Dark Matter Searches at JLAB

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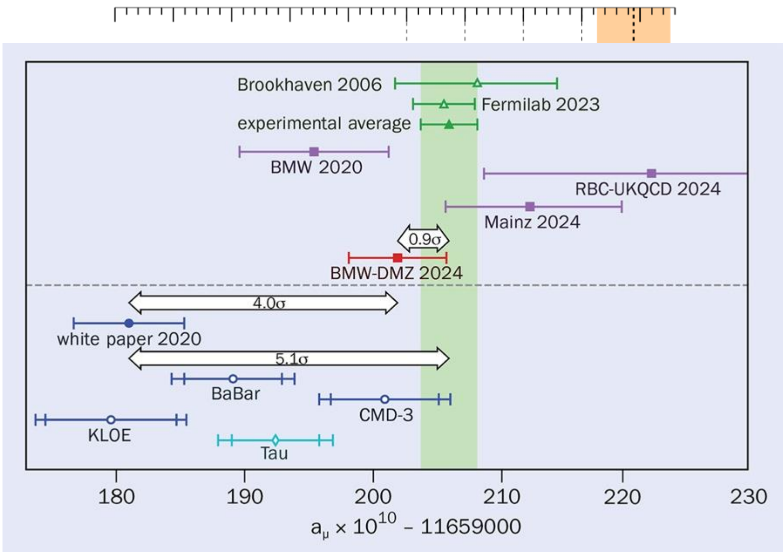
Colloquium, IJCLab, September 30, 2025

The Standard Model

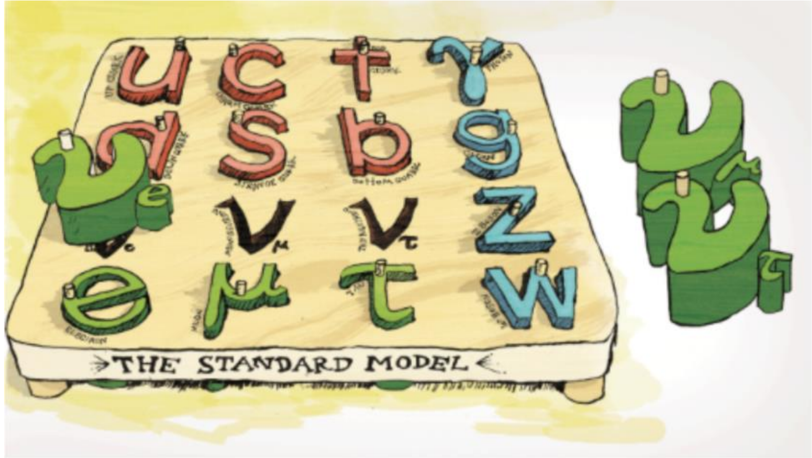
Almost all known particle physics phenomena are well described within the SM through its three basic interactions trong weak elec

The Higgs boson has been observed, and the precision anomalies are resolved:



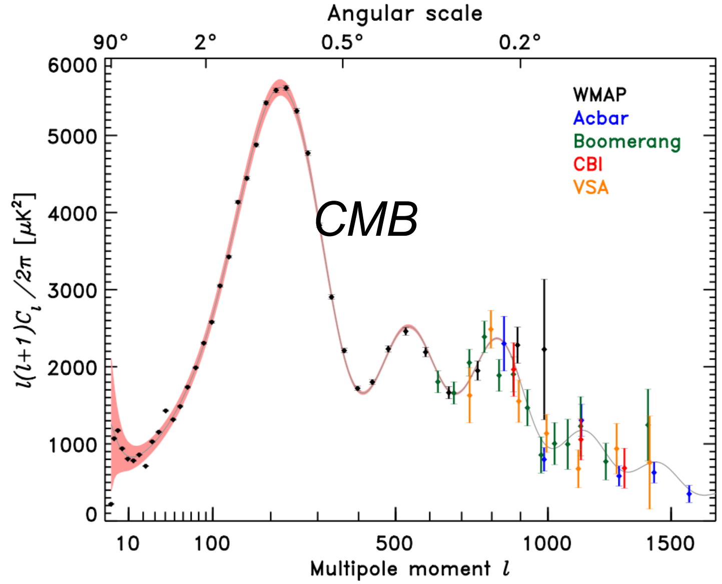
$a_\mu \times 10^{10} - 11659000$

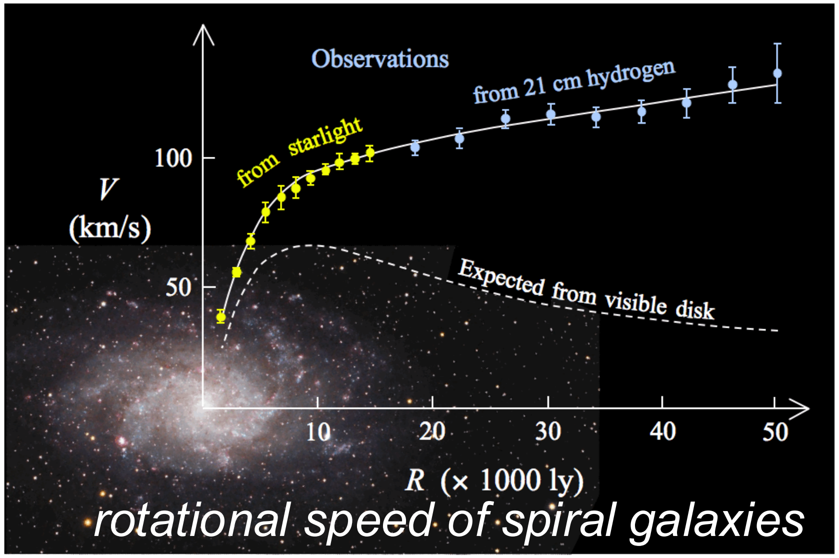
However, there are misfits

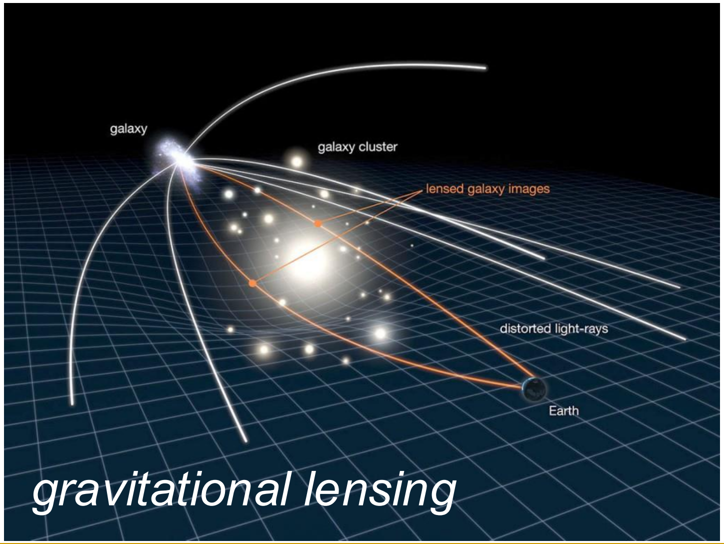


Kate SCHOLBERG

There are observations that cannot be explained



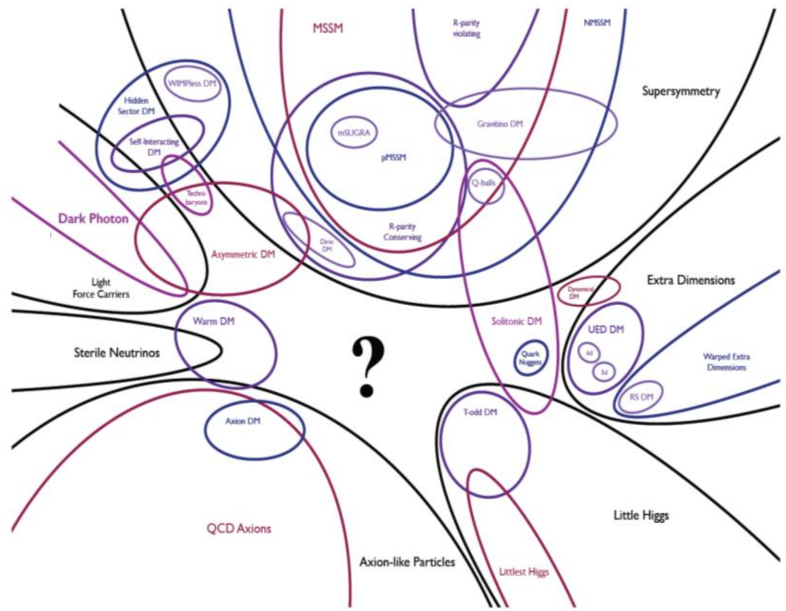




We do not know what it is that manifests itself in gravitational interactions –
an extension of the SM (axion, superpartner, …)
or
completely new physics,
so we call it Dark Matter.

Search for DM in non-gravitational interactions

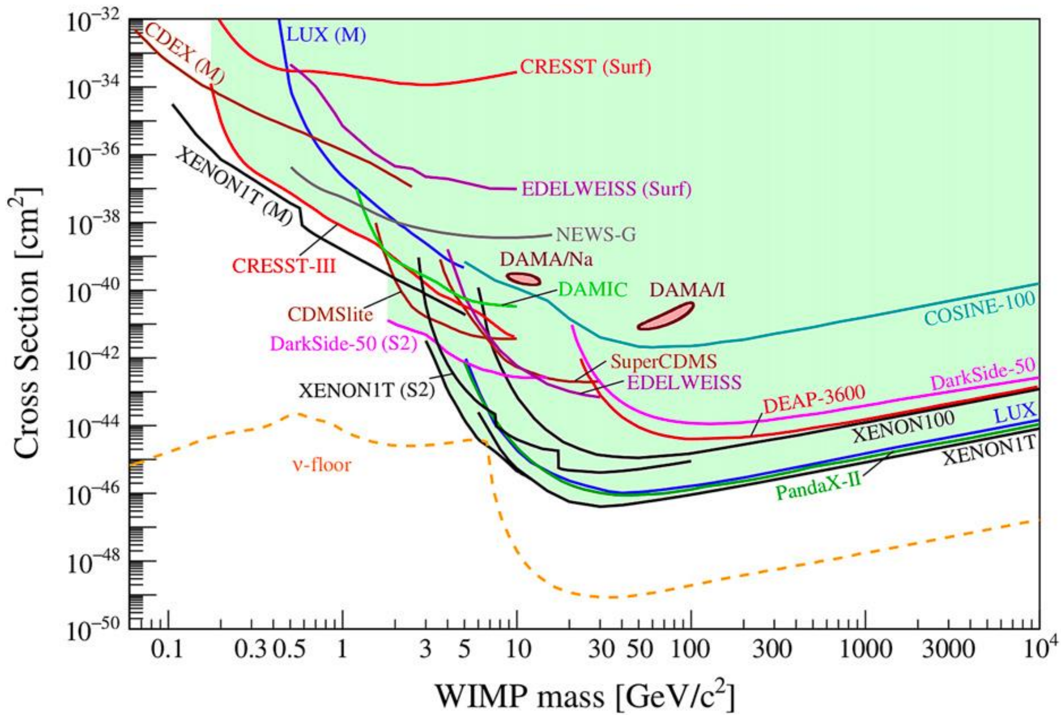
- There is no shortage of theoretical ideas about what the DM could be. Plan for experiments - search everywhere
- Three complementary techniques are being pursued to shed light on this elusive substance –
  - Direct searches using highly sensitive ultra-low background detectors
  - Indirect searches, both ground and space-based, looking for SM particles resulting from the annihilation of DM particles
  - Accelerator searches, trying to create DM particles from interactions of SM particles



T.Tait from arXiv:1401.6085v1 [hep-ex]

Case for low mass, hidden sector DM

- The LHC, as well as direct and indirect detection experiments, have significantly constrained one of the best-motivated weak-scale DM models, WIMPs as dark matter candidate.
- Next generation experiments (e.g. SuperCDMS, LZ, …) will likely cover a large portion of the remaining parameter space.

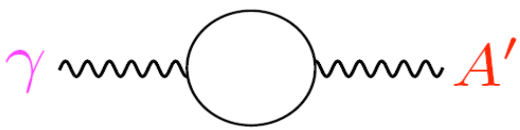


- *With phase space for WIMPs shrinking, the scenarios involving a light hidden sector dark matter with masses in the MeV-GeV range has garnered a good deal of attention.*
- *Models with hidden U(1) gauge symmetry are particularly attractive as they can be tested experimentally.*

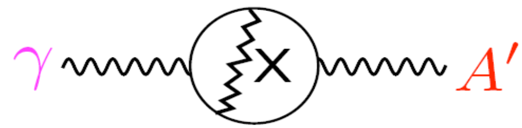
Electron machines for DM searches

Well-motivated searches focus on the simplest case: a heavy particle that is charged under EM and DM, and couples to the Standard Model photon through kinetic mixing.

B. Holdom, Phys. Lett. B 166, 196 (1986).



$\epsilon \sim 10^{-4} - 10^{-2}$

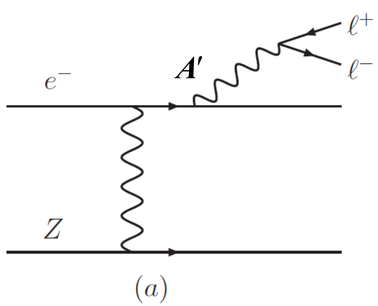


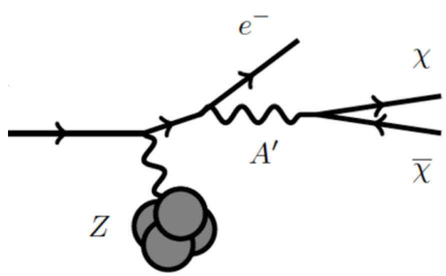
$\epsilon \sim 10^{-5} - 10^{-3}$

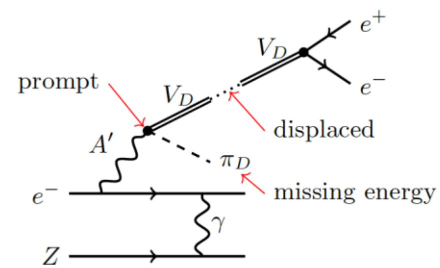
(if SM unifies in a GUT)

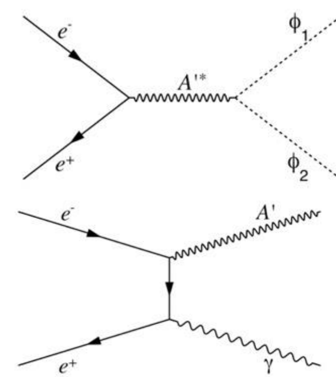
$$\varepsilon^2 = \frac{\alpha'}{\alpha}$$

Bremsstrahlung and detection, or a search for missing energy/momentum.



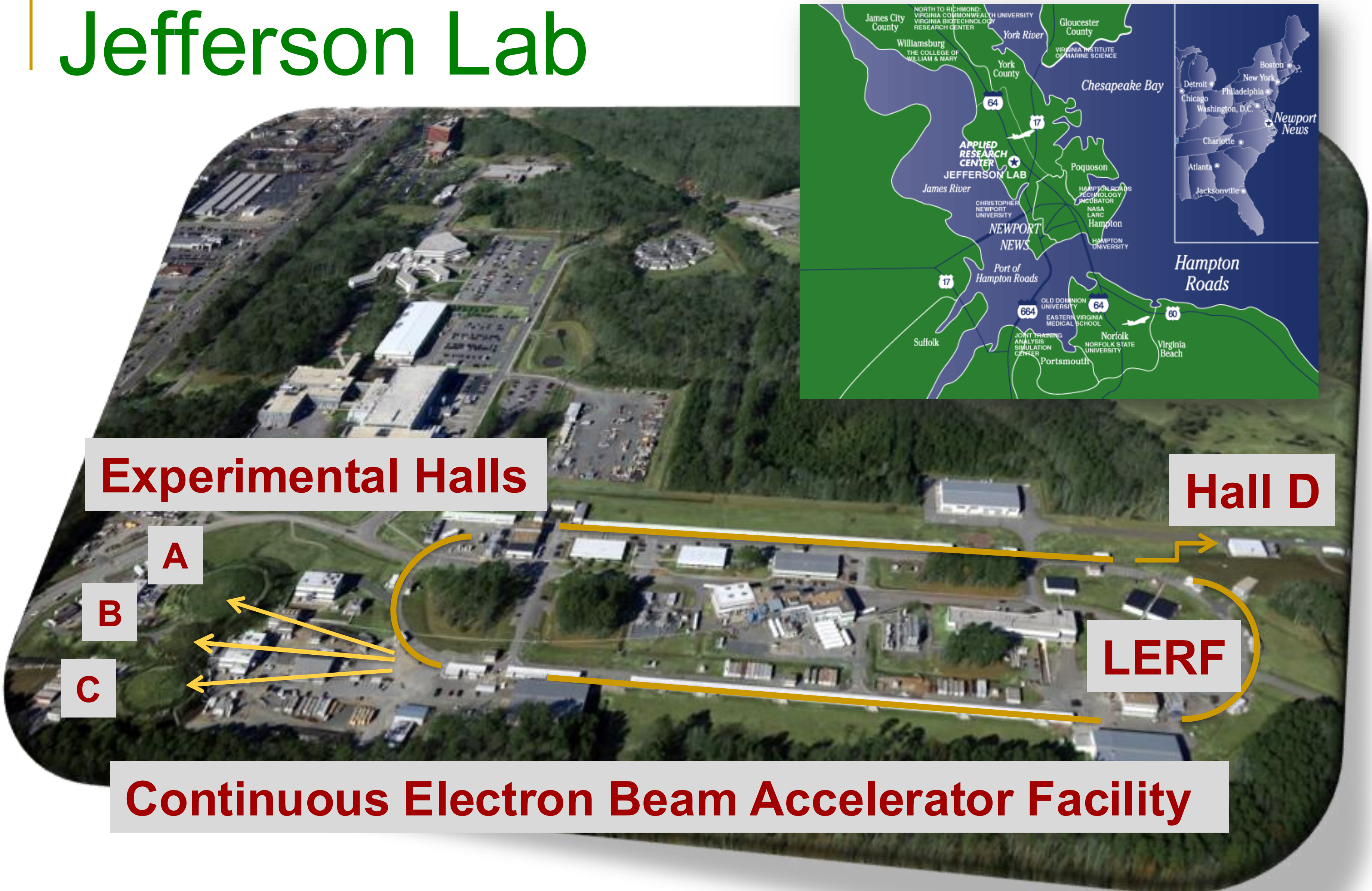






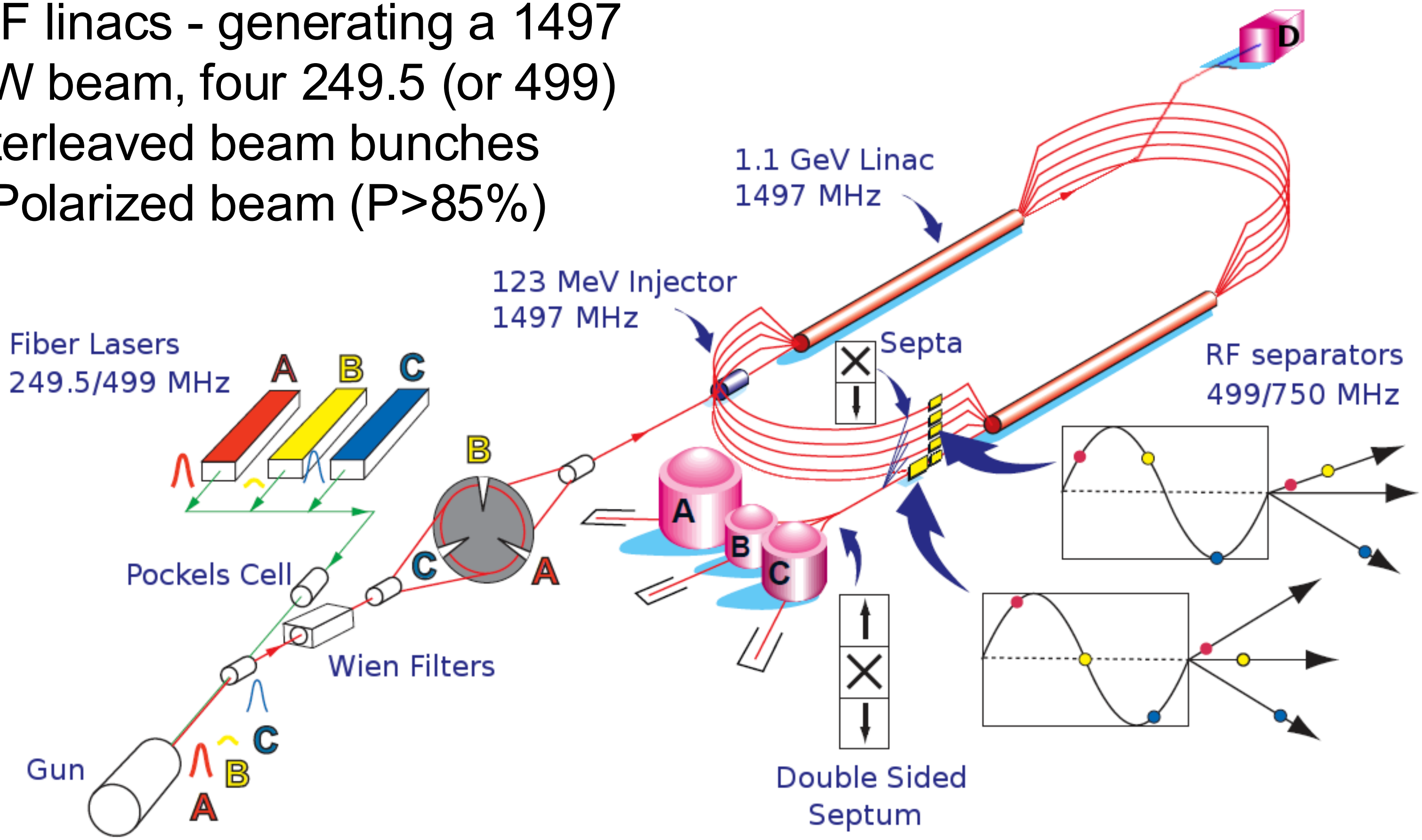
and a precision measurements in electroweak .

Jefferson Lab



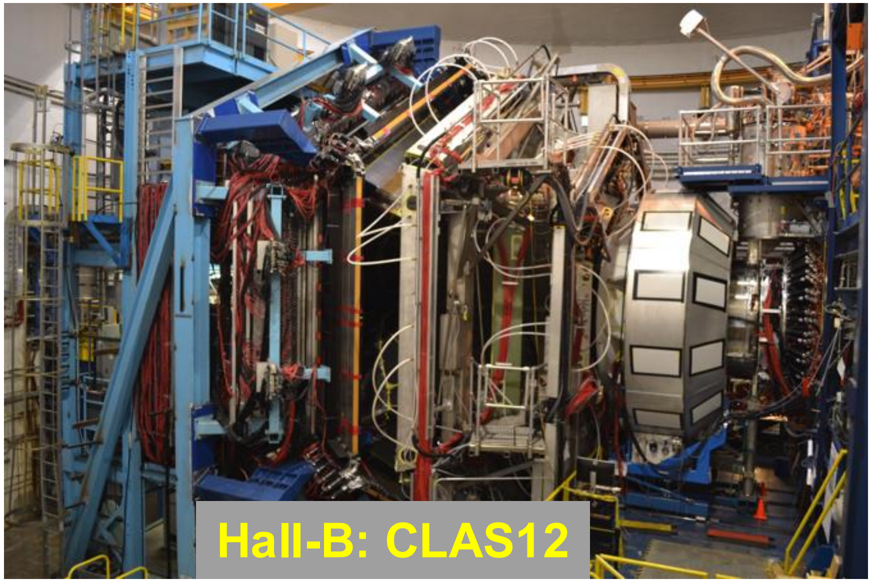
CEBAF12

- CW SRF linacs - generating a 1497 MHz CW beam, four 249.5 (or 499) MHz interleaved beam bunches
- Highly Polarized beam (P>85%)



- Design energy (max) 2.2 GeV/pass:
  - 5 passes, 11 GeV (Halls A,B & C)
  - 5.5 passes, 12 GeV (Hall-D)
- Flexible extraction options for ABC, 1st…5th pass
- Hall A & C 1 MW high power dumps

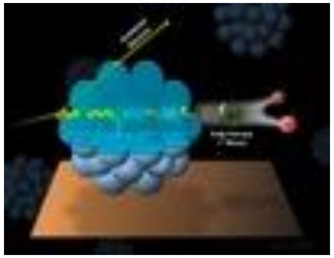
Experimental Setups



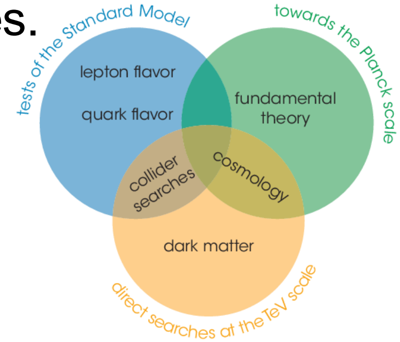
JLAB Physics program

- Nucleon and nuclear structure studies, spatial and momentum tomography, form-factors …

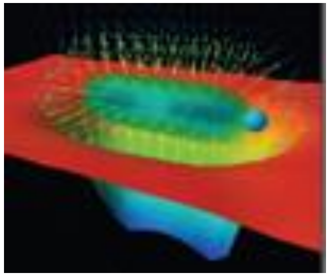
- Cold nuclear matter, NN correlations, hadronization, color transparency…



- Low-energy test of the Standard Model and fundamental symmetries, and search for Dark Matter particles.



- Exploring origin of confinement – meson and baryon spectroscopy, exotics …



Total of 91 approved experiments, 35 completed to date.

JLAB Dark Matter Search Experiments

Hall-B

Hall-A

APEX

JEF with GluEx
Hall-D

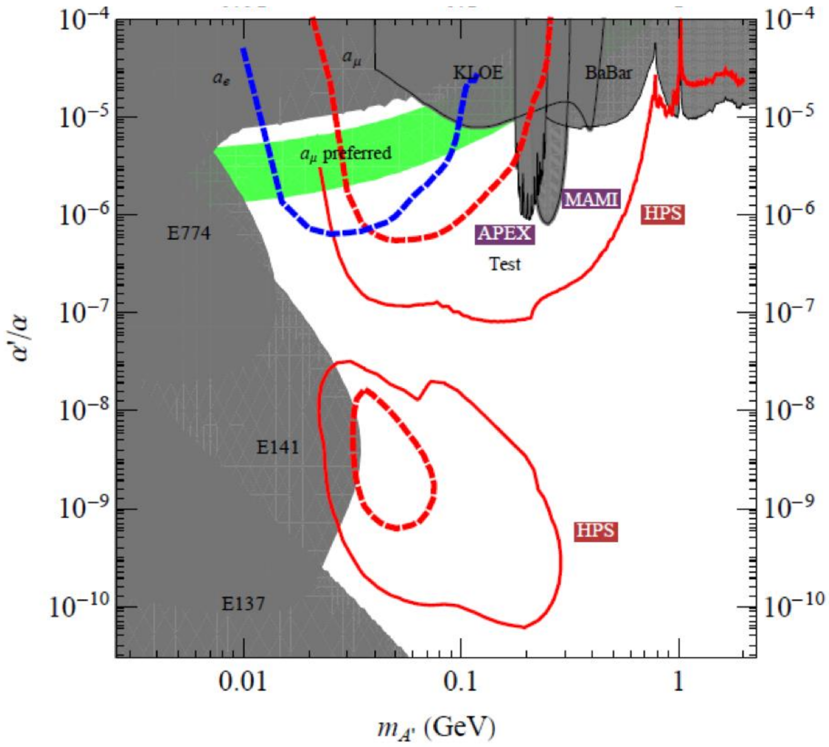
BDX
Beyond Hall A beam dump

Search for X17
Hall-B

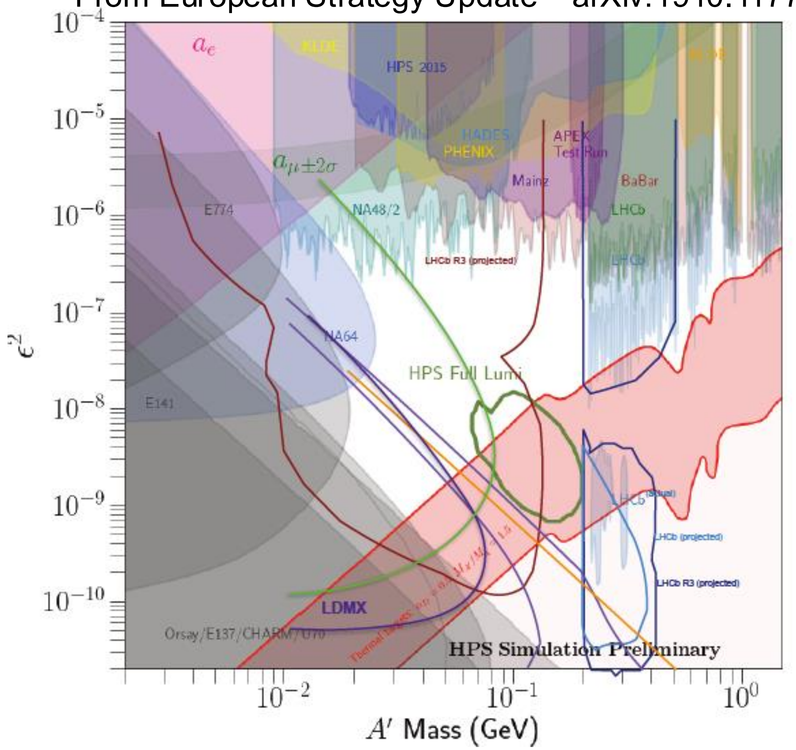
PVES with Moller and SoLID
Hall-A

Evolution of the field

This is where we started (from the PAC 39 presentation)



From European Strategy Update – arXiv:1910.11775



2012: There was an empty field to explore, and only a little competition was out there. We were aiming to do a lot, and with good intentions, we asked and got 180 beam days of running. The largest beam time that was awarded to any Hall-B experiment.

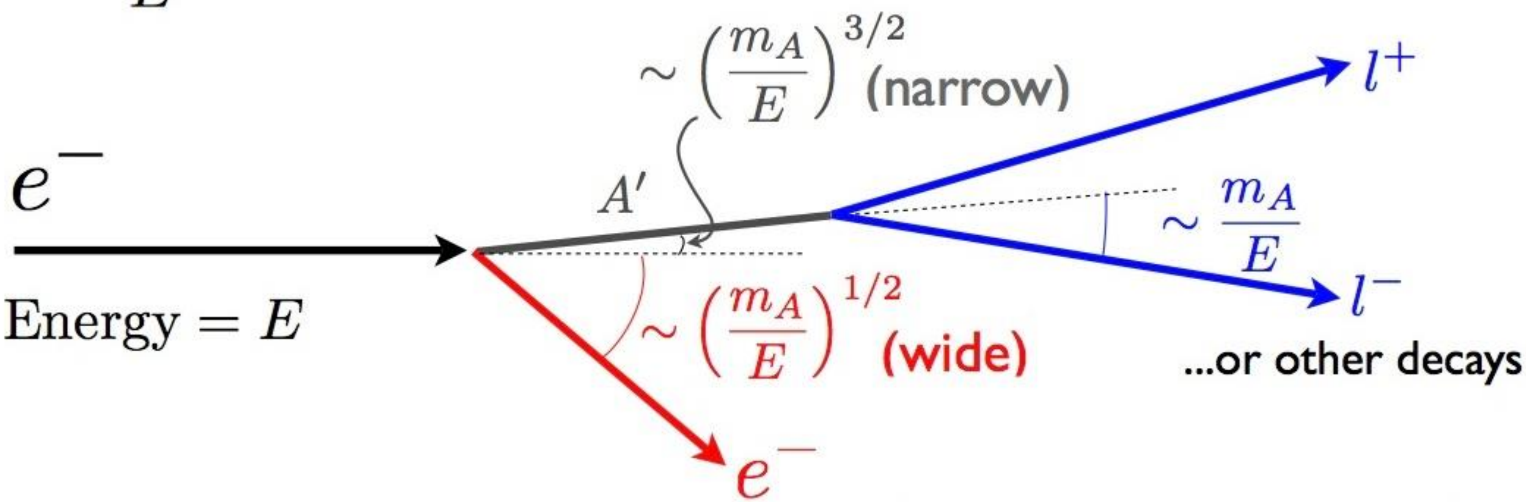
Present: The field became crowded rather quickly, limits were set, and more are expected from the planned experiments. However, HPS still has a unique reach in well-motivated regions of parameter space.

Fixed target experiments: kinematics

$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2(1-x)/x}$$

$$x = \frac{E_A}{E}$$

Kinematics **very different** from massless photon bremsstrahlung

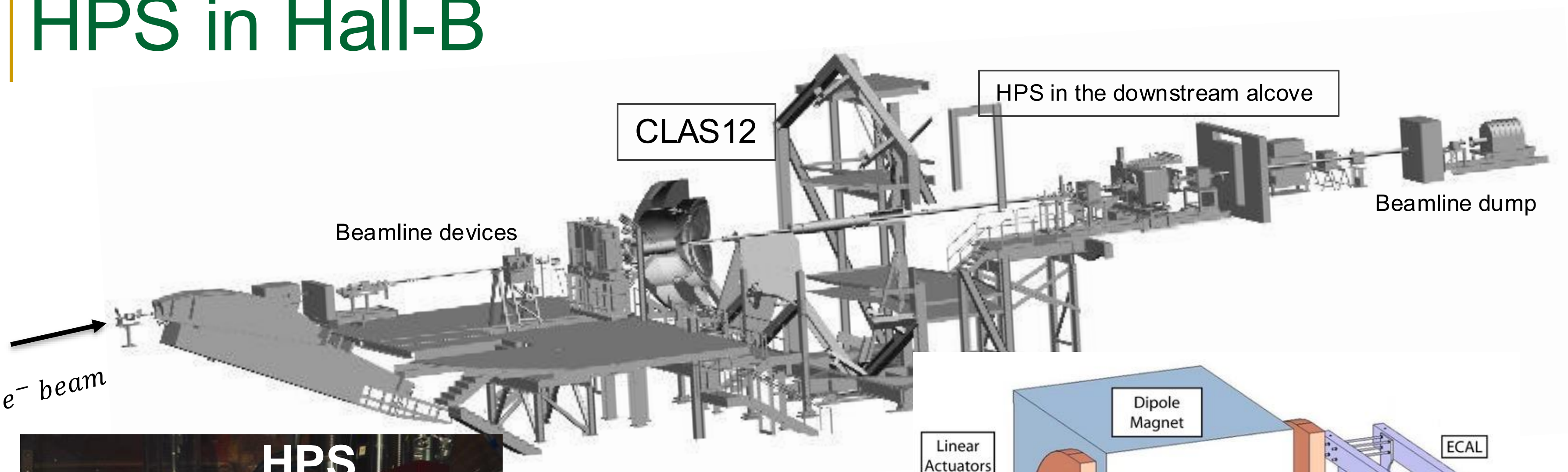


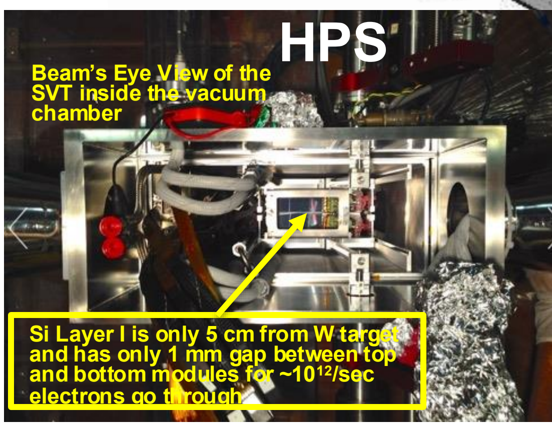
Heavier product (here A') takes most of beam energy

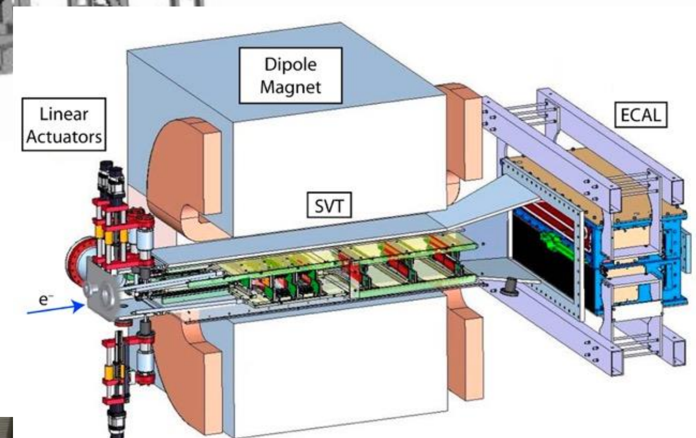
$$E_A \sim E - m_A$$
$$E_e \sim m_A$$

J.D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev. **D80**, 2009, 075018

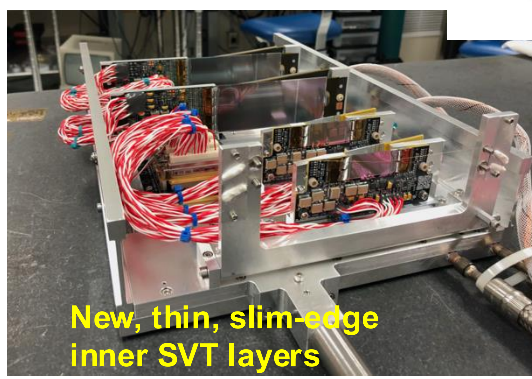
HPS in Hall-B





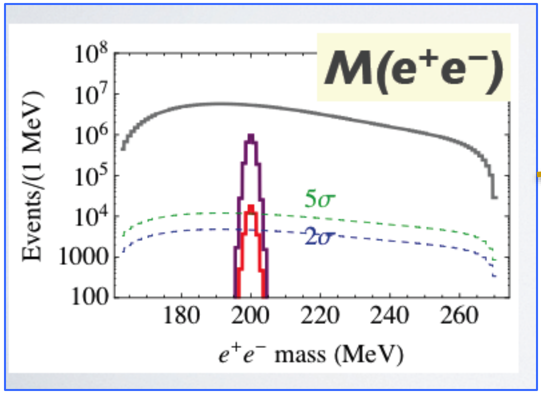


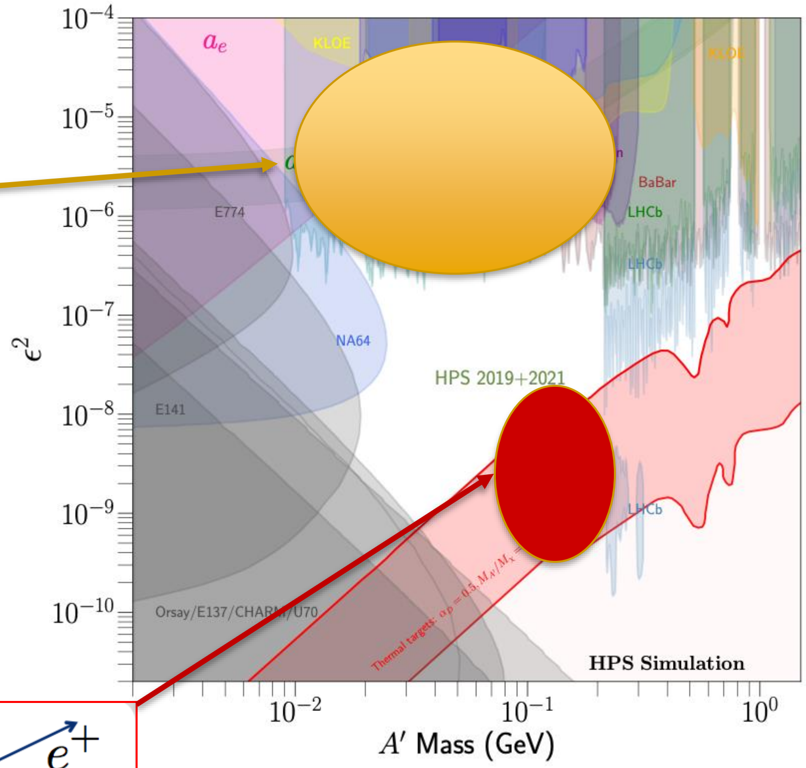
For 2019-2021 physics runs:



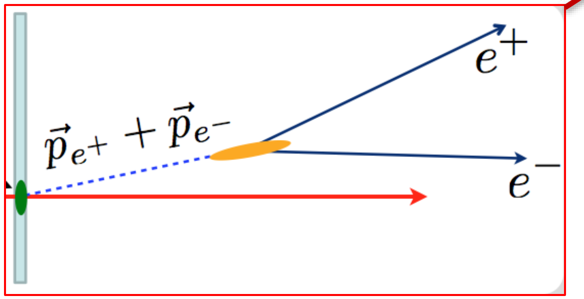
HPS reach

- The experiment exploits both, the resonance and displaced vertex search strategies

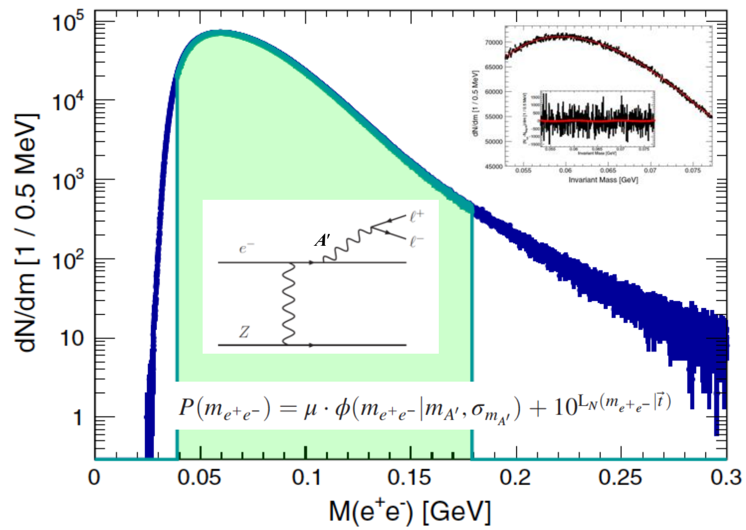




- With displaced vertex search, HPS will cover uncharted region of A' masses from 80 MeV to 200 MeV and the couplings as low as $\varepsilon^2 \sim few \times 10^{-10}$

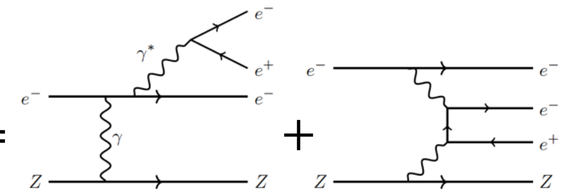


Recent results: resonance search



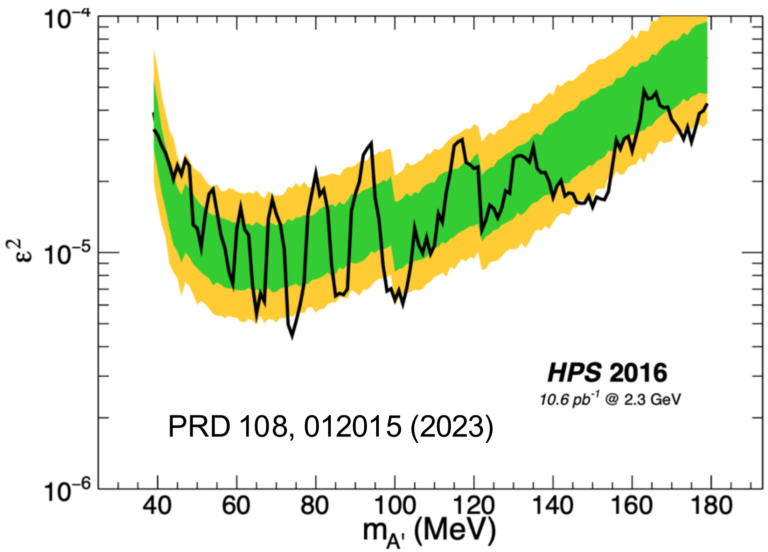
$$\left.\frac{d\sigma_{A'}}{dm}\right|_{m=m_{A'}} = \frac{3\pi m_{A'}\epsilon^2}{2N_{\text{eff}}\alpha}\left.\frac{d\sigma_{\gamma^*}}{dm}\right|_{m=m_{A'}} \qquad \epsilon^2_{\text{up}} = \frac{2\alpha N^{\text{up}}_{\text{sig}}}{3\pi m_{A'} f_{\text{rad}} \cdot \frac{dN_{\text{bkg}}}{dm}}.$$

Bgk=

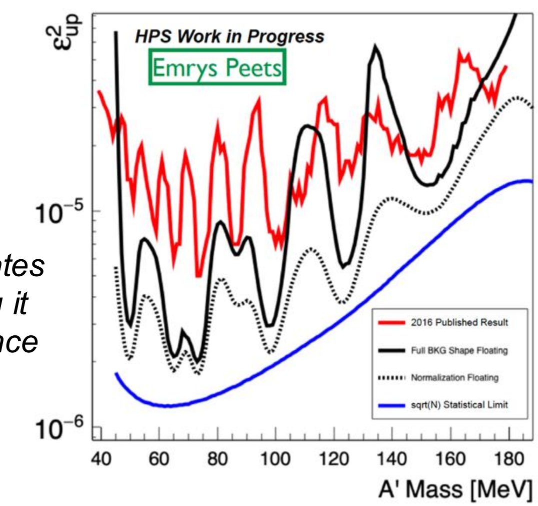


+ WABs

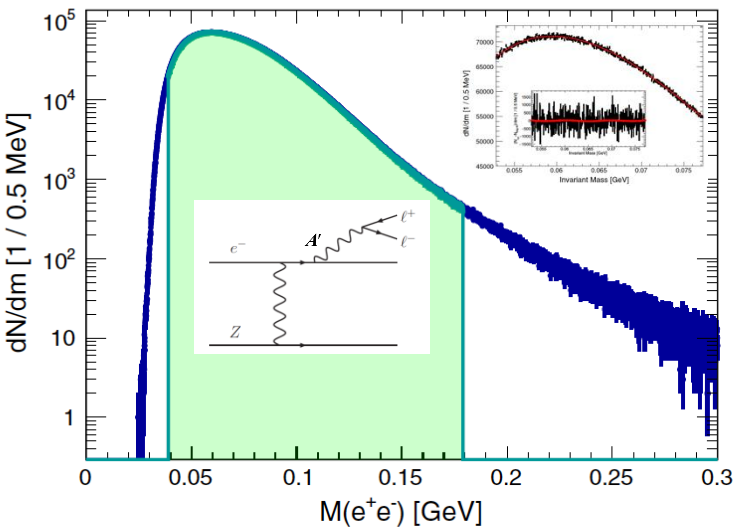
$$f_{\text{rad}} = \frac{\frac{dN_{\gamma^*}}{dm}}{\frac{dN_{\text{bkg}}}{dm}} = \frac{\frac{dN_{\gamma^*}}{dm}}{\frac{dN_{\text{tri}}}{dm} + \frac{dN_{\text{wab}}}{dm}}$$

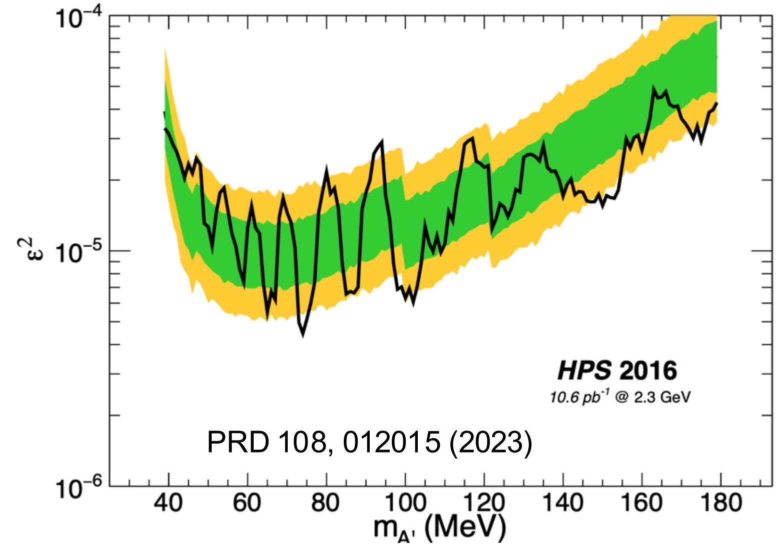


Background modeling dominates the systematic, and improving it can make the prompt resonance search more competitive.



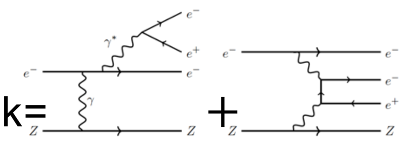
Recent results: resonance search





$$\left.\frac{d\sigma_{A'}}{dm}\right|_{m=m_{A'}} = \frac{3\pi m_{A'}\epsilon^2}{2N_{\text{eff}}\alpha}\left.\frac{d\sigma_{\gamma^*}}{dm}\right|_{m=m_{A'}} \qquad \epsilon^2_{\text{up}} = \frac{2\alpha N^{\text{up}}_{\text{sig}}}{3\pi m_{A'} f_{\text{rad}}\cdot \frac{dN_{\text{bkg}}}{dm}}.$$

Bgk=

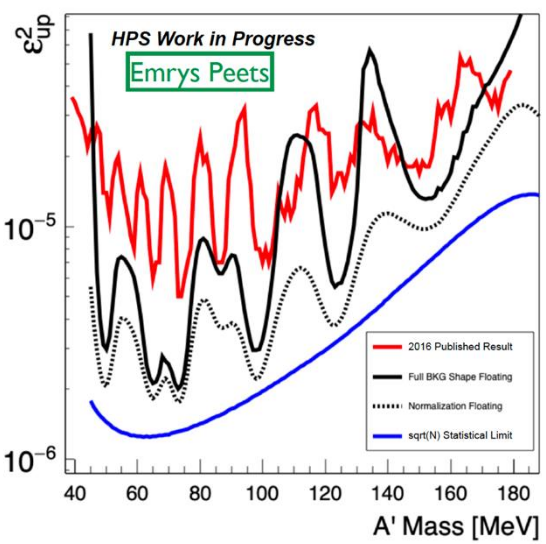


+ WABs

$$f_{\text{rad}} = \frac{\frac{dN_{\gamma^*}}{dm}}{\frac{dN_{\text{bkg}}}{dm}} = \frac{\frac{dN_{\gamma^*}}{dm}}{\frac{dN_{\text{tri}}}{dm} + \frac{dN_{\text{wab}}}{dm}}$$

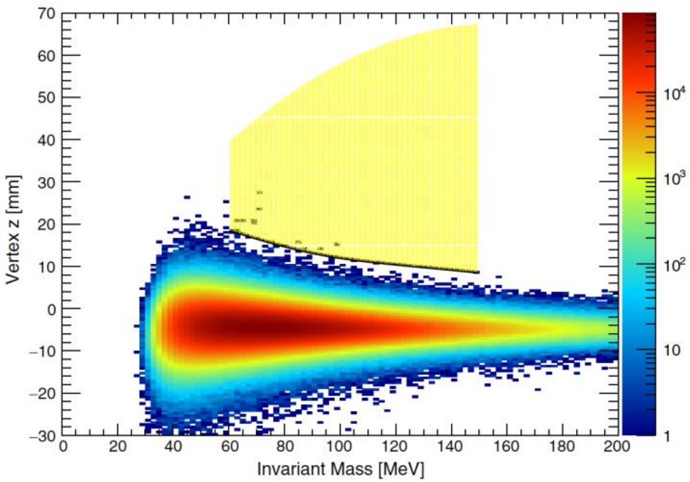
Background modeling dominates the systematics, and improving it can make the prompt resonance search more competitive.

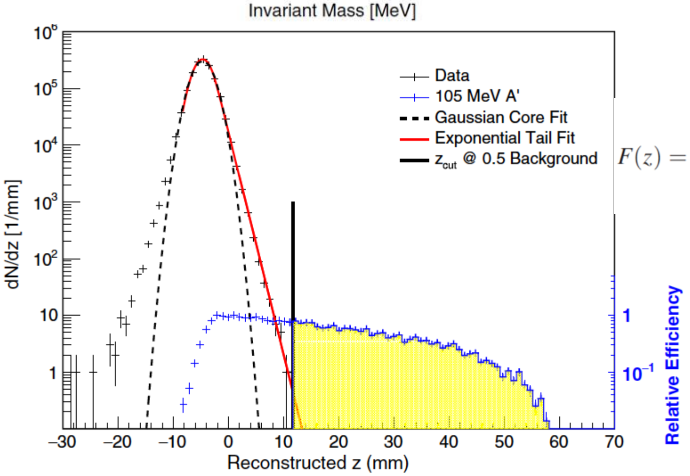
$$P(m_{e^+e^-}) = \mu \cdot \phi(m_{e^+e^-}|m_{A'}, \sigma_{m_{A'}}) + 10^{L_N(m_{e^+e^-}|\vec{t})}$$



Recent results: displaced vertex search

In each overlapping mass slice, z-distribution fits define the z_{cut} beyond which the background fit function predicts <0.5 events.

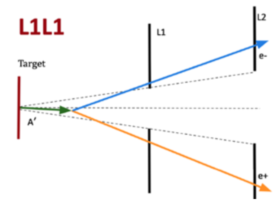




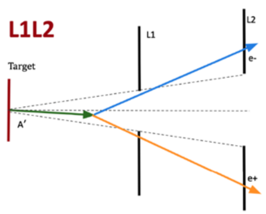
$$F(z) = \begin{cases} Ae^{-\frac{(z-\mu_z)^2}{2\sigma_z^2}} & \text{if } \frac{z-\mu_z}{\sigma_z} < b, \\ Ae^{\frac{b^2}{2}-b\frac{z-\mu_z}{\sigma_z}} & \text{if } \frac{z-\mu_z}{\sigma_z} \geq b. \end{cases}$$

A′ decay

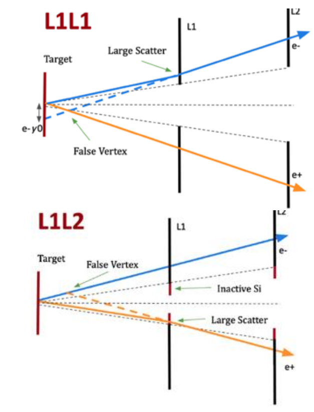
A short decay length, both daughter particles have a layer 1 hit



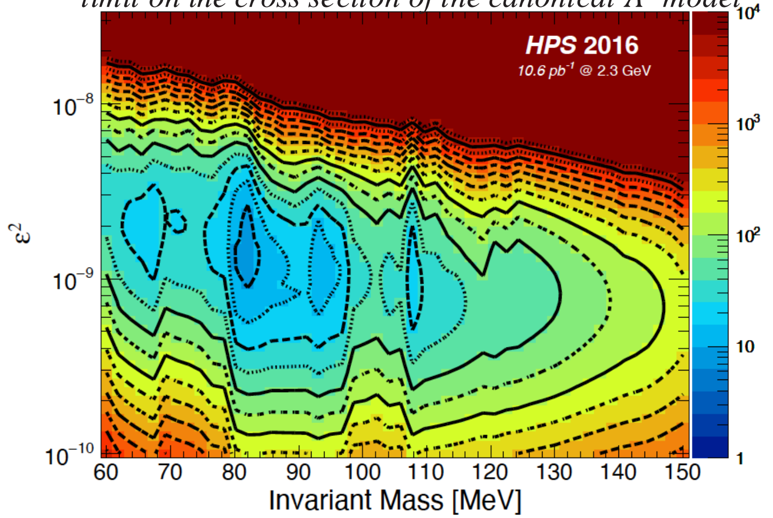
A long decay length, one of daughter particles misses layer 1 hit



A prompt background processes

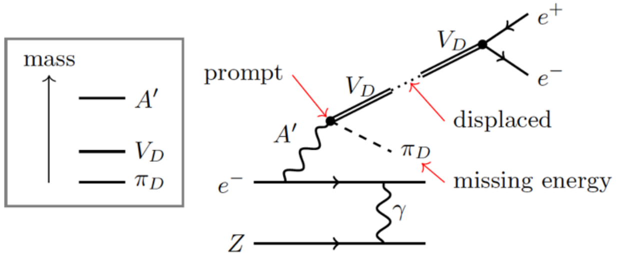


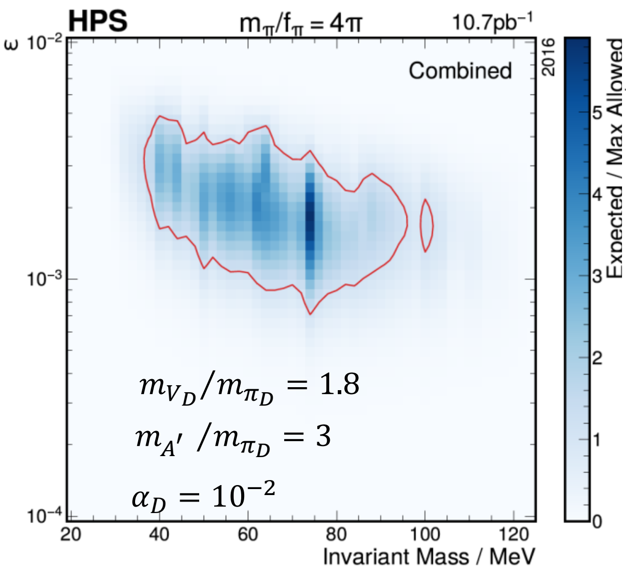
The optimum interval method (OIM) is used to set a limit on the cross section of the canonical A′ model

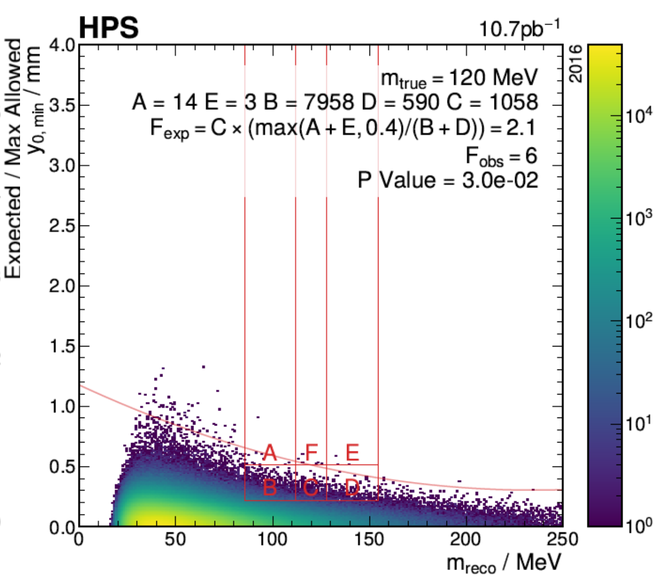


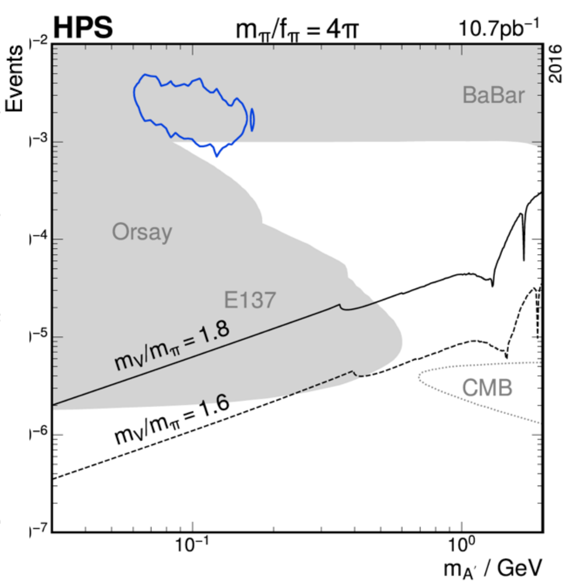
SIMPs search

- A hidden sector with QCD-like $SU(3)_D$ gauge symmetries, giving rise to strongly interacting massive particles, dark pions (π_D) and dark vector mesons (V_D).
- Models allow $3\pi_D \rightarrow 2\pi_D$ annihilation to deplete DM relic density, and $\pi_D\pi_D \rightarrow \pi_D V_D$ with $V_D \rightarrow SM$ through a virtual A'.
- In HPS, the signature of this channel will appear in the low P_{sum} region. Analysis followed the same strategy as for canonical A'displaced search, with improved selection criteria.







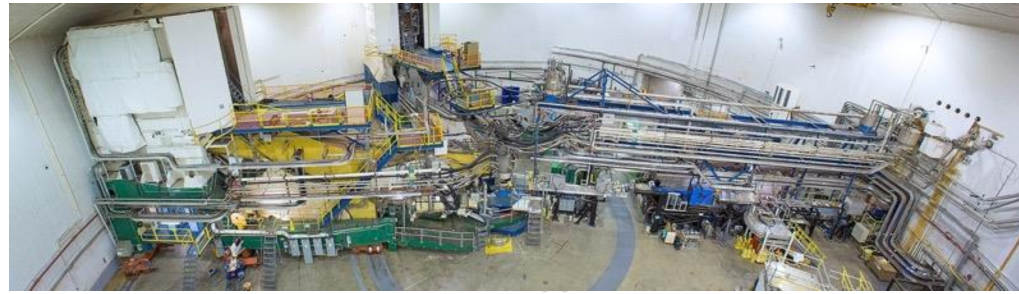


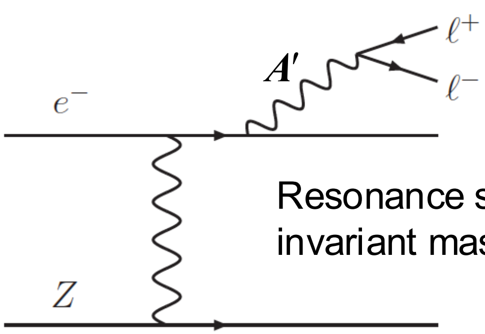
Publication is in preparation.

The A' Experiment in Hall-A (APEX)

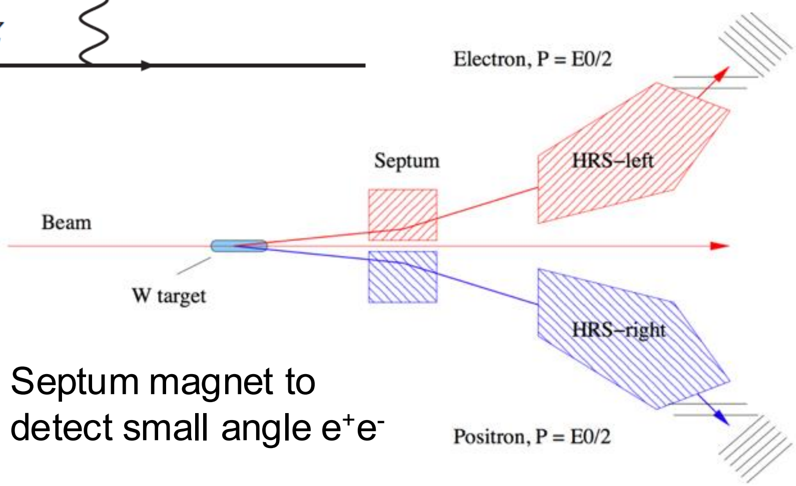
First experiment took data before CEBAF 12 GeV upgrade

Spectrometer-based search for 50-500 MeV A' decaying promptly to e^+e^- pairs in the electron scattering off of a high-Z target

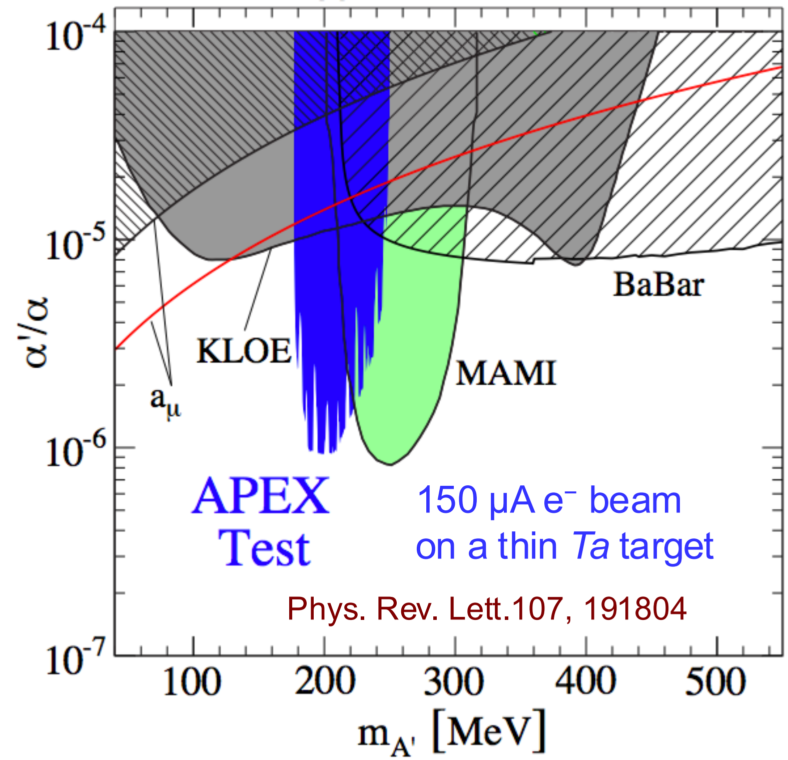




Resonance search in the invariant mass of e^+e^-

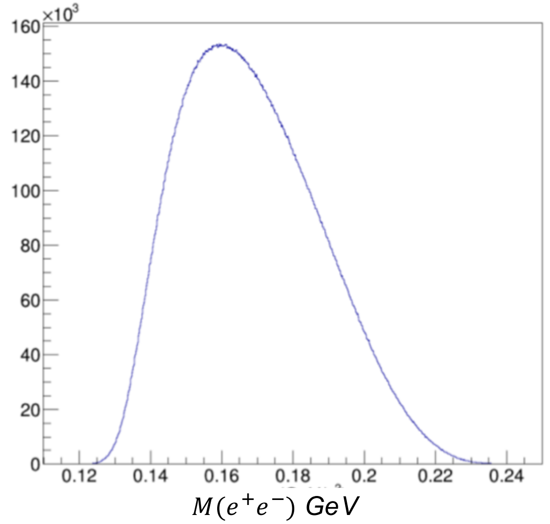


Septum magnet to detect small angle e^+e^-

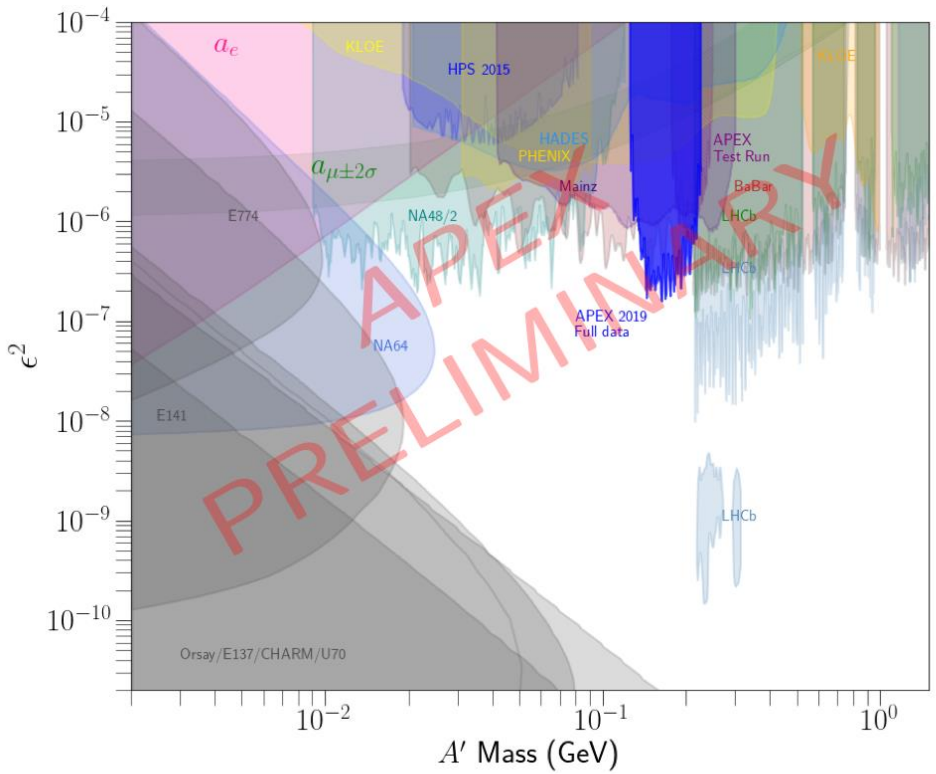


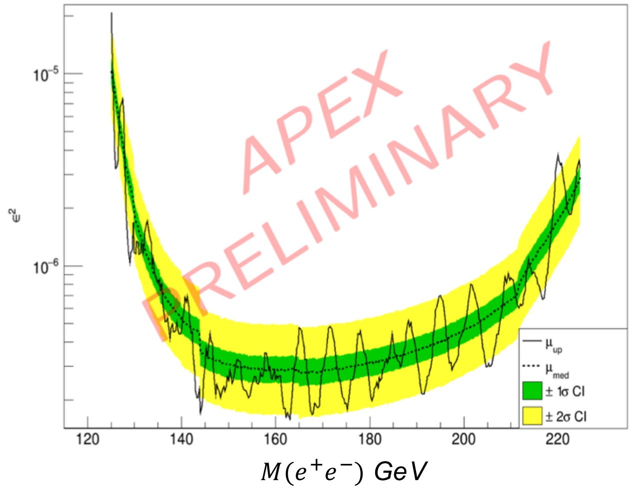
APEX Physics run (2019) at 2.0 GeV

Total of ~56M e^+e^- pairs (compared to ~0.77M of the test run).



$$\frac{d\sigma(A')}{d\sigma(\gamma^*)} = \left(\frac{3\pi\epsilon^2}{2N_{eff}\alpha}\right)\frac{m_{A'}}{\delta m}$$

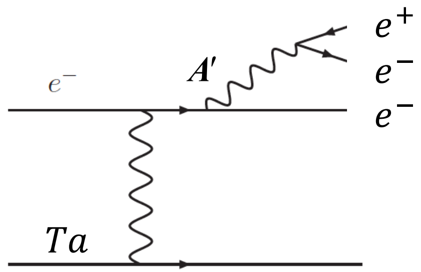


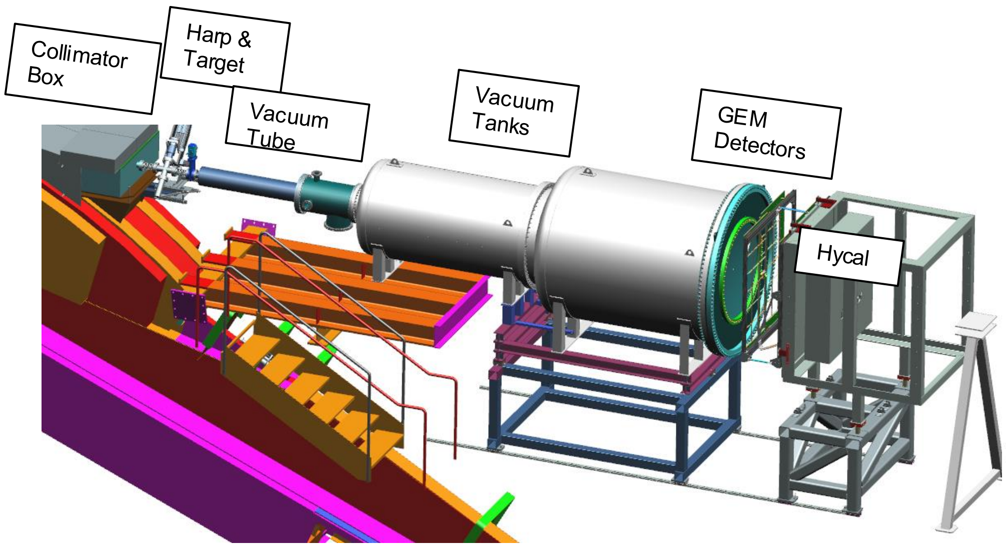


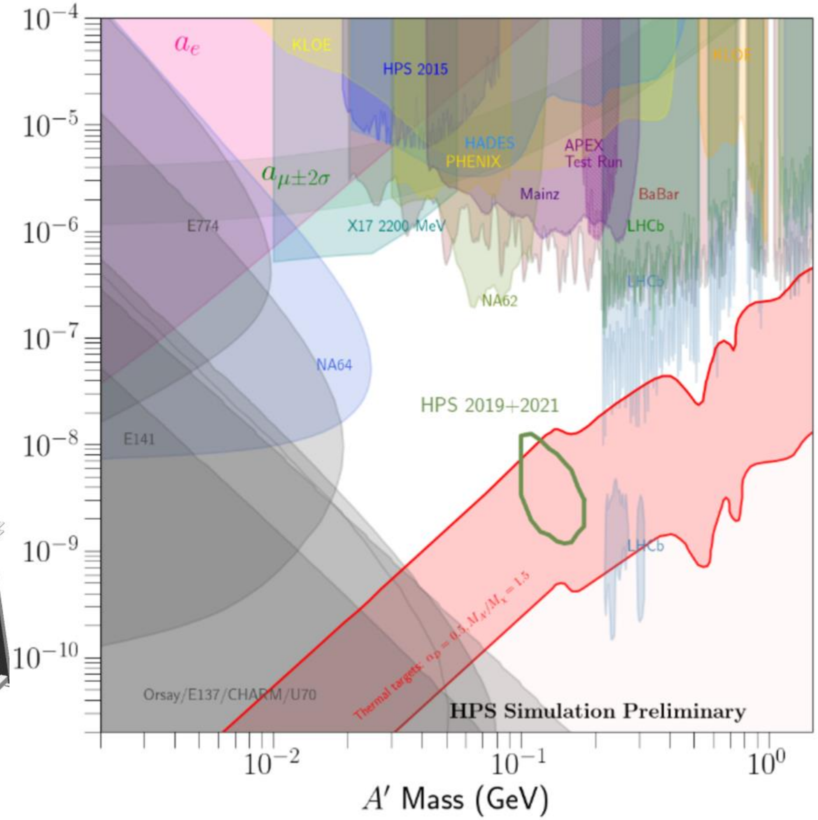
O. Jevons, IOP Joint APP, HEPP and NP Annual Conference 2024

Search for New Particles in the 3 - 60 MeV Mass Range

- The experiment is scheduled to start data taking in June, with two beam energies: $2.2\ \mathrm{GeV}$ and $3.3\ \mathrm{GeV}$, using a 1 μm-thick *Ta* target.
- The scattered electron and decay e^+e^- pairs will be detected in the $PbWO_4$ calorimeter.

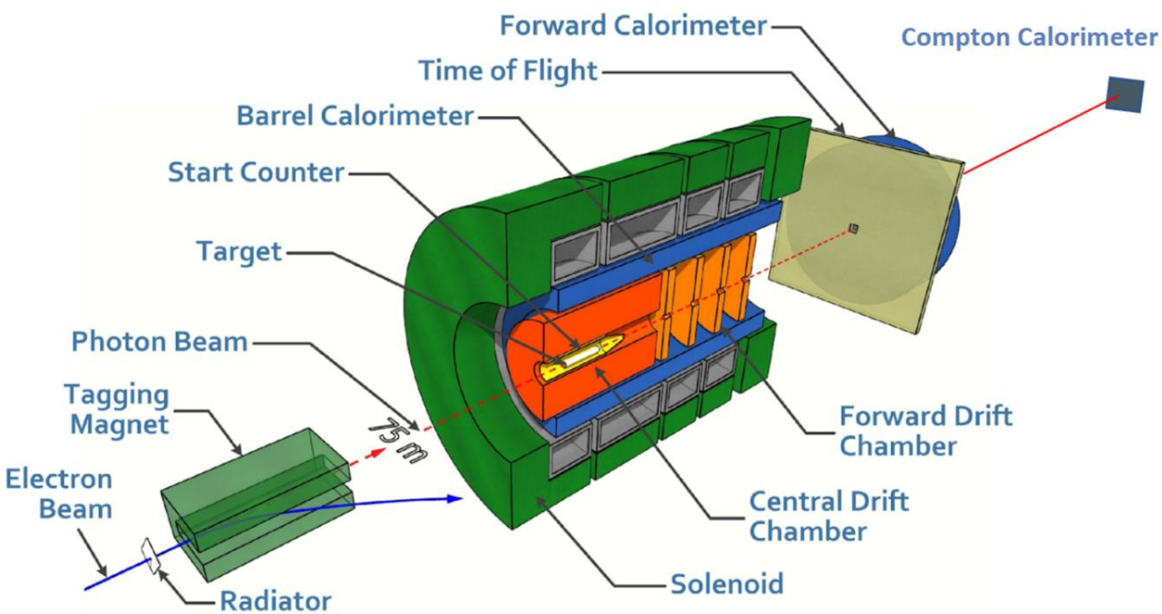


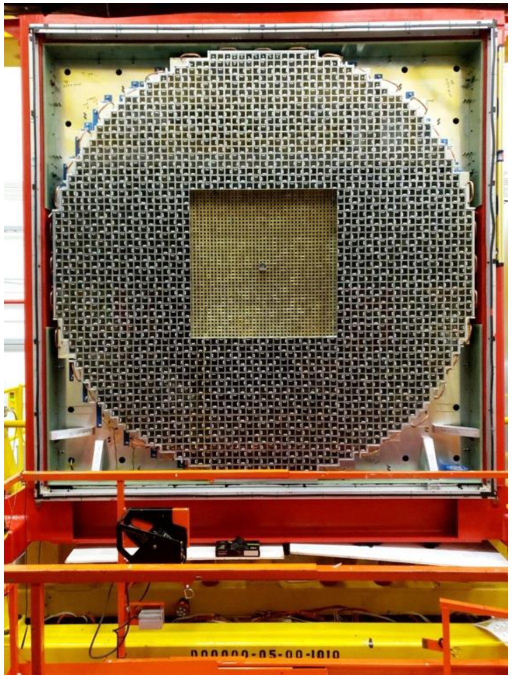




JEF program with GlueX in Hall-D

- The JLab Eta Factory (JEF) experiment will study rear decays of η and η'
- The experiment took $\sim 75\%$ of the expected data in 2025 with the upgrade of FCAL.
- The $\eta(')$ mesons will be produced through $\gamma p \to \eta^{(')} p'$ with an 8-12 GeV tagged photon beams (the expectations for the full dataset are 6x10^7 tagged η and 5x10^7 tagged η').

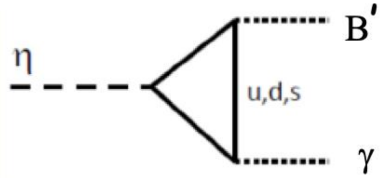


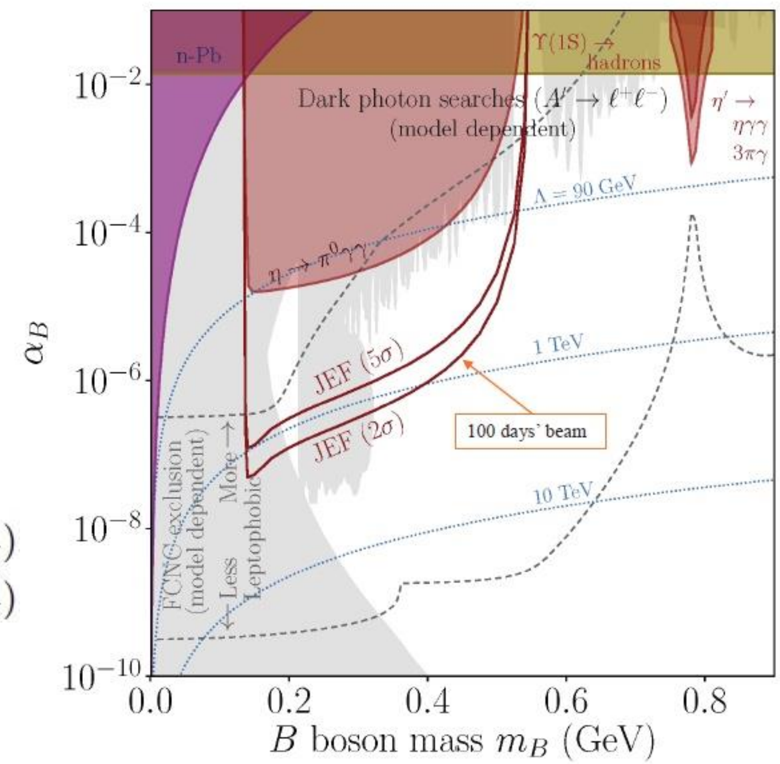


DM searches using JEF data

- The JEF experiment is designed to provide highly sensitive probes over a broad range of physics topics, including the search for new sub-GeV gauge bosons:
  - leptophobic dark vector boson

$$\eta, \eta' \to B'\gamma \to \pi^0\gamma\gamma, \ (0.14 < m_{B'} < 0.62 \text{ GeV})$$
$$\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma, \ (0.62 < m_{B'} < 1 \text{ GeV})$$





  - dark photons or "leptophilic vector bosons"

$$\eta, \eta' \to A'\gamma \to e^+e^-\gamma.$$

  - hydrophilic scalar particles

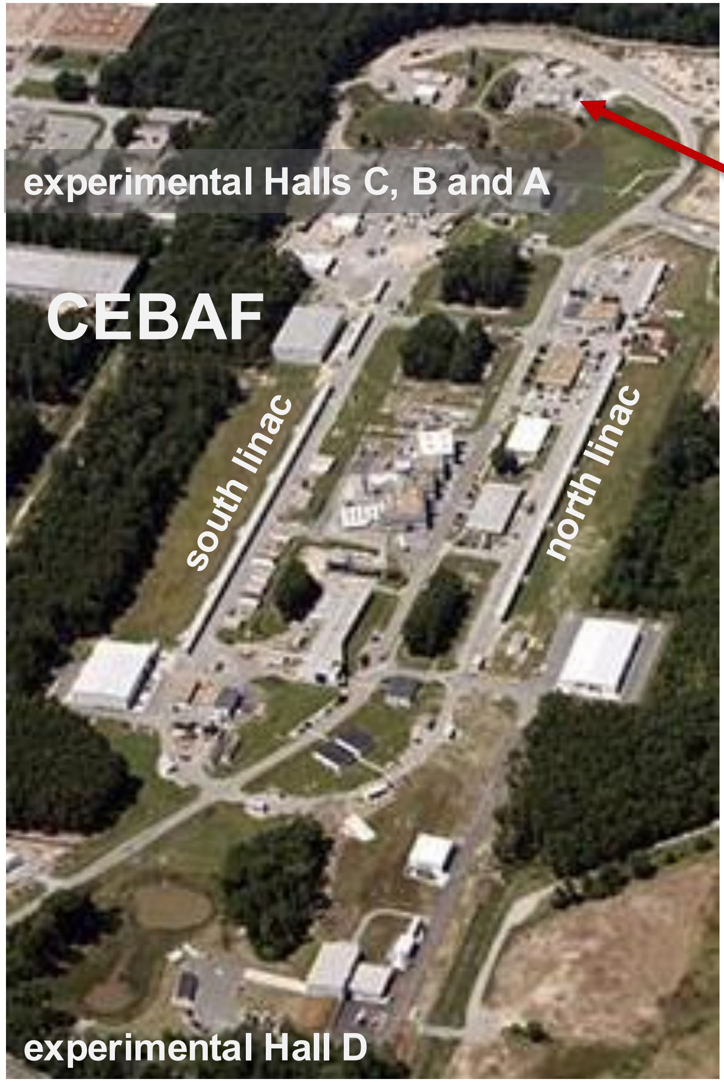
$$\eta \to \pi^0 S \to \pi^0\gamma\gamma, \ \pi^0 e^+e^-, \ (10 \text{ MeV} < m_S < 2m_\pi)$$
$$\eta, \eta' \to \pi^0 S \to 3\pi, \ \eta' \to \eta S \to \eta\pi\pi, \ (m_S > 2m_\pi)$$

  - axion-like light pseudoscalars

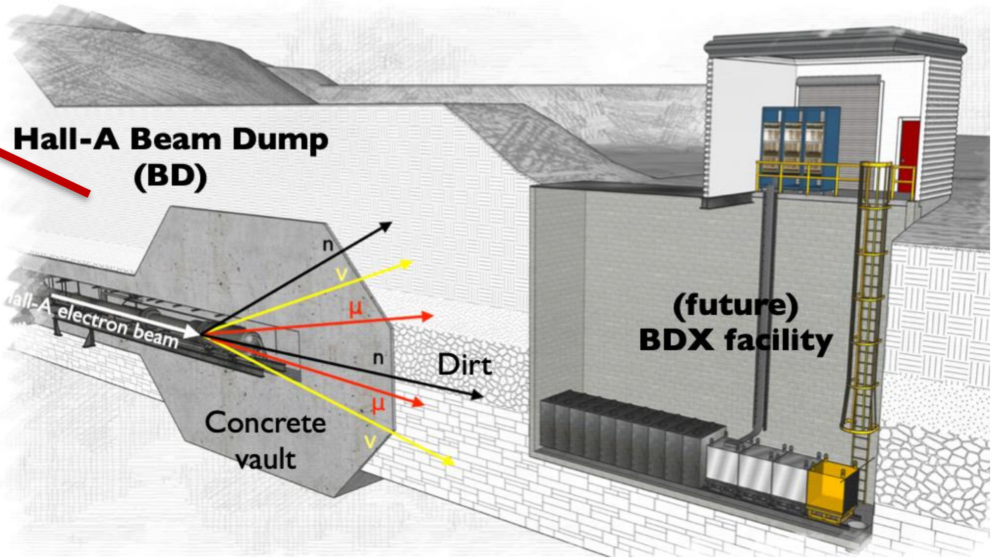
$$\eta, \eta' \to \pi\pi a \to \pi\pi\gamma\gamma, \ \pi\pi e^+e^-$$

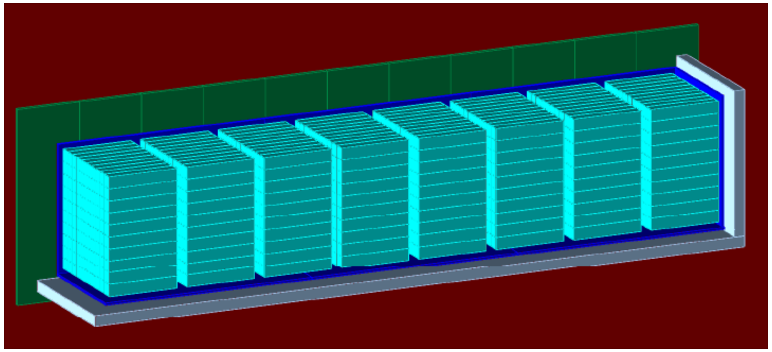
https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF2_RF0_Liping_Gan-017.pdf

BDX at JLAB



New underground facility behind Hall-A dump

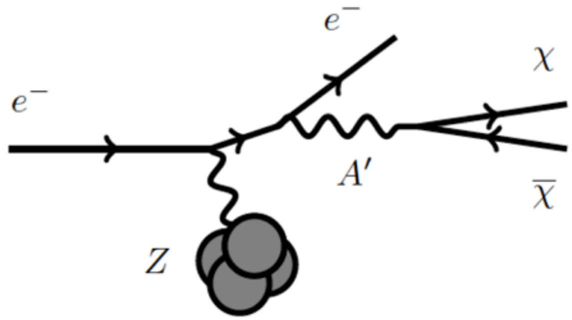




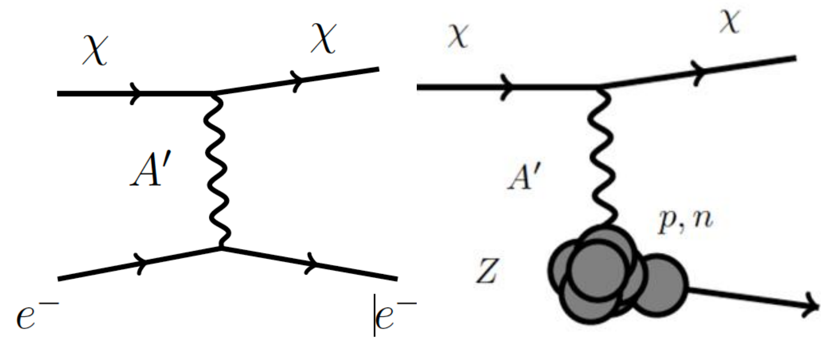
EM calorimeter**BGO** (from BGO-OD experiment)
$PbWO_4$ (from PANDA experiment and Prad HyCal)

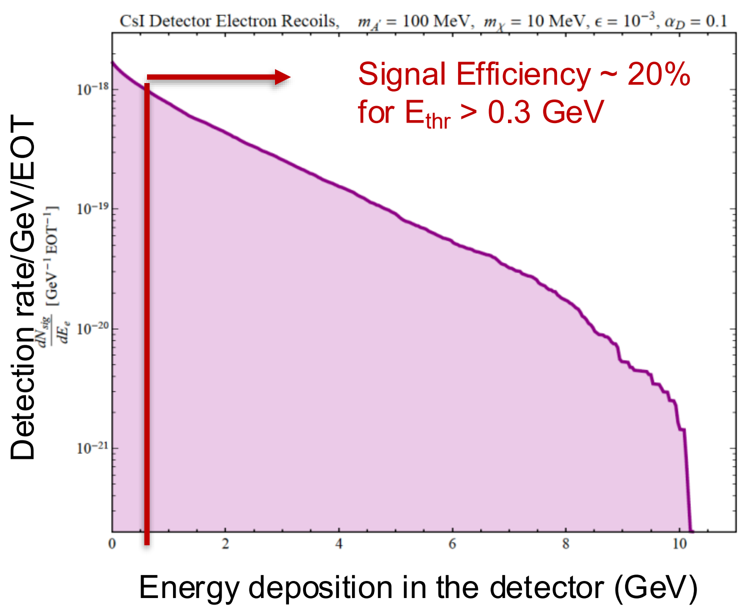
LDM production and detection

$\chi\bar{\chi}$ pair production in electron-nucleon collisions via the radiative process



χ scattering of an electron, nucleon or nucleus in the detector



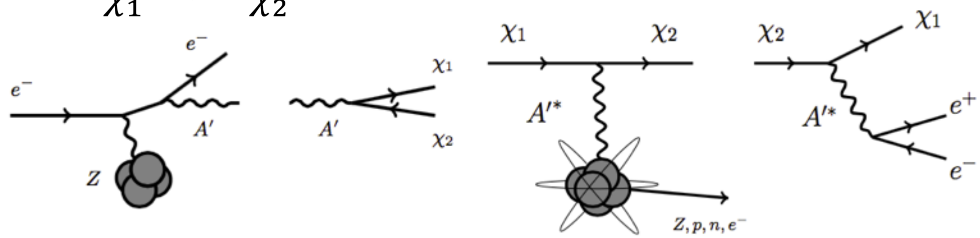


off-shell $m_{A'} < 2m_\chi \Rightarrow N_\chi \sim \frac{\alpha_D \varepsilon^4}{m_\chi^2 m_{A'}^2}$

on-shell $m_{A'} > 2m_\chi \Rightarrow N_\chi \sim \frac{\alpha_D \varepsilon^4}{m_{A'}^4}$

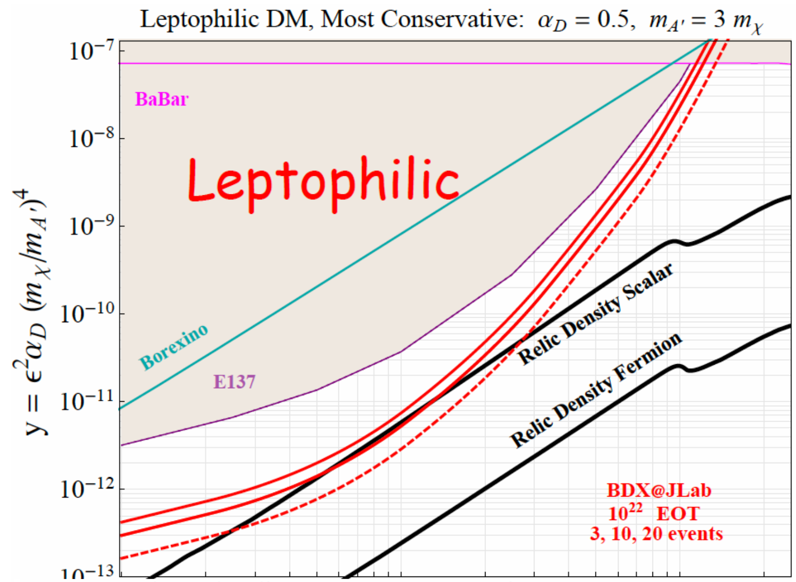
Other well-motivated case – inelastic DM

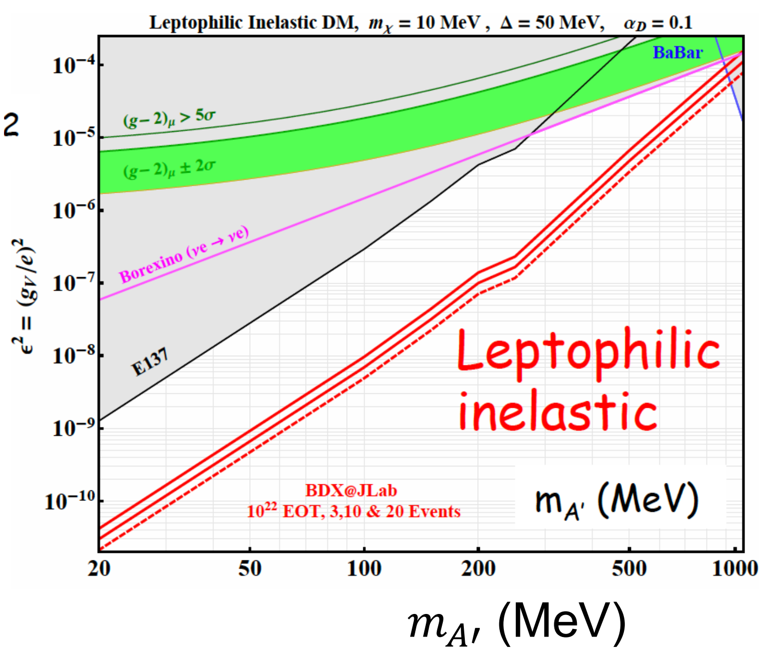
$m_{\chi_1} < m_{\chi_2}$

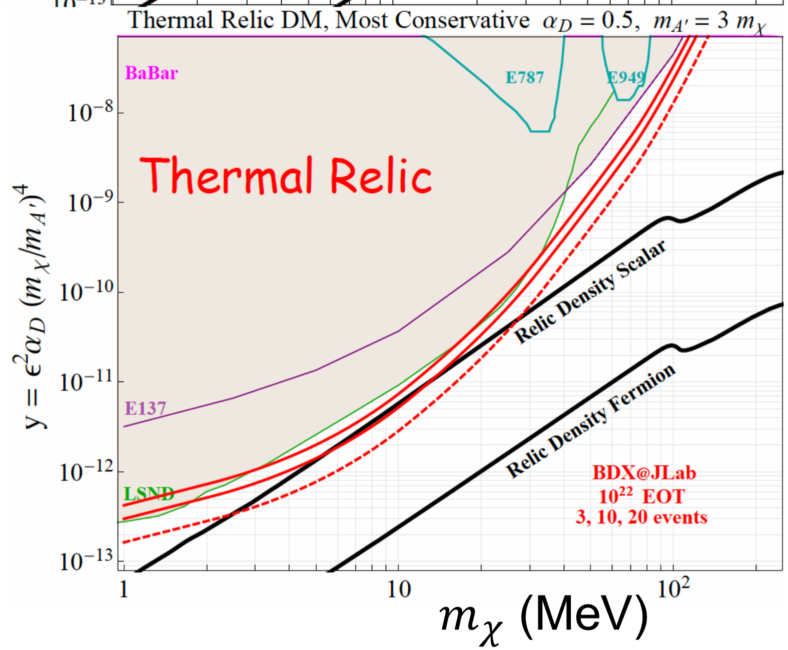


BDX reach

- Many different scenarios of LDM will be studied
- With 10^{22}, 11 GeV EOT, ~40 weeks of Hall-A running at ~60 μA, BDX will be the first electron experiment to reach the neutrino irreducible floor

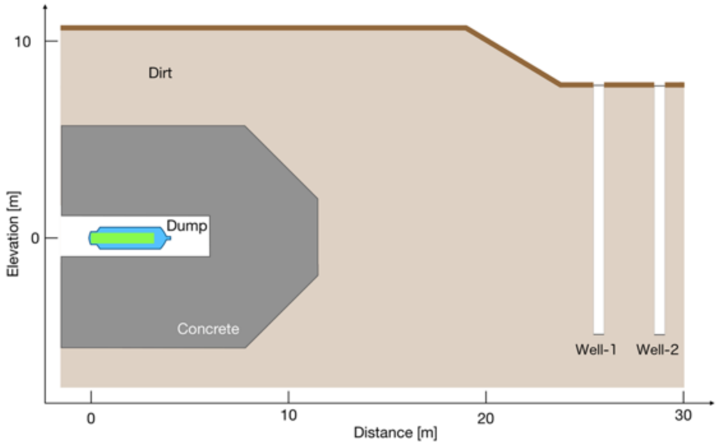






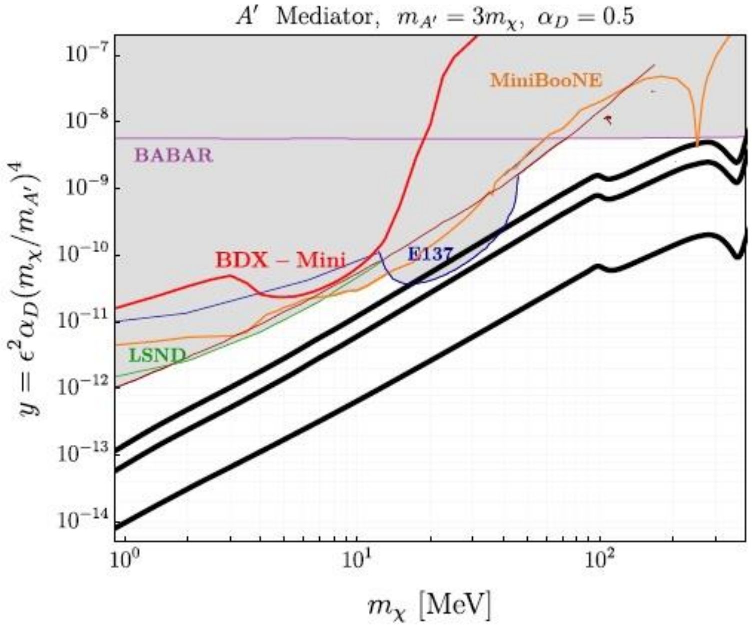
BDX-mini

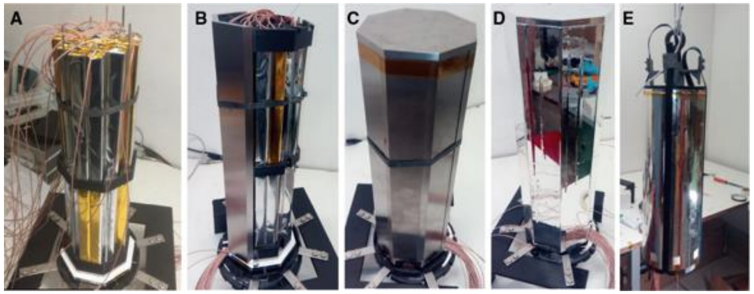
Data taking in 2020, E_b=2.18 GeV



Lowering the detectors in the wells

2.56×10^{21} EOT



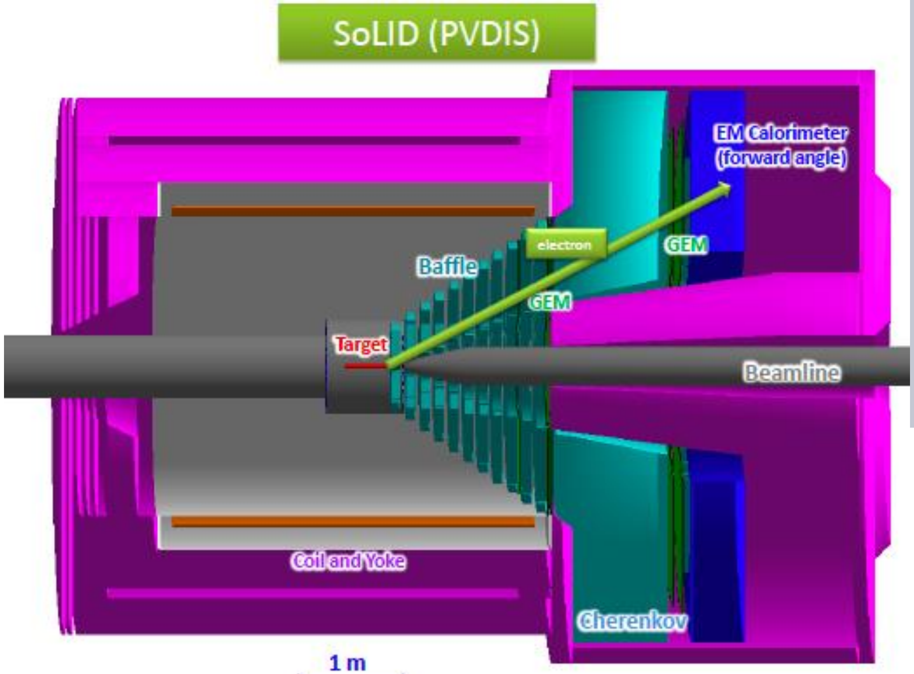


$PbWO_2$ calorimeter, 44 modules, total of $\sim 4 \times 10^{-3} m^3$

New generation PVES experiments

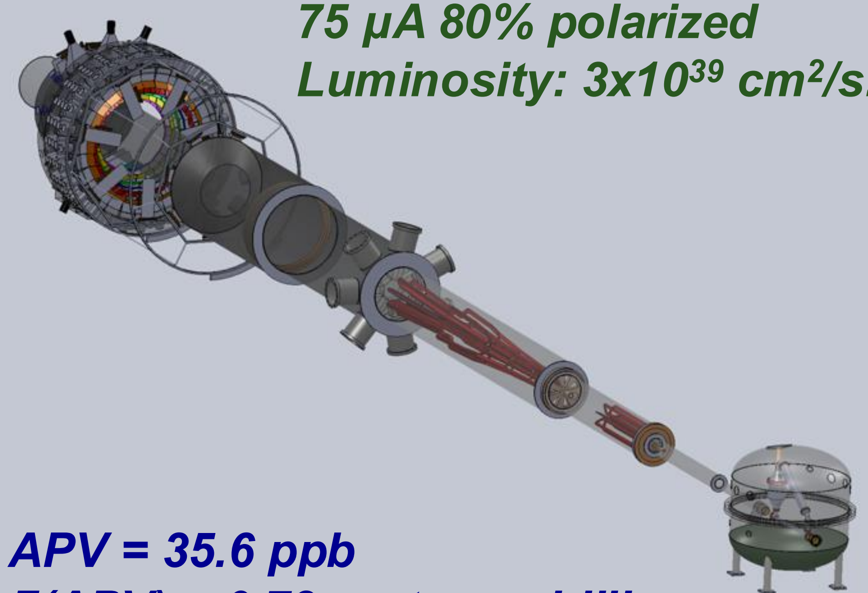
Moller and SoLID in Hall-A

- **Parity violating deep inelastic scattering**
- **Luminosity: 10^{39} cm^{-2} sec^{-1}**



Møller – PV e^-e^- scattering

E_b = 11 GeV
75 μA 80% polarized
Luminosity: 3x10^{39} cm^2/s!

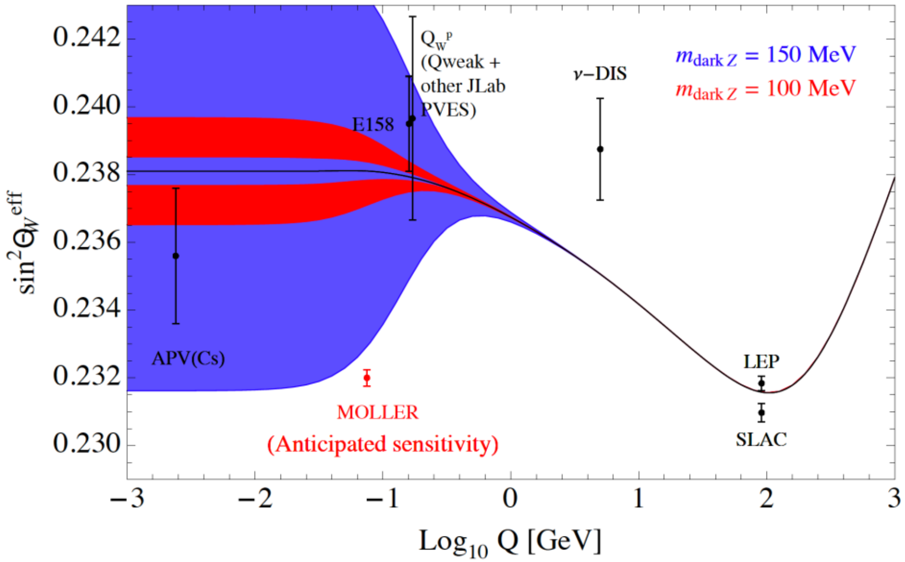


APV = 35.6 ppb
δ(APV) = 0.73 parts per billion
$\delta(Q_W^e) = \pm$ 2.1 % (stat.) $\pm$ 1.0 % (syst.)

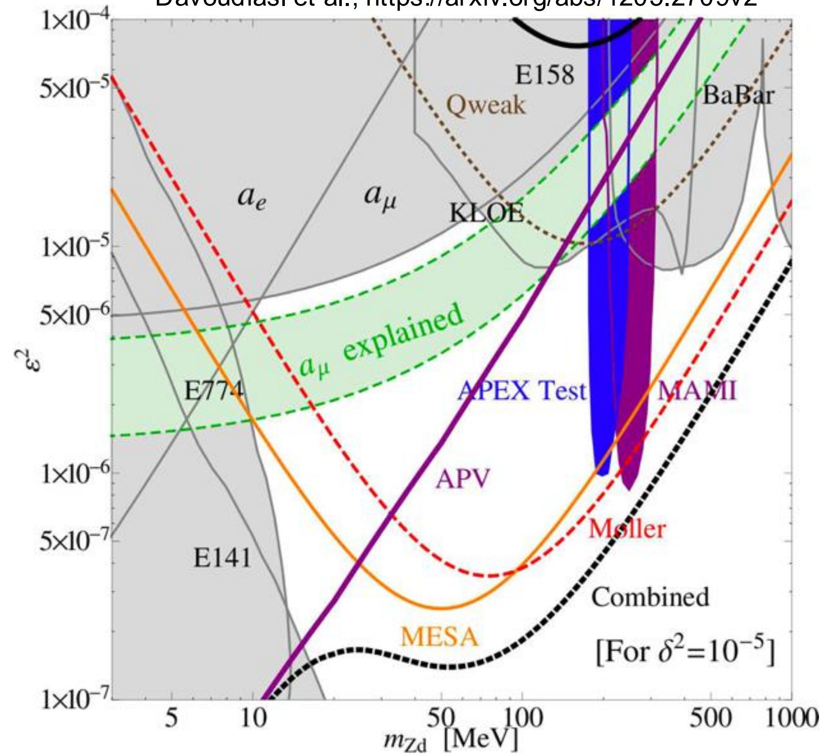
Sensitivity to dark force carriers

- Mass mixing between the ordinary Z boson and a relatively light Z_d boson, the "dark"-Z, arising from a $U(1)_d$ gauge symmetry
- Interference of Z-Z_d – a new source of party violation that can be measure at low Q^2
- Will put constrain 50 – 500 MeV Z_d that $\Gamma(Z_d \rightarrow e^+e^-) \ll 1$

Z_d explains (g-2) anomaly

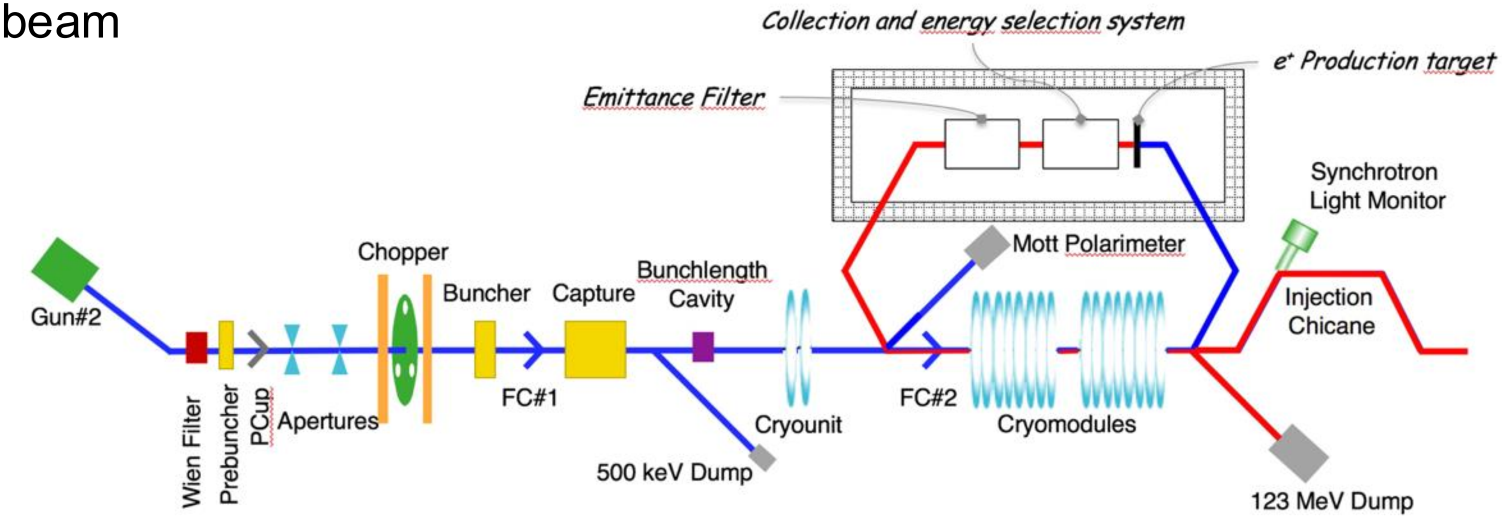


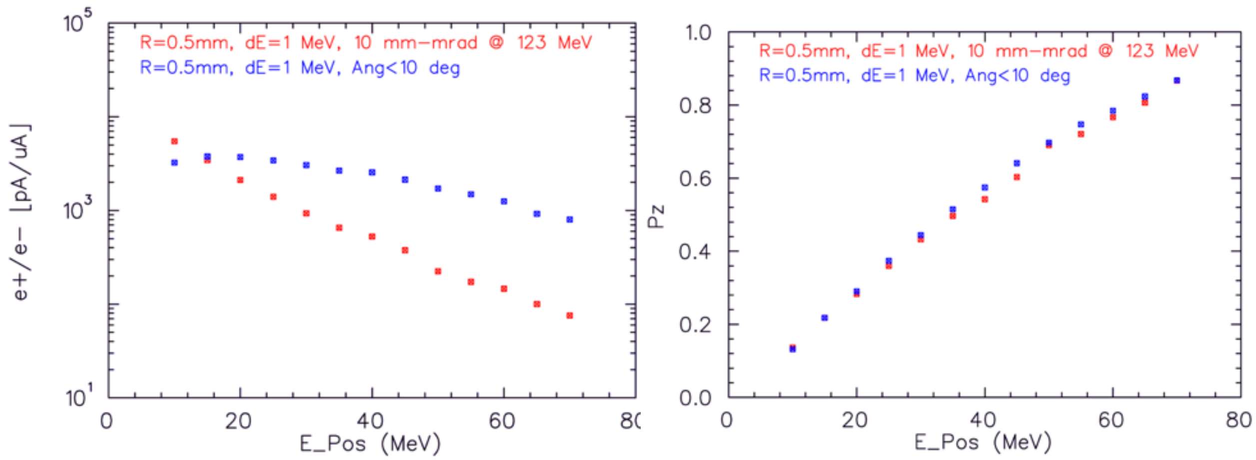
Davoudiasl et al., https://arxiv.org/abs/1205.2709v2



CEBAF with positron beams

Positrons would be created at the CEBAF injector, using the 123 MeV electron beam



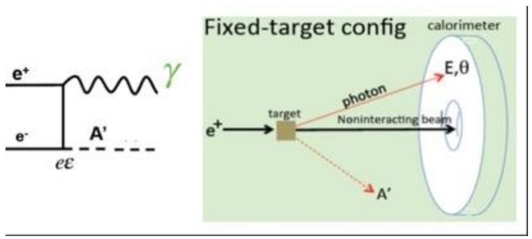


- High energy e+ into CEBAF for high polarization, low current beams (~60% and 100 nA)
- Low energy e+ for high current beams (>1 μA)

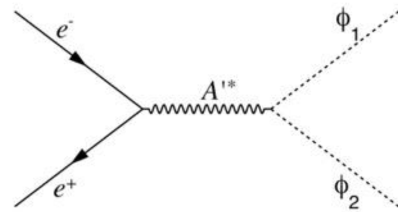
Dark photon searches with positron beams

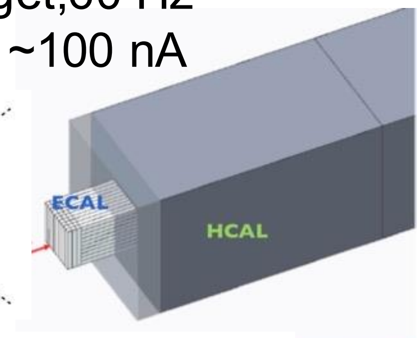
Can reach A' masses of 100 MeV with up 11 GeV e+ beam.

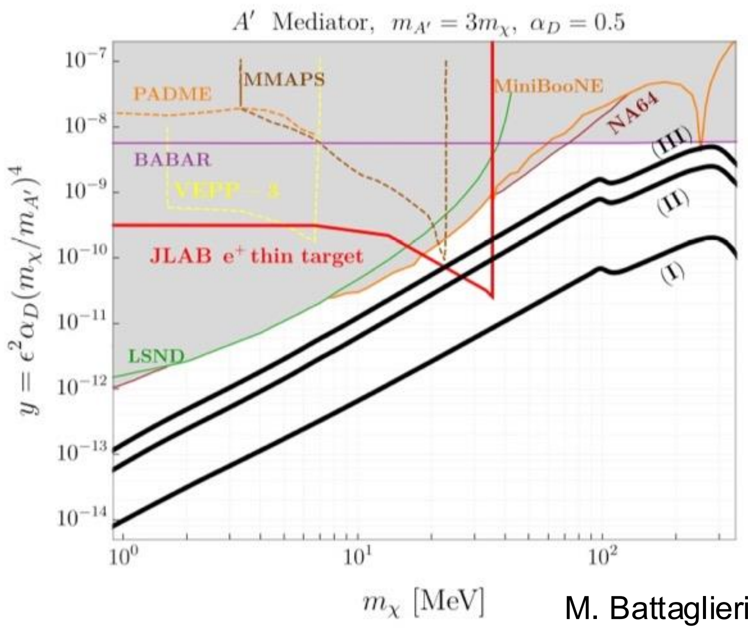
Thin target, CW beam of ~100 nA

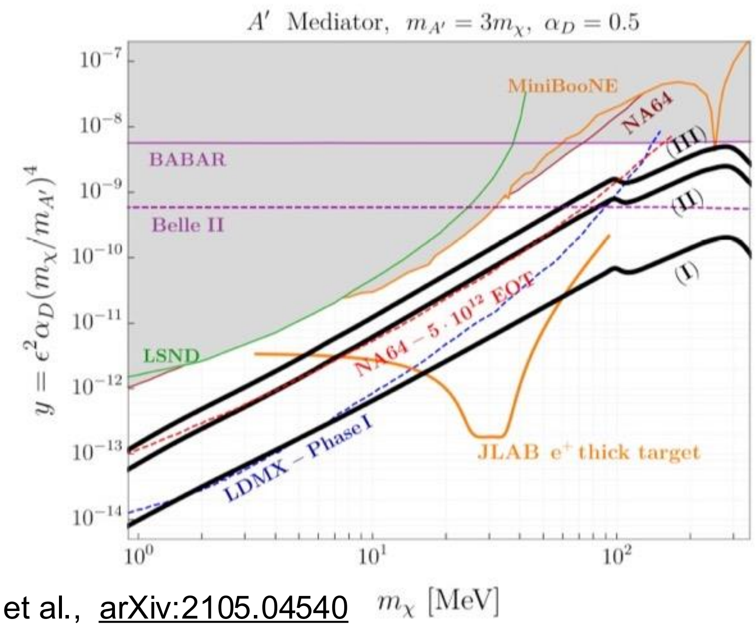


Thick active target,60 Hz pulsed beam of ~100 nA









M. Battaglieri et al., arXiv:2105.04540

Summary

- Available high-intensity, high-polarization electron beams with superb stability enabled JLAB to pursue a rigorous experimental program of precision tests of fundamental symmetries and search for physics beyond the Standard Model
- A program to search for light dark matter and dark force carriers is underway.
- The first experiments (APEX and HPS) demonstrated the expected performance of the experimental apparatus and electron beams, yielding the first results.
- A number of new experiments have been proposed and approved over the past 5-10 years, building a solid program for DM searches at JLAB
- In the next few years, these experiments will dramatically restrict the theoretically motivated parameter space of couplings and masses or make a remarkable discovery.