

The Heavy Photon Search Experiment

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Abstract: The Heavy Photon Search (HPS) experiment searches for an electro-produced dark photon using an electron beam provided by the CEBAF accelerator at the Thomas Jefferson National Accelerator Facility. HPS has successfully completed two engineering runs. In 2015 using a 1.056 GeV, 50 nA electron beam, 1.7 days (10 mC) of data was obtained and 5.4 days (92.5 mC) of data was collected in 2016 using a 2.3 GeV, 200 nA electron beam. In addition, HPS will complete its first physics run in the summer of 2019. HPS looks for dark photons through two distinct methods, a resonance search in the e^+e^- invariant mass distribution above the large QED background (large dark photon-SM particles coupling region) and a displaced vertex search for long-lived dark photons (small coupling region). HPS employs a compact spectrometer, matched to the forward kinematic characteristics of A' electro-production. The detector consists of a silicon tracker for momentum analysis and vertexing and a lead tungstate (PbWO_4) electromagnetic calorimeter for particle ID and triggering. Both analyses are complete for the 2015 engineering run and demonstrate the full functionality of the experiment that will probe hitherto unexplored parameter space with higher luminosity runs. Results from the 2015 dataset will be presented as well as an update on 2016 analysis and the status of the 2019 physics run.

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1 Introduction

There has been strong evidence for the existence of Dark Matter (DM) for several decades, despite the fact that nothing is known about the particle nature of DM. Weakly interacting massive particles (WIMPs) have been a well motivated candidate, however the mass of the particles in this scenario have a lower bound [1]. Lighter thermal relics are also a great candidate but require a new physical force to achieve the correct relic abundance. We consider the case where DM interacts via a vector mediator [2]. This new vector mediator could kinematically mix with the photon of the Standard Model (SM), as shown in figure 1. This would allow for the interaction of the dark sector with the SM via electromagnetism suppressed by a mixing parameter ϵ , as shown in figure 2. This new boson is commonly called a Dark Photon (A').

HPS is a fixed target experiment consisting of a silicon tracker for momentum analysis and vertexing and a PbWO_4 electromagnetic calorimeter for particle ID and triggering [3]. The experiment employs an electron beam and tungsten target to probe A' scenarios which decay exclusively to electron-positron pairs. Two separate analyses are performed to search for signals which have either prompt or displaced decays.

2 Dark Photons in Fixed Target Experiments

Fixed target experiments are well suited to search for sub-GeV Dark Photons due to very large production cross sections for low-mass states. [4] The kinematics of A' production result in an A' with most of the beam energy and a soft recoil electron as shown in figure 3. The two dominant

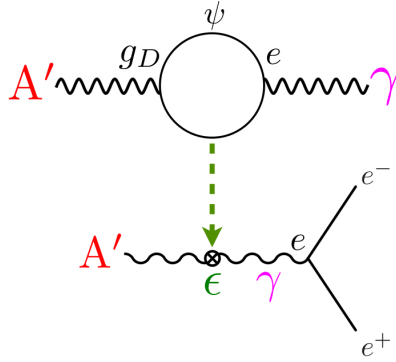


Figure 1: The dark sector could include massive fermions which might couple to the SM photon. This would kinematically mix the A' and the SM photon.

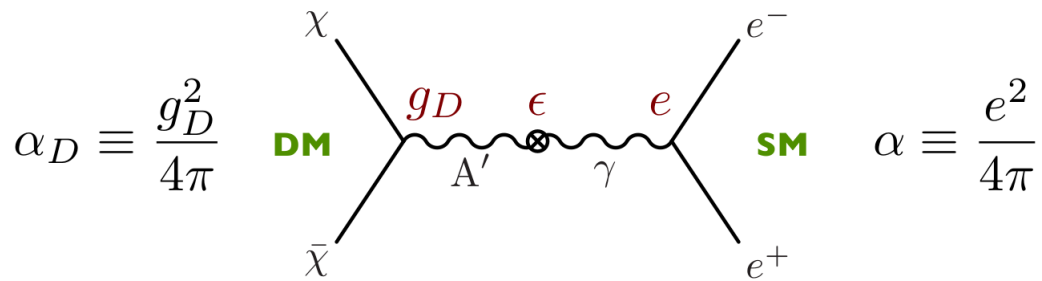


Figure 2: The mixing of the photon and A' would couple DM to the SM.

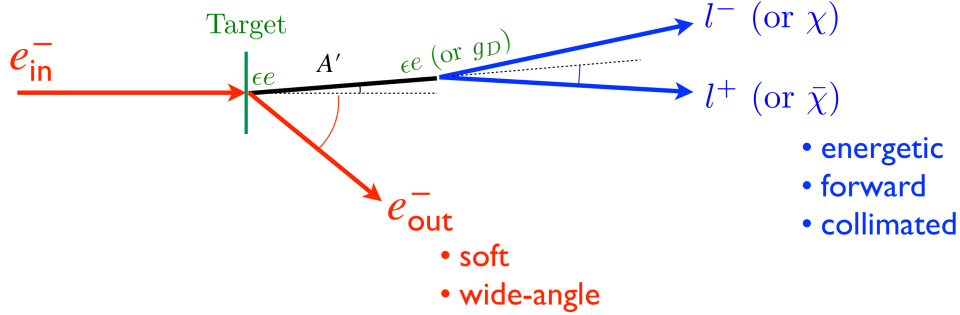


Figure 3: A cartoon of A' production in fixed target experiments.

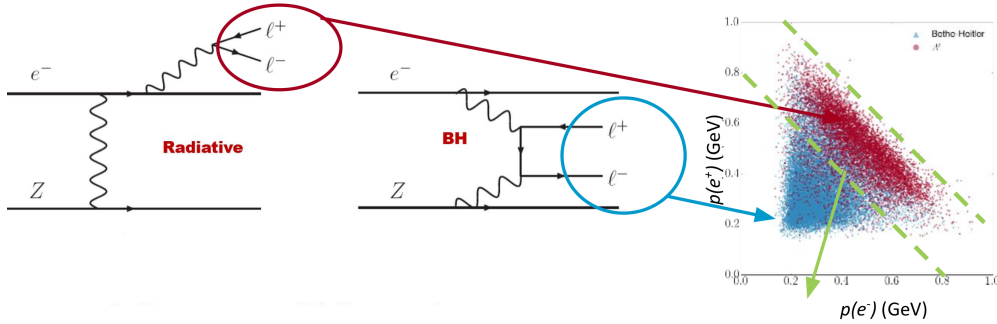


Figure 4: The two dominant backgrounds in fixed target experiments searching for visible A' decays are radiative tridents and Bethe-Heitler (BH). The BH background can be suppressed with a simple kinematic cut on the electron and positron momenta.

backgrounds for visible decays of Dark Photons are radiative tridents and Bethe-Heitler tridents (BH), shown in figure 4. The radiative trident rate provides a reference for the expected signal rate. The signal is typically parameterized by the mass of the A' and the mixing parameter, ϵ , to the SM photon. The lifetime of the A' has a complicated relationship to these parameters, which is described in figure 5. The projections of existing limits and upcoming experiments with projected sensitivity to this physics are shown in figure 6.

3 The HPS Experiment

The HPS apparatus is located in Hall B of the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility of the Department of Energy. The experiment is designed as a general search for visible decays of the A' . The apparatus is a compact e^+e^- spectrometer immediately downstream of a thin target in a multi-GeV electron beam. It consists of a $PbWO_4$ calorimeter (ECal) and a low-mass, high-rate (up to 4 MHz/mm²) silicon tracker (SVT). A drawing of the detector is shown in figure 7. The ECal is used as a trigger to eliminate order 10 MHz of scattered single electrons from the beam. The tracker was designed with 6 layers of axial-stereo pairs of strip sensors read out by the APV25 ASIC designed for the CMS experiment [5]. It is capable of reconstructing vertices several mm downstream of the target. The SVT is supported by kinematic mounts that allow it to be opened and closed for beam tuning operations. The nominal running position of the tracker leaves a 1 mm gap between the sensors of the first layer.

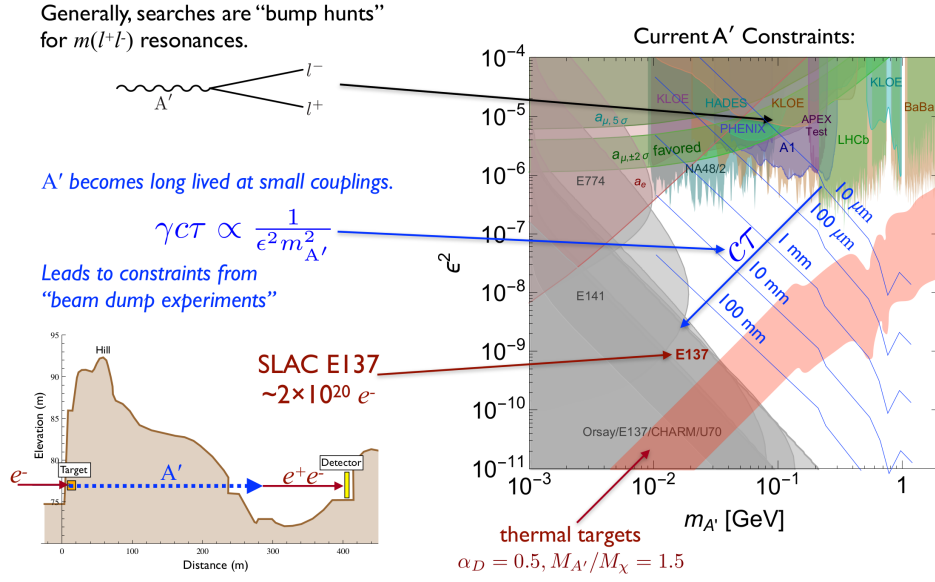


Figure 5: This is the parameter space used to summarize searches for visible decays of Dark Photons. ϵ^2 over 10^{-6} has already been almost entirely excluded. Low-mixing and low-mass scenarios have also been excluded by multiple beam dump experiments. HPS is a search designed to be sensitive in the most difficult part of the parameter space to probe, where the A' lifetime is on the order of mm. The figure on the right is taken from [6].

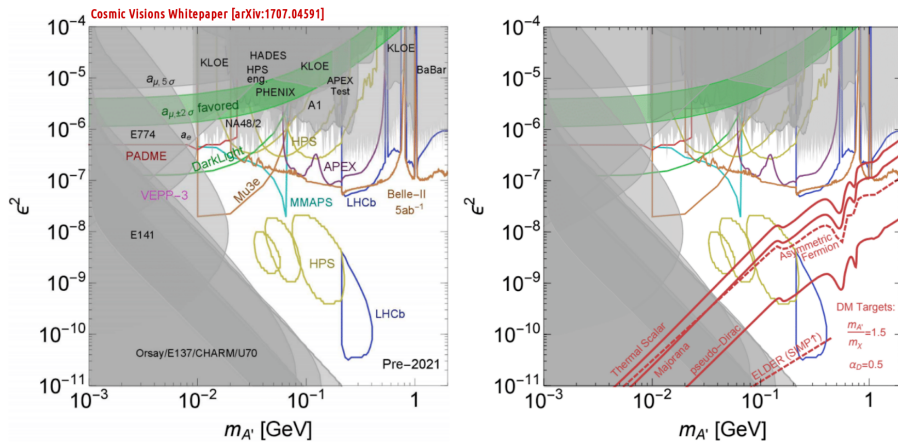


Figure 6: A summary of excluded regions and projections of future experiments searching for visible decays of A' . This figure was taken from [6].

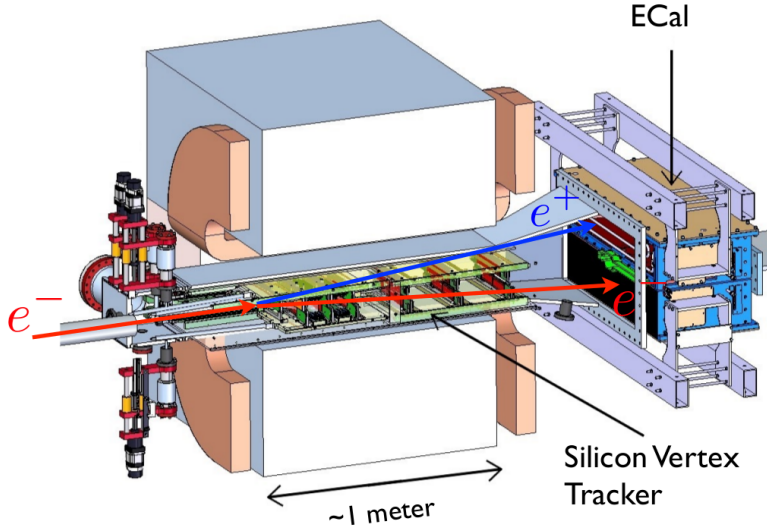


Figure 7: A graphic of the HPS apparatus showing the path of an incoming beam electron and an e^+e^- pair coming from the target.

3.1 Engineering Runs

HPS has performed two engineering runs, one in 2015 with a beam energy of 1.06 GeV, and one in 2016 with a beam energy of 2.3 GeV. These runs are summarized in figure 8. The apparatus has performed exceptionally well, and is still approved for 165 more days of beam time. The first physics run is underway during this summer (2019) with a beam energy of 4.56 GeV.

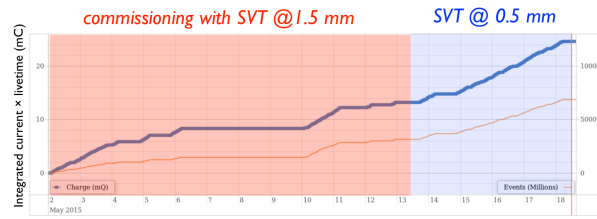
The results of the resonance search performed on the 2015 dataset have been published [7]. This analysis measures the mass resolution using Møllers and the expected signal rate is calibrated by using tridents. The background shape is fit using a Chebyshev polynomial and a likelihood ratio is used to quantify the significance of any excess. No signal was observed so the likelihood ratio is inverted to determine a 2σ upper limit for each signal mass. The excluded region from this analysis is shown in figure 9. This result only used about 1% of the approved run time of the experiment.

A displaced vertex search is currently being performed on the 2016 dataset. Preliminary results of this search analysis were presented at the APS April Meeting 2019 [8]. This search reconstructs the position of the e^+e^- vertices and searches for an excess of vertices downstream of the target. The total signal expected for the maximum signal point is on the order of a tenth of an event, so there is not enough luminosity to set any limits using the 2015 dataset. The preliminary result of this analysis is shown in figure 10.

3.2 HPS Upgrades and 2019 Physics Run

Two significant upgrades were executed on the HPS apparatus before the 2019 physics run. The first is to the SVT, adding a new "Layer 0" (L0) which is closer to the target, allowing access to shorter decay lengths which significantly increases the acceptance of the experiment. The improvement in vertex resolution with the addition of L0 is shown in figure 11. Also, the original first layer was replaced with the same new technology used in L0, which moves the active region of the detector closer to the beam. Layers 2 and 3 were also moved closer to the beam as occupancy allowed, ultimately increasing the acceptance at longer decay lengths. Figure 12 shows how the upgrades are expected to improve the performance of the experiment. The technology of the new

2015 Engineering Run
 50 nA @ 1.06 GeV
 1.7 days (10 mC) of
 physics data



2016 Engineering Run
 200 nA @ 2.3 GeV
 5.4 days (92.5 mC) of
 physics data

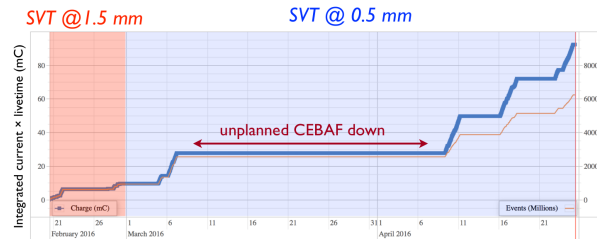


Figure 8: The integrated beam current and total number of triggered events throughout the two HPS engineering runs in 2015 and 2016.

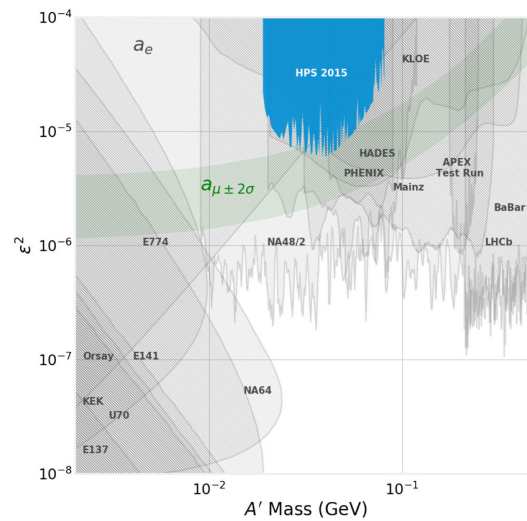


Figure 9: The region of the A' parameter space excluded by the 2015 resonance search analysis. [7]

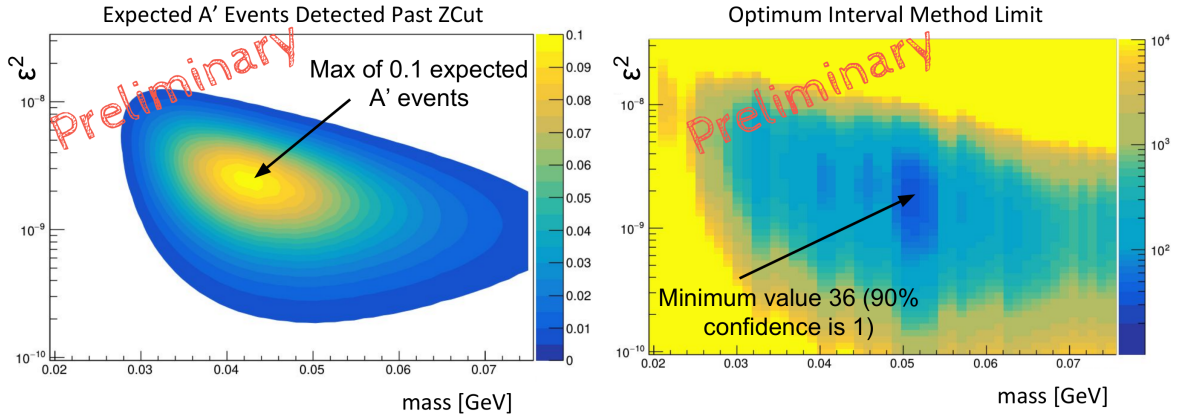


Figure 10: The signal expectation and limit set using the optimum interval method for the 2015 dataset. It can be seen that at the maximum only about 0.1 signal events are expected.

L0 sensors has about half the material, being 200 microns thick. It has 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. Replacing Layer 1 with this new technology will also decrease difficult backgrounds such as wide-angle bremsstrahlung photons converting in the inactive region of the sensor and trident production in this region from scattered electrons. This new sensor technology is produced by CNM Barcelona and is shown in figure 13.

The other upgrade to the apparatus is the addition of a hodoscope for triggering on positrons. This allows for a single cluster trigger to be used for physics production data taking, since the hodoscope will allow for the reduction of photons as shown in figure 14. 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 layers of hodoscope hits with a position that matches the position and time of the cluster in the ECal.

HPS is a challenging experiment for the CEBAF to deliver the required beam to. The SVT has wires installed that allow the determination of the beam position and size at the target location. An example of one such scan is shown in figure 15. The CEBAF has demonstrated the ability to deliver beam within the acceptable specifications for physics data production. Squeezing the beam to an adequate size on the target can take many hours of tuning work. After the completion of the upgrade program, the HPS reach has been re-evaluated. The new reach estimates for the 2019 data run are shown in figure 16.

4 Conclusion

The HPS detector has performed well for the 2015 and 2016 engineering runs, producing results that establish the physics performance of the experiment. The preliminary vertex analysis demonstrates that new sensitivity is expected with larger datasets, beginning with data from the Summer 2019 run. HPS underwent a successful upgrade program before this run to improve the reach of the experiment. Because of the extreme proximity of the silicon to the primary beam, the HPS experiment presents major challenges to beam delivery by CEBAF, requiring extensive beam tuning during operations. The 2019 run is currently on-going and should produce a dataset which allowing for sensitivity to A' with mm-to-cm decay lengths for the first time.

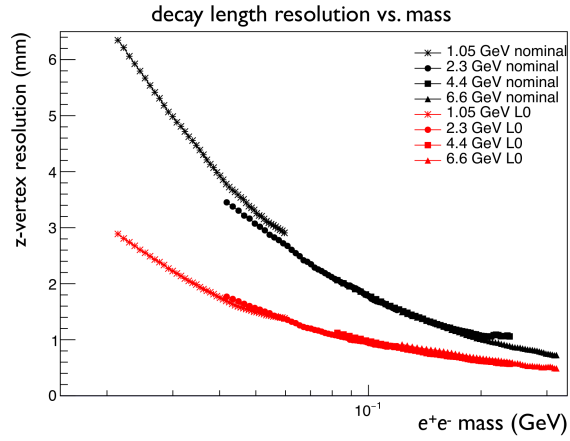


Figure 11: The decay length resolution in MC with and without the L0 upgrade.

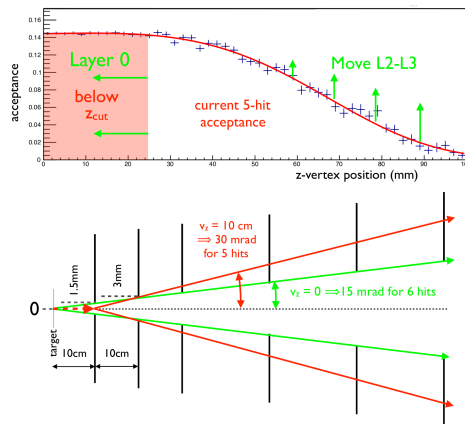


Figure 12: The acceptance of signal as a function of vertex position, showing how the addition of L0 and repositioning of Layers 2 and 3 will increase the acceptance. Below we see a cartoon depiction of how the new geometry improves this performance.

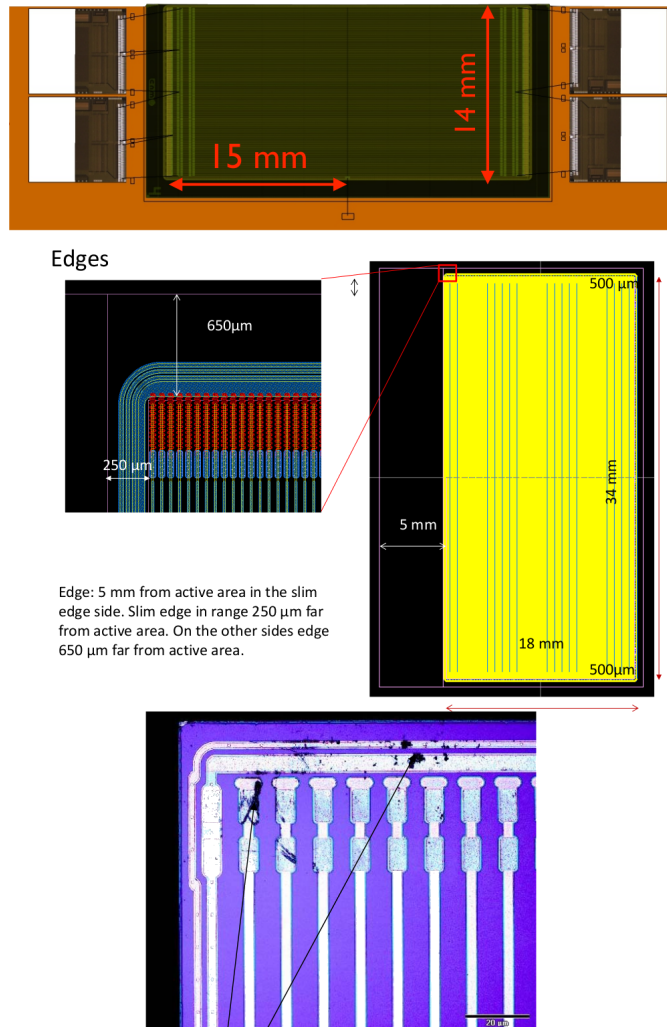


Figure 13: A collection of drawing and pictures of the new L0 sensor technology.

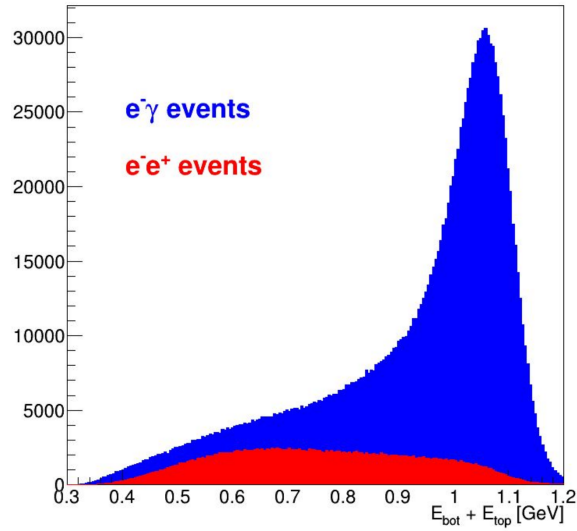


Figure 14: The number of events triggered events with photons and events with positrons. The blue region is suppressed in the trigger with the hodoscope upgrade.

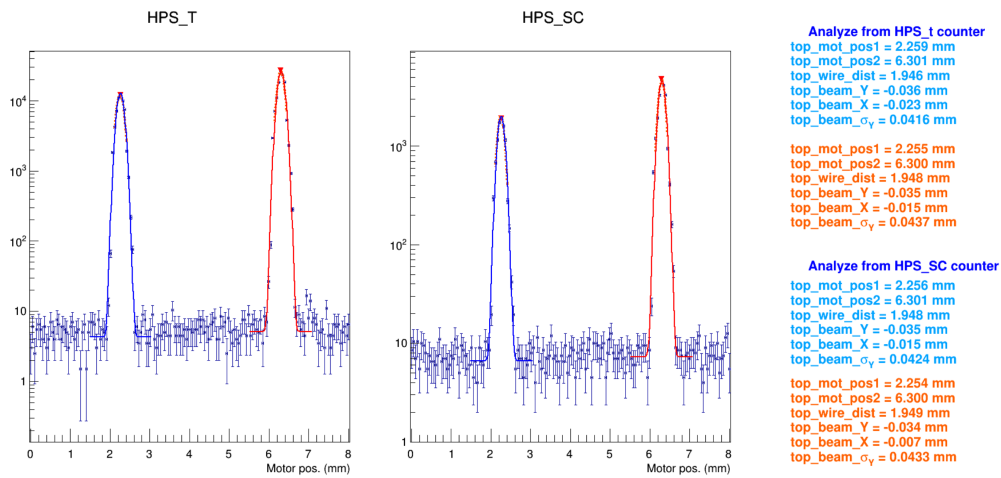


Figure 15: An example of an analyzed SVT wire scan. Here we see a beam spot size of about 42 μm within 50 μm of the center of the detector. This demonstrates the CEBAF is capable of delivering physics production quality beam to the experiment.

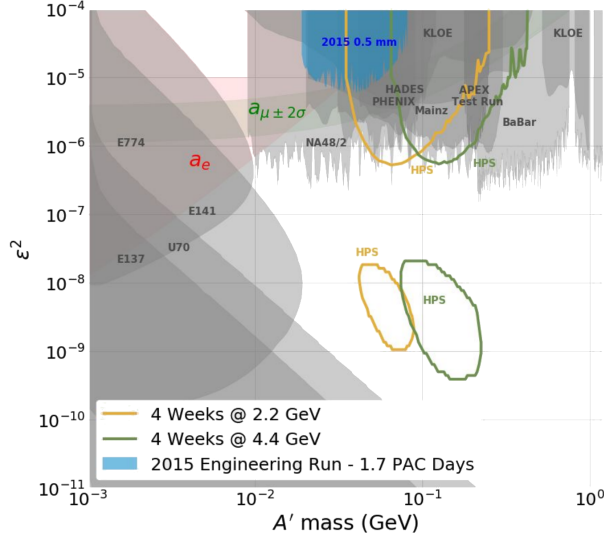


Figure 16: The reach estimate for the run in the summer of 2019 for two different beam energies. The 2.2 GeV estimate assumes a 200 nA beam incident on a 4 um W target. The 4.4 GeV estimate assumes a 300 nA beam incident on an 8 um W target. The 2019 data run is at a beam energy of about 4.5 GeV.

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