Frascati Physics Series Vol. LVI (2012)
DARK FORCES AT ACCELERATORS
October 16-19, 2012

HEAVY PHOTON SEARCH

John Jaros for the HPS Collaboration
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

Abstract

The Heavy Photon Search Experiment (HPS) is a new experiment at Jefferson Lab designed to look for massive vector gauge bosons (heavy photons) in the mass range 20-1000 MeV/c^2 which couple to electrons with couplings α'/α in the range 10^{-5} to 10^{-10} . The experiment utilizes a compact forward spectrometer employing silicon microstrip detectors for vertexing and tracking and a $PbWO_4$ electromagnetic calorimeter for fast triggering, and is designed to measure the invariant mass and decay vertex location of electro-produced heavy photons. As its first stage, the HPS Collaboration mounted the HPS Test Run Experiment, which ran parasitically in Hall B at JLAB during Spring 2012. The run demonstrated the technical feasibility of the design and confirmed critical background assumptions. On the basis of this successful test run, the experiment has been approved for physics running. The experimental design and results from the Test Run are discussed, along with the collaboration's plans for stage two, the full HPS experiment.

1 Introduction

The Heavy Photon Search (HPS) is a new, dedicated experiment at Jefferson Laboratory designed to search for a heavy photon (aka A', dark photon, or hidden sector photon) in the mass range 20-1000 MeV/c^2 and coupling ϵe to electric charge, where $\alpha'/\alpha = \epsilon^2$ is in the range 10^{-5} to 10^{-10}. The search enjoys unique sensitivity by employing both invariant mass and secondary decay vertex signatures, and will explore virgin territory in heavy photon parameter space. Experimentally, HPS explores new territory as well, looking at very forward angles, large acceptances, and high rates in fixed target electroproduction.

HPS, like other experiments described at this workshop, is motivated by the possibility that there exist sectors of particles and interactions which are essentially hidden from us by virtue of their weak couplings to ordinary matter. Hidden sector photons are of especial interest because they are expected on very general theoretical grounds in many Beyond Standard Model theories, could explain the presently observed discrepancy between the experimental and theoretical values for the muon's anomalous magnetic moment, and may even explain the unexpectedly high flux of electrons and positrons recently seen in the cosmic rays (see [1] for a recent review). Through kinetic mixing, heavy photons are expected to mix with the Standard Model photon, which induces their weak couplings to electric charge [2, 3]. So heavy photons couple to electrons, can be produced by electron bremsstrahlung off heavy nuclear targets, and can decay to e^+e^- pairs. Since the coupling of heavy photons to e^+e^- pairs is much weaker than the canonical electromagnetic coupling, heavy photon production is buried in a huge background of pairs from massive virtual photons (QED tridents). The weak coupling is also responsible for the heavy photon's very narrow decay width. Consequently, a heavy photon would appear as a very sharp mass resonance above the QED background, and, for a wide range of coupling strengths, have a distinct secondary decay vertex. HPS exploits both signatures.

These signatures will uncover some bread and butter physics as well. QED predicts the existence of as yet unseen atoms comprised of bound μ^+ and μ^- mesons [4], and it predicts their production at levels sufficient for detection in HPS [5]. True Muonium decays to e^+e^- pairs with a decay signature just like the heavy photon's, a sharp mass bump (at $2m_\mu$) and a finite decay length.

It offers additional physics for HPS, and a perfect heavy photon calibration signal.

The idea for HPS came from a seminal paper by Bjorken, Essig, Schuster, and Toro [9] which explored the phenomenology of heavy photons in fixed target experiments, capitalizing on the interest stirred by papers which proposed Dark Matter annihilating to pairs of heavy photons as the source of the e^+ excess in the cosmic rays [6], [7]. Besides setting exclusion limits in the mass/coupling parameter space by reinterpreting existing results, the authors suggested a number of search strategies. HPS derives from the vertexing concept put forward in their paper.

HPS was presented to the Jefferson Laboratory Program Advisory Committee in December, 2010 as a two staged proposal [8]. The first, the HPS Test Run, a minimalist version of the experiment to demonstrate the technological approach, confirm background estimates, and begin the search, was approved early in 2011, and was subsequently proposed and funded by DOE HEP. It was installed at JLAB in April 2012, commissioned and run. The second stage, HPS proper, was approved conditionally, contingent on the outcome of the Test Run. A subsequent Program Committee reviewed the Test Run results in 2012. Since then, the HPS Collaboration has revised the design of the second stage experiment, proposed it to DOE HEP [10] and begun long lead-time preparations. Stage II HPS will be reviewed by DOE in July, 2013. With approval and funding, HPS plans to be ready for installation at Hall B at JLAB in September, 2014, have a commissioning run late 2014, and take data in 2015.

This paper will review and motivate the design of the experiment, present results from the HPS Test Run experiment, outline the revised design of Full HPS, and give its reach. The HPS design has evolved since the time this work was presented at the Dark 2012 Workshop. The current version is included here.

2 HPS Design Considerations

As emphasized in [9], fixed target experiments enjoy a considerable luminosity advantage over colliding beam experiments in searching for heavy photons in the mass range 20-1000 MeV/c^2. Since it is this range that has been largely unexplored, and since this is the mass range preferred by models attributing high energy electrons and positrons in the cosmic rays to dark matter annihilations, it is natural to conduct a fixed target search. Electron bremsstrahlung provides a natural production mechanism, shown in fig.1 for signal and virtual photon background. The kinematics of A' bremsstrahlung, reviewed in [9], dictate the experimental design. For A' masses well above the electron mass, the A's are radiatively produced at very forward angles with nearly the full energy of the electron beam. Their decay products are boosted forward with typical polar angles $\approx m_{A'}/E_{beam}$, so good forward acceptance is a design prerequisite. Bump hunting requires good momentum and angular resolution, which is most easily accomplished with charged particle spectrometry, and vertex detection requires the first sensor layers be relatively close to the target, to minimize extrapolation errors. So the HPS apparatus places its detectors as close to the beamline as possible to maximize acceptance, just downstream of the target to optimize vertex resolution, and within a magnet to make a precise momentum measurement. Silicon microstrip sensors are chosen as the tracking detectors, providing optimal spatial resolution, high rate capability, and good radiation hardness. Downstream of the analyzing magnet, the magnetic field has bent the electrons and positrons respectively to beams right and left as they enter an electromagnetic calorimeter, providing charge discrimination. The ECal, using an array of $PbWO_4$ crystals, provides a fast trigger on events with both an electron and a positron.

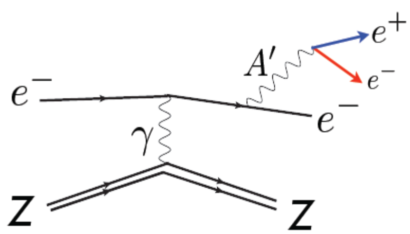

Figure 1: *Feynman diagram for radiative A' electro-production. Radiative QED background arises from a similar diagram, with the A' replaced by a virtual photon, $\gamma*$. The QED Bethe-Heitler diagram also contributes to the background.*

The viability of the experiment depends on generating large integrated luminosities, because the A' production cross section is small and the trident background comparatively huge. The radiative cross section for A' production on a tungsten target with a 2 GeV electron is roughly a nanobarn for a coupling $\alpha'/\alpha \approx 10^{-6}$ and mass 100 MeV/c^2, but falls (rises) by a decade as the mass doubles (halves). Getting luminosities high and keeping occupancies low is best done by running with essentially 100 % duty factor and with sensors which have very short response times. The CEBAF accelerator at Jefferson Laboratory provides nearly DC beam (beam bunches every 2 ns), a range of beam energies from 2-11 GeV, and excellent beam quality. Silicon microstrip detectors and $PbWO_4$ crystals readout by APDs can be run at very high rates, are radiation hard, and have pulse lengths $\approx$ 60 ns, so can handle very high rates. High rate data acquisition is also required, and available.

Target thickness plays an important role in maximizing the detector's capabilities. By minimizing target thickness, but boosting beam current to keep their product constant, one minimizes multiple Coulomb scattering of beam electrons in the target, and thereby minimizes occupancies and trigger rates. HPS uses 4 - 8 μm tungsten targets and currents in the range of 100-400 nA to accumulate large luminosity samples which don't overwhelm trigger rates. Beam spot sizes and halo are also important. Small beam spots offer important constraints which help improve track angular resolution, boost vertex resolution, and thereby reduce tails in the vertex distribution. Since detectors are placed close to the beam (the first layer of the tracker is a mere 1/2 mm from the beamline), beam stability is at a premium. Excess beam halo would contribute to detector occupancy; spurious tracks would add to tracking confusion. CEBAF beams can have transverse sizes as small as 40 μm $\times$ 200 μm, have halo at the level of 10^{-5} and below, and have excellent stability, so are well suited to HPS needs.

The experiment demands excellent control of beam-induced backgrounds. Beam electrons passing through the target inevitably multiple Coulomb scatter, so detectors must be placed well beyond the rms multiple Coulomb scattering angle. By staying outside of a 15 mrad cone, the apparatus avoids all but the tails of the multiply scattered beam. The beam may also interact in the target, radiating bremsstralung photons in the forward direction. They too must be avoided. The electrons which have radiated, now degraded in energy, are swept into the horizontal plane by the magnetic field of the analyzing magnet, producing what is called "the sheet of flame," a horizontal swath of extremely high background. The apparatus avoids it entirely by staying outside of a "dead zone," defined by $\theta_y < 15$ mrad (y is the vertical dimension). This splits the apparatus into upper and lower halves. Finally, the passage of an intense electron beam through air, or even helium gas, generates an unacceptably large number of delta rays, resulting in high occupancy and tracking confusion. HPS avoids this background by situating the tracker in vacuum, and passing the electron beam in vacuum throughout its passage through the apparatus. The costs are the added complications of connecting power, data cables, and cooling lines through vacuum feedthroughs; of providing remote vertical motion for the sensors (needed to position them close to the beam); and of selecting materials that are vacuum compatible. The benefit is a significant reduction of beam backgrounds.

3 The HPS Test Run Apparatus

Application of the design principles discussed above led to the HPS Test Run apparatus, shown in fig.2. The electron beam enters from the left and is transported everywhere in vacuum. It impinges on a thin W foil target located 10 cm before the silicon tracker within the magnet vacuum chamber, which in turn is situated in a dipole analyzing magnet roughly a meter in length. Motion controls on the upstream end of the vacuum chamber allow the tracker modules to be moved close to the beam.

The Silicon Vertex Tracker (SVT) for the HPS Test Run is shown in fig.3. It uses Hamamatsu microstrip sensors readout by APV25s, the readout chip developed by CMS for operations at the LHC. Signal to noise is ≈ 25, which should result in ≈ 6 μm spatial resolution. Analogue readout proceeds at 40 MHz into a 3 microsecond pipeline. A trigger selects 6 consecutive pulse heights correlated to the event time, and initiates sending them to the data acquisition system. The multiple measurements allow a pulse shape to be fit, and the precise time of the hit to be determined within $\pm$ 2 ns. Altogether there are 5 layers of sensors, split top-bottom to avoid the dead zone, each layer comprised of two sensors, one measuring the vertical coordinate, the other at small angle stereo (50 or 100 mrad) to measure the bend plane coordinate. Care is taken to minimize the sensor thickness in order to minimize multiple Coulomb scattering

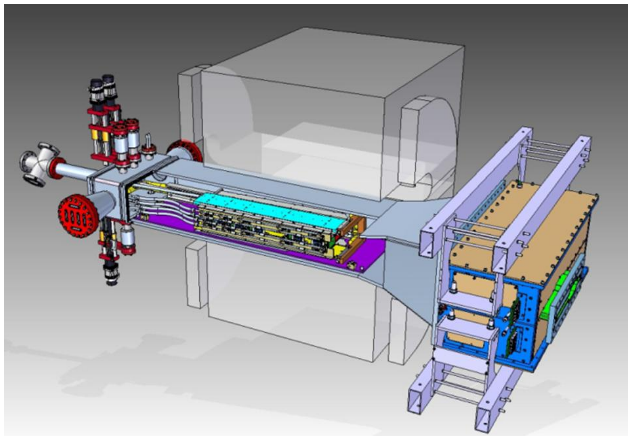

Figure 2: *The HPS Test Run apparatus*

in the sensors. The 5 layers are mounted on top and bottom support plates which are hinged at the downstream end and can be precisely positioned at the upstream end. Cooling for the readout chips is provided, both to remove the heat generated and to improve the radiation hardness of the sensors.

The electromagnetic calorimeter is shown in fig.4. It is a $PbWO_4$ crystal calorimeter, consisting of separate top and bottom modules, each arranged in 5 layers. There are 442 crystals in all. The front face of each crystal is 1.3 cm $\times$ 1.3 cm; the crystals are 16 cm long. The crystals are readout with APDs; output pulses are shaped and preamplified, and sent to a JLAB FADC250, a 250 MHz flash ADC, which records them in an 8 sec pipeline. The FADC also provides inputs to the trigger every 8 ns. A thermal enclosure keeps temperature constant to about 1°C to stabilize the ECal gain.

High rate data acquisition is essential for HPS to handle the high luminosity and expected trigger rates. Detailed simulation studies lead us to calculate trigger rates in the range of 25-50 kHz at the planned luminosities. These triggers are dominated by accidentals involving scattered beam electrons, but there is a substantial contribution from QED tridents, both radiative and Bethe-Heitler, as well. The experiment has separate data acquisition systems for the SVT and ECal. The SVT uses the SLAC ATCA-based architecture. Trigger selected data from the APV25 readout chip is sent to the Cluster on

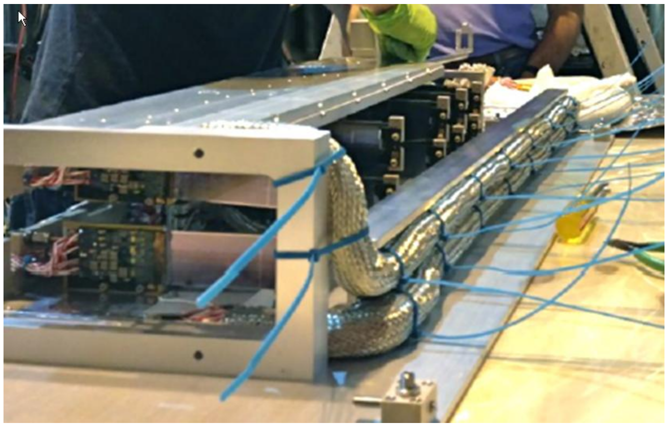

Figure 3: *The HPS Test Run silicon vertex tracker, looking upstream. The structure is split top-bottom.*

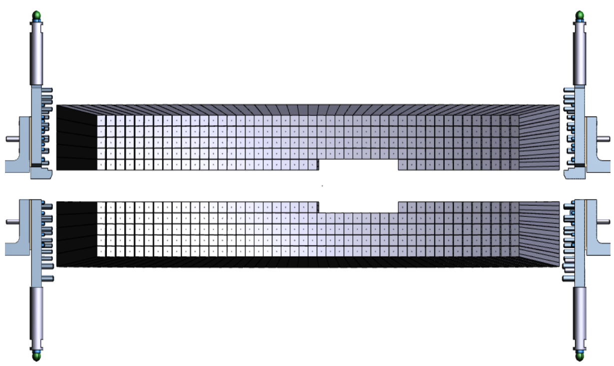

Figure 4: *Beam's eye view of the HPS Test Run Electromagnetic Calorimeter. Like the tracker, it is split top-bottom. The missing crystals accommodate the passage of the electron beam.*

Board (COB) ATCA module. The COB provides digitization, threshold setting, and data formatting, and in turn sends formatted data to be melded with ECal data to the JLAB DAQ. A single ATCA crate with two COBs handled the full HPS Test Run SVT with its 20 sensors and roughly 12k channels.

The ECal DAQ and Trigger utilize the JLAB FADC250, which is packaged 16 to a VXS module. Every 8 ns, the FADC transfers pulse height and time information from each channel to the Crate Trigger Processor, which identifies clusters of energy deposition in the top and bottom modules, then passes the cluster information to the Sub System Processor, which looks for pairs of clusters, one from each of the two modules, which satisfy energy and position criteria designed to select heavy photon decays and minimize background QED processes. Once a trigger is generated, a signal is sent back to the readout chips of the SVT and to the FADCs to initiate transfer of the raw data associated with that trigger. The ECal DAQ system can operate well over the 50 kHz limit which is imposed by the overall data transfer capability at JLAB.

4 HPS Test Run Results

The Test Run apparatus was designed to be run with electron beams, but scheduling conflicts at JLAB prevented our getting dedicated electron beam time. Instead, we ran parasitically with the HDice experiment using their several GeV photon beam in the Spring of 2012. A thin Au converter ≈ 70 cm upstream of our detector served as our target and produced a modest rate of e^+e^- pairs. This photon running was in fact adequate for commissioning the entire detector and DAQ, and let us demonstrate its technical feasibility. A dedicated photon run during the last 8 hours of CEBAF 6 running provided us high quality data, much lower backgrounds, and the opportunity to measure normalized trigger rates. These data let us demonstrate the performance potential of the detector, and most significantly, let us conclude that the backgrounds *expected in electron running* are also understood and under control.

Performance of the SVT was very good. About 97 % of channels worked as advertized and had a signal to noise ratio ≈ 25. In good channels, the efficiency for mips exceeded 98 %, and track time resolution was better than 3 ns. Tracks were reconstructed with high efficiency and good purity. Even with preliminary alignment constants, tracks were extrapolated to the target with few mm resolution, in agreement with Monte Carlo expectation. Residuals were also as expected from simulation. The extrapolated track position at the converter has a resolution of a few mm, in agreement with the simulation which assumes perfect alignment.

The ECal provided a reliable trigger. Only about 10 % of channels failed to report good data because of HV distribution and noise problems, so large regions of the detector performed as expected. Pre-run gain adjustments provided adequate energy scale uniformity for trigger purposes. An energy calibration was derived by extrapolating tracks of known momentum into the ECal. After accounting for channel to channel threshold and gain non-uniformities, the observed cluster energy distribution was in reasonable agreement with Monte Carlo.

One critical goal of the Test Run was to confirm the level of backgrounds expected in electron running. These backgrounds, which simulation has shown to be due to the tails of the multiple Coulomb scattering of beam electrons in the target, determine both the occupancy levels in the silicon detectors and the trigger rate in the ECal. Confirming the simulations quantitatively was critical to establishing that HPS can run at the proposed luminosities with electron beams. It was possible to do so with photon running because e^+e^- pairs which are produced in the conversion target are subject to essentially the same multiple Coulomb scattering as beam electrons in electron running. The angular distribution of the outgoing pairs is in fact the convolution of two distributions, first the intrinsic angular distribution associated with pair creation, then the multiple Coulomb scattering of the pairs as they exit the target. Since HPS is only sensitive to scatters beyond the dead zone of 15 mrad, it is primarily the tails of the intrinsic angular distribution and the multiple Coulomb scattering distributions which come into play. EGS5 accurately simulates both multiple Coulomb scattering and pair creation and has been verified with data. It was used to simulate the integrated trigger rates expected in the HPS Test Run configuration for three different converter thicknesses, 0.18 %, 0.45 %, and 1.60 % X_0. The trigger rate is given by integrating the observed angular distribution over the acceptance and normalizing to the integrated beam current, and is dominated by hits just beyond $\theta_y = 15$ mrad. As shown in fig.5, the data is in good agreement with the EGS5 prediction, and substantially lower than predicted by GEANT4. So the EGS5 simulation is confirmed; consequently estimates of HPS occupancies and trigger rates using EGS5 for electron beam running are reliable. HPS is ready for electron beams.

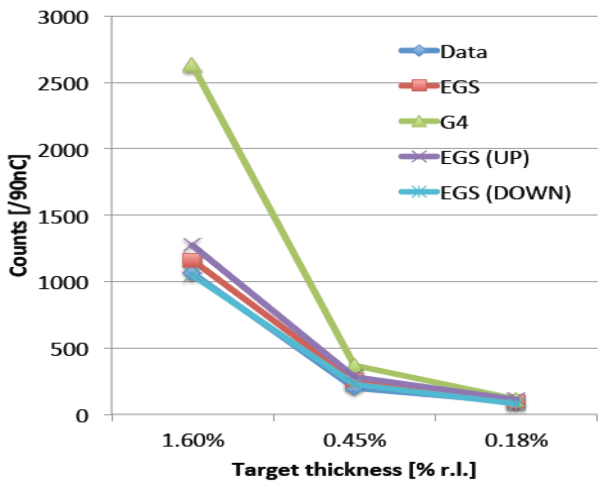

Figure 5: *Normalized trigger rates (number of triggers/90 nC of electrons on target) versus the converter target thickness. The data are in good agreement with the EGS5 prediction.*

5 The HPS Experiment

Since the time of the Dark 2012 Conference, the HPS Collaboration has revised its original design, in part to benefit from lessons learned with the test run, and in part to simplify the design so it could be proposed, funded, and built in time for a scheduling opportunity at JLAB appearing late 2014 and early 2015. The new design, described in the proposal to DOE [10], and shown schematically in fig.6, uses the existing ECal design, but incorporates fixes to the problems encountered and new preamplifiers to get better sensitivity to very small pulse heights. The SVT has been extended from 5 layers to 6, and layers 4, 5, and 6 have been doubled in width to improve acceptance. The greater length and extra layer also improve momentum resolution and track purity. A new support scheme will provide better rigidity, planarity, and cooling to the SVT modules, and the readout will be modified to handle the near doubling in channel number. The SVT DAQ, which had limited trigger rates to 16 kHz in the Test Run, is being modified to handle 50 kHz. The TDAQ, which will still use the JLAB FADC250, is undergoing trigger logic

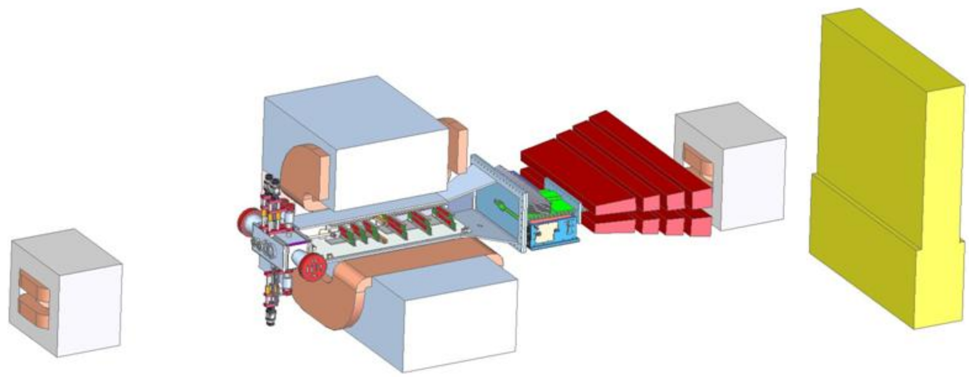

Figure 6: *The full HPS experiment. The six-layer tracker is located inside the good field region of the analyzing dipole in the magnet vacuum chamber. The ECal is positioned just downstream, followed by the muon system.*

and trigger monitoring revisions to supply robust trigger diagnostics. A muon system is being incorporated into the design, which will roughly double HPS acceptance for heavy photons beyond dimuon threshold and allow the first searches for heavy photon decays in the dimuon channel in HPS parameter space. Finally, the beamline is being equipped with beam diagnostics and protection collimators which will insure the safety of the detectors which are placed so close to the incident electron beam.

The performance expected from HPS has been studied extensively with full Monte Carlo simulations. The trigger simulation, for example, includes a faithful representation of all physics and background channels, electrons, photons, hadrons, and even x-rays and synchrotron radiation, and incorporates the time development of pulses from all the detectors, fully simulating the impact of out of time beam backgrounds. Trigger rates at the canonical currents and target thicknesses proposed are $\approx$ 20 kHz, easily within the capability of the DAQ. Similarly, extensive studies of pattern recognition and track reconstruction with full Monte Carlo overlaid with backgrounds, has demonstrated that tracking is $\approx$ 98 % efficient, and only 5 % of tracks have hits not correctly associated with the track. These miss-hits can cause large tails in the vertex resolution along the beam direction. A series of track quality and anti-confusion cuts will suppress these tails by three or more orders of magnitude, and make it possible to distinguish a genuine secondary vertex from the tails of the trident vertex distribution beyond 1.0-1.5 cm.

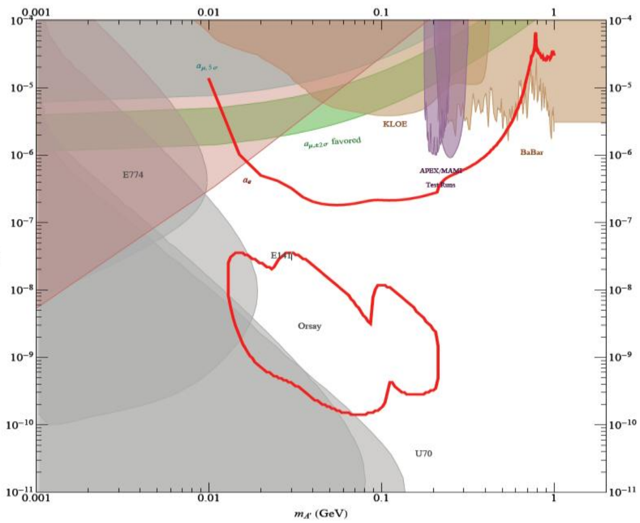

Figure 7: *Reach of the HPS Experiment with running at 1.1 GeV (1 week), 2.2 GeV (3 weeks), and 6.6 GeV (3 weeks). HPS also plans additional running.*

The reach of HPS is shown in fig.7. This is the data that we plan to take in a commissioning run late in 2014 and a regular data taking run in 2015. We plan additional running in 2016 and beyond.

6 Conclusions

The HPS Collaboration has designed, built, installed, and commissioned its first stage, the HPS Test Run, at JLAB. The experiment incorporates several design features to accommodate running a large acceptance, forward spectrometer in an intense electron beam. The detector and DAQ capabilities needed to search for heavy photons have been demonstrated. In addition, EGS5 simulations of multiple Coulomb scattering tails have been confirmed with Test

Run data, leading to a good understanding of the backgrounds that will be presented by electron beams. A proposal for Stage II, the full HPS experiment, has been submitted to DOE. A revised version of that proposal will be reviewed in Summer, 2013. With funding expected soon afterwards, HPS plans to complete construction in time for installation in the Fall 2014, with subsequent commissioning and data taking.

7 Acknowledgements

The work presented here is that of the HPS Collaboration. Support from DOE HEP at SLAC is gratefully acknowledged. Special thanks to Sho Uemura for his help in preparing this paper for publication.

References

1. J. L. Hewett, H. Weerts, R. Brock, J. N. Butler, B. C. K. Casey, J. Collar, A. de Govea and R. Essig *et al.*, arXiv:1205.2671 [hep-ex].
2. B. Holdom, Phys. Lett. B **166** (1986) 196.
3. P. Galison and A. Manohar, Phys. Lett. B **136** (1984) 279.
4. S. J. Brodsky and R. F. Lebed, Phys. Rev. Lett. **102**, 213401 (2009) [arXiv:0904.2225 [hep-ph]].
5. A. Banburski and P. Schuster, Phys. Rev. D **86**, 093007 (2012) [arXiv:1206.3961 [hep-ph]].
6. N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer and N. Weiner, Phys. Rev. D **79** (2009) 015014 [arXiv:0810.0713 [hep-ph]].
7. M. Pospelov and A. Ritz, Phys. Lett. B **671** (2009) 391 [arXiv:0810.1502 [hep-ph]].
8. A. Grillo *et al.* [HPS Collaboration], HPS Proposal to JLab PAC37 PR-11-006, http://www.jlab.org/exp_prog/PACpage/PAC37/proposals/Proposals/
9. J. D. Bjorken, R. Essig, P. Schuster and N. Toro, Phys. Rev. D **80**, 075018 (2009) [arXiv:0906.0580 [hep-ph]].

10. P. Hansson Adrian *et al.* [HPS Collaboration], Heavy Photon Search Experiment at Jefferson Laboratory: Proposal for 2014-2015 Run, https://confluence.slac.stanford.edu/display/hpsg/Project+Overview