Opportunities for Dark Matter Searches at JLab

Mariangela Bondí
INFN - Sezione di Catania

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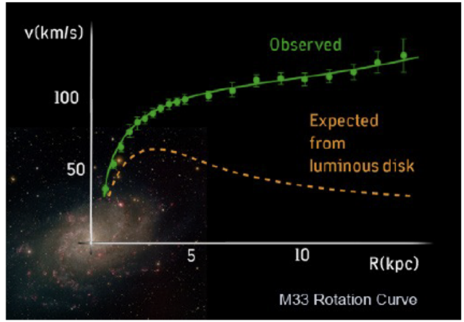
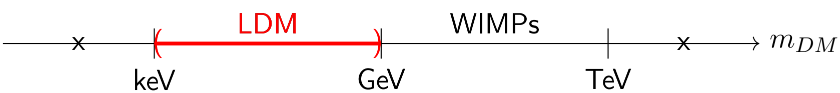
Dark Matter

- Dark Matter is there but **we know nothing about the particle content of DM**
  - Plenty of cosmological/ astrophysical observations: CMB anisotropies, galaxy rotation curves, gravitational lensing,cluster collisions...
- No hints on DM particle properties (mass, cross section)
- Common assumption: **thermal origin of DM**:
  - DM in thermal equilibrium with SM in early Universe. Current relic abundance set by the strength of the SM-LDM interaction ("freeze-out mechanism")
  - constrain on available mass range
- Light Dark Matter: mass range 1 MeV÷1 GeV



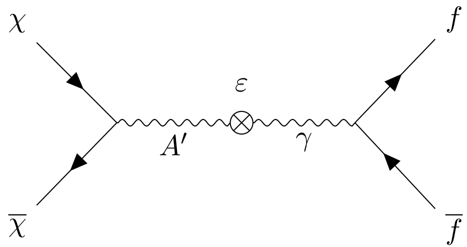
Thermal DM



Light Dark Matter - Dark Photon model

Light Dark Matter: DM is made by sub-GeV particles, interacting with SM via a new force (acting as a “portal” between SM and the new “Dark Sector”).

- **“vector-portal”**”[1]: DM-SM interaction trough a new U(1) gauge-boson (“dark-photon”) coupling to electric charge



Model parameters:

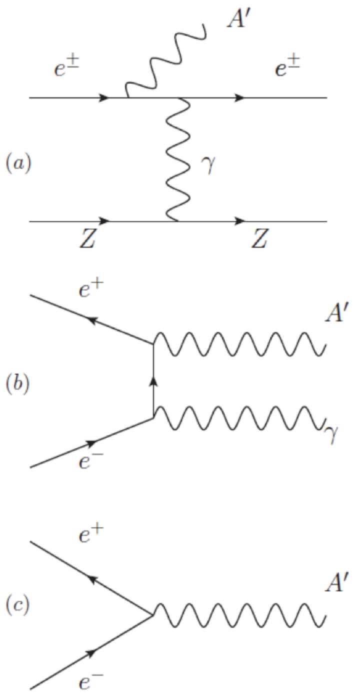
- Dark Photon mass $m_{A'}$, coupling to SM ε
- Dark Matter mass m_χ, coupling to DM g_D $(\alpha_D \equiv g_D^2/4\pi)$

$$y \equiv \frac{g_D^2 \epsilon^2 e^2}{4\pi} \left(\frac{m_\chi}{m_{A'}}\right)^4 \sim \langle \sigma v \rangle_{relic} m_\chi^2$$

[1] For a comprehensive review: 1707.04591, 2005.01515, 2011.02157

Dark Photon Production Mechanisms With Lepton Beams

Three main production mechanisms in fixed targets, lepton beam experiments:



a) **A'-strahlung**:

- Radiative A emission in nucleus EM field
- Scales as $Z^2\alpha^3_{EM}$.
- Forward-boosted, high-energy A emission

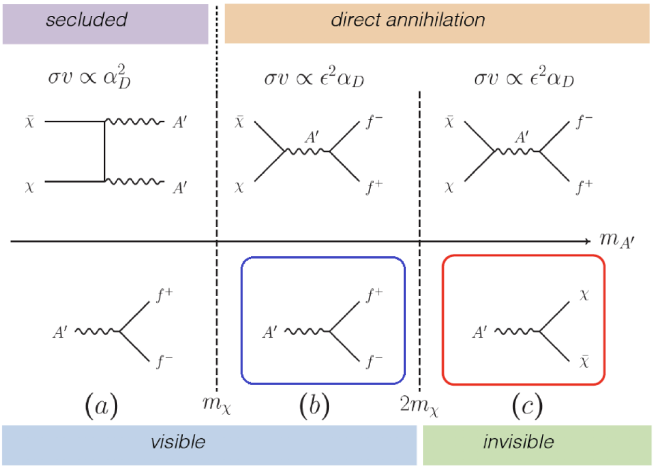
b) e+e− annihilation:

- scales as $Z\alpha^2_{EM}$.
- Forward-backward A' emission in the CM

c) **Resonant** e+e− annihilation

- scales as $Z\alpha_{EM}$.
- resonant Breit-Wigner like cross section with $mA' = \sqrt{2m_e E}$

Mass Hierarchy Determines Search Strategy and Interpretation



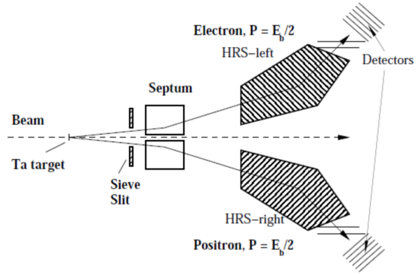
(a) Secluded scenario: does not lend itself to decisive laboratory tests.

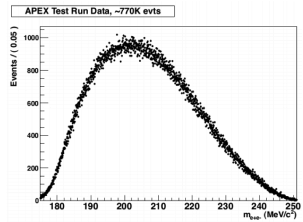
(b) Visible decay scenario. Experiments @ JLAB: HPS, APEX

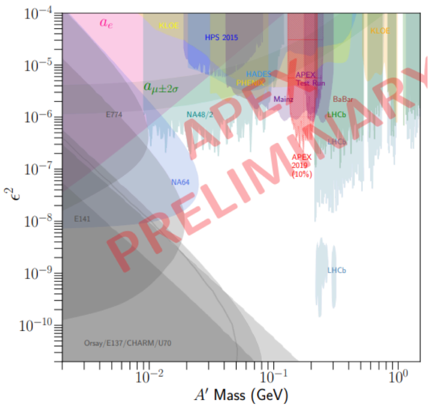
(c) Invisible decay scenario. Experiments @ JLAB: BDX, BDX-MINI

APEX: A-Prime EXperiment

- e- fixed target experiment installed in **HALL A**.
- Dark photon searched as a narrow resonance in e+e- mass over a smooth QED background
- Two High Resolution Spectrometers (HRSs) in coincidence to measure events with an e- in one arm and e+ in the other
  - Standard HRS detector stack in both arms: Scintillators: S0 and S2(timing), VDC (tracking), Cherenkov and Calorimeters (PID)





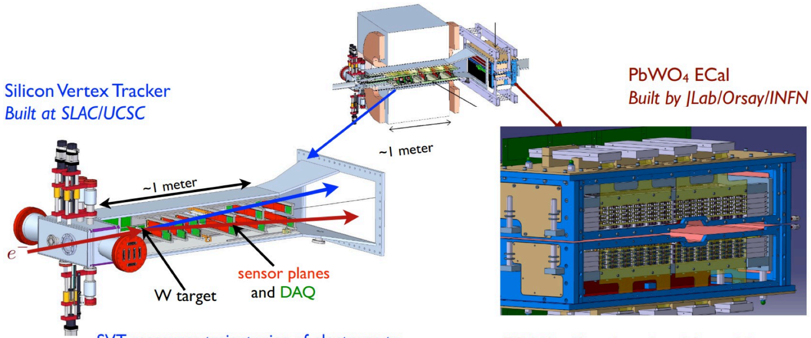


- 2010 test run[a]: beam 2.2 GeV@150 uA on tantalum foil
- Full run in 2019: accumulated over 100x statistics than test run

[a] 10.1103/PhysRevLett.107.191804

HPS: Heavy Photon Search

e- fixed target experiment installed in **HALL B**.



SVT measures trajectories of electrons to reconstruct e^+e^- mass and ***vertex position***.

ECal identifies e^+e^- pairs with precision timing to reject single e^- backgrounds.

Key points

- CEBAF e- beam:1.1-6.6 GeV
- Thin W target : 10^{-3}X0
- Si tracker inside a dipole magnet: momentum measurement / vertexing
- PbWO4 calorimeter [a] downstream: PID / trigger
- plastic-scintillator based hodoscope in front of the ECAL (positron side) to suppress backgrounds from photons.

Signature

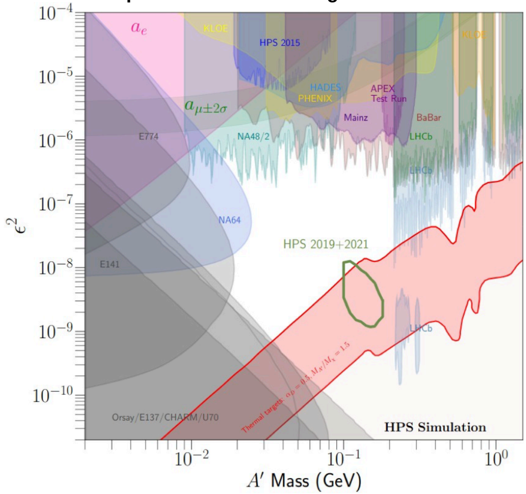
- Resonance search (aka "bump-hunt"): Narrow e+e-resonance over a QED background ($\epsilon \sim 10^{-3}$)
- Detached vertex search: Search for two tracks showing a common production vertex downstream the target ($\epsilon \sim 10^{-4}$).

[a] I. Balossino et al., NIMA 854, (2017) 89

HPS Status and Results

- HPS already completed 2 "engineering" runs (2015 [a]/2016[b]) and 2 "production" runs (2019/2021).
  - Results from engineering runs allowed to optimize the detector and demonstrate the HPS capabilities - upper limits set for the A' parameters space, although no new regions were explored.
  - Results from production runs will investigate for the first time unexplored territories in the A' space - analysis ongoing, stay tuned for results!
- More runs to come! 102 "PAC" measurement days (204 calendar days) still to run.

Expected reach combining 2019 and 2021 data



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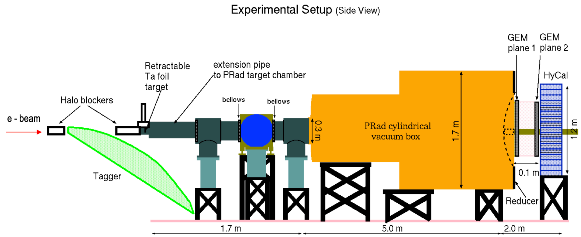
[a] P.H.Adrian et al. (Heavy Photon Search Collaboration), Phys. Rev. D 98, 091101(R)

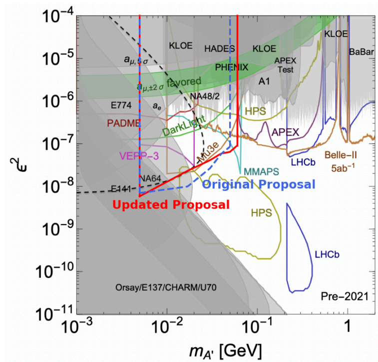
[b] arxiv:2212.10629 - accepted by PRD

X17 search at JLab

Direct detection search for hidden sector particles using the magnetic-spectrometer-free PRad setup in **Hall-B**[a]:

- Discover or establish an experimental upper limit on the electroproduction of the hypothetical X17 particle, claimed in two ATOMKI low-energy proton-nucleus experiments.
- Search for "hidden sector" intermediate particles in [3 60] MeV mass range
- Experimental approach:
  - bump hunt
  - direct detection of all final state particles (e', e+e- or $\gamma\gamma$)

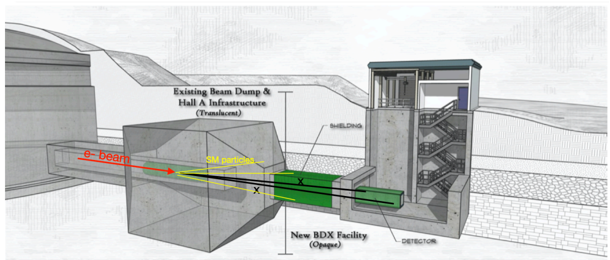


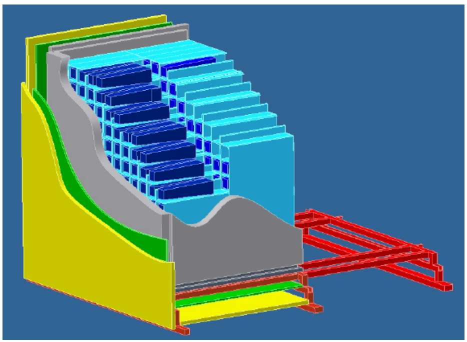


[a] arXiv:2108.13276v3

BDX: Beam Dump eXperiment

- BDX is a JLAB experiment approved by PAC46
- Detector installed O(20 m) behind **Hall-A beam-dump**
- Two step experiment:
  - **production** of LDM beam
  - **detection** of LDM particle: scatters on e- in the detector realising visible signal (O(GeV) EM shower)



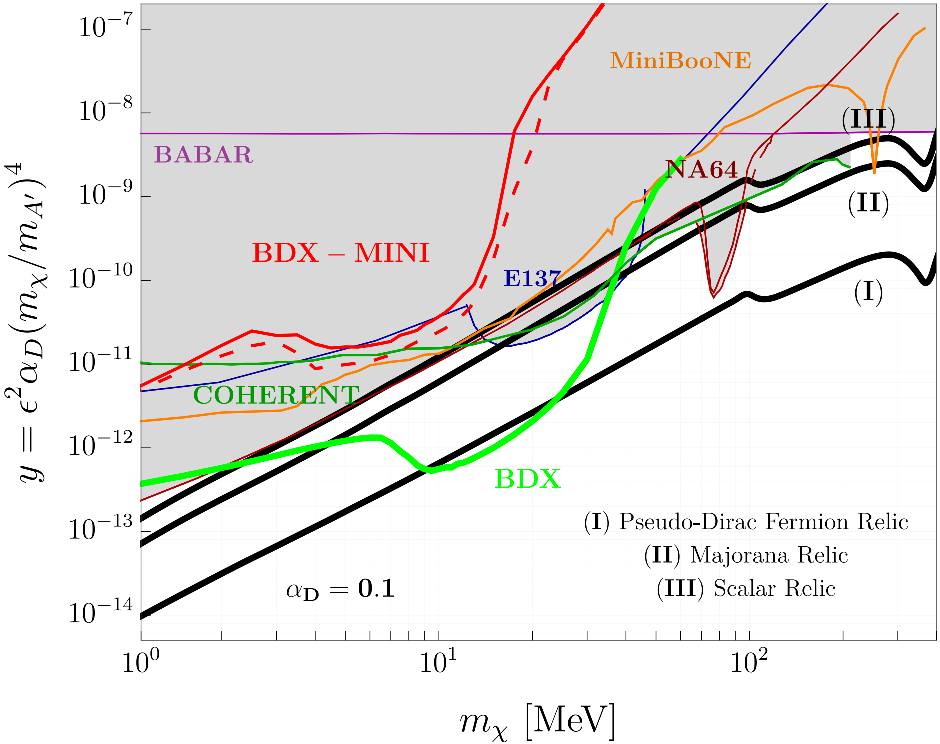


Key points

- 11 GeV e- beam, current: 65 uA
- charge: 1E22 EOT
- Fully parasitic wrt Hall-A physics program
- New experimental hall behind Hall A beam dump
- BDX detector:
  - EM calorimeter: CsI(Tl) crystals+SiPM readout (active volume $\sim 0.5\ m^3$)
  - Dual active-veto layer made of plastic scintillator counters + SiPM readout
  - Passive lead layer surrounding the calorimeter

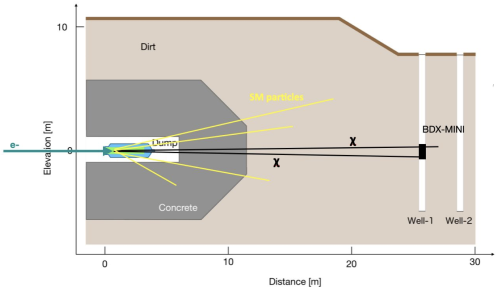
BDX sensitivity

BDX will improve of 2 orders of magnitude current exclusion limits in LDM parameter space



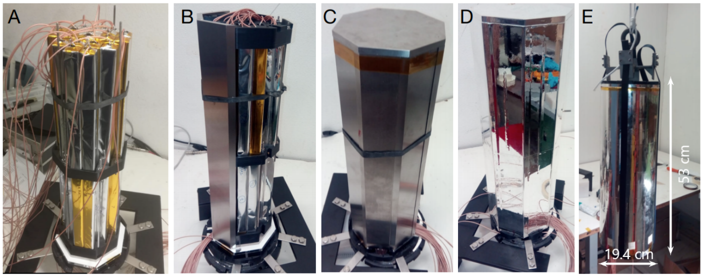
BDX-MINI@JLAB: Pilot experiment

Small-scale, low energy version of full BDX experiment



Experimental setup

- 2.2 GeV, 150 uA e^- beam
- SM particles shielded by concrete and soil
- Detector installed in a well 25 m downstream



BDX-MINI detector[a]

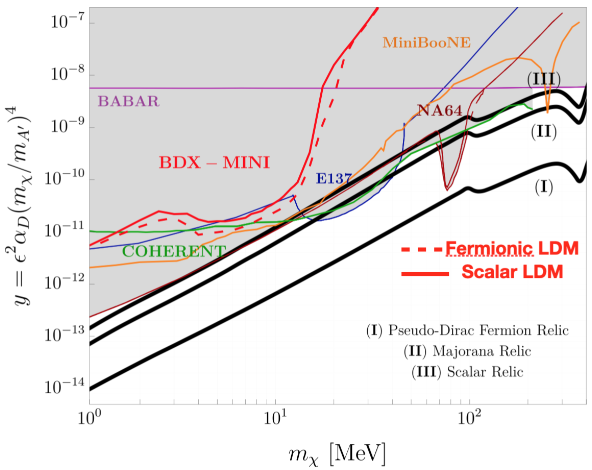
- PbWO4 -based EM calorimeter (44 crystals), SiPM readout
  - 0.15% of BDX active volume
- 8 mm passive Tungsten shielding
- 2 plastic scintillator active veto layers, SiPM readout

[a] M. Battaglieri et al., EPJ C 81(2021)164

BDX-MINI@JLAB: Results

- **Blind approach:** fix the selection cuts by optimizing the experiment sensitivity.
- Upper limit is derived in the LDM parameters space
- This pilot experiment[a] is sensitive to the parameter space covered by some of the most sensitive experiments to date.

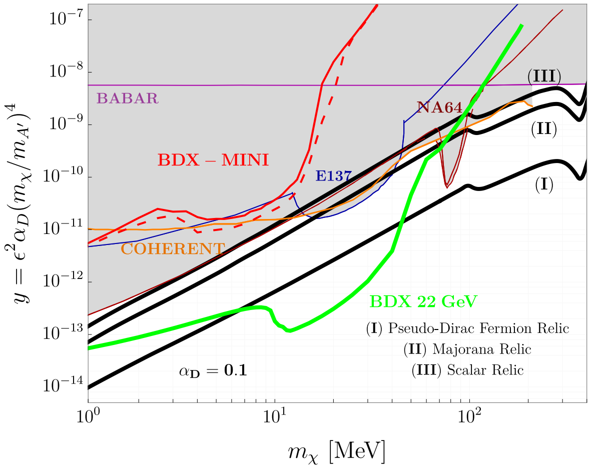
[a] M.Battaglieri and et al, Phys. Rev. D 106, 072011



BDX @ 22 GeV

- BDX@22 GeV[a] can complement BDX measure
- 90% CL BDX sensitivity:
  - Ideal case of a zero-background measurement
  - energy threshold: 300 MeV
  - an overall 20% signal efficiency.

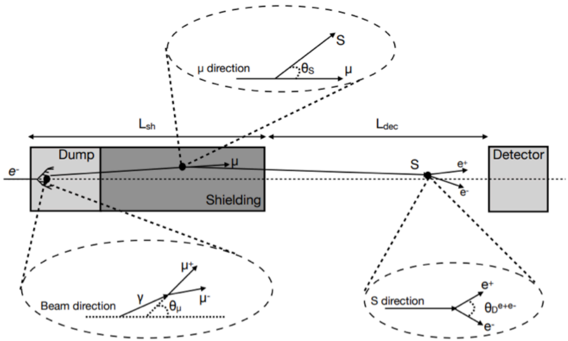
[a] arXiv:2306.09360

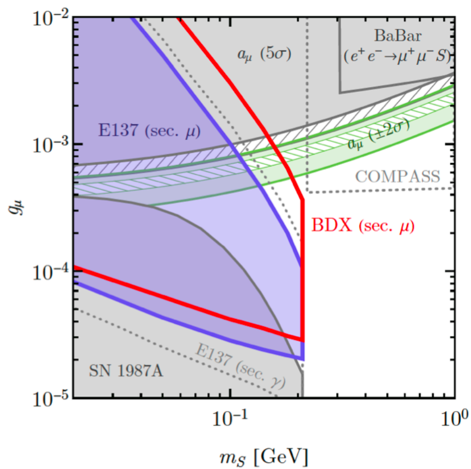


Probing muon-philic forces with seconday muon beam

- Sizable flux of high energy muons produced in a thick target by the interaction of the e- beam:
  - 11 GeV (22 GeV) e- hitting Hall-A beam dump: $3{\cdot}10^8\ \mu/\mathrm{s}$ ($\sim 2{\cdot}10^9\ \mu/\mathrm{s}$)
- Use the secondary muon beam to produce exotic particles accounting for g-2 anomaly

μBDX[2]: Muon beam dump experiment to probe the visible decay into e+e-($\gamma\gamma$)





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

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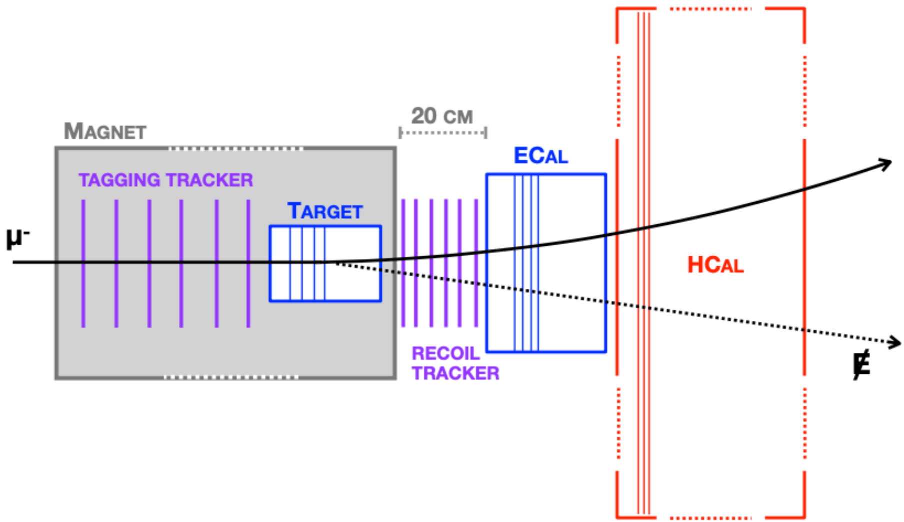
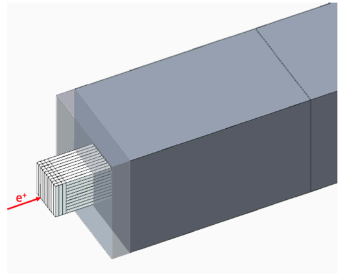
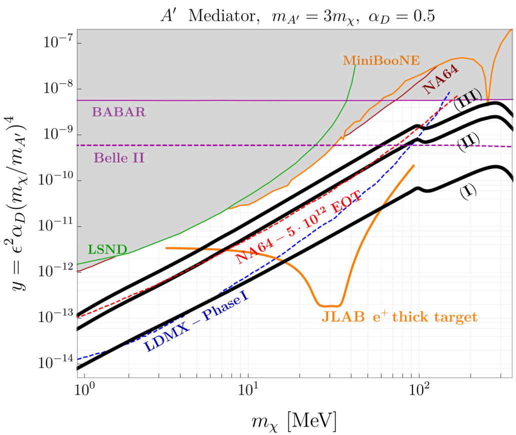
Fixed-target, missing-momentum search strategy to probe invisibly decaying particles (M3 experiment @Fermilab like)



LDM search using e^+ beam: Missing energy approach



- Missing energy[a] 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: $E_{miss} = E_{beam} \ E_{ECAL}$
- HCAL to detect neutral particles escaping the ECAL mimicking signal



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

Conclusions

- Jefferson Lab features a rich LDM experimental program (HPS, BDX-mini, APEX)
- New developments are expected in the nearby future: the Beam Dump eXperiment can run in the next few years provided the new hall is built
- The realization of a positron beam at Jefferson Lab paves the way to new competitive LDM experiments
- High-intensity muon secondary beam will complement the current program