The HPS experiment at Jefferson Lab

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HEAVY PHOTON SEARCH

DM

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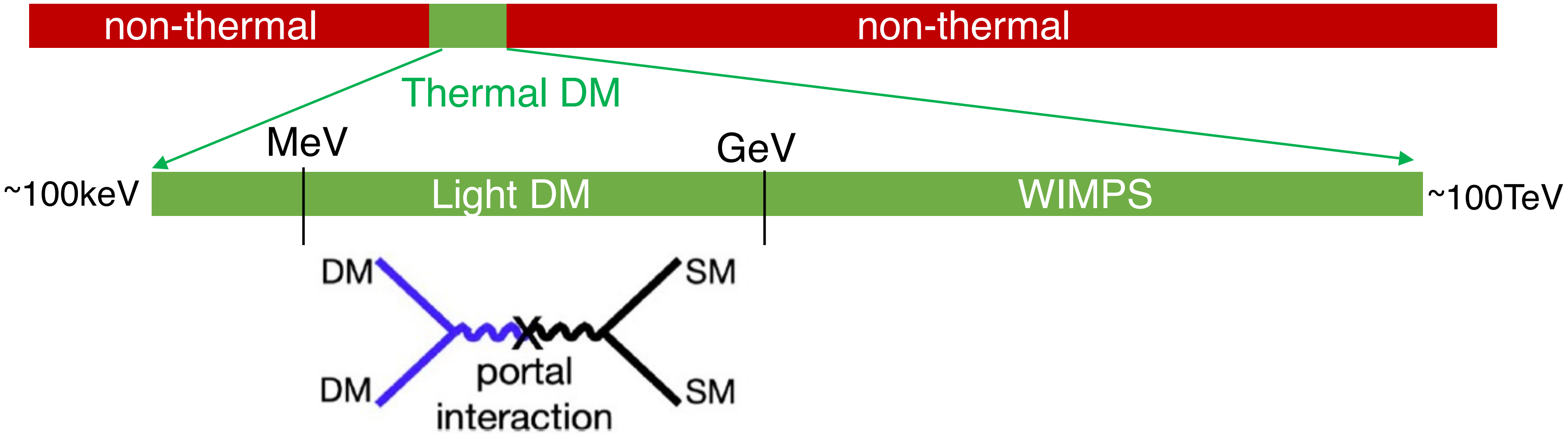
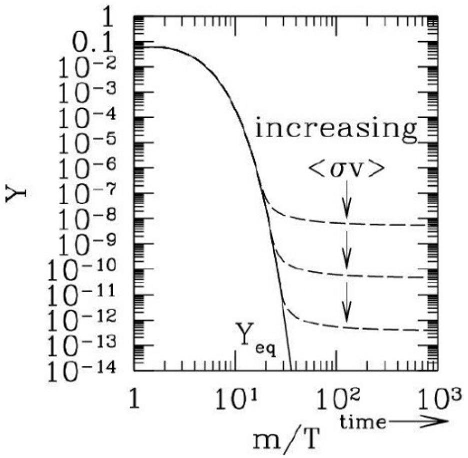
Light Dark Matter

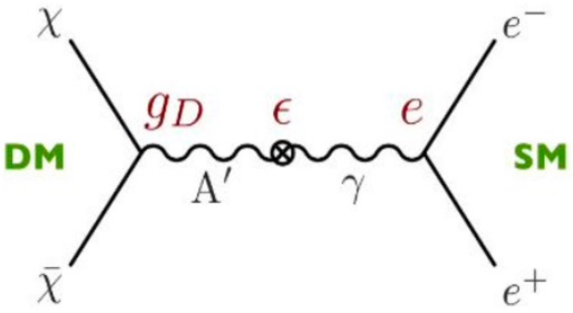
- WIMPs are well-motivated DM candidates but the accessible parameter space is running out
- Increasing interest in expanding the thermal DM search to **“Light” DM in the MeV-GeV mass range**



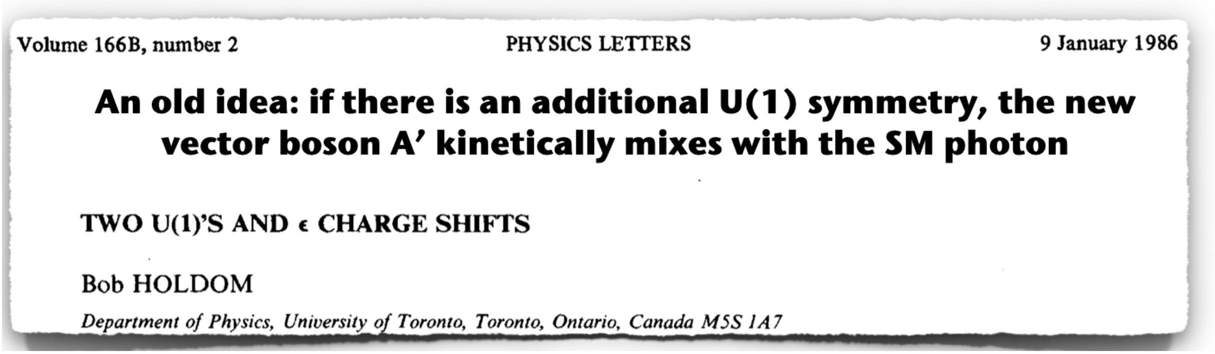


- A **portal interaction** is needed to preserve the **thermal origin** of the observed DM abundance

- A simple way to realize such a portal is through the existence of the **dark photon** (or heavy photon or A’)



Dark Photon



Volume 166B, number 2 PHYSICS LETTERS 9 January 1986

An old idea: if there is an additional U(1) symmetry, the new vector boson A' kinetically mixes with the SM photon

TWO U(1)'S AND ϵ CHARGE SHIFTS

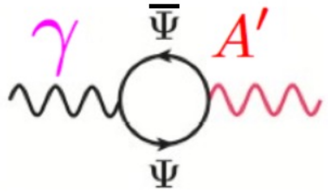
Bob HOLDOM

Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

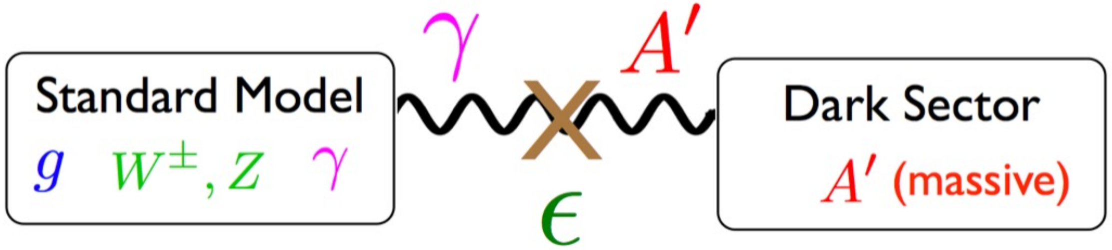
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic mixing"

Loops of heavy particles charged under photon and A'



A' acts as a "portal" between the SM and the new sector



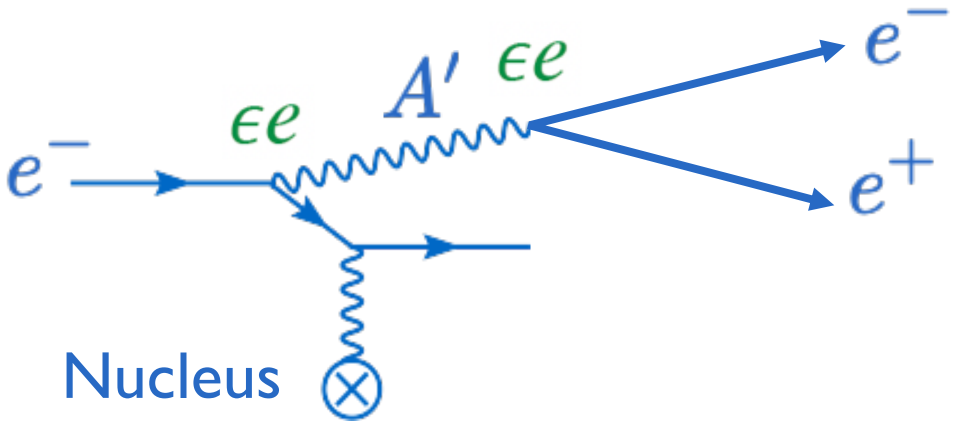
☝ *"where there are photons, there could be also dark photons"* ☝

HPS – Heavy Photon Search experiment

- Designed to search for *A'* in the **20-220 MeV/c^2** mass range and coupling **ε^2 >10^{-10}**
- **Thin target experiment** (4-20 μm tungsten) running in Hall-B at **Jefferson Lab**
- Make use of an **intense** (50-500 nA) **electron-beam** in the ~**1-6 GeV** energy range

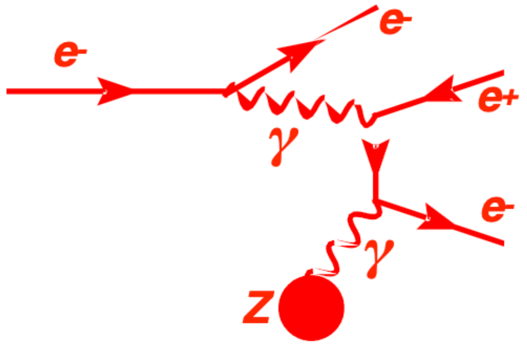
Production and decay channel

- Electrons can radiate heavy photons in a process analogous to bremsstrahlung
- *A'* can then decay into an e^+-e^- pair

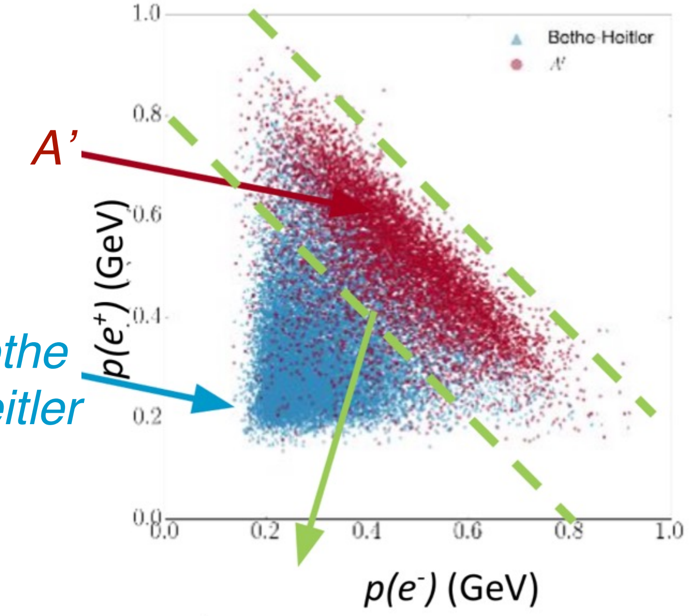


Background

Bethe-Heitler

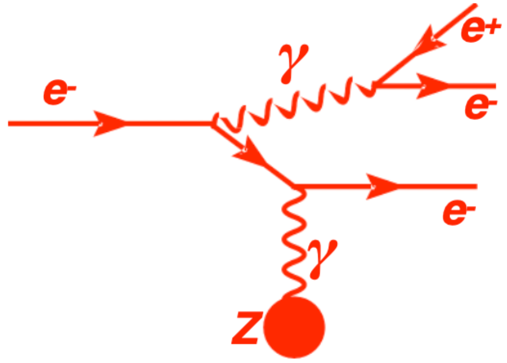


- Larger cross section but different kinematics
- Reducible



Suppressed with a cut on the e^+ and e^- momenta

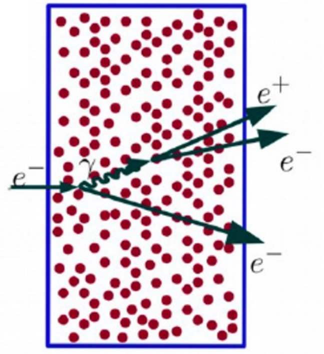
Radiative



- Identical kinematics to A′s;
- Irreducible prompt background
- Provide reference for expected signal rate
- A' production rate suppressed by

$$\sim \epsilon^2 m_e^2 / m_{A'}^2$$

Wide-Angle Bremsstrahlung



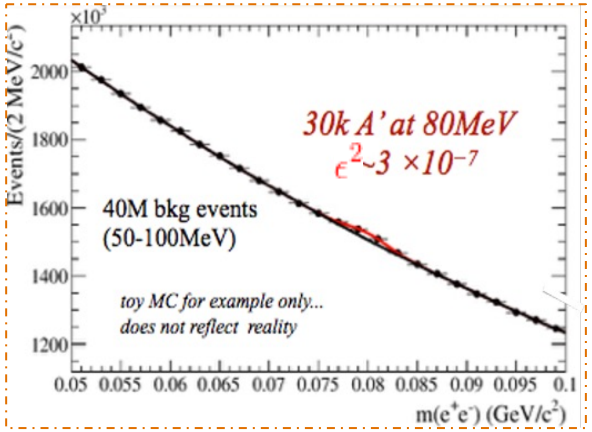
- A hard, wide angle, bremsstrahlung photon converts in the target or detector material and the resulting positron is paired with the recoil electron.
- Different kinematic signature that can be used to estimate its contribution
- Reducible via analysis selections

HPS – Search strategies

- **Production rate for A' strongly suppressed** relative to analogous processes involving regular photons
- Experiments must always contend with an **overwhelming QED background**

Bump hunting

Searches for narrow e^+e^- resonances atop a continuum background

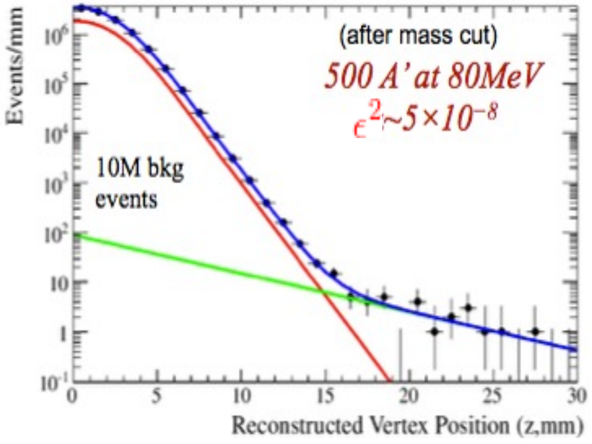


Typical sensitivity to $\varepsilon^2 > 10^{-7}$

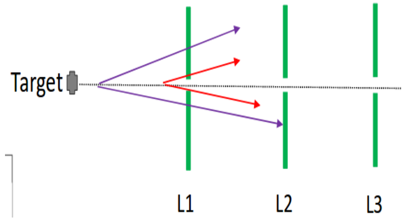
Reaching lower couplings through brute force is difficult, requiring orders of magnitude more luminosity

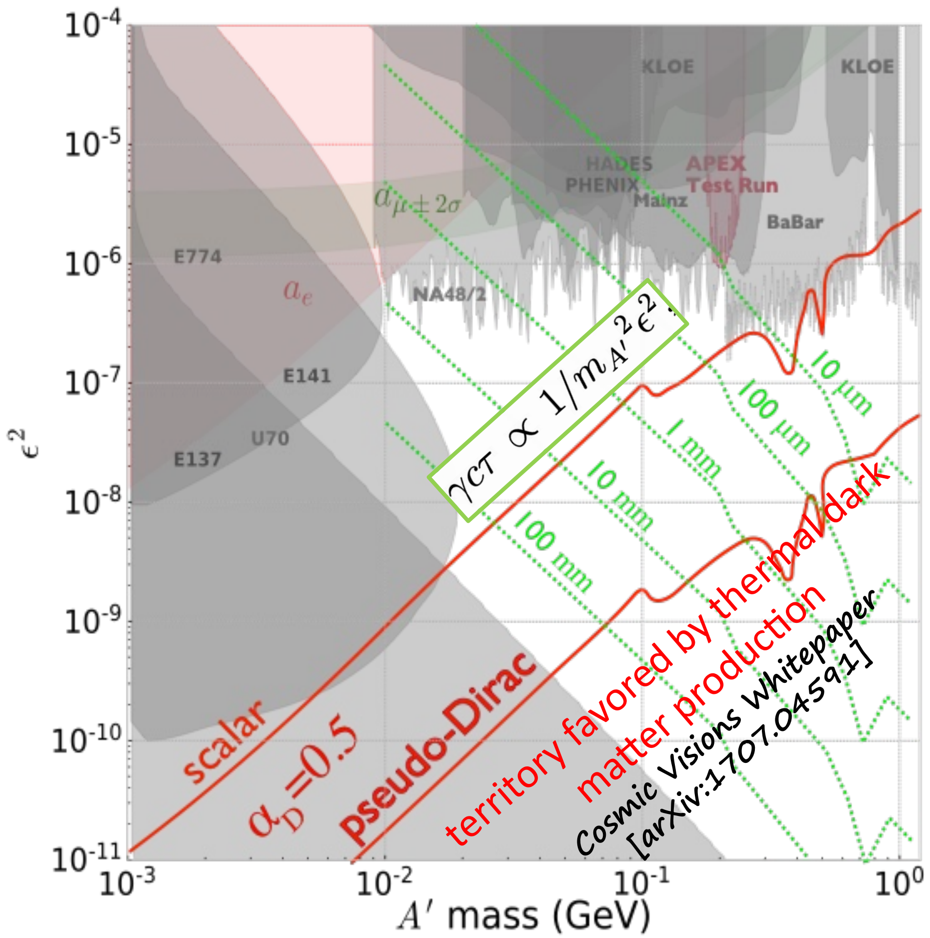
Detached vertex

Eliminate prompt backgrounds by vertex reconstruction

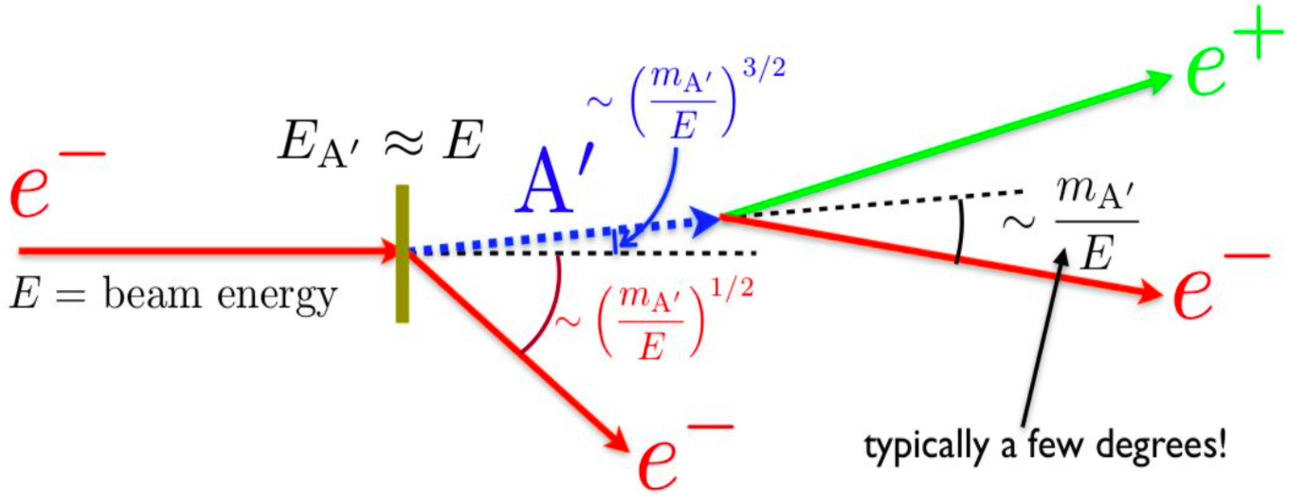


At smaller couplings and lower masses, dark photons are long lived and can travel macroscopic distances before decaying





Kinematics



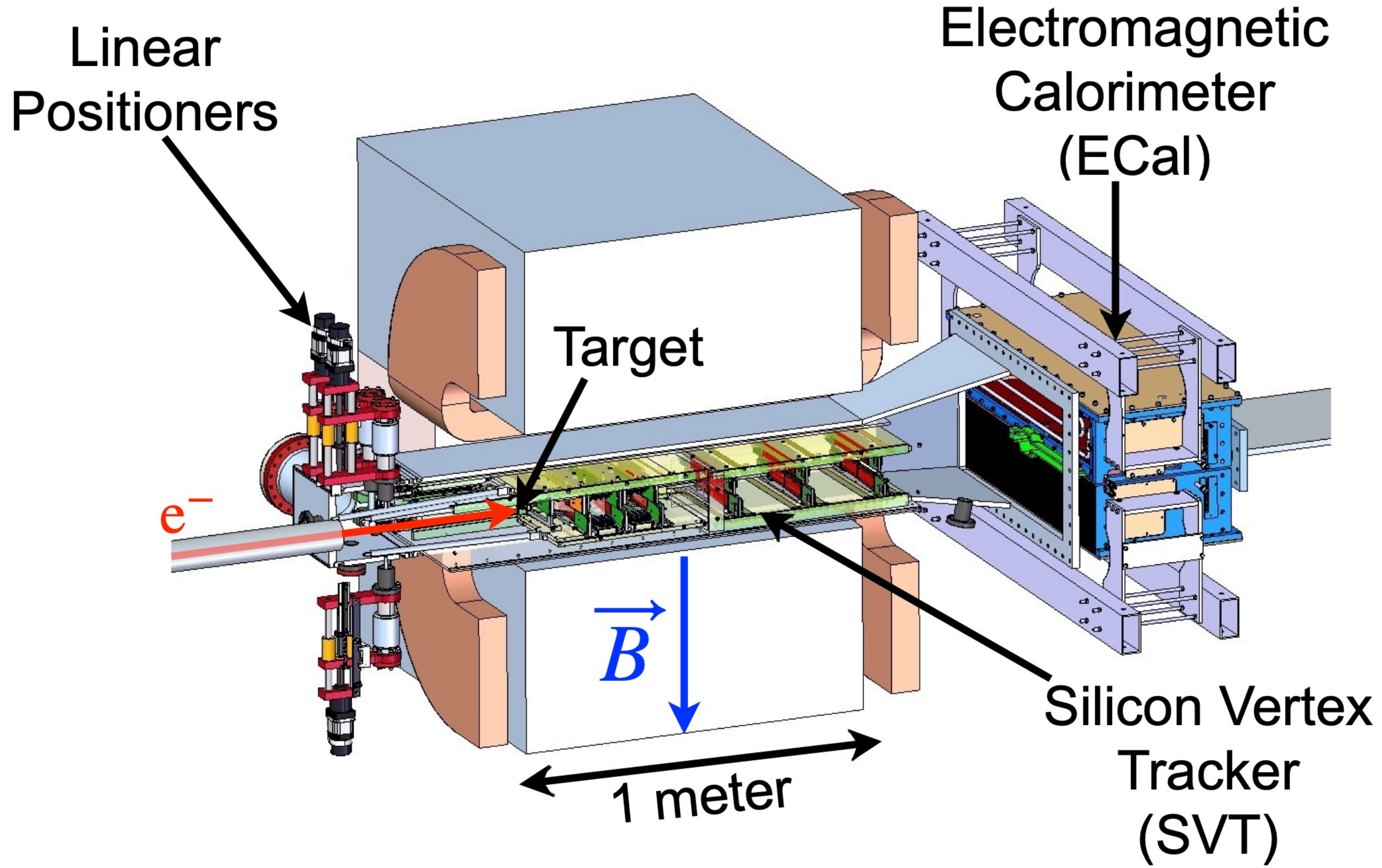
- A' takes most of beam energy and has its momentum closely aligned with the beam direction
- Decay products are forward emitted with a small opening angle and have typical momenta $E_{beam}/2$

  - very forward detector acceptance

  - first tracking layer must be very close to the interaction point

  - multiple scattering dominates mass and decay length uncertainties

Experimental setup



- A compact **e^+e^- spectrometer** built inside of a dipole analyzing magnet
- Fast and highly **granular detectors** to provide triggering, tracking and vertexing, and particle identification
- e^+e^- pair boosted in the very forward direction -> **far forward acceptance**
- A high rate beam e^- degraded by passage through the target is spread along the horizontal plane, so all the detector subsystems are split above and below the beam plane

Jefferson Lab and CEBAF

HIGH

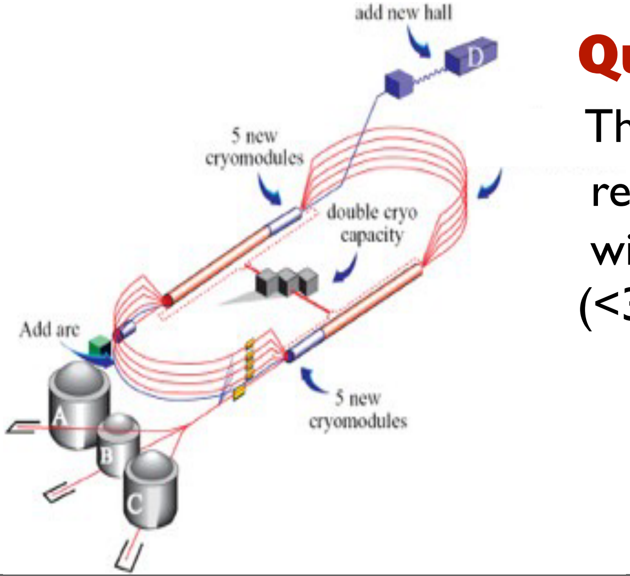
Intensity

Beam currents up to 100 μA Hall A, C, and 800 nA Hall B

JLab (Newport News, VA) has the Continuous Electron Beam Accelerator Facility (**CEBAF**) that can simultaneously deliver intense continuous e^- beams of different energies to 4 halls

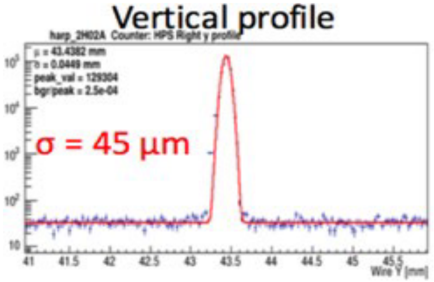
Frequency

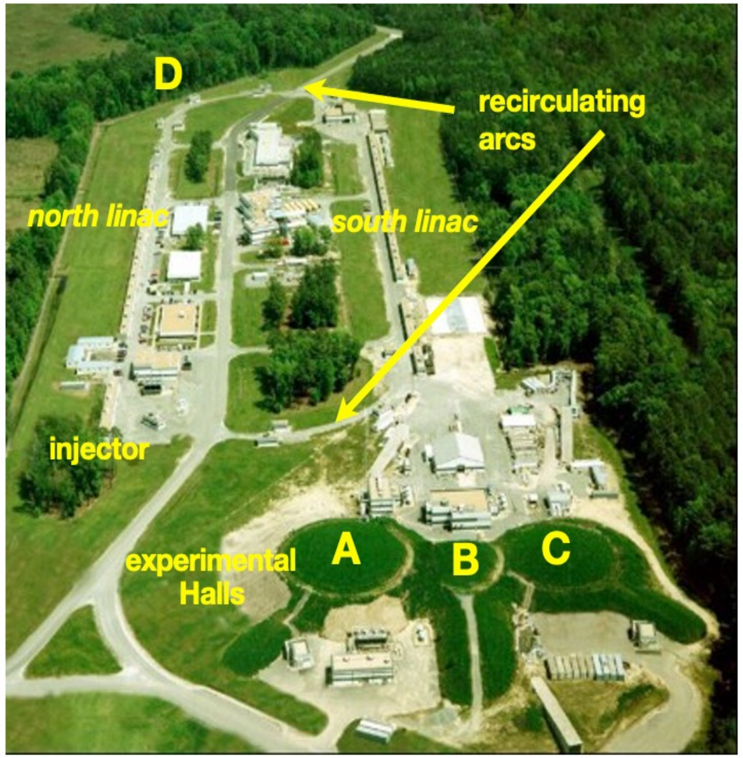
Very high repetition rate (2 ns) beam with low per-bunch charge (~10000 e^-)
Spread out beam background over time for manageable occupancies to not sp
the clean tracking and vertexing



Quality

The extraordinary proximity of the SVT to the beam requires a very small beamspot (<50 μm vertically) with vanishing low halo rate (10^{-6}) and excellent stability (<30 μm vertical variation)



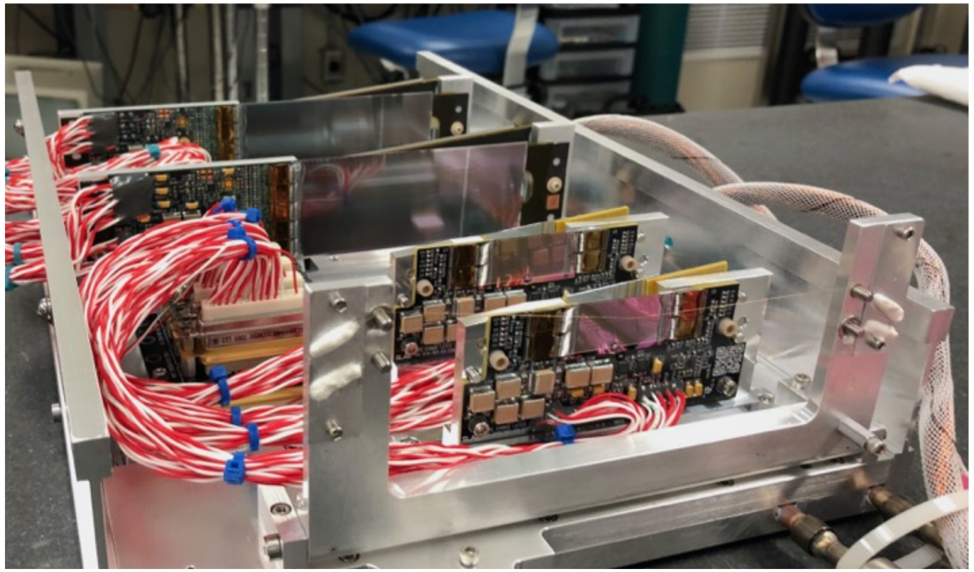


“The Heavy Photon Search beamline and its performance“, N. Baltzell et al., NIMA 859, (2017) 69.

Silicon Vertex Tracker

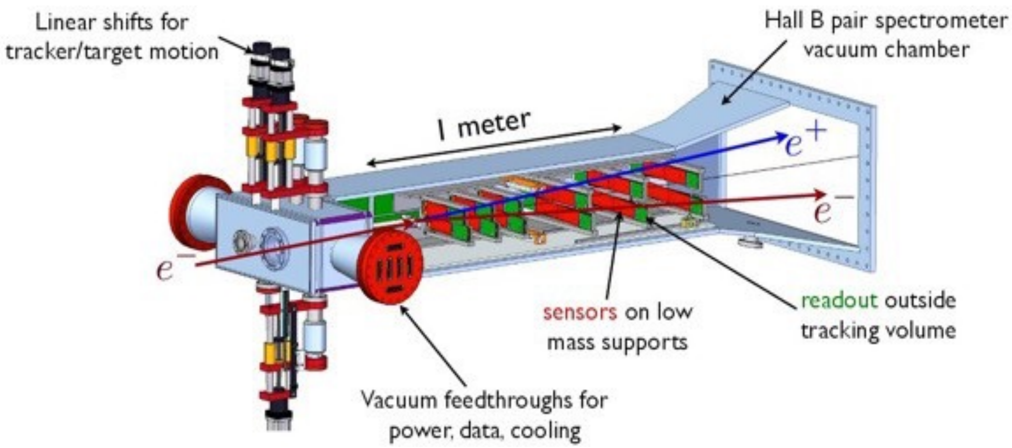
REQUIREMENTS

- Smallest amount of material possible in the tracking volume
- Rejection of prompts better than 10^{-6}
- Largest usable acceptance to low-mass A′ (decay products nearly collinear with the beam)



ORIGINAL DESIGN

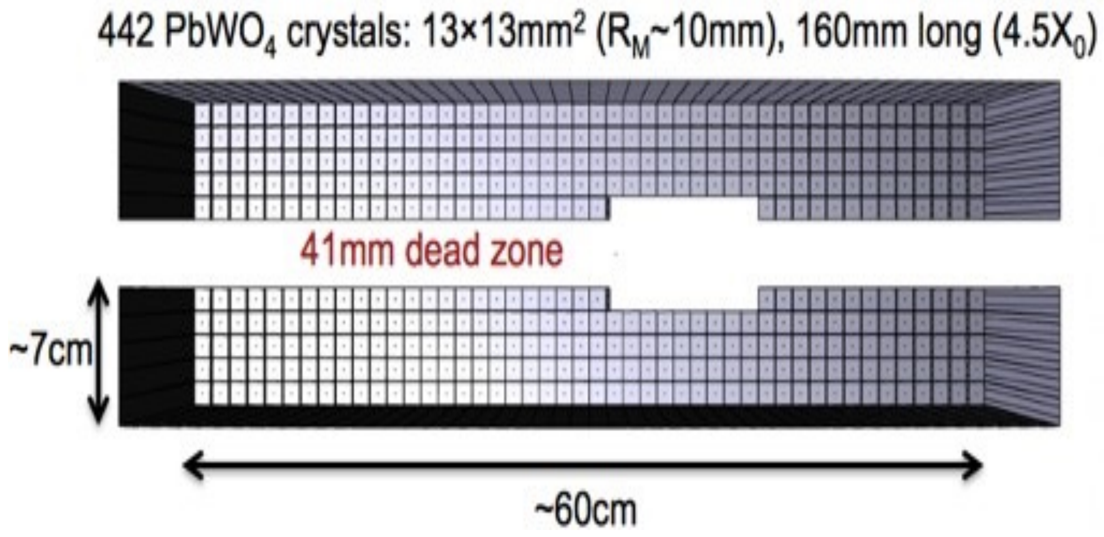
- 6 layers of detectors, split top-bottom, extending from 10 cm to 90 cm downstream of the target
- First layer just 500 μm away from the beam.
- Each layer has 2 Si microstrip sensors at small crossing angle
- Thin layers (0.7% X_0 per layer) to minimize Multiple Coulomb Scatt. dominating mass and vertexing uncertainties
- Spatial resolution of each layer is 6 um in the vertical plane and either 60 um or 120 um in the horizontal (bending) plane, depending on the layer.



Electromagnetic calorimeter

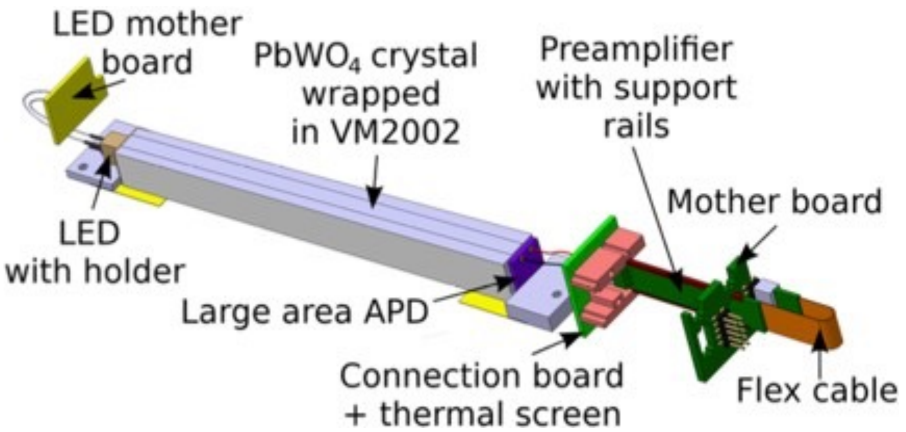
REQUIREMENTS

- Trigger for e^+e^- pairs with sufficient energy and time resolution to eliminate the overwhelming background of scattered single beam e^-
- Offline identification of e^+ and e^-, with sufficient timing to tag their energy deposits to a single CEBAF bunch, to be used to demand coincidence in the SVT



DESIGN

- 442 $PbWO_4$ crystals arranged in two identical arrays — placed symmetrically above and below the beam plane downstream of the SVT
- Light readout by 10x10 mm^2 LA-APD connected to custom pre-amp
- From the first row of each half, the nine crystals closest to the beam are removed as the rate of scattered beam electrons is intolerably high in that region, well in excess of 1 MHz



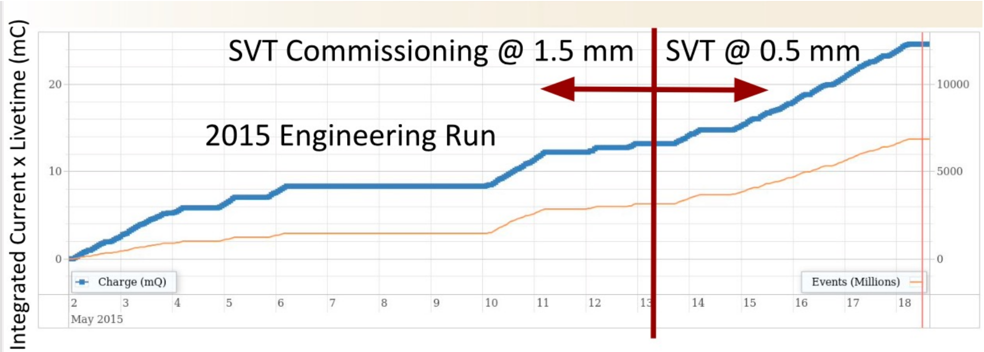
"The HPS elecgtromagnetic calorimeter", I. Balossino et al., NIMA 854, (2017) 89

2015-2016 Engineering runs

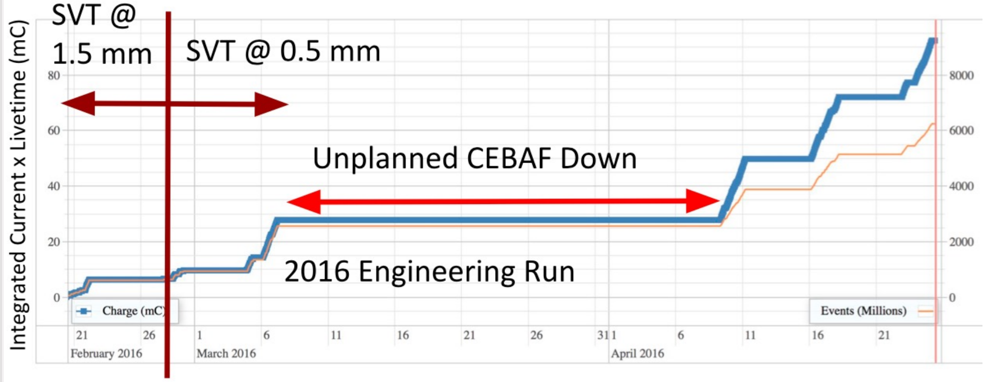
Two engineering runs were completed in 2015 and 2016 with the baseline HPS detector

Run	Energy (GeV)	Target (% X_0 W)	Beam Time Used	$\int \mathcal{L}$ pb^{-1}
2015	1.056	0.125	9.5 days	1.17
2016	2.30	0.125	5.5 days	10.75

In Spring 2015, HPS operated on nights and weekends over 2.5 weeks at a beam energy of 1.056 GeV. After a period of beam and detector commissioning and studies, a small physics dataset was collected with which to develop the analysis techniques for the experiment and perform a first search for heavy photons

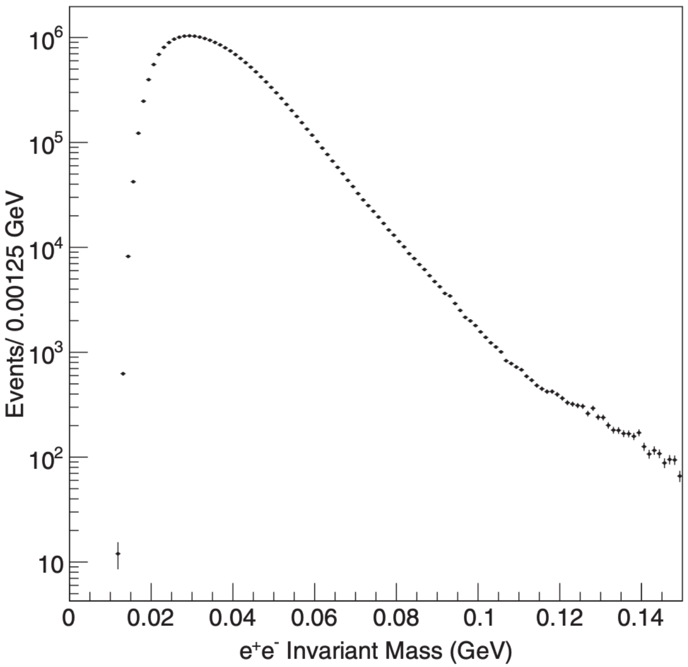


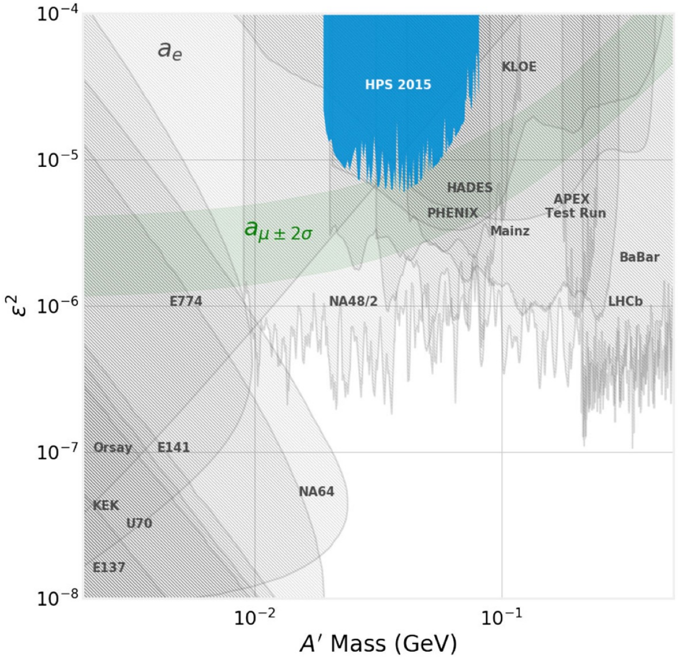
In Spring of 2016, data were collected on weekends over a 10 week period at a beam energy of 2.3 GeV. The detector was successfully commissioned much more quickly than in 2015, resulting in a significantly larger dataset with which to search for new phenomena



2015-2016 Engineering runs

The first HPS physics publication described the resonance search with the small dataset from the 2015 engineering run.





"Search for a dark photon in electroproduced e+e- pairs with the Heavy Photon Search experiment at Jlab " P.H. Adrian at al., PRD 98, (2018) 091101(R).

2015 dataset was far too small to allow for significant reach for long-lived A′.
Results have been reported in theses and conference proceedings

[18] O. Moreno, Search for a heavy photon in the 2015 engineering run data of the heavy photon search experiment (2016).
[19] S. Uemura, Search for a heavy photon in the 2015 engineering run data of the heavy photon search experiment (2016).
[20] H. Szumila-Vance, Searching for heavy photons with detached vertices in the heavy photon search experiment (2017).
[21] O. Moreno and M. Solt (HPS), Search for a Dark Photon in Electro-Produced e^+e^- Pairs with the Heavy Photon Search Experiment at JLab, PoS **ICHEP2018**, 076 (2019), arXiv:1812.02169 [hep-ex].
[22] S. J. Paul, Searching for a dark photon in the hps experiment (2018).
[23] M. R. Solt, Search for a heavy photon in the 2015 engineering run data of the heavy photon search experiment (2020).

Resonance and displaced vertex searches on the 2016 dataset are completed. The related publication is currently in draft.

Analysis of the engineering run datasets have fostered a number of key improvements to the apparatus

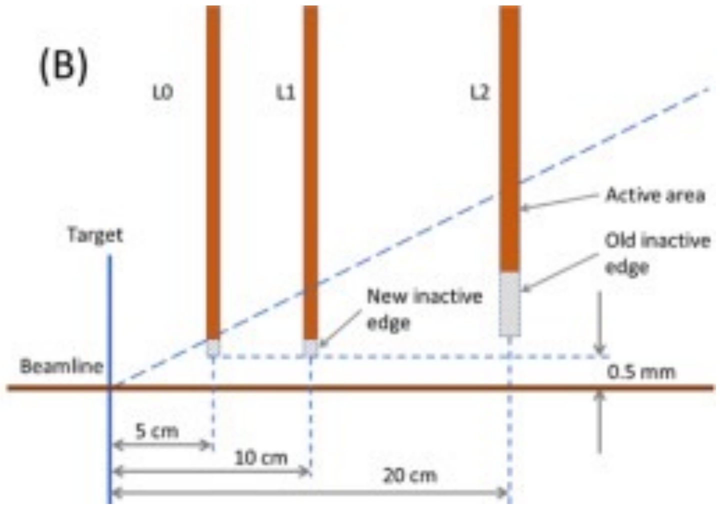
SVT upgrade

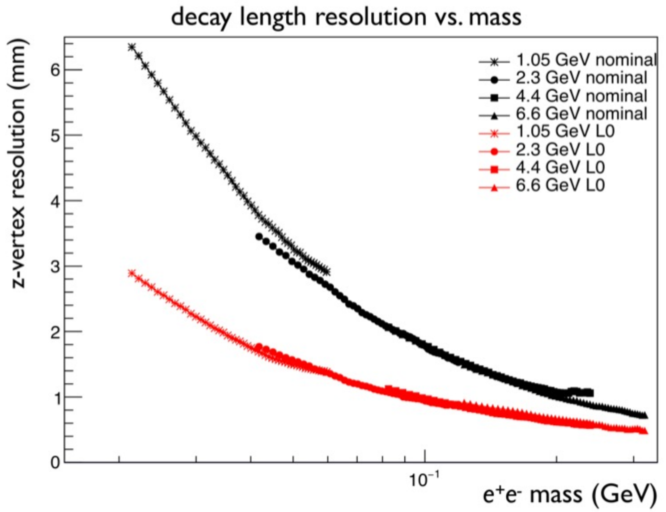
- **A seventh double-layer** (L0) was **added** to the **SVT at 5 cm from the target**, using thinner silicon to reduce material and slim edge processing to maintain the 15 mrad acceptance

- **L0 sensors have about half the material**, being 200 microns thick. They have a 55 micron readout pitch split into two 15 mm by 14 mm active areas, to decrease the per-strip occupancy. **The inactive region near the beam is only 250 microns**, allowing closer placement of the active region to the beam.

- **This module design was also used to replace the previous first layer (L1)** to improve resolution, allow it to be positioned closer to the beam, and decrease wide-angle bremsstrahlung photons converting in the inactive region of the sensor

- **Other layers** were similarly **moved closer to the beam** as occupancies allowed to increase forward acceptance for displaced decays.





"The Heavy Photon Search Experiment", C. Bravo on behalf of the HPS collaboration ., arXiv:1910.04886v1
"Design and performance of silicon strip sensors with slim edges for HPS experiment", V. Fadeyev et al., NIMA 969, (2020) 163991.

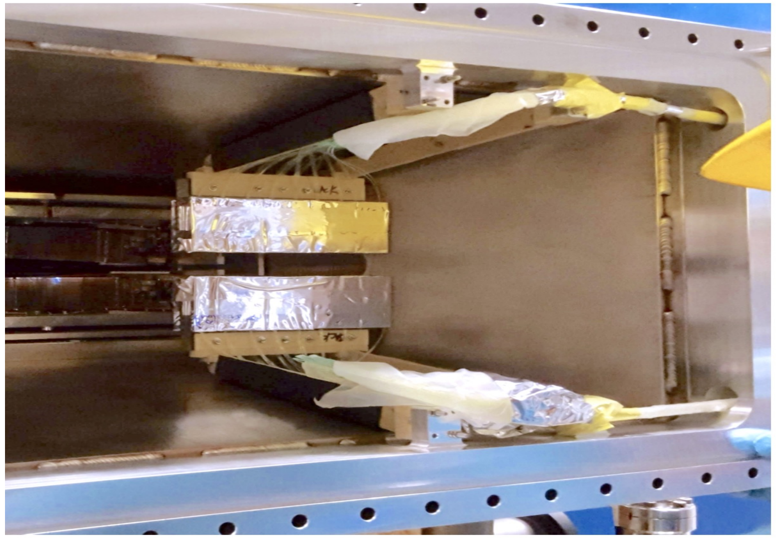
Positron Hodoscope

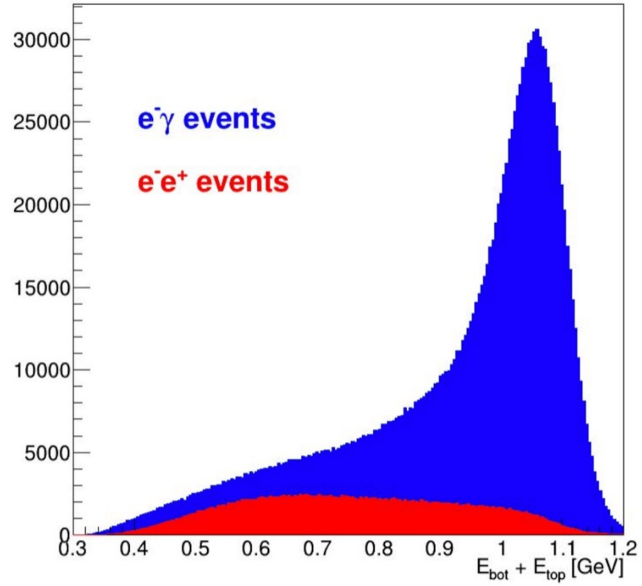
- After the engineering runs, it was found that the hole in the acceptance resulting from the high-occupancy crystals removed from the Ecal design, allows up to half of electrons from $A' \rightarrow e^+e^-$ decay to escape detection.

- To recover these events, a **single-arm, positron trigger** was implemented in advance of the first physics run in 2019.

- The rate of positrons is not high, but the positron side of the ECal is flooded with photons from bremsstrahlung in the target. For a single-arm positron trigger to work with an acceptable rate, t**he HPS detector was instrumented with a scintillation hodoscope** covering the positron side of the ECal **to discriminate positrons from photons**.

- The hodoscope uses two layers of scintillating tiles with a wavelength-shifting fiber that carries the light out to a multichannel PMT. The trigger requires two hits on two hodoscope layers with a position that matches the position and time of the cluster in the ECal.



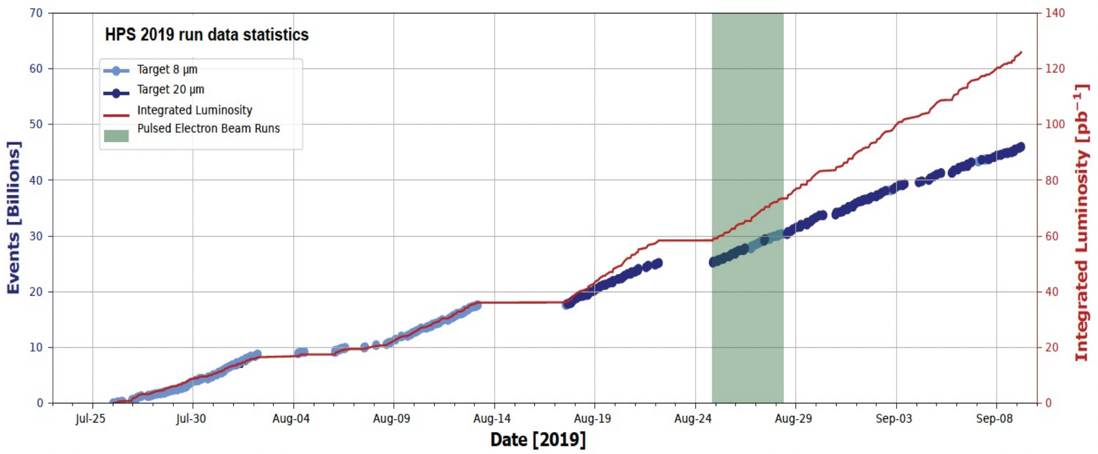


2019-2021 Physics runs

Two physics runs were completed in 2019 and 2021 with the upgraded detector

Run	Energy (GeV)	Target (% X_0 W)	Beam Time Used	$\int \mathcal{L}$ pb^{-1}
2019	4.55	0.25/0.625	30 days	122
2021	3.74	0.625	28 days	168

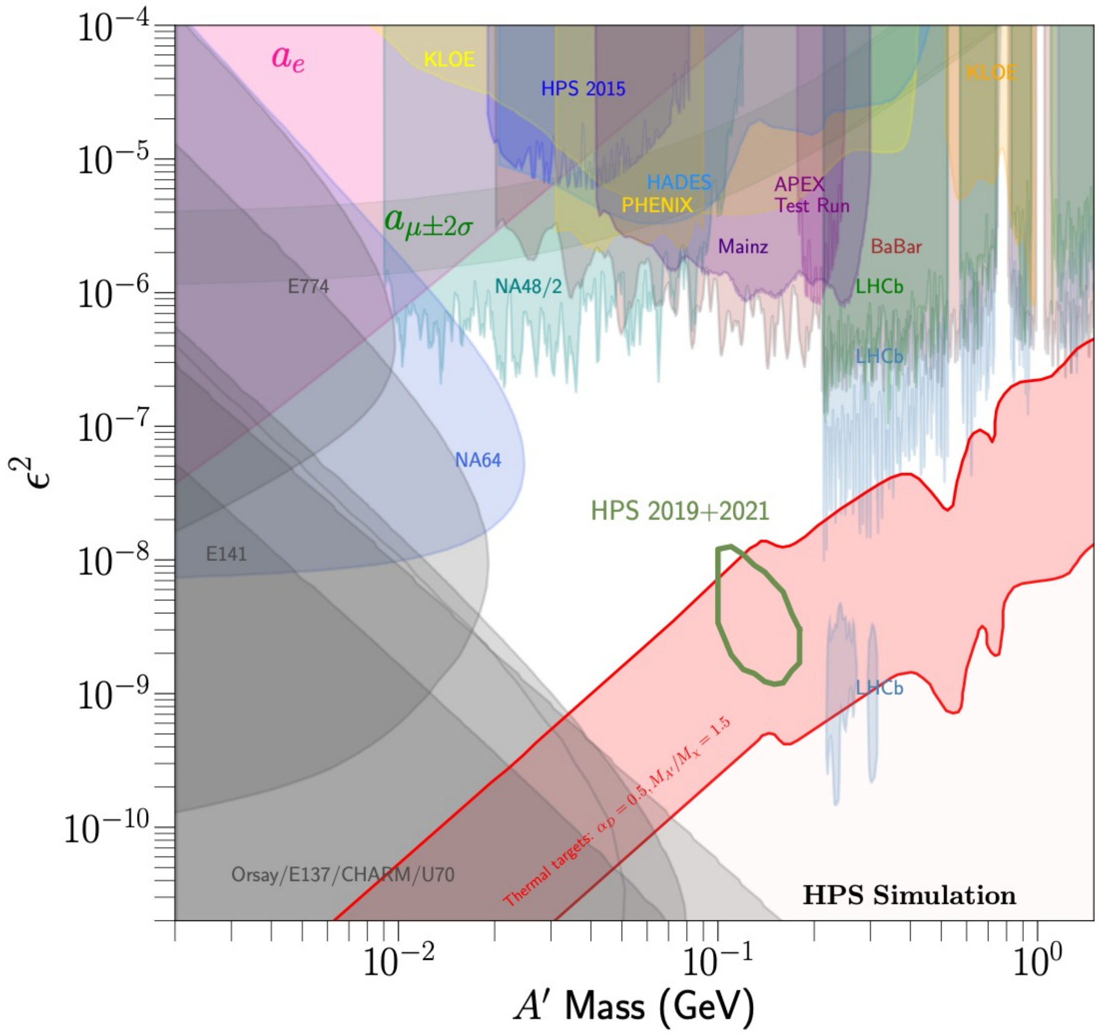
In the summer of 2019, data were collected during dedicated operation in Hall B over a period of 11 weeks at a beam energy of 4.55 GeV. Despite significant operational difficulties with CEBAF during this period, HPS successfully collected the first large physics dataset for the experiment



More data were collected in the fall of 2021 during dedicated operation in Hall B over 8 weeks at a beam energy of 3.74 GeV

2019-2021 Physics runs

- Detector upgrade was a success. Upgraded performances as expected
- The 2019 and 2021 datasets are large enough to provide significant sensitivity in the long-lived dark photon search
- The expected reach of the HPS displaced vertex search with the combined 2019 and 2021 datasets covers an highly motivated, yet unprobed region of parameter space

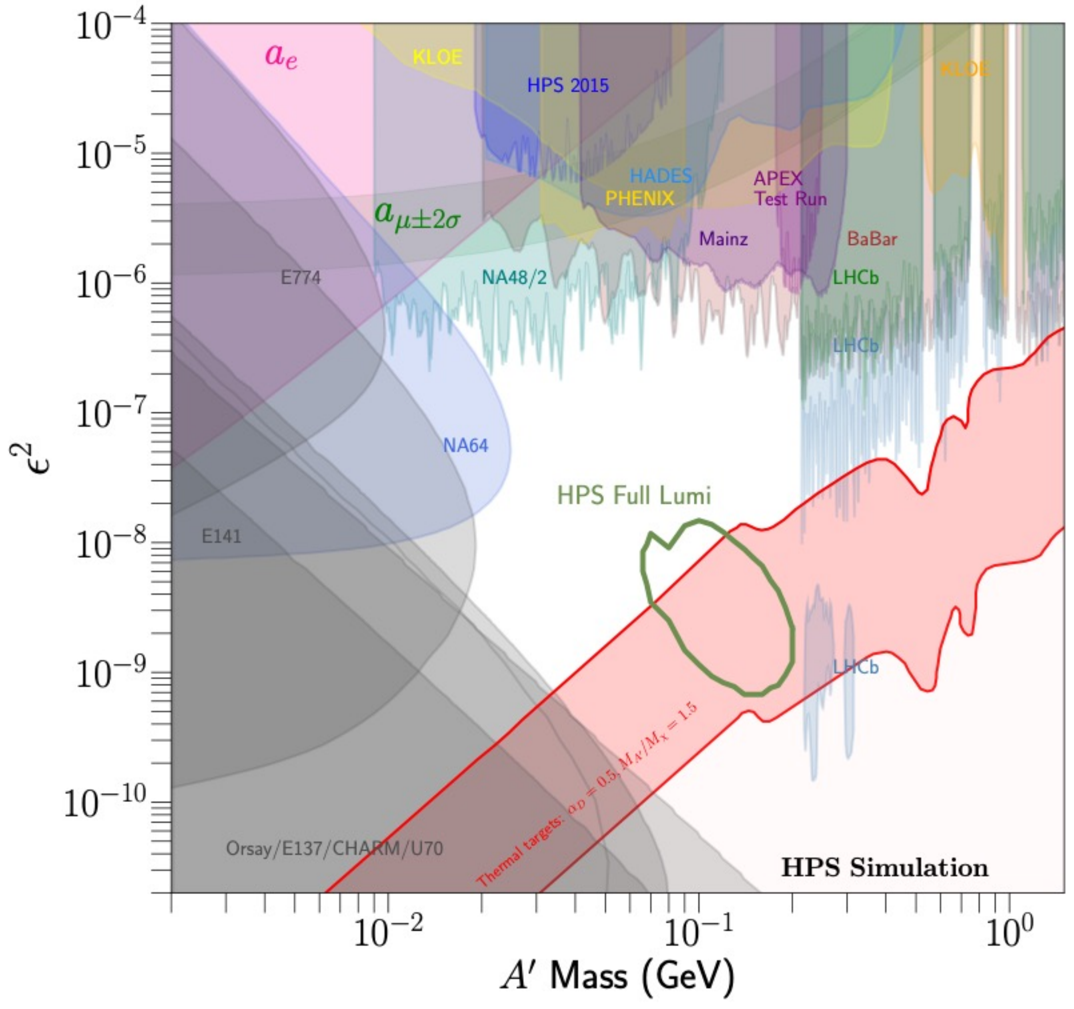


"The Heavy Photon Search Experiment", N. Baltzell et al., arXiv:2203.08324

Conclusions

- HPS is currently in the heart of its experimental campaign
- First physics data taking in 2019 and 2021 were successful
- Analysis from runs in 2019 and 2021 are expected to yield exclusions, or potential discovery, of A's
- The experiment has still 107 PAC-approved data-taking days left
- Probing other dark sector models with displaced vertices, such as SIMP (Strongly Interactive Massive Particles), is currently under investigation.

Stay Tuned !



Projected reach assuming to complete the remaining PAC-approved days with two more periods of operations at 2 and 4 GeV

Thank you !