Update on the Heavy Photon Search Experiment

C. Bravo, P. Butti, C. Field, N. Graf, M. Graham, R. Herbst, J. Jaros, T. Maruyama, O. Moreno, T. Nelson*,†, B. Reese, P. Schuster, M. Solt, N. Toro

SLAC National Accelerator Laboratory, Menlo Park, CA 94025

V. Fadeyev, R. Johnson, A. Spellman

University of California, Santa Cruz, CA 95064

N. Baltzell, M. Battaglieri, S. Boyarinov, V. Burkert, C. Cuevas, A. Deur, H. Egiyan, L. Elouadrhiri, V. Kubarovsky, R. Paremuzyan, B. Raydo, Y. Sharabian, S. Stepanyan*, M. Ungaro, H. Szumila-Vance, B. Wojtsekhowski

Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606

R. Essig

Stony Brook University, Stony Brook, NY 11794-3800

M. Diamond

University of Toronto, Toronto, ON M5S, Ca

T. Cao, M. Holtrop*, K. McCarty

University of New Hampshire, Department of Physics, Durham, NH 03824

G. Charles, R. Dupre, D. Marchand, C. Munoz-Camacho, S. Niccolai

Institut de Physique Nucleaire d'Orsay, IN2P3, BP 1, 91406 Orsay, France

N. Dashyan, N. Gevorgyan, H. Voskanyan

Yerevan Physics Institute, 375036 Yerevan, Armenia

M. Bondí, A. Celentano, R. De Vita, L. Marsicano

Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dellÚniversita, 16146 Genova, Italy

S. Bueltmann

Old Dominion University, Norfolk, Virginia 23529

G. Kalicy

The Catholic University of America, Washington, DC 20064

*Co-spokesperson
†Contact person

K. Griffioen, B. Yale

The College of William and Mary, Department of Physics, Williamsburg, VA 23185

M. De Napoli, N. Randazzo

Istituto Nazionale di Fisica Nucleare, Sezione di Catania
e Dipartimento di Fisica dell'Università, Catania, Italy

M. Carpinelli, D. D'Urso, V. Sipala

Università di Sassari e Istituto Nazionale di Fisica Nucleare, 07100 Sassari, Italy

G. Simi

Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, Italy

A. D'Angelo

Istituto Nazionale di Fisica Nucleare, Sezione di Roma-TorVergata
e Dipartimento di Fisica dell'Università, Roma, Italy

A. Filippi

Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Torino, Italy

B. McKinnon, D. Sokhan

University of Glasgow, Glasgow G12 8QQ, United Kingdom

S. Paul

Tel Aviv University, Tel Aviv, Israel
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1. INTRODUCTION

Establishing the nature of dark matter is one of the major open challenges of modern 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 electrons, ϵe, where e is the electron charge and $\epsilon \leq 10^{-2}$. Since they couple to electrons, heavy photons are radiated in electron scattering and can subsequently decay into an e^+e^-. If ϵ is large enough, $\epsilon^2 \approx 10^{-6}$, they would appear as a narrow mass peak in the e^+e^- invariant mass distribution, which can be observed above the copious QED trident background. For suitably small couplings, $\epsilon^2 < 10^{-8}$, heavy photons travel detectable distances before decaying, providing a second signature. The Heavy Photon Search (HPS) experiment in Hall-B at JLab exploits both these signatures to search for heavy photons over a wide range of couplings, $\epsilon^2 > 10^{-10}$, 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 (SVT), a scintillation hodoscope (SH), and a $PbWO_4$ electromagnetic calorimeter (ECal).

The first HPS proposal was presented to PAC 37 in 2011 [2], which recommended conditional approval C2 for 180 PAC days contingent upon a successful Test Run. The Test Run experiment was funded and built in time for commissioning early in 2012, where it ran parasitically on a photon beam in Hall B. Early results from the test run were presented to PAC 39 in 2012 [3], which boosted HPS approval to C1 with an "A" rating. HPS proceeded with design of the full experiment, shown in Figure 1, proposed to DOE HEP in Summer 2013 and funded that fall subsequent to a review attended by JLab management. In Spring 2014, HPS requested formal

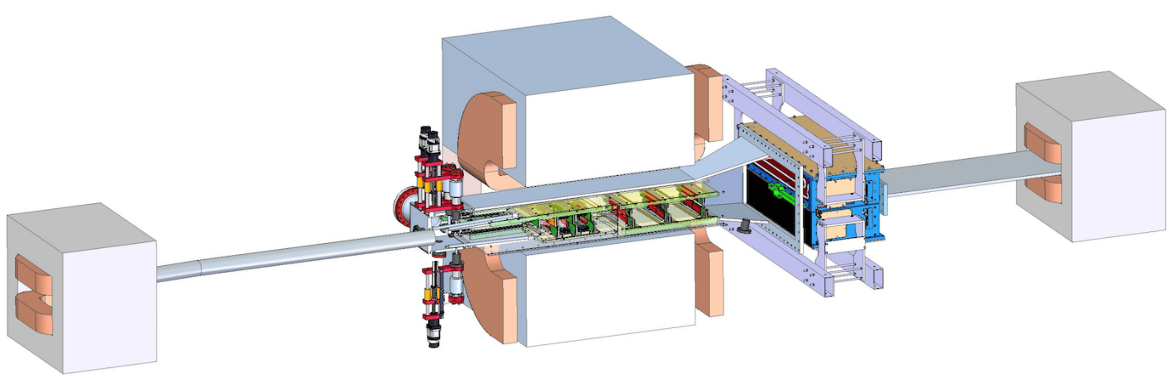

FIG. 1: The engineering design model of the baseline HPS detector showing the SVT inside a vacuum chamber in the spectrometer magnet and the ECal downstream, between a pair of magnets forming a chicane.

approval from JLab , which granted 25 PAC days for an engineering run and requested performance demonstrations before granting additional time. Later that spring, PAC 41 selected HPS for "High Impact Status". HPS completed two engineering runs in 2015 and 2016 with 1.1 GeV and 2.3 GeV beams, respectively. The small data samples from the engineering runs led to the first physics results from HPS, and the performance demonstrations JLab had requested [4, 5]. JLab accordingly granted HPS unconditional approval. The engineering runs provided data for six PhD dissertations, led to improved understanding of backgrounds and better calculations of physics processes, and motivated important upgrades of the SVT and trigger system.

The proposed upgrades were reviewed and approved by DOE OHEP in FY19. In the first physics run with the upgraded detector, HPS collected roughly 45% of the expected physics-quality data at 4.56 GeV. The detector performance was as expected. This data will be sufficient to explore an uncharted region of mass and coupling using a displaced vertex search method. We expect to release the first physics result from this data in early 2021. After maintenance and repairs, which are ongoing, the HPS detector will be ready for the next physics run scheduled in the summer of 2021 with a 3.8 GeV electron beam.

The landscape of heavy photon searches has evolved since the first HPS proposal. While a significant fraction of parameter space at large ϵ has been ruled out by fixed target and collider experiments, new target regions, motivated by hidden sector scenarios of light dark matter, have emerged [1]. The parameter space that HPS will probe using a displaced vertex search with 2 GeV to 5 GeV electron beams lies in the most desirable region. There is stiff competition for this parameter space from experiments coming online in 2021-2023 at CERN (FASER, SHIP, NA62, LHCb), and FNAL (SeaQuest). Therefore, running HPS is time-critical in order to be first to either discover a new force or significantly constrain allowed parameter space for light dark matter theories.

In this update, we present the status of the HPS experiment, physics results from the engineering runs, and the performance of the upgraded detector during the first physics run. A run plan for future operations beyond 2021 and expected reach are discussed as well. So far HPS has used 45.5 PAC days of the approved 180 days for the engineering and first physics runs combined, and expects to use 27.5 PAC days during the scheduled 2021 run. With this, we request approval of the remaining 107 PAC days of beam time for HPS, which we plan to use to run with beam energies from ≈ 2 GeV to ≈ 4 GeV.

2. MOTIVATION FOR DARK PHOTON SEARCHES

Dark photons are the mediator of a broken hidden-sector $U(1)'$ gauge symmetry. Such hidden-sector gauge symmetries are common in theories beyond the Standard Model, and have long been recognized as giving rise to a simple and appealing portal from the Standard Model sector to a "hidden sector" [6]. Beyond being motivated by theoretical considerations, dark photons are also strongly motivated by the existence of dark matter. In particular, dark photons remain one of the simplest mechanisms by which dark matter can interact with ordinary matter, which allows the dark matter to be produced from Standard Model particles in the hot thermal plasma present in the early Universe. Dark-photon mediated interactions between dark and ordinary matter also give rise to a multitude of signatures at colliders, fixed-target experiments, direct-detection experiments, in astrophysical systems, and in cosmology. Dark photons also provide a simple mechanism by which dark matter particles can interact with themselves through non-gravitational forces; such "self-interactions" have been invoked to provide an explanation for the observed distribution of dark matter on "small" ($\sim$kiloparsec-size) scales in galaxies and galaxy clusters in the Universe. These puzzles are commonly and collectively referred to as the "small-scale problems of cold dark matter", where cold dark matter refers to non-relativistic and collisionless dark matter particles, i.e., particles that do not self-interact (such as WIMPs).

The past few years have also seen tremendous progress in precisely understanding and elucidating the interactions that sub-GeV dark matter might have with the Standard Model sector. It was realized that interactions mediated by dark photons with masses in the MeV to GeV scale are among the least constrained possibilities; they also give rise to several mechanisms that allow sub-GeV dark matter to be produced in the early Universe with a relic abundance that is consistent with the observed dark matter abundance. A comprehensive search for a dark photon in the MeV to GeV mass range is therefore essential, making dark photons popular targets in numerous experimental searches. While the allowed regions in the kinetic-mixing versus dark-photon-mass parameter space have slightly decreased in size in the past decade, significant gaps remain. HPS is poised to probe these gaps in unexplored dark photon parameter space quickly and efficiently.

3. SUMMARY OF 2015/2016 ENGINEERING RUNS

Engineering runs in 2015 and 2016 constituted the first operation of the HPS experimental apparatus. In May 2015, HPS commissioned the beamline and detectors using a 1.1 GeV beam and accumulated 10 mC of physics data on a 4 μm tungsten target. The 2016 Engineering Run took place the following spring at 2.3 GeV. Acceptable running was established at 200 nA on an 8 micron tungsten target. During four weekends, 92.5 mC on target was collected.

The engineering runs established excellent beam conditions: small spot sizes, good stability, and minimal halo. The SVT was successfully moved into the nominal data taking position, just 500 μm from the beam line, and all systems worked as designed. Design level beamline performance, ECal and trigger performance, track finding efficiency, momentum resolution, vertex resolution, and trident yields made the case for full HPS approval, which JLab granted in the spring of 2016.

The 2015 data was the basis for the first two HPS analyses, a resonance search and a displaced vertex search, appearing in theses during 2016 [7, 8] and four HPS students completed Ph.D. dissertations using this data. The first HPS analysis note describing the resonance search was completed in early 2017, followed by a public presentation of results at JLab . Publication followed in 2018 as a Phys. Rev. D Rapid Communication [9], and was selected as an "Editors' Suggestion." Limits from this result on A' couplings and mass are shown in Figure 7. An analysis note describing the displaced vertex search was also prepared in 2017 and the result was reported at ICHEP but only published as proceedings, since limited statistics rendered the result insensitive to predictions for minimal A' production rates [10]

The development of analysis techniques has continued with the 2016 data, which has been the subject of two Ph.D. dissertations with two more nearing completion. The results of both the resonance and displaced vertex searches with 2016 data were recently unblinded, with no significant signal observed in either search. The process of setting limits and incorporating systematics is underway and being documented in internal notes, under review by analysis committees prior to the public release of these results, which will together be the subject of a publication in PRD. The preliminary results of both searches are shown in Figure 2; the upper limit on ϵ^2 as a function of mass for the resonance search, and the upper limit on A' production rate in the mass-coupling plane relative to the signal expectation for the displaced vertex search. Neither search excludes new parameter space for the minimal A' production model, but demonstrate significant improvements to both analyses.

4. FIRST PHYSICS RUN

The first scheduled physics run of HPS took place in the summer of 2019, where analysis of data from 2015 and 2016 motivated key upgrades to the apparatus in advance of operations. First, wide-angle bremsstrahlung was identified as a significant background to the trident sample, leading to its inclusion in the MC. This change, along with a more accurate `MadGraph` [11] calculation for tridents, led to a good data/MC agreement for the spectrum of the total energy of pairs but also a modest decrease in sensitivity. Second, the first vertex analysis with 2015 data pointed to several shortcomings in our reach estimates, which overestimated the acceptance for long-lived A' decays.

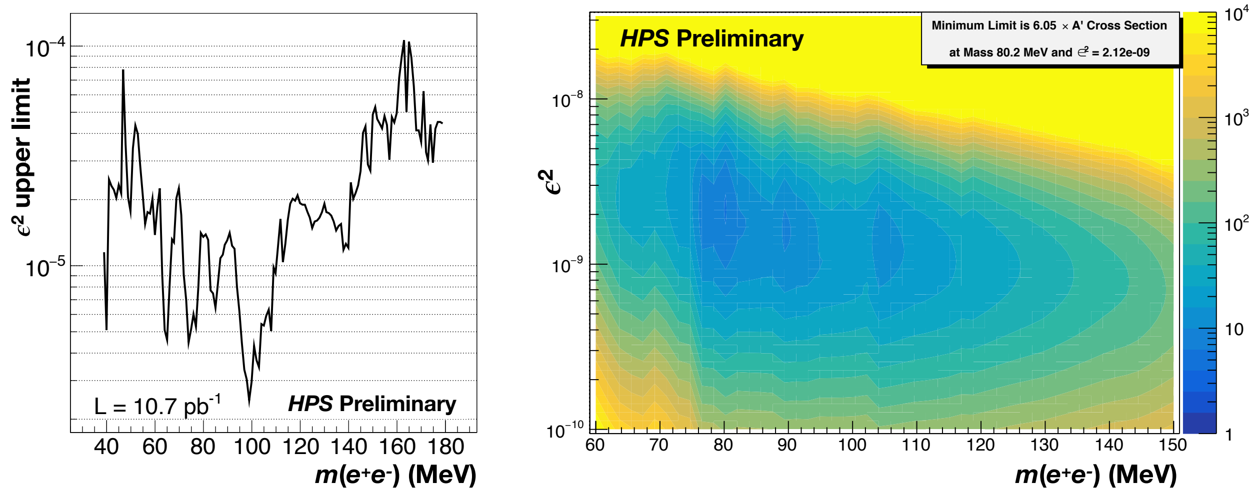

FIG. 2: Preliminary results of the resonance search (left) and displaced vertex search (right) with data collected during the 2016 Engineering Run at a beam energy of 2.3 GeV. The resonance search excludes no new parameter space but represents a significant improvement in analysis techniques over those used for the 2015 data. The displaced vertex search includes only e^+e^- pairs where both tracks have hits in the first SVT layer, and excludes A' production at a rate six times higher than predicted. Inclusion of other tracks will modestly improve this limit.

Finally, the removal of several ECal crystals with unsustainably high rates had diminished the efficiency of the two-arm "pair trigger" for A' to e^+e^- events. Upgrades aimed at recovering reach lost to these issues and subsequent operation of the detector in 2019 are described below, along with early results on detector performance and the expected reach of the 2019 dataset.

4.1. Detector Upgrades

The design of the HPS SVT is aggressive, with peak occupancy of $\approx$4 MHz/mm^2, and only 500 μm (1.5 mm) between the edges (active regions) of the silicon in the first layer and the beamline to allow acceptance down to 15 mrad for particles originating at the target. Nonetheless, the challenges – for both the beamline and the SVT – presented by this design did not limit operation of the detector during the engineering runs. With analysis of the engineering run data indicating less sensitivity than initially predicted, partly due to vertex resolution and acceptance of the SVT, upgrades to a somewhat more aggressive design were motivated.

The goals of these upgrades are improving the z-vertex resolution and providing better angular acceptance for decays downstream of the target. With resolution limited by scattering in the first layer, the first goal calls for thinner silicon closer to the target, and therefore closer to the beam for the same angular acceptance. The second goal calls for moving the silicon in the subsequent layers of the detector closer to the beam to improve forward acceptance for electrons and positrons from long-lived A' decays. The challenges include increased occupancy and radiation exposure, and the need for special thin sensors in the first layers with slim edges to allow the active region even closer than 1.5 mm from the beamline.

The realization of these upgrades included a new "Layer 0", placed half the distance from the target as the previous first layer, use of that same silicon to replace the previous first layer to move the active area closer to the beam, and similar re-positioning of the next two layers closer to the beam to improve angular acceptance for particles from decays downstream of the target. Figure 3 shows the upgraded arrangement of the front four layers of the SVT.

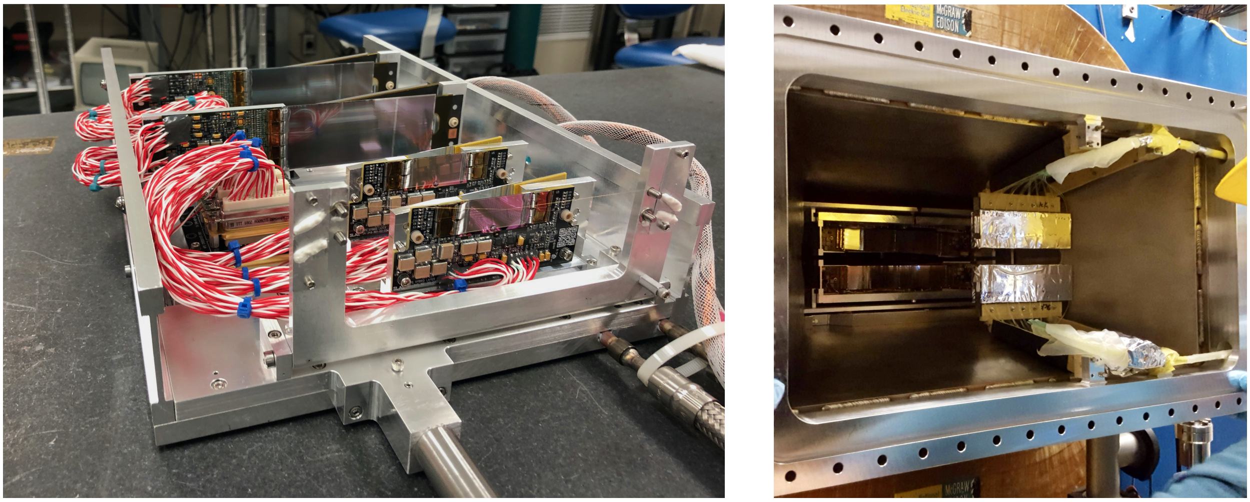

FIG. 3: On the left, the bottom half of the upgraded front four (of seven) layers of the SVT showing the small slim-edge sensors of the first two layers. On the right, the positron hodoscope shown installed behind the longer SVT modules of layers 5-7.

To avoid unsustainably high rates from scattered beam electrons, nine modules from the rows of crystals nearest to the beam for each of the top and bottom ECal halves were removed. This created a hole in the acceptance where almost half of the electrons from $A' \to e^+e^-$ decay will escape detection. With the pair trigger – requiring hits in the ECal for both particles – events with an e^- lost in the ECal hole, but otherwise tracked in SVT, are not recorded. To recover these events, a single-arm, positron trigger has been implemented. The rate of positrons is not high, but the positron side of the ECal is flooded with photons from bremsstrahlung in the target. For a single-arm positron trigger to work with an acceptable rate, the HPS detector was instrumented with a scintillation hodoscope covering the positron side of the ECal to distinguish electrons from photons.

The hodoscope is installed inside the vacuum chamber between the SVT and the vacuum flange in front of the ECal as shown in Figure 3. Each half of the hodoscope consists of two layers of overlapping scintillator tiles. Signals from the hodoscope tiles are used in the trigger in coincidence with the corresponding ECal module forming a single-arm positron trigger. During the 2019 run, the trigger rate for production data taking was 10.5 kHz for each half of the hodoscope.

4.2. 2019 Operations

Plans for the 2019 HPS physics run called for 4.5 “PAC weeks” during 63 days, from June 17 through August 18, at a 4.5 GeV beam energy with a current of 300 nA on an 8 μm tungsten target. With one week for setup this would give 725 mC of charge on target, for an integrated luminosity of 229 pb^{-1}.

The progress of data collection is shown in Figure 4, with extended gaps due to difficulties re-tuning the beam after changes to accommodate the other halls. We soon observed degradation of some SVT DAQ components on front-end boards during periods of bad beam and difficulty tuning, prompting additional controls for beam tuning. Initial operation was with a beam current of 150 nA, to mitigate the damage rate while the problem was studied, but ramped up as beam operations improved, limited by the effects of x-rays on the surface currents and occupancies in the first SVT layer. To increase the overall luminosity of the experiment at the expense of slightly

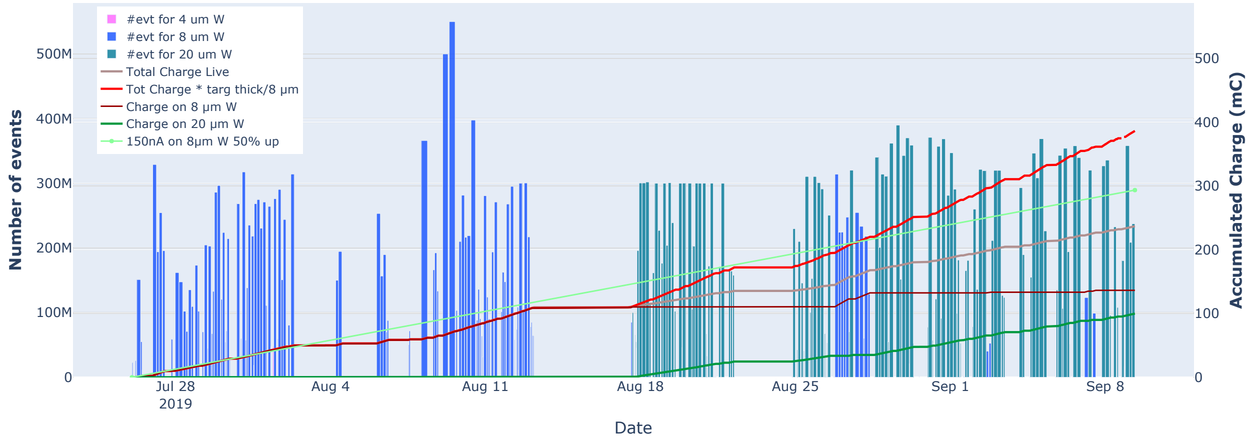

FIG. 4: Number of events in each run and the accumulated charge for the 2019 data taking period. The red curve is the total charge scaled to using an 8 μm W target for the entire run period.

higher background, a thicker 20 μm tungsten target was installed on August 13$^{\text{th}}$, as indicated on the figure by blue-green bars. By the end of the run 237 mC of charge were delivered on target during production runs (gray line). Scaling the amount of charge by target thickness normalized to 8 μm tungsten, the total charge was the equivalent of 386 mC on an 8 μm tungsten target, for an integrated luminosity of 122 pb^{-1} and an accumulated sample of 40 billion events (red line).

4.3. 2019 Detector performance

The sensitivity of the HPS experiment depends on two signatures: reconstruction of an e^+e^- invariant mass peak and reconstruction of the e^+e^- production vertex, in the case of the displaced vertex search. Together with the acceptance of the detector and trigger, and the reconstruction efficiency, these define the key performance parameters for the apparatus. While the process of calibrating and refining event reconstruction with the upgraded detector is still ongoing for the 2019 dataset, some early results, presented below, demonstrate the performance of the apparatus and underpin the expected physics reach of the dataset.

Energy and Momentum Measurement

An initial calibration of the ECal with cosmic rays prior to operation provided sufficient precision for triggering, where subsequent offline analysis of scattered full-energy beam electrons collected with a special trigger is used to derive the calibration for analysis. Some preliminary results are shown in Figure 5, where sampling fraction corrections for lower-energy clusters are derived from single-particle MC simulations.

The curvature-plane measurements of the SVT in the magnetic field are made by stereo pairs of sensors, so the momentum scale and resolution of the SVT depend on careful internal alignment of all 40 sensors. As a result, the momentum resolution is the last of the key performance parameters to be met with a new dataset, in particular with an upgraded detector. With only preliminary global alignment complete, the bottom half of the SVT already delivers reasonable momentum resolution, as shown in Figure 5. Also shown are the sum of the electron momentum and photon energy in $e^- + \gamma$ bremsstrahlung events, where the peak position and resolution can be used to calibrate the lower-energy constituents. The internal sensor-by-sensor alignment needed to achieve the full design resolution and correct the momentum scale in both halves of the SVT is ongoing.

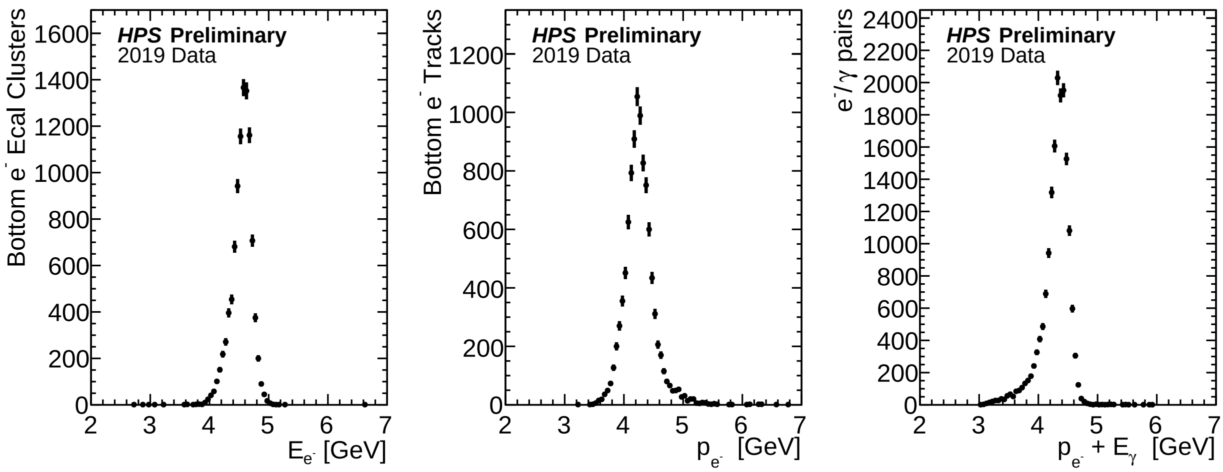

FIG. 5: The calibrated ECal energy of scattered full energy electrons (left) and the momentum of tracks matched to those ECal clusters (center) demonstrate preliminary calibration of the bottom half of the detector. In wide-angle bremsstrahlung events with both an electron and a photon reconstructed, the sum of the e^- momentum and γ energy provides a calibration test for lower particle energies (right).

Vertex Resolution

The experimental reach for the displaced vertex search depends critically on precise reconstruction of the spatial origin, or vertex, of e^+e^- pairs. While full alignment is required to achieve the design resolution, the precision with which the z-position of vertices can be determined is limited by multiple scattering after only preliminary alignment of the sensors closest to the target.

The decay length, or z-vertex, resolution is estimated using a data sample of e^+e^- pairs collected with the physics trigger and selected with simple cuts to reduce backgrounds from converted wide-angle bremsstrahlung, accidentals, and mis-reconstructed tracks and vertices. The resolution is extracted by fitting the core of the distribution with a Gaussian, and compared to the resolution for a sample of trident Monte Carlo without backgrounds, and reconstructed with perfect geometry. Figure 6 shows the comparison between data and MC as a function of the invariant mass of the vertex, which affects the resolution primarily through the opening angle between the tracks. Agreement between the data and MC is currently at the 20% level, where further alignment and background reduction are required to achieve the full factor of two improvement expected from the SVT upgrade.

Kinematic Distributions and Signal Rates

A key kinematic distribution in understanding signal and background rates, and therefore acceptance and reach, is the energy sum of the e^+e^- pair. An A' signal, like radiative tridents, peaks with an energy sum near the beam energy, while the dominant background from Bethe-Heitler tridents peaks at low energy sum. To verify the expected distribution and demonstrate the effectiveness of the positron trigger in reclaiming pairs where the electron does not hit the ECal, the scalar momentum sum of the e^+e^- pair ($\mathrm{P_{sum}}$) for reconstructed events using SVT tracks is compared to the spectrum where the electron track is not matched to an ECal cluster, as well as the

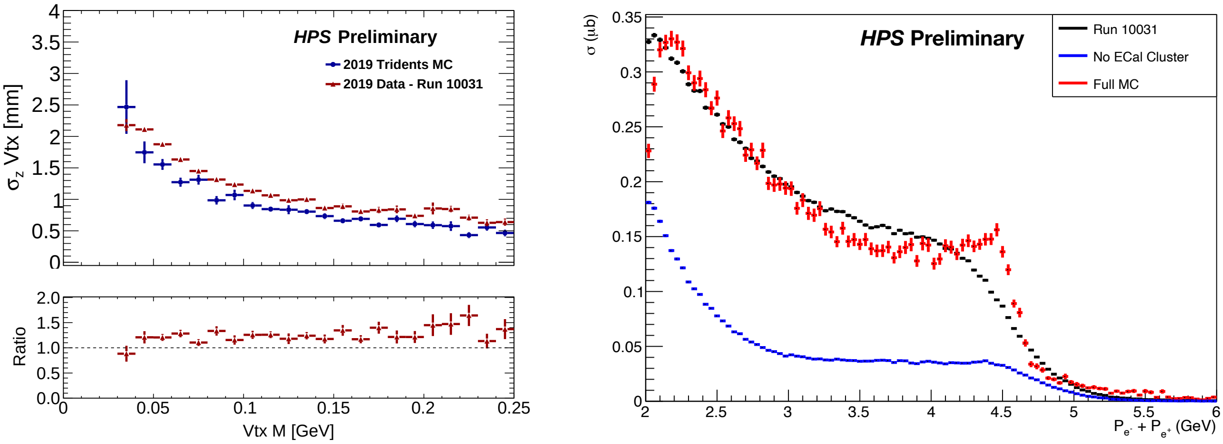

FIG. 6: The z-vertex resolution (left) and P_{Sum} distribution (right) from the 2019 data run. The z-vertex resolution as a function of mass (red) is compared to ideal trident Monte Carlo (blue), showing that roughly 80% of the resolution improvement from the upgrade has been achieved after preliminary alignment. The P_{Sum} plot shows the spectrum of loosely selected events from the positron trigger (black) along with those that have no nearby cluster (blue) and would not have passed the previous pairs trigger. The MC P_{Sum} distribution normalized to the observed data rate (red) is also shown, where data is smeared by momentum resolution that is currently far from the ideal resolution of MC.

expected spectrum from Monte Carlo in Figure 6. The additional acceptance for signal from the positron trigger is roughly consistent with expectation given anticipated background contributions to the total rate.

4.4. Data analysis progress and the expected reach

The resonance search, simple in principle, requires careful attention to calibration and alignment of the detector and a detailed understanding of efficiencies and rates for both signal and key backgrounds. Building on experience gained from the recent completion of the 2016 analyses, the process of building the foundations for the analysis are underway, and results are expected in early 2021. While little or no new sensitivity is expected, the resonance search forms the basis for the displaced vertex search, which should follow within a year, and should offer a window into highly motivated parameter space, as shown in Figure 7.

5. FUTURE OPERATIONS

While HPS data from 2019 holds the promise of sensitivity to new physics, collection of larger datasets at multiple energies is required to achieve the full potential of the experiment. In particular, sensitivity to A' from displaced decays spans a range of mass and coupling for each beam energy that depends on the size of the dataset, motivating operation at more than one beam energy for multiple weeks at each energy. Data from 8-12 PAC weeks at one energy gives sensitivity at a wide range in coupling over a large enough range in mass that sensitivity for different CEBAF beam energies overlaps. The goal of the overall run plan for HPS is therefore to collect sufficient data at the available beam energies to ensure continuous, overlapping coverage between 50 MeV and the di-muon threshold at a range of couplings. This region includes parameter space often motivated by thermal dark matter in this mass range, where a dark photon is the preferred medi-

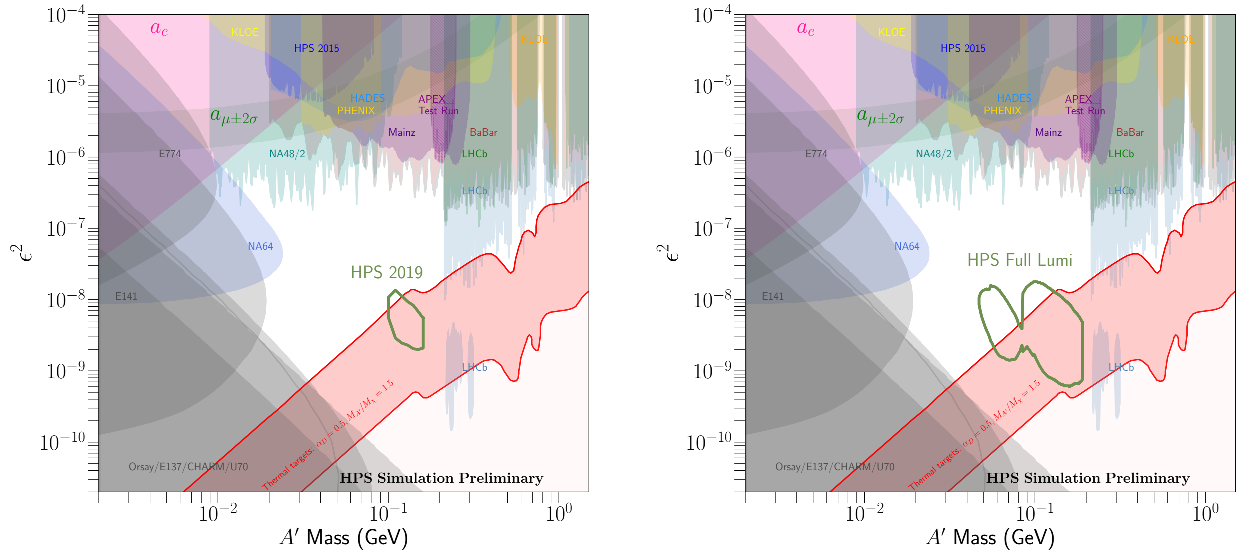

FIG. 7: The reach anticipated from the displaced vertex analysis on the 2019 dataset (left, green contour) and proposed future operations (right, green contour) that utilize the remainder of the approved running time for HPS. Modest new reach for the resonance search, not shown here, is also anticipated for the full luminosity. 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, 12].

ator of DM-SM interactions responsible for setting the observed dark matter abundance through freeze-out: the so-called "thermal targets."

5.1. Scheduled Run in 2021 at 3.8 GeV

The sensitivity and complementary of HPS with other experiments is best just below the di-muon mass threshold, which is accessed by operation between roughly 3-5 GeV beam energy. Accordingly, the first goal is the collection of a large dataset at a beam energy in the vicinity of 4 GeV. HPS is currently scheduled to operate for 60 days during the summer of 2021 at a beam energy of ≈3.8 GeV. Assuming typical 50% uptime, the resulting dataset would correspond to roughly four PAC weeks. Prior to operation, HPS will perform maintenance on the detector, including repairing damage to the SVT sustained during operations in 2019. In particular, the front-end boards – damaged by radiation – will be completely replaced with a more robust design, and damaged sensor modules in the first two layers will be replaced with new modules assembled with an improved sensor design. Work on these projects is already underway. Together with improvements to beamline diagnostics and tuning procedures, these changes will ensure against the operational issues experienced during the 2019 run.

5.2. HPS Operations Beyond 2021

After operation in 2021, there will be 107 PAC days (≈15 weeks) of approved running time still allocated to the HPS experiment. Splitting future running time – including the 2021 Run – equally between ≈2 GeV and ≈4 GeV would be roughly 9 PAC weeks at each energy, enough to provide overlapping coverage in mass as desired. Because sensitivity in mass-coupling space grows more rapidly at higher energy, because the higher-mass region more strongly overlaps the thermal targets, and because HPS is more complementary to other proposed experiments there, it may be advantageous to run longer at ≈4 GeV than at ≈2 GeV. For this reason, we propose that future operations beyond 2021 include 8 PAC weeks at ≈4 GeV and 7 PAC weeks at ≈2 GeV and request re-approval of 107 PAC days to implement this run plan. The overall sensitivity of HPS in the displaced vertex search for the complete dataset after this run plan is shown in Figure 7. The capability to explore the highly motivated parameter space at intermediate couplings distinguishes HPS from other proposals and makes a uniquely compelling case for exploiting this potential with as much operating time as can be made available.

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