Snowmass Letter of Interest —Topical Group: RF6

The Heavy Photon Search Experiment

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ABSTRACT

The Heavy Photon Search (HPS) experiment is designed to search for a new vector boson A' in the mass range of 20 MeV/c^2 to 220 MeV/c^2 that kinetically mixes with the Standard Model photon with couplings $\varepsilon > 10^{-10}$. After short engineering runs in 2015 and 2016, HPS took first physics data in 2019. Future operations in 2021 and beyond are planned, with the potential to discover dark photons in highly-motivated regions of the mass-coupling parameter space. In addition to the minimal Dark Photon, HPS has the ability to search for strongly interacting dark sectors (SIMPs) and potentially also other dark sector scenarios.

1 Introduction

Establishing the nature of dark matter is one of the major open challenges of modern particle physics. The LHC, as well as direct and indirect detection experiments, have significantly constrained one of the best-motivated weak-scale dark matter models with a class of particle candidates known as weakly interacting massive particles (WIMPs). In contrast, similarly motivated scenarios involving light hidden sector dark matter with mediators in the MeV-GeV range are relatively unexplored[1]. Models with a hidden $U(1)$ gauge symmetry, with a "dark" or "hidden sector" photon, are particularly attractive and can be tested experimentally. If they exist, these "heavy" photons undergo kinetic mixing with ordinary photons, which induces their weak coupling to charged electrons, εe, where e is the electron charge and $\varepsilon \leq 10^{-2}$. Since they couple to electrons, heavy photons are radiated in electron scattering and can subsequently decay into e^+e^- pairs. If ε is large enough, they would appear as a narrow mass peak in the e^+e^- invariant mass distributions, which can be observed above the copious QED trident background. For suitably small couplings, $\varepsilon^2 \lesssim 10^{-8}$, heavy photons may travel detectable distances before decaying, providing displaced decay vertices as a second signature. The Heavy Photon Search (HPS) experiment in Hall-B at JLab exploits both these signatures to search for heavy photons decaying to e^+e^- over a wide range of couplings, $\varepsilon^2 > 10^{-10}$, and masses, 20 MeV/c^2 < $m_{A'} < 220$ MeV/c^2, using a compact, large-acceptance forward spectrometer consisting of a silicon microstrip vertex tracker, a finely-segmented lead tungstate ($PbWO_4$) electromagnetic calorimeter, and a scintillation hodoscope.

2 Motivations and Overview

A number of existing and future experiments have sensitivity to sub-GeV dark photons at larger couplings ($\varepsilon^2 \gtrsim 10^{-8}$) through searches for narrow e^+e^- or $\mu^+\mu^-$ resonances atop a continuum background. In particular, fixed target experiments exploiting the production of dark photons with electron beams through a process analogous to photon bremsstrahlung produce large signal yields at lower masses with a production cross section proportional to $1/{m_{A'}}^2$[2]. Requiring high intensities to reach small couplings, these experiments typically spread out final state particles into large spectrometers to achieve reasonable occupancies and reaching lower couplings through brute force is difficult. However, at smaller couplings and lower masses, dark photons become long lived and can travel macroscopic distances before decaying, with $\gamma c\tau \propto 1/{m_{A'}}^2\varepsilon^2$, offering another possibility to eliminate backgrounds. In the extreme case – at very small couplings and masses – high intensity, high energy beam dumps with a detector behind a shield and decay region offer sensitivity to very small couplings with relatively simple detectors. However, at intermediate couplings — too small for large spectrometers and too large for beam dumps where decay lengths are in the range of $\approx 1-100$ mm — the key to sensitivity is reduction of prompt backgrounds through high-purity reconstruction and identification of long-lived A' decays.

Inspired by the potential for dark photons to explain some notable astrophysical anomalies[3–6], the above principles were applied to the development of the HPS detector concept which was constructed beginning in 2013 for installation and commissioning in Spring 2015. Shown in Figure 1, HPS is a compact e^+e^- spectrometer consisting of a small, high-rate silicon tracking and vertexing detector (SVT) built inside of a standard dipole analyzing magnet as part of a three-magnet chicane in an alcove downstream of the CLAS12 detector in Hall B of the JLab CEBAF. HPS provides sensitivity to a range of A' masses by operating at a range of beam energies from 1-6 GeV. HPS uses intense electron beams (50 - 500 nA) on thin (0.125%-0.625% X_0) tungsten targets to maximize signal rates relative to QED backgrounds and places the silicon sensors as close as possible to the target and the through-going beam to provide the best possible acceptance for A' daughters which peaks strongly in the forward direction. With 14 planes of silicon microstrips and 2 ns hit time resolution, the SVT allows for the reconstruction of four-momentum and trajectories of A' daughters down to 15 mrad from the beam direction. A $PbW0_4$ electromagnetic calorimeter and scintillator hodoscope - also split above and below the beam with similar acceptance - have precision timing to trigger on positrons to eliminate the dominant rate of single-scattered electrons.

3 Status and Outlook

HPS collected small physics datasets during opportunistic engineering runs – a few days each – in the spring of 2015 and 2016 at 1.056 GeV and 2.3 GeV beam energies respectively. The detector performed as expected and this data was used to develop the analysis techniques for A' searches, both a simple e^+e^- resonance search and a search additionally requiring displaced vertices. Results of searches with the 2015 data have been published and a publication with results from the 2016 data is underway[7,8]. Analysis of these datasets motivated upgrades to the apparatus including a new silicon layer and the addition of the hodoscope, which were commissioned in advance of first physics operations in Summer 2019 at a beam energy of 4.55 GeV. Calibration, reconstruction, and analysis of the 2019 dataset is ongoing, where the expected sensitivity is shown in Figure 2. HPS is currently approved for approximately four more months of operation, including a run in 2021, where the expected sensitivity for dark photons from the full run plan is also shown in Figure 2.

In addition to the "minimal" dark photon model, HPS also has good sensitivity to other dark sector models that result in long-lived signatures. In some cases, such as axion-like particles (ALPs) with electron couplings, this is a straightforward

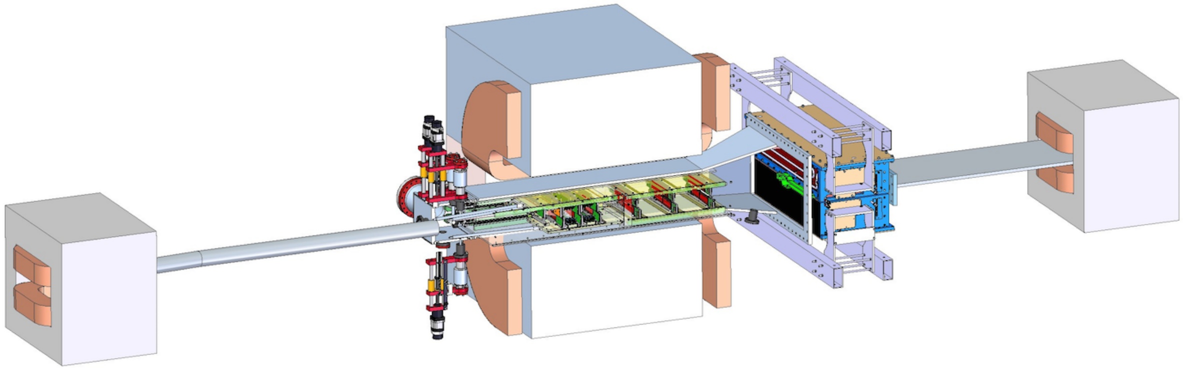

Figure 1. The engineering design model of the baseline HPS detector showing the SVT inside a vacuum chamber in the spectrometer magnet and the electromagnetic calorimeter downstream, between a pair of magnets forming a chicane.

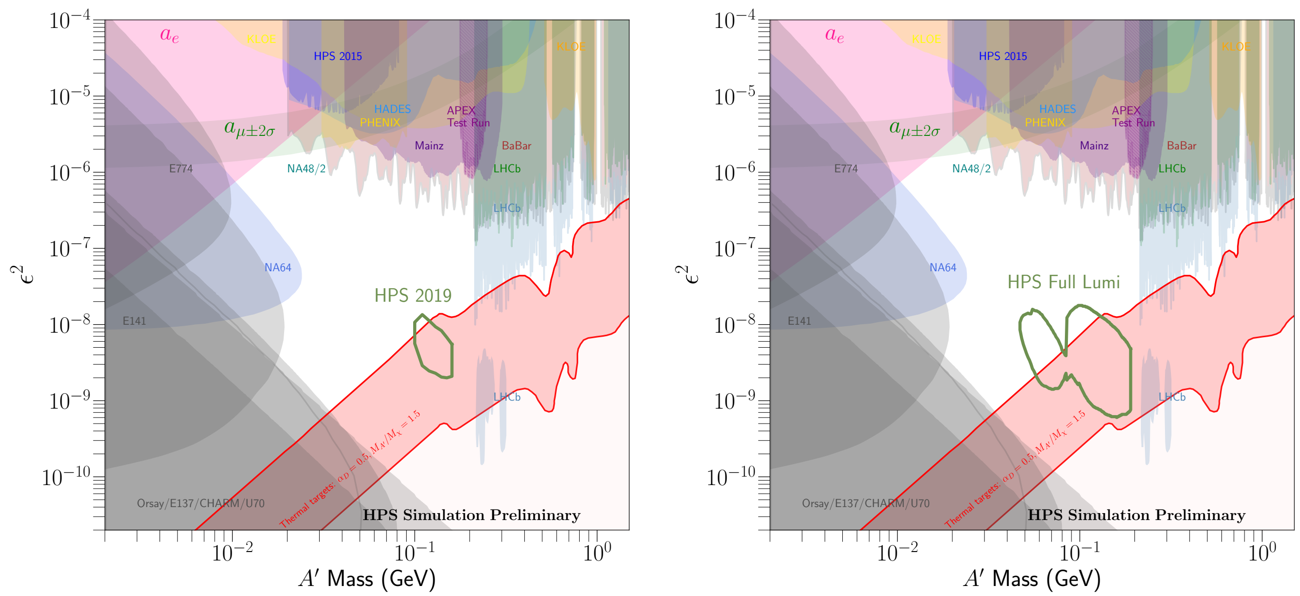

Figure 2. The reach anticipated from the displaced vertex analysis on the 2019 dataset (left, green contour) and proposed future operations (right, green contour) that utilize the remainder of the approved running time for HPS. Existing limits from beam dump, collider and fixed target experiments are also shown along with regions favored and excluded by measurements of the anomalous magnetic moments of the muon and electron respectively. A comprehensive review of all exclusions can be found in[1,16].

re-interpretation of the dark photon search. In other cases, a somewhat different analysis strategy is required. For example, models with a strongly interacting dark sector (SIMPs) have long-lived vector mesons that can decay through kinetic mixing to e^+e^- pairs with somewhat different kinematics, and HPS is currently developing a search for SIMPs with the 2016 dataset with a result expected in the near future[9,10]. Sensitivity to other models, such as inelastic dark matter (iDM), have not been explored but could motivate changes to the configuration of the detector and new modes of operation for the experiment[11]. Finally, during the previous Snowmass exercise, some variations on the HPS apparatus were studied with the aim of accessing other parts of the A' parameter space, including some configurations that became the basis for the upgrades described above[12]. Within the context of the current exercise, these concepts should be revisited and updated in light of new constraints, other proposals, new models, and new facilities at which the experiment might operate, such as LESA or a plasma wakefield accelerator facility.[13–15]

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