The Heavy Photon Search Experiment at Jefferson Lab

HPS Collaboration
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Introduction

The effective coupling of the heavy photon to electric charge allows its production through a process analogous to bremsstrahlung radiation and its decay to e^+e^- pairs[1]. The Heavy Photon Search (HPS) is a fixed target experiment that utilizes this mechanism in its search for heavy photons (dark photons, A') in the mass range of 18 MeV/c^2 to 500 MeV/c^2. It accomplishes this by using Jefferson Lab's (JLab) high luminosity electron beam incident on a thin tungsten target to produce heavy photons which subsequently decay to e^+e^- pairs.

At the energies at which the HPS experiment is operating, the electroproduced A' will carry most of the incident beam energy. Consequently, the A' decay products will be highly boosted, necessitating a detector with very forward acceptance. Maximizing the acceptance requires placing the detector as close as possible to the "dead zone" around the beam which is defined by the intense flux of multiple Coulomb scattered beam particles along with radiative secondaries emanating from the target. In order to avoid additional background from beam gas interactions, the detector operates in vacuum. Minimizing the material budget of the active area of the detector is essential for reducing the multiple scattering that dominates both the mass and vertex resolutions, and optimizes the experimental sensitivity. Capitalizing on the CW performance of CEBAF 12, and incorporating very fast detectors and high rate front end electronics, allows HPS to spread out backgrounds in time, and acquire the high luminosities needed to search for a tiny signal hidden in a huge background.

These design principles led to the realization of the HPS detector. Specifically, HPS utilizes a compact, large acceptance forward spectrometer consisting of a silicon vertex tracker (SVT) along with a highly segmented lead tungstate electromagnetic calorimeter (Ecal). The SVT is comprised of six measurement layers each consisting of a pair of closely-spaced silicon sensors. A stereo angle is introduced between the two sensors within each layer allowing for the measurement of both the vertical and bend coordinate of a hit, in turn, enabling full 3D hit reconstruction. The sensors are placed within 1/2 mm of the beam. The SVT is installed inside a vacuum chamber immediately downstream of a thin ($0.125\%X_0$) tungsten foil target. The vacuum chamber is placed inside an analyzing magnet providing a .25 Tesla field for the precise measurement of track momenta. The Ecal, placed downstream of the tracker, provides the primary trigger for the experiment and is also used for electron identification [2]. Together, the subsystems provide the complete kinematic information required to reconstruct the invariant mass and vertex position of a decaying heavy photon. An overview of the HPS Detector is shown in Figure 1. With such a setup, and by virtue of placing detectors just 10 cm from the target, HPS is capable of identifying heavy photons which have secondary decay vertices in addition to those which appear as resonance bumps above background. This gives the experiment access to two regions of parameter space, to comparatively large coupling constants using a traditional bump hunt, and to very small couplings, using vertexing to eliminate almost all of the trident background produced at the target.

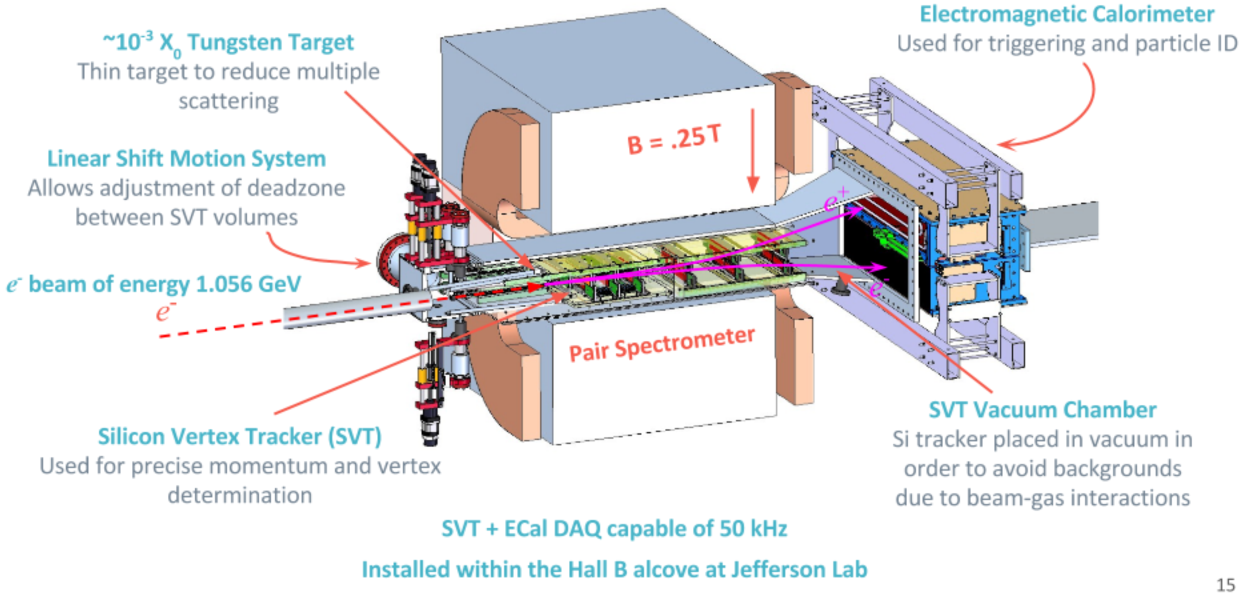

Figure 1: Schematic view of the Heavy Photon Search detector used during the 2015 and 2016 engineering run.

The HPS detector was installed and commissioned within the Hall B alcove at JLab early in the spring of 2015. Shortly afterwards, an engineering run took place utilizing the Continuous Electron Beam Accelerator Facility (CEBAF) operating at an energy of 1.056 GeV and current of 50 nA. This engineering run marked the first time that the full experiment took data. Detector performance from this run demonstrated that HPS was ready for physics, and led to lab approval of the full HPS proposal. The momentum, mass and vertex resolutions were all as predicted. Furthermore, the trigger and data taking efficiencies were as expected. In total, 1165 nb^{-1} (7.25 mC of charge) of data was collected.

Resonance Search

If a heavy photon does indeed exist and has a mass that is within the acceptance of the HPS detector, it will appear as a resonance above the copious QED trident invariant mass distribution. Such a signal is expected to be Gaussian in nature, with a mean equal to the mass, $m_{A'}$, of the A' and with a mass dependent width, $\sigma_{m_{A'}}$, given by the mass resolution parameterization shown in Figure 2.

Since the mass of the A' is unknown a priori, the e^+e^- invariant mass spectrum needs to be scanned for any significant peaks. Customarily, a search for a resonance is performed within a window constructed around the mass hypothesis of interest. Within the window, the distribution of A' signal events is modeled using the probability distribution function

$$P(m_{e^+e^-}) = \mu \cdot \phi(m_{e^+e^-}|m_{A'}, \sigma_{m_{A'}}) + B \cdot p(m_{e^+e^-}|\mathbf{t}) \quad (1)$$

where $m_{e^+e^-}$ is the e^+e^- invariant mass, μ is the signal yield, B is the number of background events within the window, $\phi(m_{e^+e^-}|m_{A'}, \sigma_{m_{A'}})$ is a Gaussian probability distribution describing the signal and $p(m_{e^+e^-}|\mathbf{t})$ is a Chebyshev polynomial of the first kind with coefficients

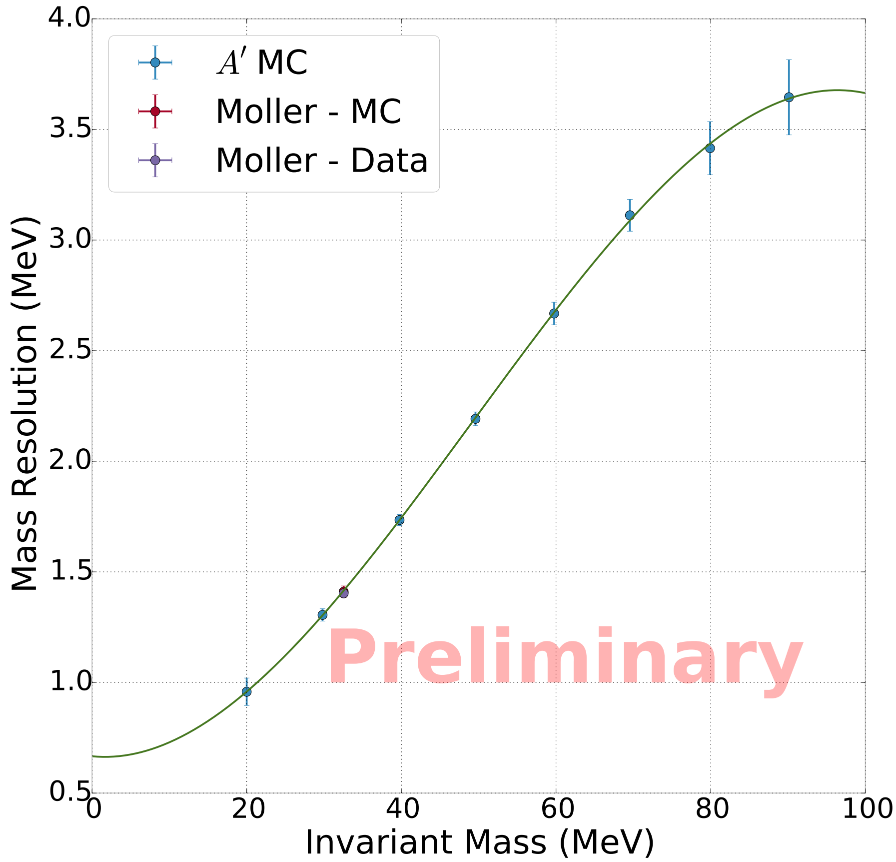

Figure 2: The mass resolution as a function of mass calculated using the invariant mass distributions of A' (blue) and Moller (red) Monte Carlo as well as Moller data (purple).

$\mathbf{t} = (t_1, ...t_j)$ that is used to describe the background shape. In this instance, a 7th order Chebyshev polynomial is used to describe the background. Furthermore, $m_{A'}$ and $\sigma_{m_{A'}}$ are constant and set to the A' mass hypothesis and expected experimental mass resolution, respectively. Estimating the signal yield as well as the background normalization and shape within a window is done by the method of maximum likelihood.

A search conducted on the unblinded portion (74 nb^{-1}) of the 2015 HPS engineering run data found no significant resonances. Since no significant resonances were found, a 50% power constrained [3] 2σ upper limit on the number of signal events at each mass hypothesis was set. The resulting upper limits are shown in Figure 3. The signal upper limits where then used to place a limit on ϵ^2. The 2σ limit on the coupling (blue) along with the projections to the full engineering run data set (maroon) are shown in Figure 4.

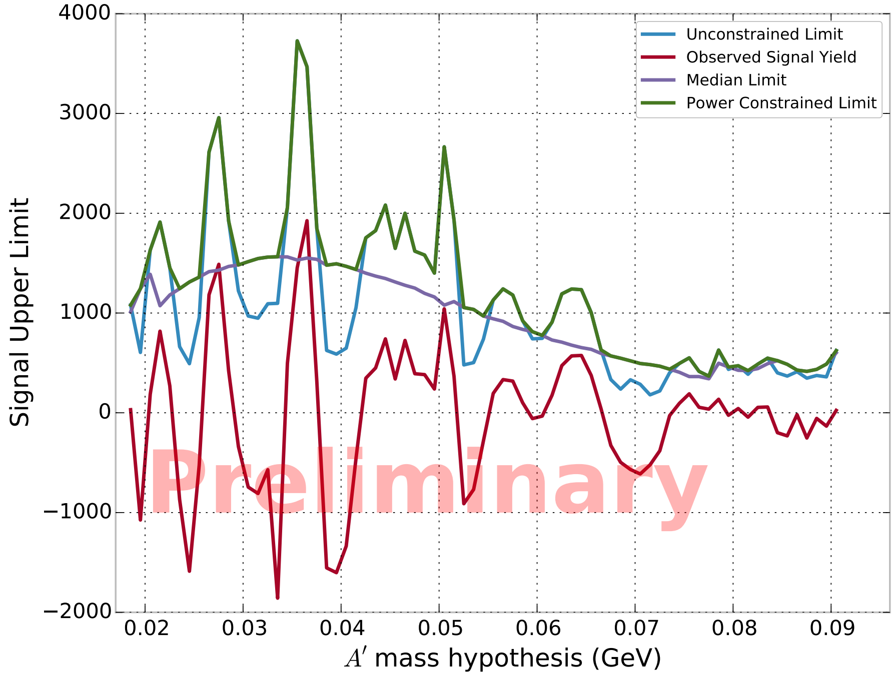

Figure 3: 2σ unconstrained (blue) and power constrained (green) upper limits on the signal yield at each mass hypothesis along with the observed signal yield (maroon).

Estimated Reach

The results of this search (light blue) are shown along with existing limits in Figure 5. The HPS search represents only 1.7 days of running and does not exclude any new parameter space. However, HPS expects to collect much more data in the next few years. The figure also shows the limits which would be obtained in a bump hunt search by running at 4.4 GeV, 400 nA (pink) and 2.2 GeV, 200 nA (orange) for 4 weeks each. HPS is still evaluating its first vertexing results from 2015, and is in the process of updating its vertexing reach projections. It is already clear that the 2015 data, with just 1.7 days of running, will not be sensitive to a heavy photon with canonical couplings. With modest upgrades to the detector and trigger, however, and with multi-week runs, HPS expects to search a substantial and unexplored region in the mass-coupling parameter space for heavy photons, and expects to have sensitivity to other hidden sector particles as well.

Conclusions

The Heavy Photon Search is the first new experiment dedicated to searching for signs of a massive hidden sector force particle at accelerators. Finding such a particle could be the first indication that hidden sectors exist, and that dark matter resides in such a sector. HPS results complement analyses of data taken with existing detectors, and extends their reach considerably in the mass range of 18 to 500 MeV/c^2. Originally proposed in 2010, HPS

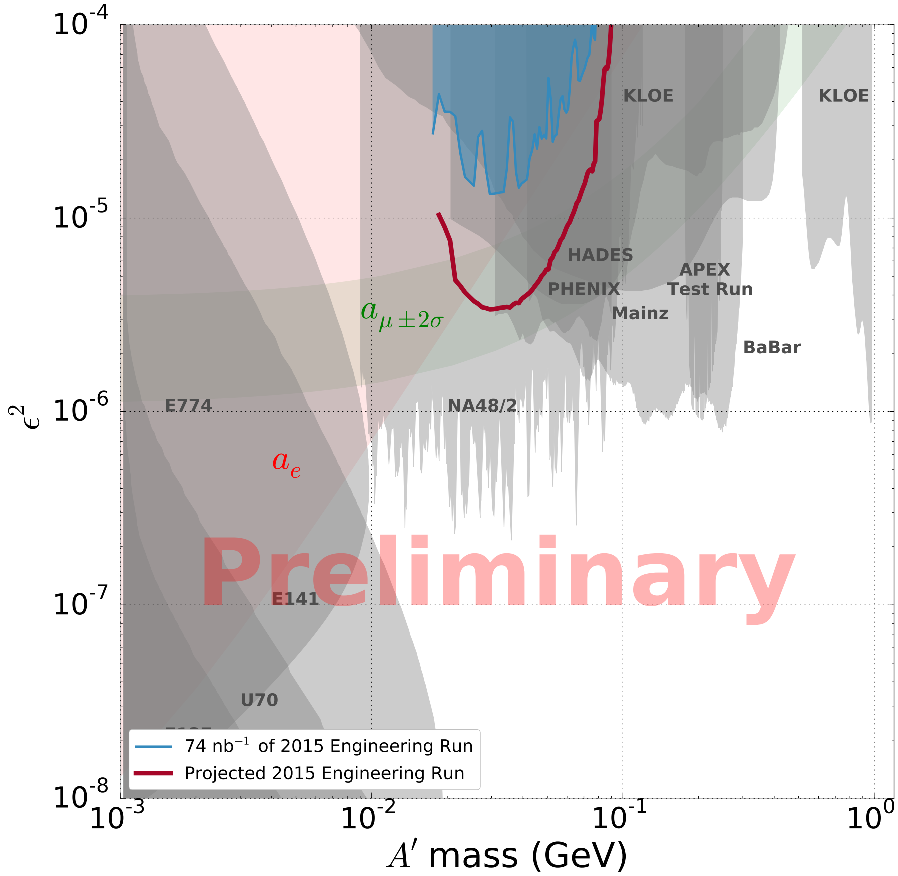

Figure 4: 2σ upper limit (blue) on the coupling strength derived using 74 nb^{-1} of the engineering run data set along with the projected sensitivity (maroon) using the full data set.

was fully realized and installed in Hall B at Jlab in 2015, and took engineering run data in both 2015 and 2016. The experiment has explored new experimental territory, measuring electromagnetic interactions at small angles from the beam, placing detectors within 1/2 mm of the beam, and enduring very high trigger and data taking rates, high occupancies, and high radiation doses. With these first bump hunt results from its 2015 engineering run, it has demonstrated the viability of its approach, and promises to produce exciting results in the near future.

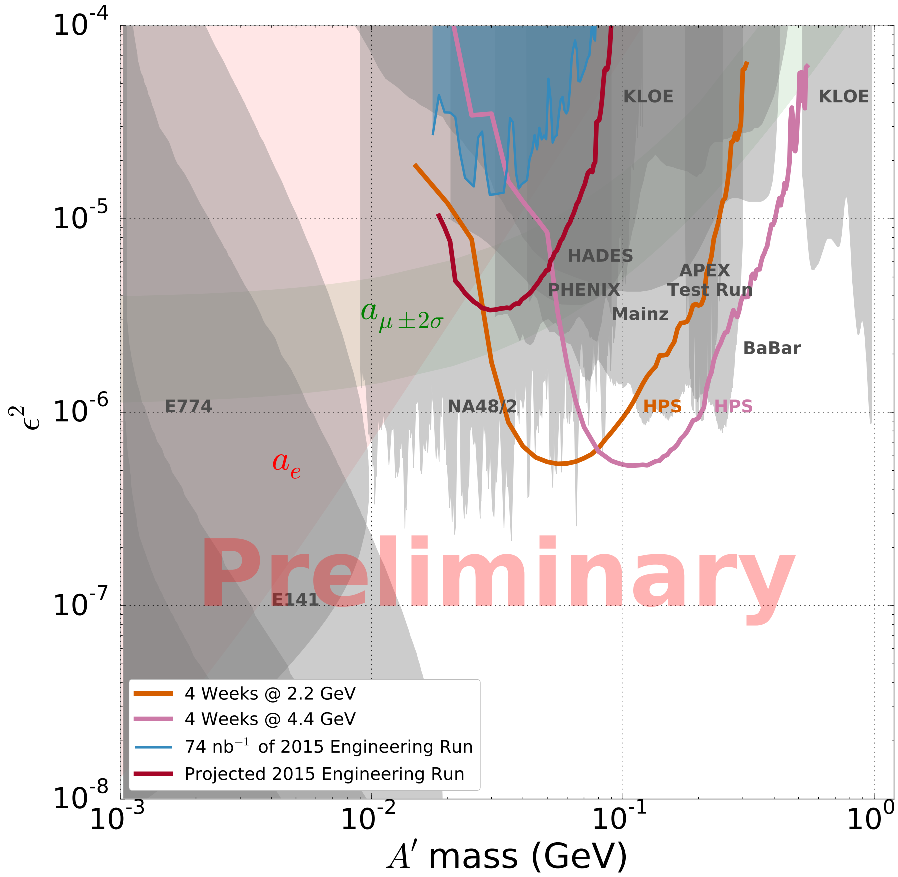

Figure 5: The projected reach of the Heavy Photon Search experiment at 2σ along with existing constraints. The projections assume running for 4 weeks using a 2.2 GeV, 200 nA (orange) or a 4.4 GeV, 400 nA beam (pink).

References

[1] James D. Bjorken, Rouven Essig, Philip Schuster, and Natalia Toro. New Fixed-Target Experiments to Search for Dark Gauge Forces. *Phys. Rev.*, D80:075018, 2009.

[2] I. Balossino, N. Baltzell, M. Battaglieri, M. Bondì, E. Buchanan, D. Calvo, A. Celentano, G. Charles, L. Colaneri, A. D'Angelo, M. De Napoli, R. De Vita, R. Dupré, H. Egiyan, M. Ehrhart, A. Filippi, M. Garçon, N. Gevorgyan, F.-X. Girod, M. Guidal, M. Holtrop, V. Iurasov, V. Kubarovsky, K. Livingston, K. McCarty, J. McCormick, B. McKinnon, M. Osipenko, R. Paremuzyan, N. Randazzo, E. Rauly, B. Raydo, E. Rindel, A. Rizzo, P. Rosier, V. Sipala, S. Stepanyan, H. Szumila-Vance, and L.B. Weinstein. The {HPS} electromagnetic calorimeter. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 854:89 – 99, 2017.

[3] Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. Power-Constrained Limits. 2011.