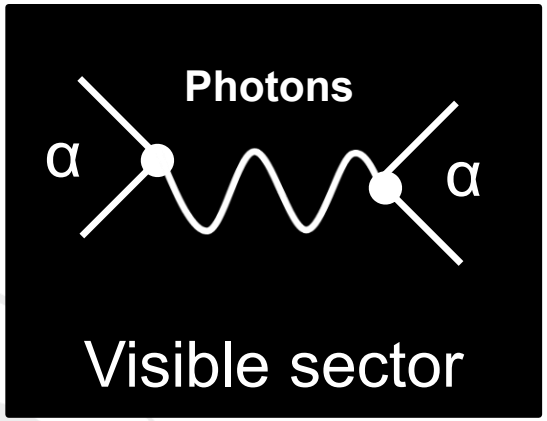
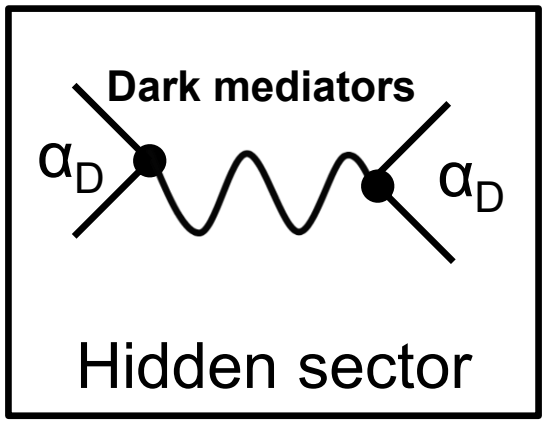
[Future] **Program of** [PRad and] **Dark Sector Searches at Jefferson Lab**

People have always been fascinated by what is hidden from their view and by what might be found inside objects

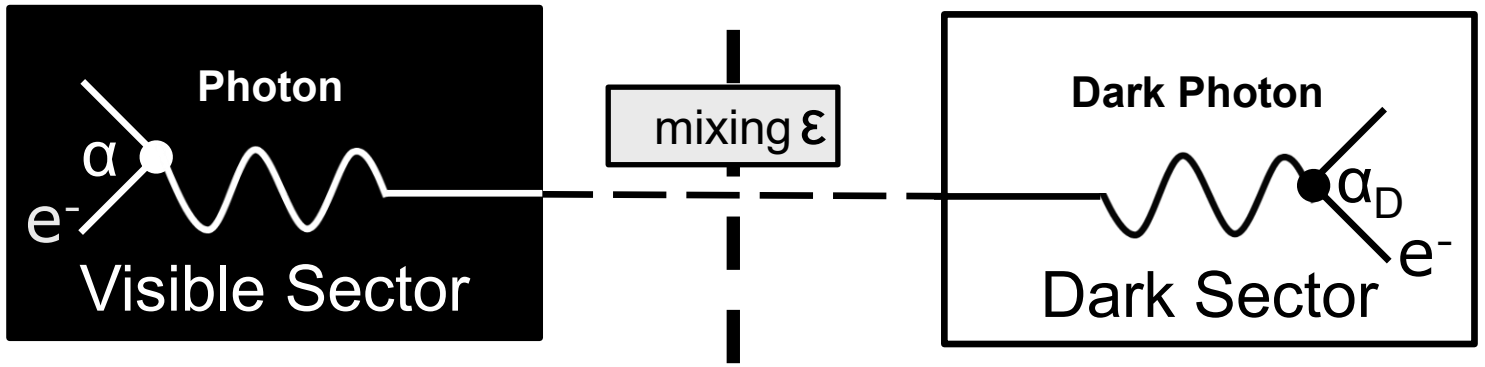


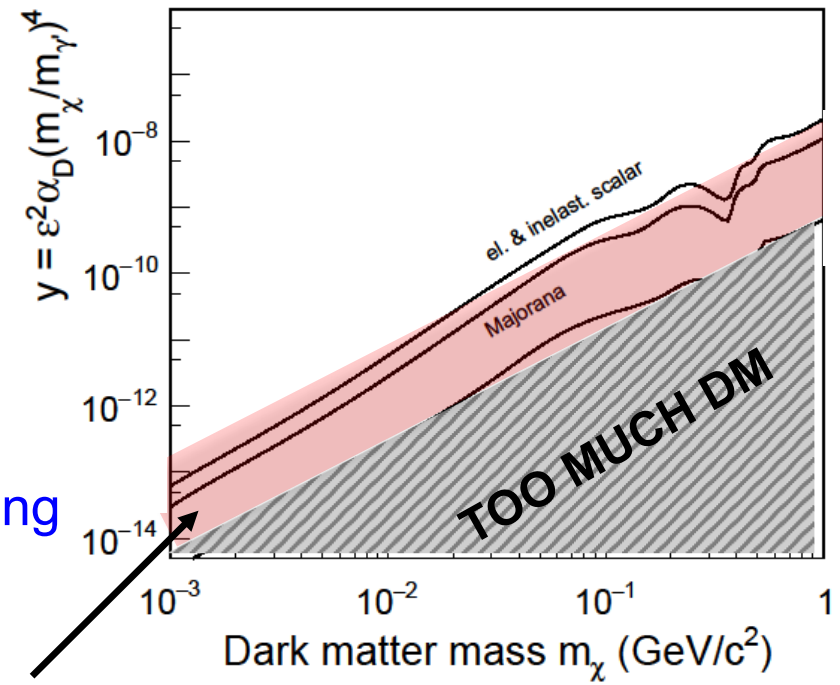


Patrick Achenbach
JGU Mainz
(formerly at JLab)

Oct. 2o25

Electrons as a Portal to Light Dark Matter





- *U(1)* gauge boson (dark photon)
- Dark photon as portal between DM and SM through kinetic mixing
- If Dark Matter was produced in the hot early Universe a known combination of unknown mass and unknown coupling relates to the known Dark Matter density today: **thermal targets**

$$\langle \sigma_{\text{annih}} v \rangle \sim \frac{g^4}{2\pi m^2} \simeq 6 \times 10^{-37} \text{cm}^2 \left(\frac{g}{0.1}\right)^4 \left(\frac{m}{100\,\text{GeV}}\right)^{-2}$$

A Light Dark Sector can be probed with high-intensity electron beams with experiments exploring a well-defined parameter space including testable targets

Dark Photon Searches with Electrons

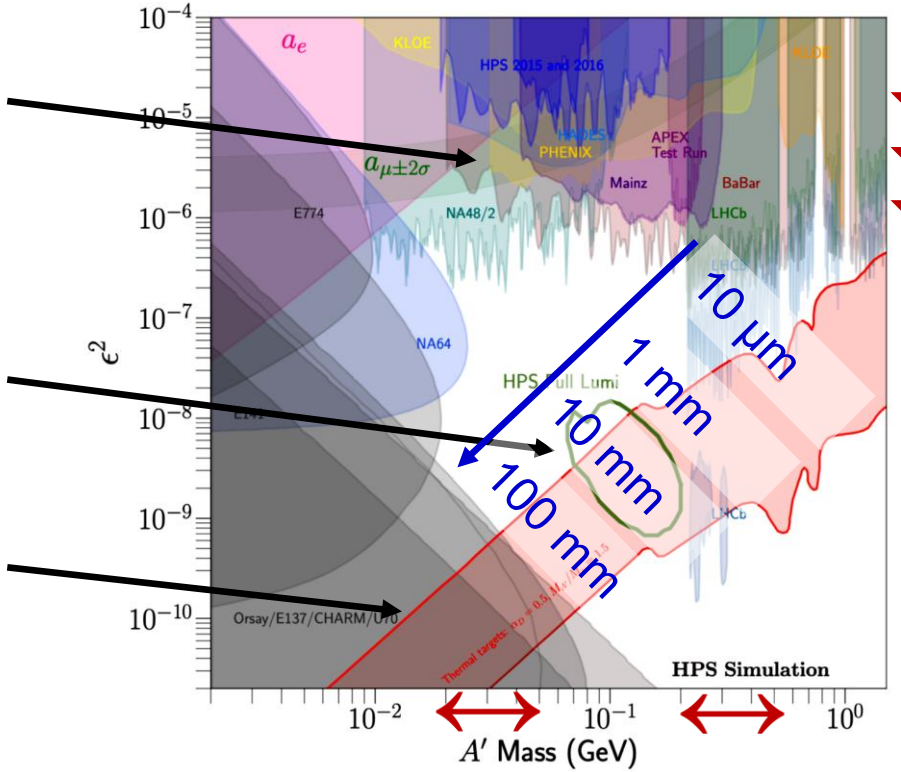
Probing Sub-GeV mediator and sub-GeV Dark Matter particles

Prompt A' bump hunts in e^+e^- invariant mass spectrometry

$$\gamma c\tau \propto \frac{1}{\epsilon^2 m_{A'}^2}$$

Displaced A' *O*(10 mm) bump hunt vertexing experiments

Very long-lived A' *O*(100 m) beamdump experiments

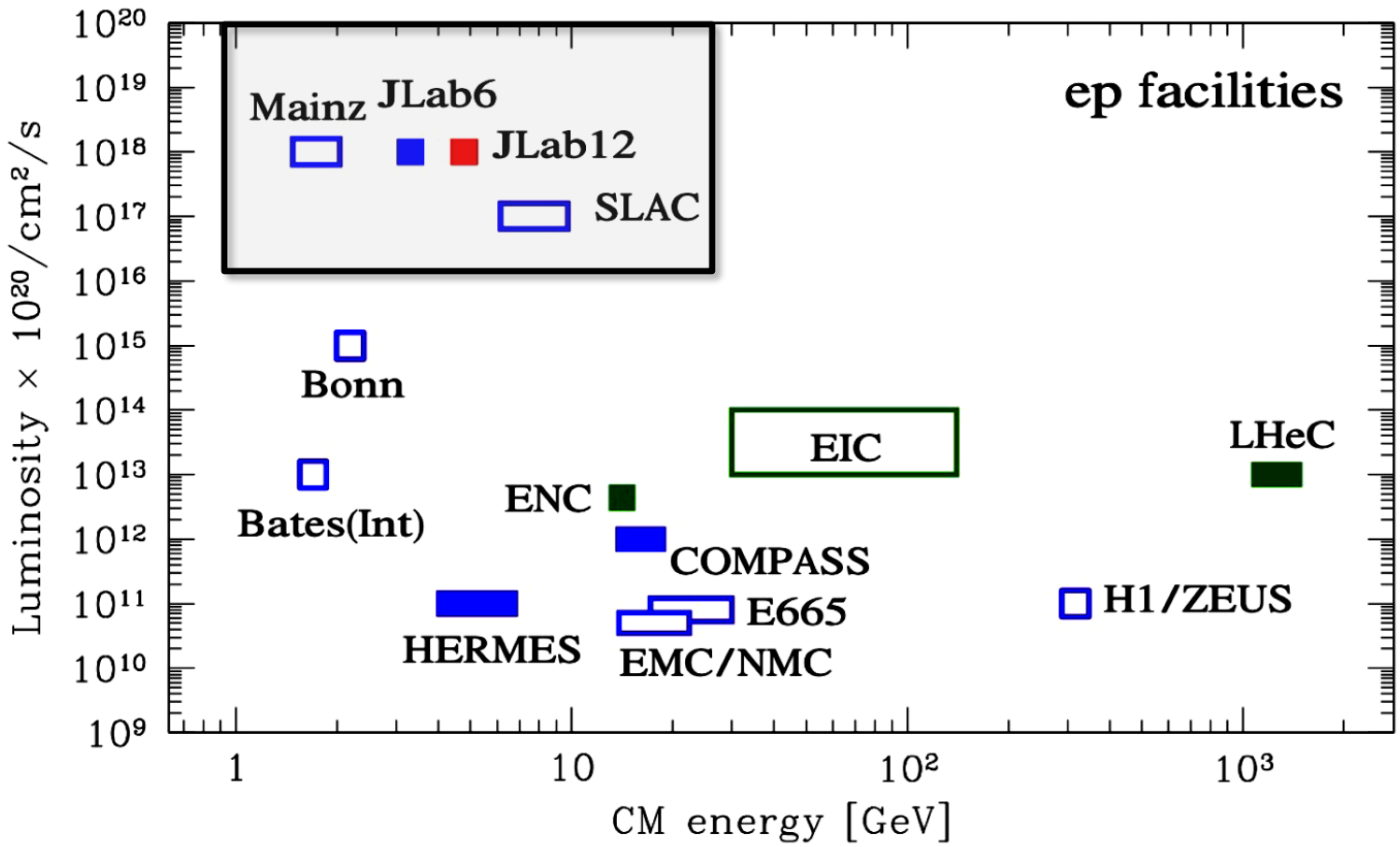


Sensitivity to thermal targets needs high-intensity beams

MeV mass scale requires MeV-to-GeV beams and keV-to-MeV resolutions

Such searches live in the realm of existing hadron physics facilities

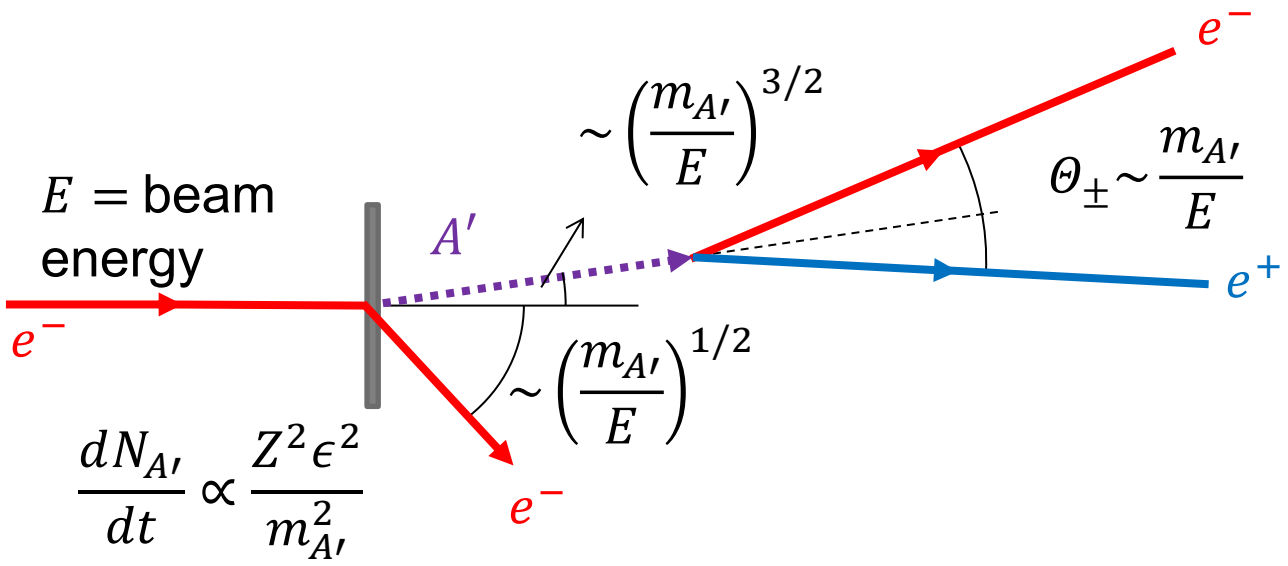
Luminosities of Electron Beam Facilities



MAMI, MESA, CEBAF, and SLAC at the high-luminosity frontier

→ **Pioneering bump hunt at MAMI** [H. Merkel et al., PRL 106, 251802 (2011)]

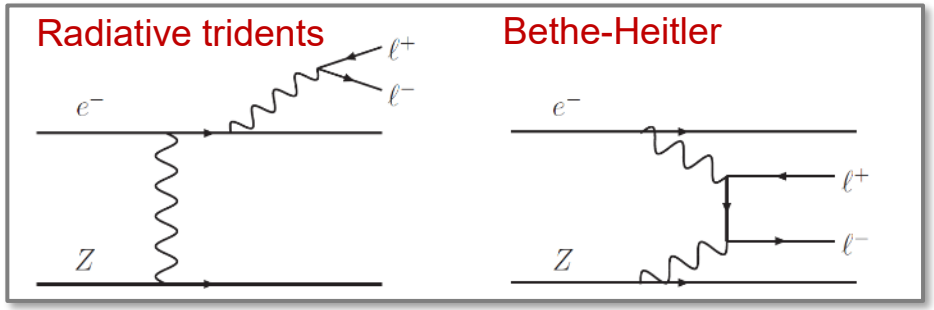
Dark Photon e^+e^- Visible Decay Searches



Concept of experiments

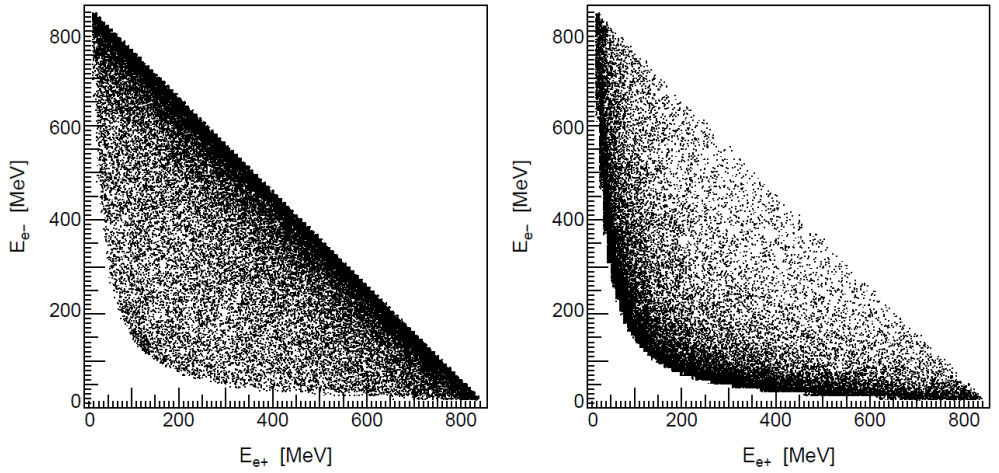
- 4-vector determination of e^+ and e^-
- Coincidence timing between two detection arms
- Reconstruction of invariant mass spectrum

Back-grounds:



A' electro-production

- *A'* is emitted in forward cone → Detection symmetrically in forward detection
- *A'* carries away most of electron's energy → Energy sum near beam energy
- In any *A'* search unavoidable subtraction of continuous QED background



Dark Matter Searches at Electron Beam Dumps

Primary target

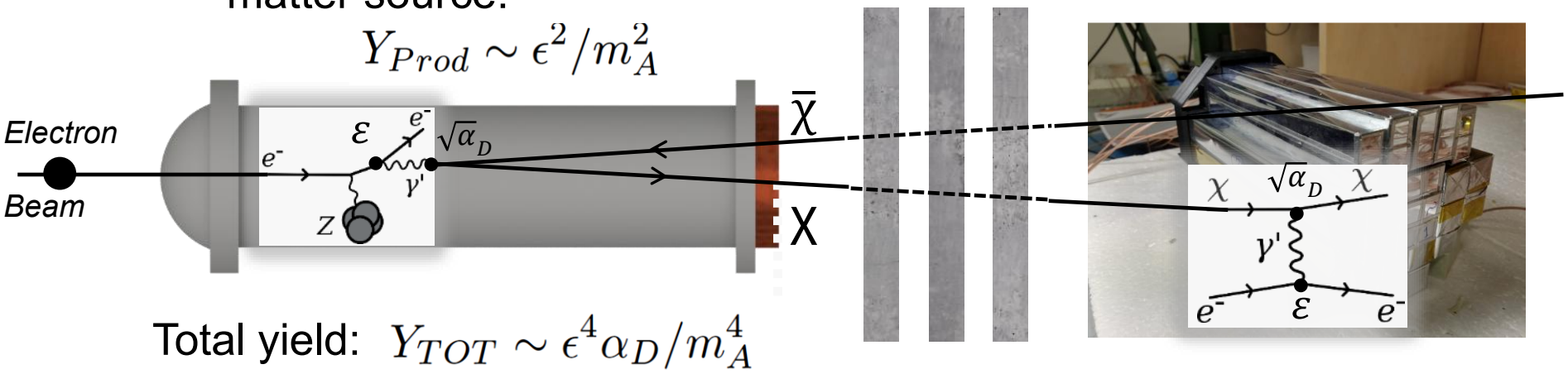
Beam dump = high energy and high intensity dark matter source:

$$Y_{Prod} \sim \epsilon^2/m_A^2$$

Lead wall and dirt

Scattering in detector:

$$Y_{Det} \sim \epsilon^2 \alpha_D / m_A^2$$



Total yield: $Y_{TOT} \sim \epsilon^4 \alpha_D / m_A^4$

- Radiative (or annihilative) production of (massive) dark photon *A'* with ε
- Subsequent decay to SM particle pairs with ε or dark matter pairs with α_D
- For $m_{A'} > 2\, m_\chi$ invisible decay channel dominant: $\Gamma(A' \to \bar{\chi}\chi)/\Gamma_{\text{total}} \simeq 1$

Allows searches in low-mass regime with large numbers of EOT

Dark Sector Searches with MeV-to-GeV-Energy, Fixed-Target Electron and Positron Beams

Selection of experiments:

- No e^+e^- collider expts. (BaBar, BESIII, …)
- No very-early expts.
- No meson decay expts.
- *Apologies for missing ones*

Expts. color code:

- A' visible decay searches
- A' invisible decay searches
- Dark matter/sector searches

Facilities color code:

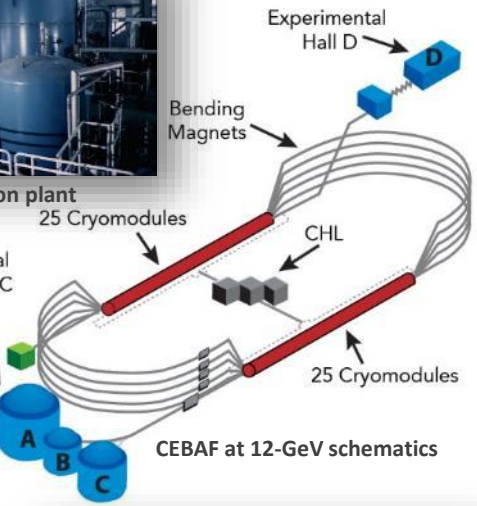
- Jefferson Lab in VA,US
- MAMI/MESA in Mainz, GER

Experiments…	***Beams/Facilities…***
Old:	
SLAC E137 (re-analyzed)	e- at SLAC
Recent:	
A1 (completed)	e- at MAMI/Mainz
APEX (completed)	e- at Jefferson Lab
BDX-MINI (completed)	e- at Jefferson Lab
HPS/HPS (partially completed)	e- at Jefferson Lab
PADME (running)	e+ at Frascati
Near Future:	
PRad X17 Search (scheduled)	e- at Jefferson Lab
HPS/HPS (to be scheduled)	e- at Jefferson Lab
BDX (approved, needs infrastructure)	e- at Jefferson Lab
MAGIX/MAGIX (under construction)	e- at MESA/Mainz
DarkMESA (under preparation)	e- at MESA/Mainz
Far Future:	
A' Search (conditionally approved)	e+ at Jefferson Lab
Lohengrin (under preparation)	e- at ELSA/Bonn
LDMX (under preparation)	e- at SLAC

Dark Sector Experiments at Jefferson Lab

Jefferson Lab Operating the 12-GeV CEBAF

Refrigeration plant



CEBAF at 12-GeV schematics

Superconducting niobium RF cavities

Cryomodules in the accelerator tunnel

Recirculation arcs

Linearly pol. photon beam

A

B

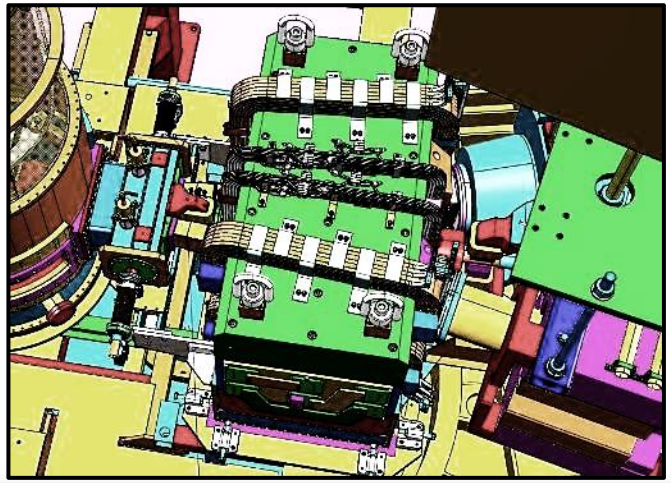
C

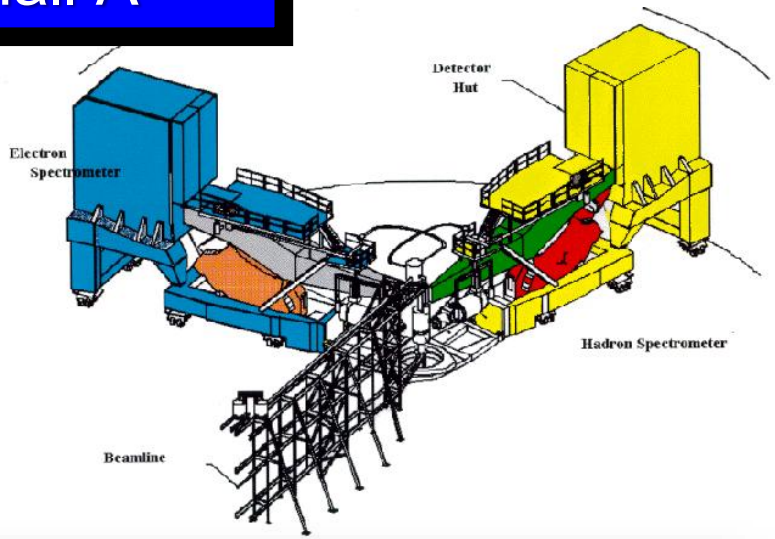
D

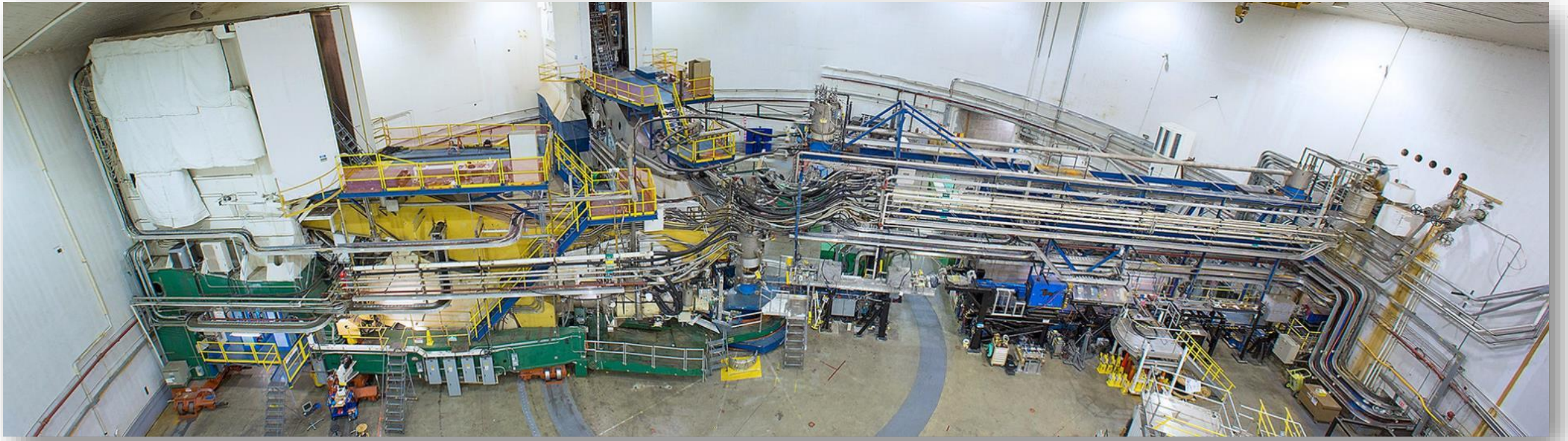
3 electron beams, cw, E_{max}= 10.6 GeV, P ~ 90%

Dark Photon Search in Jefferson Lab Hall A

- Using two QQDQ High-Resolution spectrometers: Right and Left HRS
  - $\Delta p/p = 10^{-4}$, $\Delta\Omega$ = 6 msr
  - Angular range $\theta = 12.5° - 150°$
  - Septum to access $\theta < 12.5°$



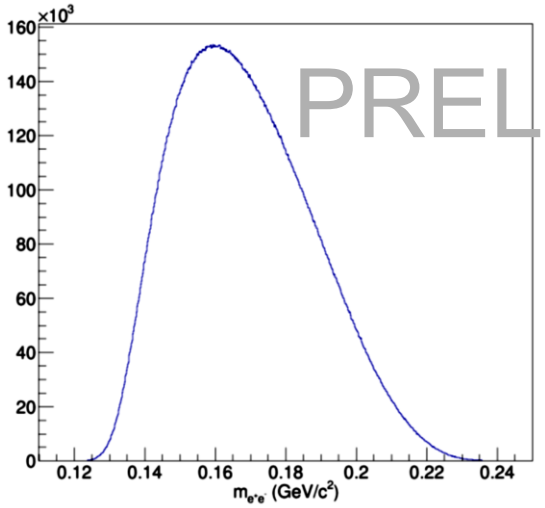


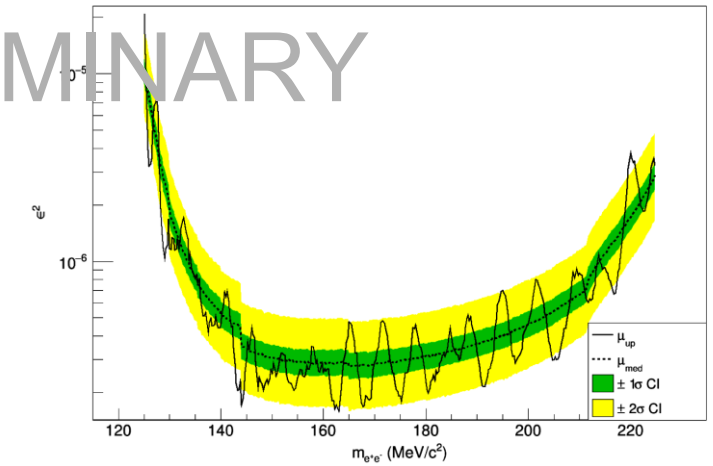


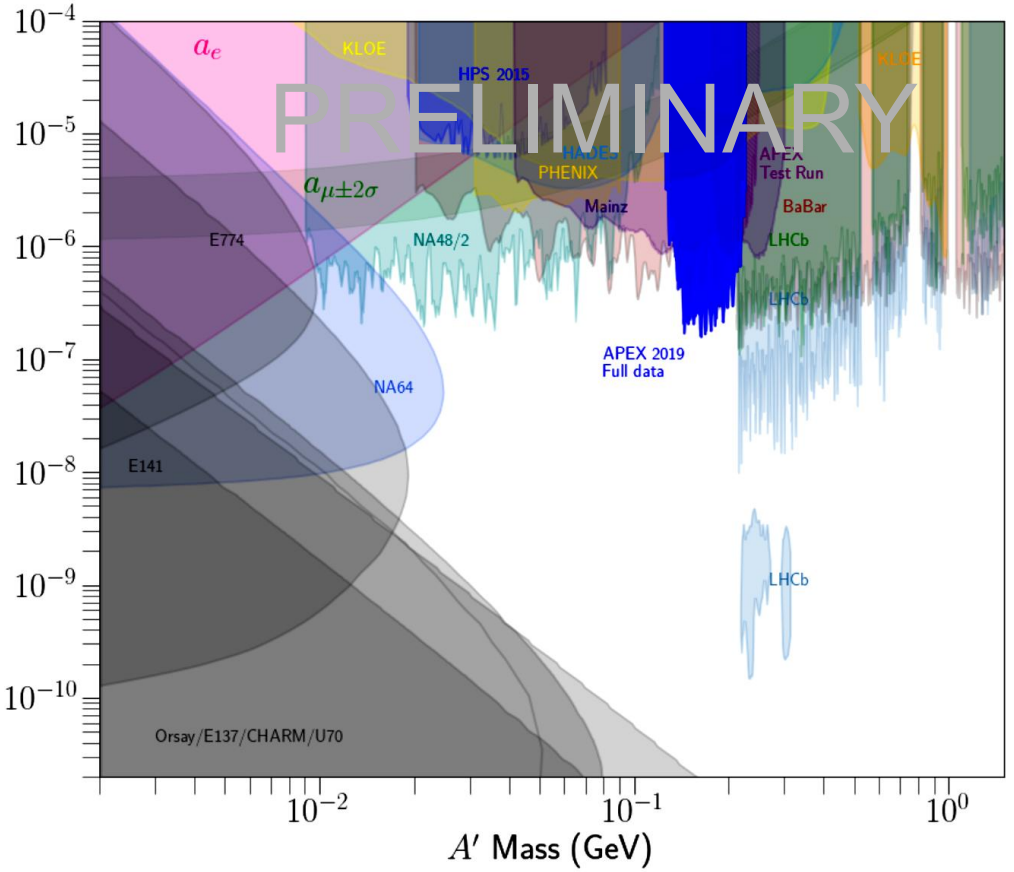
APEX Preliminary Results

Bump search in the invariant mass spectrum

- Reconstructed invariant mass of e+e- pairs:
  - ~ 7.7 x 10^5 events in 2010 test run
  - ~ 5.6 x 10^7 events in 2019 run



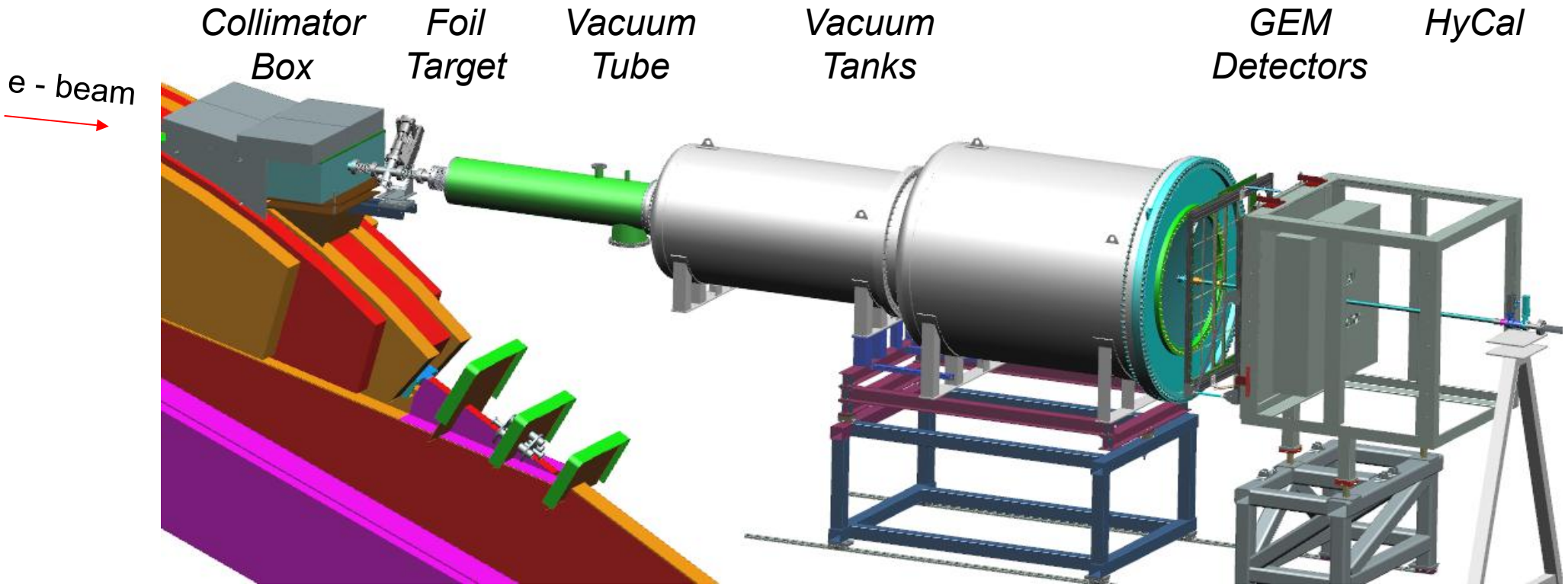




X17 Search in Jefferson Lab Hall B

Experimental setup based on existing PRad equipment

- Thin foil target (1 μm Ta)
- Large vacuum tanks to minimize scattering
- Two planes of GEM detectors for tracking
- HyCal calorimeter for electron/positron detection



Experimental Method and Analysis Strategy

Electroproduction on heavy nucleus in forward directions

- $e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta$, with $X \rightarrow e^+e^-$ (with tracking)

  and $X \rightarrow \gamma\gamma$ (without tracking)

  in mass range of 3 - 60 MeV/c^2

- Detection of all final state particles
  - Scattered electron e' with 2 GEMs and $PbWO_4$ calorimeter
  - Decay e^+ and e^- with 2 GEMs and $PbWO_4$ calorimeter
  - Decay $\gamma\gamma$ pair with $PbWO_4$ calorimeter and anti-coincidence in GEMs

  → full control of kinematics

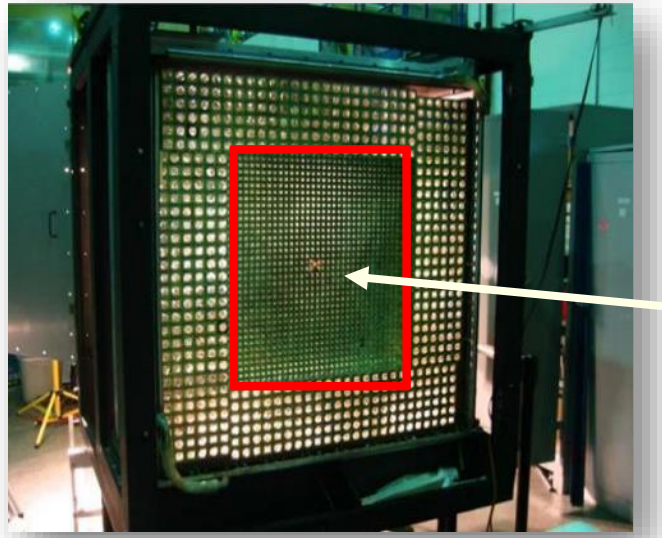
  → full control of background

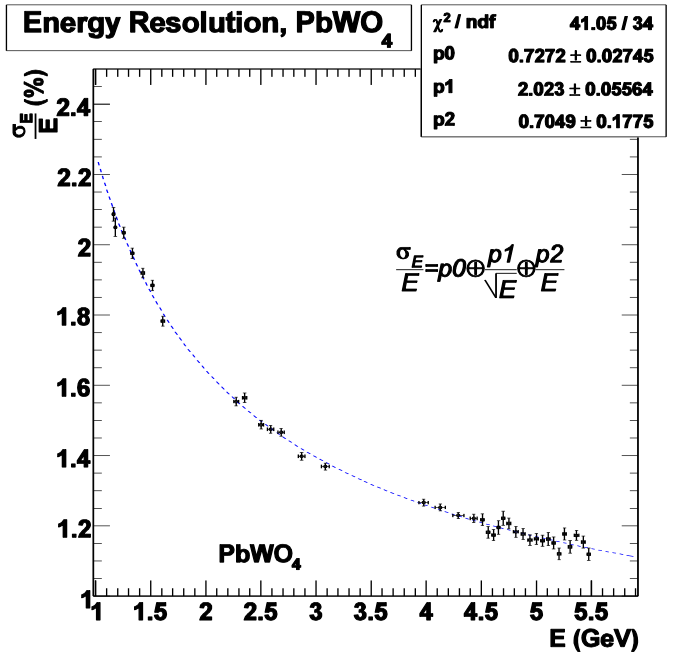
- Bump hunting in invariant mass spectrum over SM background

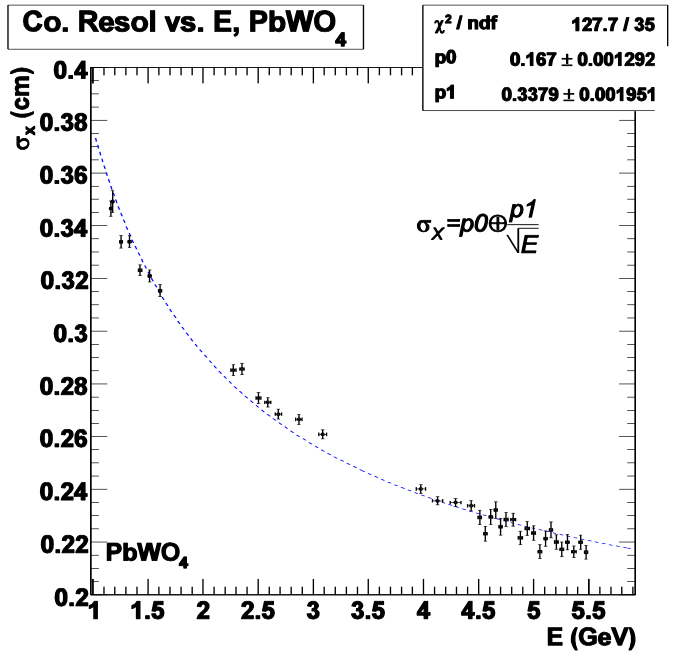
Electromagnetic Calorimeter

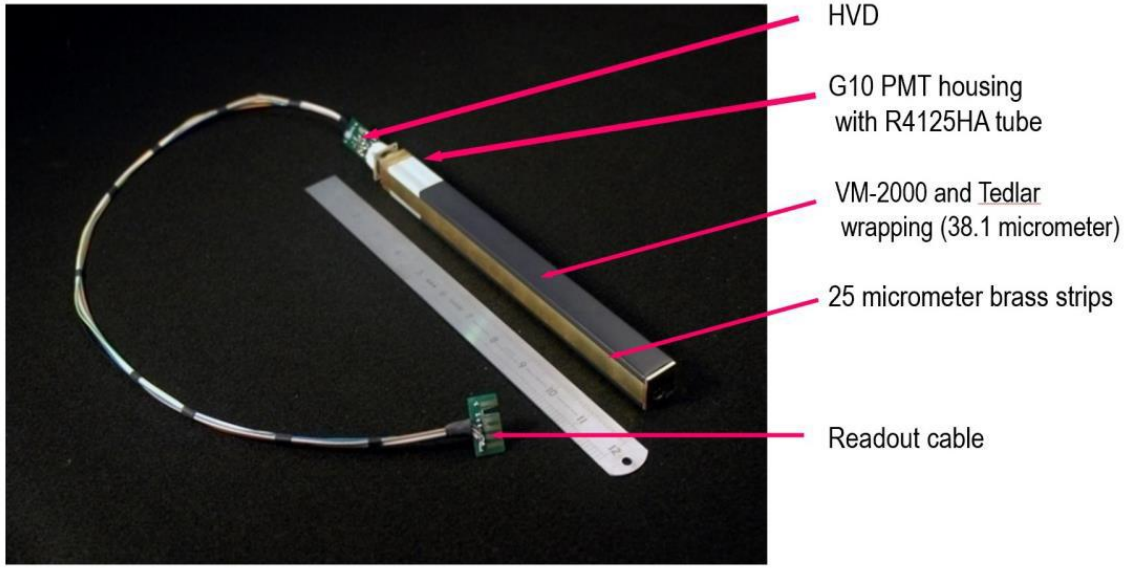
Hybrid Calorimeter HyCal from PrimEx

- 34 x 34 =1156 $PbWO_4$ modules, each 2 x 2 x 18 cm^3
- 68 x 68 cm^2 total detection area
- 2 x 2 or more crystals removed for beam passage
- New Flash-ADC readout electronics









Two Planes of Large-Area GEM Detectors

Tracking of Charged Particles

- Located in front of $PbWO_4$ behind vacuum window
- Optimized relative distance of 40 cm for resolution
- Position resolution of σ = 72 μm
- Electronics based on APV-25 readout system

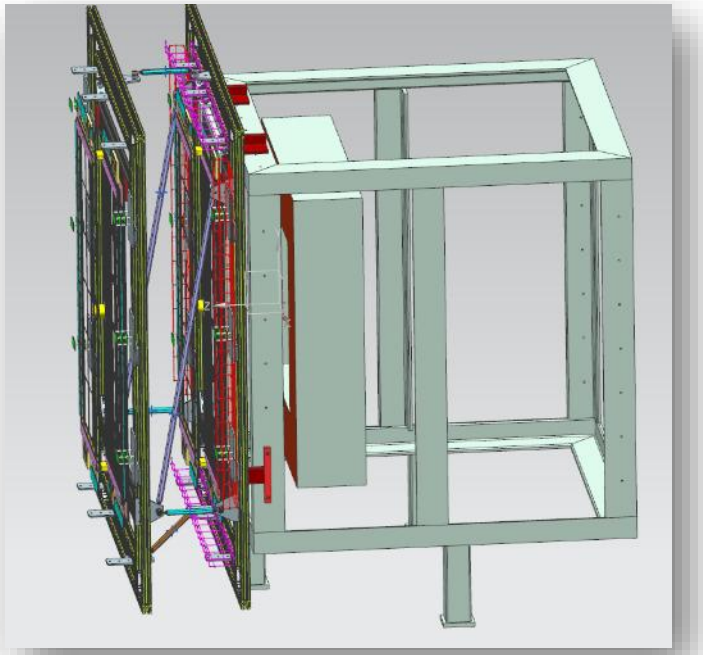
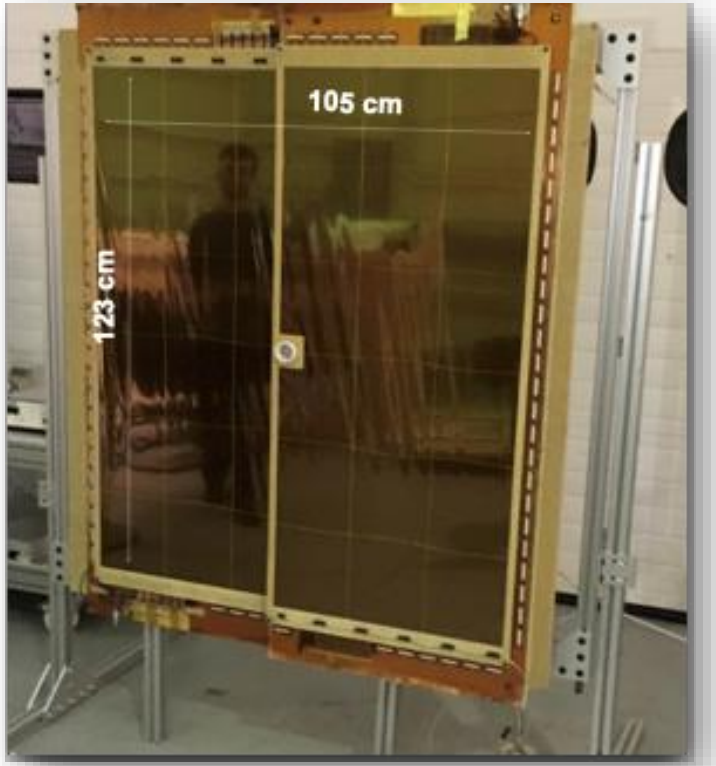


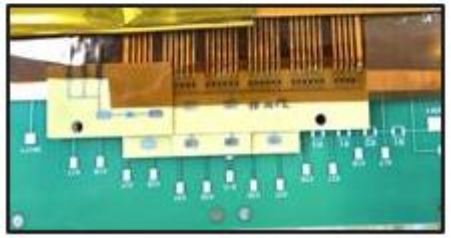
Photo of the old (!) GEMs



GEM Detector Construction Status

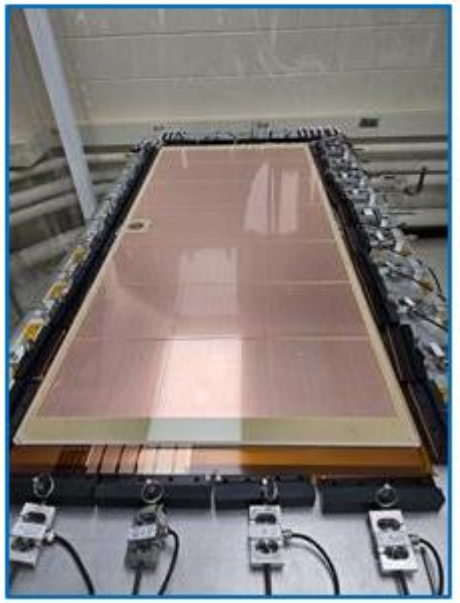
- Two planes (4 layers) of **newly constructed and characterized GEMs**

Procurement

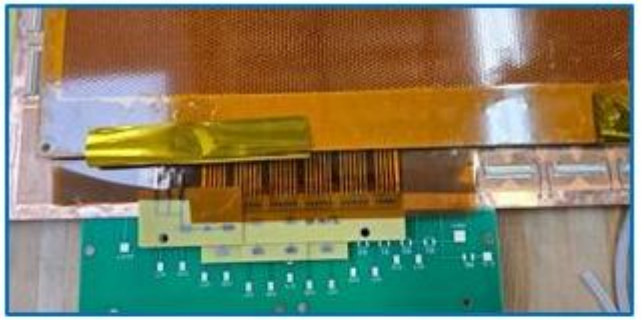


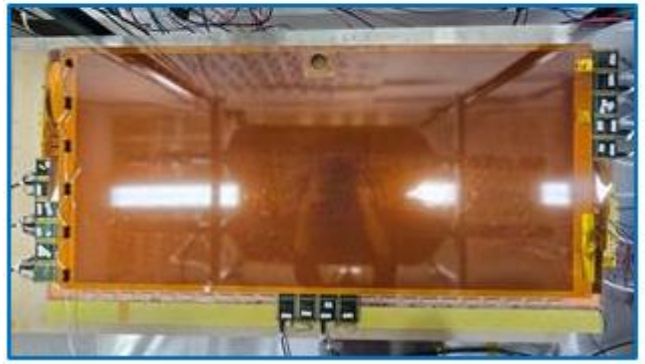
Pre-cleanroom activities

Cleanroom activities



Post-cleanroom activities





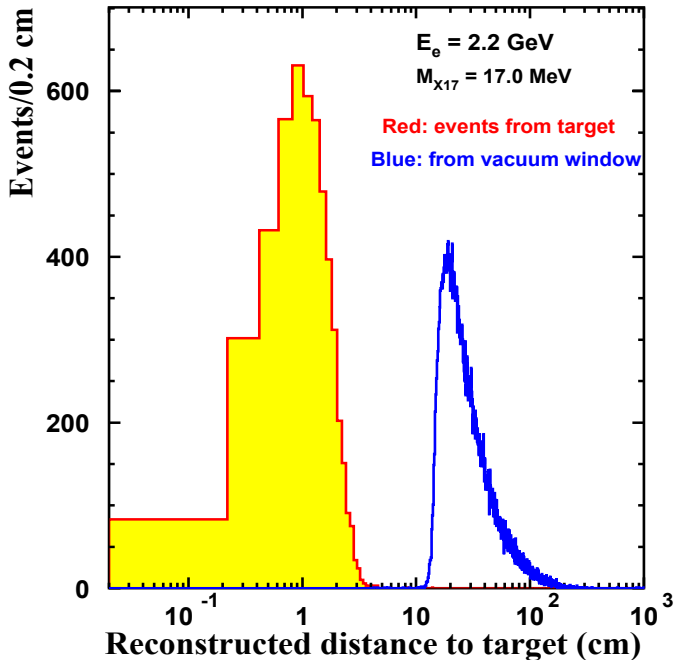
- Frames
- Foils
- Honeycomb plates

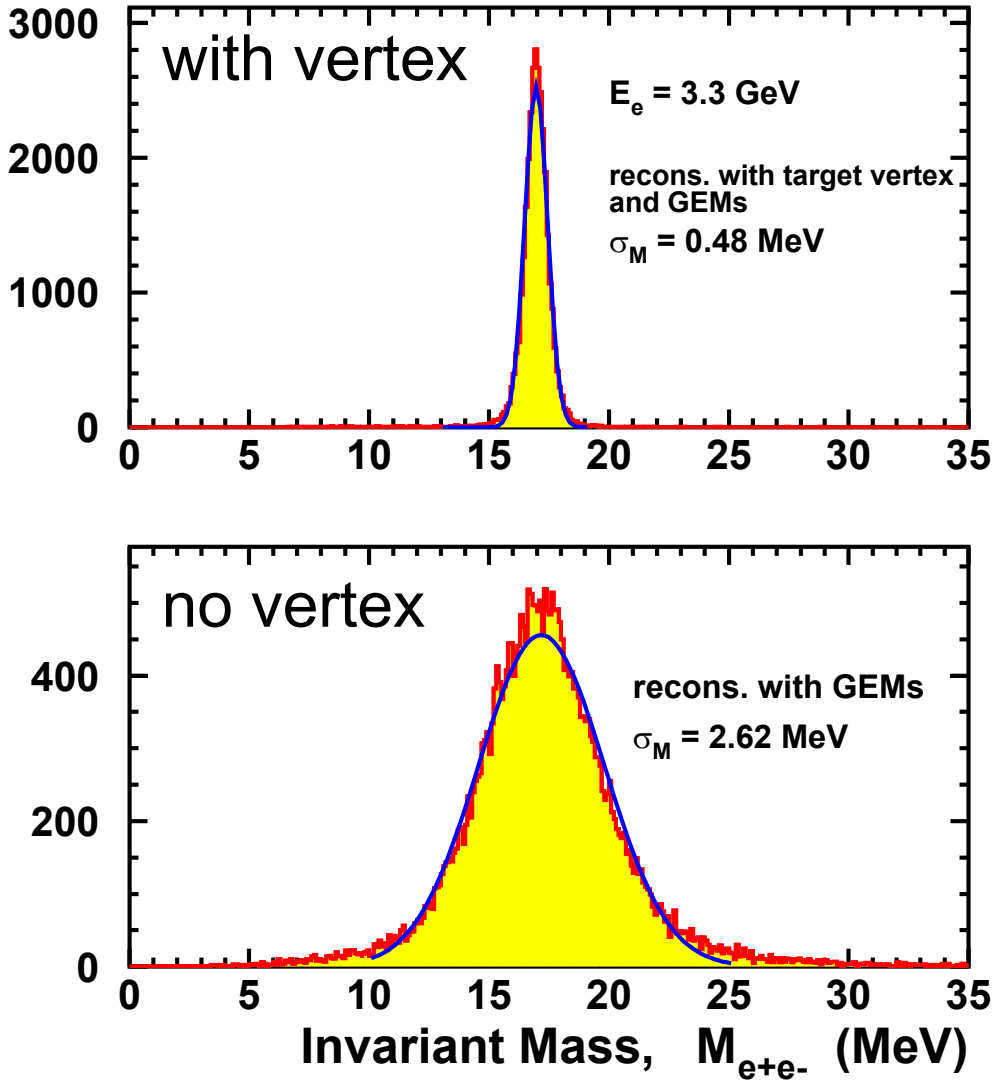
DAQ was tested at UVa with 25 kHz event rate

Invariant Mass and Vertex Resolutions

Invariant mass reconstruction

- Vertex, GEMs and $PbWO_4$ calorimeter σ_m =0.48 MeV/c^2 for X17 particle
- Two GEM planes (with $PbWO_4$) discriminate events not originating from the target
- GEMs do not to measure the “decay length”

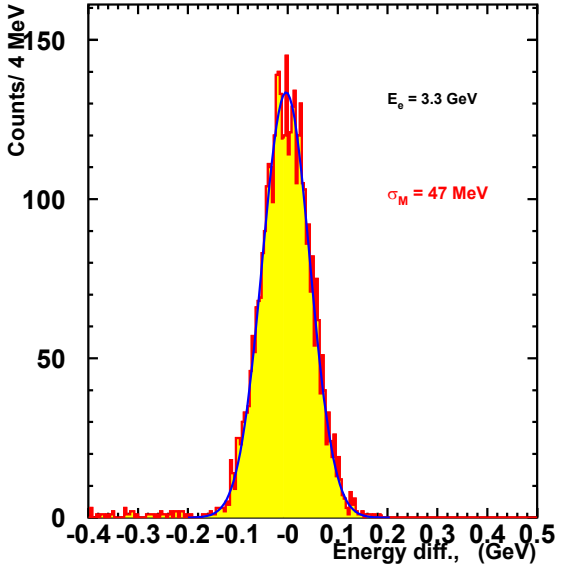




Energy Sum and Angular Resolutions

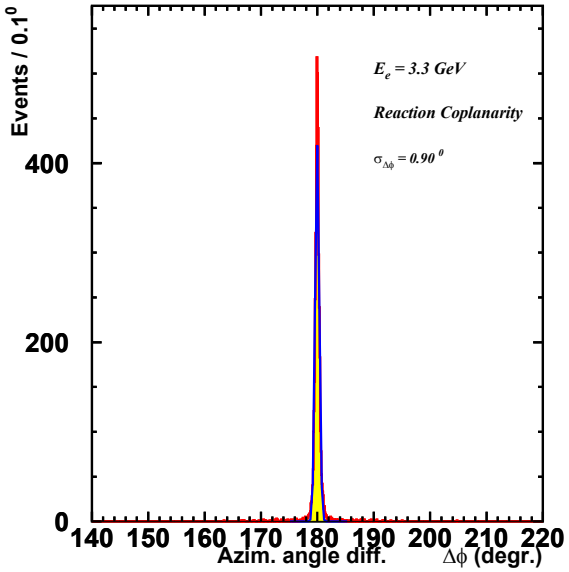
- Energy resolution of $PbWO_4$ (2.6% @ E = 1 GeV) and 1μm thin target provide tight energy selection cut:

  σ_E = 47 MeV @ 3.3 GeV beam



- GEMs position resolution (σ = 72 μm) and the 1 μm thin target provide tight coplanarity criterion:

  $\sigma_{\Delta\varphi}$ = 0.9 between $\vec{p}_{e'}$ and ($\vec{p}_{e+}$ + $\vec{p}_{e-}$)

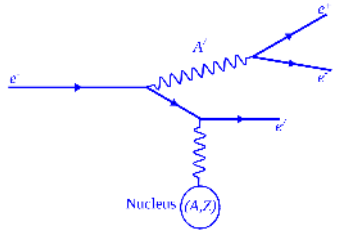


Physics Background Simulations

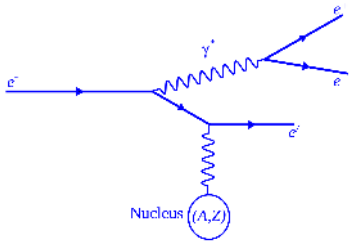
Physics background was simulated in two different ways:

1) GEANT4 based Monte Carlo background simulations
   - PRad experimental setup
   - Physics processes from GEANT package
   - Large statistics of beam electrons incident on target
   - Events with $N_{cluster} \geq 3$ analyzed in same way as signals

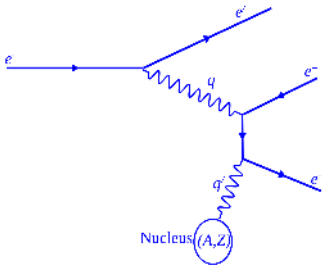
2) MadGraph5 EM event generator background simulations
   - Large statistics (~2M) of radiative trident events
   - Events were fed into the GEANT MC simulation
   - Same analysis procedure was applied for these events



X production channel



Radiative tridents



Bethe-Heitler

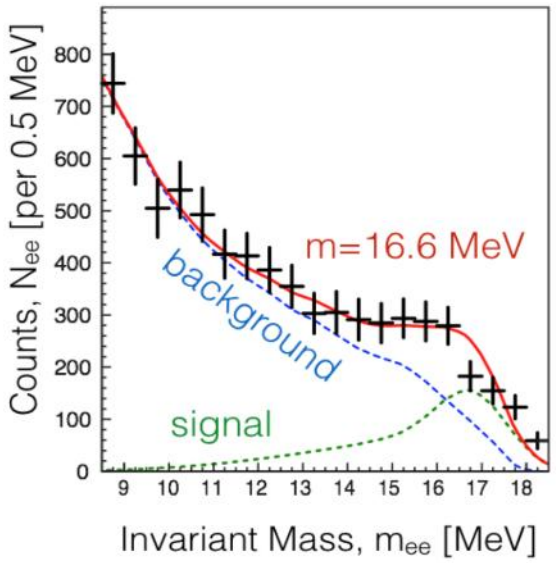
Kinematic Goal of X17 Search Experiment

Search for hidden sector mediators in the 17-MeV/c^2 mass range

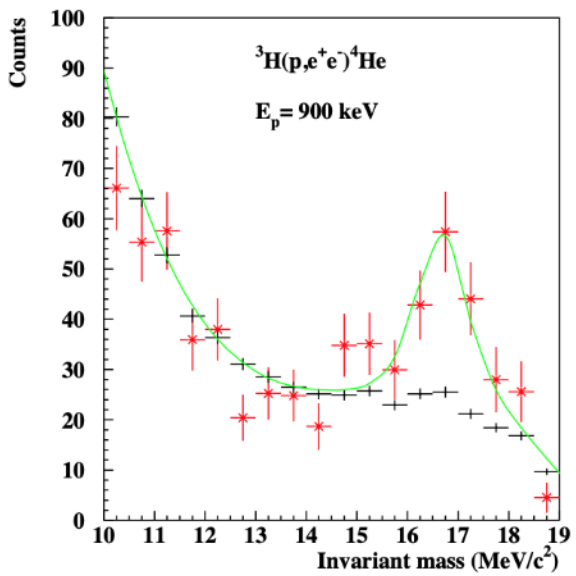
Observed anomaly: excess of e^+e^- pairs in ^{8}Be*, ^{4}He* and ^{12}C* decays

- Suggested explanation: hypothetical X17 particle
- Requires independent experimental verification

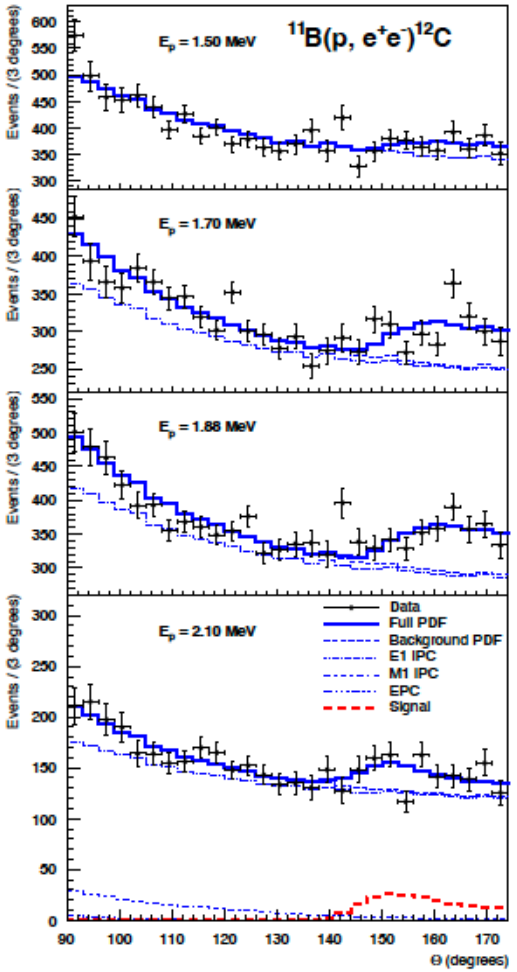
PRL 116, 042501 (2016)



PRC 104, 044003 (2021)

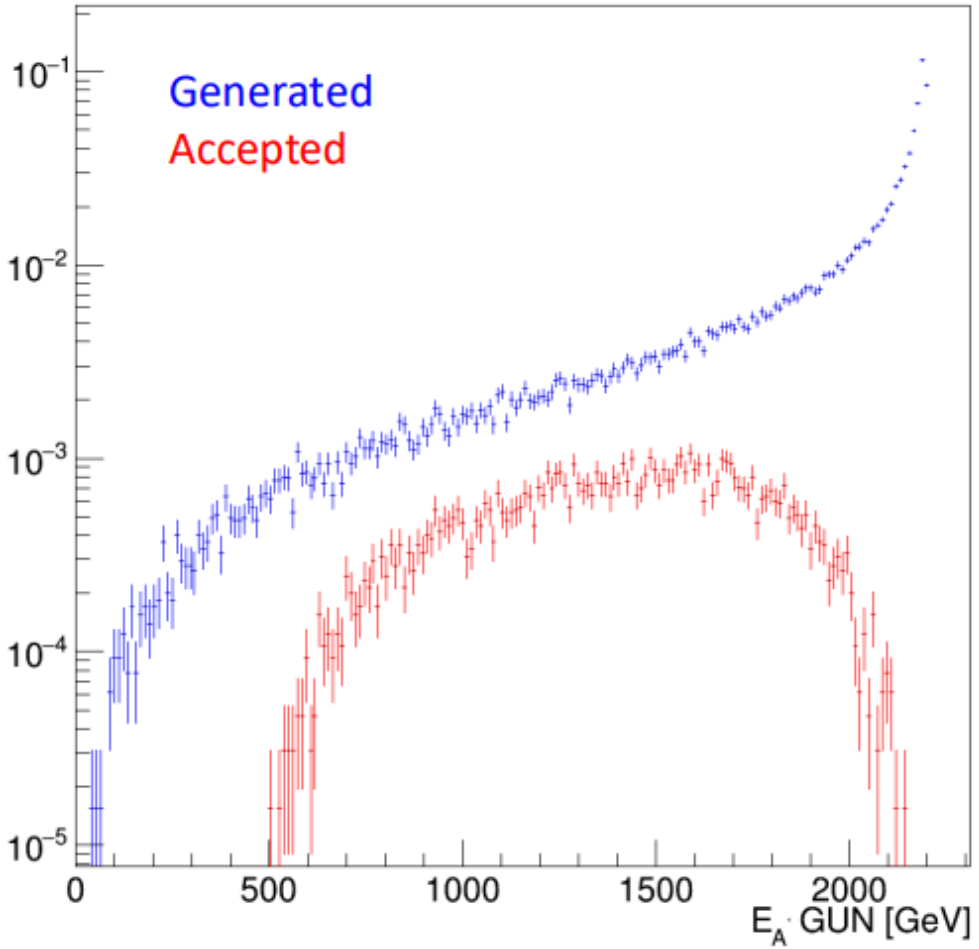


PRC 106, L061601 (2022)

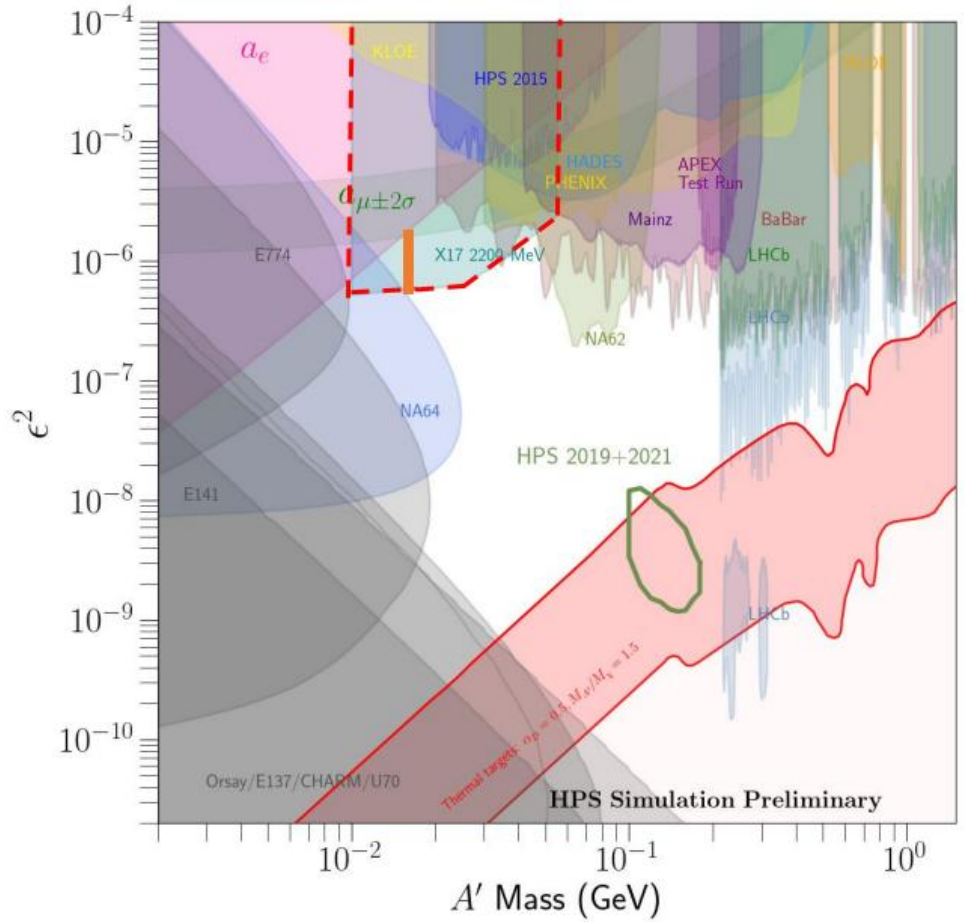


Reach Projection of X17 Search

M = 17 MeV

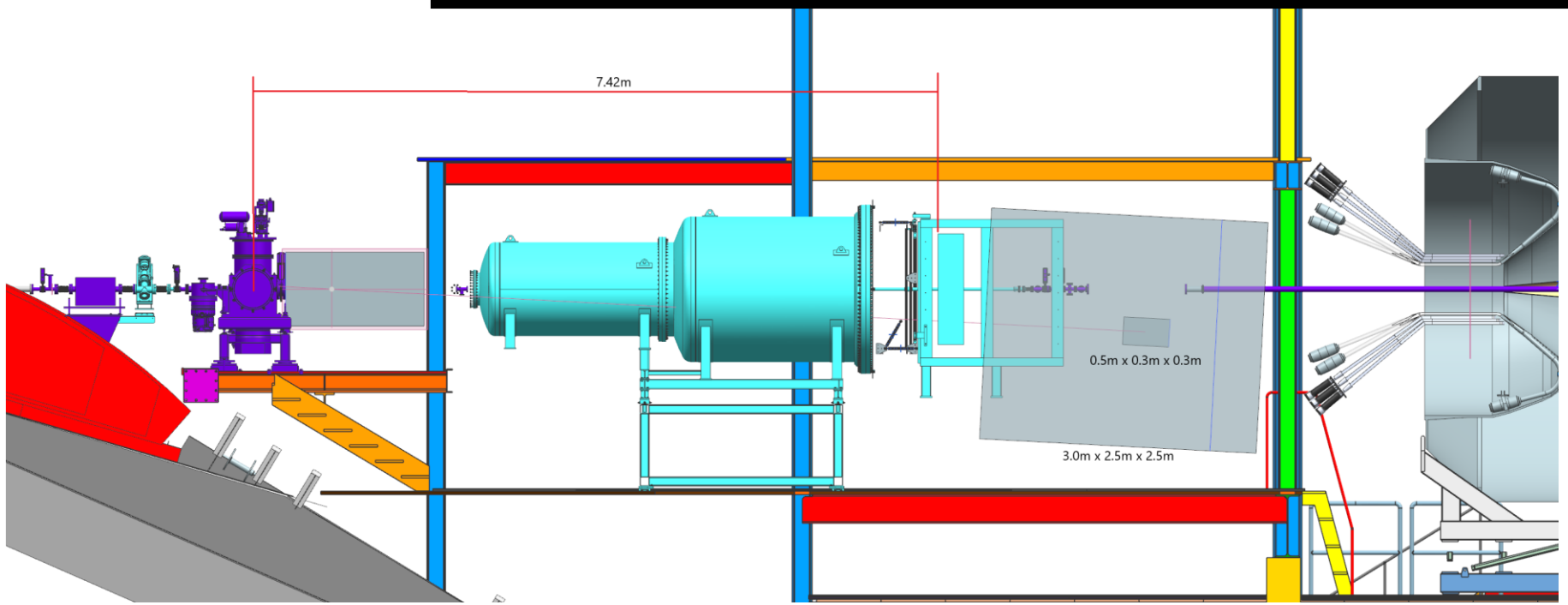


E_{beam} = 2.2 GeV; I_{beam} = 50 nA; 40 PAC days



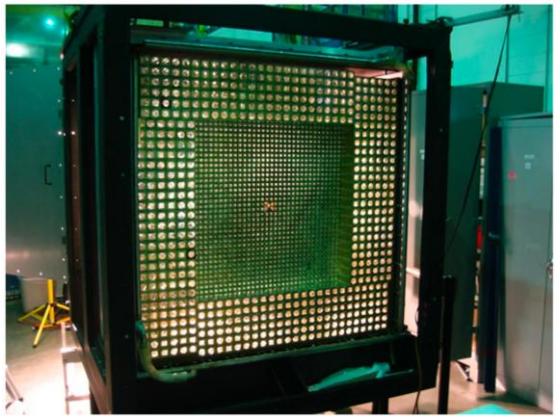
Experiment excludes or validates X17
for masses 3 − 60 MeV and couplings $\varepsilon^2 \approx 5\times10^{-7}$–$10^{-6}$

Positron Annihilation in Jefferson Lab Hall B



A' Search with Ce+BAF

- 50 nA positron beam, energy of 2.2, 4.4, and 11
- GeV 5-cm-long target of liquid hydrogen
- Detection of photon from $e^+ + e^- \rightarrow A' + \gamma$ with HyCal
- Setup includes sweeper magnet and beam dump

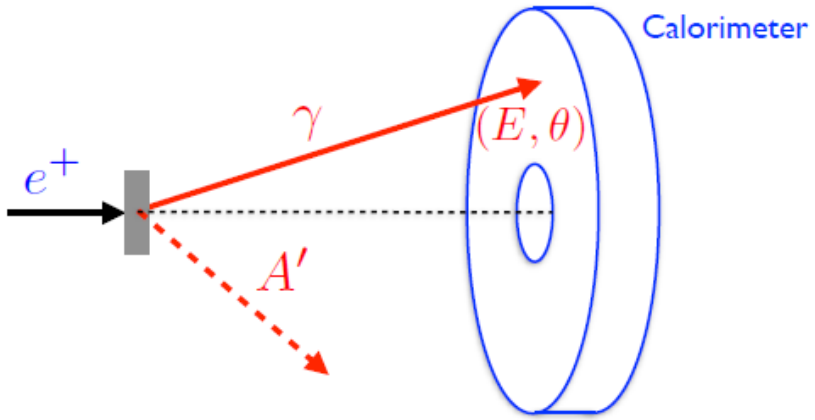


Reach Projection for Invisible Decay Search

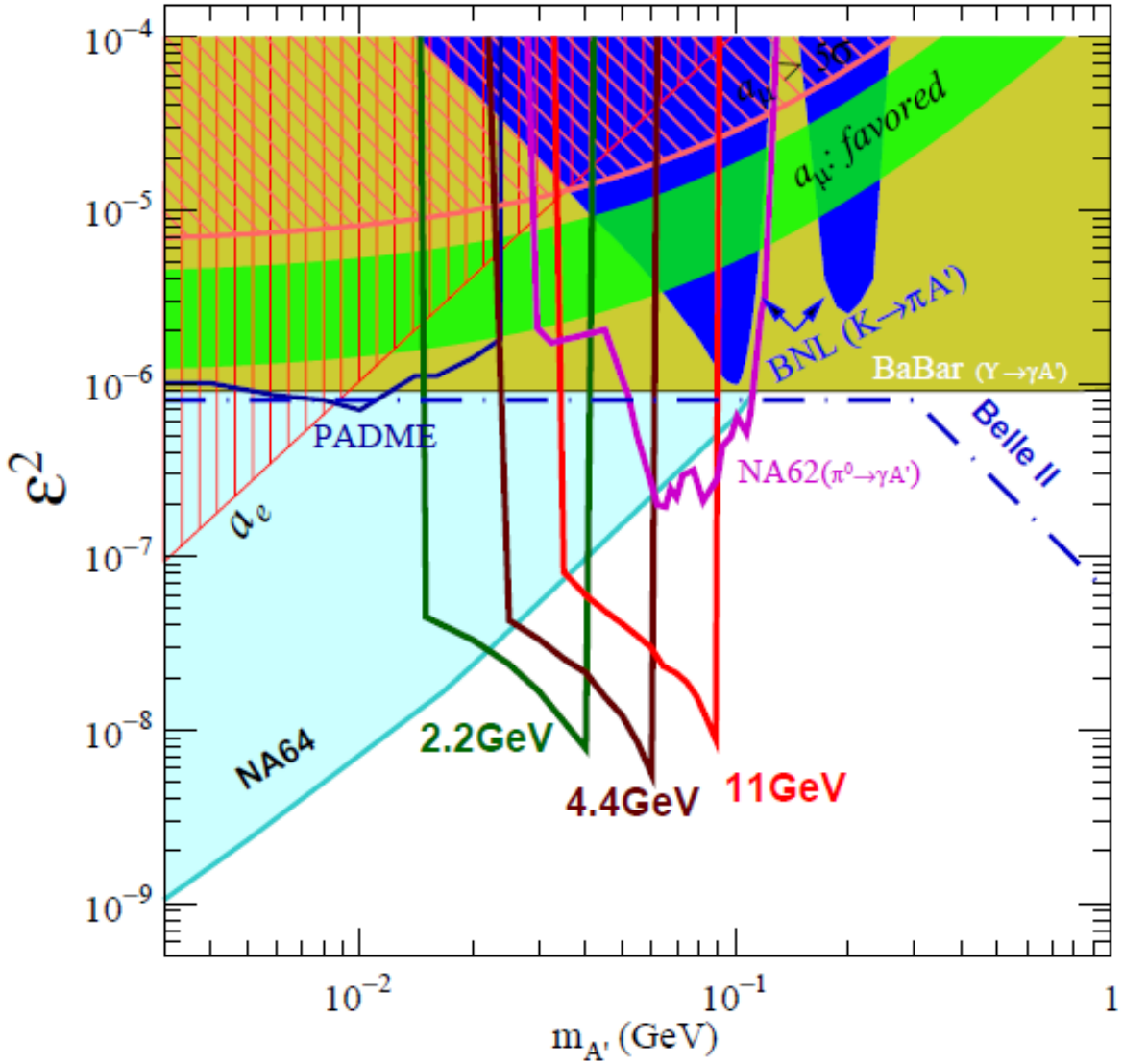
A' search

- Mass range from 15 to 90 MeV
- Sensitivity reaches ε ≥ 10^{-4}
- Sensitivity does not depend on coupling of A′ to quarks or possible semi-visible decay

$$e^+e^- \to \gamma + X$$

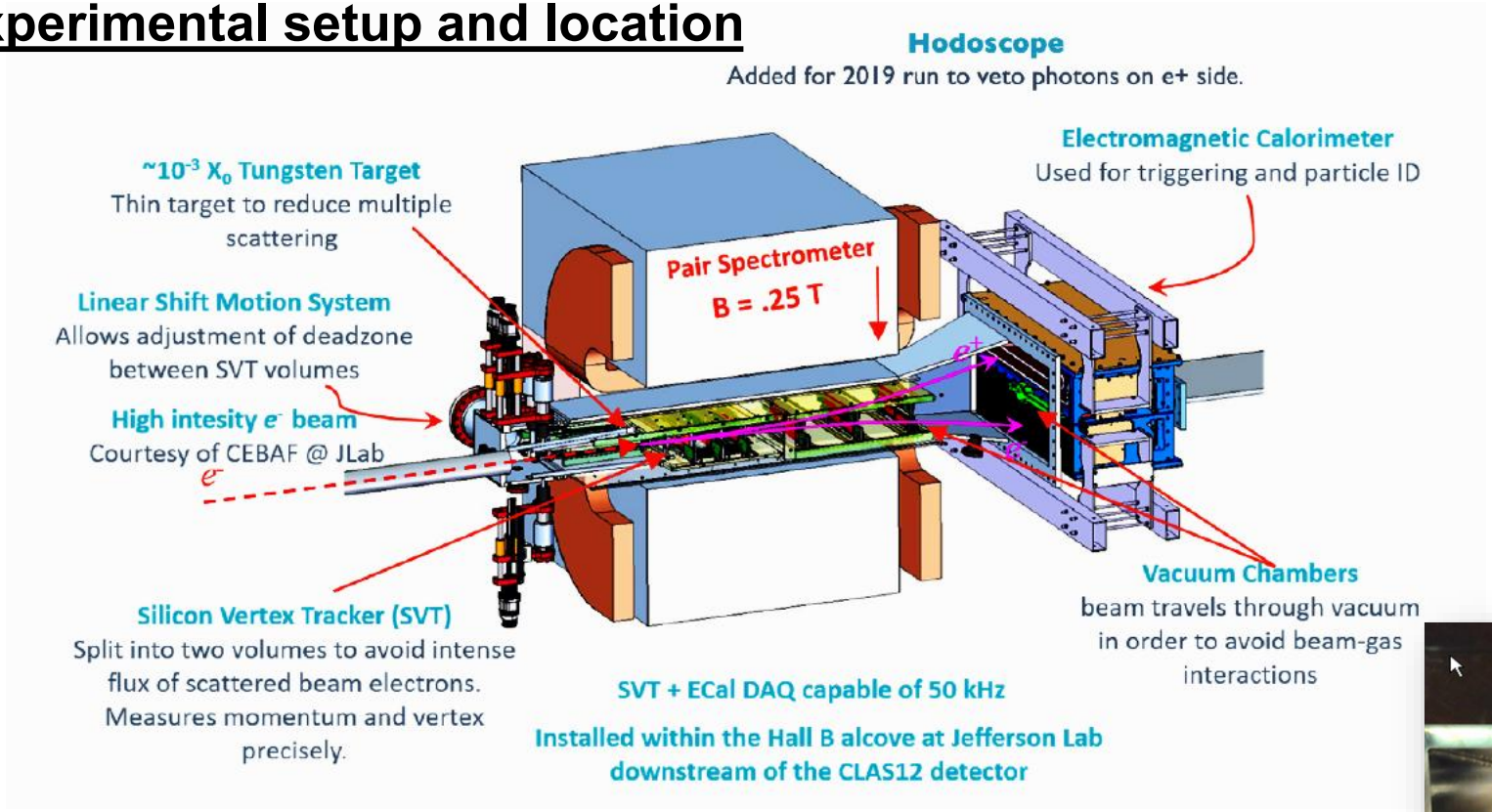


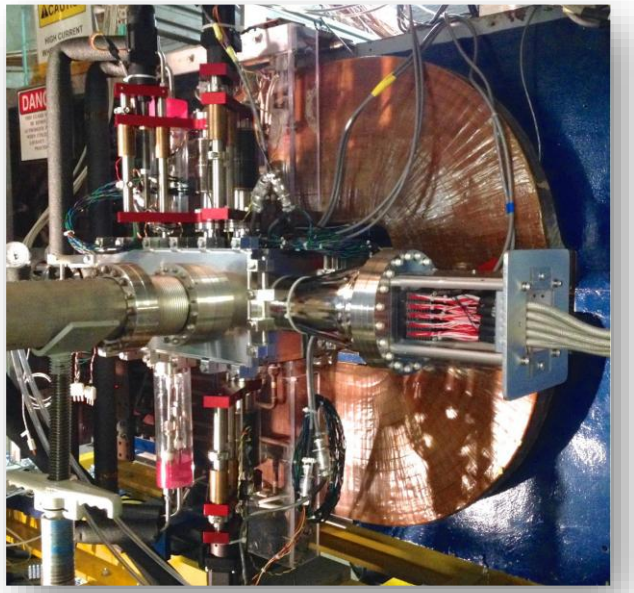
$$M^2_{\rm rec} = 2m_e\left(E_+ - E_\gamma(1+\frac{E_+}{2m_e}\theta^2_\gamma)\right)$$

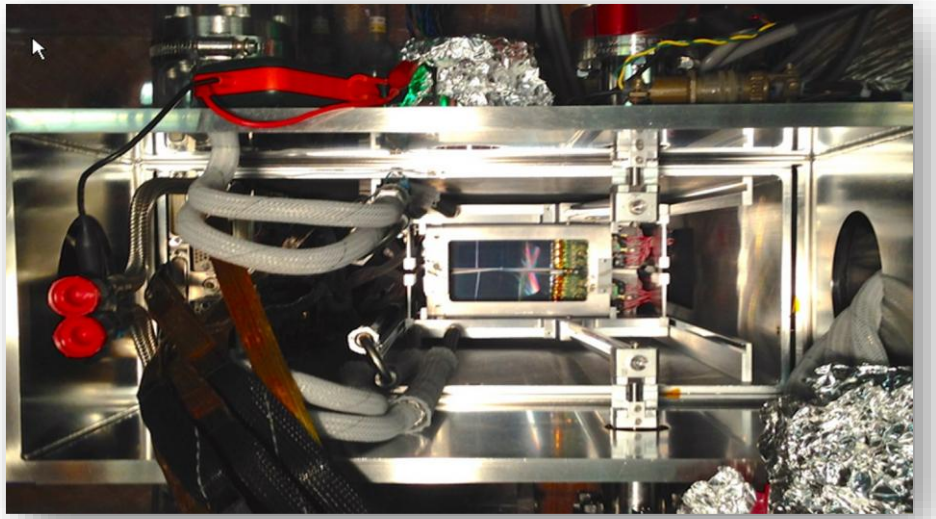


HPS Experiment in Jefferson Lab Hall B Alcove

Experimental setup and location





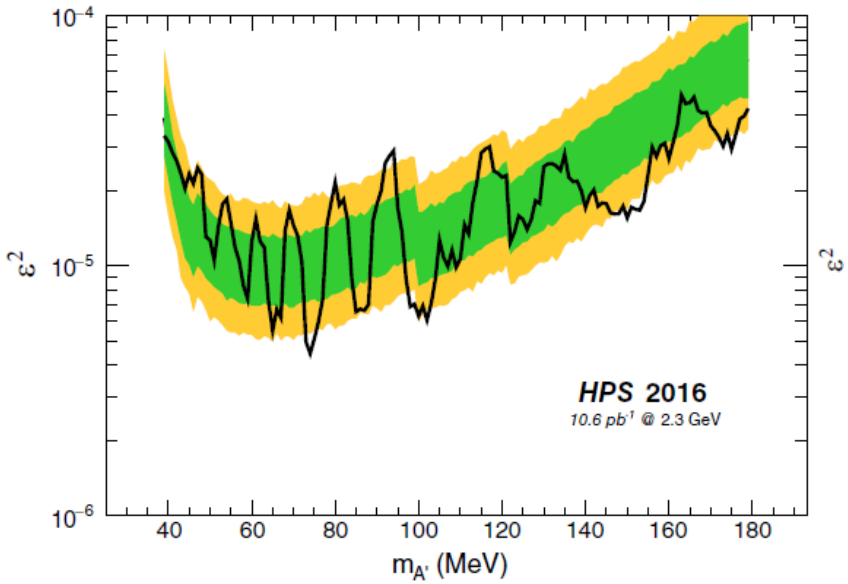


HPS Results

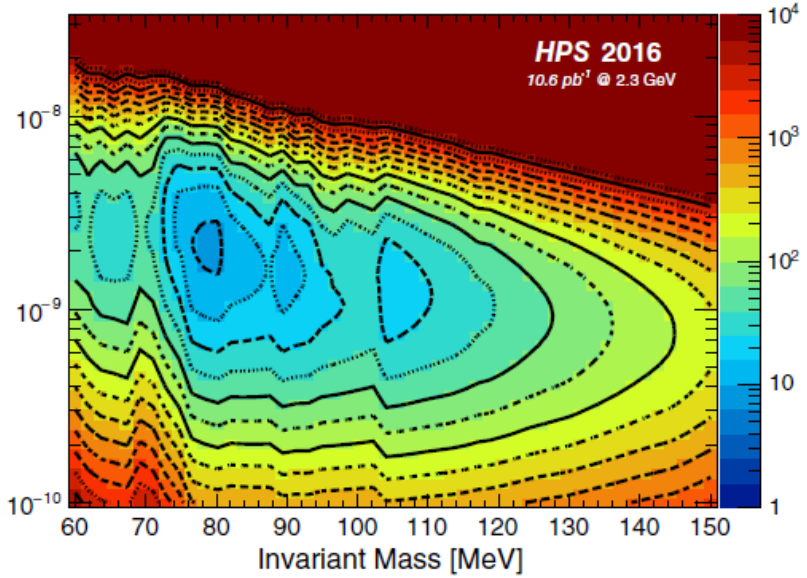
Minimum A' Searches

- Engineering run 2016: ~5 d at 2.3 GeV (most analyzed dataset)

Bump hunt



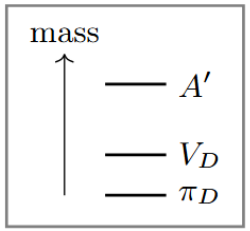
Displaced vertex search

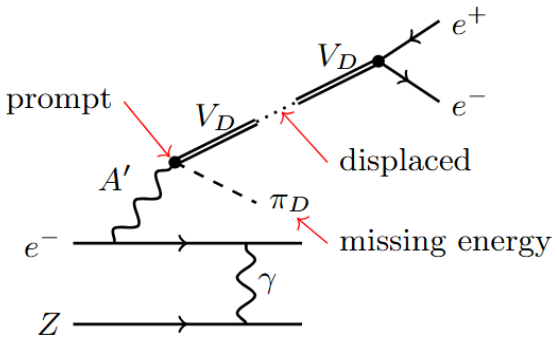


[Phys. Rev. D 108, 012015 (2023)]

- Run 2019: ~ 14 d at 4.55 GeV
- Run 2021: ~ 24 d at 3.74 GeV
- Future runs: ~ 100 more days

Strongly Interactive Massive Particle (SIMP) Search



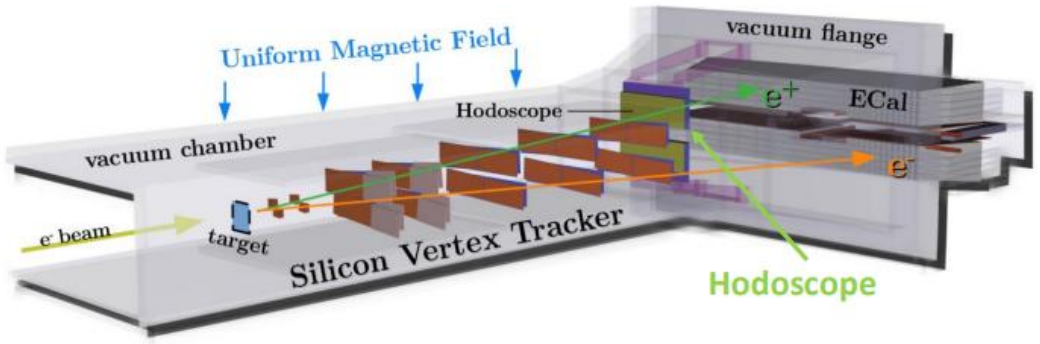


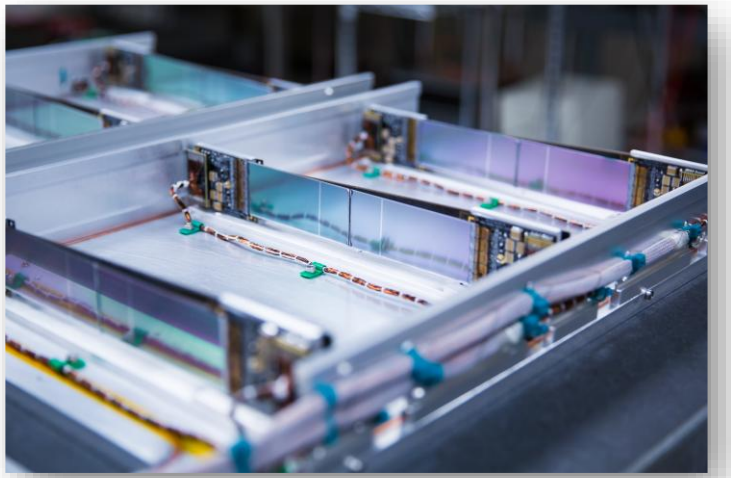
- Low-energy theories features many different states:
  - Dark pions (pseudo-Goldstone bosons of chiral symmetry breaking)
  - Dark ρ mesons (spin-1 bosons)
  - …
- Displaced vertex searches for electroproduced SIMPs with the 2016 HPS dataset in preparation

Expected Improvements Compared to 2021 Run

- **Operations**
  - SVT alignment, field-off runs with acceptance in all layers, fully surveyed detector
- **Hardware**
  - SVT modules, ECal chiller, DAQ update, servicing of Frascati magnet system
- **Optimized run periods**
  - Optimum is ~7 weeks at 4 GeV and ~6 weeks at 2 GeV beam energy
  - HPS has requested **60 PAC days of two-pass running**, to be followed by a final one-pass run

[Timothy Nelson, “HPS Overview”, HPS Collaboration Meeting (June 2025)]





HPS Sensitivity in Minimal A' Scenario

Projected sensitivity of HPS 2019+2021 runs

"Existing data (75 days) opens up significant region of sensitivity"

[Timothy Nelson, "HPS Overview", HPS Collaboration Meeting (June 2025)]

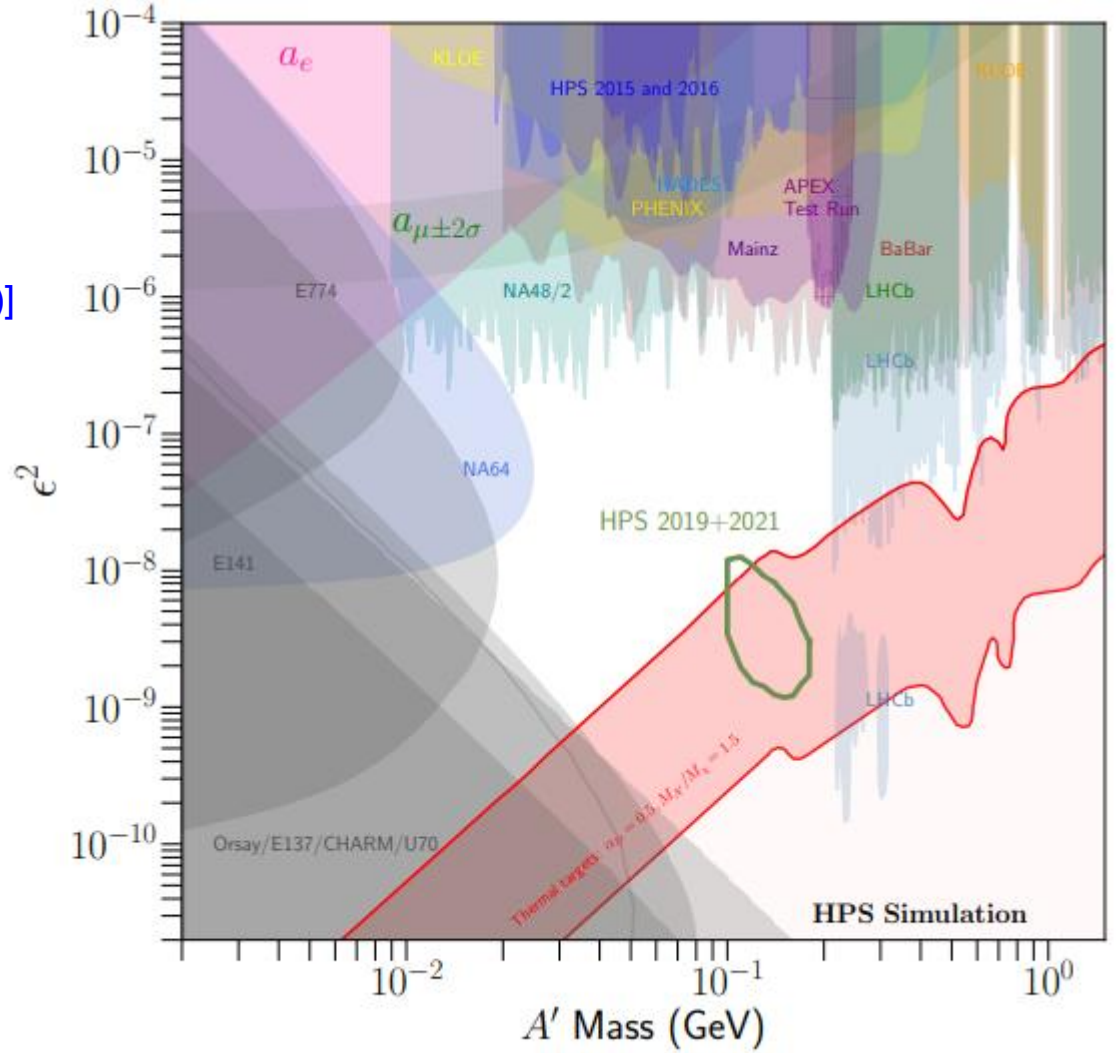
Two physics runs completed with upgraded detector

2019 run:

- E_{beam} = 4.55 GeV
- Int. Luminosity: 128 pb^{-1}
- Targets: 8 μm and 20 μm W foils

2021 run:

- E_{beam} = 3.74 GeV
- Int. Luminosity: 168 pb^{-1}
- Target: 20 μm W foil

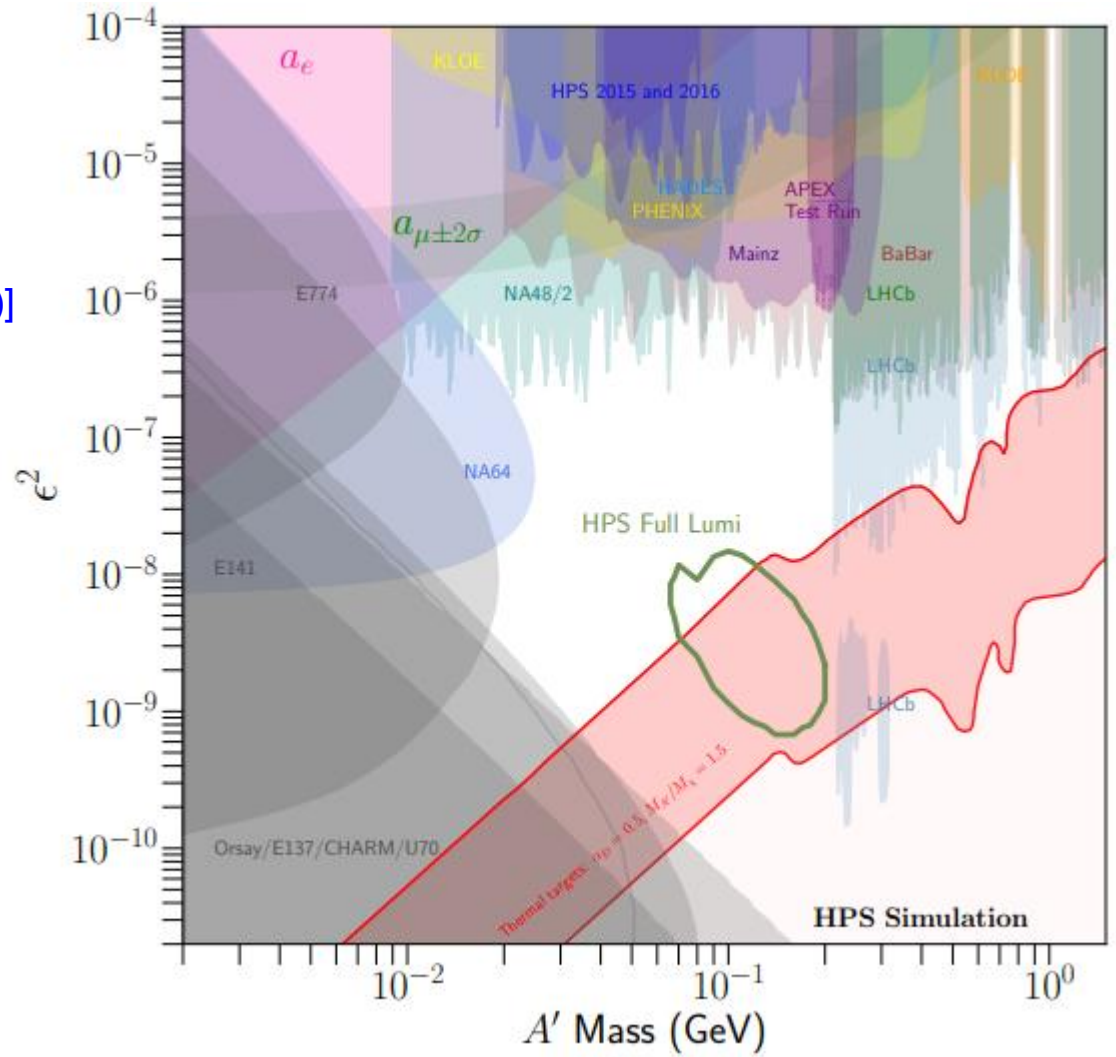


HPS Sensitivity in Minimal A' Scenario

Projected sensitivity of HPS with full luminosity

"Future run plan (105 days) more than doubles this region"

[Timothy Nelson, "HPS Overview", HPS Collaboration Meeting (June 2025)]



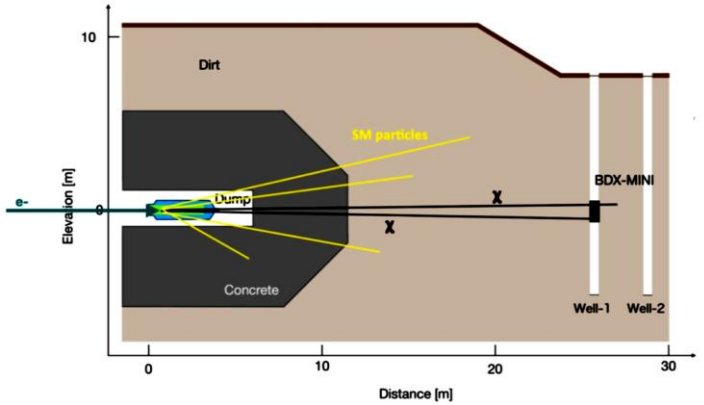
BDX-MINI at Jefferson Lab Hall A Beamdump

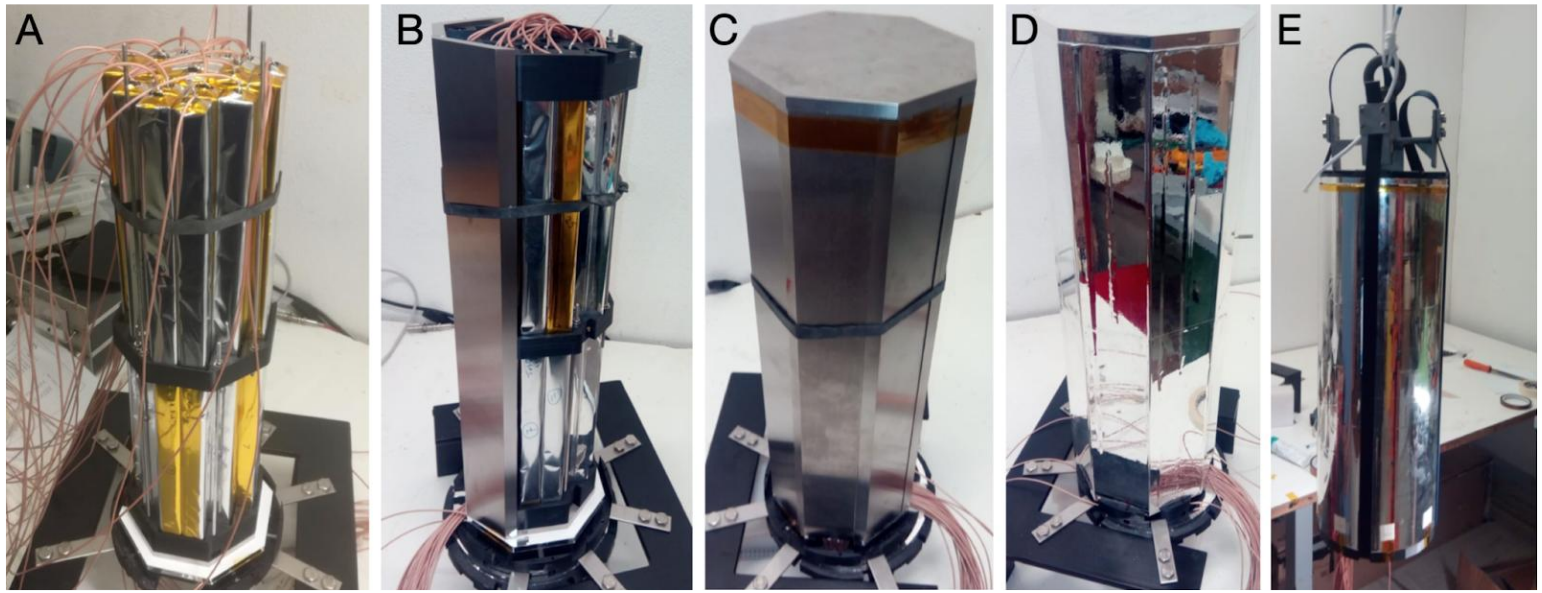
Scope

- Small-scale, low-energy version of a beam dump experiment
- Data-taking in 2019-20

Experimental setup and location

- Detector installed 25 m from dump
- Shielded by concrete and soil
- 2.2 GeV, 150 μA electron beam
- Integrated charge: 2.6 x 10^{21} EOT
- approx. 50 PWO crystals

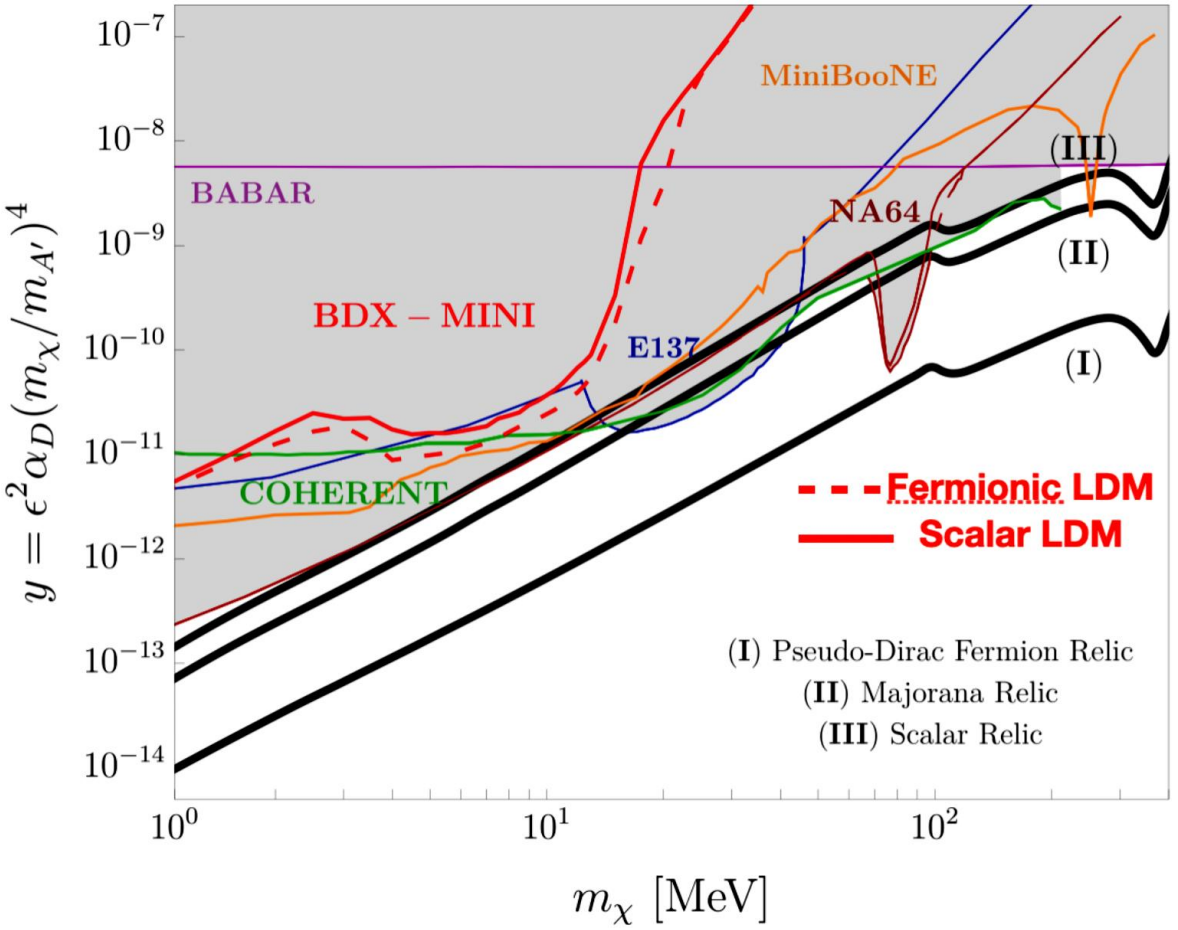




[M. Battaglieri et al., EPJC 81, 164 (2021)]

BDX-MINI Results

[M. Battaglieri et al. PRD 106, 072011 (2022)]

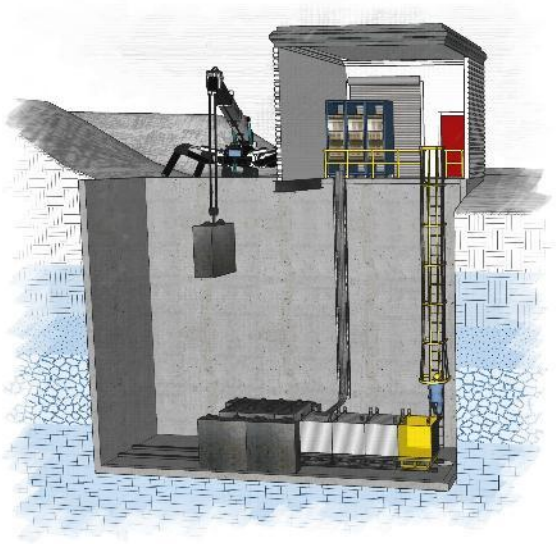


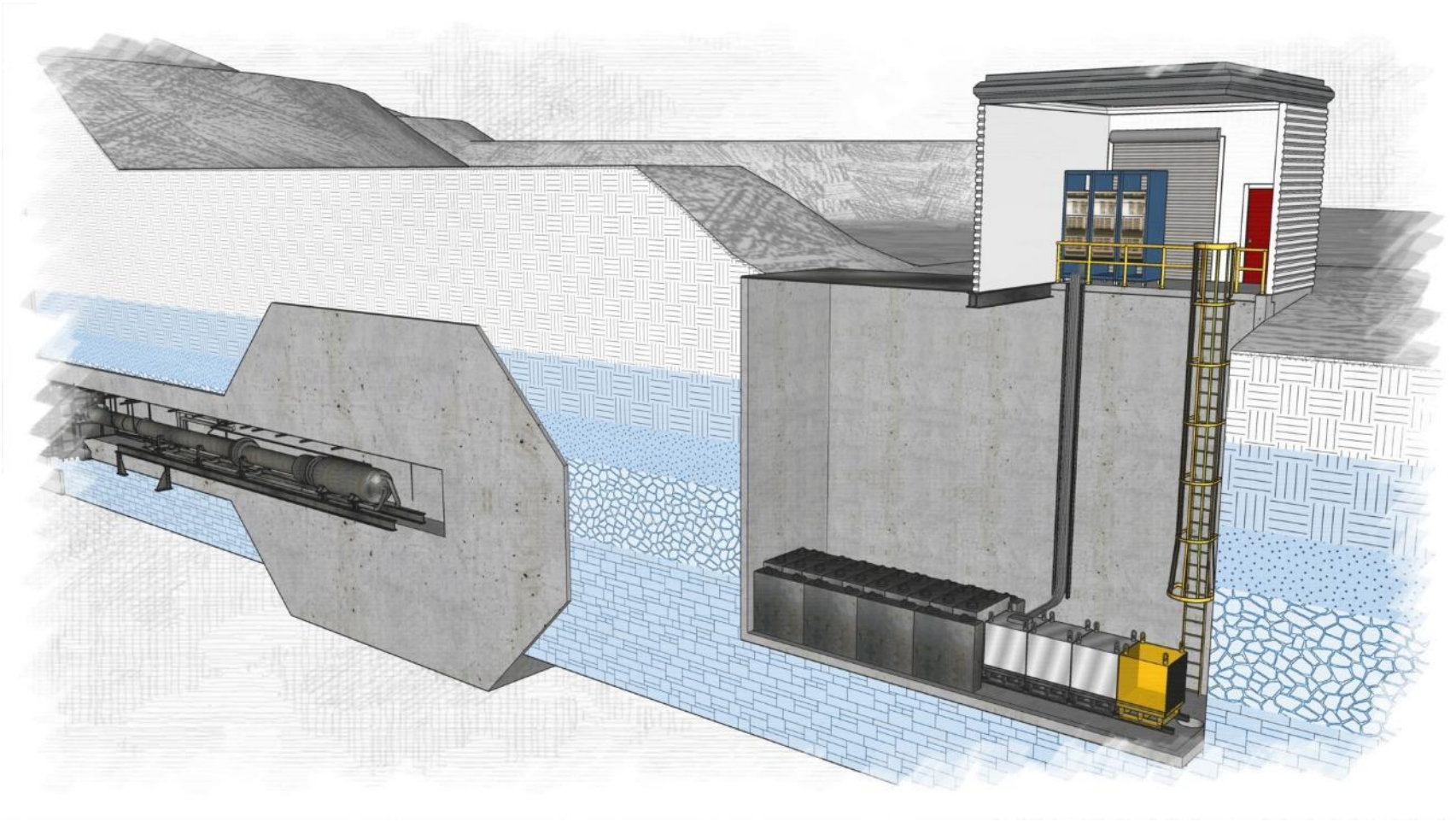
Analysis and results

- Blinding: selection cuts fixed by optimizing sensitivity
- Analysis allowing some controlled background
- Sensitive to parameter space covered by some of most sensitive experiments to date
- BDX-MINI demonstrated capabilities and readiness

BDX at Jefferson Lab Hall A Beamdump

- Detector hosted inside a vault ~20 m downstream of Hall-A beamdump
- 5.5 m concrete + 8 m dirt + 5.5 m steel shielding
- No sizable overburden
- Installation from overground:

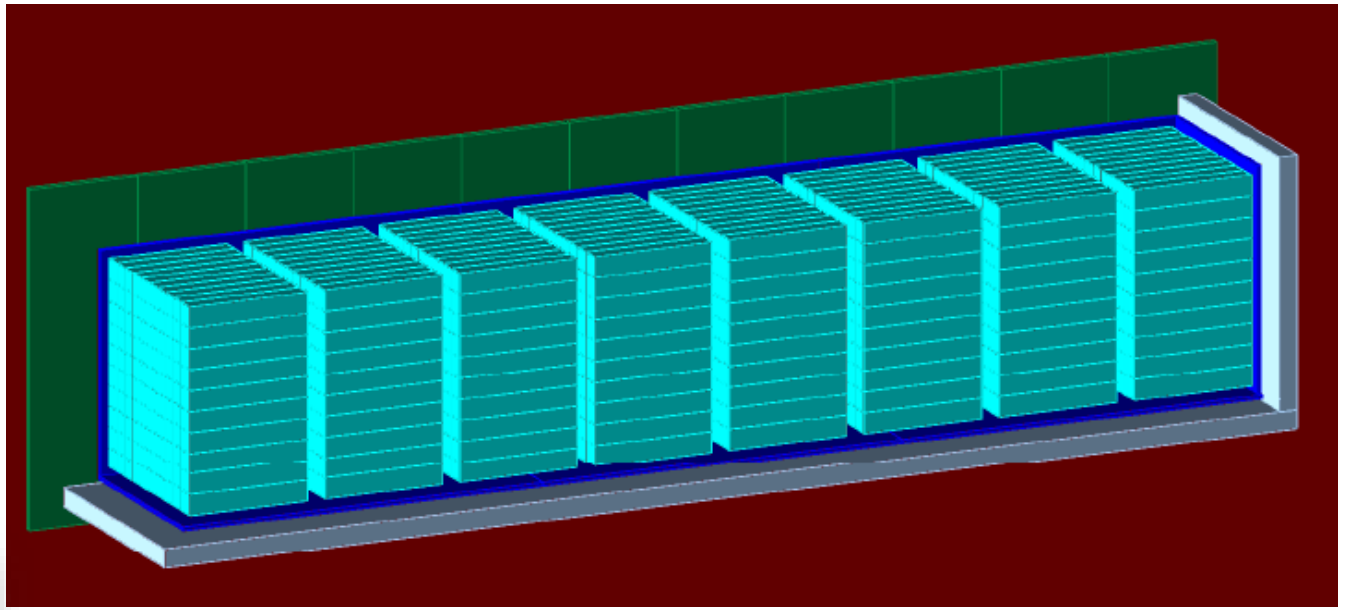


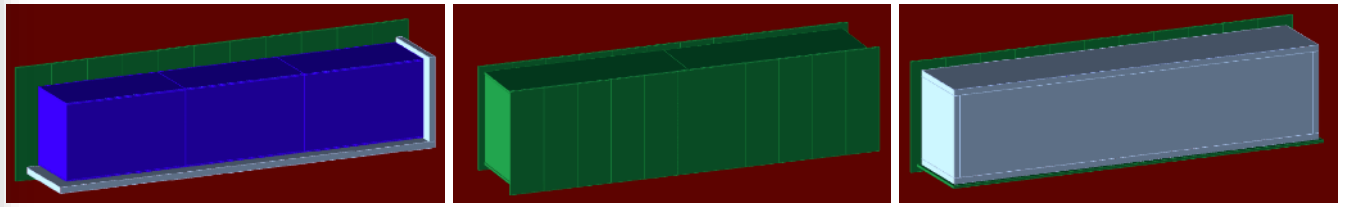


BDX Detector

Electromagnetic Calorimeter

- Target for DM interaction
- Sensitive to ~ 100 MeV electromagnetic shower
- Homogeneous 4 tons





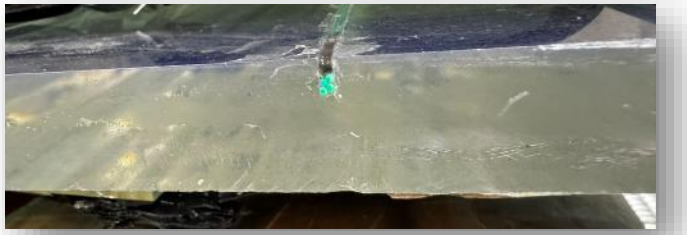
Crystals

- **BGO** (from BGO-OD experiment)

- **$PbWO_4$** (from PANDA experiment and Prad/PrimEx HyCal)

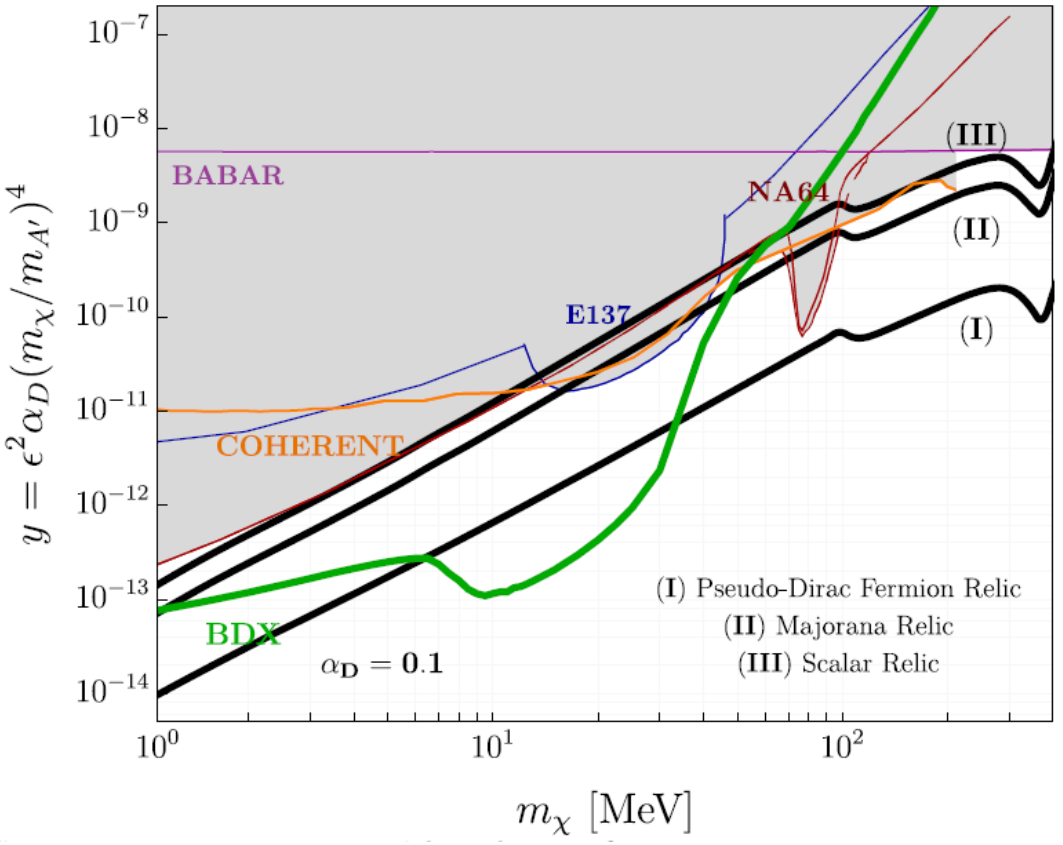
Active veto

- 2-cm thick **plastic scintillator**
- 5-cm thick **lead layer**



BDX Physics Reach

- **Running conditions**
  - Parasitic to MOLLER experiment
  - 11 GeV, 65 μA electron beam
  - 10^{22} EOT
  - Conservative cut E_{tot} > 300 MeV
  - Anti-coincidence with veto



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

In Conclusion

Summary of Dark Sector Searches at Jefferson Lab

BDX-MINI demonstrated power of beam dump experiments (paper in 2022)

HPS pioneered displaced vertex and SIMP searches (paper in 2023 and in preparation)

PRad-X17 is the *next* Dark Sector search experiment at Jefferson Lab:

- Validate existence or set an experimental upper limit on a search for X17
- Search for hidden sector particles in the 3 – 60 MeV/c2 mass range
- Non-magnetic electroproduction experiment, providing a) large detection acceptances; b) detection of all 3 final state particles; c) tight control of background
- Experiment passed the readiness review and is scheduled to run in Spring 2026

BDX will be able to probe relic target for different DM candidates (could run in 2027-29)