

The Heavy Photon Search Test Detector

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Abstract

The Heavy Photon Search (HPS), an experiment to search for a hidden sector photon in fixed target electroproduction, is preparing for installation at the Thomas Jefferson National Accelerator Facility (JLab) in the Fall of 2014. As the first stage of this project, the HPS Test Run apparatus was constructed and operated in 2012 to demonstrate the experiment's technical feasibility and to confirm that the trigger rates and occupancies are as expected. This paper describes the HPS Test Run apparatus and readout electronics and its performance. In this setting, a heavy photon can be identified as a narrow peak in the e^+e^- invariant mass spectrum, above the trident background or as a narrow invariant mass peak with a decay vertex displaced from the production target, so charged particle tracking and vertexing are needed for its detection. In the HPS Test Run, charged particles are measured with a compact forward silicon microstrip tracker inside a dipole magnet. Electromagnetic showers are detected in a PbWO₄ crystal calorimeter situated behind the magnet, and are used to trigger the experiment and identify electrons and positrons. Both detectors are placed close to the beam line and split top-bottom. This arrangement provides sensitivity to low-mass heavy photons, allows clear passage of the unscattered beam, and avoids the spray of degraded electrons coming from the target. The discrimination between prompt and displaced e^+e^- pairs requires the first layer of silicon sensors be placed only 10 cm downstream of the target. The expected signal is small, and the trident background huge, so the experiment requires very large statistics. Accordingly, the HPS Test Run utilizes high-rate readout and data acquisition electronics and a fast trigger to exploit the essentially 100% duty cycle of the CEBAF accelerator at JLab.

Keywords: silicon microstrip, tracking, vertexing, heavy photon, dark photon, hidden sector, electromagnetic calorimeter

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29 **1. Introduction**

30 The heavy photon (A'), aka a “hidden sector” or
31 “dark” photon, is a massive particle which couples
32 weakly to electric charge by mixing with the Standard
33 Model photon [1]. Consequently, it can be radiated by
34 electrons and subsequently decay into e^+e^- pairs, al-
35 beit at rates far below those of QED trident processes.
36 Heavy photons have been suggested by numerous be-
37 yond Standard Model theories [2], to explain the dis-
38 crepancy between theory and experiment of the muon’s
39 $g - 2$ [3], and as a possible explanation of recent as-
40 trophysical anomalies [4, 5, 6]. Heavy photons couple
41 directly to hidden sector particles with “dark” or “hid-
42 den sector” charge; these particles could constitute all
43 or some of the dark matter [7]. Current phenomenology
44 highlights the $20 - 1000 \text{ MeV}/c^2$ mass range, and sug-
45 gests that the coupling to electric charge, ϵe , has ϵ in the
46 range of $10^{-3} - 10^{-5}$. This range of parameters makes
47 A' searches viable in medium energy fixed target elec-
48 troproduction [8], but requires large data sets and good
49 mass resolution to identify a small mass peak above the
50 copious QED background. At small couplings, A' be-
51 come long-lived, so detection of a displaced decay ver-
52 tex can reject the prompt QED background and boost
53 experimental sensitivity.

54 The HPS experiment [9] uses both invariant mass and
55 secondary vertex signatures to search for A' . It uses a
56 $\approx 1 \text{ m}$ long silicon tracking and vertexing detector in-
57 side a dipole magnet to measure charged particle trajec-
58 tories and a fast electromagnetic calorimeter just down-
59 stream of the magnet to provide a trigger and identify
60 electrons. The experiment utilizes very high-rate front-
61 end electronics and runs at high trigger rates (up to
62 50kHz), exploiting the 100% duty cycle of the JLab CE-
63 BAF accelerator to accumulate the needed statistics.

64 The HPS Test Run, using a simplified version of the
65 HPS apparatus, was proposed and approved at JLab as
66 the first stage of HPS. Its purposes included demonst-
67 rating that the apparatus and data acquisition systems are
68 technically feasible and the trigger rates and occupan-
69 cies to be encountered in electron-beam running are as
70 simulated. Given dedicated running time with electron
71 beams, the HPS Test Run apparatus is capable of search-
72 ing for heavy photons in unexplored regions of parame-
73 ter space. The key design criteria for HPS and the HPS
74 Test Run are the same:

- 75 • large and uniform acceptance in the forward region
76 close to the beam in order to catch boosted A' de-
77 cay products,
- 78 • beam passage through the apparatus in vacuum, to

79 eliminate direct interactions with the detector and
80 minimize beam gas interactions,

- 81 • detector components that can survive and effi-
82 ciently operate in a high radiation environment
83 with local doses exceeding 100 Mrad.
- 84 • high-rate electronics with excellent timing resolu-
85 tion to minimize out of time backgrounds,
- 86 • a flexible, redundant and efficient trigger selecting
87 electron and positron pairs at rates up to 50 kHz,
- 88 • data handling rates of 100 MB/s to permanent stor-
89 age,
- 90 • excellent track reconstruction efficiency for elec-
91 trons and positrons,
- 92 • good angular and momentum resolution to recon-
93 struct invariant mass precisely,
- 94 • excellent vertex resolution to discriminate dis-
95 placed A' decays from prompt QED backgrounds,

96 The HPS Test Run apparatus was installed on April
97 19, 2012, and ran parasitically in the photon beam of
98 the HDice experiment [10] until May 18. The JLab
99 run schedule precluded any dedicated electron beam
100 running, but the HPS Test Run was allowed a short
101 and valuable dedicated photon beam run at the end of
102 scheduled CEBAF running. This final running provided
103 enough data to demonstrate the functionality of the ap-
104 paratus, document its performance, and explore trigger
105 rates, as shown below.

106 This paper reviews the HPS Test Run apparatus, doc-
107 umenting the performance of the trigger, data acqui-
108 sition, silicon tracking detector, and the electromag-
109 netic calorimeter at the level required for calculating the
110 physics reach of the HPS experiment.

111 **2. Detector Overview**

112 The HPS Test Run apparatus was designed to run
113 in Hall B at JLab using the CEBAF 499MHz electron
114 beam at energies between 2.2 and 6.6 GeV and cur-
115 rents between 200 and 600 nA. The overall design of
116 the experiment follows from the kinematics of A' pro-
117 duction which typically results in a final state particle
118 within a few degrees of the incoming beam, especially
119 at low $m_{A'}$. Detectors must therefore be placed close
120 to the beam. The intense electron beam enlarges down-
121 stream after multiple scattering in the target and elec-
122 trons which have radiated in the target disperse horizon-
123 tally in the field of the analyzing magnet. Together they

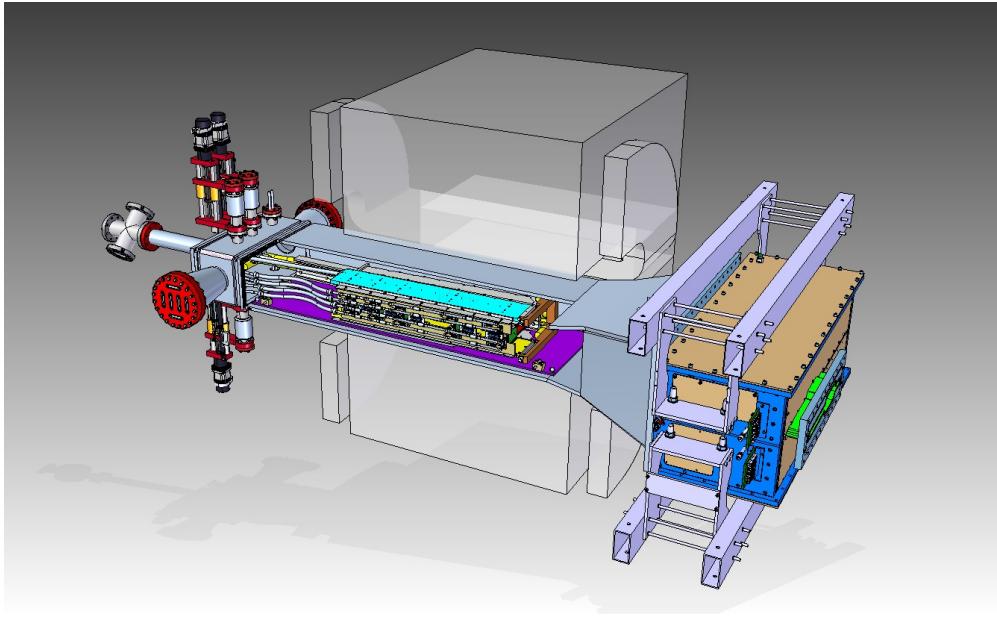


Figure 1: Rendering of the HPS Test Run apparatus installed on the beam line.

124 constitute a “wall of flame” which must be completely
 125 avoided. Accordingly, the apparatus is split vertically
 126 to avoid a “dead zone”, the region within ± 15 mrad of
 127 the beam plane. In addition, the beam is transported in
 128 vacuum through the tracker to minimize beam-gas inter-
 129 action backgrounds. Even with these precautions, the
 130 occupancies of sensors near the beam plane are high,
 131 dominated by the multiple Coulomb scattering of the
 132 primary beam, so high-rate detectors, a fast trigger, and
 133 excellent time tagging are required to minimize their
 134 impact. The trigger comes from a highly-segmented
 135 lead-tungstate (PbWO_4) crystal calorimeter located just
 136 downstream of the dipole magnet.

137
 138 A rendering of the apparatus installed on the beam line
 139 is shown in Figure 1 and an overview of the coverage,
 140 segmentation and performance is given in Table 1.

141 The silicon vertex tracking and vertexing detector for
 142 the HPS Test Run, or SVT, resides in a vacuum cham-
 143 ber inside the Pair Spectrometer (PS) dipole magnet in
 144 Hall B at JLab. The magnetic field strength was 0.5 T
 145 oriented vertically throughout the run. The SVT has
 146 five measurement stations, or “layers,” beginning 10 cm
 147 downstream of the target. Each layer comprises a pair
 148 of closely-spaced silicon microstrip sensors respon-
 149 sible for measuring a single coordinate, or “view”. In-
 150 troduction of a small (50 or 100 mrad) stereo angle

151 between the two sensors of each layer provides three-
 152 dimensional tracking and vertexing throughout the ac-
 153 ceptance of the detector. In order to accommodate the
 154 dead zone, the SVT is built in two halves that are ap-
 155 proximately mirror reflections of one another about the
 156 plane of the nominal electron beam. Each layer in one
 157 half is supported on a common support plate with inde-
 158 pendent cooling and readout.

159 The electromagnetic calorimeter (ECal) is also split
 160 into two halves. Each half of the ECal consists of
 161 221 PbWO_4 crystals arranged in rectangular formation.
 162 There are five rows with 46 modules in each row except
 163 the row closest to the beam plane which has 37. The
 164 light from each crystal is read out by an Avalanche Pho-
 165 todiode (APD) glued on the back surface of the crys-
 166 tal. Signals from the APDs are amplified using custom-
 167 made amplifier boards before being sent to the data ac-
 168 quisition electronics.

169 The Data Acquisition system combines two architec-
 170 tures, the Advanced Telecom Communications Archi-
 171 tecture (ATCA) based SVT readout system and VME-
 172 bus Switched Serial (VXS) based digitization and trig-
 173 gering system for the ECal.

3. The HPS Test Run Beamline

174 Since an electron beam was unavailable, the HPS Test
 175 Run detected the electrons and positrons produced by

Table 1: Overview of the coverage, segmentation and performance of the HPS Test Run detector.

System	Coverage (mrad)	# channels	ADC (bit)	Time resolution (ns)	# layers	Segmentation	Performance
SVT	$15 < \theta_y < 70$ (5 hits)	12780	14	≈ 2 ns	5 (stereo layers)	$\approx 120 \mu\text{m} r - \phi$ $\approx 6 \mu\text{m} z$	$\sigma_{d0,y} \approx 100 \mu\text{m}$ $\sigma_{d0,x} \approx 300 \mu\text{m}$ $\sigma_{d0,z} \approx 1 \text{ mm}$
Ecal	$15 < \theta_y < 60$	442	12	4 ns	1	$1.33 \times 1.33 \text{ cm}^2$ $1.6 \times 1.6 \text{ cm}^2$	$\sigma(E)/E \approx 4.5\%$

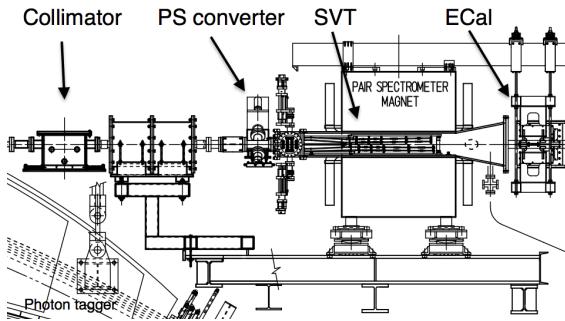


Figure 2: Layout of the HPS parasitic run.

interactions of the secondary photon beam with a thin foil just upstream of the detectors. The HPS Test Run studied the performance of the detectors and the multiple coulomb scattering of the electrons and positrons. Figure 2 shows the layout of the setup on the beam line. The SVT was installed inside the Hall B pair spectrometer magnet vacuum chamber with the ECal mounted downstream of it. Both the SVT and the ECal were retracted off the beam plane compared to nominal electron beam running to allow clean passage of the photon beam through the system.

The photon beam was generated in the interaction of 5.5 GeV electrons with a $10^{-4} X_0$ gold radiator located ≈ 9 m upstream of the PS. The primary beam and scattered electrons are deflected away from detectors by the dipole magnet of the photon tagging system. During the dedicated HPS Test Run period, the collimated (6.4 mm diameter) photon beam passes through the PS pair converter gold foil and later the HPS system. The PS pair converter was located ≈ 77 cm upstream of the first layer of the SVT.

Data was taken on three different converter thicknesses with photon fluxes between 0.4 and $1.3 \times 10^8/\text{s}$ at photon energies between 0.55 and 5.5 GeV produced by a 30 to 90 nA electron beam. Data was measured for both polarities of the PS dipole magnet. The photon beam line during the HPS Test Run produced a relatively large number of e^+e^- pairs originating upstream

Converter thickn. (% X_0)	Duration (s)	e^- on radiator (μC)
0	1279	88.1
0.18	2640	193.5
0.45	2149	140.7
1.6	911	24.4

Table 2: Measured integrated currents for the dedicated photon runs.

of the converter position. This contribution was measured during data taking with “empty” converter runs, i.e. removing the converter but with all other conditions the same. The runs taken during the time dedicated to HPS Test Run are summarized in Table 2.

4. Silicon Vertex Tracker

The Silicon Vertex Tracker (SVT) enables efficient reconstruction of charged particles and precise determination of their trajectories. These measurements allow A' decays to be distinguished from background via simultaneous estimation of the invariant mass of e^+e^- decay products and the position of decay vertices downstream of the target.

The design of the SVT is primarily driven by direct physics requirements and constraints from the environment at the interaction region. The A' decay products have momenta in the range of 1 GeV/c, so multiple scattering dominates mass and vertexing uncertainties for any possible material budget. The SVT must therefore minimize the amount of material in the tracking volume. The signal yield for long-lived A' is very small, so the rejection of prompt vertices must be exceedingly pure, on the order of 10^{-7} , in order to eliminate all prompt backgrounds. To achieve the required vertexing performance the first layer of the SVT must be placed no more than about 10 cm downstream of the target. At that distance, it is found that the active region of a sensor can be placed as close as 1.5 mm from the center of the beam, defining the 15 mrad “dead zone” mentioned previously, to maximize low-mass A' ac-

ceptance with decay products nearly collinear with the beam axis. At the edge of this “dead zone”, the radiation dose approaches 10^{15} electrons/cm²/month, or roughly 3×10^{14} 1 MeV neutron equivalent/cm²/month [11], requiring the sensors to be actively cooled. Meanwhile, very low-energy delta rays from beam-gas interactions multiply the density of background hits, so the SVT must operate inside the beam vacuum. Finally, in order to protect the sensors, the detector must be movable so that it can be retracted during periods of uncertain beam conditions.

4.1. Layout

The layout of the SVT is summarized in Table 4.1 and rendered in Figure 3. Each of the layers is comprised of a pair of closely-spaced silicon microstrip sensors mounted back-to-back to form a module. A 100 mrad stereo angle is used in the first three layers to provide higher-resolution 3D space points for vertexing. Using 50 mrad in the last two layers breaks the tracking degeneracy of having five identical layers and minimizes fakes from ghost hits to improve pattern recognition. Altogether, the SVT has 20 sensors for a total of 12780 readout channels.

Layer	1	2	3	4	5
<i>z</i> from target (cm)	10	20	30	50	70
Stereo angle (mrad)	100	100	100	50	50
Bend res. (μm)	≈ 60	≈ 60	≈ 60	≈ 120	≈ 120
Non-bend res. (μm)	≈ 6	≈ 6	≈ 6	≈ 6	≈ 6
# of sensors	4	4	4	4	4
Dead zone (mm)	± 1.5	± 3.0	± 4.5	± 7.5	± 10.5
Power cons. (W)	6.9	6.9	6.9	6.9	6.9

Table 3: Layout of the SVT.

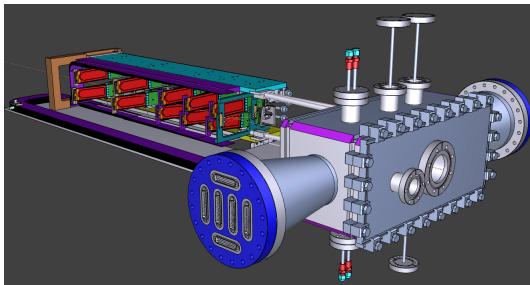


Figure 3: A rendering of the SVT showing the modules on their support plates held by the hinged C-support on the left and the motion levers on the right. The sensors are shown in red and the hybrid readout boards in green. The beam enters from the right through a vacuum box with flanges for services.

259

The SVT is built in two separate halves that are mirror reflections of one another about the plane of the nominal electron beam. Each half consists of five modules mounted on a support plate that provides services to the modules and allows them to be moved as a group relative to the dead zone. The two halves of the tracker are connected to hinges mounted on a C-shaped support just beyond the last layer that defines the nominal spacing between the upper and lower halves of the tracker. A shaft attached to each support plate in front of layer one extends upstream and connects to a linear shift that transfers motion into the vacuum box through bellows to open and close the two halves around the dead zone. The C-support is mounted to an aluminum baseplate that defines the position of the SVT with respect to the vacuum chamber. Figure 4 shows a photograph of both completed detector halves prior to final assembly.



Figure 4: Both halves of the HPS Test Run SVT after final assembly at SLAC. The cooling manifolds and integrated cable runs are clearly seen.

276

4.2. Components

The sensors for the SVT are *p*-on-*n*, single-sided, AC-coupled, polysilicon-biased microstrip sensors fabricated on <100> silicon and have 30 (60) μm sense (readout) pitch over their $4 \times 10 \text{ cm}^2$ surface. This sensor technology was selected to match the requirement of $< 1\% X_0$ per layer, single-hit resolution better than 50 μm and tolerance of a radiation dose of approximately 1.5×10^{14} 1 MeV neutron equivalent/cm² for a six month run. The sensors were purchased from the Hamamatsu Photonics Corporation for the cancelled Run 2b upgrade of the DØ experiment [12] which satisfied the requirement that the technology must be mature and available within the time and budget constraints.

Despite having only small spots with very high occupancy (up to 4 MHz/mm²) closest to the primary beam,

293 the rates are still high and lowering the peak occupancy
 294 to approximately 1% for tracking requires a trigger window
 295 and hit time tagging of roughly 8 ns. The ECal
 296 readout and trigger described in Sec. 5.3 can achieve
 297 such resolution. To reach this performance the sen-
 298 sors for the SVT are readout by the APV25 ASIC de-
 299 veloped for the CMS experiment at CERN [13]. The
 300 APV25 can capture successive samples of the shaper
 301 output in groups of three at a sampling rate of approx-
 302 imately 40 MHz. By fitting the known $CR-RC$ shaping
 303 curve to these samples, the initial time of the hit can
 304 be determined to a precision of 2 ns for $S/N \approx 25$ [14].
 305 For electron beam running, six-sample readout and the
 306 shortest possible shaping time (35 ns) is used to best
 307 distinguish hits that overlap in time. The APV25 ASICs
 308 are hosted on simple FR4 hybrid readout boards, out-
 309 side the tracking volume, with a short twisted-pair pig-
 310 tail cable to provide power and configuration and signal
 311 readout. Along with a single sensor, these are glued
 312 to a polyamide-laminated carbon fiber composite back-
 313 ing making up a half-module. A window is machined
 314 in the carbon fiber leaving only a frame around the pe-
 315 riphery of the silicon to minimize material. A 50 μm
 316 sheet of polyamide is laminated to the surface of the
 317 carbon fiber with 1 mm overhang at all openings to en-
 318 sure good isolation between the back side of the sensor,
 319 carrying high-voltage bias, and the carbon fiber which
 320 is held near ground.

321 The sensor modules for the SVT consist of a pair
 322 of identical half-modules, sandwiched back-to-back
 323 around an aluminum cooling block at one end and a sim-
 324 ilar PEEK spacer block at the other. Figure 5 shows a
 325 single module after assembly. The cooling block pro-

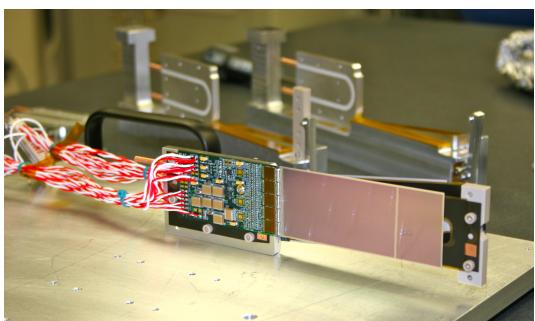


Figure 5: A prototype module assembly (foreground) with the
 50 mrad (left) and 100 mrad (right) module assembly fixtures
 in the background. A pair of cooling blocks and a spacer block
 can be seen on the fixtures.

325 vides the primary mechanical support for the module as
 326 well as cooling via copper tubes pressed into grooves
 327 in the plates. The spacer block defines the spacing be-

329 tween the sensors at the far end of the module, stiffens
 330 the module structure, and improves the stability of the
 331 sensor alignment. The average support material in the
 332 tracking volume is approximately 0.06% X_0 per double-
 333 sided module for a total material budget of 0.7% per
 334 layer.

335 The total SVT power consumption budget of about
 336 50 W is removed by a water/glycol mixture circulated
 337 through a flexible manifold attached to the copper tubes
 338 in the cooling blocks. During the HPS Test Run the
 339 sensors were operated at around 23° C. The power con-
 340 sumption is dominated by five APV25 ASICs on each
 341 hybrid board consuming approximately 2 W, radiant
 342 heat load is less than 0.5 W per sensor and leakage cur-
 343 rent is only significant in a small spot after irradiation.

344 4.3. Production, Assembly and Shipping

345 Hybrids with APV25 ASICs underwent quick qualifi-
 346 cation testing and each half-module was run at low tem-
 347 perature ($\approx 5^\circ \text{C}$) and fully characterized for pedestals,
 348 gains, noise and time response after assembly. Of 29
 349 half-modules built, 28 passed qualification testing, leav-
 350 ing eight spare modules after completion of the SVT.
 351 Only sensors capable of 1000 V bias voltage without
 352 breakdown were used. Full-module assembly and me-
 353 chanical surveys were performed at SLAC before final
 354 assembly, testing and shipping of the SVT to JLab. A
 355 custom shipping container with nested crates and redun-
 356 dant isolation for shock and vibration was built in or-
 357 der to safely send the partly assembled SVT to JLab.
 358 At JLab, the entire SVT was integrated with the full
 359 DAQ and the power supplies before moving the module-
 360 loaded support plates to Hall B for final mechanical as-
 361 sembly and installation inside of the vacuum chamber.

362 4.4. Alignment

363 The SVT was aligned using a combination of optical,
 364 laser and touch probe surveys at SLAC and JLab. The
 365 optical survey of individual modules with a precision of
 366 a few μm was combined with a touch-probe survey of
 367 the overall SVT support structure, with 25-100 μm pre-
 368 cision, to locate the silicon sensor layers with respect
 369 to the support plates and the mechanical survey balls
 370 on the base plate. After full assembly and installation
 371 of the SVT at JLab, a mechanical survey of the SVT
 372 base plate position inside the pair spectrometer vacuum
 373 chamber is used to determine the global position of the
 374 SVT with respect to the CEBAF beam line. The re-
 375 sulting survey-based alignment has the position of the
 376 silicon sensors correct to within a few hundred microns
 377 measured from tracks in the HPS Test Run data. A more

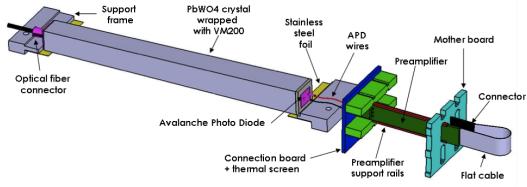


Figure 6: A schematic view of an ECal module.

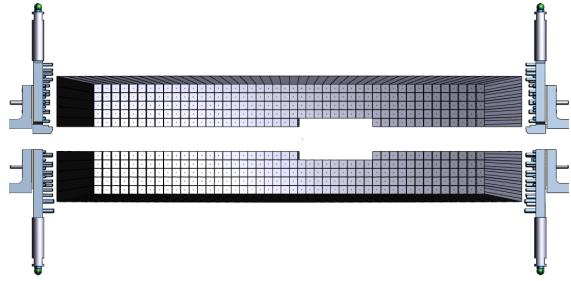


Figure 7: Rendered layout view of the ECal looking downstream.

378 sophisticated global track-based alignment technique to
379 reach final alignment precision well below $50\text{ }\mu\text{m}$ is being
380 developed.

381 5. Electromagnetic Calorimeter

382 The electromagnetic calorimeter (ECal), installed
383 downstream of the PS dipole magnet, performs two es-
384 sential functions for the experiment: it provides a trigger
385 signal to select what events to read out from the detector
386 sub-systems and is used in the analysis to identify elec-
387 trons and positrons. The technology and design choices
388 are largely driven by the need for a compact forward de-
389 sign covering the SVT A' acceptance and able to fully
390 absorb electrons and positrons with energy between 0.5-
391 6.5 GeV. It needs granularity and signal readout speed to
392 handle 1 MHz/cm^2 of electromagnetic background and
393 be radiation hard. The PbWO₄ crystal inner calorime-
394 ter of the CLAS detector [15], in operation since 2005
395 in Hall B, meets all the requirements set by HPS. The
396 modules from this calorimeter have been subsequently
397 repurposed for HPS.

398 5.1. Components

399 The ECal module shown in Figure 6 is based on a
400 tapered 160 mm long PbWO₄ crystal with a $13.3 \times$
401 13.3 mm^2 ($16 \times 16\text{ mm}^2$) front (rear) face wrapped in
402 VM2000 multilayer polymer mirror film. The scintilla-
403 tion light, approximately 3 photoelectrons/MeV, is read
404 out by a $5 \times 5\text{ mm}^2$ Hamamatsu S8664-55 Avalanche
405 Photodiode (APD) with 75% quantum efficiency glued
406 to the rear face surface using MeltMount 1.7 thermal
407 plastic adhesive. The low gain of APDs (~ 200) was
408 compensated with custom-made preamplifier boards,
409 which provide a factor of 2333 amplification of the APD
410 signal.

411 5.2. Layout

412 Similar to the SVT, the ECal is built in two separate
413 halves that are mirror reflections of one another about

414 the plane of the nominal electron beam to avoid inter-
415 fering with the 15 mrad “dead zone”. As shown in Fig-
416 ure 7, the 221 modules in each half, supported by alu-
417 minum support frames, are arranged in rectangular for-
418 mation with five layers and 46 crystals/layer except for
419 the layer closest to the beam where nine modules were
420 removed to allow a larger opening for the outgoing elec-
421 tron and photon beams. Each half was enclosed in a
422 temperature controlled box ($< 1^\circ\text{ F}$ stability and $< 4^\circ\text{ F}$
423 uniformity) to stabilize the crystal light yield and the op-
424 eration of the APDs and its preamplifiers. Four printed
425 circuit boards mounted on the backplane penetrated the
426 enclosure and were used to supply the $\pm 5\text{ V}$ operating
427 voltage for the preamplifiers, 400 V bias voltage to the
428 APDs, and to read out signals from the APDs. Each half
429 of the ECal was divided into 12 bias voltage groups with
430 a gain uniformity of about 20%.

431 During the HPS Test Run, both halves were held in
432 place by four vertical bars attached to a rail above, plac-
433 ing the front face of the crystals 147 cm from the up-
434 stream edge of the magnet, with a 8.7 cm gap between
435 the innermost edge of the crystals in the two halves.

436 5.3. Signal readout

437 After a 2:1 signal splitter, 1/3 of an amplified APD
438 signal was fed to a single channel of a JLab flash ADC
439 (FADC) board [16]. 2/3 of the signal was sent to a
440 discriminator module and then to a TDC for a timing
441 measurement. The FADC boards are high speed VXS
442 modules digitizing up to 16 APD signals at 250 MHz
443 and storing samples in $8\text{ }\mu\text{s}$ deep pipelines with 12-bit
444 resolution. When a trigger is received, the part of the
445 pipeline from 5 samples before and 30 after the signal
446 which crossed a programmable threshold (for the HPS
447 Test Run this was set to $\approx 70\text{ MeV}$) are summed and
448 stored in a 17-bit register for readout. In addition a
449 4 ns resolution timestamp of the threshold crossing is
450 reported in the readout for each pulse. This scheme

451 significantly compresses the data output of the FADC. 486
 452 During offline data analysis, a calibrated pedestal value 487
 453 is subtracted to obtain the actual summed energy. Two 488
 454 20-slot VXS crates with 14 (13) FADC boards were em- 489
 455 ployed in the HPS Test Run to read out the top (bottom) 490
 456 half of the ECal. In the HPS Test Run 385 out of 442 491
 457 modules (87%) were used in offline reconstruction, 39 492
 458 modules were disabled or not read out (no FADC chan- 493
 459 nel available, no APD bias voltage or masked out due 494
 460 to excessive noise) and 18 were masked offline due to 495
 461 noise.

462 6. Trigger and Data Acquisition

463 The DAQ system handles acquisition of data from the 486
 464 ECal and SVT sub-detectors with two DAQ architec- 487
 465 tures. The SVT DAQ is based on Advanced Telecom 488
 466 Communications Architecture (ATCA) hardware while 489
 467 the ECal uses VMEbus Switched Serial (VXS) based 490
 468 hardware. Data from the sub-detectors are only read 491
 469 out when a trigger signal from the trigger system is re- 492
 470 ceived.

471 6.1. Trigger system

472 The trigger system is designed to select time coinci- 505
 473 dences of electromagnetic clusters in the top and 506
 474 bottom halves of the ECal. Figure 8 shows a schematic 507
 475 overview of each stage of the system. Each channel on 508
 476 the FADC board has an independent data path to send 5- 509
 477 bit pulse energy and 3-bit pulse arrival time information 510
 478 every 32 ns to a trigger processing board (CTP), which 511
 479 is in the same crate. The 3-bit pulse arrival time allows 512
 480 the trigger to know the pulse timing at 4 ns resolution. 513
 481 Contrary to the readout path described in Sec. 5.3, this 514
 482 energy is a pedestal-subtracted time-over-threshold sum 515
 483 with programmable offsets and minimum threshold dis- 516
 484 criminator for each channel. With input from all FADC 517
 485 channels, i.e. one half of the ECal, the CTP performs

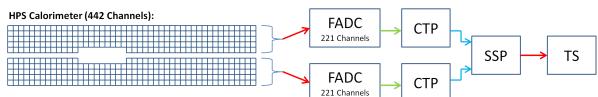


Figure 8: Block diagram of the ECAL trigger system consisting of the FADC that samples and digitizes signals for each detector channel and sends them for cluster finding in the CTP. The CTP clusters are sent to the SSP where the final trigger decision is taken based on pairs of clusters in both halves of the ECal. The decision is sent to the Trigger Supervisor (TS) that generates the necessary signals to read out the sub-detectors.

486 cluster finding and calculates cluster energy and tim- 487
 487 ing information. The 3x3 fixed-window, highly parallel, 488
 488 FPGA-based cluster algorithm simultaneously searches 489
 489 for up to 125 clusters with energy sum larger than the 490
 490 programmable energy threshold (≈ 270 MeV). Crystals 491
 491 in the fixed-window are included in the sum if the lead- 492
 492 ing edge of the pulse occurred within a 32 ns time win- 493
 493 dow to take into account clock skew and jitter through- 494
 494 out the system. The CTP only accepts clusters with the 495
 495 locally highest energy 3x3 window to deal with over- 496
 496 lapping and very large clusters. The sub-system board 497
 497 (SSP) receives the clusters from the top and bottom half 498
 498 CTP at a maximum of 250MHz and searches for pairs 499
 499 of clusters in an 8 ns wide coincidence window. The 500
 500 SSP sends triggers to the trigger supervisor (TS), which 501
 501 generates all the necessary signals and controls the en- 502
 502 tire DAQ system readout through the trigger interface 503
 503 units installed in every crate that participate in the 504
 504 readout process.

505 The trigger system is free-running and driven by the 505
 506 250 MHz global clock and has essentially zero dead 506
 507 time at the occupancies expected for HPS. The trigger 507
 508 supervisor can apply dead time if necessary, for exam- 508
 509 ple on a ‘busy’ or ‘full’ condition from the front-end 509
 510 electronics. The system is designed to handle trigger 510
 511 rates above 50 kHz and has a latency set to $\approx 3 \mu\text{s}$ to 511
 512 match that required by the SVT APV25 ASIC. During 512
 513 the HPS Test Run, for the most part the trigger system 513
 514 required only a single cluster in either the top or bot- 514
 515 tom Ecal halves and was tested to trigger rates above 515
 516 100 kHz by lowering thresholds.

517 6.2. SVT Data Acquisition

518 The SVT DAQ is based on the Reconfigurable Clus- 518
 519 ter Element (RCE) and cluster interconnect concept 519
 520 developed at SLAC as generic building blocks for DAQ 520
 521 systems. The RCE is a generic computational build- 521
 522 ing block, housed on a separate daughter card called 522
 523 Data Processing Module (DPM), that is realized on an 523
 524 ATCA front board called the Cluster On Board (COB), 524
 525 see Figure 9. The first generation RCE used in the HPS 525
 526 Test Run consisted of a Virtex 5 FPGA with 1 GB of 526
 527 DDR3 RAM. A schematic overview of the system is 527
 528 shown in Figure 10. The analog outputs of up to 12 528
 529 SVT half-modules (60 APV25 ASICs) are digitized on 529
 530 the Rear-Transition-Module (RTM), a custom board on 530
 531 the back side of the ATCA crate, interfacing the HPS- 531
 532 specific readout to the generic DAQ components on the 532
 533 COB. A pre-amplifier converts the APV25 differential 533
 534 current output to a different voltage output scaled to the 534
 535 sensitive range of a 14-bit ADC operating at the system 535
 536 clock of 41.667 MHz. The RTM is organized into four



Figure 9: The SVT DAQ COB board with four data processing daughter cards (DPMs) visible on the left side.

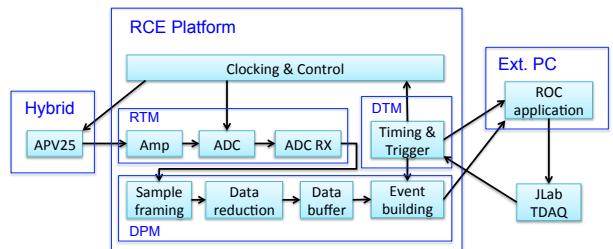


Figure 10: Block diagram overview of the SVT DAQ.

sections with each section supporting three SVT half-module hybrids (15 APV25 ASICs). The RTM also includes a 4-channel fiber-optic module and supporting logic which is used to interface to the JLab trigger system supervisor. Each section of the RTM is input to a DPM which applies thresholds for data reduction and organizes the sample data into UDP datagrams. The DPM also hosts an I²C controller used to configure and monitor the APV25 ASICs. A single ATCA crate with two COB cards was used, one supporting four DPMs and one supporting three DPMs and one DPM that is configured as the trigger and data transmission module. The two COB cards and their DPMs are interconnected with a 10 Gb/s switch card [17] which also hosts two 1Gb/s Ethernet interfaces to the external SVT DAQ PC.

The external PC supports three network interfaces: two standard 1 Gb/s Ethernet and one custom low-latency data reception card. The first is used for slow control and monitoring of the 8 DPM modules and the second serves as the interface to the JLAB data acquisition system. The third custom low-latency network interface is used to receive data from the ATCA crate and supports a low latency, reliable TTL trigger acknowledge interface to the trigger DPM. This PC hosts the SVT control and monitoring software as well as the Read Out Controller application used to interface with

the JLab DAQ.

In order to minimize cable length for the analog APV25 output signal the ATCA crate was located approximately 1 m from the beam line, next to our cable vacuum feed-throughs. Before shielding with lead-blankets was arranged, we observed two failures of normally reliable ATCA crate power supplies, time-correlated to beam instabilities.

Although trigger rates during the HPS Test Run were significantly lower, this system was tested at trigger rates up to 20 kHz and 50 MB/s. With optimized event blocking and improved ethernet bandwidth, together with utilizing the overlapping readout and trigger functionality of the APV25, the system is capable of being read out at 50 kHz trigger rate.

6.3. General Data Acquisition and Online Computing

Every crate participating in the readout process contains a Readout Controller (ROC) that collects digitized information, processes it, and sends it on to the event builder. For the ECal, both VXS crates run ROC applications in a single blade Intel-based CPU module running CentOS Linux OS. For the SVT DAQ, the ROC application runs on the external PC under RHEL. The event builder assembles information from the ROCs into a single event which is passed to the event recorder that writes it to a RAID5-based data storage system capable of handling up to 100 MB/s. The event builder and other critical components run on multicore Intel-based multi-CPU servers. The DAQ network system is a network router providing 10 Gb/s high-speed connection to the JLab computing facility for long-term storage. For the HPS Test Run, both the SVT and ECal ROC had a 1 Gb/s link to the network router.

7. Reconstruction and Performance

7.1. SVT Performance

For the duration of the HPS Test Run all SVT modules and APV25 chips were configured to their nominal operating points [18] with all sensors reverse-biased at 180 V. The sensors were operated within a temperature range of 20 – 24°C. Approximately 97% of the 12,780 SVT channels were found to be operating normally; the fraction of dead or noisy channels varied from 2.4% to 4.7% throughout the HPS Test Run. Most of these losses were due to 2-4 misconfigured APV25 ASICs, a known noisy half-module and problems in two particular APV25 ASICs.

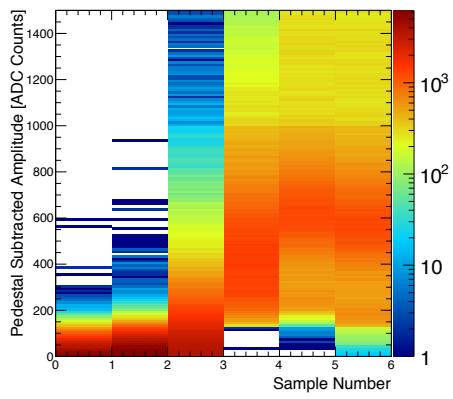


Figure 11: Accumulation of six pedestal-subtracted samples from individual SVT channels associated with hits on tracks.

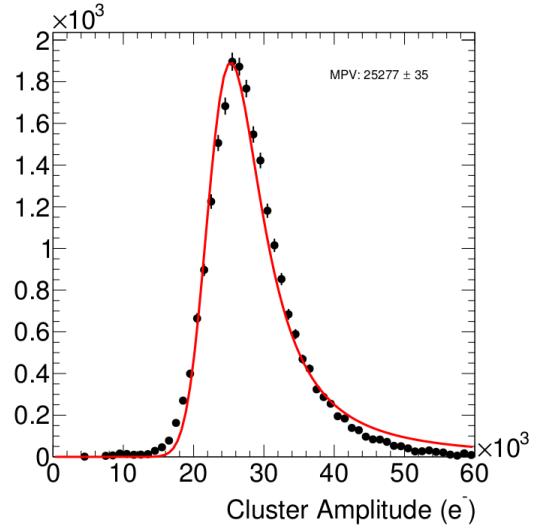


Figure 12: The cluster charge distribution for hits associated with a track follow the characteristic Landau shape.

7.1.1. Cluster and Hit Reconstruction

After a trigger is received, the amplitude of every APV25 analogue output is sampled and digitized in six consecutive time bins, separated by roughly 25 ns. A data reduction algorithm is applied requiring three out of six samples to be above two times the noise level and that the third sample is larger than the second or that the fourth sample is larger than the third. The typical, pedestal subtracted, pulse shape obtained is shown in Figure 11. As the figure demonstrates, the SVT was well timed-in to the trigger with the rise of the pulse at the 3rd sampling point. In order to find the time, t_0 , and amplitude of each hit, the six samples from each channel are fitted to an ideal $CR - RC$ function. Note that in the HPS Test Run the APV25 ASICs were operating with a 50 ns shaping time. These hits are passed through a simple clustering algorithm which forms clusters by grouping adjacent strips with the position of a cluster on the sensor determined by the amplitude-weighted mean. With a linear gain up to ≈ 3 MIPs, the cluster charge for hits associated with a track follow the characteristic Landau shape, see Figure 12. A noise level between $1.1 - 1.5 \times 10^3$ electrons was established through multiple calibration runs giving a signal to noise ratio of 21 – 25. Lab-based radioactive source tests were used to provide the absolute charge normalization. After clustering hits on a sensor, the hit time for each cluster is computed as the amplitude-weighted average of the individually fitted t_0 on each channel. The t_0 resolution is studied by comparing the cluster hit time with the average of all cluster hit times on the track shown in Figure 13. After correcting for offsets from each sensor (time-of-flight and clock phase) and accounting for the correlation be-

tween the t_0 and track time, the extracted t_0 resolution is 2.6 ns. This is somewhat worse than the approximately 2 ns resolution expected for S/N=25 which we attribute to the true pulse shape differing from our idealized fit function which will be improved in the future. Reducing the APV25 ASIC pulse shaping time to 35 ns will also improve time resolution. These results show that we can operate with the six sample readout mode of the APV25 chip and achieve time resolution adequate for pileup rejection during electron running in HPS.

Good agreement was obtained between observed and simulated occupancies after taking into account dead or noisy channels. The hit reconstruction efficiency was estimated by measuring the number of good tracks with a hit close to the extrapolated intersection of a given sensor that was excluded from the track fit itself. Tracks which intersect regions with known bad channels or pass very close to the edge region are excluded. The hit reconstruction efficiency, see Figure 14, was measured to be above 98% and fairly uniform across the SVT.

The spatial resolution of similar microstrip sensors is well established by test beam data, against which the charge deposition model in the simulation is validated. This resolution can be parameterized as a function of the total signal to single-strip noise and the crossing angle of tracks through the sensor. The single-hit resolution for charged particles with signal-to-noise ratio above 20, as demonstrated here, is relatively constant at approximately $6 \mu\text{m}$ for tracks that enter approximately normal to the sensors as in HPS.

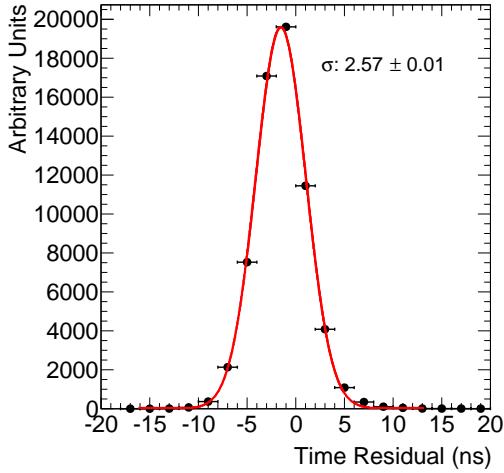


Figure 13: The residual of individual cluster times with the average of all clusters on the track.

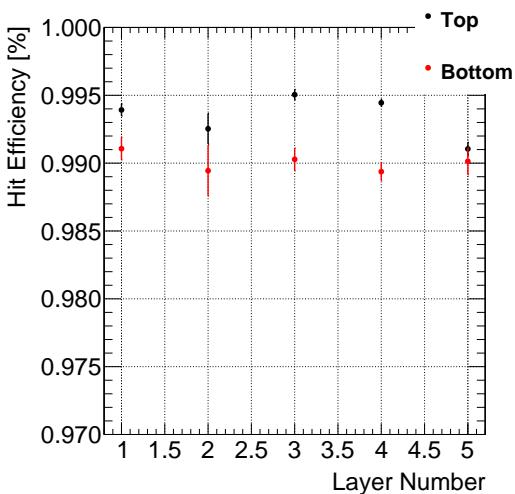


Figure 14: The hit reconstruction efficiency as a function of detector layer.

672 7.1.2. Momentum and Vertexing Resolution

673 By selecting e^+e^- pairs from the triggered events we
 674 are able to study basic distributions of pair production
 675 kinematics. Pairs of oppositely charged tracks, one in
 676 the top and one in the bottom half of the SVT, with
 677 momentum larger than 400 MeV were selected. The pair
 678 production kinematics are relatively well reproduced as
 679 shown in Figure 15.

680 The expected momentum resolution from simulation
 681 is between 4-5% for tracks in the momentum range of
 682 the HPS Test Run. By comparing, between data and
 683 simulation, the shapes of the kinematic distributions for
 684 single- and two-track events, we estimate an agreement
 685 with the nominal scale and resolution to within 10%.

686
 687 In the HPS Test Run, as well as in electron running with
 688 HPS, the dominant source of uncertainty in the track-
 689 ing and vertexing is multiple Coulomb scattering. For
 690 the vertexing performance the foremost difference com-
 691 pared to electron beam running is that the target was
 692 located approximately 67 cm upstream from our nomi-
 693 nal target position; giving almost collinear tracks in the
 694 detector. The increased lever arm over which tracks are
 695 extrapolated widens the resolution with up to a factor
 696 of eight (depending on momentum) compared to what
 697 is achieved at the nominal electron target position for
 698 HPS. Figure 16 shows the horizontal and vertical po-
 699 sitions of the extrapolated track at the converter pos-
 700 ition. While residual alignments show small shifts, the
 701 good agreement between data and simulated events of
 702 the widths indicates a good understanding of the ma-
 703 terial budget and distribution in the SVT. Having the
 704 dominant contribution to the vertex resolution approx-
 705 imately right demonstrates that the resolution in HPS,
 706 with a target at 10 cm, will be as calculated.

707 7.2. ECal Performance

708 The integrated pulse of each FADC channel was con-
 709 verted to energy by subtracting a pedestal and applying
 710 a conversion factor to convert ADC counts to energy.
 711 The pedestals are measured using special runs where
 712 each trigger records 100 samples of signals from the
 713 APDs with 4 ns between each sample. The pedestals
 714 were extracted from the part of the window before the
 715 actual hit in the calorimeter. Modules with signal above
 716 the threshold are clustered using a simple algorithm
 717 similar to the one deployed for the trigger (see Sec. 6.1).
 718 Due to the high effective readout threshold of 73 MeV
 719 the average number of crystals in a cluster was ~ 3 and
 720 the simple clustering algorithm worked well for recon-
 721 struction of the detected shower energy. An average

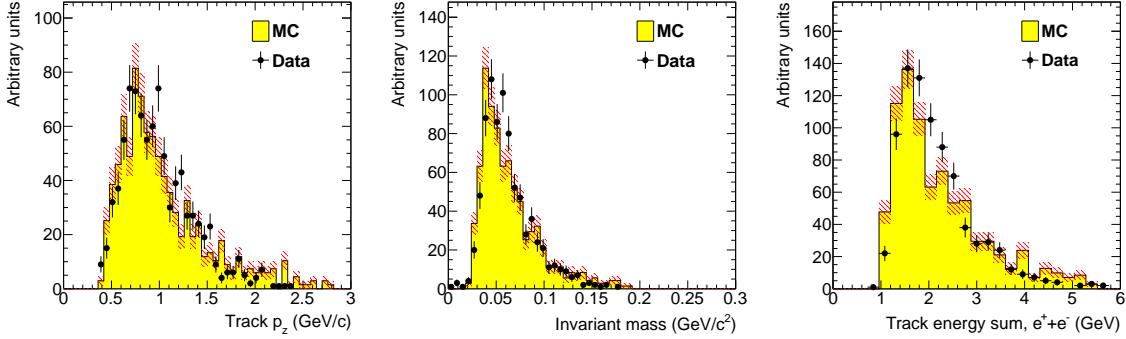


Figure 15: Kinematic distributions for $e^+ e^-$ pairs selected by opposite charged tracks in the top and bottom half of the tracker: track momentum in the top half of the SVT (left), invariant mass (middle) and the sum of the track energy for the pair (right).

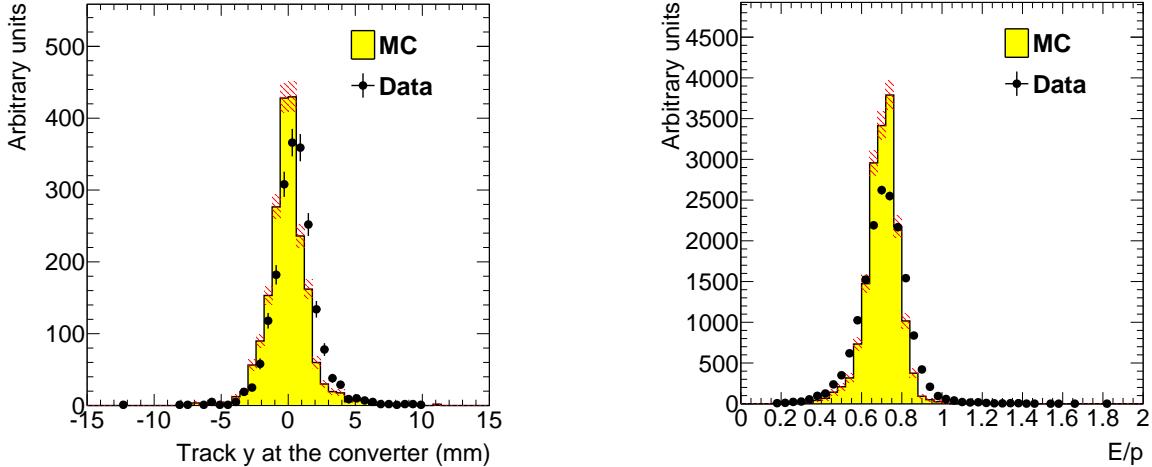


Figure 16: Vertical (top) and horizontal (bottom) extrapolated track position at the converter taking into account the measured fringe field.

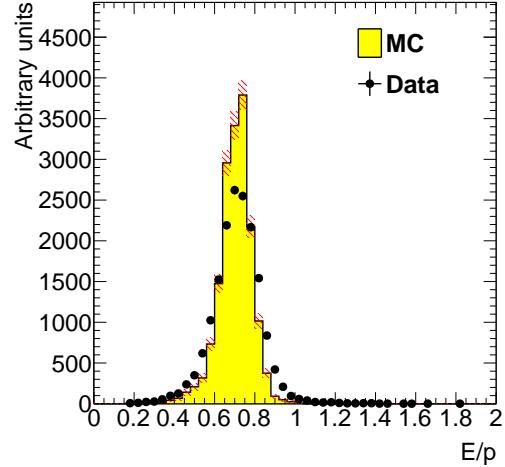


Figure 17: The ECal energy over track momentum ratio (E/p) comparing data and simulation for single cluster triggers in the top half of the ECal.

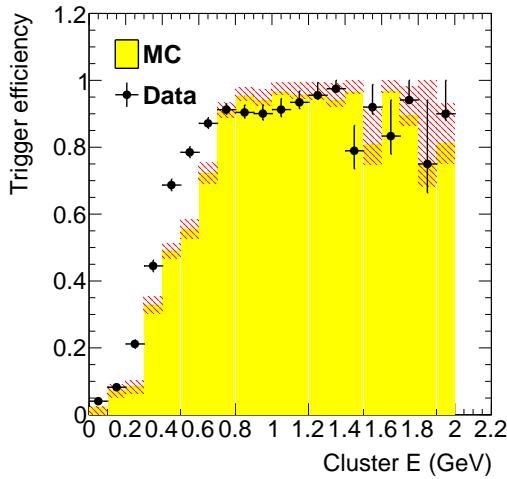
noise level of approximately 15 MeV was measured in special pedestal runs.

The ratio of the ECal cluster energy E to the momentum p of a matched track in the SVT was used to determine the conversion factors from ADC counts to energy. To compare data and simulation, all inoperable or noisy channels in the SVT and ECal were disabled in both data and simulation so that any efficiency or bias that affect the data should be reflected in the simulation. Iteratively, conversion coefficients for each crystal were adjusted until the E/p ratio in data and simulation were similar. The distribution of the E/p ratio in data and simulation are compared in Figure 17. The peak position of the distribution indicates the sampling fraction

736 of the ECal, the fraction of the incident particle energy
 737 measured in the cluster. The width and tails of the distribution
 738 in data indicates imperfect calibration and noise
 739 of the ECal modules. This level of calibration and the
 740 agreement with simulation was found to be sufficient to
 741 study normalized event rates in the HPS Test Run.

742 7.3. Trigger Performance

743 As described above in Sec. 6, the energy from each
 744 crystal is measured differently in the trigger and what
 745 is readout from the ECal. The trigger performance
 746 was studied by simulating the trigger for each event
 747 and comparing to how the events were actually trig-
 748 gered. To eliminate trigger bias, we use a tag and probe
 749 method: to study the trigger performance in one half
 750 of the ECal, we select events which triggered the other
 751 half and where there was exactly one probe cluster in
 752 the ECal half under study. We then measure trigger ef-
 753 ficiency as the fraction of tagged events that fired the
 754 trigger in the probe half as a function of the probe clus-
 755 ter energy, shown in Figure 18. The trigger turn-on is



756 Figure 18: Trigger efficiency in both halves of the ECal for data and
 757 simulation as a function of cluster energy.

758 slow and reaches an uneven plateau just below 1 GeV
 759 for two reasons; gain variations between different crys-
 760 tals lead to the threshold variations and the nonlinearity
 761 of the time-over-threshold integral means that the effec-
 762 tive threshold is higher for clusters that span multiple
 763 crystals. The effective trigger threshold is therefore de-
 764 pendent on position and energy of the particle as well as
 765 cluster multiplicity.

Converter (% X_0)	1.60	0.45	0.18
EGS5	1162 ± 112	255 ± 28	94 ± 17
GEANT4	2633 ± 250	371 ± 38	114 ± 18
Observed	1064 ± 2	196 ± 1	92 ± 1

766 Table 4: Observed and predicted event rate (in Hz) normalized to
 767 90 nA for three different converter thicknesses. The uncertainty on
 768 the prediction includes systematic uncertainties from ECal alignment,
 769 background normalization, beam current normalization and limited
 770 statistics in the simulation.

771 As a cross-check we simulate the FADC trigger path
 772 by converting from readout hits (with fixed-size win-
 773 dow integration) to trigger hits (time-over-threshold in-
 774 tegration). The CTP clustering algorithm and the trigger
 775 decision from the SSP are simulated before we com-
 776 pare the trigger decision and trigger time to what was
 777 reported by the actual trigger. For every event, the trig-
 778 ger reports the trigger decision as a bit mask (top half,
 779 bottom half or both) and the time the trigger fired. The
 780 turn-on from the trigger threshold was measured to be
 781 1280 in units of ADC counts as expected. The threshold
 782 was not perfectly sharp because of uncertainties in the
 783 conversion from readout to trigger hits described above,
 784 but based on comparisons with simulation we found that
 785 the trigger worked exactly as specified.

786 7.4. Trigger Rate Comparisons

787 Trigger rates observed in the HPS Test Run are dom-
 788 inated by multiple Coulomb scattered e^+e^- pairs in the
 789 converter. In simulated events, the rate of triggers de-
 790 pend on the modeling of the pairs' angular distribution
 791 and the subsequent multiple Coulomb scattering in the
 792 converter. Rates from different converter thicknesses
 793 are used to study the varying multiple Coulomb scat-
 794 tering contribution (pair production angle is constant).
 795 Restricting clusters to a well calibrated region of the
 796 ECal and subtracting the "no converter" background we
 797 see agreement with the rates predicted by the EGS5 sim-
 798 ulation program, see Table 7.4. This gives further con-
 799 fidence that the dominant source of background occu-
 800 pancy for HPS, multiple Coulomb scattered beam elec-
 801 trons, is well described [19, 20, 21].

8. Summary and Outlook

802 The HPS Test Run experiment, using a simplified
 803 version of the apparatus planned for the full HPS ex-
 804 periment in a parasitic photon beam, demonstrated the
 805 feasibility of the detector technologies proposed for
 806 the silicon vertex tracker, electromagnetic calorimeter,
 807 and data acquisition systems. Performance from each

802 of these subsystems has been shown to be adequate
 803 to conduct the full experiment successfully. Studies
 804 of multiple Coulomb scattering tails of electrons and
 805 positrons from photon conversions further backs expec-
 806 tations from simulation, giving credence to estimates
 807 of the detector backgrounds expected in electron beam
 808 running for HPS.

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 815 of operating CEBAF6. The tremendous support from
 816 home institutions and supporting staff also needs praise
 817 from the authors.

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