HPS Physics Readiness

HPS Collaboration

(Dated: November 6, 2015)

I. INTRODUCTION

The Heavy Photon Search Experiment successfully installed, commissioned, and ran in Hall B at the Thomas Jefferson National Accelerator Facility during CEBAF's 2015 Spring Run. The ECal, trigger, and data acquisition systems had already been successfully commissioned during a brief run in December 2014. It remained to install the Silicon Tracker (SVT), which was completed at the end of February 2015, integrate its data acquisition system with that of the experiment as a whole, and commission the whole experiment with beams. This was accomplished during March 2015, while the Hall B beamline was also being commissioned with 2 GeV electrons. Progress was interrupted when a site wide power failure occurred March 25. The consequent loss of the CHLs delayed CEBAF operations until April 19, when CEBAF operations were restored with a single CHL and 1 GeV beams were delivered to Hall B. Calibration of Hall B BPMs, careful optics matching with the accelerator, and implementation of beamline setup procedures allowed efficient HPS running on nights and weekends, with weekdays going to CLAS 12 torus installation. HPS ran until May 18 thanks to a two week extension granted by the lab. This extension led to the first HPS data taking with a fully functioning detector, design spec beams, design currents, and trigger and data rates, and the SVT in design position, just 0.5 mm from the beams. All aspects of the experiment worked very well and in the end roughly 2 PAC days of 1 GeV data were taken at the 0.5 mm setting. The engineering run was a great success.

The HPS Experiment was originally proposed to PAC37, which approved it (C2) in 2010 for 180 days, contingent upon a successful Test Run. PAC39, which met soon after the conclusion of the HPS Test Run Experiment in Spring 2012, awarded HPS a scientific rating of "A" and granted HPS C1 approval, leaving final approvals in the hands of JLAB management. In Summer 2013, HPS proposed the full experiment to DOE, which reviewed and funded it. This review also served as JLAB management's de facto review of the experiment. HPS addressed the reviewers' comments and recommendations in a report to DOE HEP and JLAB in Spring 2014. The same document requested formal JLAB approval, leading to JLAB management awarding 25 PAC days to HPS for an Engineering Run in 2014-2015. Management asked to see performance demonstrations from the experiment before granting additional time. Later in Spring 2014, PAC 41 listed HPS among JLAB's "high impact" experiments, noting that it was extremely timely and should be executed ASAP, and granted it 25 PAC days for commissioning and running at 2.2 GeV and an additional 14 PAC days for running at 4.4 GeV. After taking into account the roughly 10 PAC days utilized during the Spring 2015 Engineering Run, HPS still has 15 PAC days remaining. HPS is tentatively scheduled during the opportunistic physics running in the Spring of 2016, subject to available beams from CEBAF and non-interference with CLAS12 construction in Hall B.

The purpose of this document is twofold. First, in response to management's request for performance demonstrations, it will review the performance achieved during the 2015 Engineering Run, and demonstrate that HPS is fully ready to take, process, and analyze high quality physics data. The status of each of the HPS subsystems are discussed in the following sections: Beamline, ECal and Trigger, Silicon Tracker, and Data Taking and Processing. HPS physics performance is also demonstrated. Second, based on the performance it has demonstrated, HPS includes here its request for full and unconditional approval and asks it be granted the remainder of its 180 PAC days.

II. BEAMLINE PERFORMANCE

The beamline for the HPS Engineering Run was configured according to the design presented in the proposal [1]. The whole system worked as expected right from the start. A few changes were made after the commissioning run in November-December 2014 to address issues such as beam skewness and stability, which, in the end, were not present during the main part of the Spring run when Hall-B was the only hall to run. Beam for the run was made available during swing and graveyard shifts during the week and over weekends, requiring that it be restored to the Hall and quality beam delivered to the HPS target almost daily. Once BPM calibrations were completed by the end of April 2015 and sound procedures for restoring beams were established, the time to set up a high quality beam was shortened to about 2 - 3 hours. During beam restoration, the Hall-B wire scans were used to monitor beam position and the profile at different locations. The beam profile at the harp closest to the target (actually 234 cm upstream), called 2H02A, was the best monitor of whether the beam was acceptable. In Figure 1, the beam position (top) and the beam width (bottom) are shown in both the horizontal (X) and vertical (Y) directions. The position reproducibility was better than 50 μm. The Y-width, the critical parameter for bringing the SVT close to the beam, was better than 60 μm, well within specifications.

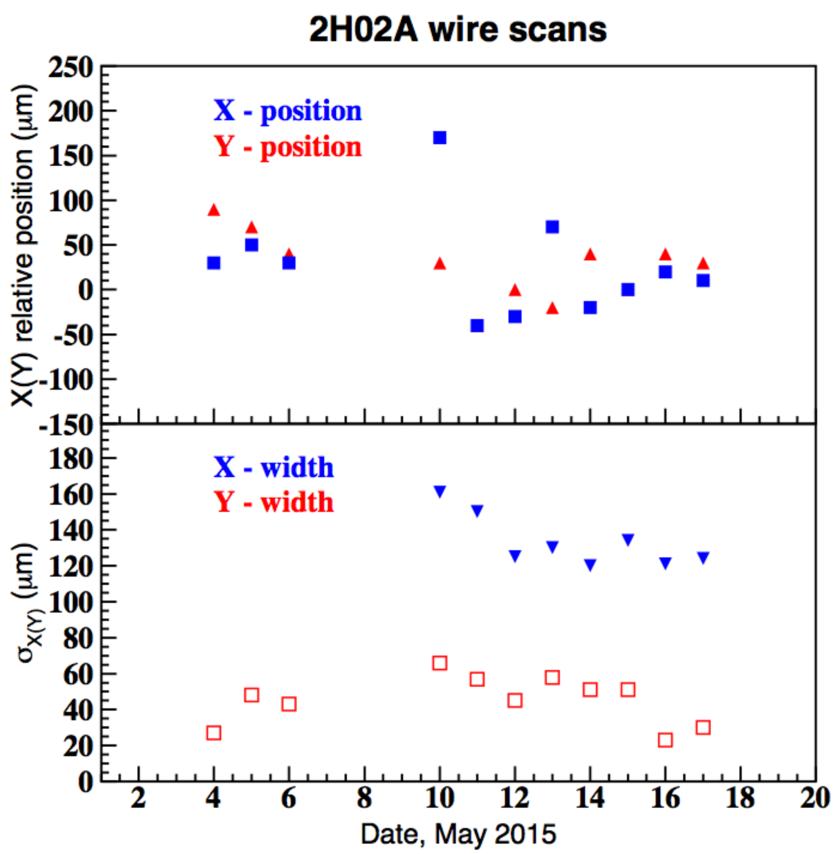

FIG. 1: The horizontal and vertical beam positions (top) and widths (bottom) as measured on 2H02A wire harp, mounted 234 cm upstream of the HPS target, after establishing the production beam during the HPS engineering run in May 2015.

It was possible to run the SVT Layer 1 at its proposed position, just 0.5 mm away from the beam plane, because of the excellent beam properties: remarkably reproducible beam profile (very close to the optics design), essentially absent beam tails, and stable beam positions.

In the end, using calibrated Beam Position Monitors (BPMs) and a feedback system that controls the beam motion at Hz level, beam position stability at the target was on the order of the beam width, $\sigma \sim 50$ μm. As a precaution, we inserted the SVT protection collimator, a 10 mm thick tungsten block with 3×10 mm^2 hole, to protect from any accidental beam motion or irregularities in the beam setup. Prior to bringing the SVT close to the beam plane, we looked for short-term beam excursions during trips and recovery with a specially designed system. Studies were done by moving the harp wire or collimator edge close to the beam and recording a time history of count rates in the downstream halo counters and the calorimeter within 15 μsec bins. Any beam motion towards the obstacle will markedly increase the count rates. No significant rate increases were observed in multiple beam trips and recoveries. In addition to the collimator and the feedback system based on BPMs, the beam Fast Shutdown (FSD) system was deployed using the beam halo counters that could interrupt beam delivery within 5 ms if the rates in halo counters exceeded a fixed threshold. This level of protection proved to be adequate to run the experiment safely at its design conditions - 50 nA, 1 GeV beam on 4 μm tungsten target.

III. ECAL AND TRIGGER PERFORMANCE

As described in our proposal to JLab management [2], several improvements and additions were made to the electromagnetic calorimeter (ECal) after the first test run in 2012 . The key improvements that made significant impact on ECal performance were: 1) new large area (10x10 mm2) APDs, Hamamatsu S8664-1010; 2) LED based light monitoring system; 3) new, improved amplifiers and motherboards; 4) a flexible mounting system.

The ECal was installed, surveyed, and connected to electronics in the hall in October 2014. It was initially calibrated in situ using transversely penetrating cosmic muons. This allowed gains to be matched to the few % level. This was possible because the new APDs and low noise amplifiers allowed reliable measurements of the very low energy deposited by the cosmics, just ~ 18 MeV. Calibration at this level provided a reliable trigger on day one of our data taking. In both runs, November-December 2014 and April-May 2015, all 442 channels of the ECal worked as intended. Data at two beam energies, 2 GeV and 1 GeV, were taken at the proposed luminosities. Rates in individual counters were as expected from simulations. For the crystals closest to the beam this rate was ~ 1.3 MHz. No degradation of the ECal performance has been observed after exposure to radiation. Pedestals do show a dependence on rate, but this has been taken care of in on-line/off-line software.

A study of Coulomb scattered beam electrons using the cosmics calibration gives the energy resolution as $\sigma_E/E = 5\%/\sqrt{E}$. Further refinement of the gains using these same electrons improved the energy resolution and in regions that exclude the calorimeter edges it is 4%, in comparison to 3.6% expected from simulation, see Figure 2 (top). The entire pulse wave form is readout by the FADC for each crystal, allowing the start time of the signal to be extracted with high precision. This procedure gives ~ 0.3 ns time resolution for individual modules, as shown by the bottom plot in Figure 2. After corrections for small channel-to-channel time offsets, this excellent resolution lets us apply tight timing cuts in the cluster reconstruction algorithm and in the cluster pair selection, thus avoiding out of time accidentals.

The total trigger rate for running with 50 nA electron beam on 4 μm W target was 18 kHz with 12% dead time, 90% of which was from our primary A′ trigger. This rate is in good agreement with expectations. The trigger starts with a 3×3 clustering algorithm in the Crate Trigger Processor (CTP) which requires hits in good time coincidence, a cluster seed energy above threshold, and computes the total cluster energy and time. The singles triggers allow cuts on the number of hits per cluster and cluster energy. The pairs triggers add cuts on the two-cluster energy sum and difference, geometric co-planarity, and a "transverse energy" requirement. The firmware allows four simultaneous physics triggers (two singles and two pairs) plus a random trigger. For production running, we use cuts optimized for A′ selection without prescaling, which are based on real random triggers and trigger simulations. The other 4 triggers were configured to support trigger diagnostics and calibration reactions (e.g. elastics) with appropriate rates. The two singles triggers were prescaled by 2^{13} and 2^{11}, and an additional loose pair trigger by 2^{11}. Random triggers were taken at a rate of 100 Hz. Trigger efficiency was studied by including diagnostics information from the Sub-System Processor (SSP) in the data stream. This included the raw Ecal cluster data and a record of which clusters passed each trigger cut. Comparison of this data with the normal calorimeter readout for actual triggers, online and event-by-event, shows excellent agreement, better than 1%. We also measured the dead time online by counting the random trigger pulser in an ungated scaler, and one which was gated off when the DAQ was busy. This was repeated

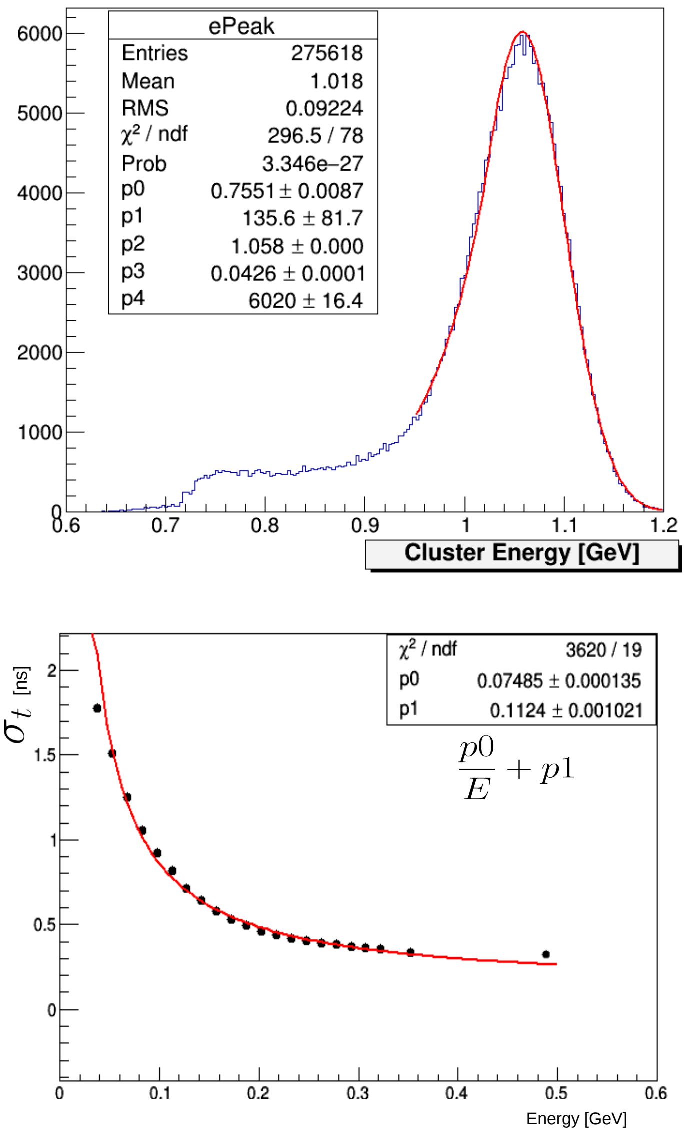

FIG. 2: Reconstructed energy of Coulomb scattered electrons in ECal (top). The energy resolution after the first pass calibration using Coulomb scattered electrons is $\sim 4.2\%$. Single channel time resolution as a function of detected energy (bottom).

with the scaler readout of the Faraday cup in the Hall-B beam dump. The two methods agree very well and give a stable dead time of 12%. A screenshot from the online monitoring display in Figure 3 shows gated and -ungated trigger rates, and pre-scaled rates, for each trigger type. Livetime and beam current are also shown. It includes a strip chart to aid visual monitoring.

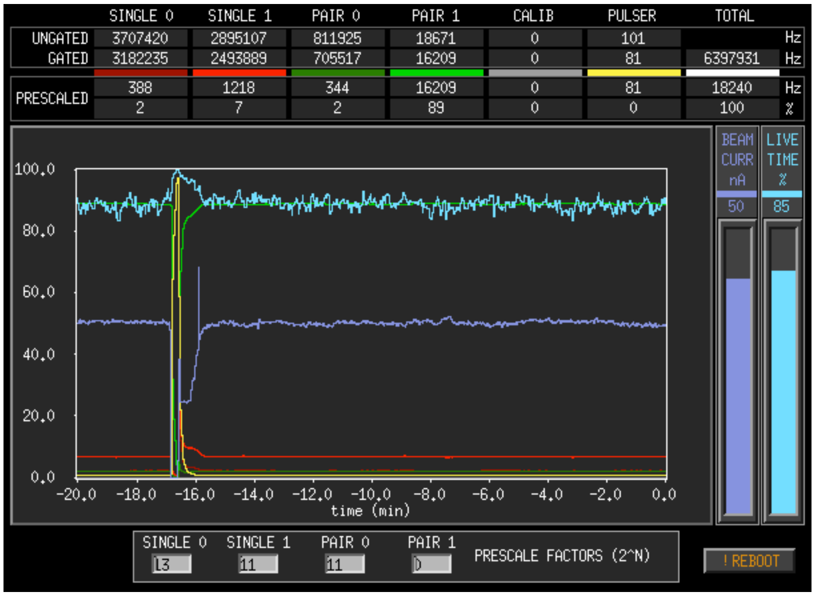

FIG. 3: Online monitoring tool for trigger and DAQ.

IV. SVT AND SVT DAQ STATUS

HPS gets good low mass acceptance for heavy photons by positioning the layer one detectors of the Silicon Vertex Tracker (SVT) a scant 500 μm from the beam. Studies described above in Section II demonstrated that the beam spot was small enough, the beam position stable enough, and the beam tails low enough to make this possible. Positioning is accomplished with the help of precision linear shifts, which raise or lower the first three layers of the SVT to within 15 mrad of the beam direction. When beam conditions warrant, the detector is moved into place; when a beam trip or excessive halo counter noise (indicating beam motion) occurs, the SVT bias voltage is turned off, and the detector is retracted to a safe position. Once good beams are restored, the bias voltage is turned up and the detector moved back into place. Trips are rare enough that little luminosity is lost with this procedure.

Data from the SVT in the running configuration showed maximum occupancies on the innermost strips of about 1%, just as simulation had predicted. The silicon microstrip detectors performed as expected, with S/N $\sim$ 25, timing resolution $\sim$ 2 ns, essentially perfect efficiency, and only a few dead channels out of a total of 23,004 in the system. Small increases in noise in the innermost layers occurred over the course of the run as the detector was irradiated, in line with expectation and without negative impact. The SVT alignment, which a pre-run survey showed to be within $\sim 100\ \mu$m of design targets, has been refined with beam-based alignment and the alignment program Millepede, and is already adequate to demonstrate good physics performance. Further refinements are being made which will improve precision and accuracy. Scattered 1 GeV beam electrons constitute most of the observed tracks; they can be extrapolated upstream to the target and downstream to the Ecal front face with about $\sim 100\ \mu$m and 1 mm resolution respectively, as expected. As shown in Figure 5, using the latest round of alignment corrections, the SVT momentum scale is accurate to $\sim 1\%$, and the (multiple scattering limited) momentum resolution using a Kalman-style fitter is $\sigma_p/p = 6.7\%$, within 10% of design. The momentum resolution will be proportionately better when higher energy beams are used.

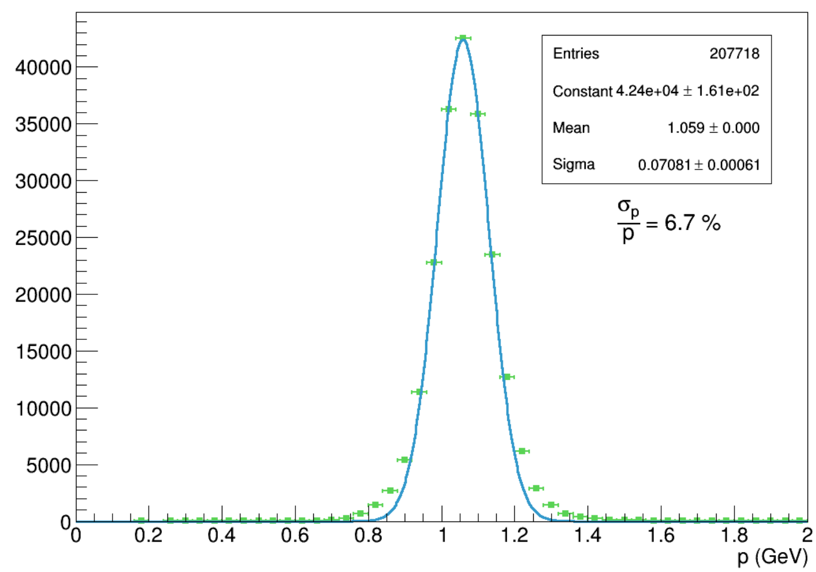

FIG. 4: Distribution of measured momenta for Coulomb scattered full energy electrons.

Several tracking refinements have already been incorporated in the reconstruction software: an accurate fringe field map (needed to extrapolate tracks accurately to the ECal and target); beam-based silicon detector alignment constants; and the Kalman Style track fitter (Generalized Broken Line or GBL) mentioned above. Tracking efficiency is presently at the 95% level/track, which is more than adequate for the physics, and is expected to improve further. Elastic beam electron-target electron scatters (Moller events) provide good checks of SVT performance.

HPS relies on both good invariant mass resolution and excellent vertexing capability in its search for heavy photons. The Moller invariant mass peak, shown in Figure 5 (top), demonstrates that tracking resolution is already very good. The mass resolution is within 20% of design and the mass scale offset within 3%. The vertexing resolution of the SVT is shown in Fig. 5b. The width of the Gaussian core of the vertex position distribution is within 10% of the Monte Carlo simulations, and the fraction of events in the non-Gaussian tail of the distribution,which constitutes the main background in the vertexing search, closely agrees with Monte Carlo simulations.

All in all, the SVT is operating reliably in its design location, efficiently taking data, and already demonstrating performance adequate for physics measurements.

The SVT DAQ also performed well. Full readout and integration of the SVT with the rest of HPS were achieved just before the power outage by late March. Once beams were restored, the SVT could be timed in and first tracks seen. Initial running of the SVT was in "safe" position, with layer 1 a full millimeter beyond the nominal position 500 μm from the beams. This was still adequate to see tracks and even get some physics acceptance. Once the final beam stability studies had been completed, the SVT was moved into its nominal 0.5 mm running position. It first began taking "real" data at trigger rates of 10-15 kHz. The SVT DAQ handled these rates, but incurred rather large dead times, in the 15-20% range, owing to fixed dead times associated with readout of the SVT front end chips. The event sizes of roughly 6 kB/event were larger than had been anticipated, further stressing data transfers and exacerbating storage requirements, and resulting in general DAQ trips from time to time. Two changes improved the SVT DAQ performance. First, the SVT timing was slightly changed to correct a small inefficiency coming from late arriving hits. Second, and more significantly, event buffering in the SVT front end readout chip was implemented, which allowed up to 4 triggers to be sent in close succession before a dead time penalty was imposed at the trigger supervisor level. With this new buffering scheme, the SVT DAQ handled trigger rates up to the 20 kHz level with only 10-15% dead time. The higher trigger rate capability let us relax some of the trigger cuts, thereby increasing trident acceptance. While the present data transfer rates are already adequate for running HPS, additional improvements have been made which provide another factor of two head room, and bring the trigger rate capability of the SVT up to its design value of about 50

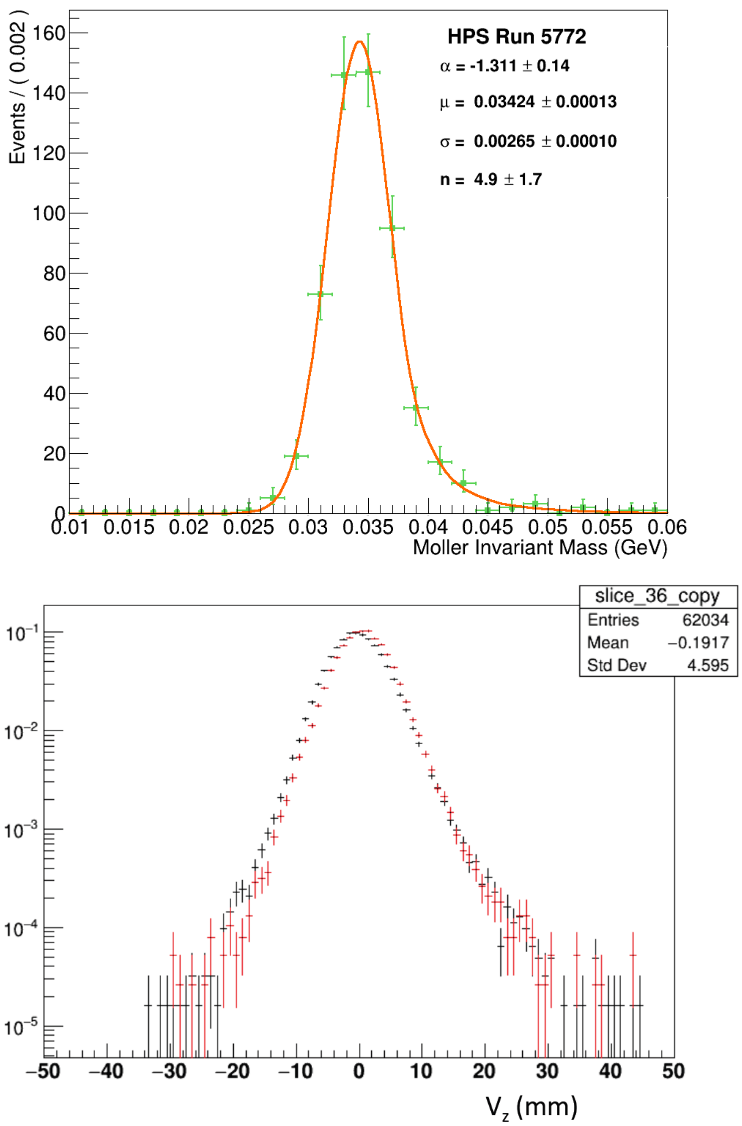

FIG. 5: The invariant mass peak from Moller electrons (top). The distribution of the vertex positions from e^+e^- pairs along the beam direction for the mass range 38.5 MEV to 42.9 MEV (bottom). Vertex Z = 0 corresponds to the target location; black points are from data and red points are from Monte Carlo..

kHz without incurring additional deadtime.

V. DATA TAKING AND PROCESSING

As has already been stated in this document, the DAQ worked very well, allowing for a full system event rate of 18 kHz and a transfer rate to disk of 200 MB/s at about 90% livetime. This data was then transferred to the tape silo during the day while the DAQ was not operating and stored on tape at a rate of 150 MB/s.

The CODA data acquisition software performed adequately for the experiment. Some improvements of the DAQ system, which will also be very important for CLAS12, have already been implemented for the next run. The DAQ computers have been moved to 64-bit Linux, with more CPU cores, more memory and better networking. This will allow for better performance and a higher transfer rate of data, without the data transfer interfering with the DAQ performance. As described in the last section, the SVT DAQ has been upgraded to support 45 kHz trigger rates, still maintaining about 90% livetime.

The setup in the counting house now has nine operational workstations for monitoring the experiment. We have detailed monitoring systems for the beamline, ECAL, the SVT and the trigger system, which are monitored continuously during the run. In addition to the individual monitoring of the HPS subsystems, we have a system in place to monitor the overall data quality. The collaboration has built up a considerable amount of data taking expertise, including shift taking expertise and individual system expertise. This, together with the expertise of the CEBAF operators, made it possible to recover fairly quickly from the daytime shutdowns and allowed us to take production quality data during our engineering run.

We have completed the third reconstruction pass through the data. Our data blinding policy dictates that we process only 10% of the data until the physics analyses are mature, at which point the full data set will be released. Performance studies and physics analyses have already shown that we have taken high quality data. We are now finalizing the calibrations, alignment, and reconstruction procedures and will run a final processing of the data shortly. Several physics analyses are now underway.

VI. REQUESTS FOR APPROVAL

In its 2015 Engineering Run, HPS proved that it is a working experiment ready to conduct a meaningful search for heavy photons. It took enough data to begin the search at low masses. The Hall B beamline delivered the needed small spots, low beam halo, and beam position stability at the $< 60\ \mu$m level, as needed for the experiment. This beam allowed the SVT to be positioned as per design just 500 μm from the beam and operate there efficiently and reliably. The ECal pre-run calibration with cosmic rays was more than adequate to determine the ECal's energy response, set the needed trigger thresholds, and record events with low noise and good positional and energy resolution. A sophisticated, high-rate trigger which exploited both energy and position information of clusters in the ECal performed perfectly; online diagnostics proved all the algorithms fully efficient; and tridents were recorded at the expected levels in the data. Data taking worked well, with high rates of data routinely transferred and stored.

Operationally, the Collaboration maintained the HPS subsystems, monitored performance of the detector and trigger, worked effectively with MCC to monitor beams, and took good data. Offline, reconstruction has proceeded efficiently, delivering a Pass1 for initial studies in less than a month after data taking. The analysis crew is hard at work generating final calibrations, alignments, and reconstruction improvements. Early analysis has already shown that a very large fraction ($\sim 85\%$) of all the beam data taken had the detector fully operational. HPS's sensitivity to heavy photons is directly proportional to the number of QED tridents observed and depends on the experiment's invariant mass resolution and vertex resolution. The observed rate for tridents with $\mathrm{E}_{e^+} + \mathrm{E}_{e^-} > 0.8 \times \mathrm{E}_{\mathrm{beam}}$, where the A$'$ signal is optimized, agrees with simulation to within about 30%. Improvements in alignment and calibration will likely improve the agreement. The invariant mass resolution is already very close to design and the trident vertex distribution already exhibits the low tails needed for a significant measurement. HPS physics performance, trigger efficiency, and reconstruction efficiency are as proposed or better, and the experiment is fully ready to search for heavy photons.

Accordingly, the HPS Experiment requests that its conditional status (C1) be removed, that it be granted full and unconditional approval and classified as an approved experiment, and that it be allotted the remainder of its PAC approved running time.

[1] HPS Proposal for 2014-2015 Run,
https://confluence.slac.stanford.edu/display/hpsg/HPS+Proposals.

[2] HPS Plans for 2014 and beyond, HPS-NOTE 2015-013 (2015).