# Opportunities beyond hadron physics: the physics case

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J-FUTURE Workshop, Messina, Italy

March 29, 2022

# Outline


Introduction to vector-mediated Light Dark Matter

$A'$ Searches At Jefferson Lab
- APEX
- Heavy Photon Search
- BDX-mini
- BDX

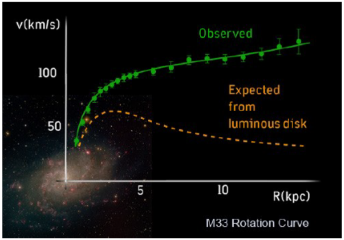
LDM opportunities with a primary $e^+$ beam
- PADME-like
- Missing Energy

Opportunities with secondary beams at JLab
- Muon Beam
- Neutrino Beam

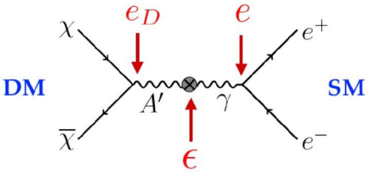
Conclusions

# Vector Mediated Light Dark Matter

- **Plenty of cosmological/ astrophysical observations:** CMB anisotropies, galaxy rotation curves, gravitational lensing,cluster collisions...
- No hints on DM particle properties (mass, cross section) from particle physics experiment
- "vector-portal": DM-SM interaction trough a new U(1) gauge-boson ("dark-photon") coupling to electric charge




$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$



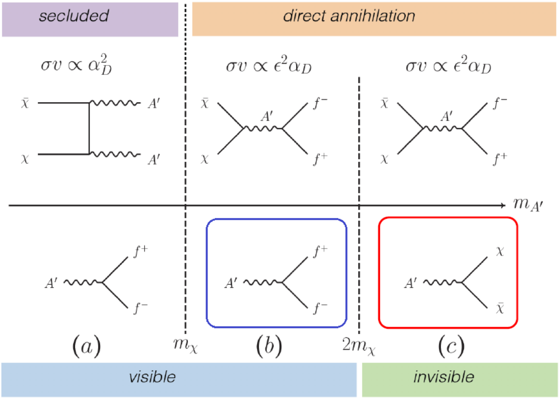

$$\alpha \equiv \frac{e^2}{4\pi}$$

# Dark Photon Signatures

(a) **secluded scenario**. No constraints provided by cosmology for accelerator-based experiments: any $\varepsilon$ value is allowed

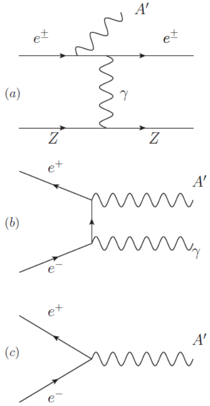
(b) **visible decay scenario** (although off-shell $\chi\bar{\chi}$ production is allowed)

(c) **invisible decay scenario** $A'$ decays to Dark Sector *invisible* particles



# Dark Photon Production Mechanisms With Lepton Beams

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



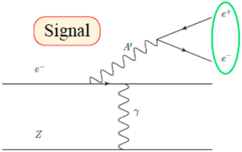

(a) $A'$-**strahlung**: Radiative $A'$ emission in nucleus EM field - scales as $Z^2\alpha_{EM}^3$. Forward-boosted, high-energy $A'$ emission

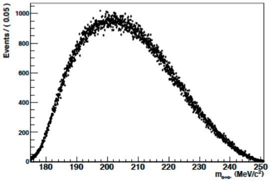
(b) $e^+e^-$ annihilation: scales as $Z\alpha_{EM}^2$. Forward-backward $A'$ emission in the CM

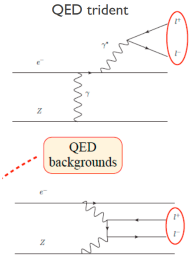
(c) **Resonant** $e^+e^-$ annihilation: resonant Breit-Wigner like cross section with $m_{A'} = \sqrt{2m_e E}$ - $Z\alpha_{EM}$ scaling.

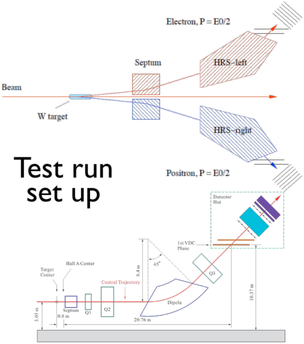
# APEX

- dark photon searched for as peak of invariant mass (reconstructed from both arms) : $e^-$ in LHRS and $e^+$ in RHRS
- Standard HRS detector stack in both arms: Scintillators: S0 and S2 (timing), VDC (tracking), Cherenkov and Calorimeters (PID)



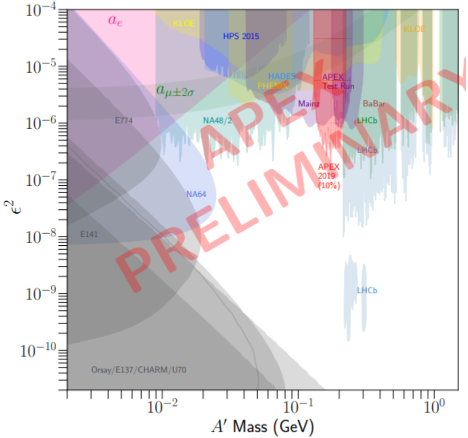



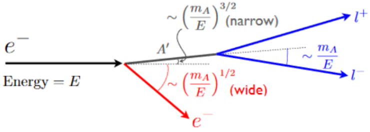
# APEX estimated limits

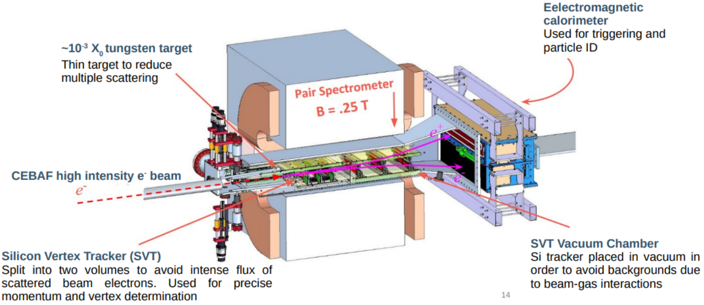
Preliminary test on blinded invariant mass spectrum: limits for 10% spectrum



# Heavy Photon Search (HPS)

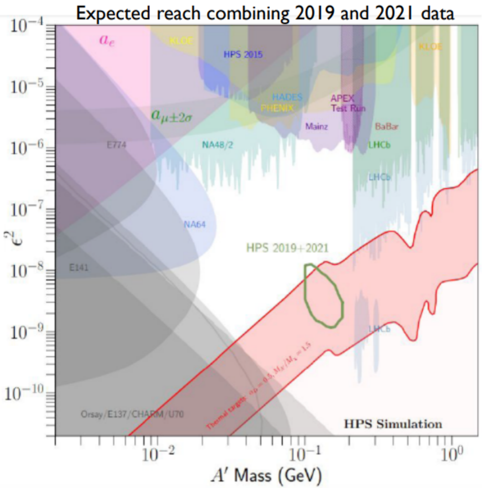
- $A'$ radiative production via $e^-$ beam impinging on thin tungsten target
- Search for visible $A'$ decay
- $e^+e^-$ pair detection via tacker+ECAL



# HPS status and estimated reach

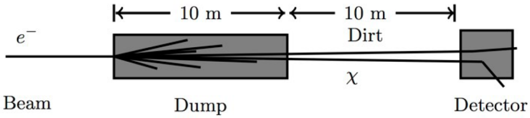
- First engineering run in 2015
- Analysis of data from 2016 physics run is complete
- Collaboration busy with calibration and analysis of 2019 and 2021 data.
- Physics goals expanded to other long-lived particle searches, e.g., SIMPs.



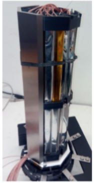
# BDX-mini

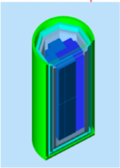
**Electron beam dump experiment at Jefferson Lab**

- CEBAF 2 GeV $e^-$ beam impinging on the dump
- secondary beam of $\chi$ particles beam produced through all previously discussed physics reactions
- Compact $\mathrm{PbWO_4}$ detector ($3.7 \times 10^3$ $cm^3$) placed in a pipe dug 25 m behind the dump
- Neutral-current scattering on atomic e- through $A'$ exchange, recoil releasing visible energy O(100 MeV)




See EPJ C 81:164 (2021)

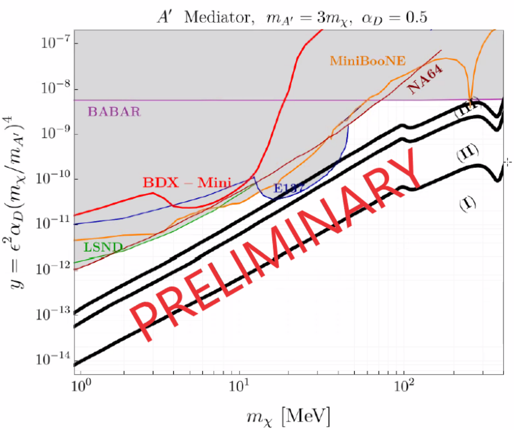




# BDX-mini reach

Measurement took place in spring-summer 2020

- collected $\sim 3 \times 10^{21}$ EOT
- beam enrgy: 2.176 GeV
- beam current up to 150 $\mu$A
- beam-on and beam-of measurements alternate (50% beam-on time) to estimate cosmic backgrounds



# BDX: Beam Dump eXperiment

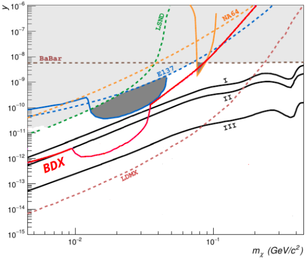
Natural evolution of BDX-mini: 11 GeV $e^-$ beam - approved experiment at Jefferson Lab

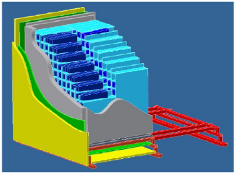
**Experimental Setup:**

- Detector installed O(20 m) behind Hall-A beam -dump, in a new experimental hall (see M. Bondì talk)
- Passive shielding layer between beam dump and detector to reduce SM beam-related background

**Detector Design:**

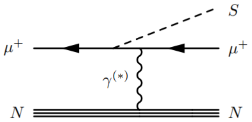
- EM calorimeter: CsI(Tl) crystals+SiPM readout (active volume $\simeq 0.5\ m^3$)
- Dual active-veto layer made of plastic scintillator counters + SiPM readout
- Passive lead layer surrounding the calorimeter

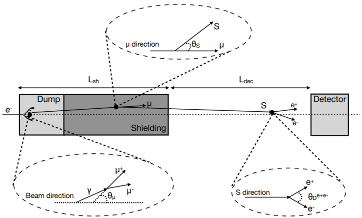


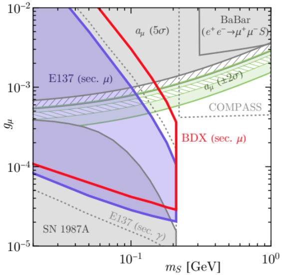



# Probing muon-philic forces with BDX

- Sizable flux of high energy muons produced in the dump by the interaction of the $e^-$ beam (see Talk by A.Fulci)
- Use the secondary muon beam to produce exotic particles accounting for $g-2$ anomaly




see Phys. Rev. D 98, 115022 (2018)

# Light Dark Matter Opportunities With Positron Beams

- Ongoing discussion on the possibility to realize positron beam at JLab
- LDM experiments with $e^+$ can fully exploit annihilation processes
- b) and c) can be a more efficient production process than a), given the better $\alpha$ scaling


The European Physical Journal A
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An Experimental Program with Positron Beams at Jefferson Lab

ISSN: 1434-6001 (Print) 1434-601X (Online)

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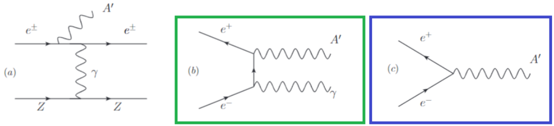
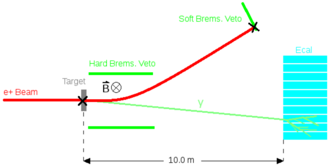
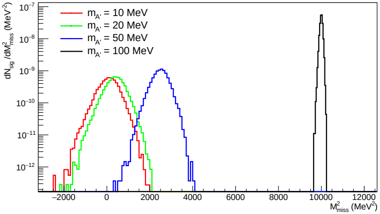


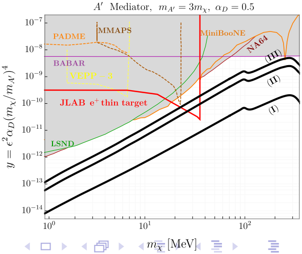
# Thin Target Setup

**Thin target approach: PADME-like eperiment**

- 100 nA, 11 GeV $e^+$ beam impinging on 100 $\mu m$ thin carbon target
- $A'$ produced via $e^+e^- \to \gamma A'$ process
- outgoing photon measured in electromagnetic calorimeter and missing mass computed: $M^2_{miss} = (P_{beam} + P_{target} - P_\gamma)^2$
- search for a $M^2_{miss}$ peak over smooth SM background

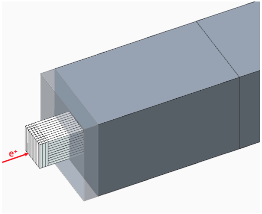


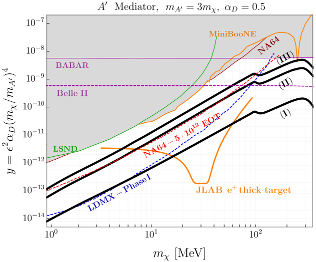



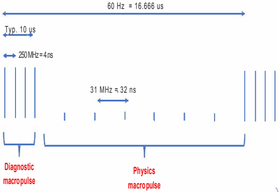
# Thick Target Setup

- Missing energy experiment with a 11 GeV positron beam
- $e^+$ impinging on active thick target (ECAL); $A'$ produced via resonant process $e^+e^- \rightarrow A'$
- large missing energy as LDM production signature: $E_{miss} = E_{beam} - E_{ECAL}$
- HCAL to detect neutral particles escaping the ECAL mimicking signal



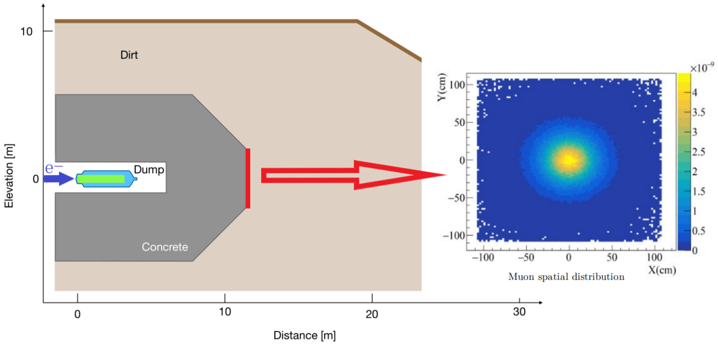




Non-trivial beam structure necessary:



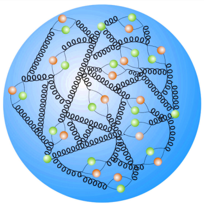
# Extracted muon beam at JLab

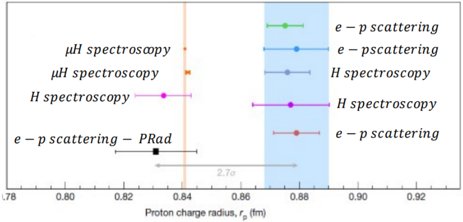
- Secondary muons produced in the Hall-A beam dump can be extracted and directed towards a new hall behind the dump bunker
- Muons may be tagged with a time of flight (TOF) system.
- Feasibility study ongoing (see A. Fulci talk)



# Proton radius measurement with muon beam

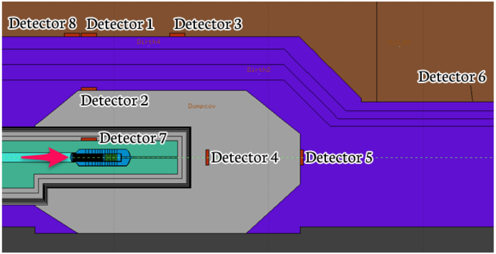
- Proton radius can be measured with 2 techniques:
  - Leptonic scattering
  - Spectroscopic measurement
- $\sim 3\sigma$ discrepancy between methods $\rightarrow$ Proton radius puzzle
- Electron scattering measurement affected by radiative corrections $\rightarrow$ need for intense muon beam for complementary $\mu p$ scattering. Collect muons behind Hall-A?



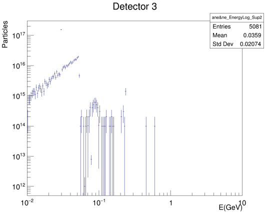


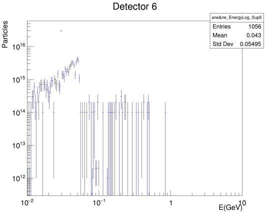
# Secondary $\nu$ beam at JLab

- A large flux of neutrinos is produced in the Hall-A beam-dump from $\pi$ and $\mu$ decay
- Energy range $\sim$few MeVs - O(100 MeV)
- Intensity $10^{-3}\ \frac{\nu}{m^2 EOT}$ at $\sim$10 m above the dump
- Weak angular dependence




Courtesy of A. Fulci



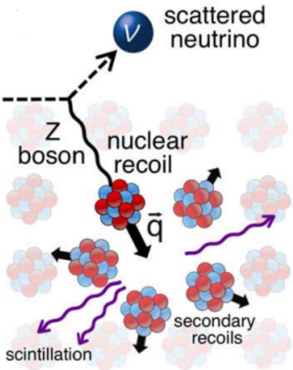
# CE$\nu$NS measurement at JLab

Coherent Elastic Neutrino Nucleus Scattering ( CE$\nu$NS):

- Low energy neutrinos ($< 50$ MeV) coherently scatter on entire target nucleus: $q < \frac{1}{R_N}$
- Cross section scaling with $N^2$
- Low recoil energy due to kinematics: $\Delta E_{max} \simeq \frac{2E_n^2}{M}$ O(100 KeV) in IAR
- First measurement in 2017 on CsI(Na)

Why interesting?

- sterile neutrinos
- neutrino magnetic moment
- non standard interactions (NSI) mediated by exotic particles
- weak nuclear charge




Possibility to run an *CE$\nu$NS* experiment at JLab currently under study (See M.Bondì talk)

# Conclusions

- Jefferson Lab features a rich BSM 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
- Secondary beams produced in the Hall-A dump (muons, neutrinos) can be exploited to explore "hot" physics scenarios (proton radius, CE$\nu$NS).