Exploring the Dark Sector with Visible Probes

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LDMA '19

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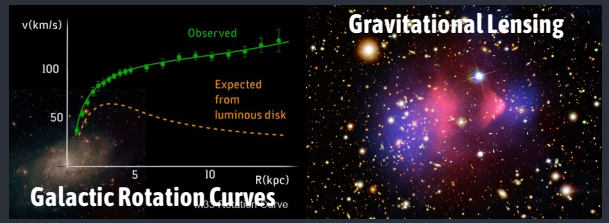
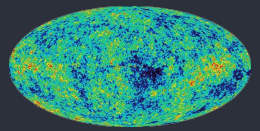
The Hunt For Dark Matter

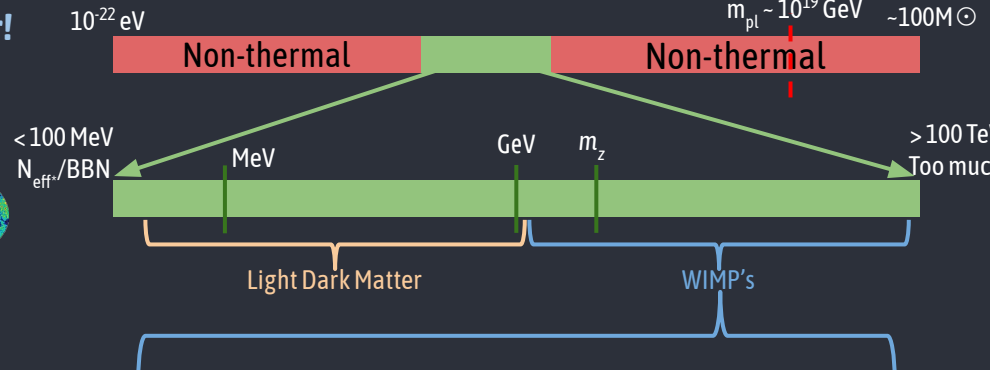
There is strong evidence for the existence of Dark Matter!

arXiv:0404175

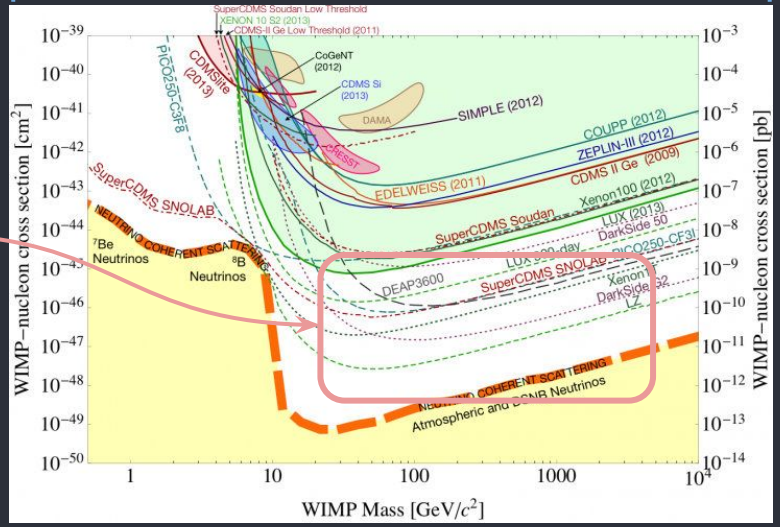




Structure of Cosmic Microwave Background



Broad and impressive program has been built to understand the upper half of the thermal mass window (~GeV - TeV), but searches for WIMP Dark Matter in the most favorable areas have yielded nothing → Next gen (e.g. SuperCDMS, LZ or LHC) experiments will cover a large portion of the remaining parameter space.



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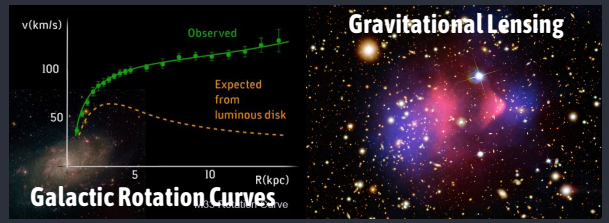

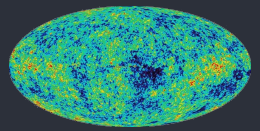

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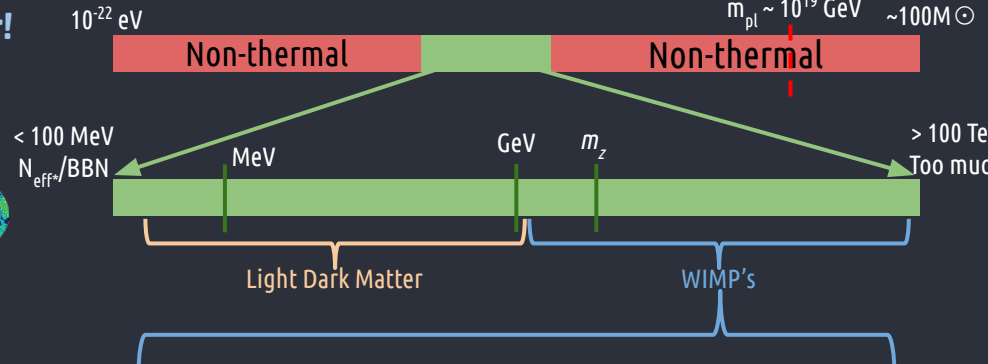

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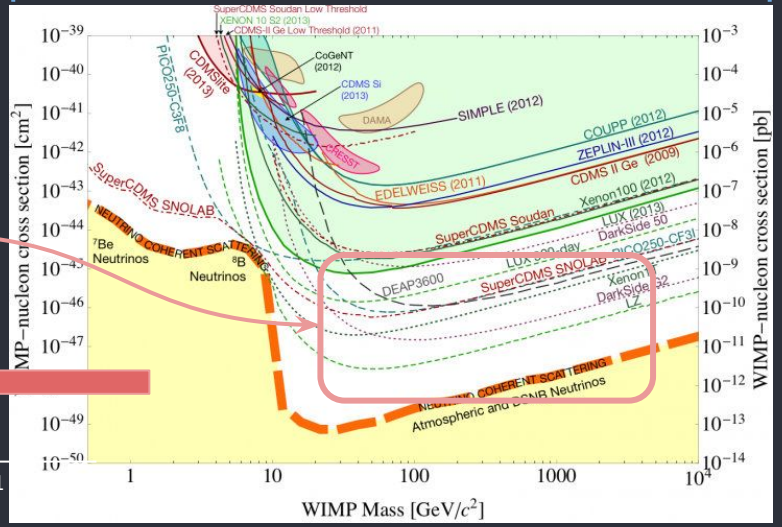
What about the lower half (~MeV - GeV)?



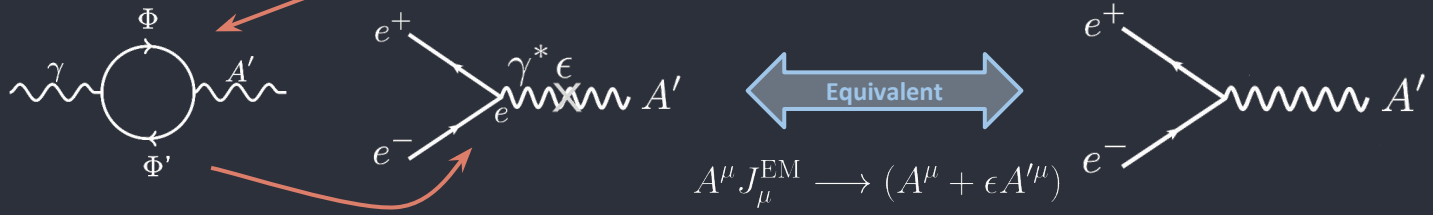
Dark Photon Primer

Light Dark Matter in the broad vicinity of the weak scale is a natural/simple generalization of WIMPs → **Requires a new force** to achieve the correct thermal relic abundance

Holdom, Phys. Lett. B166, 1986

Simplest scenario: DM is charged under a new $U(1)'$ gauge field mediated by a $U(1)'$ gauge boson (dark/heavy photon, A′)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$



$$A^{\mu} J^{\rm EM}_{\mu} \longrightarrow (A^{\mu} + \epsilon A'^{\mu})$$

Mixing naturally generated at loop level assuming existence of heavy multiples charged under both SM charge and dark charge

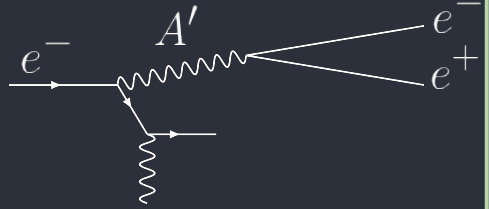
$$\epsilon \sim \frac{g_Y g_D}{16\pi^2} \ln\left(\frac{m_\Phi}{m_{\Phi'}}\right) \sim 10^{-3} - 10^{-1}$$

No split multiples? Mixing can be generated by additional loops

$$\epsilon \sim 10^{-6} - 10^{-3}$$

Production of Dark Photons

e^- Fixed Target



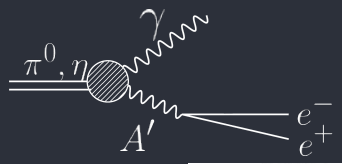
DARKLIGHT

HEAVY PHOTON SEARCH

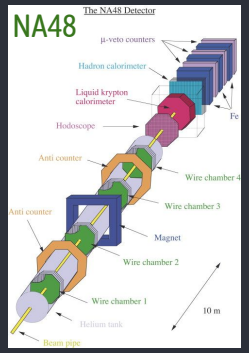
MAGIXDAW

APEX

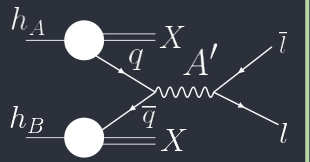
p Fixed Target



HADES

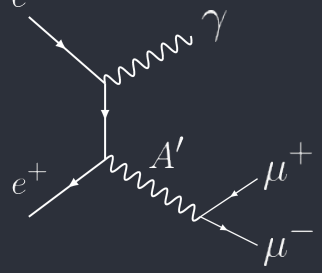


SeaQuest E906



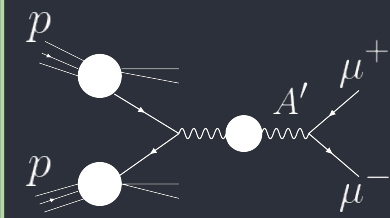
Drell-Yan

e^+e^- Colliders



Belle II

pp Colliders



LHCb

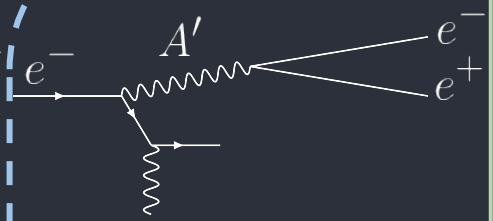
CMS

ATLAS EXPERIMENT

SLAC

Production of Dark Photons

e^- Fixed Target



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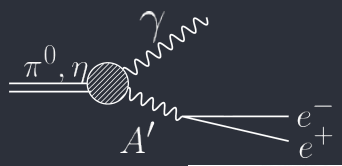

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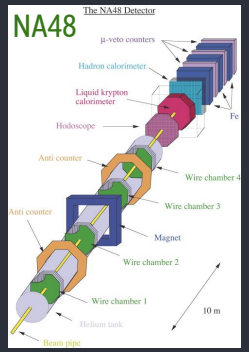

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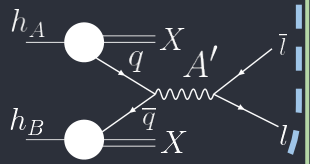

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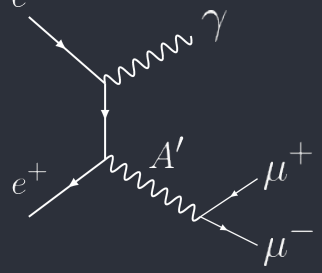

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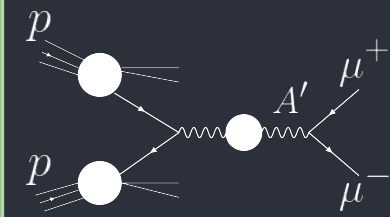

LHCb

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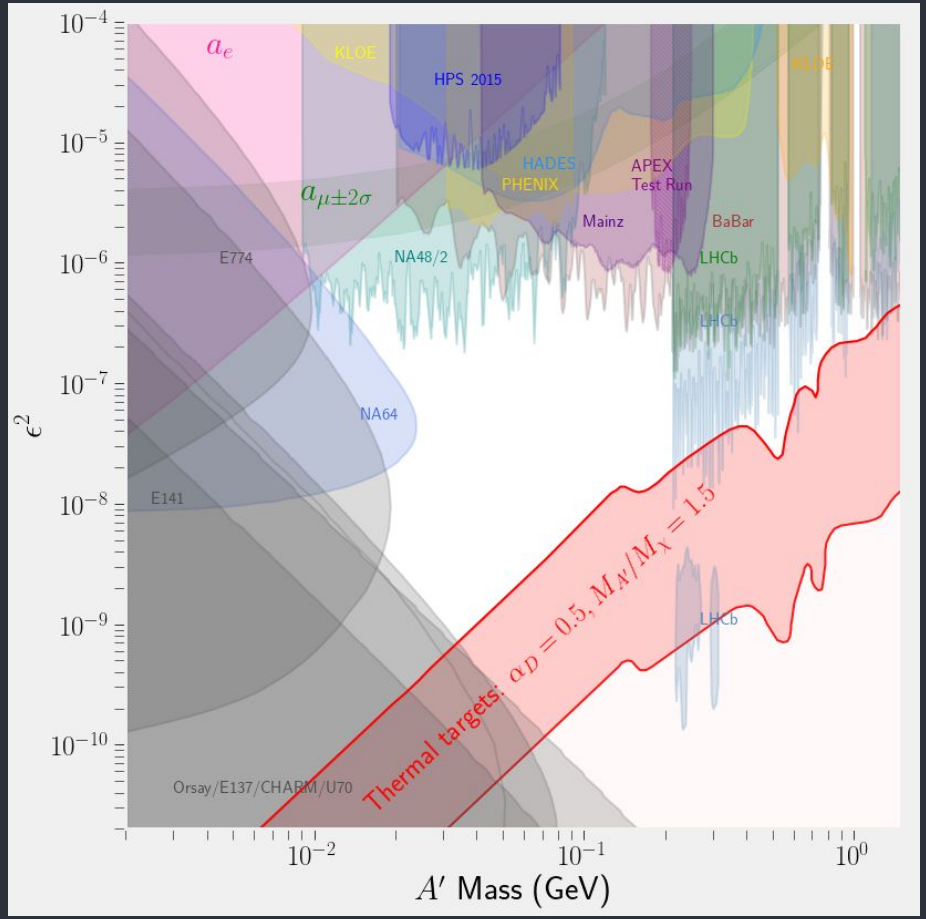
ATLAS EXPERIMENT

SLAC

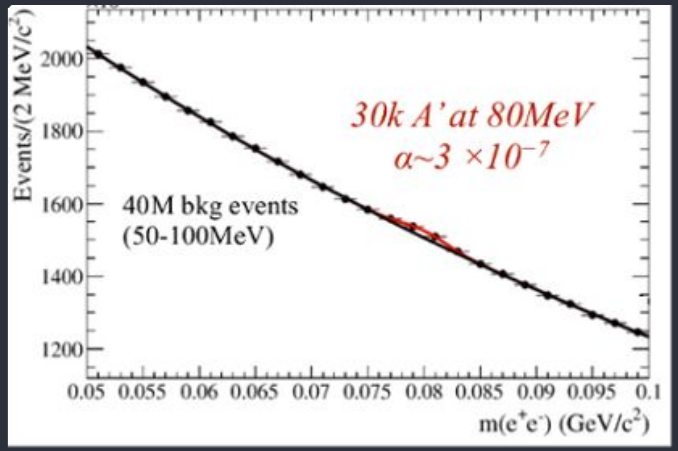
With an emphasis on recent results and an eye towards the future

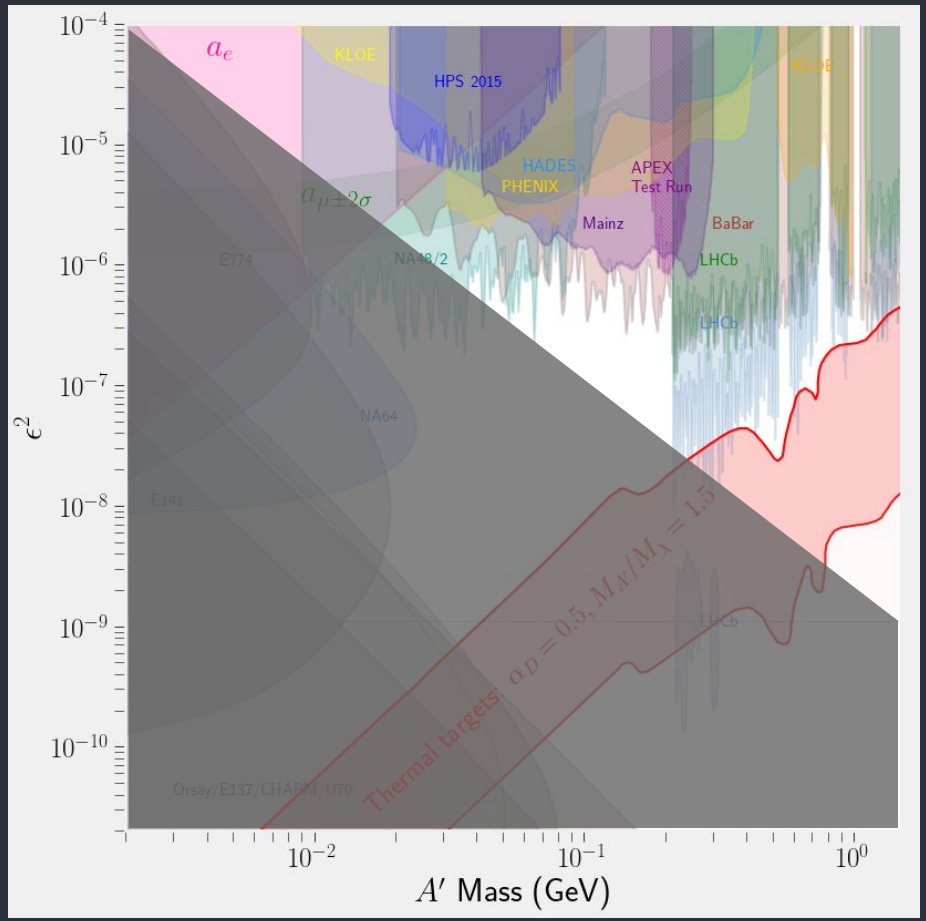
Visible Decay Parameter Space



Visible Decay Parameter Space

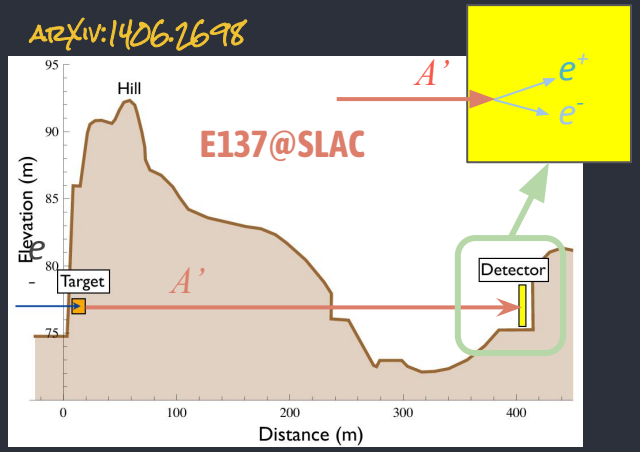
"Bump Hunt" searches: Look for an excess above a continuous background → Large signal yield limits these types of searches to large coupling

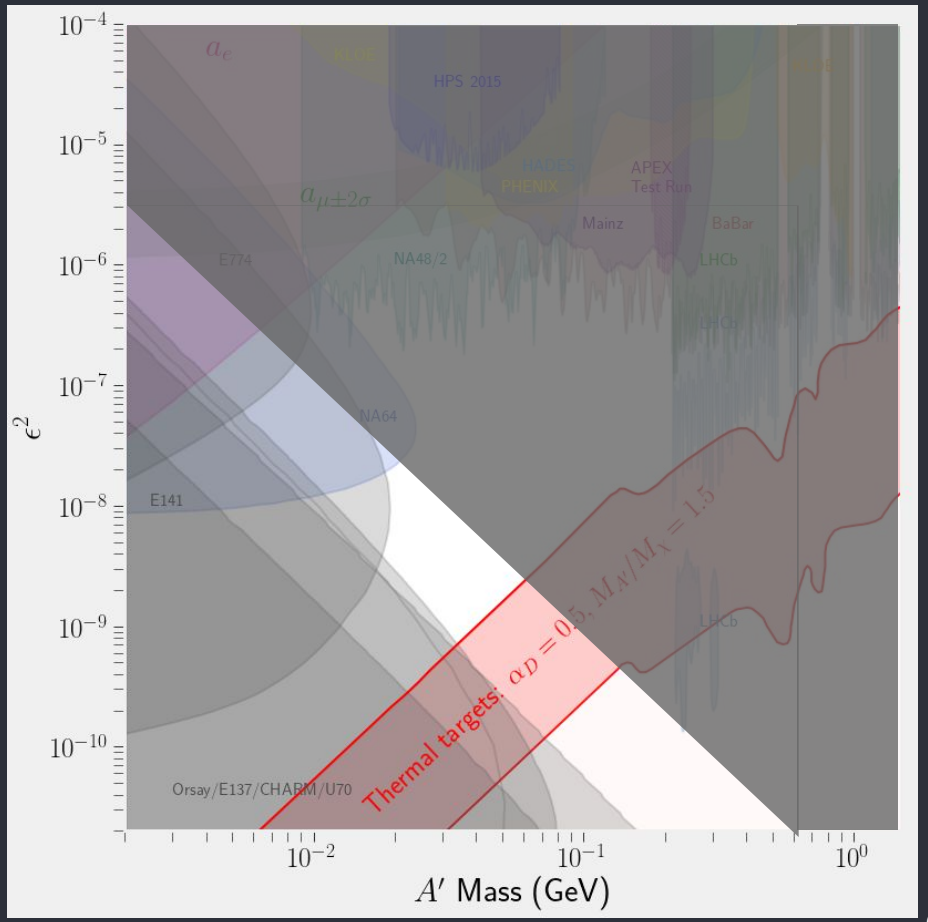




Visible Decay Parameter Space

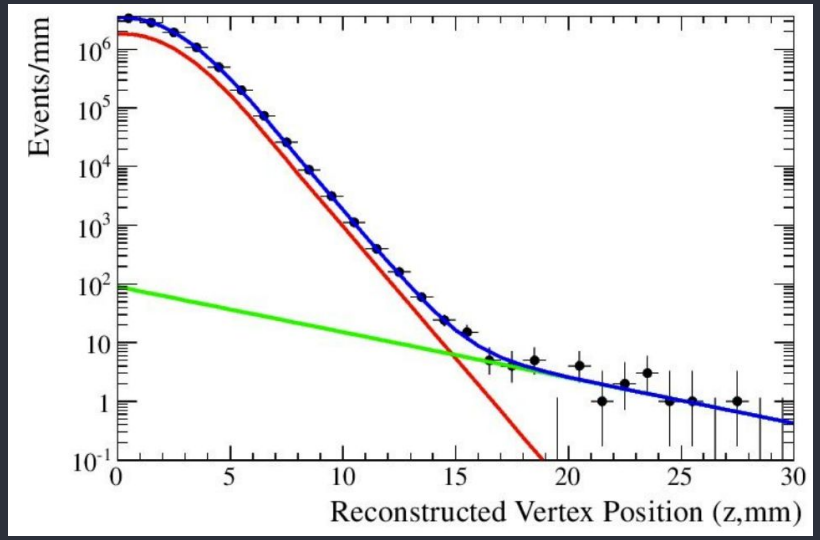
A' becomes long lived for small coupling $\gamma c\tau \propto \frac{1}{\epsilon^2 m_{A'}^2}$

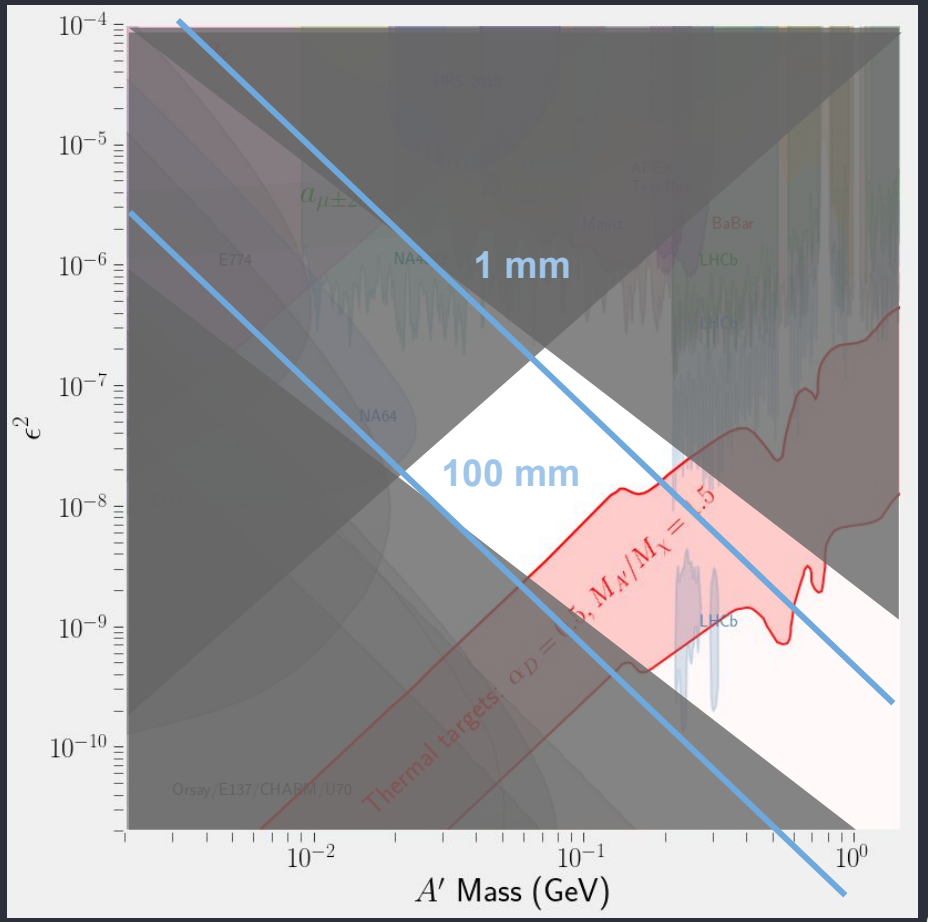




Visible Decay Parameter Space

A' decay length on the order of mm - ~100 mm → Requires precision vertex measurement

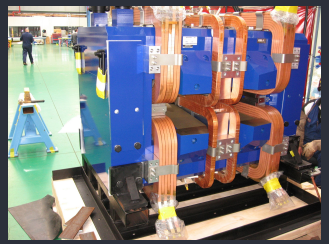


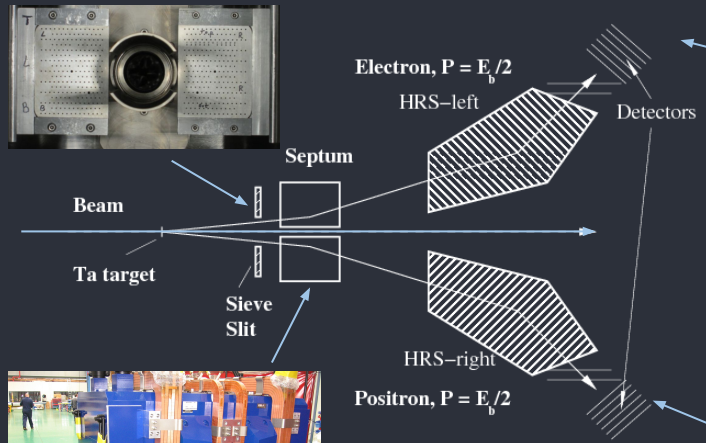


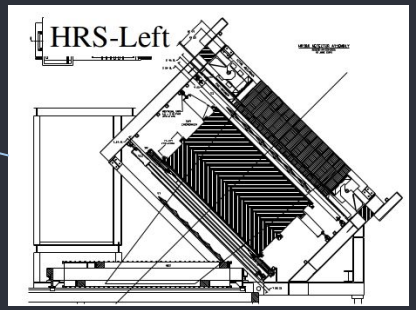
APEX at Jefferson Lab

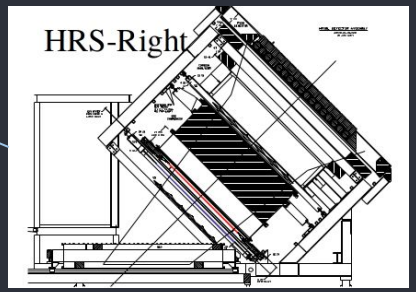
PHYS.REV.LETT. 107 (2011) 191804

e^- fixed target experiment taking place in Hall A at Jefferson Lab searching for dark photons in the mass range 65 to 550 MeV









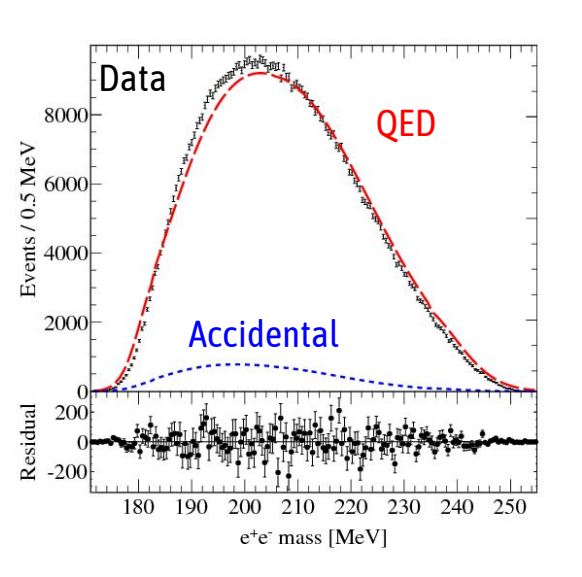
Detector package
- VDC for tracking
- Pair of scintillators for coincidence timing
- Gas Cherenkov for PID
- Lead glass calorimeter for pion rejection

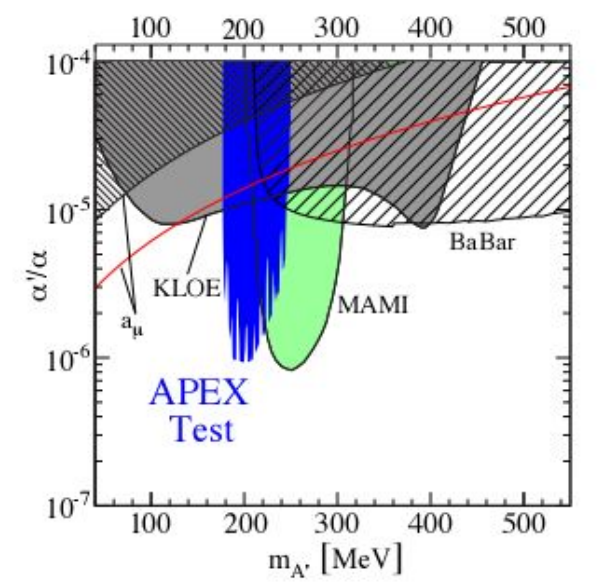
APEX at Jefferson Lab: 2010 Test Run

PHYS.REV.LETT. 107 (2011) 191804

Proof of concept test run in 2010 (2.2 60 GeV, 150 uA beam) verified all key aspects of the apparatus performance and achieved a physics results

Resonance search conducted in the mass range 175 - 250 MeV using ~700 k trident events

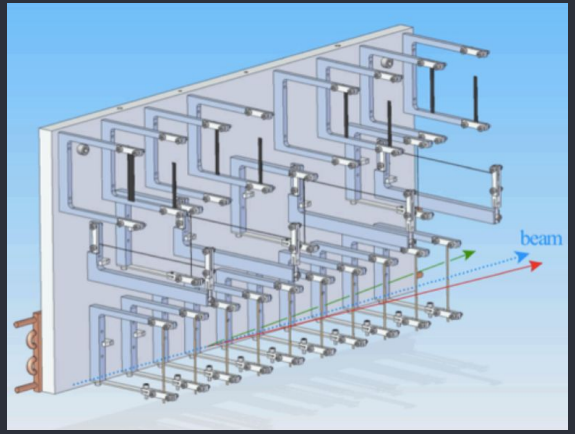


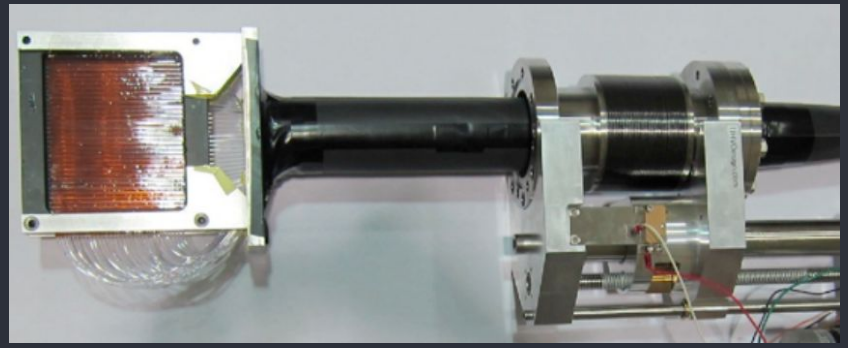


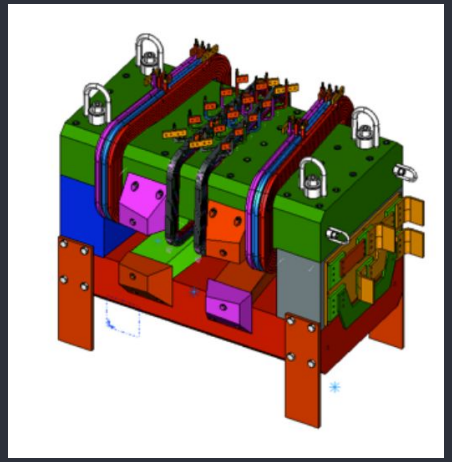
APEX at Jefferson Lab: 2019 Physics Run

Run took place from 2/1 - 3/10 using a 2.2 GeV, 100 μA (max current)

- Used extended tungsten target with 15 um foils
- New septa magnet was installed optimized for full angular acceptance
- Active sieve slit (SciFi) installed
- Spectrometer and focal plane detector package was the same as in 2010







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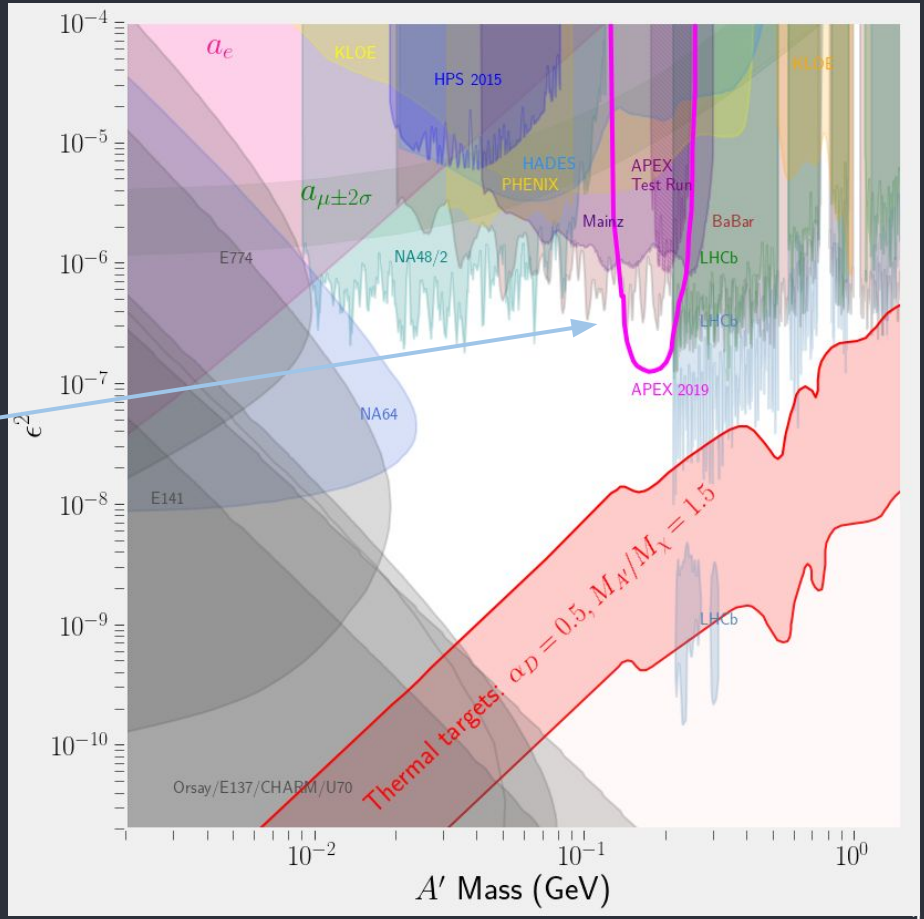
Collected 15 days worth of data (~80 M events)

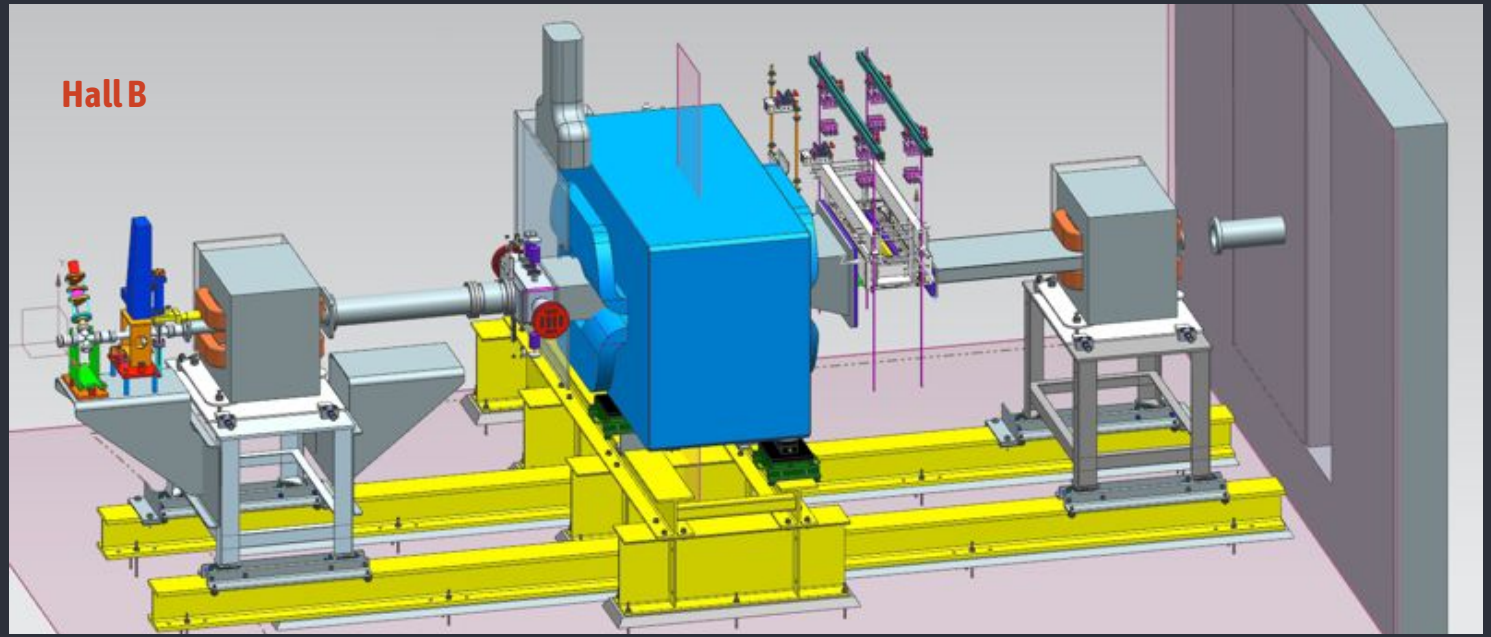
Optics calibration and reconstruction of data is ongoing



HPS @ Jefferson Lab

e^- fixed target experiment installed in Hall B at Jefferson Lab searching for dark photons in the mass range 19 MeV - 500 MeV

- Makes use of CEBAF electron beam → Energy range 1.1 - 6.6 GeV Current: 50 nA - 500 nA



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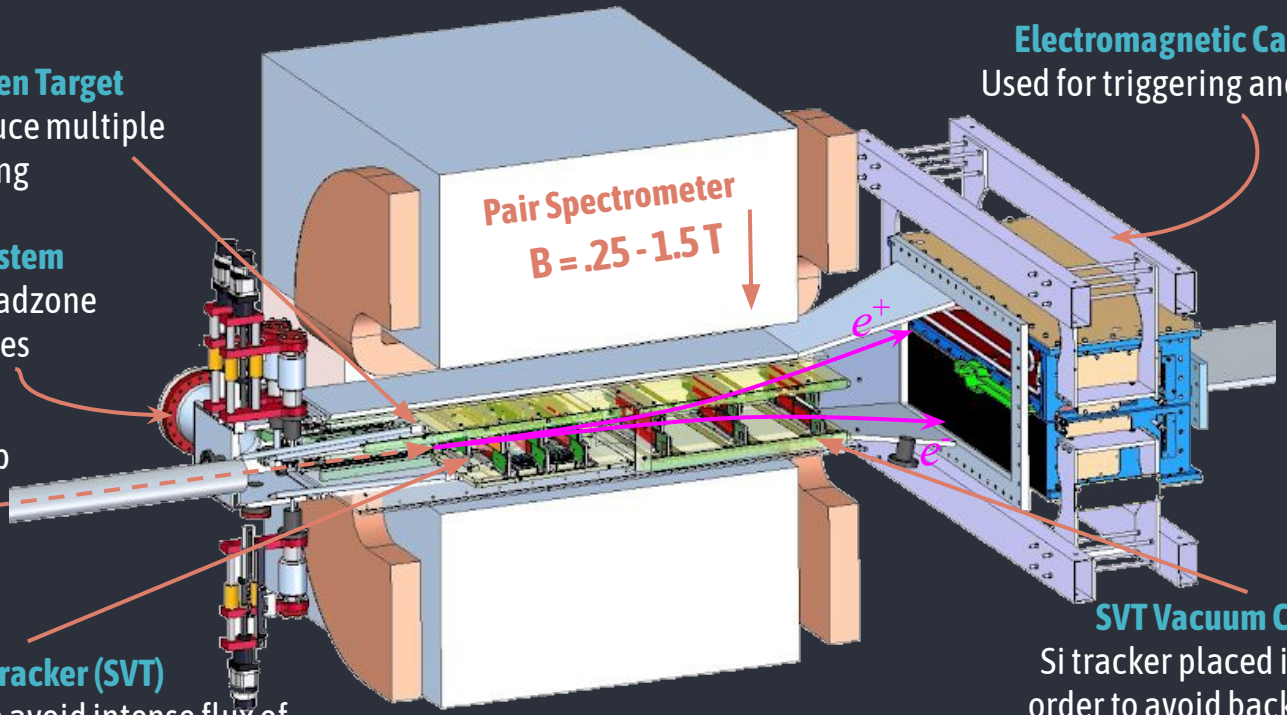


~10^{-3} X_0 Tungsten Target
Thin target to reduce multiple scattering

Linear Shift Motion System
Allows adjustment of deadzone between SVT volumes

High intensity e^- beam
Courtesy of CEBAF @ JLab

Silicon Vertex Tracker (SVT)
Split into two volumes to avoid intense flux of scattered beam electrons. Used for precise momentum and vertex determination

Electromagnetic Calorimeter
Used for triggering and particle ID

SVT Vacuum Chamber
Si tracker placed in vacuum in order to avoid backgrounds due to beam-gas interactions

SVT + ECal DAQ capable of 50 kHz

HPS @ Jefferson Lab: Engineering Runs

Two successful engineering runs

- **Spring 2015:** 50 nA, 1.056 GeV electron beam (night and weekend running) → Collected 1.7 days worth of data
- **Spring 2016:** 200 nA, 2.3 GeV electron beam (weekend running) → collected 5.4 days worth of data

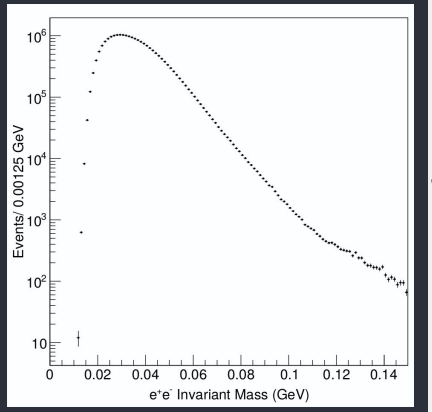
Both 2015 resonance and vertex analysis are complete

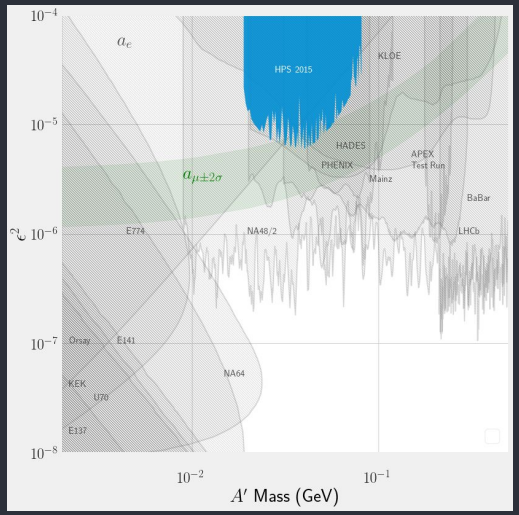
- Verified that performance of tracker and calorimeter were as expected
- Resonance search → first published result
- Vertex search did not have sensitivity

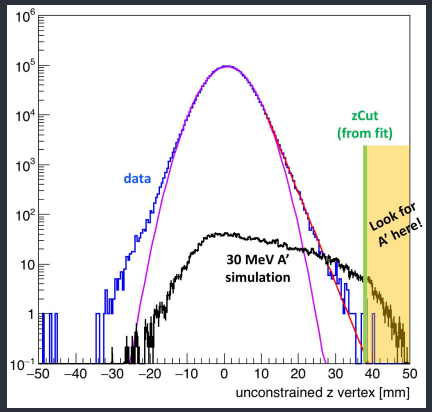
2016 resonance and vertex searches are ongoing

- Results expected early next year

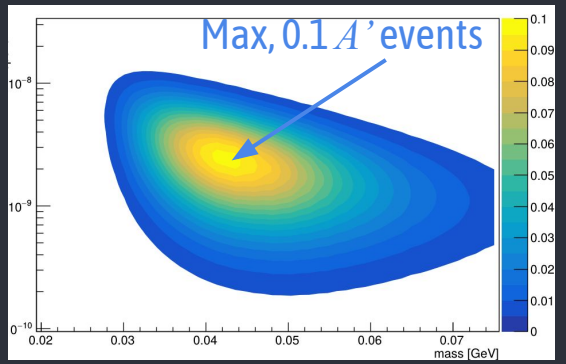
PHYS. REV. D98 (2018) NO.9, 091101







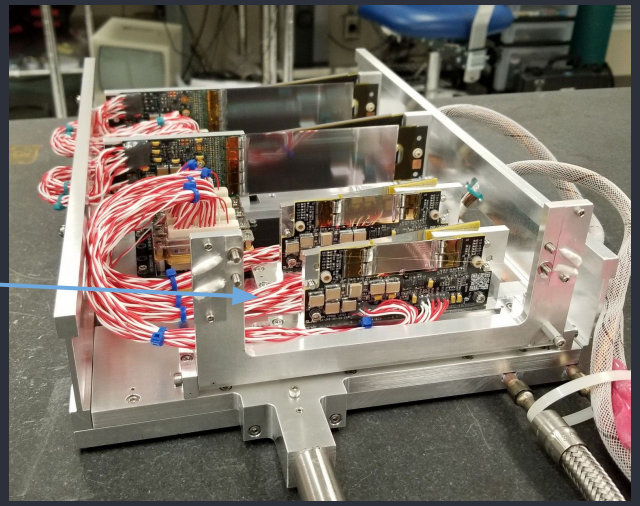
ε^2

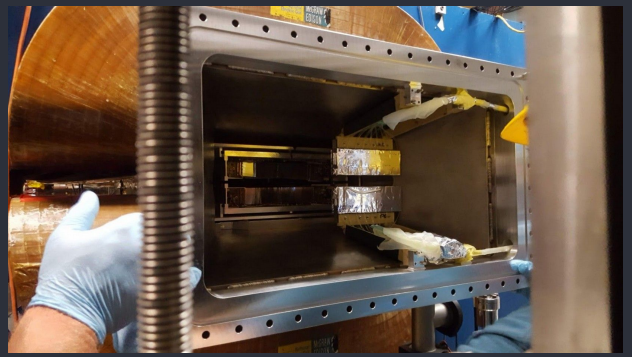


HPS @ Jefferson Lab: 2019 Physics Run

Modest upgrades were done to improve the sensitivity to long lived dark photons

- The first three layers of the SVT were moved closer to the beam plane ⟶ Increase acceptance to low mass dark photons
- Add an additional thin layer to the SVT at 5 cm ⟶ Improves vertex resolution and vertex efficiency
- Implement a positron only trigger ⟶ Will allow recovery of sensitivity lost due to the ECal hole.





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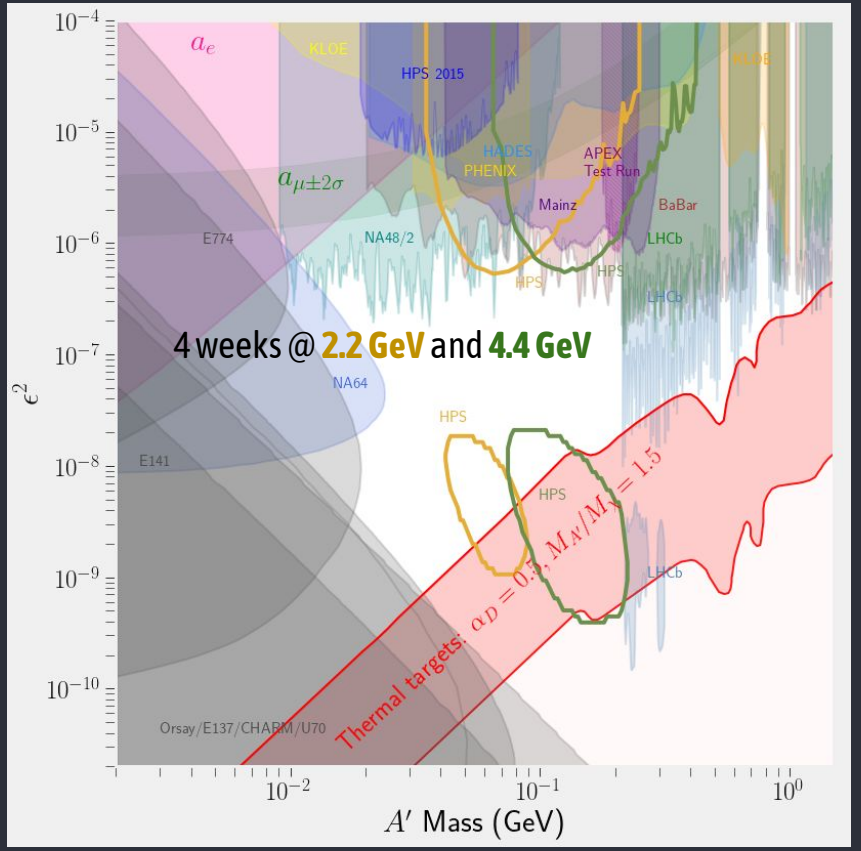
Successful run took place from 6/15 - 8/30 2019 using a 4.4 GeV beam @ 100 nA

- Alignment and calibration is ongoing
- Expected to prove large portion of precision vertex region



DarkLight @ Jefferson Lab (>2021)

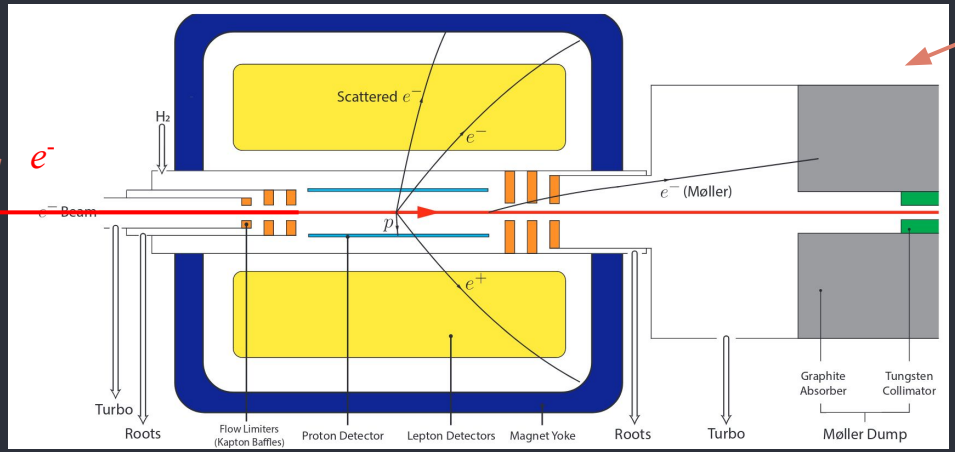
Proposed e^- fixed target experiment that will make use of the Low Energy Recirculator Facility (LERF) at Jefferson Lab to search for dark photons with mass between 10 and 100 MeV

ArXiv: 1412.4717

Solenoidal magnet providing a 0.5 T field → guides intense Moller background forward to a dump

Electron beam incident on a windowless Hydrogen target (10^{19} cm^{-2}) → A' via dark bremsstrahlung

5 mA, 100 MeV e^-



Reconstruction of the complete final state is required to mitigate backgrounds from random coincidences (elastic, Moller)

- Full acceptance Si detector for proton detection
- Gas chambers for electron detection

Aggressive pumping up and downstream to maintain beam vacuum outside of target

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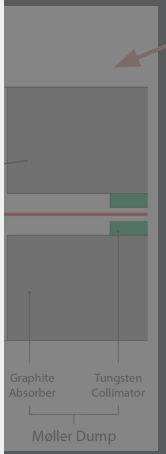

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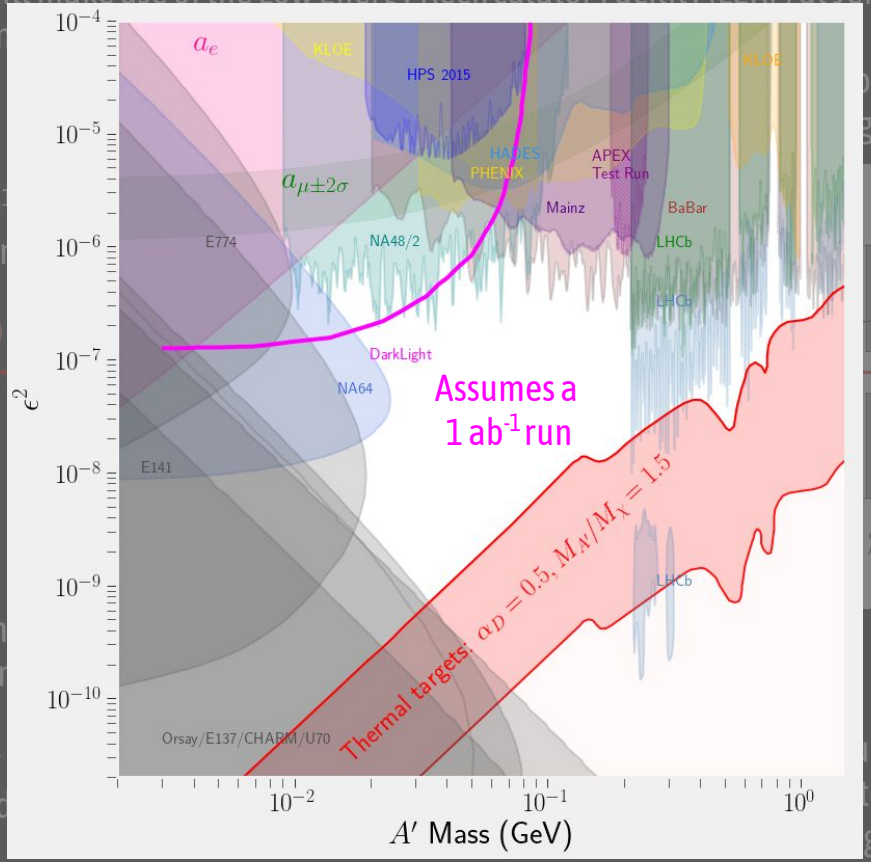
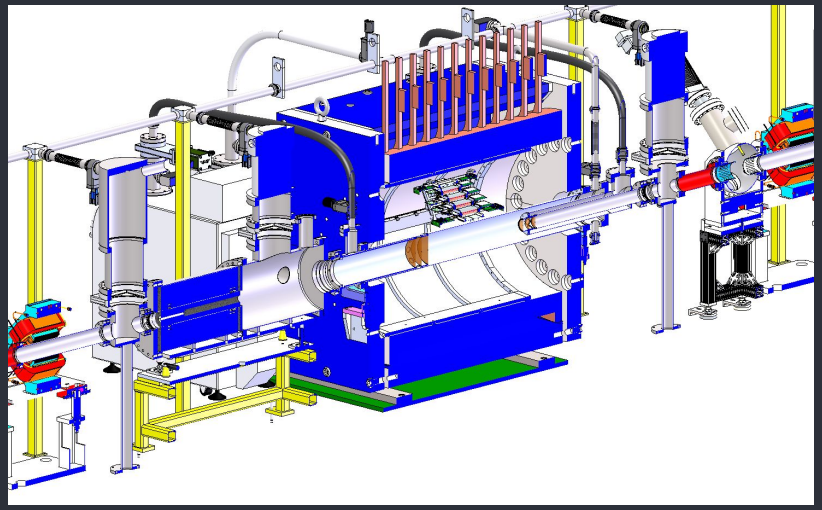
get



DarkLight @ Jefferson Lab (>2021)

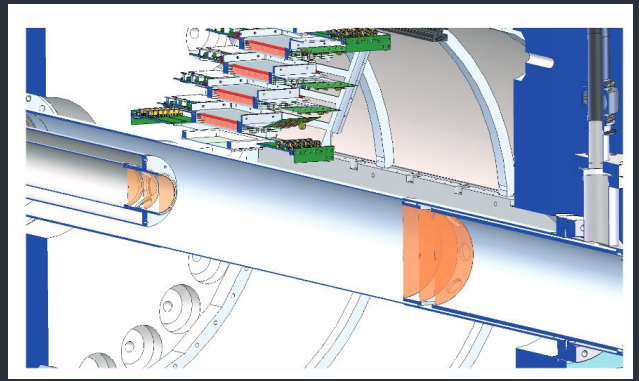
Arxiv: 1903.02648



2016 (Phase IA): Explored operation of LERF with prototype detector installed

2017 (Phase IB): Target design was improved and assembled for test at Bates

Phase IC: Proof-of-principal detector focused on low mass A'



MAGIX @ MESA (> 2023)

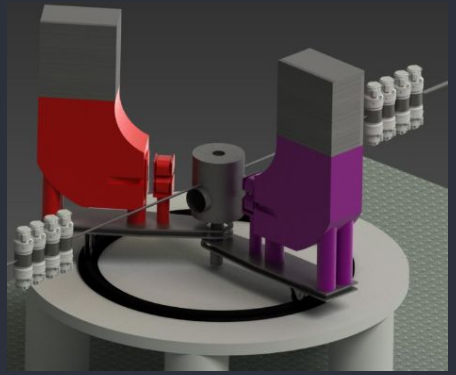
ARXIV: 1809.07168

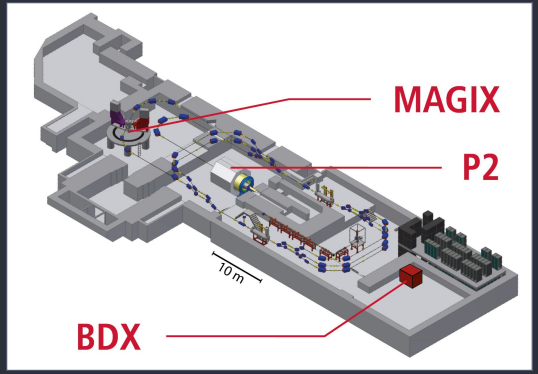
MAGIX e^- fixed target experiment making use of the energy recovery line of the MESA accelerator (E_{max} = 105 MeV @ > 1 mA) to search for dark photons in the mass range 10 - 60 MeV ($\epsilon > 5 \times 10^{-5}$)

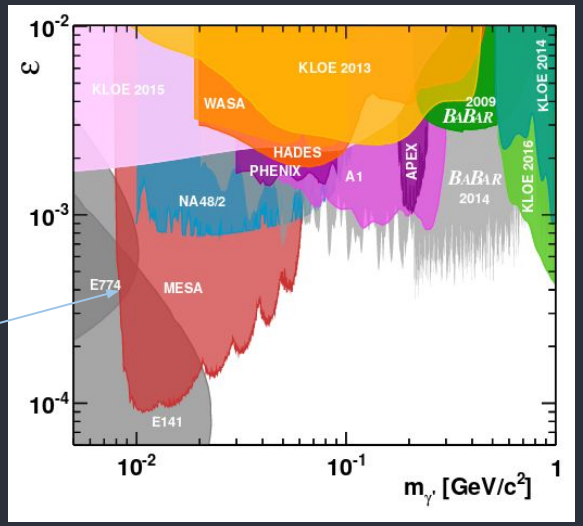
- Dark bremsstrahlung in a gas jet target (H, Ar, O_2, N_2, Xe) with thickness of 10^{19} atoms/cm^2
- Coincident measurement of e^+e^- using identical high resolution spectrometers equipped with GEM based focal plane detectors
- Search for resonance above e^+e^- invariant mass

MESA expects first beam in 2023 with MAGIX starting up shortly after

- Target luminosity: 10^{35} cm^{-2} s^{-1} (6 months of running) → will probe ^{8}Be anomaly







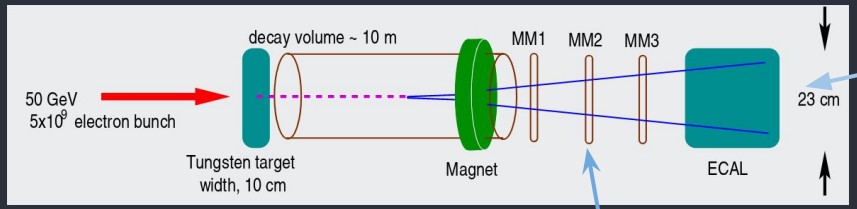
AWAKE++ (>2024)

ARXIV: 1812.11164

AWAKE++ is investigating the use of the proton-driven plasma wakefield acceleration scheme for future particle physics applications

- Using self-modulated SPS proton beam to drive strong wakefield in plasma
- Run 1 (2016-2018): Successfully demonstrated acceleration of externally injected electrons to a few GeV using proton driven plasma wakes
- Run 2 (2021 - 2024): Demonstrate the scalability of the acceleration scheme (high charge bunches accelerated to ~10 GeV)

LS3: NA64 like e^- fixed target experiment using 10^{16} EoT (collected in 3 months)



Tungsten-plastic ECAL

Micromegas tracker planes

AWAKE++ (>2024)

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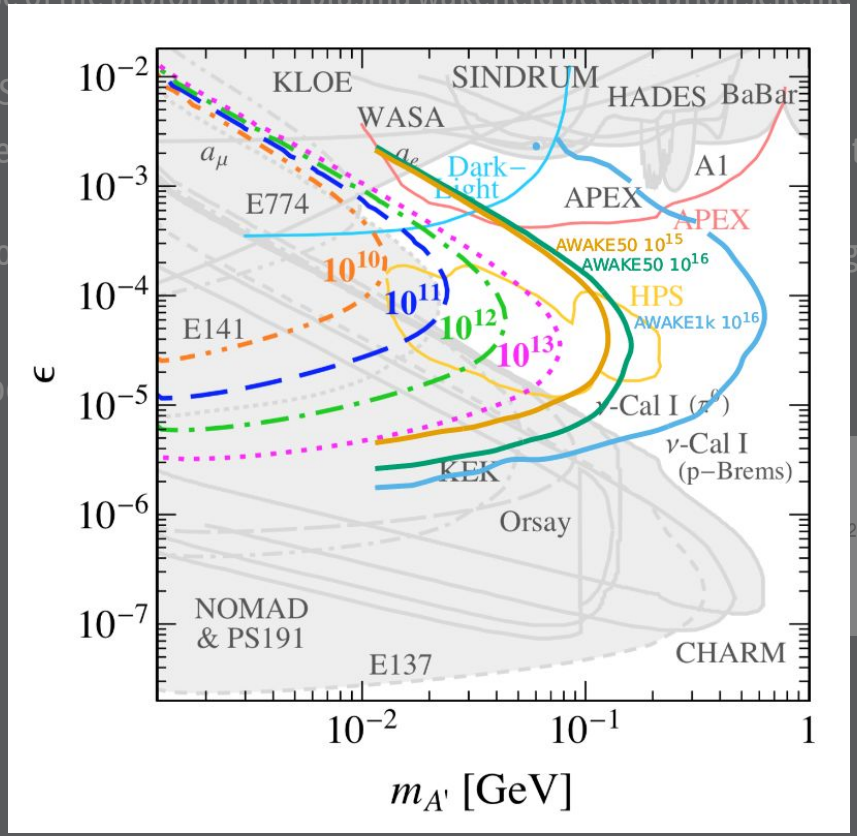
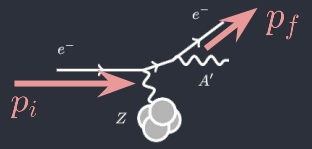


The Light Dark Matter eXperiment (>2024)

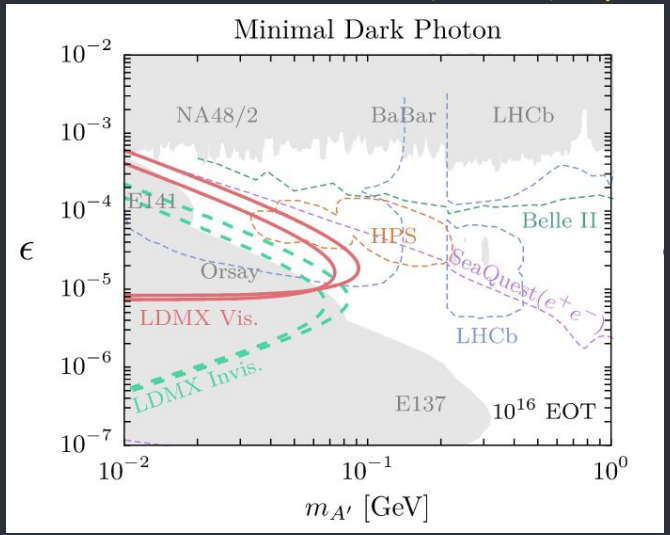
Design report: Arxiv: 1808.05219

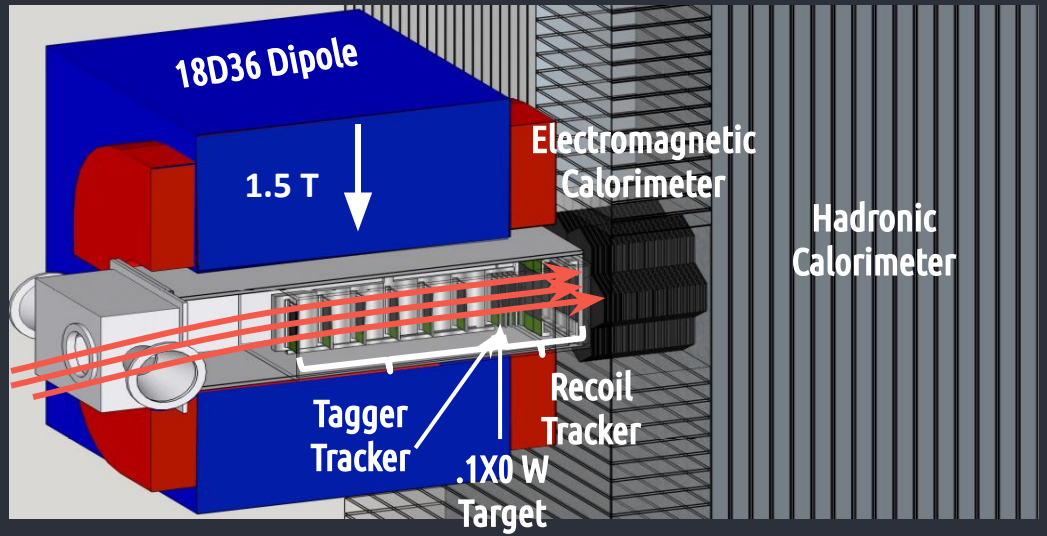
The Light Dark Matter eXperiment is a proposed e^- fixed target missing momentum search for light dark matter



$$p_{\text{miss}} = p_i - p_f$$

Phys. Rev. D 99, 075001





Use 8 or 16 GeV electron beam and 10^{16} electrons on target to search for long live A' using the displaced shower technique

Sea/SpinQuest (2017-2021)

ARXIV: 1804.00661

Fixed-target muon spectrometer using the Fermilab 120 GeV proton beam

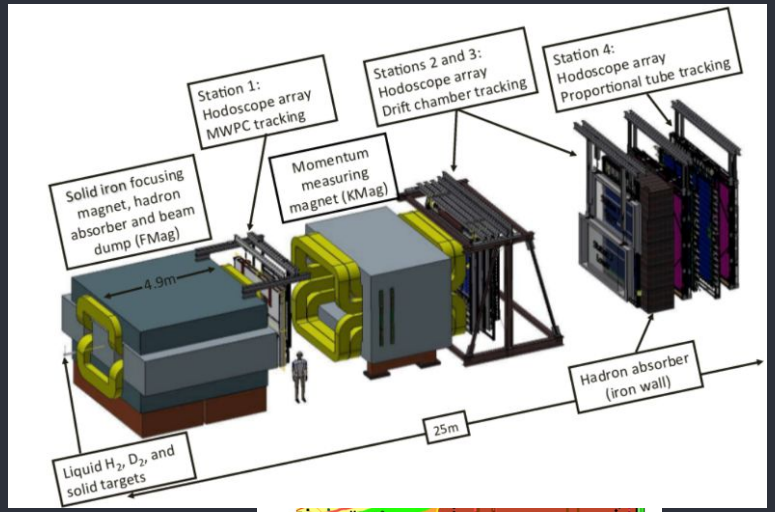
Addition of displaced vertex trigger allows for a parasitic search for dark photon searches

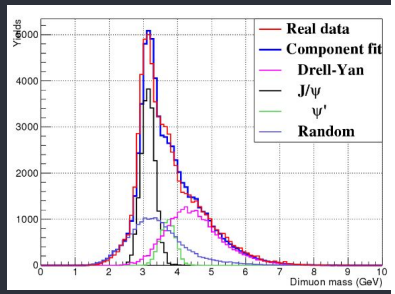
First run in 2017: Collected 5 days of good data (8×10^{15} protons on target)

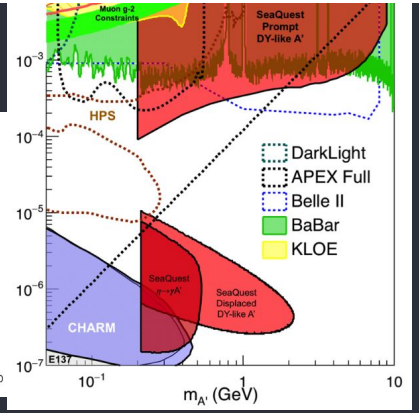
- Bump hunt using main Dimuon SeaQuest dataset is being explored
- Displaced vertex trigger was commissioned

2019: Two year run using a polarized target begins late fall

- 2017 data used to optimize displaced vertex trigger logic

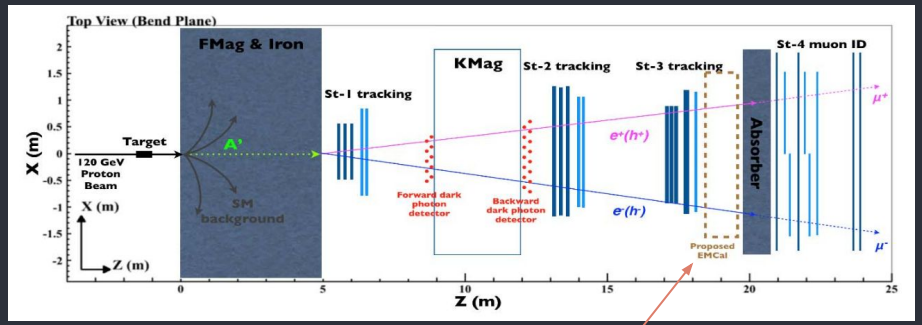


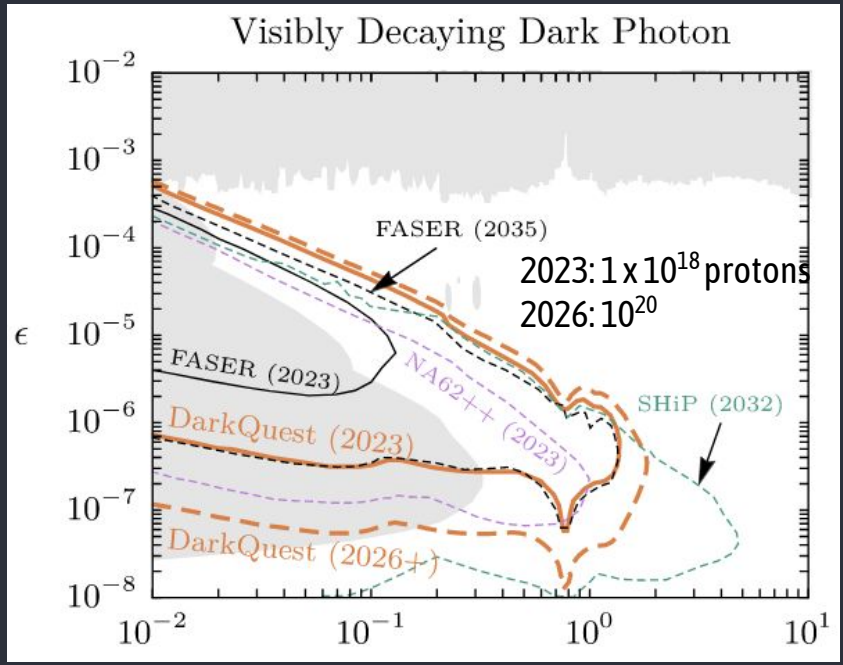




DarkQuest (>2023)

Possible upgrade to PID using a single PHENIX EMCal sector will add sensitivity to dielectron channel





Summary

Both HPS and APEX had successful runs this year

- APEX expected to cover new territory in bump hunt region while HPS will explore the precision vertex phase space

SpinQuest will start a 2 year run later this year using an optimized displaced vertex trigger

Many exciting experiments (MagiX, Awake++, DarkQuest, DarkLight) are yet to come and will cover a large portion of the remaining territory!

Stay tuned!