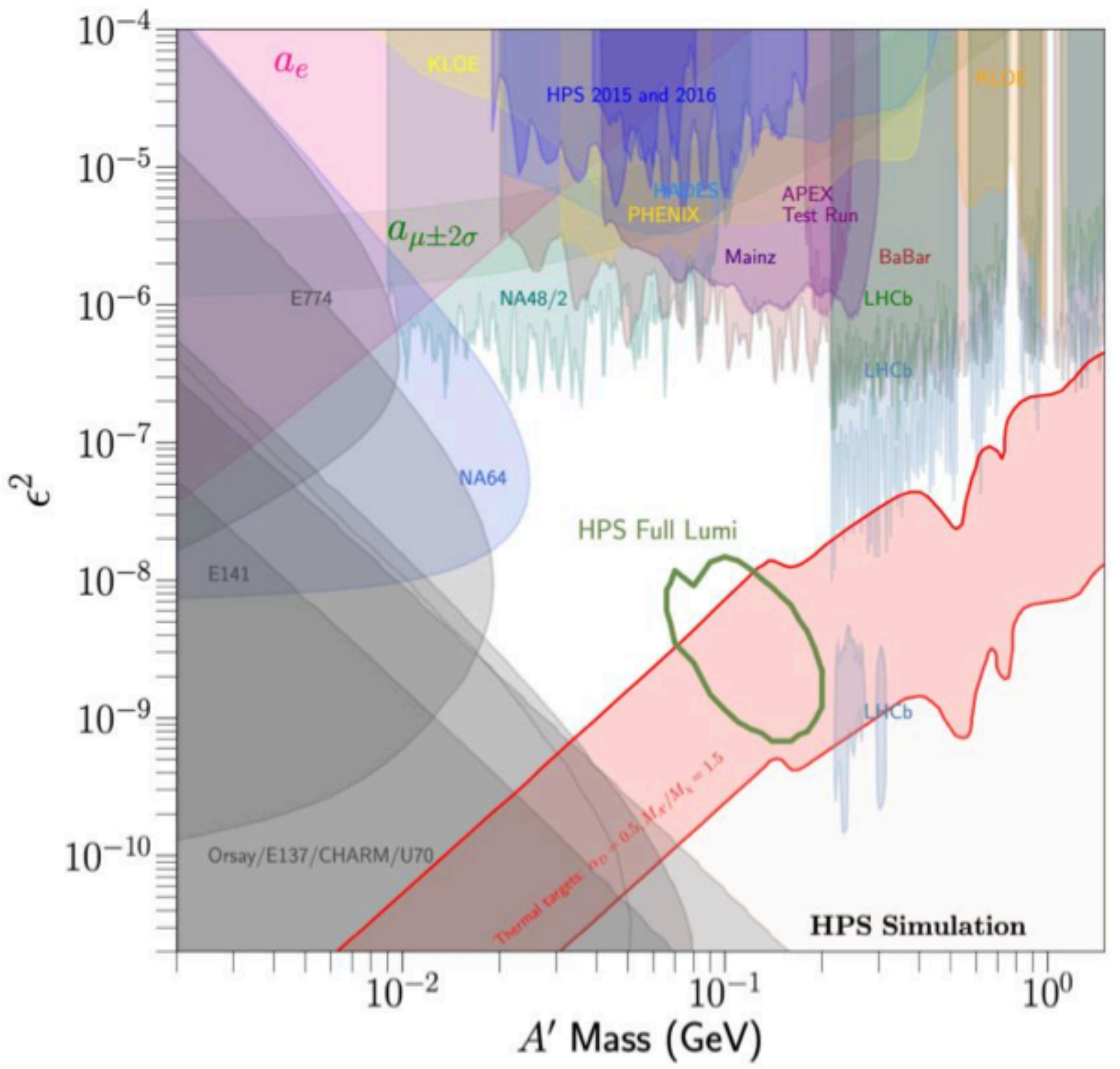
- 2.2 GeV e- fixed target experiment
- Two HRS in coincidence to measure events with an e- in one arm and e+ in the other.
- Dark photon searched as narrow resonance in e+e- mass over a smooth QED background
- Test run in 2010. Entire run in 2019

HPS: Heavy Photon Search @ Hall B

- 1.1 - 6.6 GeV e- fixed target experiment
- Detector: Silicon tracker inside a dipole magnet + ECAL
- Two signatures: resonance search and detached vertex
- 102 “PAC” measurement days still to run





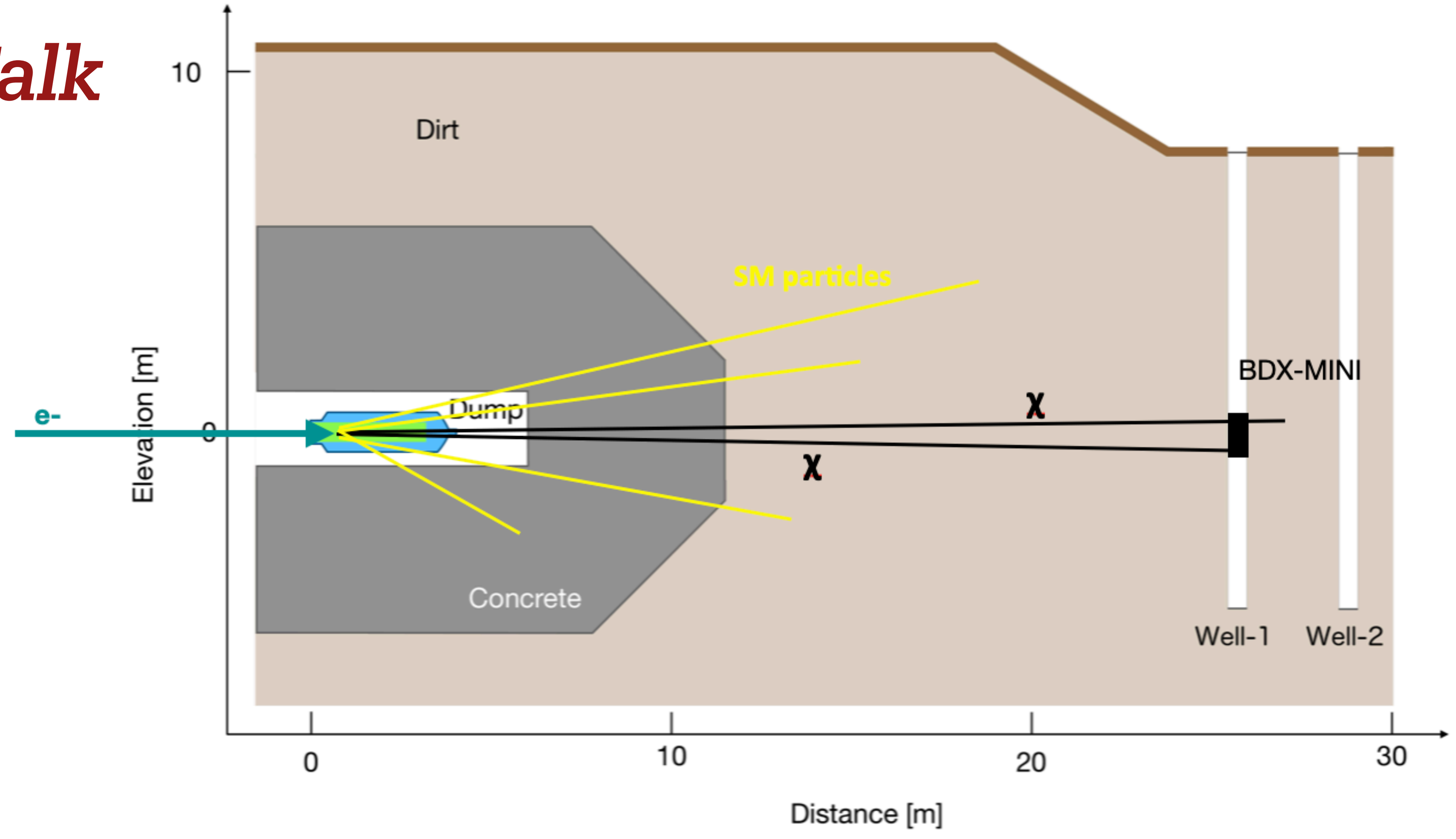


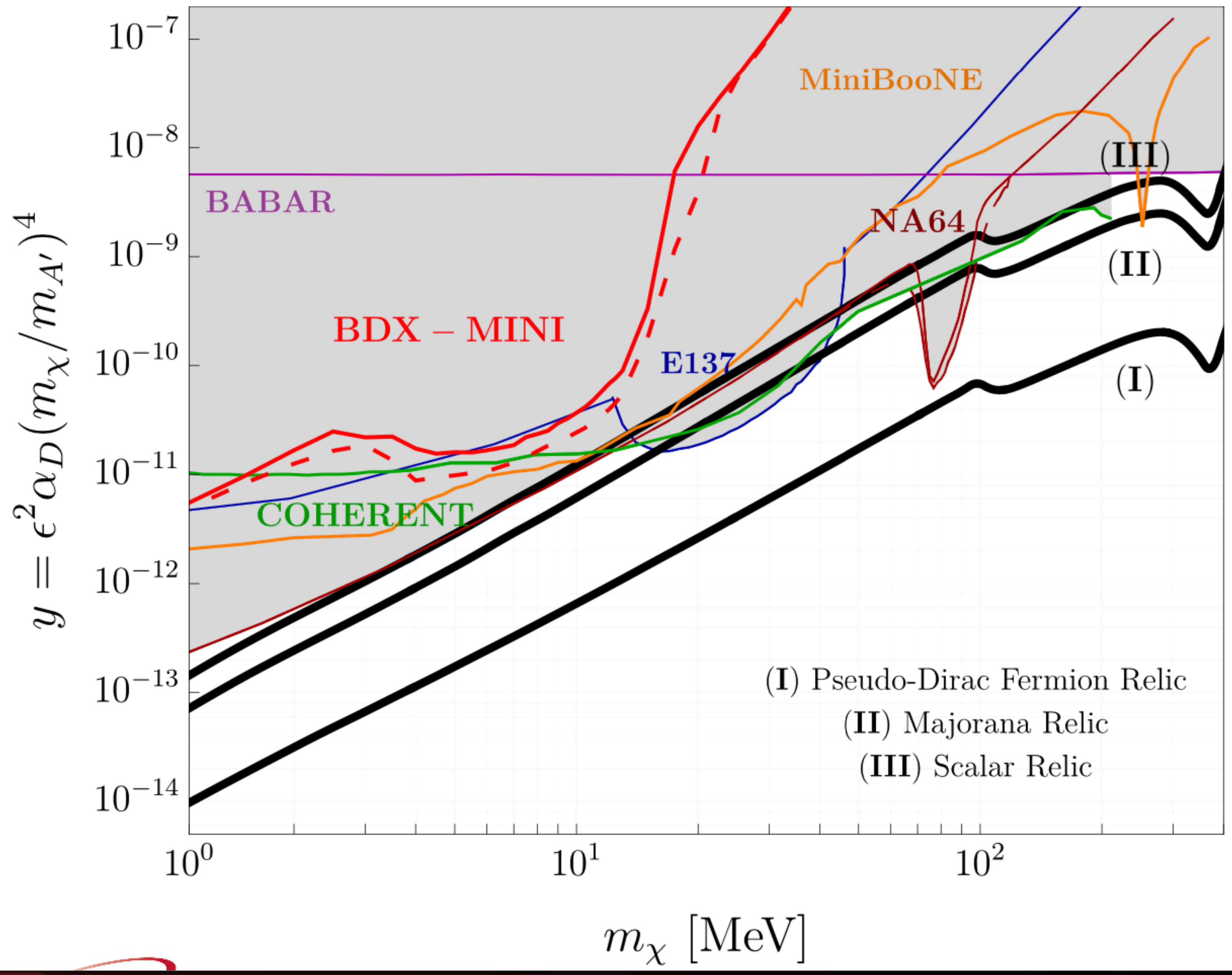
Current Dark Sector search @ JLAB: Dark photon invisible decay

BDX-MINI experiment

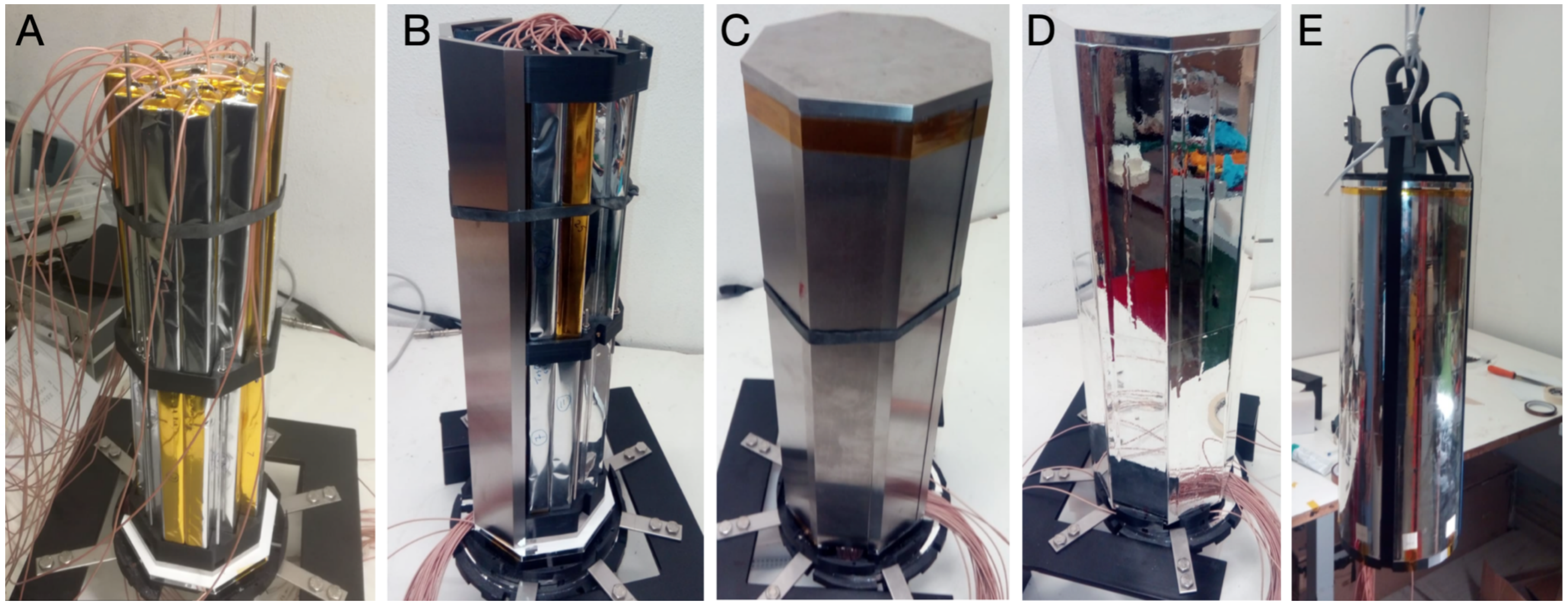
See M. Spreafico Talk

- 2.2 GeV, 150 uA e- beam impinging on Hall-A beam dump.
- Accumulated charge: 2.54E21 EOT
- SM particles shielded by concrete and soil
- Despite small size BDX-MINI is sensitive to the parameter space covered by some of the most sensitive experiments to date



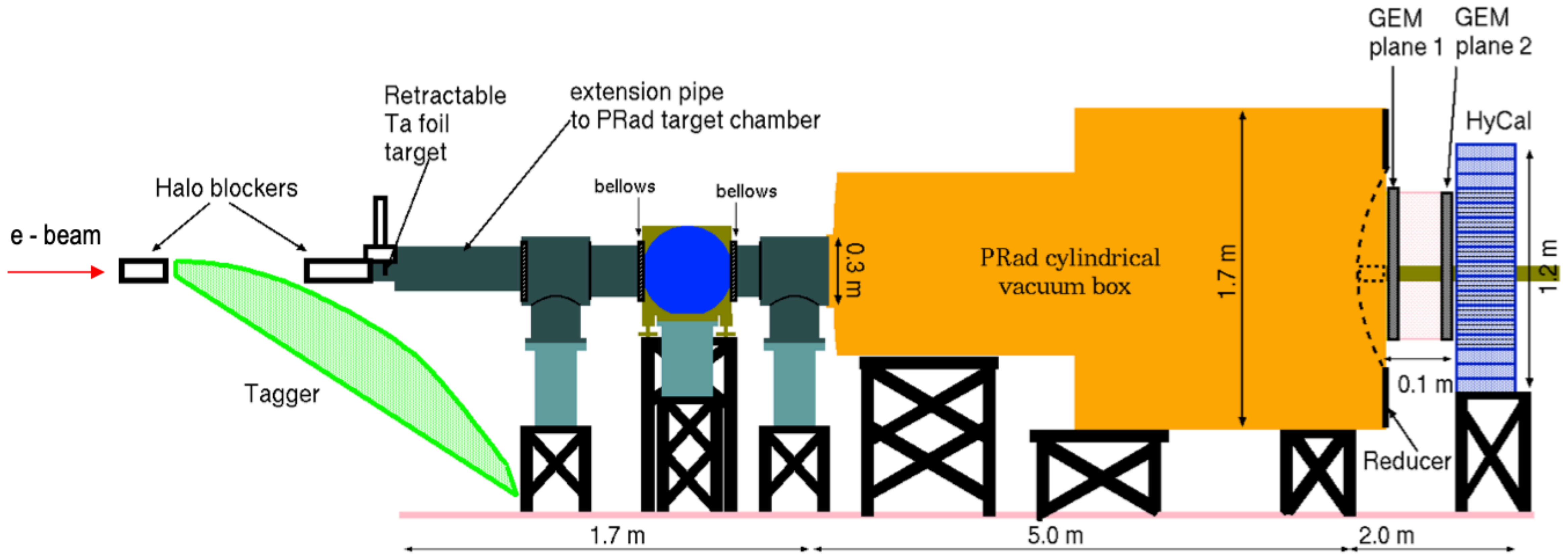


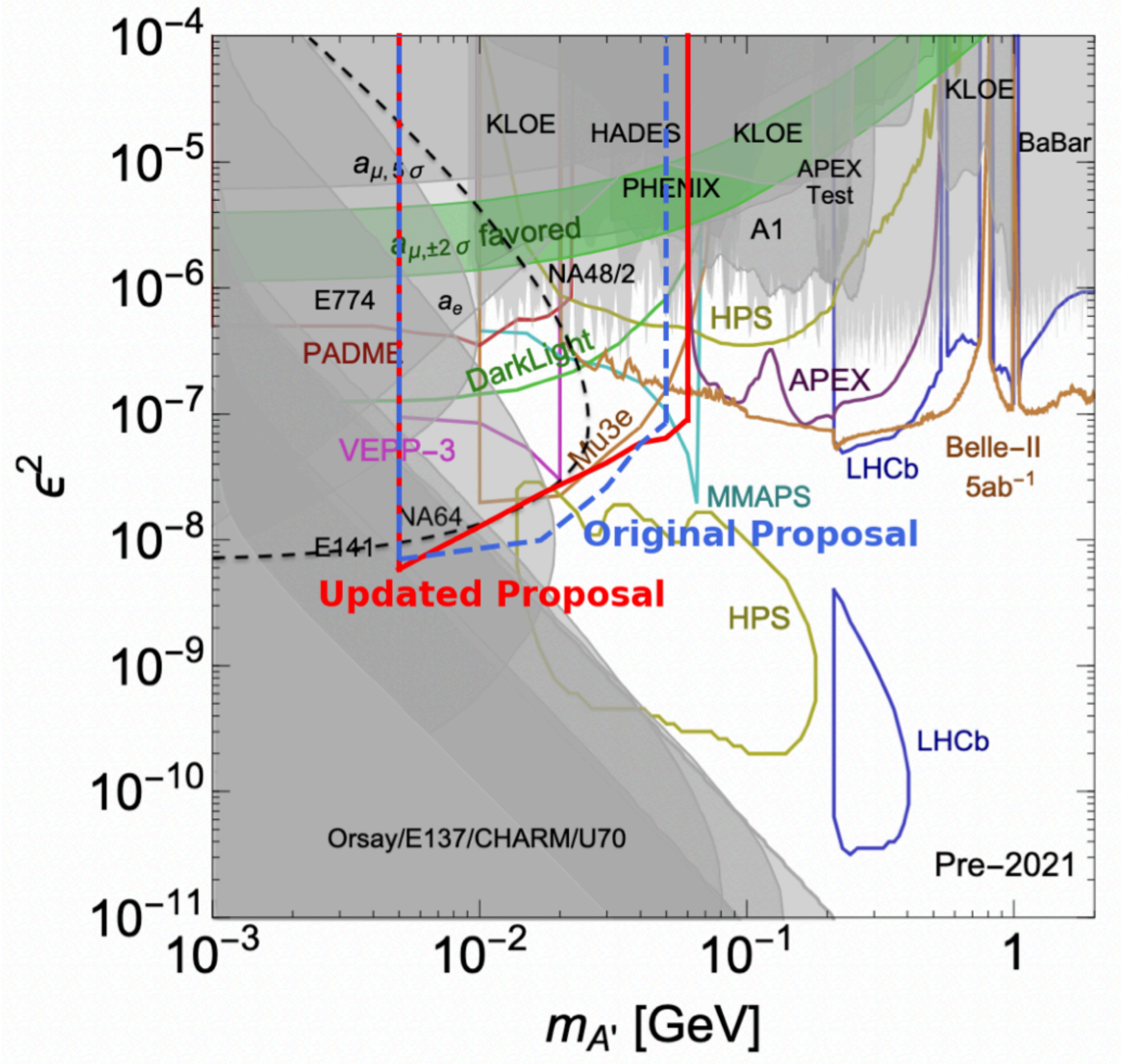
[M. Battaglieri et al., EPJC 81, 164 (2021)]



Near future Dark Sector search: X17 mystery

- Experimental setup based on PRAD-II apparatus
  - 1μm Ta solid target (2.4 E-4 X0)
  - Two planes of GEM detectors for tracking
  - PbWO4 electromagnetic calorimeter
- Searching for hidden sector particles in the 3 - 60 MeV/c2 mass range with a sensitivy of 8.9E-8 - 5.8E-9 to $\varepsilon 2$.



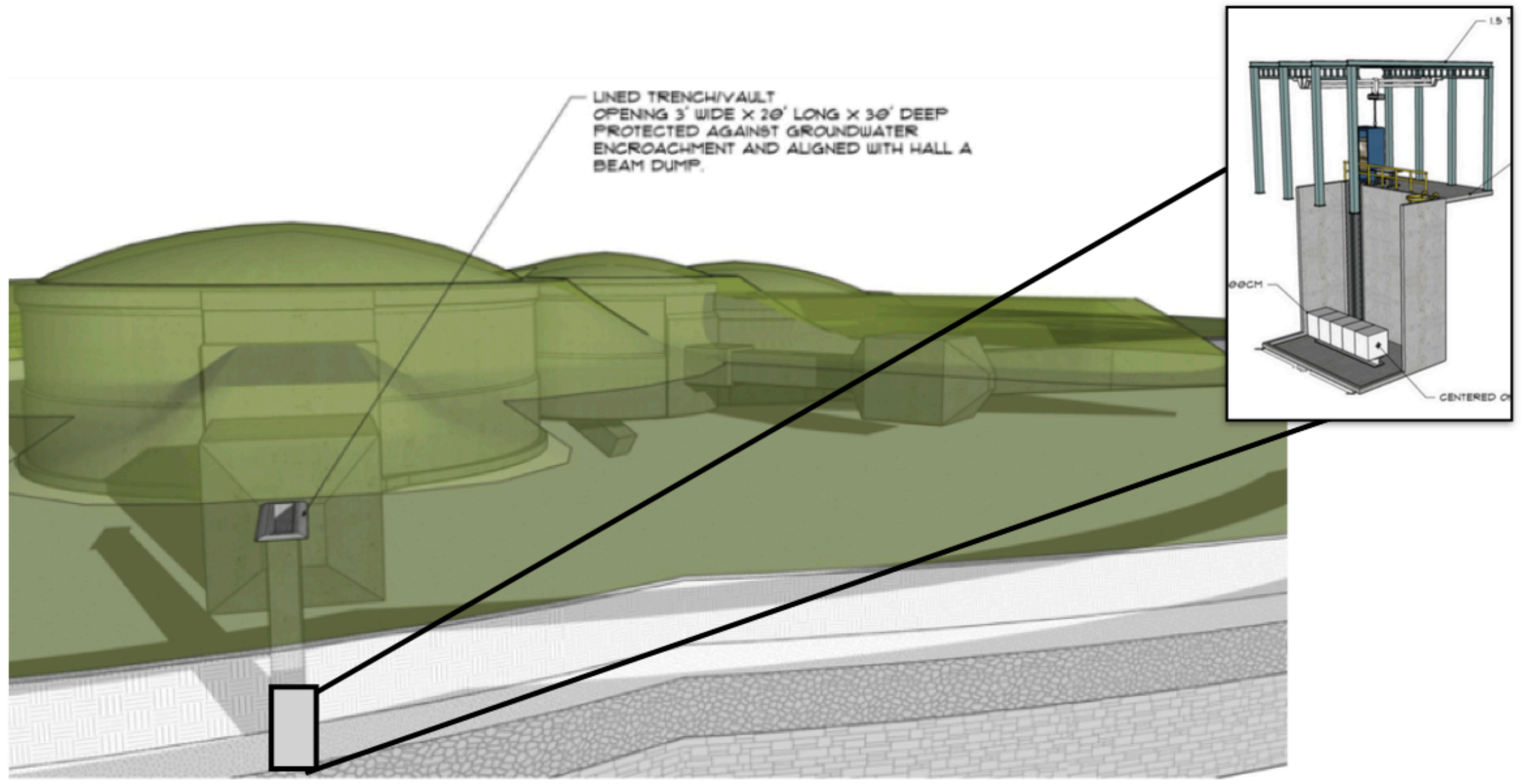


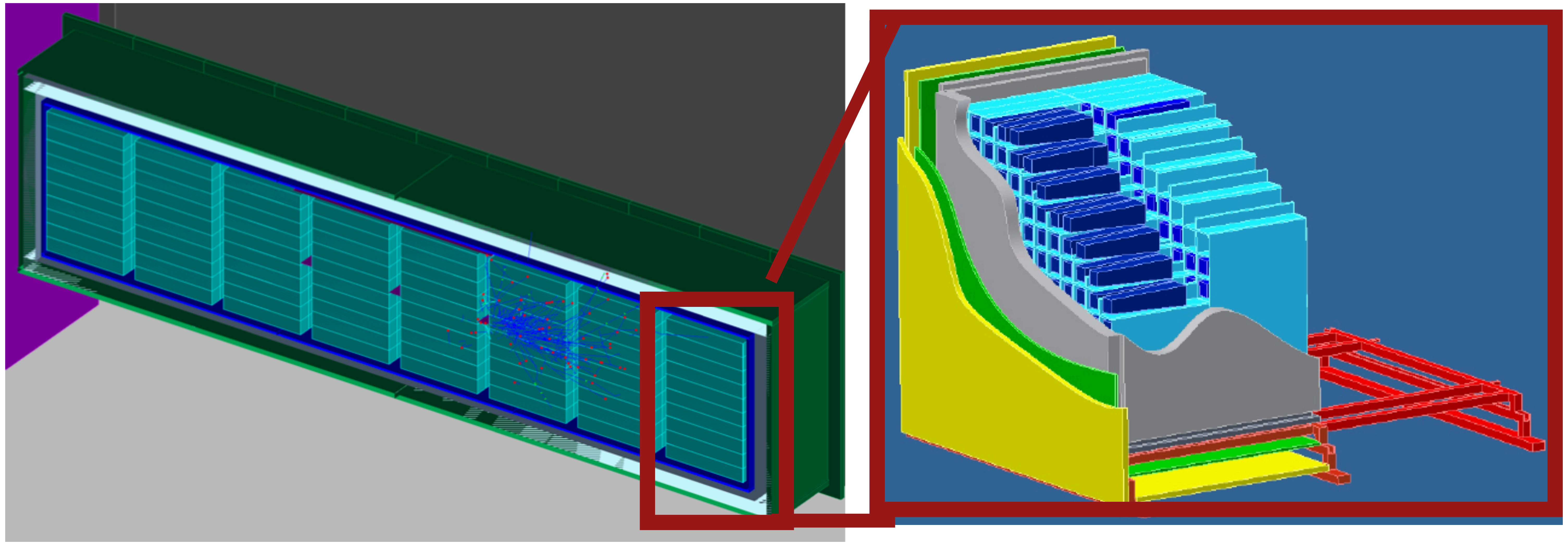
Near future Dark Sector search: invisible decay

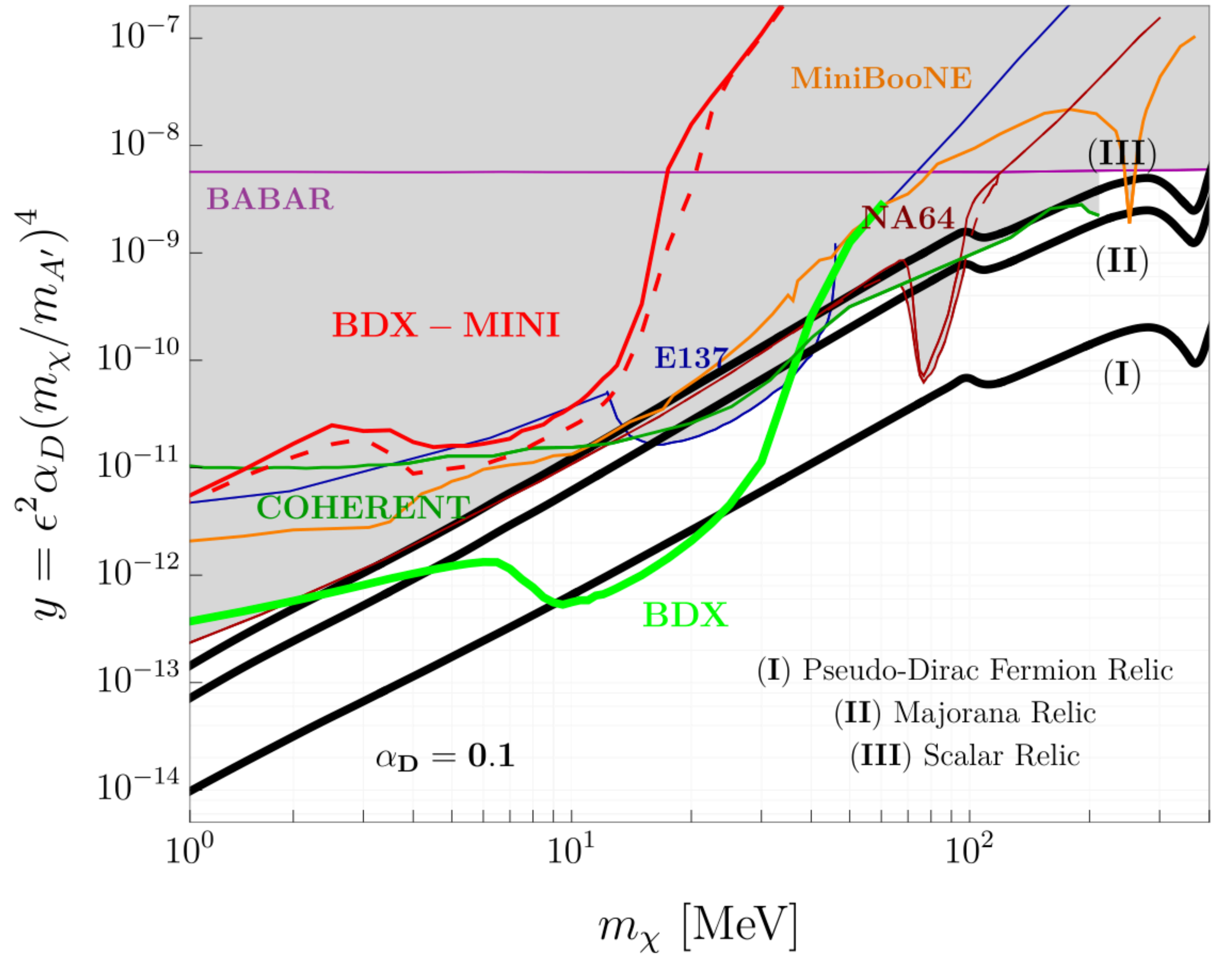
See M. Spreafico Talk

Beam Dump eXperiment: BDX

- 11 GeV e- Hall-A beam dump experiment, approved by PAC-46 in July 2018 (reconfirmed in 2023 by PAC-51). Expected to run in parallel with MOLLER experiment
- Experiment design with two goals:
  - Production and detection of Light Dark Matter
  - Reduce as much as possible the background (cosmic background and beam-related background)

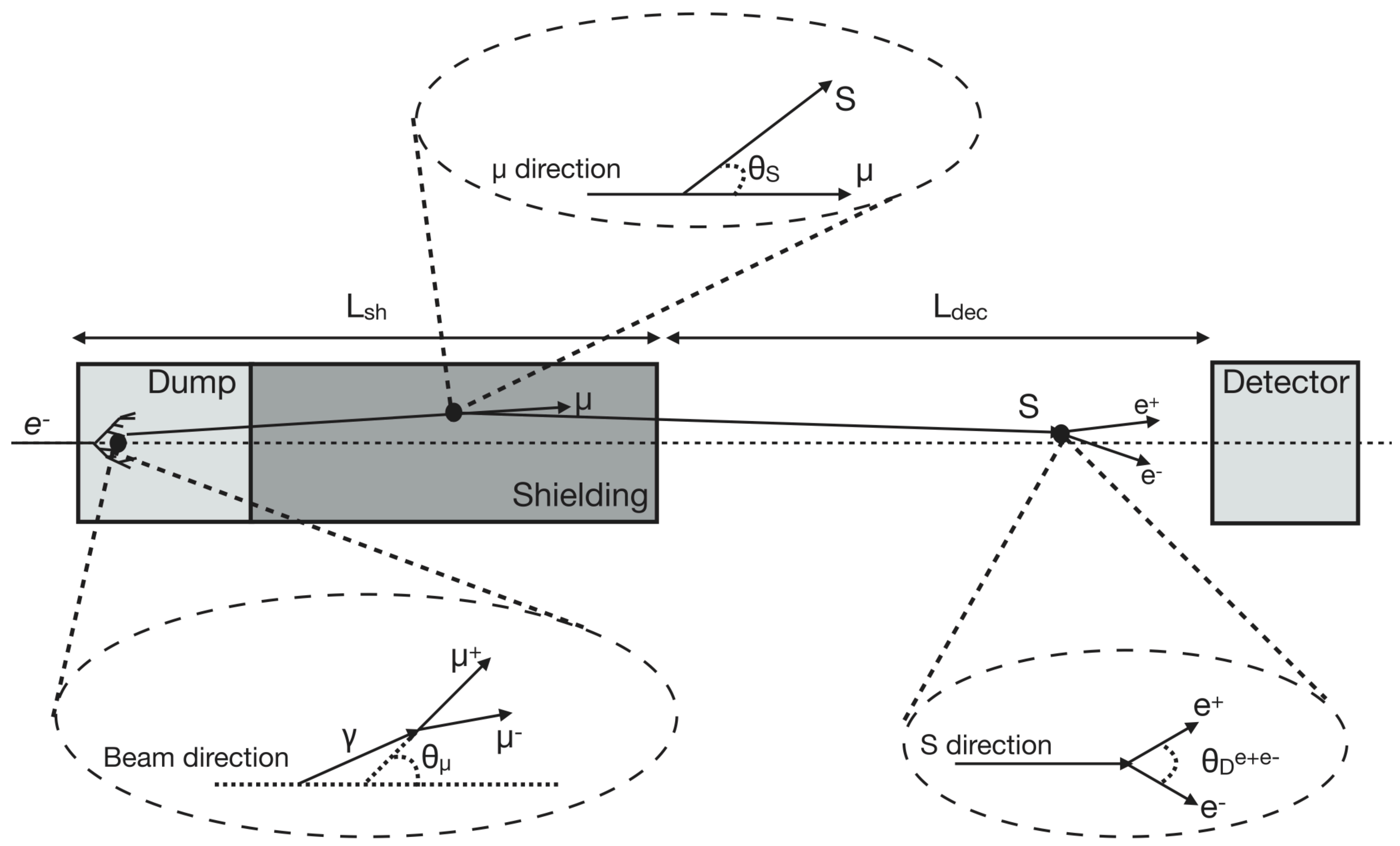




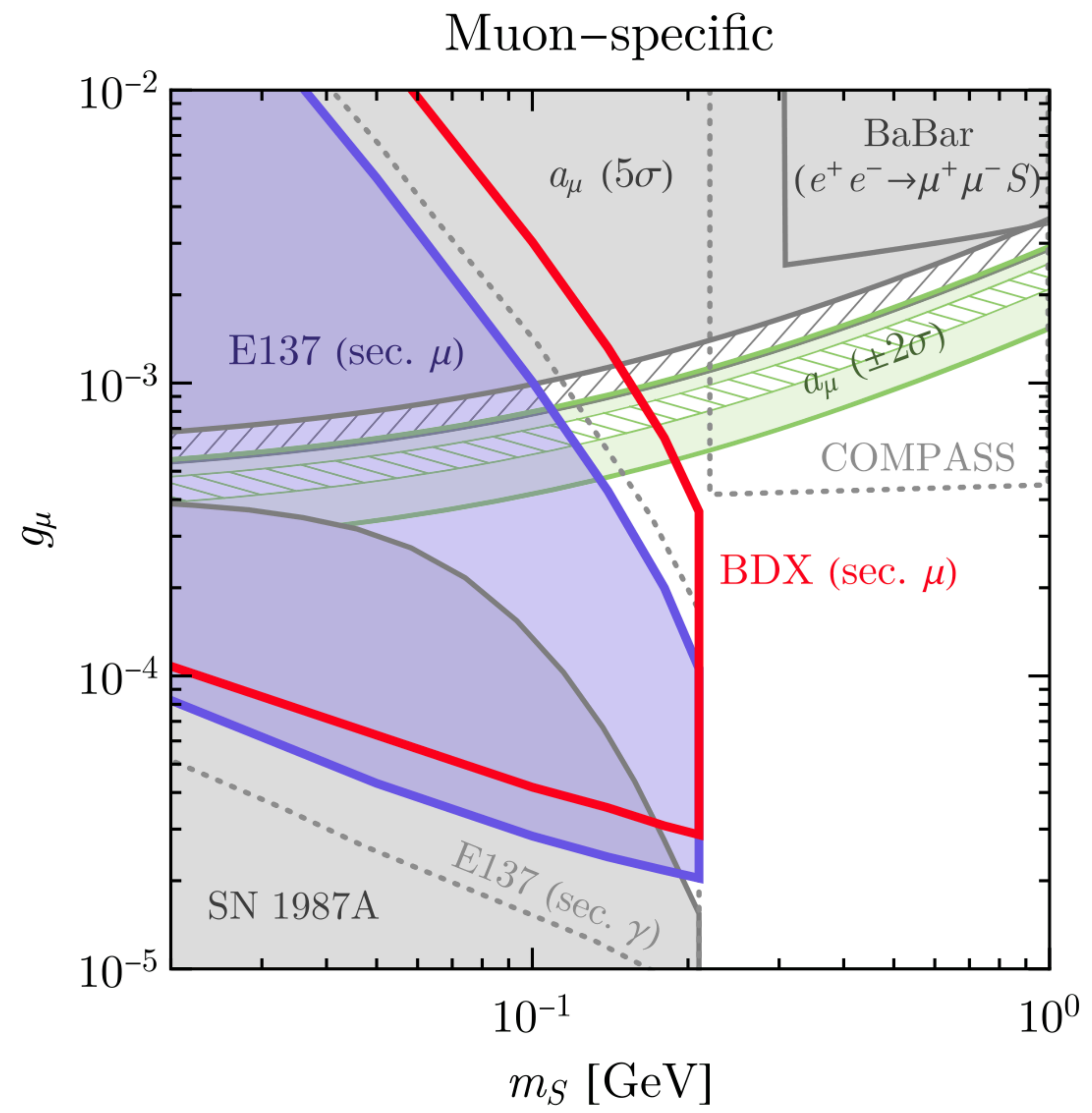


Near future Dark Sector search: probing muon-philic force

Muon Beam Dump eXperiment: μBDX



- Muon beam dump experiment to probe the visible decay into e+e- (γγ)
- Same BDX infrastructure

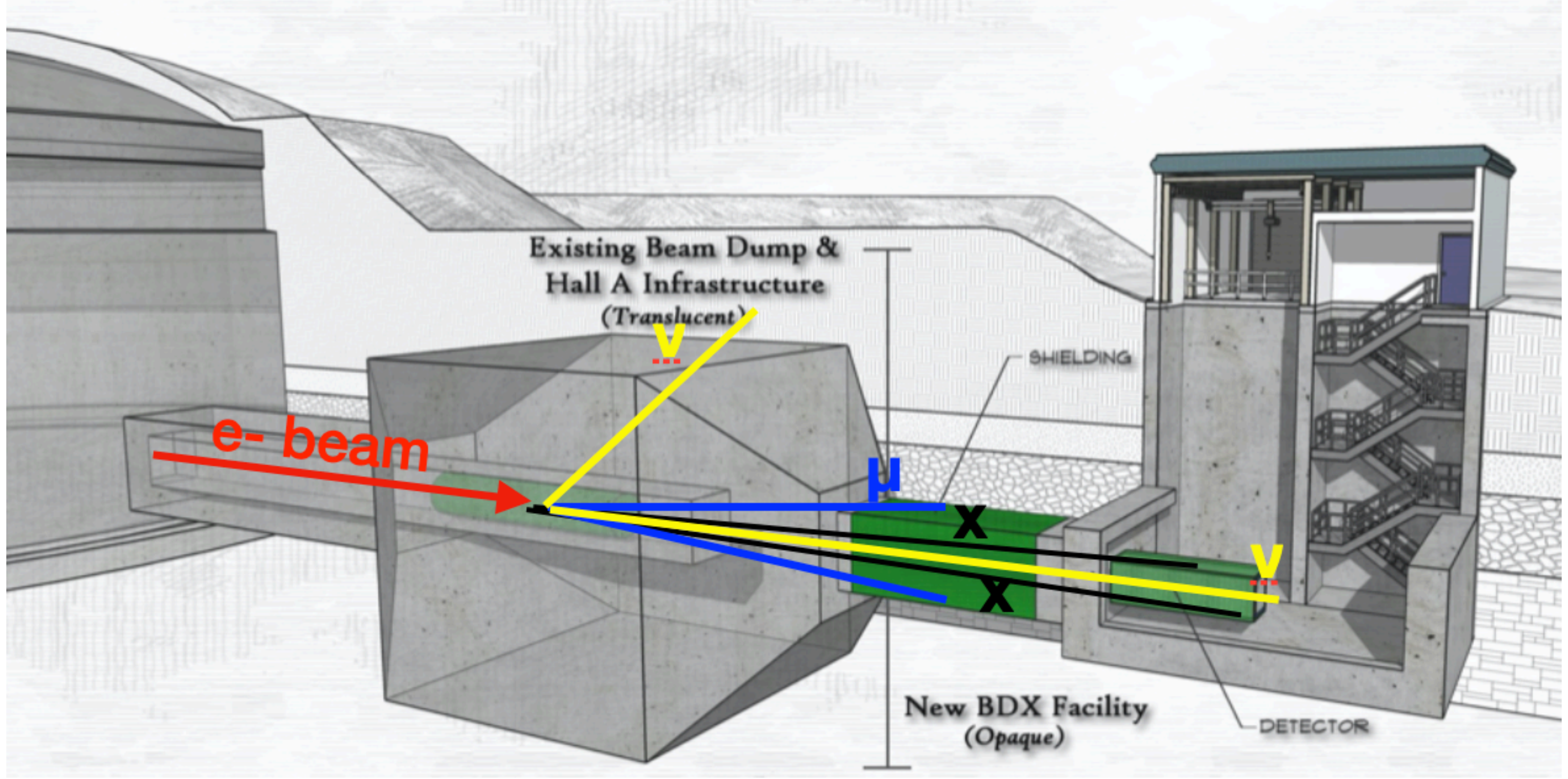


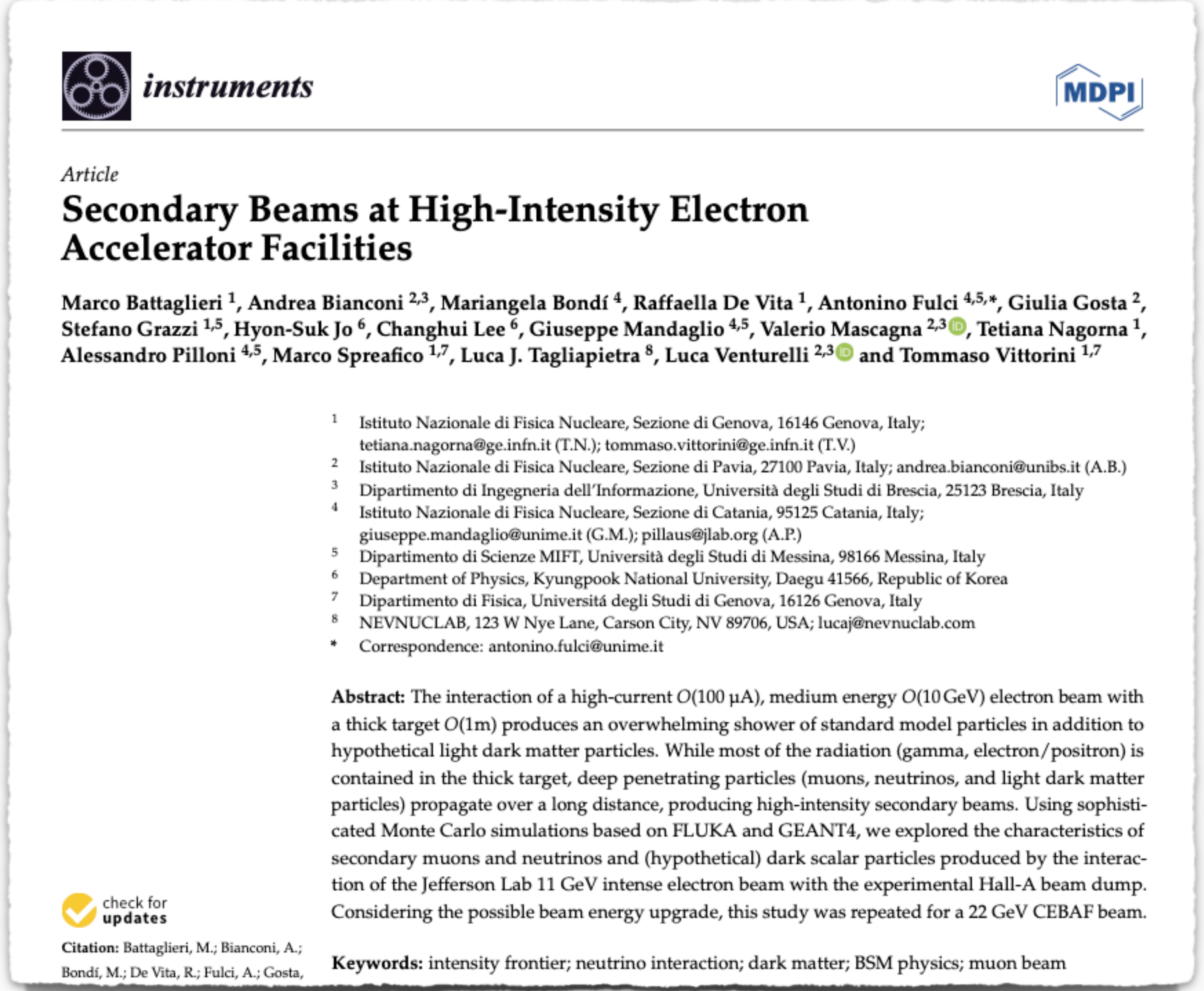
- A sizable flux of high energy muons produced in the dump by the e- beam
  - 11 GeV (22 GeV) e- beam hitting hall A beam dump: $3*10^8$ μ/s (~$2*10^9$ μ/s)
  - Use the secondary muon beam to produce exotic particles

L. Marsicano et al., PRD 98 115022(2018)

New physics perspective at JLAB with secondary beams

- High-intensity secondary beams are produced in the dump(s) fully parasitically
  - Muons,
  - Neutrinos,
  - LDM particles (if exists)
- Energy upgrade will be beneficial for the secondary muon beam, extending the energy range and the flux
- New infrastructure needed




instruments
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Article

Secondary Beams at High-Intensity Electron Accelerator Facilities

Marco Battaglieri [1], Andrea Bianconi [2,3], Mariangela Bondí [4], Raffaella De Vita [1], Antonino Fulci [4,5,*], Giulia Gosta [2], Stefano Grazzi [1,5], Hyon-Suk Jo [6], Changhui Lee [6], Giuseppe Mandaglio [4,5], Valerio Mascagna [2,3], Tetiana Nagorna [1], Alessandro Pilloni [4,5], Marco Spreafico [1,7], Luca J. Tagliapietra [8], Luca Venturelli [2,3] and Tommaso Vittorini [1,7]

1 Istituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italy; tetiana.nagorna@ge.infn.it (T.N.); tommaso.vittorini@ge.infn.it (T.V.)
2 Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, 27100 Pavia, Italy; andrea.bianconi@unibs.it (A.B.)
3 Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Brescia, 25123 Brescia, Italy
4 Istituto Nazionale di Fisica Nucleare, Sezione di Catania, 95125 Catania, Italy; giuseppe.mandaglio@unime.it (G.M.); pillaus@jlab.org (A.P.)
5 Dipartimento di Scienze MIFT, Università degli Studi di Messina, 98166 Messina, Italy
6 Department of Physics, Kyungpook National University, Daegu 41566, Republic of Korea
7 Dipartimento di Fisica, Università degli Studi di Genova, 16126 Genova, Italy
8 NEVNUCLAB, 123 W Nye Lane, Carson City, NV 89706, USA; lucaj@nevnuclab.com
* Correspondence: antonino.fulci@unime.it

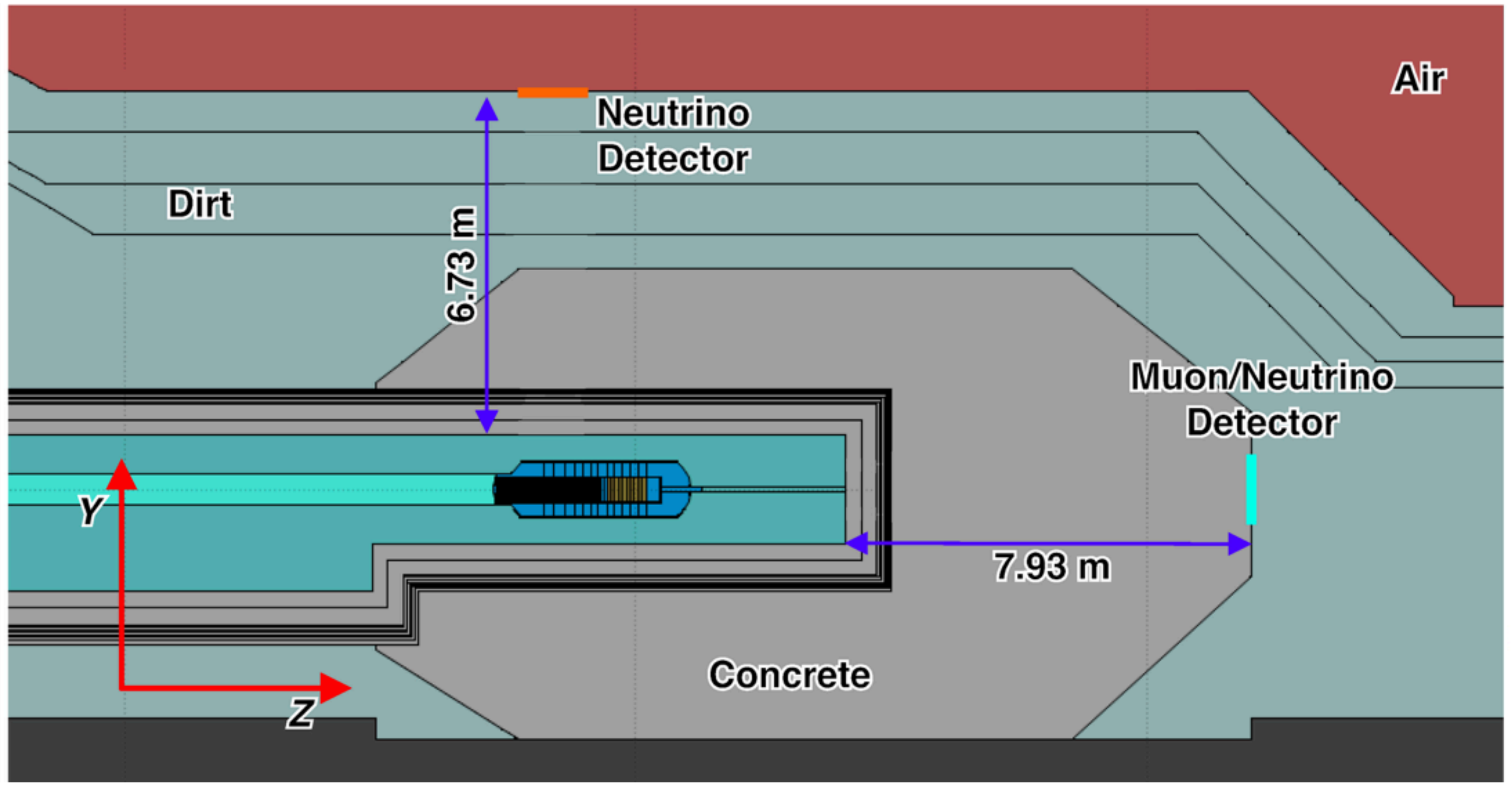
Abstract: The interaction of a high-current $O(100\ \mu A)$, medium energy $O(10\,GeV)$ electron beam with a thick target $O(1m)$ produces an overwhelming shower of standard model particles in addition to hypothetical light dark matter particles. While most of the radiation (gamma, electron/positron) is contained in the thick target, deep penetrating particles (muons, neutrinos, and light dark matter particles) propagate over a long distance, producing high-intensity secondary beams. Using sophisticated Monte Carlo simulations based on FLUKA and GEANT4, we explored the characteristics of secondary muons and neutrinos and (hypothetical) dark scalar particles produced by the interaction of the Jefferson Lab 11 GeV intense electron beam with the experimental Hall-A beam dump. Considering the possible beam energy upgrade, this study was repeated for a 22 GeV CEBAF beam.

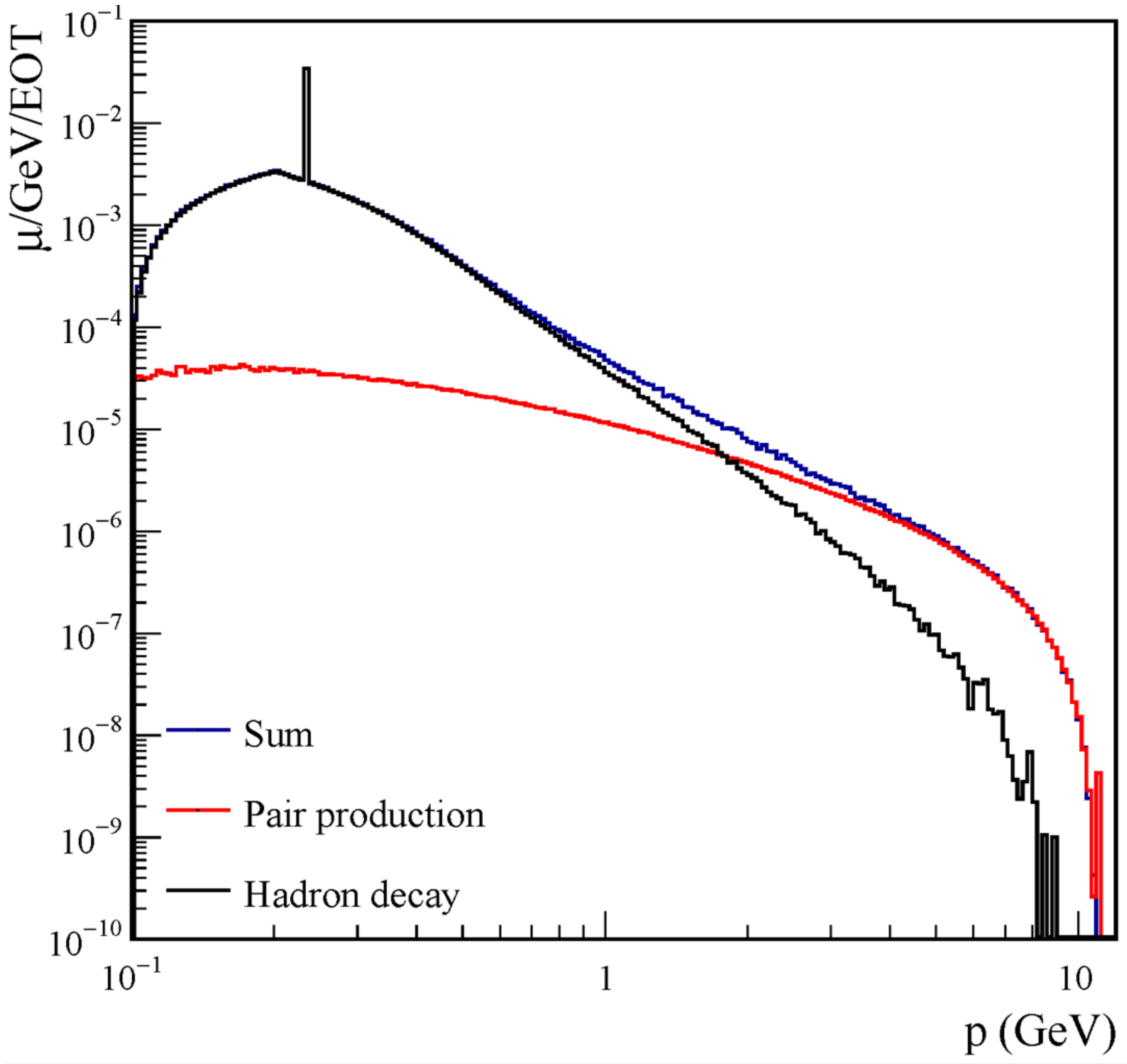
Citation: Battaglieri, M.; Bianconi, A.; Bondí, M.; De Vita, R.; Fulci, A.; Gosta,

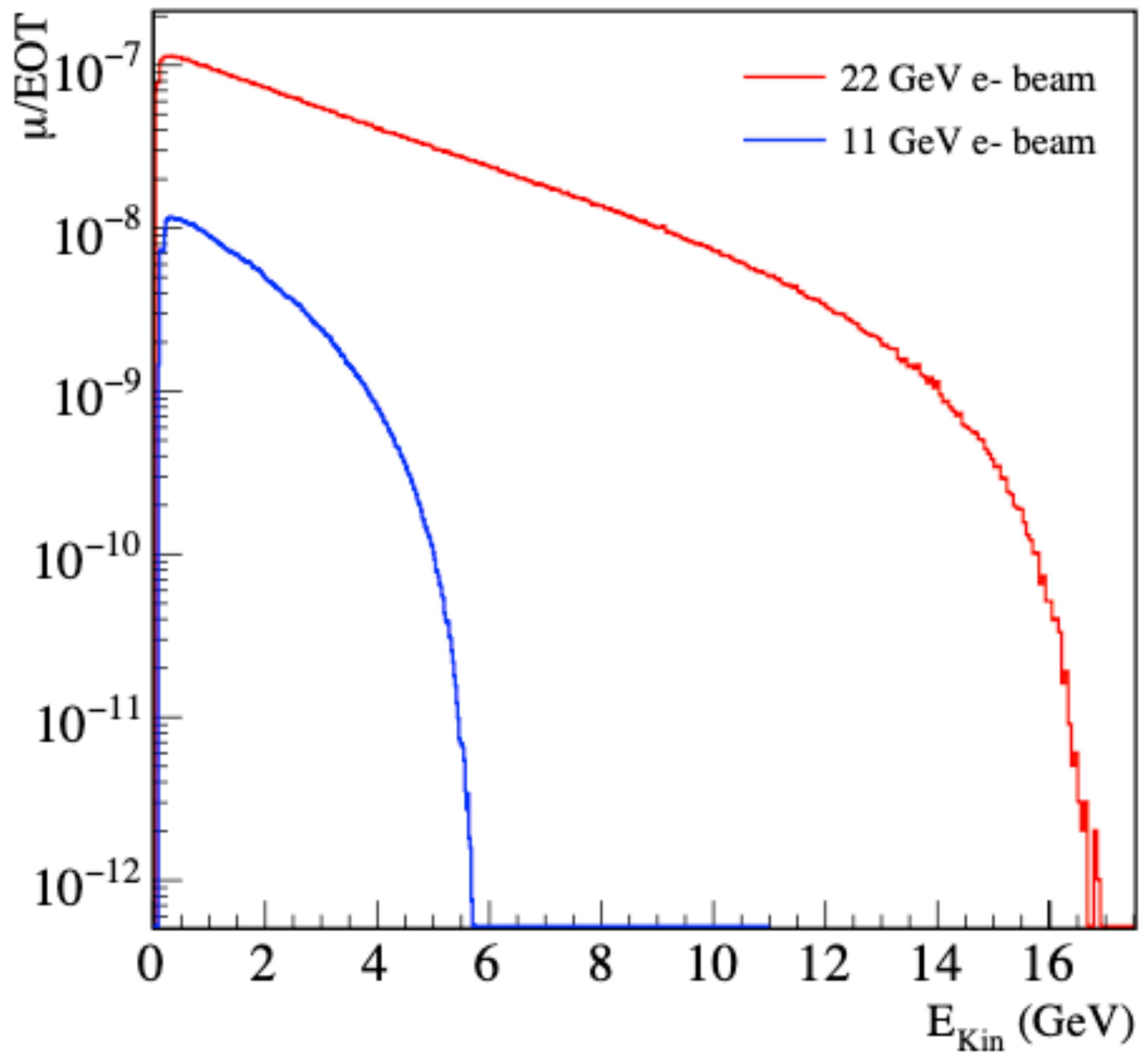
Keywords: intensity frontier; neutrino interaction; dark matter; BSM physics; muon beam

Muon flux @ JLAB-HALL-A

- Muon flux estimated using FLUKA for 11GeV and 22 GeV primary e- beam on Hall-A BD
- High-energy muon produced via 2 processes:
  - Photo-production of π and k which subsequently decay into muons
  - Direct μ-μ+ pair production
- Bremsstrahlung-like energy spectrum



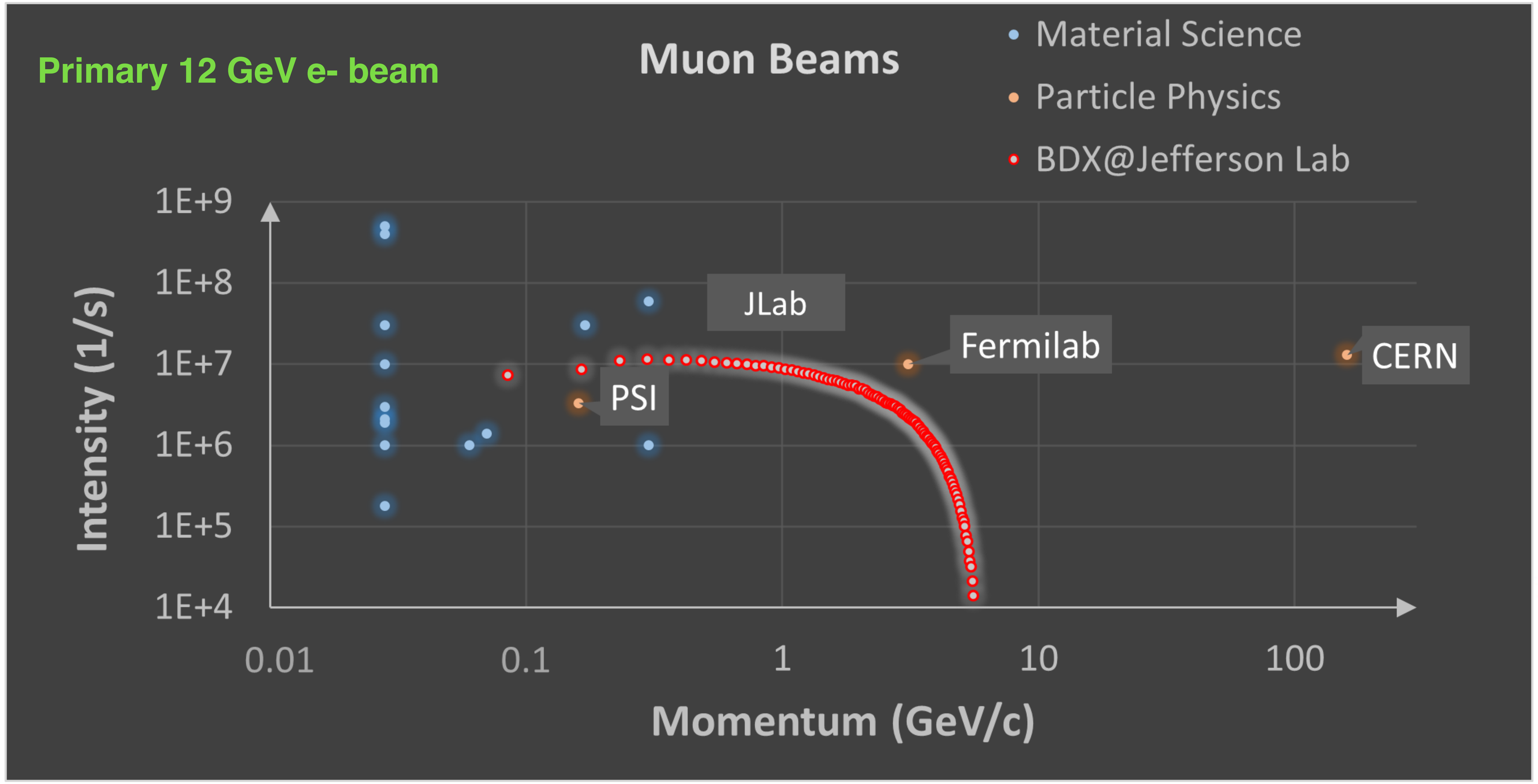


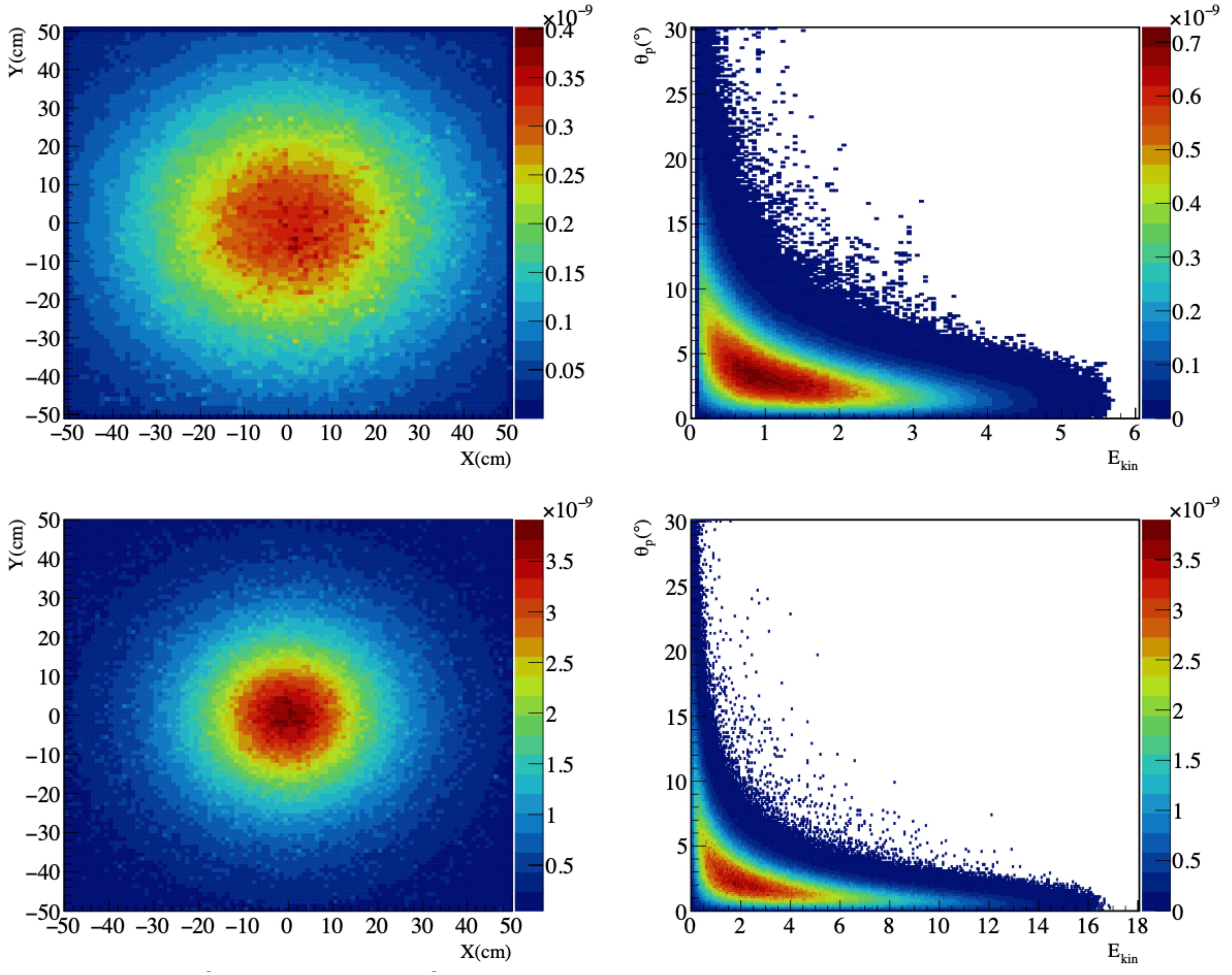


- Significant advantage at 22 GeV (higher muon rate and higher energy)

Muon flux @ JLAB-HALL-A

- The flux increases with the energy of primary beam:
  - Muon flux (11 GeV e- beam): 9E-7 μ/EOT
    - Rate ~ 3E8 μ/s
  - Muon flux (22 GeV e- beam): 5E-6 μ/EOT
    - Rate ~2E9 μ/s
  - Muon flux profile σx and σy ~ 20 cm

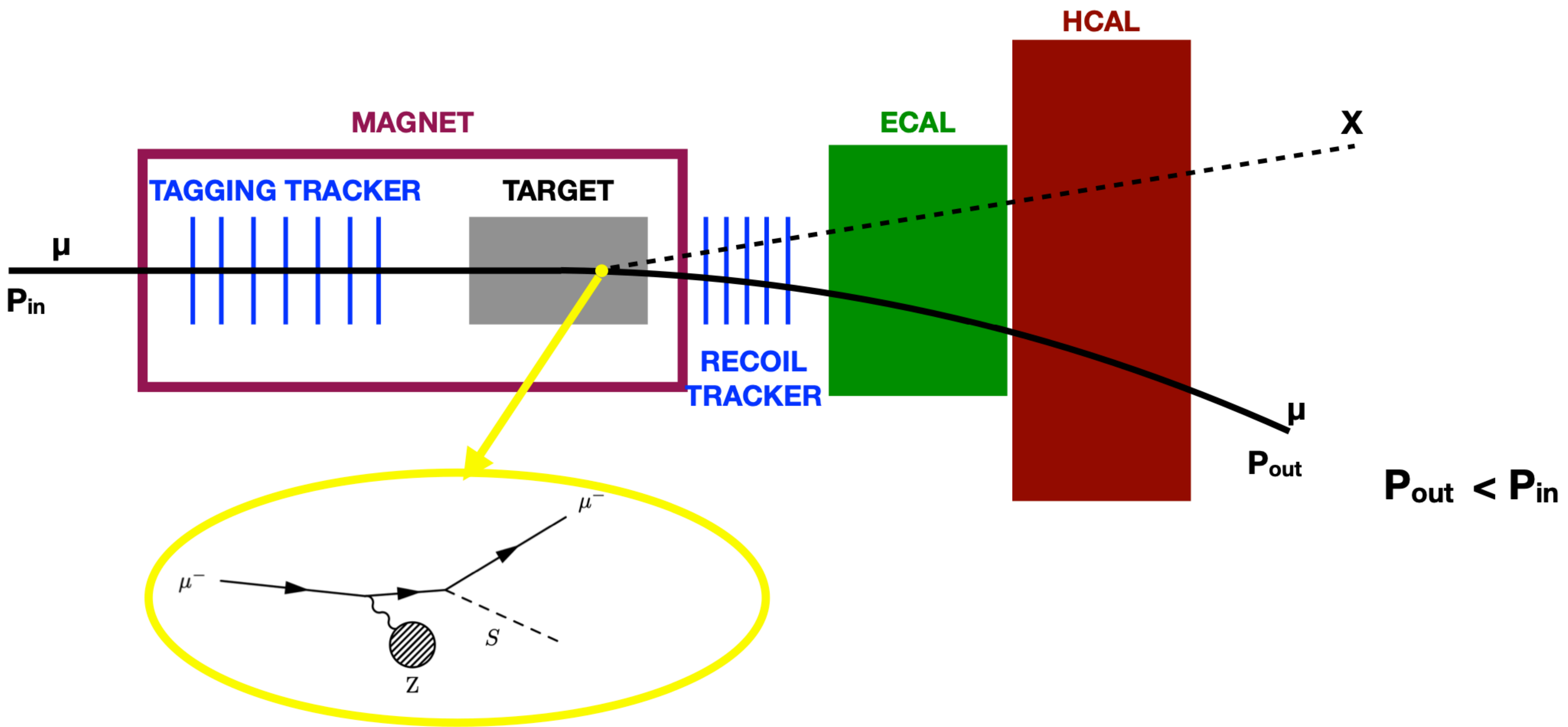


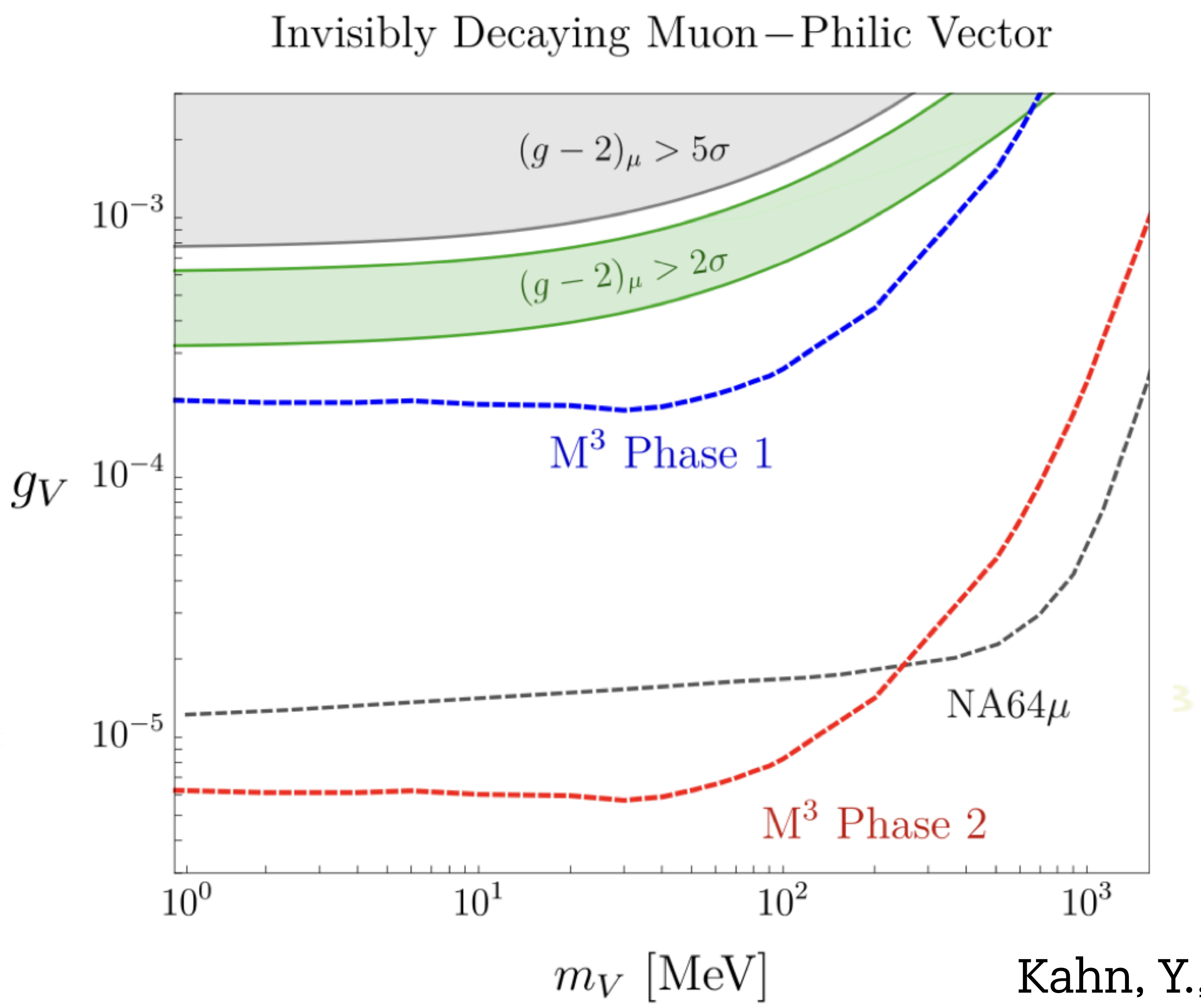


Beam Energy	Flux μ/EOT		σ_x (cm)	σ_y (cm)
	100 × 100 cm^2	25 × 25 cm^2		
11 GeV	9.8×10^{-7}	1.5×10^{-7}	24.6	25.1
22 GeV	7.6×10^{-6}	1.9×10^{-6}	20.9	20.9

Future experiment: Probing of muon-philic forces

- *μ3BDX @ JLAB*
  - Fixed-target missing momentum experiment a la M3 to probe invisibly decaying particle
  - Requirements:
    - High intensity O(GeV)-muon beam
    - Thick active target O(20Xo)
    - Momentum resolution < 1%
  - **Background**
    - Reducible background
      - Single bremsstrahlung: μN-> μNγ
      - Bremsstrahlung-initiated hadronic events
      - Muon pair production
    - Irreducible background
      - Neutrino pair production



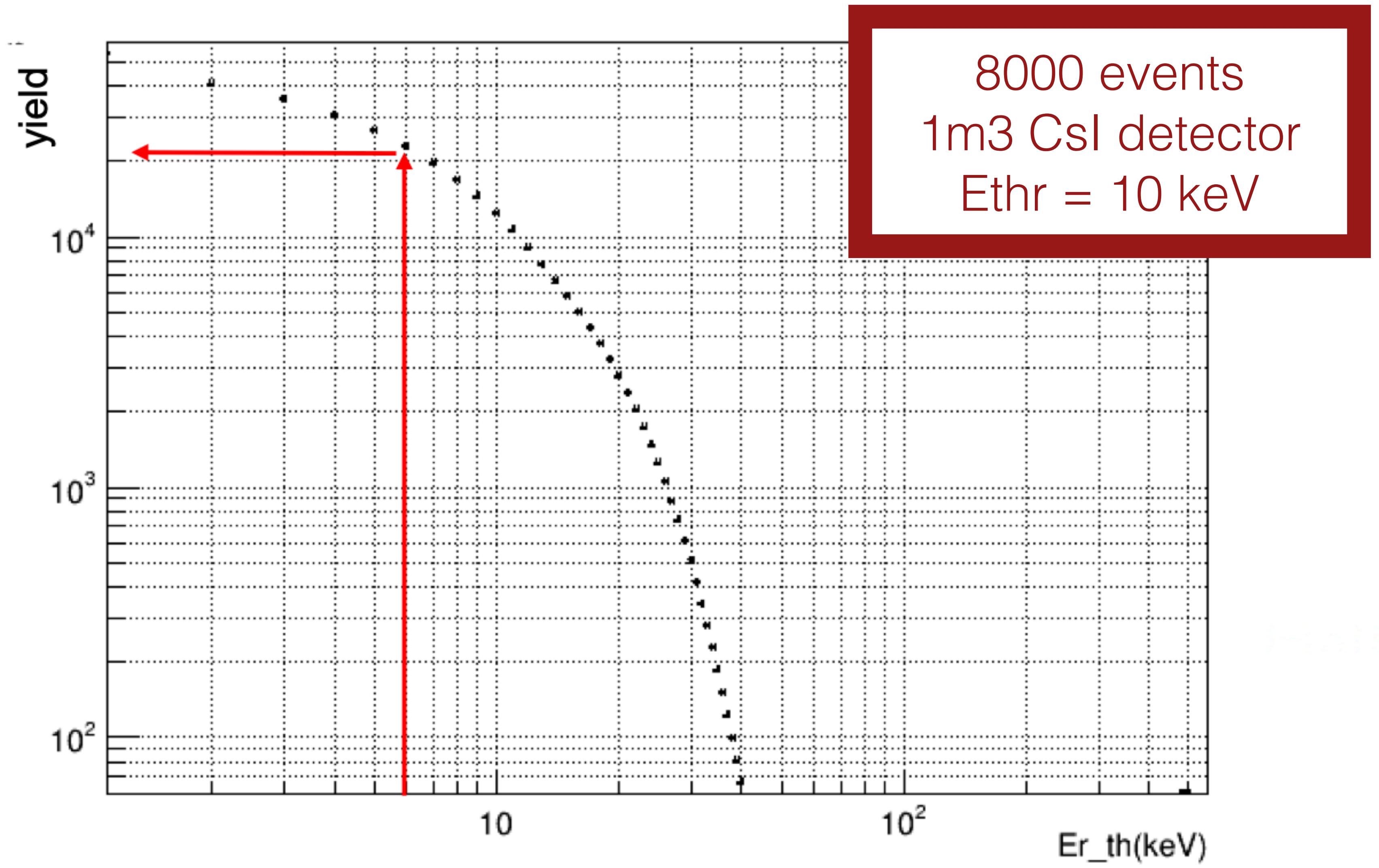


- Reach of M3 experiment (MOT ~ 10^{13}, muon energy ~ 15 GeV)
- Reach for JLAB experiment under evaluation

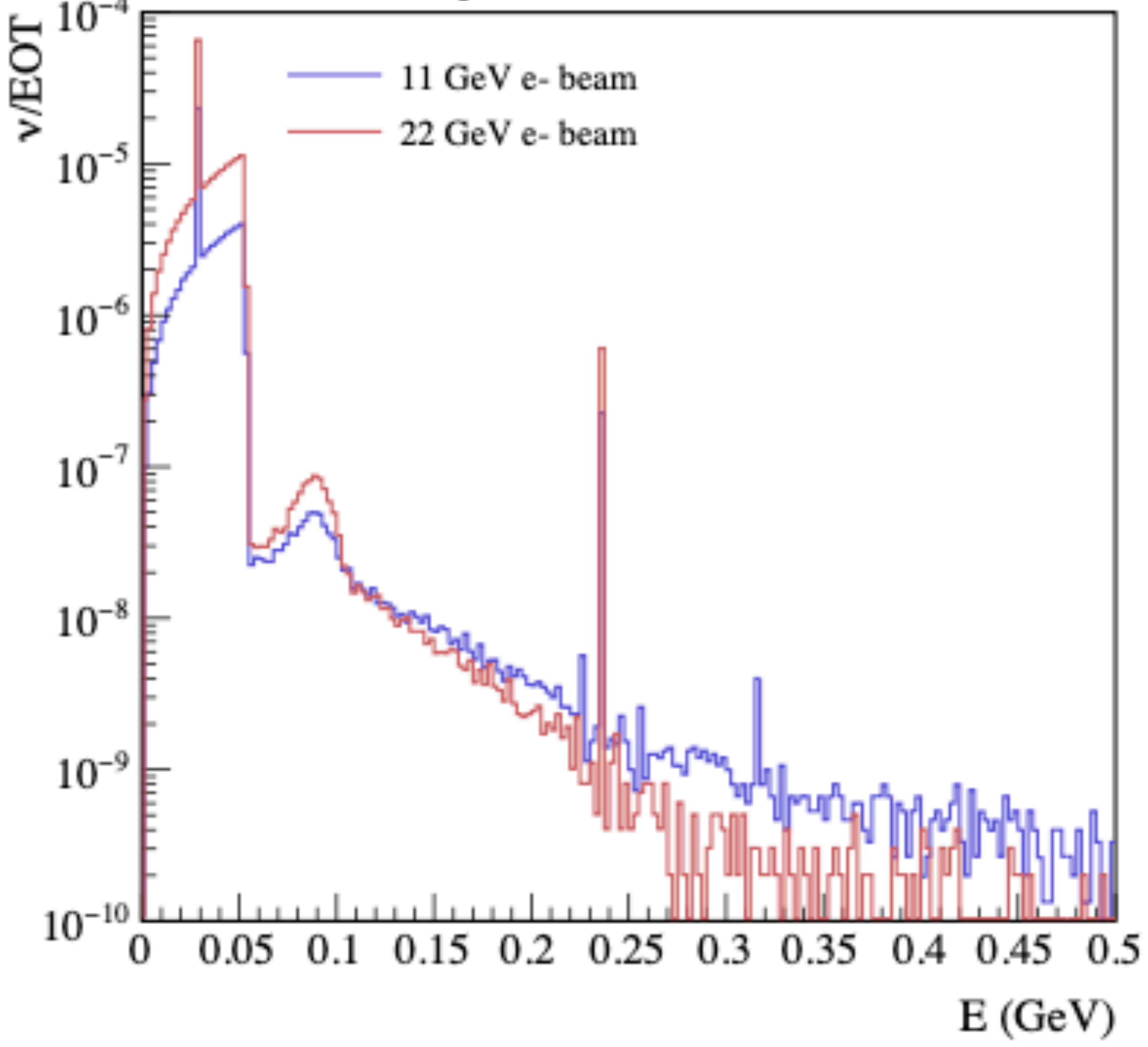
Kahn, Y., Krnjaic, G., Tran, N. et al. High Energ. Phys. 2018, 153 (2018).

Neutrino Beam @ JLAB-HALL-A

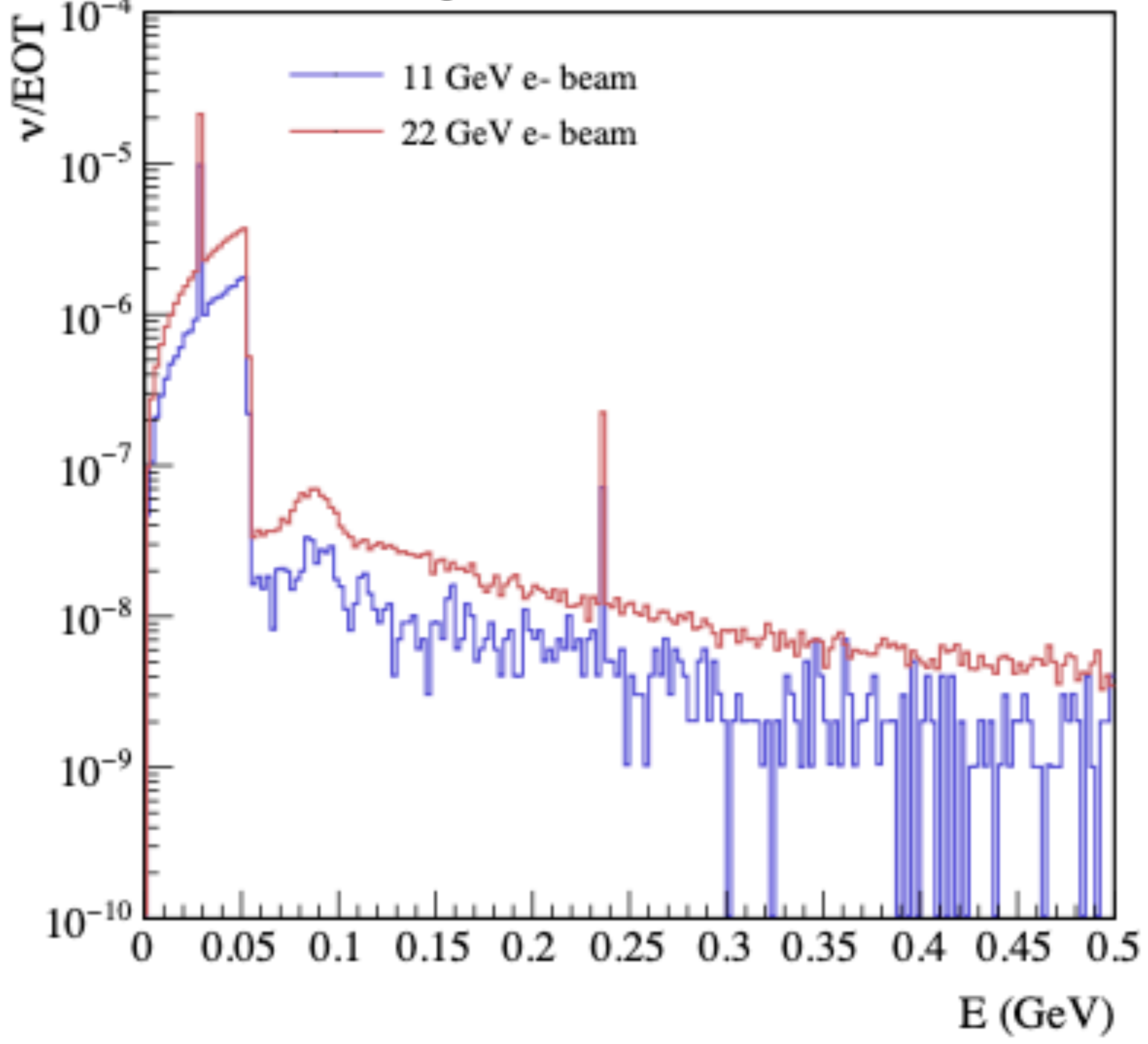
- Neutrino flux estimated using FLUKA for 11 GeV and 22 GeV primary e- beam on Hall-A BD
- Low energy part due to pion and muon decay at rest
  - π decay produces a prompt 28.5 MeV ν_μ along with a μ witch subsequently decays producing a ν_e ν_μ
- High energy ν from in-flight pion and kaon decay
- Coherent Elastic nu-Nucleus scattering measurement @ JLAB



Off-axis



On-axis



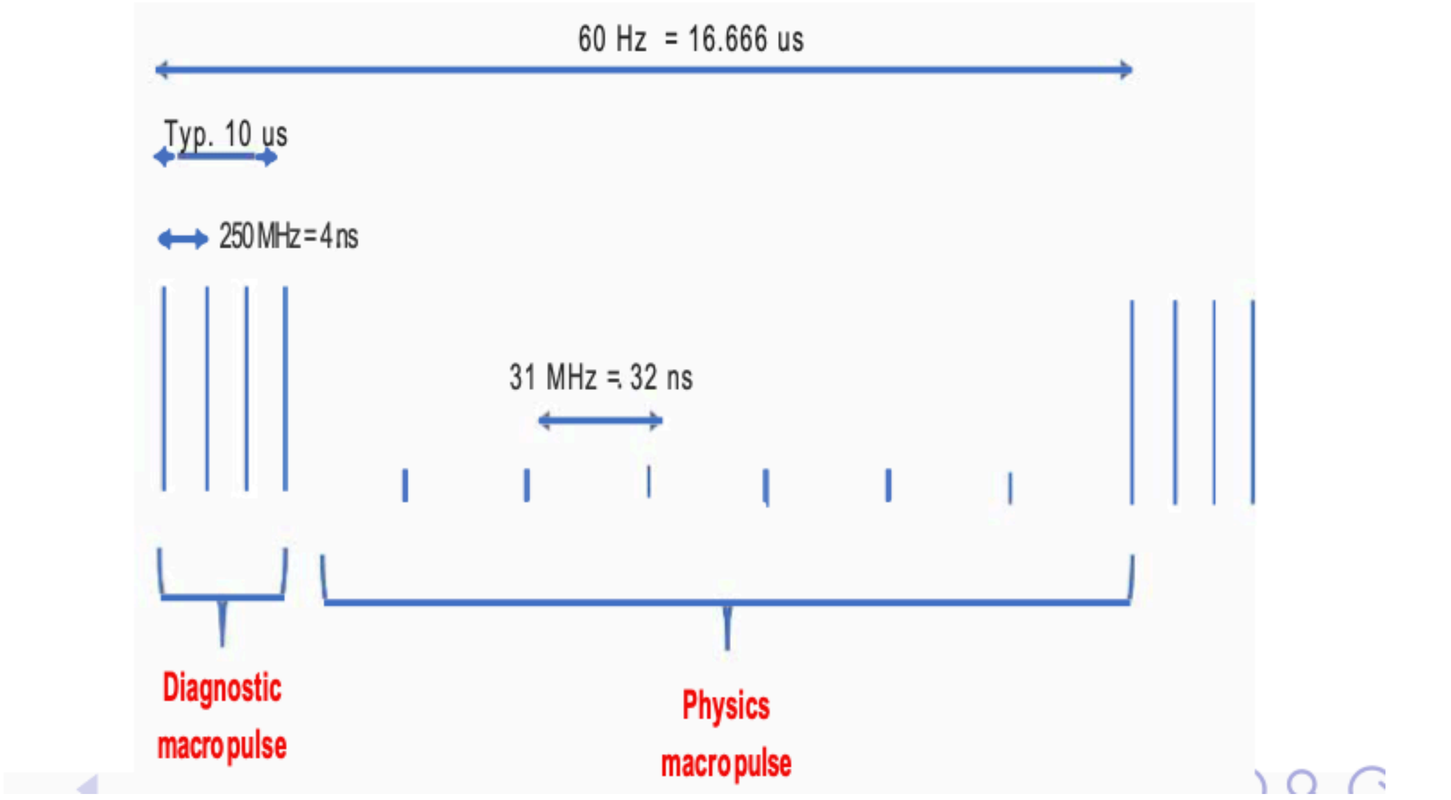
Beam Energy	Off-Axis Flux [ν/EOT/m^2]	On-Axis Flux [ν/EOT/m^2]
11 GeV	6.7×10^{-5}	2.9×10^{-5}
22 GeV	1.9×10^{-4}	6.3×10^{-5}

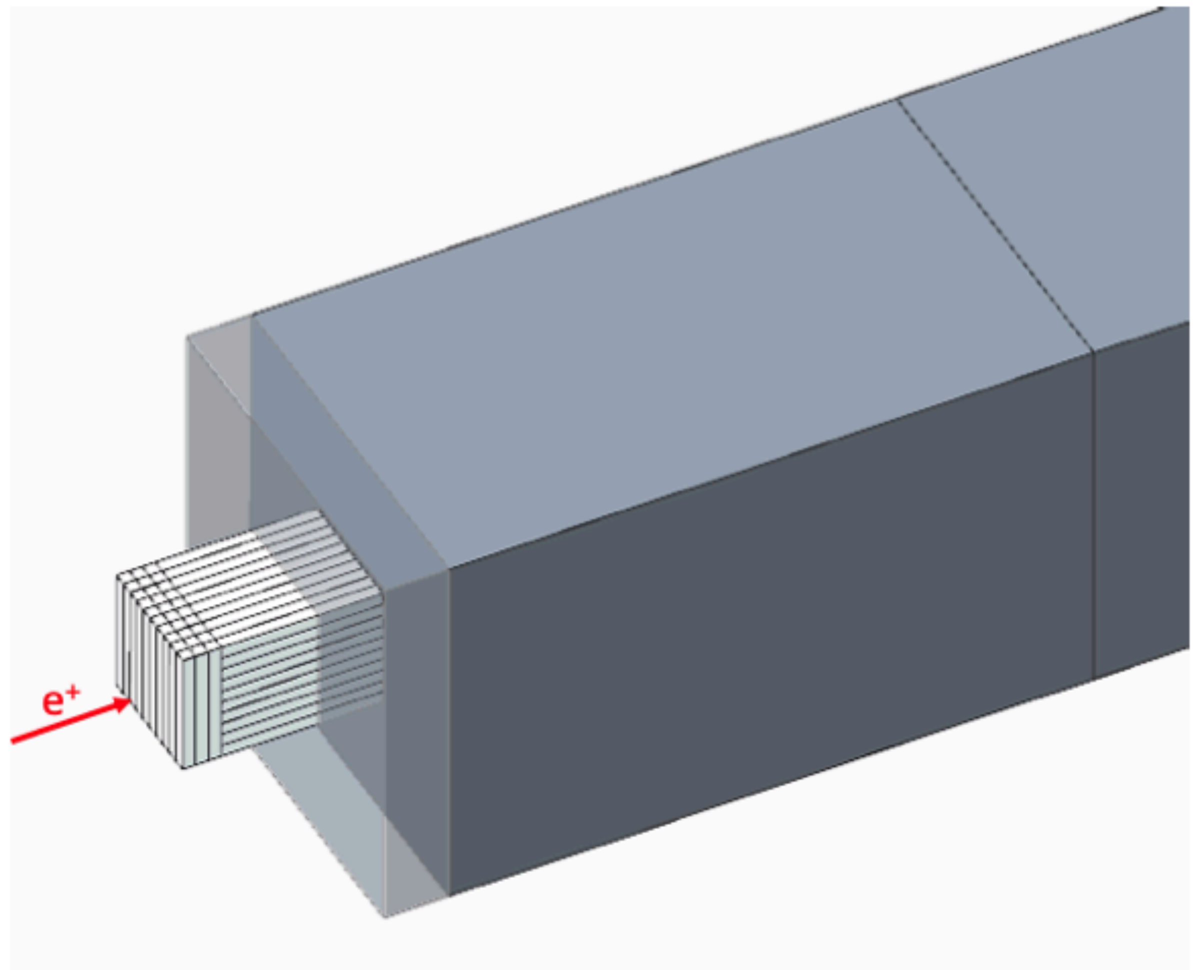
- Flux comparable the integrated flux of the flagship DAR-neutrino facility SNS@Oak Ridge National Lab

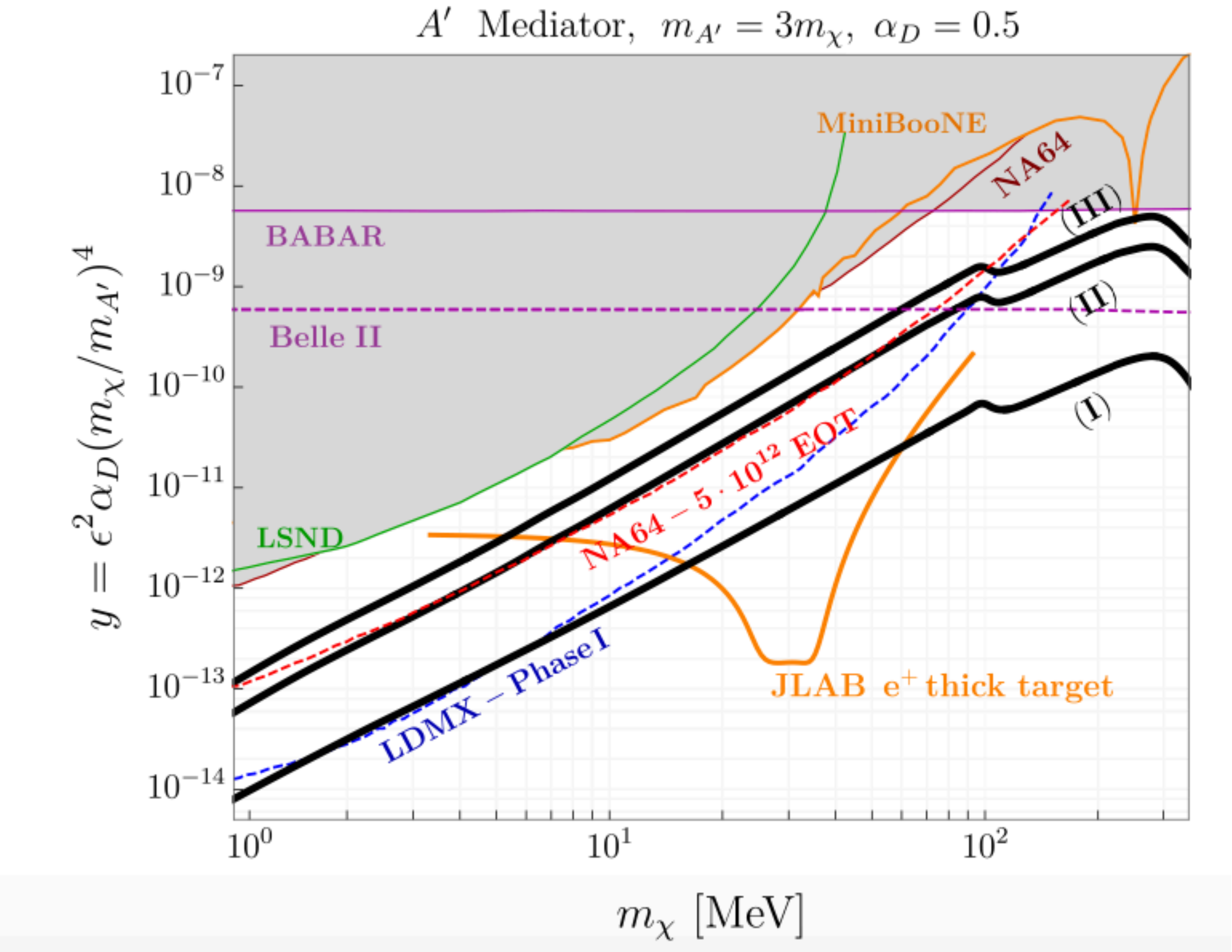
LDM experiment with e+ beam: missing energy experiment

- Missing energy experiment with a 11 GeV positron beam
- e+ impinging on active thick target (ECAL); A′ produced via resonant process e-e+->A'
- Large missing energy as LDM production signature: $E_{miss} = E_{beam} - E_{ecal}$
- Signature is the presence of a peak in the missing energy (E_{miss}) distribution whose position depends solely on the A mass (mA = sqrt(2me E_{miss})
- HCAL to detect neutral particles escaping the ECAL mimicking signal.

Non-trivial beam structure necessary:







M. Battaglieri et al., Eur. Phys. J. A 57, 253 (2021)

Conclusions

- An extensive program to explore the Dark Sector making use of the high-intensity ~10GeV electron beam available at JLAB is in full swing
- A new generation of dedicated and optimized experiments at high-intensity frontier will test the dark sector scenario
- A high-intensity positron beam available in the near future at Jefferson Lab will optimize LDM searches via annihilation
- Other high-intensity muon and neutrino secondary beams will complement the current program
- BDX & Beyond workshop is planned in June/July 2025. It will be focused on the physics cases that can be investigated using secondary beams at JLab. It will be an opportunity to discuss new perspectives, strategies, and collaborations