Experimental Readiness Review Report for the Heavy Photon Search – Phase 2 Experiment

June 12, 2017

Committee: Glenn Young (Chair), Yulia Furletova (SVT), Vashek Vylet (Radiation), Bert Manzlak (EHS&Q)

An Experimental Readiness Review for the Heavy Photon Search – Phase 2 was convened by Patrizia Rossi and held on Monday June 12, 2017.

The Heavy Photon Search, HPS, searches for evidence of a massive neutral particle A' that could be a component of the dark matter thought to form some 23% of the universe's mass. Such a heavy neutral particle could be produced after inelastic scattering of an electron from a nucleus resulting in production of a massive neutral particle which in turn could couple with regular photons via kinetic mixing, resulting finally in a massive photon decaying to e^+e^-. The search is done by scattering an electron beam of energy 1 GeV or greater in order to obtain good kinematic reach for the experiment and looking for such a decay with a rest mass less than a few hundred Mev/c^2. This requires an experiment look for electrons and positrons of energies well below 1 GeV and produced at angles of a few degrees to the beam. The planned reach of HPS spans masses between 10 and 200 MeV/c^2, and spans two ranges of couplings ε^2 where ε^2 is the ration of the dark fine structure constant to the familiar EM fine structure constant α. Large values of ε^2, 3x 10^{-7} or larger, result in prompt decays appearing to emanate from the target and would yield a sharp mass peak in the e^+e^- invariant mass spectrum. Weaker couplings result in a displaced decay vertex, and by covering a range of vertices of order 10-100 cm the HPS experiment reaches a planned sensitivity of ε^2 for these decays from 2x 10^{-10} to 3x 10^{-8}.

An apparatus including some 6 layers of silicon strip detectors placed close to the beam and backed by a high resolution EM Calorimeter has been prepared by the HPS Collaboration and operated in Hall B in the alcove downstream of CLAS. Two successful runs have been made, one each in 2015 and 2016, to test the concept, the performance of the detectors individually, and the performance of device and then to obtain first search results for the A. These runs used 15 of 180 PAC days approved for HPS and have obtained first limits on production of a heavy photon A' as a function of ε^2 vs $M_{A'}$. The limits obtained are consistent with exclusion zones reported and/or planned by other experiments both at JLab and elsewhere. HPS has demonstrated a tour de force, obtaining such good beam parameters, notably a small vertical emittance, that they were able to operate their silicon detectors very close to beam, within 0.5 mm, an impressive achievement. A notable advantage of HPS over many planned and/or approved experiments is an ability to see displaced decay vertices that are expected for A with weaker coupling to the standard photon, i.e. small ε^2 of order 10^{-8} to 10^{-10}.

The data obtained by the HPS Collaboration have been analyzed and preliminary results presented. These results point to two key compelling improvements to the existing apparatus which would extend its present search capability and thus offer better use of beamtime. HPS could continue to run without them and improve its search region mostly by adding counting statistics, but both proposed improvements extend reach well beyond what just increased counting statistics would offer.

One improvement is to improve acceptance for displaced vertices by two stratagems – one is adding Layer-0 at 5cm downstream, halfway from target to existing Layer-1, the other is a set of strategic shifts of Layers-2 and -3 towards beamline, building on expertise already demonstrated in operating very close to the beam axis. The new Layer-0 detector would have to be both thinned and built with one narrow edge, necessitating some modest technical development beyond the sensors already deployed.

The other improvement is to add a trigger hodoscope focused on positrons. This recovers acceptance lost from an e^+e^- pair trigger by the earlier necessary removal of 2x9 elements of the EMCal in the e^- direction due to very high rates in those counters.

Together these improvements help both rate/triggering capability and greatly improve vertex resolution as well as acceptance for displaced vertices, which is a feature presently unique to HPS in the group of experiments pursuing dark photons.

Response to Charge Elements

We address the six charge elements in the next sections of this report.

1. What are the reasons for the HPS upgrade and what will be different from the previous setup?

The two test runs show that the SVT and EMCal operate as designed. These test runs used 15 of 180 allotted PAC days for HPS. Analysis of the data taken has resulted already in an area excluded in the search plan defined by ε^2 vs $M_{A'}$, all of which presently is corresponding to prompt decay. However, investigation by the collaboration of the acceptance for displaced decay vertices reveals this acceptance was significantly less than planned, worsening for ever more displaced vertices. This has been traced to an incomplete understanding of the acceptance for these events in the original design, now supplanted by a corrected modeling of the acceptance that leads also to an understanding of how such vertices are missed and thus to how to place new detectors and revise the placement of existing ones to substantially improve it. This analysis has also led to an understanding of the loss in pair acceptance arising from the removal of a 2x9 sub-array of the EMCal modules on the electron side of the spectrometer, which had been done to avoid overwhelming the trigger and DAQ due to excessive rates of produced electrons in these counters.

The improved apparatus will keep nearly all features of the prior setup and improve it in two main ways. A new Layer-0 of silicon detectors will be added halfway in z between the target and the existing Layer 1 and placed with its inner active edge at the same polar angle as the current Layer-1's active edge. This will be coupled with moving the existing Layer-2 and -3 silicon slightly closer to the beam axis (by 0.5 mm or so) to improve acceptance for displaced vertices. The result will be a major expansion of the overall acceptance for displaced vertices, opening a region of parameter space not currently addressed by another active or proposed experiment. The parameter search space extends to coupling values ε^2 as small as 2x 10^{-10} for A' mass values in the range 50-200 MeV/c^2. Another key benefit of this is improved vertex resolution by nearly a factor of two, which also aids in background rejection.

The second improvement builds on the observation that triggering on only the positron of pairs that would lose their electron into the removed region of the EMCal can be done to recover that key lost acceptance and can be done in a manner that adds little to the experiment backgrounds and also does little to degrade its resolution. This is accomplished by addition of a tagging hodoscope inside the vacuum chamber but behind the silicon in order to tag charged particles, in particular positrons that are headed to the EMCal. This hodosope would operate in coincidence with the trigger from the EMCal, which is necessary in order not to add a (very large) background trigger rate that would arise from WAB photons if one had only a trigger on single EMCal clusters.

The balance of the apparatus will be substantially the same as operated for the two test runs.

2. Has the entire beam-line, target, detector configuration been defined (including ownership, maintenance and control during beam operations)?

Yes, this has been done already for the prior operation of HPS in 2015 and 2016. Personnel are identified, all coming from the collaboration and substantially from the Hall B permanent staff.

In particular:

a. Are there any beam line changes required to run the HPS experiment with CLAS12 in place?

Yes, there are changes from CLAS12 in location of one girder including a collimator and beam harp, together with beam pipe configuration changes in the region downstream of CLAS12 but upstream of the Faraday cup and beam dump. These are simple changes which have been exercised for the previous runs and shown not to cause problems. They have also been reversed successfully in short order, over two days, in order to configure the beamline for CLAS12 operations, as was done for the February 2017 KPP run. This demonstrates there is minimal impact on CLAS12, that impact on the beam operations schedule can be minimized or even eliminated, and that the two experiments are fully compatible in sharing the Hall B beamline.

b. Can HPS equipment remain in the alcove while CLAS12 operates?

Yes, the spectrometer magnet, detectors and cabling can all remain mounted and just move into place for a beam run. The chicane magnets have to be moved onto the beamline in preparation for an HPS run and must be moved off the beamline afterwards, but remain in the alcove. One section of beamline must be changed, but the parts for the other configuration, be it CLAS12 or HPS as the case may be, can remain in the area and do not need to be rigged out for storage elsewhere. There is one harp, CLAS12 harp 2H01A, that becomes HPS harp 2H02A, that must be moved from upstream of the CLAS12 HTCC to its position for HPS operation and must be returned to its original position for CLAS12 operation, but this has been accomplished before by the Hall B staff and can be done in one day.

3. What is the status of the new equipment to run HPS phase II? If the construction is not completed, what is the completion schedule and commissioning?

In particular we want to hear about:

a. **The SVT detector upgrade: hardware details, rates, radiation damage expected on added SVT layer, tracking efficiency**

The HPS group has presented two improvements which they are planning to finish before the next summer of 2018. The first one is to improve acceptance for low mass A', which could be achieved by moving the sensors of Layer 2 and 3 towards the beam. This option does not require any extra detector hardware, involves only minor modifications to the detector box already built by the Collaboration, and could be done during a period dedicated for final tests of the SVT system.

Another upgrade is related to an improvement of Z-vertex reconstruction efficiency for A' with larger coupling decaying at Z close to 0. This upgrade would require additional Layer-0, placed 5cm away from Z=0 (Layer-1 is located at 10cm downstream of the target). The Layer-0 detector would have to be thinned, to reduce multiple Coulomb scattering, and built with one edge having a compact guard ring structure, to allow for it to be used at the same polar angles as the existing Layers but at a shorter Z distance from the target.

The HPS group has presented a detailed overview of a proposed sensor upgrade, as well as timeline and cost required for this upgrade.

<u>Findings:</u>

L0 Sensor:

-Signal-to-noise ratio:

Due to reduced thickness (150um) of the Layer-0 sensor, its signal-to-noise ratio is expected to be worse compared to the "standard" 300um thick layers. The noise level can be reduced by reducing its capacitance. The Collaboration proposes to do this by shortening the Layer-0 strip length to 3.5 cm, less than one fourth that of the existing Layers while maintaining the experiment's acceptance. This is possible because the existing silicon was obtained from another experiment which needed longer strips than HPS requires, whereas Layer-0 can be custom tailored to HPS's need. The Layer-0 strips will in addition be split in half electrically and read out from each end, which reduces by half both their noise and occupancy. The HPS Collaboration did present analyses of noise sources that showed acceptance and signal/noise can be obtained.

Comment:

By thinning down a sensor its capacitance would be increased by the same factor. Noise and signal to noise ratio both should be measured with a source, as soon as a prototype sensor will be ready for tests. A Sr90 source would be suitable for this type of measurement.

-Occupancy:

Occupancy in Layer-0 will be reduced by splitting the strip in half electrically and reading the sensor from both ends. Capacitive coupling has been eliminated from the strips, and therefore would lead to a reduced resolution of a hit and therefore to reduced vertex resolution for operating with minimum ionizing particles. However due to the low particle energy, a high multiple Coulomb scattering and thus tracking resolution is the result, with tracking resolution at the level of 7% and thus vertex-constrained invariant mass resolution around 3%. Thus, the resolution loss due to removal of the capacitive coupling is not expected to be significant in light of these larger uncertainties inherent to the kinematics of the particles to be detected.

Beam halo effect for layers 0,1,2,3:

Due to a movement of Layers-0, 2 and 3 towards the beam, the occupancy coming from a beam-halo, could affect the operation, as well as cause a possible damage of innermost parts of the sensors after extended periods of running; this damage might occur after runs as short as three months. Spare modules/sensors need to be in hand for a possible replacement. The Collaboration presented a plan to have spare sensors and an estimate of how often the sensors would need replacement. The expected halo-beam spread should be investigated and estimated for different (especially for high) beam currents. The Collaboration also checked that L x-rays from the tungsten target, which would be above the planed threshold for Layer-0, would not cause on occupancy problem.

Hybrid design:

The hybrid circuit design schematic is expected to be identical to the previous one with one fewer APV25 chip. However, the hybrid physical layout is expected to be very different. No final design is available yet, but is expected to be ready before delivery of the sensors.

b. The trigger scintillator: hardware details

The trigger scintillator hodoscope must be constructed. Manufacturing plans exist for it, as does a basis of experience which draws upon both the CLAS12 PCAL and the CLAS Beam Offset Monitor. The collaboration has previously demonstrated mastery of the needed technology. The scintillator tiles and wavelength shifting fiber optics would use spare parts from the building of the PCAL for CLAS12, the multi-anode PMTs are already in hand from prior work, and the vacuum-feedthrough needed for the fiber optics to reach the PMTs would draw upon a similar design used for the existing CLAS Beam Offset Monitor. Hall B design and engineering staff would handle the added features and changes needed for the HPS vacuum enclosure, which will require a modest amount of shop work to modify and then Hall B staff work to reinstall in the spectrometer magnet. The other detector support features for the SVT and EMCal can accommodate the needed changes. The timeline for this work is estimated at 8 months, which is consistent with the time required for similar work on the CLAS12 PCAL. No difficulties are foreseen in these modifications.

The readout electronics for the PMTs draws upon devices already in use. The trigger circuits will need to be expanded to accommodate the new information from the trigger hodoscope. This can be accommodated by deploying more of existing trigger VME-based trigger boards and a straightforward modification of existing trigger firmware. It is thus not an area of concern for technical or schedule matters.

Comment: The Committee does express its concern about the probability of meeting what is a success-oriented schedule, in particular the one for fabricating the new parts needed for the SVT, but endorses the effort planned to do it.

4. Are the responsibilities for carrying out each job identified, and are the manpower and other resources necessary to complete them on time in place?

The assignments are made among the collaborating institutions to fabricate the two new detectors, SVT and trigger hodoscope, and make the needed mechanical modifications to both the SVT supports to allow mounting Layer-0 and moving Layer-2 and -3, as well as to make the modifications to the vacuum chamber. Existing assignments for beamline, operations, trigger and firmware, analysis code and reply and modelling were not particularly discussed but exist and are clearly functioning, as evidenced by the collaboration's ability to carry out needed simulation work, operate the experiment and perform the analyses shown.

Comment: As part of the response to the second and third recommendations listed below, the Collaboration should identify to JLab Physics Division management the key people involved, especially for: the Layer-0 design and prototyping; the layout and prototyping/fabrication of the revised SVT hybrid; the modification to the vacuum chamber to accommodate the trigger hodoscope; the design, production and testing of the vacuum feedthroughs for the fiber optics of the trigger hodoscope; and the needed modification to the trigger hardware and firmware.

5. Are the radiation levels expected to be generated in the hall acceptable? Is any local shielding required to minimize the effects of radiation in the hall equipment?

The experiment has run previously with the same shielding and beam environment as proposed for the future runs and was well within radiological control limits. The HPS RSAD was updated in 2016 and will be updated before the next HPS run. No changes to targets or beam current request are planned. The added silicon and trigger scintillator elements do not intercept the beam envelope nor modify the shielding, meaning the same radiological conditions as obtained earlier should exist during the upcoming runs. The closer placement of silicon Layer-0 to the beamline than the existing Layer-1 through -6 means that a similar beam tune-up process will have to be employed as was developed earlier, e.g. by de-powering DAQ boards during beam tuning to avoid SEUs, both to prevent creating radiological background as well as to avoid damage to the detectors and unsustainable counting and background rates. The prior program established for this by the HPS group working with the CEBAF accelerator and RadCon staff is expected to suffice. CLAS12 added more shielding to the beamline downstream of the tagger magnet. This will improve radiation background for HPS. The beam transport and beam dump will stay unchanged. CLAS12 uses the same beam transport system and beam dump.

Comment: Final beam and detector envelope should be reviewed by operations staff in conjunction with the HPS collaboration prior to running. The beam tuning program should also be reviewed in order to refresh all participants' memories prior to starting beam operations for HPS-2.

6. What is the status of the specific documentation and procedures (COO, ESAD, RSAD, ERG, OSP's, operation manuals, etc.) to run the experiments? This includes demonstrated readiness and a draft of milestones for expedient analysis of the data.

The existing documentation and procedures used for HPS Phase 1 will be updated as needed. The run page exists and will be re-used. The COO will need an update for the new PDL. The ESAD has been updated to include the new scintillation hodoscope for the positron side. The RSAD will be reviewed and updated as noted above. The detector operations manuals and procedures will be updated as needed and a new one added for the scintillation hodoscope. The Hot Checkout system will be used as before. The run and analysis plans exist in draft form and can be modified drawing upon experience gained with data analysis over the next months.

Comment: Final versions of all documentation will need to be reviewed with cognizant JLab authorities before running.

End of Response to Charge Elements

The Committee believes the experiment has a good plan to go forward. Three Recommendations are presented next for the Collaboration's response.

Recommendations

There are three recommendations made concerning HPS Phase 2. The bold-faced parts are the actual Recommendations. Further commentary summarizing the Committee's concerns follows.

1. A new Physics Division Liason needs to be appointed as soon as possible.

2. A plan for fabricating the SVT and installing it into HPS, including milestones for development, prototyping, manufacturing, delivery and installation, and testing, needs to be formulated and submitted to JLab.

This should include specific dates for the thinned wafers and the revised hybrids. This should also note where there are possible delays in production, as well as possible problems during design or fabrication and indicate if time contingency is allocated.

The schedule should show which parts of the jobs could be done in parallel to maintain the capability for operating SVT both with and without Layer-0.

A date certain for when the final decision about which configuration (with or without Layer-0) will be used during the next data taking should be given as part of this.

3**. A plan for fabricating the trigger hodoscope and installing it into HPS, including milestones for development, prototyping, manufacturing, delivery and installation, and testing, needs to be formulated and submitted to JLab.**

This should include needed modifications to the trigger hardware and firmware.